(Brief) Review of Electroweak Measurements at the LHC

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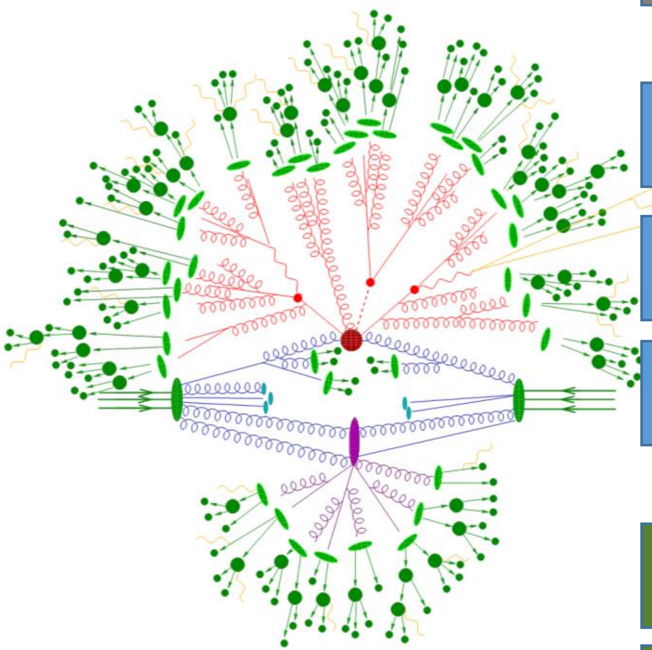
Often, similar results have been obtained by ATLAS and CMS; this talk picks ATLAS results for demonstration due to personal biases

SM Measurements at the LHC

Sketch of a pp collision event



Soft QCD

Flavor

PDF

QCD

SM Parameters

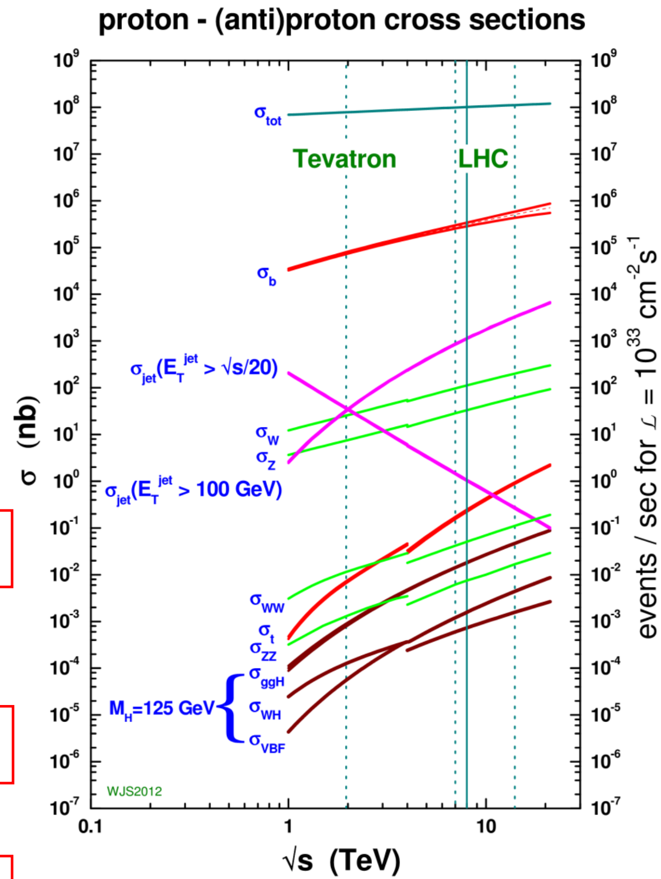
EW

EWSB

Tracks
Hadrons
Protons

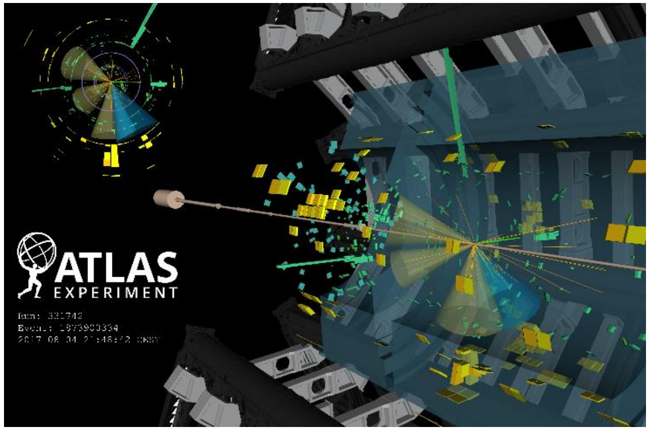
Jets
Photons
Photon + Jets
W/Z + Jets
W/Z
Top quark

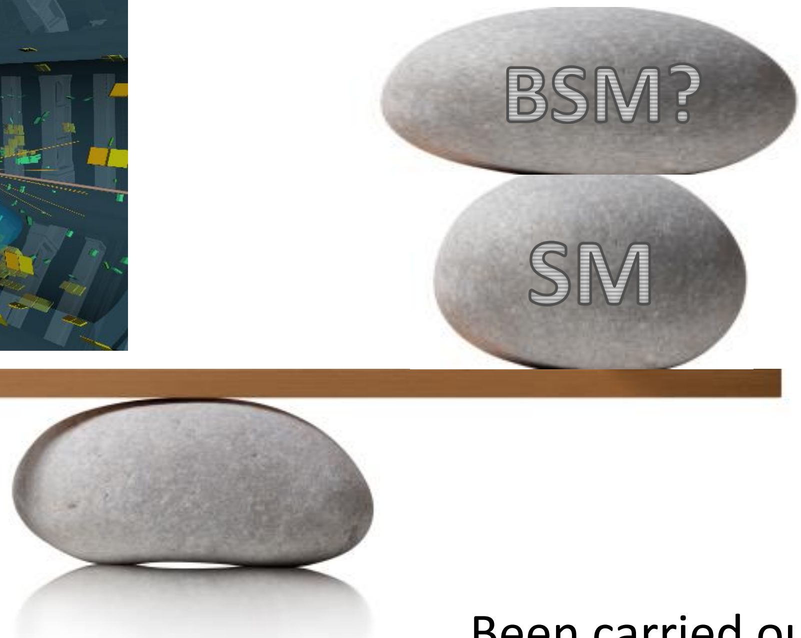
Multiboson
Higgs boson
VV scattering



This talk covers physics with single or multiple bosons

Methodology





SM alternatives or extensions …

QCD + EW interactions

Measurements (indirect searches)
=> optimized phase space for precision test of the SM

Direct searches
=> optimized phase space for searching for BSM signals of particular types

Been carried out in a vast variety of final states and phase spaces

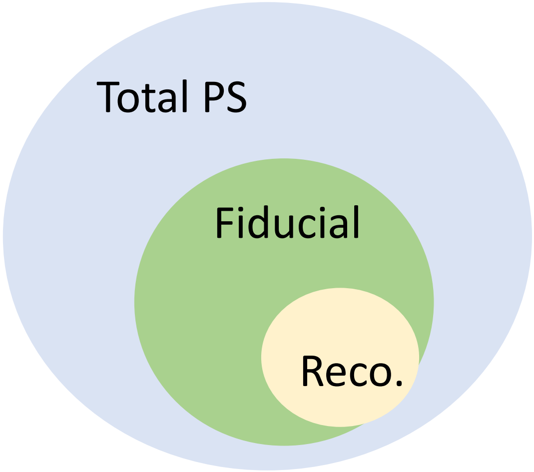
As of today, no clear sign of BSM was found

Expedition will continue with O(100) to O(1000) fb^{-1} of data

Methodology

❖ Fiducial and Total cross sections

$$\sigma_{fid} = \frac{N_{obs} - N_{bkg}}{C \cdot \mathcal{L}}, \sigma_{tot} = \frac{N_{obs} - N_{bkg}}{A \cdot C \cdot \mathcal{L} \cdot Br}$$



- ❖ Perform measurements in a fiducial phase space close to selection criteria at reconstruction
  - Minimal extrapolation ⇔ less theory dependence
- ❖ In order to report σ_{tot}, a extrapolation is needed to correct for acceptance from σ_{fid}

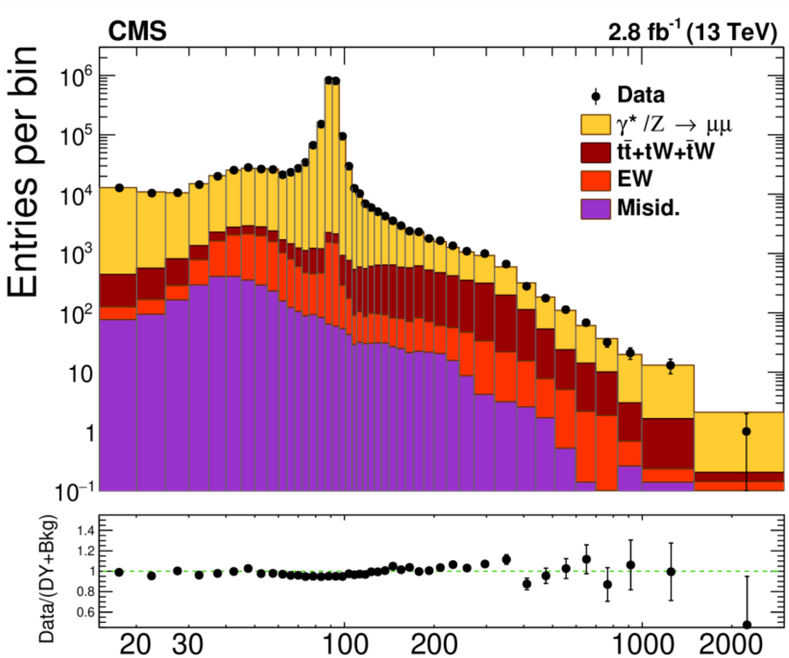
❖ Differential measurements

- ○ Bin migration due to detector resolution
  - Unfolding techniques
- ○ Unfolded spectra directly comparable to MC prediction

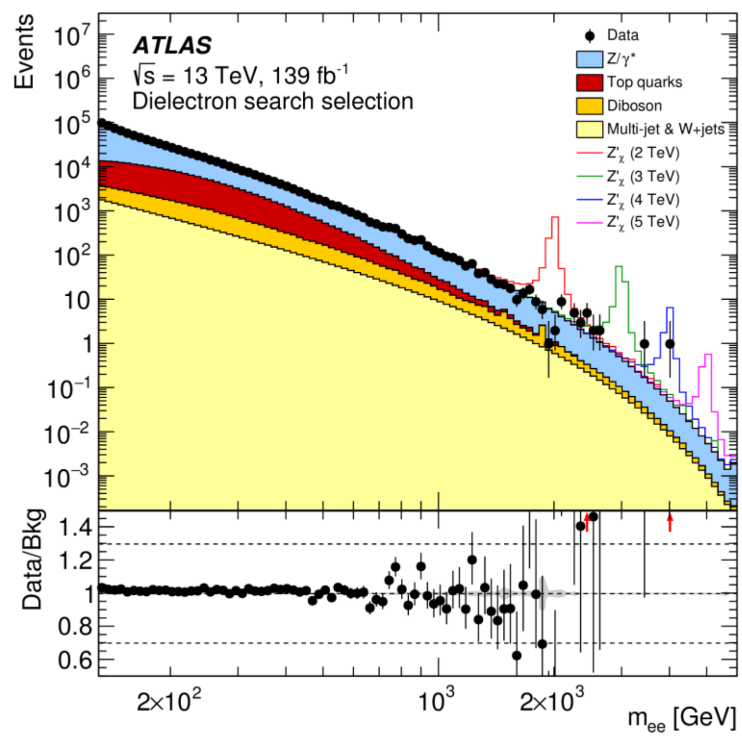
Boson

- ❖ Precision handle for detector calibration, studies of QCD (PDF etc.) and SM parameters, as well as probe of BSM physics

- ❖ At the LHC, W/Zs are studied with their leptonic decays, hadronic channels are infeasible due to large backgrounds



arXiv:1812.10529



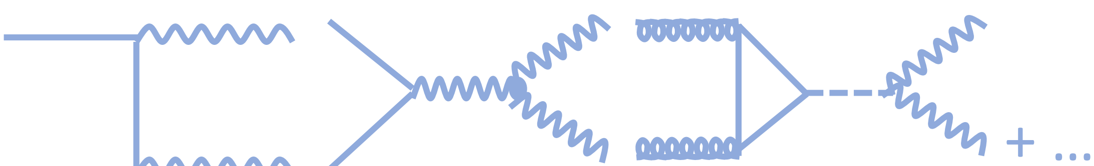
Covering a large kinematic region

arXiv:1903.06248

Diboson

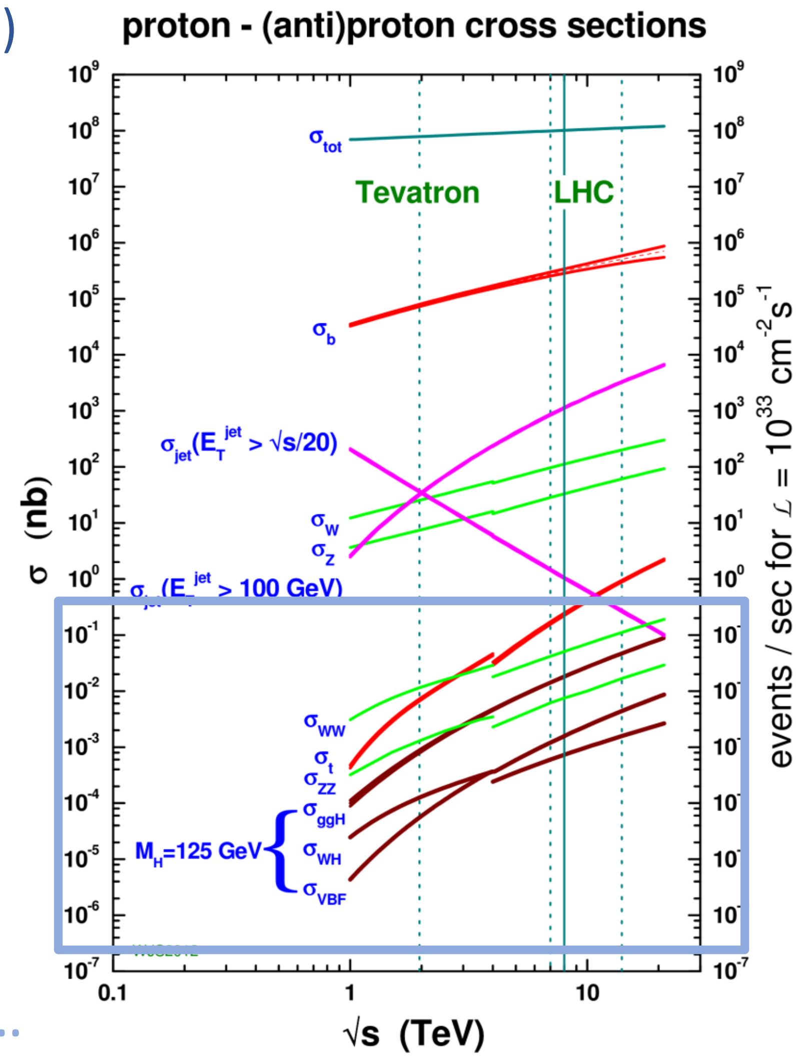
❖ Typical production σ at LHC: O(fb) - O(10^2pb)

- Multiple diagrams contribute and interfere; **delicate cancellation** among diagrams restores unitarity
- **Self-interactions** are direct consequence of non-Abelian SU(2) x U(1) gauge symmetry
- **Higgs contribution** due to EWSB
- Complex final state system (multiple leptons or jets); Handles to suppress backgrounds
- Large high-order QCD corrections and nontrivial contribution from gluons
- Many channels not thoroughly explored in past experiments; many new possibilities

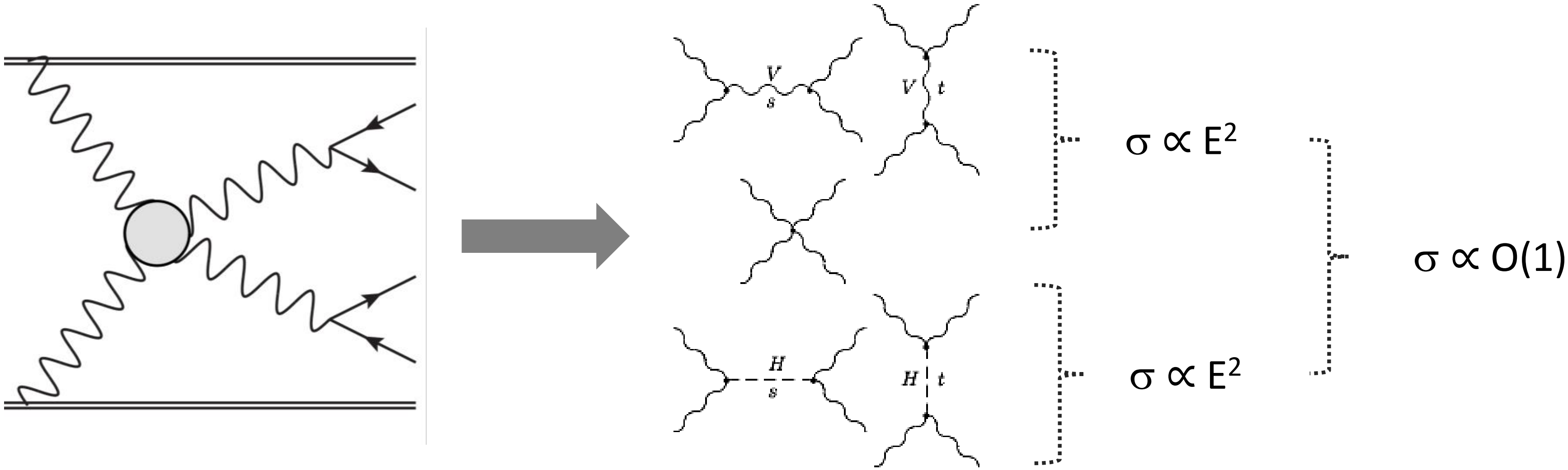


Tree-level qq->VV

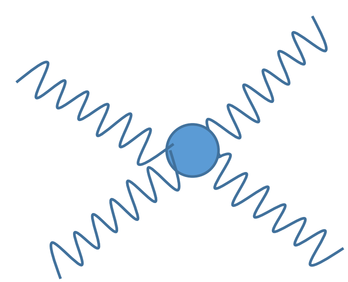
Higgs contributes at O(α_s^2)



VV Scattering and VVV



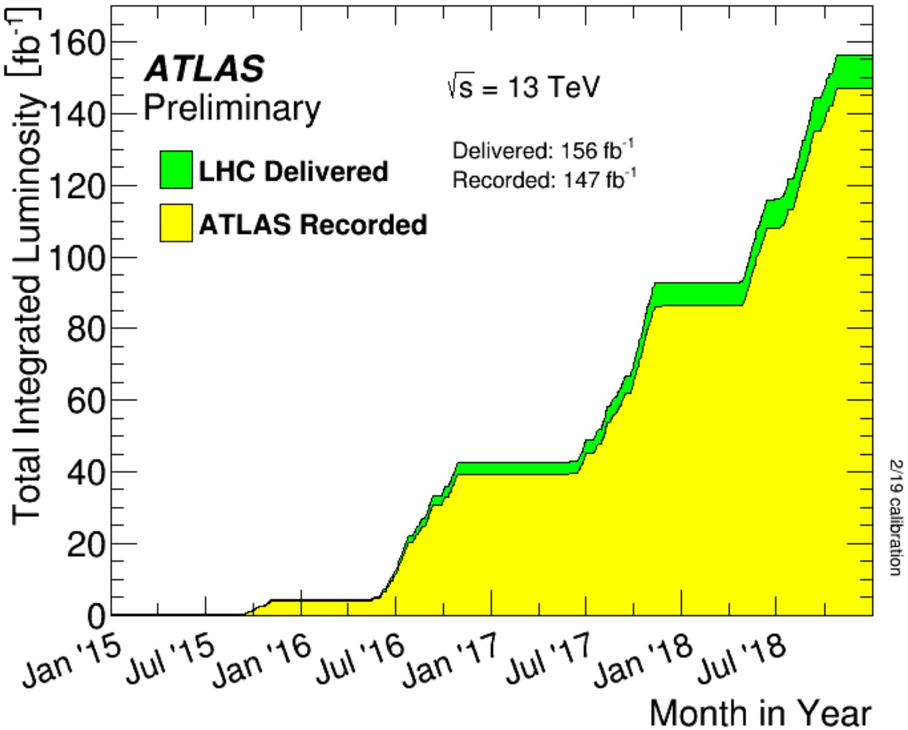
- **Probe EWSB through longitudinal VV→VV scattering**
  - SM Higgs boson unitarizes SM VV scattering cross-section at high $\hat{s}$
  - Sensitive to anomaly in EWSB or new physics resonance in the production
- **Production of VV scattering and VVV**
  - Unique channels to study four boson self-interaction and search for new physics via aQGCs
  - Relative rare process → Less studied in past experiments

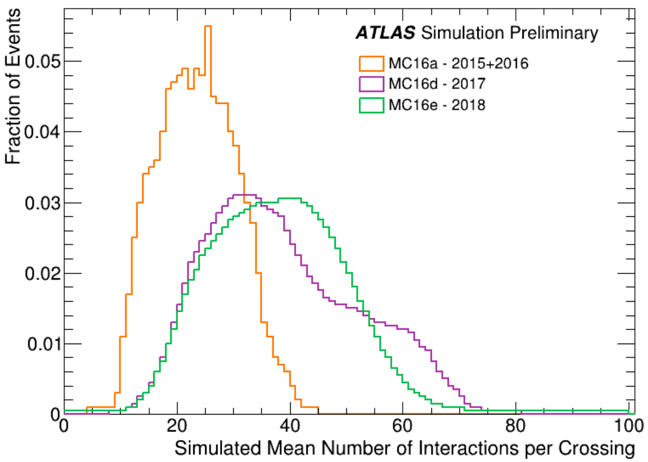


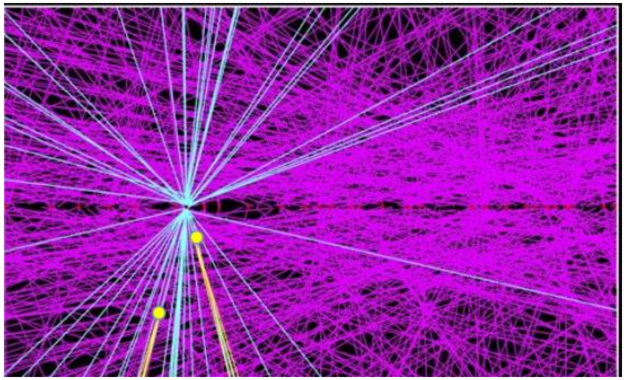
Key Ingredients

Efficient data-taking and reasonable trigger thresholds

Single e/μ ~ 25 GeV; Diphoton ~ 20 GeV; Jet ~ 400 GeV; plus multi-object triggers…





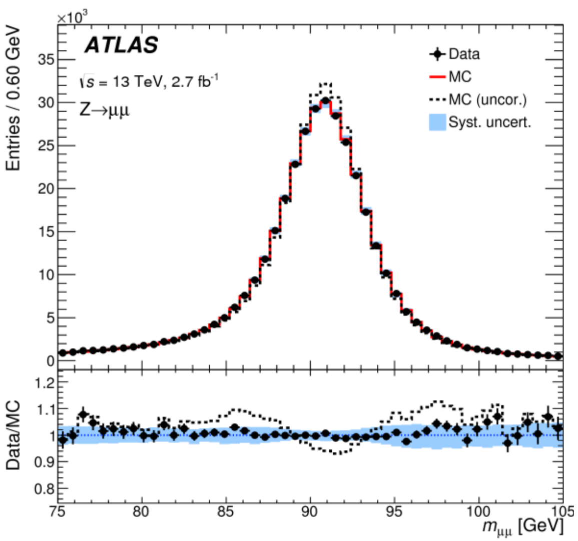


"Pile – up" effects

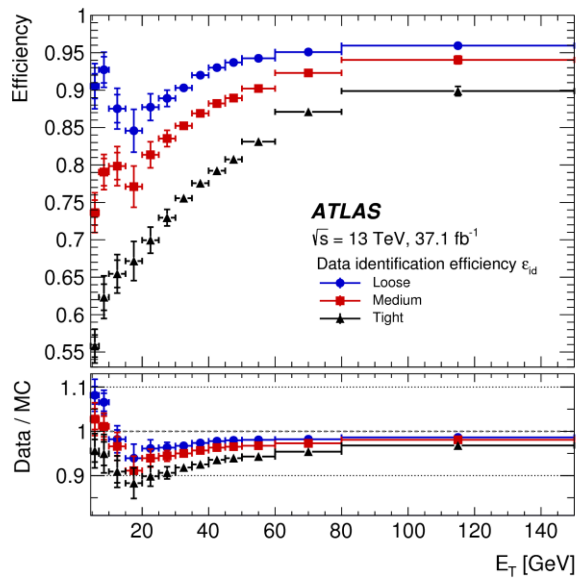
Key Ingredients

Good Precision for object measurements:

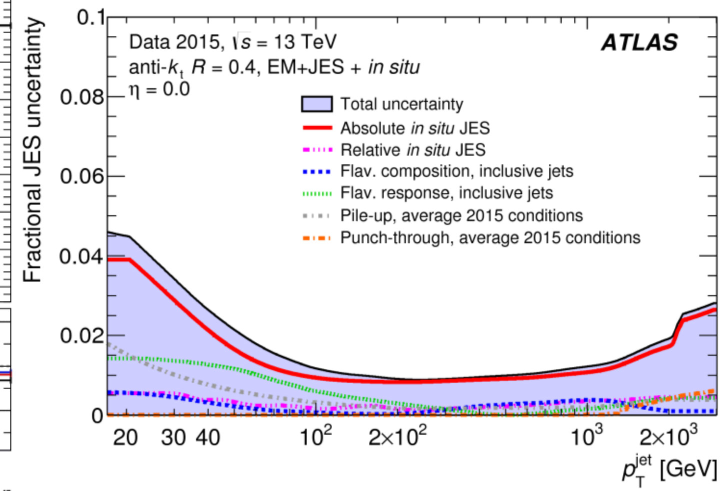
Percent or sub-percent precision with careful detector calibrations



muon momentum scale and resolution EPJC 76 (2016) 292

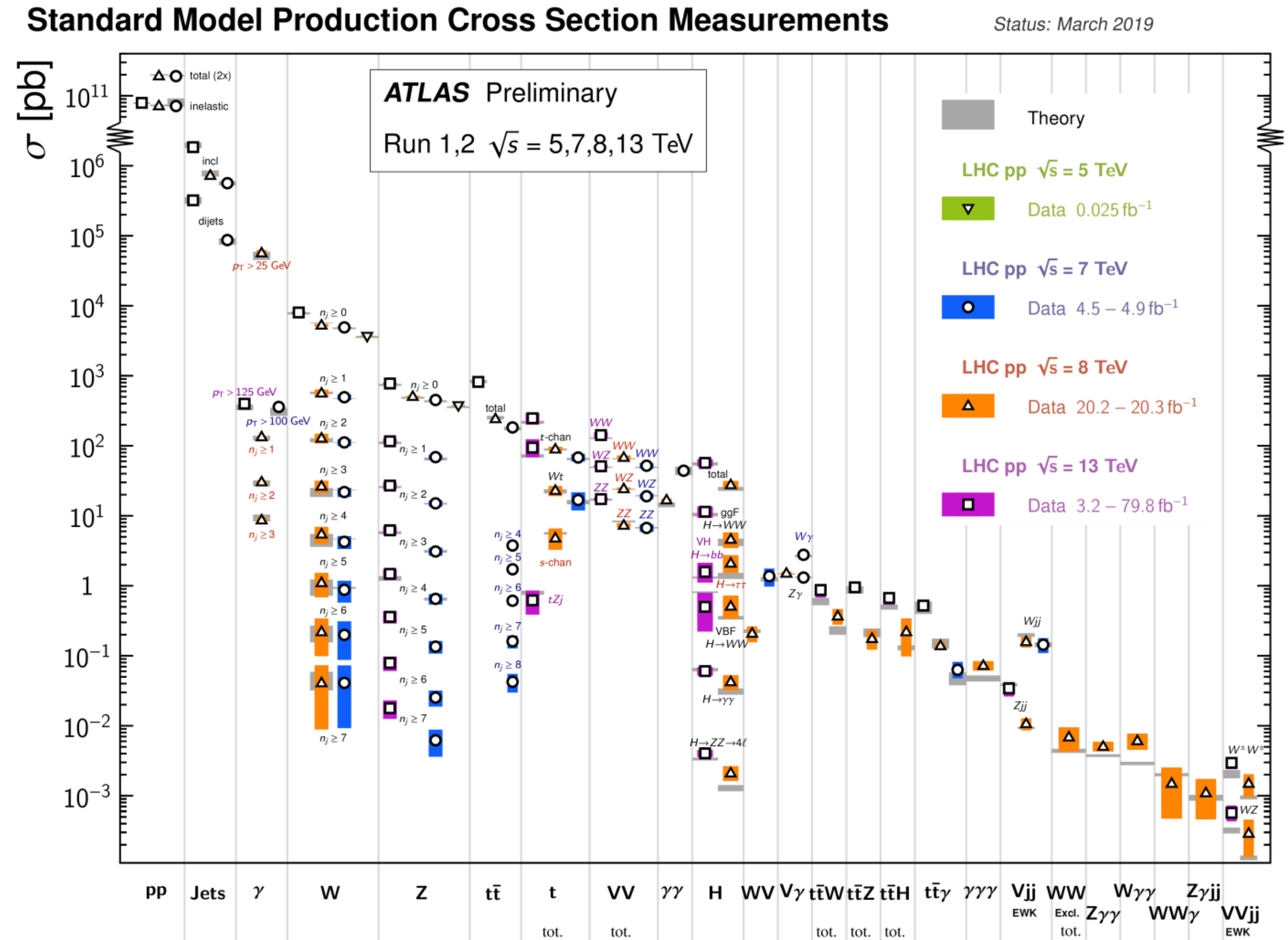


Electron ID efficiency arXiv:1902.04655



Jet energy scale PRD 96 (2017) 072002

Achievements So Far – Triumph of the SM



14
Orders of magnitude for production σ

500+
explored phase spaces

<1%
best precision achieved

9 TeV - m(jj)
highest probed energy for hard scattering

More ATLAS results seen under https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
CMS results under http://cms-results.web.cern.ch/

Highlights of EW Measurements

- **Single boson and SM parameters**
- **Diboson production**
- **Triboson production**
- **Vector-boson scattering**

W Mass Measurement at 7 TeV

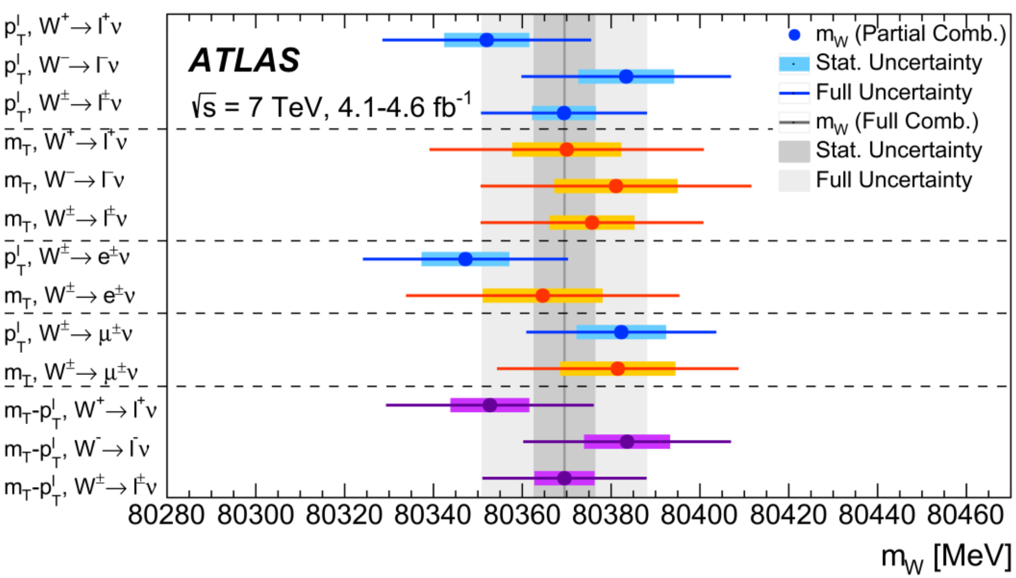
EPJC 78 (2018) 110

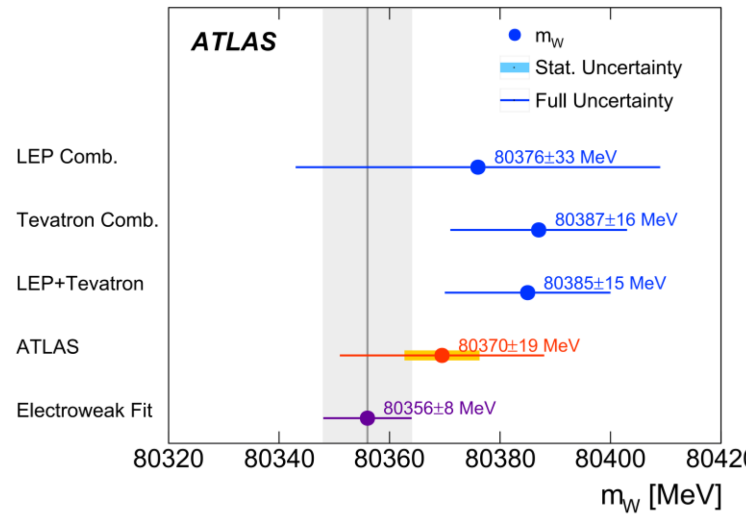
Template fits to both pT(l) and mT(W)

=> recoil and lepton measurements constrained from Z boson

=> scrutiny of theory uncertainties

=> two variables complementary to each other





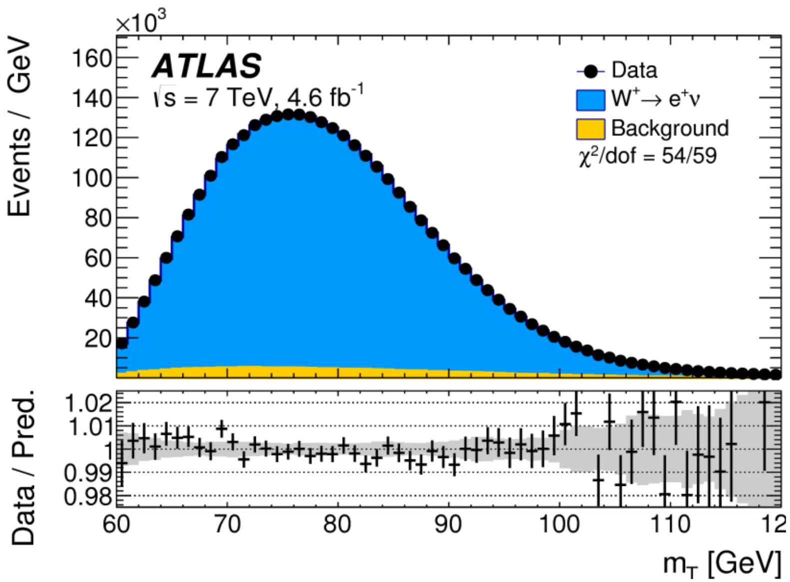
Already with great precision, further improvement with single digits will be challenging!

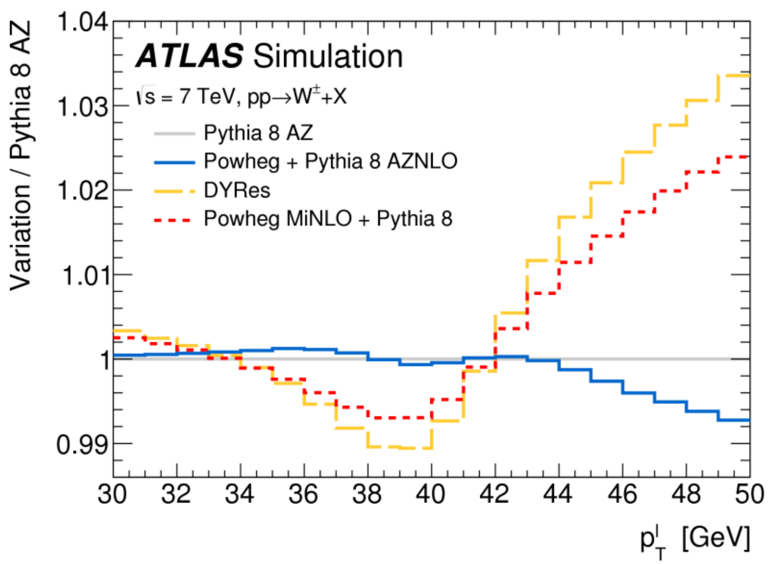
$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$

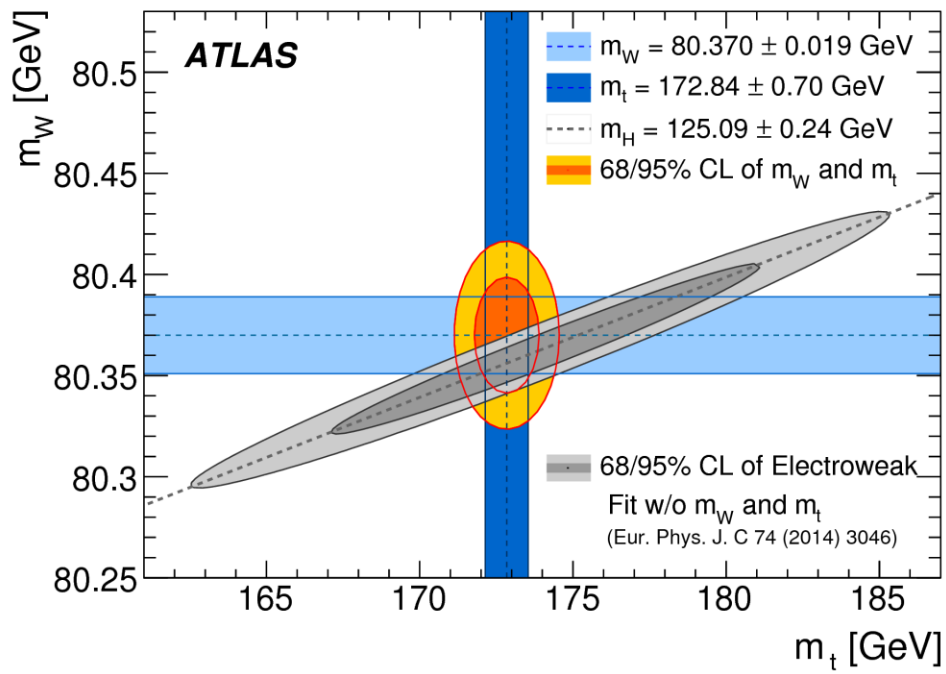
e: 7, μ: 6, recoil: 3, bkg: 5

QCD:8, EW:6, PDF:9

W Mass Measurement at 7 TeV



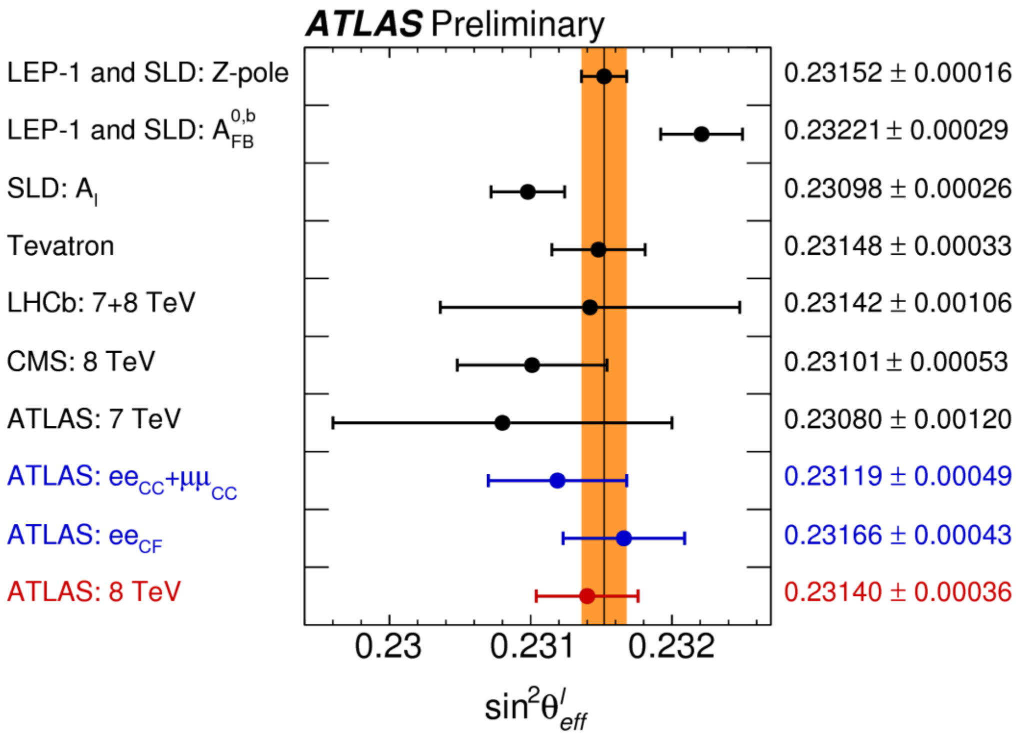


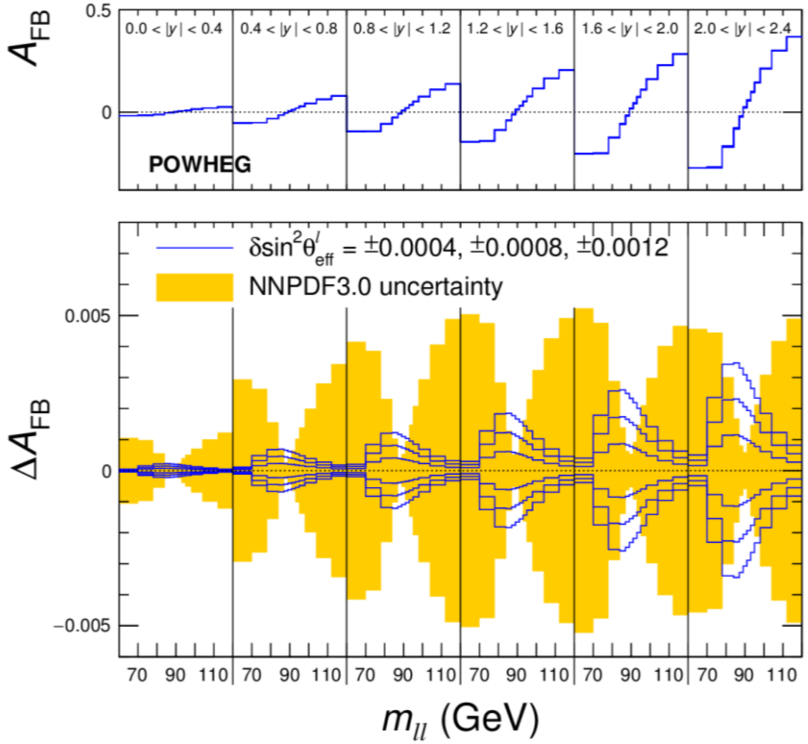


Selected figures for W mass measurement

Weak Mixing Angle

Sensitivity in forward-backward asymmetry measurements





EPJC 78 (2018) 701

ATLAS-CONF-2018-037

Careful binning & fighting with uncertainties

Already pretty precise!

Weak Mixing Angle

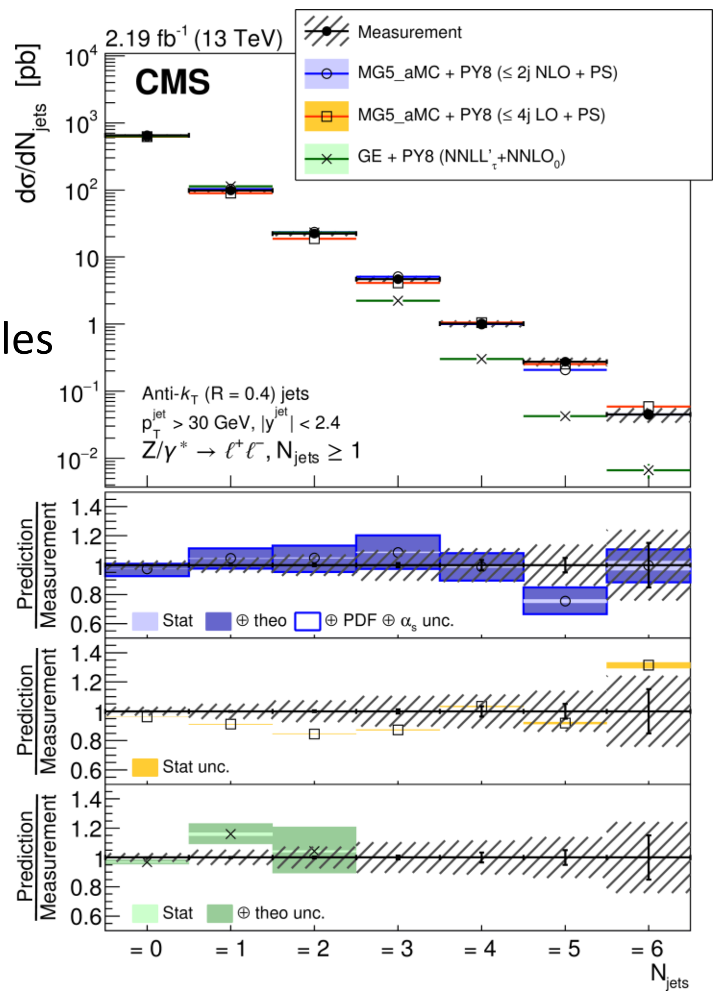
Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC} + \mu\mu_{CC}$	$ee_{CC} + \mu\mu_{CC} + ee_{CF}$
Total	65	59	42	48	34
Stat.	47	39	29	30	21
Syst.	45	44	31	37	27
	Uncertainties in measurements				
PDF (meas.)	7	7	7	7	4
p_{T}^{Z} modelling	< 1	< 1	1	< 1	< 1
Lepton scale	5	4	6	3	3
Lepton resolution	3	1	3	1	2
Lepton efficiency	1	1	1	1	1
Electron charge misidentification	< 1	0	< 1	< 1	< 1
Muon sagitta bias	0	4	0	2	1
Background	1	1	1	1	1
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	36	37	21	32	22
QCD scales	5	5	9	4	6
EW corrections	3	3	3	3	3

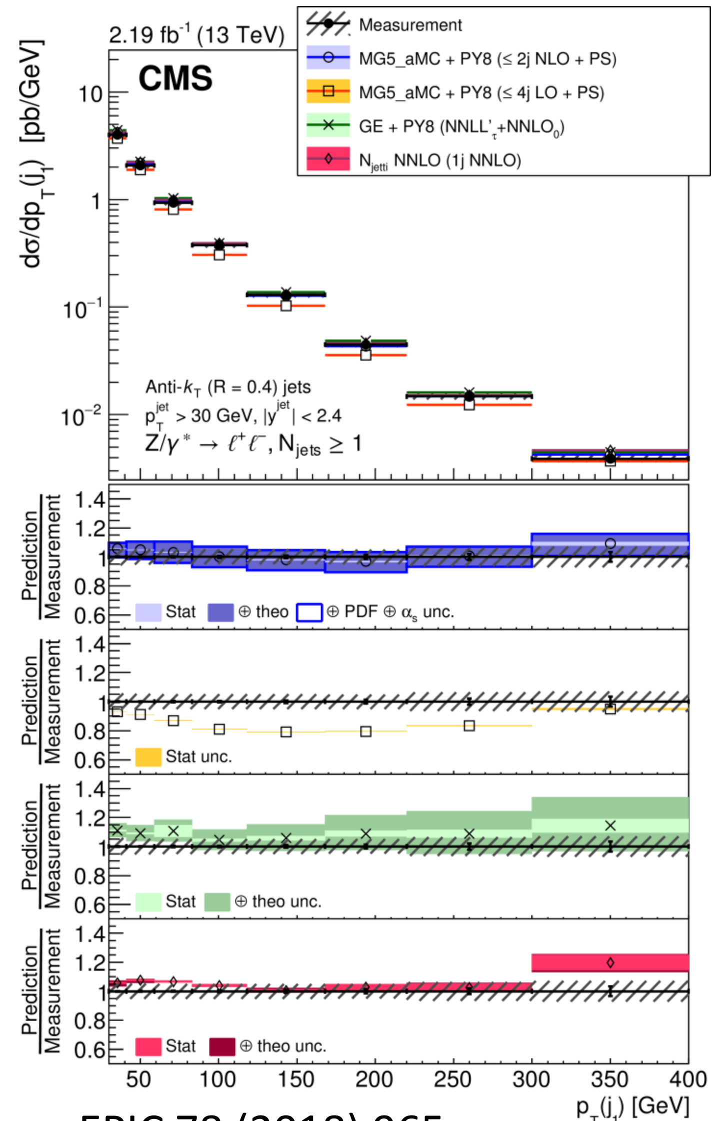
Example from ATLAS: PDF, lepton reconstruction, MC leading uncertainties

W/Z + jets

Not really targeting for an EW measurement, but very important!

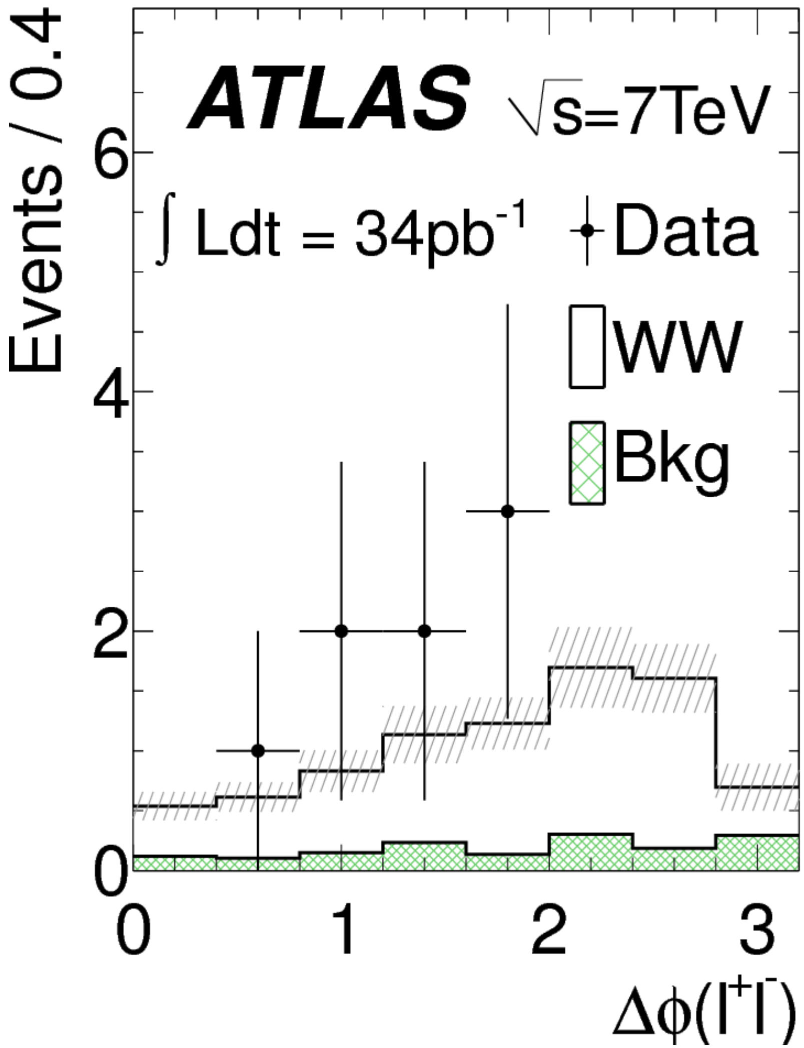
Examples





EPJC 78 (2018) 965

Diboson Measurements – Started from O(10) Events

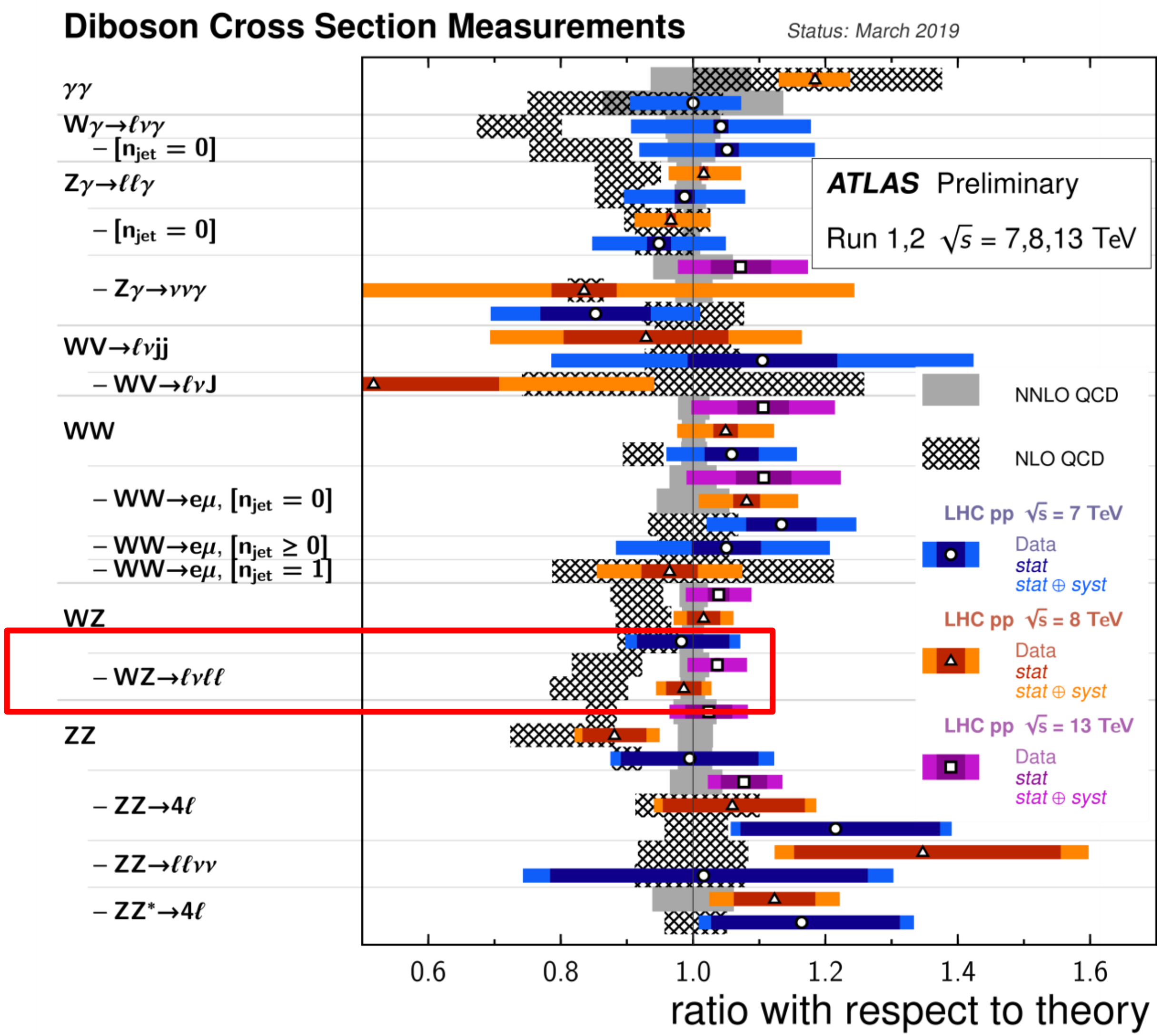


PRL 107 (2011) 041802

Since 2010

We pursued for the "re-establishment" of the SM at the LHC

Diboson Measurements



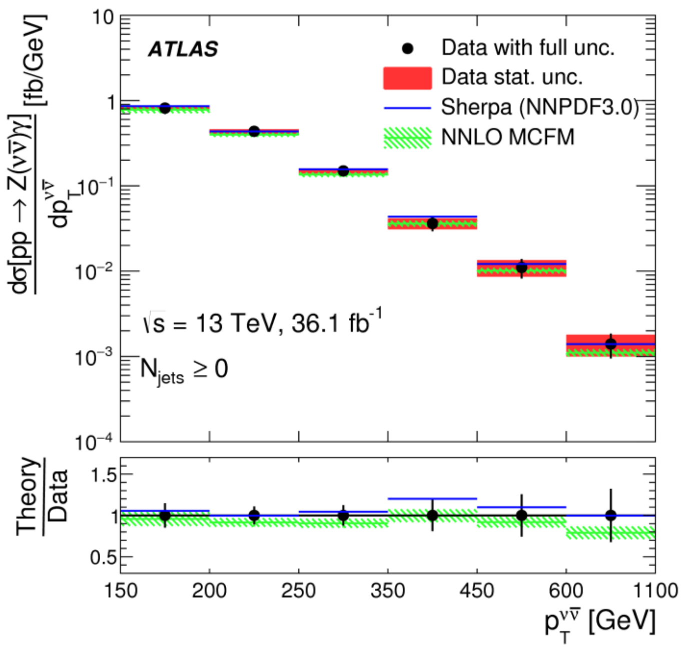
Hitting 5% precision in measurements,

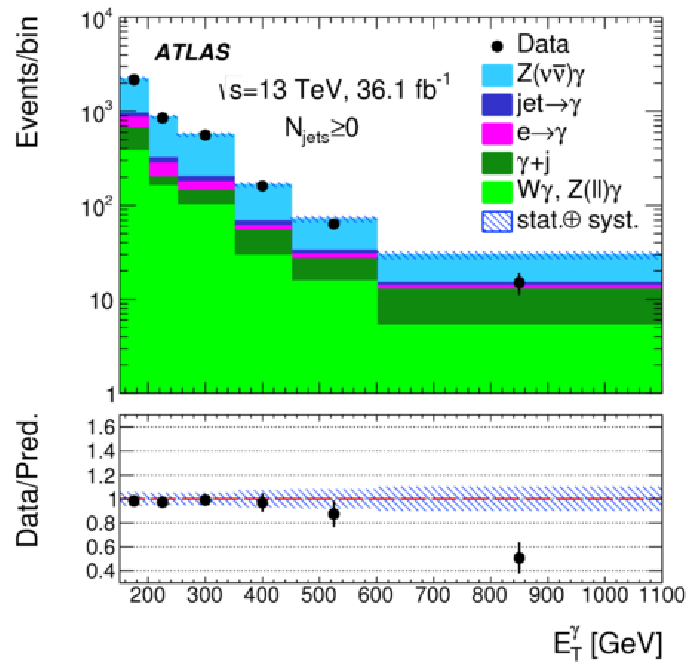
Confronting theoretical predictions at NNLO in QCD and NLO in EW

Recent: Z(→νν) + γ

JHEP 12 (2018) 010

❑ Good sensitivity to neutral TGCs, w.r.t. the charged-lepton decays of Z





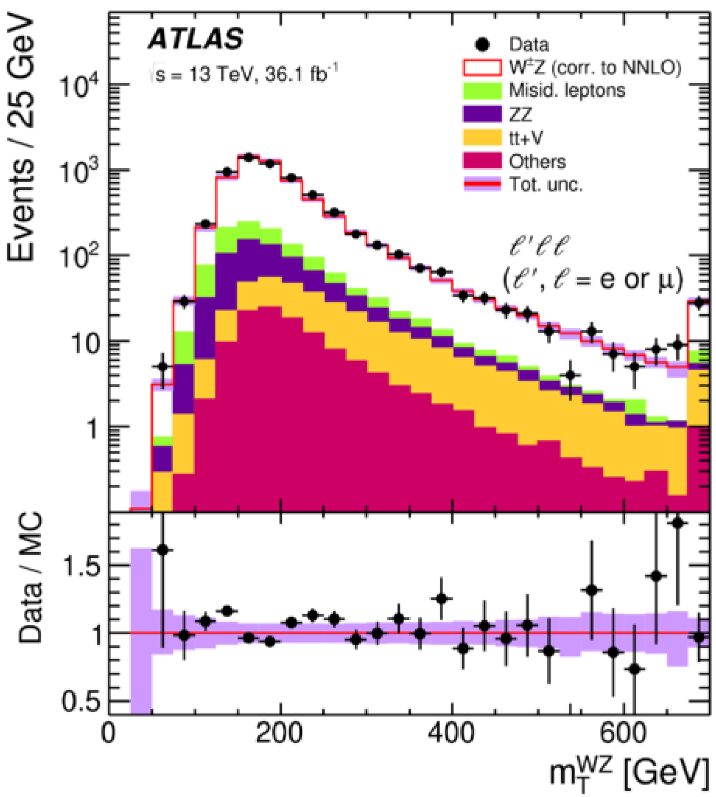
Parameter	Limit 95% CL	
	Measured	Expected
h_3^γ	$(-3.7\times10^{-4}, 3.7\times10^{-4})$	$(-4.2\times10^{-4}, 4.3\times10^{-4})$
h_3^Z	$(-3.2\times10^{-4}, 3.3\times10^{-4})$	$(-3.8\times10^{-4}, 3.8\times10^{-4})$
h_4^γ	$(-4.4\times10^{-7}, 4.3\times10^{-7})$	$(-5.1\times10^{-7}, 5.0\times10^{-7})$
h_4^Z	$(-4.5\times10^{-7}, 4.4\times10^{-7})$	$(-5.3\times10^{-7}, 5.1\times10^{-7})$

Greatly improved on the previous limits

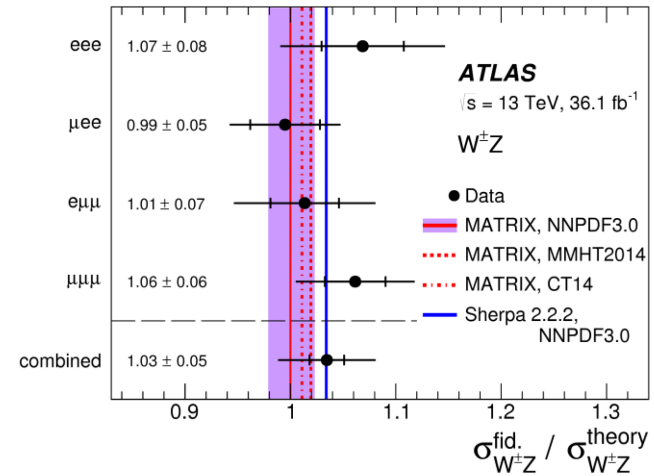
Recent: WZ Measurements

EPJC 79 (2019) 535

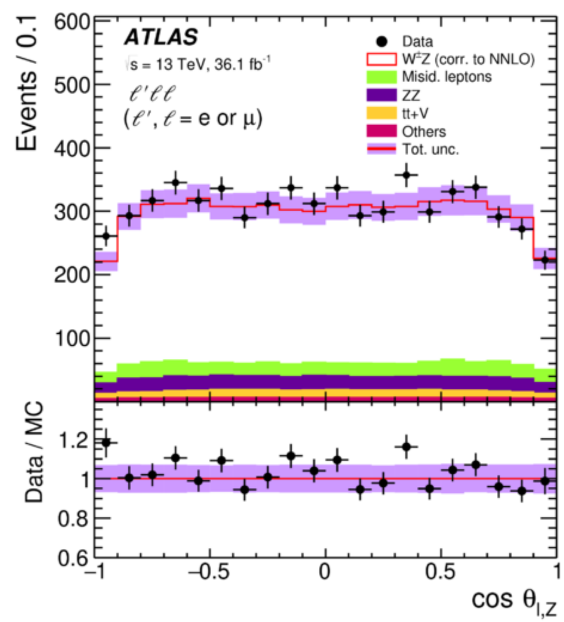
- Most precise diboson channels (so far)



< 5% uncertainty



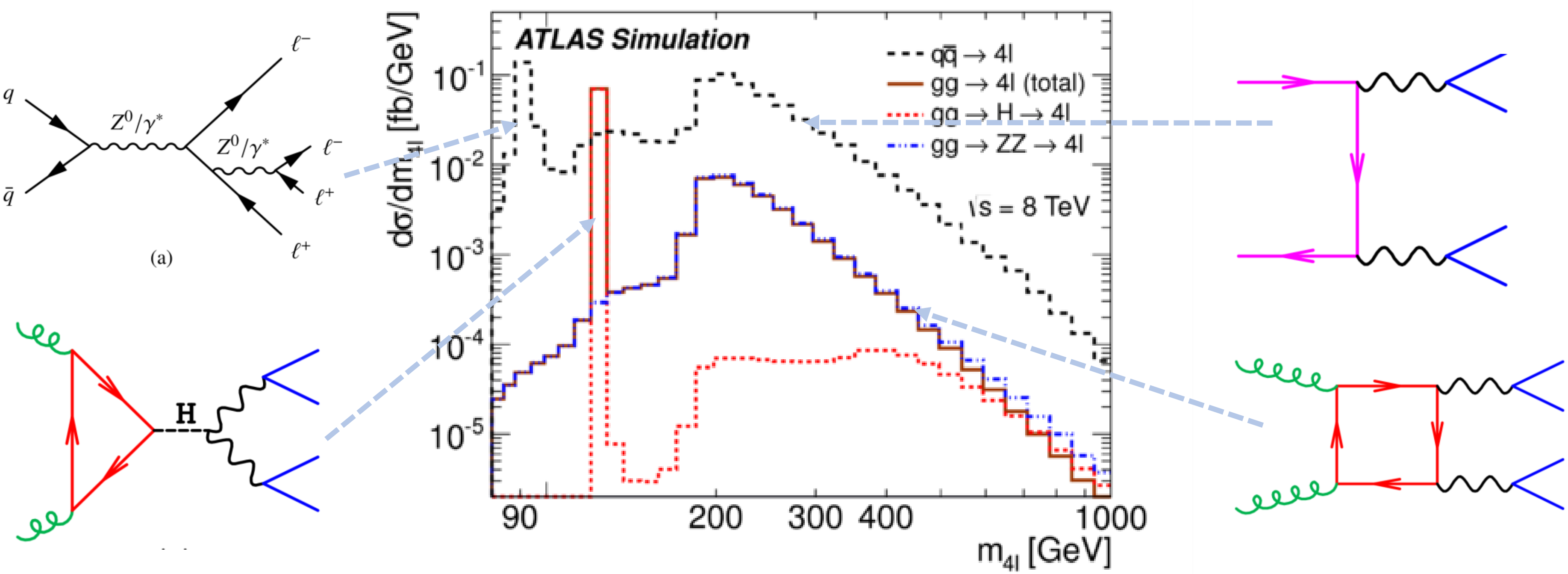
First attempt to study the polarization of bosons



Inclusive 4l Lineshape

JHEP 04 (2019) 048

- ❑ Sensitive to many interesting physics: ZZ, Higgs, off-shell Higgs, and new physics



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JHEP 04 (2019) 048

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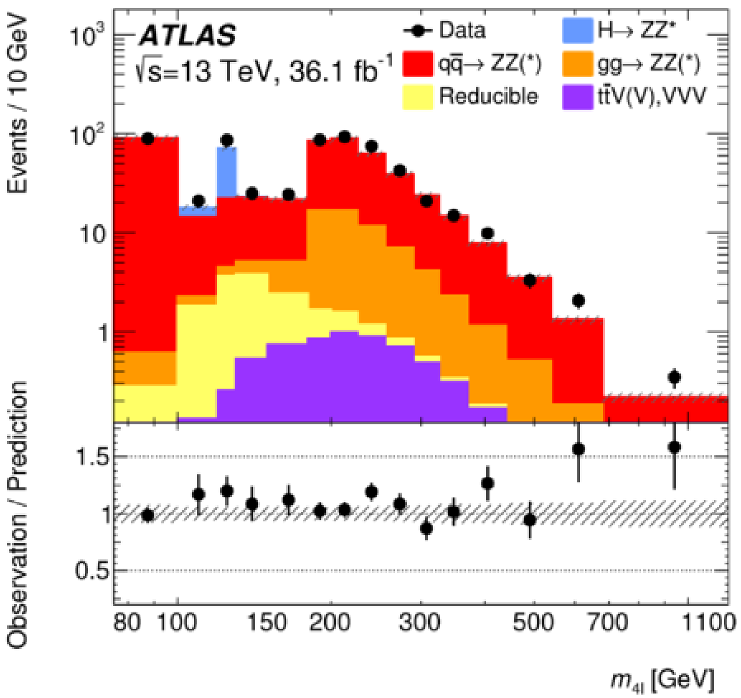
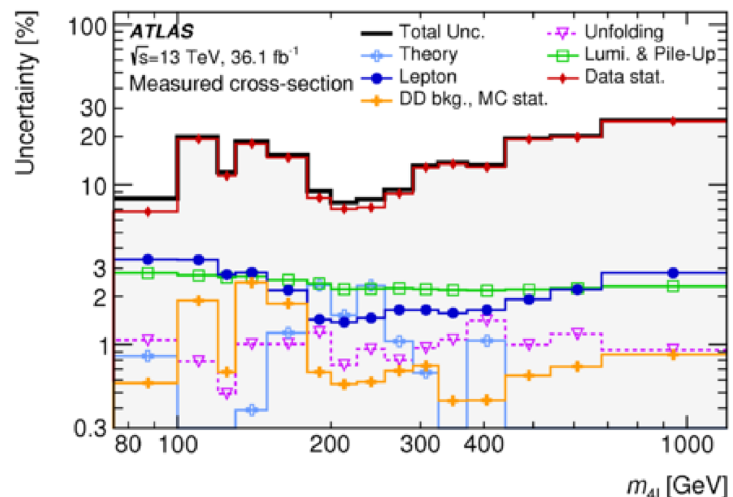
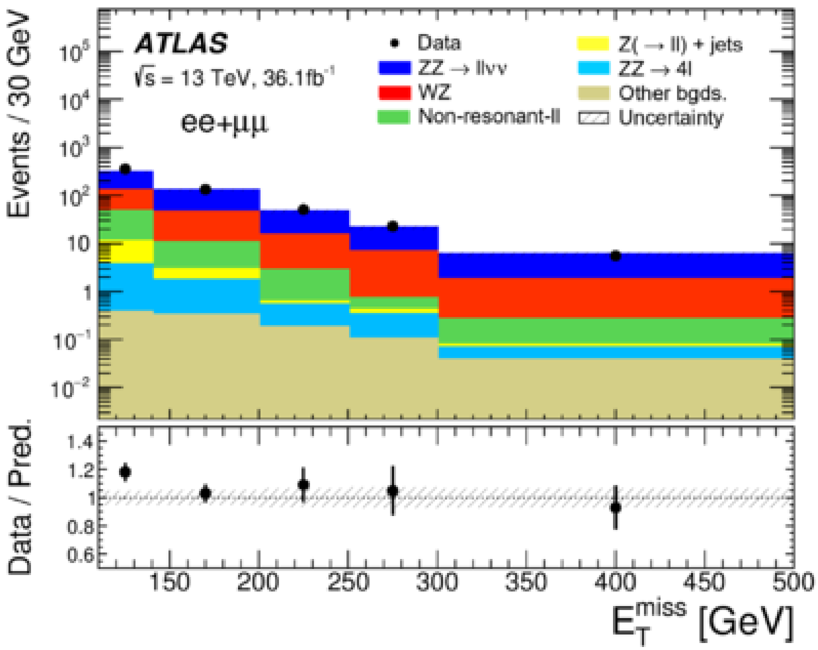


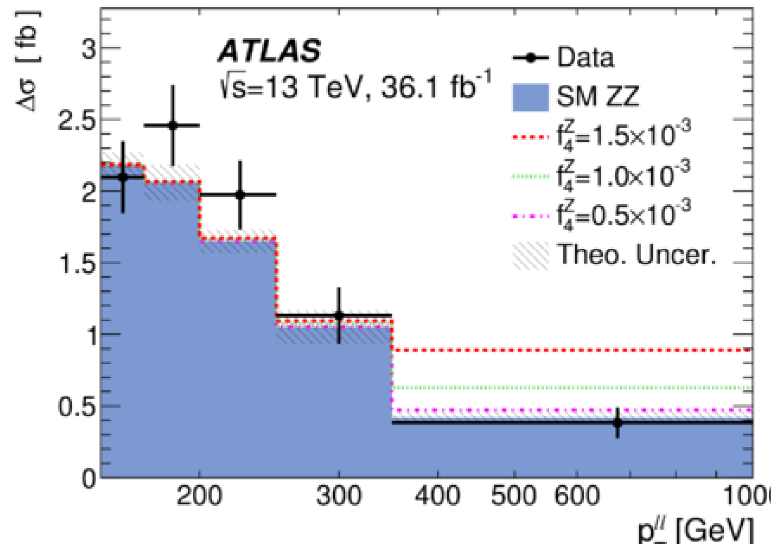


- Mass range 80 – 1000 GeV
- Can be interpreted to constrain offshell Higgs, gluon-gluon production
- Br(Z→4l) = (4.7 +/- 0.4) x 10^{-6},

ZZ→llνν

- Complementary to four charged leptons, but strong in searching for aTGCs, due to larger branching ratio

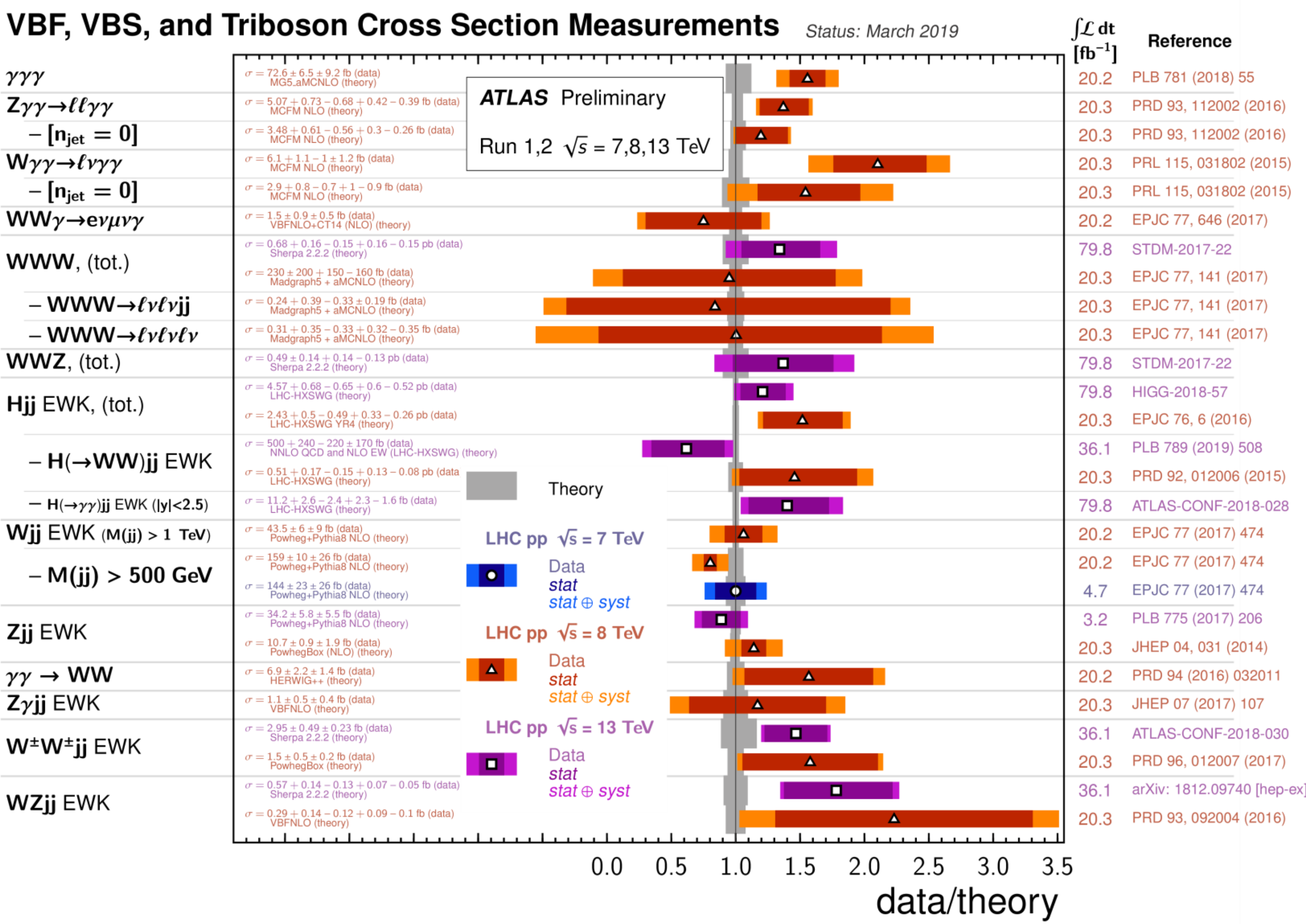




		Measured	Predicted
	ee	12.2 ± 1.0 (stat) ± 0.5 (syst) ± 0.3 (lumi)	11.2 ± 0.6
$\sigma^{\rm fid}_{ZZ\to\ell\ell\nu\nu}$ [fb]	$\mu\mu$	13.3 ± 1.0 (stat) ± 0.5 (syst) ± 0.3 (lumi)	11.2 ± 0.6
	$ee+\mu\mu$	25.4 ± 1.4 (stat) ± 0.9 (syst) ± 0.5 (lumi)	22.4 ± 1.3
$\sigma^{\rm tot}_{ZZ}$ [pb]	Total	17.8 ± 1.0 (stat) ± 0.7 (syst) ± 0.4 (lumi)	15.7 ± 0.7

Carefully optimized to gain precision in those difficult channels, yielding a best sensitivity to neutral couplings w.r.t. ZZ

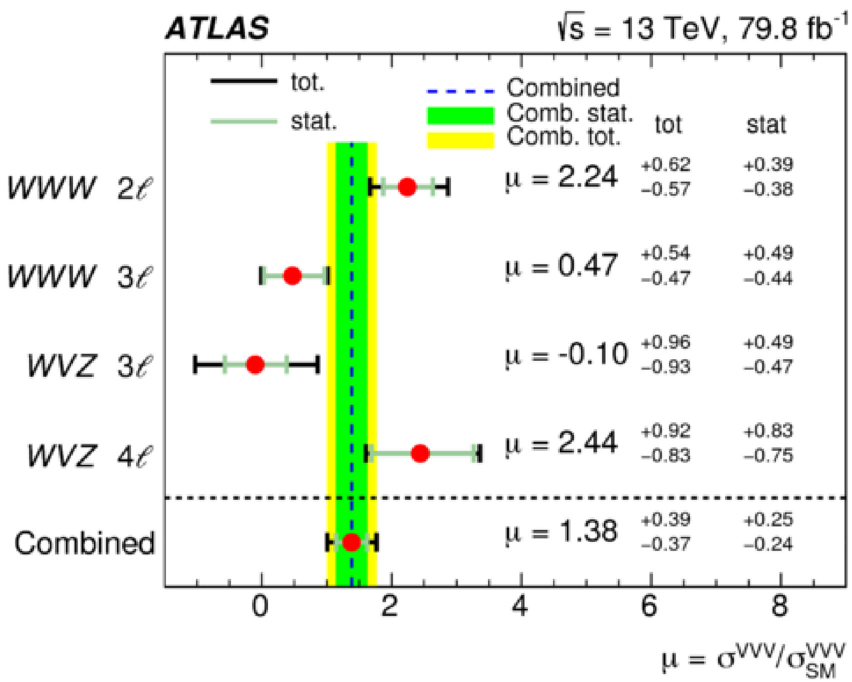
VBF, VBS, Triboson

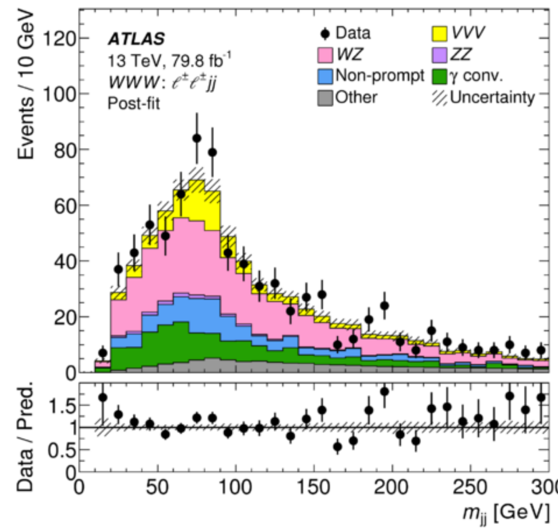


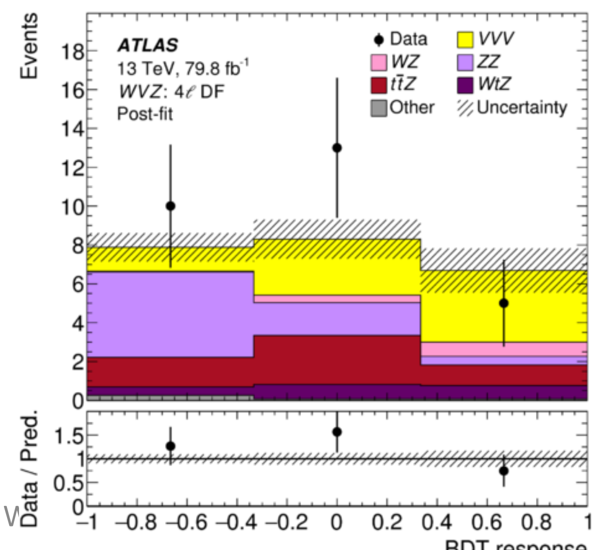
Three Massive Bosons

Submitted to PLB, arXiv:1903.10415

- Rare processes, sensitive to quartic couplings in the SM





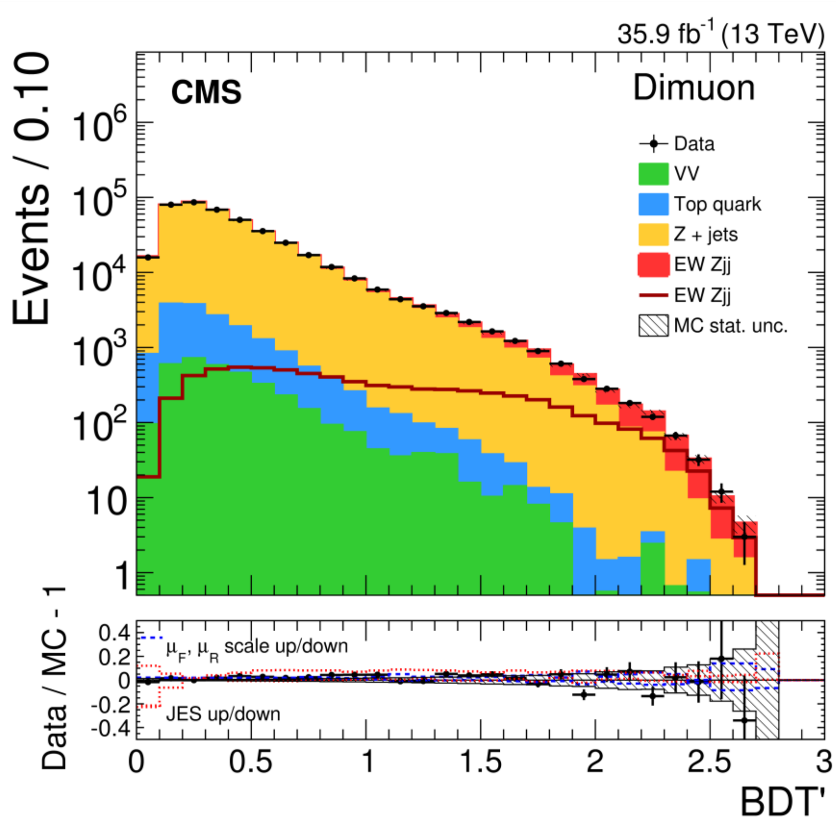


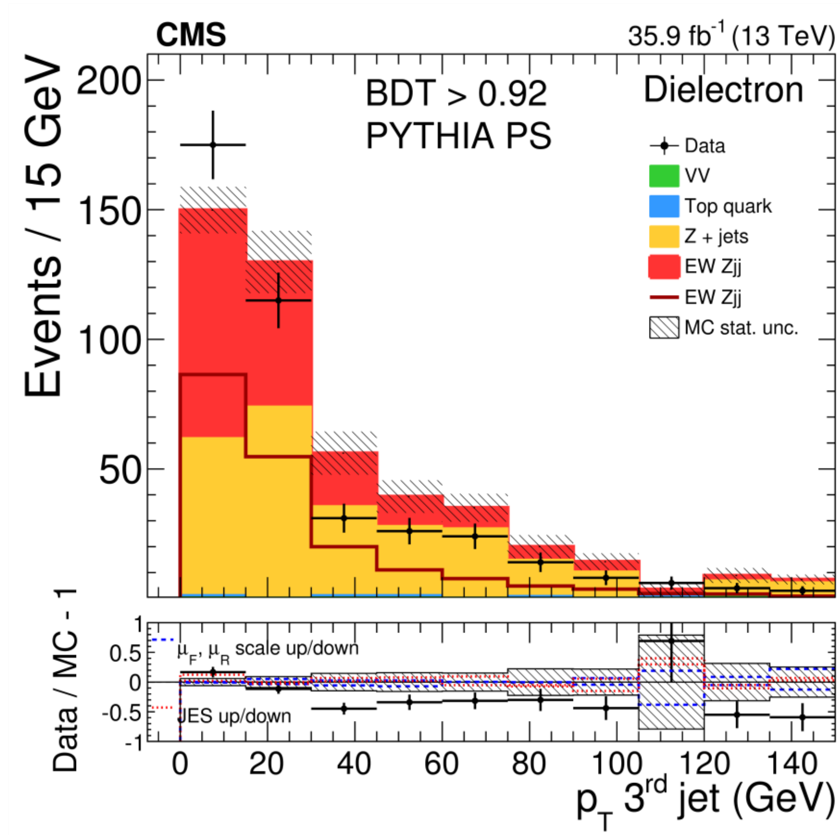
First evidence of three massive boson production, observed (expected) sig. = 4.0 (3.1) σ

VBS Zjj

EPJC 78 (2018) 589

- Large amount of events, to be used to examine the relevant modelling



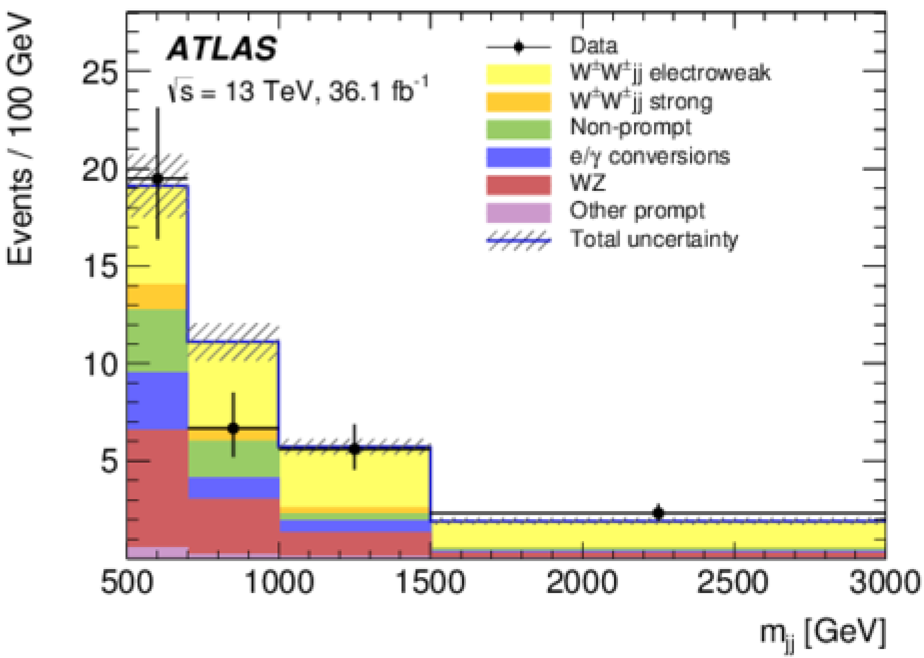


Same-sign VBS WWjj

Submitted to PRL, arXiv:1906.03203

- "Golden channel" to study VBS

	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	Combined
WZ	1.48 ± 0.32	1.09 ± 0.27	11.6 ± 1.9	7.9 ± 1.4	5.0 ± 0.7	3.4 ± 0.6	30 ± 4
Non-prompt	2.2 ± 1.1	1.2 ± 0.6	5.9 ± 2.5	4.7 ± 1.6	0.56 ± 0.05	0.68 ± 0.13	15 ± 5
e/γ conversions	1.6 ± 0.4	1.6 ± 0.4	6.3 ± 1.6	4.3 ± 1.1	—	—	13.9 ± 2.9
Other prompt	0.16 ± 0.04	0.14 ± 0.04	0.90 ± 0.20	0.63 ± 0.14	0.39 ± 0.09	0.22 ± 0.05	2.4 ± 0.5
$W^\pm W^\pm jj$ strong	0.35 ± 0.13	0.15 ± 0.05	2.9 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.25	7.2 ± 2.3
Expected background	5.8 ± 1.4	4.1 ± 1.1	28 ± 4	18.8 ± 2.6	7.7 ± 0.9	5.1 ± 0.6	69 ± 7
$W^\pm W^\pm jj$ electroweak	5.6 ± 1.0	2.2 ± 0.4	24 ± 5	9.4 ± 1.8	13.4 ± 2.5	5.1 ± 1.0	60 ± 11
Data	10	4	44	28	25	11	122

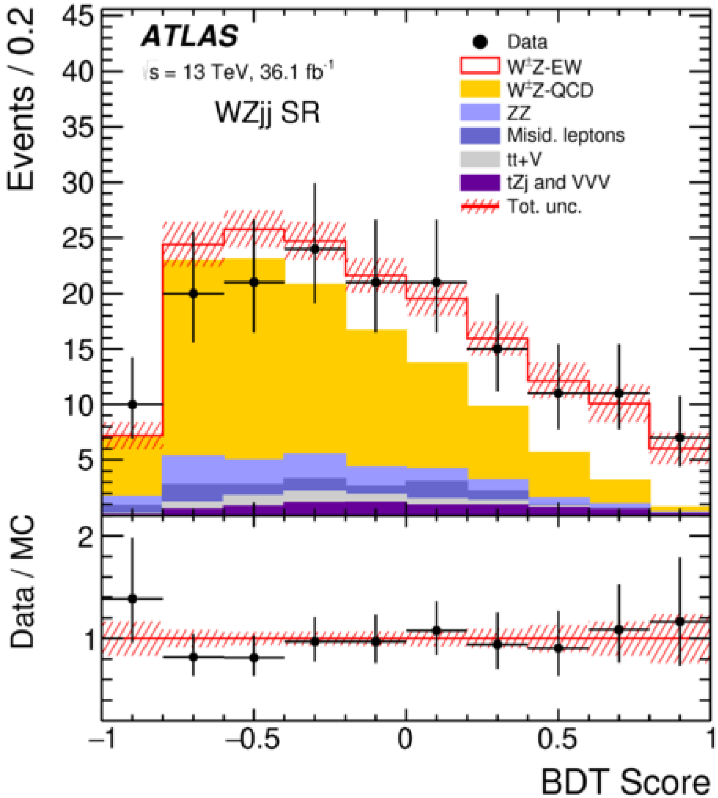


Both ATLAS and CMS have now observed this process with > 5 σ significance

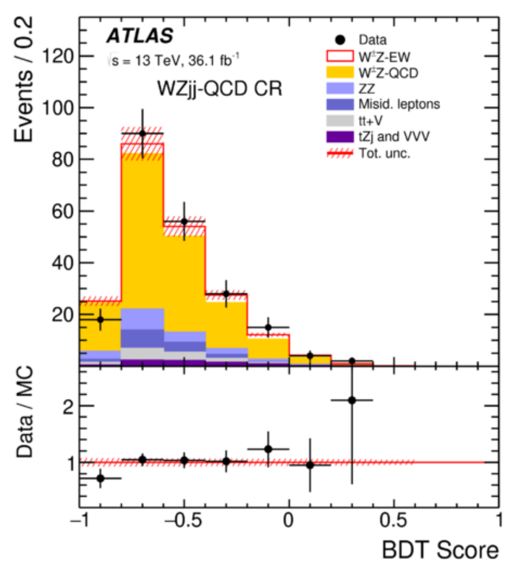
VBS WZjj

Phys. Lett. B 793 (2019) 469

- First observation of VBS WZjj (5.3 σ)



	SR	$WZjj$–QCD CR	b-CR	ZZ-CR
Data	161	213	141	52
Total predicted	200 ± 41	290 ± 61	160 ± 14	45.2 ± 7.5
$WZjj$–EW (signal)	24.9 ± 1.4	8.45 ± 0.37	1.36 ± 0.10	0.21 ± 0.12
$WZjj$–QCD	144 ± 41	231 ± 60	24.4 ± 1.7	1.43 ± 0.22
Misid. leptons	9.8 ± 3.9	17.7 ± 7.1	30 ± 12	0.47 ± 0.21
$ZZjj$–QCD	8.1 ± 2.2	15.0 ± 3.9	1.96 ± 0.49	35 ± 11
tZj	6.5 ± 1.2	6.6 ± 1.1	36.2 ± 5.7	0.18 ± 0.04
$t\bar{t}+V$	4.21 ± 0.76	9.11 ± 1.40	65.4 ± 10.3	2.8 ± 0.61
$ZZjj$–EW	1.80 ± 0.45	0.53 ± 0.14	0.12 ± 0.09	4.1 ± 1.4
VVV	0.59 ± 0.15	0.93 ± 0.23	0.13 ± 0.03	1.05 ± 0.30

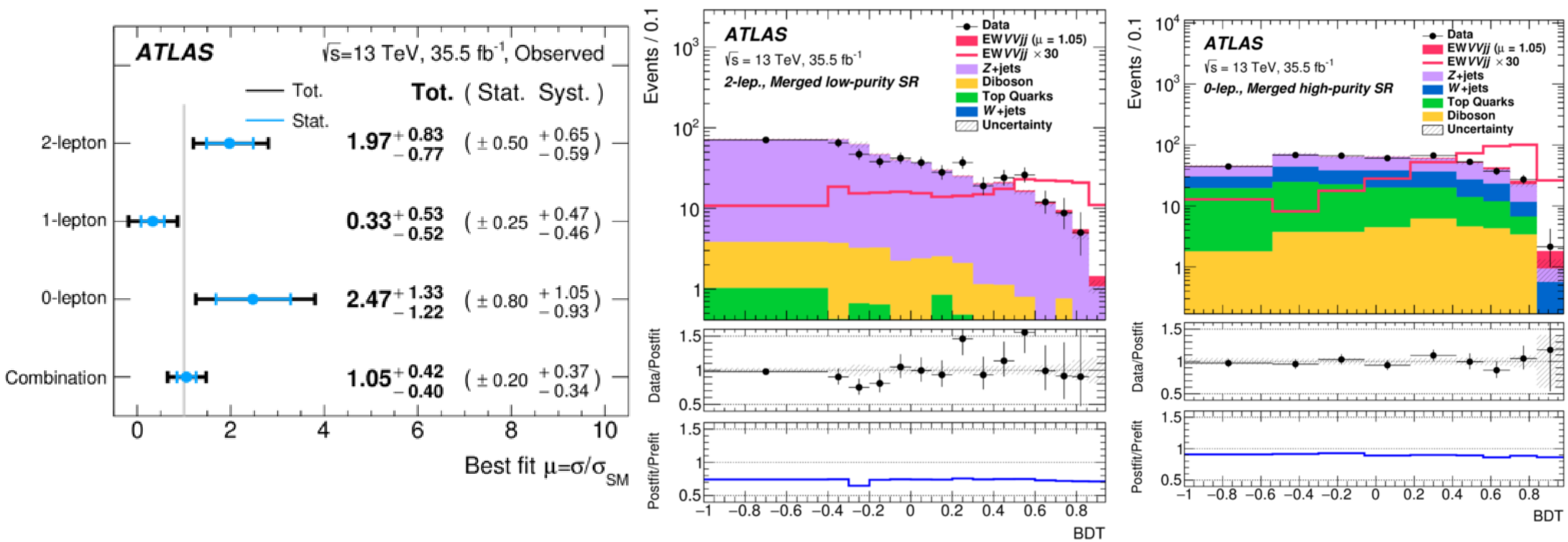


Machine learning relied on to gain sensitivity

VBS VVjj – Semileptonic Decays !!!

arXiv:1905.07714
submitted to PRD

- Larger Br., combining VBS WW/WZ/ZZ "collectively" to gain sensitivity to new physics (at large pT etc.)



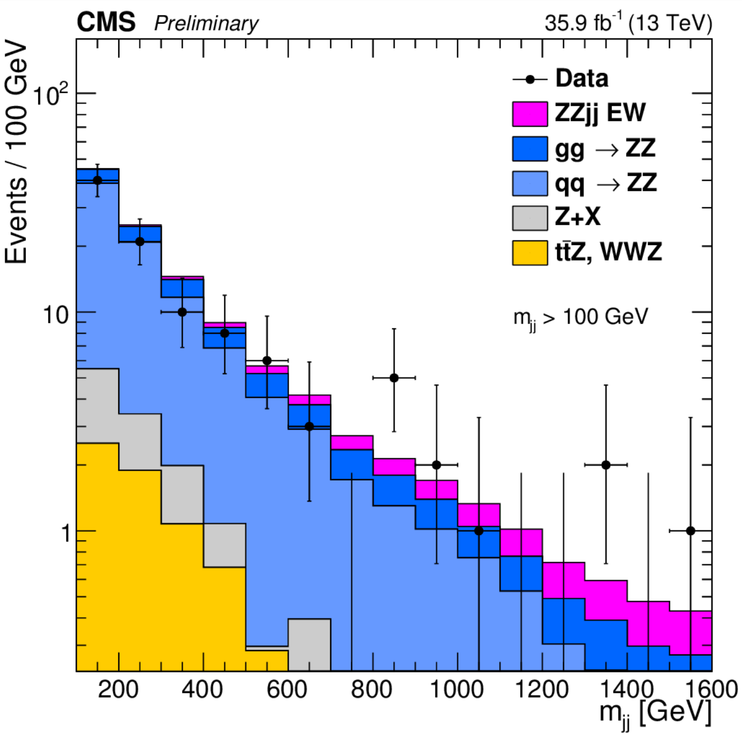
Used both "merged" jets and resolved jets

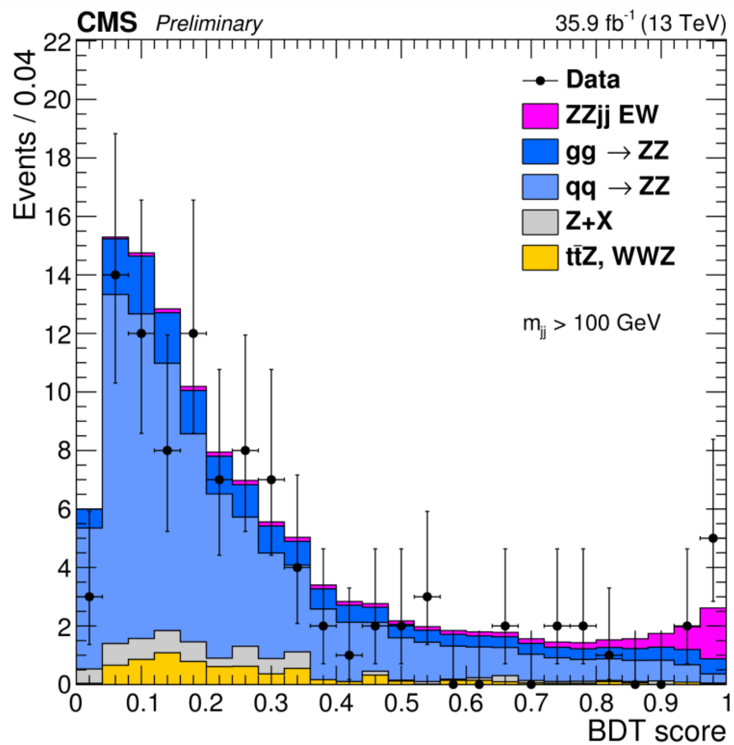
Observed (expected) significance 2.7 (2.5) σ

VBS ZZjj

CMS-PAS-SMP-16-019

- Rarest of this kind; observation of this process will be another milestone in the EW physics program





No sufficient significance to claim an evidence yet; highly anticipated channel with full Run-II data

Summary

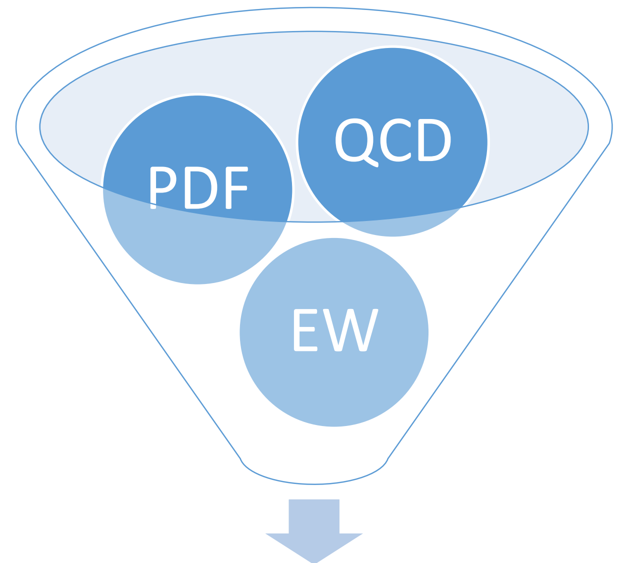
Studies of EW interactions at the LHC have been discussed in a brief way

So far, <u>no obvious deviation from the SM</u> were found (<u>also from direct searches</u>)

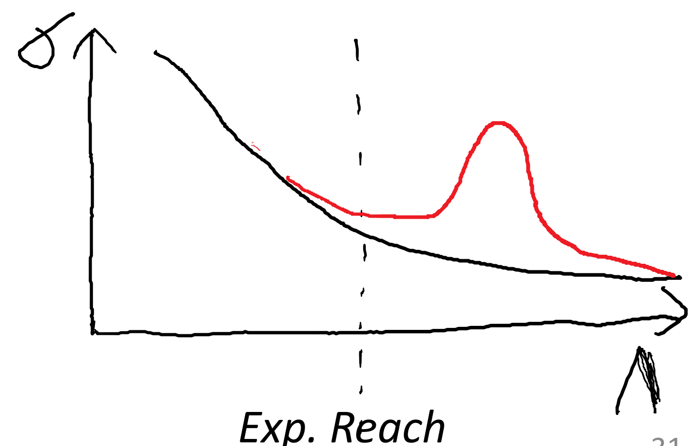
Many of these results interpreted into constraints on BSM physics, e.g. anomalous couplings / EFT

In many places, test of the SM enters into a <u>precision era</u>

<u>Scrutiny of a larger data sample is needed</u> to bring the understanding of the EW physics to a next-level precision



Observation of BSM only through Precision measurements???



Summary

Many of the measurements are entering a stage limited by systematic uncertainties now (or soon) at the LHC

CEPC provides enormous amount of Z bosons (10^{12}), as well as W bosons, and with the precision detection apparatus, can be a ideal machine for extending the knowledge of EW physics.

W, Z masses, weak mixing angle; QCD through Z decays
WW production and the involved TGCs
Z rare decays
Neutral couplings …

New Physics Everywhere or Nowhere ???