Recent Precision W/Z Measurements at the LHC

-- 31st Rencontres des Blois on Particle Physics and Cosmology --

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on behalf of ATLAS, CMS and LHCb collaborations

INTRODUCTION

- Drell-Yan (DY) process proposed in the 1970 paper served as a milestone in the building of QCD as the theory of the strong interaction
  - After 50 years we are still interested in studying this process!
- It is a key stone of the LHC program, crucial for a detailed understanding of LHC data:
  - **Probing the proton structure:** valence and sea quarks PDF, determining proton strangeness
  - **Improvement of QCD tools**: high jet multiplicities, regime dominated by soft gluon radiation
  - **Measuring fundamental electroweak parameters**: m_W and $\sin^2\vartheta^{\ell}_{\rm eff}$
  - **Standard candles:** in-situ determination of the detector performance (lepton calibration), monitoring the luminosity.
  - **Search for new physics:** high dilepton mass final states and rare decays (latter strictly speaking not DY)

Information | References (9) | Citations (1518) | Files | Plots

Massive Lepton Pair Production in Hadron-Hadron Collisions at High-Energies

S.D. Drell, Tung-Mow Yan (SLAC)

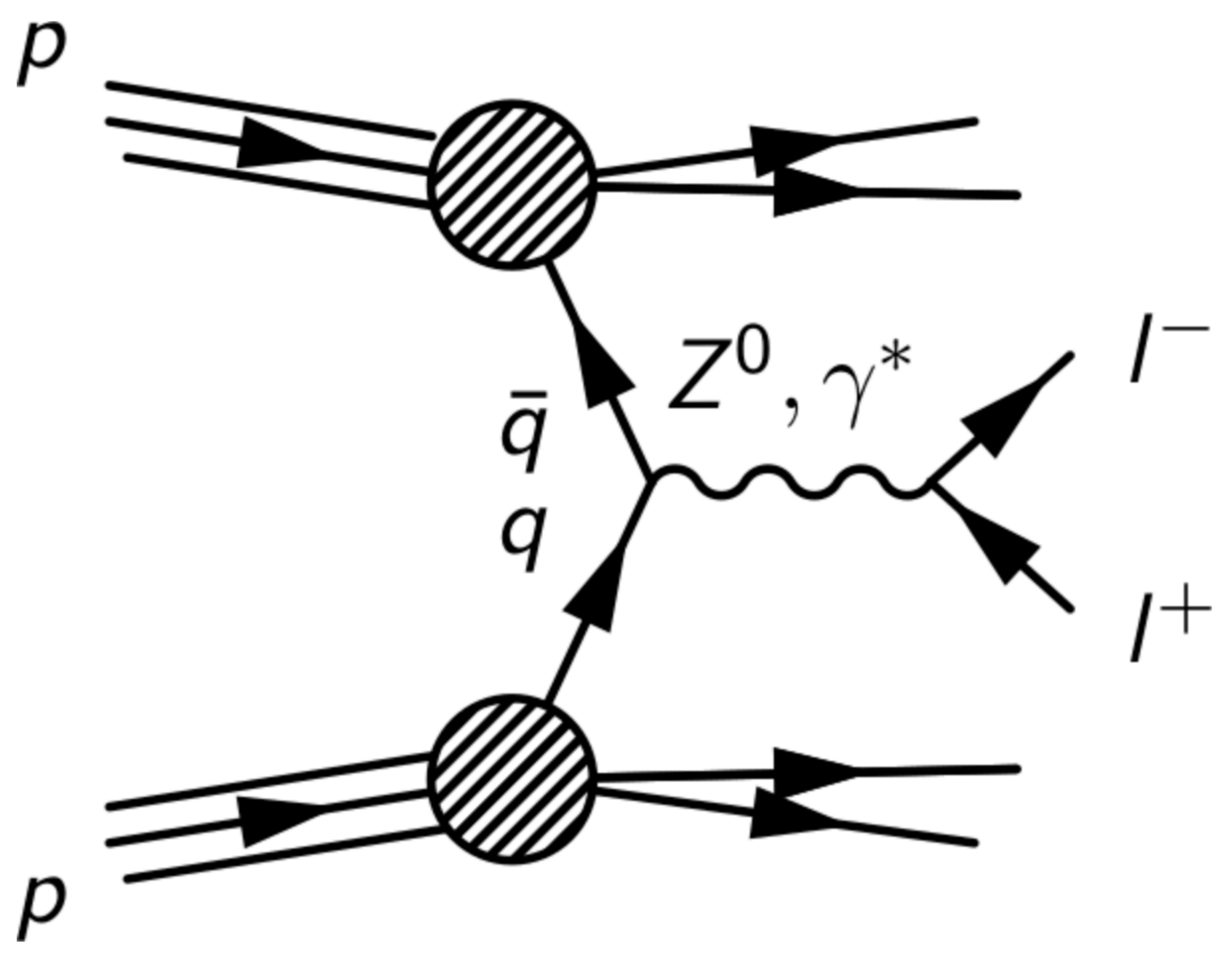
Jun 1970 - 12 pages

Phys.Rev.Lett. 25 (1970) 316-320
Erratum: Phys.Rev.Lett. 25 (1970) 902
DOI: 10.1103/PhysRevLett.25.902.2, 10.1103/PhysRevLett.25.316
SLAC-PUB-0755

Abstract (APS)
On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, s→∞, Q2s finite, Q2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as Q2s→1 is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW2 near threshold.

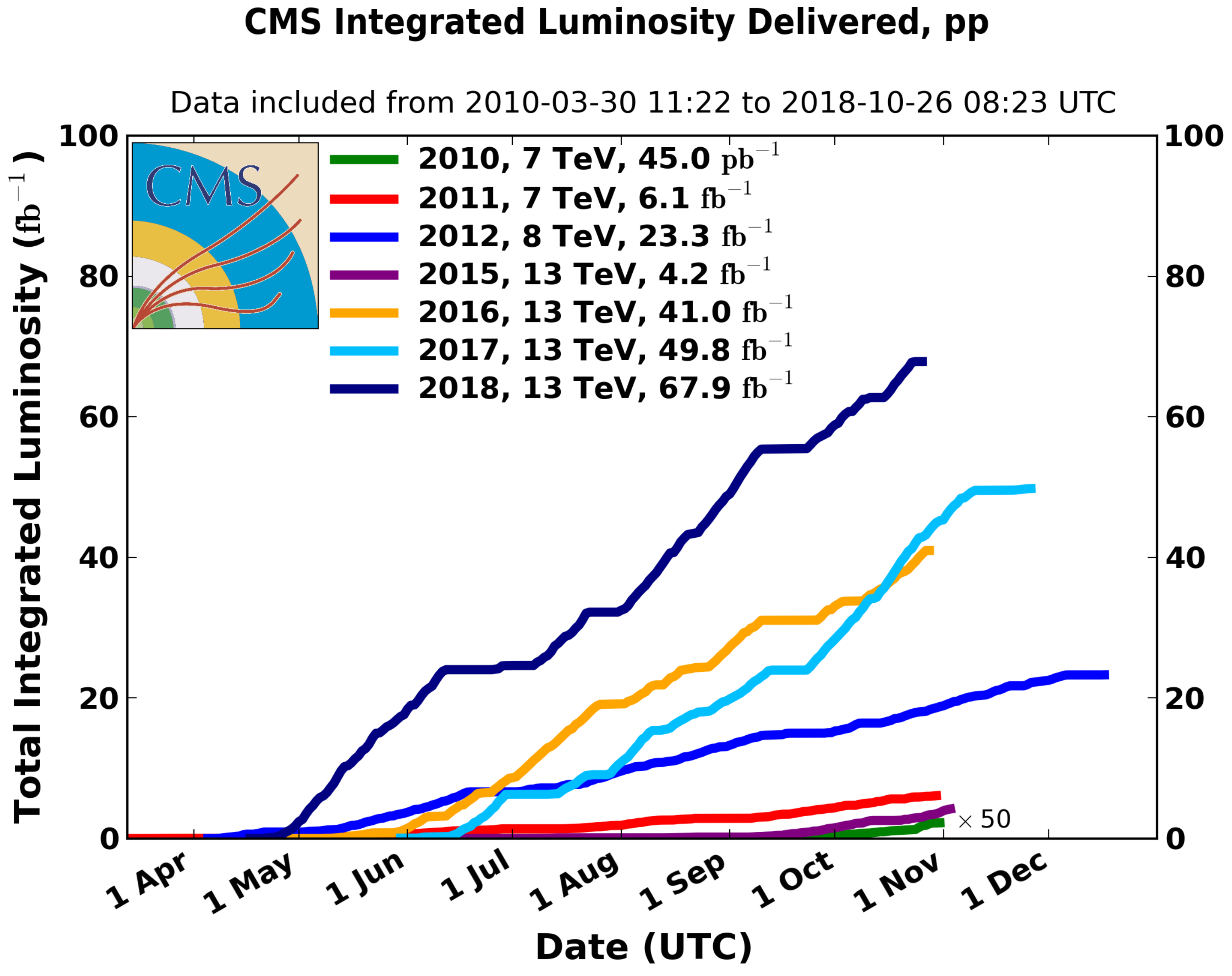
Keyword(s): INSPIRE: HADRON HADRON: INTERACTION | INTERACTION: HADRON HADRON | LEPTON: PAIR PRODUCTION | PAIR PRODUCTION: LEPTON | MODEL: PARTON | LEPTON: HADROPRODUCTION | HADROPRODUCTION: LEPTON | SCALING | DIFFERENTIAL CROSS SECTION: MASS | MASS: DIFFERENTIAL CROSS SECTION | ELECTRON P: DEEP INELASTIC SCATTERING | DEEP INELASTIC SCATTERING: ELECTRON P

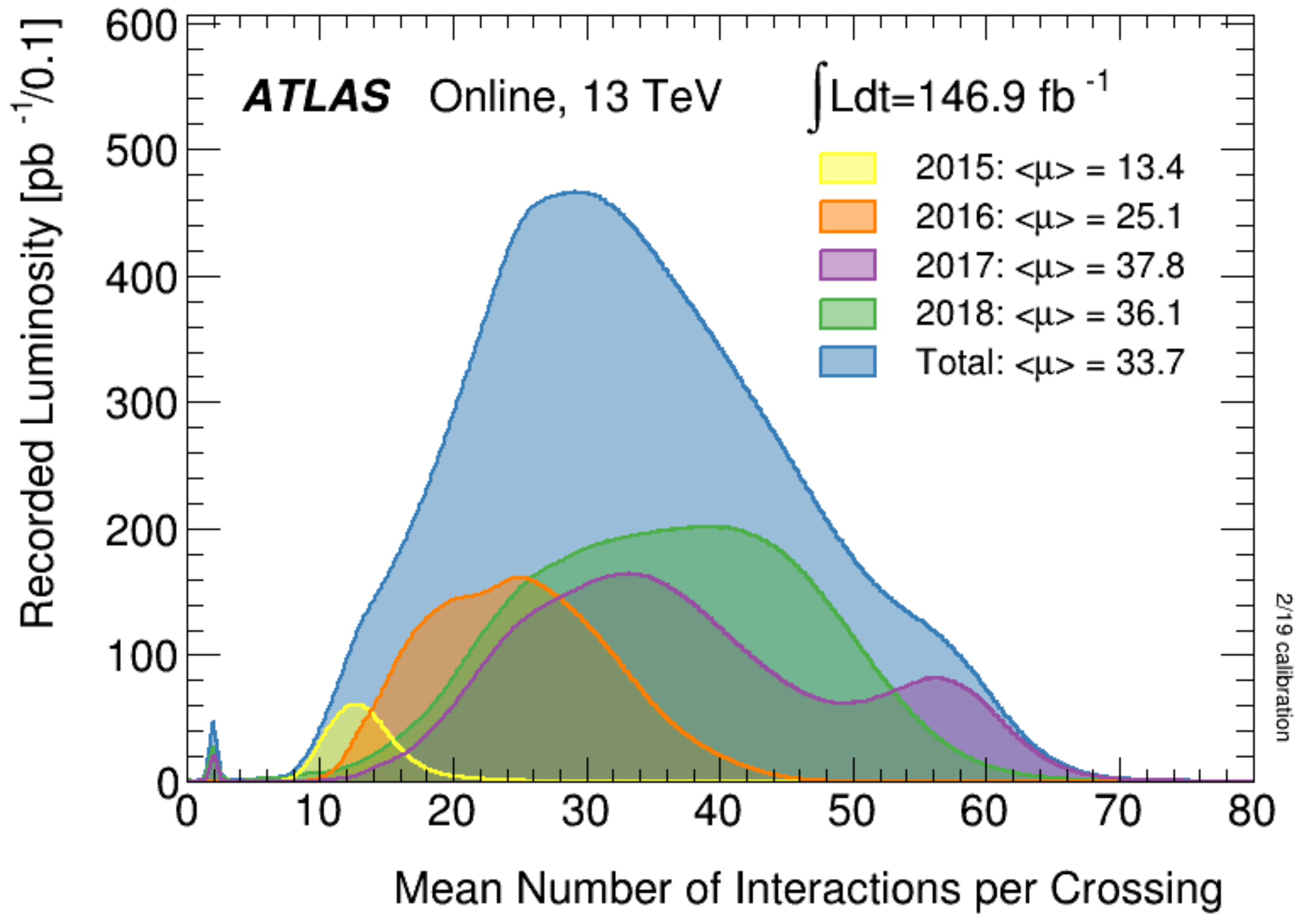
Record added 1970-06-01, last modified 2018-03-02



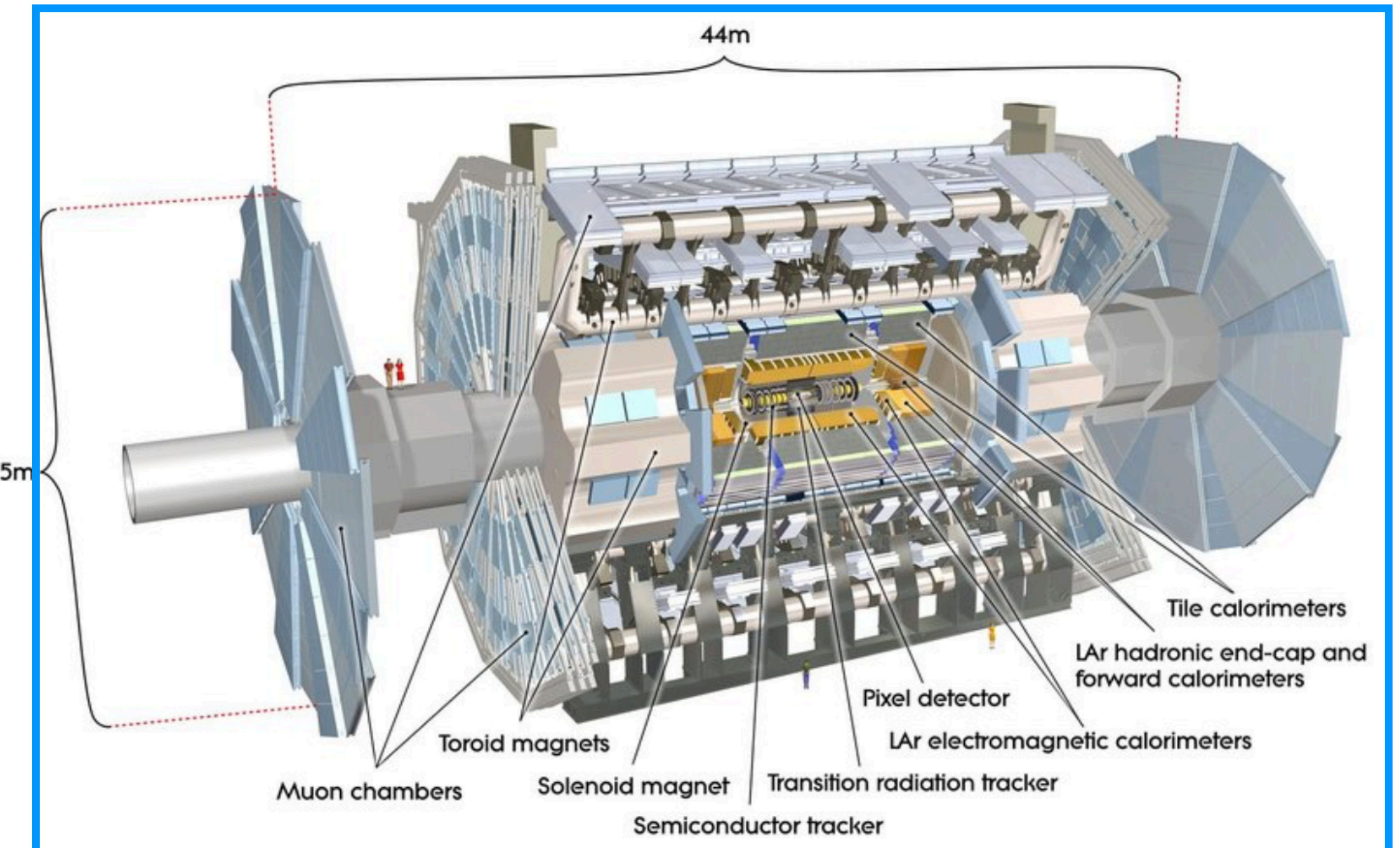
EXPERIMENTAL LANDSCAPE

- DY cross section is huge: for pp collisions (at $\sqrt{s}$ = 13 TeV, roughly scales with $\sqrt{s}$): σ ~2nb for $Z/\gamma^* \rightarrow ll$ (66 < m_{ll} < 116 GeV), 10 times higher $W \rightarrow l\nu$
- ATLAS and CMS collected ~20 fb^{-1} of pp data at 8 TeV, ~140 fb^{-1} at 13 TeV
  - LHCb less (~2 fb^{-1} and ~6 fb^{-1} respectively), complementarity in rapidity
  - ATLAS and CMS also collected ~250 pb^{-1} at 5.02 TeV and and 350 pb^{-1} at 13 TeV with low pile up ($\langle\mu\rangle$ = 2)
- Precision DY measurements performed mainly through the leptonic decays: electron and muon reconstruction and the hadronic recoil for the W events
  - Hadronic recoil is essential for the reconstruction of W bosons: MET = $| - (\vec{p}_T + \vec{u})|$, u≡recoil, it represents the experimental measure of the W boson p_T
- High statistics and mature detector understanding translate into precise multi-dimensional cross section measurements, and precise determination of EWK parameters.
  - **Focus on reducing and controlling systematic uncertainties!**

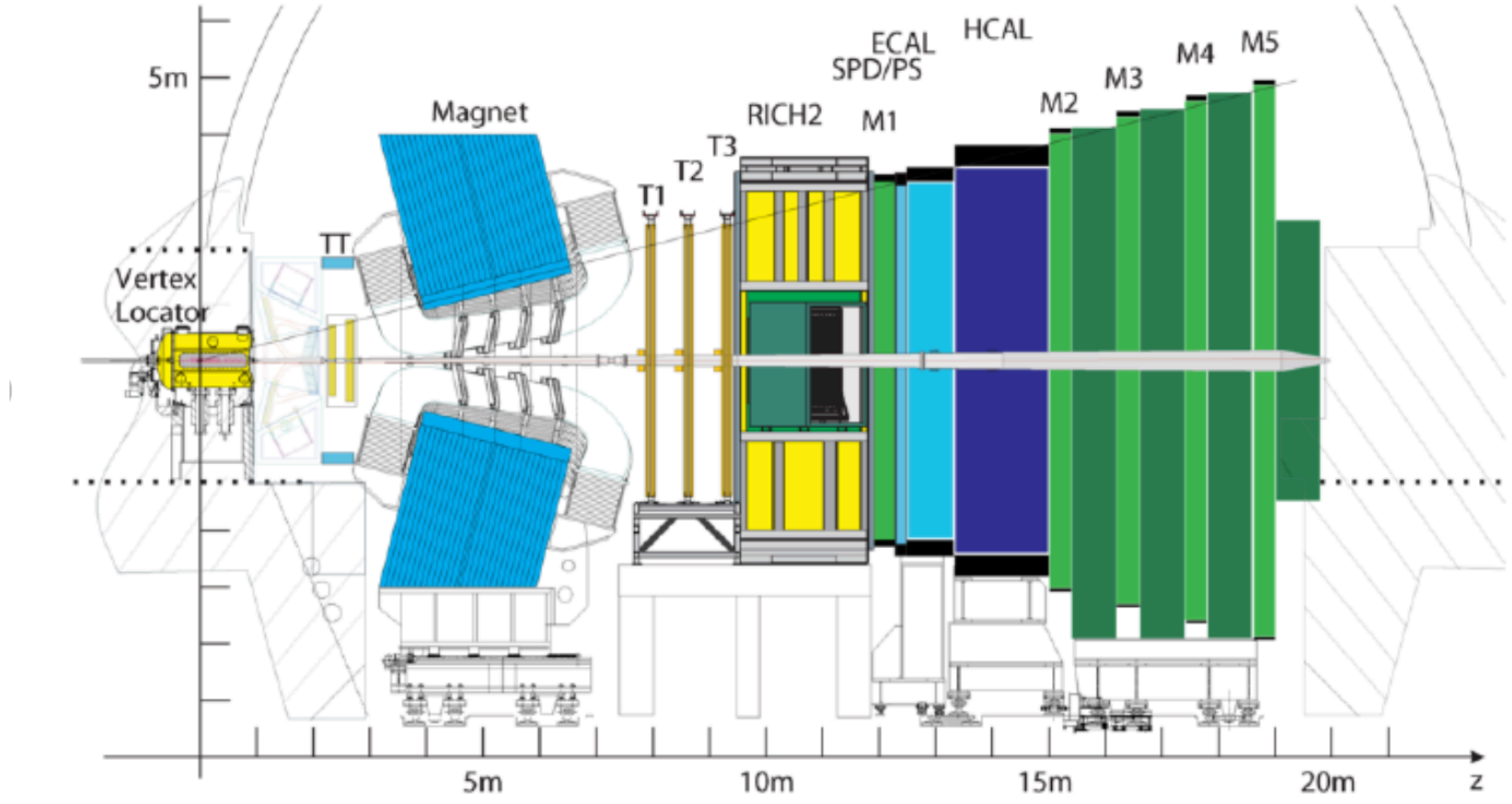




DETECTOR PERFORMANCE

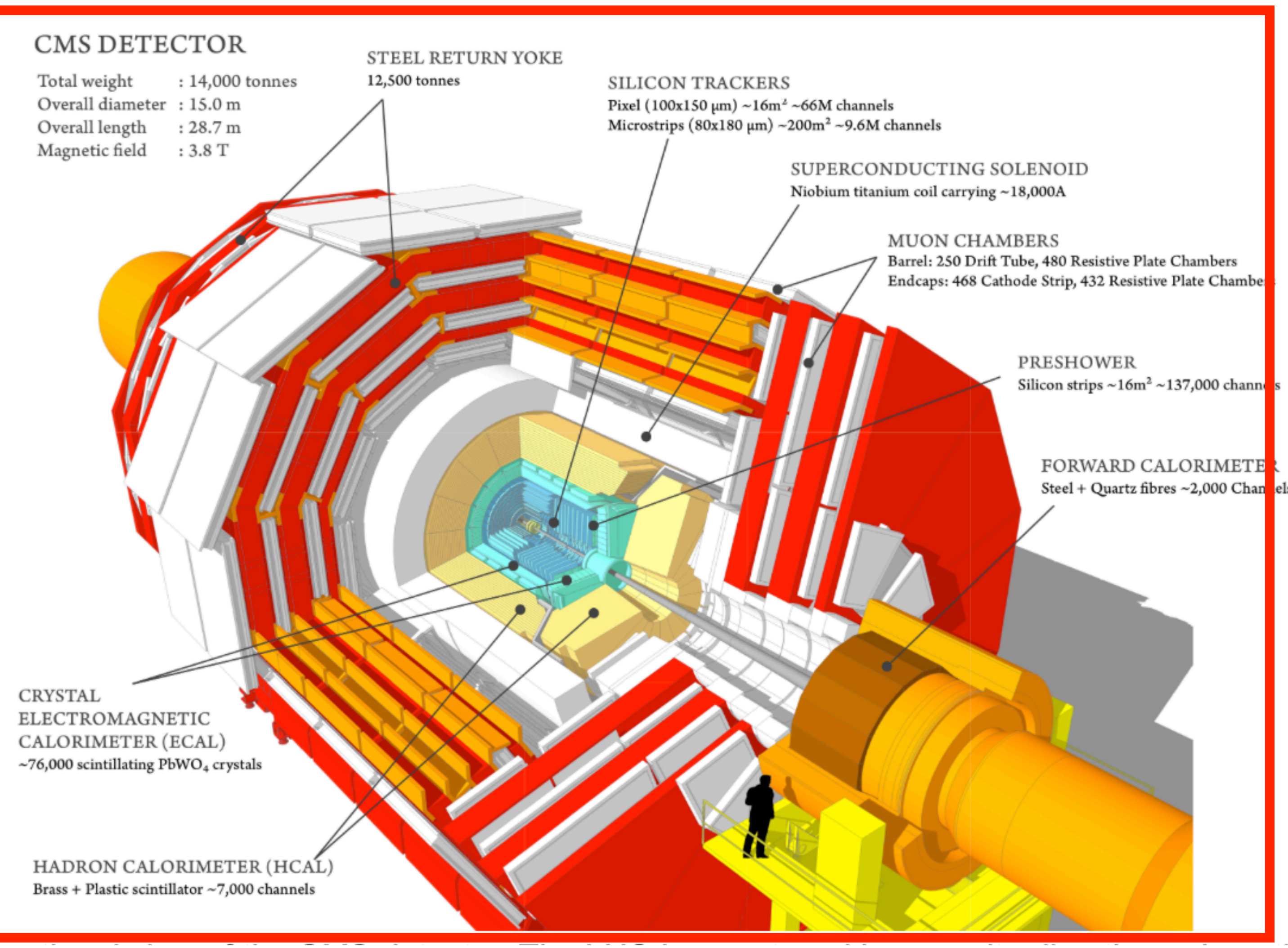


Muon system: trigger system & precision tracking
toroidal B-field ~ 0.5T, |η|<2.7
Inner detector: silicon pixels: secondary vertex
Solenoidal B-field = 2T, |η|<2.5
silicon strips: momentum measurement
Transition radiation tracker: particle ID, track
Calorimeter: coverage |η|<4.9



VELO: impact parameter resolution σ = 20 μm
RICH: particle ID ε = 95% mis-ID ~ 5%
Tracking 2<η<5 Δp/p = 0.4% - 0.6%
muon system ε = 97%, mis-ID = 1-3%

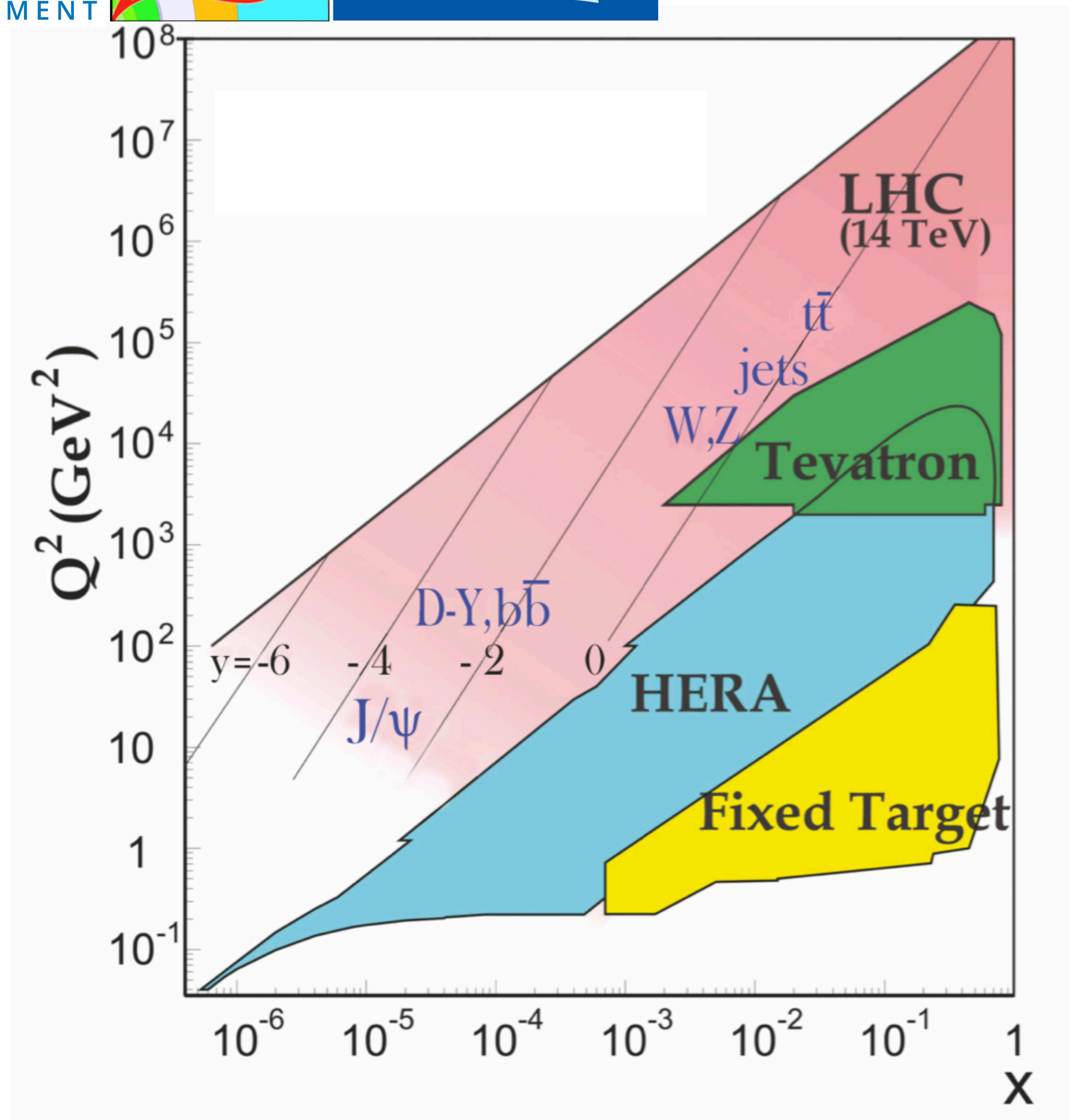
Muon system: trigger system & precision tracking |η|<2.4
steel return yoke provides B-field transverse
Inner detector silicon strips: momentum measurement silicon pixels: secondary vertex Solenoidal B-field = 3.8T, |η|<2.5
Calorimeters |η|<5.0



- **Lepton efficiencies controlled at ~% level or better**
- **Momentum scale ~10^{-3}, resolution ~%**
- **Luminosity uncertainty ~2%**

PROBING THE PROTON STRUCTURE

From PDG

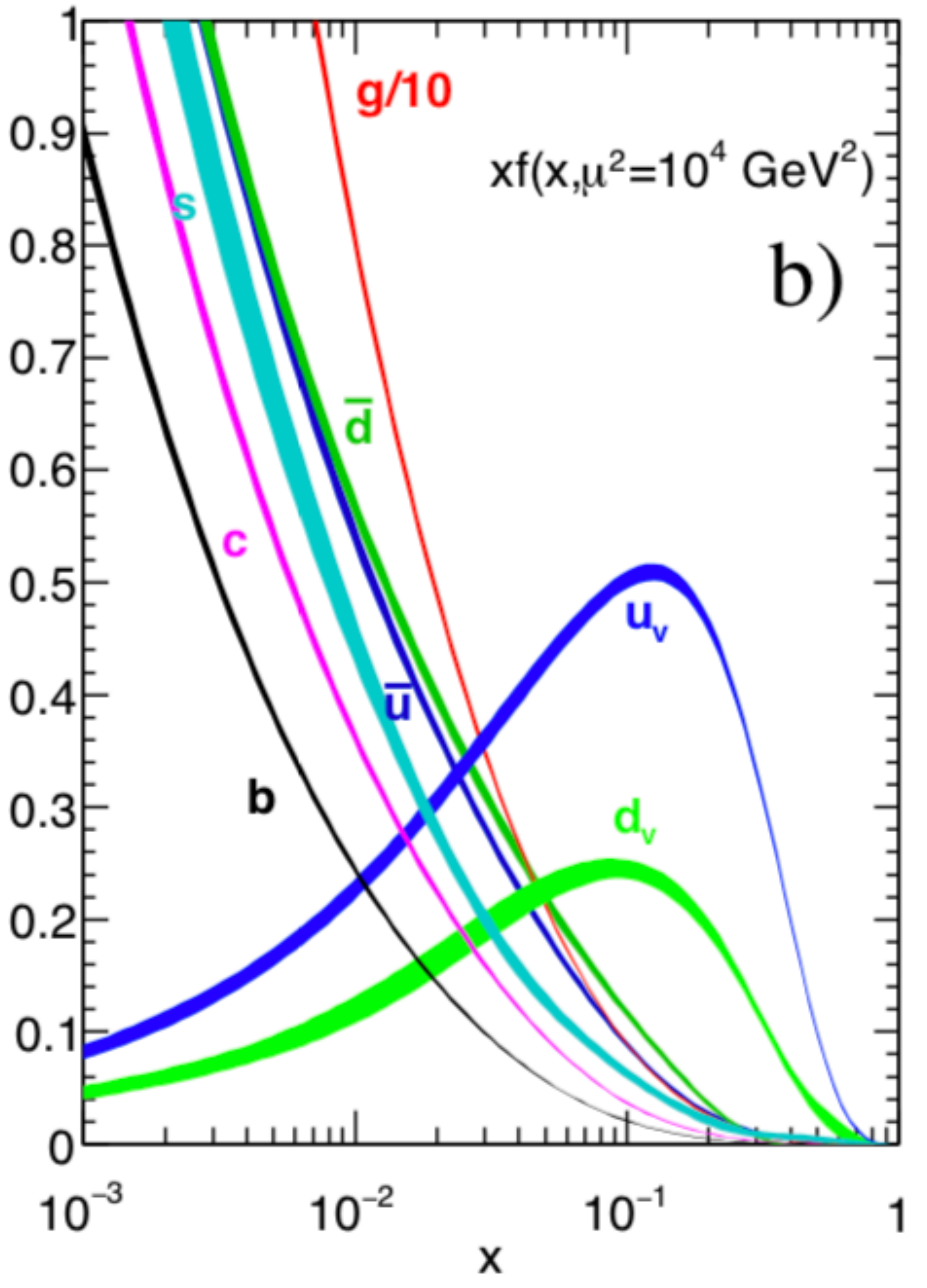


Process	Subprocess	Partons	x range
$\ell^\pm\{p,n\}\to\ell^\pm X$	$\gamma^* q\to q$	$q,\bar q,g$	$x\gtrsim 0.01$
$\ell^\pm n/p\to\ell^\pm X$	$\gamma^* d/u\to d/u$	d/u	$x\gtrsim 0.01$
$pp\to\mu^+\mu^- X$	$u\bar u, d\bar d\to\gamma^*$	$\bar q$	$0.015\lesssim x\lesssim 0.35$
$pn/pp\to\mu^+\mu^- X$	$(u\bar d)/(u\bar u)\to\gamma^*$	$\bar d/\bar u$	$0.015\lesssim x\lesssim 0.35$
$\nu(\bar\nu)N\to\mu^-(\mu^+)X$	$W^* q\to q'$	$q,\bar q$	$0.01\lesssim x\lesssim 0.5$
$\nu N\to\mu^-\mu^+ X$	$W^* s\to c$	s	$0.01\lesssim x\lesssim 0.2$
$\bar\nu N\to\mu^+\mu^- X$	$W^*\bar s\to\bar c$	$\bar s$	$0.01\lesssim x\lesssim 0.2$
$e^\pm p\to e^\pm X$	$\gamma^* q\to q$	$g,q,\bar q$	$10^{-4}\lesssim x\lesssim 0.1$
$e^+ p\to\bar\nu X$	$W^+\{d,s\}\to\{u,c\}$	d,s	$x\gtrsim 0.01$
$e^\pm p\to e^\pm c\bar c X, e^\pm b\bar b X$	$\gamma^* c\to c,\ \gamma^* g\to c\bar c$	c,b,g	$10^{-4}\lesssim x\lesssim 0.01$
$e^\pm p\to$ jet+X	$\gamma^* g\to q\bar q$	g	$0.01\lesssim x\lesssim 0.1$
$p\bar p, pp\to$ jet+X	$gg, qg, qq\to 2j$	g,q	$0.00005\lesssim x\lesssim 0.5$
$p\bar p\to(W^\pm\to\ell^\pm\nu)X$	$ud\to W^+, \bar u\bar d\to W^-$	$u,d,\bar u,\bar d$	$x\gtrsim 0.05$
$pp\to(W^\pm\to\ell^\pm\nu)X$	$u\bar d\to W^+, d\bar u\to W^-$	$u,d,\bar u,\bar d,g$	$x\gtrsim 0.001$
$p\bar p(pp)\to(Z\to\ell^+\ell^-)X$	$uu, dd, ..(u\bar u, ..)\to Z$	$u,d,..(g)$	$x\gtrsim 0.001$
$pp\to W^- c,\ W^+\bar c$	$gs\to W^- c$	$s,\bar s$	$x\sim 0.01$
$pp\to(\gamma^*\to\ell^+\ell^-)X$	$u\bar u, d\bar d, ..\to\gamma^*$	$\bar q, g$	$x\gtrsim 10^{-5}$
$pp\to(\gamma^*\to\ell^+\ell^-)X$	$u\gamma, d\gamma, ..\to\gamma^*$	γ	$x\gtrsim 10^{-2}$
$pp\to b\bar b X,\quad t\bar t X$	$gg\to b\bar b,\quad t\bar t$	g	$x\gtrsim 10^{-5}, 10^{-2}$
$pp\to$ exclusive $J/\psi, \Upsilon$	$\gamma^*(gg)\to J/\psi, \Upsilon$	g	$x\gtrsim 10^{-5}, 10^{-4}$
$pp\to\gamma X$	$gq\to\gamma q,\ g\bar q\to\gamma\bar q$	g	$x\gtrsim 0.005$

$u\bar d,\ c\bar s\quad (u\bar s,\ c\bar d)\to W^+$

$d\bar u,\ s\bar c\quad (s\bar u,\ d\bar c)\to W^-$

$q\bar q\to Z/\gamma$

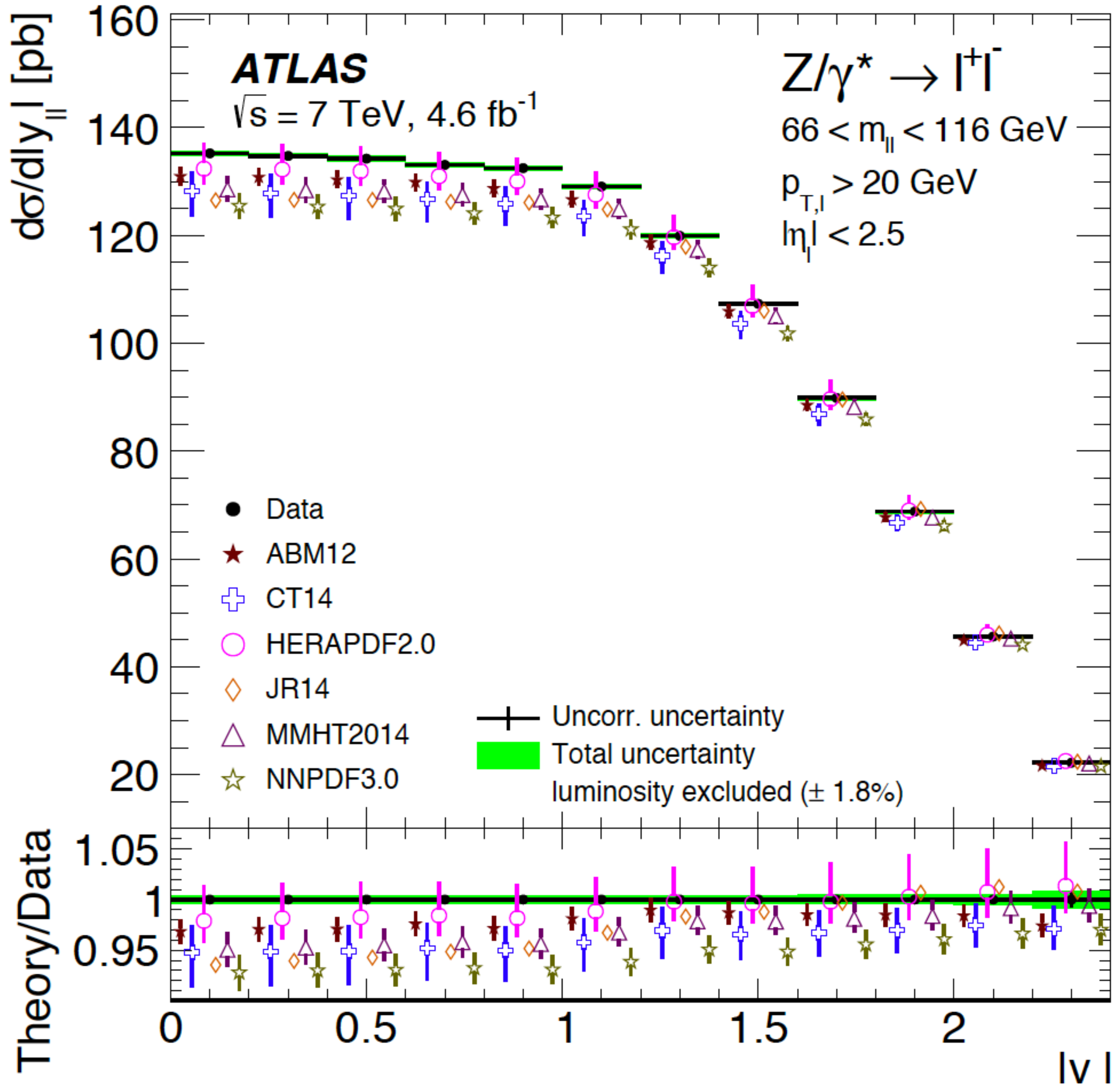


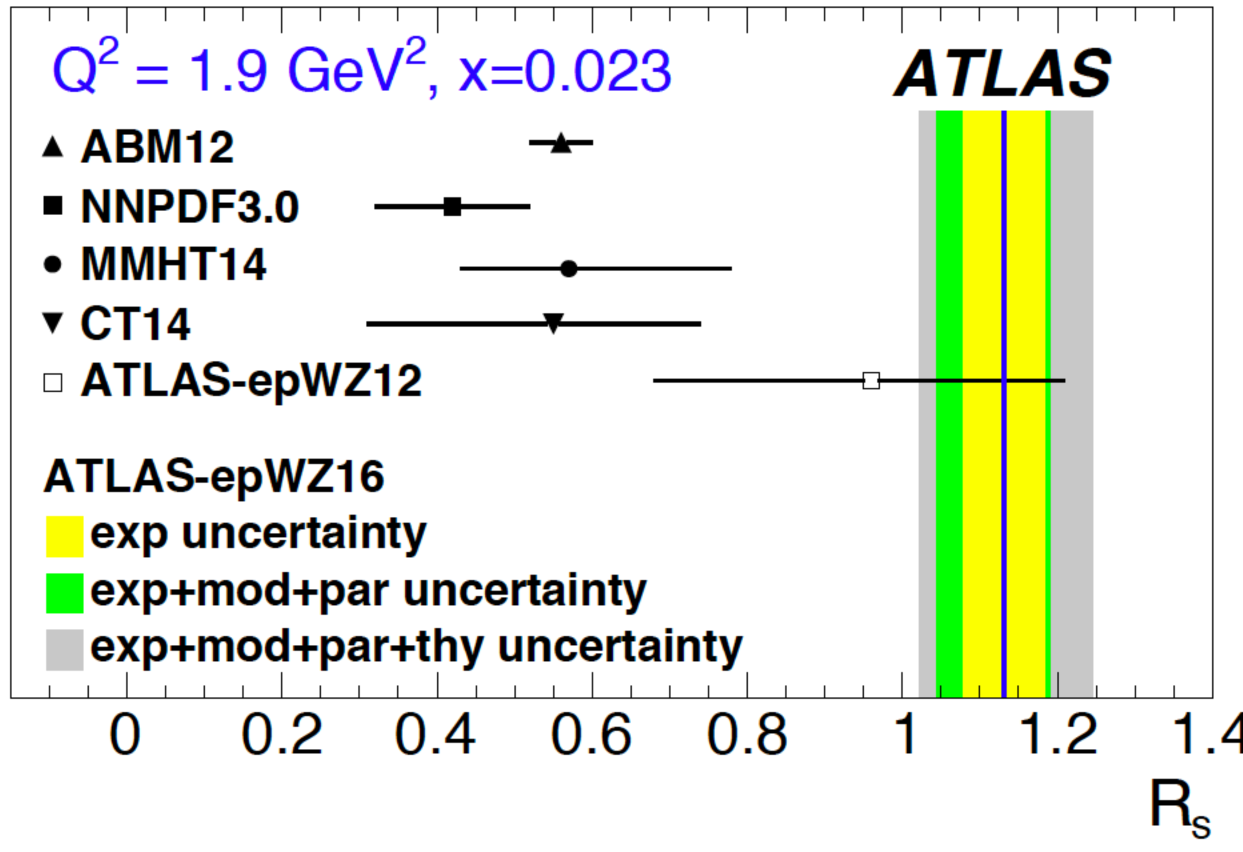
- Hadron collider data together with DIS data (fixed target and HERA) to constrain PDFs
  - DY cross section important input into global fits to extract PDFs
- The range of x and Q^2 that can be probed depends on $\sqrt{s}$ and rapidity y of electroweak bosons
- Improve sensitivity to PDFs by measuring ratios where correlations suppress many sources of unc.
  - W/Z: constraints s-quark distribution
  - W^+/W^- and charged asymmetry are sensitive to u_v and d_v.

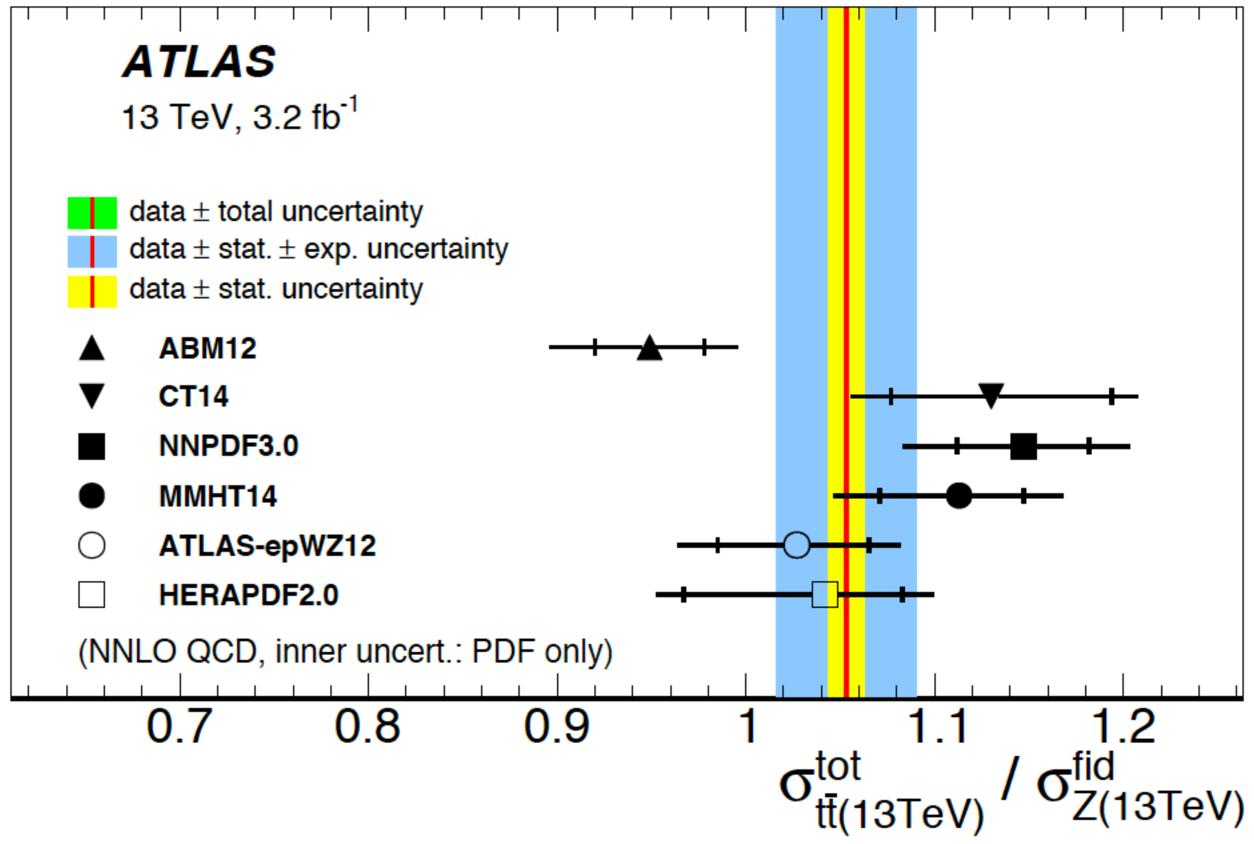
EXAMPLE W,Z CROSS SECTIONS AND RATIO TO TOP (7 TEV)

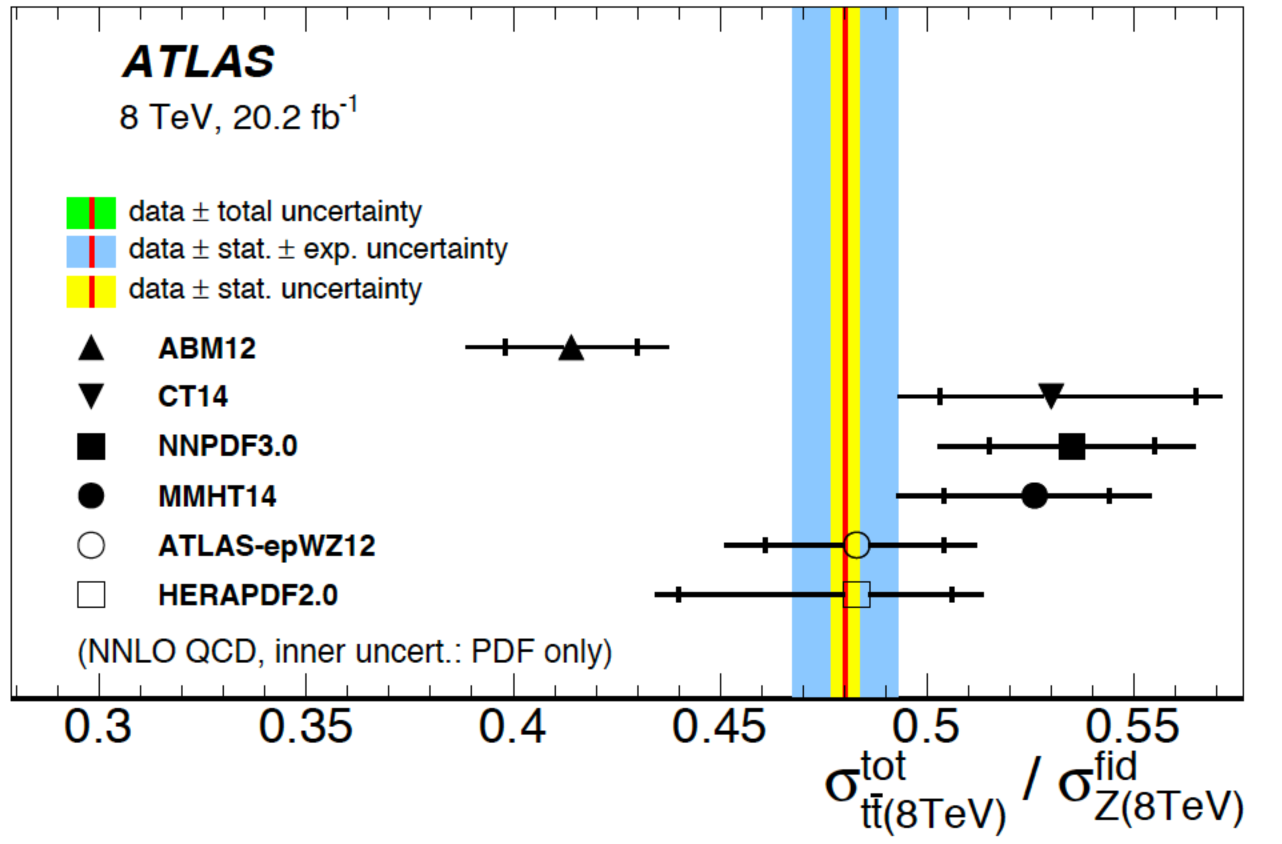
arXiv:1612.03016
arXiv:1612.03636

- Inclusive and differential W,Z cross sections at 7 TeV, Included in the global PDF fits
  - Stat. uncertainty 0.5%, systematic uncertainty dominated by luminosity (1.9%), experimental uncertainty (w/o lumi) at 1%!
  - *ATLAS result prefers unsuppressed strange sea.*
  - Results compared to different PDFs, globally consistent but pulls in different direction from neutrino Deep Inelastic Scattering data (DIS)
  - Prefers lower QCD scale
- tt/Z cross sections measured at $\sqrt{s}$ = 13,8,7 TeV
  - Single ratios, at a given $\sqrt{s}$, at different $\sqrt{s}$, as well as double ratios
  - The data demonstrate significant power to constrain the gluon distribution function for the Bjorken-x values near 0.1 and the light-quark sea for x < 0.02.
  - Results are compared to NNLO QCD + NLO EW (Z) and NNLO+NNLL accuracy for tt predictions.



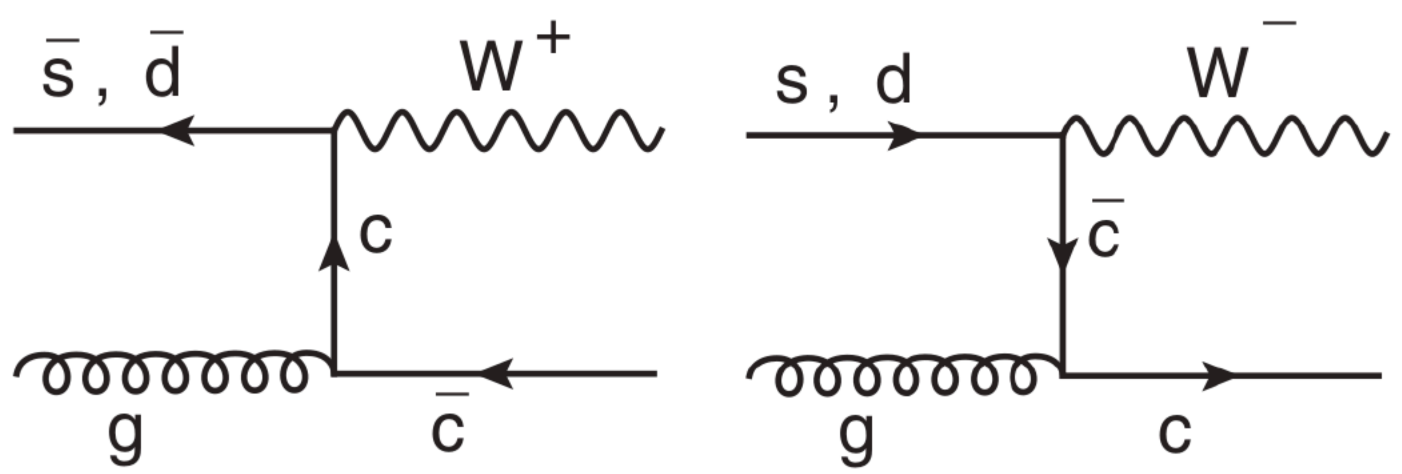




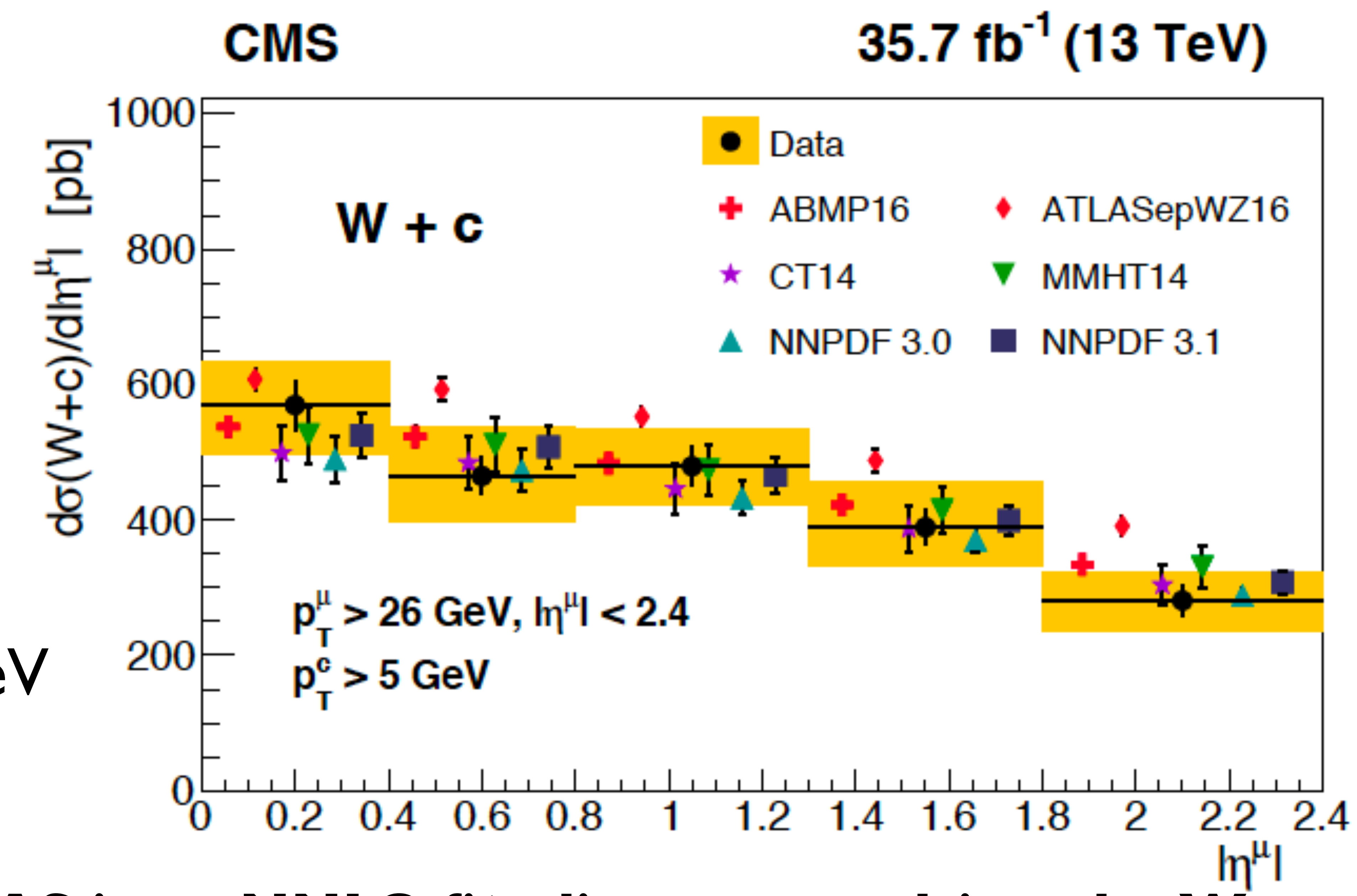


W+CHARM

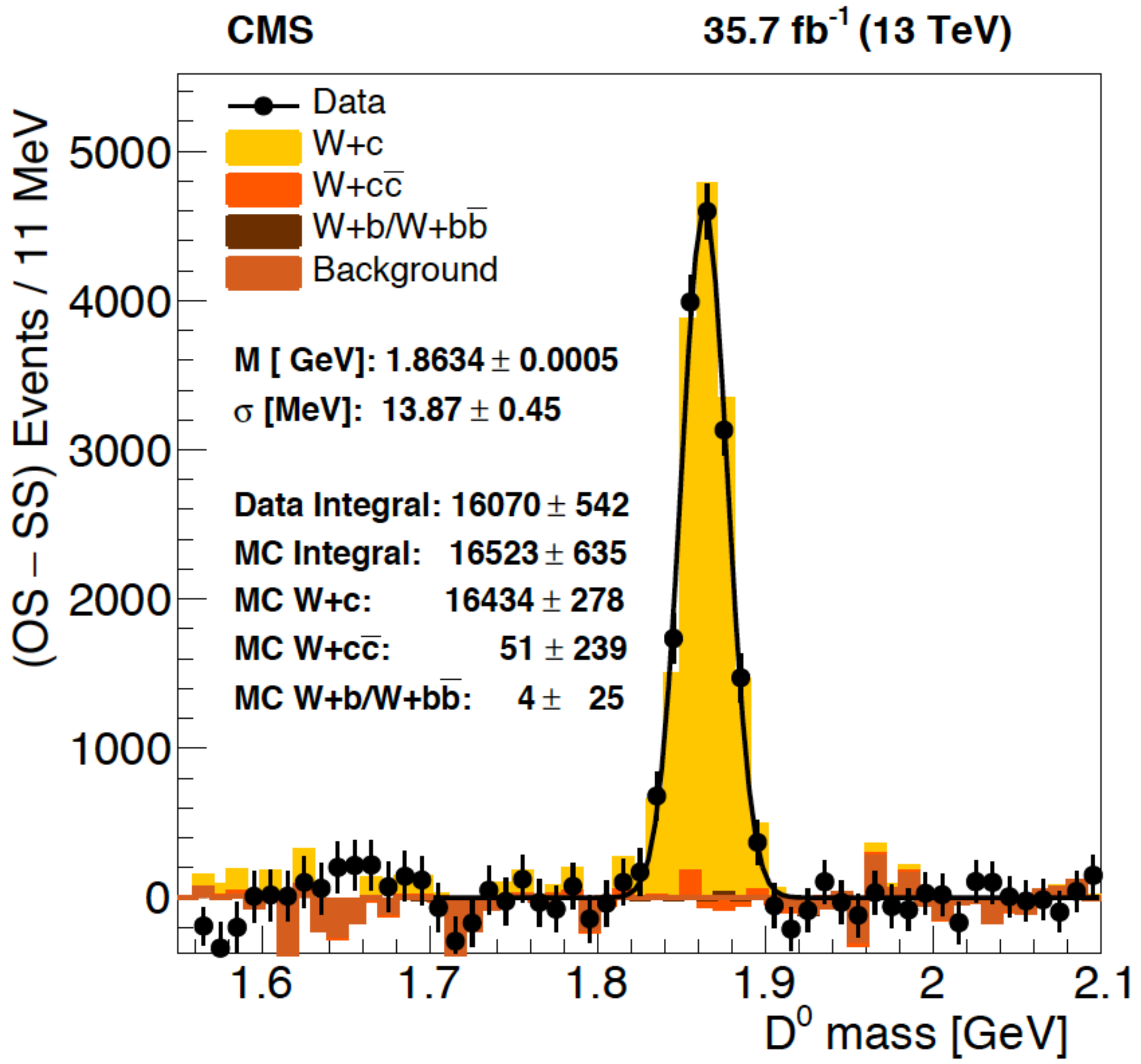
arXiv:1811.10021



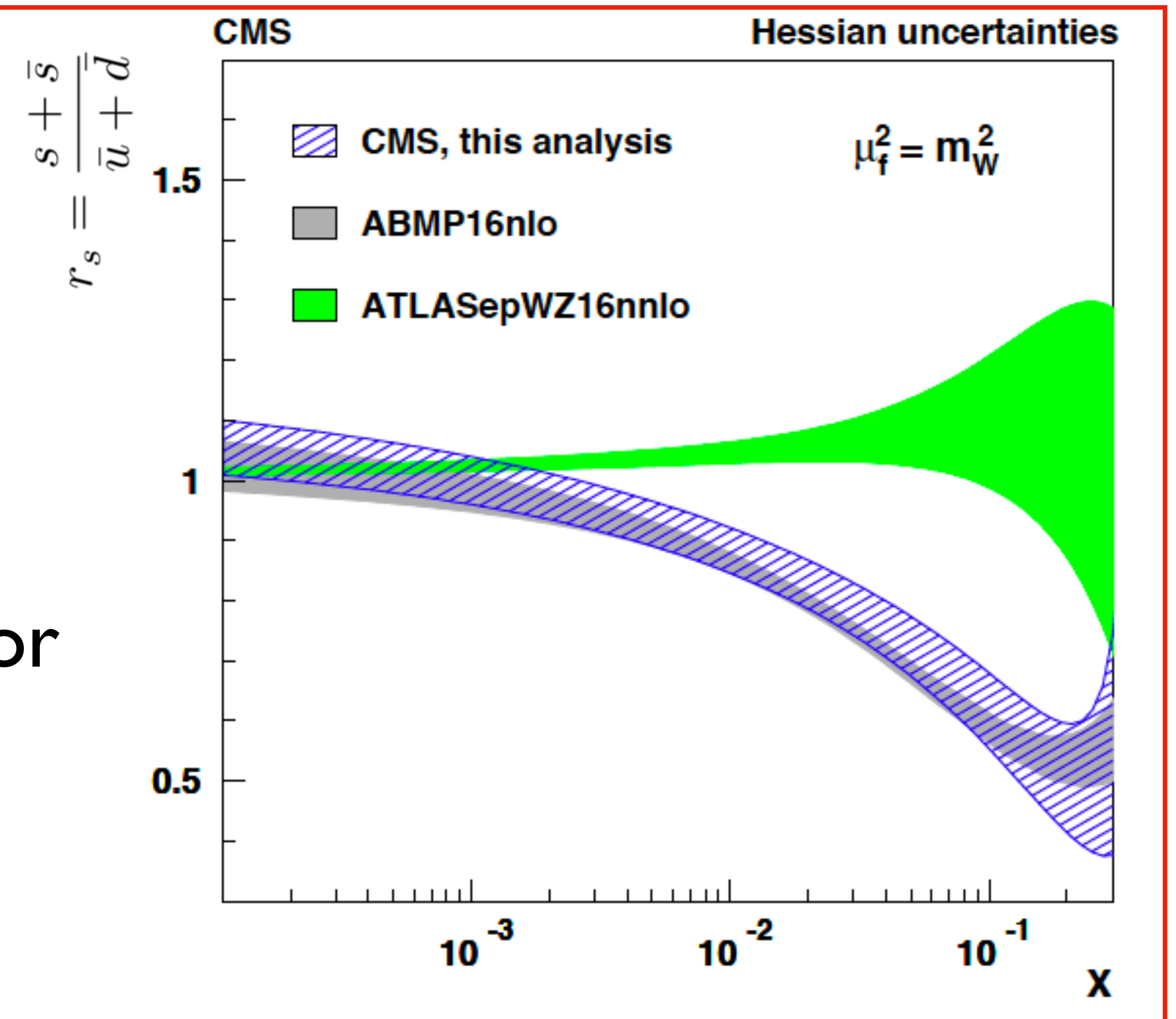
- Process sensitive to the strange quark PDF
- CMS, 13 TeV, W→ $\mu\nu$
- c→D (2010) →Dπ$_{slow}$ →Kππ$_{slow}$,
  - signal OS W and D*, $p_T(\mu)$>26 GeV, $|\eta(\mu)|$ < 2.4, E_T^{miss}>25 GeV, m_T>50 GeV **p_T(D*)> 5 GeV & $|\eta$(D*)$|$ ≤ 2.4**
- SS subtraction from OS events to suppress background



ATLAS is an NNLO fit, discrepancy driven by W+



- Perform NLO QCD fit to CMS +HERA data
- Confirmation that strange unsurpassed at low-x
- Some discussion on the ATLAS error uncertainty treatment



W CHARGE ASYMMETRY

arXiv:1904.05631

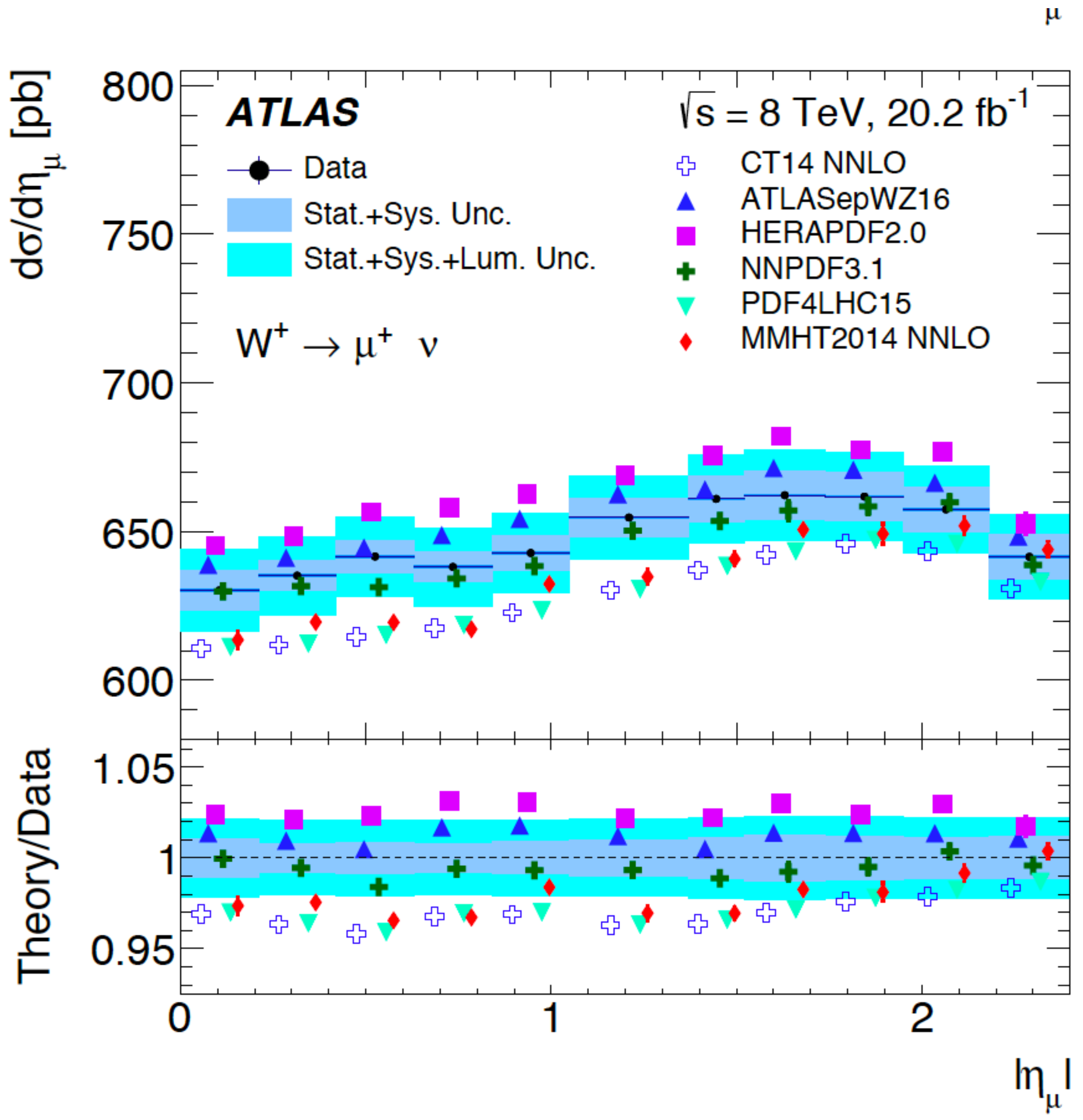
- Dominant production W boson at the LHC $d\bar{u} \rightarrow W^-$ and $u\bar{d} \rightarrow W^+$
  - Asymmetry due to valence content, increasing with lepton η (due to larger u_v than d_v at high x)

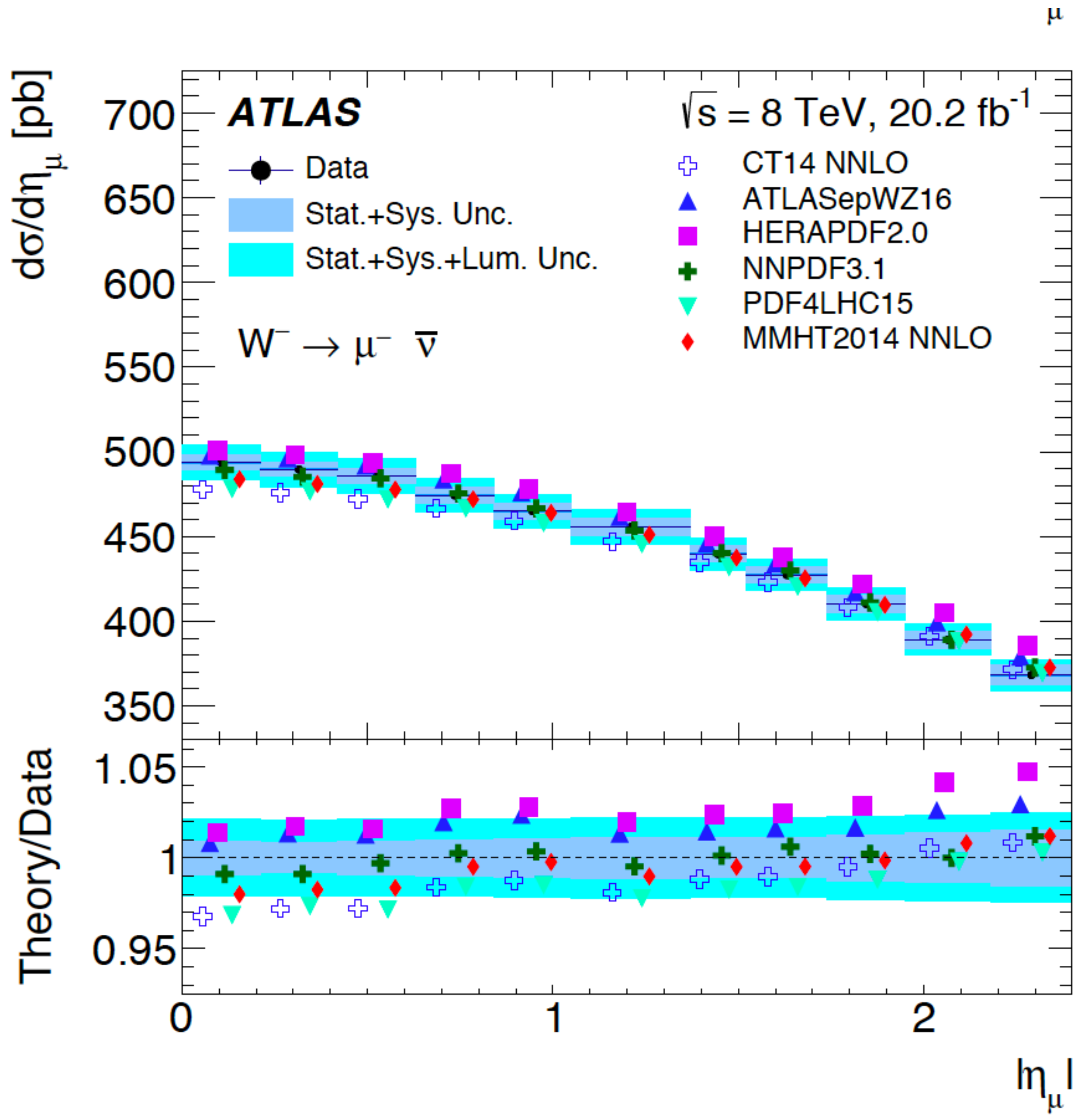
$$A_\mu = \frac{d\sigma_{W_{\mu^+}}/d\eta_\mu - d\sigma_{W_{\mu^-}}/d\eta_\mu}{d\sigma_{W_{\mu^+}}/d\eta_\mu + d\sigma_{W_{\mu^-}}/d\eta_\mu}$$

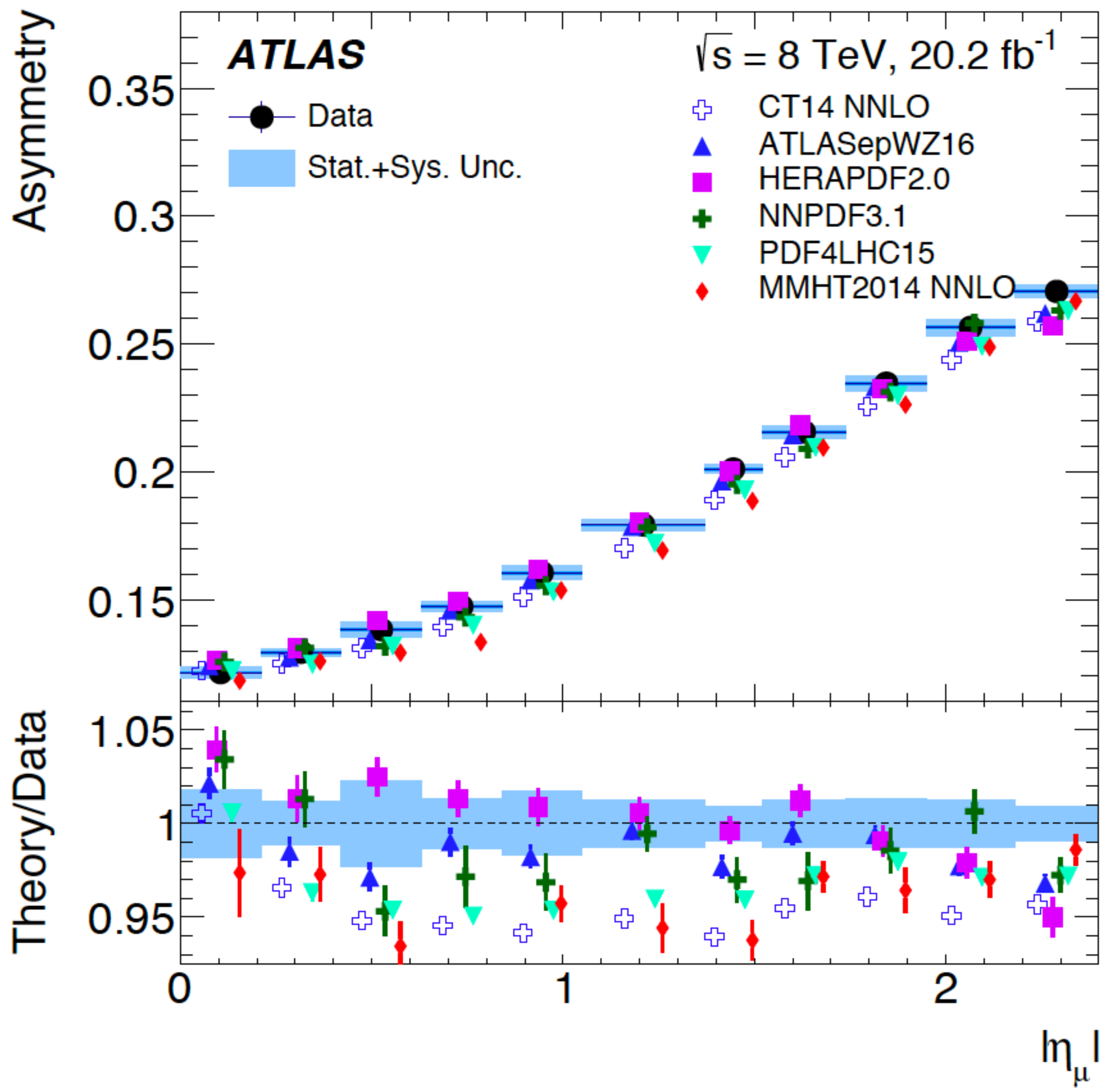
  - Asymmetry vs lepton η can provide info on PDFs d/u ratio and sea antiquarks (including strangeness)
- ATLAS result 8 TeV, $W \rightarrow \mu\nu$
- Stronger discrimination power for W^+ predictions
  - More widespread for similar uncertainty
  - Dominant uncertainty in the asymmetry is lepton reconstruction (luminosity cancels out)

- Stronger support of ATLASepWZ16, but also consistent discrepancy between W^+ and W^- for HERAPDF

- Also results from CMS (8 TeV, arXiv:1603.01803) and LHCb (7 TeV, arXiv:1408.4354)





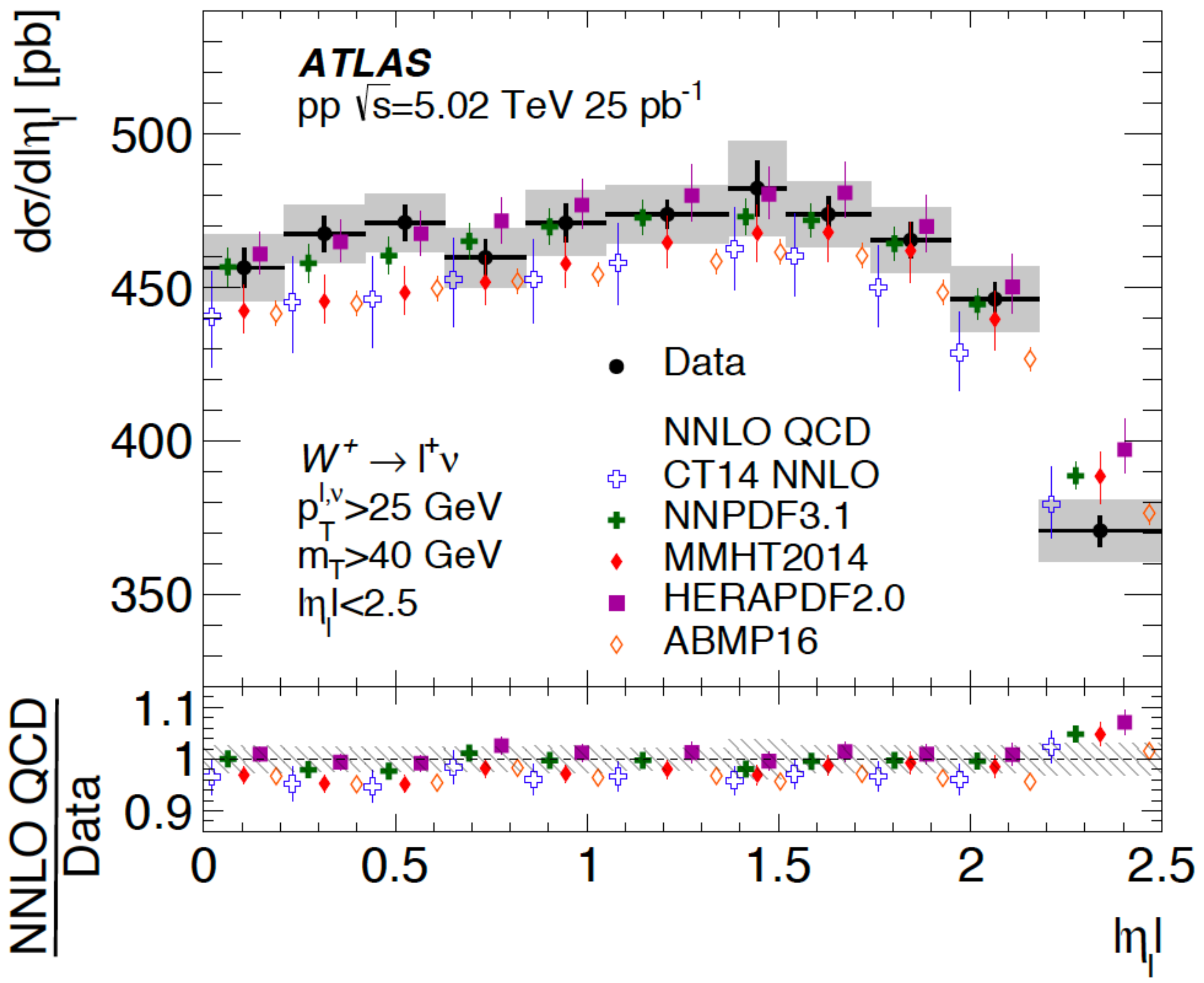


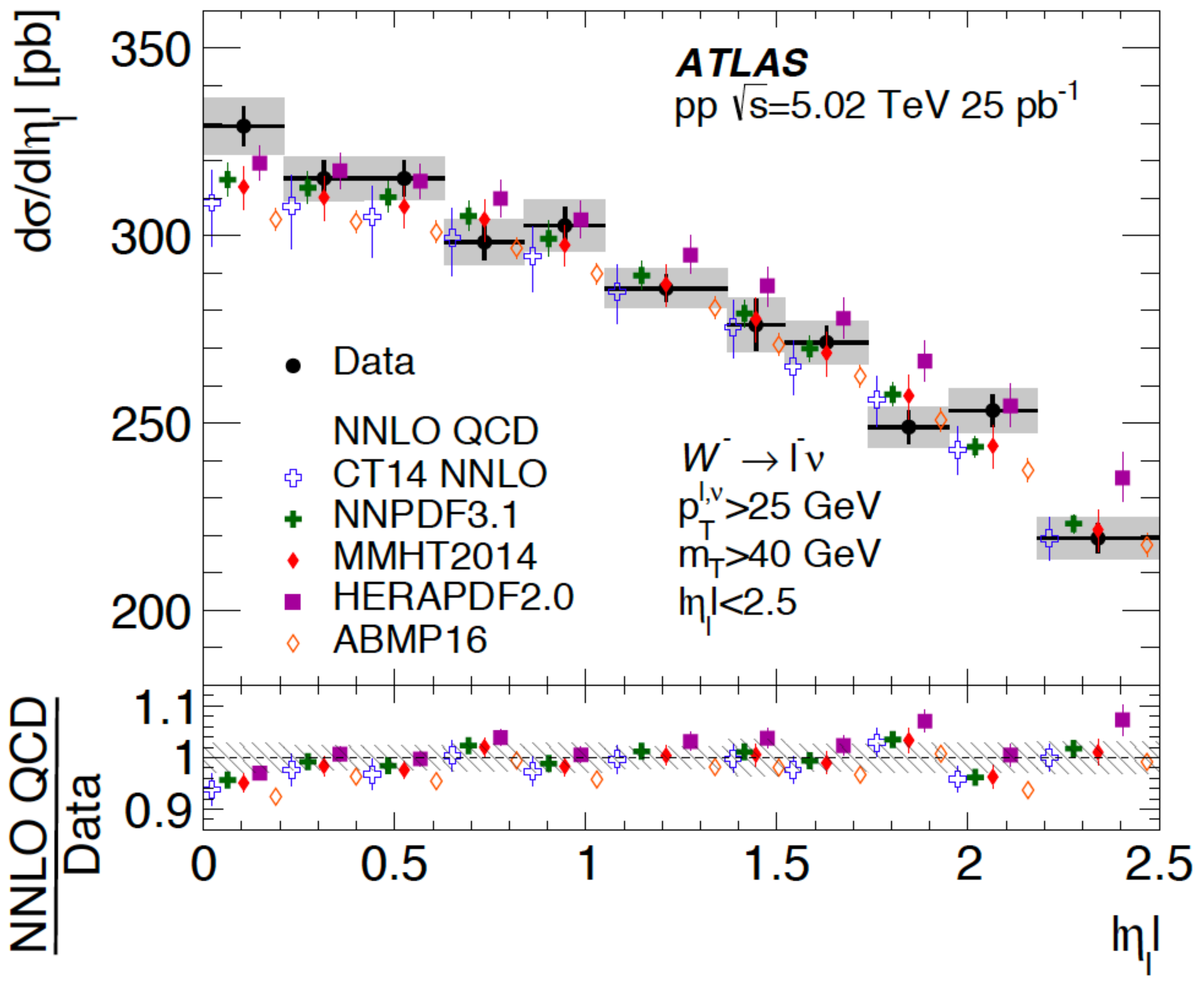
W AND Z CROSS SECTIONS AT "NON-STANDARD" ENERGIES

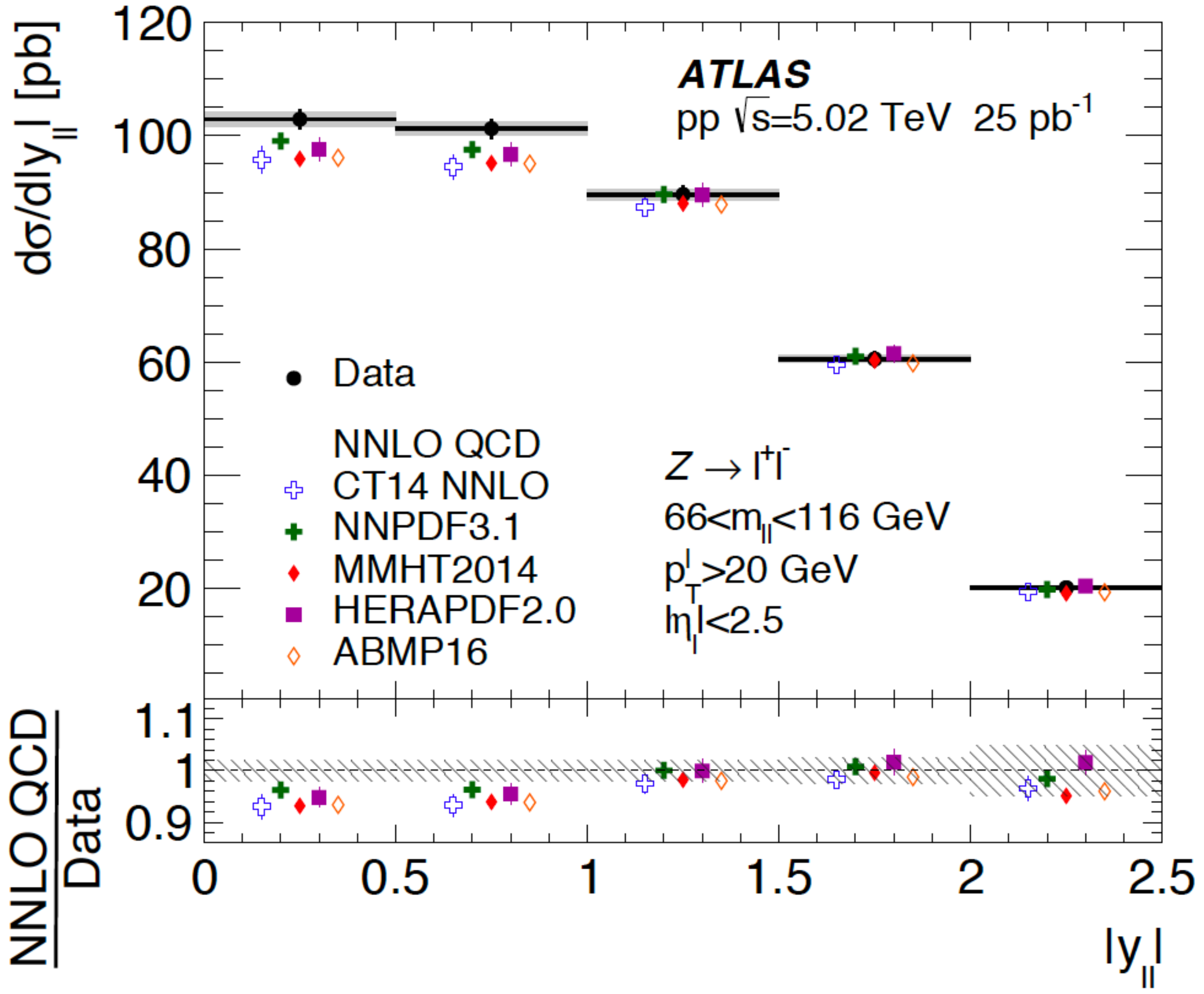
arXiv:1810.08424

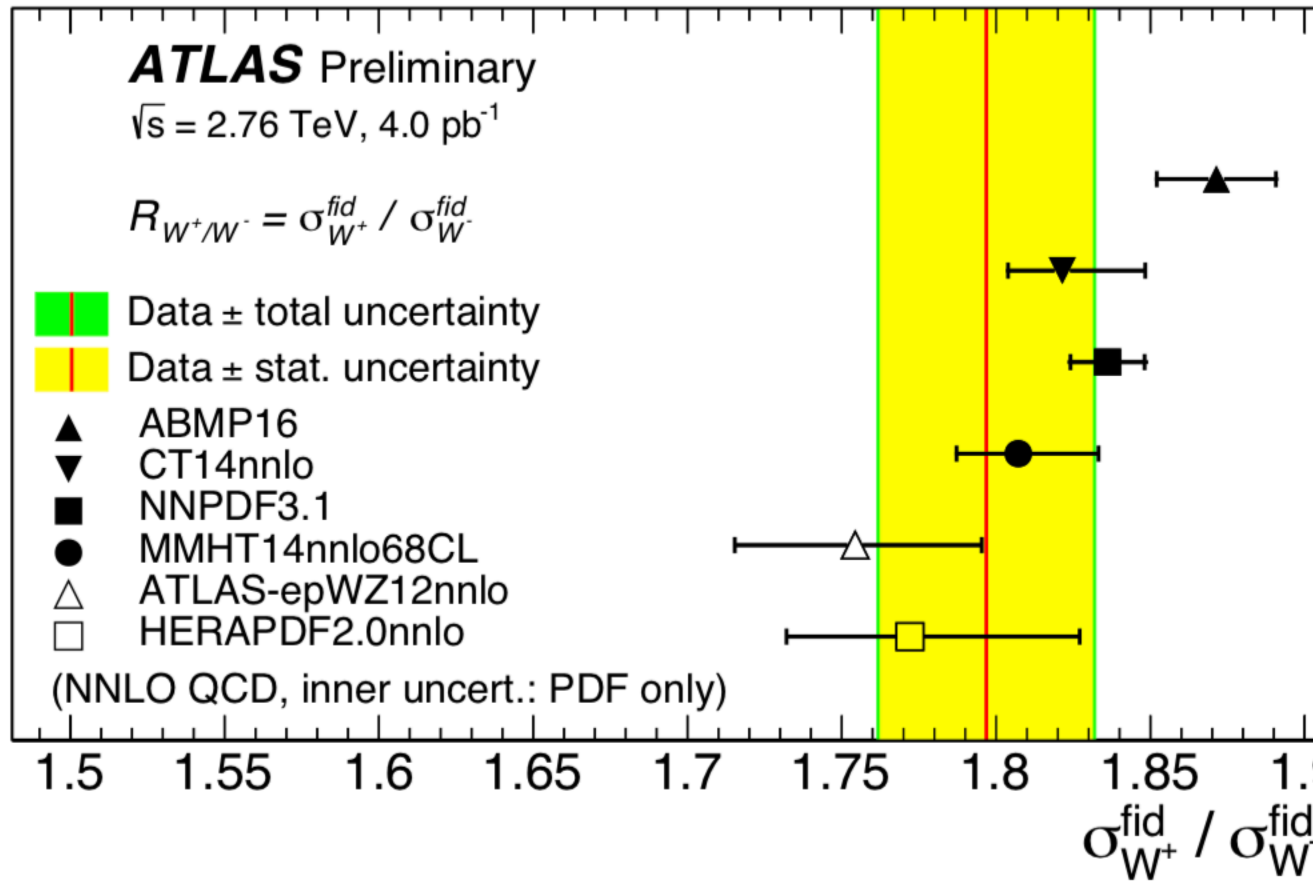
2.76 TeV preliminary

- Measurement of W and Z cross sections at different $\sqrt{s}$ (thanks you heavy ions!) very important for constraining PDFs
- ATLAS results 5.02 TeV, (2015 data, 25 pb^{-1}), 2.76 TeV (2013 data, 4 pb^{-1})
  - General agreement with each PDF set for 5 TeV W/Z data
  - Significant tension with all sets at very low η (low x) for W^- and Z
  - Good agreement for different PDF sets except ABMP and CT14 in W^+
- Asymmetry measured as well (with similar conclusion)
- Still gain in combination with larger dataset (2017)
- Cross sections at 2.76 TeV first time measured at LHC
  - Fiducial region defined by the detector acceptance and extrapolated to the full phase space for the total inclusive production cross-section.
  - Generally agreement with the predictions, still have discriminating power
  - Measured only inclusively, including asymmetry in W





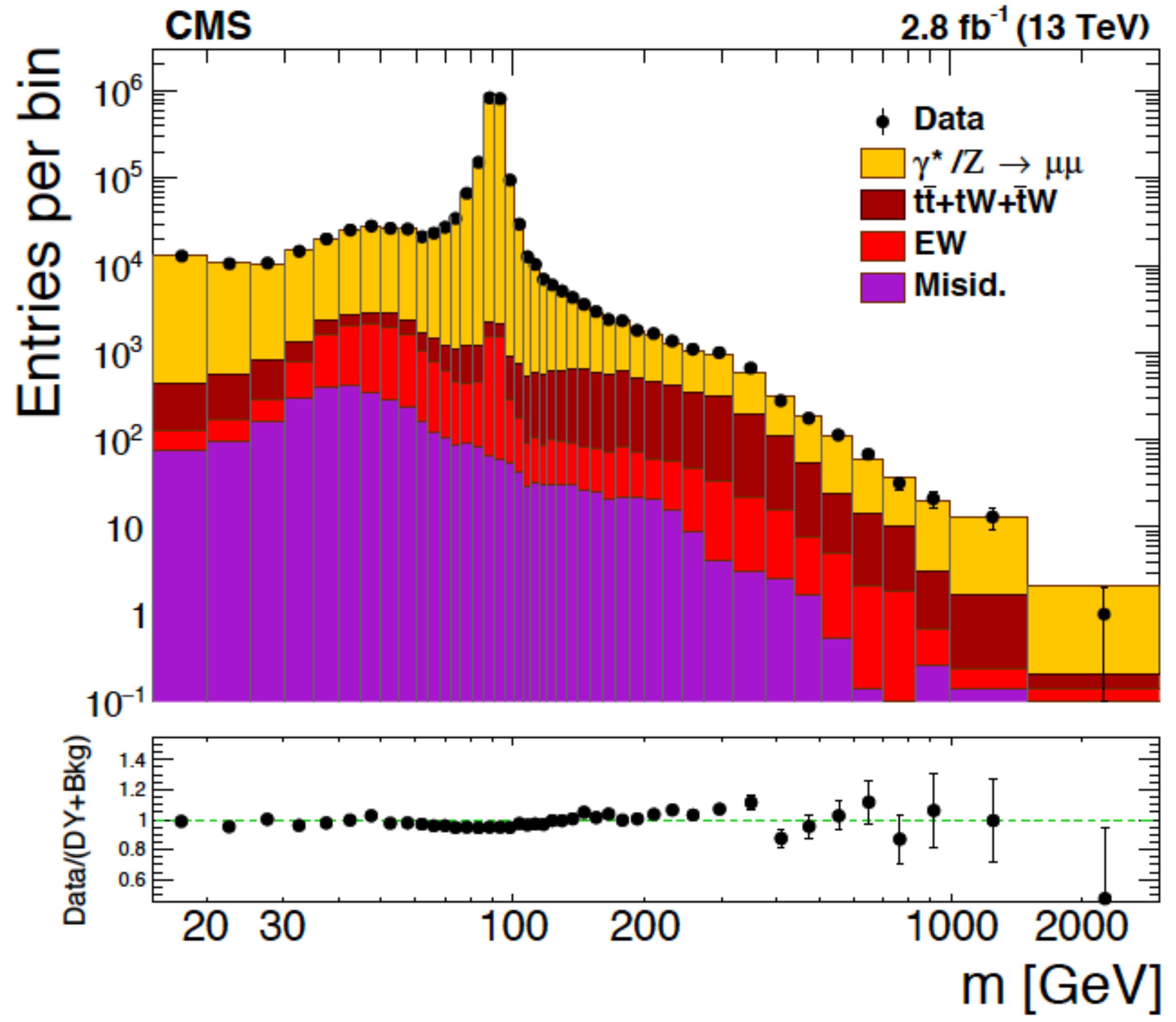


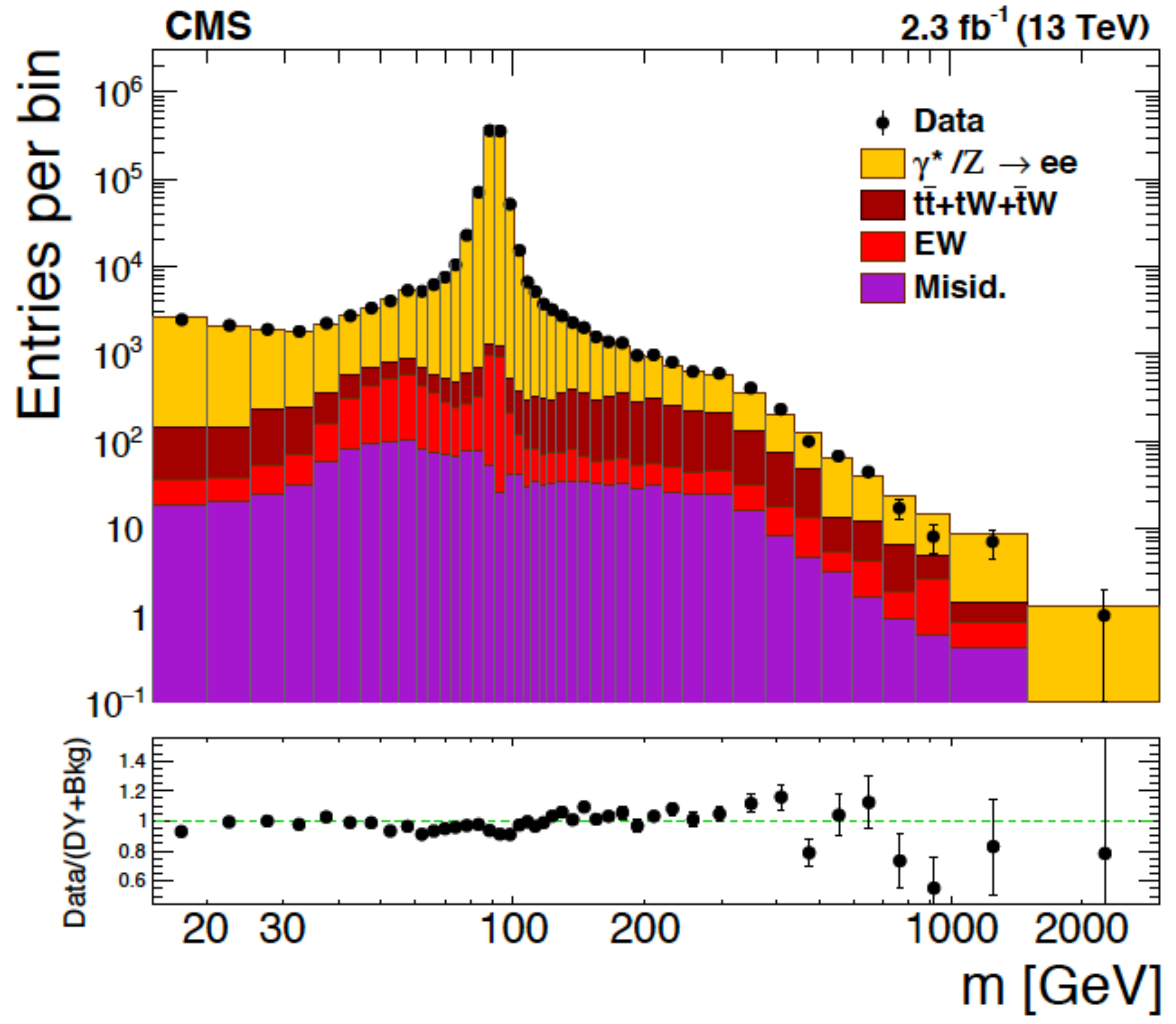


Z DIFFERENTIAL CROSS SECTIONS

arXiv:1812.10529

- Single, double and triple differential cross sections ($d\sigma/dm$, $d^2\sigma/dmdy$, $d^3\sigma/dmdyd\cos\theta^*$) of the DY process have been measured at the LHC
- Recently CMS published $d\sigma/dm$ in a wide mass range $15 < m_{ll} < 3000$ GeV using a subset of Run-2 13 TeV data (2015)
  - Low mass dominated by EM coupling of γ^* to qqbar
    - Different sensitivity to u and d quarks then on peak
  - Peak region and above Z/γ^* to $q\bar{q}$
  - High mass shape could be modified by New Physics
    - Contact Interactions are prominent example
- Cross section extrapolated the full phase space including Final State Radiation (FSR)
- For m_{ll} <400 GeV statistical uncertainties subleading, main systematic uncertainty arising from lepton efficiencies

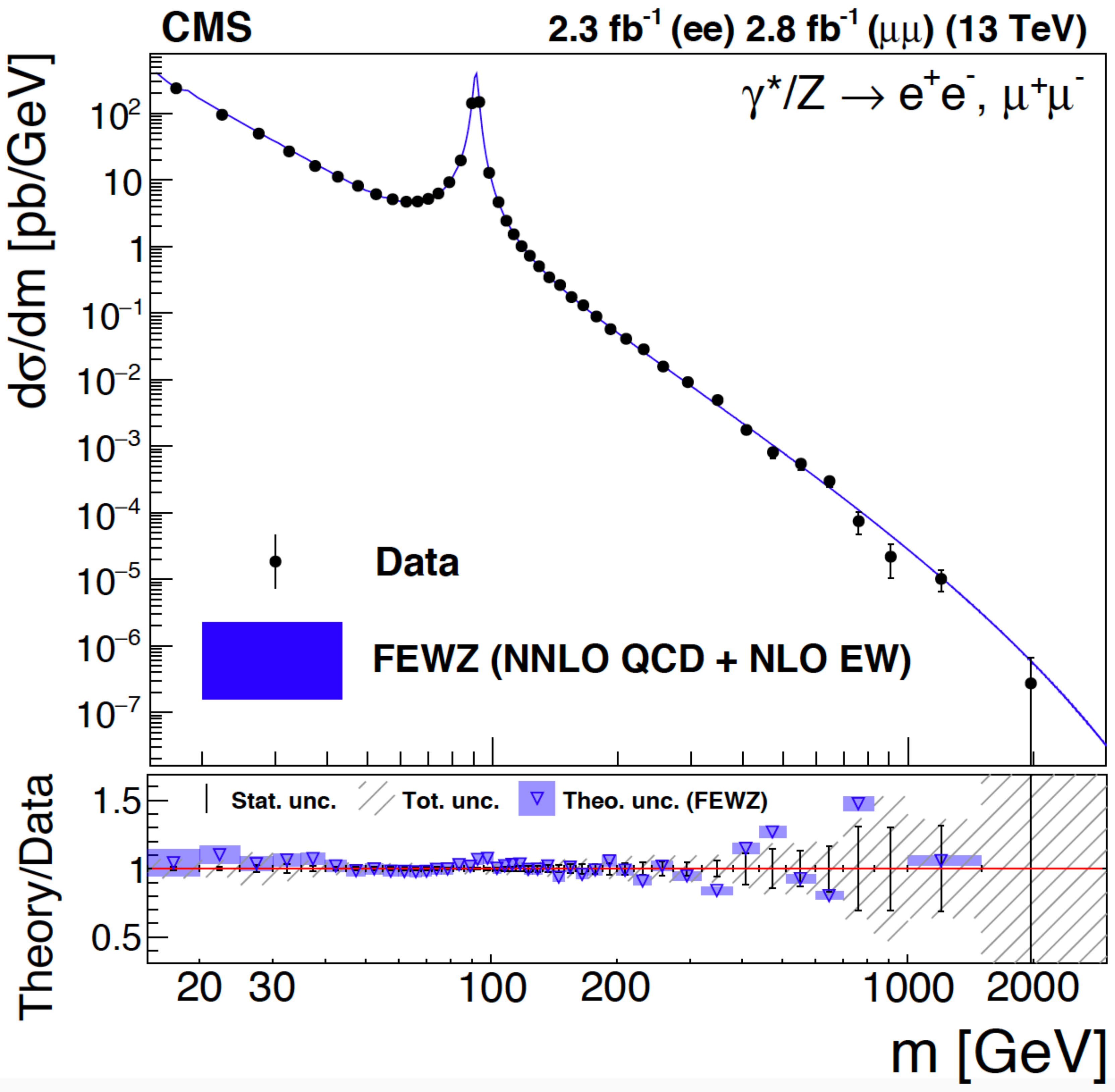


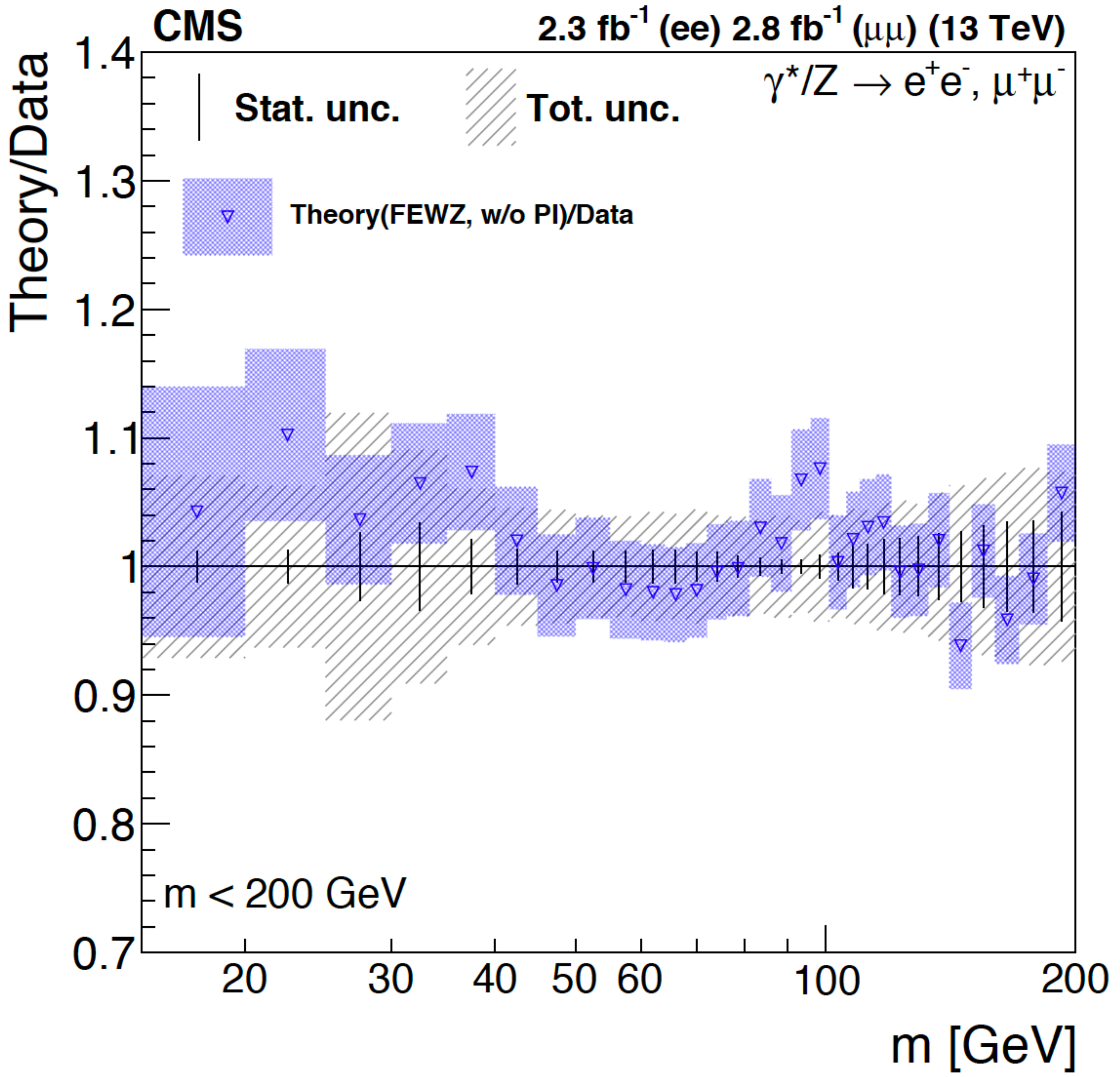


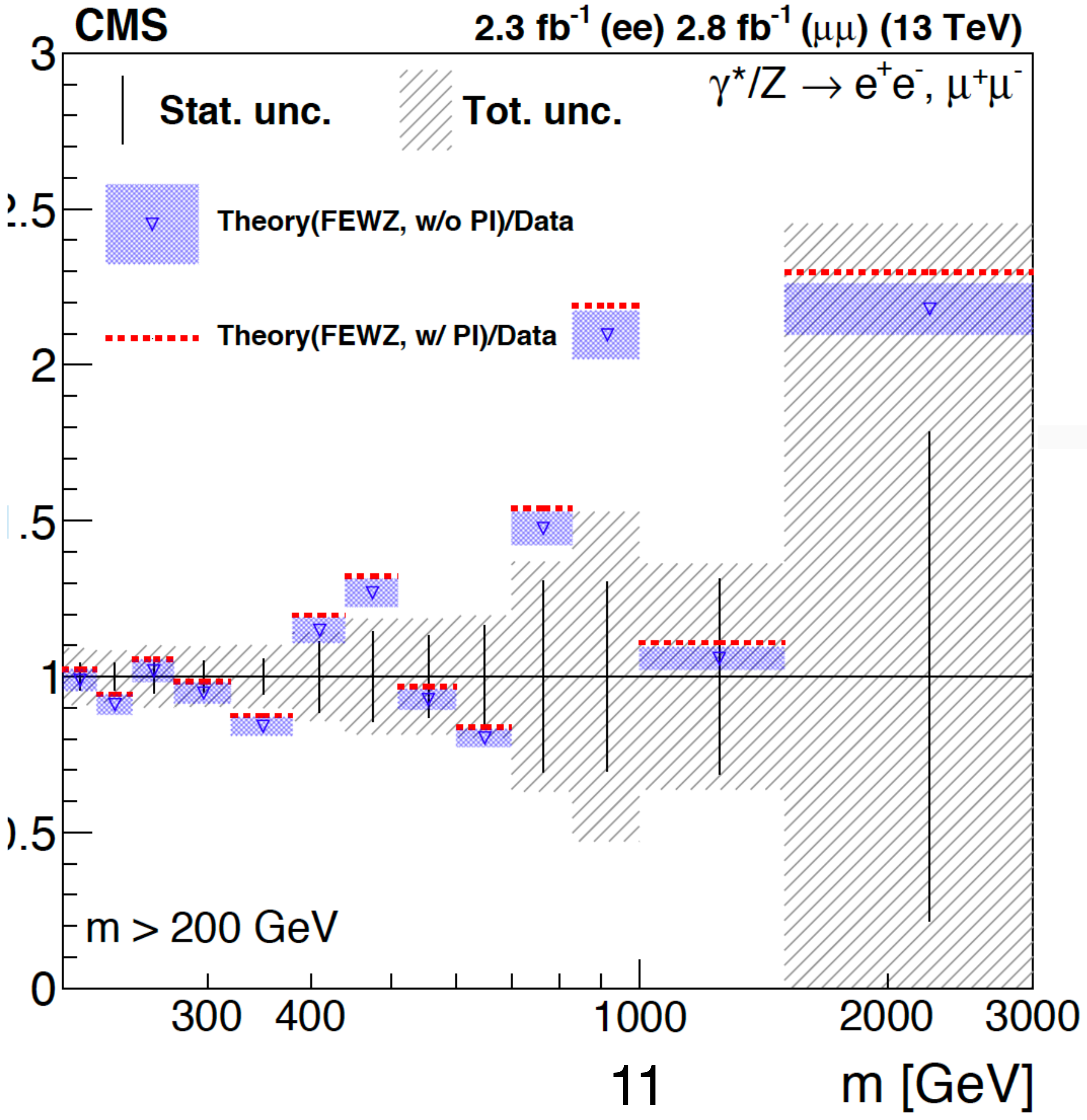
Z DIFFERENTIAL CROSS SECTIONS

arXiv:1812.10529

- Signal modelling: MadGraph5_aMC@NLO+ Pythia8, NNPDF3.0 (CUETP8M1 tune), good agreement with predictions.
- Full phase space cross sections in good agreement with FEWZ(NNLO QCD + NLO EW) with NNPDF3.0
- Predictions with photon-induced contributions also tested at high mll with FEWZ+LUXqed
  - The photon-induced contribution has a sizable effect in the high-mass region.







W+JETS

arXiv:1711.03296

- W + jets, provides a novel source of input to PDF fits that is sensitive to partons at higher x than can be accessed by inclusive W,Z data

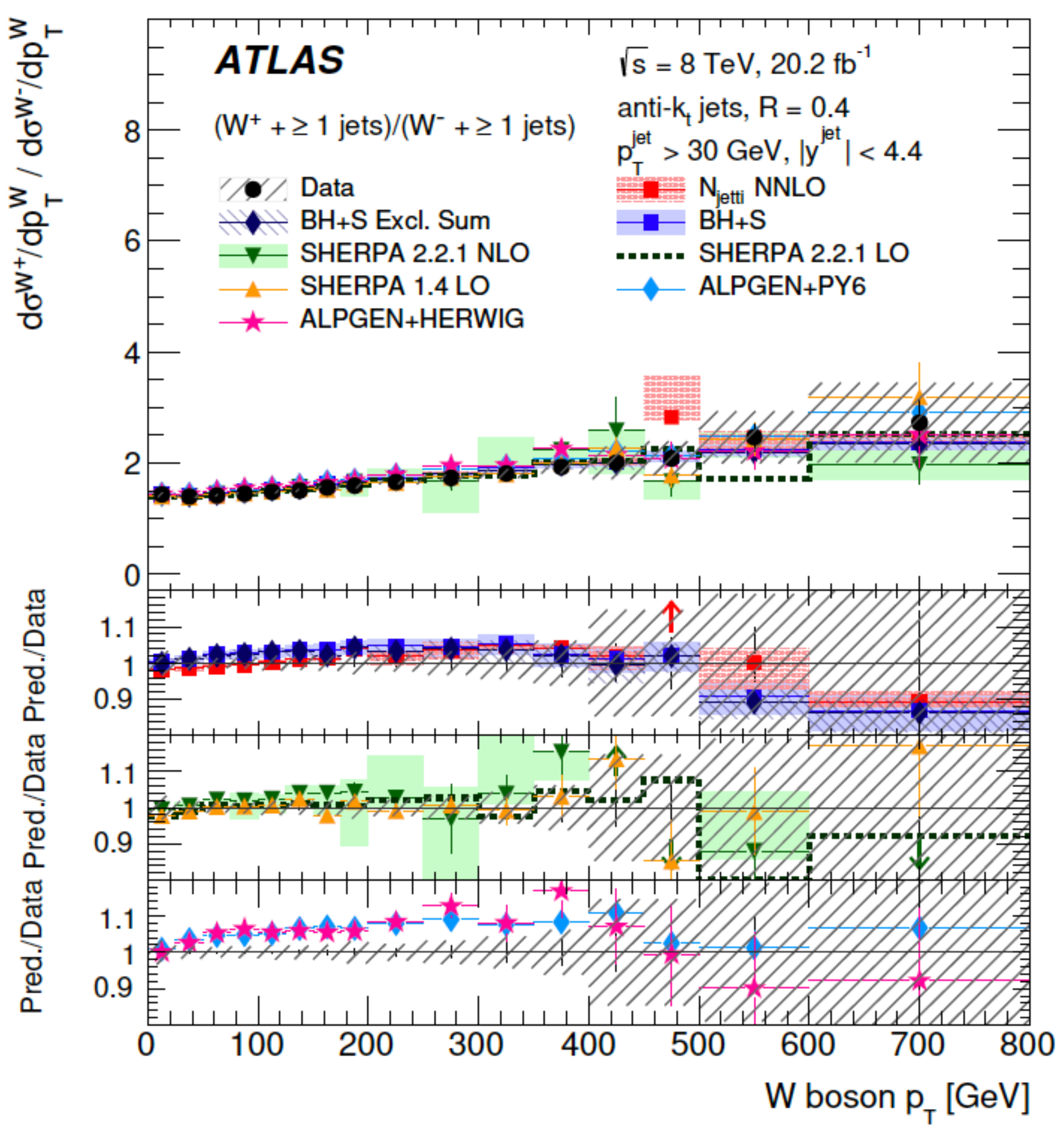
- ATLAS 8TeV data, W(eν)+jets cross sections & ratios

- Compare with various predictions (models) and publish unfolded cross section
  - Njetti, BlackHat+Sherpa, MCFM, Powheg+Pythia8, Sherpa 2.2.1, Alpgen+Pythia6, Alpgen + Herwig, Sherpa and diffrent PDFs (CT, NNPDF, CTEQ)

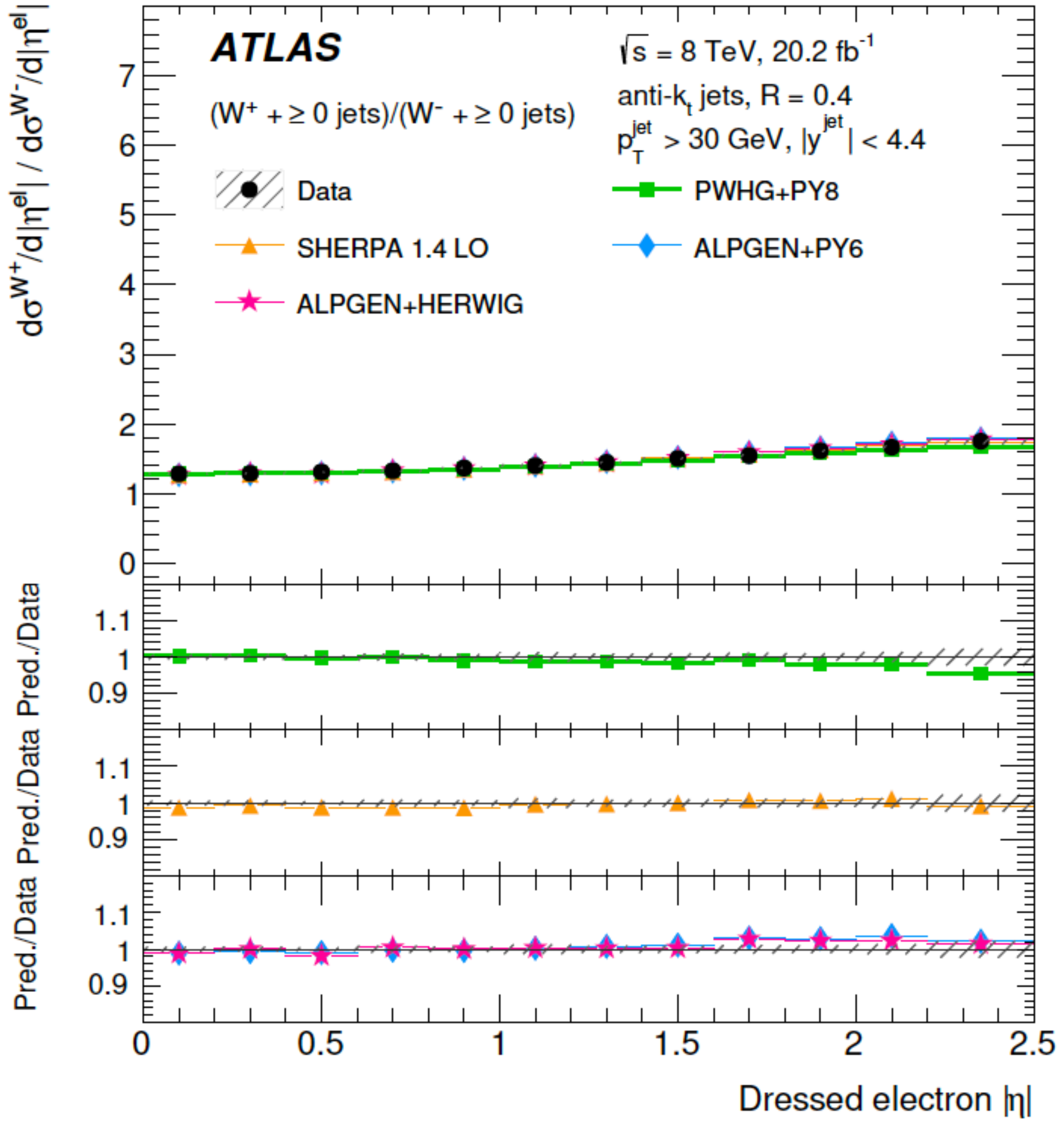
- Jets: pT> 30GeV, |y|<4.4
  Top bkg suppressed with b-veto
  Jet bkg 3-15% for W+0/1/2 jets

- Precision: 5-16% for W+0/1/2 jets
  - limited by JES and JER and unfolding

- Precision for the ratio: 0.7-4% for 0/1/2 jets
  - Limitations: JET bkg, MET uncertainty and JER



NNLO/NLO fixed order a
nd LO ME+PS consistent with data

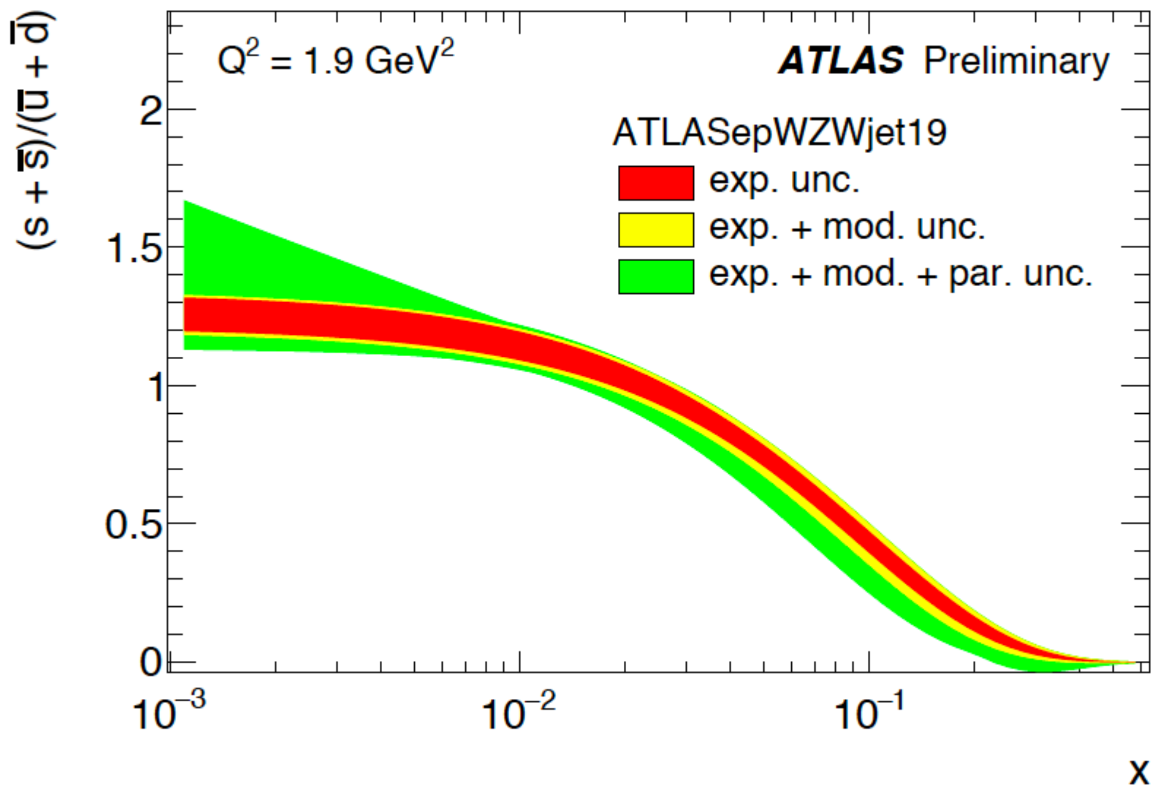


Good modeling, a
Asymmetry sensitive to PDFs

QCD analysis of W+jets @8 TeV and incl
to contain strange at slightly higher x:
ATLAS-epWZWjet19

Better constrain on $\bar{d}$ - $\bar{u}$
Strange enhancement at high x reduce
Enhancement at low x remains

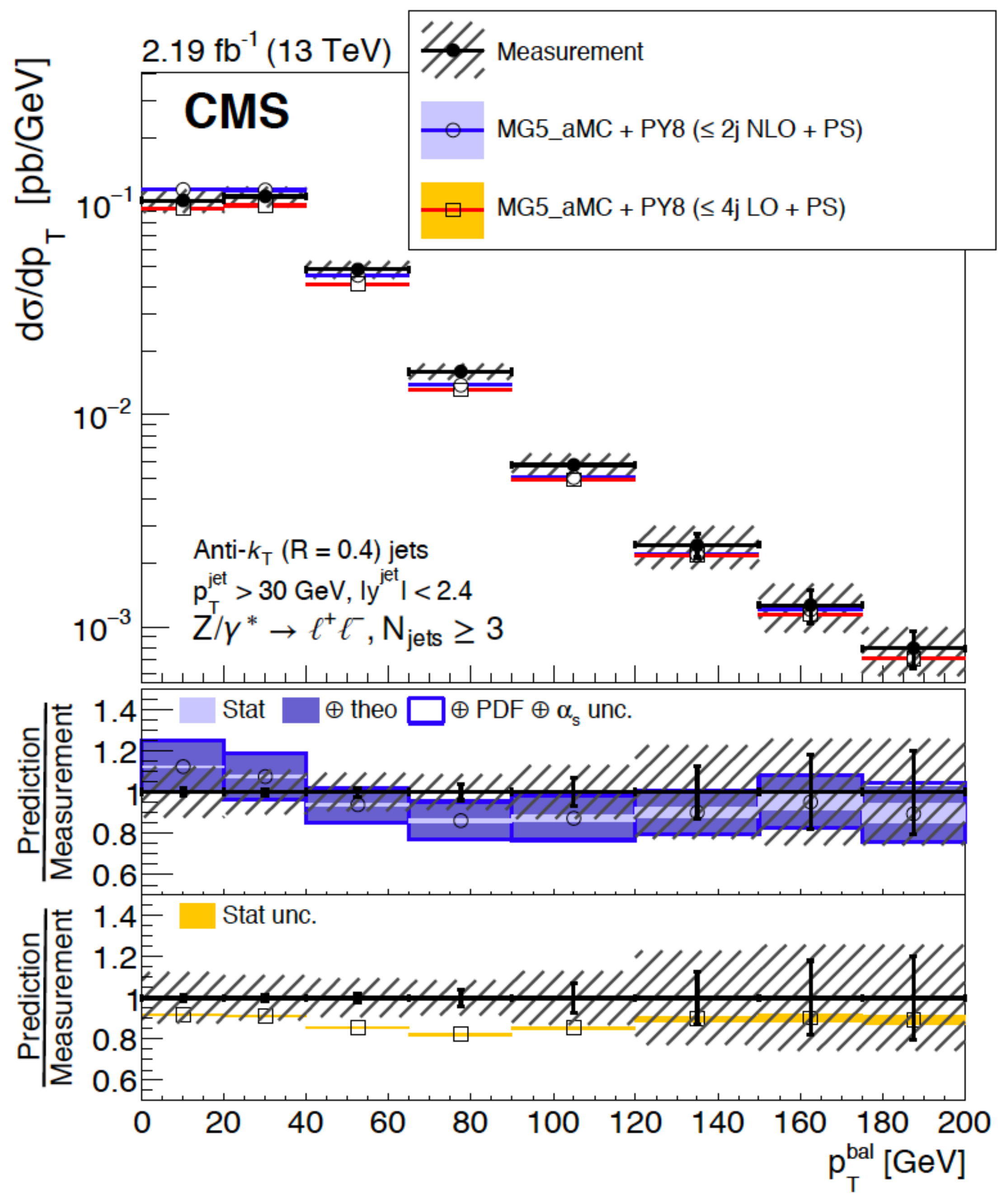
ATL-PHYS-PUB-2019-016



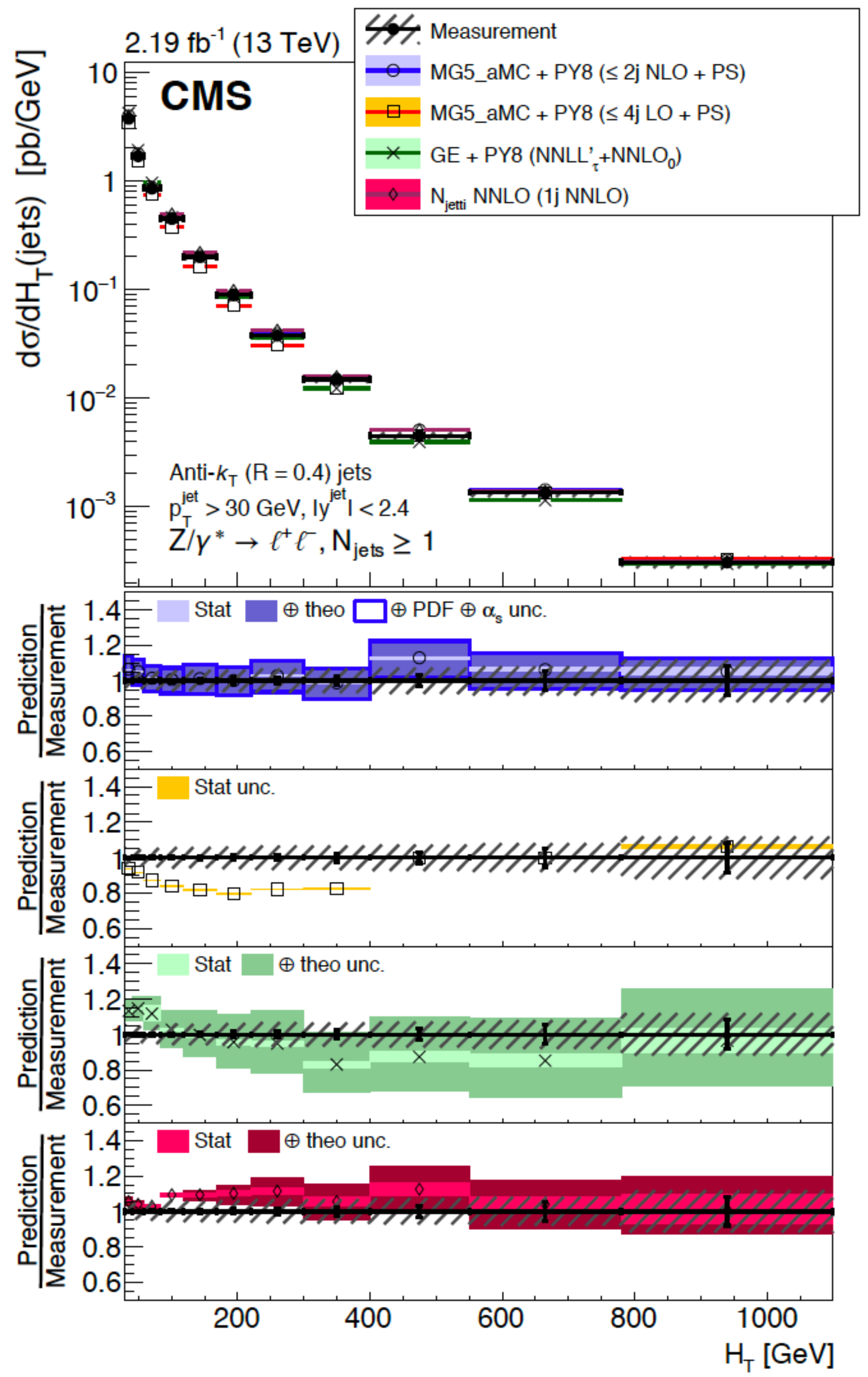
Z+JETS

arXiv:1804.05252

- CMS, 13TeV data, Z+jets differential cross sections up to 6 jets
  - The balance in transverse momentum between the reconstructed jet recoil and the Z boson measured (first time at the LHC) for different jet multiplicities,
- Compare with various predictions and publish unfolded cross section (Madgraph, Geneva, Njetti)
  - Including fully differential NNLO + parton shower in the final state and model NNLO + NNLL without parton showering.
- Jets: pT> 30GeV, |y|<2.4
  - The background contamination below 1% (inclusive cross section), tolose to 10% for Njet > 2 (due to top production).
- Uncertainties are dominated by JES and JER, followed by the trigger efficiency and luminosity



The measurements are in good agreement with the results of the NLO multiparton calculation.

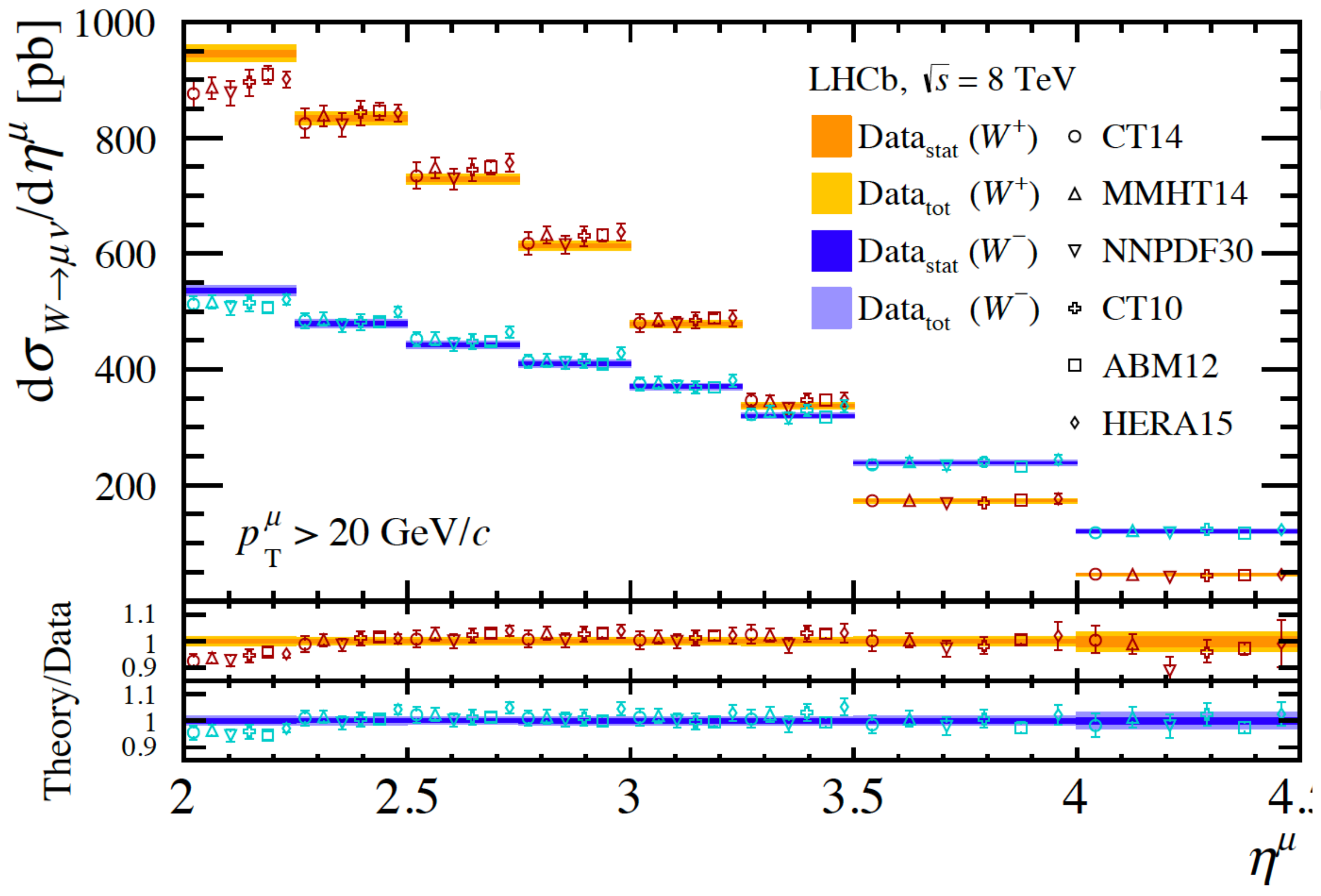


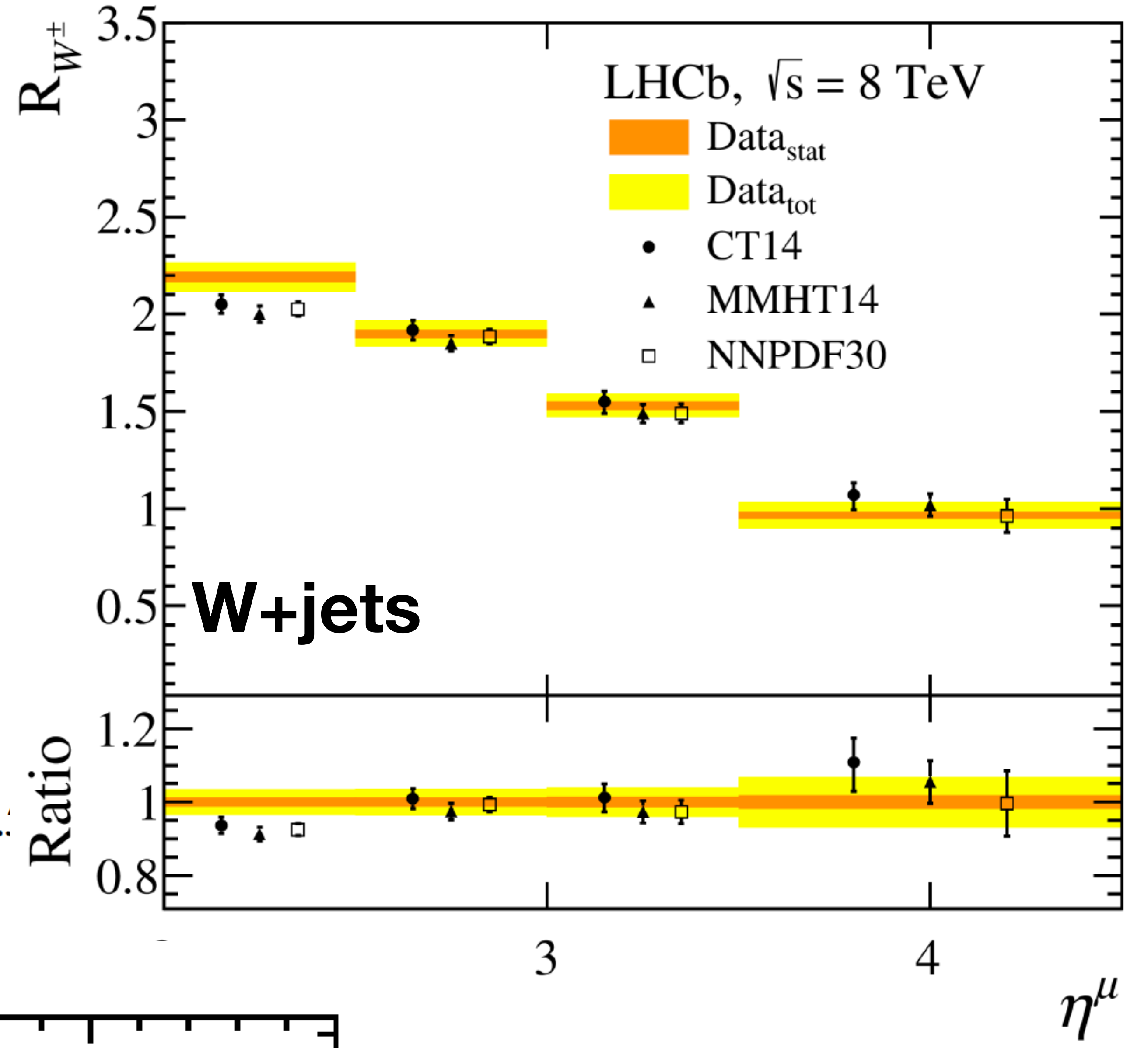
- Multiparton NLO prediction provides a very good description for jet multiplicities computed with NLO accuracy.
- NNLO+NNLL fail to describe observables sensitive to extra jets (>=2). At low pTZ, the NLO multiparton calculation better than the NNLO+NNLL, both calculations provide similar description at high pTZ.

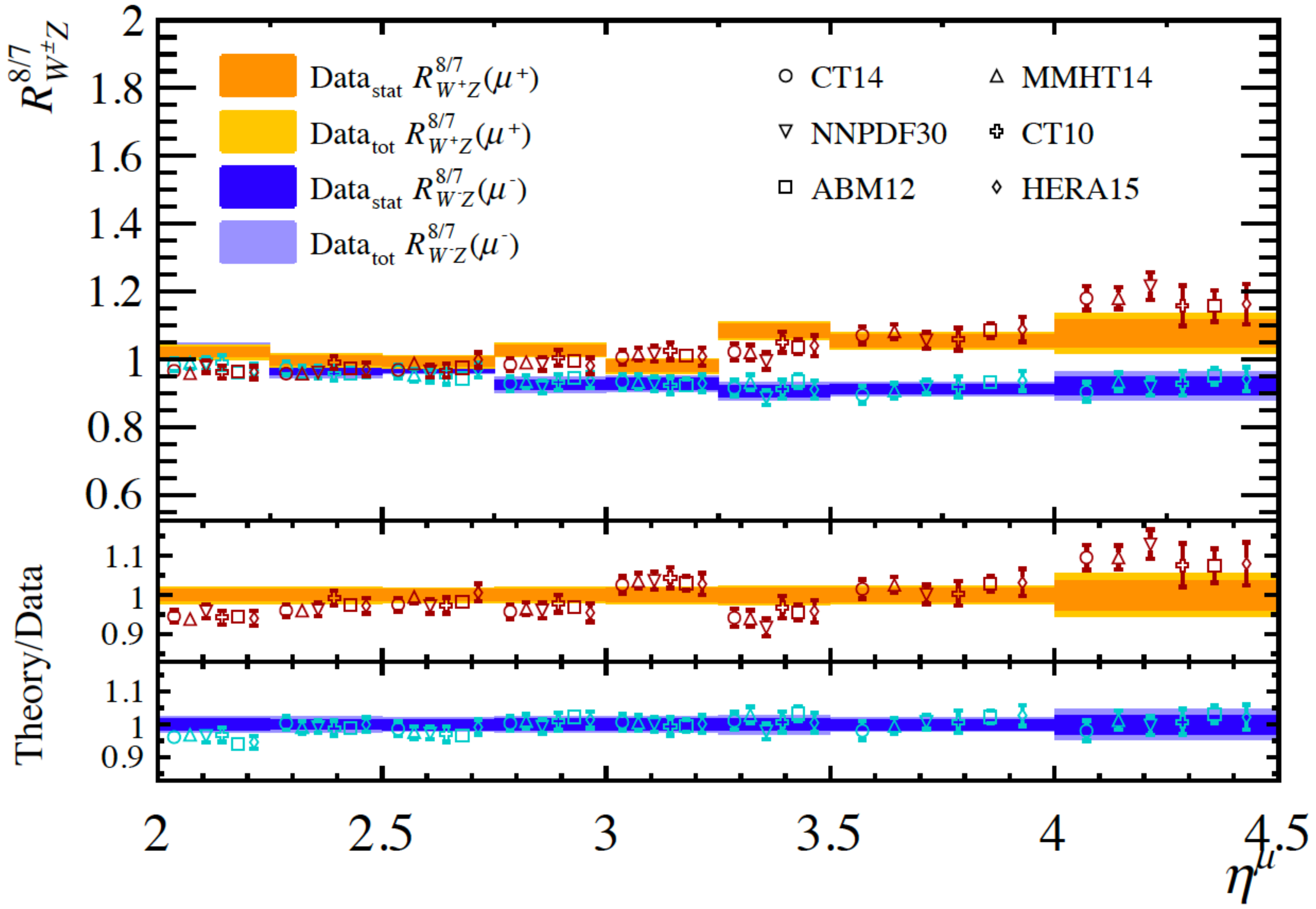
W AND Z CROSS SECTIONS IN THE FORWARD REGION

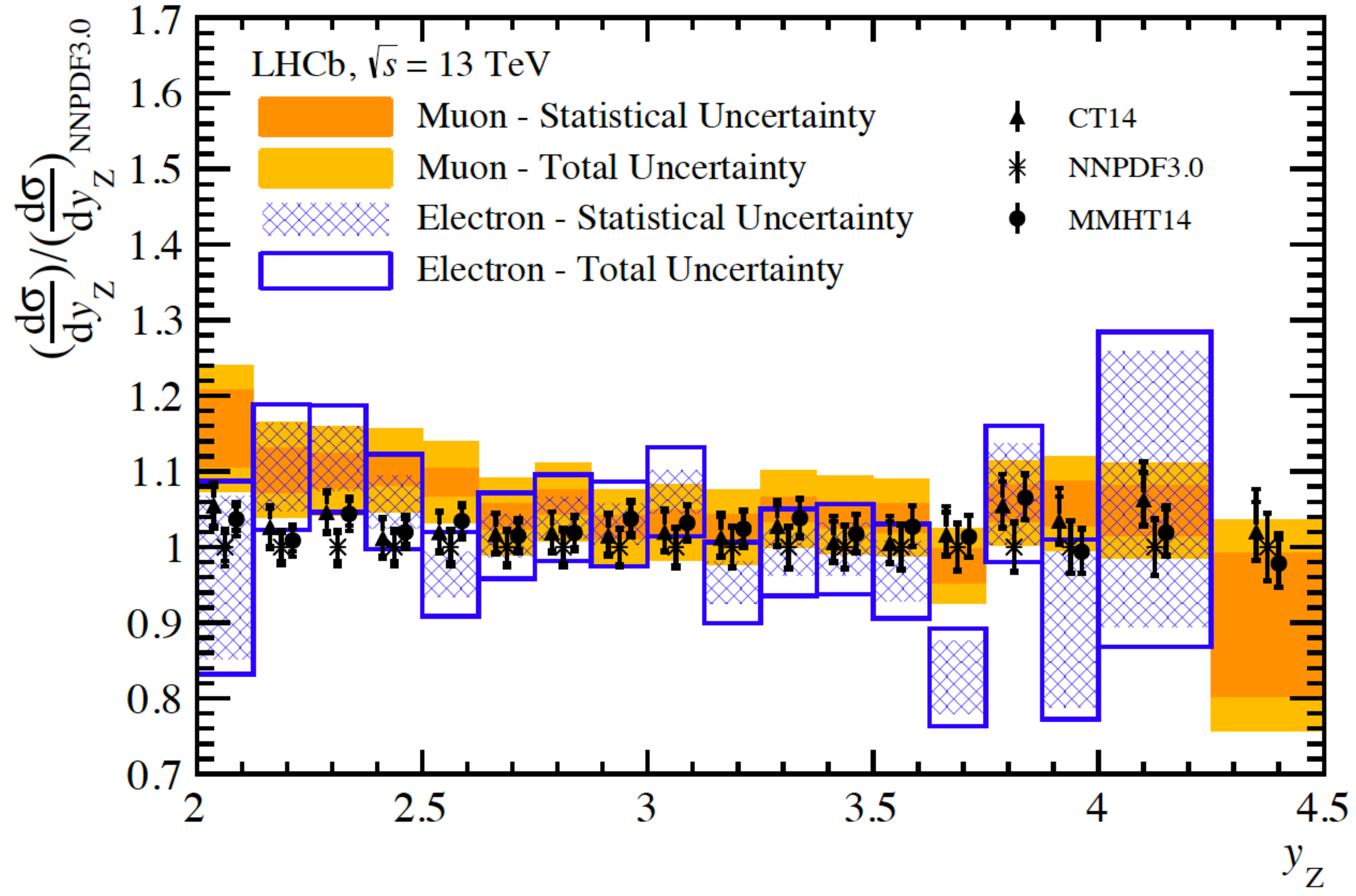
arXiv:1605.00951
arXiv:1511.08039
arXiv:1607.06495
arXiv:1608.01484

- LHCb total and differential cross-sections in the forward fiducial region at 8 TeV
- In addition to measurements of the charge ratio and asymmetry of W(+jets) and production and the ratio of W(+jets) and Z(+jets) production.
- Z-boson cross section measured at 13 TeV
- Measurements compared to fixed-order QCD calculations, and various PDFs
- Typically good agreement with predictions.







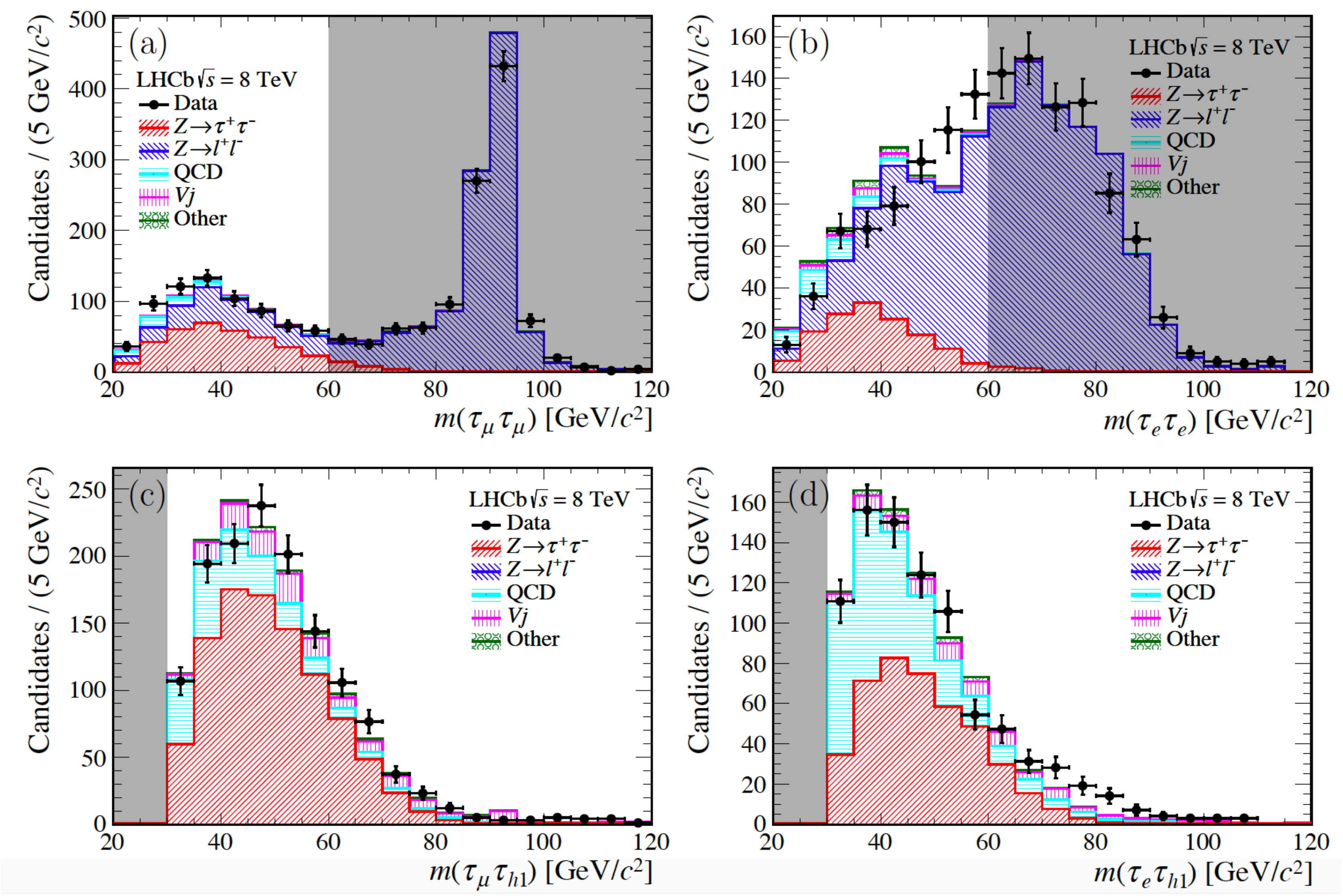


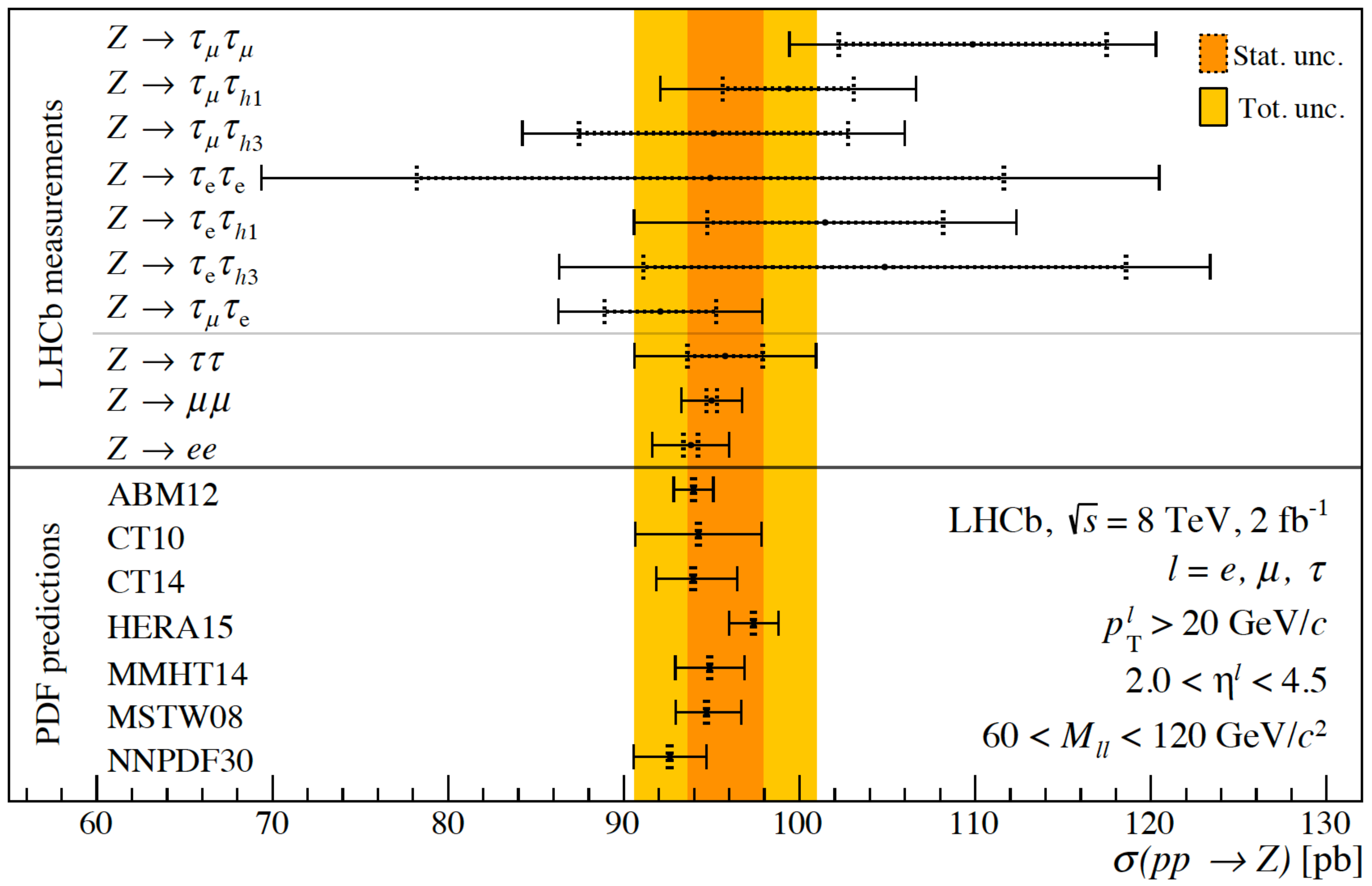
Z TO TAU CROSS SECTIONS

arXiv:1806.05008

- Z→ tautau important test of the SM (test of lepton universality)
- LHCb 8 TeV measurement, leptonic + hadronic (1,3-prong) decay modes (lh + ll) ,7 channels in total: ee, μμ, μe, μh1, μh3, eh1, eh3
- The results are consistent with the predictions.
- Z → ee and Z→ mumu cross-sections measured at LHCb. They are compatible with lepton universality at the level of 6%.

	$\tau_\mu\tau_\mu$	$\tau_\mu\tau_{h1}$	$\tau_\mu\tau_{h3}$	$\tau_e\tau_e$	$\tau_e\tau_{h1}$	$\tau_e\tau_{h3}$	$\tau_\mu\tau_e$
Tau branching fractions product	0.5	0.3	0.5	0.5	0.3	0.5	0.3
PDF, acceptance, FSR	1.3	1.9	1.5	1.3	1.9	1.5	1.3
Reconstruction	2.1	3.1	5.6	4.5	5.4	7.0	2.7
Selection	5.0	3.5	4.7	5.7	3.5	5.1	3.9
Background estimation†	3.4	3.9	3.2	19.0	5.2	8.0	2.4
Systematic	6.4	6.2	8.0	20.3	8.4	11.8	5.2
Statistical†	6.9	3.8	8.1	17.6	6.6	13.1	3.4
Beam energy	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Luminosity	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Total	9.6	7.5	11.5	27.0	10.8	17.7	6.5

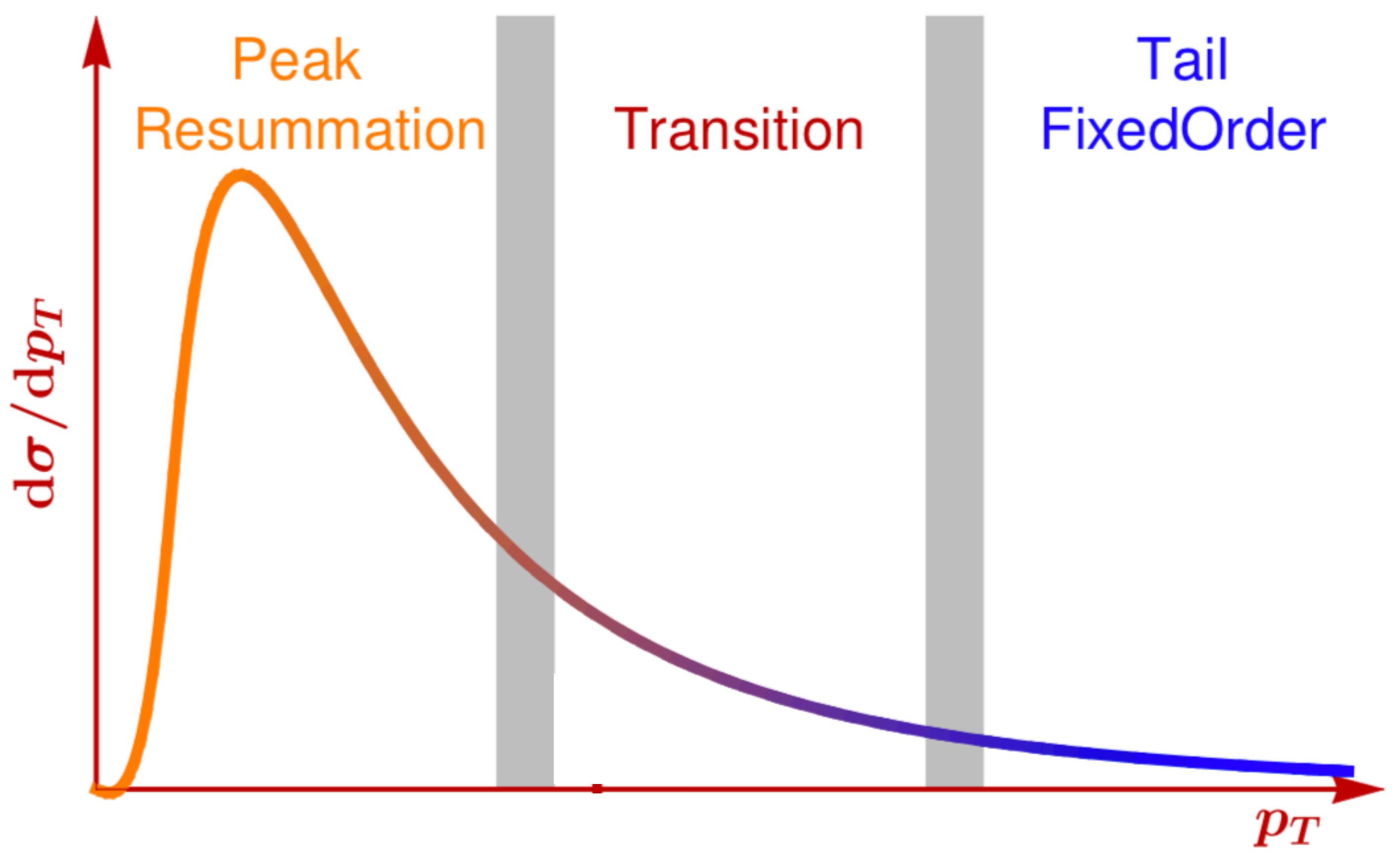




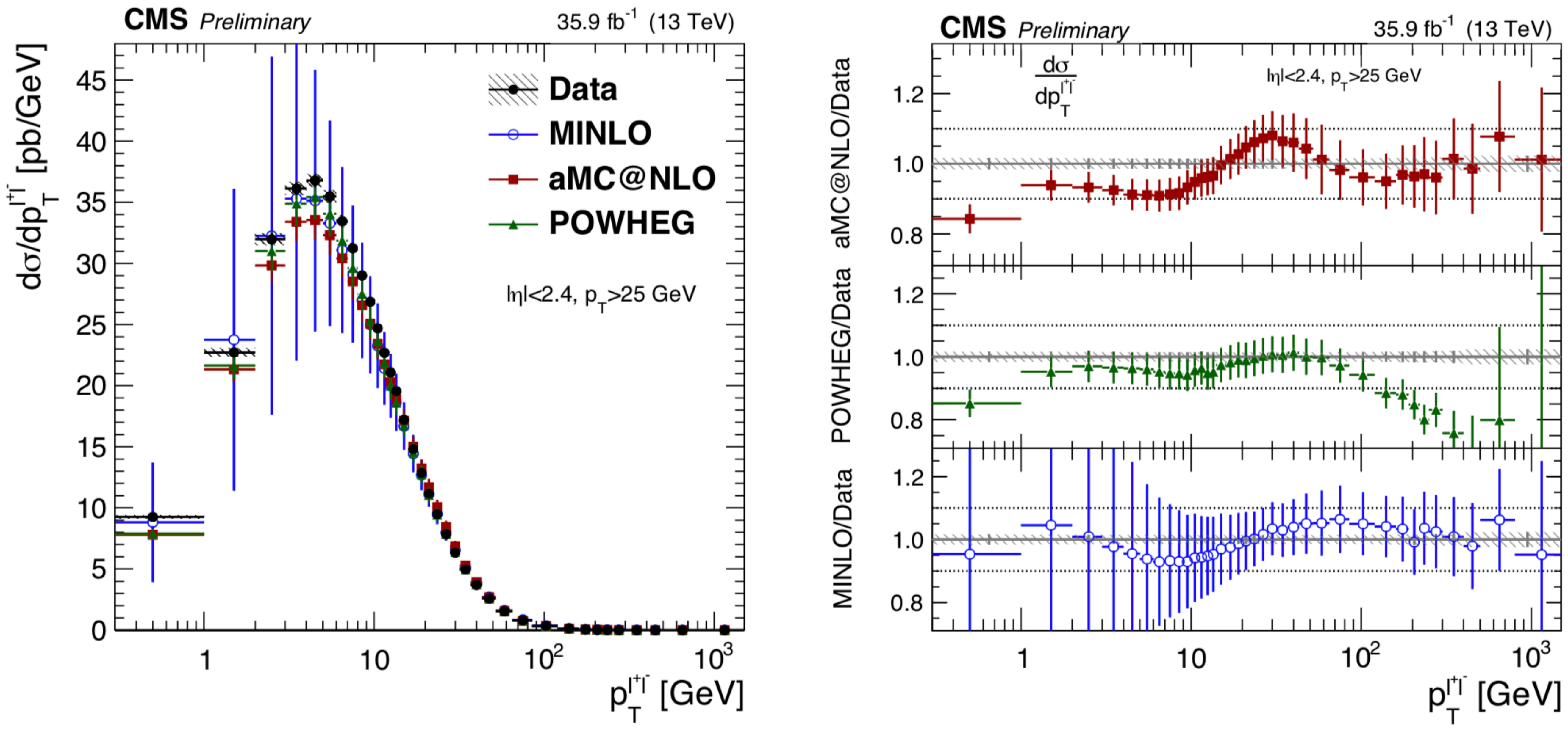
Z-BOSON TRANSVERSE MOMENTUM

SMP-17-010
arXiv:1512.02192
arXiv:1607.06495

- W and Z have non-zero pT due to the intrinsic trans. momentum of the initial state partons + initial-state radiation of gluons and quarks.
  - Measurements of pT distributions of the W and Z bosons probe various aspects of the strong interaction.
  - A key ingredient for a precise m_W measurement
- Measurement of the $p_T Z$ possible with high precision due to to well measured leptons in the final states.
- ATLAS, CMS and LHCb measure φ^* distribution (angular variable, higher precisions).
- Z-boson peak, |y|<2.4, uncertainty dominated by the lepton reconstruction (not counting luminosity).
- .The measurement is compared to predictions using parton shower modeling (MADGRAPH5 AMC@NLO, POWHE.,POWHEG + MiNLO) as well as resumed prediction Resbos and Geneva



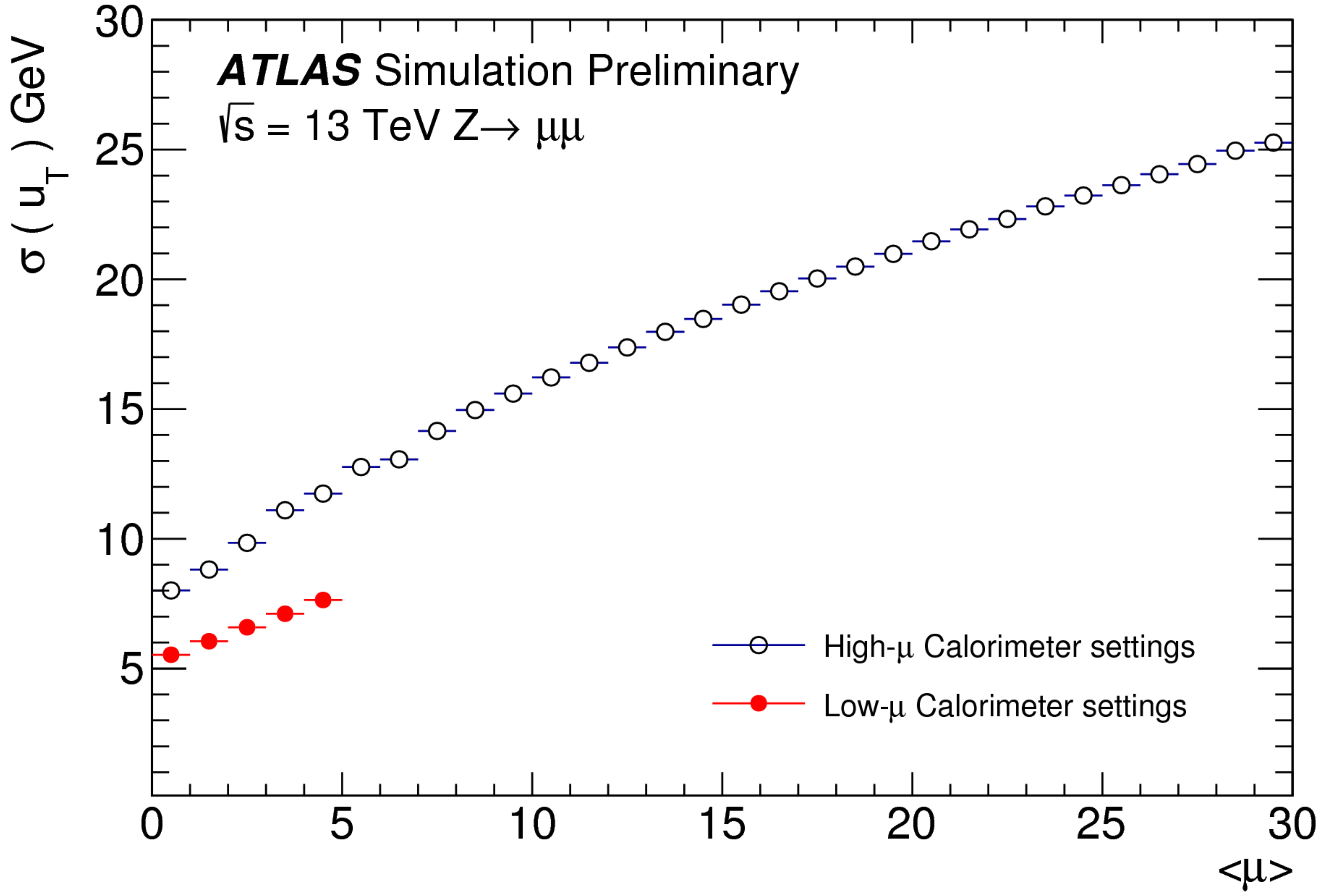
- Low p_T(W,Z) can be described using soft-gluon resummation + non-perturbative contribution from the parton intrinsic k_T.
- High pT spectrum described by fixed-order perturbative QCD.
- Parton-shower models used to compensate for missing higher-order corrections in the fixed-order QCD.

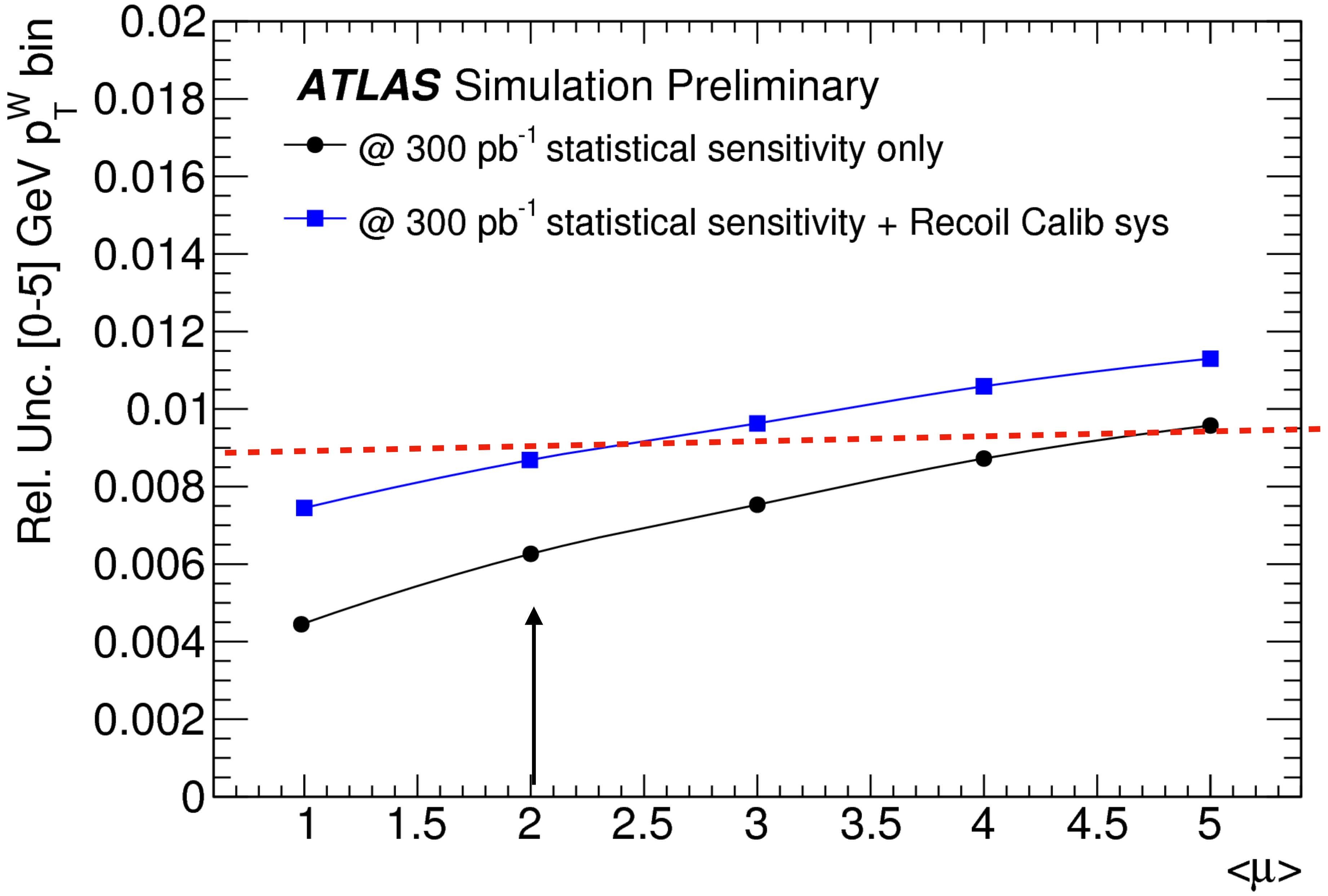


W-BOSON TRANSVERSE MOMENTUM

ATL-PHYS-PUB-2017-021

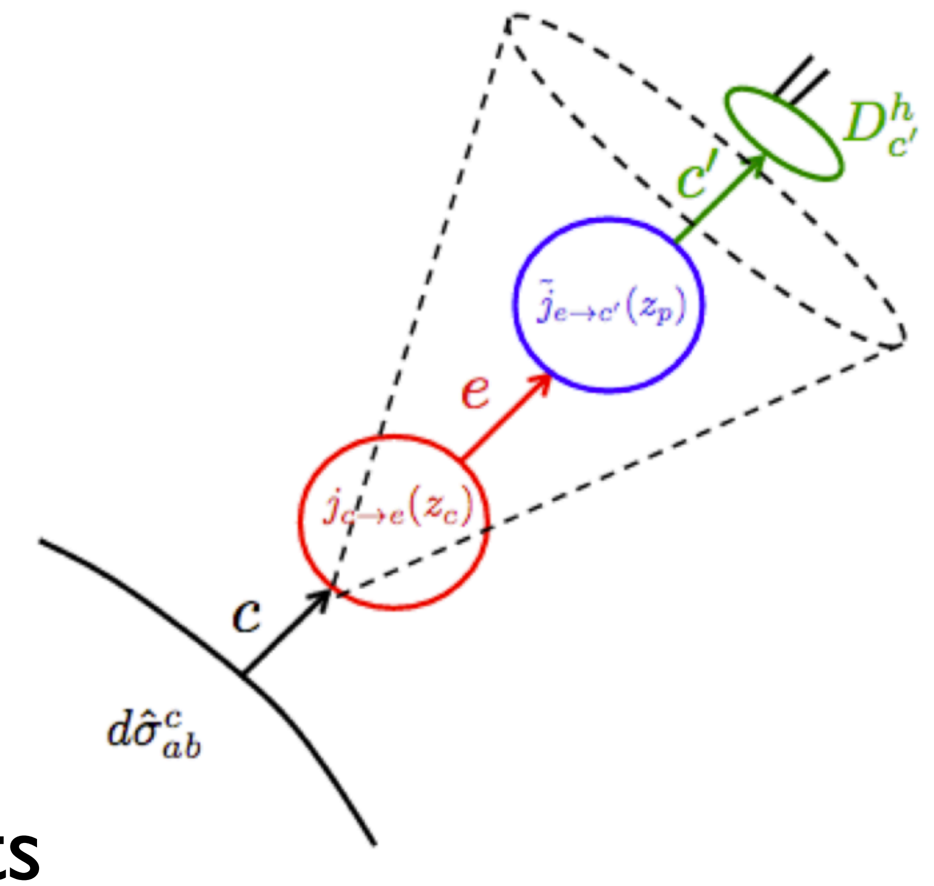
- $p_T W$ measurement is harder then $p_T Z$ due to neutrino escaping reconstruction.
  - Resolution of the hadronic recoil is much worse compared to the lepton momentum
- Plan to directly measure pTW in data in events with low $<\mu>$ data
- Target 1% precision in 5GeV-bins of pTW at low pT → x0.5 QCD modelling syst for W mass
- Requires $\sigma(uT) \lesssim 5$GeV to control bin-by-bin migration systematics
- Expected to be achieved with low μ data, lower calorimeter thresholds and new improved particle-flow algorithm
- Promising results from N3LL+NNLO predictions although still far from 1% precision





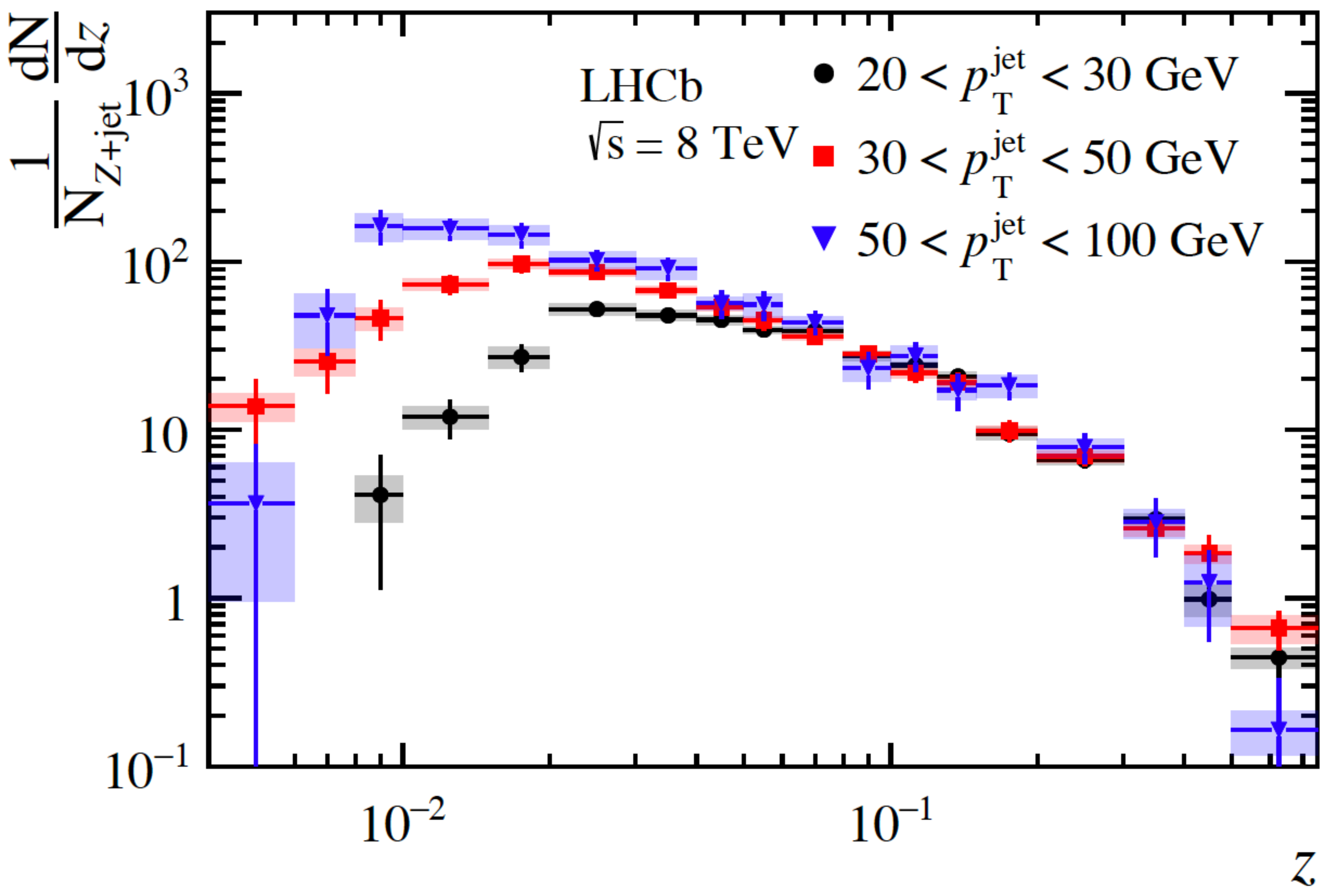
CHARGE HADRON PRODUCTION IN Z-TAGGED EVENTS

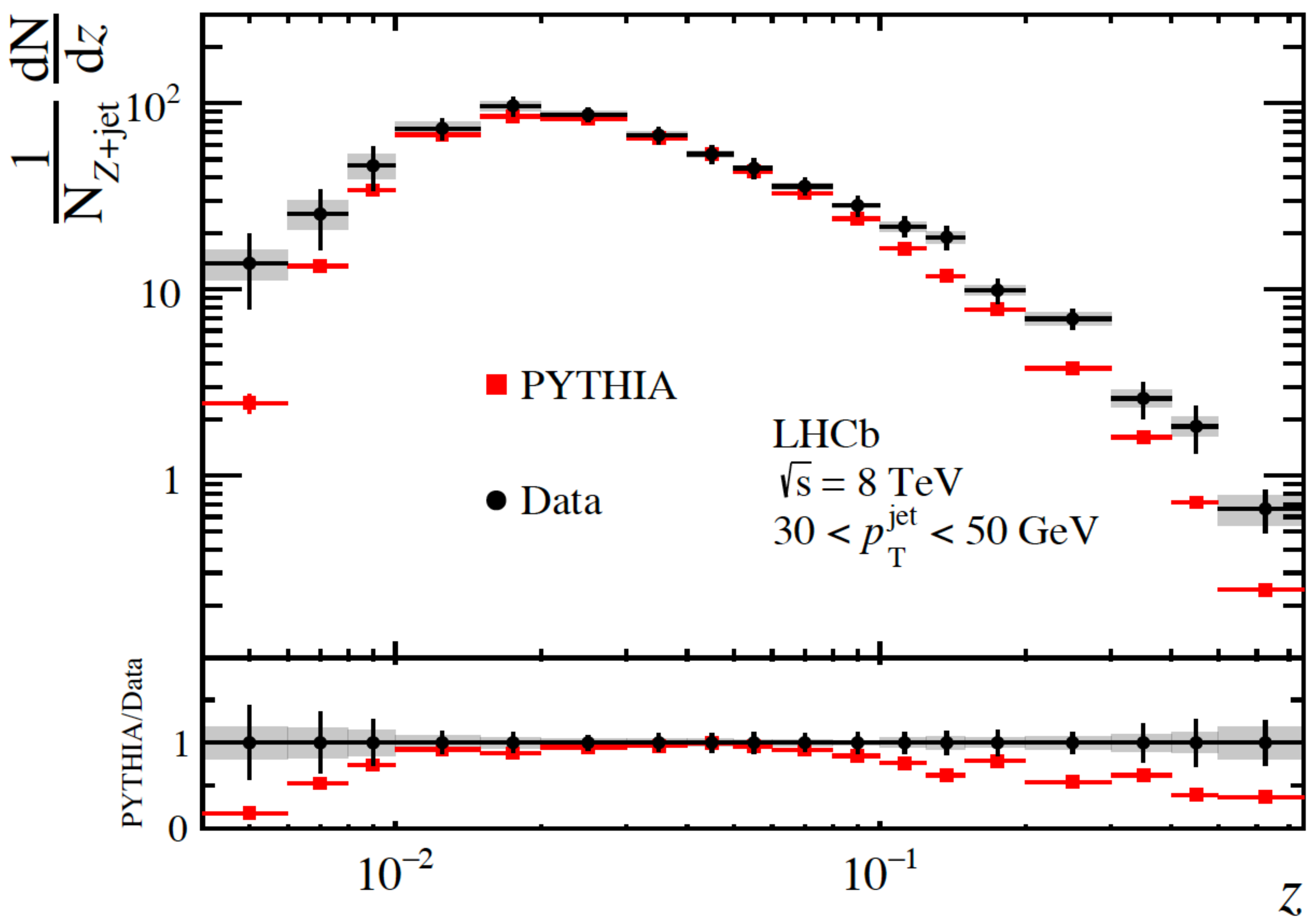
arXiv:1904.08878



- LHCb 8 TeV measurement of charged hadrons production within jets recoiling against a Z
- First measurements of jet hadronization at forward rapidities and also the first where the jet is produced in association with a Z boson.
- Predominantly light-quark jets (in other LHC measurements dominant gluon jet production)
  - The result can provide valuable information on differences between quarks and gluons regarding nonperturbative hadronization dynamics.
- The charged-hadron structure of the jet is studied longitudinally and transverse to the jet axis for jets with transverse momentum $p_T > 20$ GeV and the pseudorapidity range $2.5 < \eta < 4$.
- Unfolded distributions of the longitudinal and transverse hadron momentum fractions in jet pT bins
- Results compared to Pythia: underestimates the number of high momentum hadrons within these jets.

$$z \equiv \frac{\mathbf{p}_{\rm jet} \cdot \mathbf{p}_{\rm hadron}}{|\mathbf{p}_{\rm jet}|^2},$$



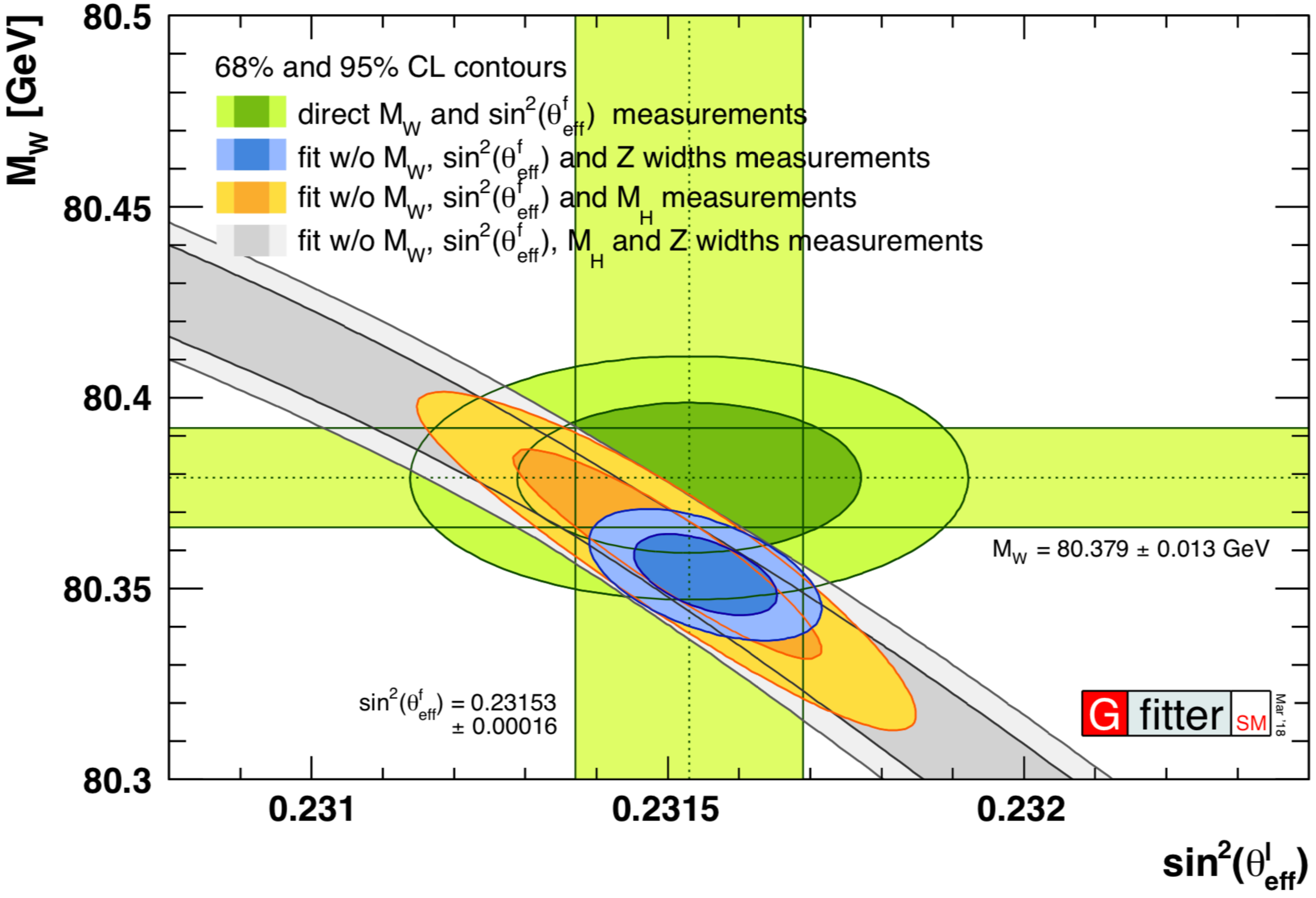


CONSISTENCY TESTS OF THE SM ELECTROWEAK SECTOR

- Tests of the consistency of the SM through higher precision measurements of its fundamental parameters (**W-boson mass**, m_W and **effective leptonic weak mixing angle** $\sin^2\vartheta^\ell_{eff}$). This requires specific efforts in both the experimental and the theory community
- Precision DY measurements require
  - Ultimate performance of detector for electrons and muons (including high |yll| events to enhance sensitivity to $\sin^2\vartheta^\ell_{eff}$), as well as hadronic recoil,
  - Measure directly $p_T W$ with low-pileup data
  - Improve theoretical predictions and unc. of $p_T W/p_T Z$
  - Validate use of improved Born approximation at the LHC
  - Finally, constraining PDFs

Gfitter 2018

Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line	w/o exp. input in line, no theo. unc
M_H [GeV]	125.1 ± 0.2	yes	$125.1^{+0.2}_{-0.2}$	$100.2^{+24.4}_{-20.6}$	$100.3^{+23.5}_{-19.9}$
M_W [GeV]	80.379 ± 0.013	–	80.363 ± 0.007	80.356 ± 0.008	80.356 ± 0.007
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1879 ± 0.0020	91.1967 ± 0.0099	91.1969 ± 0.0096
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4950 ± 0.0014	2.4945 ± 0.0016	2.4945 ± 0.0016
σ^0_{had} [nb]	41.540 ± 0.037	–	41.483 ± 0.015	41.474 ± 0.016	41.474 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.744 ± 0.017	20.725 ± 0.026	20.724 ± 0.026
$A^{0,\ell}_{FB}$	0.0171 ± 0.0010	–	0.01623 ± 0.0001	0.01622 ± 0.0001	0.01624 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1471 ± 0.0005	0.1471 ± 0.0005	0.1472 ± 0.0004
$\sin^2\theta^\ell_{eff}(Q_{FB})$	0.2324 ± 0.0012	–	0.23151 ± 0.00006	0.23151 ± 0.00006	0.23150 ± 0.00005
$\sin^2\theta^\ell_{eff}$(TEV)	0.2318 ± 0.0003	–	0.23151 ± 0.00006	0.23150 ± 0.00006	0.23150 ± 0.00005

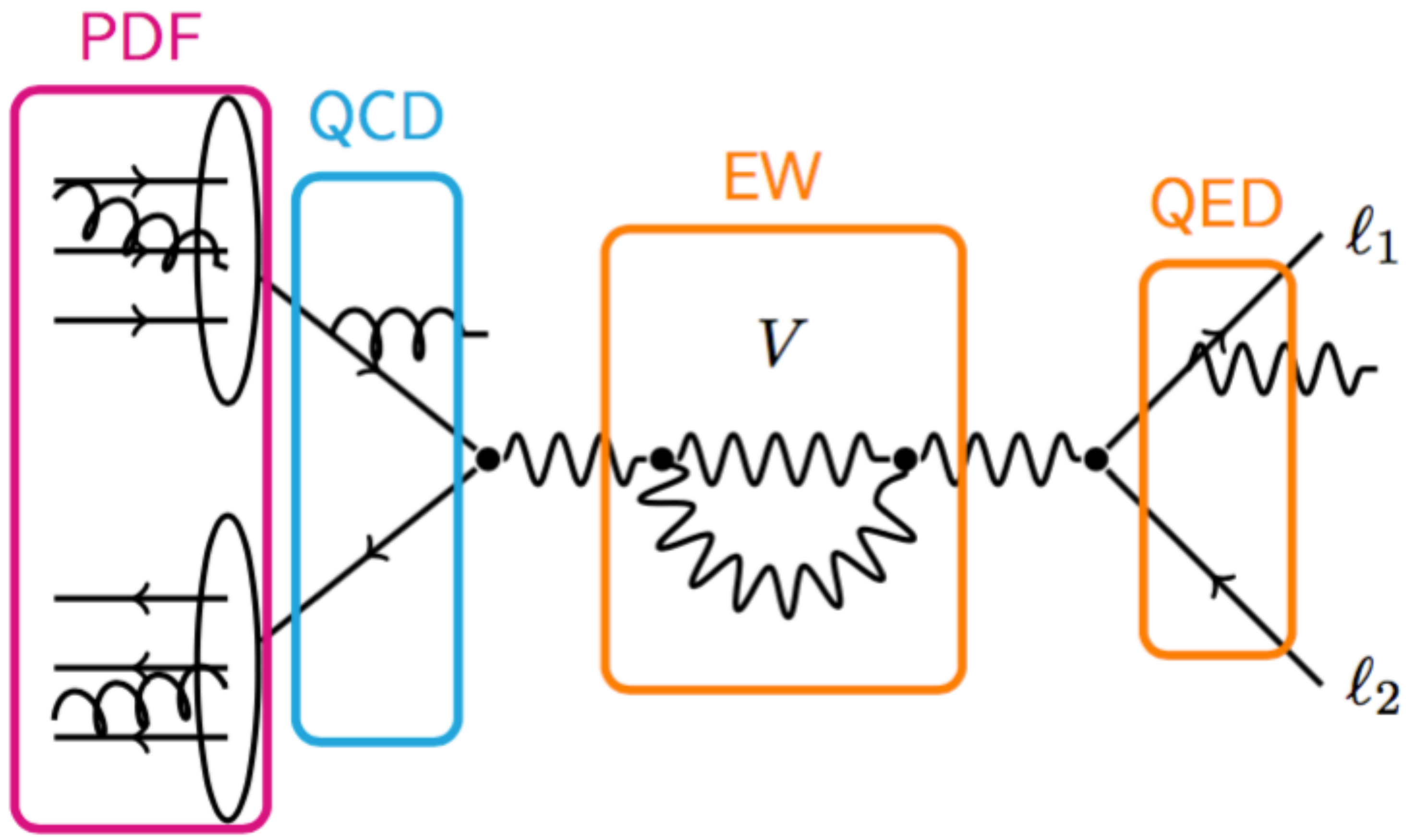


W-BOSON MASS

arXiv:1701.07240

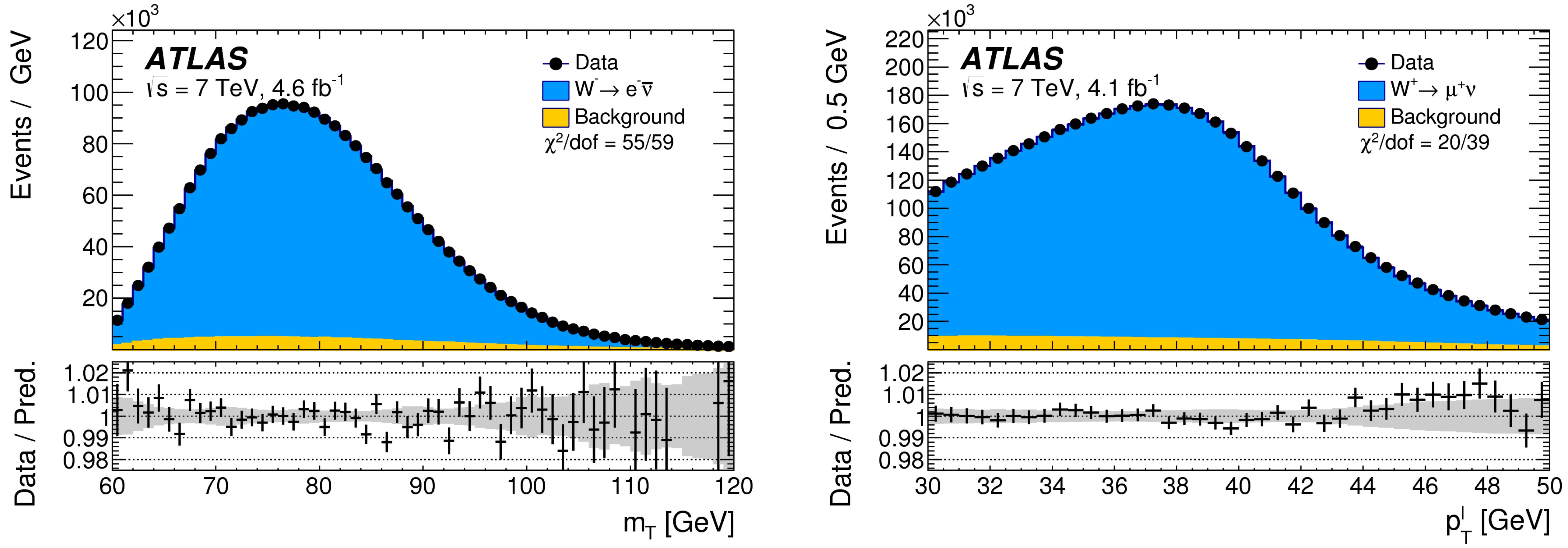
- Measurement performed with 7 TeV (2011 dataset): 7.8M $W^\pm \to \mu\nu$, 5.9M $W^\pm \to e\nu$
- Fits to the lepton pT and transverse mass (MET has very poor resolution), templates built with Powheg +Pythia 8 reweighed to the best model
- $\delta_{theory} > \delta_{experimental} > \delta_{stat}$

  (cf. Tevatron: $\delta_{theory} \sim \delta_{experimental} \sim \delta_{stat}$)

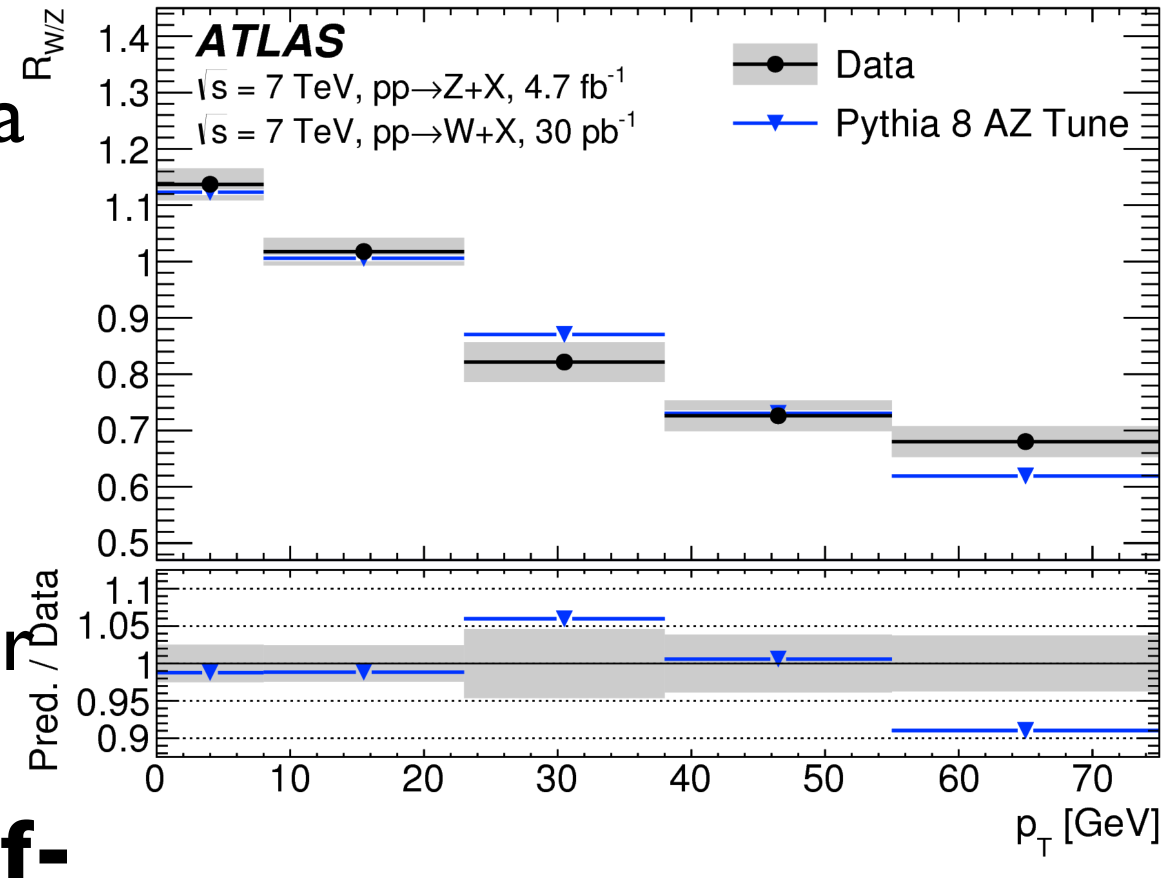


$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

BW parametrisation (Z boson running α_{EM}) | Pythia 8 Parton Shower | Perturbative QCD fixed order predictions (NNLO)



- Primary approach is to use the well-measured Z p_T and extrapolate to W p_T :uncertainties are on possible differences between W and Z : **$R_{W/Z}$ (p_T)**
- The optimal values QCD parameters in Pythia 8 from the ATLAS $p_T Z$ 7 TeV measurement
- W boson p_T cannot rely on the fixed-order perturbative QCD - large logs need to be resummed for low p_T region
  - Non-perturbative effects: Parton Shower or by analytical resummation
- **Predictions based on several state-of-the-art-programs (DYRES, RESBOS, Powheg MinLo) predicted harder value of R (wrt data)**

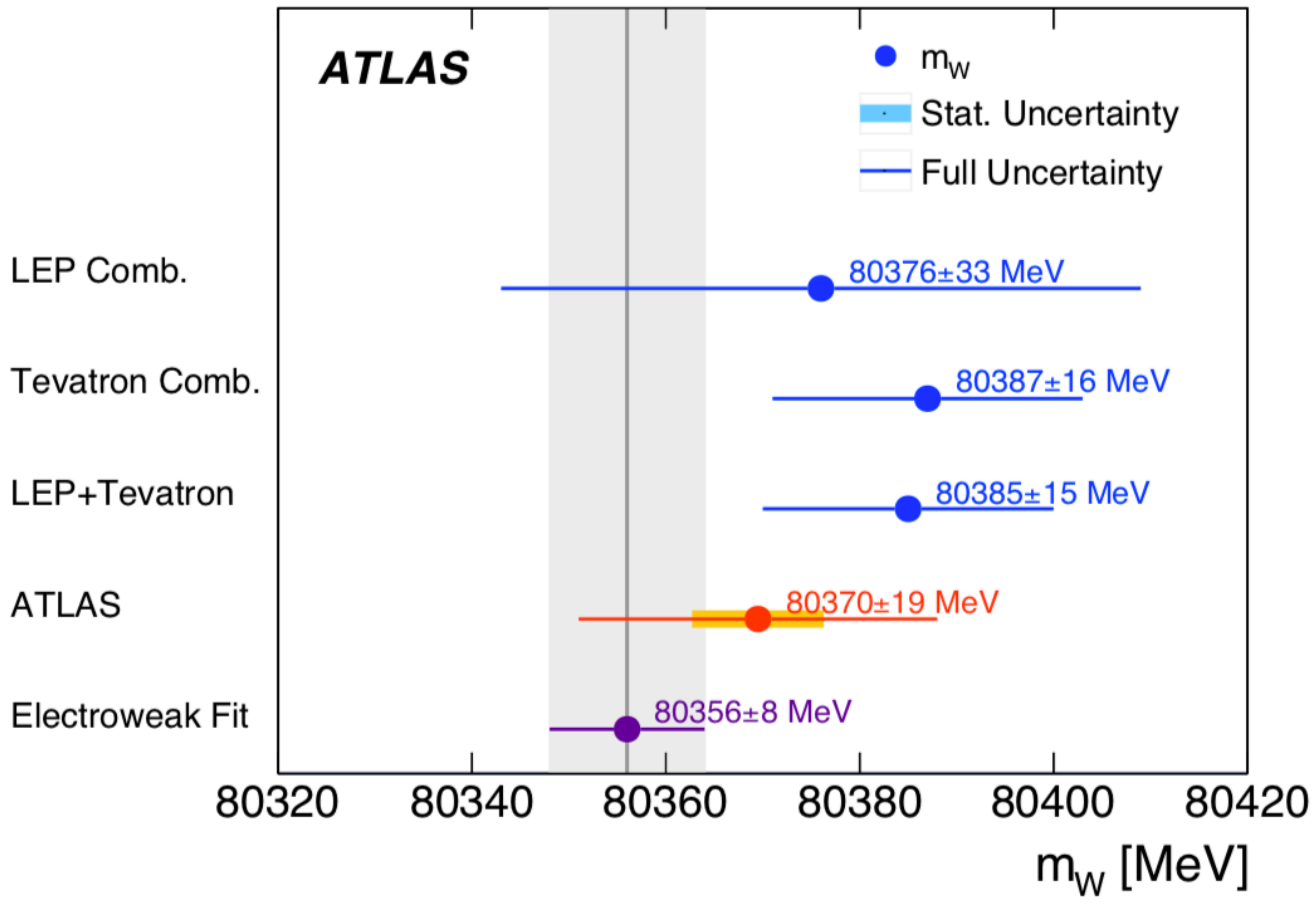


W-BOSON MASS

arXiv:1701.07240

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
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

- **PDFs**
  - impact on boson rapidity, *Ai* and on p_T^W; unc. estimated with Hessian method.
  - The envelope from MMHT2014 and CT14 NNLO PDFs
  - HO correction to *y* by varying μ_R and μ_F ⇒ much smaller wrt PDF unc. negligible.
- **Parton Shower uncertainty**
  - Experimental uncertainty of the AZ tunes
  - Heavy quark masses
  - HO corrections in PS estimated through the μ_F variation in QCD ISR
    - Decorrelation between light *W/Z* (correlated), heavy quark *Z* and heavy quark *W* prod.
  - PDF uncertainty comparing different PDFs
- **Angular coefficients uncertainties**
  - Experimental uncertainty of the *Ai* measured with $Z \to \ell\ell$ at 8 TeV
- **Electroweak corrections**
  - Pair production, pure weak and IFI interference, subleading

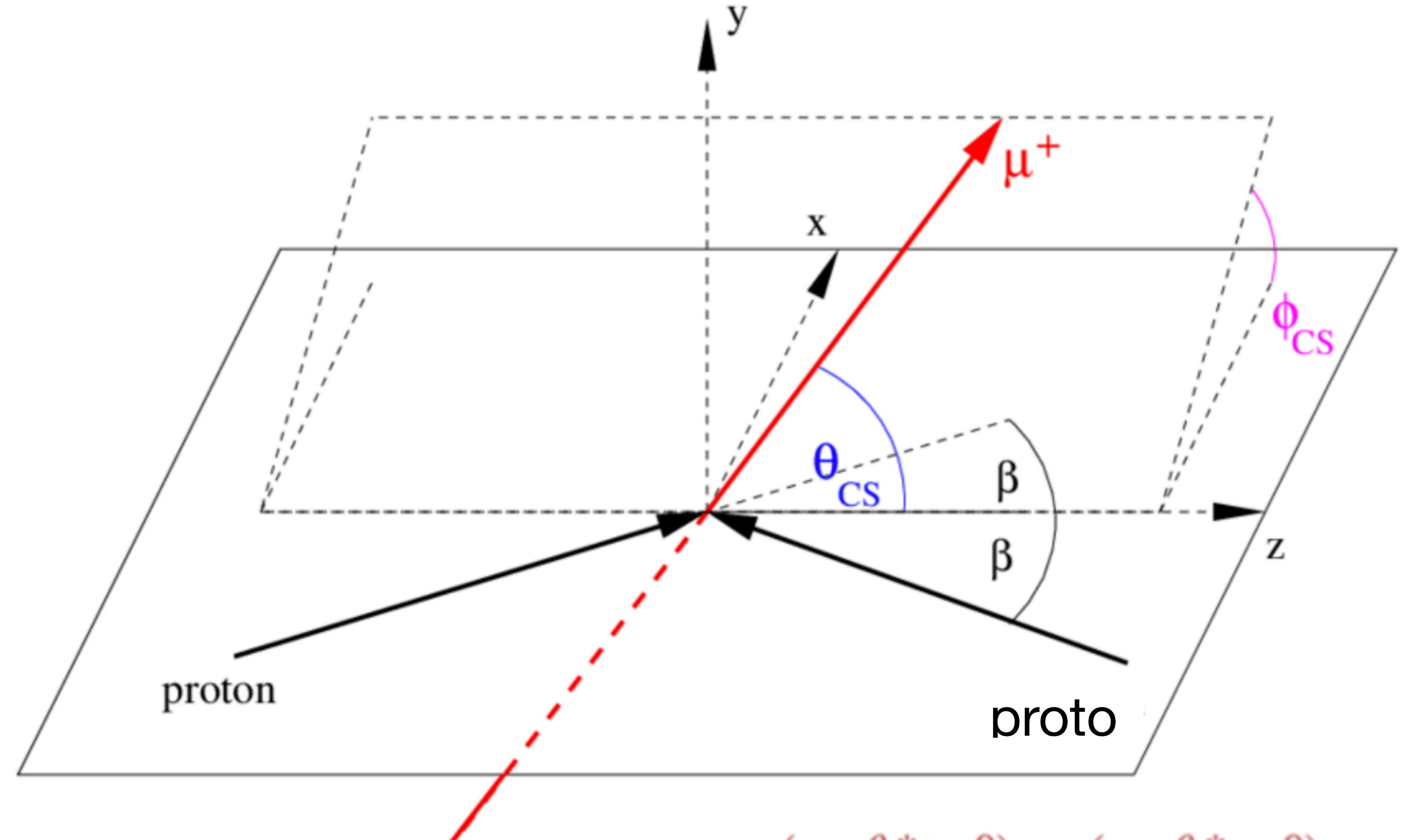


WEAK MIXING ANGLE -CMS

- effective leptonic WMA

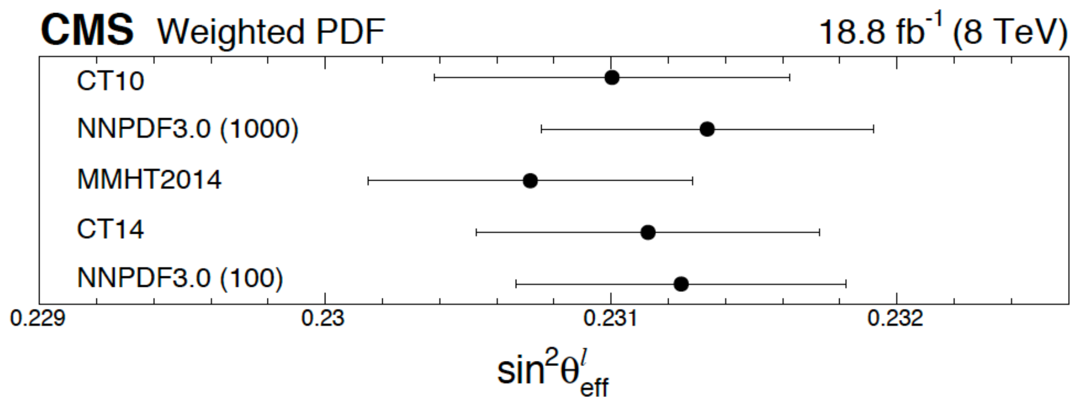
arxiv:1806.00863

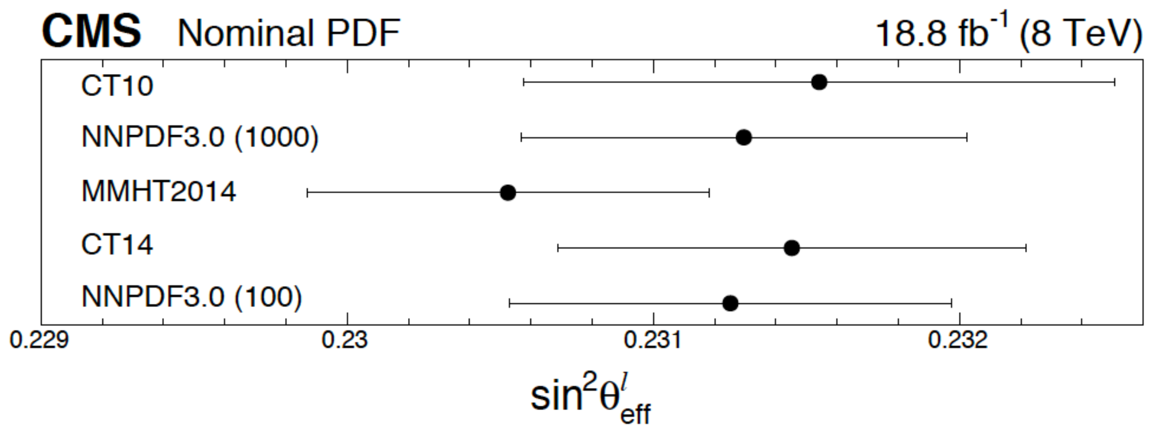
ATLAS-CONF-2018-037

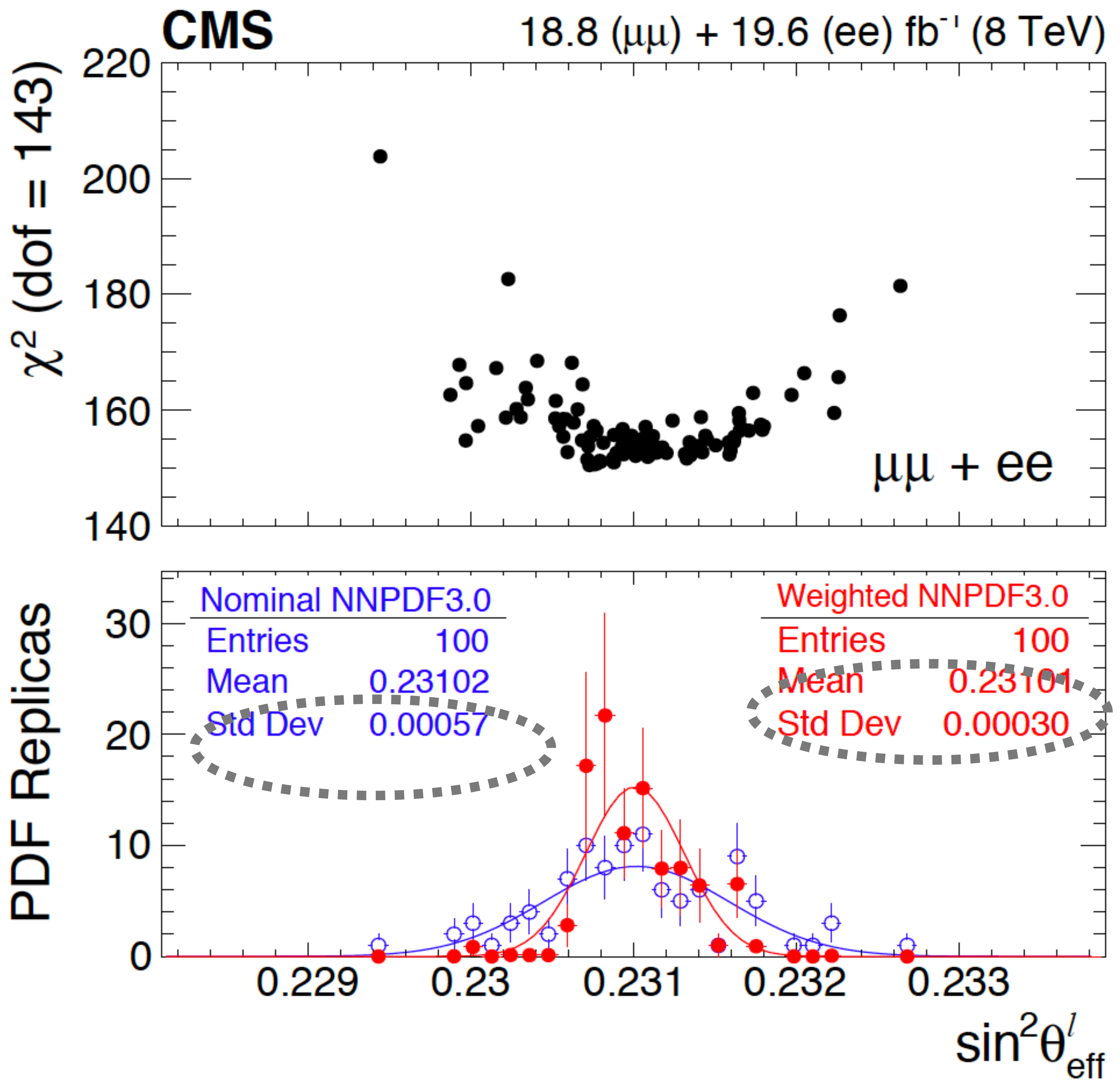


$$A_{FB} = \frac{\sigma(\cos\theta^* > 0) - \sigma(\cos\theta^* < 0)}{\sigma(\cos\theta^* > 0) + \sigma(\cos\theta^* < 0)}$$

- Measured via asymmetry in lepton angular distributions in Z decays induced by the V-A coupling structure of Z bosons to fermions.
- Most-precise measurement from LEP+SLD combination (**16×10^{-5}**), **~3σ discrepancy**
- Recently, legacy Tevatron combination result published followed by the CMS and ATLAS
  - CMS and Tevatron results based on fiducial AFB measurements asymmetry in Collin-Soper frame in reconstructed mll,yll bins
- CMS measurement, $\sqrt{s}$ = 8 TeV, ~20fb-1, $\mu^+\mu^-$ + e^+e^-, |yll| < 2.4
- $\sin^2\vartheta^{\ell}_{eff}$ extracted from template fit to AFB
  - templates built from Powheg MC and NNPDF3.0
  - Measurement performed in 12 m_{ll} x 6 yll bins
- Experimental systematics dominated by statistics, including limited MC (similar in ATLAS)
- PDF uncertainty constrained by Bayesian χ^2 reweighting
- PDFs represented by Hessian eigenvectors using CT10 CT14, and MMHT2014 also studied.







$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23101 \pm 0.00036\,(\text{stat}) \pm 0.00018\,(\text{syst}) \pm 0.00016\,(\text{theo}) \pm 0.00031\,(\text{PDF})$$

WEAK MIXING ANGLE - ATLAS

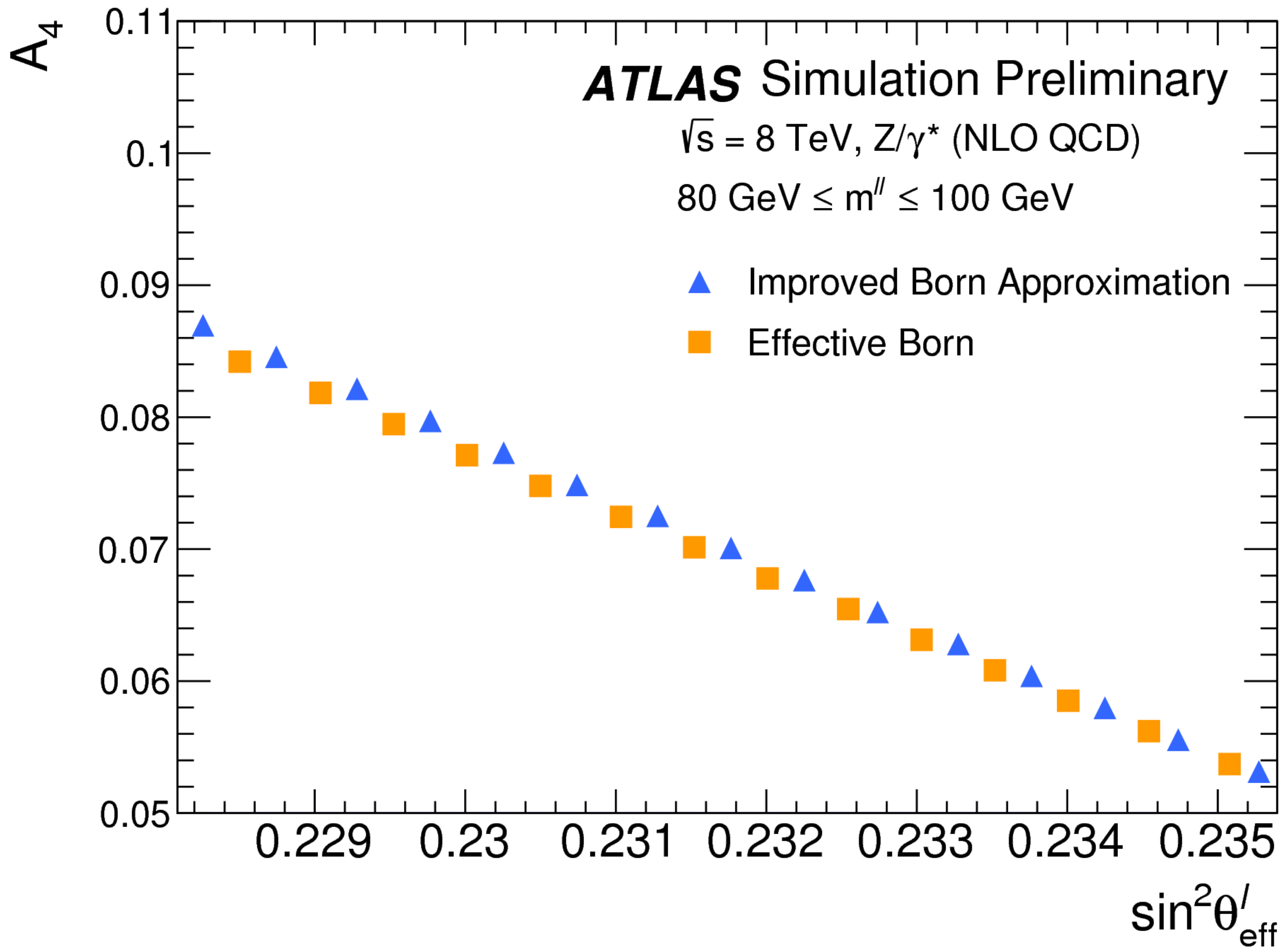
- effective leptonic WMA

arxiv:1806.00863
ATLAS-CONF-2018-037

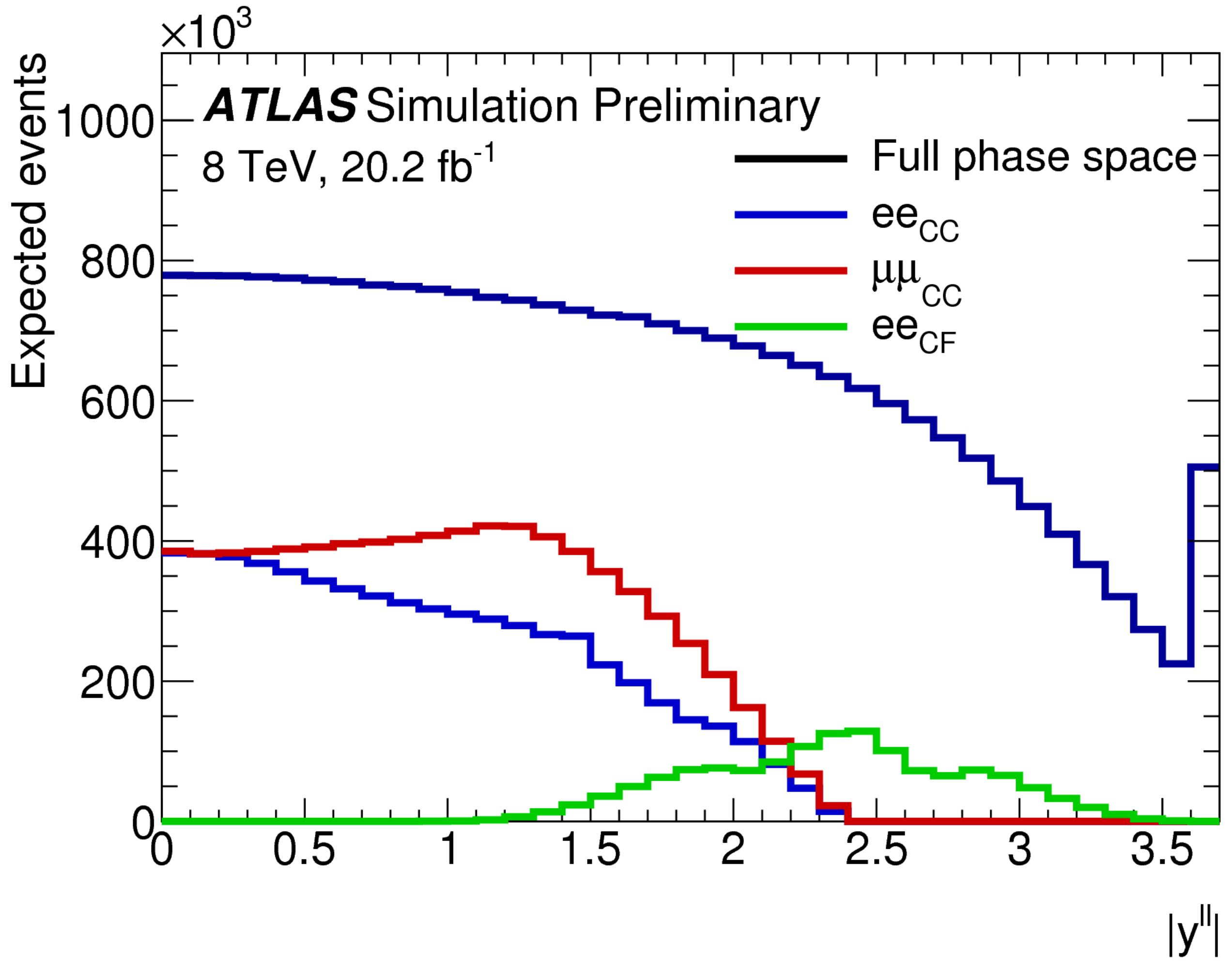
- ATLAS measurement based on methodology of angular coefficients $A_i(m_{ll}, p_T^{ll}, y_{ll})$

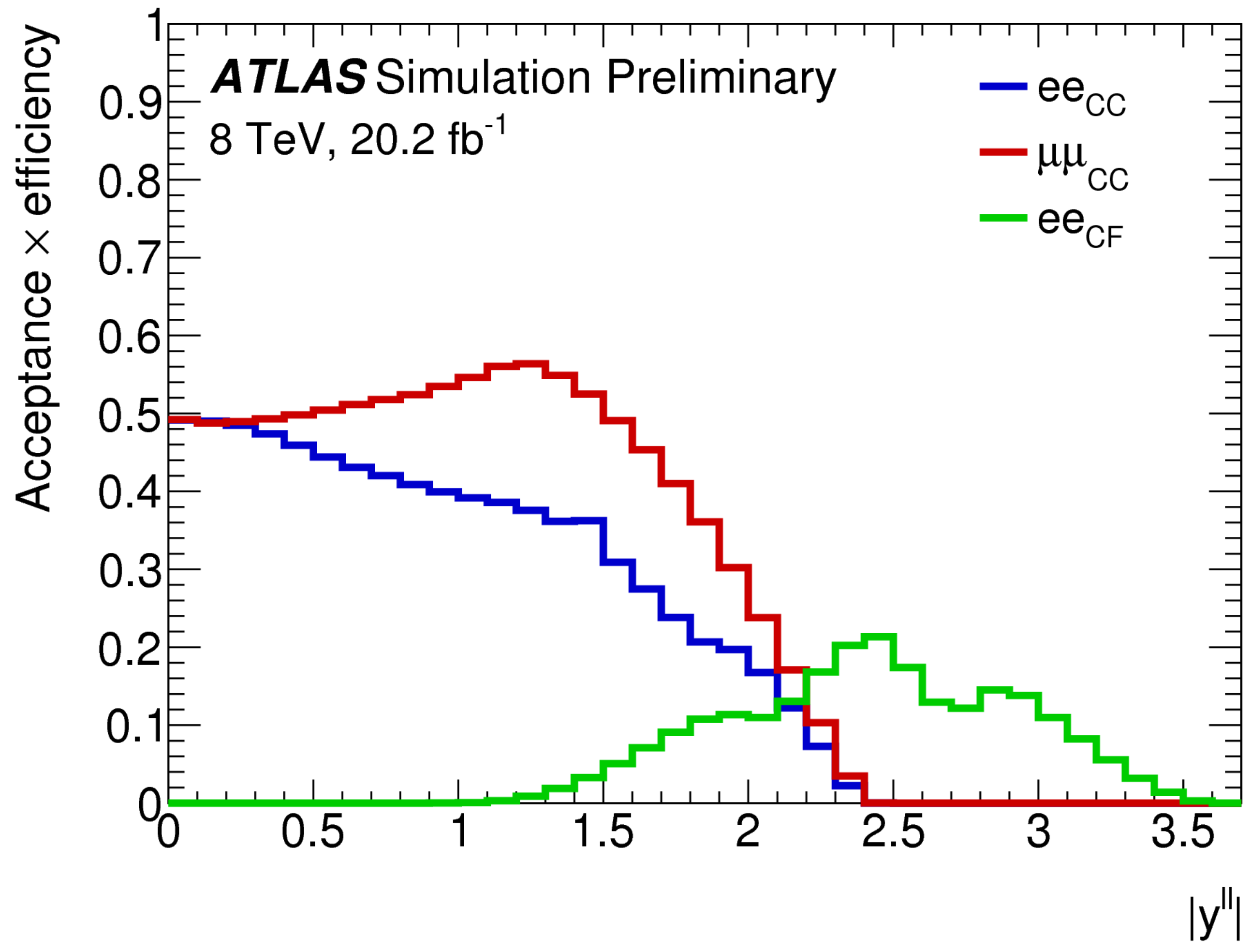
$$\frac{d\sigma}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}} \Big\{(1+\cos^2\theta) + \frac{1}{2} A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi\Big\}.$$

- pp→Z→ll cross section in full lepton phase space determined by 5 variables that separate Z production from decay kinematics
- Angular coefficients encapsulate all QCD production dynamics
- AFB = 3/8 A4 in full phase space of decay leptons at all orders in QCD
  - Direct measurement of angular coefficients A4 and A3 leads to measurement of $\sin^2\vartheta^{\ell}_{eff}$
- Based on effective linear relation: ***A4 = a x*** $\boldsymbol{\sin^2\vartheta^{\ell}_{eff}}$ ***+ b*** predicted in each measurement bin (A3 sensitive only at high p_TZ, not used here)
- Technically more challenging than AFB, but some advantages
  - Angular variables can constrain experimental systematics
  - Measurements in full phase space via analytical extrapolation reduced theory uncertainties
- Possibly more sensitive to NLO EW effects that can break harmonic decomposition compared to AFB (corrected for)

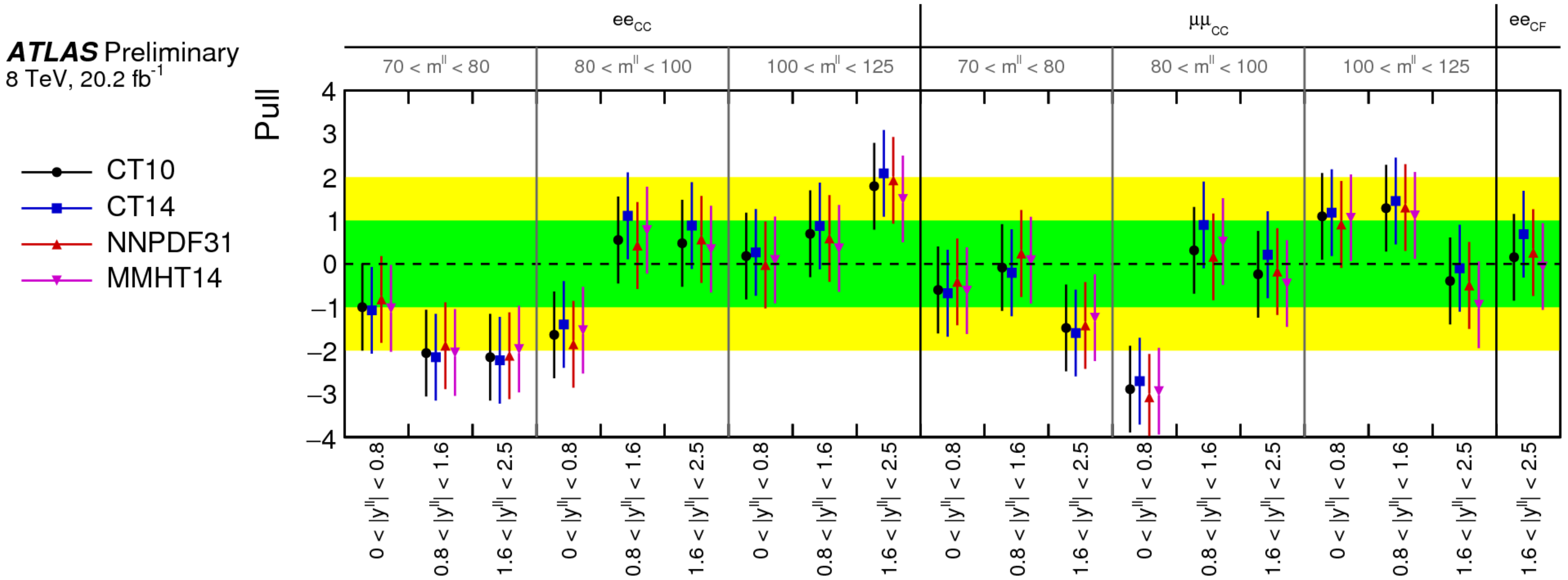


WEAK MIXING ANGLE: ATLAS ANALYSIS





- Results based on 8 TeV dataset, 3 analysis channels
  - 6M eeCC events (0 < |η| < 2.4)
  - 7.5M μμCC events (0 < |η| < 2.4)
  - **1.5M eeCF events (0 < |η| < 2.5 and 2.5 < |η| < 4.9)**
- Binned in mll and |yll|
- Background is small even in the eeCF



- Test compatibility of all measurement bins (19 plus one reference one) as individual measurements of $\sin^2\vartheta^{\ell}_{eff}$
- Overall p-value only 3.4% (3σ pull from low |yll| μμCC channel)

WMA: UNCERTAINTIES

arxiv:1806.00863
ATLAS-CONF-2018-037

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC}+\mu\mu_{CC}$	$ee_{CC}+\mu\mu_{CC}+ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
	Uncertainties				
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
	Uncertainties in measurements				
PDF (meas.)	8	9	7	6	4
p_{T}^{Z} modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

- Stat uncertainty on eeCF smaller than combined eeCC+μμCC!
- Dominant syst. uncertainty from PDFs: 24 x10^{-5}
- Next dominant uncertainty from MC stats: 12x10^{-5}

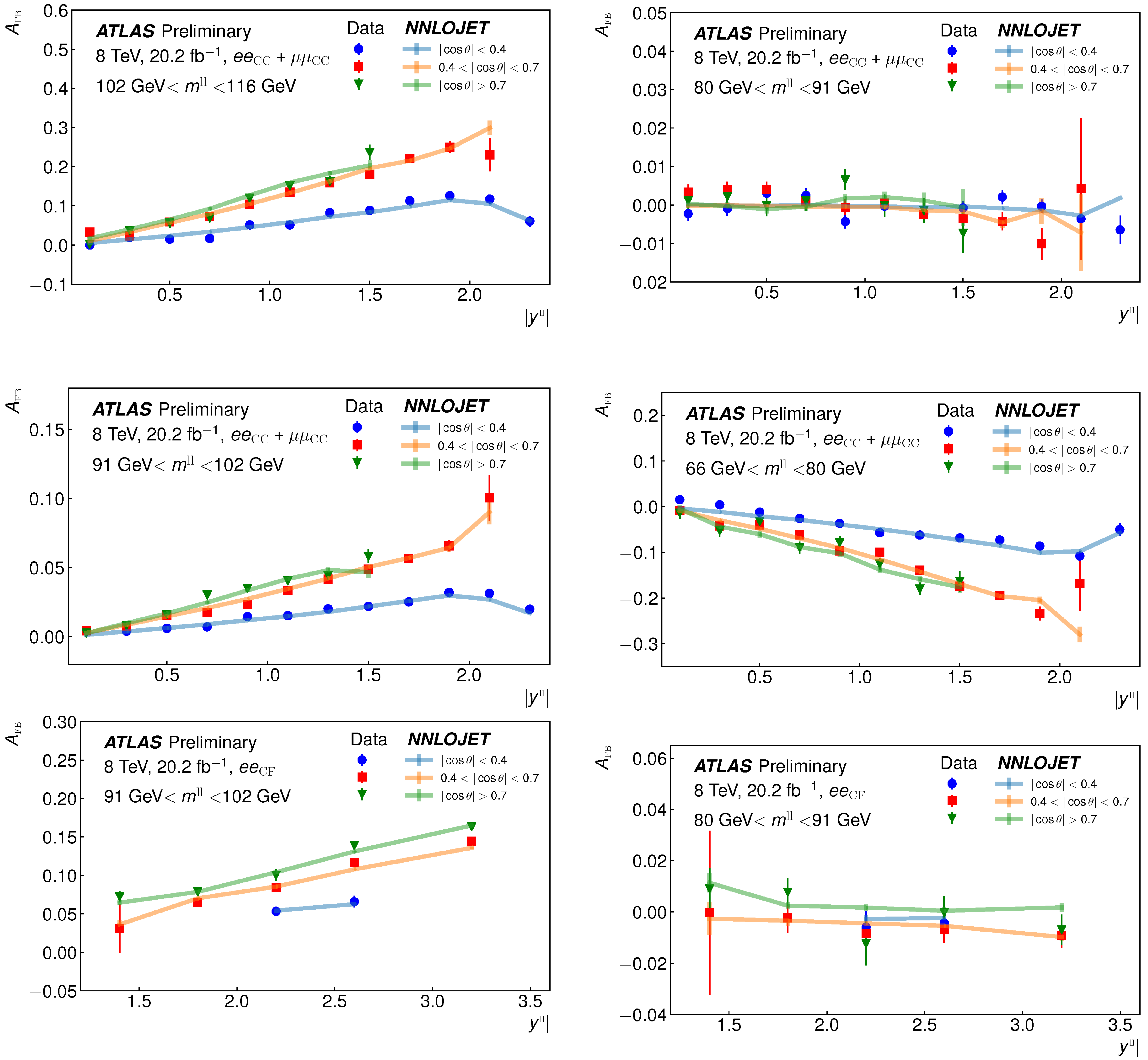
	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^{\ell}_{\rm eff}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

- Fit using MMHT14 provides best overall result, best fit $\chi 2$ and also smallest uncertainties from PDFs after profiling
- Results quite close for CT14 and NNPDF31, uncertainties a bit larger.
- CT10nnlo also shown since it fits best the ensemble of ATLAS W/Z precision data at 7 TeV used for measurement of m_W.
- Overall range of $\sin^2\vartheta^{\ell}_{\rm eff}$ spanned by all PDF sets is 28 x 10^{-5}

WEAK MIXING ANGLE: Z3D

arxiv:1806.00863
ATLAS-CONF-2018-037

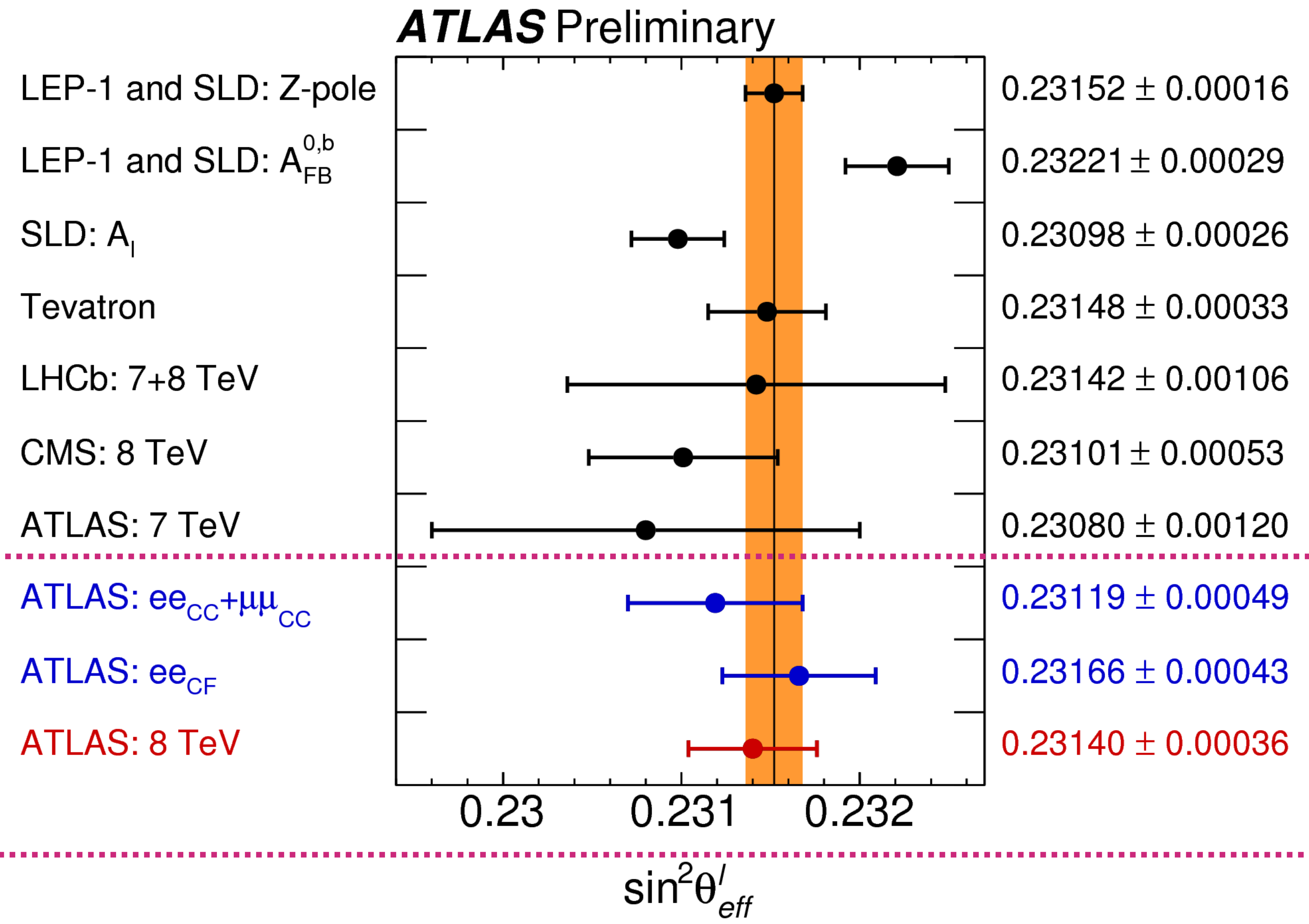
- Unfolded fiducial measurement of the triple-differential Drell-Yan cross section $d^3\sigma/dmdyd\cos\theta^*$, over a wide range of dilepton masses performed by ATLAS (Z3D), **arXiv: 1710.05167**
- Based on these results, a set of differential measurements of the AFB are derived data are compared to NNLO QCD predictions from NNLOJET
- The data and the theory predictions, obtained for $\sin^2\vartheta^{\ell}_{\mathrm{eff}} = 0.23148$, agree well over the whole range of measurements
- The interpretation of these data in terms of $\sin^2\vartheta^{\ell}_{\mathrm{eff}}$ performed using the same tools for the EW form factor corrections as in angular distribution measurement
- $\sin^2\vartheta^{\ell}_{\mathrm{eff}}$ obtained using AFB are found to be in agreement with those obtained using A4.
- Fully quantitative combination of the two approaches, including the use of the cross sections themselves to further constrain the PDFs to come.



WEAK MIXING ANGLE

arxiv:1806.00863
ATLAS-CONF-2018-037

$$\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.23140 \pm 0.0021\,(\mathrm{stat.}) \pm 0.00024\,(\mathrm{PDF}) \pm 0.00016\,(\mathrm{syst.})$$

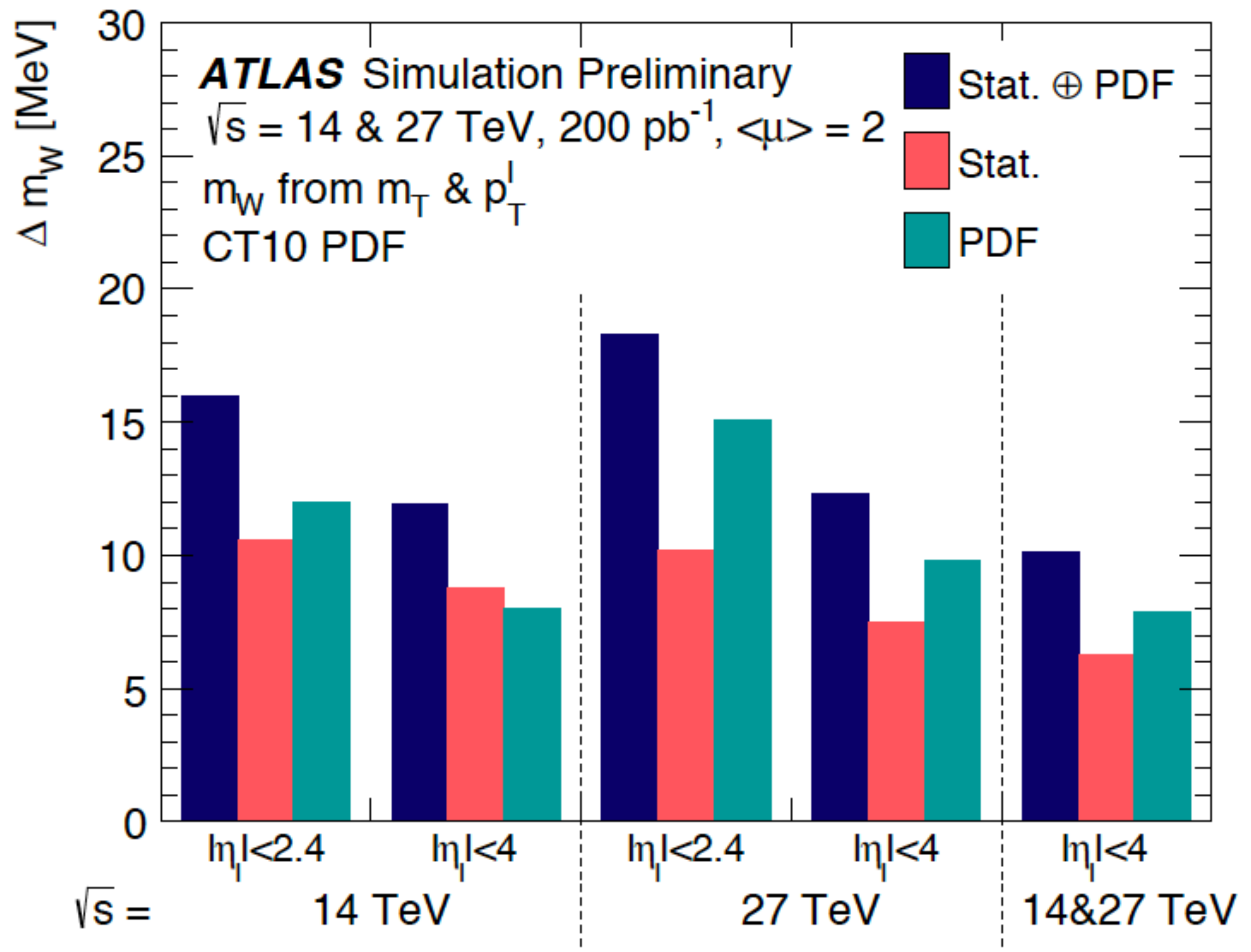


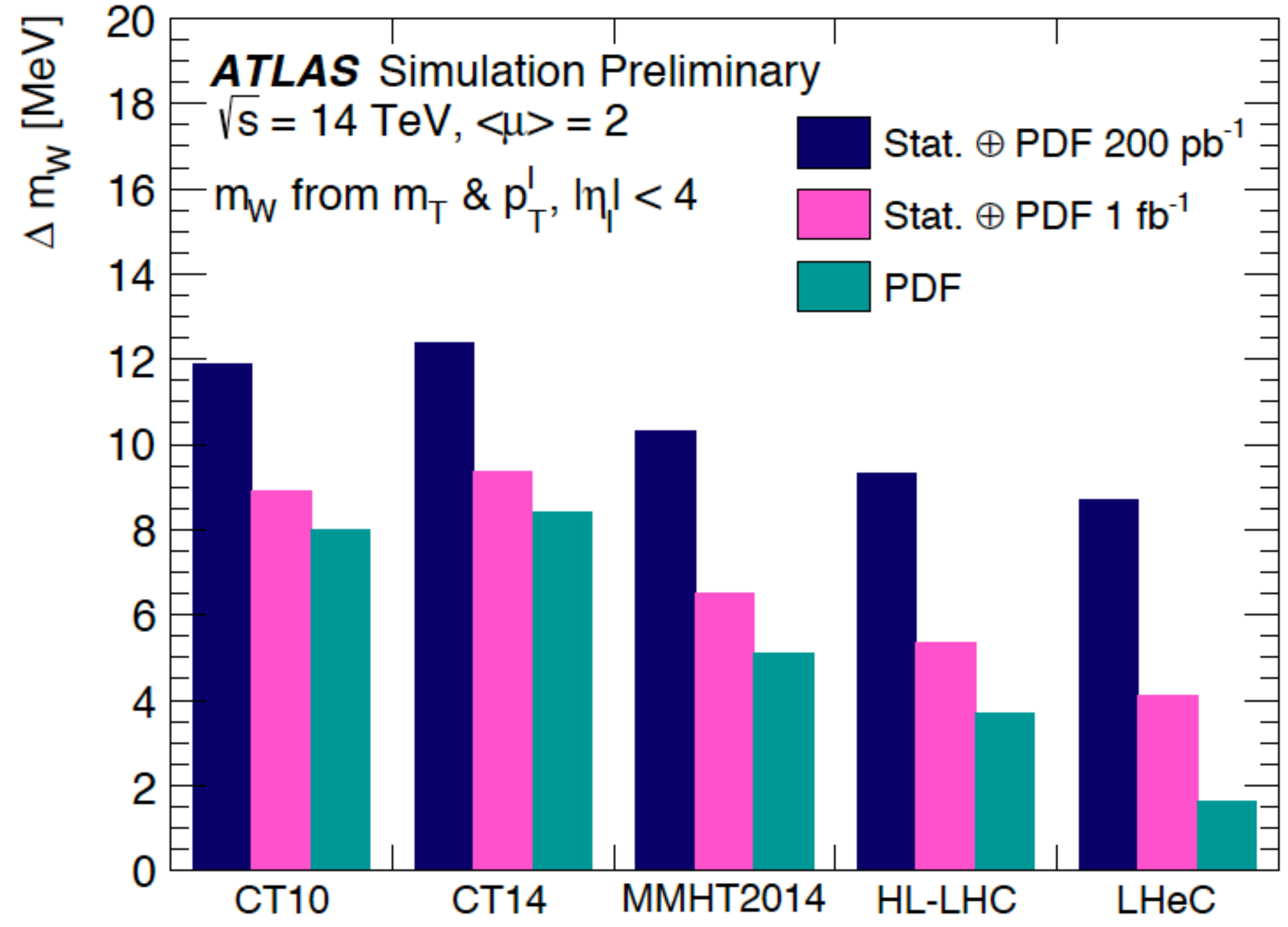
- LHC Run1 measurements dominated by statistical and PDF uncertainties
- Measurement at13/14TeV: higher statistics can more strongly constrain PDFs, stat uncertainty reduced (also in MC!)

HL/HE-LHC : W-BOSON MASS

arXiv:1902.04070
ATL-PHYS-PUB-2018-026

- ATLAS prospects for m_W at **H**igh**L**uminosity-**LHC** ($\sqrt{s}$ = 14 TeV, 3000 fb^{-1}) and **H**igh **E**nergy-**LHC** ($\sqrt{s}$ = 27 TeV, 15 ab^{-1})
- The increased acceptance provided by the new inner detector in ATLAS, (ITk) extends the coverage up to $|\eta| < 4$ and allows further constraints on PDFs from cross section measurements reducing the corresponding uncertainties in m_W.
  - Only electron channel considered
  - Assume low-pile up data (1 week of <μ>~2 => δm_W ~10 MeV stat.)
- Reference with CT10 and reweighed to various different PDFs: CT14, MMHT2014, HL-LHC and LHeC
  - LHeC PDF set represents the impact of a proposed future high-energy, high-luminosity ep scattering experiment





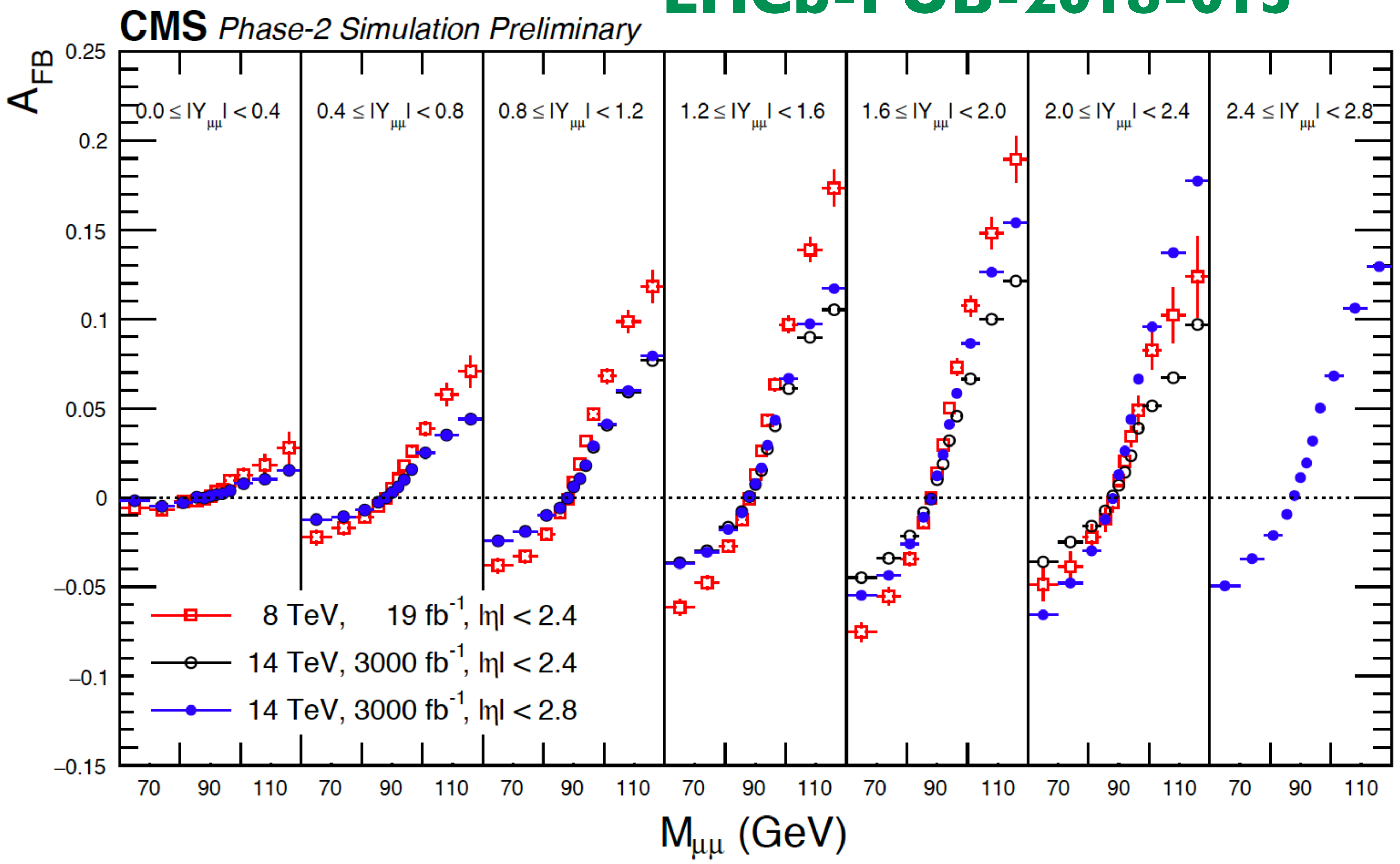
Stat. (200 pb^{-1} of low-mu data) — PDF unc.

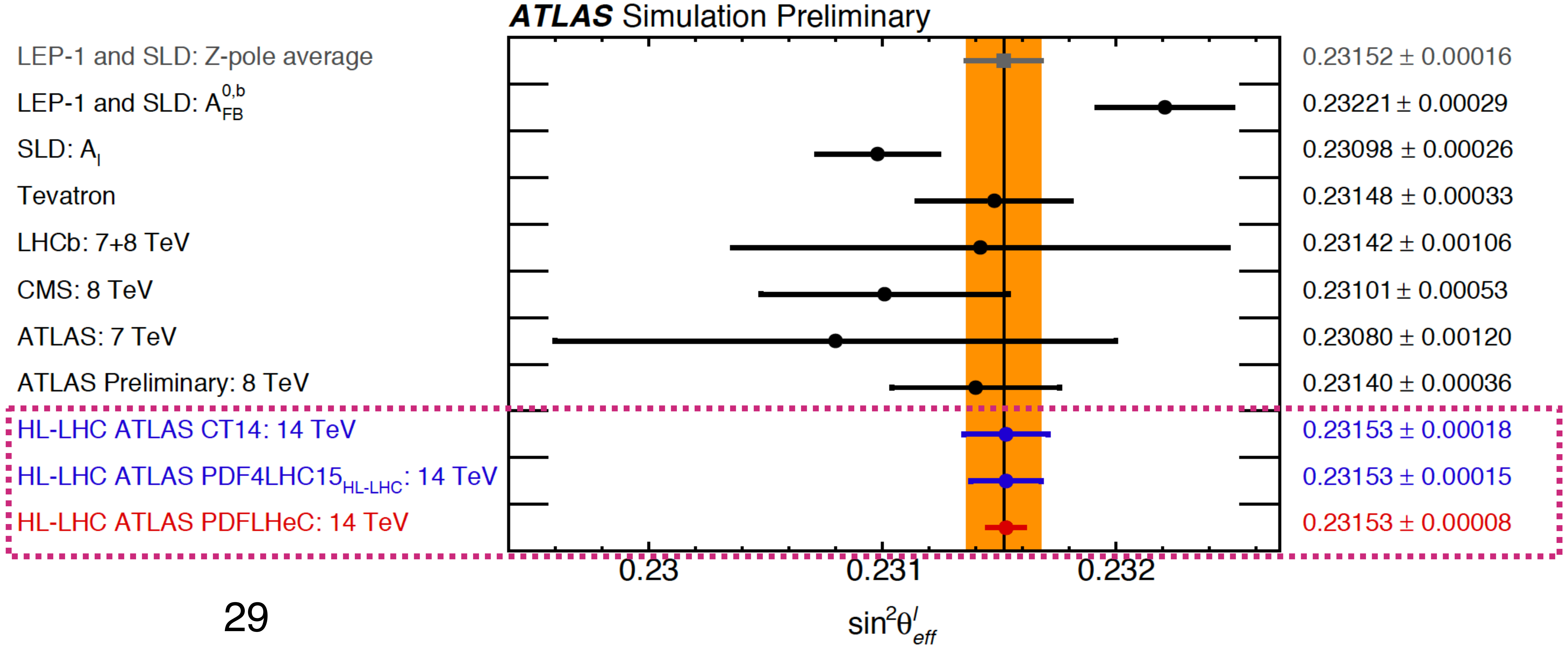
$\sqrt{s}$ [TeV]	Lepton acceptance	Uncertainty in m_W [MeV] HL-LHC	LHeC
14	$\lvert\eta_\ell\rvert < 2.4$	11.5 (10.0 ⊕ 5.8)	10.2 (9.9 ⊕ 2.2)
14	$\lvert\eta_\ell\rvert < 4$	9.3 (8.6 ⊕ 3.7)	8.7 (8.5 ⊕ 1.6)

HL-LHC: WEAK MIXING ANGLE

arXiv:1902.04070
ATL-PHYS-PUB-2018-037
CMS-PAS-FTR-17-001
LHCb-PUB-2018-013

- ATLAS, CMS and LHCb considered prospects for the $\sin^2\vartheta^{\ell}_{eff}$ at HL-LHC
  - $\sqrt{s}$ = 14 TeV, 3000 fb^{-1}, (LHCb 300 fb^{-1})
- $\sin^2\vartheta^{\ell}_{eff}$ extracted from measurements of AFB in dilepton events ($\mu^+\mu^-$ LHCb and CMS, ATLAS e^+e^-)
  - Extended rapidity coverage (ATLAS and CMS), selection of low pT events due to flexible full software trigger and real time analysis scheme (LHCb)
  - Improvement in PDFs:
    - In situ constraint (e.g. ATLAS exploiting CC, CF and FF configurations)
    - Globals fits including ancillary DY measurements at HL-LHC
    - Including expected data from LHeC collider
  - Each of the experiments could reach precision of LEP/SLD
  - Including LHeC data PDF uncertainty reduced by a factor of 5, total uncertainty halved.





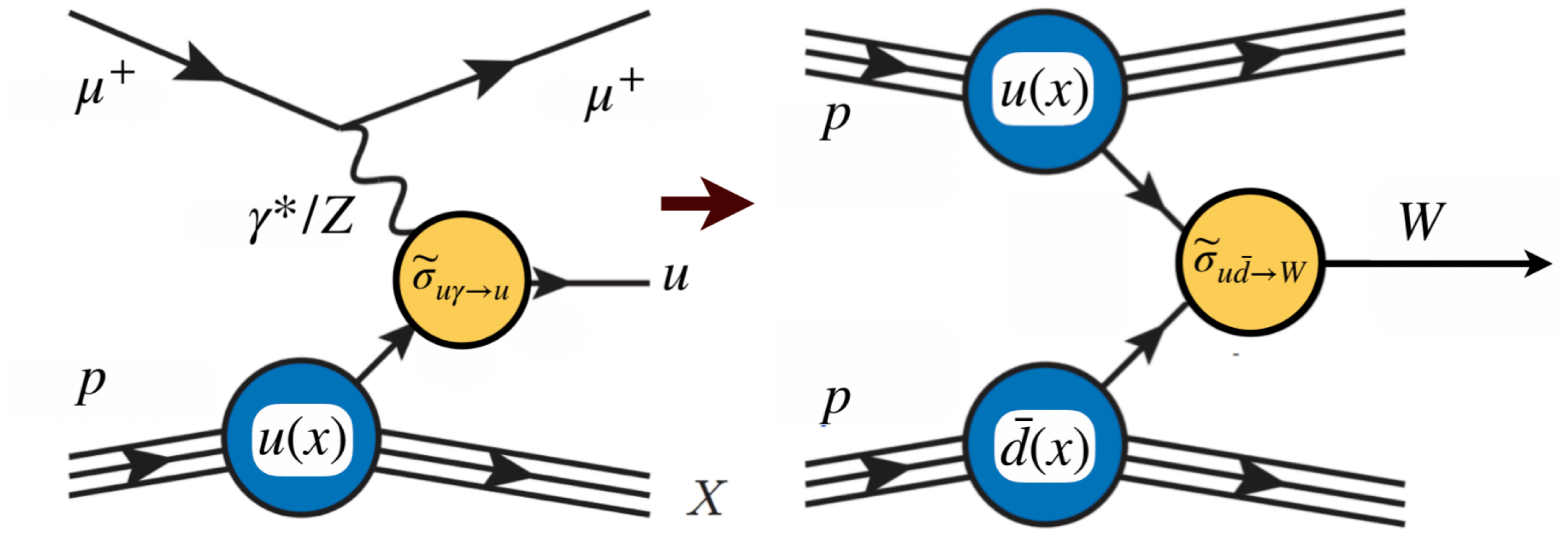
SUMMARY

- DY production is a key stone of the LHC program, crucial for a detailed understanding of LHC data
- Impressive progress over the past few years:
  - Detector performance is subleading uncertainty in cross section measurements
  - Many constrains in the global PDF from LHC data: W,Z cross sections, W asymmetry, W/Z ratios, W,Z+jets
  - Precision of theoretical tools is now challenged by the precision of experimental measurements
  - m_W and $\sin^2\vartheta^{\ell}_{\mathrm{eff}}$ from the LHC matches precisions from Tevatron legacy measurements!
- Full Run-2 potential yet to be exploited
- At HL-LHC measurements of m_W and $\sin^2\vartheta^{\ell}_{\mathrm{eff}}$ could reach precision of the electroweak fit.

For more details please have a look at presentations by Carlos, Ewelina, Elena, Mauro, and Oscar.

BACKUP

$$\sigma_{l\,p\to\mu X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x) \;\rightarrow\; \sigma_{p\,p\to W} = \widetilde{\sigma}_{u\bar{d}\to W} \otimes u(x) \otimes \bar{d}(x)$$



- The probabilities for short-distance and long-distance processes factorize
- The long-distance factors are universal and can be empirically obtained from ancillary measurements.
- Idea behind PDF "industry"