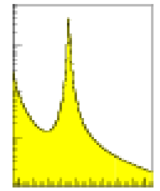
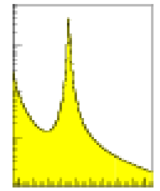




Event 4

Overview of Drell-Yan Measurements in CMS and of Their Relevance to PDFs

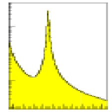
Dimitri Bourilkov

University of Florida

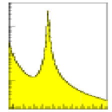
on behalf of the CMS Collaboration

LHC EW Precision Sub-group Meeting, CERN, November 13, 2018

Overview

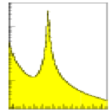


- Precision measurements at LHC and PDFs
- Setting the stage – a touch of theory
- Overview of Drell-Yan (DY) measurements in CMS:
  - Recent results from 8 TeV
  - Results from 13 TeV
- Relevance for improved PDF determinations
- Outlook



Introduction I

- **Examples of precision measurements at LHC:**
  - Effective electroweak (EW) mixing angle $\sin^2\theta_{lept}^{eff}$ from the forward-backward asymmetry A_{FB} of lepton pairs e^+e^- or $\mu^+\mu^-$ in Drell-Yan events close to the Z pole $\Rightarrow$ provides an indirect measurement of the mass M_W by using EW radiative corrections to connect to the on-shell relation $\sin^2\theta_W=1-M_W^2/M_Z^2$
  - A ± 0.00030 measurement of $\sin^2\theta_{lept}^{eff}$ corresponds to a ± 15 MeV indirect measurement of M_W; given that LHC is a Z factory, PDF uncertainties are the limiting factor
  - Direct M_W measurements
  - Top mass

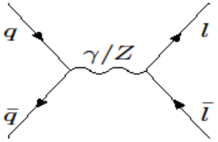


Introduction II

- PDFs play a crucial role both in discoveries (Higgs), searches for new phenomena, and precision physics
- Precision measurements @ LHC will require PDFs approaching percent level uncertainties
- This will require combining DIS, fixed target DY, Tevatron @ LHC inputs
  - Larger datasets coupled with precise theory predictions
    - EW gauge bosons, Drell-Yan
    - Inclusive jets
    - Top pairs
  - Statistical uncertainties often well below 1% $\Rightarrow$ control of correlated systematics?

Setting the Stage

A Touch of Theory



parton cross section

$$\frac{d\sigma}{d\Omega} = |\gamma_s + Z_s + \text{New Physics ?!}|^2$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}[A_0(1+\cos^2\theta) + A_1\cos\theta]$$

$$A_0 = Q_q^2 Q_l^2 + 2Q_q Q_l v_q v_l \Re\chi(s) + (v_q^2 + a_q^2)(v_l^2 + a_l^2)|\chi(s)|^2$$

$$A_1 = 4Q_q Q_l a_q a_l \Re\chi(s) + 8 v_q a_q v_l a_l |\chi(s)|^2$$

$$\sigma = \frac{4\pi\alpha^2}{3s}A_0 \qquad A_{FB} = \frac{3A_1}{8A_0}$$

$$\chi(s) = \frac{s}{(s - M_Z^2) + \imath s\frac{\Gamma_Z}{M_Z}} \quad v_f = \frac{1}{2s_W c_W}(T_f^3 - 2s_W^2 Q_f) \quad a_f = \frac{1}{2s_W c_W}T_f^3$$

arXiv:hep-ph/0003275

parton distribution functions (p.d.f.): pp$\longrightarrow$ $l_1 l_2$

$$\frac{d^2\sigma}{dM_{ll}dy}[pp \to l_1 l_2] = \sum_{ij}\frac{1}{1+\delta_{ij}}\left(f_{i/p}(x_1)f_{j/p}(x_2) + (i \leftrightarrow j)\right)\hat{\sigma}$$

$\hat{\sigma}$ - the cross section for the partonic subprocess $ij \to l_1 l_2$
$x_1 = \sqrt{\tau}e^{y}$, $x_2 = \sqrt{\tau}e^{-y}$, $M_{ll} = \sqrt{\tau s} = \sqrt{\hat{s}}$ - mass
y - rapidity of the lepton pair

$$\sigma_{F\pm B}(y, M) = [\int_0^1 \pm \int_{-1}^0]\sigma_{ll}d(\cos\theta^*)$$

$$A_{FB}(y, M) = \frac{\sigma_{F-B}(y, M)}{\sigma_{F+B}(y, M)}$$

the probability to find a parton i with momentum fraction x_i in the (anti)proton is $f_{i/p(\bar{p})}(x_i)$
for a ($x_1 \geq x_2$) pair we have 4 combinations $u\bar{u}, d\bar{d}, \bar{u}u, \bar{d}d$

y	0	2	4
M = 91.2 GeV			
x_1	0.0065	0.0481	0.3557
x_2	0.0065	0.0009	0.0001
M = 200 GeV			
x_1	0.0143	0.1056	0.7800
x_2	0.0143	0.0019	0.0003
M = 1000 GeV			
x_1	0.0714	0.5278	-
x_2	0.0714	0.0097	-

A Touch of Theory

Forward-backward Asymmetry

D. Bourilkov

$$A^0_{FB}(M_Z^2) = \frac{3}{4} A_q \cdot A_l$$

$$A_q = \frac{2(1 - 4|Q_q| sin^2\theta_{eff})}{1 + (1 - 4|Q_q| sin^2\theta_{eff})^2}$$

$$A_l = \frac{2(1 - 4 sin^2\theta_{eff})}{1 + (1 - 4 sin^2\theta_{eff})^2}$$

for $\sin^2\theta^{lept}_{eff}(M_Z^2) = 0.232$

$$A_{FB} = 0.0716 \quad (up - q)$$

$$A_{FB} = 0.1005 \quad (down - q)$$

$$\frac{\delta\, A_{FB}}{\delta\, \sin^2\theta^{lept}_{eff}(M_Z^2)} = -4.2 \quad (up - q)$$

$$\frac{\delta\, A_{FB}}{\delta\, \sin^2\theta^{lept}_{eff}(M_Z^2)} = -5.6 \quad (down - q)$$

arXiv:hep-ph/0003275

CERN   Lepton Pairs at LHC ...   LHC SM Workshop

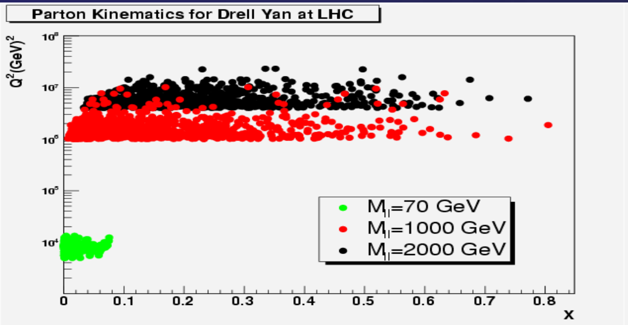
Table 9: Statistical precision which can be obtained on $\sin^2\theta^{lept}_{eff}(M_Z^2)$ from measurements of A_{FB} in $Z \to ee$ from one LHC experiment with 100 fb^{-1}. Results are given for different jet rejection factors ρ for the forward calorimetry $2.5 < |\eta| < 4.9$.

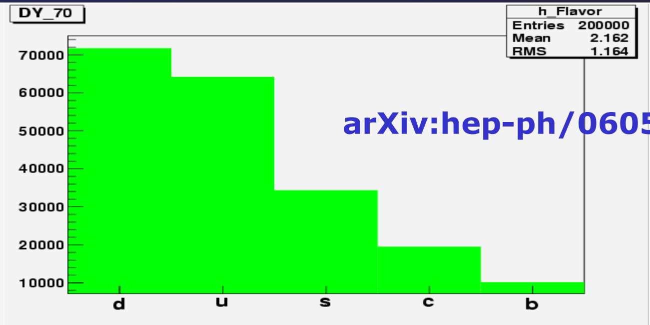
Cuts	ρ	A_{FB} (%)	ΔA_{FB} (%)	$\Delta \sin^2\theta^{lept}_{eff}(M_Z^2)$
$\|\eta\| < 2.5$ both $e^\pm$	-	0.774	0.020	6.6×10^{-4}
$\|\eta\| < 2.5$ both $e^\pm$, $\|y(e^+e^-)\| > 1.0$	-	1.66	0.030	4.0×10^{-4}
$\|\eta\| < 2.5$ one $e^\pm$	10^4	2.02	0.017	1.4×10^{-4}
$\|\eta\| < 4.9$ the other $e^\pm$	10^2	1.98	0.018	1.4×10^{-4}
	10^1	1.68	0.021	1.7×10^{-4}
$\|\eta\| < 2.5$ one $e^\pm$	10^4	3.04	0.022	1.35×10^{-4}
$\|\eta\| < 4.9$ the other $e^\pm$	10^2	2.94	0.023	1.41×10^{-4}
$\|y(e^+e^-)\| > 1.0$	10^1	2.31	0.030	1.83×10^{-4}

The most important systematic contribution is that coming from the uncertainties in the pdf's. A study using several "modern" pdf's (MRST, CTEQ3 and CTEQ4) gave agreement between the resulting values of A_{FB} within the 1% statistical errors of the study (5×10^5 events were generated for each pdf set). This uncertainty must be reduced by a factor of 10 if it is to be smaller than the expected statistical precision on A_{FB} shown in Table 9. It remains to be seen whether (a) the differences arising from the various pdf's will shrink with increased statistical sensitivity of the study and (b) whether the current pdf's actually describe the measured data sufficiently well (since the pfd's are fitted to common data, variations are not necessarily indicative of the actual uncertainties). New measurements from the Tevatron (and ultimately the LHC itself) will improve the understanding of the pdf's, but it is unclear at this stage whether this will be sufficient. It may be possible to fit simultaneously $\sin^2\theta_{\rm eff}^{\rm lept}(M_Z^2)$ and the pdf's, or alternatively, it may be necessary to reverse the strategy and use the measurement of A_{FB} combined with existing measurements of $\sin^2\theta_{\rm eff}^{\rm lept}(M_Z^2)$ to constrain the pdf's.

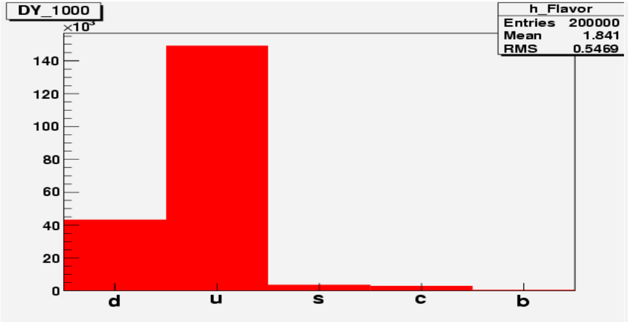
arXiv:hep-ph/0003275

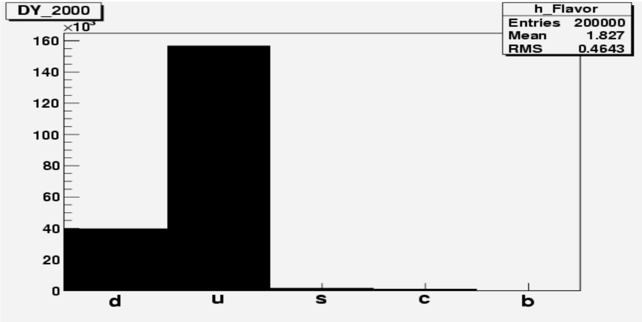
Drell-Yan Parton Kinematics & Flavor Composition





arXiv:hep-ph/0605240





able 1: x_1 and x_2 for different masses and ra-
pidities.

y	0	2	4
M = 91.2 GeV			
x_1	0.0065	0.0481	0.3557
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M = 1000 GeV			
x_1	0.0714	0.5278	–
x_2	0.0714	0.0097	–

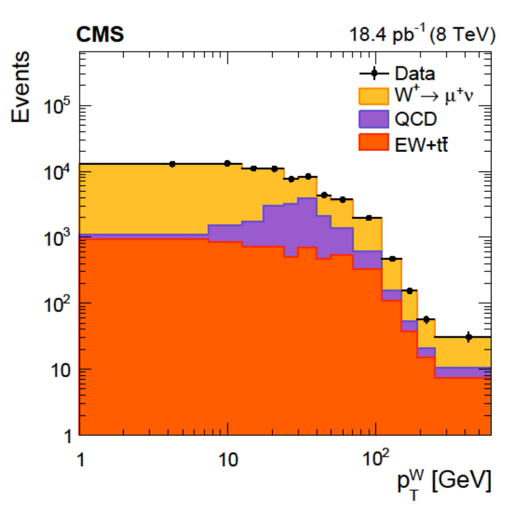
Different X ranges probed for different masses; quite low X @ Z => HERA input can be important (HERALHC workshop)

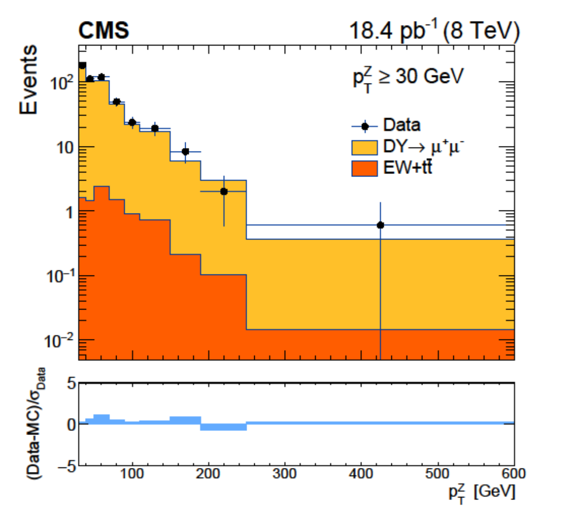
Measuring PDFs is precision physics; at the start we will be constrained by PDFs; actually they are known quite well for DY@LHC

CMS Measurements at 8 TeV

W/Z p_T Spectra @ 8 TeV

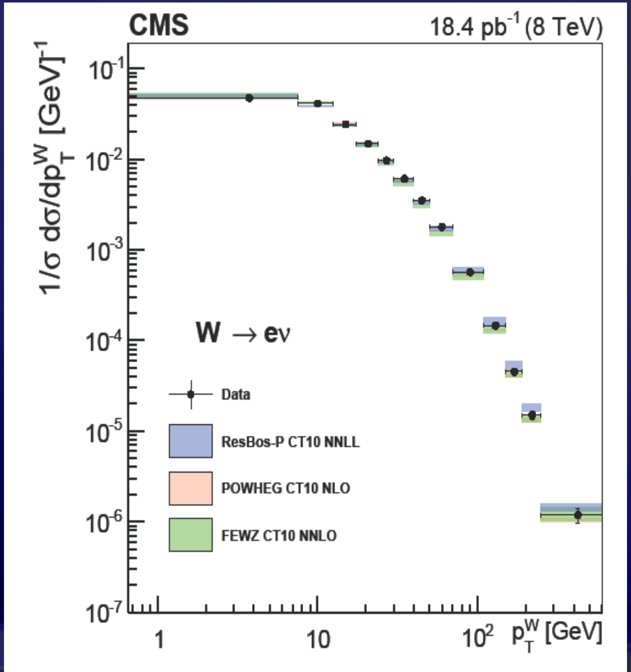
- Measured @ 8 TeV using special low lumi data 18.4 pb^{-1}
- $Z \rightarrow \mu\mu$, $W \rightarrow e\nu$ or $W \rightarrow \mu\nu$
- Data compared to QCD@NNLO
- JHEP (2017) 2017:96

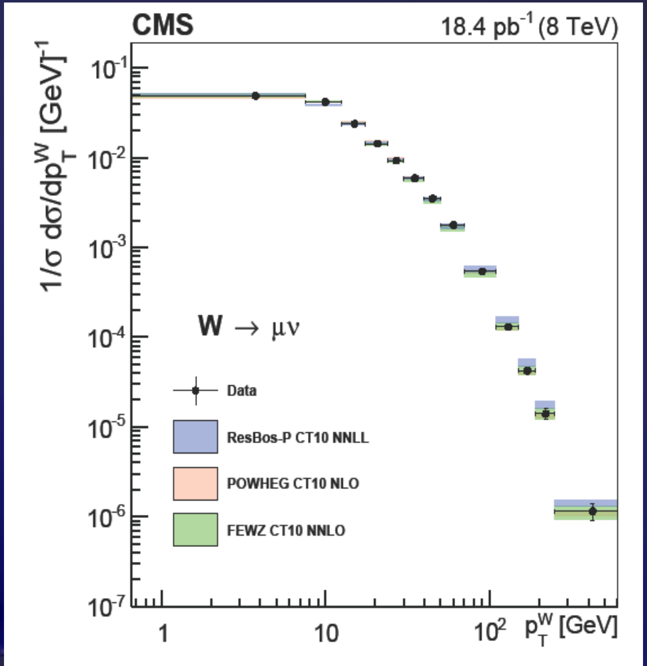




W/Z p_T Spectra @ 8 TeV

- **Good agreement between data and QCD@NNLO**
- **JHEP (2017) 2017:96**





W/Z p_T Spectra @ 8 TeV

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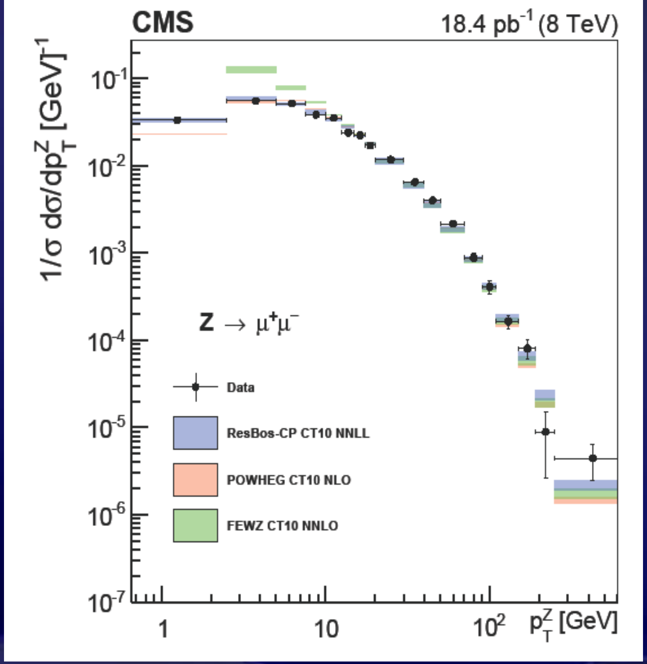
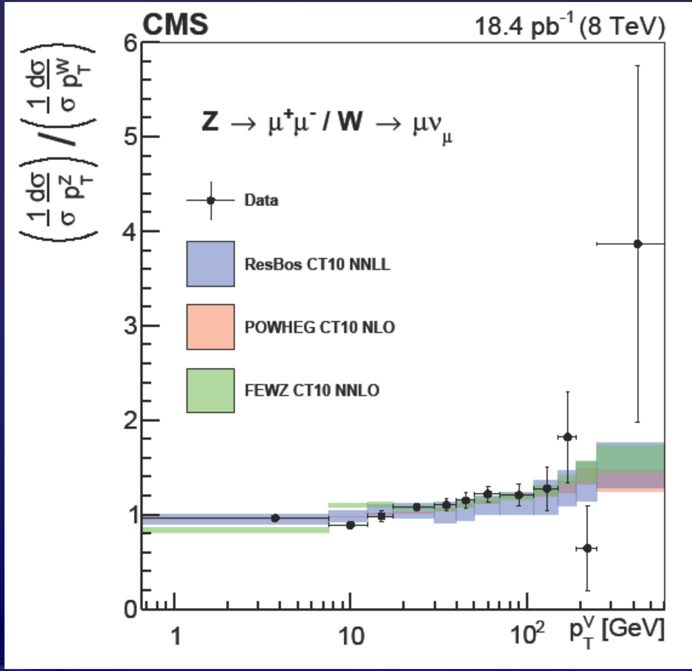
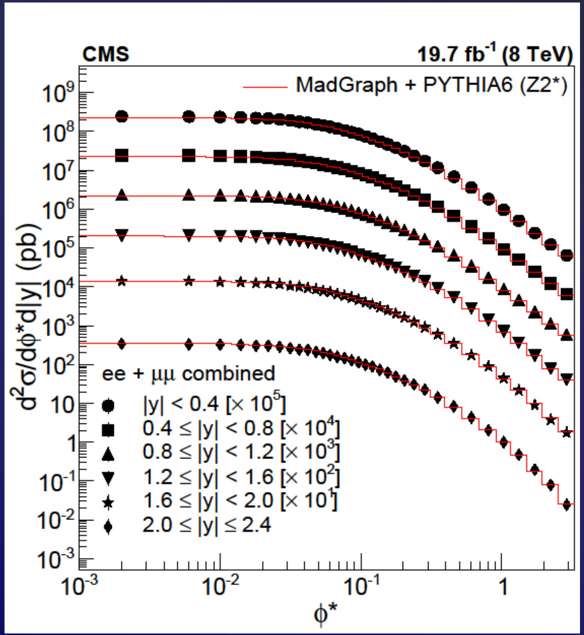


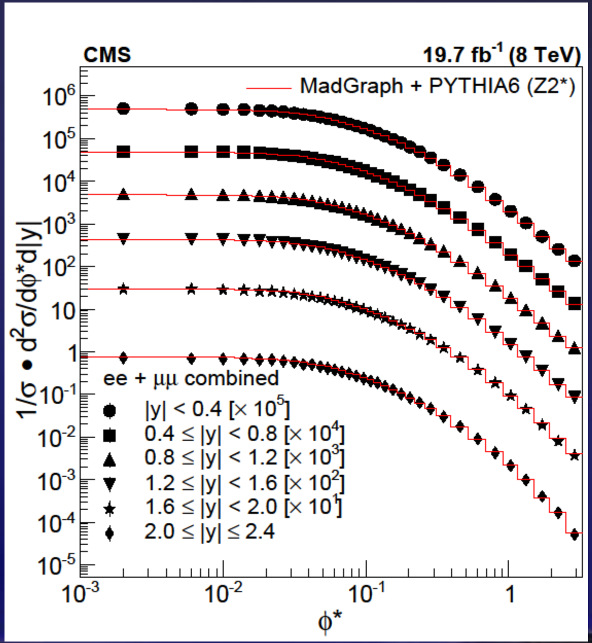


Differential Z Cross Section in ϕ^* and y

- 19.7 fb^{-1} of 8 TeV data
- alternative to the p_T measurement, more precise
- JHEP (2018) 2018:172



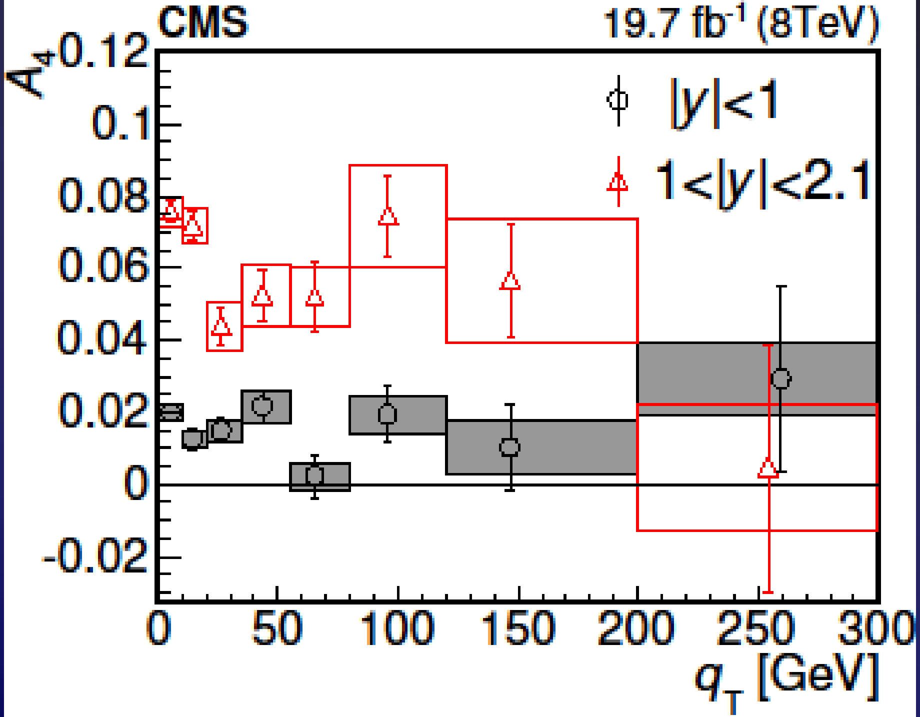
normalized



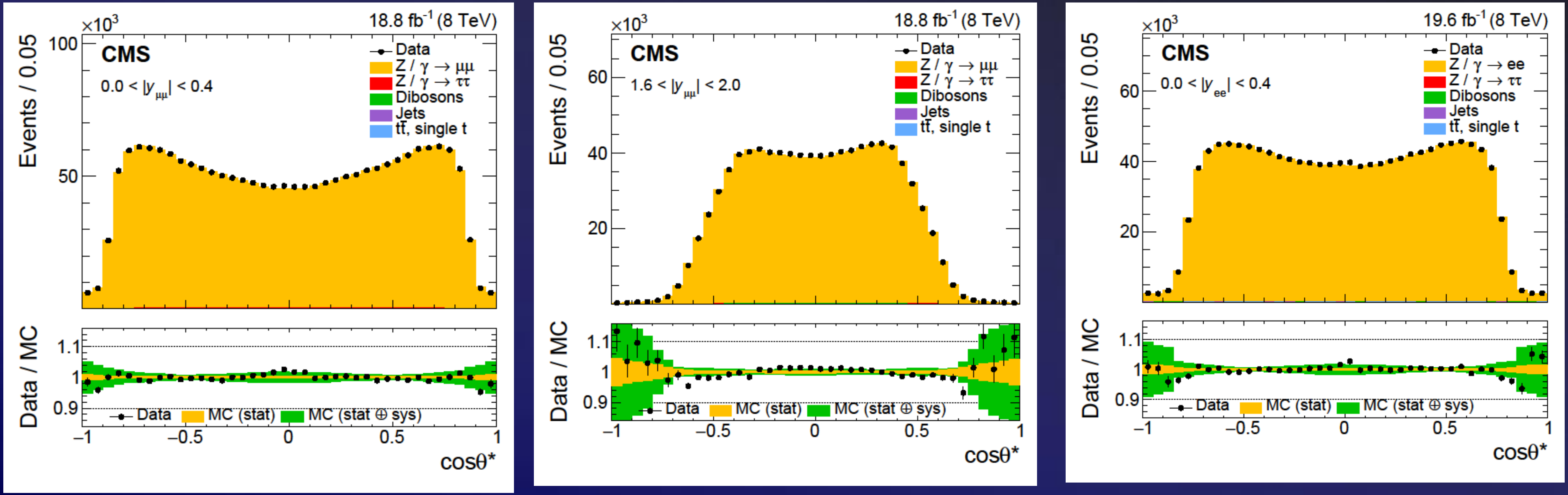
$$\phi^* = \tanh((\eta^- - \eta^+)/2 \sim q_T/m_{ll}$$

A_{FB} & Angular Coefficients @ 8 TeV

- 19.7 fb^{-1} of 8 TeV data
- Angular coefficients A_0 to A_4 measured as function of the Z boson y and p_T
- A_4 related to A_{FB}
- Phys. Lett. B 750 (2015) 154

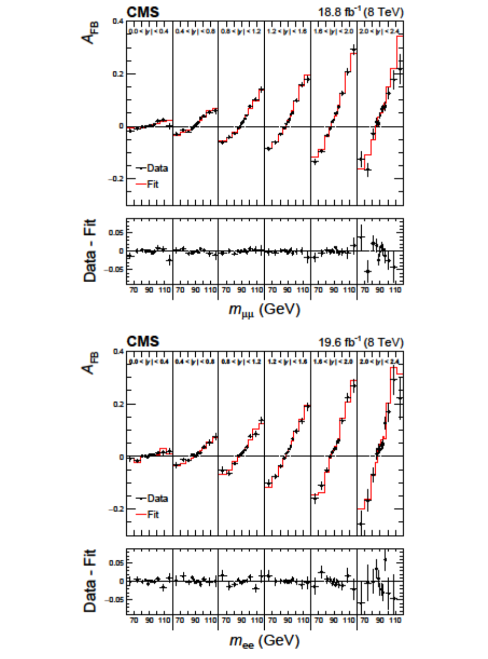


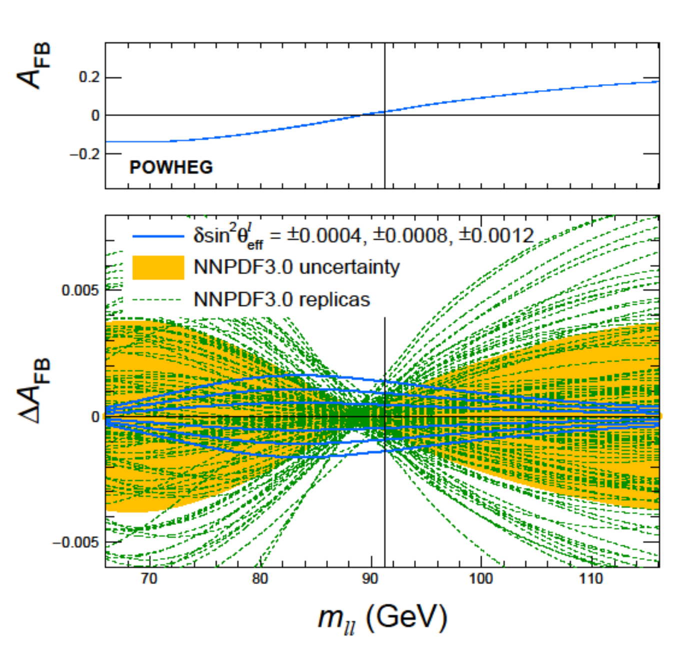
A_{FB} & Weak Mixing Angle @ 8 TeV

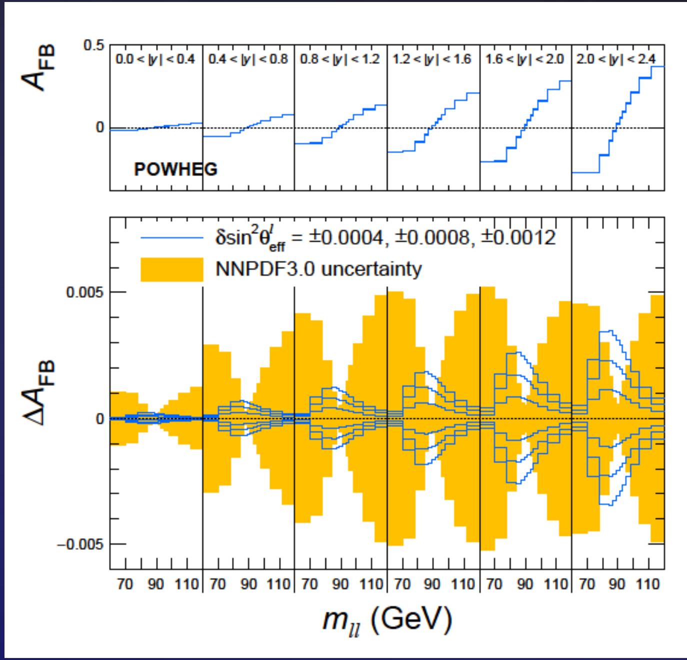


- 19.6 fb^{-1} of 8 TeV data
- Acceptance for e^+e^- or $\mu^+\mu^-$ in different y bins
- EPJC 78 (2018) 701

A_{FB} & Weak Mixing Angle @ 8 TeV





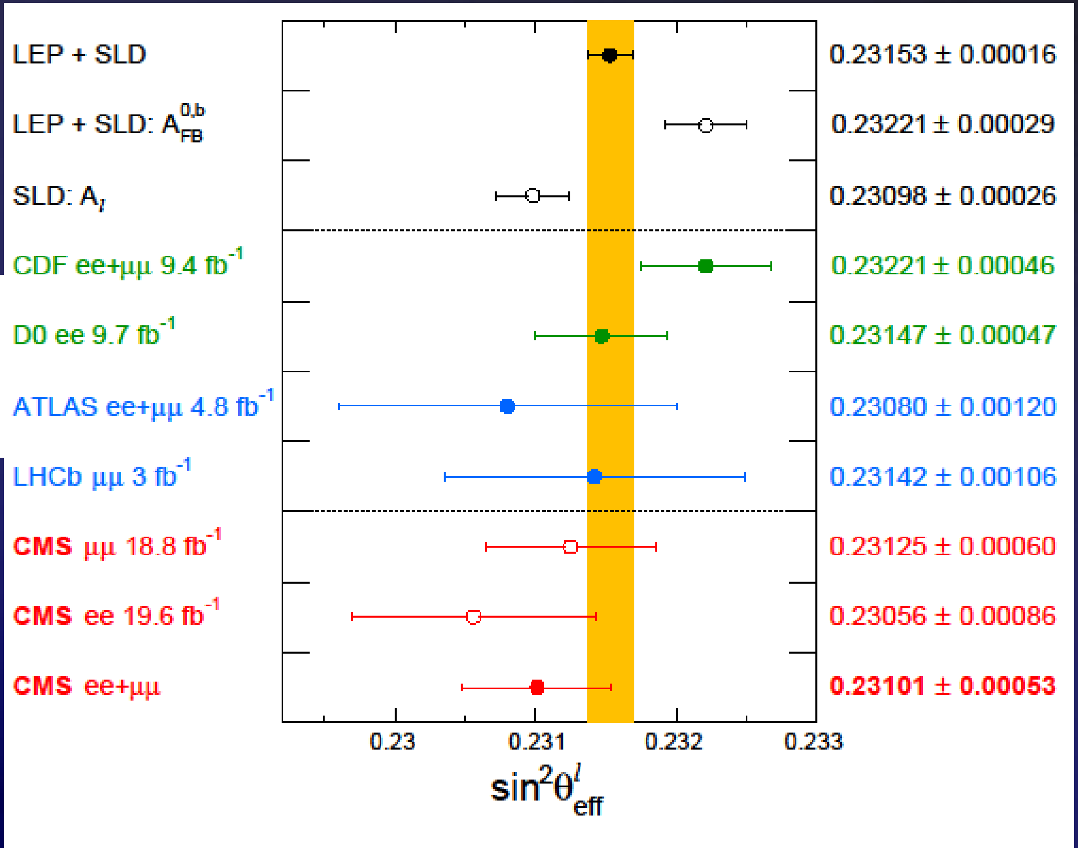


- **6 rapidity bins 0-2.4 and 12 mass bins 60-120 GeV**
- **A_{FB} has different dependence on mass and $\sin^2\theta_{lept}^{eff}$**
- **EPJC 78 (2018) 701**

A_{FB} & Weak Mixing Angle @ 8 TeV

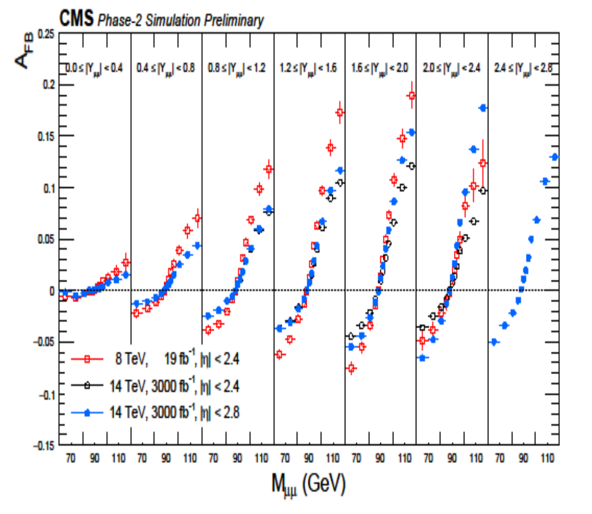
Channel	Statistical uncertainty
Muons	0.00044
Electrons	0.00060
Combined	0.00036

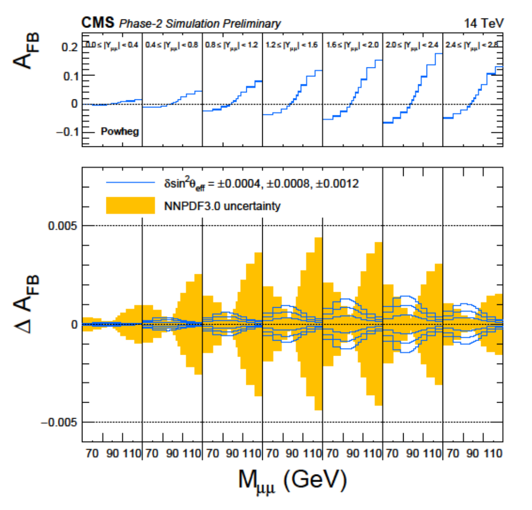
Channel	Not constraining PDFs	Constraining PDFs
Muons	0.23125 ± 0.00054	0.23125 ± 0.00032
Electrons	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030

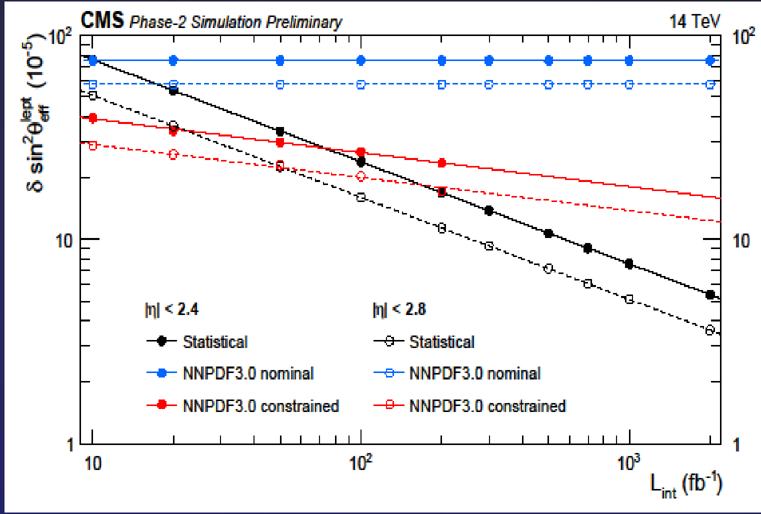


- **A_{FB} off peak are used to constrain the NNPDF replicas by χ^2 reweighting**
- **EPJC 78 (2018) 701**

A_{FB} & Weak Mixing Angle @ HL-LHC



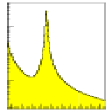




- **Projections for HL-LHC: constraining PDFs looks promising and will improve with more data**
- **CMS-PAS-FTR-17-001**

CMS Measurements at 13 TeV

Inclusive W/Z Production @ 13 TeV



- **43 pb^{-1} @ 13 TeV**
- **Inclusive cross sections and ratios in good agreement with QCD@NNLO**

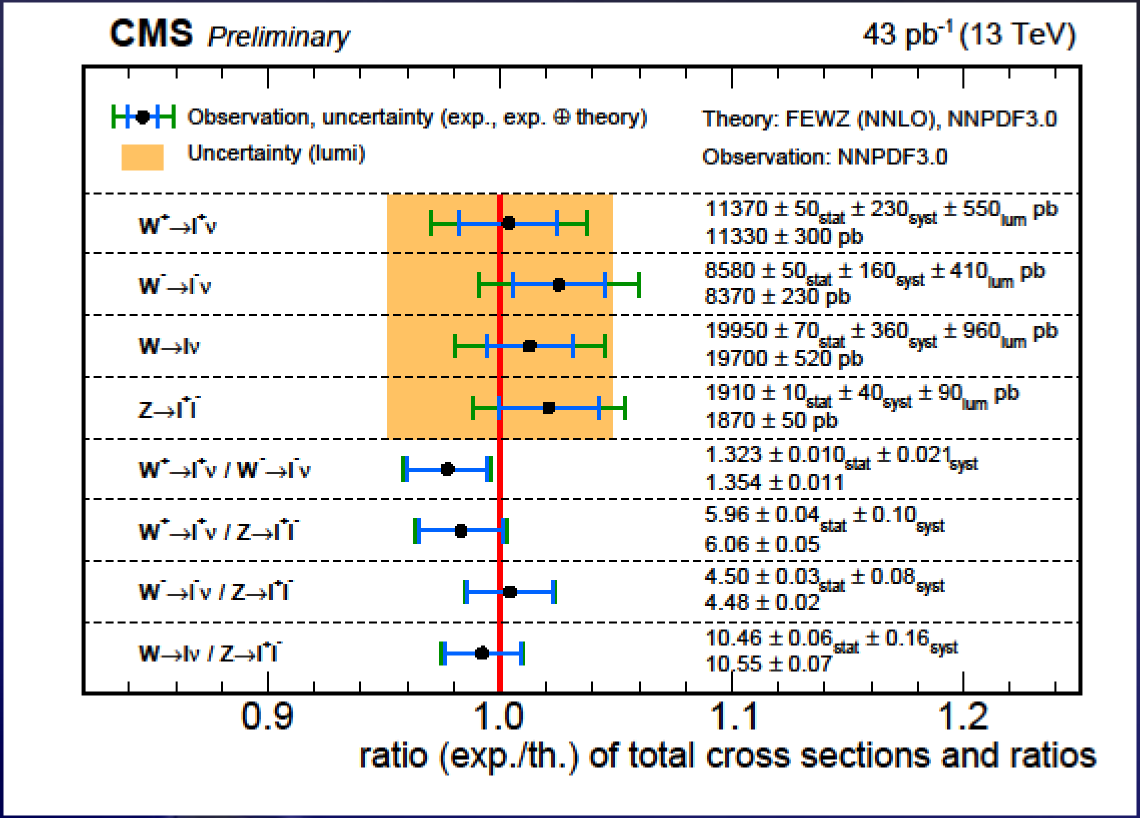
CMS-PAS-SMP-15-004

Channel		$\sigma \times \mathcal{B}$ [pb] (total)	NNLO [pb]
W^+	$e^+\nu$	$11390 \pm 90\,(stat) \pm 340\,(syst) \pm 550\,(lumi)$	11330^{+320}_{-270}
	$\mu^+\nu$	$11350 \pm 60\,(stat) \pm 320\,(syst) \pm 550\,(lumi)$	
	$\ell^+\nu$	$11370 \pm 50\,(stat) \pm 230\,(syst) \pm 550\,(lumi)$	
W^-	$e^-\nu$	$8680 \pm 80\,(stat) \pm 250\,(syst) \pm 420\,(lumi)$	8370^{+240}_{-210}
	$\mu^-\nu$	$8510 \pm 60\,(stat) \pm 210\,(syst) \pm 410\,(lumi)$	
	$\ell^-\nu$	$8580 \pm 50\,(stat) \pm 160\,(syst) \pm 410\,(lumi)$	
W	$e\nu$	$20070 \pm 120\,(stat) \pm 570\,(syst) \pm 960\,(lumi)$	19700^{+560}_{-470}
	$\mu\nu$	$19870 \pm 80\,(stat) \pm 460\,(syst) \pm 950\,(lumi)$	
	$\ell\nu$	$19950 \pm 70\,(stat) \pm 360\,(syst) \pm 960\,(lumi)$	
Z	e^+e^-	$1920 \pm 20\,(stat) \pm 60\,(syst) \pm 90\,(lumi)$	1870^{+50}_{-40}
	$\mu^+\mu^-$	$1900 \pm 10\,(stat) \pm 50\,(syst) \pm 90\,(lumi)$	
	$\ell^+\ell^-$	$1910 \pm 10\,(stat) \pm 40\,(syst) \pm 90\,(lumi)$	
Quantity		Ratio (total)	NNLO
R_{W^+/W^-}	e	$1.313 \pm 0.016\,(stat) \pm 0.028\,(syst)$	$1.354^{+0.011}_{-0.012}$
	μ	$1.334 \pm 0.011\,(stat) \pm 0.031\,(syst)$	
	ℓ	$1.323 \pm 0.010\,(stat) \pm 0.021\,(syst)$	
$R_{W^+/Z}$	e	$5.94 \pm 0.07\,(stat) \pm 0.16\,(syst)$	$6.06^{+0.04}_{-0.05}$
	μ	$5.98 \pm 0.05\,(stat) \pm 0.14\,(syst)$	
	ℓ	$5.96 \pm 0.04\,(stat) \pm 0.10\,(syst)$	
$R_{W^-/Z}$	e	$4.52 \pm 0.06\,(stat) \pm 0.12\,(syst)$	$4.48^{+0.03}_{-0.02}$
	μ	$4.49 \pm 0.04\,(stat) \pm 0.10\,(syst)$	
	ℓ	$4.50 \pm 0.03\,(stat) \pm 0.08\,(syst)$	
$R_{W/Z}$	e	$10.46 \pm 0.11\,(stat) \pm 0.26\,(syst)$	$10.55^{+0.07}_{-0.06}$
	μ	$10.47 \pm 0.08\,(stat) \pm 0.20\,(syst)$	
	ℓ	$10.46 \pm 0.06\,(stat) \pm 0.16\,(syst)$	

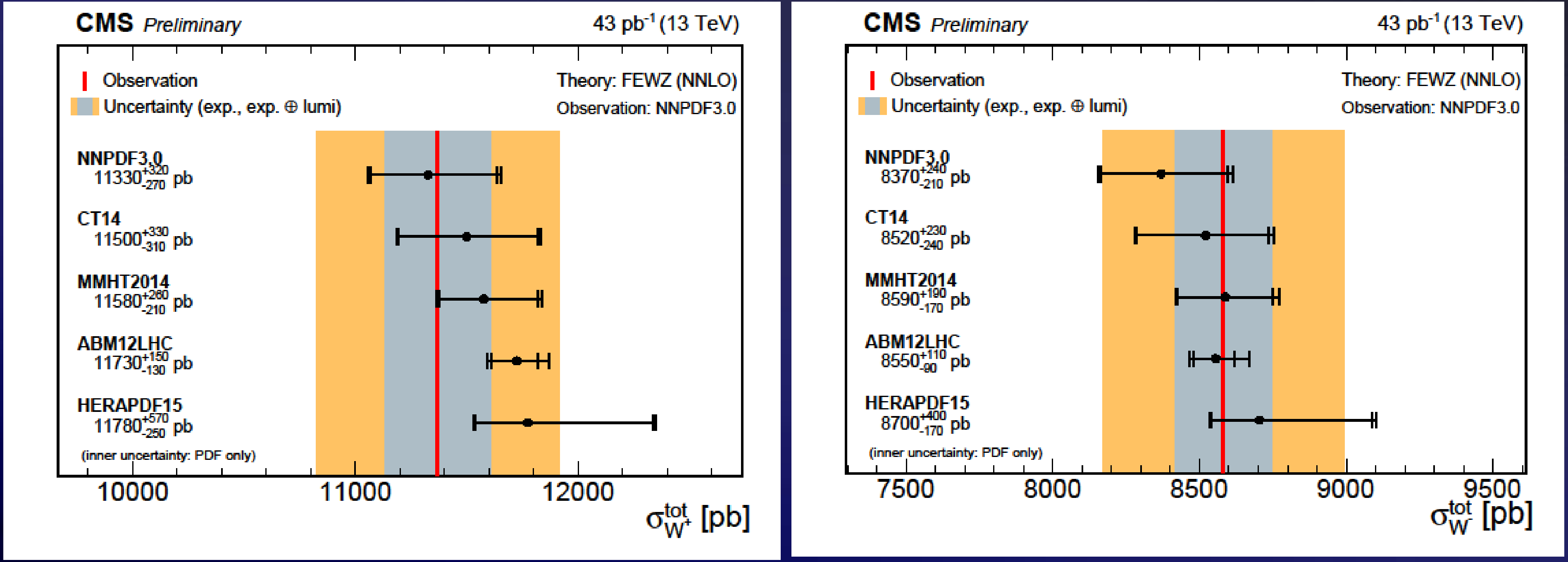
Inclusive W/Z Production @ 13 TeV

Inclusive cross sections & Ratios sensitive to PDFs

CMS-PAS-SMP-15-004

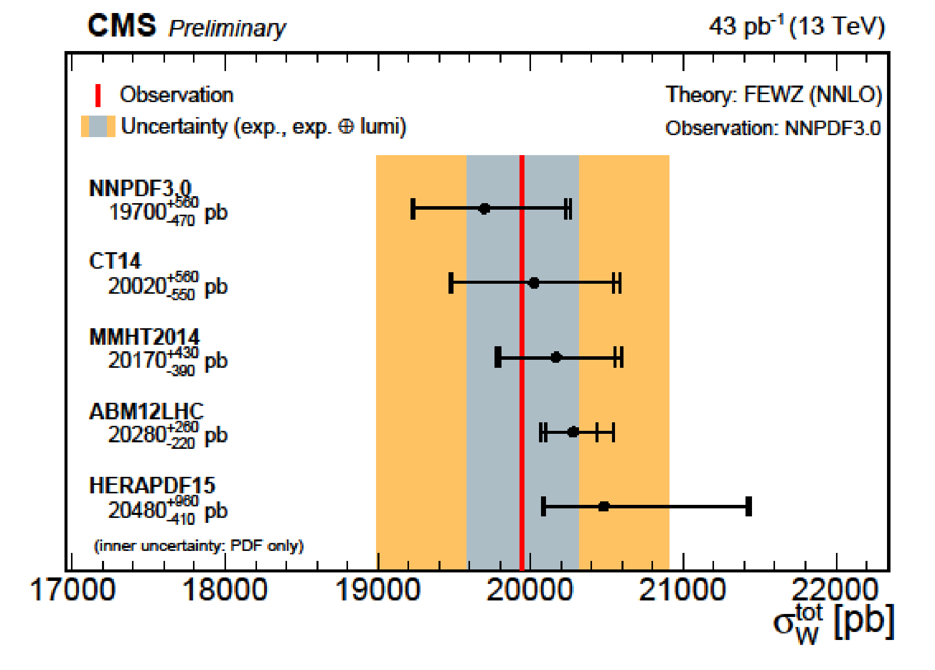


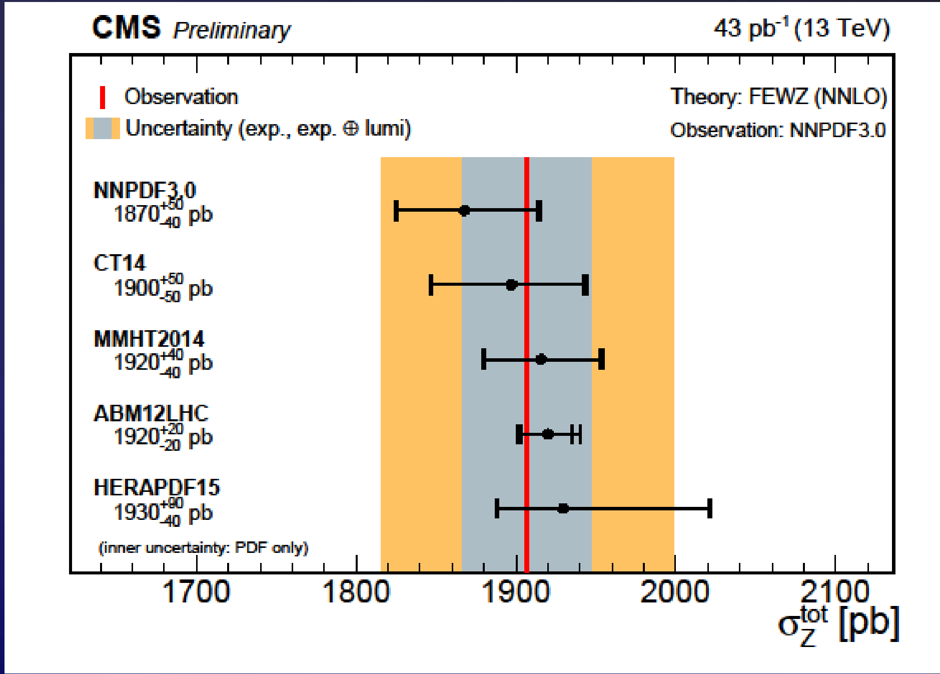
Inclusive W/Z Production @ 13 TeV



CMS-PAS-SMP-15-004

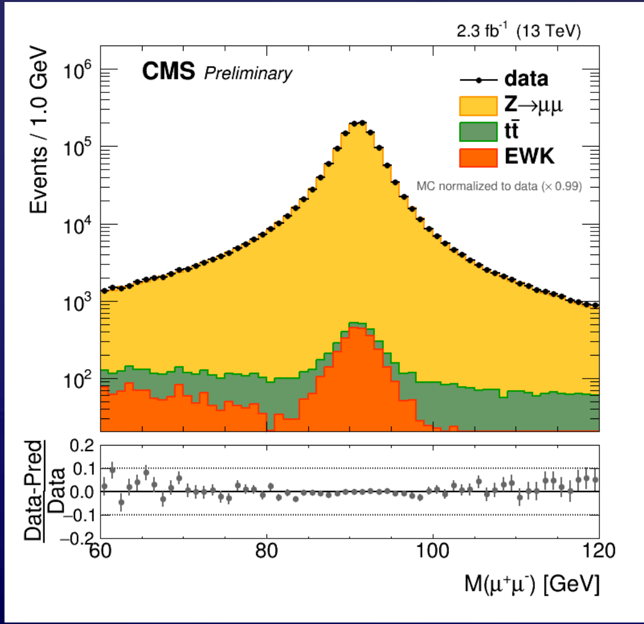
Inclusive W/Z Production @ 13 TeV

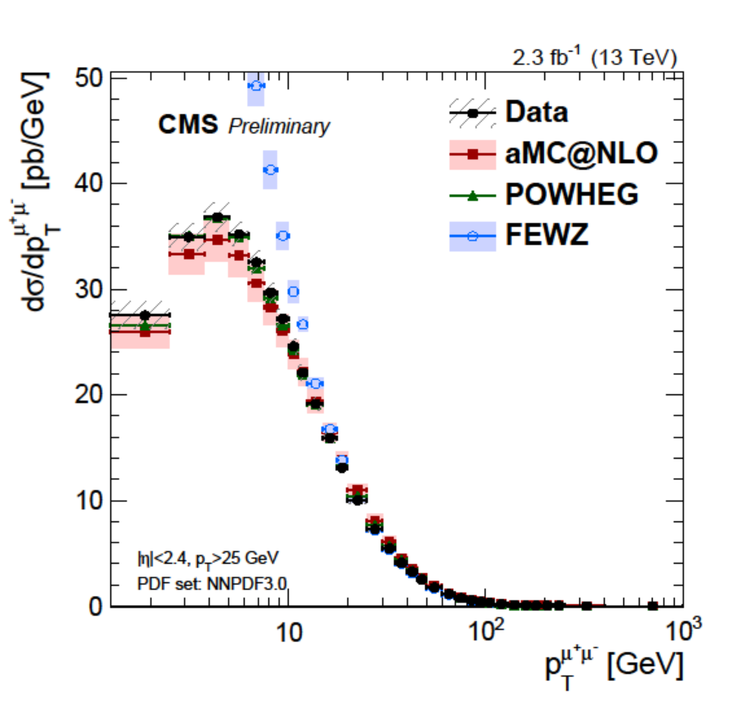




CMS-PAS-SMP-15-004

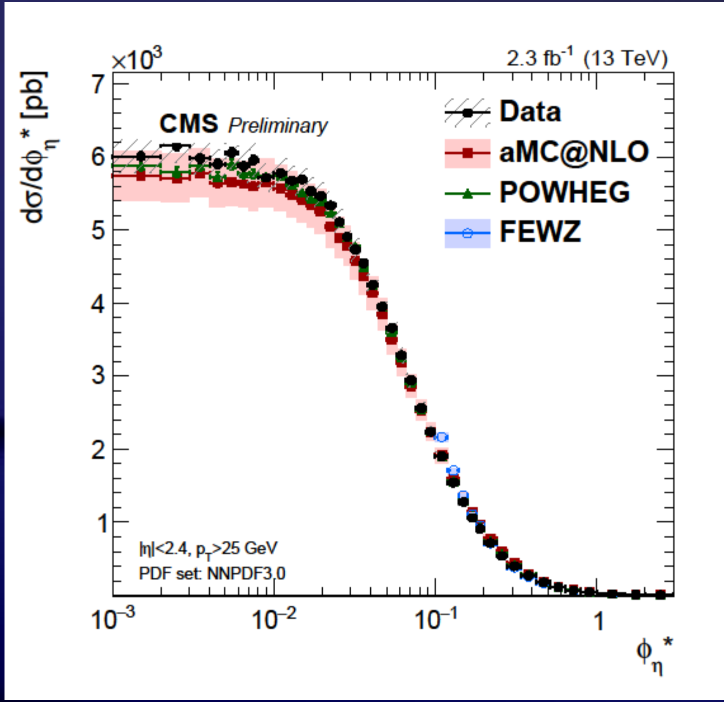
Z Production @ 13 TeV

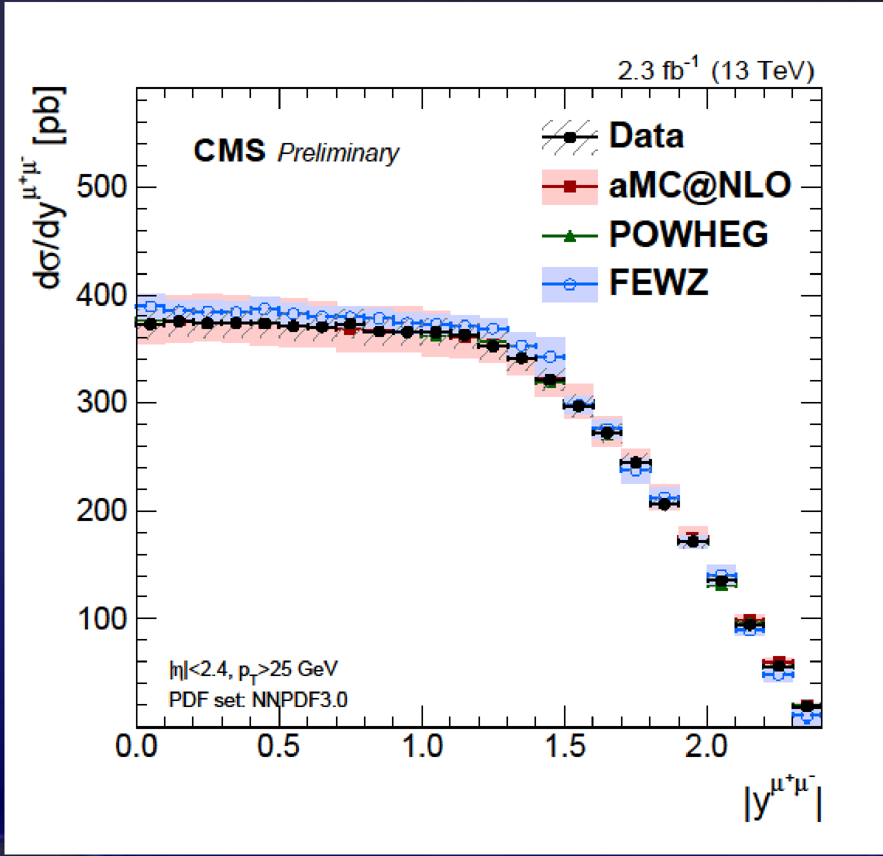




- 2.3 fb^{-1} @ 13 TeV: y, p_T and ϕ^* distributions
- CMS-PAS-SMP-15-011

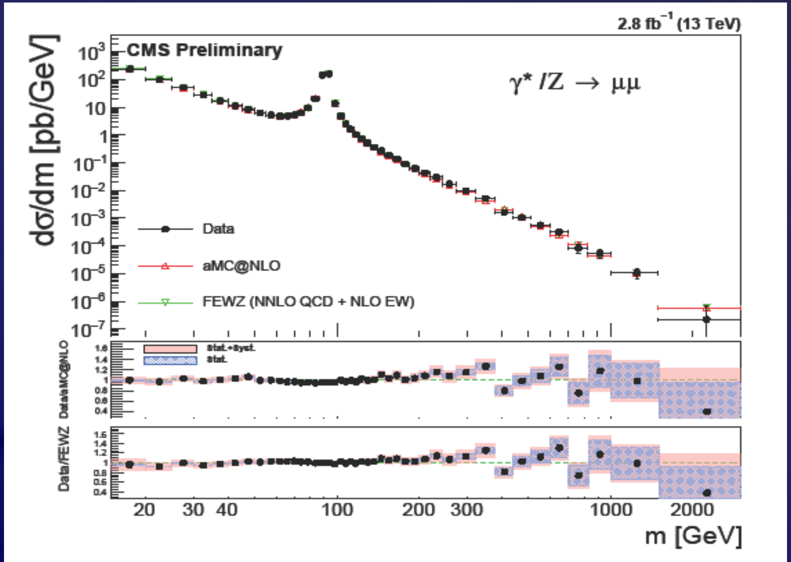
Z Production @ 13 TeV

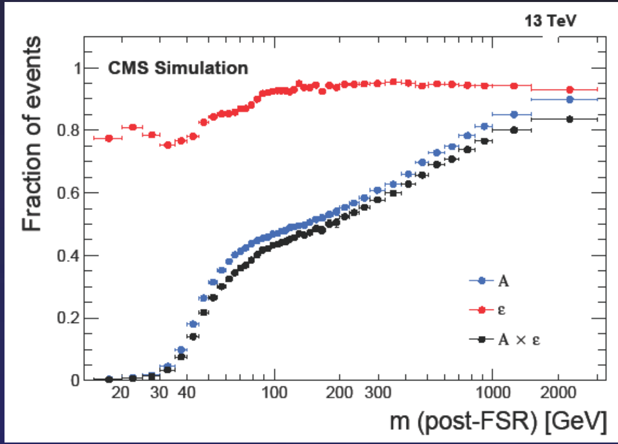


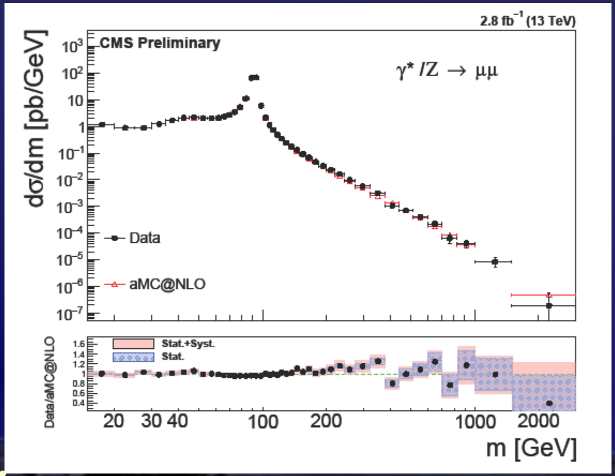


- CMS-PAS-SMP-15-011

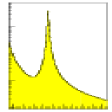
DY @ 13 TeV



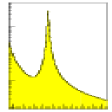




- Spectra @ 7, 8 & 13 TeV
- M from 15-3000 GeV with 2015 data: 2.8 fb^{-1}
- CMS-PAS-SMP-16-009



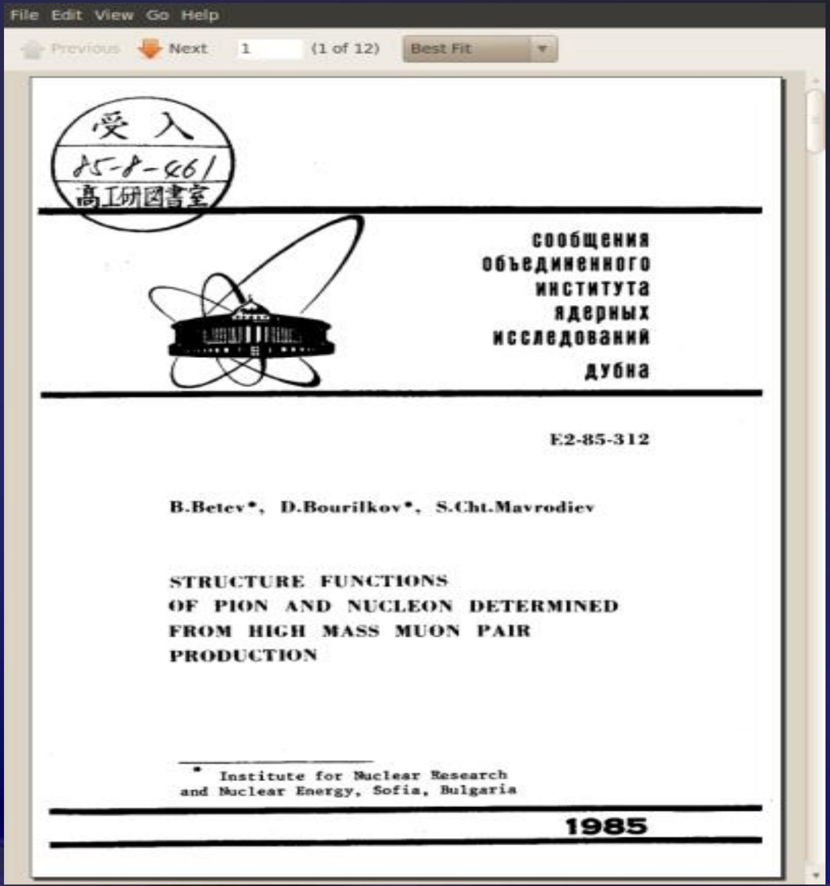
Relevance for Improved PDF Determinations



PDFs from DY @ Fixed Target Experiments

The double differential DY spectra in (M,y) or (M,x_f) have long been a staple of PDF extractions from data together with DIS

One example: PDFs from fixed target p-Platinum and π-Tungsten Drell-Yan experiments below and above the Υ resonances (γ* exchange)



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дубна

E2-85-312

B.Betev*, D.Bourilkov*, S.Cht.Mavrodiev

STRUCTURE FUNCTIONS
OF PION AND NUCLEON DETERMINED
FROM HIGH MASS MUON PAIR
PRODUCTION

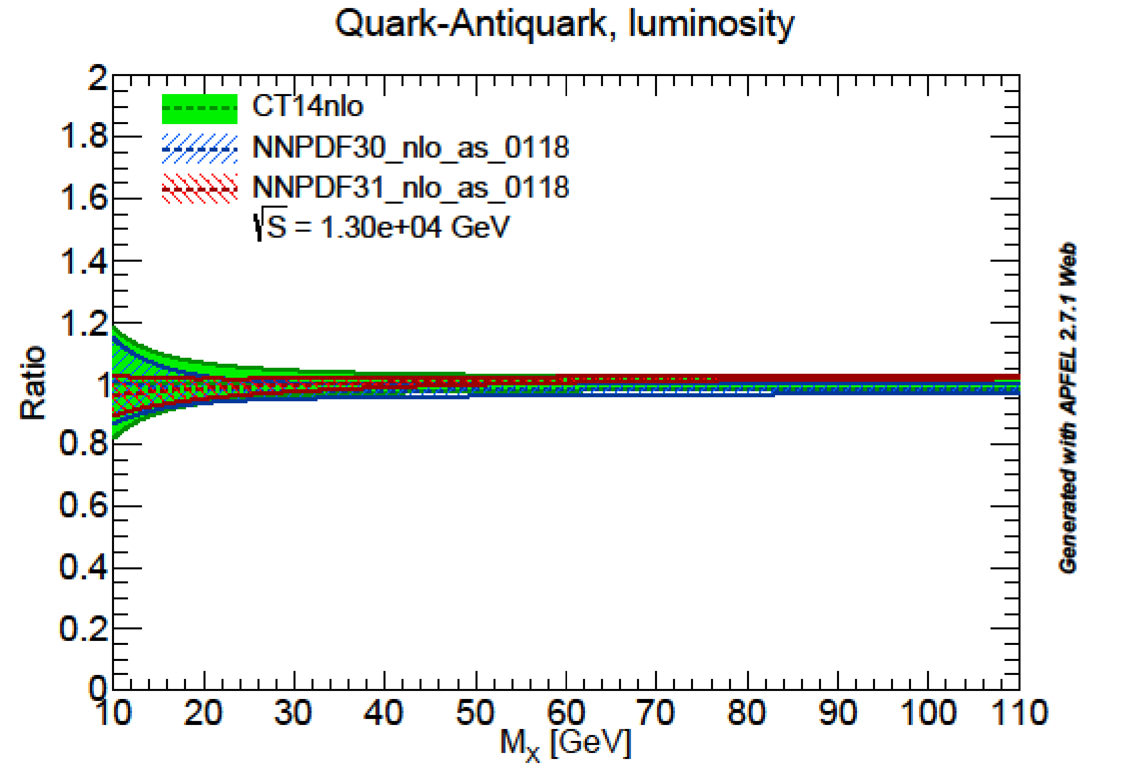
* Institute for Nuclear Research
and Nuclear Energy, Sofia, Bulgaria

1985

Modern PDFs

- PDFs play a central role: determined from collider (ep, ppbar & pp) and fixed target DIS & DY data (can be at low momentum transfers: non-perturbative & higher twist effects, and/or nuclear effects)
- PDF4LHC recommendations (arXiv:1510.03865) based on modern NLO and NNLO PDF sets:
  - CT14, MMHT2014, NNPDF30
  - Individual PDFs for SM measurements
  - PDF4LHC15_mc for BSM searches
- Individual PDF uncertainties are getting smaller, even at the mass edges

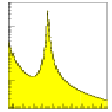
Parton Luminosity @ Z & Low Mass



PDF uncertainties much smaller, below 10-20% even at masses ~10 GeV

NNPDF31 shows the smallest uncertainties and predicts higher cross sections for most of the mass range 10 to 110 GeV

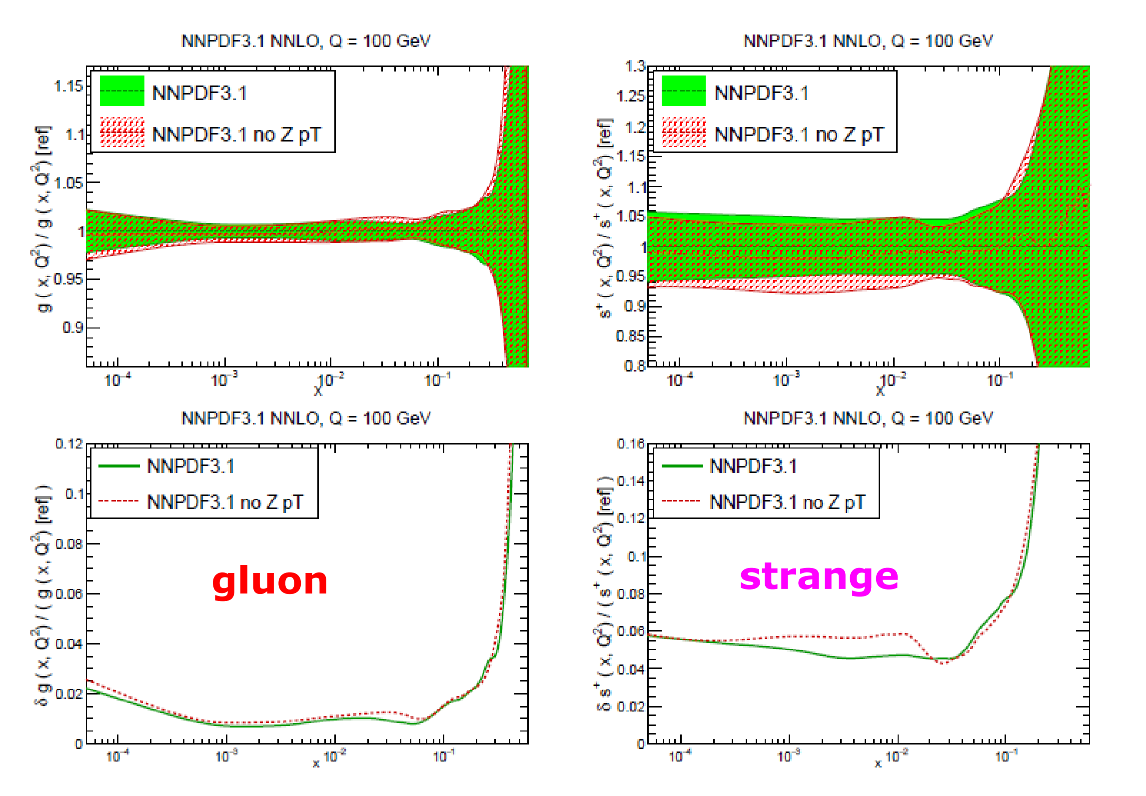
NNPDF3.1



- NNPDF31 uses LHC data from Run I @ 2.76, 7 and 8 TeV
- Inclusion of Run II data in PDF fits
- NNPDF31: EW corrections (and photon induced processes) not included in fits ⇒ eliminates points
- Fitting the LHC data requires NNLO theory
- Tension between LHC and nuclear targets data (DIS, DY – deuterium: SLAC, BCDMS, NMC, E886, heavy nuclei: ν data, E605). Precise determination of SM parameters ⇒ may be advantageous to use PDF sets produced excluding all nuclear data

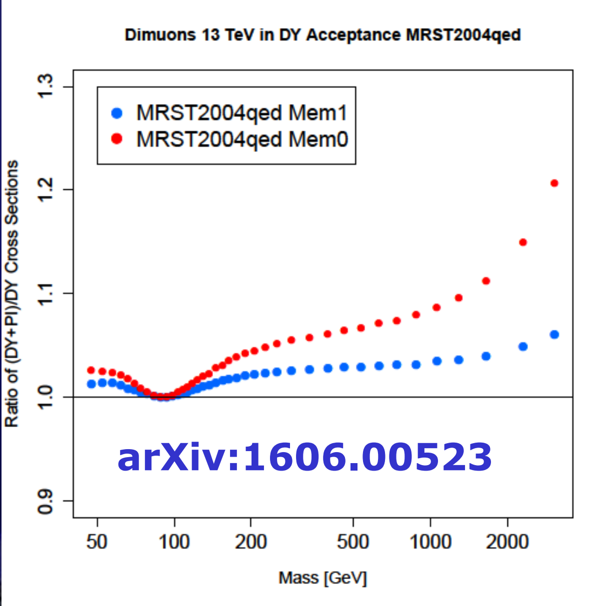
Example: Relevance of Z p_T

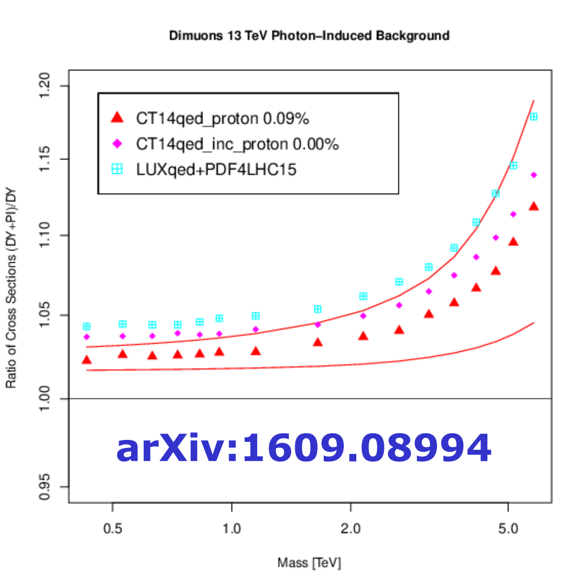
- The impact of Z p_T data @ 8 TeV from ATLAS & CMS: improves the precision of g & s PDFs
- Overall g weight reduced by new ttbar differential cross sections
- arXiv:1706.00428



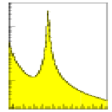
Loose Ends

- E.g. the NNPDF31 fit uses NO EW corrections; kinematic cuts applied to exclude bins: EW corrections < experimental errors
- Photon induced corrections will become important in the push to the percent level, especially if moving away from the Z pole





Outlook



- The Drell-Yan process provides a W/Z factory at the LHC and helps to test the SM to the highest momentum transfers
- Improved measurements and theory predictions key to refining the PDFs ⇒ for precision measurements and for searches, where DY is often the main irreducible background
- CMS has a rich and varied program of DY measurements: results at 8 and 13 TeV presented, many 13 TeV analyses in the works
- Only a handful used in PDF fits so far ⇒ more are available, and the expected new results will help to improve the proton PDFs and reduce further their uncertainties