Precision tests of the SM at the LHC with the ATLAS and CMS detectors

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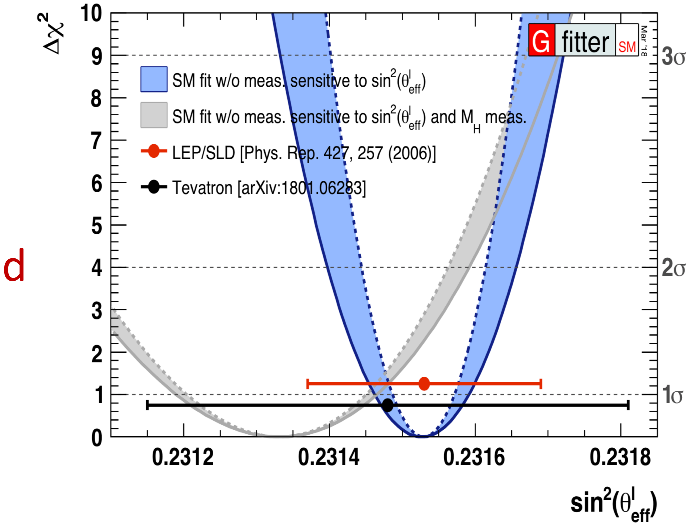
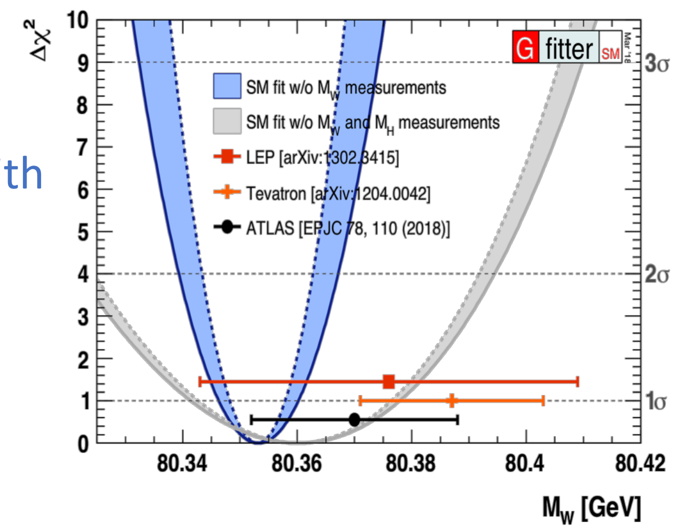
Introduction

http://gfitter.desy.de/Standard_Model/



- Precise EW measurements + theoretical calculations successfully predicted top quark & Higgs boson masses
- Provide critical test of SM consistency and constrain allowed New Physics parameters
- EW gauge & Higgs sector described by 4 parameters: α, G_F, m_Z, m_H
- Other parameters predicted by theory → over-constrained



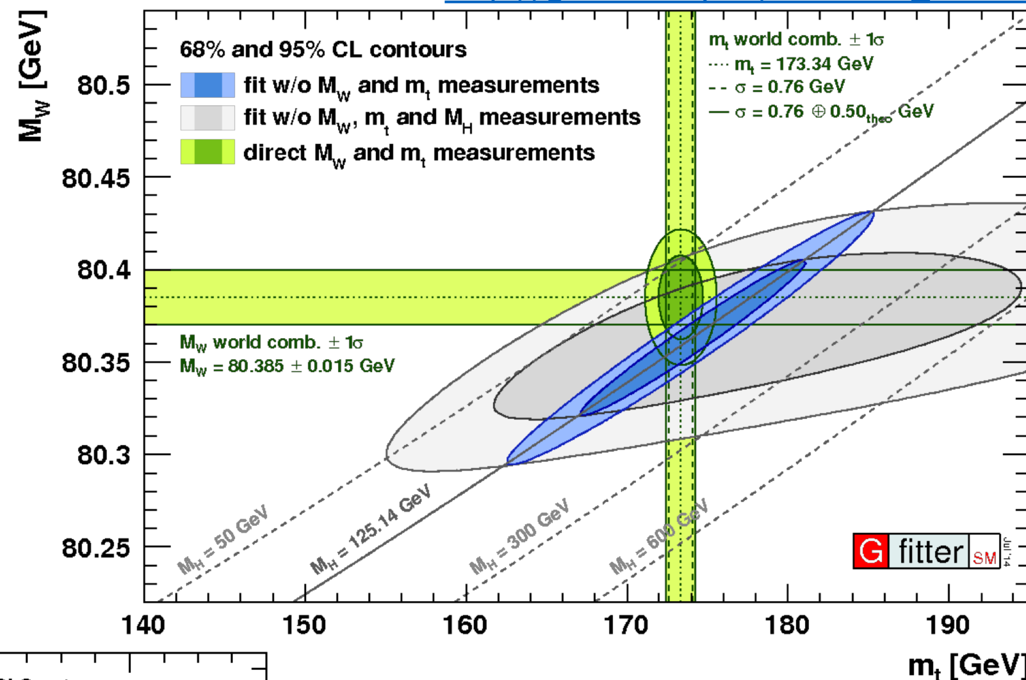
- Ultimate aim: direct precision measurements of EW mixing angle (±10^{-4}) and W boson mass (±10 MeV), competitive with global fit uncertainties
- Need excellent understanding of experimental and pdf uncertainties
- Rich program of Z/W measurements: Z→ll angular coefficients, A_{fb}, W charge asymmetry, Z/W p_T, differential cross-sections…
- Gauge boson self-interactions studied via EW Z/W+jj and VV(V) production (not discussed today)

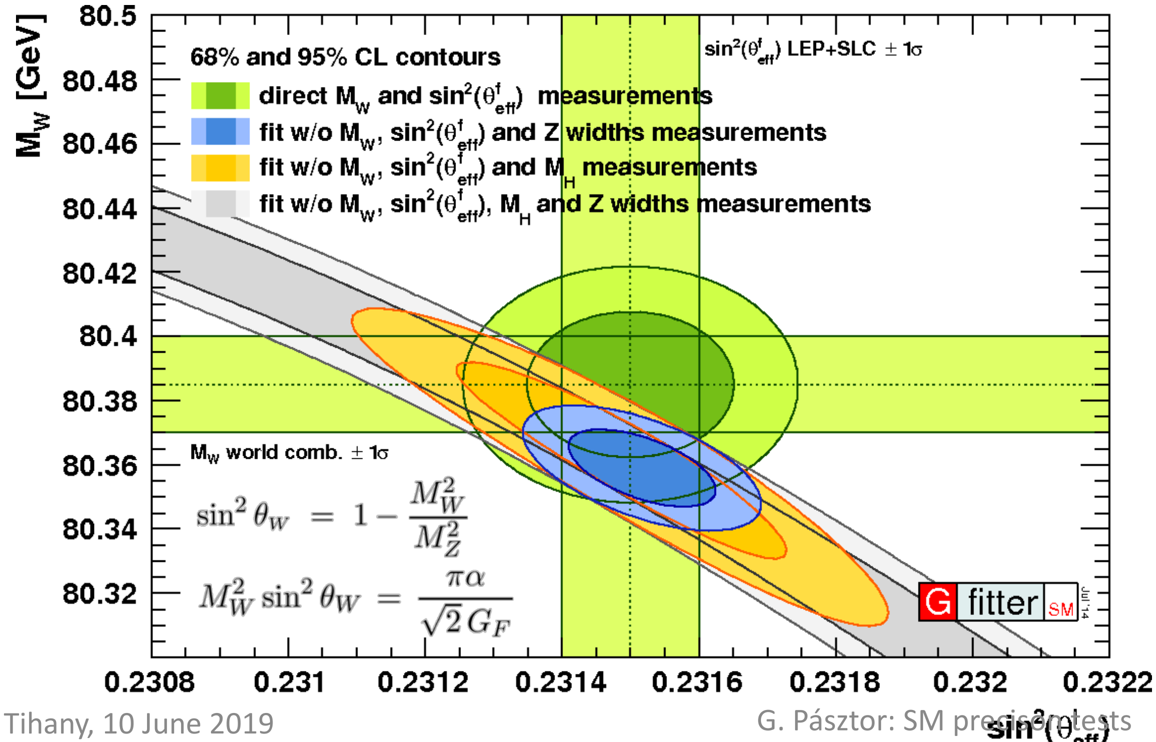
	EW Fit	World average
$\sin^2\theta_W$	0.23153 ± 0.00006	0.23152 ± 0.00016
m_W [GeV]	80.354 ± 0.007	80.379 ± 0.013

On the menu today

http://gfitter.desy.de/Standard_Model/

- Top mass
- W mass
- Effective weak mixing angle, $\sin^2\theta^l_{eff}$
- Higgs mass (→ next talk)

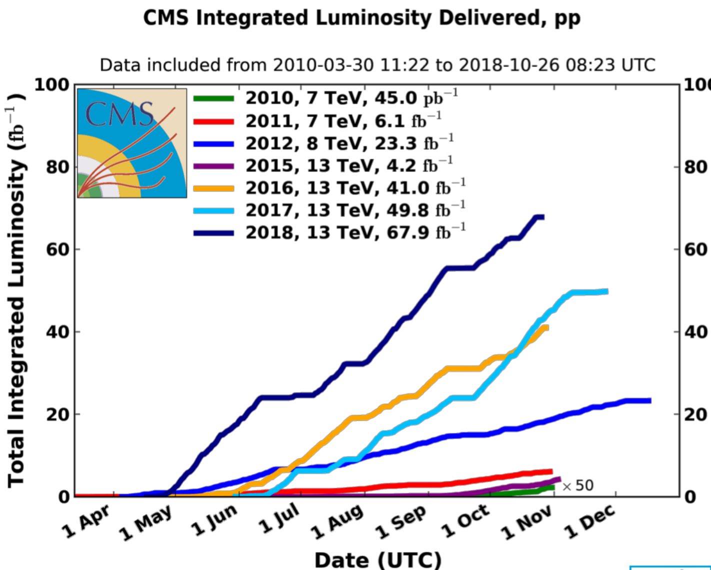


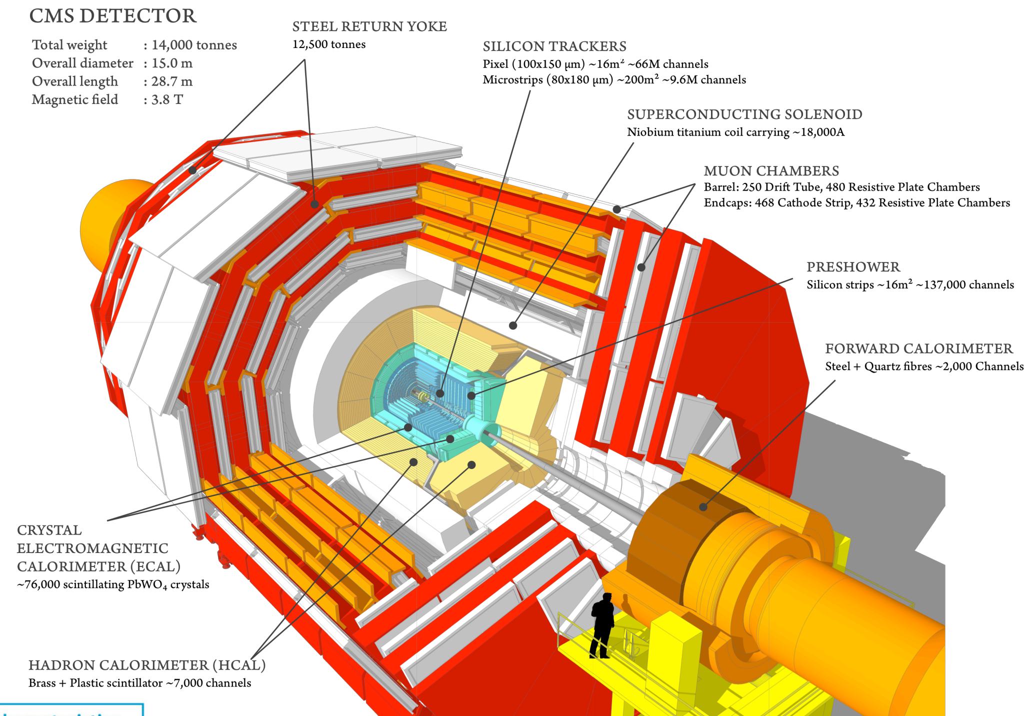


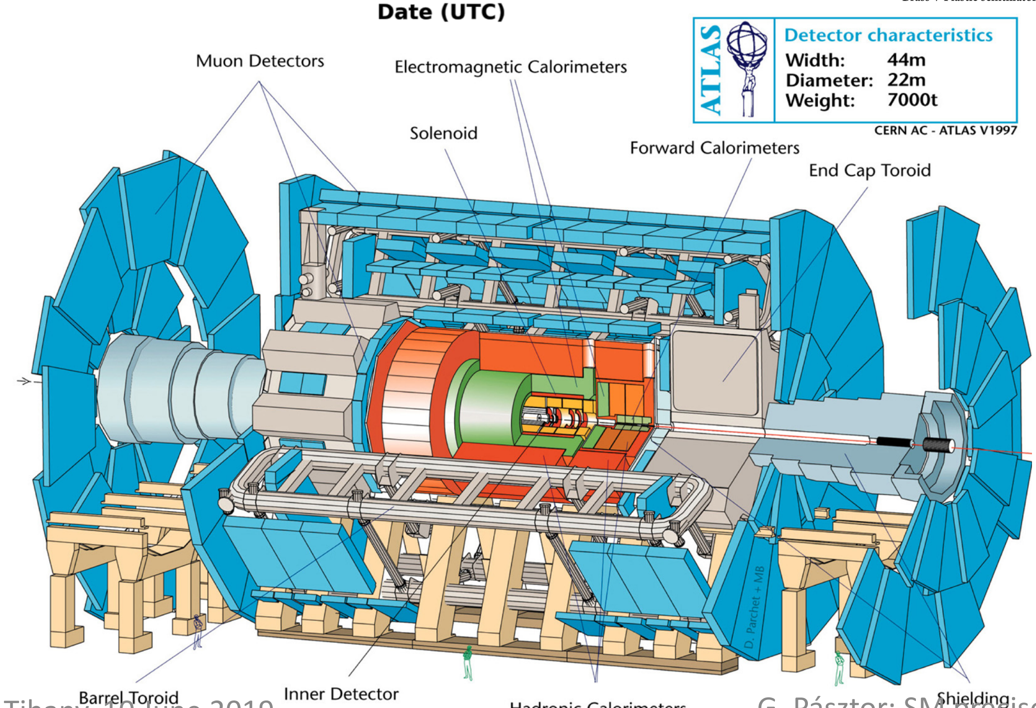
- Differential Z/W xsections
- Z angular coefficients, A_i
- Z forward-backward asymmetry, A_{FB}
- W charge asymmetry

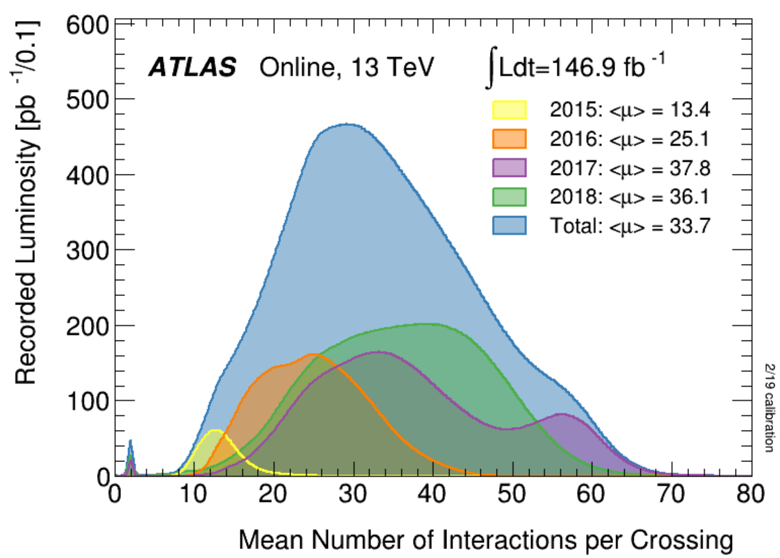
Selection from a rich harvest

The experiments









At a glance…

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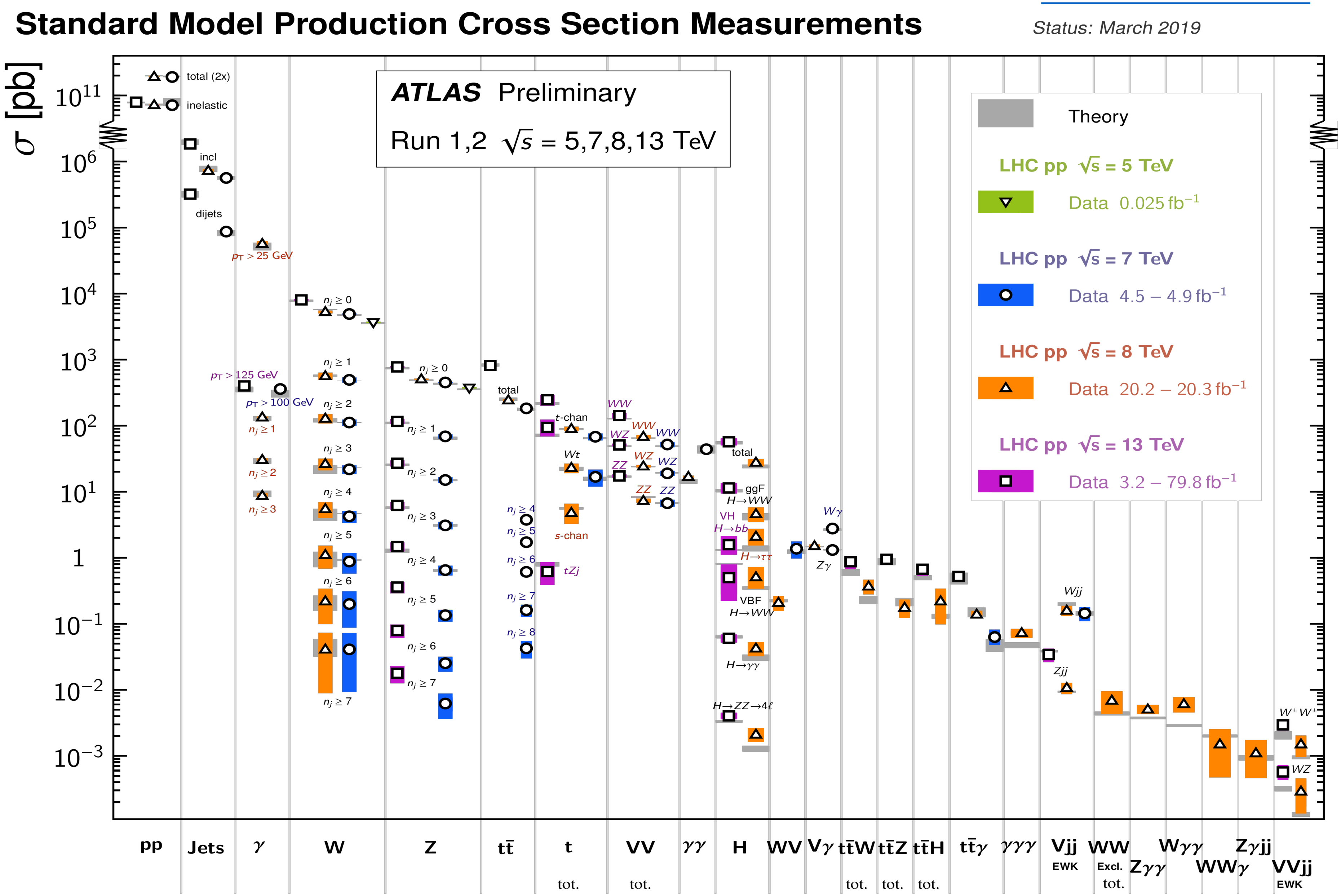
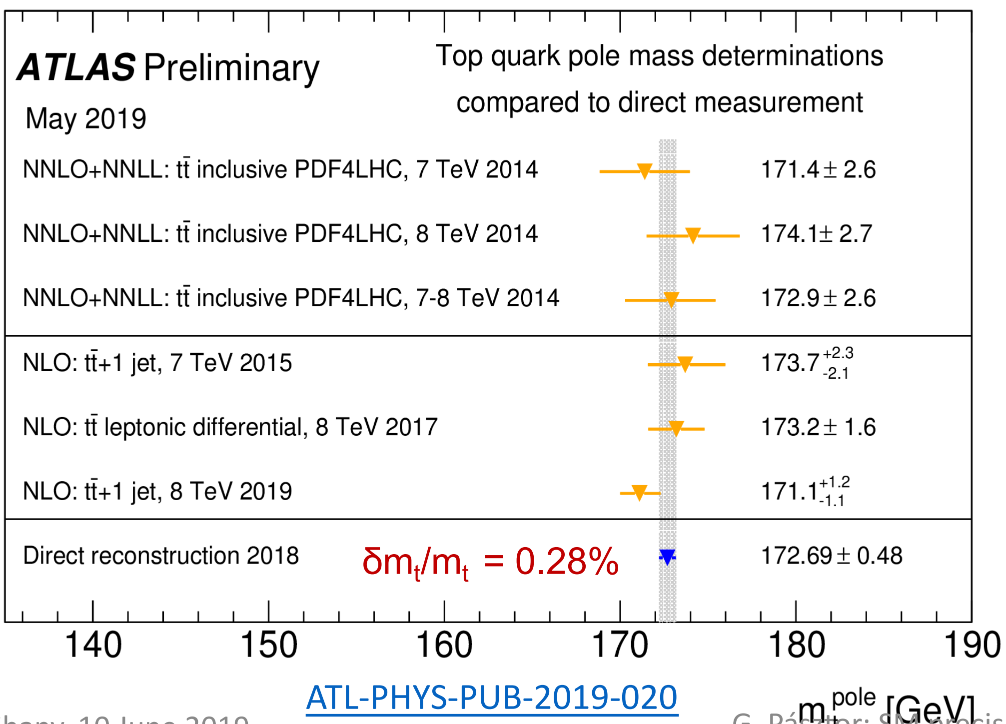


Top quark and W boson mass

Top quark mass

- SM self-consistency
  - Corrections to EW parameters
- Stability of EW vacuum
- Direct measurement from reconstructed decay products → compare to MC → interpret as pole mass
- Indirect measurements from cross-section or differential distributions → either pole mass or running mass from MS scheme



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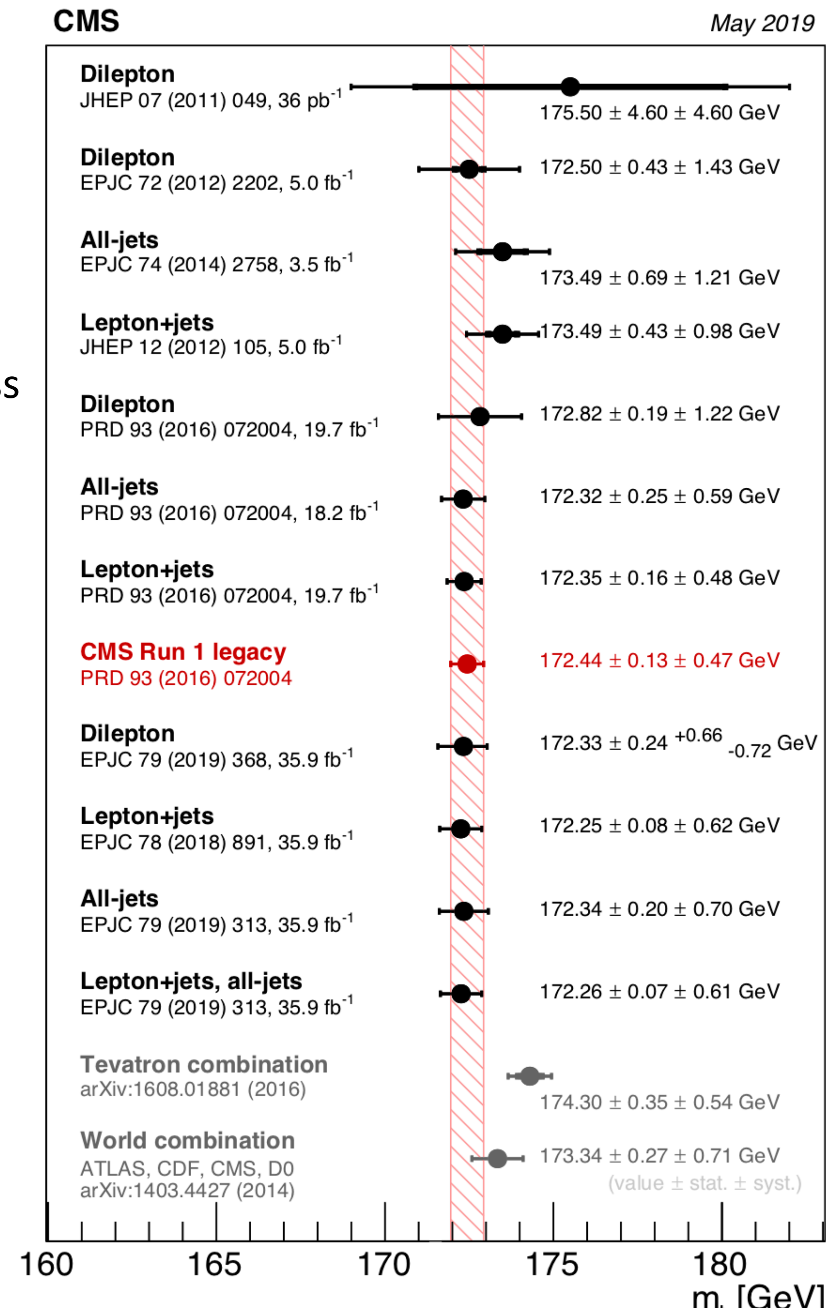
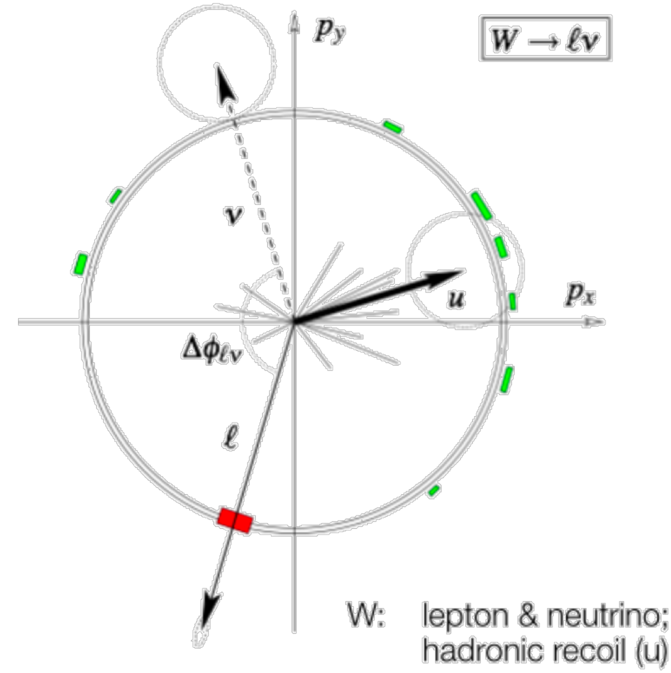
CMSPublic/PhysicsResultsTOPSummaryFigures



W boson mass

- Based on 4.5 fb^{-1} W → eν, $\mu\nu$ data @ 7 TeV
- Experimental challenge:
  lepton and hadronic recoil calibration
- Multijet background from template fits
- Dominant uncertainty from physics modelling
- Template fit to p^l_T and m_T
  - p^l_T sensitive to p^W_T modelling
  - m_T sensitive to hadronic recoil u_T
- Templates from Powheg+Pythia8, reweighted to best theoretical model
  - $d\sigma/d\eta$, W polarisation from DYNNLO
  - $d\sigma/dp_T$ from Pythia8, AZ tune
- Z events heavily used for calibration and validation



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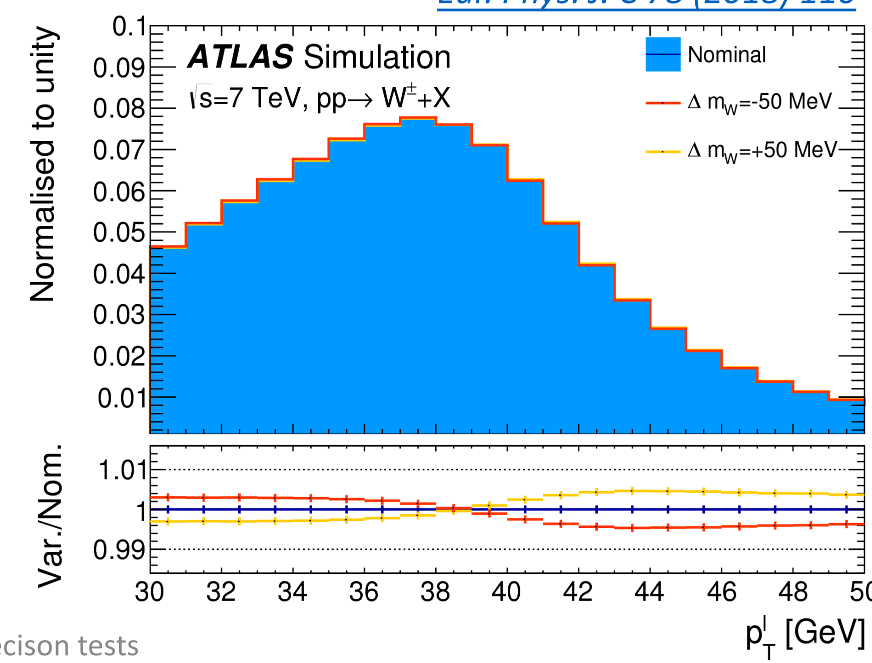

W boson mass

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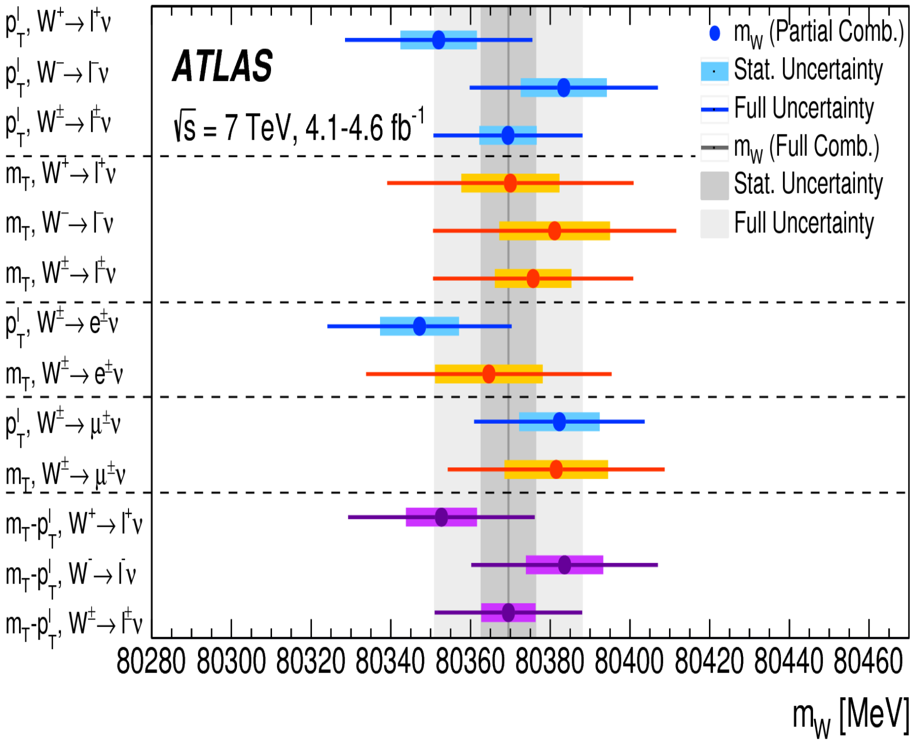

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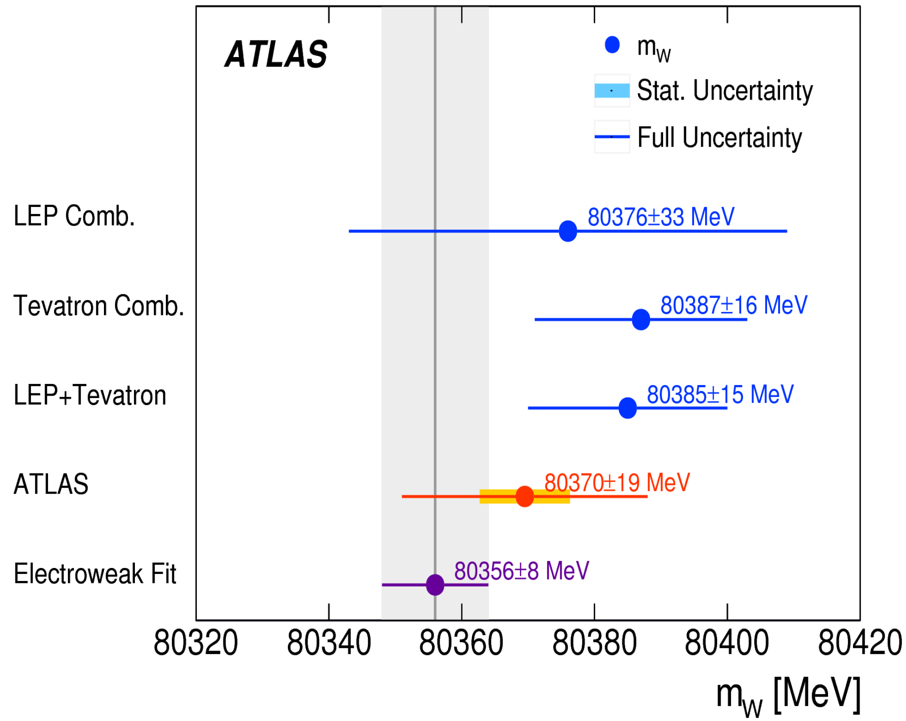

$$m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV} = 80370 \pm 19\text{MeV}$$

[Eur. Phys. J. C 78 (2018) 110]

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

QCD uncertainty: p_T^W distribution, extrapolation from Z to W; aim direct measurement at low PU

W boson mass at HL-LHC with upgraded detector

- Optimal MET reconstruction
  - Low detector occupancy
  - Extended pseudorapidity coverage
- Improved PDF
  - Possibility of new DIS data

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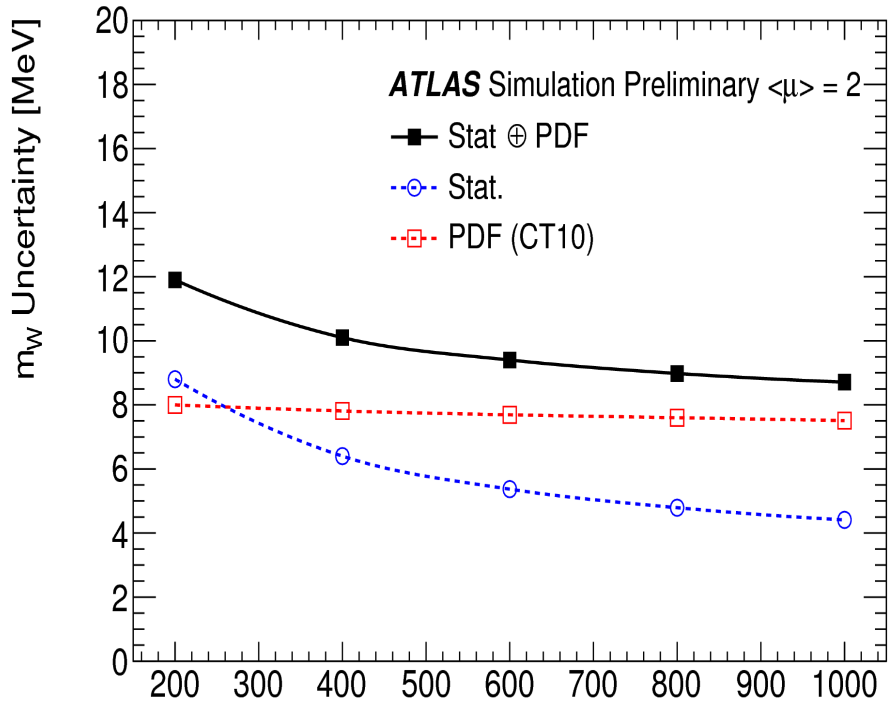

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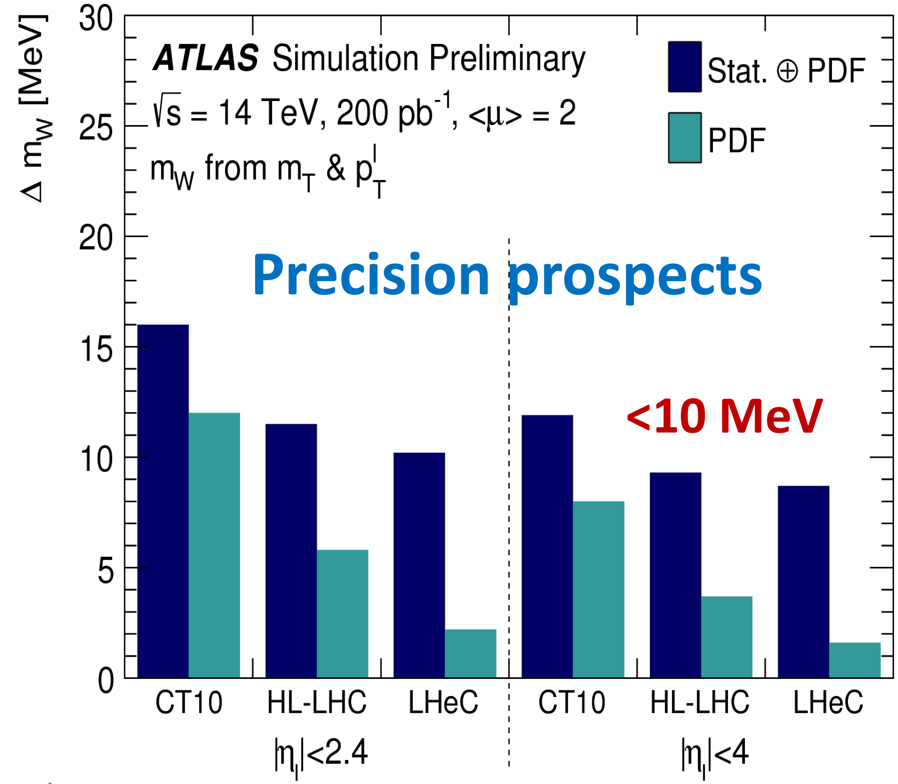


Weak mixing angle (Z angular coefficients and A_{FB})

Z→ ll angular coefficients (A_i) and forward-backward asymmetry (A_{FB})

- Lepton (ℓ^-) angular distributions in boson ($\ell\ell$) restframe (θ^*, φ^*: polar, azimuth ∢)

$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \Big[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)$$
$$+A_3\sin\theta^*\cos\phi^* + \boxed{A_4\cos\theta^*} + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\Big].$$

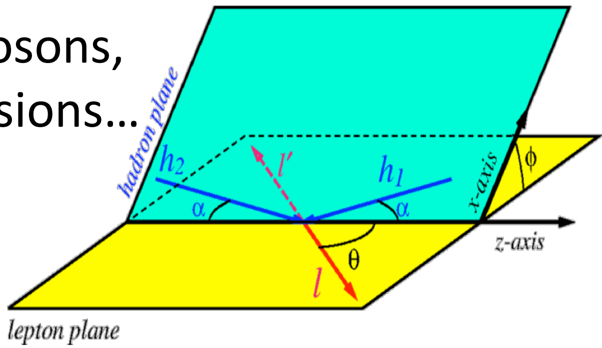
- Forward – backward asymmetry due to A_4 term:

$$A_{FB} = \frac{3}{8}A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

with $\sigma_{F(B)}$ total xsec for $\cos\theta > 0$ ($\cos\theta < 0$)

  - Related to V-A structure of ℓ couplings

- A_{FB} depends on $m_{\ell\ell}$, $\sin^2\theta_W$, quark flavour
- Precise measurement around m_Z → $\sin^2\theta_W$, u, d weak couplings
- Deviation from SM could arise from new neutral gauge bosons, quark-lepton compositeness, SUSY particles, extra dimensions…
- Collins-Soper (CS) frame to reduce uncertainty due to the incoming quarks' p_T



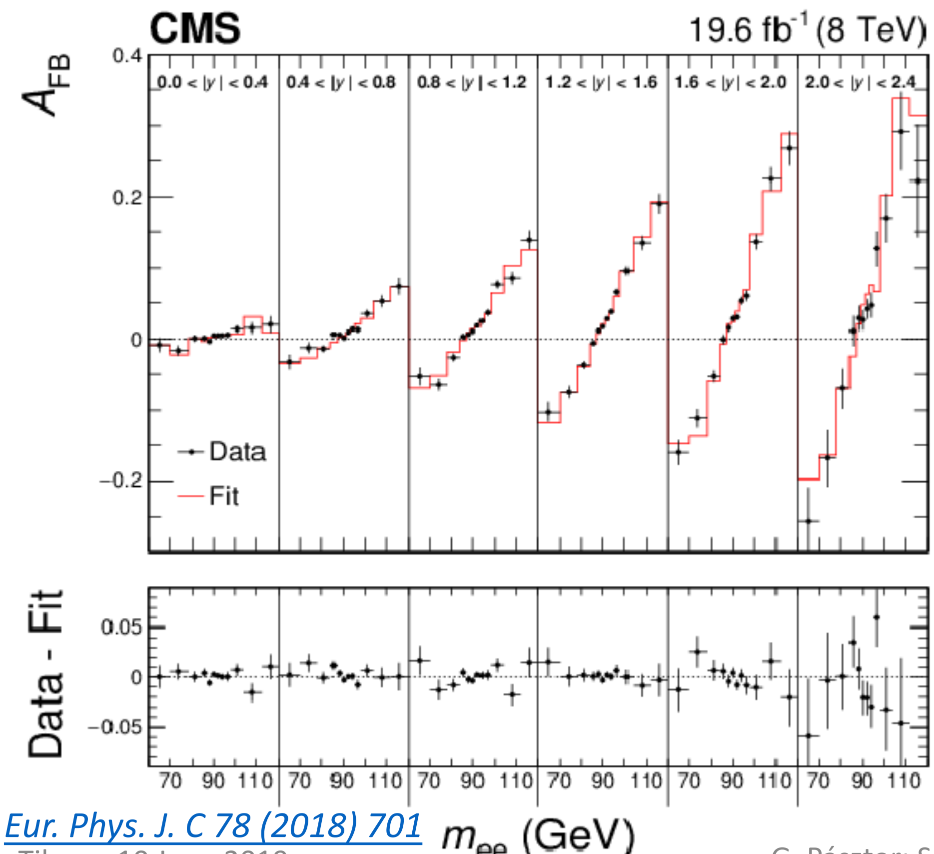
Weak mixing angle and forward-backward asymmetry

- HO corrections modify the LO relations
- Introduce effective mixing angle: $v_f / a_f = 1 - 4|Q_f| \sin^2 \theta_{eff}^f$
- Fit measured A_{FB}
- $\sin^2\vartheta^{\ell}_{eff}$ = 0.23101 ± 0.00036 (stat) ± 0.00018 (syst) ± 0.00016 (theo) ± 0.00031 (pdf)

  = 0.23101 ± 0.00053

$\sin^2\theta^f_{eff} = k_l \sin^2\theta_W$

from HO calculations



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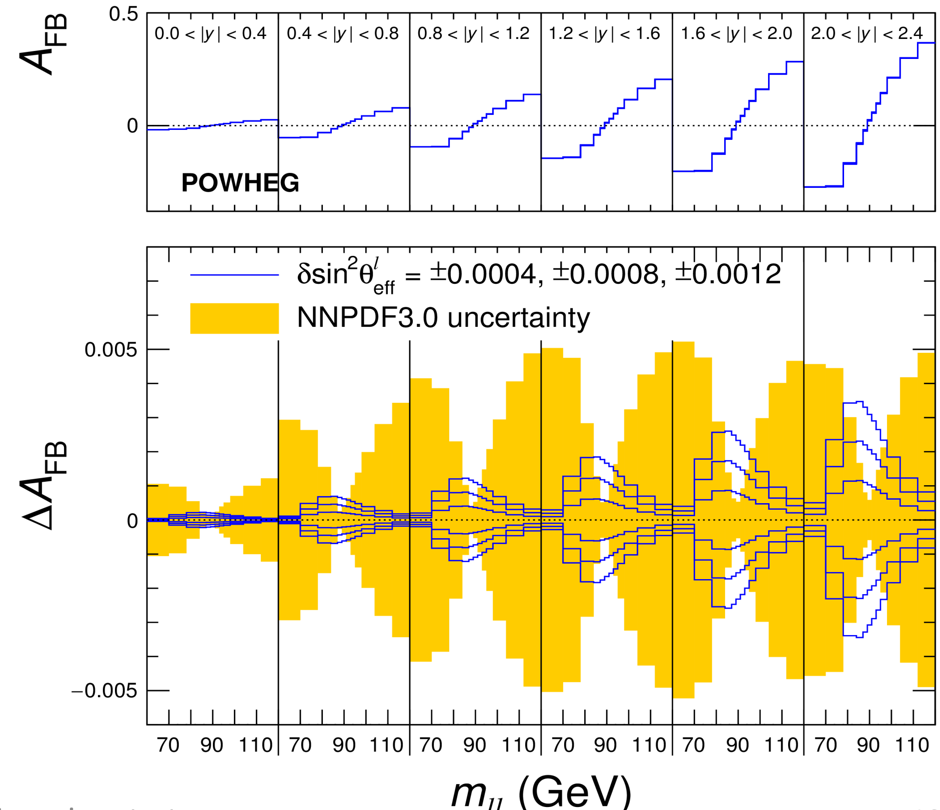

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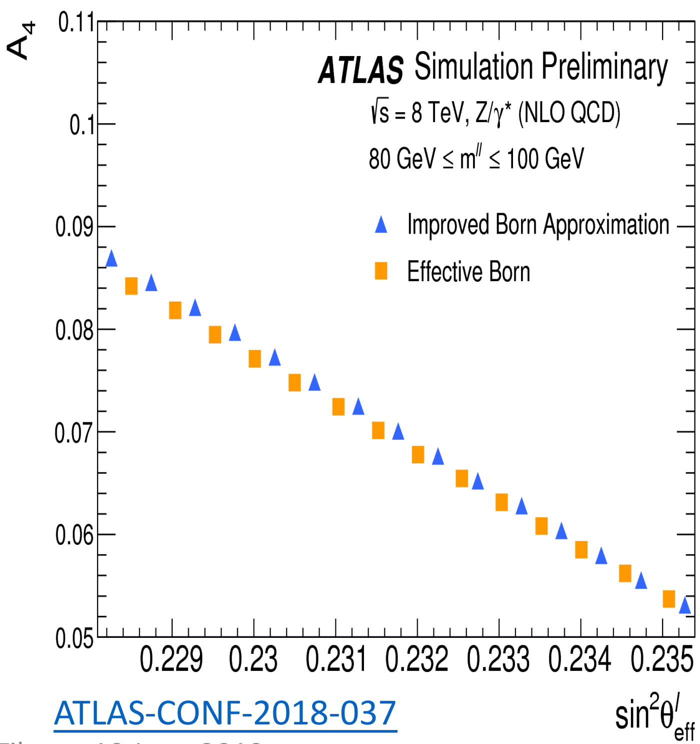
Weak mixing angle and A_4 angular coefficient

- Fold $P_i(\cos\theta_{CS},\phi_{CS})$ angular distributions to detector level
- Fit reconstructed $\cos\theta_{CS}$, ϕ_{CS}, m_{ll}, y_{ll} distributions in born-level m_{ll}, y_{ll} bins
- Extract A_4 in full decay lepton phase space, dominated by statistical uncertainties
- Infer $\sin^2\theta^f_{eff}$, dominated by QCD and PDF uncertainties
- $\sin^2\theta^l_{eff}$ = 0.23140 ± 0.00021 (stat.) ± 0.00024 (PDF) ± 0.00016 (syst.)

  = 0.23140 ± 0.00036



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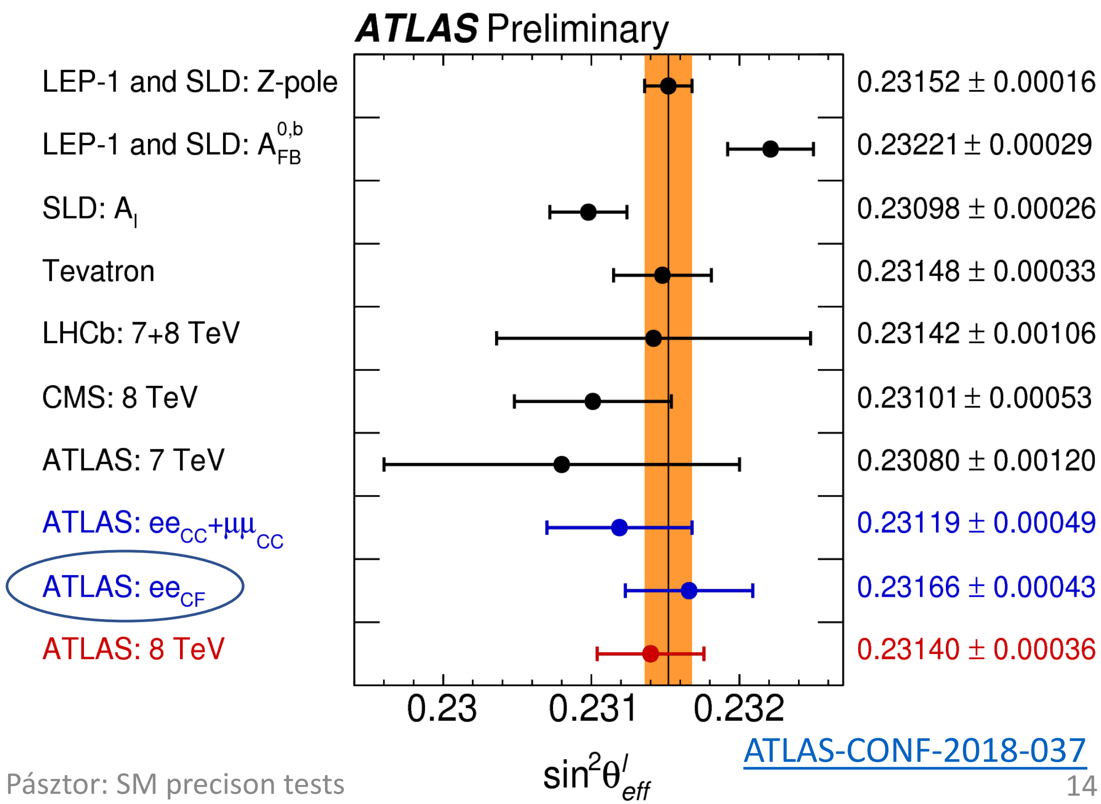


ATLAS-CONF-2018-037

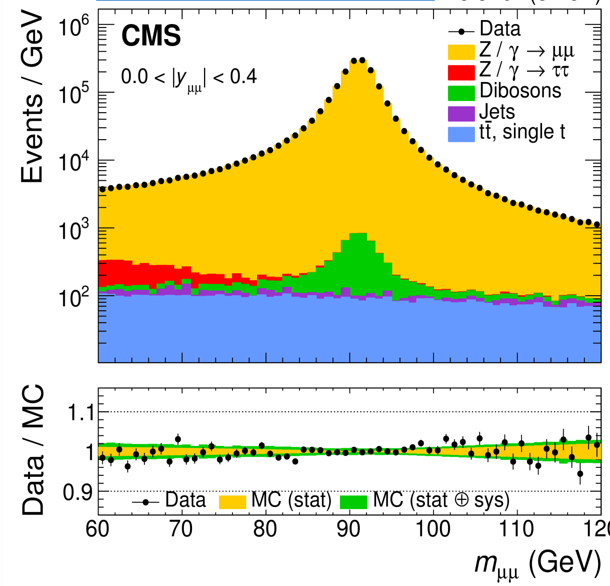
Z/γ^* and W differential cross-sections

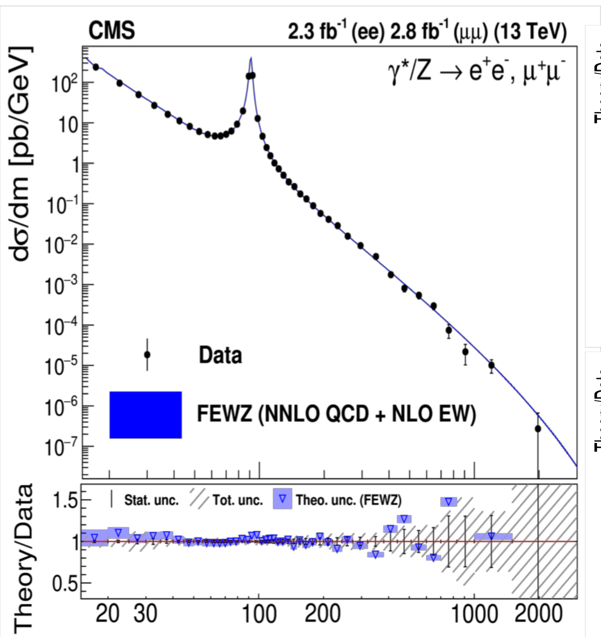
Drell-Yan cross-section measurements

- Test of higher-order EW and QCD predictions
- Sensitive to resummation techniques
- Constrains parton distribution functions
- Needed for precise EW measurements (m_W, $\sin^2\theta_W$)
  - m_W from fit to lepton p_T distribution
  - Precise Z measurements to obtain prediction for W p_T

$$\frac{d\sigma(W)}{dp_T} = \left[\frac{d\sigma(W)/dp_T}{d\sigma(Z)/dp_T}\right]_{\text{theory}} \times \left[\frac{d\sigma(Z)}{dp_T}\right]_{\text{measured}}$$

CMS-PAS-SMP-17-010





arXiv:1812.10529

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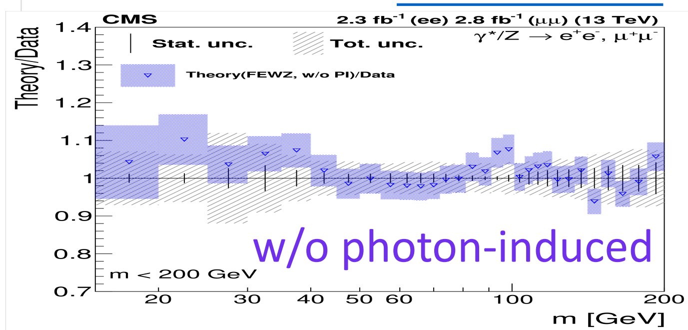
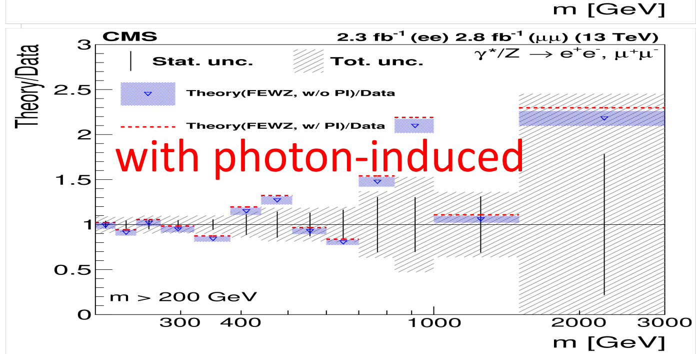


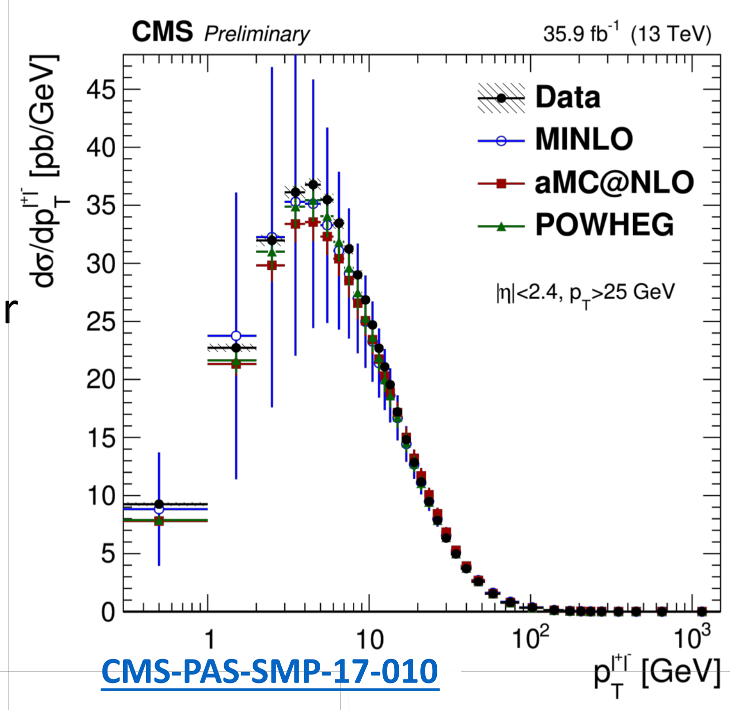


- For $Z \to \mu\mu$ (ee): $p_T^l > 22$ (30), 10 GeV, $|\eta^l| < 2.4$ (2.5)
- Corrected for FSR (dressed leptons)
- Good agreement with FEWZ (NNLO QCD + NLO EW) with NNPDF3.0
- At high m_{ll} photon-induced contributions tested with FEWZ + LUXqed

Z boson p_T @ 13 TeV

- Fiducial selection (leptons after FSR)
- Normalised xsection: <0.5% uncertainty for p_T^{ll} < 50 GeV
- Compared to fixed-order, resummed and parton shower predictions
  - FO: Z at NNLO QCD (FEWZ) and Z+j at NNLO QCD (ZjNNLO). LO EW
  - Resummed (NNLL): Geneva, Resbos
  - PS: MadGraph5_aMC@NLO (0,1,2j at NLO, FxFx), Powheg (NLO), Powheg+MiNLO (0,1j at NLO)

$|m_{ll}$ - 91.2 GeV$|$ < 15 GeV



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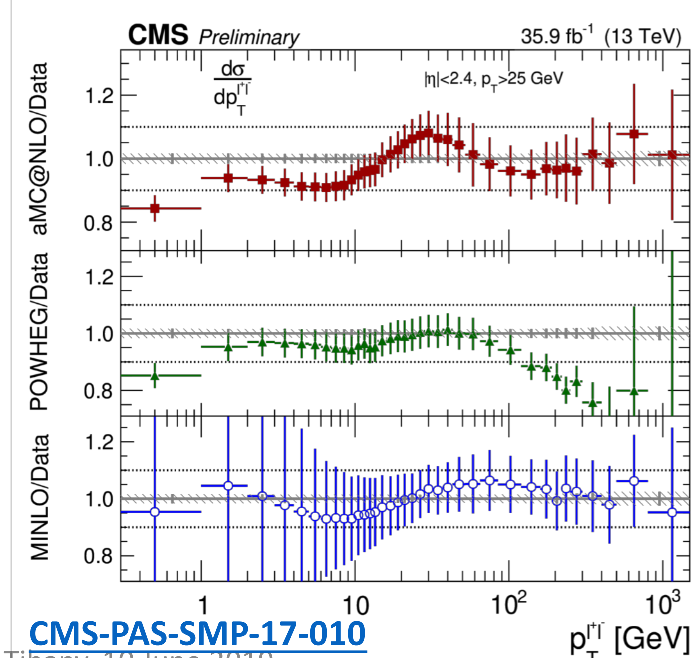

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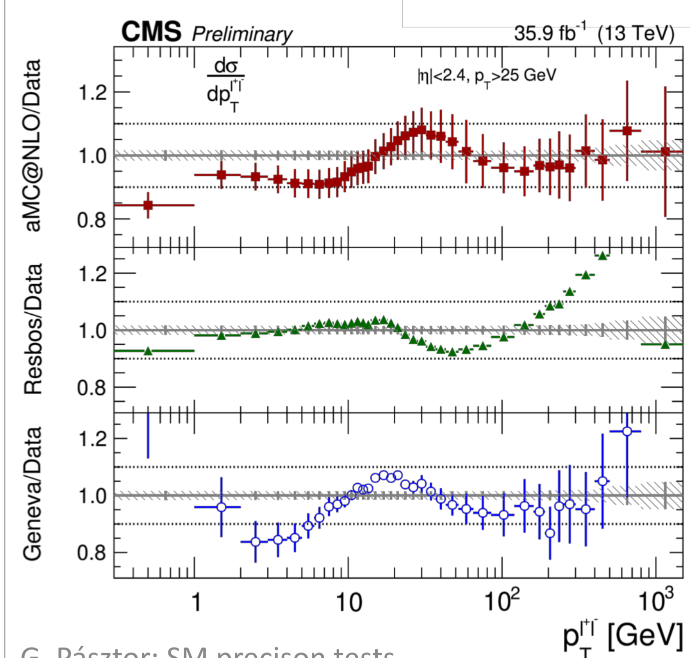
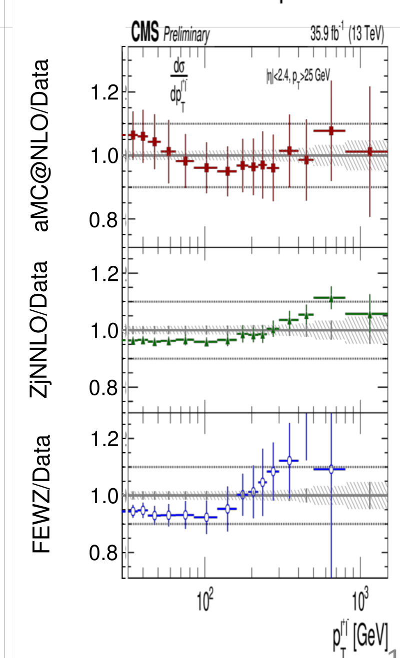
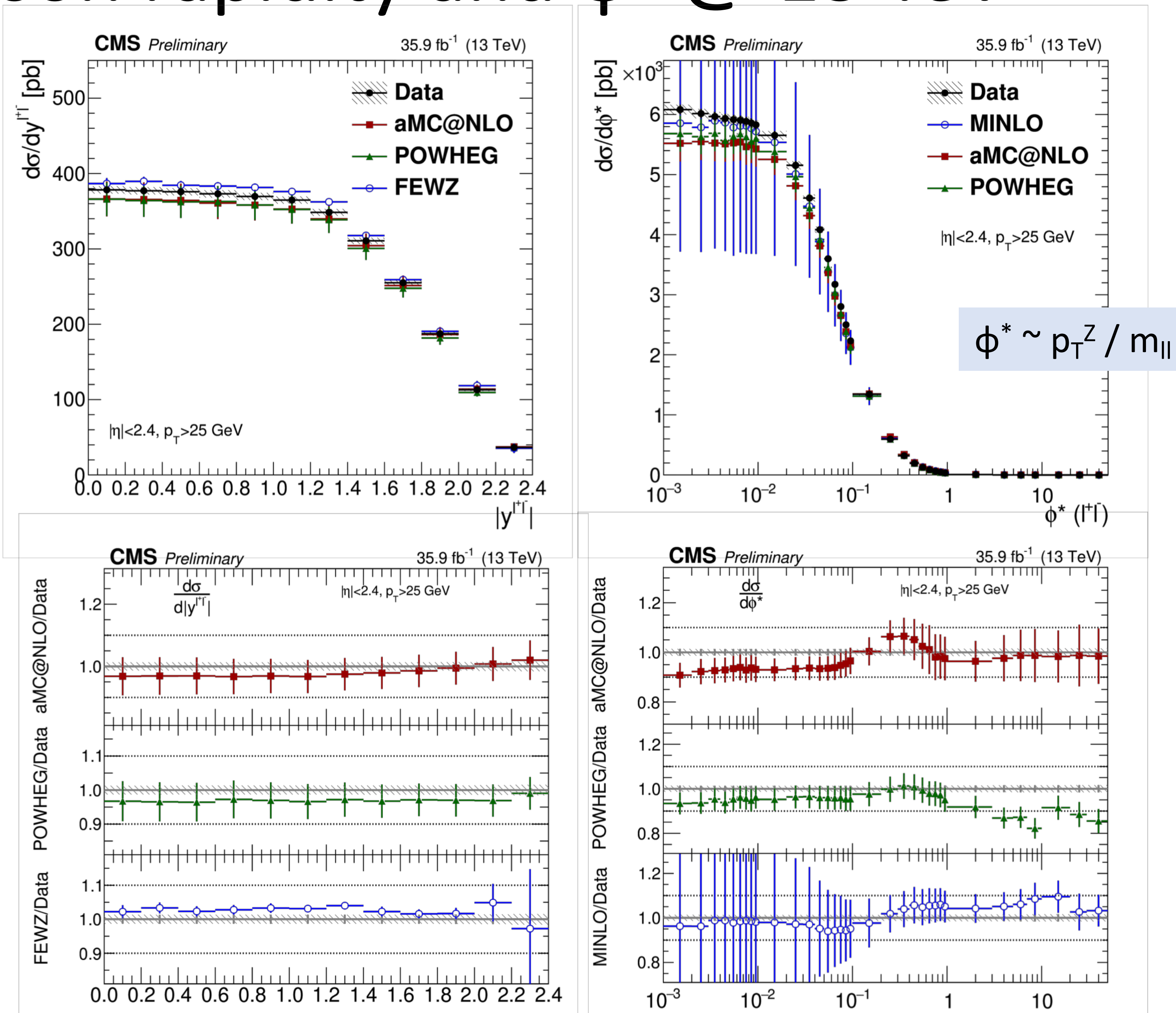




Z boson rapidity and ϕ^* @ 13 TeV

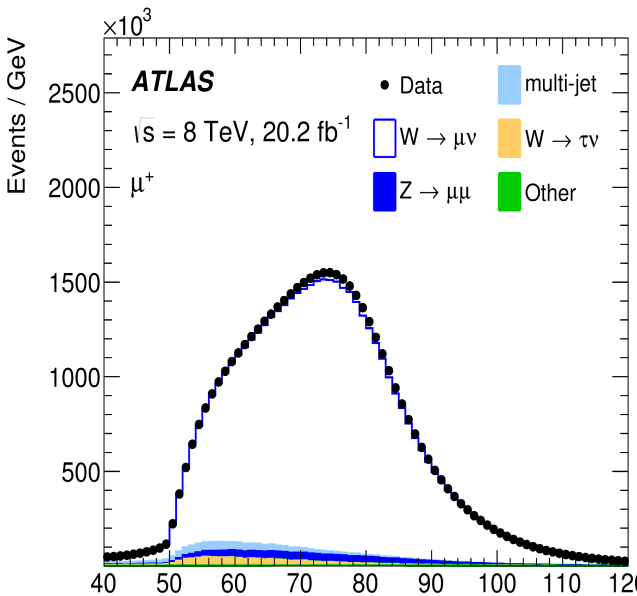


[CMS-PAS-SMP-17-010](CMS-PAS-SMP-17-010) [CMS-PAS-SMP-17-010](CMS-PAS-SMP-17-010)

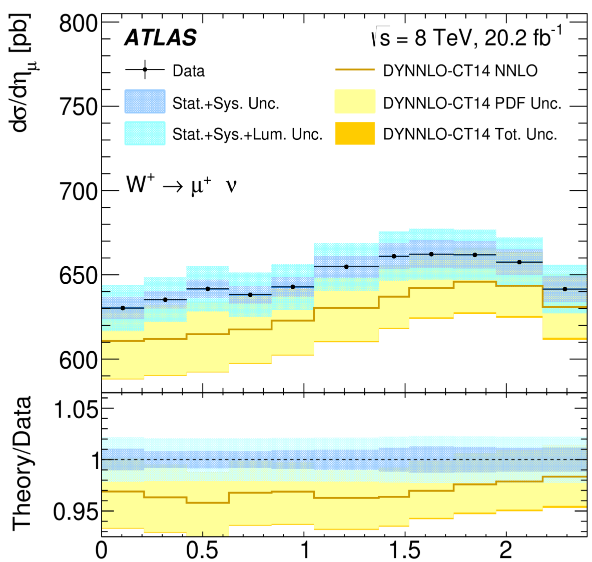
W differential cross-sections and charge asymmetry @ 8 TeV

- Proton's uud valence quark content → more W⁺ produce $u\bar{d} \to W^+$ $d\bar{u} \to W^-$)
- Charge asymmetry: $\mathcal{A}(\eta) = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$ with $\sigma_\eta^\pm = \frac{d\sigma}{d\eta}(pp \to W^\pm + X \to \mu^\pm \nu + X)$
- $\mathcal{A}$ constrains u(x)/d(x) pdf ratio for Bjorken x = 0.001 – 0.1
- Luminosity uncertainty (1.9%) dominates, sum of other sources ~1-1.5%
- Compared to DYNNLO with different PDF sets
- With ~1% precision can discriminate among PDF sets

Fiducial selection (Born-level):
p_T^μ, p_T^ν > 25 GeV
$|\eta^\mu|$ < 2.4
m_T > 40GeV



arXiv:1904.05631



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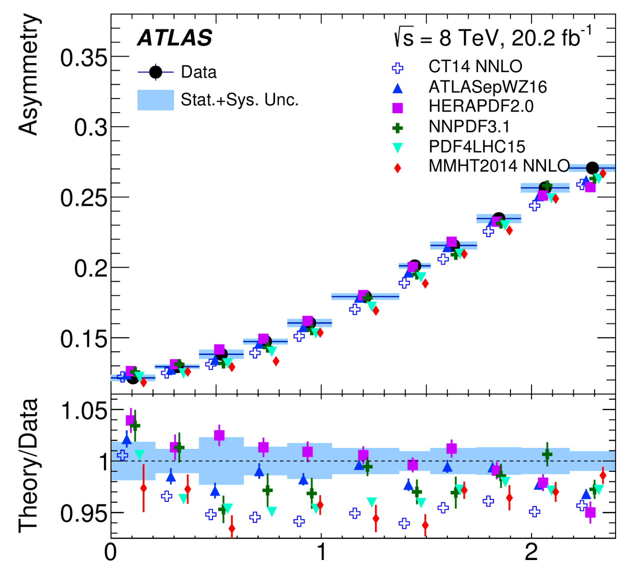
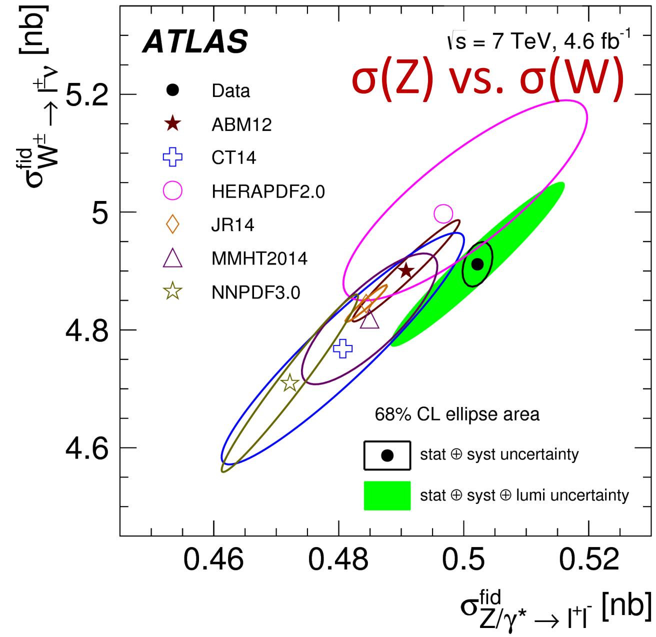


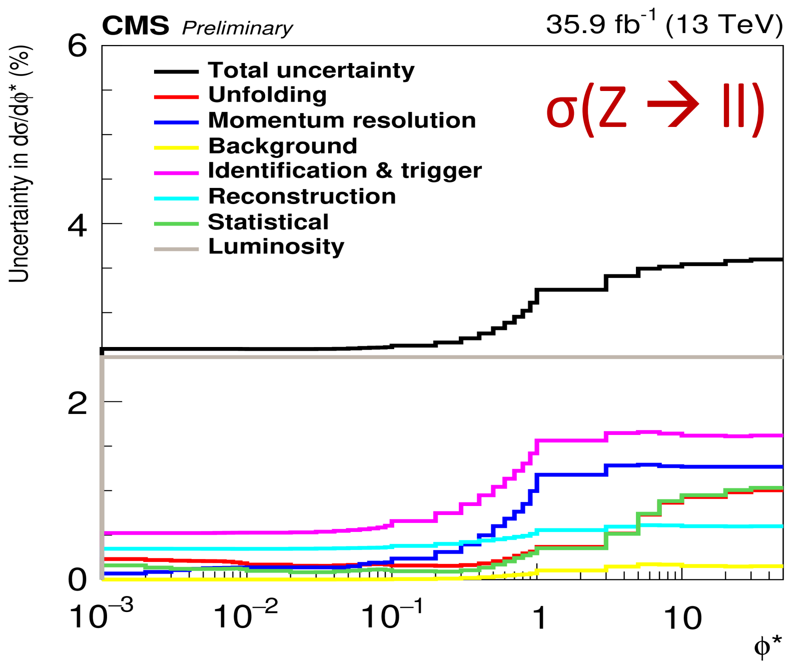
arXiv:1904.05631

Luminosity calibration

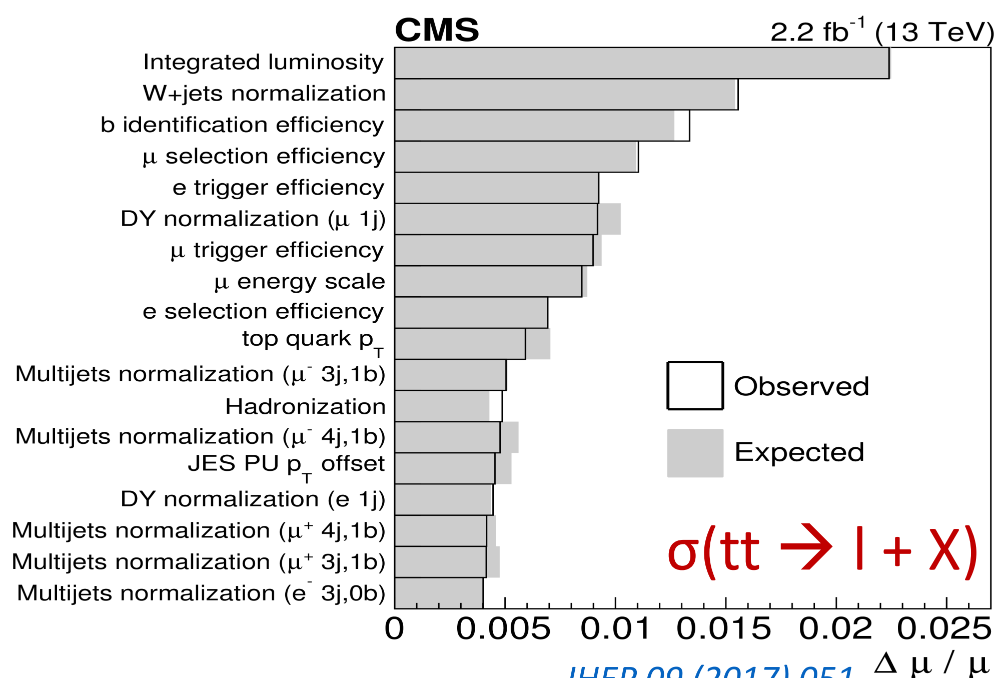
[Eur. Phys. J. C 77 (2017) 367]

- Dominant systematic error for precision cross-section measurements with well-controlled systematics (leptonic Z, W, top decays): $N_{\text{Events}} = \sigma \int L$
- Preliminary calibration in Run 2: 2-2.5% / year
- 1% would make it subdominant in most cases
- Need to keep in mind for Phase 2 detector upgrades



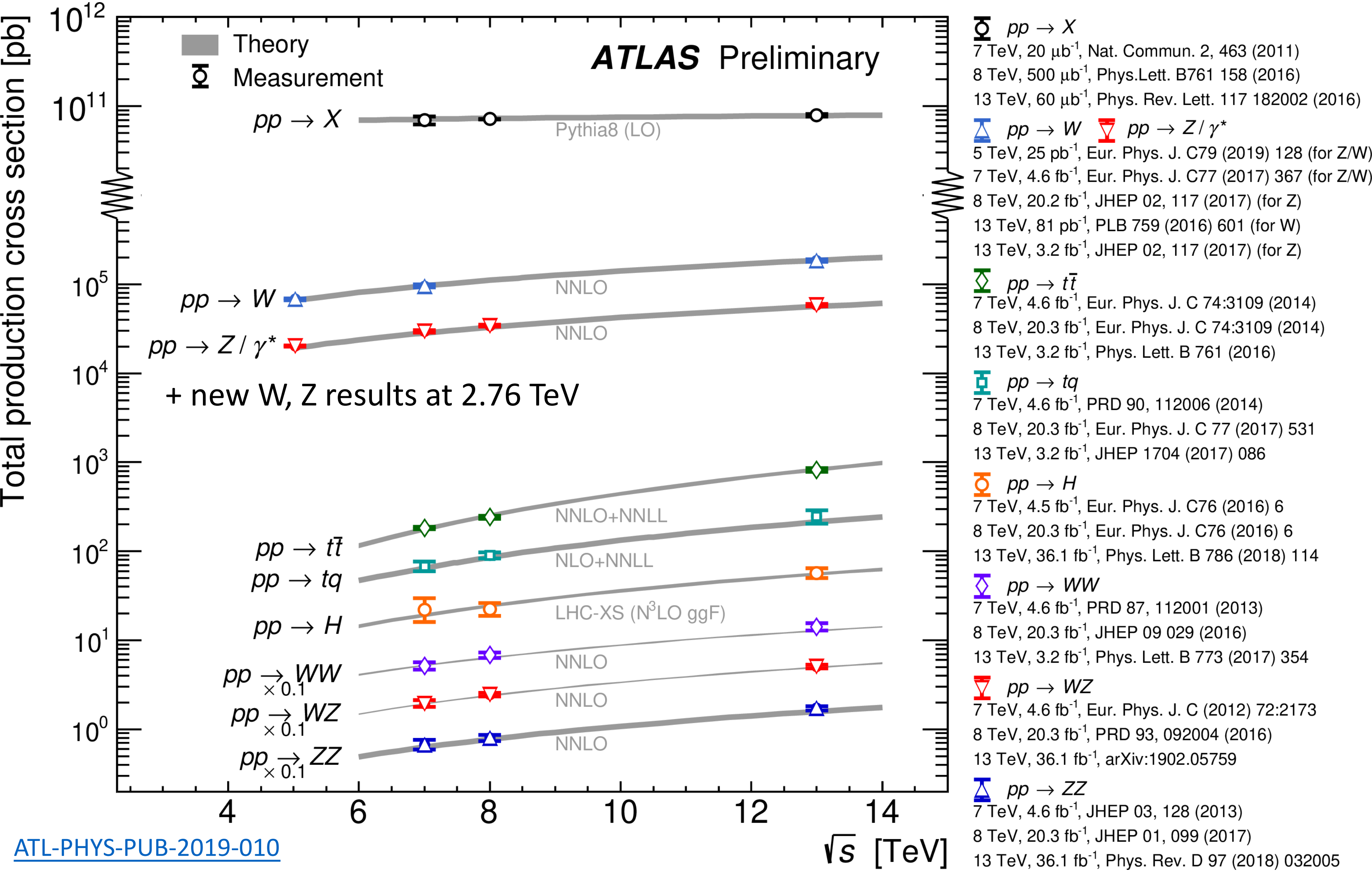


[CMS-PAS-SMP-17-010]



[JHEP 09 (2017) 051]

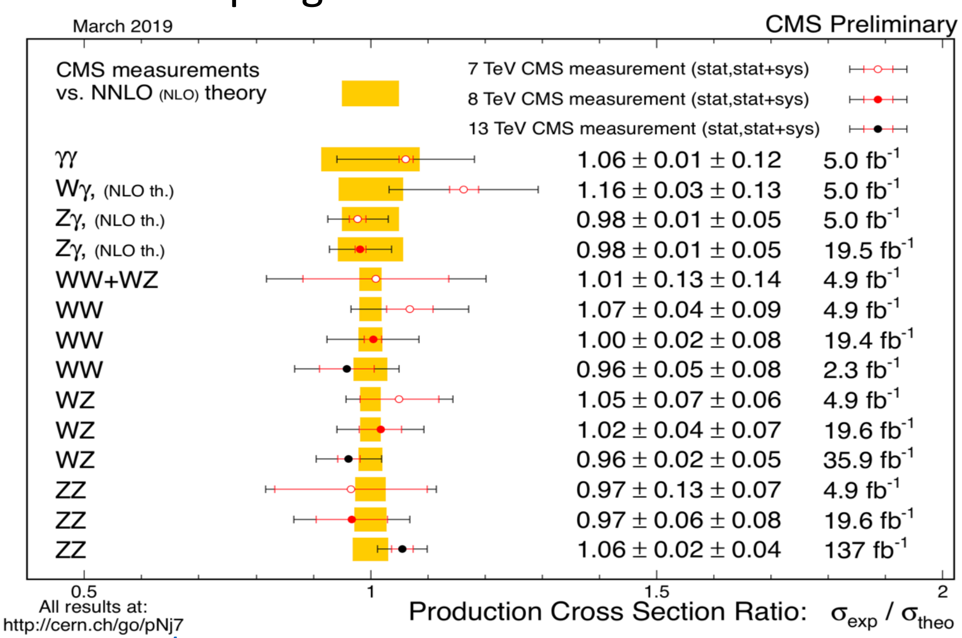
Total production cross-section measurements



ATL-PHYS-PUB-2019-010

Summary

- LHC became a precision machine
  - $\sigma(m_W)$ = 18 MeV @ 7 TeV ATLAS
  - $\sigma(\sin^2\theta^l_{eff})$ ~ 0.0004 @ 8 TeV ATLAS, CMS
- Individual experiments approach precision of LEP/SLD and Tevatron combined
- PDF uncertainty important
- Many results on diboson production, VBF, VBS (not covered here)
  - Constraints on triple and quartic gauge couplings



CMSPublic/PhysicsResultsCombined

http://gfitter.desy.de/Standard_Model/