# W Mass Highlights and other Precision Measurements

# CLHCP, QINGGAO 17 November 2024

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## Standard Model as a Gauge Theory derived from symmetry principles $\overline{SU(2)}_{I} \otimes \overline{U(1)}_{Y} \otimes SU(3)_{C}$ + vacuum expectation value $g_2(\sin\theta_W)$ $g_1(\alpha)$ $g_3(\alpha_s)$

## Mass of electroweak gauge bosons and interaction strength predicted precisely

#### All EW parameters/observables can be expressed by three accurately measured independent parameters:

 $M_{\rm Z} = (91.1876 \pm 0.0021) \,\,{\rm GeV}$ 

 $G_F = 1.1663787(6) \times 10^{-5} \text{ GeV}^{-2}$ 

 $\alpha^{-1} = 137.035999150(33)$ 

+ fermion masses and their mixings





## Motivation for precision electroweak physics

### **At higher orders**

## Test self-consistency of Standard Model

- Electroweak sector is over-constrained
- Identify tensions between direct & indirect measurements
- Deviations may be due to new physics





# **Top Mass Prediction from Precision Electroweak data**



**Top discovery at Tevatron** 

## $M_{top} = 175 -> 173 \text{ GeV}$

### World average: $m_{top} = 173.1 \pm 0.6 \text{ GeV}$ (0.35%)









July 21-27

### **Updated with EPS'01 results**



## **Overnight update**



## **Experimental data**

## **Tevatron (Fermilab)**



## SLC (SLAC)







## LEP (CERN)

## LHC (CERN)

















## **Overview of Standard Model measurements at LHC**

#### Standard Mod



#### **Publication list**

| tatus: Febru        | ary 2022              | FIGUL                    | 0055 5600                                        | on measurements                                                                                    | $\sqrt{s} = 5, 7, 8, 13 \text{ TeV}$                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|---------------------|-----------------------|--------------------------|--------------------------------------------------|----------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Model               | E <sub>CM</sub> [TeV] | ∫£ dt[fb <sup>-1</sup> ] | Measurement                                      | Theory                                                                                             | Reference                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| PP                  | 8                     | 50×10 <sup>-6</sup>      | σ = 96.07 ± 0.18 ± 0.91 mb                       | σ = 99.55 ± 2.14 mb (COMPETE HPRIR2)                                                               | PLB 761 (2015) 158                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| PP .                | 7                     | 8×10-5                   | or = \$5.35 = 0.38 = 1.3 mb                      | σ = 97.26 ± 2.12 mb (COMPETE HPR1R2)                                                               | Nucl. Phys. B. 486-548 (2014)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| w                   | 13                    | 0.061                    | σ = 190.1 ± 0.2 ± 6.4 nb                         |                                                                                                    | PLB 759 (2015) 601                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| w                   | 8                     | 20.2                     | $\sigma = 112.60 \pm 3.1$ mb                     | σ = 110.919889503 ± 3.7 rb (DYNNLD + CT14NNLO)                                                     | EPJC 79 (2019) 760                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| w                   | 7                     | 4.6                      | or = \$8.71 ± 0.028 ± 2.191 nb                   | cr = 95.9 ± 2.9 mb (DVNNLO + CT14NNLO)                                                             | EFUC 77 (2017) 387                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| z                   | 13                    | 3.2                      | $\sigma = 58.43 \pm 0.03 \pm 1.66 \text{ nb}$    | σ = 55.96 + 1.5 - 1.7 nb (DYNNLO+GT14 NNLO)                                                        | JHEP 02 (2017) 117                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| z                   | 8                     | 20.2                     | or = 34.24 ± 0.03 ± 0.02 nb                      |                                                                                                    | JHEP 02 (2017) 117                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| z                   | 7                     | 4.6                      | σ = 29.53 ± 0.03 ± 0.77 nb                       | σ = 20.31 + 0.60 - 0.0 nb (DVNNLO+GT14 NNLO)                                                       | JHEP 02 (2017) 117                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| ŧĔ                  | 13                    | 36.1                     | σ = 826.4 ± 3.6 ± 19.6 pb                        | σ = 832 + 40 - 45 pb (top++ NNLO+NNLL)                                                             | EPUC 80 (2020) 528                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| ŧĨ.                 | 0                     | 20.2                     | σ = 242.9 ± 1.7 ± 8.6 pb                         | cr = 252.9 + 13.3 - 14.5 pb (top++ NNLO+NNLL)                                                      | EFUC 74 (2014) 3109                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| ŧť                  | 7                     | 4.6                      | σ = 182.9 ± 3.1 ± 6.4 pb                         | σ = 177 + 10 - 11 pb (top++ NNLO+NNLL)                                                             | EPJC 74 (2014) 3109                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| t <sub>e-shan</sub> | 13                    | 3.2                      | σ - 247 ± 6 ± 46 pb                              | σ - 217 ± 10 pb (NLO+NLL)                                                                          | JHEP 04 (2017) 086                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| E <sub>1-chan</sub> | 8                     | 20.3                     | σ = 89.6 ± 1.7 + 7.2 − 6.4 pb                    | σ = 87.8 + 3.4 - 1.9 pb (NLO+NLL)                                                                  | EPUC 77 (2017) 531                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| E1-chan             | 7                     | 4.6                      | σ = 68 ± 2 ± 8 pb                                | σ = 64.6 + 2.7 - 2 pb (NLD+NLL)                                                                    | PRD 90, 112006 (2014)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Wt                  | 10                    | 3.2                      | or = 94 ± 10 + 28 − 23 pb                        | or = 71.7 ± 3.9 pb (NLO+NNUL)                                                                      | JHEP 01 (2018) 63                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| Wt                  | 8                     | 20.3                     | $\sigma = 23 \pm 1.3 \pm 3.4 \pm 3.7 \text{ pb}$ | $\sigma = 22.4 \pm 1.5 \text{pb} (\text{NLO+NLL})$                                                 | JHEP 01, 064 (2016)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| Wt                  | 7                     | 2.0                      | or = 16.8 ± 2.9 ± 3.9 pb                         | σ - 15.7 ± 1.1 pb (NLO+NLL)                                                                        | PLB 716, 142-159 (2012)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| н                   | 13                    | 139                      | or = 55.5 ± 3.2 + 2.4 - 2.2 pb                   | or = 55.6 ± 2.5 pb (LHC HKSWG YR4 )                                                                | ATLAS-CONF-2022-002                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| н                   |                       | 20.3                     | or = 27.7 ± 3 + 2.3 - 1.9 pb                     | σ = 24.5 + 1.3 - 1.8 pb (LHC-HXSWG YR4)                                                            | EPUC 76 (2016) 8                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| H                   | 7                     | 4.5                      | or = 22.1 + 6.7 - 5.3 + 3.3 - 2.7 pb             | σ = 19.2 + 1 - 1.4 pb (LHC-HKSWG YFH)                                                              | EFUC 76 (2016) 6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| PL VBF. Mul <       | 2.5 13                | 139                      | $\sigma = 4 \pm 0.3 \pm 0.3 - 0.4  \text{pb}$    | σ = 3.51 ± 0.07 pb (LHG-HXSWG)                                                                     | ATLAS-CONF-2021-053                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| H VBF               | 8                     | 20.3                     | ar = 2.43 + 0.5 - 0.49 + 0.33 - 0.25 pb          | ar = 1.6 ± 0.04 pb (DRD-HKSWG YH4)                                                                 | menor ve (soue) e                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| VH                  | 8                     | 20.3                     | or = 1.03 + 0.37 - 0.36 + 0.26 - 0.21 pb         | σ = 1.12 ± 0.03 p0 (NNLG(QCD)+NLO(EW))                                                             | JHEP 12 (2017) 024                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| WPL [34] < 2.5      | 19                    | 139                      | or = 1.56 + 0.2 - 0.21 + 0.15 - 0.18 pb          | σ = 1.203 ± 0.024 pb (Powneg Box NLO(GCD))                                                         | ArLAS-CONF-2021-053                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| 281.[78] < 2.5      | 13                    | 139                      | or = 0.7 ± 0.13 + 0.1 - 0.12 pb                  | or = 0.199 ± 0.03 po (Powneg Box NLO(QCD))                                                         | ATLAS CONF-2021-053                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| EEM                 | 13                    | 139                      | $\sigma = 560 \pm 80 + 70 - 80 \text{ fb}$       | or = 500 ± 50 m (LHCHCSWG NLO CCD + NLO EW)     Or = 100 ± 0 + 10 m (LHCHCSWG NLO CCD + NLO EW)    | ATLAS-CONF-2021-053                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| LIM                 | 8                     | 20.3                     | or = 220 ± 100 ± 70.15                           | 07 = 133 + 0 - 1310 (LHUHKSWG NEO GOD + NEO EW)                                                    | FLD 764 (2016) 173                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| ww                  | 13                    | 30.1                     | 0 = 100.04 ± 1.7 ± 10.0 p0                       | 0 = 120.4 + 3.2 - 2.9 pb (MNLO)                                                                    | EP-00 / 5 (2015) 554                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| www.                | 8                     | 20.3                     | 0 - 08.2 ± 1.2 ± 4.6 00                          | $\sigma = 65 \pm 1.2 \pm 1.1$ pp (NNLO)                                                            | PLB /63, 114 (2016)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| WW                  | /                     | 4.6                      |                                                  | 0 = 49.04 ± 1.00 - 9.00 (NNLO)                                                                     | First rest of the last sector the sector sec |
| W/2                 | 13                    | 38.1                     | r = 51 = 0.0 = 2.5 p0                            | $\sigma = 99.1 \pm 1.1 \pm 1$ po (weinfulk (NNLO))<br>$\sigma = 22.02 \pm 0.4$ sty (AATERY (NNLO)) | EPUL / 2 (2013) 332                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| WE.                 | 9                     | 201.0                    |                                                  | C = 10.24 ± 0.3 p0 (MATTA (MALD))<br>C = 10.24 ± 0.3 = 0.4 cb (MATTA (MALD))                       | EP ID 79 (5010) 9175                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| WZ.                 | 7                     | 4.0                      | 0 = 12 + 1.4 - 1.5 ± 190                         | 0 = 12.54 ± 0.5 - 0.4 pb (WAIRIA (WALD))                                                           | EPSO 12 (2012) 2113                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| 22                  | 13                    | 00.1                     | r - 73 - 64 - 64 - 63rb                          | c = 8 284 + 0.242 - 0.151 eb (NMLO) & Sheeps (NCO))                                                | 34EP 61 000 (2017)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| 77                  | 7                     | 4.6                      | a = 67+07+05-0400                                | a = 6 725 + 0 105 - 0 155 ob (NHLO)                                                                | LED 41, 000 (2011) DI D 795 (2014) 311                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|                     | ,                     | 20.0                     | r 48+08+16-13ch                                  | c = 5.51 + 0.22 eb (MI C-MBI)                                                                      | 1 D 700, 009, 040 (2014)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| a Day               | 19                    | 2013                     | x = \$20 + 130 + 140 fb                          | cr = 600 + 72 fb (Maderards + eMCNLO)                                                              | EU 100, 200 240 (2010)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| a Day               | 13                    | 30.1                     |                                                  | c = 222 + 22 B (MCSM)                                                                              | MED 11 172 (2015)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| 177                 | 12                    | 128                      | a = 990 + 50 + 70 th                             | cr = 840 = 90 fb (Madurach5 + cMCNLO)                                                              | For. Plan. J. C 81 (2021) 707                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| 112                 | 13                    | 20.3                     | $\sigma = 126 \pm 52 - 48 \pm 24.05$             | $\sigma = 215 \pm 30$ fb (HELACALO)                                                                | HEP 11, 172 (2015)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| MANNA I             | 19                    | 138                      | ar = 0.82 + 0.01 + 0.00 ph                       | rr = 0.511 + 0.018 pb (NLO OCD )                                                                   | a Yie 2001 12045                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| WW7                 | 13                    | 79.8                     | or = 0.55 ± 0.14 + 0.15 = 0.13 pb                | $\sigma = 0.351 \pm 0.036$ pb (5bergs 2.2.2)                                                       | PLB 798 (2019) 134913                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| 12.7                | 10                    | 100                      |                                                  | - 10 - 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 +                                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |

15 orders of magnitude

CMS has similar plots (<u>see</u>) and explored similar phase space

#### Standard Model Production Cross Section Measurements

Status: February 2022





## Drell-Yan process and measurement of SM parameters

The Drell-Yan process is a standard candle for precision measurements at the LHC



The p<sub>T</sub> of the W, Z bosons comes from from higher order corrections to the leading order Drell–Yan processes...

..... and from non-perturbative effects such as the primordial  $k_T$  of the incoming partons.









## **Z Mass Reconstruction**



# $m_{ll}^2 = (p_{l+} + p_{l-})^2 \approx 2p_{l+} \cdot p_{l-} \approx 2E_{l+}E_{l-}(1 - \cos\theta_{l+l-})$ $\frac{d\hat{\sigma}}{dm_{ll}^2} \approx \frac{\Gamma_Z M_Z}{(m_{ll}^2 - m_Z^2)^2 + \Gamma_Z^2 M_Z^2} \times \frac{d\hat{\sigma}}{d\cos^2_{\theta}}$

- Only depending on direct measurements of energy and/or momentum of particles plus
- the angle between them
- Map out  $m_z \& \Gamma_z$  in the Breit-Wigner resonance
- Errors determined by experimental resolutions.





#### Factorize the production dynamic and the decay kinematic properties of the dilepton system

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T dy dm} \left( 1 + \cos^2\theta + \sum_{i=0}^7 A_i(y, p_T, m) P_i(\cos\theta, \phi) \right).$$

 $A_i$  angular coefficients: dynamics Fiducial cuts removed by analytic integration of (cos  $\theta$ ,  $\phi$ ) in the full phase space of the decay leptons through the measured Ai coefficients

### Rapidity



## **Run-1 8 TeV data only**

## of the decay leptons

#### ATLAS-CONF-2023-013

lepton angular  $\cos \theta$  and  $\phi$ distributions in the Collins-Soper frame

- negligible theoretical uncertainties for all measurements
- **First comparison to N3LO QCD** predictions and N4LL resummation





### **Transverse Momentum**









## W boson mass measurement





# W mass reconstruction challenge $m_{l\nu}^{2} = (E_{l} + E_{\nu})^{2} - (\vec{p}_{e,T} + \vec{p}_{\nu,T})^{2} - (p_{e,z} + p_{\nu,z})^{2}$



 $m_{l\nu,T}^2 = (E_{l,T} + E_{\nu,T})^2 - (\vec{p}_{e,T} + \vec{p}_{\nu,T})^2$  $\approx 2\vec{p}_{l,T}\cdot\vec{p}_{\nu,T}\approx 2E_{l,T}E_T^{miss}(1-\cos\theta_{l\nu})$  $E_T = \sqrt{m^2 + p_T^2} \approx p_T$  $\vec{p}_T^{miss} = -\sum_{T} \vec{p}_T(observed)$ 

#### **Transverse mass**

UA1: 40 years ago  $M_{W} = 83 \pm 4 \text{ GeV}$ Γw < 6.5 GeV





## **CDFW Mass Measurement**

Shots to prevent cancer show early promise p. 126

M

0

Visualizing a key step in cytokine signaling pp. 139 & 163

Service of the servic

Silk-wrapped food wins BII & Science Prize p. 146

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#### HEAVYWEIGHT W boson mass measures higher than expected pp. 125, 136, & 170

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### High-precision measurement of the W boson mass with the CDF II detector

### 8 April 2022



Science Vol 376, Issue 6589, pp. 170–176 (2022)

## The CDF Experiment





# The Central Outer Tracker (COT) Detector essential to the W mass measurement precision

30,000 high-voltage of Gold-plated Tungsten wires in Argon-Ethane gas



Alignment with cosmic rays specifically updated for this W mass measurement Calibrate with Z,  $J/\psi$ ,  $\Upsilon(1S)$  (Blind Z mass:  $M_Z = 91192.0 \pm 6.4_{stat} \pm 4.0_{sys}$ (PDG: 91187 ± 2.1))





## W mass extraction

Binned maximum likelihood fits to the templates

of  $p_T^l$ ,  $m_T$ ,  $p_T^v$  with W mass [80, 81] GeV

| Distribution                       | W boson mass (MeV)                         |
|------------------------------------|--------------------------------------------|
| m <sub>T</sub> (e,ν)               | $80,429.1 \pm 10.3_{stat} \pm 8.5_{syst}$  |
| $p_{\mathrm{T}}^{\ell}(e)$         | $80,411.4 \pm 10.7_{stat} \pm 11.8_{syst}$ |
| p <sub>T</sub> <sup>v</sup> (e)    | $80,426.3 \pm 14.5_{stat} \pm 11.7_{syst}$ |
| $m_{T}(\mu, \nu)$                  | $80,446.1 \pm 9.2_{stat} \pm 7.3_{syst}$   |
| $p_{\mathrm{T}}^{\ell}(\mu)$       | $80,428.2 \pm 9.6_{stat} \pm 10.3_{syst}$  |
| $p_{\mathrm{T}}^{\mathrm{v}}(\mu)$ | $80,428.9 \pm 13.1_{stat} \pm 10.9_{syst}$ |
| Combination                        | $80,433.5 \pm 6.4_{stat} \pm 6.9_{syst}$   |

Consistency in two channels and three kinematic fits





# **Comparison with ATLAS measurement**

#### CDF ullet

- proton anti-proton collisions
- larger statistics uncertainty
- PDF: valence quark(~80%), less theoretical uncertainty

#### $\mathsf{ATLAS} \to \mathsf{LHC}$ $\bullet$

- W events statistics by more than one order of magnitude
- gluon and sea quark are important, less precise than valence quark PDF, more sensitive to proton PDF



# mw **4** `

### W mass uncertainty (MeV)

|        | CDF        | ATLAS (7 T |
|--------|------------|------------|
| Stat   | 6.4        | 6.8        |
| PDF    | <u>3.9</u> | <u>9.2</u> |
| Bkg    | 3.3        | 4.5        |
| EW     | 2.7        | 5.5        |
| е      | 33         | 6.4        |
| mu     | 0.0        | 6.6        |
| recoil | 2.5        | 2.9        |
| QCD    | 2.2        | 8.3        |
| Total  | 9          | 19         |
|        |            |            |

**First ATLAS** measurement

 $<\mu>=9.1$ 







## Updated W mass measurement from ATLAS

### Determine the W boson mass from the dependence of the leptonic transverse momentum $(p_T)$ and the transverse mass $(m_T)$



Revisited measurement from 2017, using the same data, but with more advanced physics model and profile likelihood fitting: Advantage: Reduce systematic uncertainties during the fit **Disadvantage:** Computational expensive, challenging to investigate systematics

#### arXiv:2403.15085



![](_page_17_Picture_6.jpeg)

![](_page_17_Picture_14.jpeg)

![](_page_17_Picture_15.jpeg)

# W mass: physics modeling and analysis improvements

### **Physics modeling**

- **Baseline: Pythia AZ tune (based on Z boson)** 
  - Z Boson Data, Parton Shower Variations
- **New Verifications:** •
  - AZ tune describes hadronic recoil spectrum of W's in low-pileup data at 5 TeV within experimental uncertainties
  - DYTurbo (resumed calculation) also agrees with AZ Tune.
- **Treatment of angular coefficients unchanged** •
- **Parton Distribution Functions:** 
  - Studied full set of available PDF Sets at NNLO: CT10, CT14, CT18, MMHT2014, MSHT20, NNPDF3.1, NNPDF4.0
    - New Baseline CT18

## **Analysis improvements**

- Multijet Background Estimation
  - Systematic shape variations using PCA
  - New transfer function from CR to SR
  - Reduction of uncertainty by 2 MeV
- **EWK uncertainty evaluated at detector level** •
  - increase uncertainty by 1-2 MeV •
- **Recovering data in the electron channel** •
  - Increased statistics by 1.5%
- Add W width as NP parameter •
- Improving random generator setup for the electron energy calibration

![](_page_18_Picture_22.jpeg)

![](_page_18_Picture_35.jpeg)

## W mass and width measurements from ATLAS

![](_page_19_Figure_1.jpeg)

## mw = 80366.5 ± 15.9 MeV (0.02% uncertainty) $\Gamma_{\rm W} = 2202 \pm 47 \,\,{\rm MeV}$

Most precise single-experiment measurement of  $\Gamma_W$ 

Previous measurement from 2017:  $m = 80370 \pm 19$  MeV

#### Overview of $\Gamma_w$ measurements ATLAS DELPHI Eur. Phys. J. C 47 (2006) 309 Γ<sub>w</sub> = 2404 ± 173 MeV $\sqrt{s} = 7 \text{ TeV}, 4.6 \text{ fb}^{-1}$ OPAL Eur. Phys. J. C 47 (2006) 309 Γ<sub>w</sub> = 1996 ± 140 MeV L3 Eur. Phys. J. C 47 (2006) 309 $\Gamma_{w} = 2180 \pm 142 \text{ MeV}$ ALEPH Eur. Phys. J. C 47 (2006) 309 $\Gamma_{w} = 2140 \pm 108 \text{ MeV}$ Combination Phys. Rep. 532 (2013) 119 Tw = 2195 ± 83 MeV Phys. Rev. Lett. 103 (2009) 231802 $\Gamma_w = 2028 \pm 72 \text{ MeV}$ Measurement CDF Stat. Unc. Phys. Rev. Lett. 100 (2008) 07180 $\Gamma_{w} = 2032 \pm 72 \text{ MeV}$ Total Unc. SM Prediction ATLAS This work Γ<sub>w</sub> = 2202 ± 47 MeV 2500 1500 2000 $\Gamma_{W}$ [MeV]

| Unc. [MeV ]             | Total | Stat. | Syst. | PDF | $A_i$ | Backg. | EW | е  | μ  | $u_{\mathrm{T}}$ | Lumi | $m_W$ | PS |
|-------------------------|-------|-------|-------|-----|-------|--------|----|----|----|------------------|------|-------|----|
| $p_{\mathrm{T}}^{\ell}$ | 72    | 27    | 66    | 21  | 14    | 10     | 5  | 13 | 12 | 12               | 10   | 6     | 55 |
| m <sub>T</sub>          | 48    | 36    | 32    | 5   | 7     | 10     | 3  | 13 | 9  | 18               | 9    | 6     | 12 |
| Combined                | 47    | 32    | 34    | 7   | 8     | 9      | 3  | 13 | 9  | 17               | 9    | 6     | 18 |

![](_page_19_Figure_8.jpeg)

![](_page_19_Picture_9.jpeg)

## W mass measurements at LHCb

## W mass determination in the forward acceptance

![](_page_20_Picture_3.jpeg)

JHEP 01 (2022) 036

## Only a 2016 dataset analysis, with a full Run 2 analysis still possibly coming $m_W = 80364 \pm 32 \text{ MeV}$

![](_page_20_Picture_7.jpeg)

![](_page_20_Picture_8.jpeg)

# Combination of W mass measurements: ATLAS, LHCb, CDF, DØ

## Measurements performed at different times, using different baseline PDFs and QCD tools

### existing results extrapolated to a common baseline

![](_page_21_Figure_3.jpeg)

mw<sup>combined</sup> ... and repeat, for different PDFs M. Boonekamp, LHC EW WG General Meeting, July 2024

### Tension between combination and CDF W mass is of 3.6 $\sigma$

EPJ C (2024) 84:451

PDF uncertainty correlation matrices for the CT18 PDF set

ATLAS, LHCb, DØ Combination :  $m_W = 80369.2 \pm 13.3$  MeV

![](_page_21_Figure_10.jpeg)

## First W mass measurement at CMS

#### Nominal theory-dependent fit

 $M_W = 80360.2 \pm 9.9 \text{ MeV}$ 

Helicity cross section fit reduced theory uncertainty at the cost of larger statistical unc.

![](_page_22_Figure_4.jpeg)

![](_page_22_Figure_5.jpeg)

![](_page_22_Figure_6.jpeg)

#### **CMS-PAS-SMP-23-002** J. Bendavid, CMS CERN seminar

![](_page_22_Figure_9.jpeg)

 $\mathbf{V}$ s forces us to use indirect observables to infer constraints on the mass  $\Rightarrow$  many systematic uncertainties to control

![](_page_22_Picture_11.jpeg)

![](_page_22_Picture_12.jpeg)

# First W mass measurement at CMS

- Measured with uncertainty of 9.9 MeV
  - Precision comparable to CDF, but consistent with SM
- Uses a well-understood portion of 13 TeV data
  - 16.8 fb<sup>-1</sup> from 2016 run (~ 30 pileup)
  - Large sample (>100M) of  $W \rightarrow \mu v$
- Theoretical modelling
  - Use most accurate model & uncertainties available
  - Rely on in-situ constraints from the W data itself
- Muon calibration: from  $J/\psi$ , validated with the Z
- Fit to granular distribution of p<sub>T</sub><sup>μ</sup> x η<sup>μ</sup> x charge

![](_page_23_Figure_11.jpeg)

#### <u>CMS-PAS-SMP-23-002</u> J. Bendavid, CMS CERN seminar

![](_page_23_Figure_13.jpeg)

![](_page_23_Picture_14.jpeg)

![](_page_23_Figure_15.jpeg)

![](_page_23_Picture_16.jpeg)

# First W mass measurement at CMS

![](_page_24_Figure_1.jpeg)

Measurement is performed with ~10% of Run 2 data

 $m_W = 80360.2 \pm 9.9 \text{ MeV}$ 

### W mass uncertainty (MeV)

| EP <mark>fit</mark>   |        | ATLAS, 7 TeV re-analysis | CMS        |
|-----------------------|--------|--------------------------|------------|
| ,                     | Stat   | 9.8                      | 7.1        |
|                       | PDF    | 5.7                      | <u>2.8</u> |
|                       | Bkg    | 2.0                      | 1.7        |
|                       | EW     | 5.4                      | 1.9        |
|                       | e      | 6.0                      | _          |
|                       | mu     | 5.4                      | 5.0        |
| $\Delta \mathbf{r}$ ) | recoil | 2.3                      | _          |
| <br>80.45             | QCD    | 4.4                      | <u>3.1</u> |
| eV)                   | Total  | 16 MeV                   | 9.9 Me     |

Exploit state-of-the-art improvements in theoretical QCD & EW calculations & uncertainty modeling, in-situ constraints from data...

![](_page_24_Picture_7.jpeg)

W boson measurements in low-pileup dataset from ATLAS

![](_page_25_Picture_2.jpeg)

## Precise measurements of W and Z transverse momentum spectra at 5 and 13 TeV **ATLAS-CONF-2023-028**

![](_page_26_Figure_1.jpeg)

Pile-up events add energy to the recoil and hinder the experimental extraction of W pT

Take dataset with very low multiple hard interactions per bunch crossing ATLAS collected such dataset at  $\sqrt{s} = 5$  and 13 TeV

![](_page_26_Picture_4.jpeg)

![](_page_26_Picture_5.jpeg)

![](_page_26_Picture_6.jpeg)

## Precise measurements of W and Z transverse momentum spectra at 5 and 13 TeV

# Precise measurements and predictions of the spectra for $p_T < \sim 30$ GeV are particularly interesting for future measurement of the W-boson mass at LHC

Compared to DYTURBO predictions with different PDF sets

![](_page_27_Figure_3.jpeg)

**DYTURBO** resummed predictions show the best agreement and generally match the data at the percent level

Eur. Phys. J. C 84 (2024) 1126

### $\sqrt{s} = 5 \text{ TeV}$

#### **Compared with different MC predictions**

![](_page_27_Figure_8.jpeg)

![](_page_27_Picture_9.jpeg)

## Precise measurements of W and Z transverse momentum spectra at 5 and 13 TeV

# Precise measurements and predictions of the spectra for $p_T < \sim 30$ GeV are particularly interesting for future measurement of the W-boson mass at LHC

Compared to DYTURBO predictions with different PDF sets

![](_page_28_Figure_3.jpeg)

DYTURBO resummed predictions show the best agreement and generally match the data at the percent level

Eur. Phys. J. C 84 (2024) 1126

### $\sqrt{s} = 13 \text{ TeV}$

#### **Compared with different MC predictions**

![](_page_28_Figure_8.jpeg)

![](_page_28_Picture_9.jpeg)

## **Expectations for W mass measurement with low-pileup dataset**

- Measurement will use both  $p_T$  and  $m_T$  information •
- Profile likelihood
- Less sensitive to pile-up effects
  - Better lepton reconstruction
  - Smaller uncertainties for W recoil  $\rightarrow$  better m<sub>T</sub> measurement
- Improved theoretical uncertainties:
  - Updated PDF distribution
  - Updated QCD modeling
  - Updated Electroweak modeling
- Limited by statistical uncertainty
  - 5 TeV: 255 pb<sup>-1</sup>
  - 13 TeV: 338 pb<sup>-1</sup>

![](_page_29_Figure_15.jpeg)

Uncertainty low-pileup analysis: ~ 15 MeV Combination with 7 TeV: ~ 10 MeV

![](_page_29_Picture_17.jpeg)

![](_page_29_Picture_19.jpeg)

![](_page_29_Picture_20.jpeg)

# Anomalous magnetic moment g-2 of the tau lepton

### Sensitive to new physics in the $\gamma \tau \tau$ vertex

![](_page_30_Figure_2.jpeg)

![](_page_30_Picture_3.jpeg)

## Tau (g-2) in the Standard Model

![](_page_30_Figure_7.jpeg)

![](_page_30_Picture_8.jpeg)

![](_page_30_Picture_11.jpeg)

g-2 of tau lepton:  $\gamma\gamma \rightarrow \tau\tau$ 

# **5.3** $\sigma$ observed

![](_page_31_Figure_2.jpeg)

#### **Detailed overview by Dayong Wang, Friday Plenary**

![](_page_31_Picture_5.jpeg)

# Top quark mass

![](_page_32_Picture_2.jpeg)

## Top quark mass measurements

Measured in different channels with different techniques

![](_page_33_Picture_2.jpeg)

Best single measurement is from CMS, lepton+jets profile likelihood new result with 13 TeV data

#### $m_{top} = 171.77 \pm 0.37 \text{ GeV}$

#### Uncertainty reached ~ 0.2%

40% improvement relative to previous measurement

<u>CMS-TOP-20-008</u>

#### **ATL-PHYS-PUB-2023-015**

| ATLAS+CMS Preliminary                  | m <sub>top</sub> summary, √s = 7-13 TeV                                                                                                                                   | June 20                                        |
|----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------|
| World comb. (Mar 2014) [2] stat        | total stat                                                                                                                                                                |                                                |
| total uncertainty                      | $m_{top} \pm total (stat \pm syst \pm recoil)$                                                                                                                            | s                                              |
| LHC comb. (Sep 2013) LHCtopWG          | 173.29 ± 0.95 (0.35 ± 0.88)                                                                                                                                               | 7 TeV                                          |
| World comb. (Mar 2014)                 | 173.34 $\pm$ 0.76 (0.36 $\pm$ 0.67)                                                                                                                                       | 1.96-7                                         |
| ATLAS, I+jets                          | 172.33 $\pm$ 1.27 (0.75 $\pm$ 1.02)                                                                                                                                       | 7 TeV                                          |
| ATLAS, dilepton                        | 173.79 ± 1.41 (0.54 ± 1.30)                                                                                                                                               | 7 TeV                                          |
| ATLAS, all jets                        | 175.1±1.8 (1.4±1.2)                                                                                                                                                       | 7 TeV                                          |
| ATLAS, single top                      | 172.2 ± 2.1 (0.7 ± 2.0)                                                                                                                                                   | 8 TeV                                          |
| ATLAS, dilepton                        | $172.99 \pm 0.85 \; (0.41 \pm 0.74)$                                                                                                                                      | 8 TeV                                          |
| ATLAS, all jets                        | 173.72 ± 1.15 (0.55 ± 1.01)                                                                                                                                               | 8 TeV                                          |
| ATLAS, I+jets                          | 172.08 $\pm$ 0.91 (0.39 $\pm$ 0.82)                                                                                                                                       | 8 TeV                                          |
| ATLAS comb. (Oct 2018) H <del>▼H</del> | 172.69 $\pm$ 0.48 (0.25 $\pm$ 0.41)                                                                                                                                       | 7+8 Te                                         |
| ATLAS, leptonic invariant mass         | 174.41 ± 0.81 (0.39 ± 0.66 ± 0.25)                                                                                                                                        | 13 TeV                                         |
| ATLAS, dilepton (*)                    | $172.21 \pm 0.80  (0.20 \pm 0.67 \pm 0.39)$                                                                                                                               | 13 TeV                                         |
| CMS, I+jets                            | 173.49 ± 1.06 (0.43 ± 0.97)                                                                                                                                               | 7 TeV                                          |
| CMS, dilepton                          | 172.50 $\pm$ 1.52 (0.43 $\pm$ 1.46)                                                                                                                                       | 7 TeV                                          |
| CMS, all jets                          | 173.49 ± 1.41 (0.69 ± 1.23)                                                                                                                                               | 7 TeV                                          |
| CMS, I+jets                            | 172.35 $\pm$ 0.51 (0.16 $\pm$ 0.48)                                                                                                                                       | 8 TeV                                          |
| CMS, dilepton                          | 172.82 $\pm$ 1.23 (0.19 $\pm$ 1.22)                                                                                                                                       | 8 TeV                                          |
| CMS, all jets                          | $172.32 \pm 0.64 \; (0.25 \pm 0.59)$                                                                                                                                      | 8 TeV                                          |
| CMS, single top                        | $172.95 \pm 1.22 \ (0.77 \pm 0.95)$                                                                                                                                       | 8 TeV                                          |
| CMS comb. (Sep 2015)                   | 172.44 $\pm$ 0.48 (0.13 $\pm$ 0.47)                                                                                                                                       | 7+8 Te                                         |
| CMS, I+jets                            | $172.25 \pm 0.63 \; (0.08 \pm 0.62)$                                                                                                                                      | 13 TeV                                         |
| CMS, dilepton                          | $172.33 \pm 0.70 \; (0.14 \pm 0.69)$                                                                                                                                      | 13 TeV                                         |
| CMS, all jets                          | 172.34 $\pm$ 0.73 (0.20 $\pm$ 0.70)                                                                                                                                       | 13 TeV                                         |
| CMS, single top                        | $172.13 \pm 0.77 \; (0.32 \pm 0.70)$                                                                                                                                      | 13 TeV                                         |
| CMS, I+jets                            | 171.77 ± 0.37                                                                                                                                                             | 13 TeV                                         |
| CMS, boosted                           | 172.76 $\pm$ 0.81 (0.22 $\pm$ 0.78)                                                                                                                                       | 13 TeV                                         |
| * Proliminary                          | [1] ATLAS-CONF-2013-102       [8] EPJC 79 (2019) 290         [2] arXiv:1403.4427       [9] arXiv:2209.00583         [3] EPJC 75 (2015) 320       [10] ATLAS CONF 2022.058 | [15] EPJC 77<br>[16] EPJC 78                   |
| Freiminary                             | [4] EPJC 75 (2015) 158 [11] JHEP 12 (2012) 105<br>[5] ATLAS-CONF-2014-055 [12] EPJC 72 (2012) 2202                                                                        | [17] EPJC 79<br>[18] EPJC 79<br>[19] arXiv:21( |
|                                        | [6] PLB 761 (2016) 350[13] EPJC 74 (2014) 2758[7] JHEP 09 (2017) 118[14] PRD 93 (2016) 072004                                                                             | [20] arxiv:230<br>[21] arxiv:221               |
|                                        |                                                                                                                                                                           |                                                |
| 165 170                                | 175 180                                                                                                                                                                   | 185                                            |
| m                                      | <sub>top</sub> [GeV]                                                                                                                                                      |                                                |

![](_page_33_Picture_10.jpeg)

![](_page_33_Figure_11.jpeg)

![](_page_33_Figure_12.jpeg)

![](_page_33_Picture_13.jpeg)

## **Top quark mass: Run 1 combination**

A combination of fifteen top-quark mass measurements performed by the ATLAS and CMS experiments at the LHC

## $m_{top} = 172.52 \pm 0.33 \text{ GeV}$

#### Precision < 0.2%

31% improvement over most precise single improvement

![](_page_34_Figure_6.jpeg)

![](_page_34_Picture_7.jpeg)

![](_page_34_Picture_8.jpeg)

![](_page_34_Picture_9.jpeg)

## **Closing remarks**

## The LHC has produced exceptionally precise results

## Still the Standard Model as we know it stands strong

Looking forward to the HL-LHC data and Future electron colliders such as the CEPC or FCC-ee

![](_page_35_Picture_5.jpeg)

## **Extra Slides**

![](_page_36_Picture_2.jpeg)

# Compare with previous CDFII measurements

### Uncertainty

Previous CDF results (2.2  $fb^{-1}$ )

| Source                   | Uncertainty (MeV) | Source                            | Uncertainty (MeV)      |
|--------------------------|-------------------|-----------------------------------|------------------------|
| Lepton Energy Scale      | 7                 | Lepton energy scale               | 3.0 Higher order OF    |
| Lepton Energy Resolution | 2                 | Lepton energy resolution          | 1.2 Tigher Order QL    |
| Recoil Energy Scale      | 4                 | Recoil energy scale               | 1.2 Deceil model       |
| Recoil Energy Resolution | 4                 | Recoil energy resolution          | 1.8 Recon model        |
| $u_{\rm III}$ efficiency | 0                 | Lepton efficiency                 | 0.4                    |
| Lepton Removal           | 2                 | Lepton removal                    | 1.2 Close              |
| Backgrounds              | 3                 | Backgrounds                       | 3.3 Close              |
| $p_T(W)$ model           | 5                 | p <sup>Z</sup> <sub>T</sub> model | 1.8 Now constrains a   |
| Parton Distributions     | 10 CTEQ6.6 NLC    | $p_T^W/p_T^Z$ model               | 1.3 1.3 1.3            |
| QED radiation            | 4                 | Parton distributions              | 3.9 NNPDF3.1 NNLO, mor |
| W boson statistics       | 12                | QED radiation                     | 2.7                    |
| Total                    | 19                | W boson statistics                | 6.4 More statistics    |
| ntralvalue               |                   | Total                             | 9.4                    |

#### **Central value**

Detailed treatment of parton distribution functions

Resolved beam-constraining bias in CDF reconstruction +10 MeV

New PDF and beam-constraining in upsilon events caused the shifts of central value.

| New CDF results (8.8 $fb^{-1}$ | Im<br>-1 <sub>)</sub> ar | nproved COT align<br>nd drift model |
|--------------------------------|--------------------------|-------------------------------------|
| urce Unce                      | rtainty                  | (MeV)                               |
| oton energy scale              | 3.0                      | Highor order OF                     |
| oton energy resolution         | 1.2                      | Tignel oldel QL                     |
| coil energy scale              | 1.2                      | Docoil modol                        |
| coil energy resolution         | 1.8                      | Recon model                         |
| oton efficiency                | 0.4                      |                                     |
| oton removal                   | 1.2                      | Close                               |
| ckgrounds                      | 3.3                      | Close                               |
|                                |                          |                                     |

| S | $+3.5 { m MeV}$ |
|---|-----------------|
|   |                 |

![](_page_37_Figure_10.jpeg)

![](_page_37_Figure_11.jpeg)

dded e inputs

# **Overview of Standard Model measurements in ATLAS**

#### **Standard Model Production Cross Section Measurements**

Status: February 2022

| Model                       | E <sub>CM</sub> [TeV] | ∫£ dt[fb <sup>-1</sup> | ] Measurement                                          | Theory                                                        | Reference                                      |
|-----------------------------|-----------------------|------------------------|--------------------------------------------------------|---------------------------------------------------------------|------------------------------------------------|
| рр                          | 8                     | 50×10 <sup>-8</sup>    | $\sigma = 96.07 \pm 0.18 \pm 0.91 \text{ mb}$          | $\sigma=$ 99.55 ± 2.14 mb (COMPETE HPR1R2)                    | PLB 761 (2016) 158                             |
| рр                          | 7                     | 8×10 <sup>-8</sup>     | $\sigma =$ 95.35 $\pm$ 0.38 $\pm$ 1.3 mb               | $\sigma =$ 97.26 $\pm$ 2.12 mb (COMPETE HPR1R2)               | Nucl. Phys. B, 486-548 (2014)                  |
| W                           | 13                    | 0.081                  | $\sigma = 190.1 \pm 0.2 \pm 6.4$ nb                    | $\sigma = 184.9 + 6 - 6.1$ nb (DYNNLO + CT14NNLO)             | PLB 759 (2016) 601                             |
| W                           | 8                     | 20.2                   | $\sigma = 112.69 \pm 3.1 \; \mathrm{nb}$               | $\sigma =$ 110.919889503 $\pm$ 3.7 nb (DYNNLO + CT14NNLO)     | EPJC 79 (2019) 760                             |
| W                           | 7                     | 4.6                    | $\sigma = 98.71 \pm 0.028 \pm 2.191 \ { m nb}$         | $\sigma =$ 95.9 $\pm$ 2.9 nb (DYNNLO + CT14NNLO)              | EPJC 77 (2017) 367                             |
| Z                           | 13                    | 3.2                    | $\sigma = 58.43 \pm 0.03 \pm 1.66$ nb                  | $\sigma = 55.96 + 1.5 - 1.7$ nb (DYNNLO+CT14 NNLO)            | JHEP 02 (2017) 117                             |
| Z                           | 8                     | 20.2                   | $\sigma =$ 34.24 ± 0.03 ± 0.92 nb                      | $\sigma=$ 32.94 $+$ 0.8 $-$ 0.92 nb (DYNNLO+CT14 NNLO)        | JHEP 02 (2017) 117                             |
| Z                           | 7                     | 4.6                    | $\sigma = 29.53 \pm 0.03 \pm 0.77$ nb                  | $\sigma =$ 28.31 + 0.68 – 0.8 nb (DYNNLO+CT14 NNLO)           | JHEP 02 (2017) 117                             |
| tī                          | 13                    | 36.1                   | $\sigma=$ 826.4 $\pm$ 3.6 $\pm$ 19.6 pb                | $\sigma=$ 832 $+$ 40 $-$ 45 pb (top++ NNLO+NNLL)              | EPJC 80 (2020) 528                             |
| tī                          | 8                     | 20.2                   | $\sigma = 242.9 \pm 1.7 \pm 8.6~\mathrm{pb}$           | $\sigma=$ 252.9 $+$ 13.3 $-$ 14.5 pb (top++ NNLO+NNLL)        | EPJC 74 (2014) 3109                            |
| tī                          | 7                     | 4.6                    | $\sigma = 182.9 \pm 3.1 \pm 6.4 \ \mathrm{pb}$         | $\sigma =$ 177 + 10 – 11 pb (top++ NNLO+NNLL)                 | EPJC 74 (2014) 3109                            |
| t <sub>t-chan</sub>         | 13                    | 3.2                    | $\sigma = 247 \pm 6 \pm 46 \text{ pb}$                 | $\sigma =$ 217 $\pm$ 10 pb (NLO+NLL)                          | JHEP 04 (2017) 086                             |
| t <sub>t-chan</sub>         | 8                     | 20.3                   | $\sigma = 89.6 \pm 1.7 + 7.2 - 6.4 \ { m pb}$          | $\sigma=$ 87.8 $+$ 3.4 $-$ 1.9 pb (NLO+NLL)                   | EPJC 77 (2017) 531                             |
| t <sub>t-chan</sub>         | 7                     | 4.6                    | $\sigma = 68 \pm 2 \pm 8 \text{ pb}$                   | $\sigma=$ 64.6 + 2.7 – 2 pb (NLO+NLL)                         | PRD 90, 112006 (2014)                          |
| Wt                          | 13                    | 3.2                    | $\sigma=$ 94 $\pm$ 10 $+$ 28 $-$ 23 pb                 | $\sigma = 71.7 \pm 3.9 \text{ pb} (\text{NLO+NNLL})$          | JHEP 01 (2018) 63                              |
| Wt                          | 8                     | 20.3                   | $\sigma = 23 \pm 1.3 + 3.4 - 3.7 \text{ pb}$           | $\sigma = 22.4 \pm 1.5$ pb (NLO+NLL)                          | JHEP 01, 064 (2016)                            |
| Wt                          | 7                     | 2.0                    | $\sigma = 16.8 \pm 2.9 \pm 3.9 \ { m pb}$              | $\sigma = 15.7 \pm 1.1$ pb (NLO+NLL)                          | PLB 716, 142-159 (2012)                        |
| Н                           | 13                    | 139                    | $\sigma = 55.5 \pm 3.2 + 2.4 - 2.2 \text{ pb}$         | $\sigma = 55.6 \pm 2.5$ pb (LHC-HXSWG YR4 )                   | ATLAS-CONF-2022-002                            |
| н                           | 8                     | 20.3                   | $\sigma = 27.7 \pm 3 + 2.3 - 1.9 \text{ pb}$           | $\sigma = 24.5 + 1.3 - 1.8$ pb (LHC-HXSWG YR4)                | EPJC 76 (2016) 6                               |
| н                           | 7                     | 4.5                    | $\sigma = 22.1 + 6.7 - 5.3 + 3.3 - 2.7 \text{ pb}$     | $\sigma = 19.2 + 1 - 1.4$ pb (LHC-HXSWG YR4)                  | EPJC 76 (2016) 6                               |
| H VBF, $ y_{H}  < 2.5$      | 13                    | 139                    | $\sigma = 4 \pm 0.3 + 0.3 - 0.4 \ { m pb}$             | $\sigma = 3.51 \pm 0.07$ pb (LHC-HXSWG)                       | ATLAS-CONF-2021-053                            |
| H VBF                       | 8                     | 20.3                   | $\sigma = 2.43 + 0.5 - 0.49 + 0.33 - 0.26 \text{ pb}$  | $\sigma = 1.6 \pm 0.04$ pb (LHC-HXSWG YR4)                    | EPJC 76 (2016) 6                               |
| VH                          | 8                     | 20.3                   | $\sigma = 1.03 + 0.37 - 0.36 + 0.26 - 0.21 \text{ pb}$ | $\sigma = 1.12 \pm 0.03$ pb (NNLO(QCD)+NLO(EW))               | JHEP 12 (2017) 024                             |
| WH,  y <sub>H</sub>   < 2.5 | 13                    | 139                    | $\sigma = 1.56 + 0.2 - 0.21 + 0.16 - 0.18 \ { m pb}$   | $\sigma = 1.203 \pm 0.024$ pb (Powheg Box NLO(QCD))           | ATLAS-CONF-2021-053                            |
| ZH,  y <sub>H</sub>   < 2.5 | 13                    | 139                    | $\sigma = 0.7 \pm 0.13 + 0.1 - 0.12 \ { m pb}$         | $\sigma = 0.795 \pm 0.03$ pb (Powheg Box NLO(QCD))            | ATLAS-CONF-2021-053                            |
| tĪH                         | 13                    | 139                    | $\sigma = 560 \pm 80 + 70 - 80$ fb                     | $\sigma = 580 \pm 50$ fb (LHCHXSWG NLO QCD + NLO EW)          | ATLAS-CONF-2021-053                            |
| tīH                         | 8                     | 20.3                   | $\sigma = 220 \pm 100 \pm 70$ fb                       | $\sigma = 133 + 8 - 13$ fb (LHCHXSWG NLO QCD + NLO EW)        | PLB 784 (2018) 173                             |
| WW                          | 13                    | 36.1                   | $\sigma = 130.04 \pm 1.7 \pm 10.6 \ { m pb}$           | $\sigma = 128.4 + 3.2 - 2.9$ pb (NNLO)                        | EPJC 79 (2019) 884                             |
| WW                          | 8                     | 20.3                   | $\sigma=$ 68.2 ± 1.2 ± 4.6 pb                          | $\sigma=65+1.2-1.1$ pb (NNLO)                                 | PLB 763, 114 (2016)                            |
| WW                          | 7                     | 4.6                    | $\sigma = 51.9 \pm 2 \pm 4.4 \text{ pb}$               | $\sigma=$ 49.04 $+$ 1.03 $-$ 0.88 pb (NNLO)                   | Phys. Rev. D 87 (2013) 112001, arXiv:1408.5243 |
| WZ                          | 13                    | 36.1                   | $\sigma = 51 \pm 0.8 \pm 2.3 \text{ pb}$               | $\sigma = 49.1 + 1.1 - 1 \text{ pb} (\text{MATRIX (NNLO)})$   | EPJC 79 (2019) 535                             |
| WZ                          | 8                     | 20.3                   | $\sigma = 24.3 \pm 0.6 \pm 0.9$ pb                     | $\sigma = 23.92 \pm 0.4$ pb (MATRIX (NNLO))                   | PRD 93, 092004 (2016)                          |
| WZ                          | 7                     | 4.6                    | $\sigma = 19 + 1.4 - 1.3 \pm 1 \text{ pb}$             | $\sigma = 19.34 + 0.3 - 0.4$ pb (MATRIX (NNLO))               | EPJC 72 (2012) 2173                            |
| ZZ                          | 13                    | 36.1                   | $\sigma = 17.3 \pm 0.6 \pm 0.8 \ \mathrm{pb}$          | $\sigma = 16.9 + 0.6 - 0.5$ pb (Matrix (NNLO) & Sherpa (NLO)) | PRD 97 (2018) 032005                           |
| ZZ                          | 8                     | 20.3                   | $\sigma = 7.3 \pm 0.4 + 0.4 - 0.3 \ { m pb}$           | $\sigma = 8.284 + 0.249 - 0.191$ pb (NNLO)                    | JHEP 01, 099 (2017)                            |
| ZZ                          | 7                     | 4.6                    | $\sigma = 6.7 \pm 0.7 + 0.5 - 0.4 \ { m pb}$           | $\sigma = 6.735 + 0.195 - 0.155$ pb (NNLO)                    | JHEP 03, 128 (2013), PLB 735 (2014) 311        |
| t <sub>s-chan</sub>         | 8                     | 20.3                   | $\sigma = 4.8 \pm 0.8 \pm 1.6 - 1.3  { m pb}$          | $\sigma = 5.61 \pm 0.22$ pb (NLO+NNL)                         | LB 756, 228-246 (2016)                         |
| tĪW                         | 13                    | 36.1                   | $\sigma=$ 870 ± 130 ± 140 fb                           | $\sigma = 600 \pm 72$ fb (Madgraph5 + aMCNLO)                 | PRD 99, 072009 (2019)                          |
| tīW                         | 8                     | 20.3                   | $\sigma=$ 369 $+$ 86 $-$ 79 $\pm$ 44 fb                | $\sigma = 232 \pm 32$ fb (MCFM)                               | JHEP 11, 172 (2015)                            |
| tīZ                         | 13                    | 139                    | $\sigma = 990 \pm 50 \pm 80$ fb                        | $\sigma = 840 \pm 90$ fb (Madgraph5 + aMCNLO)                 | Eur. Phys. J. C 81 (2021) 737                  |
| tīZ                         | 8                     | 20.3                   | $\sigma=176+52-48\pm24$ fb                             | $\sigma = 215 \pm 30$ fb (HELAC-NLO)                          | JHEP 11, 172 (2015)                            |
| WWW                         | 13                    | 139                    | $\sigma = 0.82 \pm 0.01 \pm 0.08$ pb                   | $\sigma = 0.511 \pm 0.018$ pb (NLO QCD )                      | arXiv:2201.13045                               |
| WWZ                         | 13                    | 79.8                   | $\sigma = 0.55 \pm 0.14 + 0.15 - 0.13$ pb              | $\sigma = 0.358 \pm 0.036$ pb (Sherpa 2.2.2)                  | PLB 798 (2019) 134913                          |
| tītī                        | 13                    | 139                    | $\sigma = 24 \pm 4 \pm 5$ fb                           | $\sigma = 12 \pm 2.4$ fb (NLO QCD + EW)                       | JHEP 11 (2021) 118                             |

2022-009 b.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB https://atlas.we ATLAS Preliminary

 $\sqrt{s} = 5, 7, 8, 13 \text{ TeV}$ 

![](_page_38_Picture_7.jpeg)

# **Overview of CMS cross section results**

ern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined https://twiki.o

|       | 14/                       | 7 7-14                              | UED 10 (2011) 122                                                                                   |
|-------|---------------------------|-------------------------------------|-----------------------------------------------------------------------------------------------------|
| eak   | W<br>W                    | 7 TeV<br>8 TeV                      | JHEP 10 (2011) 132<br>PRL 112 (2014) 191802                                                         |
| rowe  | W                         | 13 TeV                              | SMP-15-004                                                                                          |
| lect  | ∠<br>Z                    | 7 iev<br>8 TeV                      | JHEP 10 (2011) 132<br>PRL 112 (2014) 191802                                                         |
| ш     | Z                         | 13 TeV                              | SMP-15-011                                                                                          |
|       | Wγ                        | 7 TeV                               | PRD 89 (2014) 092005                                                                                |
|       | Wγ<br>Zv                  | 13 TeV<br>7 TeV                     | PRL 126 252002 (2021)<br>PRD 89 (2014) 092005                                                       |
|       | Zγ                        | 8 TeV                               | JHEP 04 (2015) 164                                                                                  |
| c     | WW                        | 7 TeV                               | EPJC 73 (2013) 2610                                                                                 |
| oso   | WW                        | o iev<br>13 TeV                     | EPJC 76 (2016) 401<br>PRD 102 092001 (2020)                                                         |
| di-E  | WZ                        | 7 TeV                               | EPJC 77 (2017) 236                                                                                  |
|       | w∠<br>WZ                  | 8 IeV<br>13 TeV                     | ЕРЈС 77 (2017) 236<br>ЈНЕР 07 (2022) 032                                                            |
|       | ZZ                        | 7 TeV                               | JHEP 01 (2013) 063                                                                                  |
|       | ZZ<br>ZZ                  | ölev<br>13 TeV                      | РLВ 740 (2015) 250<br>EPJC 81 (2021) 200                                                            |
|       | VVV                       | 13 TeV                              | PRL 125 151802 (2020)                                                                               |
|       | www                       | 13 TeV                              | PRL 125 151802 (2020)                                                                               |
|       | WWZ<br>WZZ                | 13 TeV<br>13 TeV                    | PRL 125 151802 (2020)<br>PRL 125 151802 (2020)                                                      |
| son   | ZZZ                       | 13 TeV                              | PRL 125 151802 (2020)                                                                               |
| -Bo   | WVy<br>WWy                | 8 TeV                               | PRD 90 032008 (2014)                                                                                |
| Ę     | Wγγ                       | 8 TeV                               | JHEP 10 (2017) 072                                                                                  |
|       | Wγγ<br>Ζνογ               | 13 TeV                              | JHEP 10 (2021) 174                                                                                  |
|       | ∠γγ<br>Ζγγ                | 8 TeV<br>13 TeV                     | JHEP 10 (2017) 072<br>JHEP 10 (2021) 174                                                            |
|       | VBF W                     | 8 TeV                               | JHEP 11 (2016) 147                                                                                  |
|       | VBF W                     | 13 TeV                              | EPJC 80 (2020) 43                                                                                   |
|       | VBF Z<br>VBF Z            | 7 TeV<br>8 TeV                      | JHEP 10 (2013) 101<br>EPJC 75 (2015) 66                                                             |
|       | VBF Z                     | 13 TeV                              | EPJC 78 (2018) 589                                                                                  |
| BS    | EW WV<br>ex. vv → \//\/   | 13 TeV                              | PLB 834 (2022) 137438                                                                               |
| > pr  | EW qqWγ                   | 8 TeV                               | JHEP 06 (2017) 106                                                                                  |
| Far   | EW qqWγ                   | 13 TeV                              | Accepted by PRD                                                                                     |
| ٨B    | ⊑w os ww<br>EW ss WW      | 8 TeV                               | Submitted to PLB<br>PRL 114 051801 (2015)                                                           |
|       | EW ss WW                  | 13 TeV                              | PRL 120 081801 (2018)                                                                               |
|       | ĿW qqΖγ<br>EW qqΖν        | 8 TeV<br>13 TeV                     | PLB 770 (2017) 380<br>PRD 104 072001 (2021)                                                         |
|       | EW qqWZ                   | 13 TeV                              | PLB 809 (2020) 135710                                                                               |
|       | EW qqZZ                   | 13 TeV                              | PLB 812 (2020) 135992                                                                               |
|       | tt<br>tt                  | 7 TeV<br>8 TeV                      | JHEP 08 (2016) 029<br>JHEP 08 (2016) 029                                                            |
|       | tt                        | 13 TeV                              | PRD 104 (2021) 092013                                                                               |
|       | tt<br>t <sub>t - ch</sub> | 13.6 TeV<br>7 TeV                   | Submitted to JHEP<br>JHEP 12 (2012) 035                                                             |
|       | $t_{t-ch}$                | 8 TeV                               | JHEP 06 (2014) 090                                                                                  |
|       | t <sub>t – ch</sub><br>tW | 13 TeV<br>7 TeV                     | PLB 72 (2017) 752<br>PRL 110 (2013) 022003                                                          |
|       | tW                        | 8 TeV                               | PRL 112 (2014) 231802                                                                               |
|       | tW                        | 13 TeV                              | JHEP 10 (2018) 117                                                                                  |
| do    | s-ch<br>ttγ               | 8 TeV                               | JHEP 10 (2017) 006                                                                                  |
|       | ttγ<br>t7~                | 13 TeV                              | JHEP 05 (2022) 091                                                                                  |
|       | τ∠q<br>tZq                | 8 IeV<br>13 TeV                     | JHEP 07 (2017) 003<br>JHEP 02 (2022) 107                                                            |
|       | ttZ                       | 7 TeV                               | PRL 110 (2013) 172002                                                                               |
|       | ttZ<br>ttZ                | 8 TeV<br>13 TeV                     | JHEP 01 (2016) 096<br>JHEP 03 (2020) 056                                                            |
|       | tγ                        | 13 TeV                              | PRL 121 221802 (2018)                                                                               |
|       | ttW                       | 8 TeV                               | JHEP 01 (2016) 096                                                                                  |
|       | tWZ                       | 13 TeV                              | TOP-22-008                                                                                          |
|       | tttt                      | 13 TeV                              | Submitted to PLB                                                                                    |
|       | ggH<br>ggH                | 7 TeV                               | EPJC 75 (2015) 212<br>EPIC 75 (2015) 212                                                            |
|       | ggH                       | 13 TeV                              | Nature 607 60-68 (2022)                                                                             |
|       | VBF qqH                   | 7 TeV                               | EPJC 75 (2015) 212                                                                                  |
| S     | VBF qqH<br>VBF qqH        | 8 TeV<br>13 TeV                     | EPJC 75 (2015) 212<br>Nature 607 60-68 (2022)                                                       |
| ligg: | VH                        | 8 TeV                               | EPJC 75 (2015) 212                                                                                  |
| T     | WH<br>ZH                  | 13 TeV<br>13 TeV                    | Nature 607 60-68 (2022)<br>Nature 607 60-68 (2022)                                                  |
|       |                           | 10 10 1                             |                                                                                                     |
|       | ttH                       | 8 TeV                               | EPJC 75 (2015) 212                                                                                  |
|       | ttH<br>ttH                | 8 TeV<br>13 TeV                     | EPJC 75 (2015) 212<br>Nature 607 60-68 (2022)                                                       |
|       | ttH<br>ttH<br>tH<br>HH    | 8 TeV<br>13 TeV<br>13 TeV<br>13 TeV | EPJC 75 (2015) 212<br>Nature 607 60-68 (2022)<br>Nature 607 60-68 (2022)<br>Nature 607 60-68 (2022) |
|       | ttH<br>ttH<br>tH<br>HH    | 8 TeV<br>13 TeV<br>13 TeV<br>13 TeV | EPJC 75 (2015) 212<br>Nature 607 60-68 (2022)<br>Nature 607 60-68 (2022)<br>Nature 607 60-68 (2022) |

![](_page_39_Figure_3.jpeg)

Measured cross sections and exclusion limits at 95% C.L. See here for all cross section summary plots

Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertai Light colored bars: 7 TeV, Medium: 8 TeV, Dark: 13 TeV, Darkest: 13.6 TeV, Black bars: theory prediction

18 pb<sup>-1</sup> - 138 fb<sup>-1</sup> (7,8,13,13.6 TeV)

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | $\sigma(W) = 9.5e+07 \text{ fb}$ $\sigma(W) = 1.1e+08 \text{ fb}$ $\sigma(W) = 1.8e+08 \text{ fb}$ $\sigma(Z) = 2.9e+07 \text{ fb}$ $\sigma(Z) = 3.4e+07 \text{ fb}$ $\sigma(Z) = 5.6e+07 \text{ fb}$ | 36 pb <sup>-1</sup><br>18 pb <sup>-1</sup><br>43 pb <sup>-1</sup><br>36 pb <sup>-1</sup><br>18 pb <sup>-1</sup><br>2 fb <sup>-1</sup>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\sigma(W\gamma) = 3.4e+05 \text{ fb}$ $\sigma(W\gamma) = 1.4e+05 \text{ fb}$ $\sigma(Z\gamma) = 1.6e+05 \text{ fb}$ $\sigma(Z\gamma) = 1.9e+05 \text{ fb}$ $\sigma(WW) = 5.2e+04 \text{ fb}$ $\sigma(WW) = 6e+04 \text{ fb}$ $\sigma(WW) = 6e+04 \text{ fb}$ $\sigma(WZ) = 2e+04 \text{ fb}$ $\sigma(WZ) = 2.4e+04 \text{ fb}$ $\sigma(WZ) = 2.4e+04 \text{ fb}$ $\sigma(WZ) = 5.1e+04 \text{ fb}$ $\sigma(ZZ) = 6.2e+03 \text{ fb}$ $\sigma(ZZ) = 7.7e+03 \text{ fb}$ |                                                                                                                                                                                                       | 5 fb <sup>-1</sup><br>137 fb <sup>-</sup><br>5 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>5 fb <sup>-1</sup><br>19 fb <sup>-1</sup><br>36 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>137 fb <sup>-1</sup><br>5 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>137 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>137 fb <sup>-1</sup>                                                                                                                                                                                                                                                                                                                                                            |
| 1e+03 fb<br>e+02 fb                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                       | 137 fb <sup>-</sup><br>137 fb <sup>-</sup><br>137 fb <sup>-</sup><br>137 fb <sup>-</sup><br>137 fb <sup>-1</sup><br>138 fb <sup>-1</sup><br>19 fb <sup>-1</sup><br>19 fb <sup>-1</sup><br>19 fb <sup>-1</sup><br>19 fb <sup>-1</sup><br>19 fb <sup>-1</sup>                                                                                                                                                                                                                                                                                                                                                                                                                              |
| fb<br>Φ(VBF W) = 6.2e+03 fb<br>fb<br>EW WV) = 1.9e+03 fb                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                       | 19 fb <sup>-1</sup><br>36 fb <sup>-1</sup><br>5 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>36 fb <sup>-1</sup><br>138 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>138 fb <sup>-1</sup><br>138 fb <sup>-1</sup><br>137 fb <sup>-1</sup><br>137 fb <sup>-1</sup><br>137 fb <sup>-1</sup><br>137 fb <sup>-1</sup>                                                                                                                                                                                                                                                                                                                                                     |
| $\sigma(tt) = 1.7e+05 \text{ fb}$ $\sigma(tt) = 2.4e+05 \text{ fb}$ $\sigma(tt) = 7.9e+05 \text{ fb}$ $\sigma(tt) = 8.8e+05 \text{ fb}$ $\sigma(tt) = 8.8e+04 \text{ fb}$ $\sigma(tt) = 1.6e+04 \text{ fb}$ $\sigma(tt) = 2.3e+04 \text{ fb}$ $\sigma(tw) = 2.3e+04 \text{ fb}$ $\sigma(tw) = 6.3e+04 \text{ fb}$ $\sigma(ty) = 3.5e+03 \text{ fb}$ $t+02 \text{ fb}$                                                                                                   |                                                                                                                                                                                                       | 5 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>137 fb <sup>-1</sup><br>2 fb <sup>-1</sup><br>5 fb <sup>-1</sup><br>2 fb <sup>-1</sup><br>5 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>138 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>138 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>36 fb <sup>-1</sup><br>138 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>138 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>36 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>138 fb <sup>-1</sup><br>36 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>38 fb <sup>-1</sup><br>38 fb <sup>-1</sup><br>38 fb <sup>-1</sup><br>38 fb <sup>-1</sup> |
| $\sigma(ggH) = 1.6e+04 \text{ fb}$<br>$\sigma(ggH) = 1.5e+04 \text{ fb}$<br>$\sigma(ggH) = 2.2e+03 \text{ fb}$<br>$\sigma(VBF qqH) = 2.2e+03 \text{ fb}$<br>$\sigma(VBF qqH) = 3e+03 \text{ fb}$<br>1.1e+03  fb<br>MH) = 2e+03  fb<br>.1e+03  fb<br>MH = 2e+03  fb<br>.1e+03  fb                                                                                                                                                                                        |                                                                                                                                                                                                       | 5 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>139 fb <sup>-1</sup><br>5 fb <sup>-1</sup><br>20 fb <sup>-1</sup><br>138 fb <sup>-1</sup>                                                                                                                                                                                                                                                                                                                                                                                                   |

![](_page_39_Picture_9.jpeg)

# **Overview of CMS X+jets cross section results**

ern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined https://twiki.o

![](_page_40_Figure_2.jpeg)

![](_page_40_Picture_5.jpeg)

## **Cross checks of W mass measurement**

### Comparison of the PLH fit results of the individual measurement categories as well as the combination of all between the PDF set CT10 and CT18

![](_page_41_Figure_2.jpeg)

 $m_{W}$  [MeV]

![](_page_41_Picture_4.jpeg)

42

 $m_{W}$  [MeV]

## **Cross checks of W mass measurement**

## Results are determined using a PLH approach and in comparison with a x2-minimization approach using statistical uncertainties only

![](_page_42_Figure_2.jpeg)

## **Extra Slides**

![](_page_43_Picture_2.jpeg)