W Mass Highlights and other Precision Measurements

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Standard Model as a Gauge Theory derived from symmetry principles

$$\mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y} \otimes \mathrm{SU(3)_C}$$

$$g_2\ (\sin\theta_W) \qquad g_1\ (\alpha) \qquad g_3\ (\alpha_s)$$

+ vacuum expectation value

+ fermion masses and their mixings

Mass of electroweak gauge bosons and interaction strength predicted precisely

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

$$M_Z = (91.1876 \pm 0.0021)\ \mathrm{GeV}$$

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

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

At tree level:

$$m_W = \frac{gv}{2} \qquad m_Z = \frac{\sqrt{g^2 + g'^2}\,v}{2}$$

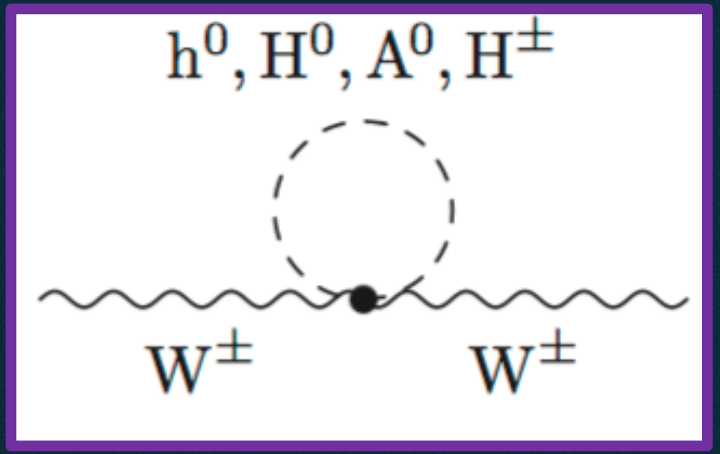
$$\sin^2\theta_W = \frac{g^2}{g^2 + g'^2} = \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

$$G_F = \frac{1}{\sqrt{2}\ v^2} = \frac{\sqrt{2}\ g^2}{8\ M_W^2}$$

Motivation for precision electroweak physics

At higher orders

$$\boxed{M_W} = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$



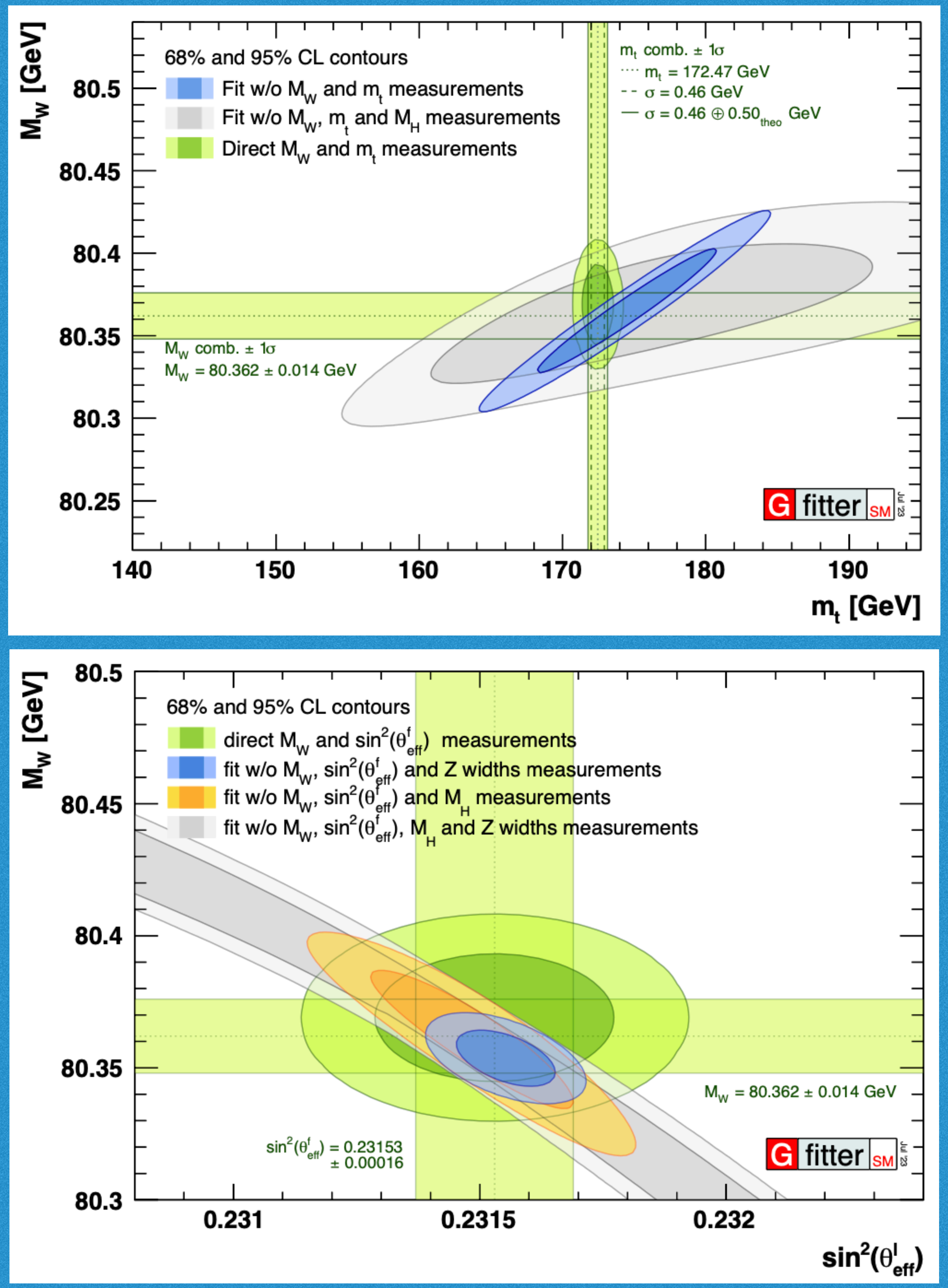
Radiative corrections

$$\Delta r \sim f\left(m_{top}^2, \log(m_h)\right)$$

$$\boxed{\sin^2\theta^l_{eff}} = \sin^2\theta_W\,(1+\Delta\kappa)$$

$$= \left(1-\frac{M_W^2}{M_Z^2}\right)(1+\Delta\kappa), \quad \Delta\kappa \sim 1.037$$

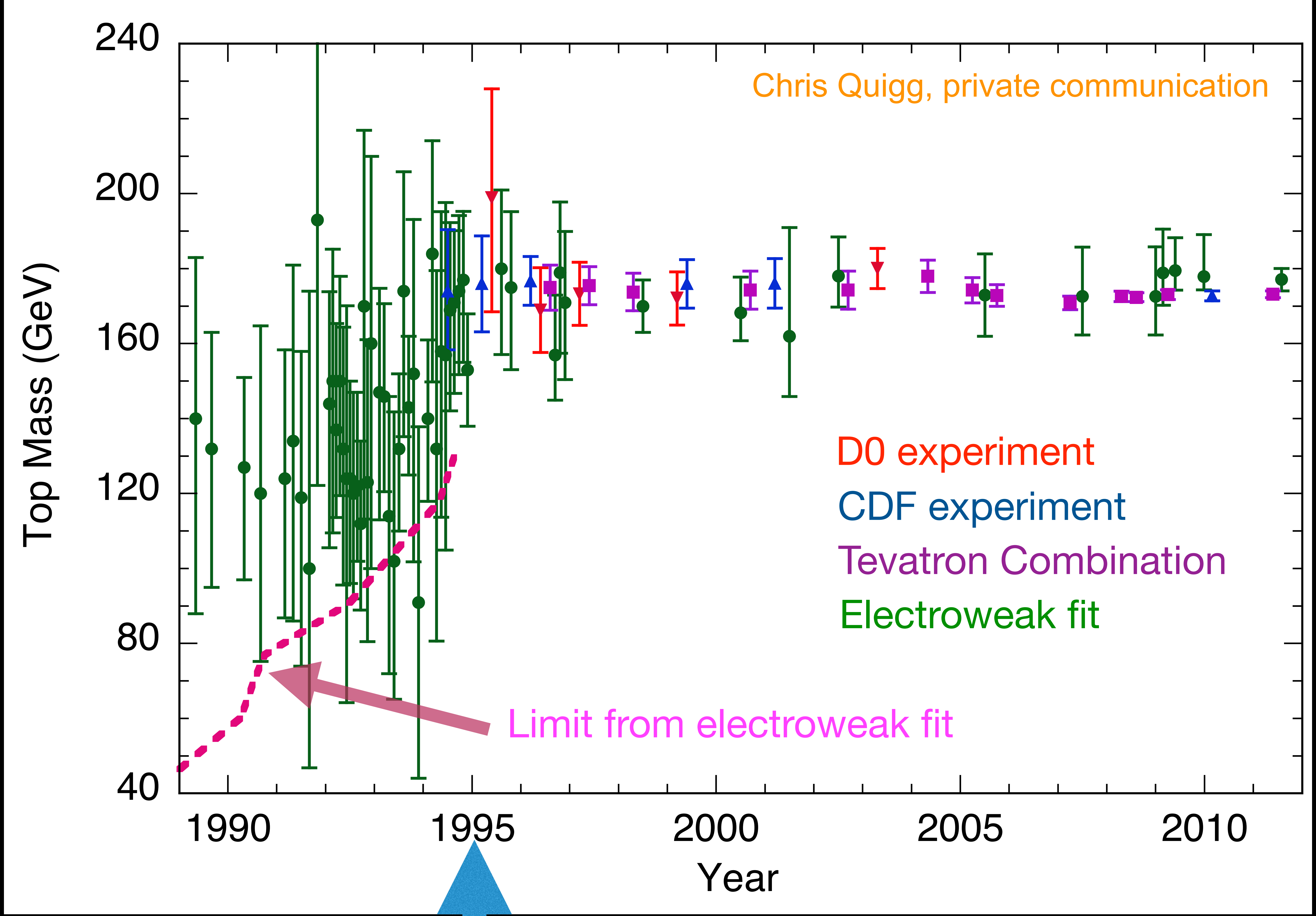
Gfitter, Y. Fischer et al., EPS 2023



Test self-consistency of Standard Model

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

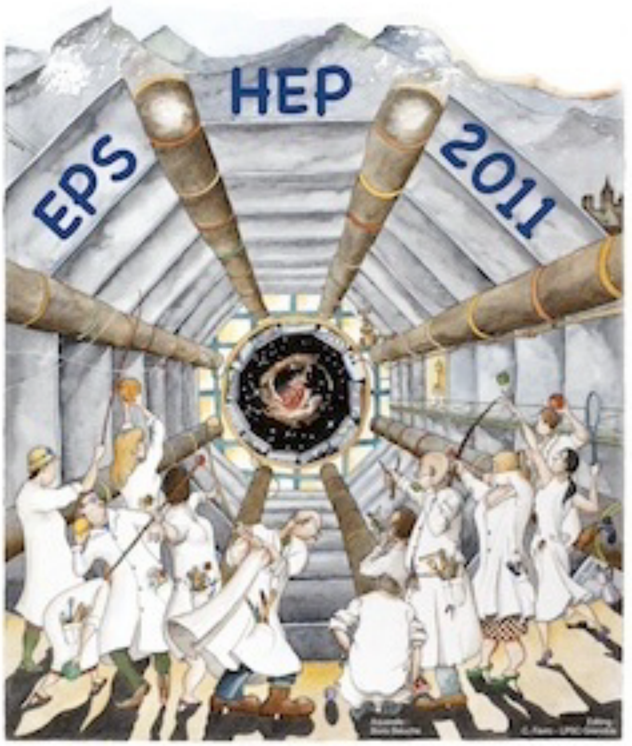
Top Mass Prediction from Precision Electroweak data



M_{top} = 175 —> 173 GeV

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

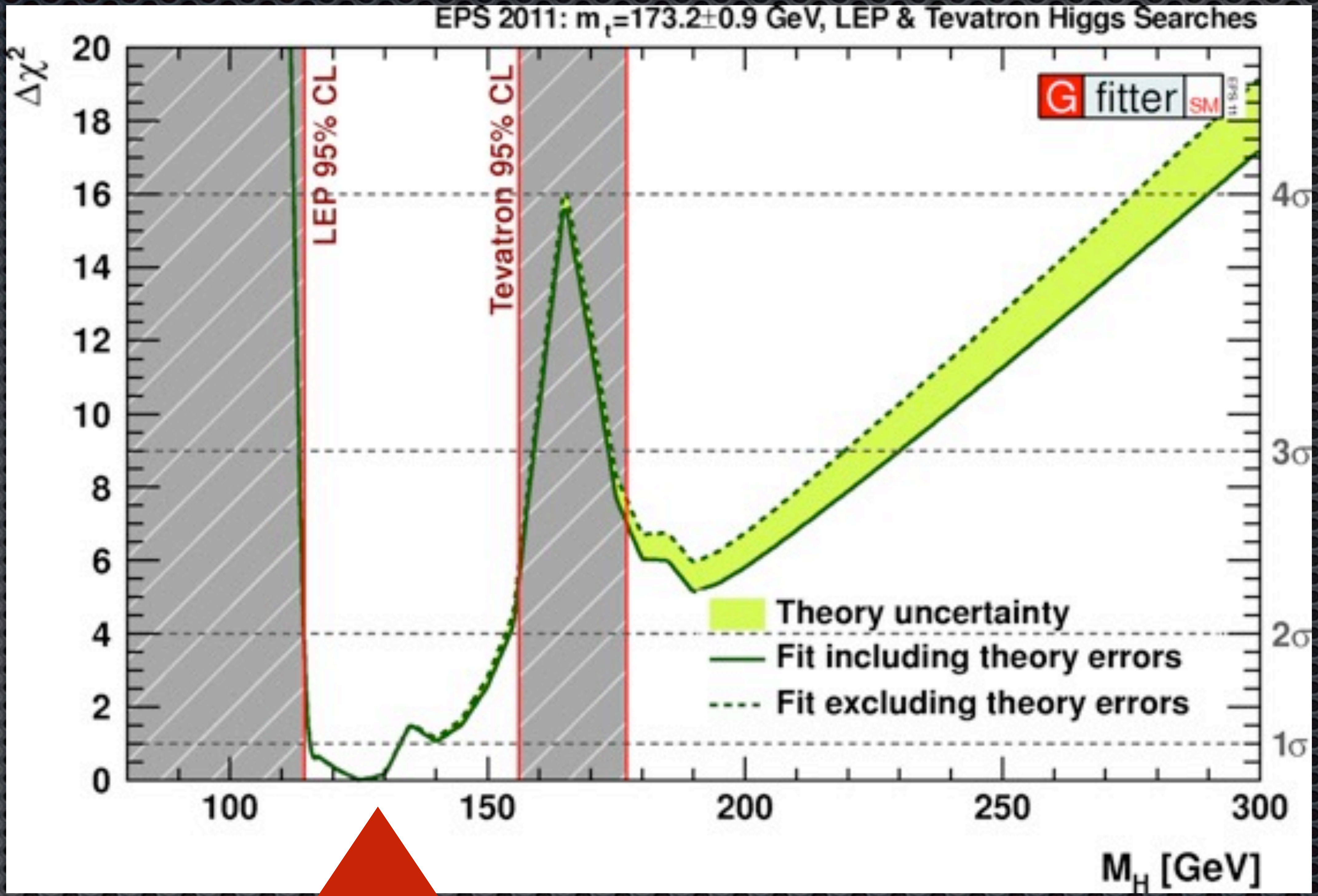
Top discovery at Tevatron



July 21-27

Overnight update

- **Updated with EPS'01 results**
  - Excludes direct searches from ATLAS and CMS from EPS



Standard Fit

m_H (minimum)= 94.5 GeV, Range m_H = [71, 124], $m_H < 166.5$ GeV @ 95%

Complete Fit

m_H (minimum)= 125.2 GeV, Range m_H = [116, 133], $m_H < 153.9$ GeV @ 95%

Thanks to Matthias Schott from the GFitter group

PANIC 2011, July 28, 2011

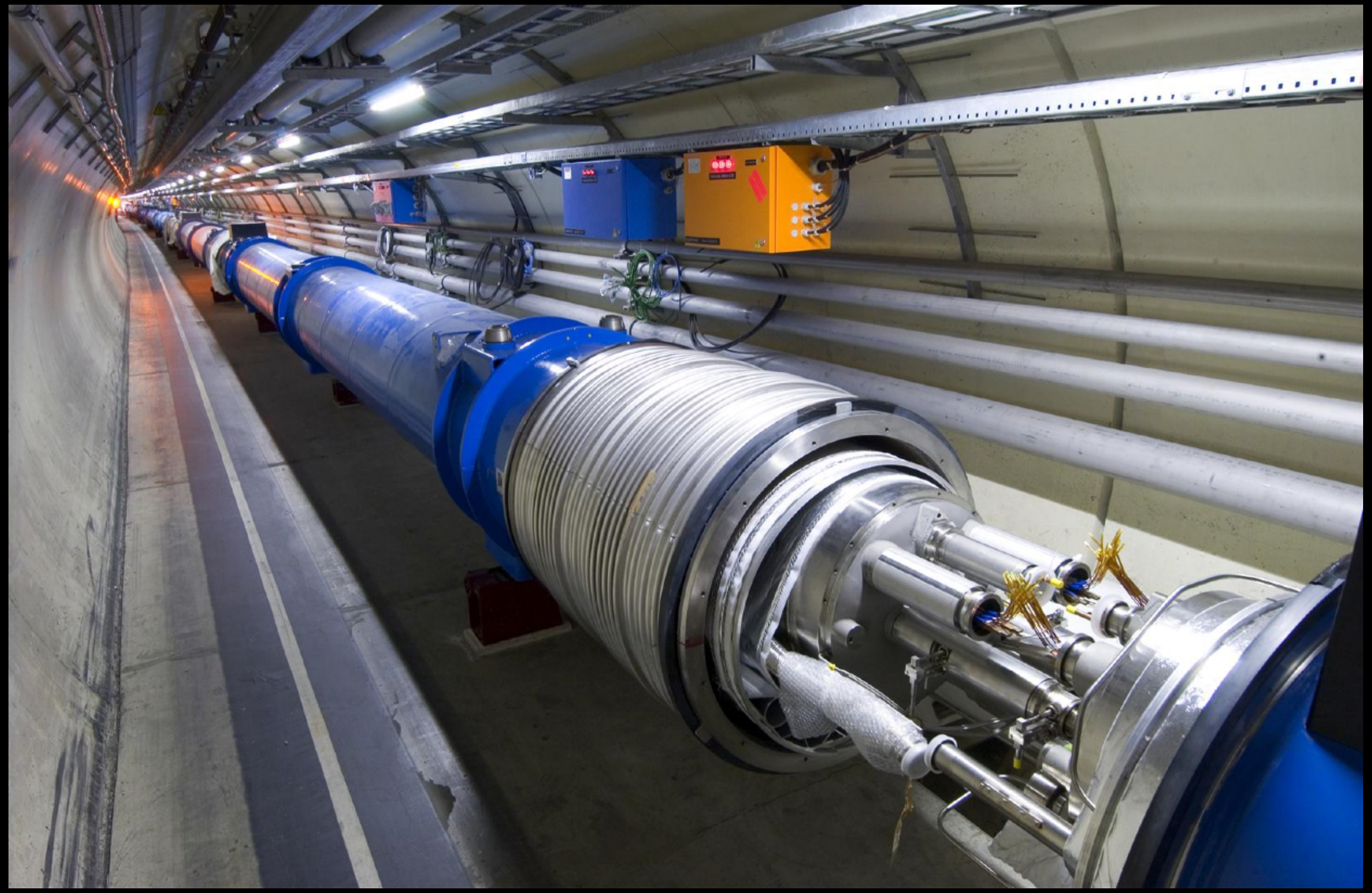
WARNING: Old Slide

Experimental data

Tevatron (Fermilab)

LEP (CERN)

LHC (CERN)



SLC (SLAC)

Experiments for today:

ATLAS EXPERIMENT

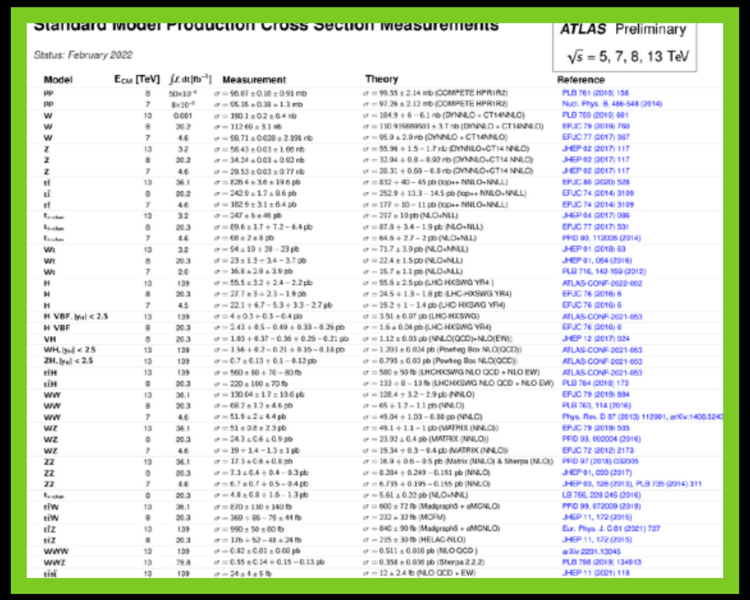
CMS

LHCb

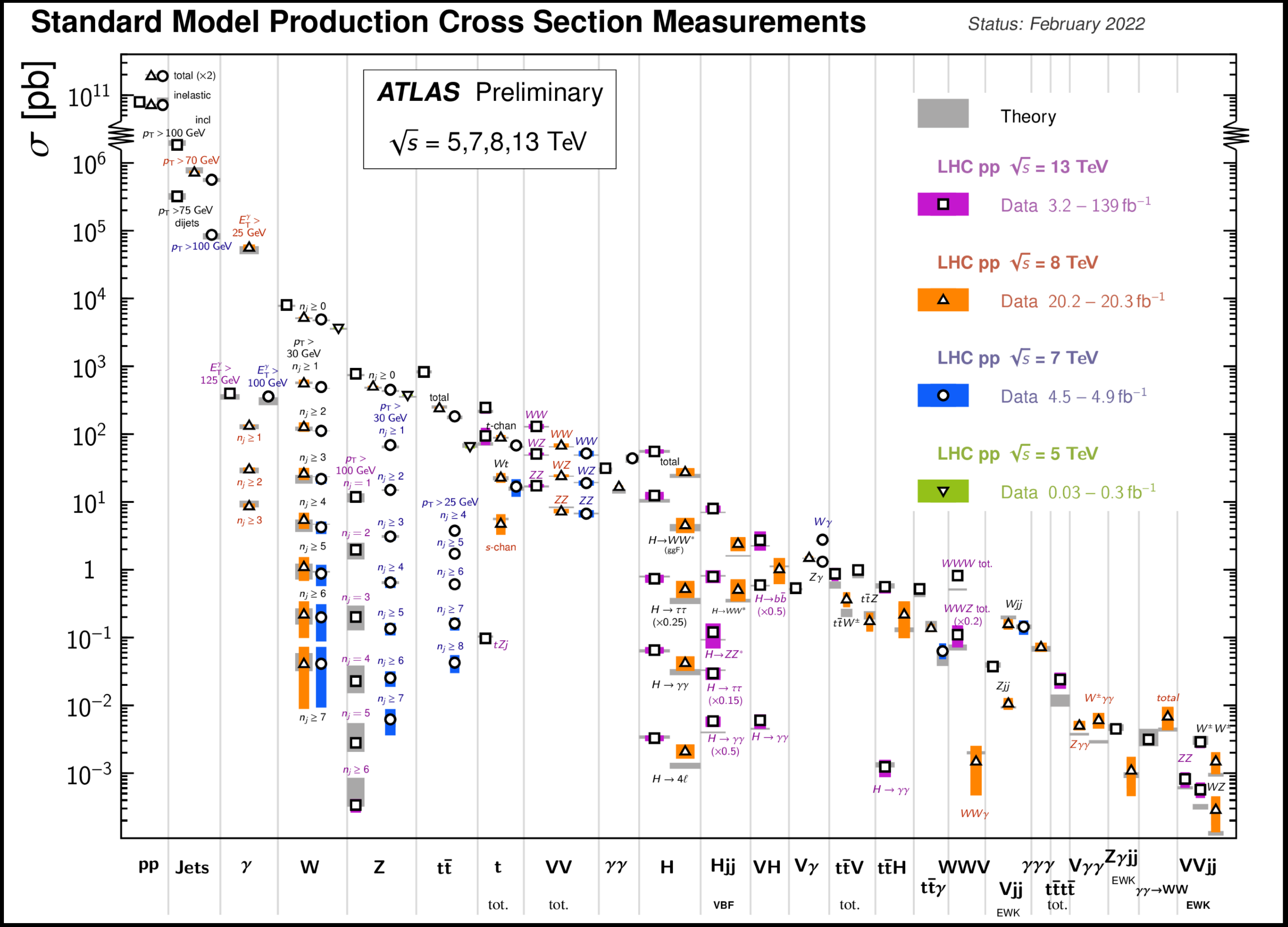
CDF II

Overview of Standard Model measurements at LHC

Publication list



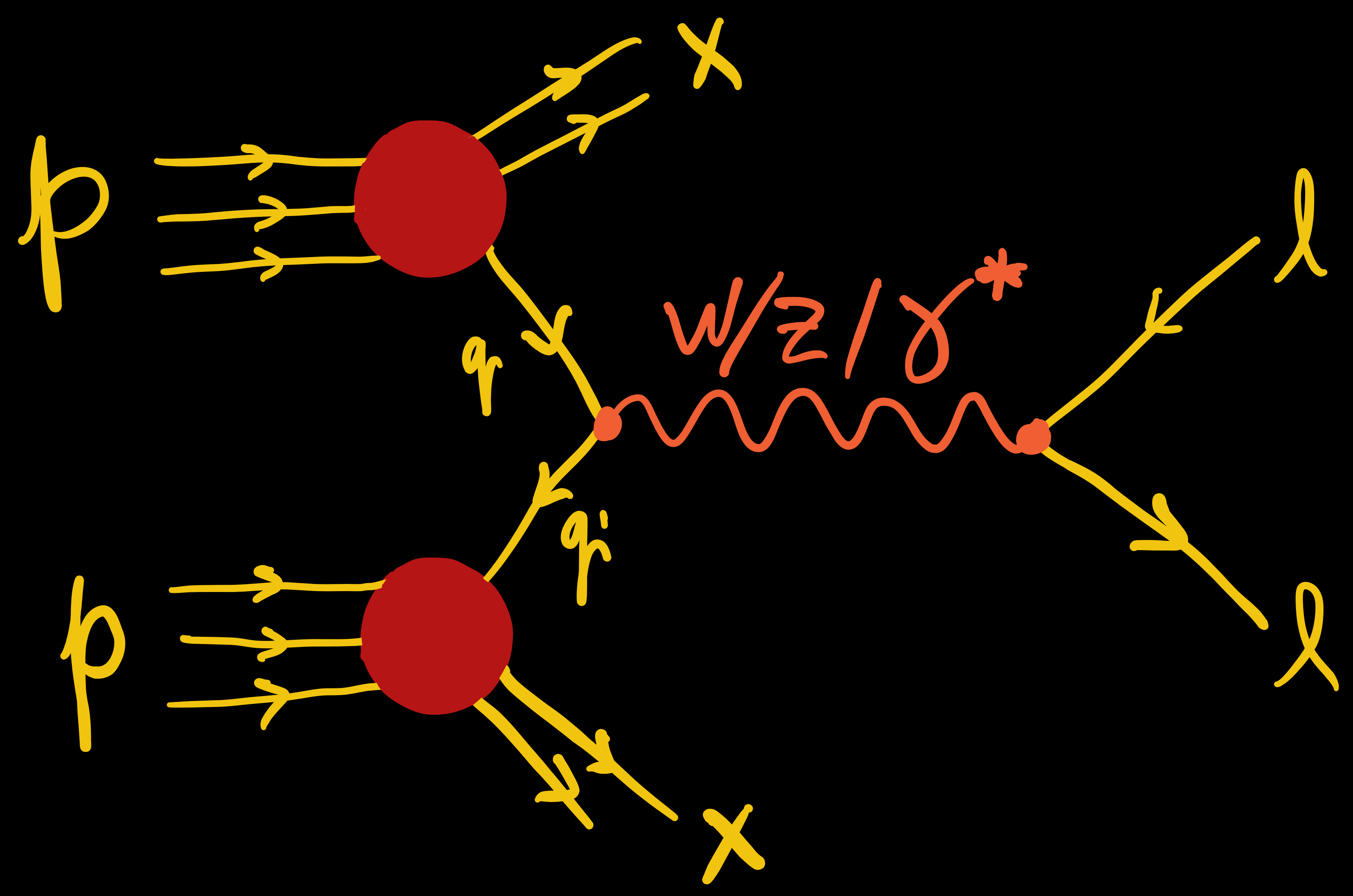
15 orders of magnitude



CMS has similar plots (see)
and explored similar phase space

Drell-Yan process and measurement of SM parameters

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

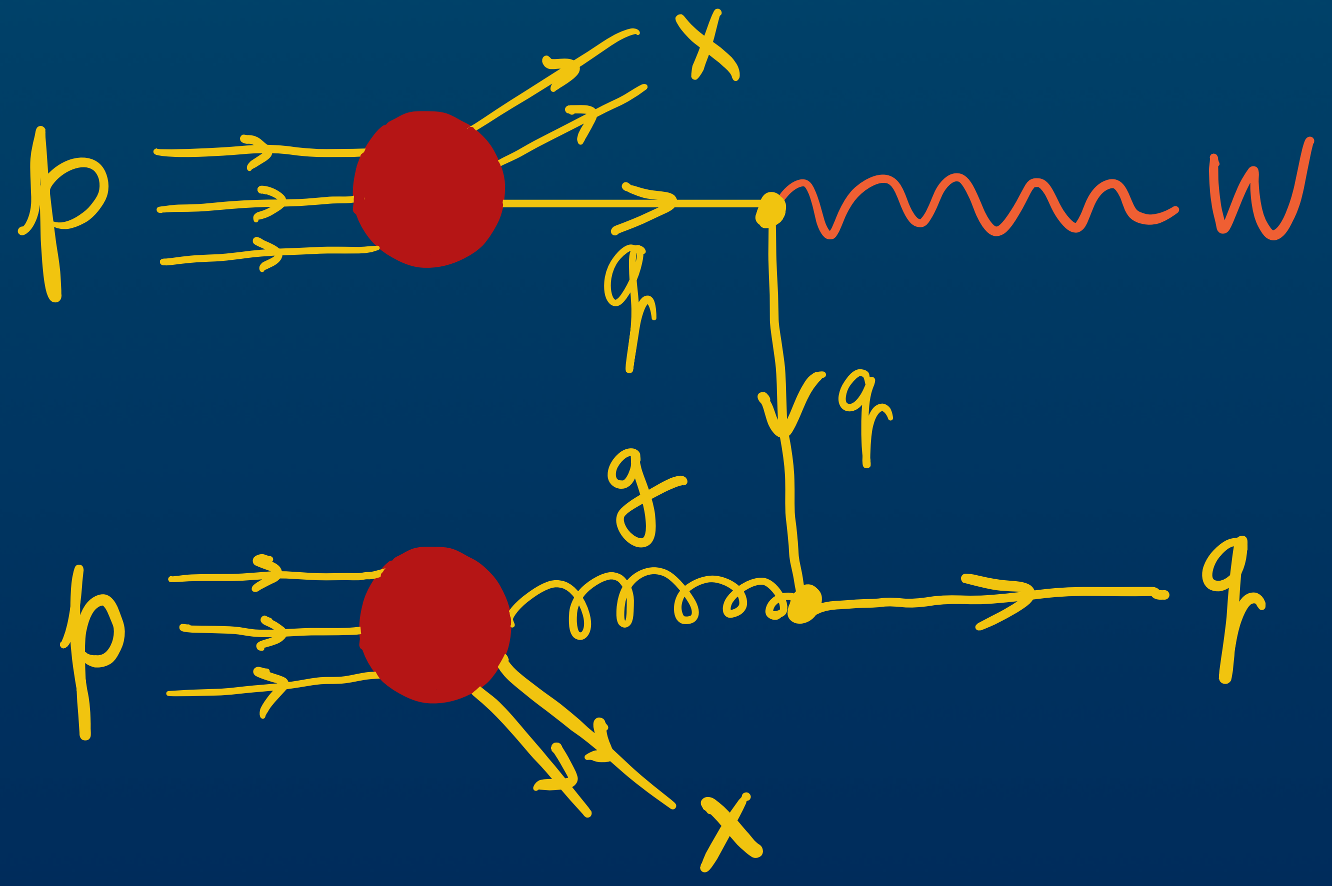


Used to measure:

- W-boson mass
- $\sin^2(\theta_W)$
- PDFs
- $\alpha_s(m_Z)$

The p_T of the W, Z bosons comes from from higher order corrections to the leading order Drell–Yan processes…

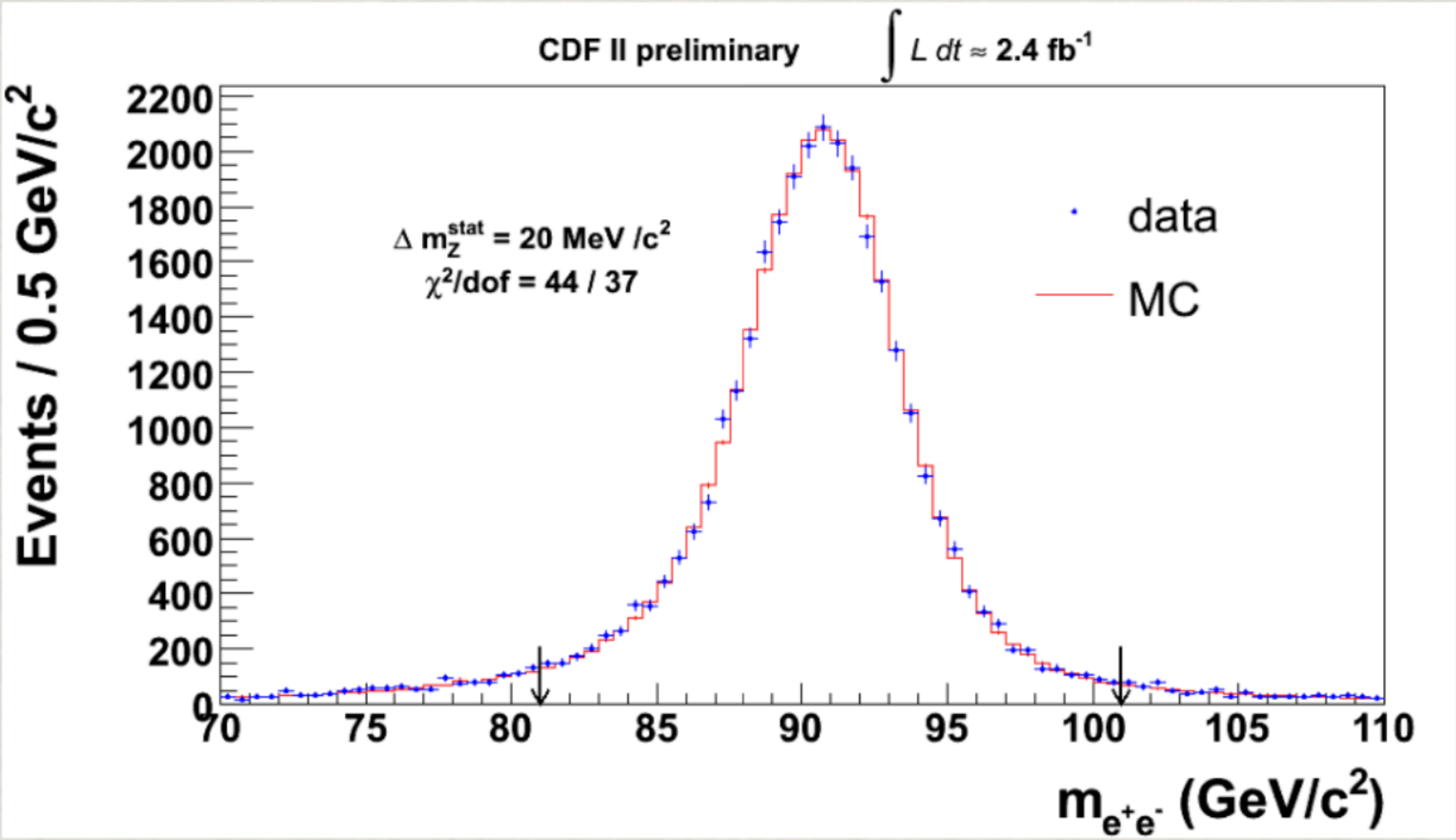
….. and from non-perturbative effects such as the primordial k_T of the incoming partons.



Z Mass Reconstruction

$$m_{ll}^2 = (p_{l^+} + p_{l^-})^2 \approx 2p_{l^+} \cdot p_{l^-} \approx 2E_{l^+}E_{l^-}(1 - \cos\theta_{l^+l^-})$$

$$\frac{d\hat{\sigma}}{dm_{ll}^2} \approx \frac{\Gamma_Z M_Z}{(m_{ll}^2 - m_Z^2)^2 + \Gamma_Z^2 M_Z^2} \times \frac{d\hat{\sigma}}{d\cos_\theta^2}$$



Only depending on direct measurements of energy and/or momentum of particles
plus
the angle between them

Map out m_Z & Γ_Z in the Breit-Wigner resonance

Errors determined by experimental resolutions.

Production properties of the Z-boson in the full phase space of the decay leptons

ATLAS-CONF-2023-013

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

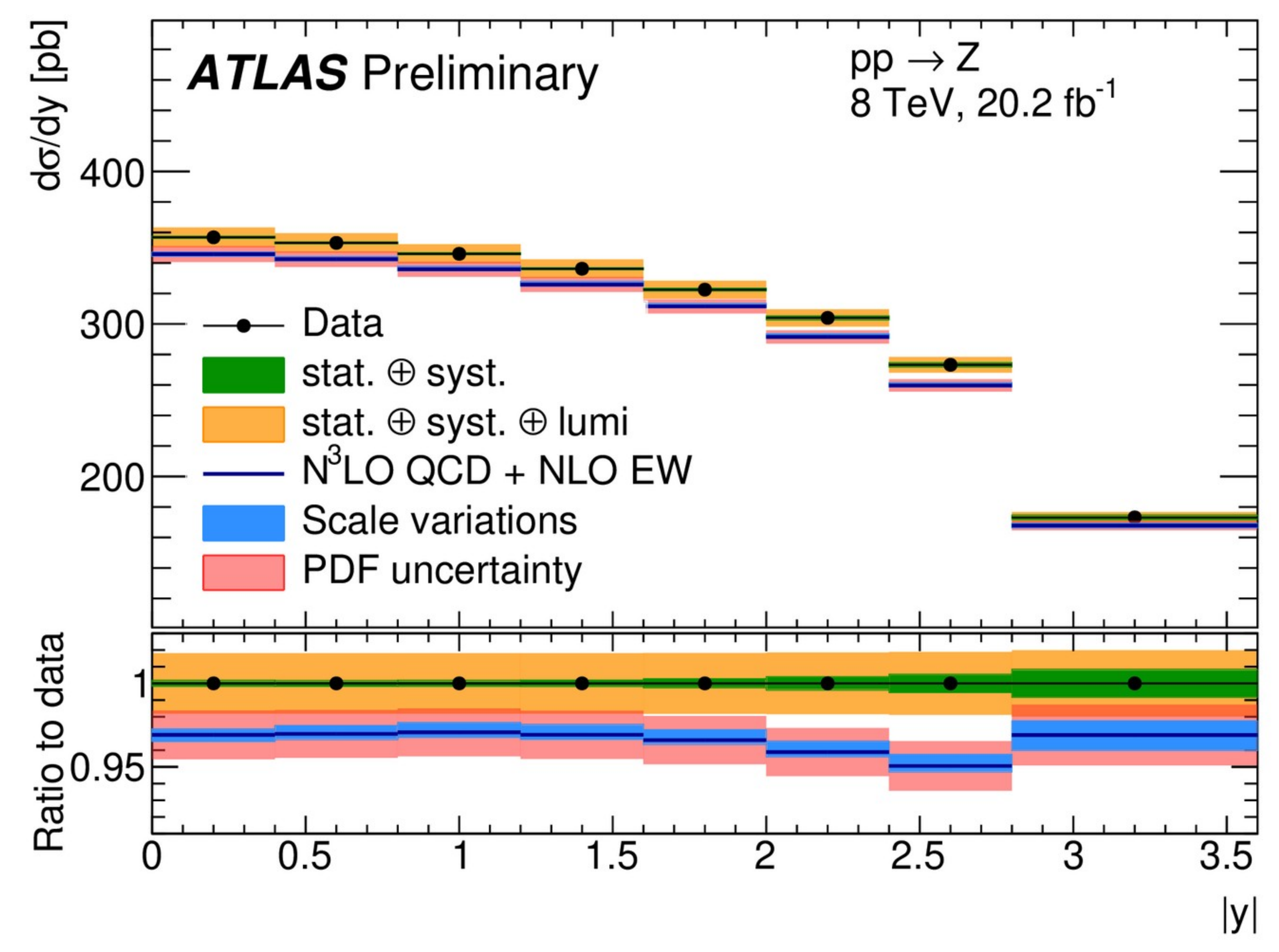
$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T\,dy\,dm}\left(1+\cos^2\theta+\sum_{i=0}^{7}A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

A_i angular coefficients: dynamics

lepton angular cos θ and ϕ distributions in the Collins-Soper frame

Fiducial cuts removed by analytic integration of (cos θ, ϕ) in the full phase space of the decay leptons through the measured Ai coefficients

Rapidity

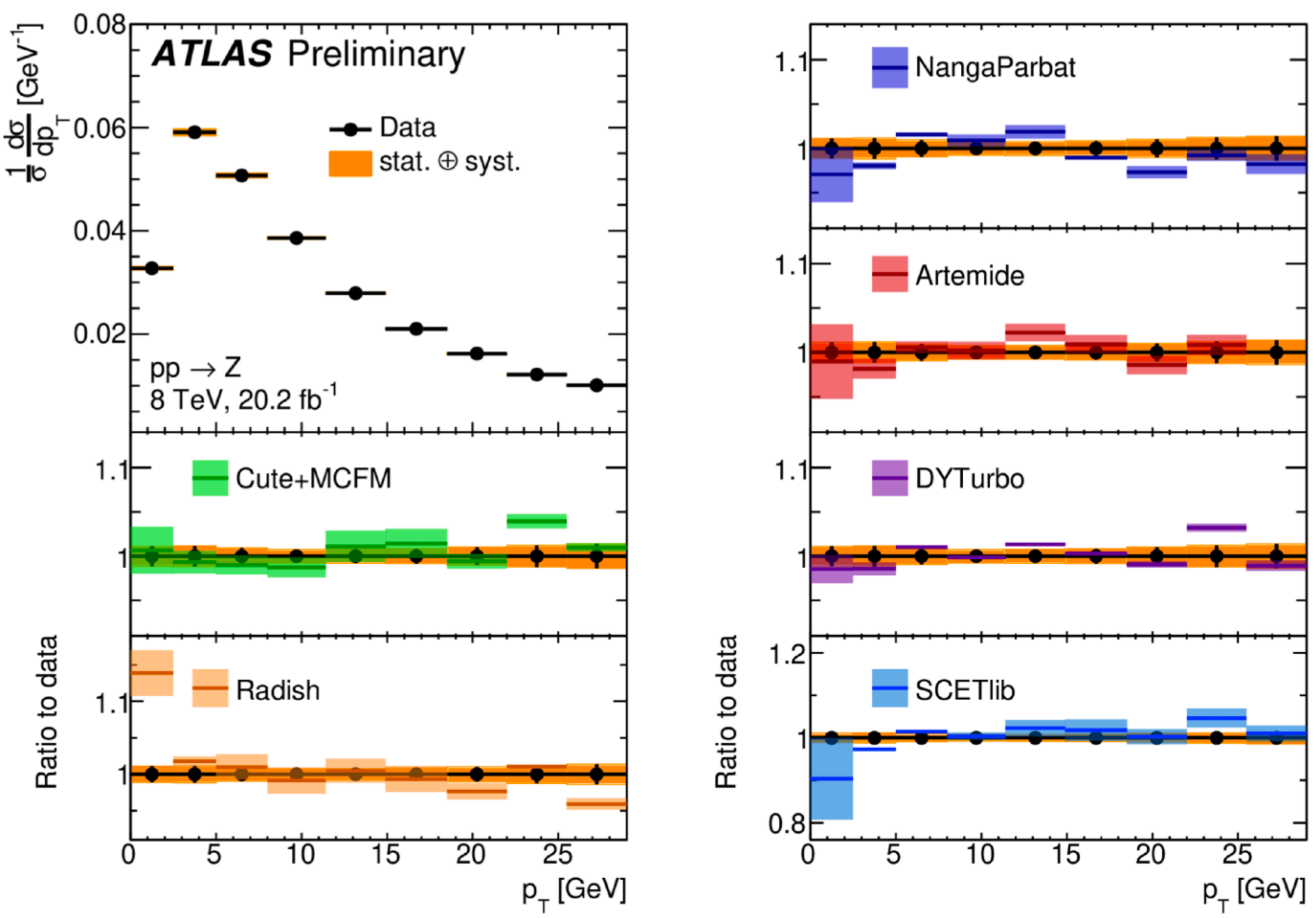


Run-1 8 TeV data only

negligible theoretical uncertainties for all measurements

First comparison to N3LO QCD predictions and N4LL resummation

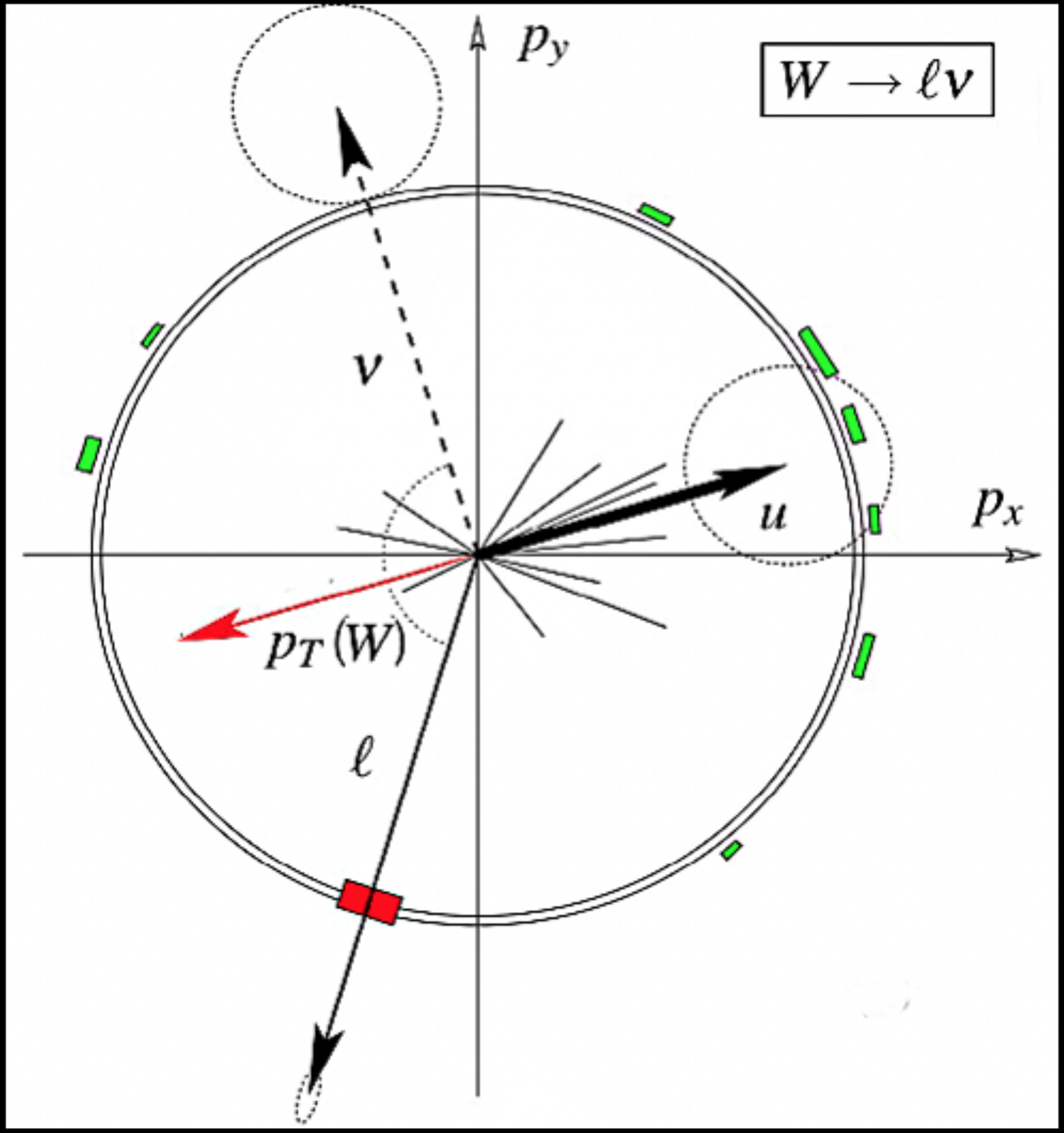
Transverse Momentum



W boson mass measurement

W mass reconstruction challenge

$$m_{l\nu}^2 = (E_l + E_\nu)^2 - (\vec{p}_{e,T} + \vec{p}_{\nu,T})^2 - (p_{e,z} + p_{\nu,z})^2$$



Transverse mass

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

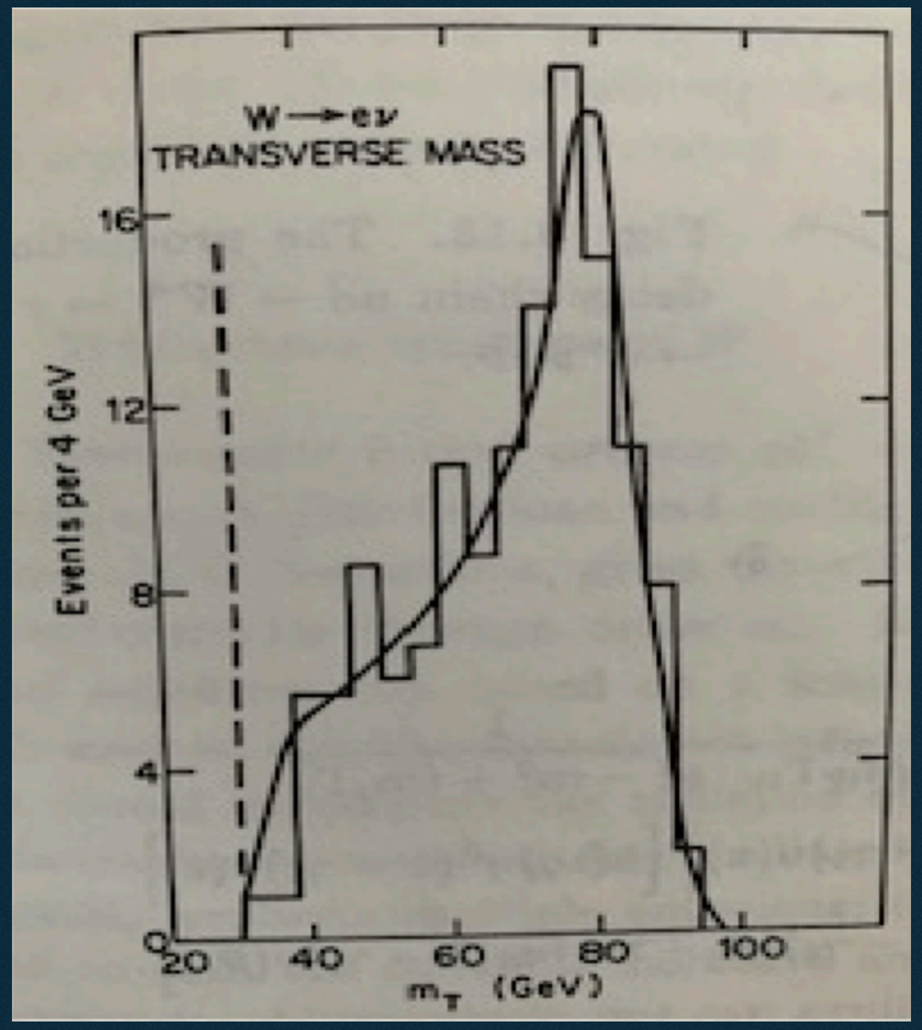
$$E_T = \sqrt{m^2 + p_T^2} \approx p_T$$

$$\vec{p}_T^{miss} = -\sum \vec{p}_T(observed)$$

UA1: 40 years ago

M_W = 83 ± 4 GeV

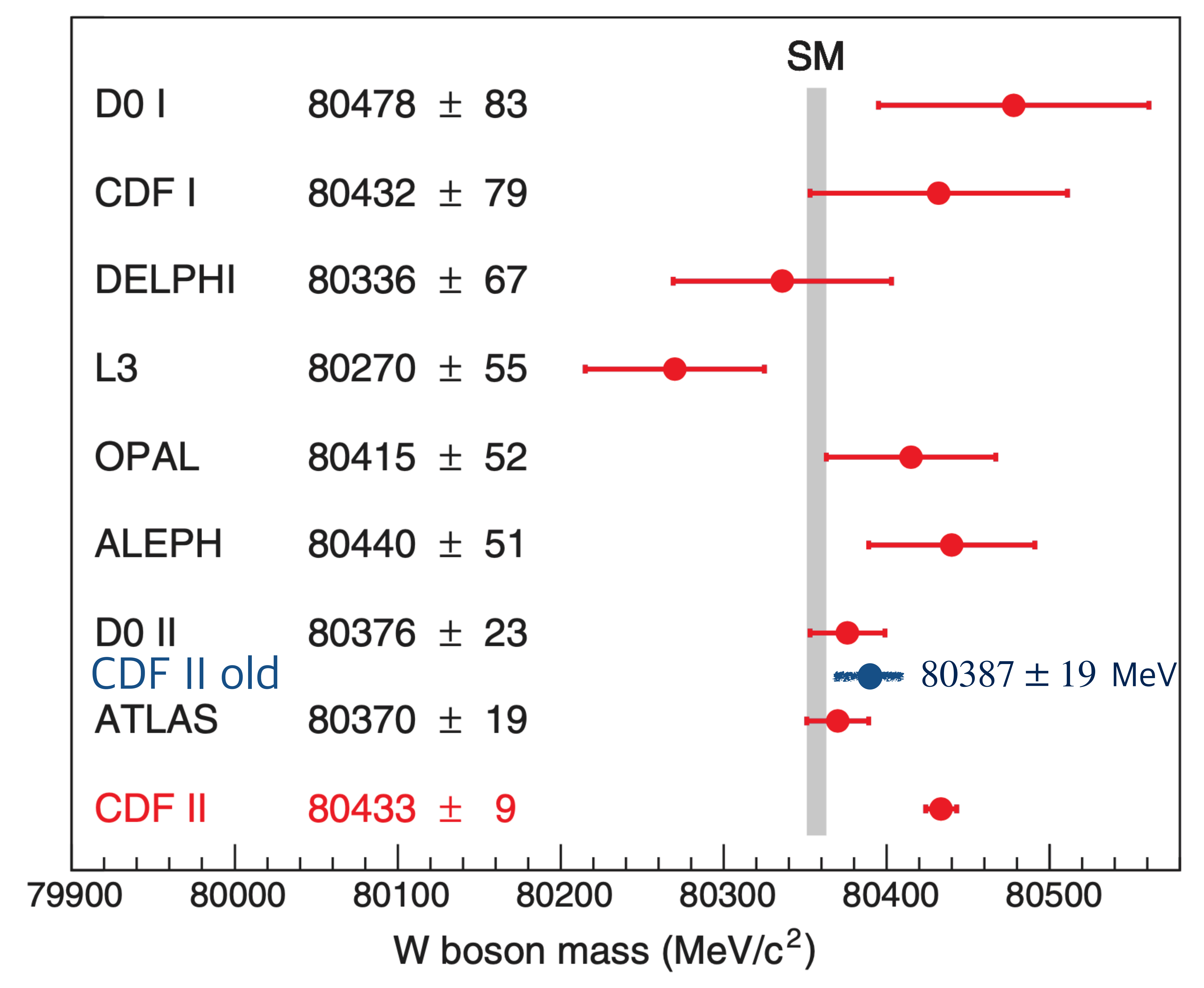
Γ_W < 6.5 GeV



CDF W Mass Measurement

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

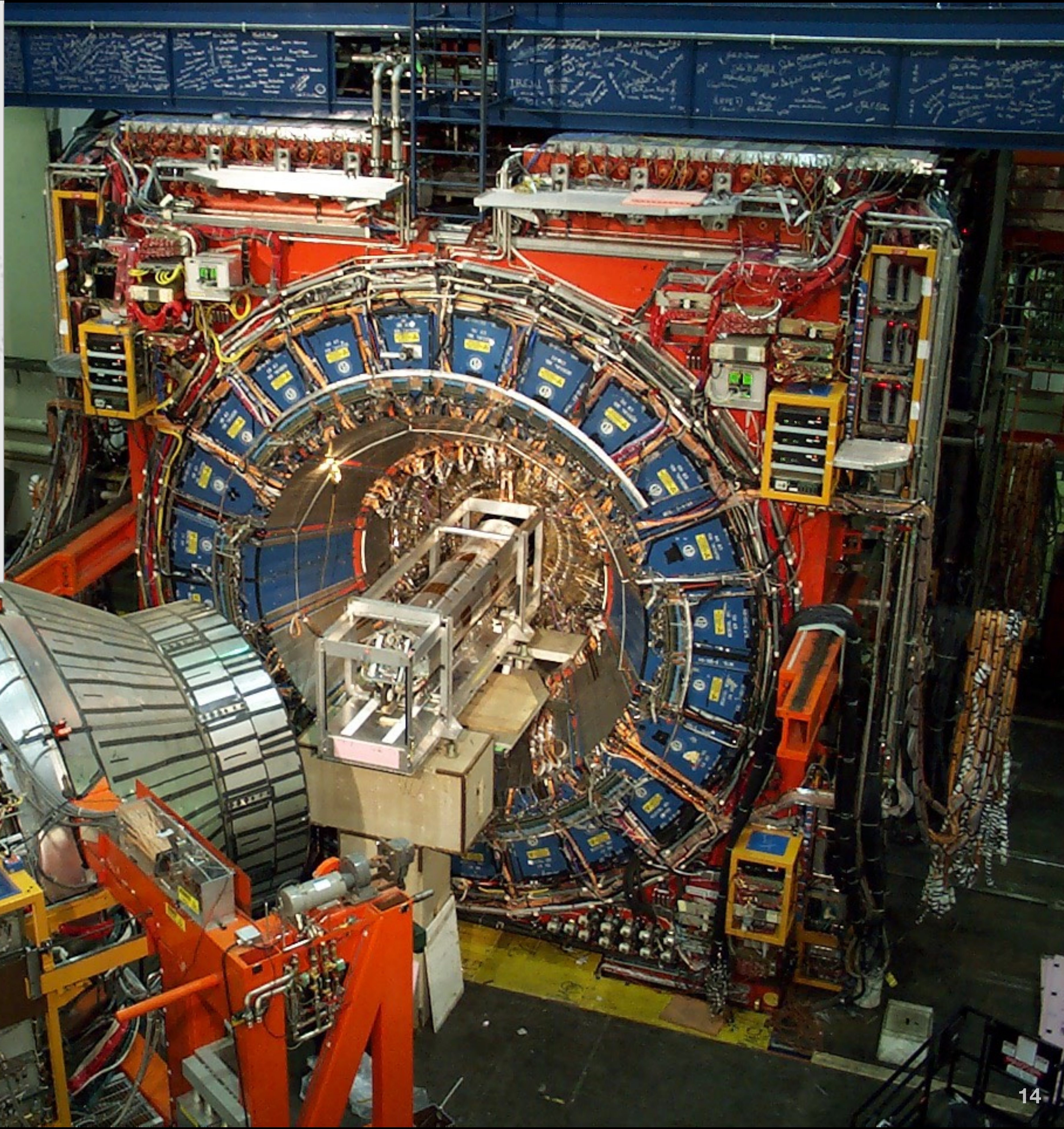
North America
- 28 institutions

Europe
- 20 institutions

Asia
- 6 institutions

The CDF Collaboration
- 13 Countries
- 54 institutions
- 401 authors

April 8th, 2022

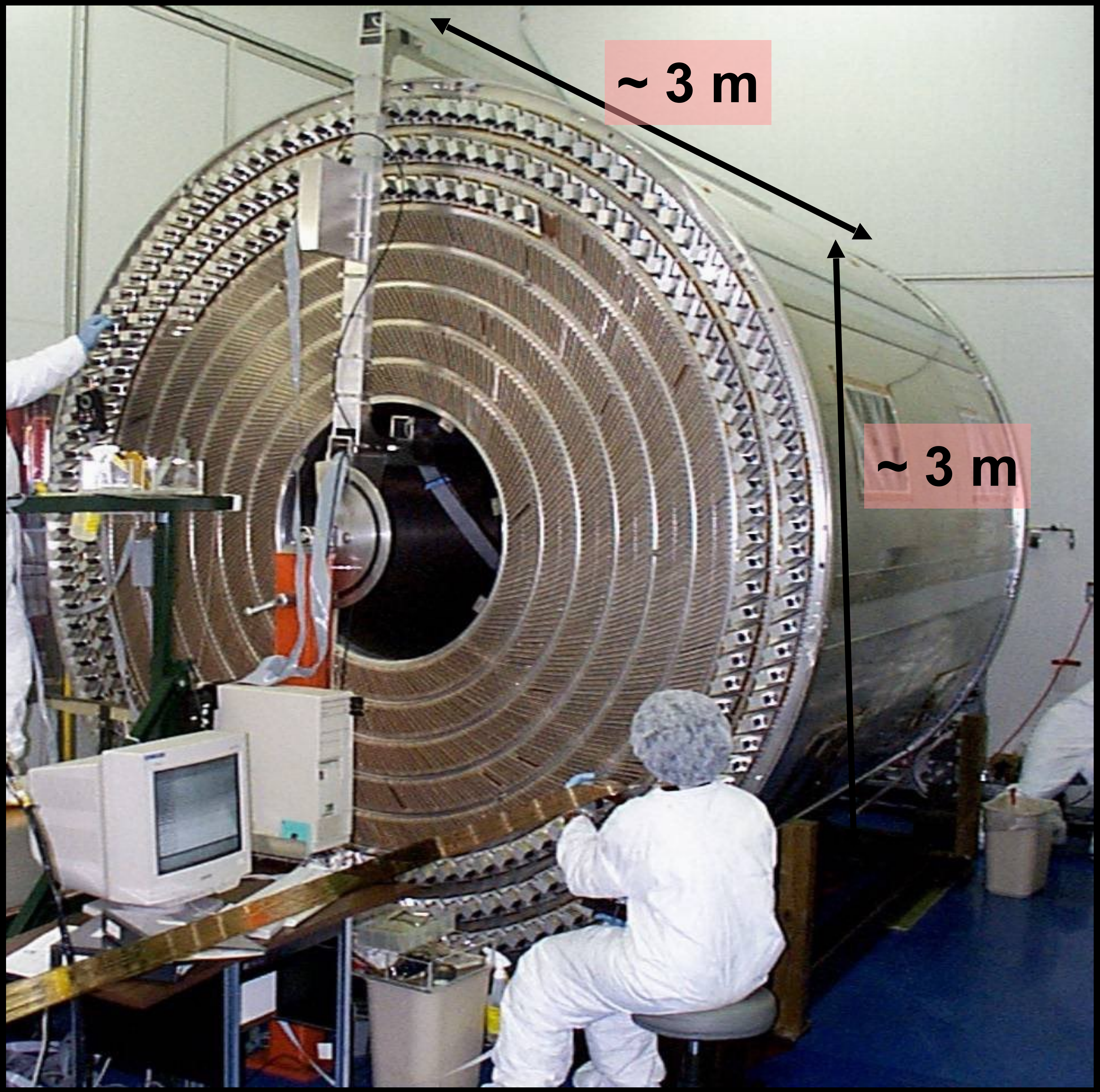


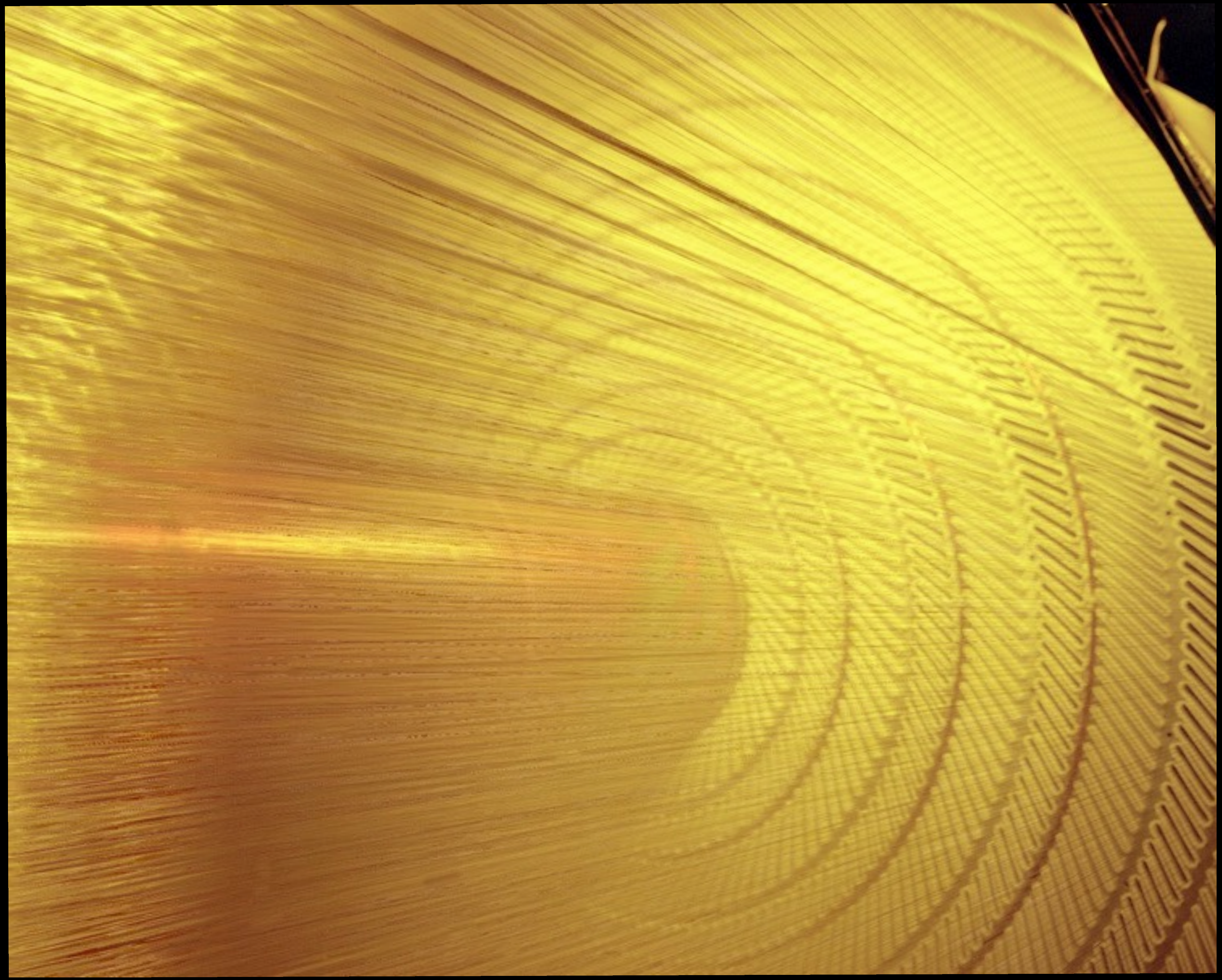
About CDF: https://cdf.fnal.gov

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



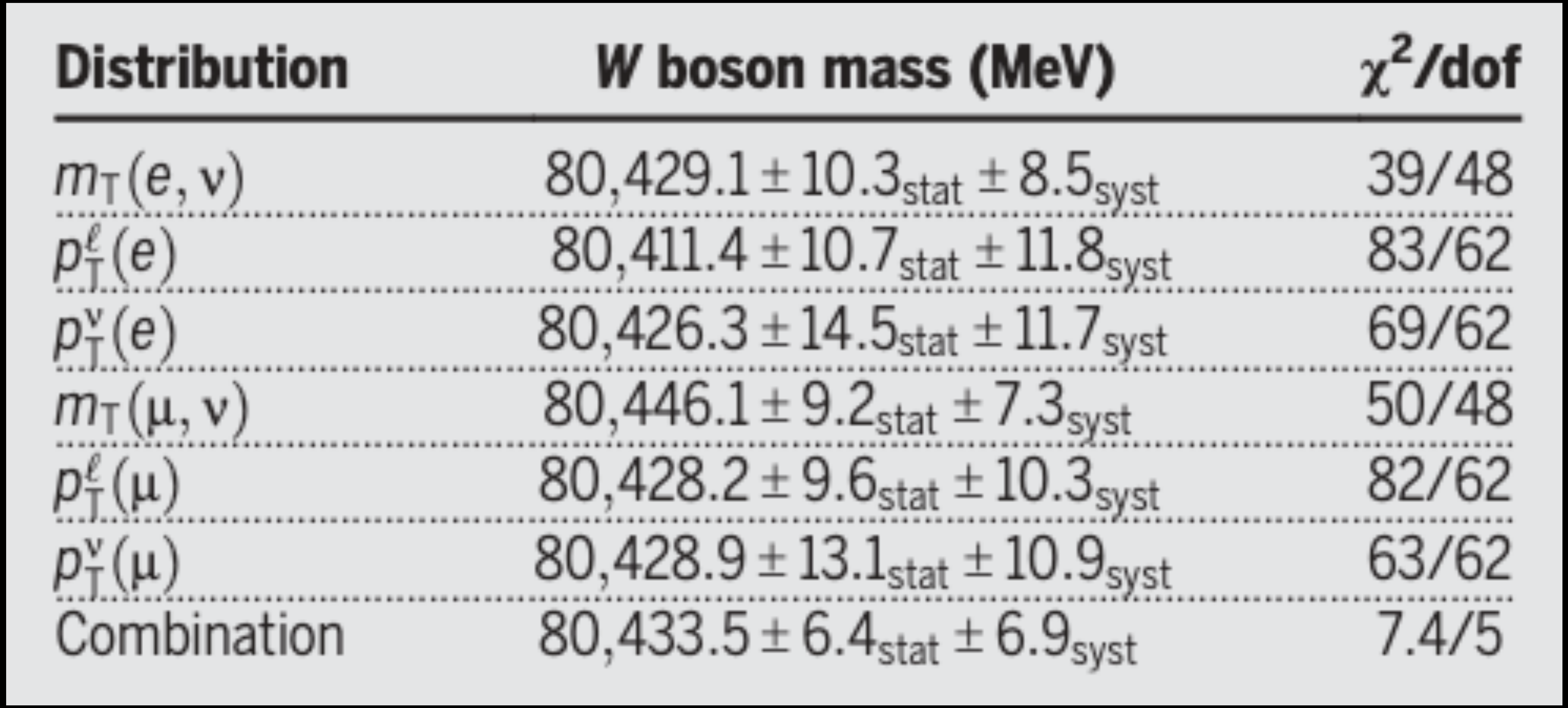


Alignment with cosmic rays specifically updated for this W mass measurement

Calibrate with Z, J/ψ, $\Upsilon(1S)$ (Blind Z mass: $M_Z = 91192.0 \pm 6.4_{stat} \pm 4.0_{sys}$(PDG: 91187 ± 2.1))

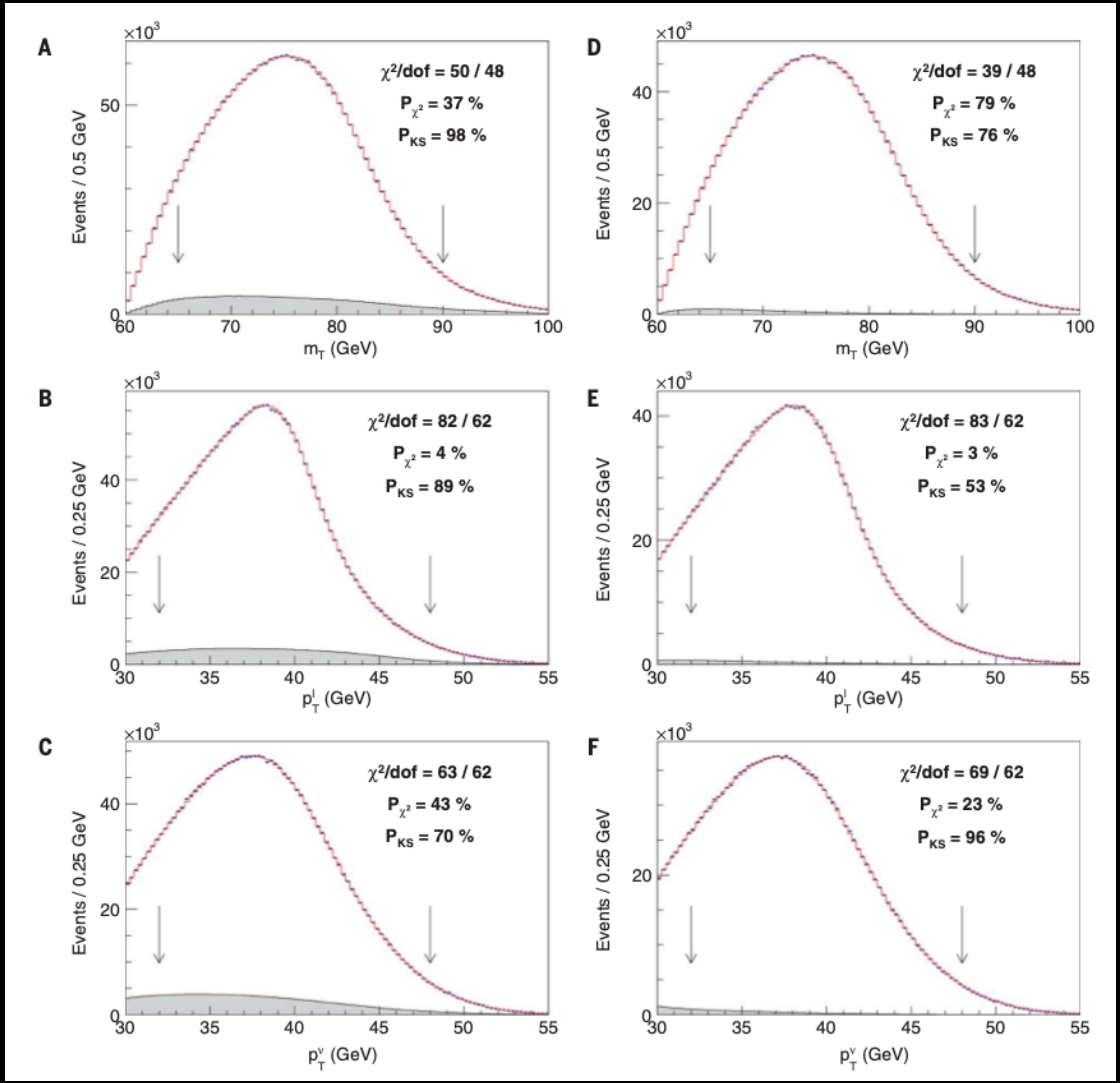
W mass extraction

- **Binned maximum likelihood fits to the templates of p_T^l, m_T, p_T^ν with W mass [80, 81] GeV**



Distribution	W boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80{,}429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$p_T^\ell(e)$	$80{,}411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$p_T^\nu(e)$	$80{,}426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$m_T(\mu,\nu)$	$80{,}446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48
$p_T^\ell(\mu)$	$80{,}428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62
$p_T^\nu(\mu)$	$80{,}428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62
Combination	$80{,}433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5

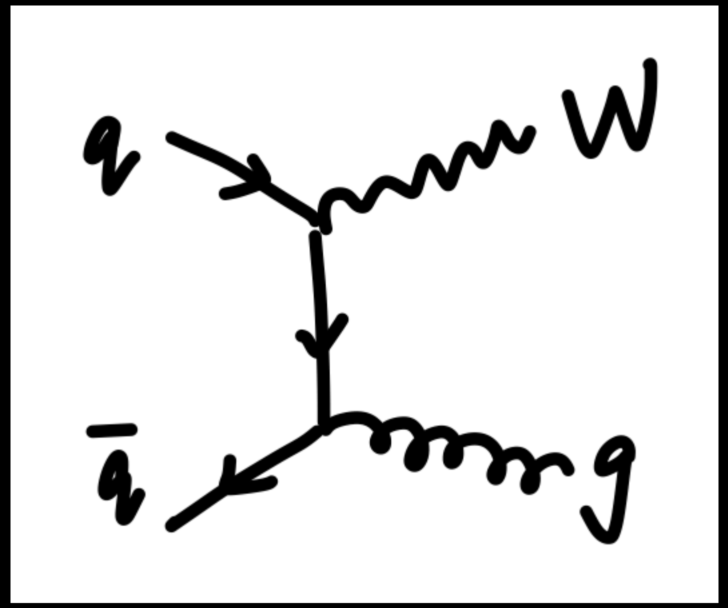
Electron **Muon**



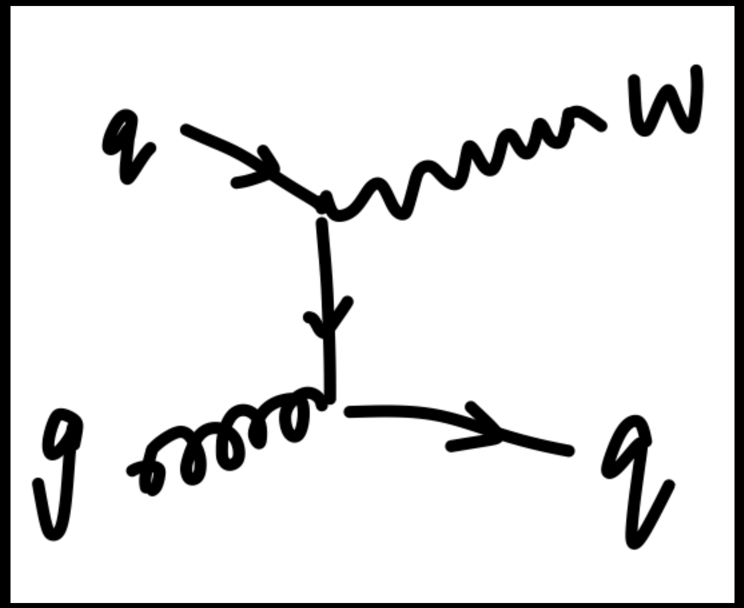
Consistency in two channels and three kinematic fits

Comparison with ATLAS measurement

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



- ATLAS → LHC
  - 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



W mass uncertainty (MeV)

	CDF	ATLAS (7 TeV)
Stat	6.4	6.8
PDF	3.9	9.2
Bkg	3.3	4.5
EW	2.7	5.5
e	3.3	6.4
mu		6.6
recoil	2.5	2.9
QCD	2.2	8.3
Total	9	19

↑

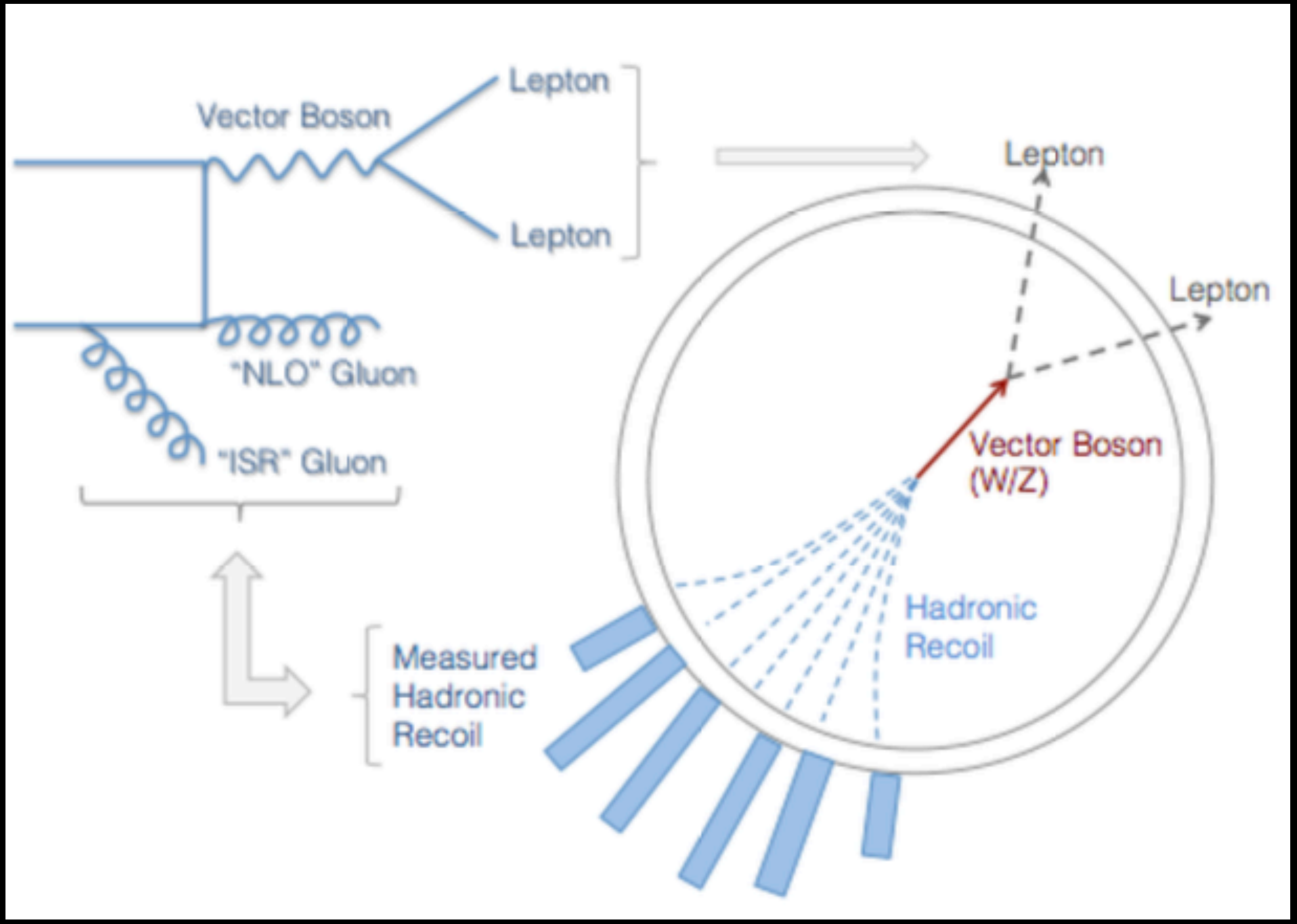
First ATLAS measurement

$< \mu > = 9.1$

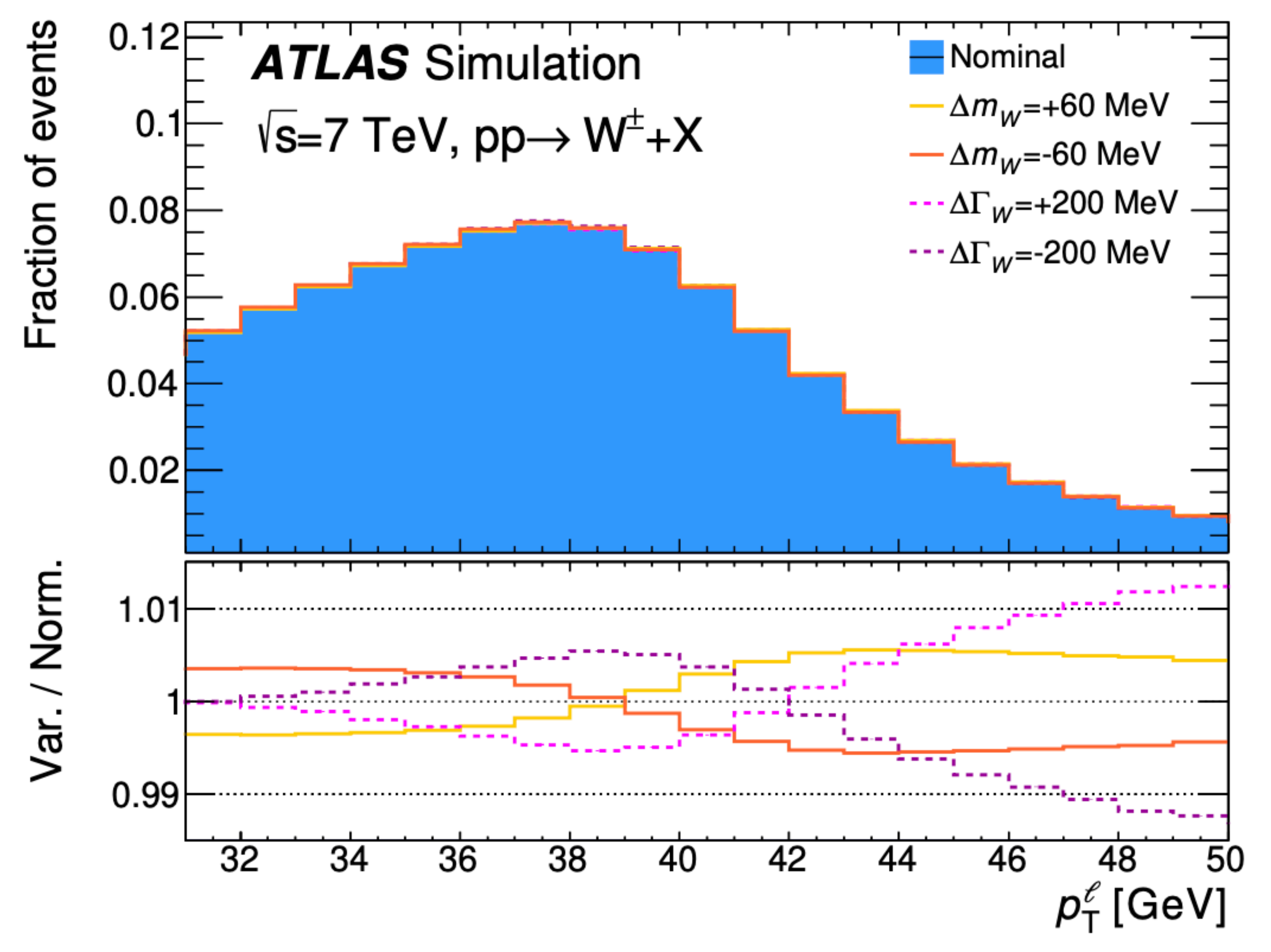
Updated W mass measurement from ATLAS

arXiv:2403.15085

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



M_W shift = ± 60 MeV, width shift = ± 200 MeV



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**

W mass: physics modeling and analysis improvements

Physics modeling

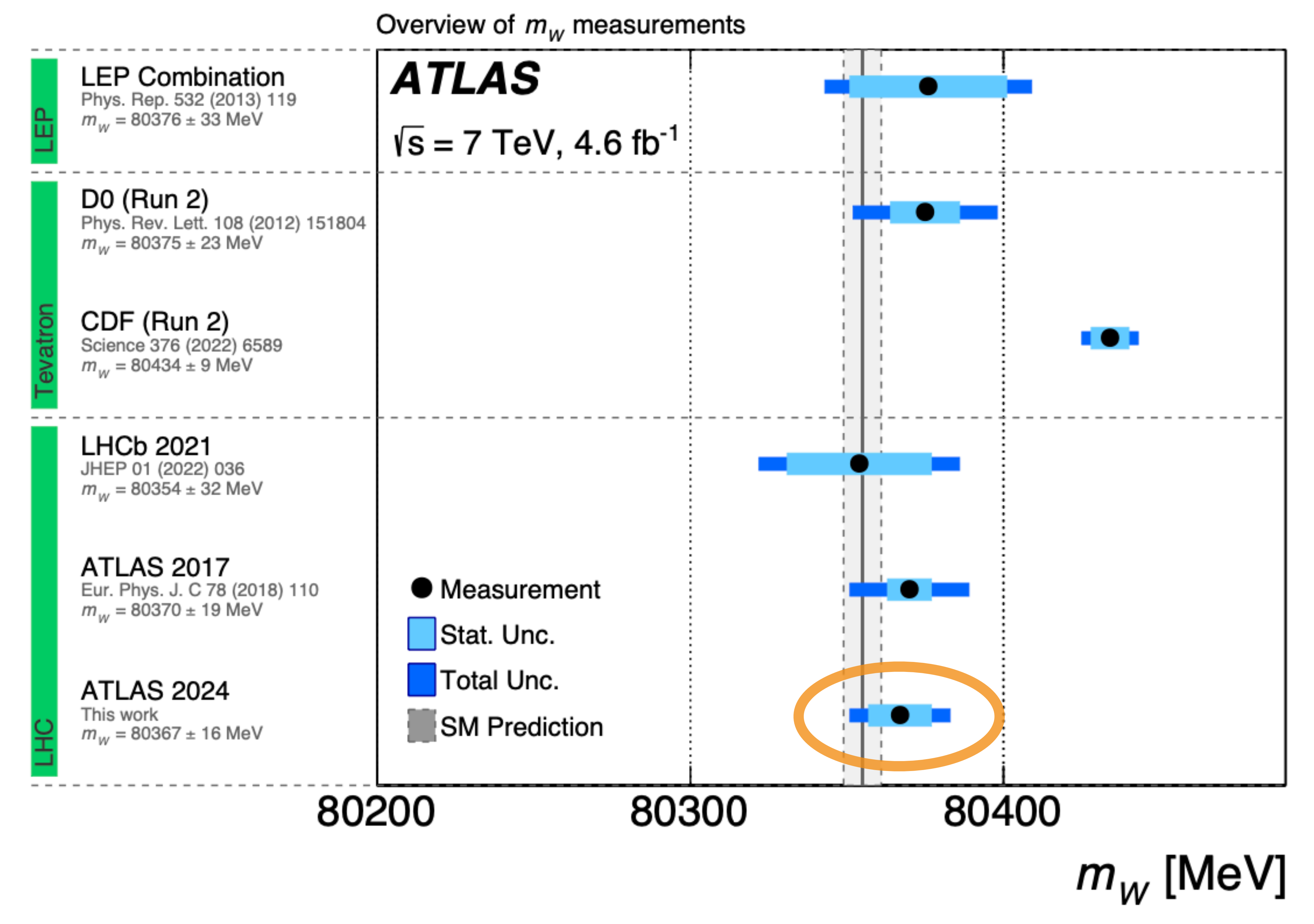
- **Baseline: Pythia AZ tune (based on Z boson)**
  - Z Boson Data, Parton Shower Variations
- **New Verifications:**
  - AZ tune describes hadronic recoil spectrum of W's in low-pileup data at 5 TeV within experimental uncertainties
  - DYTurbo (resumed calculation) also agrees with AZ Tune.
- **Treatment 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

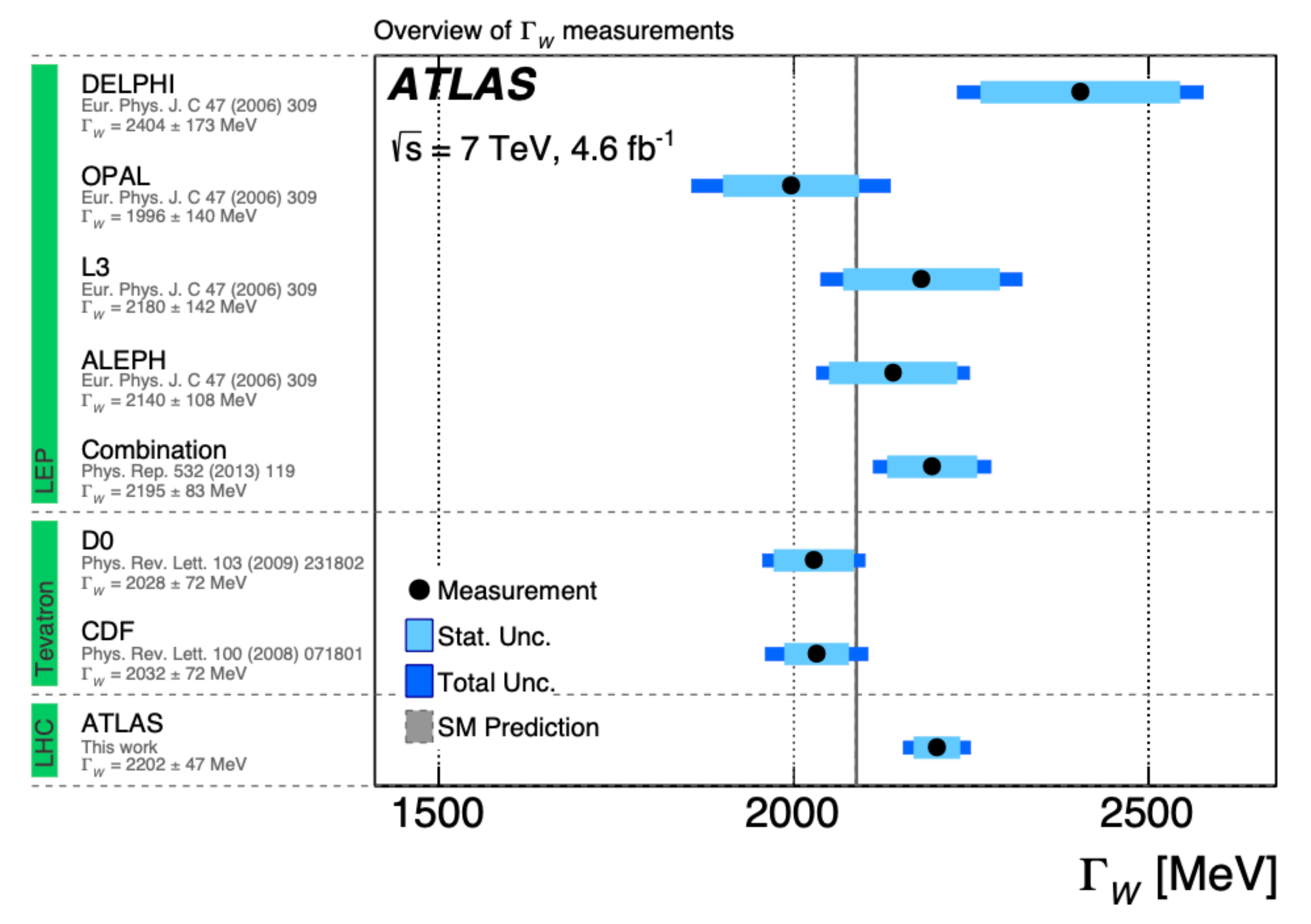
Analysis improvements

- **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**

W mass and width measurements from ATLAS

arXiv:2403.15085





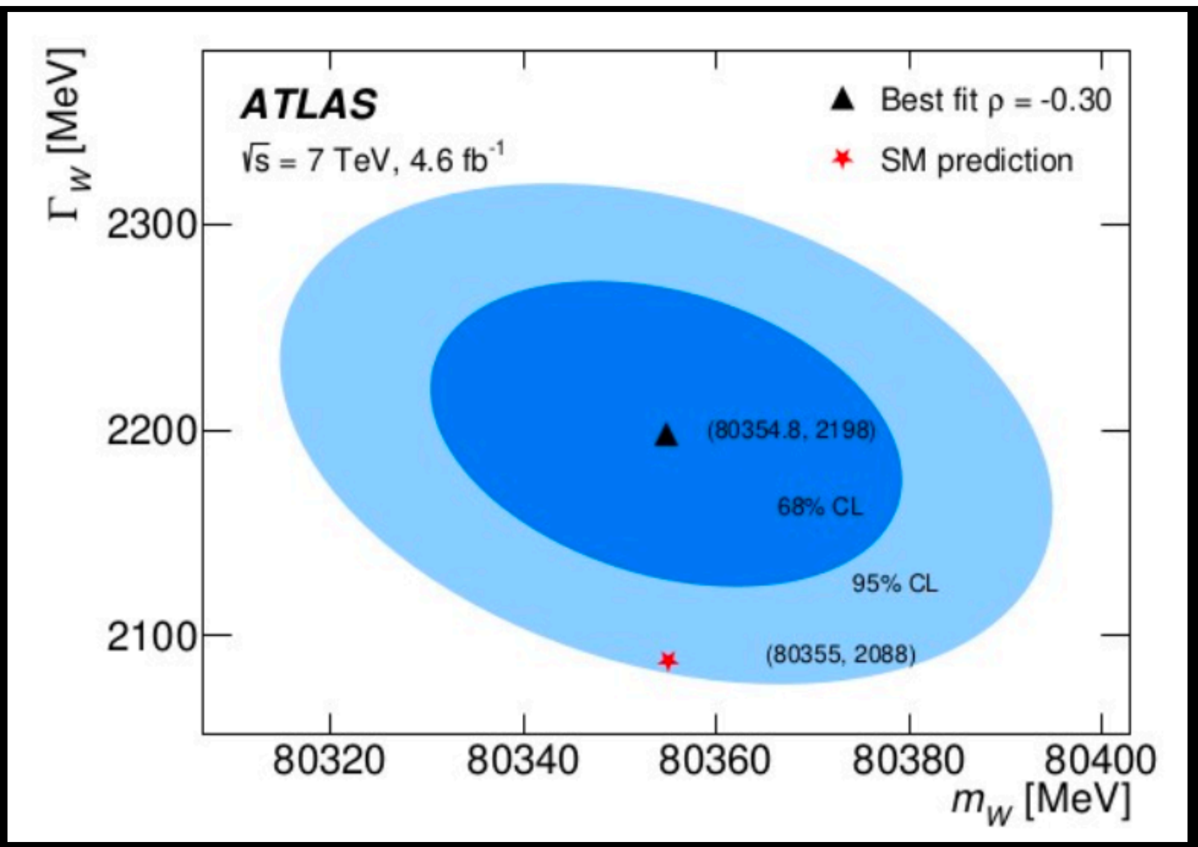
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	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

m_W = 80366.5 ± 15.9 MeV (0.02% uncertainty)

Γ_W = 2202 ± 47 MeV

Most precise single-experiment measurement of Γ_W



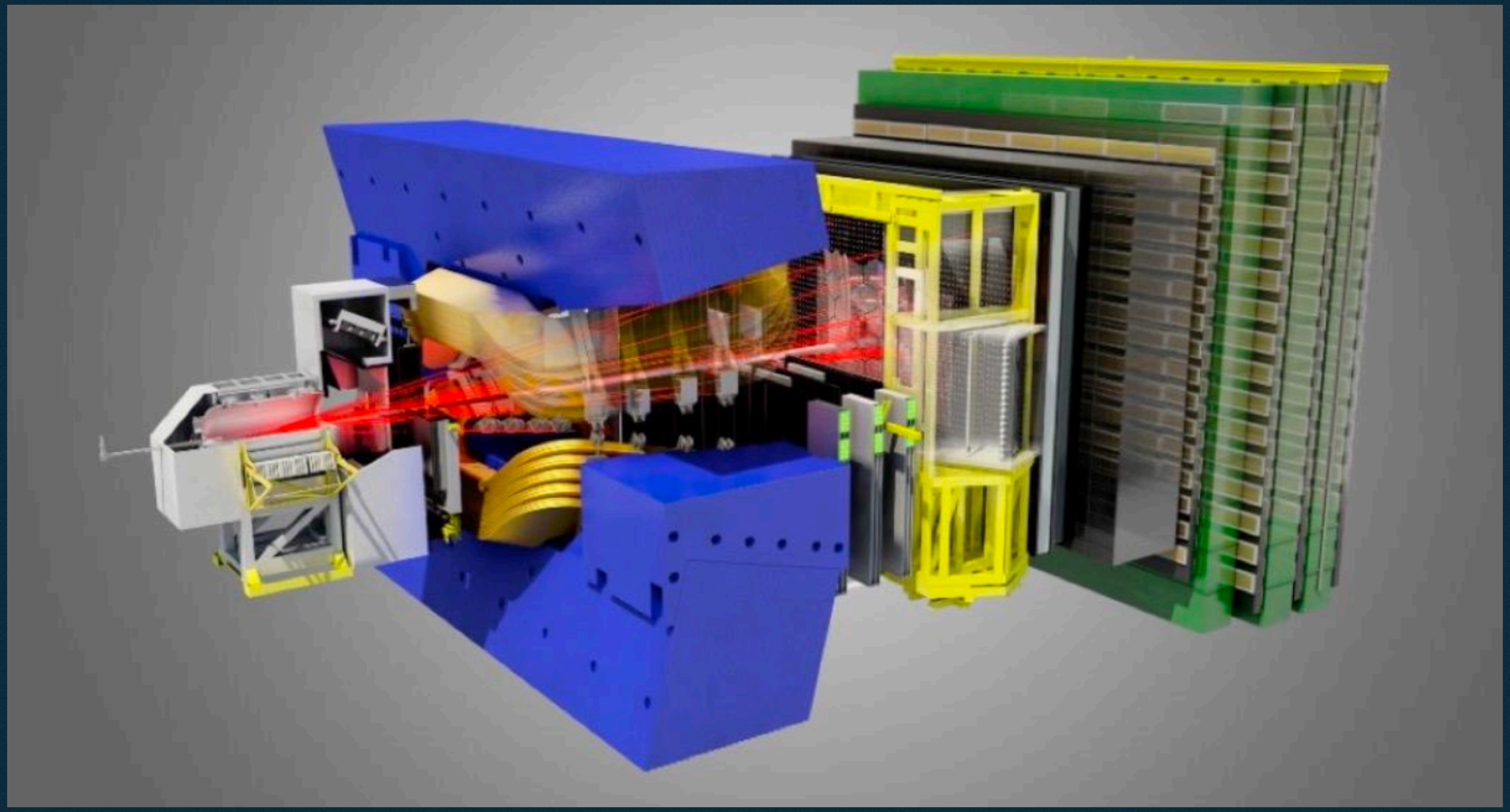
Previous measurement from 2017: m= 80370 ± 19 MeV

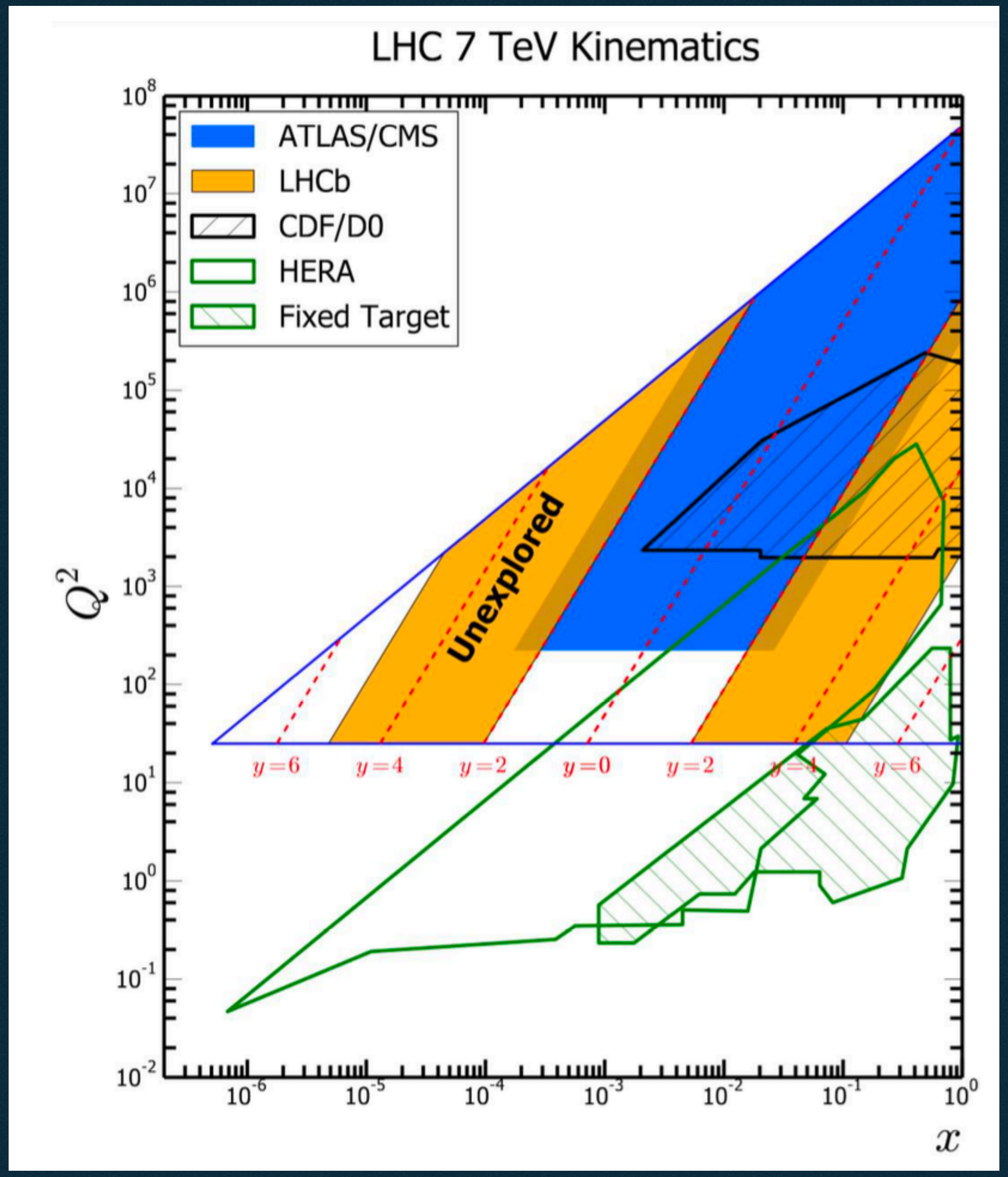
W mass measurements at LHCb

JHEP 01 (2022) 036

W mass determination in the forward acceptance

Strongly suppresses the PDF uncertainty in an LHC m_W average due to complementary geometry





Only a 2016 dataset analysis, with a full Run 2 analysis still possibly coming

$m_W = 80364 \pm 32$ MeV

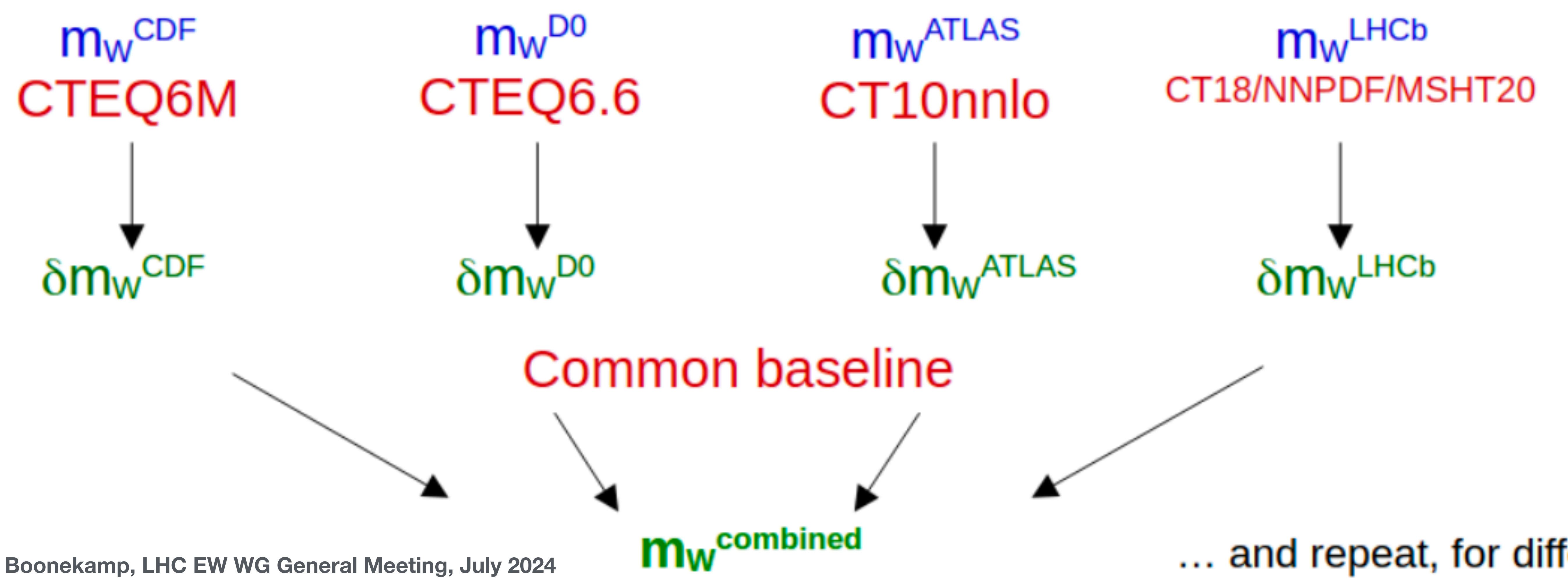
Combination of W mass measurements: ATLAS, LHCb, CDF, DØ

EPJ C (2024) 84:451

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

existing results extrapolated to a common baseline

Two-step procedure
correct to common theory and modeling
combine including correlations (e.g. proton structure)



m_W^{CDF} CTEQ6M → δm_W^{CDF}

m_W^{D0} CTEQ6.6 → δm_W^{D0}

m_W^{ATLAS} CT10nnlo → δm_W^{ATLAS}

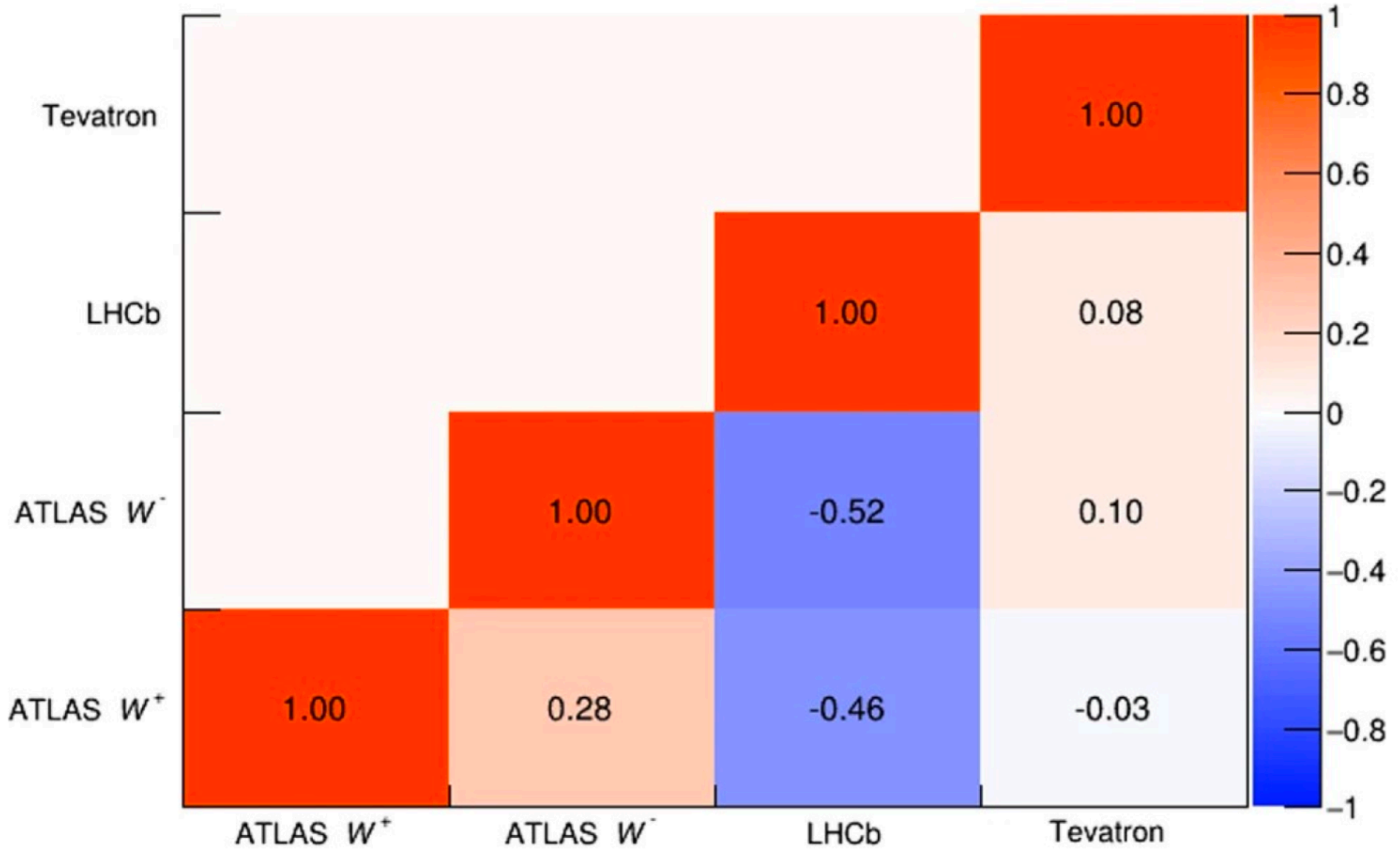
m_W^{LHCb} CT18/NNPDF/MSHT20 → δm_W^{LHCb}

Common baseline

$m_W^{combined}$

… and repeat, for different PDFs

M. Boonekamp, LHC EW WG General Meeting, July 2024



	ATLAS W^+	ATLAS W^-	LHCb	Tevatron
Tevatron				1.00
LHCb			1.00	0.08
ATLAS W^-		1.00	-0.52	0.10
ATLAS W^+	1.00	0.28	-0.46	-0.03

PDF uncertainty correlation matrices for the CT18 PDF set

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

Tension between combination and CDF W mass is of 3.6 σ

First W mass measurement at CMS

CMS-PAS-SMP-23-002

J. Bendavid, CMS CERN seminar

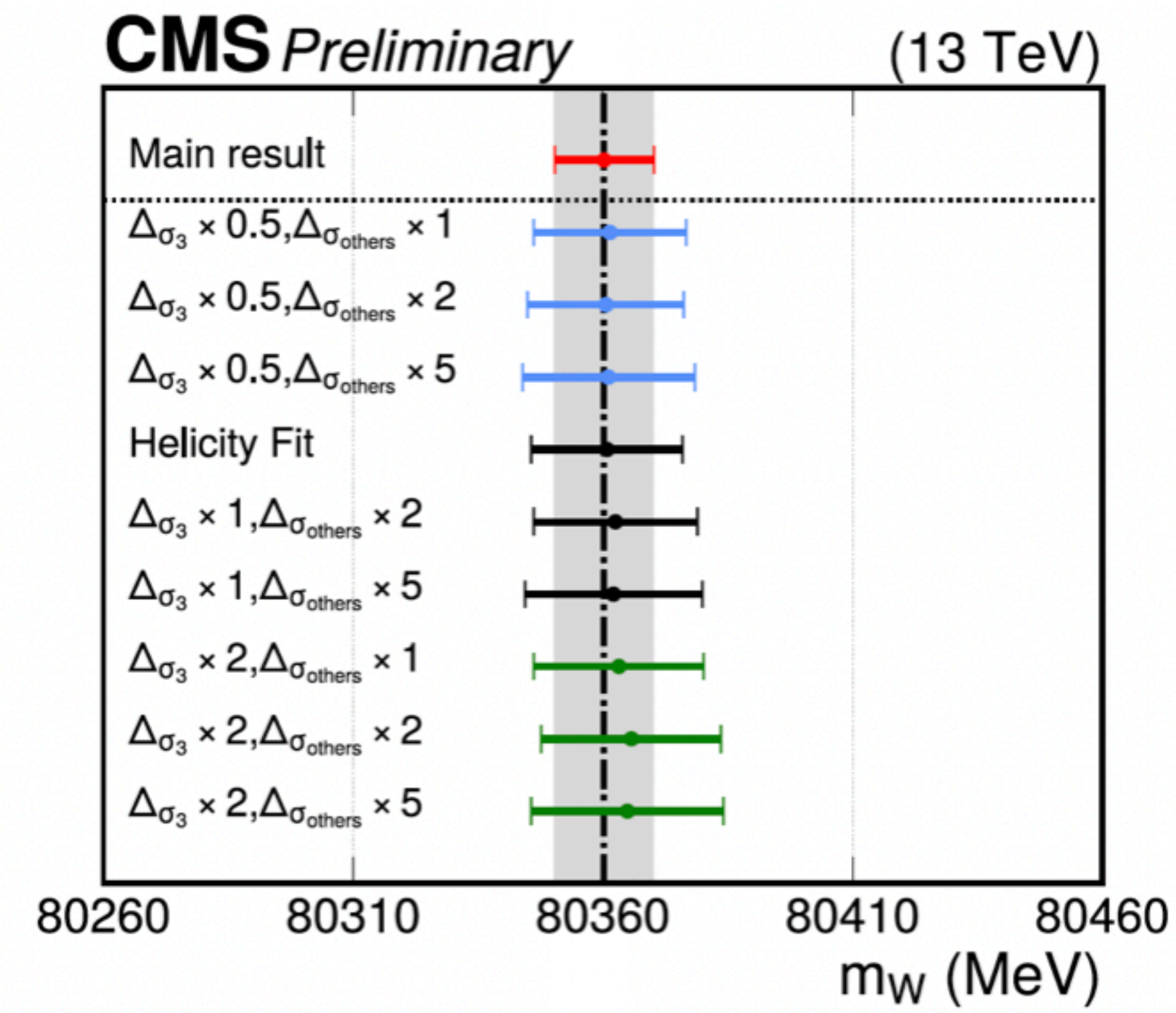
❑ Nominal theory-dependent fit

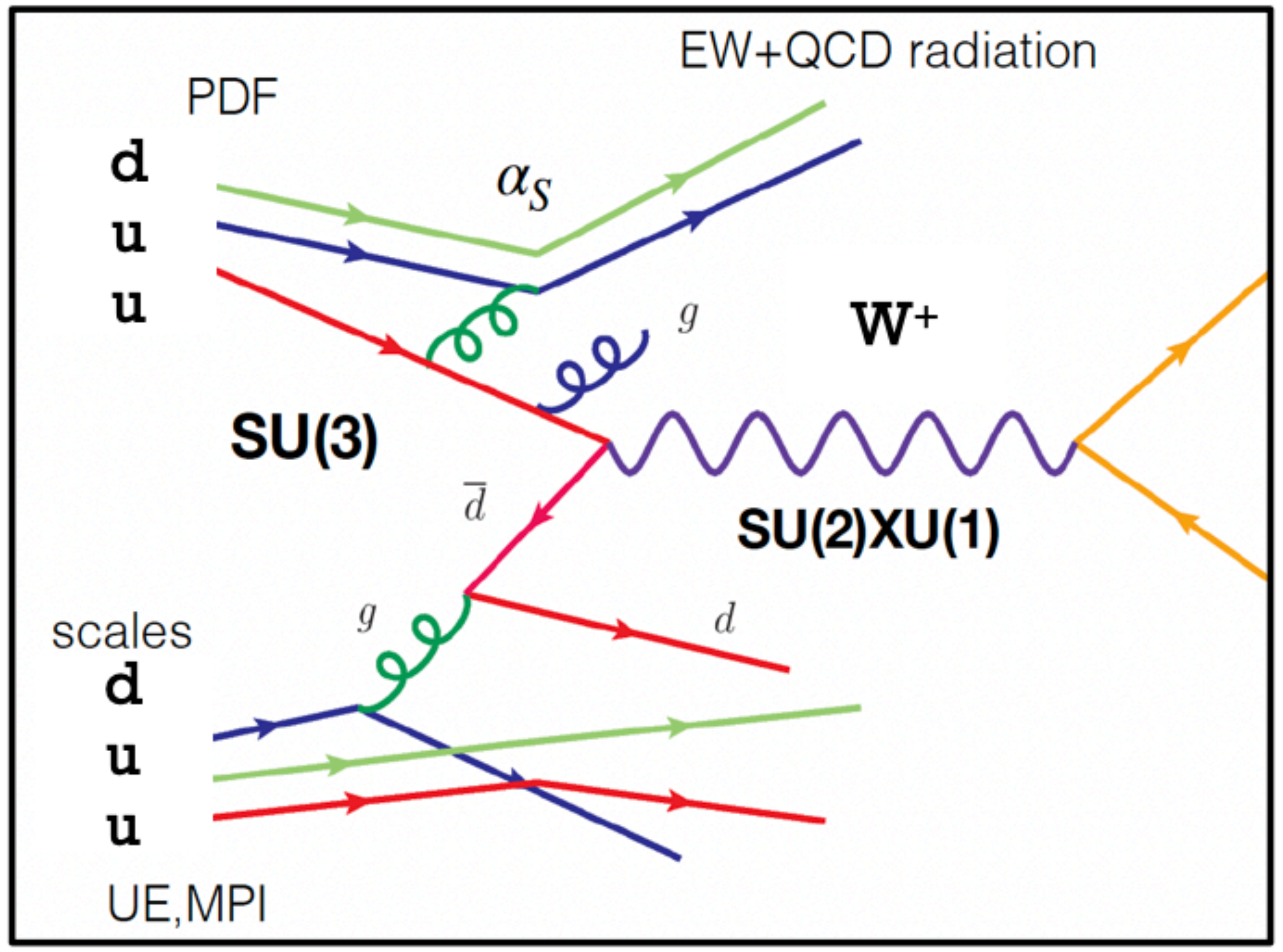
$M_W = 80360.2 \pm 9.9$ MeV

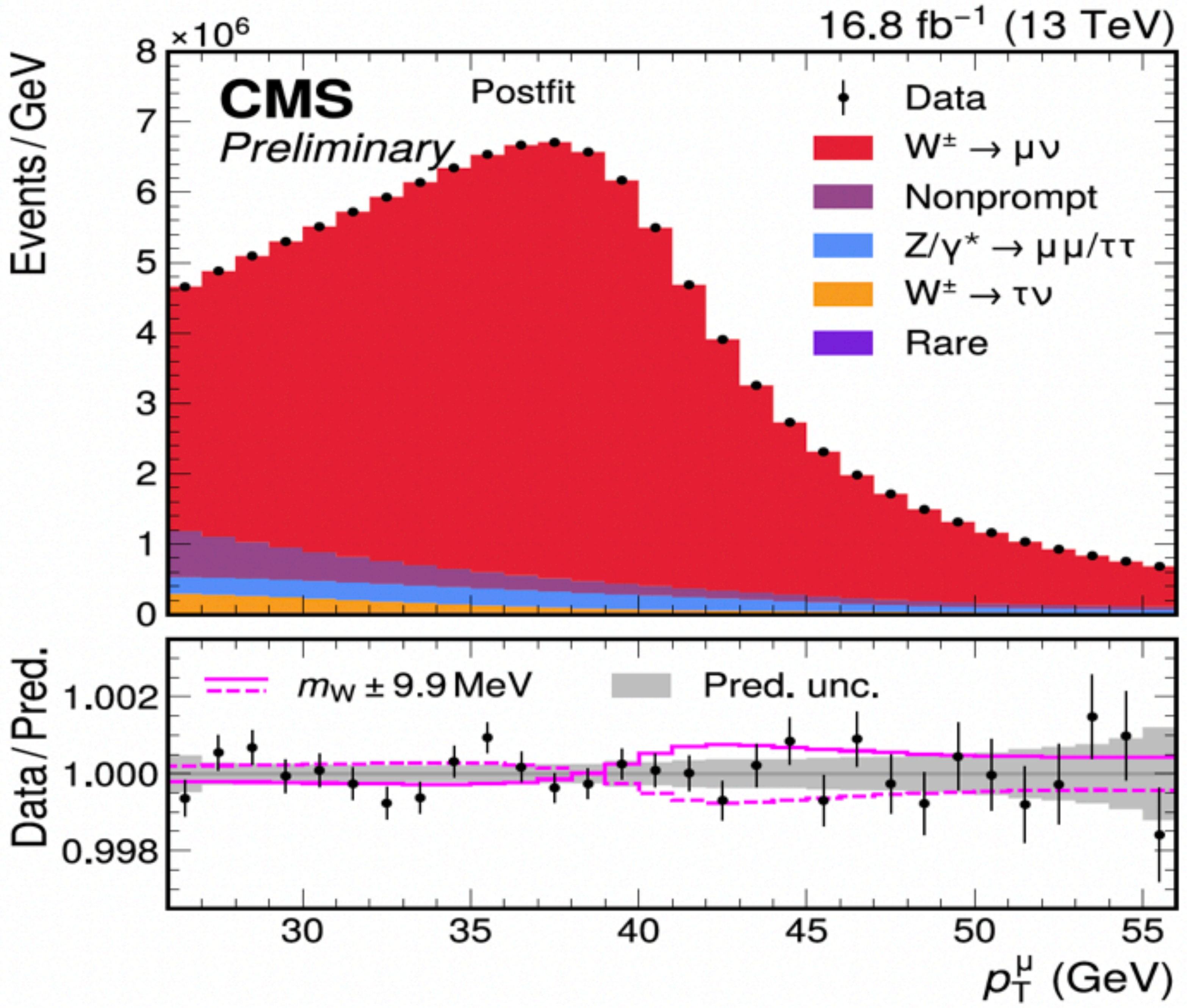
❑ Helicity cross section fit reduced theory uncertainty at the cost of larger statistical unc.

$M_W = 80360.8 \pm 15.2$ MeV

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







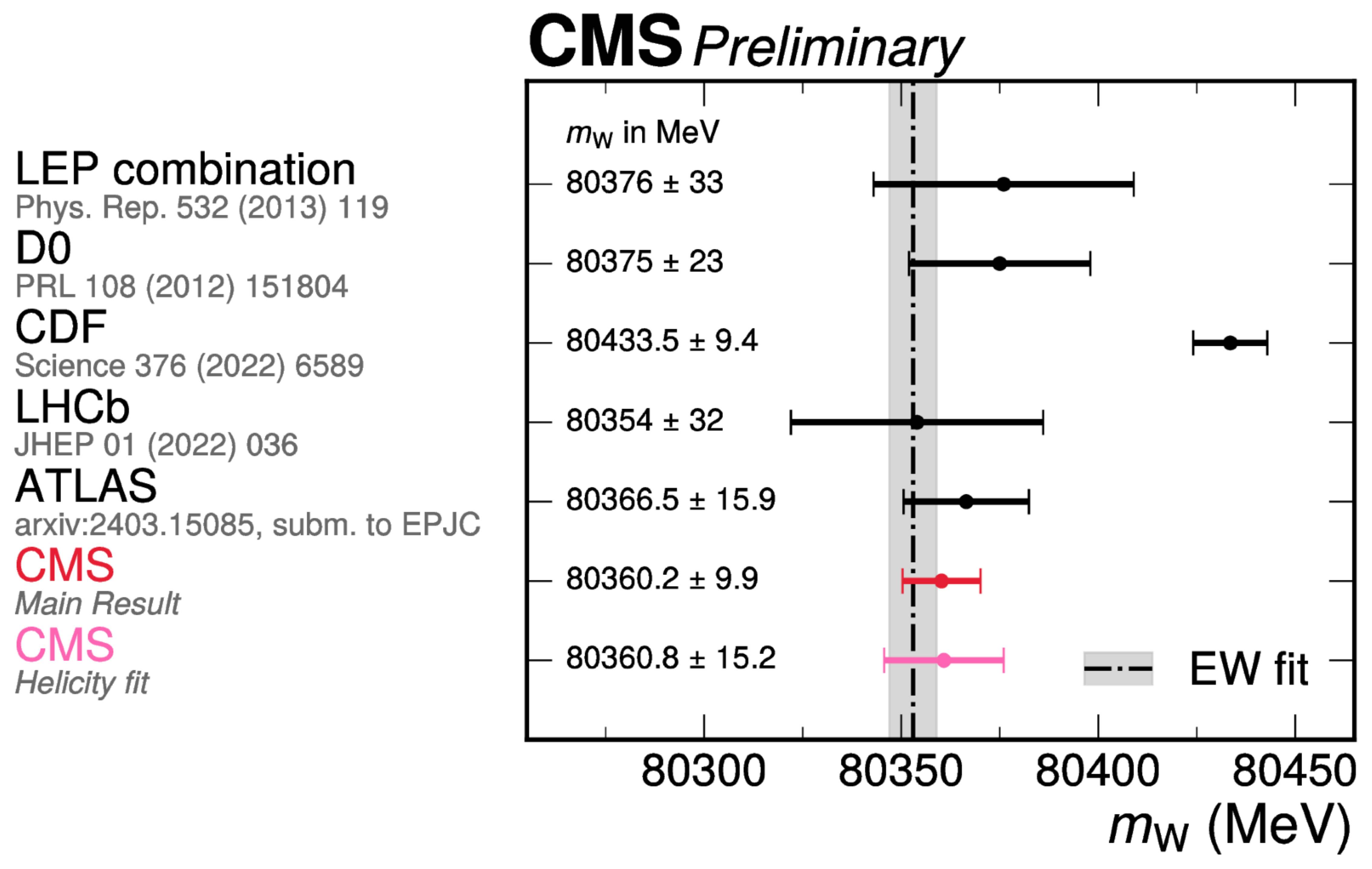
νs forces us to use indirect observables to infer constraints on the mass ⇒ many systematic uncertainties to control

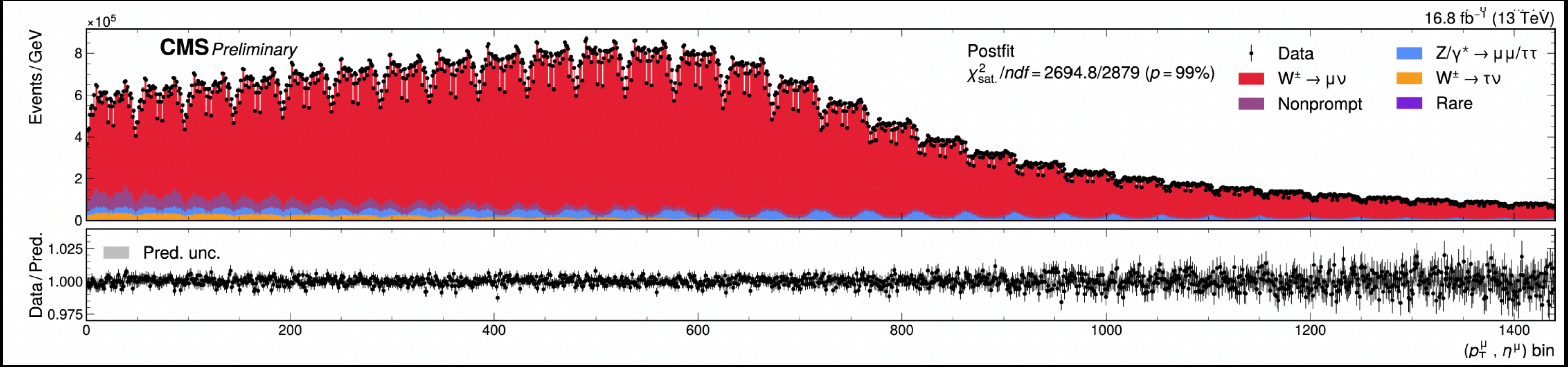
First W mass measurement at CMS

CMS-PAS-SMP-23-002

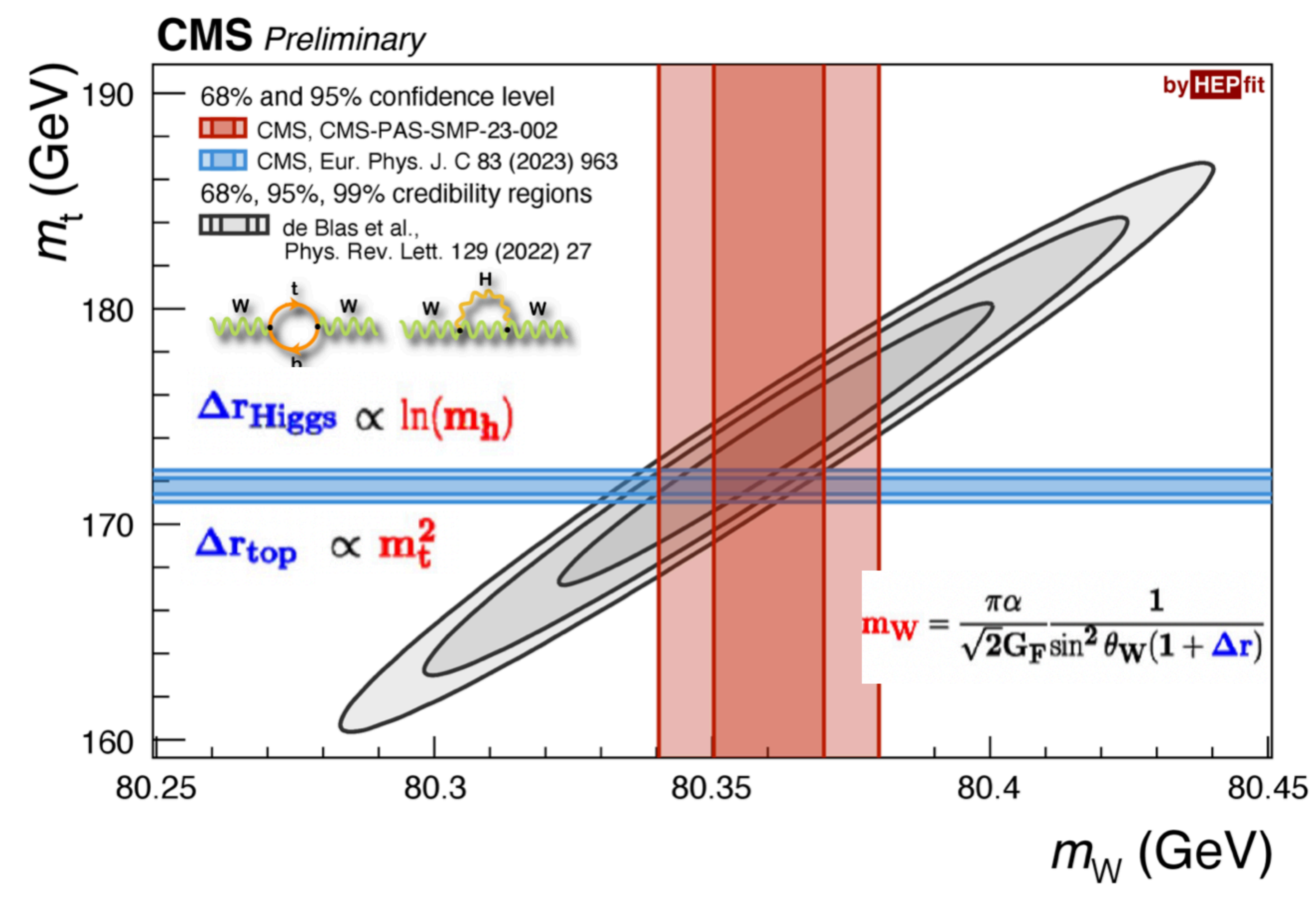
J. Bendavid, CMS CERN seminar

- 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^{-1} from 2016 run (~ 30 pileup)
  - Large sample (>100M) of W→μν
- Theoretical modelling
  - Use most accurate model & uncertainties available
  - Rely on in-situ constraints from the W data itself
- Muon calibration: from *J/ψ*, validated with the Z
- Fit to granular distribution of **p_T^μ** x **η^μ** x **charge**





First W mass measurement at CMS



W mass uncertainty (MeV)

	ATLAS, 7 TeV re-analysis	CMS
Stat	9.8	7.1
PDF	5.7	2.8
Bkg	2.0	1.7
EW	5.4	1.9
e	6.0	-
mu	5.4	5.0
recoil	2.3	-
QCD	4.4	3.1
Total	**16 MeV**	**9.9 MeV**

Measurement is performed with ~10% of Run 2 data

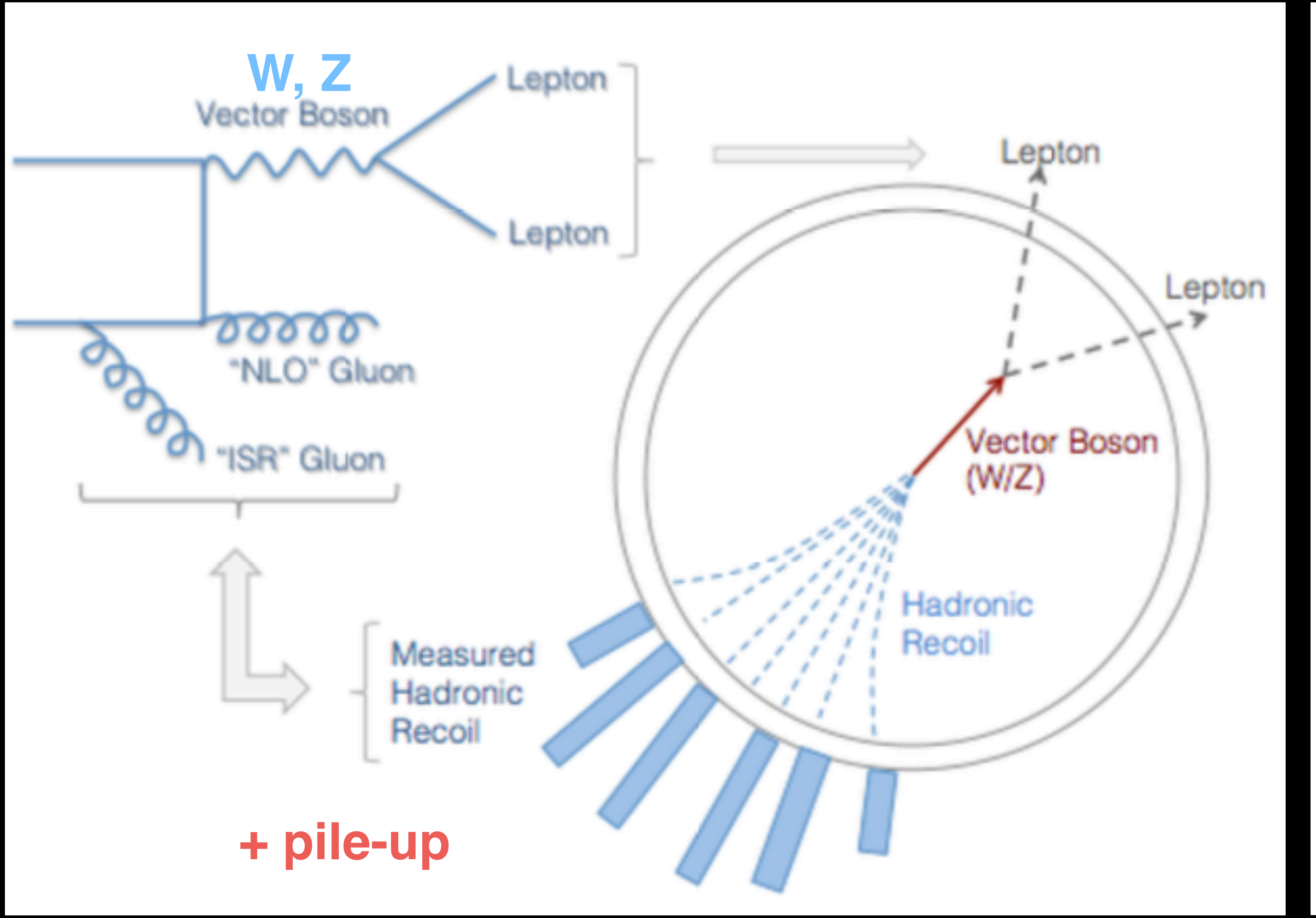
m_W = 80360.2 ± 9.9 MeV

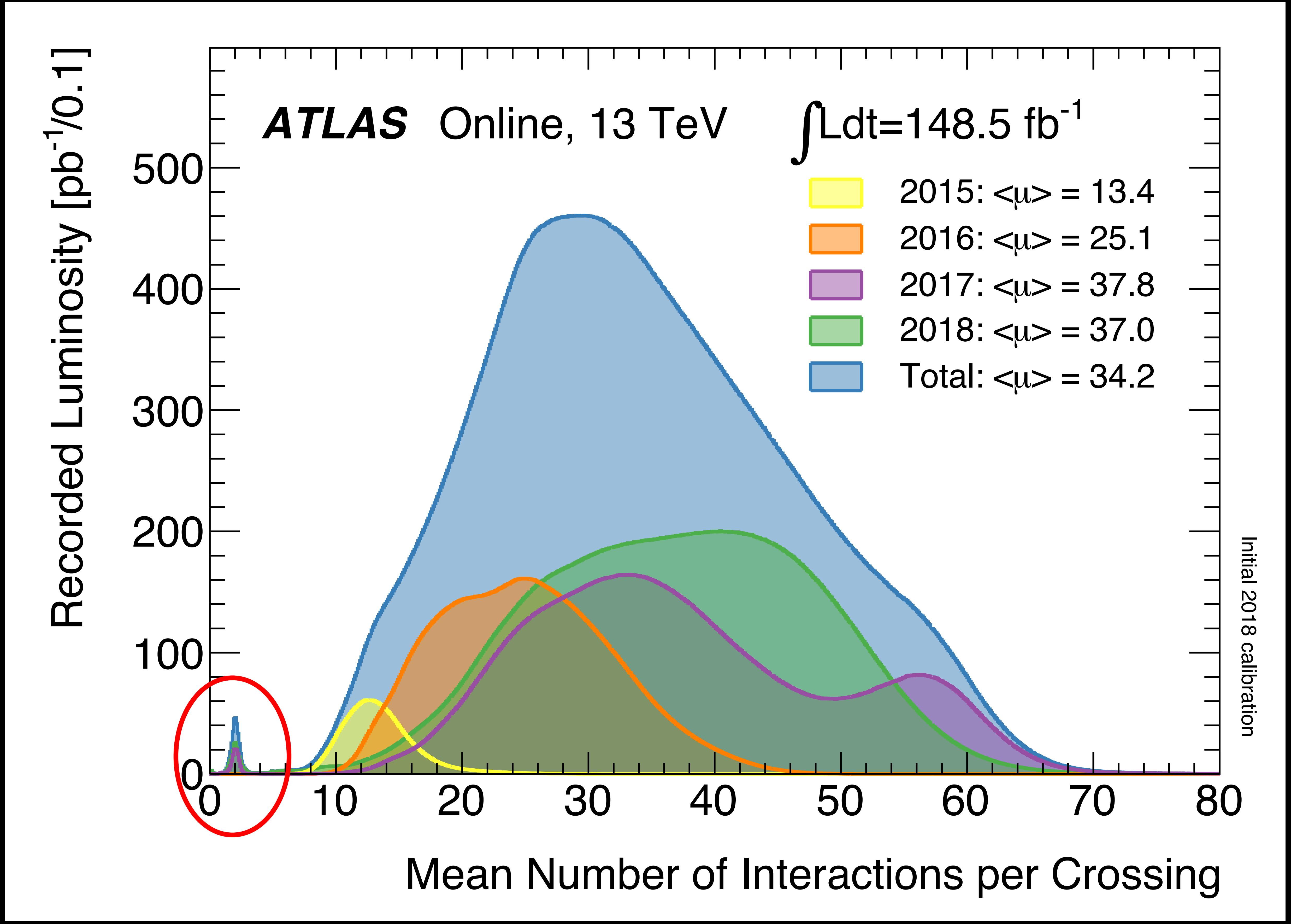
Exploit state-of-the-art improvements in theoretical QCD & EW calculations & uncertainty modeling, in-situ constraints from data…

W boson measurements in low-pileup dataset from ATLAS

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

ATLAS-CONF-2023-028





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

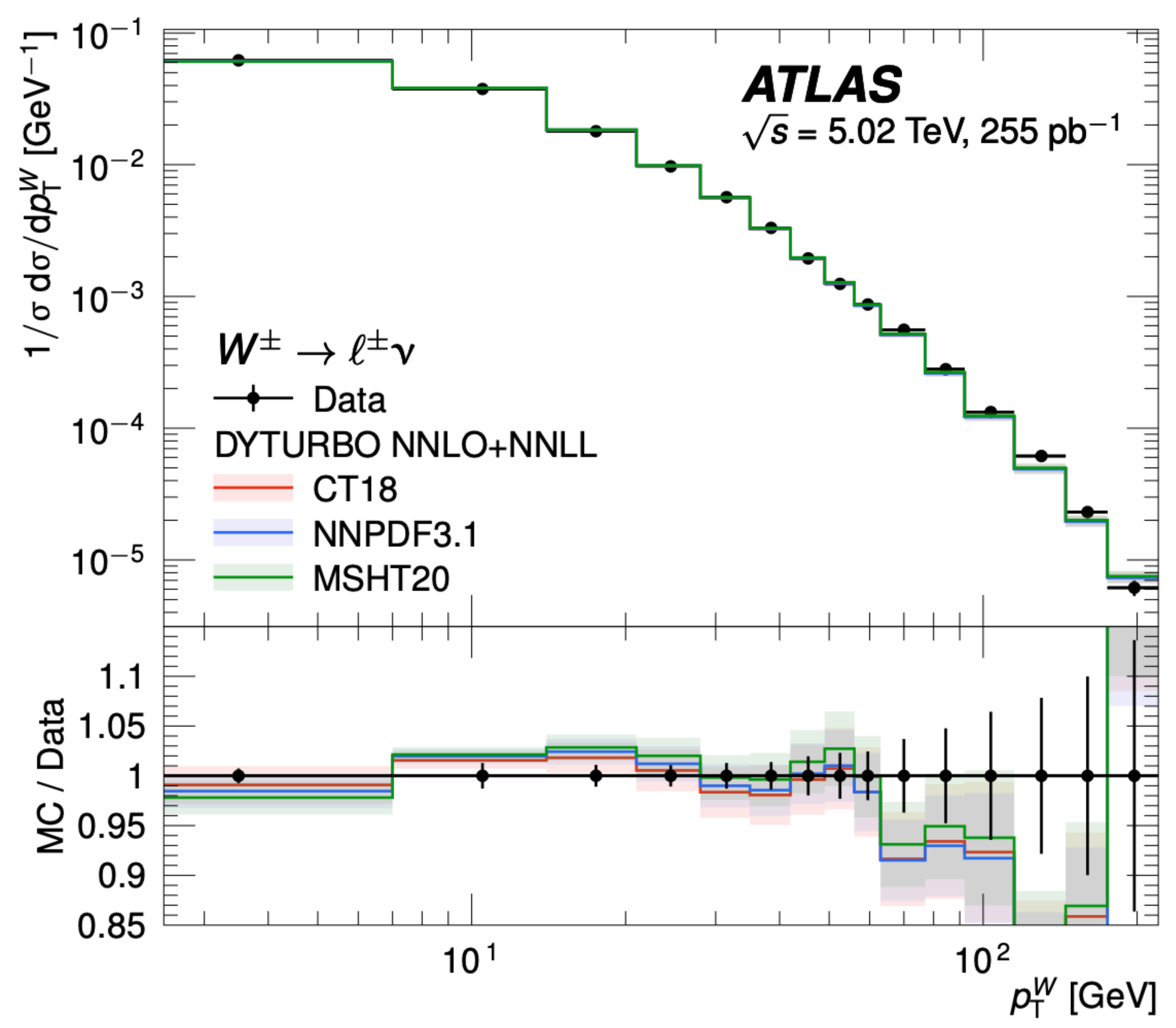
Precise measurements of W and Z transverse momentum spectra at 5 and 13 TeV

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

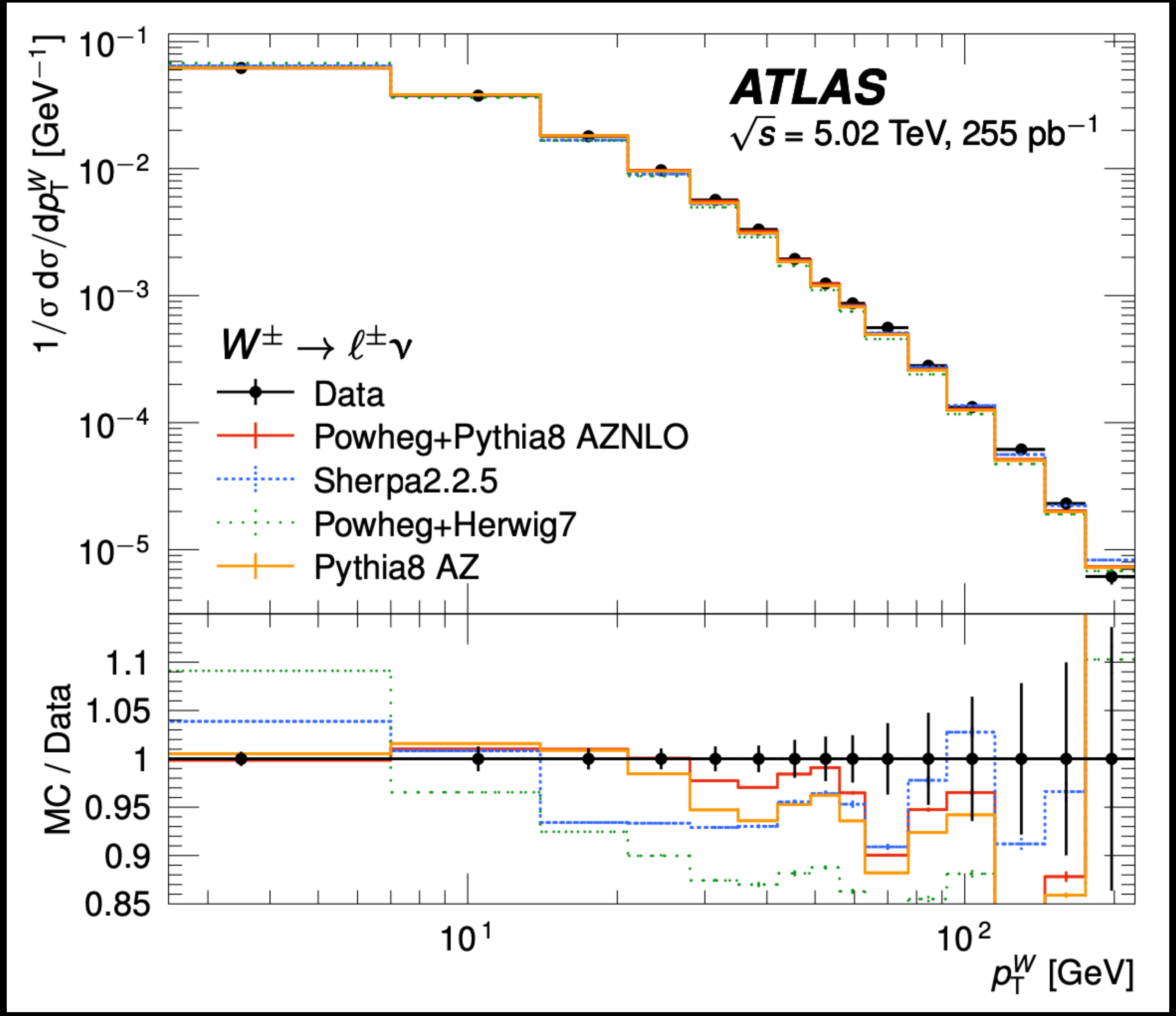
Precise measurements and predictions of the spectra for $p_T < \sim 30$ GeV are particularly interesting for future measurement of the W-boson mass at LHC

$\sqrt{s}$ = 5 TeV

Compared to DYTURBO predictions with different PDF sets



Compared with different MC predictions



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

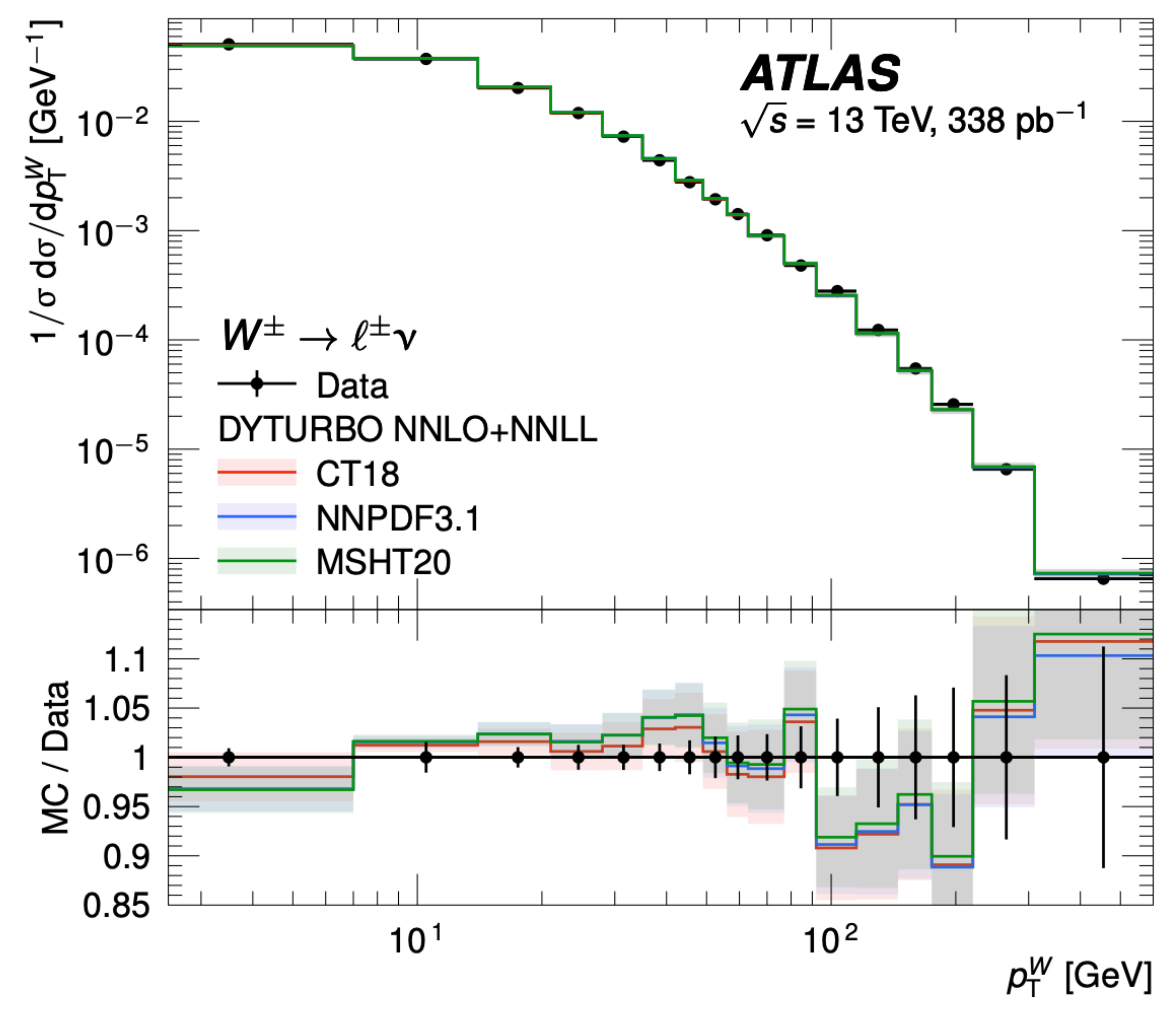
Precise measurements of W and Z transverse momentum spectra at 5 and 13 TeV

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

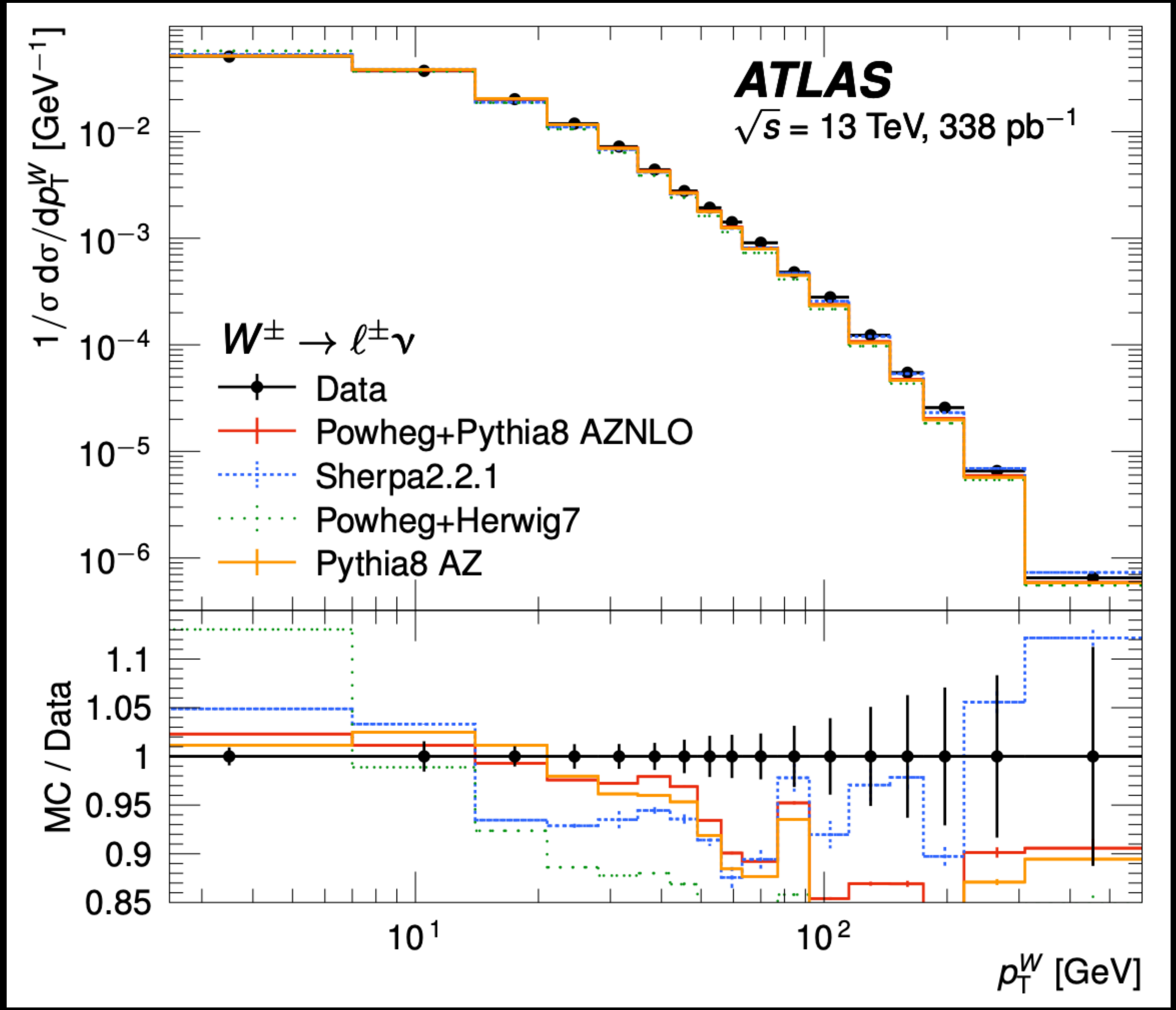
Precise measurements and predictions of the spectra for $p_T < \sim 30$ GeV are particularly interesting for future measurement of the W-boson mass at LHC

$\sqrt{s}$ = 13 TeV

Compared to DYTURBO predictions with different PDF sets



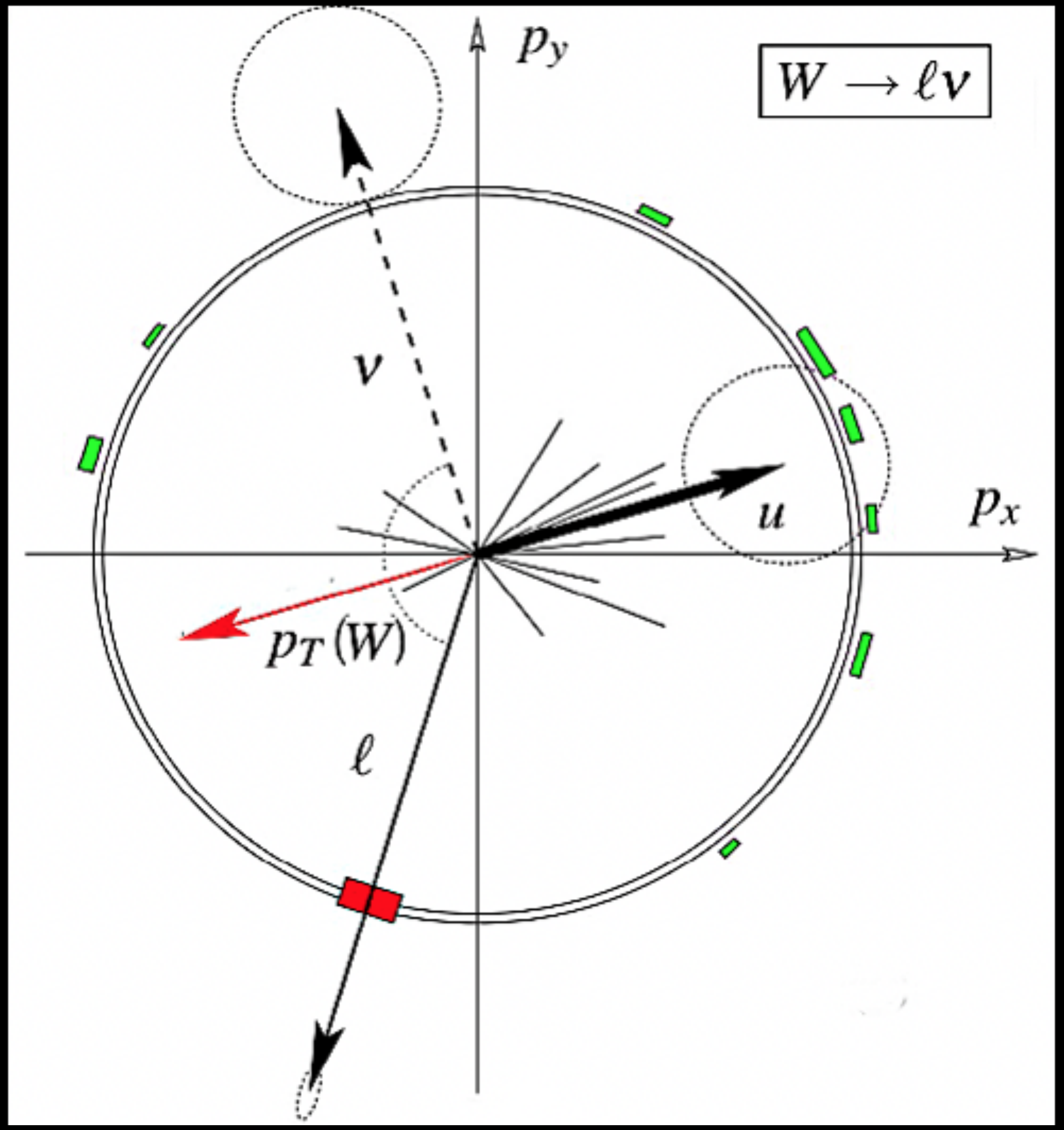
Compared with different MC predictions



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

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 → better m_T measurement
- Improved theoretical uncertainties:
  - Updated PDF distribution
  - Updated QCD modeling
  - Updated Electroweak modeling
- Limited by statistical uncertainty
  - 5 TeV: 255 pb^{-1}
  - 13 TeV: 338 pb^{-1}

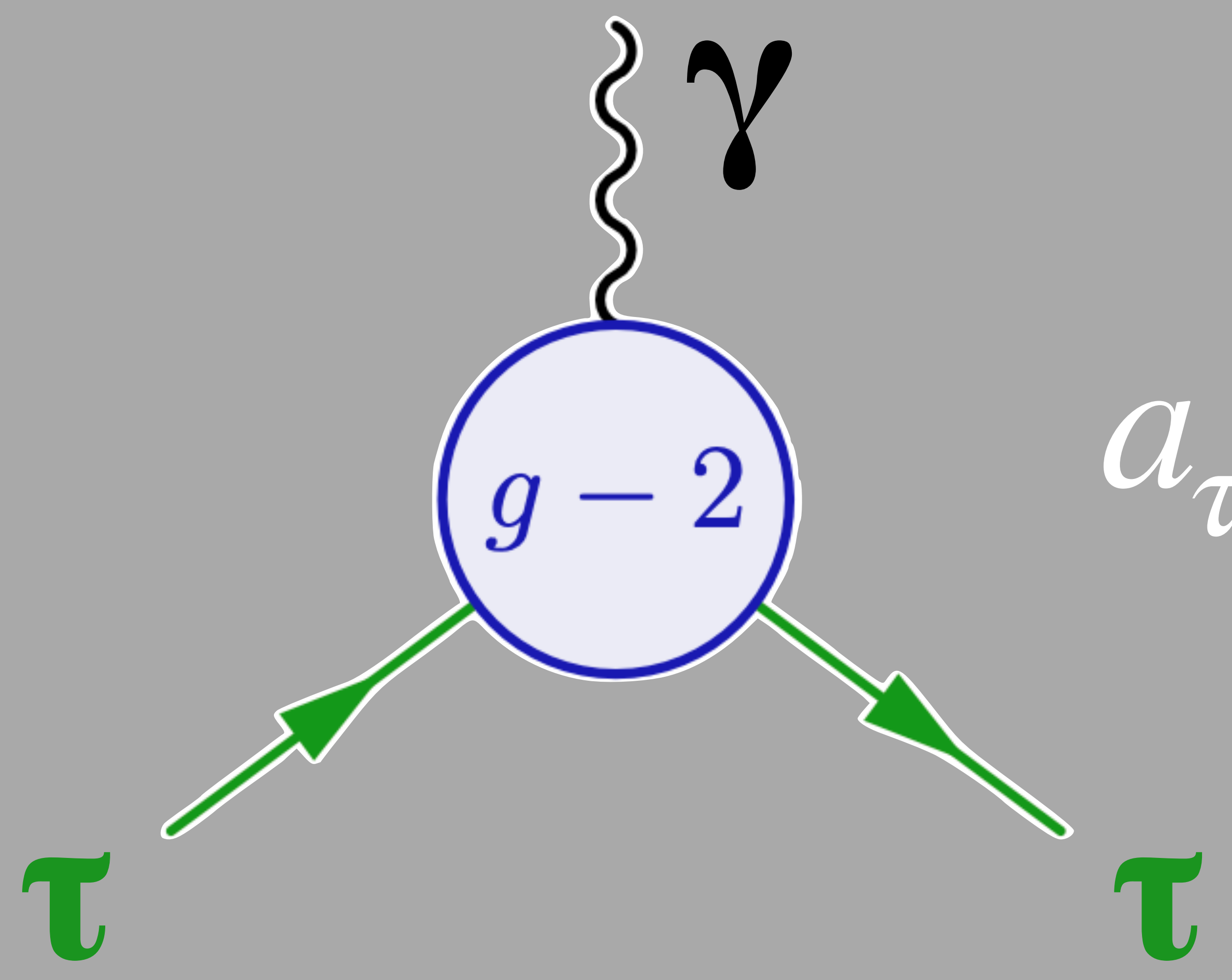


Uncertainty low-pileup analysis: ~ 15 MeV

Combination with 7 TeV: ~ 10 MeV

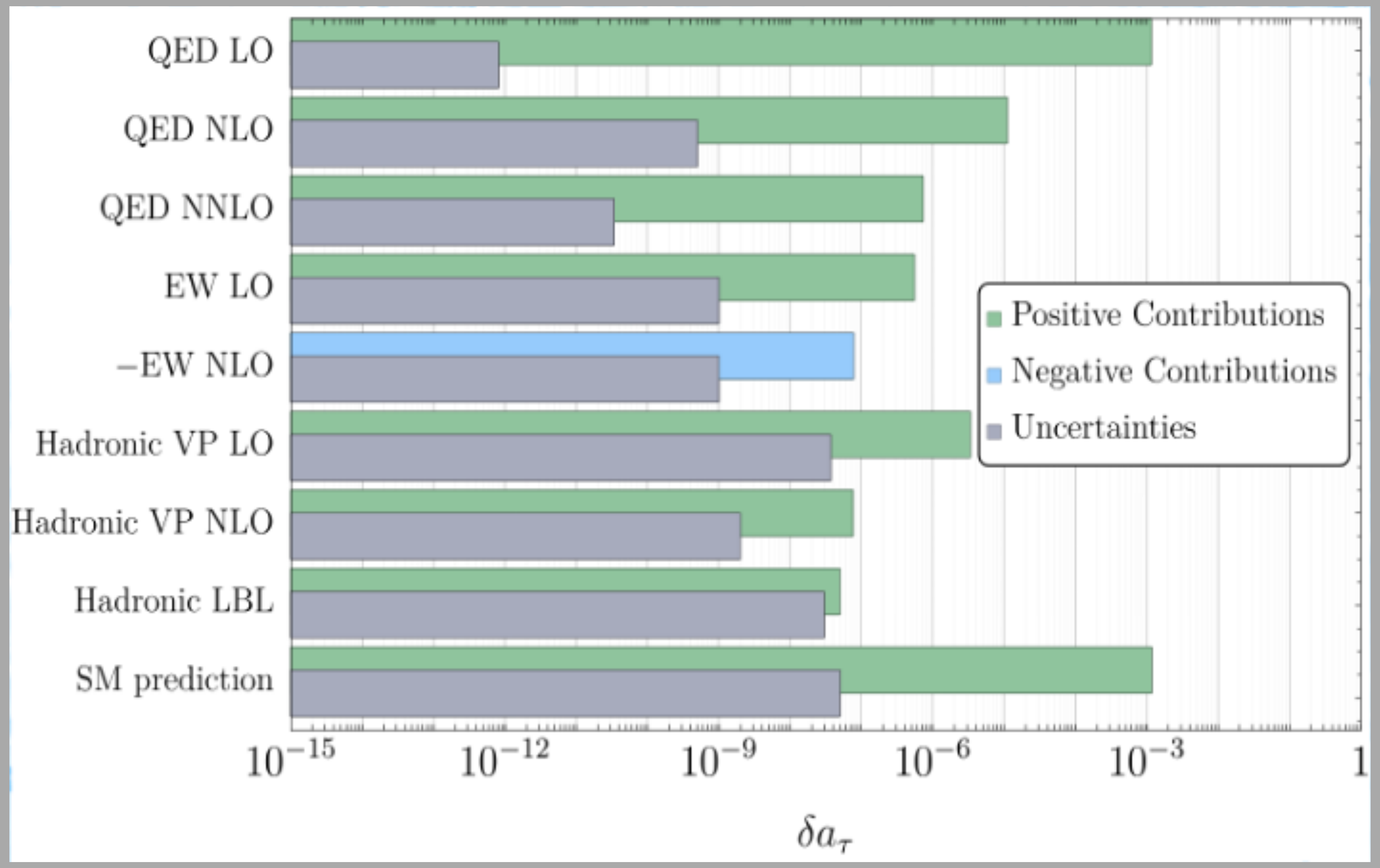
Anomalous magnetic moment g-2 of the tau lepton

Sensitive to new physics in the γττ vertex



$$a_\tau = \frac{g-2}{2} \approx \frac{\alpha}{2\pi}$$

Tau (g-2) in the Standard Model



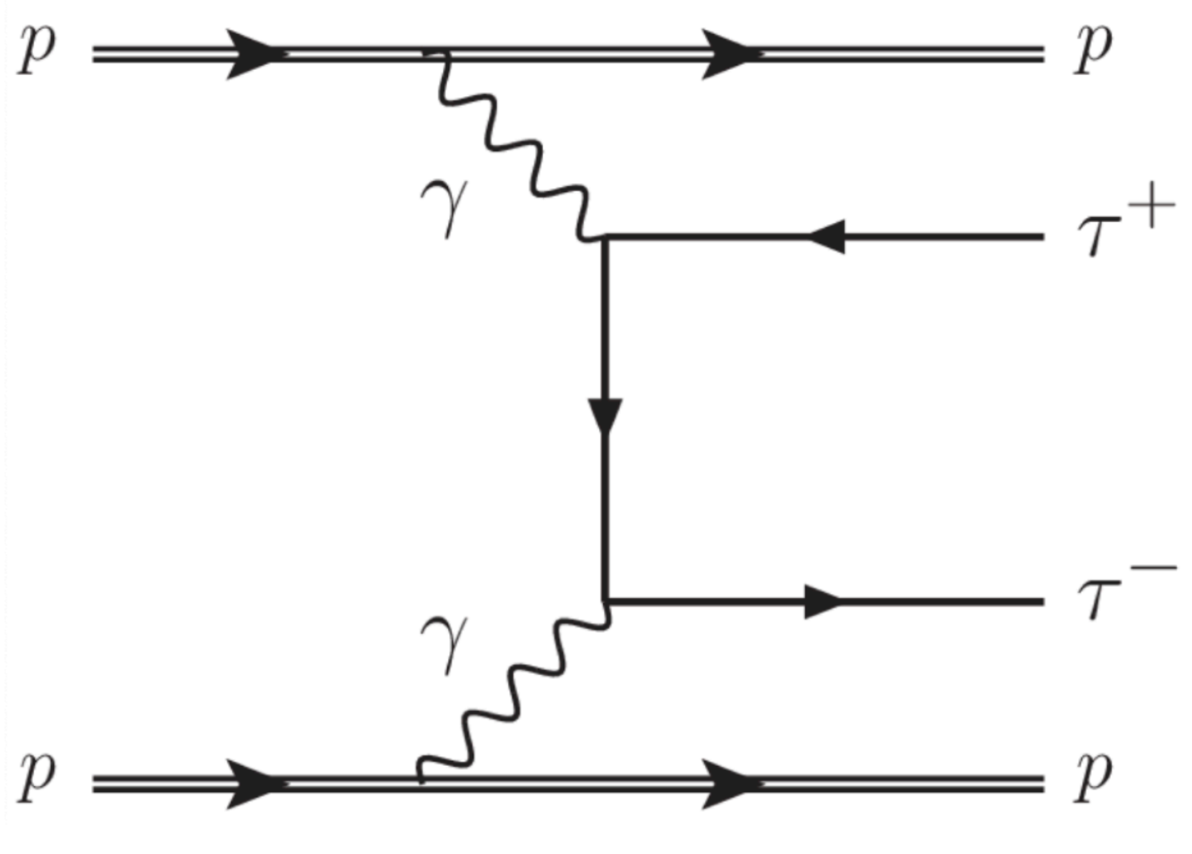
g-2 of tau lepton: $\gamma\gamma \to \tau\tau$

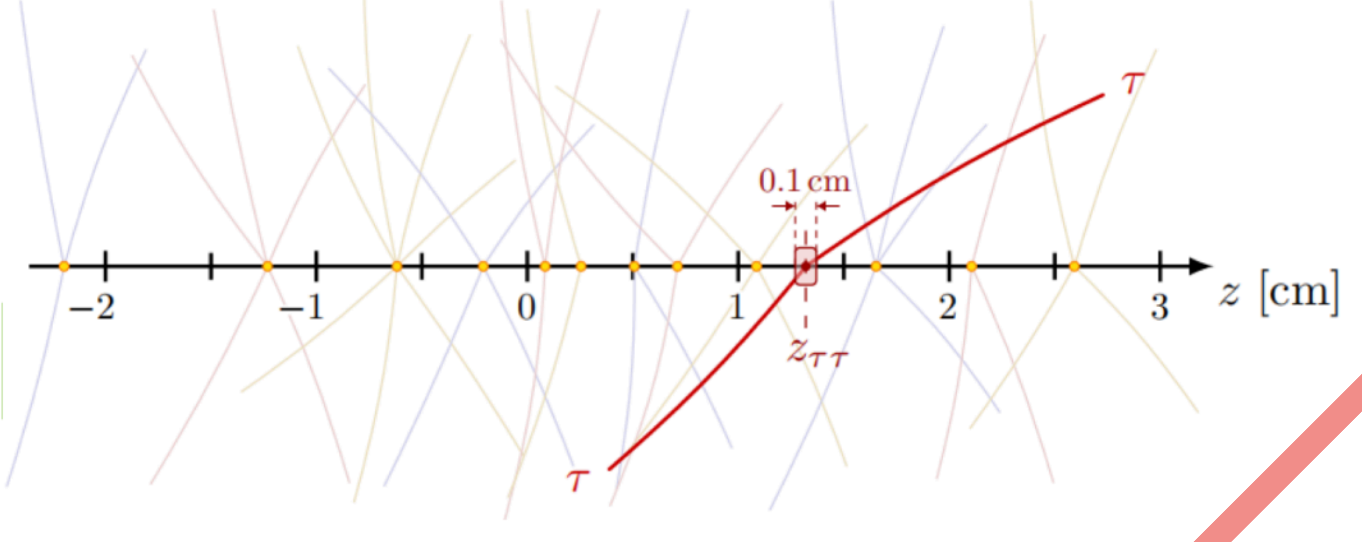
Detailed overview by Dayong Wang, Friday Plenary

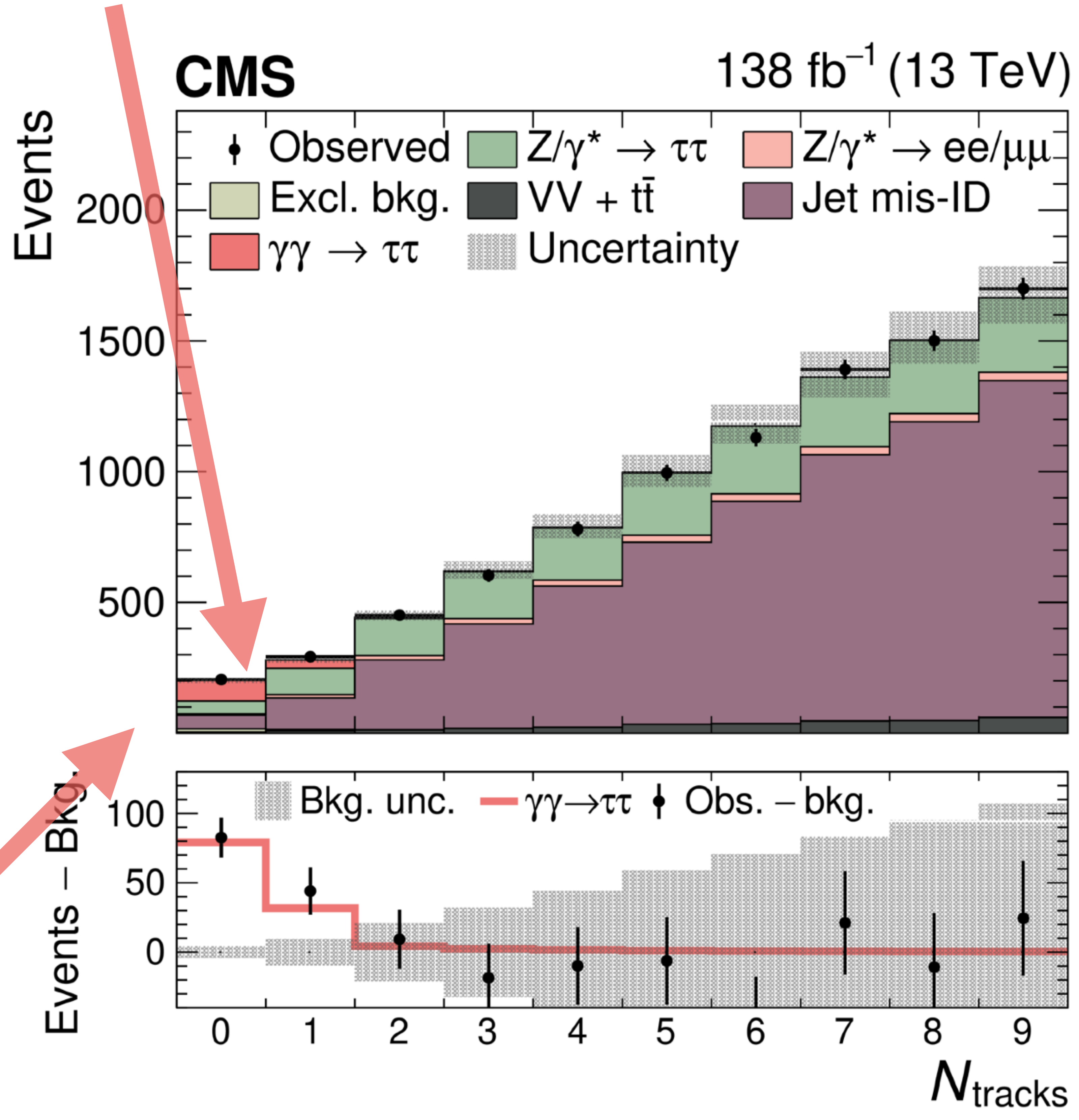
Rep. Prog. Phys. 87 (2024) 107801

First observation of $\gamma\gamma \to \tau\tau$ in pp collisions

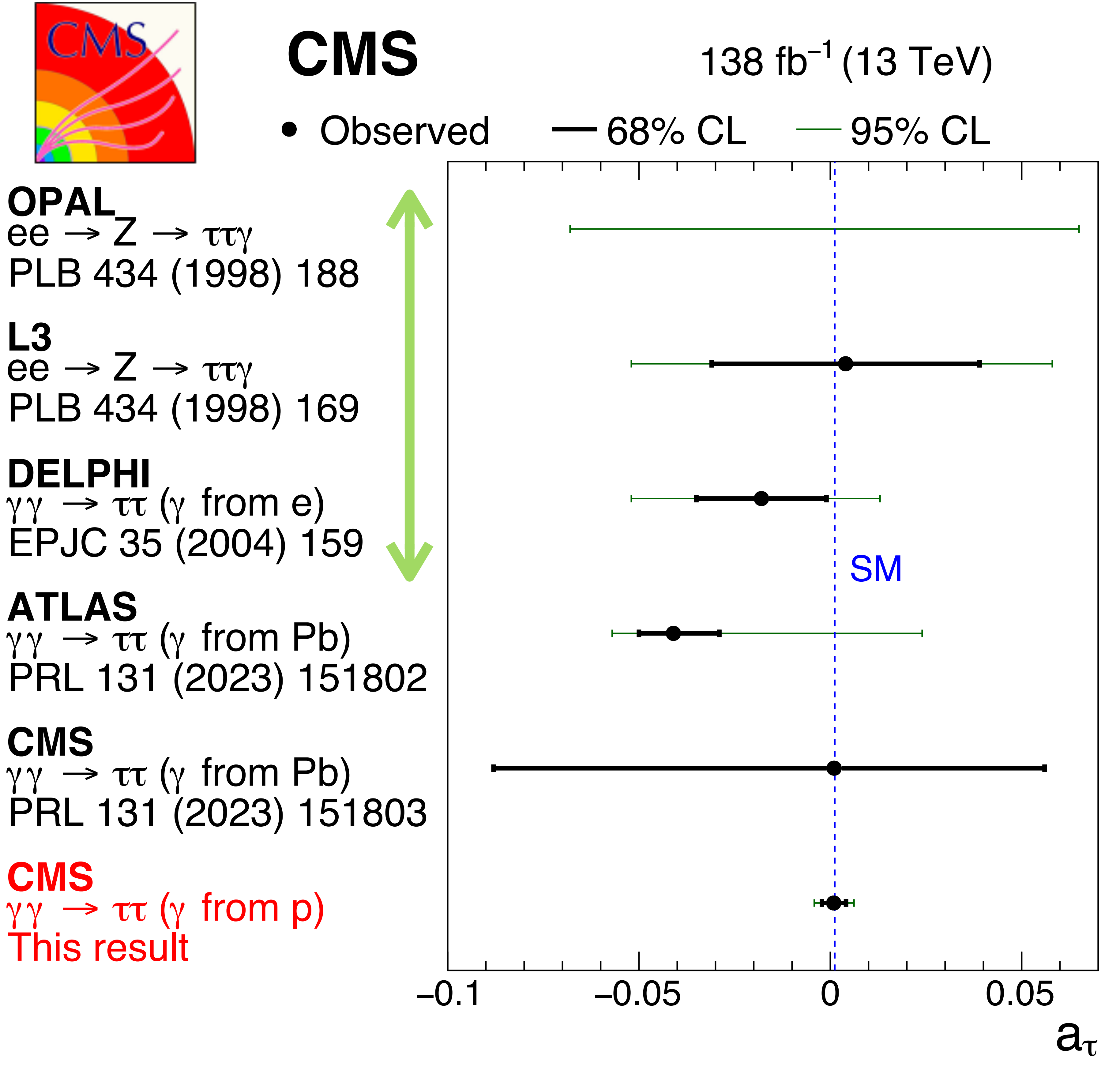
5.3σ observed







$N_{\text{Tracks}} = 0$ or 1



Observed: $a_\tau = 0.9^{+3.2}_{-3.1} \times 10^{-3}$

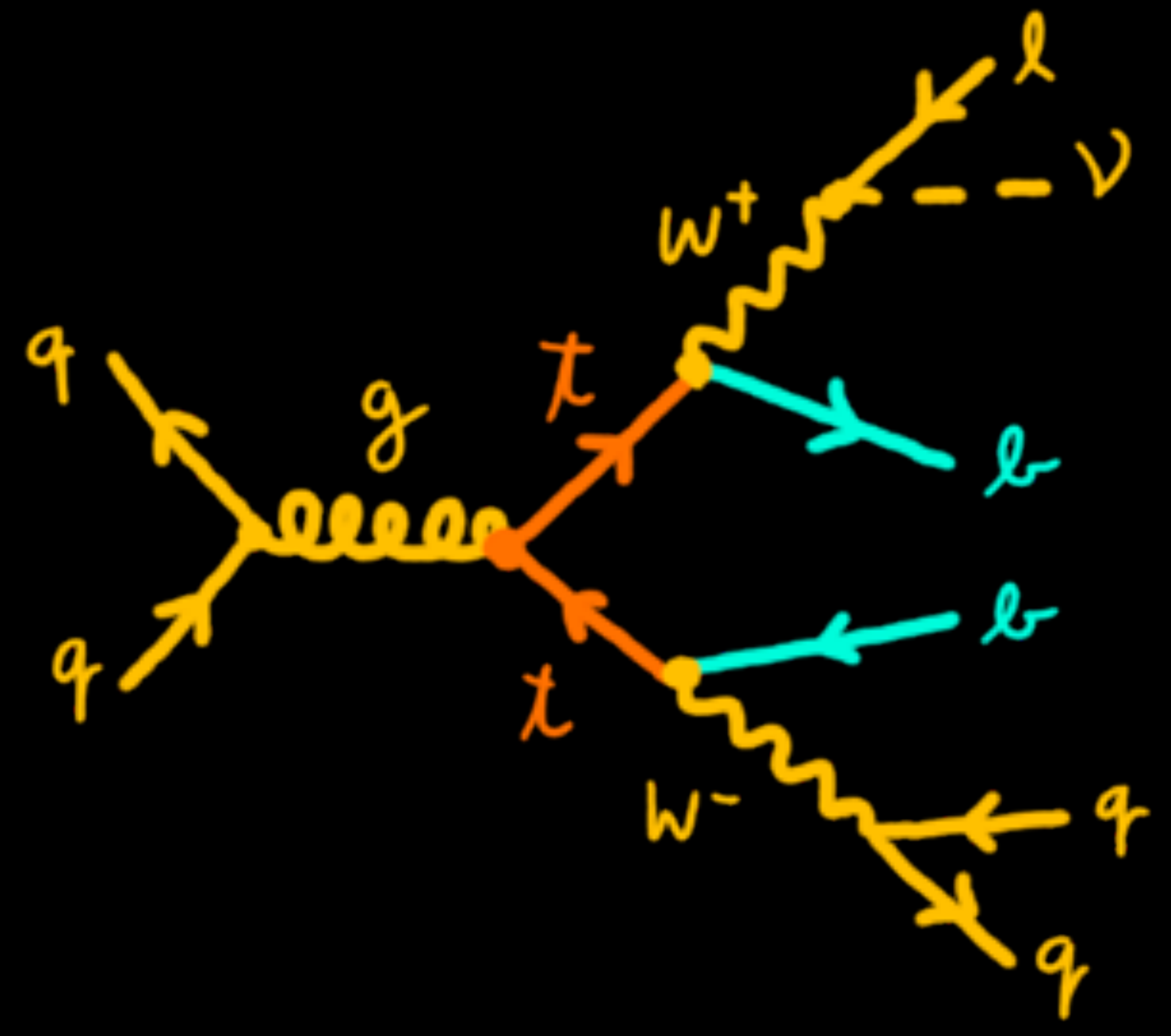
SM: $a_\tau = 1.2 \times 10^{-3}$

Top quark mass

Top quark mass measurements

ATL-PHYS-PUB-2023-015

Measured in different channels with different techniques



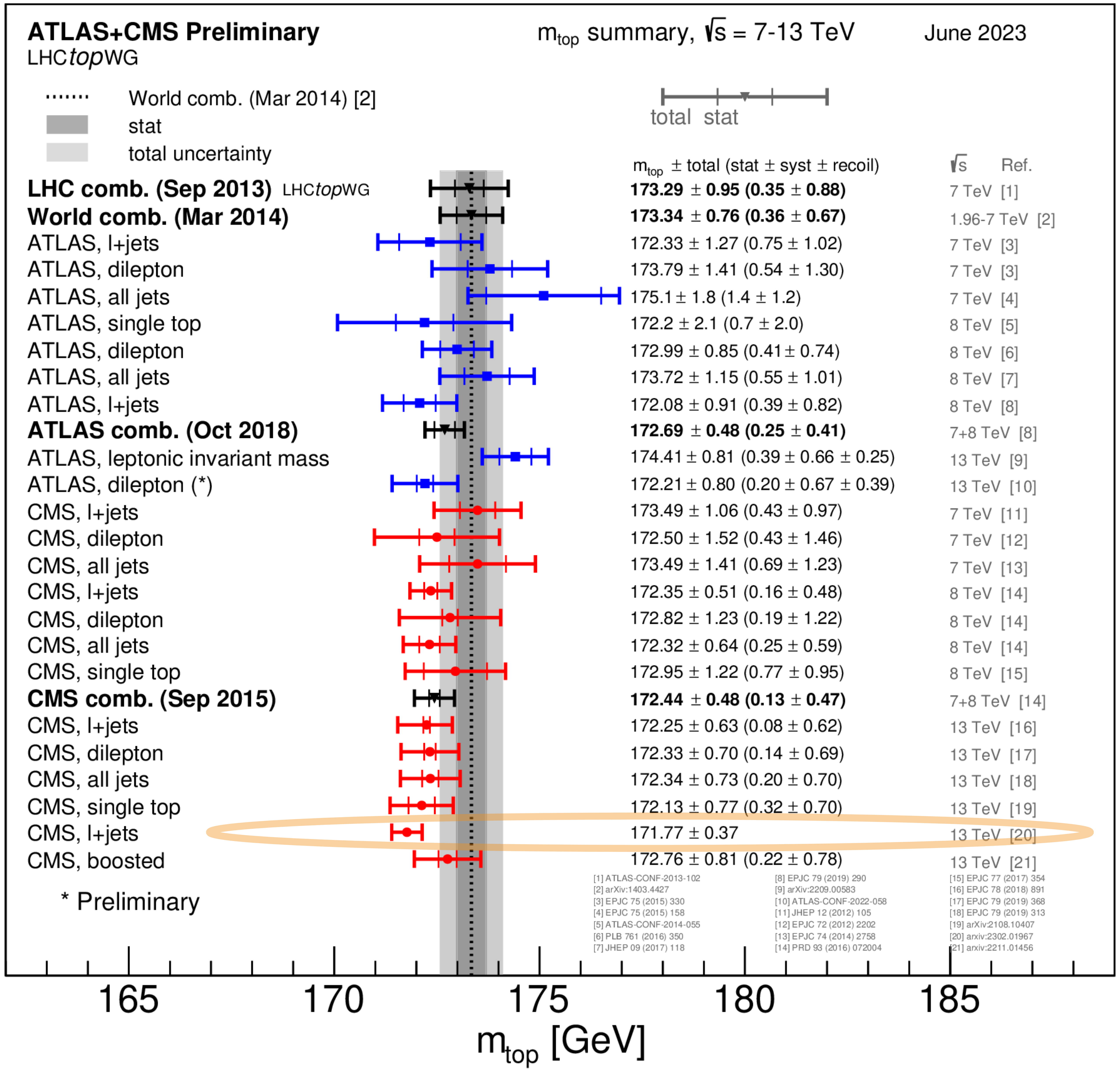
Best single measurement is from CMS, lepton+jets profile likelihood new result with 13 TeV data

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

Uncertainty reached ~ 0.2%

40% improvement relative to previous measurement

CMS-TOP-20-008



	m_{top} ± total (stat ± syst ± recoil)	√s	Ref.
LHC comb. (Sep 2013) LHC*top*WG	**173.29 ± 0.95 (0.35 ± 0.88)**	7 TeV	[1]
World comb. (Mar 2014)	**173.34 ± 0.76 (0.36 ± 0.67)**	1.96-7 TeV	[2]
ATLAS, l+jets	172.33 ± 1.27 (0.75 ± 1.02)	7 TeV	[3]
ATLAS, dilepton	173.79 ± 1.41 (0.54 ± 1.30)	7 TeV	[3]
ATLAS, all jets	175.1 ± 1.8 (1.4 ± 1.2)	7 TeV	[4]
ATLAS, single top	172.2 ± 2.1 (0.7 ± 2.0)	8 TeV	[5]
ATLAS, dilepton	172.99 ± 0.85 (0.41 ± 0.74)	8 TeV	[6]
ATLAS, all jets	173.72 ± 1.15 (0.55 ± 1.01)	8 TeV	[7]
ATLAS, l+jets	172.08 ± 0.91 (0.39 ± 0.82)	8 TeV	[8]
ATLAS comb. (Oct 2018)	**172.69 ± 0.48 (0.25 ± 0.41)**	7+8 TeV	[8]
ATLAS, leptonic invariant mass	174.41 ± 0.81 (0.39 ± 0.66 ± 0.25)	13 TeV	[9]
ATLAS, dilepton (*)	172.21 ± 0.80 (0.20 ± 0.67 ± 0.39)	13 TeV	[10]
CMS, l+jets	173.49 ± 1.06 (0.43 ± 0.97)	7 TeV	[11]
CMS, dilepton	172.50 ± 1.52 (0.43 ± 1.46)	7 TeV	[12]
CMS, all jets	173.49 ± 1.41 (0.69 ± 1.23)	7 TeV	[13]
CMS, l+jets	172.35 ± 0.51 (0.16 ± 0.48)	8 TeV	[14]
CMS, dilepton	172.82 ± 1.23 (0.19 ± 1.22)	8 TeV	[14]
CMS, all jets	172.32 ± 0.64 (0.25 ± 0.59)	8 TeV	[14]
CMS, single top	172.95 ± 1.22 (0.77 ± 0.95)	8 TeV	[15]
CMS comb. (Sep 2015)	**172.44 ± 0.48 (0.13 ± 0.47)**	7+8 TeV	[14]
CMS, l+jets	172.25 ± 0.63 (0.08 ± 0.62)	13 TeV	[16]
CMS, dilepton	172.33 ± 0.70 (0.14 ± 0.69)	13 TeV	[17]
CMS, all jets	172.34 ± 0.73 (0.20 ± 0.70)	13 TeV	[18]
CMS, single top	172.13 ± 0.77 (0.32 ± 0.70)	13 TeV	[19]
CMS, l+jets	171.77 ± 0.37	13 TeV	[20]
CMS, boosted	172.76 ± 0.81 (0.22 ± 0.78)	13 TeV	[21]

[1] ATLAS-CONF-2013-102
[2] arXiv:1403.4427
[3] EPJC 75 (2015) 330
[4] EPJC 75 (2015) 158
[5] ATLAS-CONF-2014-055
[6] PLB 761 (2016) 350
[7] JHEP 09 (2017) 118
[8] EPJC 79 (2019) 290
[9] arXiv:2209.00583
[10] ATLAS-CONF-2022-058
[11] JHEP 12 (2012) 105
[12] EPJC 72 (2012) 2202
[13] EPJC 74 (2014) 2758
[14] PRD 93 (2016) 072004
[15] EPJC 77 (2017) 354
[16] EPJC 78 (2018) 891
[17] EPJC 79 (2019) 368
[18] EPJC 79 (2019) 313
[19] arXiv:2108.10407
[20] arxiv:2302.01967
[21] arxiv:2211.01456

Top quark mass: Run 1 combination

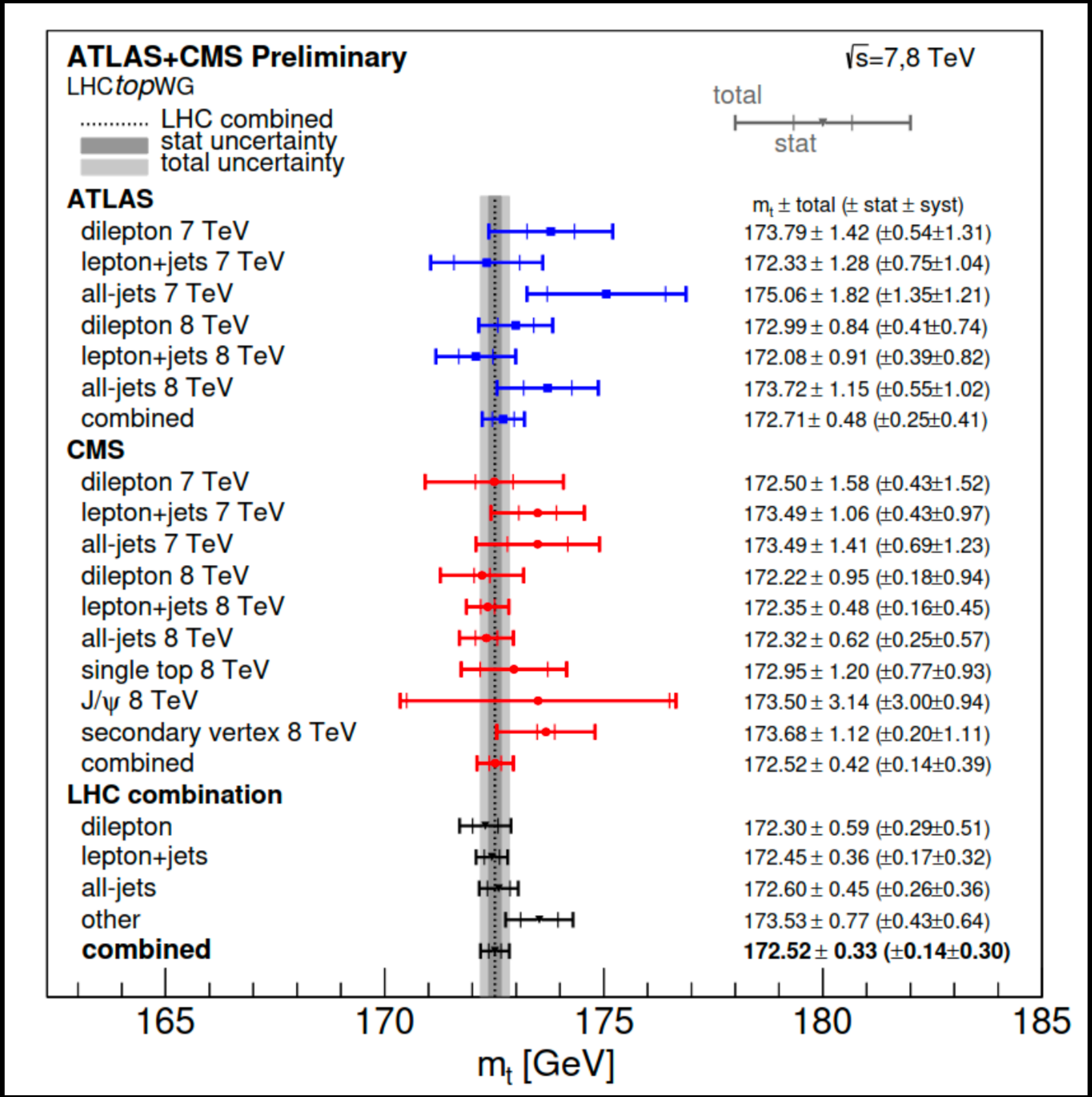
LHCTopWGSummaryPlots
Phys. Rev. Lett. 132, 26190

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

m_{top} = 172.52 ± 0.33 GeV

Precision < 0.2%

31% improvement over most precise single improvement



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

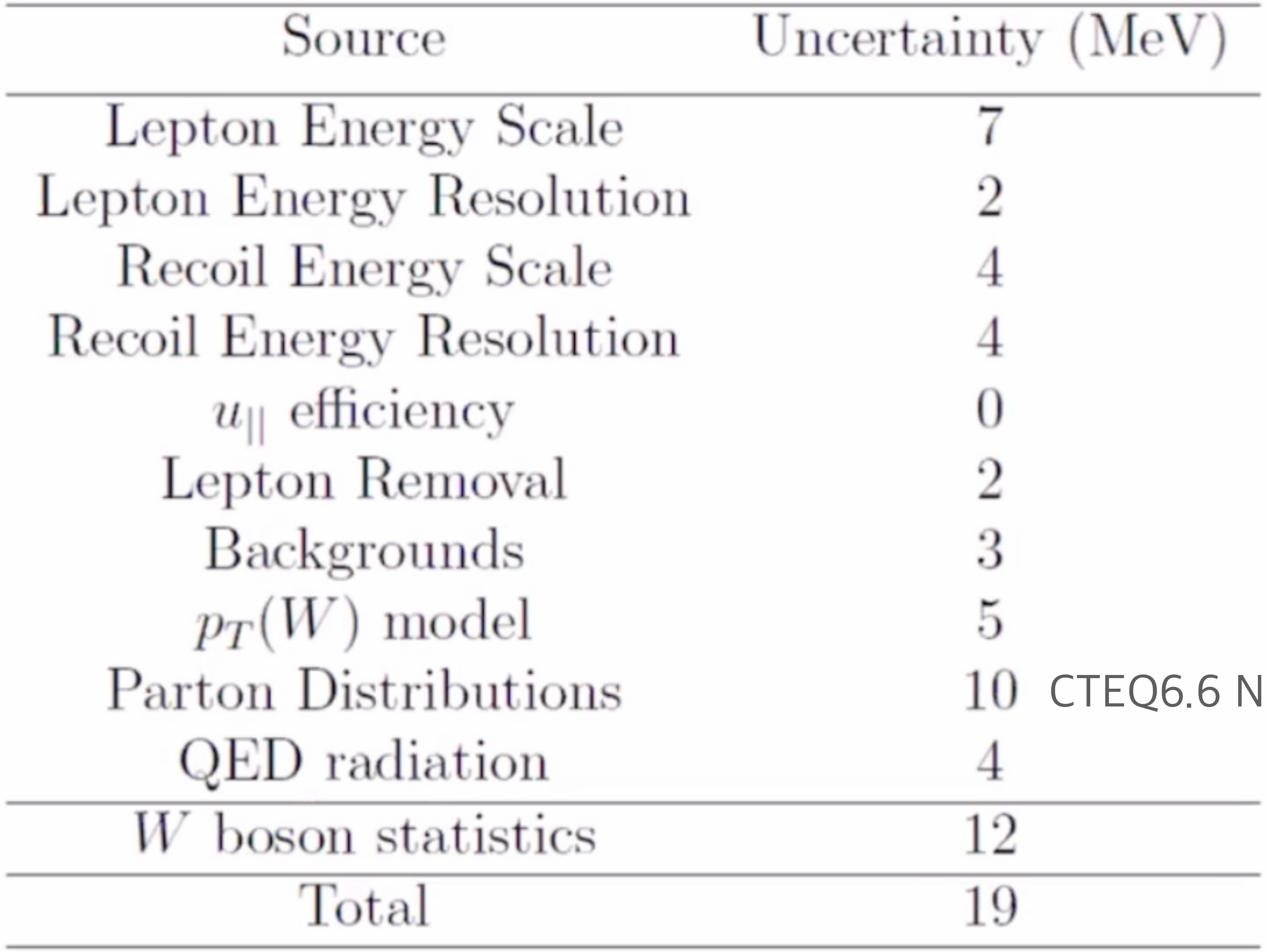
Extra Slides

Compare with previous CDFII measurements

Uncertainty

Improved COT alignment and drift model

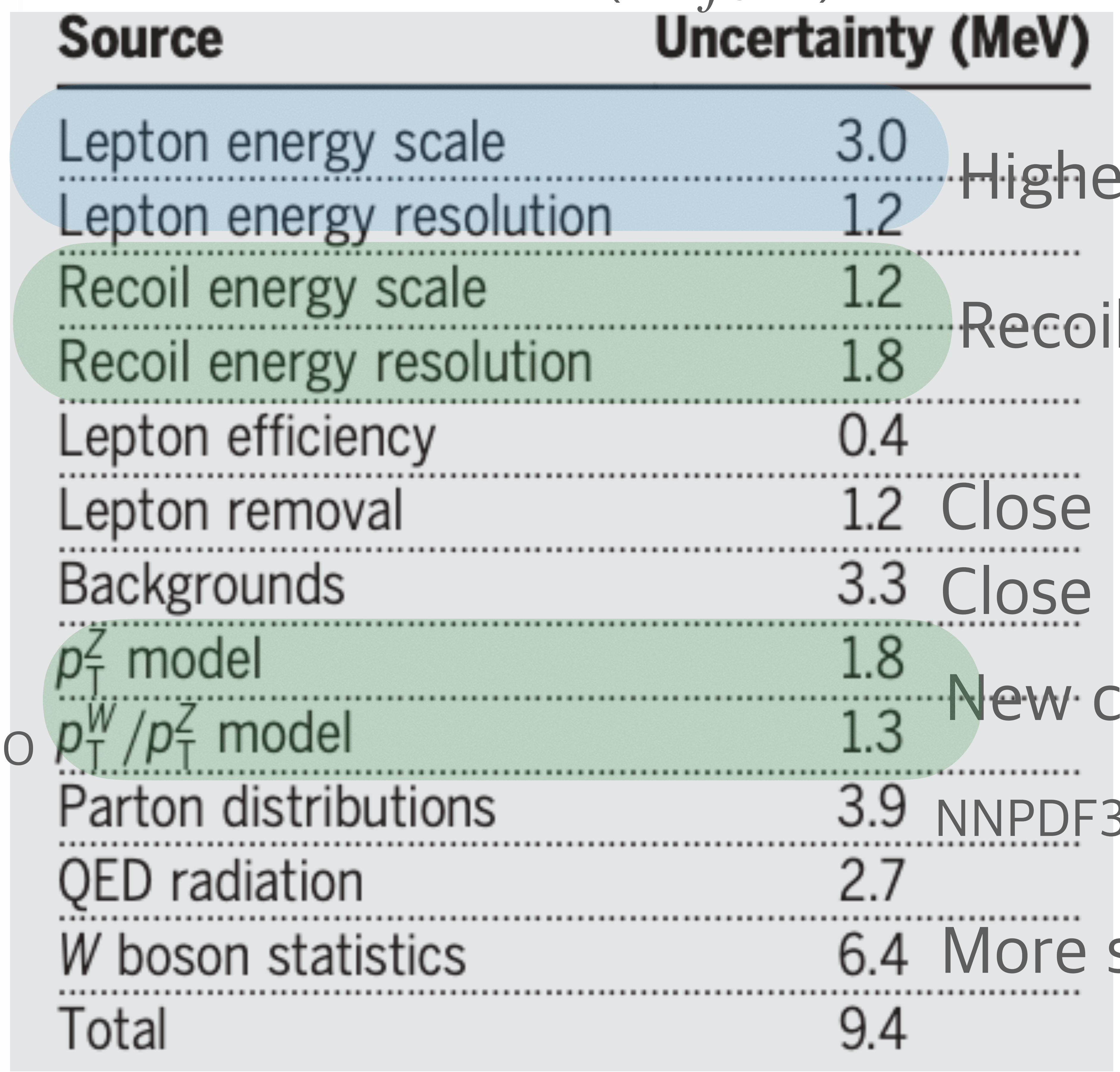
Previous CDF results (2.2 fb^{-1})



Source	Uncertainty (MeV)
Lepton Energy Scale	7
Lepton Energy Resolution	2
Recoil Energy Scale	4
Recoil Energy Resolution	4
$u_{\|\|}$ efficiency	0
Lepton Removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton Distributions	10
QED radiation	4
W boson statistics	12
Total	19

CTEQ6.6 NLO

New CDF results (8.8 fb^{-1})



Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

Higher order QED

Recoil model

Close

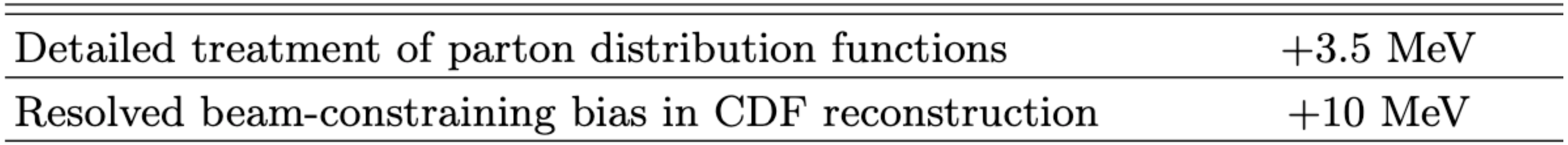
Close

New constrains added

NNPDF3.1 NNLO, more inputs

More statistics

Central value

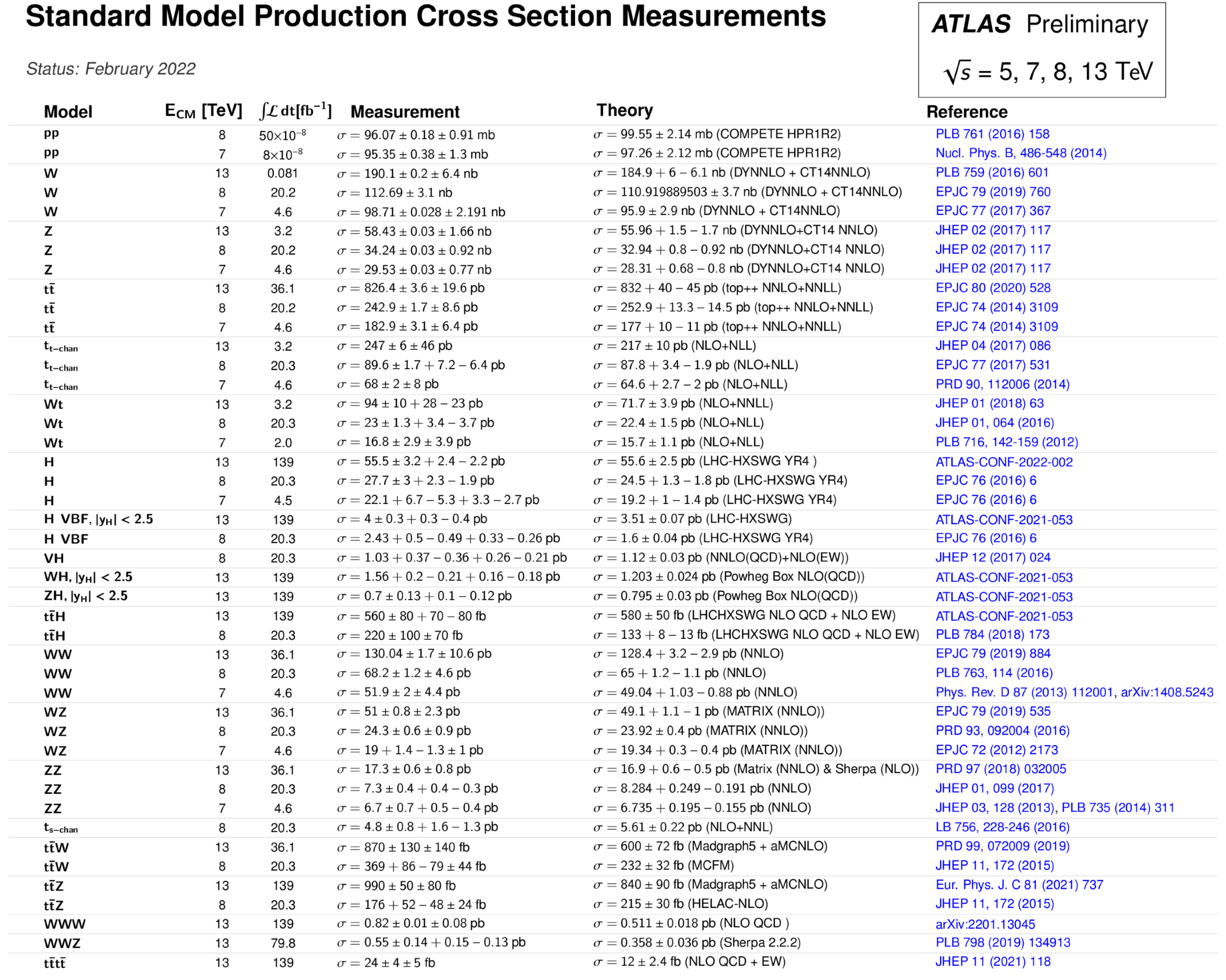


Detailed treatment of parton distribution functions	+3.5 MeV
Resolved beam-constraining bias in CDF reconstruction	+10 MeV

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

Overview of Standard Model measurements in ATLAS

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/



Standard Model Production Cross Section Measurements

Status: February 2022

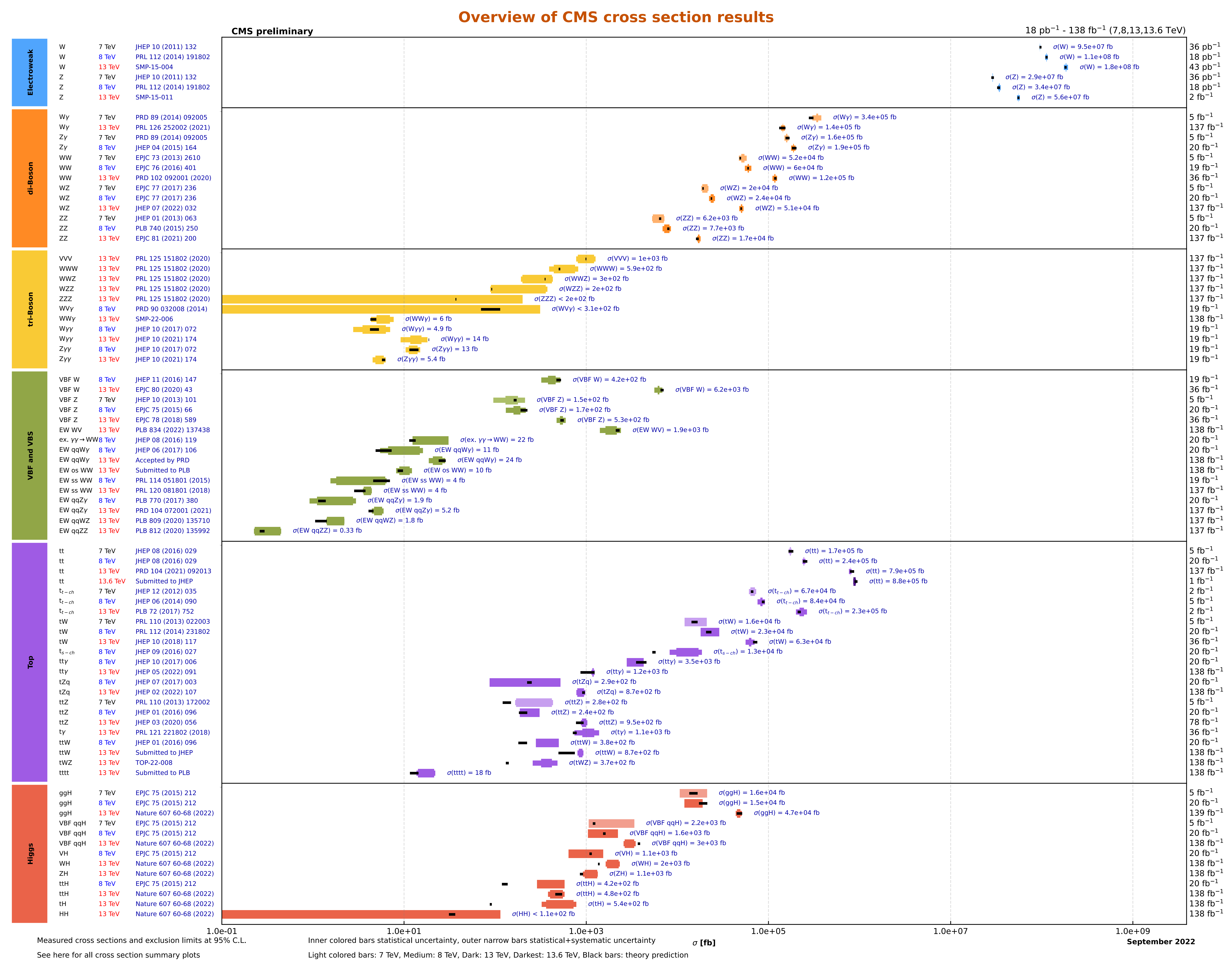
ATLAS Preliminary

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

Model	E_{CM} [TeV]	$\int\mathcal{L}\,dt[fb^{-1}]$	Measurement	Theory	Reference
pp	8	50×10^{-8}	$\sigma = 96.07 \pm 0.18 \pm 0.91$ mb	$\sigma = 99.55 \pm 2.14$ mb (COMPETE HPR1R2)	PLB 761 (2016) 158
pp	7	8×10^{-8}	$\sigma = 95.35 \pm 0.38 \pm 1.3$ 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	$\sigma = 112.69 \pm 3.1$ nb	$\sigma = 110.919889503 \pm 3.7$ nb (DYNNLO + CT14NNLO)	EPJC 79 (2019) 760
W	7	4.6	$\sigma = 98.71 \pm 0.028 \pm 2.191$ 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	$\sigma = 34.24 \pm 0.03 \pm 0.92$ 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
$t\bar{t}$	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
$t\bar{t}$	8	20.2	$\sigma = 242.9 \pm 1.7 \pm 8.6$ pb	$\sigma = 252.9 + 13.3 - 14.5$ pb (top++ NNLO+NNLL)	EPJC 74 (2014) 3109
$t\bar{t}$	7	4.6	$\sigma = 182.9 \pm 3.1 \pm 6.4$ pb	$\sigma = 177 + 10 - 11$ pb (top++ NNLO+NNLL)	EPJC 74 (2014) 3109
t_{t-chan}	13	3.2	$\sigma = 247 \pm 6 \pm 46$ pb	$\sigma = 217 \pm 10$ pb (NLO+NLL)	JHEP 04 (2017) 086
t_{t-chan}	8	20.3	$\sigma = 89.6 \pm 1.7 + 7.2 - 6.4$ pb	$\sigma = 87.8 + 3.4 - 1.9$ pb (NLO+NLL)	EPJC 77 (2017) 531
t_{t-chan}	7	4.6	$\sigma = 68 \pm 2 \pm 8$ 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	$\sigma = 71.7 \pm 3.9$ pb (NLO+NNLL)	JHEP 01 (2018) 63
Wt	8	20.3	$\sigma = 23 \pm 1.3 + 3.4 - 3.7$ pb	$\sigma = 22.4 \pm 1.5$ pb (NLO+NLL)	JHEP 01, 064 (2016)
Wt	7	2.0	$\sigma = 16.8 \pm 2.9 \pm 3.9$ pb	$\sigma = 15.7 \pm 1.1$ pb (NLO+NLL)	PLB 716, 142-159 (2012)
H	13	139	$\sigma = 55.5 \pm 3.2 + 2.4 - 2.2$ pb	$\sigma = 55.6 \pm 2.5$ pb (LHC-HXSWG YR4)	ATLAS-CONF-2022-002
H	8	20.3	$\sigma = 27.7 \pm 3 + 2.3 - 1.9$ pb	$\sigma = 24.5 + 1.3 - 1.8$ pb (LHC-HXSWG YR4)	EPJC 76 (2016) 6
H	7	4.5	$\sigma = 22.1 + 6.7 - 5.3 + 3.3 - 2.7$ pb	$\sigma = 19.2 + 1 - 1.4$ pb (LHC-HXSWG YR4)	EPJC 76 (2016) 6
H VBF, $\lvert y_H \rvert < 2.5$	13	139	$\sigma = 4 \pm 0.3 + 0.3 - 0.4$ pb	$\sigma = 3.51 \pm 0.07$ pb (LHC-HXSWG)	ATLAS-CONF-2021-053
H VBF	8	20.3	$\sigma = 2.43 + 0.5 - 0.49 + 0.33 - 0.26$ pb	$\sigma = 1.6 \pm 0.04$ pb (LHC-HXSWG YR4)	EPJC 76 (2016) 6
VH	8	20.3	$\sigma = 1.03 + 0.37 - 0.36 + 0.26 - 0.21$ pb	$\sigma = 1.12 \pm 0.03$ pb (NNLO(QCD)+NLO(EW))	JHEP 12 (2017) 024
WH, $\lvert y_H \rvert < 2.5$	13	139	$\sigma = 1.56 + 0.2 - 0.21 + 0.16 - 0.18$ pb	$\sigma = 1.203 \pm 0.024$ pb (Powheg Box NLO(QCD))	ATLAS-CONF-2021-053
ZH, $\lvert y_H \rvert < 2.5$	13	139	$\sigma = 0.7 \pm 0.13 + 0.1 - 0.12$ pb	$\sigma = 0.795 \pm 0.03$ pb (Powheg Box NLO(QCD))	ATLAS-CONF-2021-053
$t\bar{t}H$	13	139	$\sigma = 560 \pm 80 + 70 - 80$ fb	$\sigma = 580 \pm 50$ fb (LHCHXSWG NLO QCD + NLO EW)	ATLAS-CONF-2021-053
$t\bar{t}H$	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	$\sigma = 130.04 \pm 1.7 \pm 10.6$ pb	$\sigma = 128.4 + 3.2 - 2.9$ pb (NNLO)	EPJC 79 (2019) 884
WW	8	20.3	$\sigma = 68.2 \pm 1.2 \pm 4.6$ pb	$\sigma = 65 + 1.2 - 1.1$ pb (NNLO)	PLB 763, 114 (2016)
WW	7	4.6	$\sigma = 51.9 \pm 2 \pm 4.4$ pb	$\sigma = 49.04 + 1.03 - 0.88$ pb (NNLO)	Phys. Rev. D 87 (2013) 112001, arXiv:1408.5243
WZ	13	36.1	$\sigma = 51 \pm 0.8 \pm 2.3$ pb	$\sigma = 49.1 + 1.1 - 1$ pb (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	$\sigma = 19 + 1.4 - 1.3 \pm 1$ pb	$\sigma = 19.34 + 0.3 - 0.4$ pb (MATRIX (NNLO))	EPJC 72 (2012) 2173
ZZ	13	36.1	$\sigma = 17.3 \pm 0.6 \pm 0.8$ pb	$\sigma = 16.9 + 0.6 - 0.5$ pb (Matrix (NNLO) & Sherpa (NLO))	PRD 97 (2018) 032005
ZZ	8	20.3	$\sigma = 7.3 \pm 0.4 + 0.4 - 0.3$ pb	$\sigma = 8.284 + 0.249 - 0.191$ pb (NNLO)	JHEP 01, 099 (2017)
ZZ	7	4.6	$\sigma = 6.7 \pm 0.7 + 0.5 - 0.4$ pb	$\sigma = 6.735 + 0.195 - 0.155$ pb (NNLO)	JHEP 03, 128 (2013), PLB 735 (2014) 311
t_{s-chan}	8	20.3	$\sigma = 4.8 \pm 0.8 + 1.6 - 1.3$ pb	$\sigma = 5.61 \pm 0.22$ pb (NLO+NNL)	LB 756, 228-246 (2016)
$t\bar{t}W$	13	36.1	$\sigma = 870 \pm 130 \pm 140$ fb	$\sigma = 600 \pm 72$ fb (Madgraph5 + aMCNLO)	PRD 99, 072009 (2019)
$t\bar{t}W$	8	20.3	$\sigma = 369 + 86 - 79 \pm 44$ fb	$\sigma = 232 \pm 32$ fb (MCFM)	JHEP 11, 172 (2015)
$t\bar{t}Z$	13	139	$\sigma = 990 \pm 50 \pm 80$ fb	$\sigma = 840 \pm 90$ fb (Madgraph5 + aMCNLO)	Eur. Phys. J. C 81 (2021) 737
$t\bar{t}Z$	8	20.3	$\sigma = 176 + 52 - 48 \pm 24$ 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
$t\bar{t}t\bar{t}$	13	139	$\sigma = 24 \pm 4 \pm 5$ fb	$\sigma = 12 \pm 2.4$ fb (NLO QCD + EW)	JHEP 11 (2021) 118

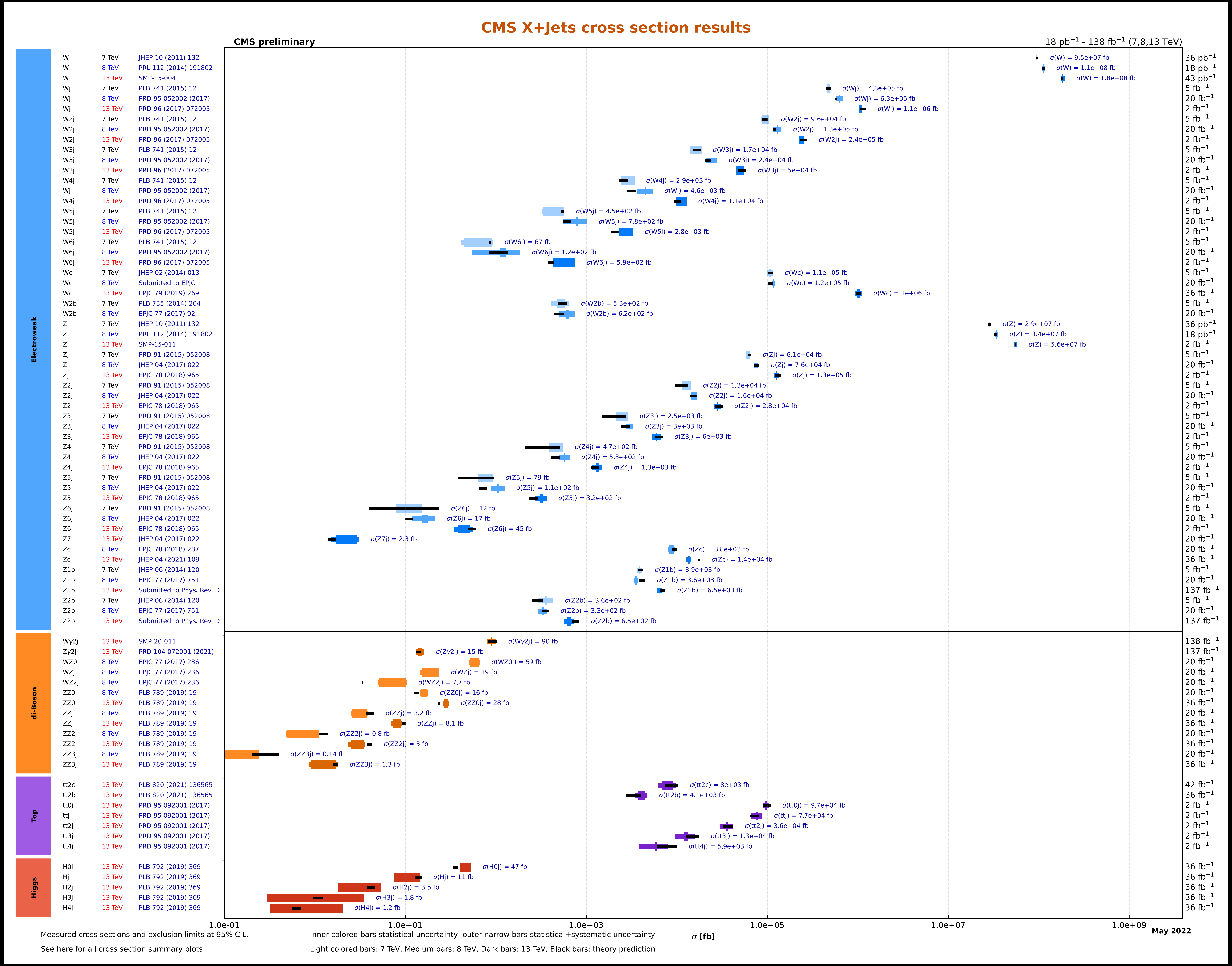
Overview of CMS cross section results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined



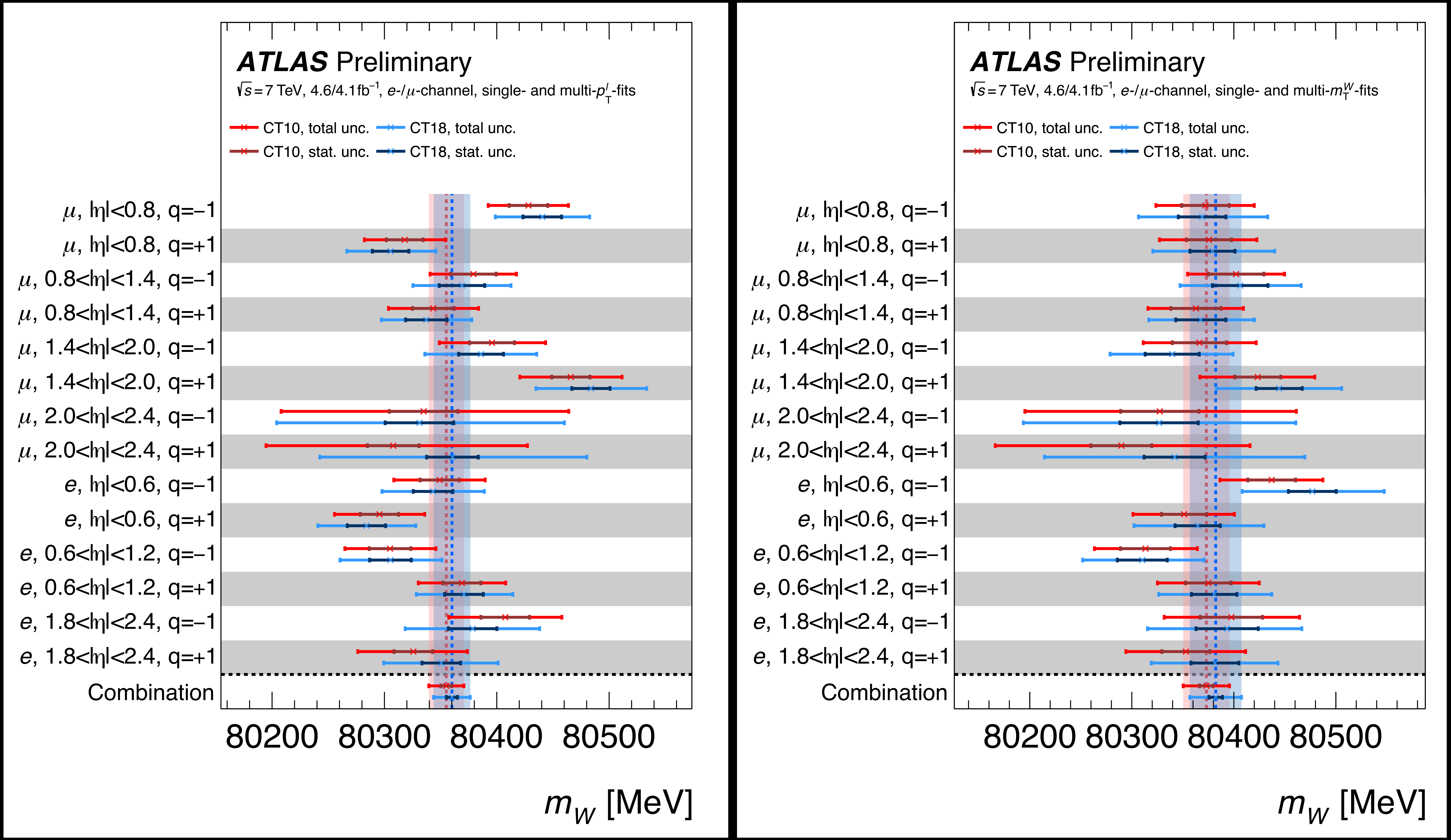
Overview of CMS X+jets cross section results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined



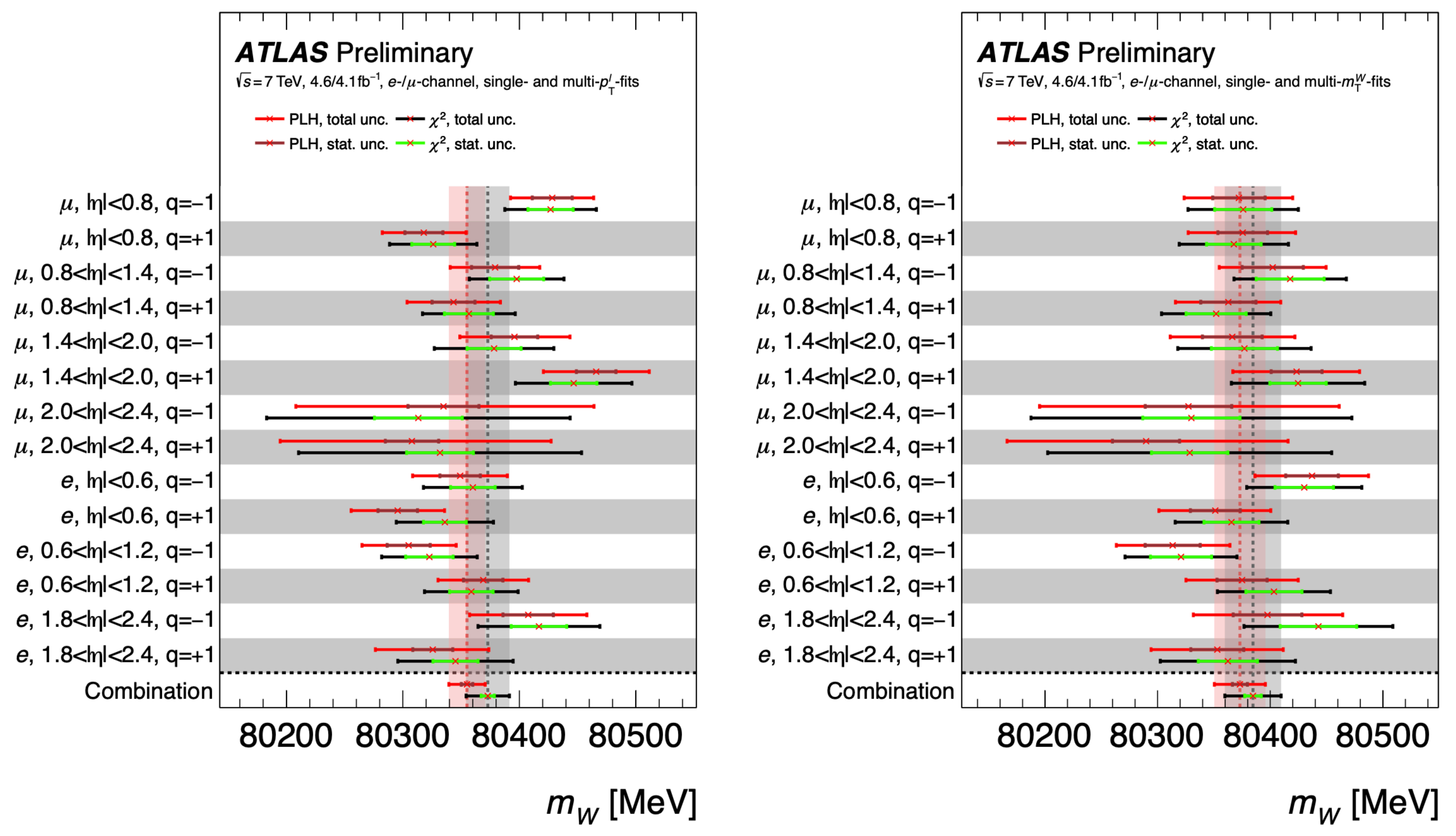
Cross checks of W mass measurement

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



Cross checks of W mass measurement

Results are determined using a PLH approach and in comparison with a χ2-minimization approach using statistical uncertainties only



Extra Slides