“Electroweak” parameters at the LHC

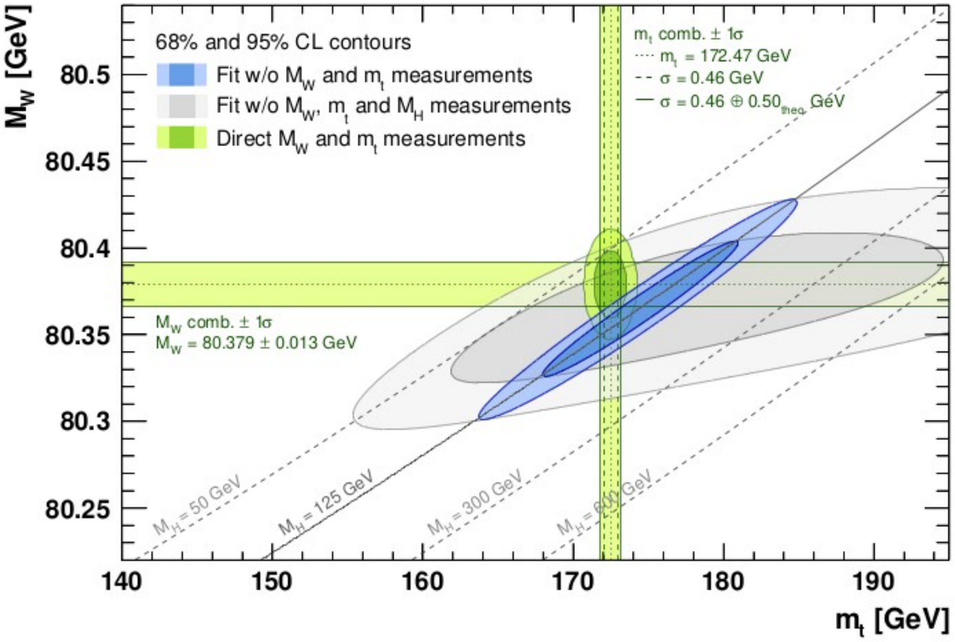
m_W, $\sin^2\theta_{eff}$, α_S

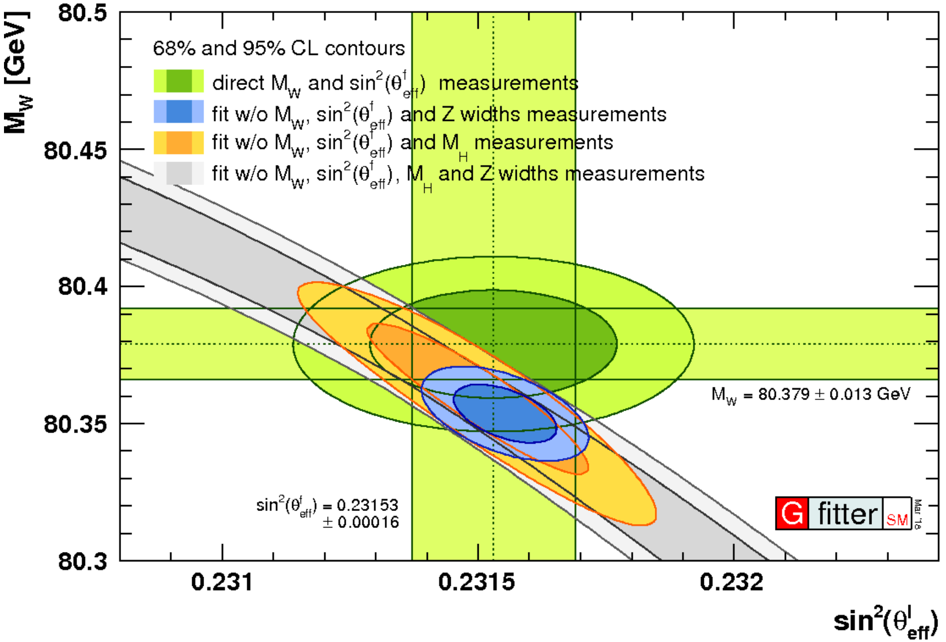
M.Boonekamp

NNPDF meeting, Gargnano 2023

Why

- m_W, $\sin^2\theta_{eff}$





(m_W, $\sin^2\theta_{eff}$) plot of particular interest, because of potential non-trivial correlations when hadron collider-measurements dominate these parameters (PDFs!)

Why

- α_S
  - Fundamental parameter of interest per se
  - Also an input in electroweak fits. At $O(\alpha\alpha_S)$:

$$M_W = \left[M_W^0 + c_t\Delta_t + c_t'\Delta_t^2 + c_Z\Delta_Z + c_\alpha\Delta_\alpha + c_{\alpha_s}\underline{\Delta_{\alpha_s}}\right]\ \text{MeV},$$

$$\sin^2\theta_{\text{eff}}^l = \sin^2\theta_{\text{eff}}^{\ell,0} - (d_t\Delta_t + d_t'\Delta_t^2 + d_Z\Delta_Z + d_\alpha\Delta_\alpha + d_{\alpha_s}\underline{\Delta_{\alpha_s}})$$

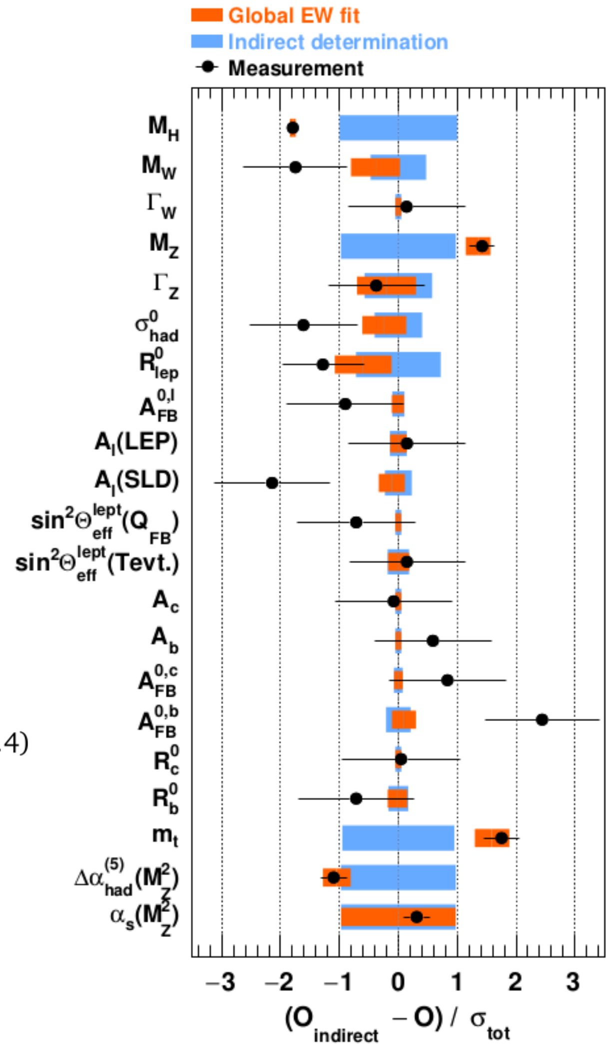
$$\Delta_t \equiv \left(\frac{m_t}{173\ \text{GeV}}\right)^2 - 1, \quad \Delta_Z \equiv \frac{M_Z}{91.1876\ \text{GeV}} - 1, \quad \Delta_\alpha \equiv \frac{\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)}{0.0276} - 1, \quad \Delta_{\alpha_s} \equiv \frac{\alpha_s(M_Z^2)}{0.119} - 1, \quad (2.4)$$

$M_W^0 = 80359.5$ $\quad c_t = 520.5$ $\quad c_t' = -67.7$ $\quad c_Z = 115000.$ $\quad c_\alpha = -503.$ $\quad c_{\alpha_s} = -71.6$

$\sin^2\theta_{\text{eff}}^{\ell,0} = 0.231533$ $\quad d_t = 27.14$ $\quad d_t' = -1.62$ $\quad d_Z = 6550.$ $\quad d_\alpha = -96.7$ $\quad d_{\alpha_s} = -4.05$

arXiv:1902.05142

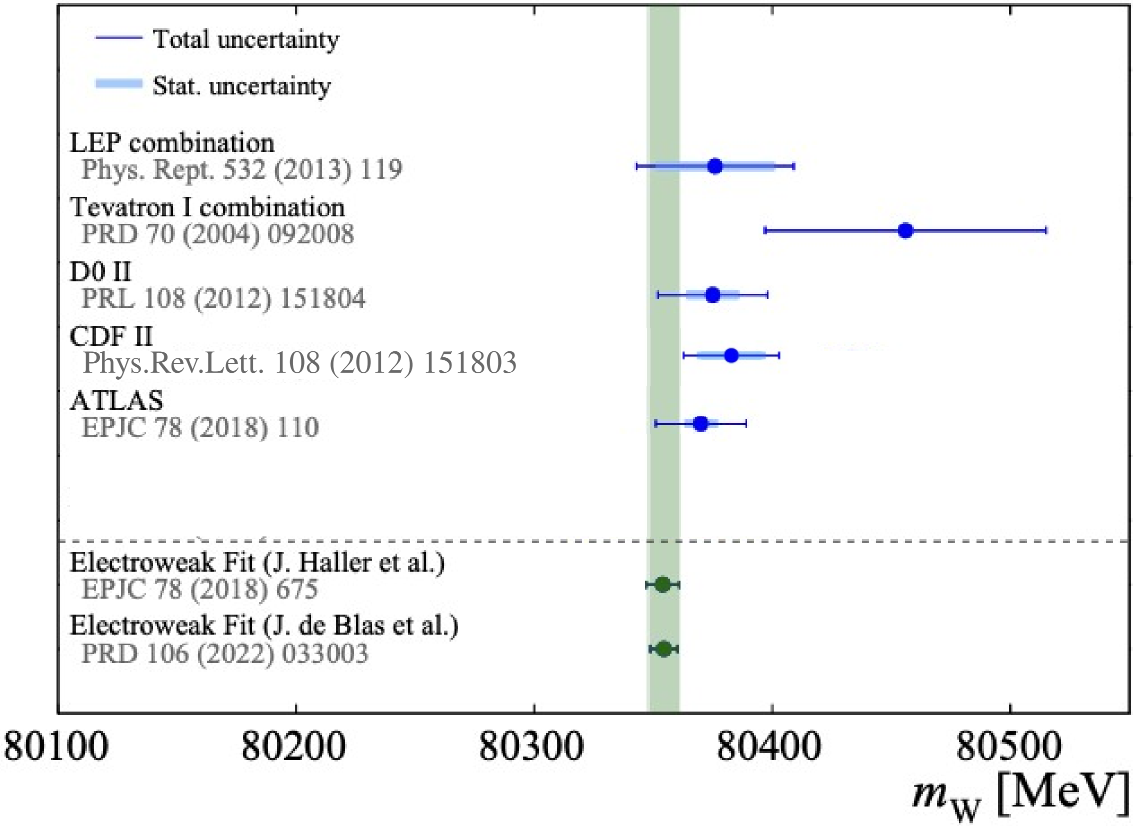
arXiv:1803.01853



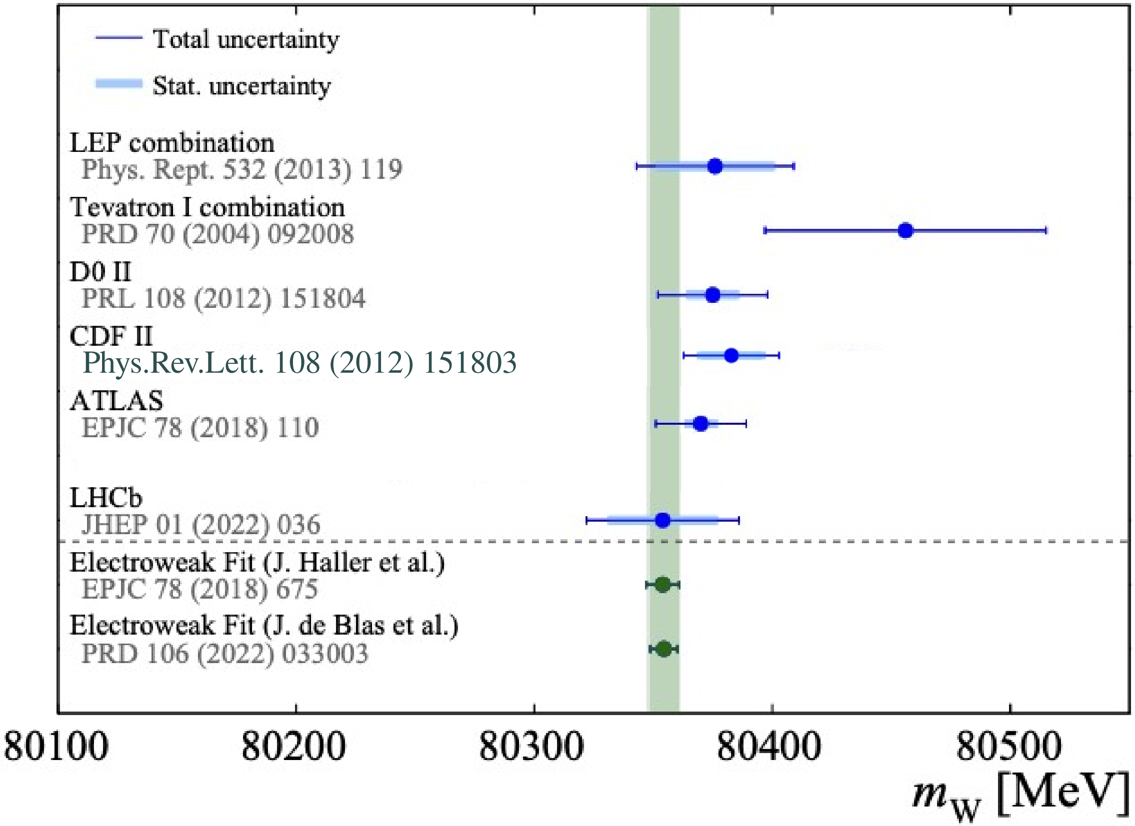
m_W measurements

Compatibility tests & combination

Measurements until 2020

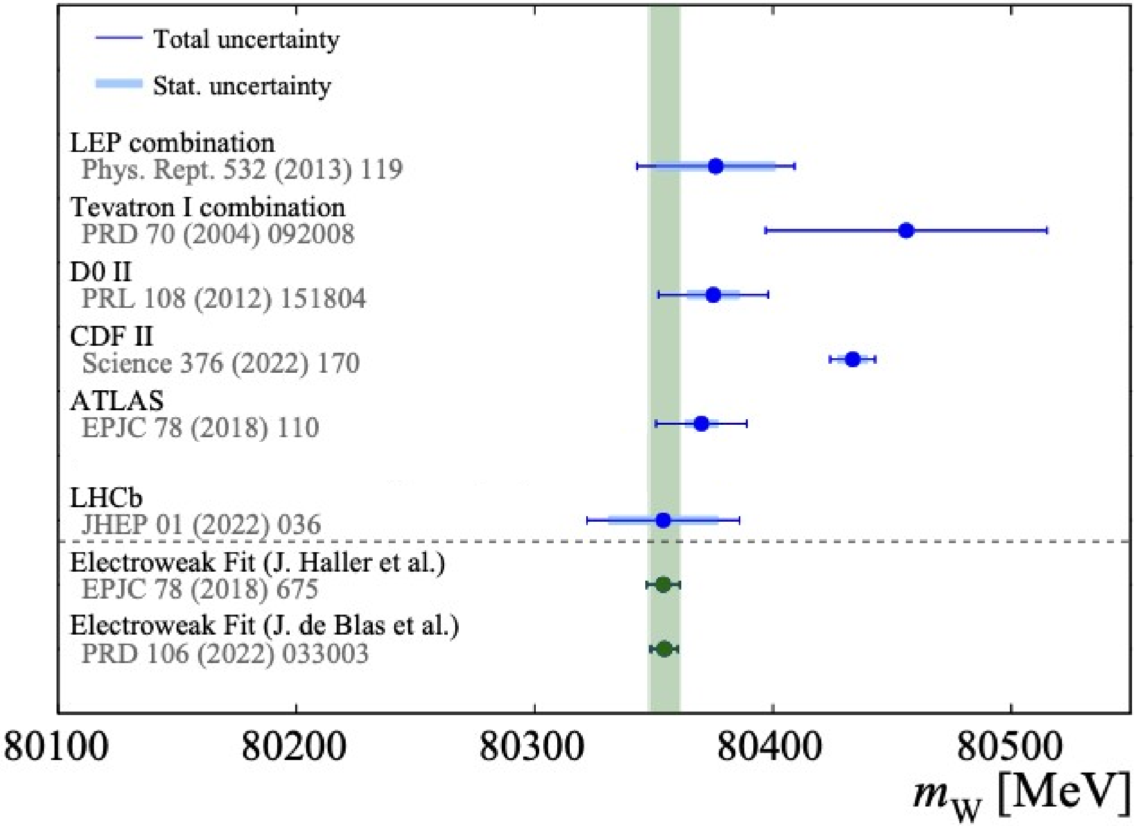


2021



Total uncertainty
Stat. uncertainty
LEP combination
Phys. Rept. 532 (2013) 119
Tevatron I combination
PRD 70 (2004) 092008
D0 II
PRL 108 (2012) 151804
CDF II
Phys.Rev.Lett. 108 (2012) 151803
ATLAS
EPJC 78 (2018) 110
LHCb
JHEP 01 (2022) 036
Electroweak Fit (J. Haller et al.)
EPJC 78 (2018) 675
Electroweak Fit (J. de Blas et al.)
PRD 106 (2022) 033003
80100
80200
80300
80400
80500
m_W [MeV]

2022



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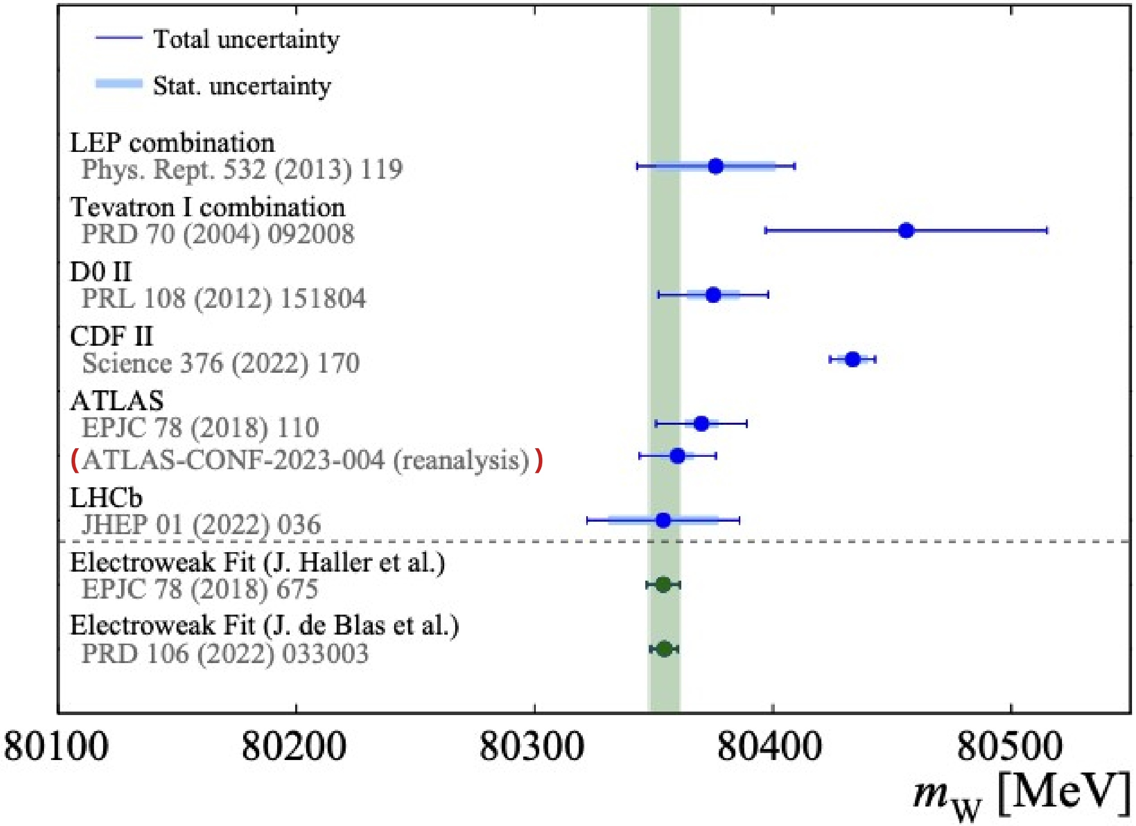
(2023)



Total uncertainty
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Tevatron I combination
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D0 II
PRL 108 (2012) 151804
CDF II
Science 376 (2022) 170
ATLAS
EPJC 78 (2018) 110
(ATLAS-CONF-2023-004 (reanalysis))
LHCb
JHEP 01 (2022) 036
Electroweak Fit (J. Haller et al.)
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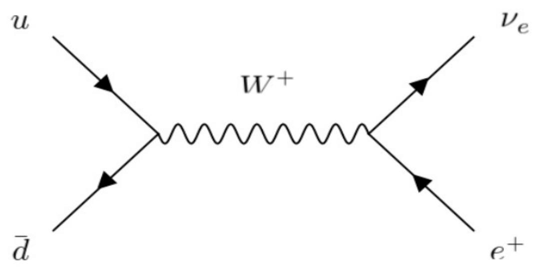
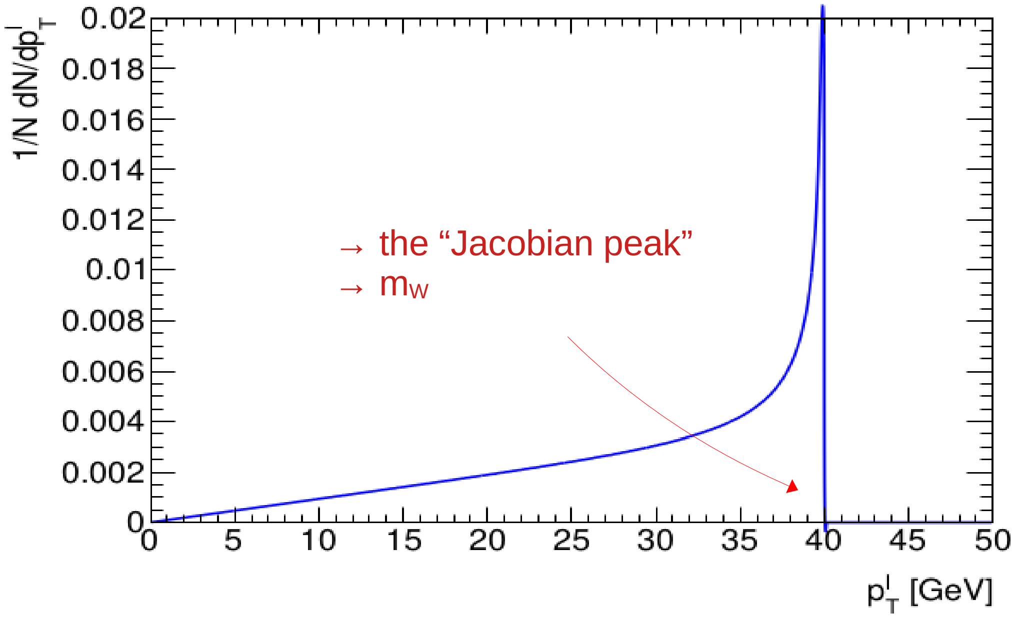
Electroweak Fit (J. de Blas et al.)
PRD 106 (2022) 033003
80100
80200
80300
80400
80500
m_W [MeV]

The W boson mass in proton collisions

- The process at leading order, no width :

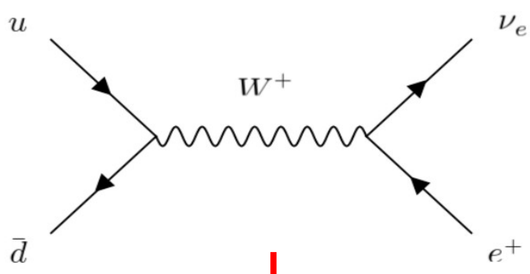


$$\frac{d\hat{\sigma}_{u\bar{d}\to\ell^+\nu}}{dp_{\mathrm{T}}^{\ell}} \propto \frac{\left(1-\frac{2p_{\mathrm{T}}^{\ell}}{m_W^2}\right)}{\sqrt{1-\frac{4p_{\mathrm{T}}^{\ell}}{m_W^2}}}$$

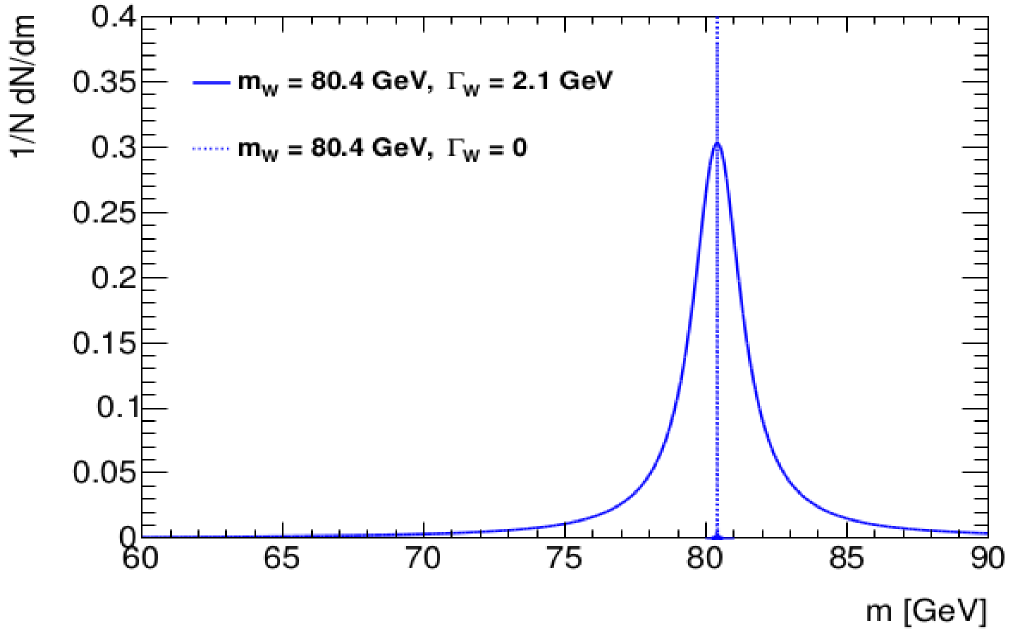


The W boson mass in proton collisions

- Natural width :



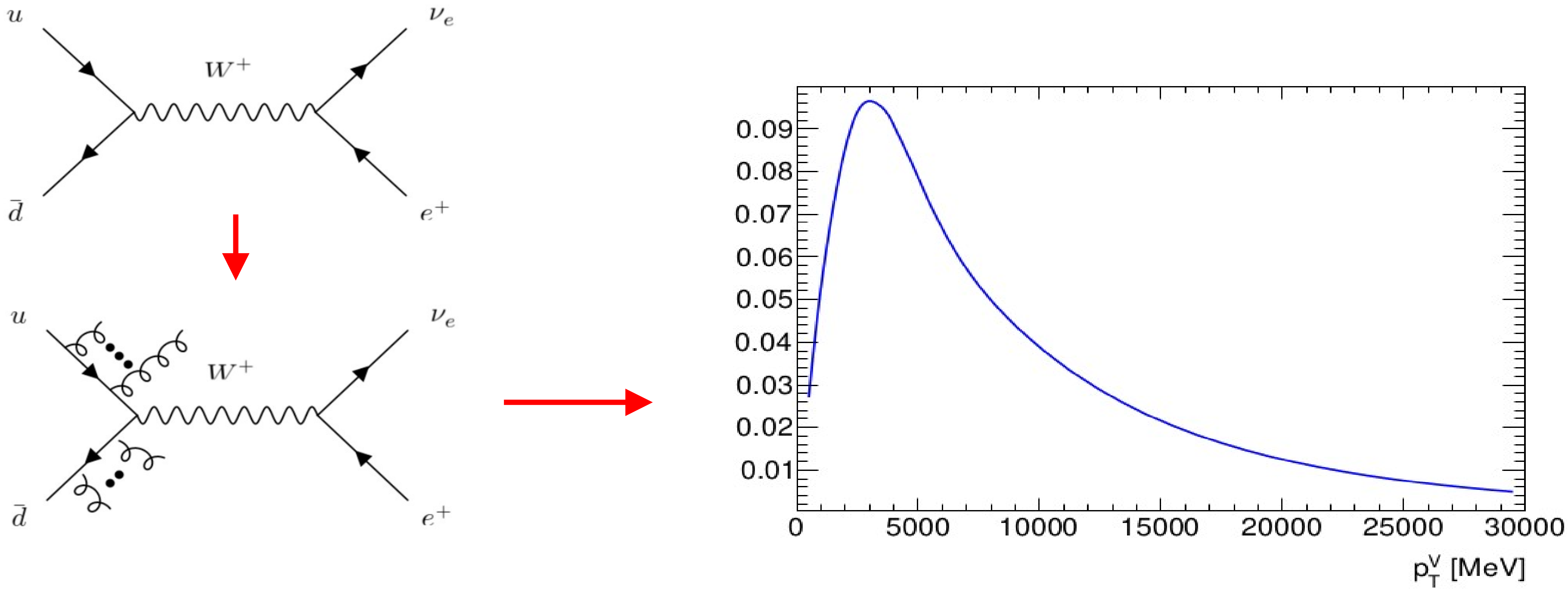
$$\delta(m^2 - m_W^2) \rightarrow \frac{m^2}{(m^2 - m_W^2)^2 + (m\Gamma_W/m_W)^2}$$



The W boson mass in proton collisions

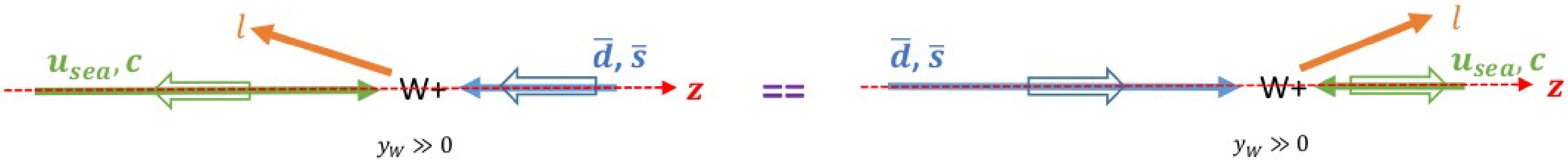
- Radiation in the initial state (QCD)

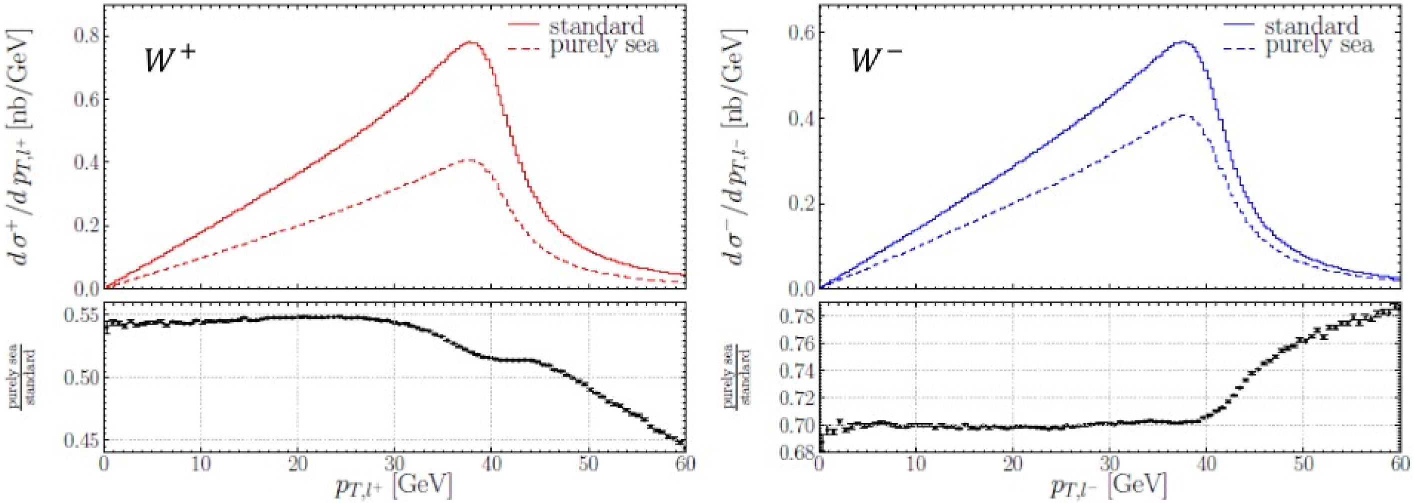
  → non trivial transverse momentum distribution



The W boson mass in proton collisions

- Polarization





Sea: symmetric, unpolarized

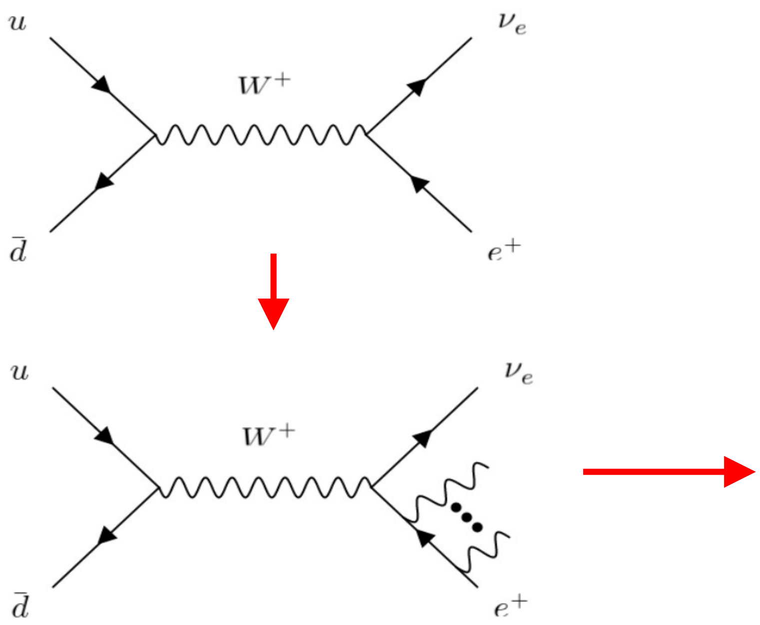
Including u_V, d_V leads to an overall polarization along z

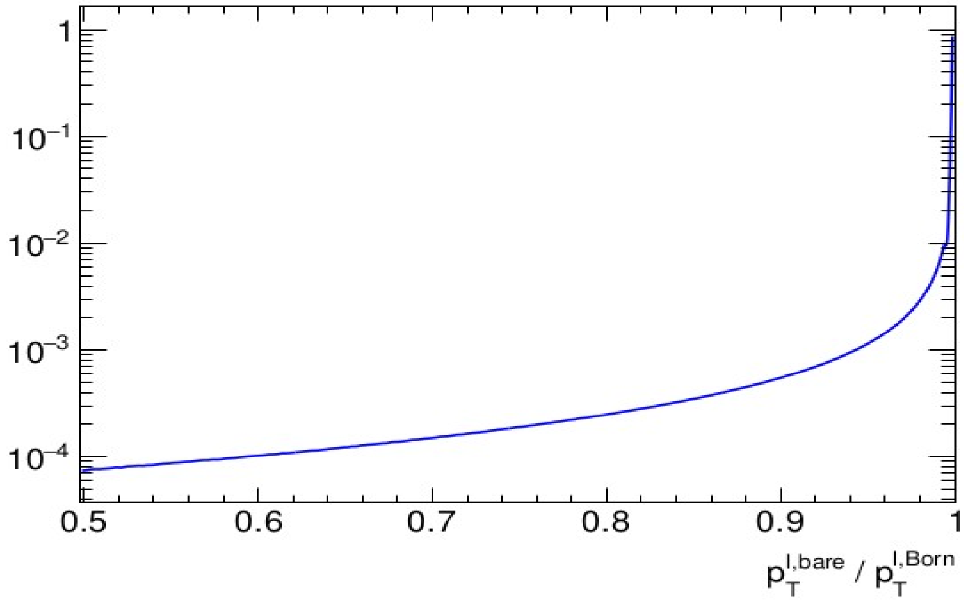
Eur.Phys.J.C69:379-397,2010

The W boson mass in proton collisions

Radiation in the final state (QED)

→ decays leptons lose a fraction of their energy



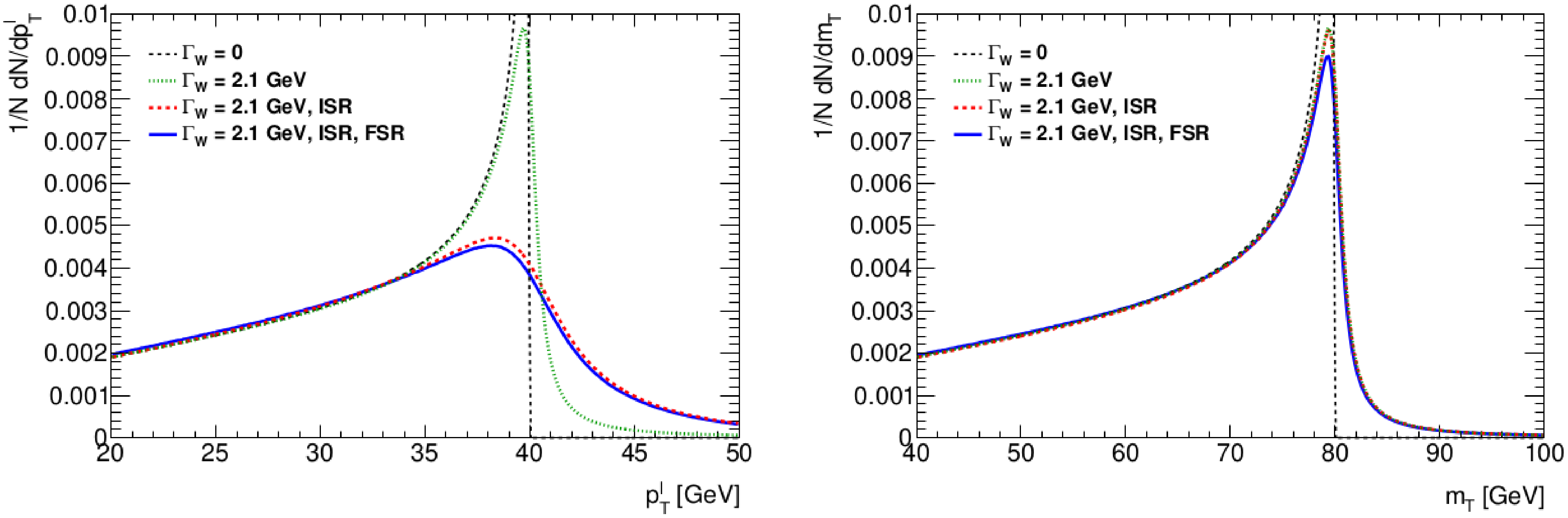


The W boson mass in proton collisions

- Summary of physics effects

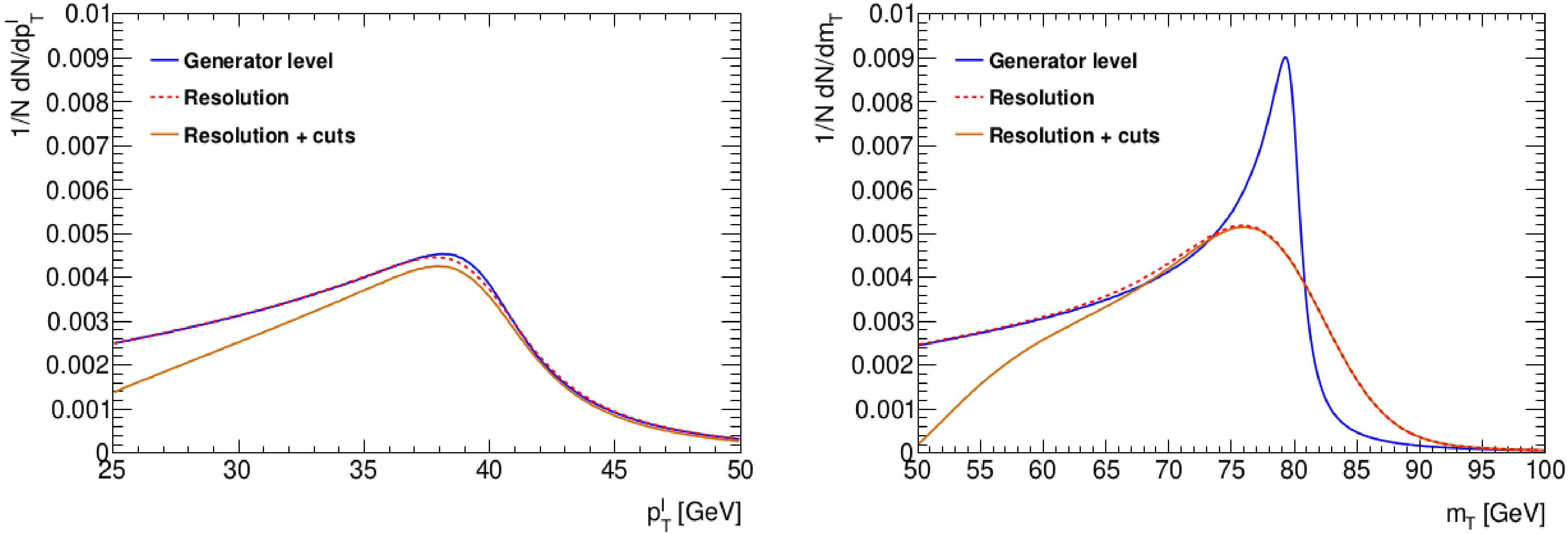
→ all carry uncertainties to be quantified

→ PDFs : boson rapidity (→acceptance); p_T, polarisation (→ distributions)



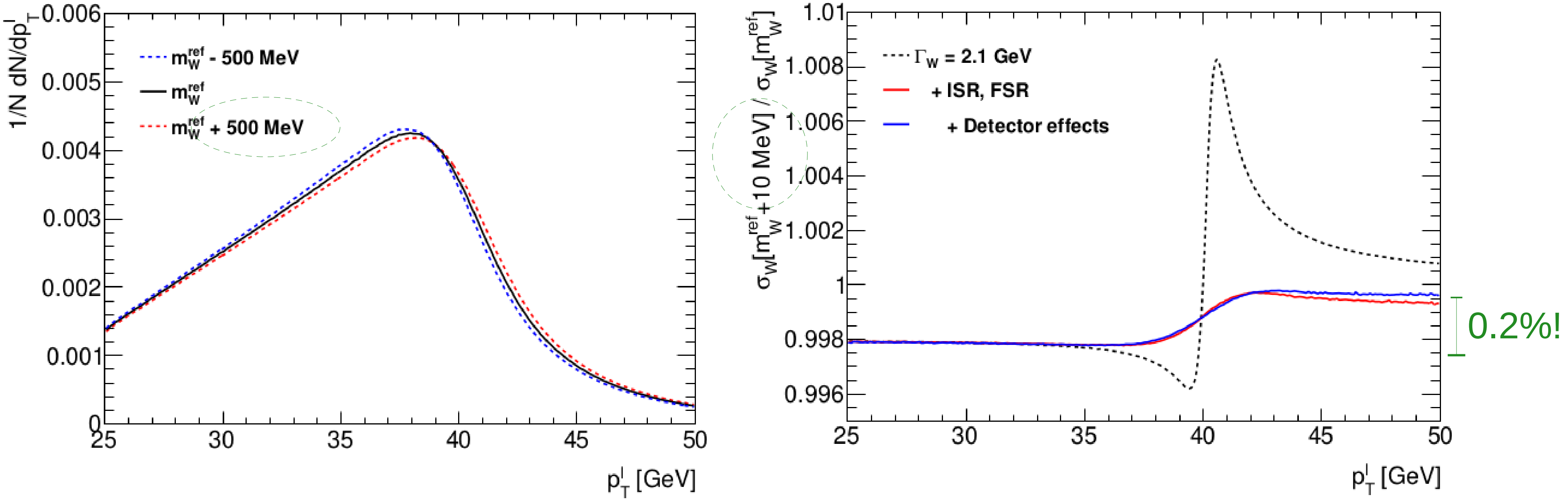
The W boson mass in proton collisions

- Detector effects, also with uncertainties :
  - Lepton calibration and resolution;   Missing E_T resolution ~ 5 – 15 GeV
  - Efficiencies and acceptance ~15% (with non-trivial kinematic dependence!)

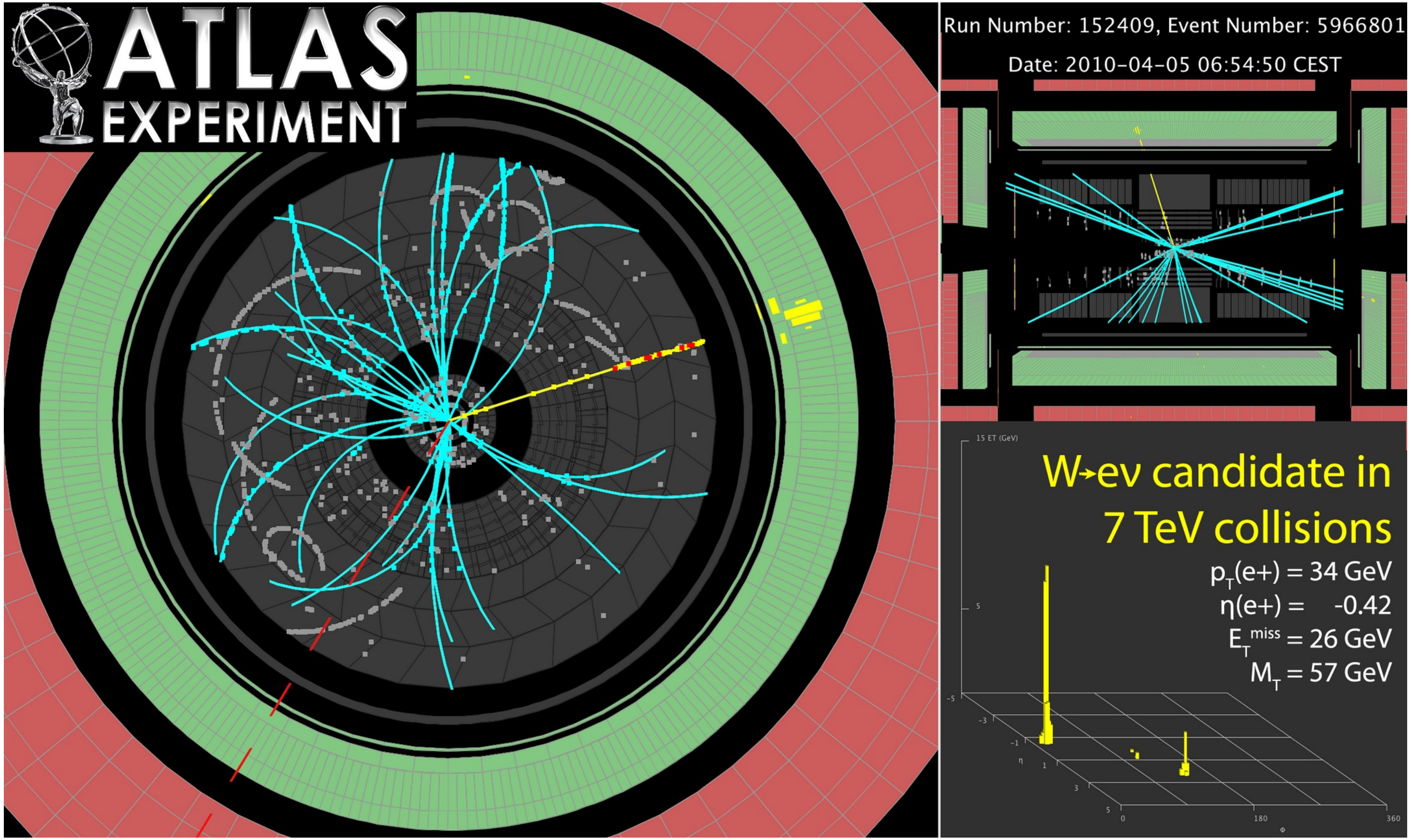


The W boson mass in proton collisions

- Mass measurement : produce models (“templates”) of the final state distributions for different mass hypotheses; compare to data



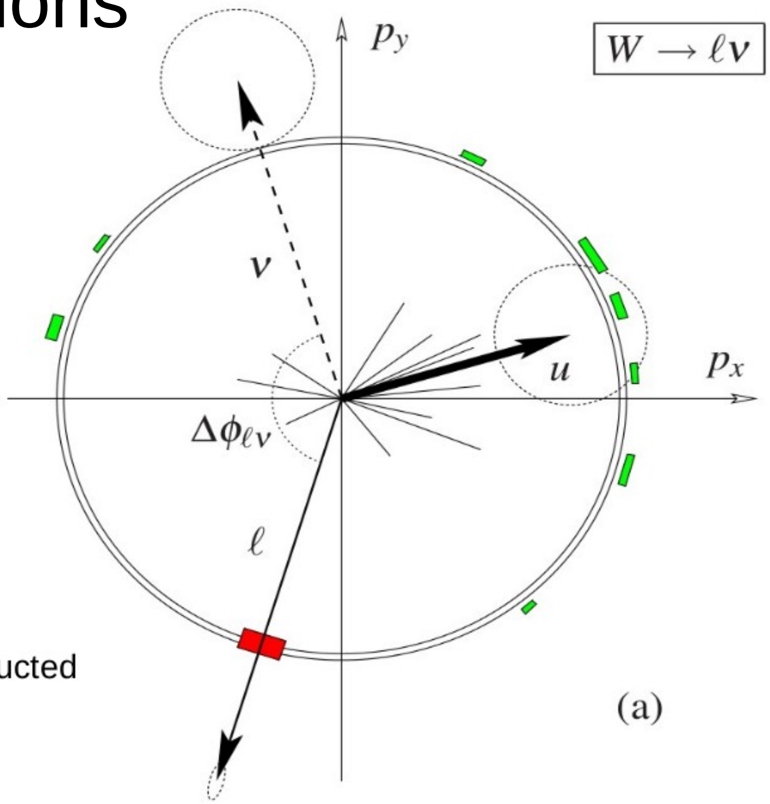
The W boson mass in proton collisions



The W boson mass in proton collisions

- Incomplete kinematics (missing neutrino!)
  → no invariant mass
  → rely on measured quantities, and exploit momentum conservation in the transverse plane

- Event representation :



- Main signature :
  single electron or muon $\vec{p}_T^{\,l}$ $\vec{p}_T^{\,l}$

- Recoil : sum of "everything else" reconstructed in the calorimeters; a measure of $p_T^{W,Z}$

  $$\vec{u}_T = \sum_i \vec{E}_{T,i}$$

- Derived quantities : $\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right)$ $m_T = \sqrt{2p_T^{\ell}p_T^{miss}(1-\cos\Delta\phi)}$

Three slides on calibration

- The Z boson mass is perfectly well know on this scale of precision, so can be used to calibrate the absolute scale of the momentum measurements

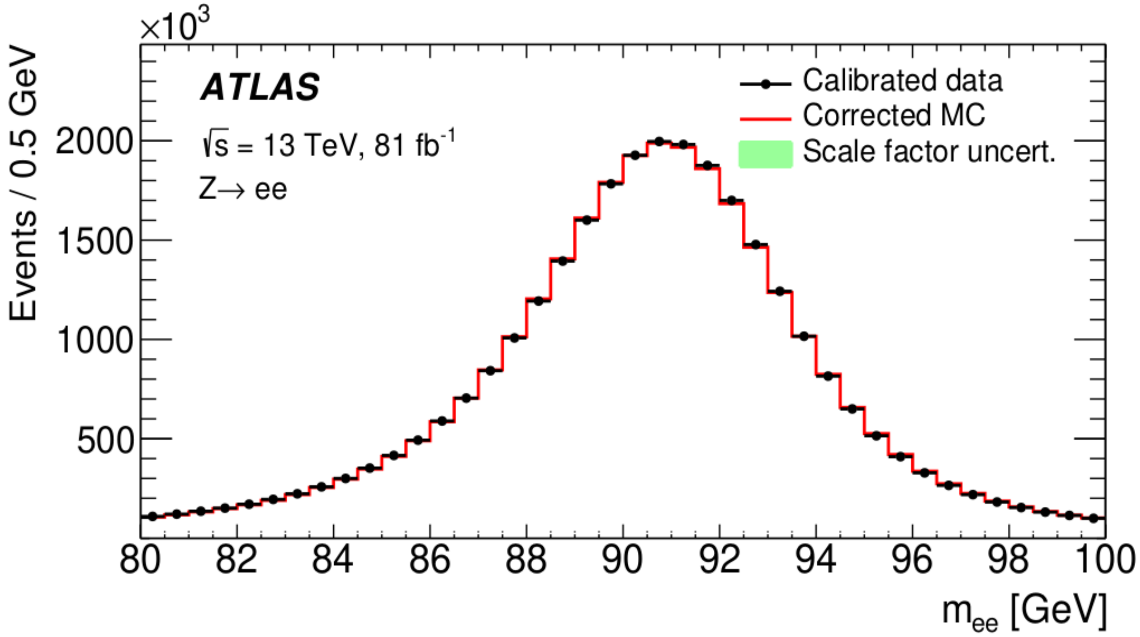
- Detector response derived from first principles to for calorimeters, ~0.05% for tracking detectors.

  ~0.01% is required here

- m_Z is known to ~0.002%,

  $m_{J/psi}$ to ~ 10^{-6}

  → used for final adjustments



Three slides on calibration

- Leptons calibration from "perfectly known" resonances

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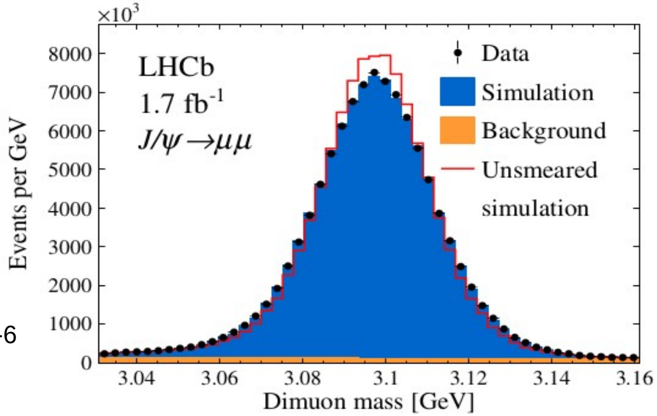
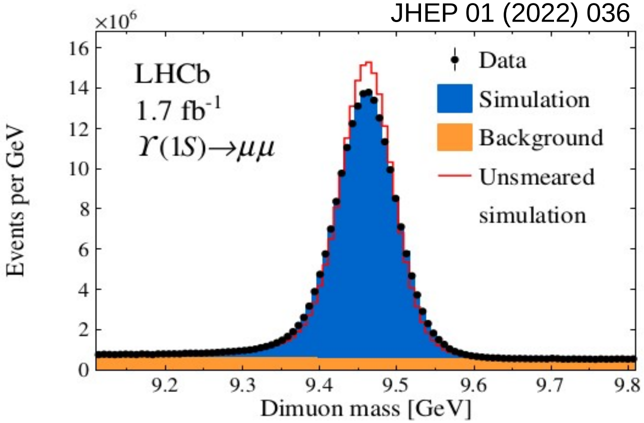
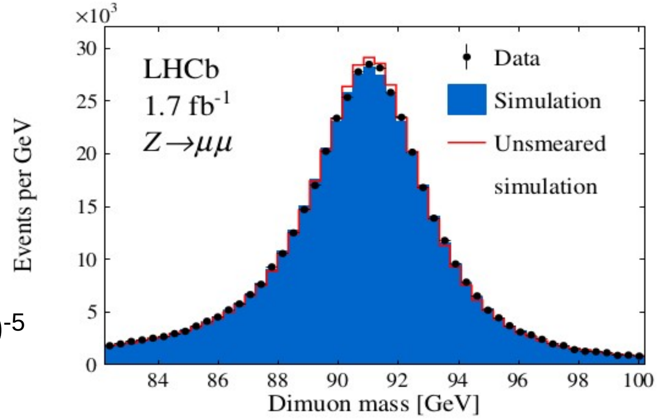




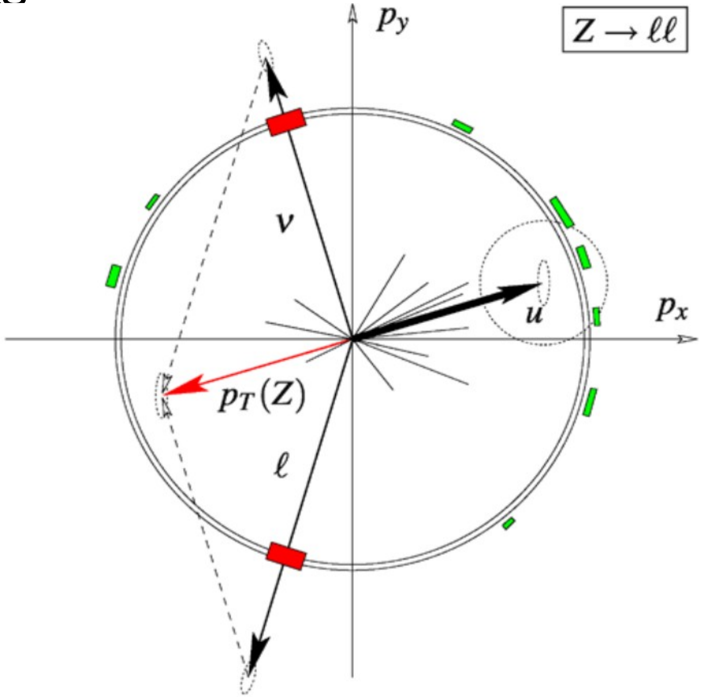
$\delta m_{J/psi} / m_{J/psi} \sim 10^{-6}$

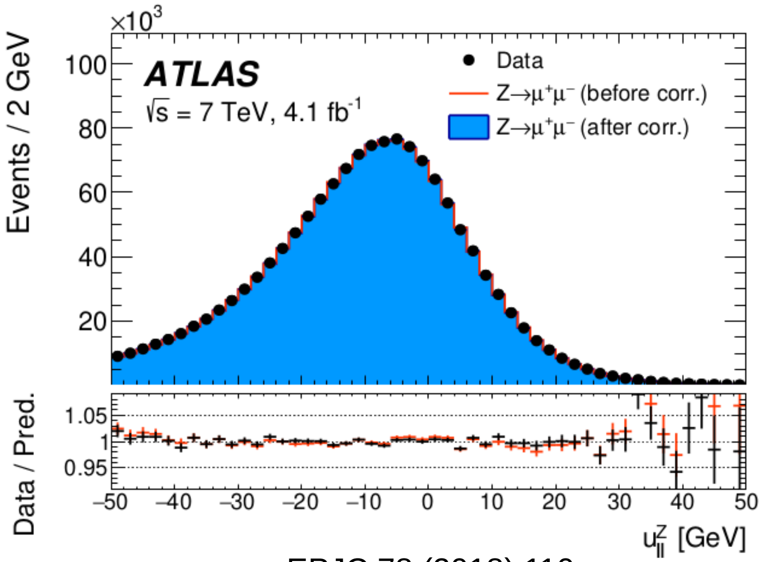


$\delta m_Z / m_Z \sim 2.10^{-5}$

Three slides on calibration

- Recoil response & resolution calibrated using over-constrained kinematics in Z events





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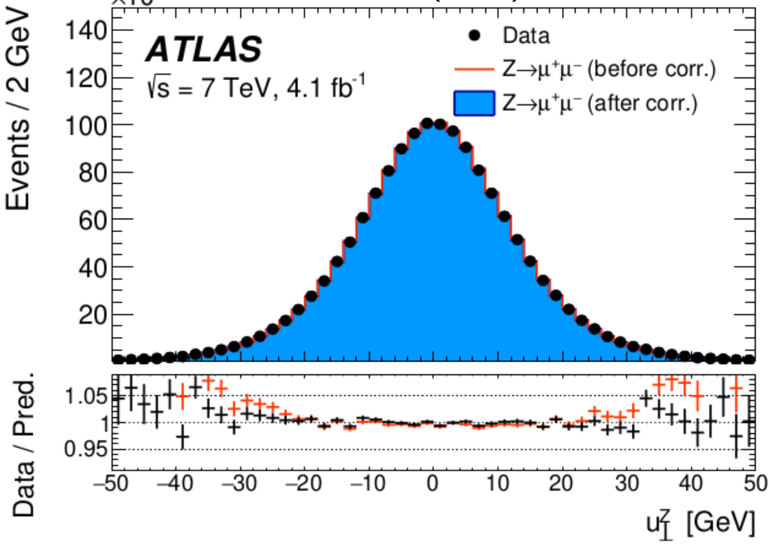


Vector-boson production at the LHC

- The magic formula, true to all orders in QCD:

$$\frac{d^5\sigma}{dp_1\,dp_2} = \frac{d^3\sigma}{dm\,dy\,dp_T}\left[\left(1+\cos^2\theta\right)+\sum_i A_i\left(p_T,y\right)f_i\left(\theta,\phi\right)\right]$$

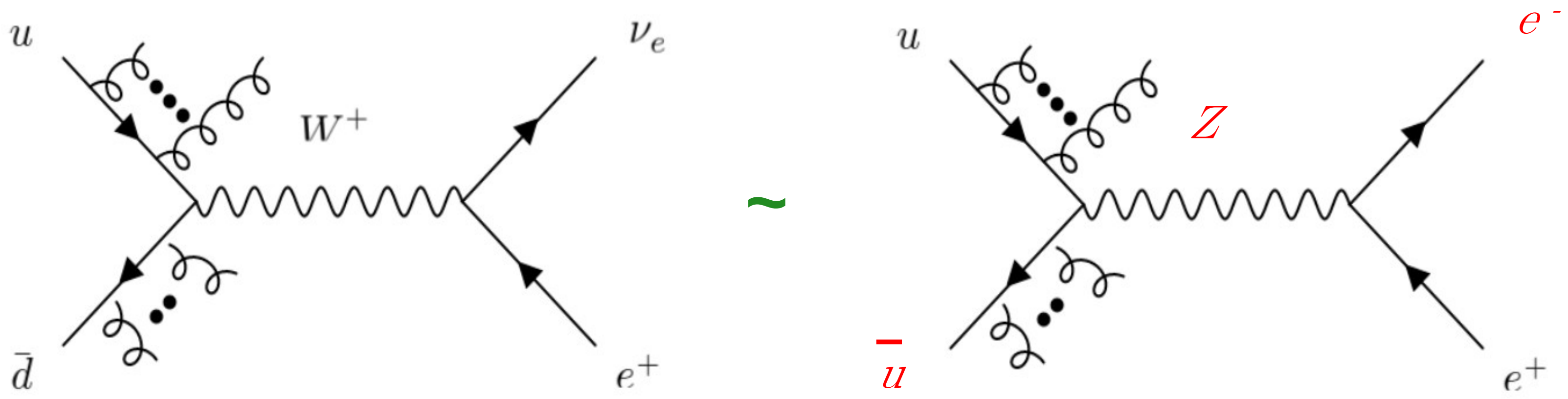
production | decay

Boson kinematics | polarization

  - Not implemented in this way in generators (which evaluate matrix elements and PDFs) but useful to factor the different QCD modelling aspects, and describe each component using the most appropriate tool

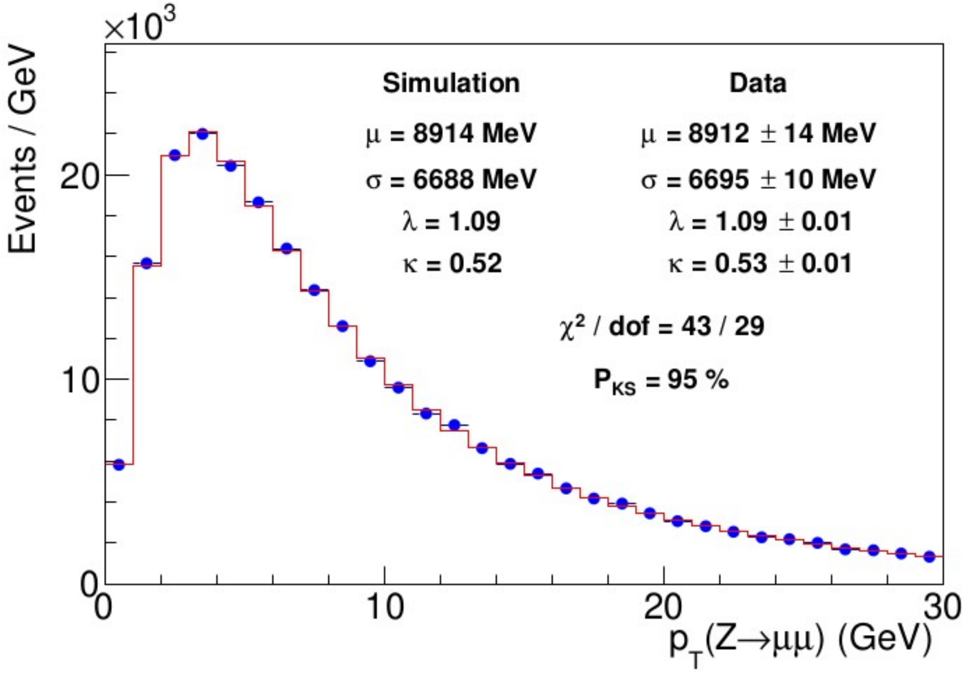
Transverse momentum distribution

- Initial state radiation involves large corrections, and is in part non-perturbative. W events are only partly measured (neutrino!)
- Approach : adjust model parameters using Z events, which are close to W's and can be measured precisely; extrapolate to W production

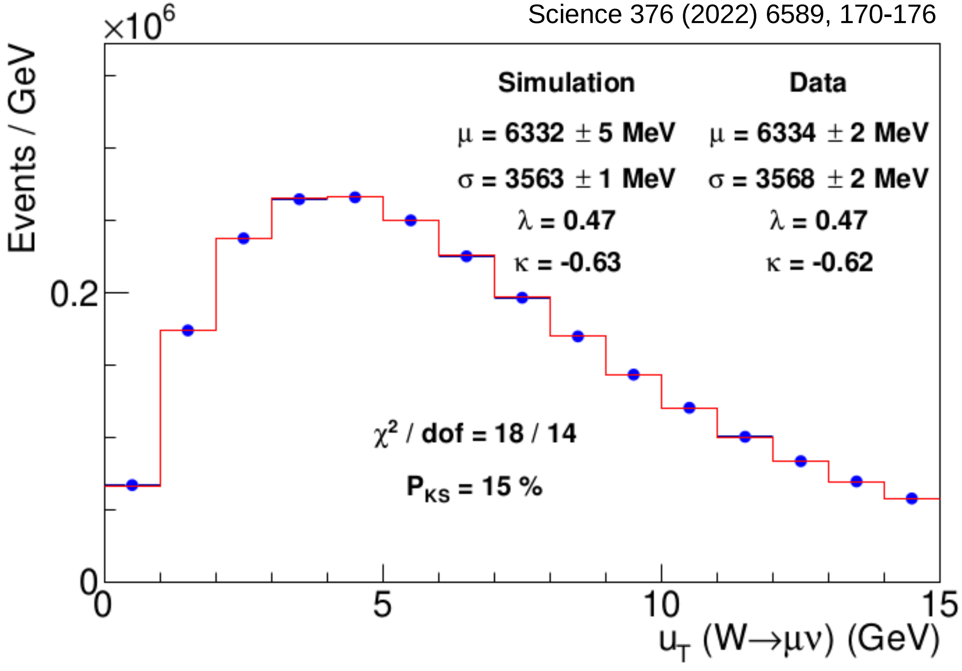


Transverse momentum distribution

- **Tevatron** : Z-based model tuning (Resbos); no extrapolation uncertainties, but validation with W events



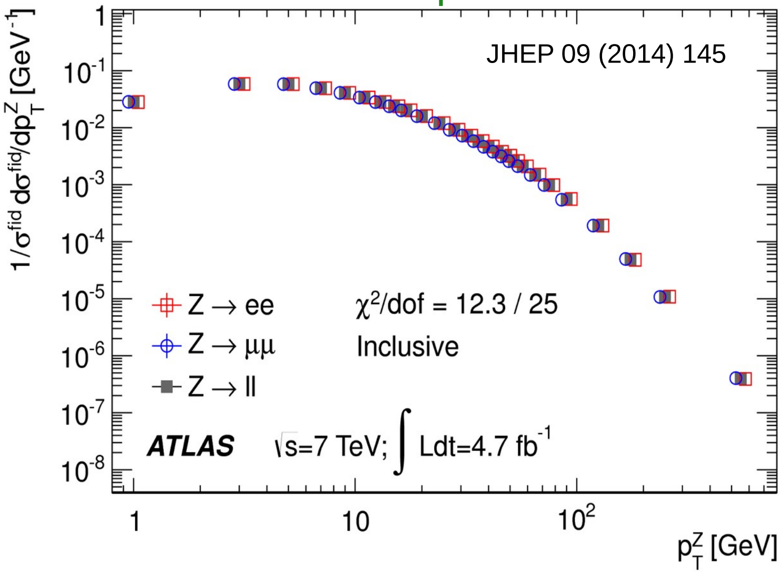
Science 376 (2022) 6589, 170-176

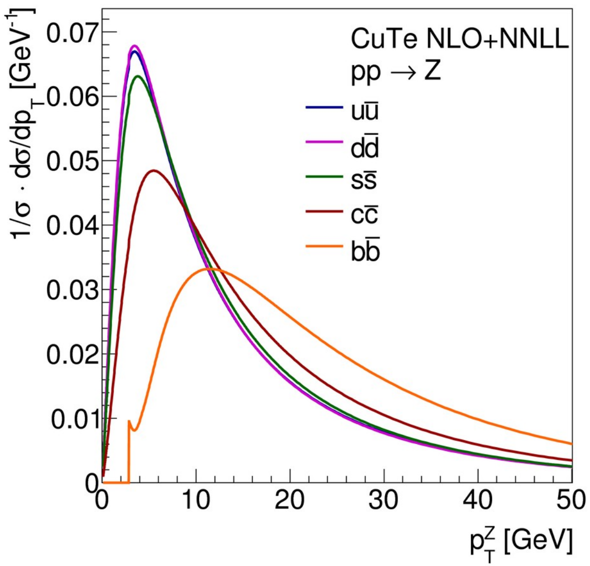


Transverse momentum distribution

- **ATLAS** : Z-based model tuning (Pythia) + Z→W extrapolation
  - Corresponding uncertainties :
    - Treatment of HQ mass and thresholds; HQ PDFs
    - PDF assumed in the shower

Measurement precision ~0.5%





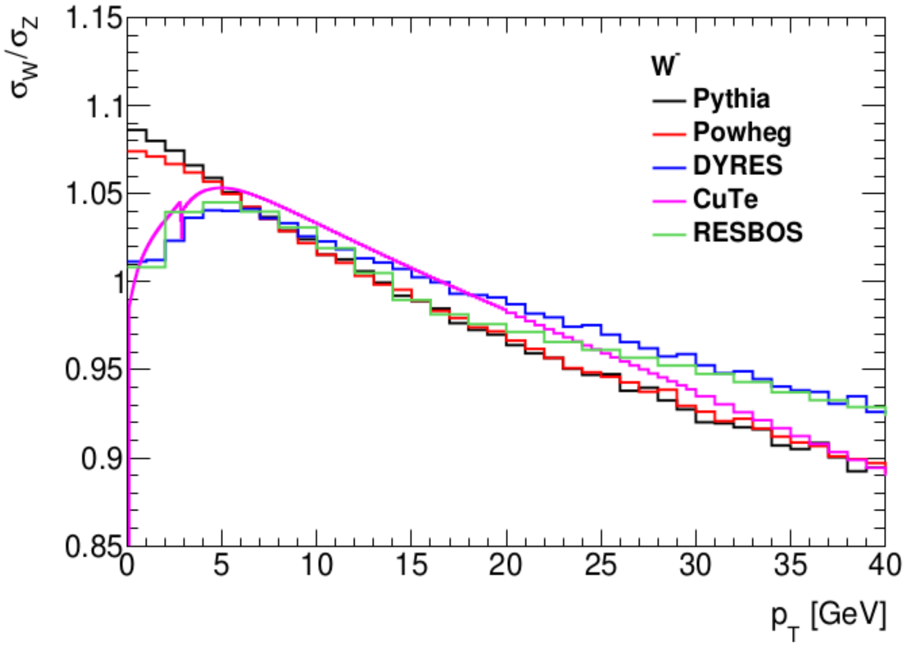
Transverse momentum distribution

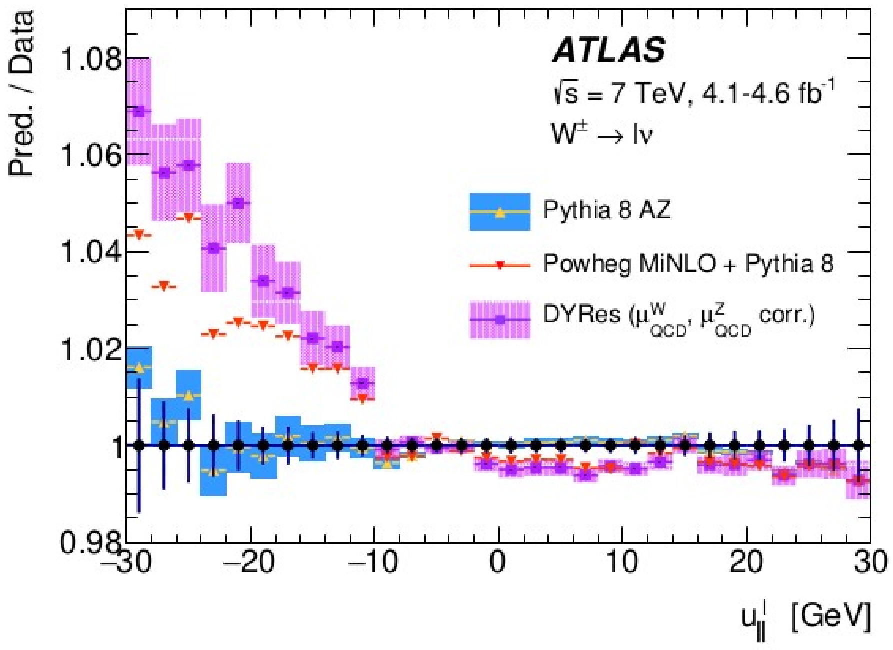
- **ATLAS** : Z-based model tuning (Pythia) + Z→W extrapolation
  - Addressed through synchronized
    - variations of the c, b PDFs *in the shower*
    - Variations of the HF quark masses (kinematic parameters in the shower)
    - Shower PDF uncertainty...

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

Transverse momentum distribution

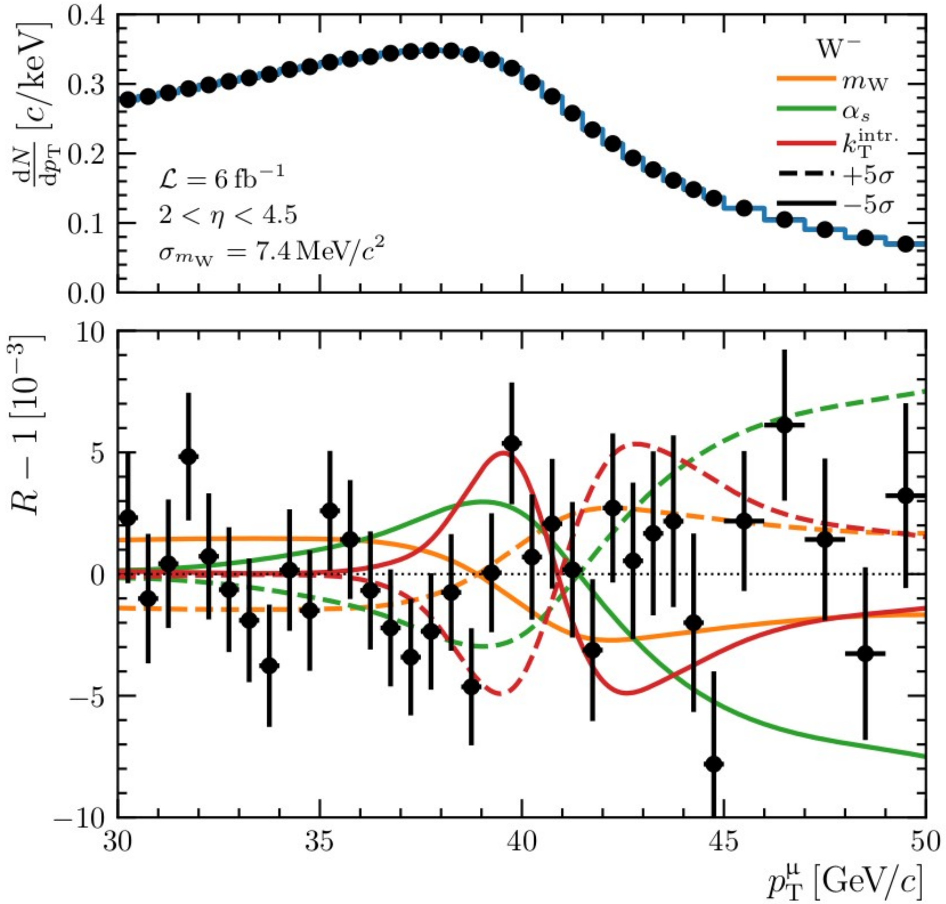
- **ATLAS** : Z-based model tuning (Pythia) + Z→W extrapolation
  - Why Pythia?!





Transverse momentum distribution

- **LHCb** :
  - Z data : p_T^Z, ϕ^*
  - simultaneous fits to m_W and p_T^W in W events
  - repeated for different models:
    - Pythia, Herwig
    - Powheg+Pythia, Herwig
    - Dyturbo



Transverse momentum distribution

- **LHCb** :
  - $\chi^2 \sim 105/102$
  - Decorrelation between p_T^Z and p_T^W addressed allowing for different values of α_S in the parton shower (clearly a knob)
    - Imposing $\alpha_S^W == \alpha_S^Z$ gives

      $\delta m_W = +39$ MeV

      $\chi^2 \sim 130/102$

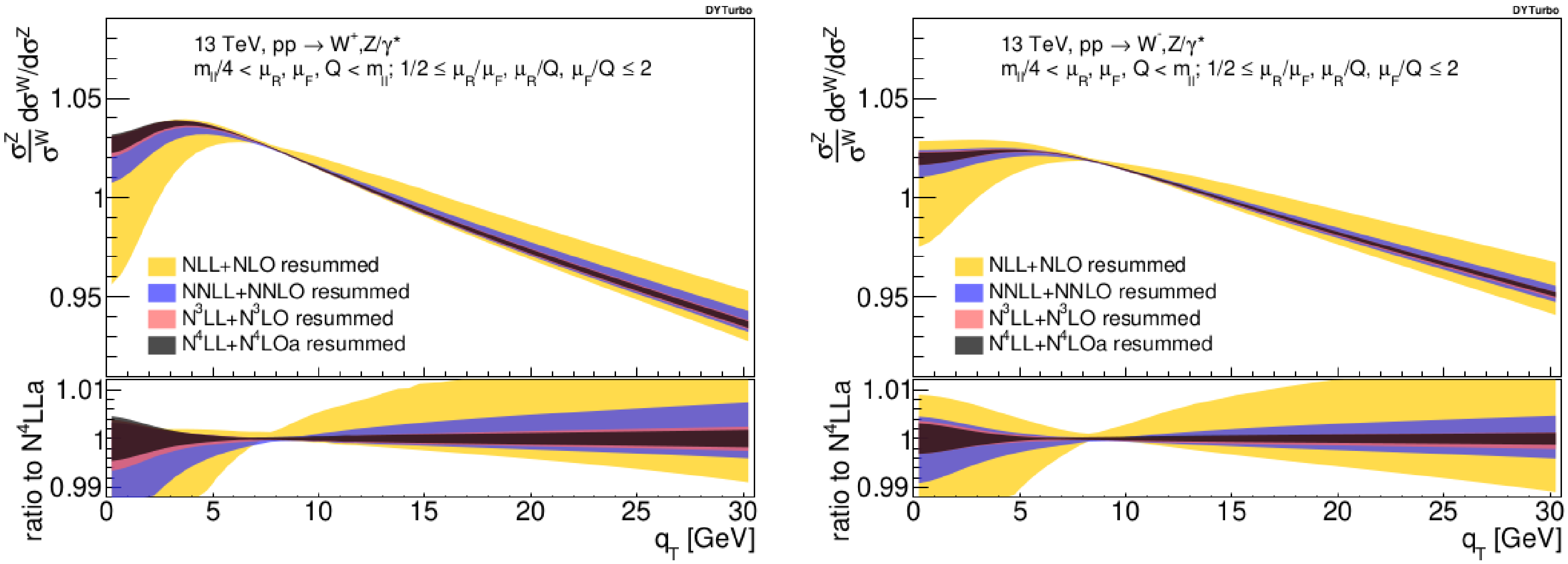
  → supports more flexible model

Parameter	Value
Fraction of $W^+ \to \mu^+\nu$	0.5288 ± 0.0006
Fraction of $W^- \to \mu^-\nu$	0.3508 ± 0.0005
Fraction of hadron background	0.0146 ± 0.0007
α_s^Z	0.1243 ± 0.0004
α_s^W	0.1263 ± 0.0003
k_T^{intr}	1.57 ± 0.14 GeV
A_3 scaling	0.975 ± 0.026
m_W	80362 ± 23 MeV

Transverse momentum distribution

- Analytical resummation – now at approximate N4LO+N4LL

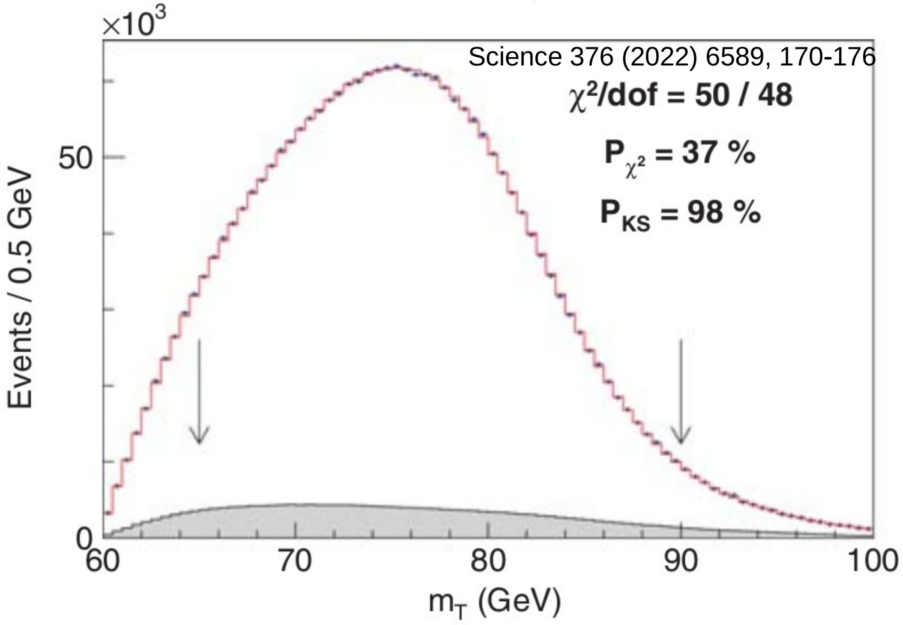
2303.12781

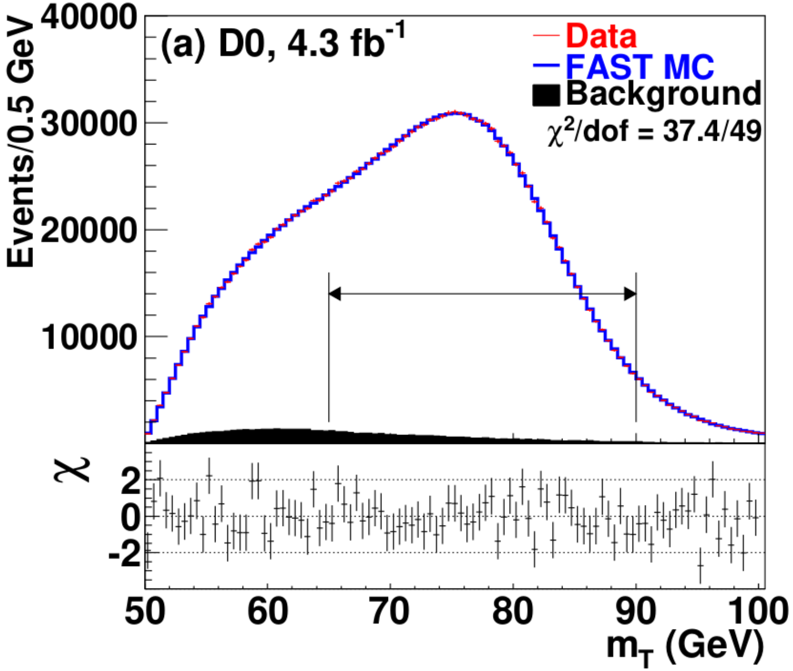


  - Essentially removing any uncertainty in the W/Z pT distribution ratio, but….
  - flavour-dependent intrinsic kT; heavy-quark mass effects; process-dependent EWK effects… are not (yet) addressed (and are the things that matter for mW)

At the end of the day...

- CDF, D0





CDF (8.8 fb^{-1}) [*Science* ***376*** *(2022) 170*]

$m_W = 80433.5 \pm 6.4$ (stat.) $\pm$ 6.9 (sys.)

PDF unc. 3.5 MeV (NNPDF3.1)

D0 (4.3+1.1 fb^{-1}) [*Phys. Rev.* ***D89*** *(2014) 012005*]

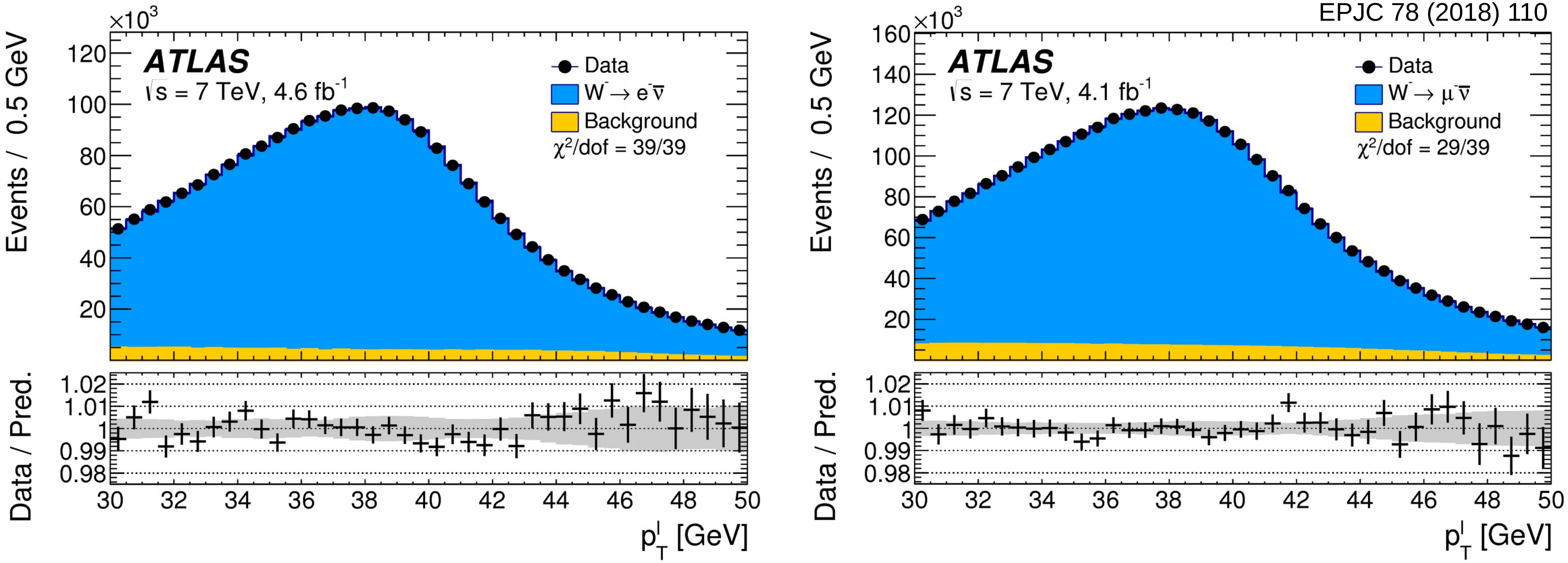
$m_W = 80375 \pm 11$ (stat.) $\pm$ 20 (sys.) MeV

PDF unc. ~10 MeV (CTEQ66)

At the end of the day...

- ATLAS

EPJC 78 (2018) 110



$m_W = 80370 \pm 7\ \text{(stat.)} \pm 18\ \text{(sys.)}\ \text{MeV}$

PDF unc. 9 MeV; envelope 8 MeV (CT10, CT14, MMHT2014)

At the end of the day...

- LHCb

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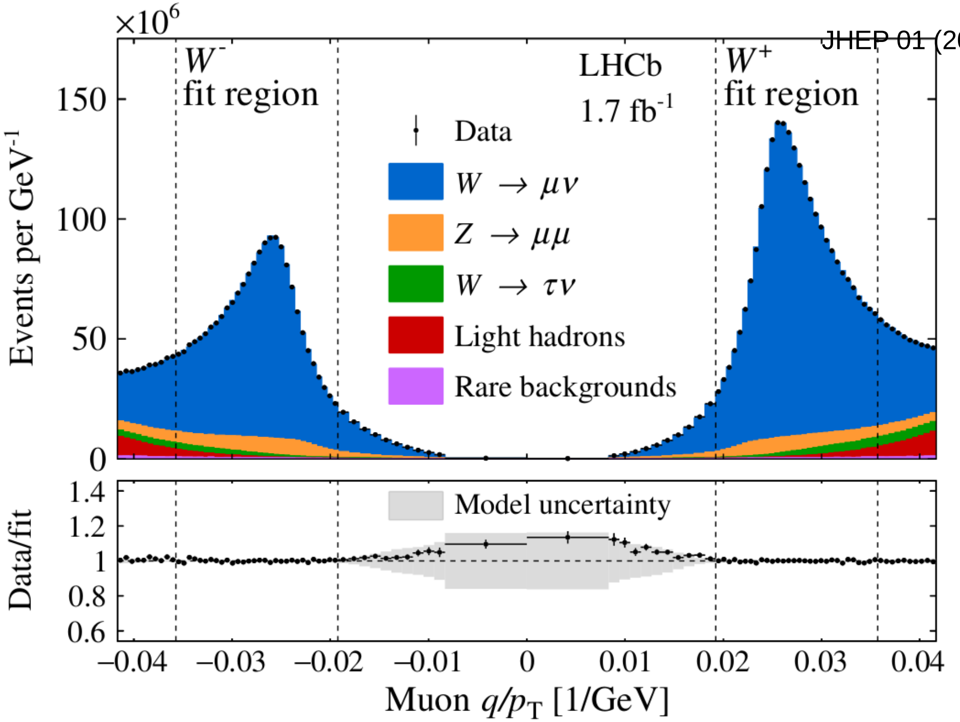


$$m_W = 80354 \pm 23_{\rm stat} \pm 10_{\rm exp} \pm 17_{\rm theory} \pm 9_{\rm PDF}\,{\rm MeV}.$$

PDF envelope 9 MeV (NNPDF3.1, CT18, MSHT20)

PDF dependence

- Recent ATLAS update (ATLAS-CONF-2023-004)
  - Analysis now/ a profile-likelihood fit (joint constraints on mW and systematics from the p_T^l and m_T distributions
  - More detailed study of the PDF dependence of the result

PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
MSHT20	$80358.9^{+13.0}_{-16.3}$	$80379.4^{+24.6}_{-25.1}$	$80356.3^{+14.6}_{-14.6}$
NNPDF3.1	$80344.7^{+15.6}_{-15.5}$	$80354.3^{+23.6}_{-23.7}$	$80345.0^{+15.5}_{-15.5}$
NNPDF4.0	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$

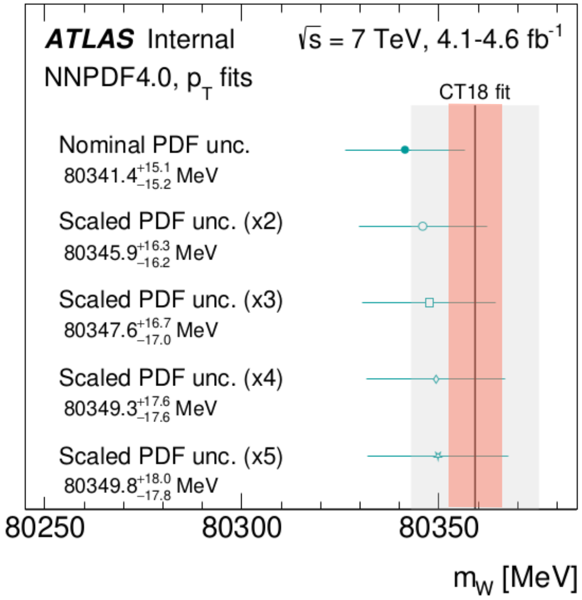
~17% improvement in uncertainty from using a profile likelihood analysis

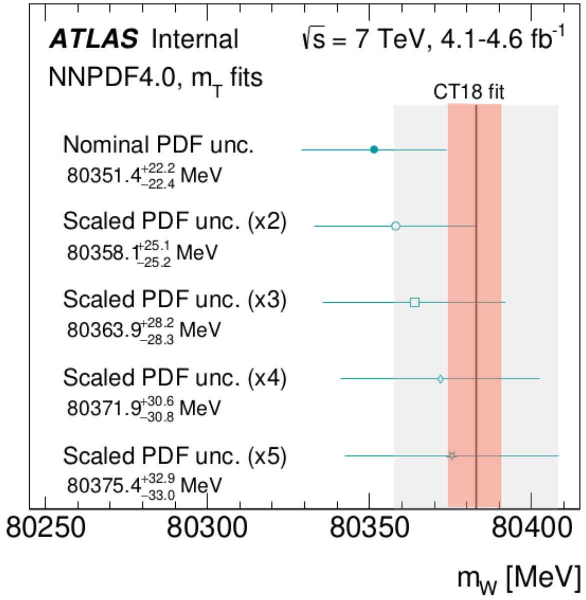
Large PDF dependence; eg NNPDF4.0 and CT18 differ by 18 MeV.

Estimated PDF uncertainties 3 → 9 MeV. What to do??

PDF dependence

- Fundamental reason for the difference is not clear, but one can study the influence of the pre-fit uncertainties on the fit result.
- Considering CT18 (worst uncertainties) and NNPDF4.0 (smallest uncertainties) as example :





Model	Model dependence
stiff	larger
↕	↕
flexible	smaller

~convergence

Comments

- The W-boson mass measurement does typically **not** use state of the art theory… which sounds unfortunate, for such an important test
  - Bad reasons : tradition; sociology; disconnection from theory caused by the lengthy experimental procedures, ….
  - Better reasons : being based on detector-level distributions, the measurement requires a fully exclusive description of the final state (QCD and QED showers, underlying event). Exclusive tools are generally behind, in terms of perturbative accuracy
- Recent developments of relevance for the measurement
  - N^3LO / $N^{3/4}LL$ QCD;
  - mixed QCD/EW corrections : fixed-order results; difficult to exploit for now
- The “dream tool” for this measurement would be a consistent interface between the exclusive MC generators and state-of-the-art perturbative accuracy. Huge challenge, but ultimately fundamental for this field.

m_W combination

ATLAS	Maarten Boonekamp, Jan Kretzschmar
CMS	Simone Amoroso, Josh Bendavid, Martin Grünewald
LHCb	Will Barter, Mika Vesterinen, Menglin Xu
CDF	Chris Hays
D0	Boris Tuchming, Chen Wang
Theory	Alessandro Vicini

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHC-TEV-MWWG

arXiv:2308.09417

Measurements of m_W

D0 (4.3+1.1 fb^{-1}) [*Phys. Rev.* ***D89*** *(2014) 012005*]

m_W = 80375 ± 11 (stat.) ± 20 (sys.) MeV

CDF (8.8 fb^{-1}) [*Science* ***376*** *(2022) 170*]

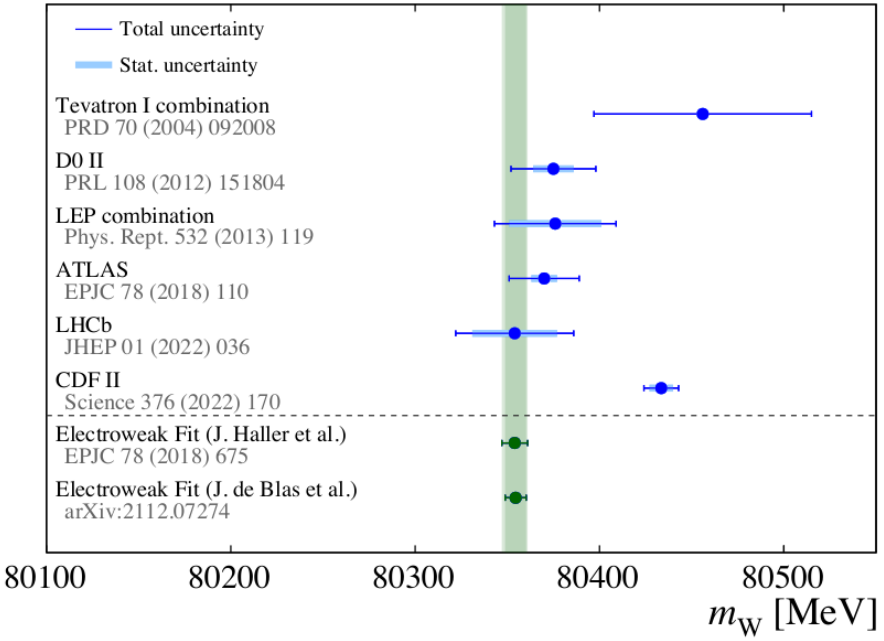
m_W = 80433.5 ± 6.4 (stat.) ± 6.9 (sys.) MeV

ATLAS (4.6 fb^{-1}) [*Eur. Phys. J.* ***C78*** *(2018) 110*]

m_W = 80370 ± 7 (stat.) ± 18 (sys.) MeV

LHCb (1.7 fb^{-1}) [*JHEP* ***01*** *(2022) 036*]

m_W = 80354 ± 23 (stat.) ± 22 (sys.) MeV



Analysis strategy

- Measurements performed at different times, using different baseline PDFs and QCD tools : “translate” existing result to common baseline
- Two-step procedure :
  - correct to common PDF & QCD accuracy
  - combination including correlations

m_W^{CDF}	m_W^{D0}	m_W^{ATLAS}	m_W^{LHCb}
CTEQ6M	CTEQ6.6	CT10nnlo	CT18/NNPDF/MSHT20
↓	↓	↓	↓
δm_W^{CDF}	δm_W^{D0}	δm_W^{ATLAS}	δm_W^{LHCb}

Common baseline

→ $m_W^{combined}$

… and repeat, for different PDFs

Measurement extrapolations

- Full procedure, decomposed into generator and PDF effects :

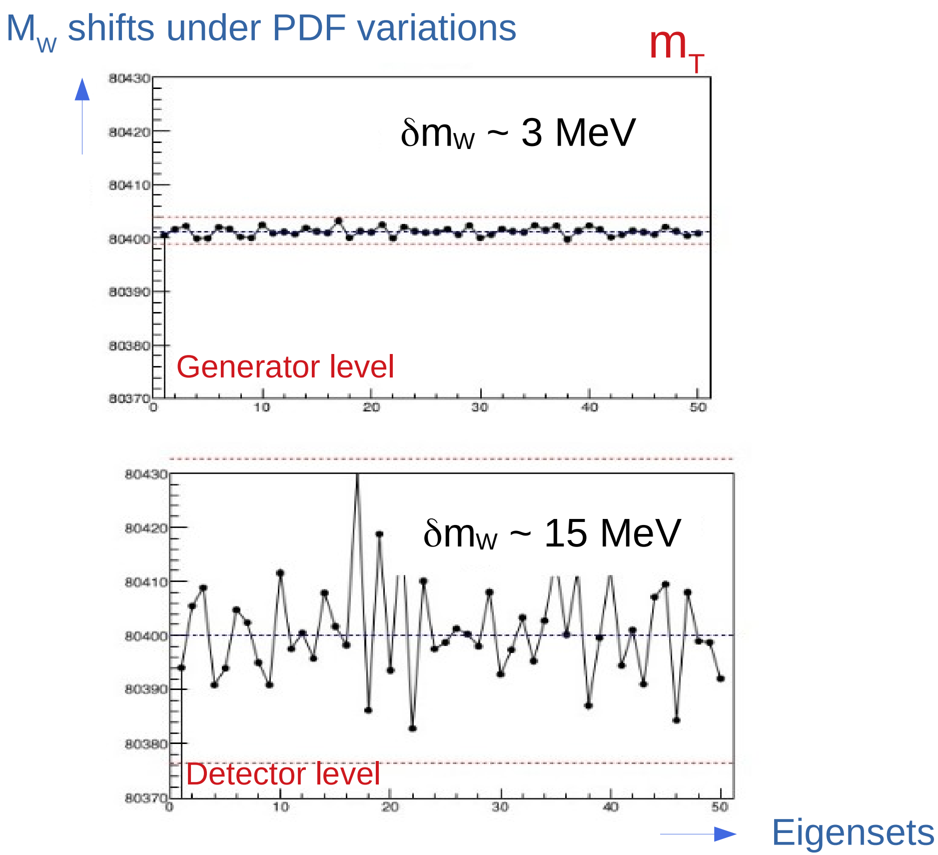
$$m_W^{updated} = \boxed{m_W^{ref.}} + \boxed{\delta m_W^{QCD}} + \boxed{\delta m_W^{PDF}}$$

published — Improved predictions, for reference PDF — PDF extrapolation

- Published measurements :
  - CDF : Resbos1 (NLO) CTEQ6M (NLO), corrected post-hoc to NNPDF3.1
  - D0 : Resbos1 (NNLO) CTEQ6.6 (NLO)
  - ATLAS : Powheg+Pythia; rapidy+spin corr. at NNLO CT10 (NNLO)
  - LHCb : Powheg+Pythia; spin corr. at NNLO <NNPDF3.1,CT18,MSHT20> (NLO)
- Extrapolations (δm_W) evaluated using generator-level reweightings and "emulation" of detector effects
  - δm_W^{PDF} PDF targets : APMB16, CT14, CT18, MMHT2014, MSHT20, NNPDF3.1, NNPDF4.0
  - δm_W^{QCD} Applies when generators or QCD improvements are beyond the quoted uncertainties.

Measurement extrapolations

- Measurement emulation
  - detector effects matter in the evaluation of PDF uncertainties and extrapolations
  - parameterised responses with ~2% accuracy allow evaluating PDF corrections with ~1 MeV precision
- Used for CDF, D0, ATLAS
  - The LHCb measurement is “live” and rerun on request for this project



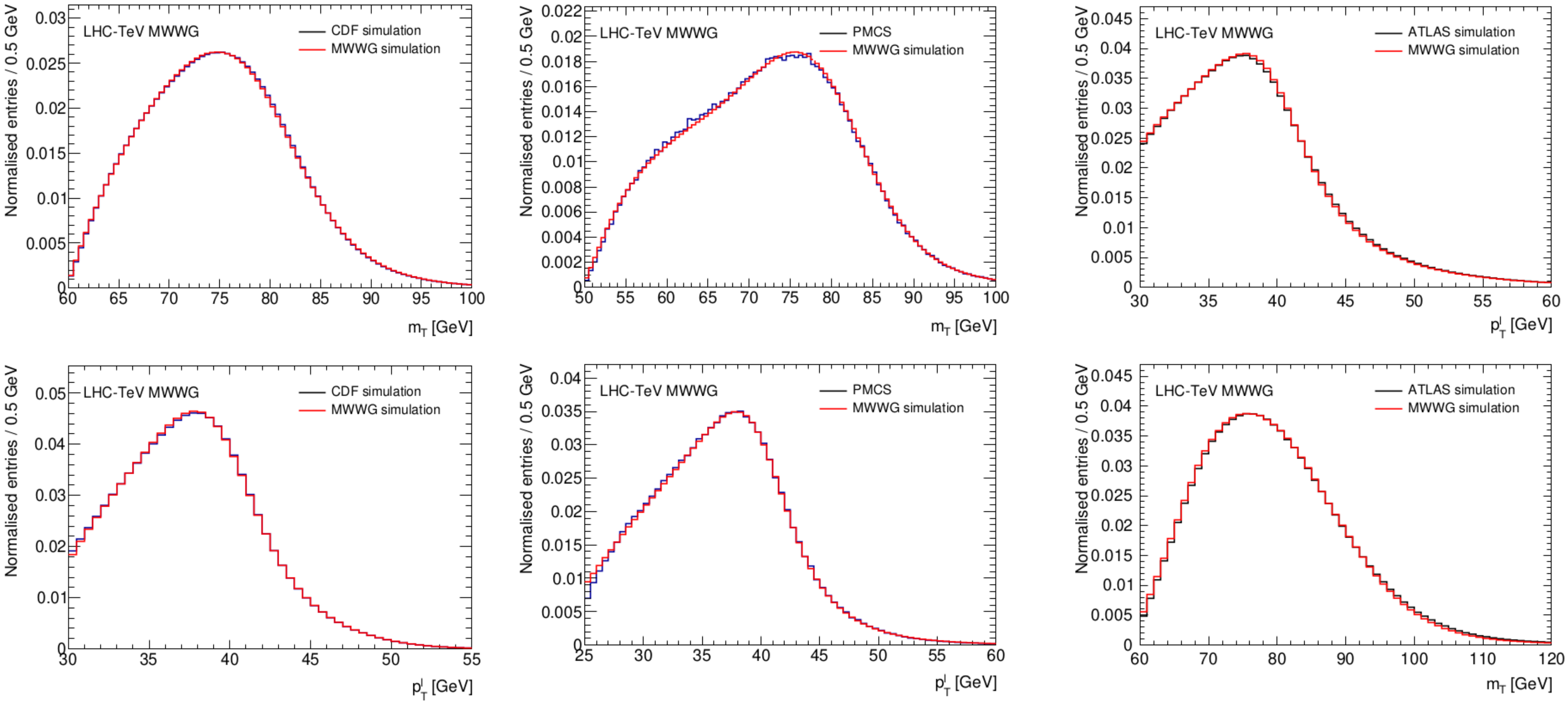
Emulation (CDF, D0, ATLAS)

- Lepton & recoil resolutions from published information

- Event selections, fit ranges as in the original measurements

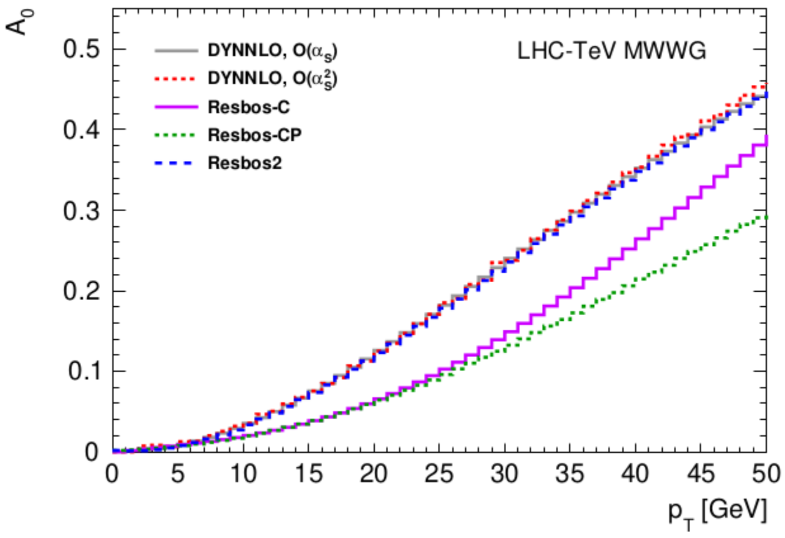
Experiment	Event requirements	Fit ranges
CDF	$30 < p_T^\ell < 55$ GeV	$32 < p_T^\ell < 48$ GeV
	$\lvert\eta_\ell\rvert < 1$	$32 < p_T^\nu < 48$ GeV
	$30 < p_T^\nu < 55$ GeV	$60 < m_T < 100$ GeV
	$65 < m_T < 90$ GeV	
	$u_T < 15$ GeV	
D0	$p_T^e > 25$ GeV	$32 < p_T^e < 48$ GeV
	$\lvert\eta_\ell\rvert < 1.05$	$65 < m_T < 90$ GeV
	$p_T^\nu > 25$ GeV	
	$m_T > 50$ GeV	
	$u_T < 15$ GeV	
ATLAS	$p_T^\ell > 30$ GeV	$32 < p_T^\ell < 45$ GeV
	$\lvert\eta_\ell\rvert < 2.4$	$66 < m_T < 99$ GeV
	$p_T^\nu > 30$ GeV	
	$m_T > 60$ GeV	
	$u_T < 30$ GeV	
LHCb	$p_T^\mu > 24$ GeV	$28 < p_T^\mu < 52$ GeV
	$2.2 < \eta_\mu < 4.4$	

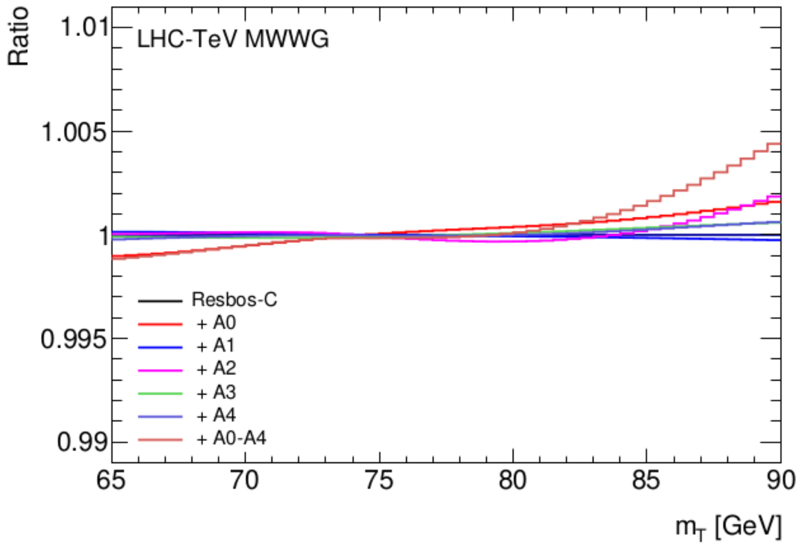
Emulation (CDF, D0, ATLAS)



QCD/generator corrections

- Main correction : spin correlations in Resbos1, used in the Tevatron experiments





  - Effect due to partial resummation of helicity cross sections in Resbos1
  - distributions become harder upon A0-A4 corrections → negative impact on measured value

QCD/generator corrections

- Main correction : spin correlations in Resbos1, used in the Tevatron experiments

Coefficient	m_T	p_T^ℓ	p_T^ν
A_0	-6.3	-2.6	-9.1
A_1	1.1	1.3	0.3
A_2	-0.7	0.4	-3.2
A_3	-2.1	-4.1	1.0
A_4	-1.4	-3.3	-1.6
$A_0 - A_4$	-9.5	-8.4	-12.5
ResBos2	-10.2 ± 1.1	-7.6 ± 1.2	-11.8 ± 1.4
Difference	-0.7 ± 1.1	0.8 ± 1.2	0.7 ± 1.4

CDF

Coefficient	m_T	p_T^ℓ	p_T^ν
A_0	-9.8	-7.3	-15.6
A_1	1.9	2.4	1.8
A_2	3.0	3.3	-2.7
A_3	-1.6	-2.9	0.4
A_4	0.2	-2.3	0.5
$A_0 - A_4$	-6.4	-6.9	-15.8
ResBos2	-7.8 ± 1.0	-6.6 ± 1.1	-16.5 ± 1.2
Difference	-1.4 ± 1.0	0.3 ± 1.1	-0.7 ± 1.2

D0

  - Effect due to partial resummation of helicity cross sections in Resbos1
  - Harder distributions upon A0-A4 corrections → negative impact on measured value

PDF extrapolations

- Measurements performed at different moments in time, using the PDF sets available at the time
  - Requires translation to a common reference before combining
  - Sometimes significant effects :

PDF set	D0	CDF
CTEQ6	−14.6	0.0
CTEQ6.6	0.0	14.2
CT10	−0.5	14.3
CT14	−8.7	5.2
CT18	−7.5	6.5
ABMP16	−17.9	−2.4
MMHT2014	−10.1	4.5
MSHT20	−12.9	2.5
NNPDF3.1	−1.0	13.1
NNPDF4.0	6.2	20.1

…

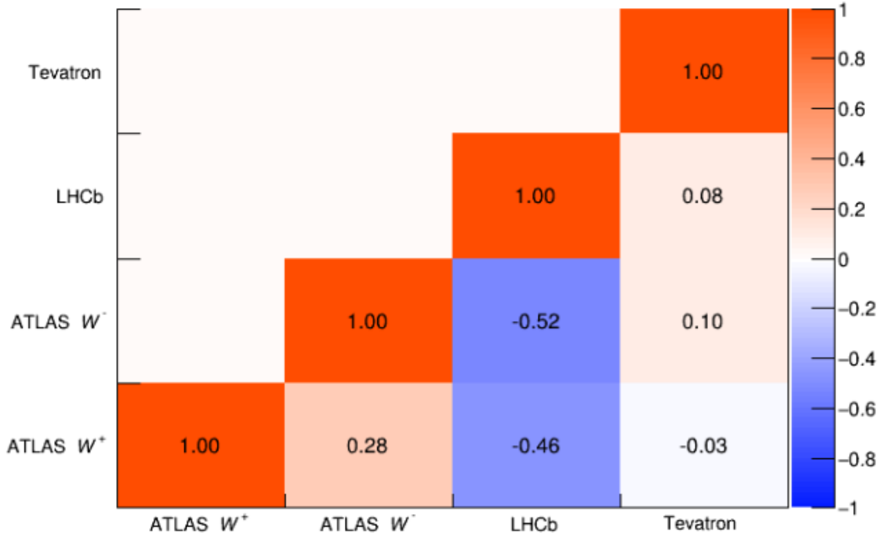
ATLAS W^+	ATLAS W^-	LHCb
–	–	–
–	–	–
0.0	0.0	–
-1.2	−5.8	1.1
12.1	−2.3	−6.0
−22.5	−3.1	7.7
−2.6	9.9	−10.8
−20.9	4.5	−2.0
−14.1	-1.8	6.0
−22.4	6.9	8.3

m_T p_T^l

PDF extrapolations

- PDF uncertainties and correlations :

PDF set	D0	CDF	ATLAS	LHCb
CTEQ6	–	14.1	–	–
CTEQ6.6	15.1	–	–	–
CT10	–	–	9.2	–
CT14	13.8	12.4	11.4	10.8
CT18	14.9	13.4	10.0	12.2
ABMP16	4.5	3.9	4.0	3.0
MMHT2014	8.8	7.7	8.8	8.0
MSHT20	9.4	8.5	7.8	6.8
NNPDF3.1	7.7	6.6	7.4	7.0
NNPDF4.0	8.6	7.7	5.3	4.1



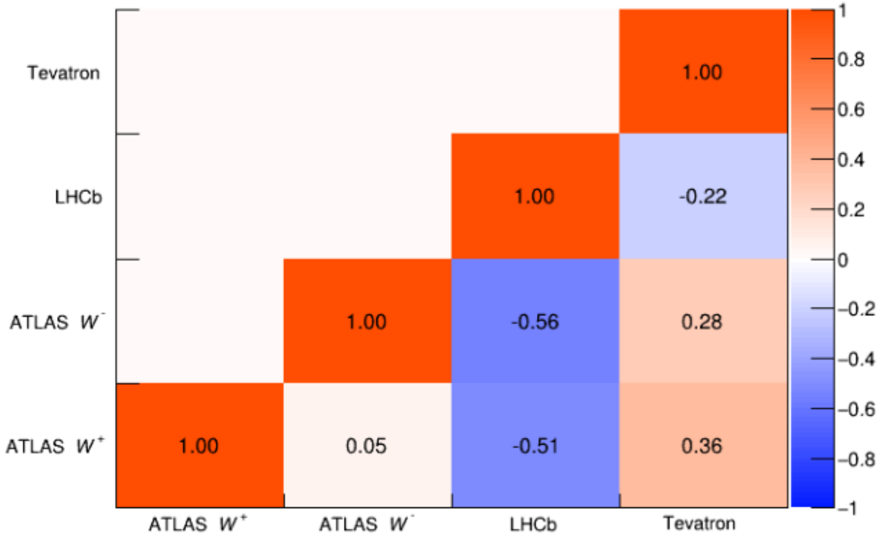
CT18

Sometime partial or negative correlations → stabilizes PDF effects on combinations?

PDF extrapolations

- PDF uncertainties and correlations :

PDF set	D0	CDF	ATLAS	LHCb
CTEQ6	–	14.1	–	–
CTEQ6.6	15.1	–	–	–
CT10	–	–	9.2	–
CT14	13.8	12.4	11.4	10.8
CT18	14.9	13.4	10.0	12.2
ABMP16	4.5	3.9	4.0	3.0
MMHT2014	8.8	7.7	8.8	8.0
MSHT20	9.4	8.5	7.8	6.8
NNPDF3.1	7.7	6.6	7.4	7.0
NNPDF4.0	8.6	7.7	5.3	4.1



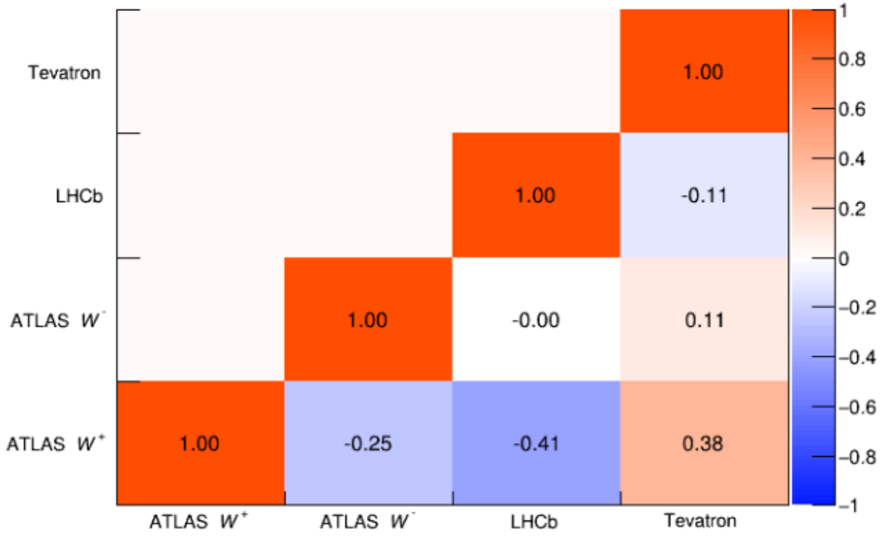
MSHT20

Sometime partial or negative correlations → stabilizes PDF effects on combinations? Model dependence!!

PDF extrapolations

- PDF uncertainties and correlations :

PDF set	D0	CDF	ATLAS	LHCb
CTEQ6	–	14.1	–	–
CTEQ6.6	15.1	–	–	–
CT10	–	–	9.2	–
CT14	13.8	12.4	11.4	10.8
CT18	14.9	13.4	10.0	12.2
ABMP16	4.5	3.9	4.0	3.0
MMHT2014	8.8	7.7	8.8	8.0
MSHT20	9.4	8.5	7.8	6.8
NNPDF3.1	7.7	6.6	7.4	7.0
NNPDF4.0	8.6	7.7	5.3	4.1



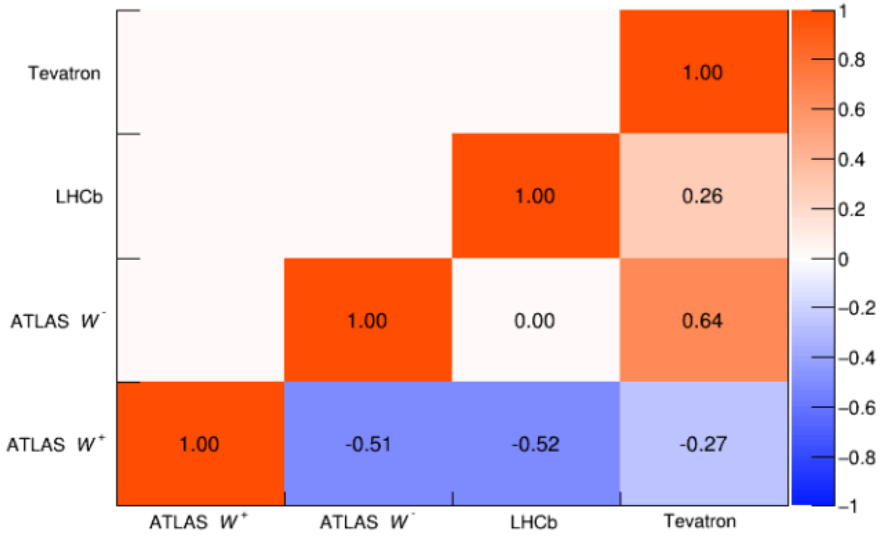
NNPDF4.0

Sometime partial or negative correlations → stabilizes PDF effects on combinations?
Model dependence!!

PDF extrapolations

- PDF uncertainties and correlations :

PDF set	D0	CDF	ATLAS	LHCb
CTEQ6	–	14.1	–	–
CTEQ6.6	15.1	–	–	–
CT10	–	–	9.2	–
CT14	13.8	12.4	11.4	10.8
CT18	14.9	13.4	10.0	12.2
ABMP16	4.5	3.9	4.0	3.0
MMHT2014	8.8	7.7	8.8	8.0
MSHT20	9.4	8.5	7.8	6.8
NNPDF3.1	7.7	6.6	7.4	7.0
NNPDF4.0	8.6	7.7	5.3	4.1



ABMP16

Sometime partial or negative correlations → stabilizes PDF effects on combinations?
Model dependence!!

Results

- Tevatron

	CDF (5 d.o.f.)		D0 (4 d.o.f.)		Tevatron Run 2 (1 d.o.f.)			
PDF set	m_W	χ^2	m_W	χ^2	m_W	σ_{PDF}	χ^2	$p(\chi^2, n)$
ABMP16	80417.3 ± 9.5	8.8	80355.4 ± 20.9	6.6	80408.2 ± 8.9	4.0	7.7	0.6%
CT14	80432.1 ± 15.5	7.7	80370.9 ± 24.9	5.9	80424.0 ± 15.2	12.6	7.2	0.7%
CT18	80432.0 ± 16.1	7.6	80372.0 ± 25.5	5.9	80424.9 ± 15.9	13.5	7.0	0.8%
MMHT2014	80425.7 ± 11.6	7.0	80364.4 ± 22.3	5.5	80417.4 ± 11.2	7.8	7.6	0.6%
MSHT20	80424.4 ± 12.2	7.6	80362.3 ± 22.5	6.1	80415.9 ± 11.8	8.6	7.8	0.5%
NNPDF3.1	80433.3 ± 10.9	7.6	80372.7 ± 21.9	5.8	80425.0 ± 10.5	6.8	7.4	0.7%
NNPDF4.0	80441.8 ± 11.6	7.2	80381.3 ± 22.2	5.7	80433.4 ± 11.2	7.8	7.4	0.7%

- LHC

	ATLAS (27 d.o.f)		LHCb		LHC (1 d.o.f)			
PDF set	m_W	χ^2	m_W	χ^2	m_W	σ_{PDF}	χ^2	$p(\chi^2, n)$
ABMP16	80352.8 ± 16.1	31	80361.0 ± 30.4	–	80354.6 ± 14.2	2.9	0.1	75%
CT14	80363.1 ± 20.4	30	80354.4 ± 32.2	–	80360.4 ± 16.4	6.5	0.0	100%
CT18	80374.5 ± 20.3	30	80347.3 ± 32.7	–	80366.5 ± 16.6	6.3	0.5	48%
MMHT2014	80372.8 ± 18.6	30	80342.5 ± 31.3	–	80364.4 ± 15.4	5.1	0.6	44%
MSHT20	80368.9 ± 17.9	45	80351.3 ± 31.0	–	80364.3 ± 15.0	4.5	0.2	65%
NNPDF3.1	80358.4 ± 17.6	29	80359.3 ± 31.1	–	80358.6 ± 15.0	5.0	0.0	100%
NNPDF4.0	80353.5 ± 16.6	35	80361.6 ± 30.6	–	80355.4 ± 14.5	3.8	0.1	75%

Results

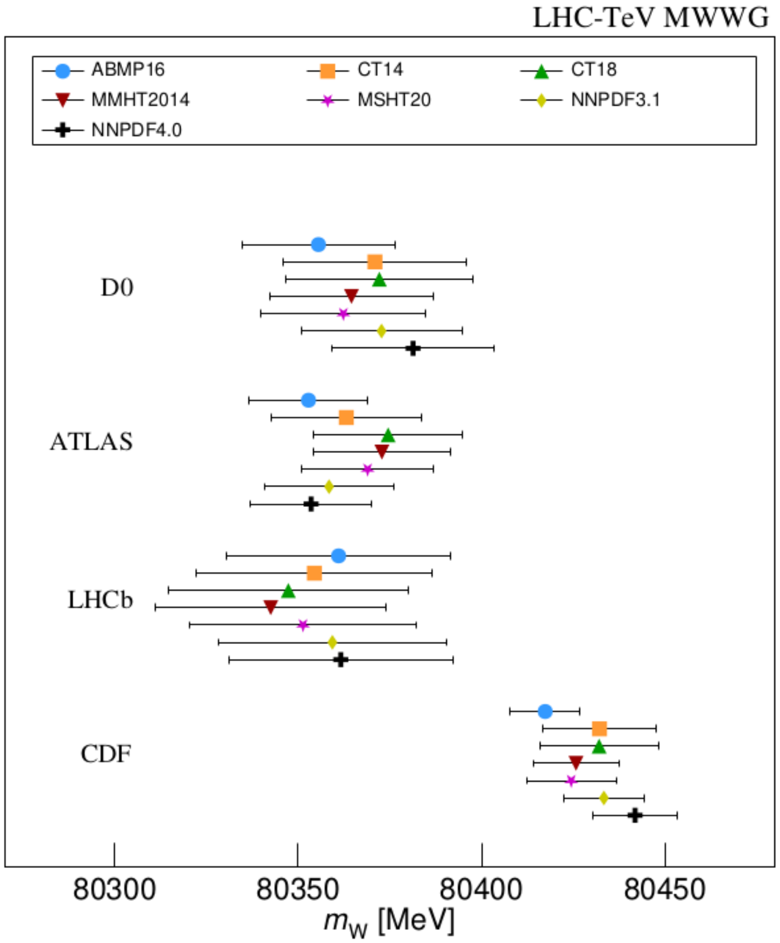
- All

All experiments (4 d.o.f.)				
PDF set	m_W	σ_{PDF}	χ^2	$\mathrm{p}(\chi^2, n)$
ABMP16	80392.7 ± 7.5	3.2	29	0.0008%
CT14	80393.0 ± 10.9	7.1	16	0.3%
CT18	80394.6 ± 11.5	7.7	15	0.5%
MMHT2014	80398.0 ± 9.2	5.8	17	0.2%
MSHT20	80395.1 ± 9.3	5.8	16	0.3%
NNPDF3.1	80403.0 ± 8.7	5.3	23	0.1%
NNPDF4.0	80403.1 ± 8.9	5.3	28	0.001%

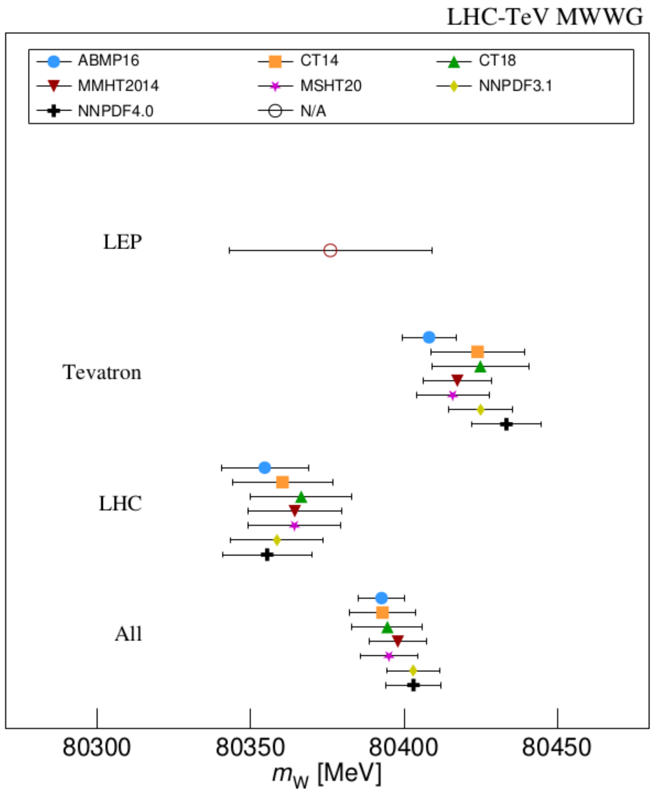
- All except CDF

All except CDF (3 d.o.f.)				
PDF set	m_W	σ_{PDF}	χ^2	$\mathrm{p}(\chi^2, n)$
ABMP16	80357.3 ± 11.2	2.6	0.4	94%
CT14	80365.4 ± 12.9	5.8	0.3	96%
CT18	80369.2 ± 13.3	6.2	0.5	92%
MMHT2014	80365.8 ± 12.1	4.7	0.8	85%
MSHT20	80365.1 ± 12.0	4.4	0.4	94%
NNPDF3.1	80364.7 ± 11.9	4.5	0.4	94%
NNPDF4.0	80364.5 ± 11.6	3.9	1.2	75%

Results


LHC-TeV MWWG
ABMP16
CT14
CT18
MMHT2014
MSHT20
NNPDF3.1
NNPDF4.0
D0
ATLAS
LHCb
CDF
80300
80350
80400
80450
m_W [MeV]

Results


LHC-TeV MWWG
ABMP16
CT14
CT18
MMHT2014
MSHT20
NNPDF3.1
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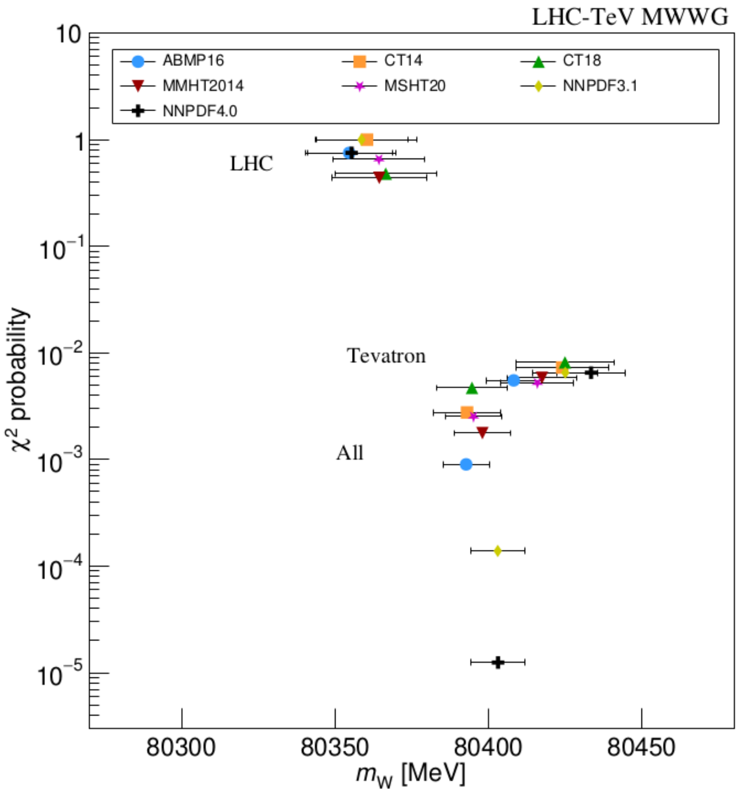
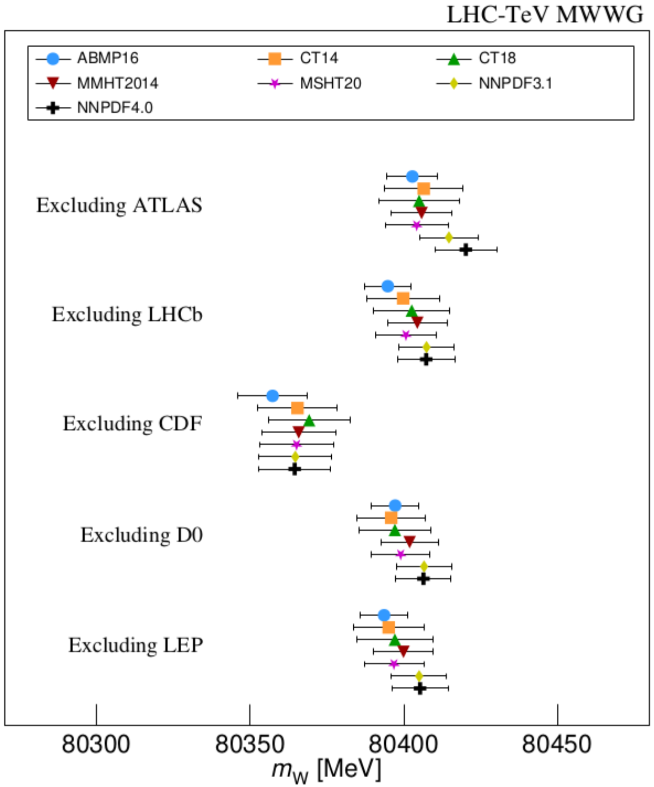
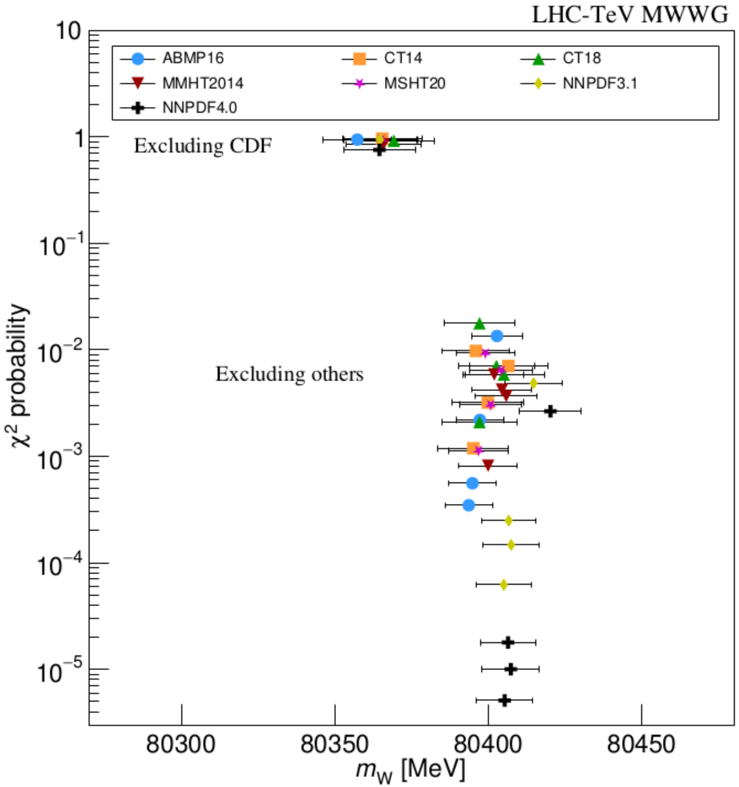
N/A
LEP
Tevatron
LHC
All
80300
80350
80400
80450
m_W [MeV]


LHC-TeV MWWG
ABMP16
CT14
CT18
MMHT2014
MSHT20
NNPDF3.1
NNPDF4.0
LHC
Tevatron
All
χ^2 probability
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
80300
80350
80400
80450
m_W [MeV]

Results


LHC-TeV MWWG
ABMP16
CT14
CT18
MMHT2014
MSHT20
NNPDF3.1
NNPDF4.0
Excluding ATLAS
Excluding LHCb
Excluding CDF
Excluding D0
Excluding LEP
80300
80350
80400
80450
m_W [MeV]


LHC-TeV MWWG
ABMP16
CT14
CT18
MMHT2014
MSHT20
NNPDF3.1
NNPDF4.0
Excluding CDF
Excluding others
χ^2 probability
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
80300
80350
80400
80450
m_W [MeV]

Combination - summary

- CT18 PDF sets used as baseline as it is most conservative, and given the observed PDF dependence of the combination results

- Full world average :

$$m_W = 80394.6 \pm 11.5 \text{ MeV} \quad P(\chi^2) = 0.5\%$$

  - Quoted for completeness, but discarded
  - We consider that the discrepancy can not be explained by an under-estimation of quoted uncertainties; error scaling does not apply

- Average of all measurements except CDF :

$$m_W = 80369.2 \pm 13.3 \text{ MeV} \quad P(\chi^2) = 91\%$$

  - PDF envelope 5 MeV (12 MeV when including ABMP16), reduced to partial or negative correlations – good!
  - An important positive result : D0, LHCb, ATLAS are all hadron-collider measurement, but experimental conditions are a different as can be

Measurement of the p_T^Z distribution

α_S extraction

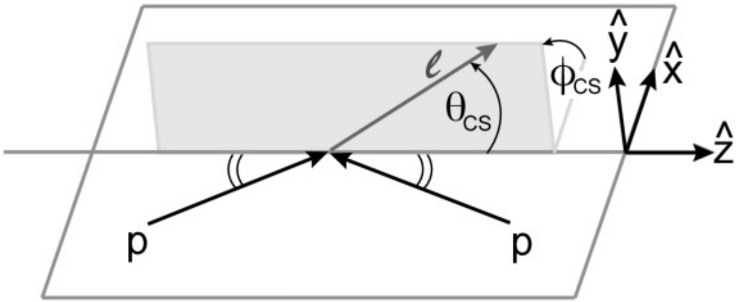
Measurement strategy

- Exploit the angular variables decomposition to perform a simultaneous 2D p_T-y measurement of
  - Unpolarised full-lepton phase space cross sections
  - Angular coefficients

$$\frac{d^2\sigma}{dp_T dy}\left(1+\cos^2\theta+\sum A_i(p_T,y)P_i(\cos\theta,\phi)\right)$$

$$\begin{cases} P_0(\cos\theta,\phi) &= \frac{1}{2}(1-3\cos^2\theta) \\ P_1(\cos\theta,\phi) &= \sin 2\theta\cos\phi \\ P_2(\cos\theta,\phi) &= \frac{1}{2}\sin^2\theta\cos 2\phi \\ P_3(\cos\theta,\phi) &= \sin\theta\cos\phi \\ P_4(\cos\theta,\phi) &= \cos\theta \\ P_5(\cos\theta,\phi) &= \sin^2\theta\sin 2\phi \\ P_6(\cos\theta,\phi) &= \sin 2\theta\sin\phi \\ P_7(\cos\theta,\phi) &= \sin\theta\sin\phi \end{cases}$$

- This is in practice a 4D measurement of the DY process in p_T,y,cosθ,ϕ



- Coefficients defined in the Collins-Soper frame

Measurements

Expected Yield

Reco (p_T^Z, y^Z, m^Z, cosθ, ϕ) bin

Cross section

Background template

$$N^{n}_{\mathrm{exp}}(A,\sigma,\theta) = \left\{ \sum_{j=1}^{\mathrm{N}^{ana}_{\mathrm{bins}}} \mathcal{L}\sigma_j \left[t^{n}_{8j}(\beta) + \sum_{i=0}^{7} A_{ij} t^{n}_{ij}(\beta) \right] \right\} \gamma^n + \sum_{B}^{\mathrm{bkgs}} T^{n}_{B}(\beta)$$

Truth (p_T^Z, y^Z, m^Z) bin

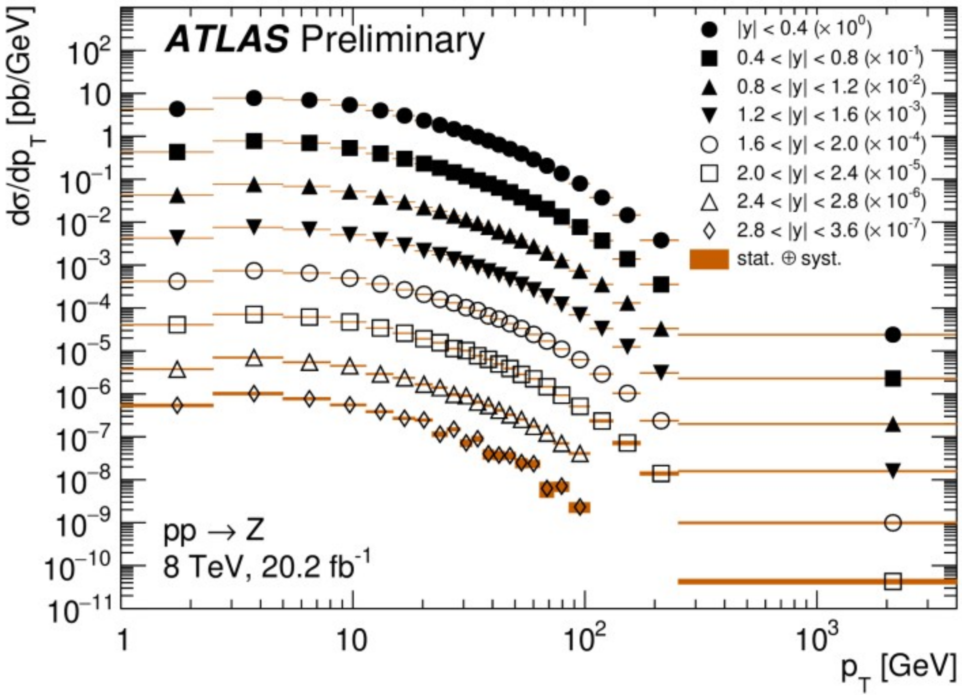
Angular coefficient

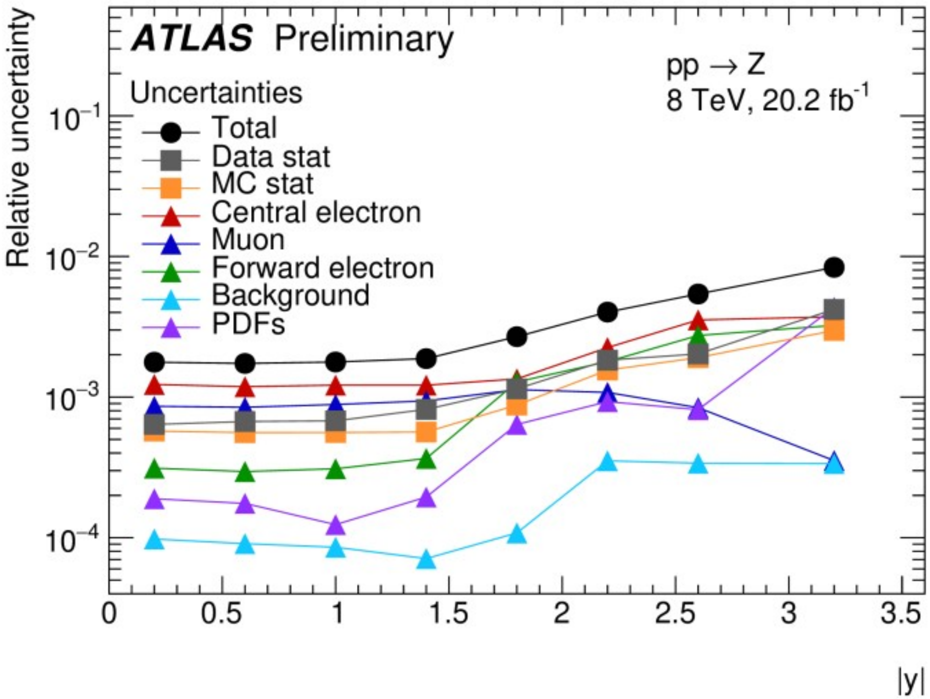
Templated polynomial

- Link detector-level observed cosθ,ϕ distributions to the MC template of spherical harmonic polynomials
- Define a likelihood with 22528 (cosθ,ϕ,p_T,y) bins
- Parameters of interests are the 8 Ai + 1 cross section in p_T-y bins: 9 parameters in 176 bins → 1584 free parameters

Results

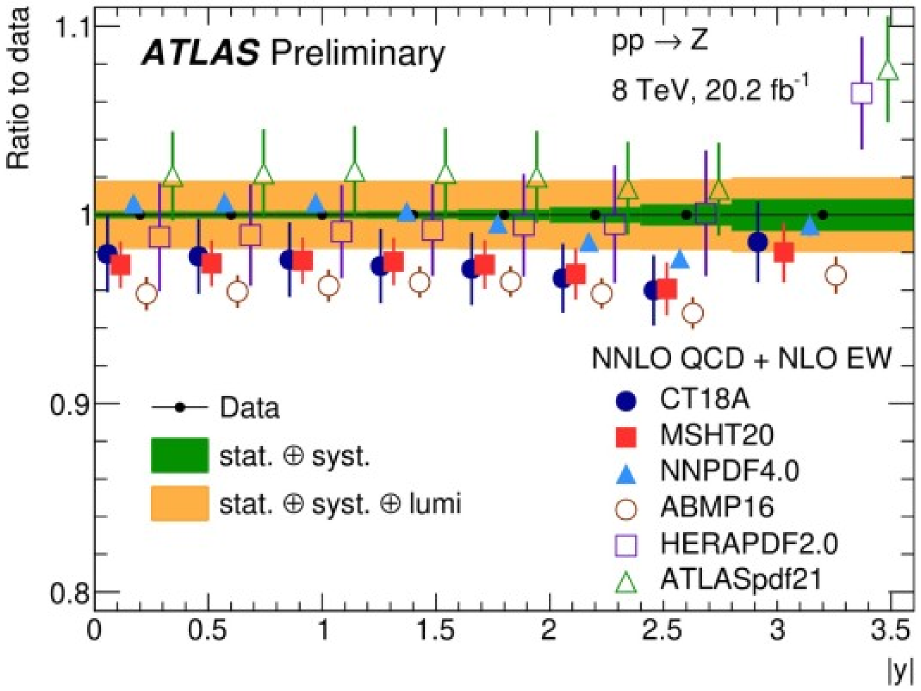
- Measurement and uncertainties





Results

- Comparison to predictions



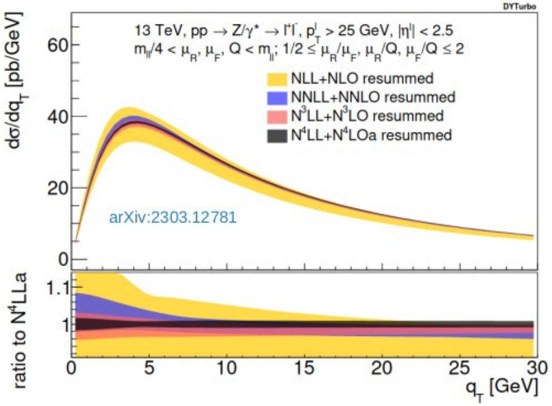
PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN^{3}LO [60]	13/8	0.11	1.2 ± 0.6
CT18A [61]	12/8	0.17	0.9 ± 0.7
MSHT20 [62]	10/8	0.26	0.9 ± 0.6
NNPDF4.0 [63]	30/8	0.0002	0.0 ± 0.2
ABMP16 [64]	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0 [65]	22/8	0.005	-1.3 ± 0.8
ATLASpdf21 [66]	20/8	0.01	-1.1 ± 0.8

NNPDF4.0 χ^2 driven by trends in the shape & small uncertainties (relevant comparison : ▲ vs ▬)

E.g MSHT20 brought in ~perfect agreement with data at the cost of only a 1σ pull in the luminosity (one unit in χ^2)

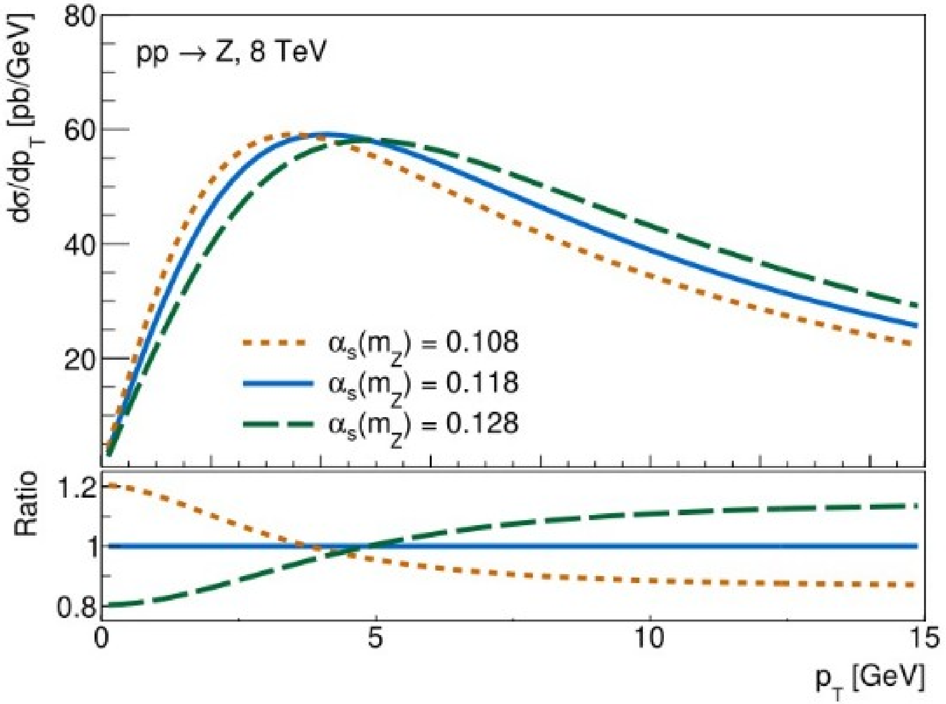
α_s for from the p_T^Z distribution

- Theoretical setup
  - MSHT20aN3LO
  - Perturbative accuracy up to aN4LL



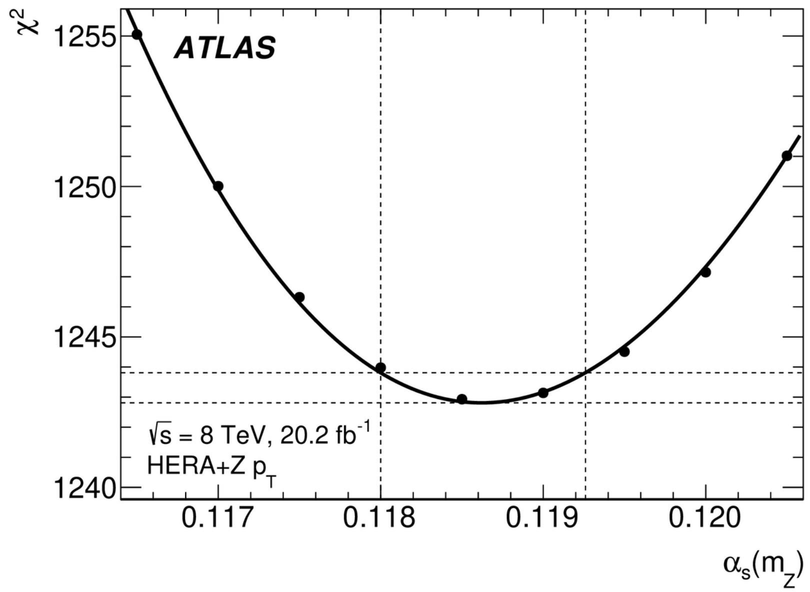
  - NP model characterized by a non-perturbative Sudakov form-factor

$$S_{\rm NP}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m_{\ell\ell}^2}{Q_0^2}\right]$$



α_s for from the p_T^Z distribution

- Results from a simultaneous fit to a_S and the non-perturbative parameter g, profiling experimental and PDF uncertainties
  - Alternative analysis performs a complete fit to HERA+ p_T^Z data
  - Other uncertainties are not profiled, and added in quadrature

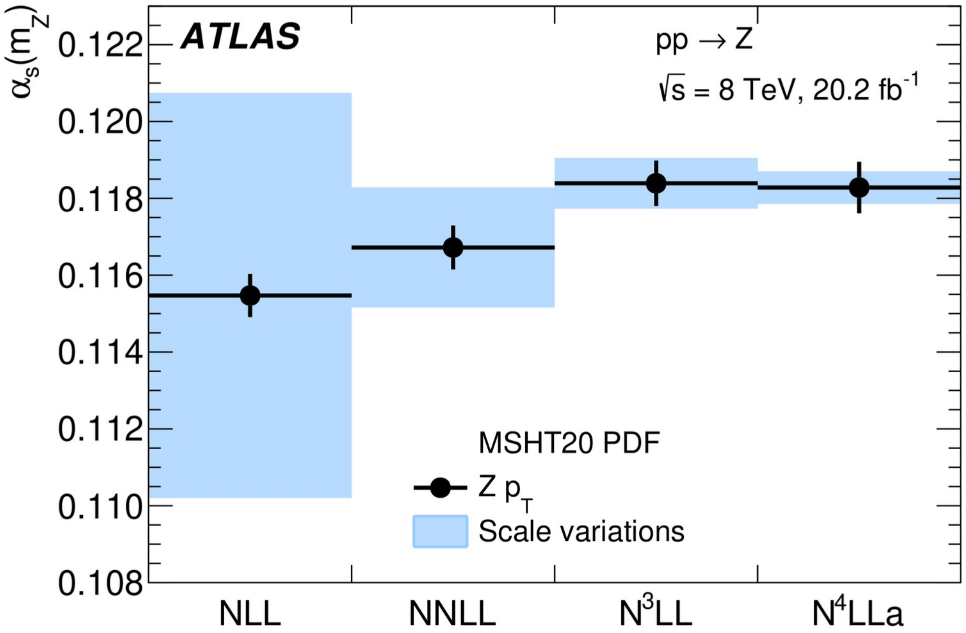


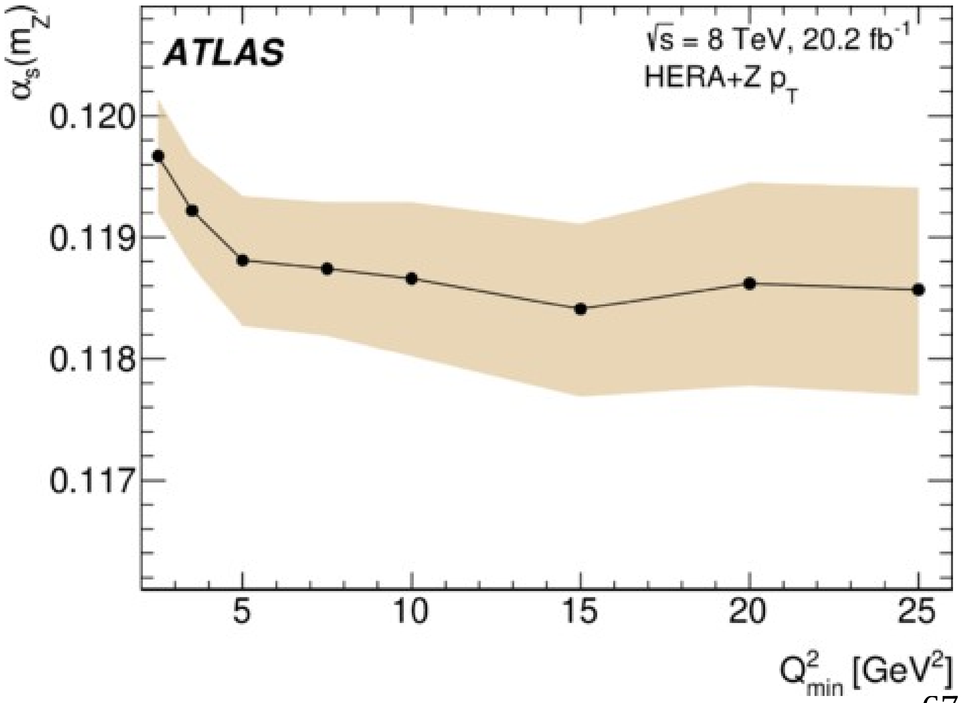
Experimental uncertainty	± 0.44	
PDF uncertainty	± 0.51	
Scale variation uncertainties	± 0.42	
Matching to fixed order	0	-0.08
Non-perturbative model	$+0.12$	-0.20
Flavour model	$+0.40$	-0.29
QED ISR	± 0.14	
N^4LL approximation	± 0.04	
Total	$+0.91$	-0.88

$(\times 10^{-3})$

α_s for from the p_T^Z distribution

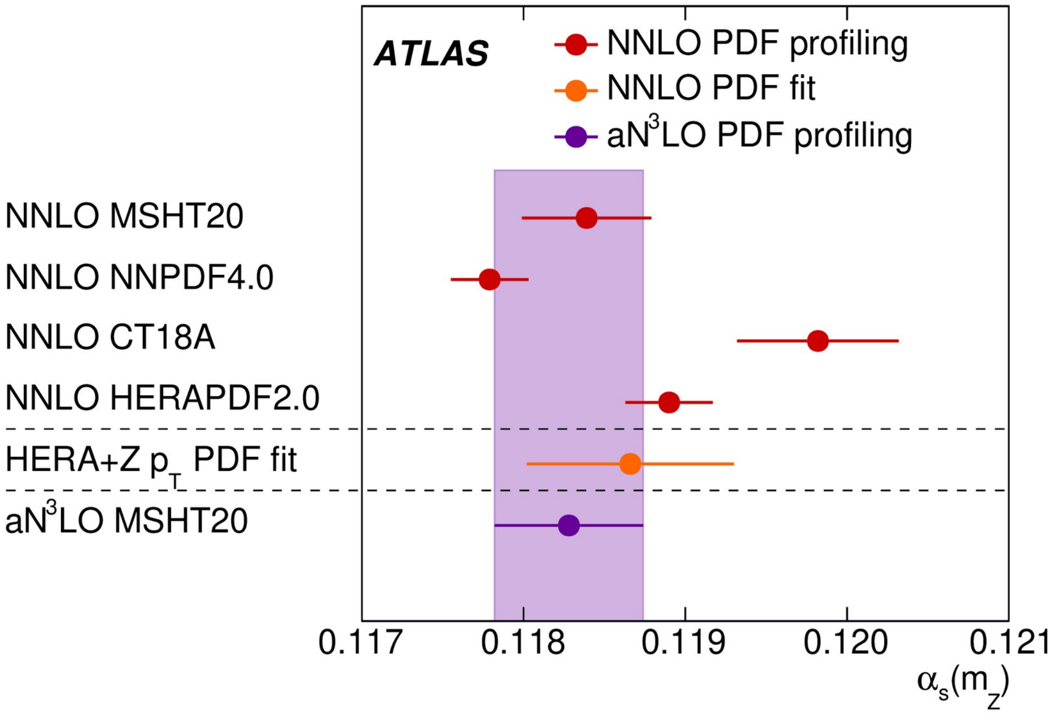
- Stability tests : perturbative convergence; cut on Q^2 of HERA data





α_s for from the p_T^Z distribution

- Stability tests : PDF dependence



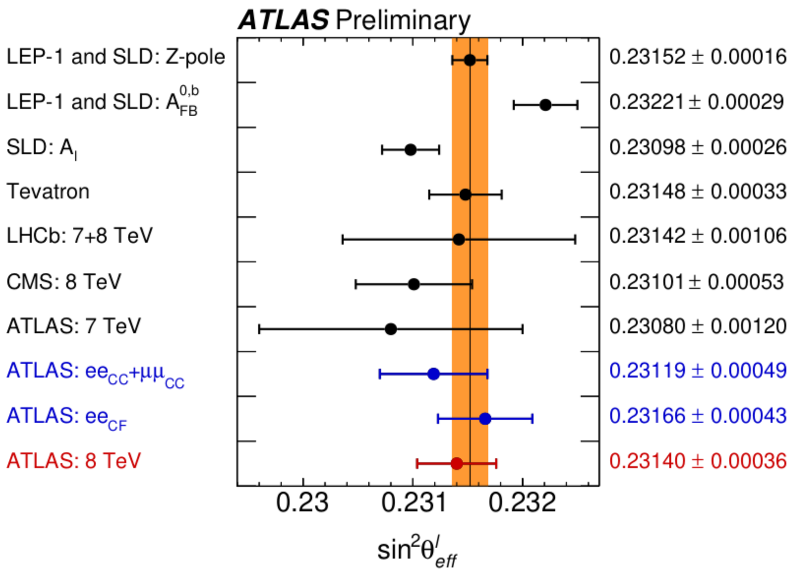
Full PDF envelope ~twice the total measurement uncertainty, but driven by CT18A (envelope still large when removing this set)

The measurement relies on a tightly, externally constrained gluon PDF. CT18 is very flexible here α_S, g(x) effects can not be disentangled

Two slides on the weak mixing angle...

Two slides on the weak mixing angle...

- In ATLAS, extracted from A_4 in the same data sample as just described :



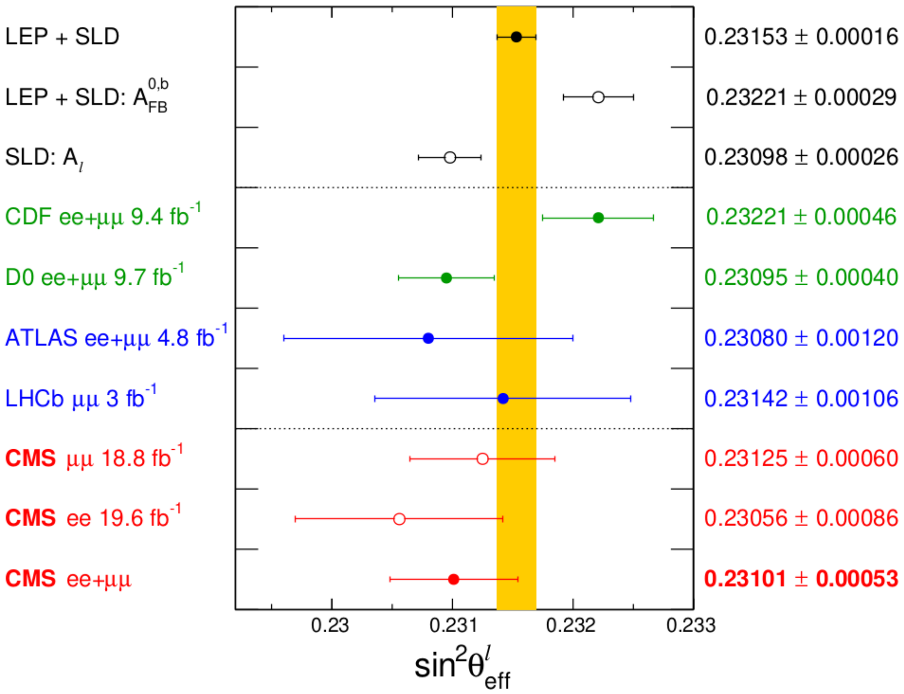
	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^\ell_{\text{eff}}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

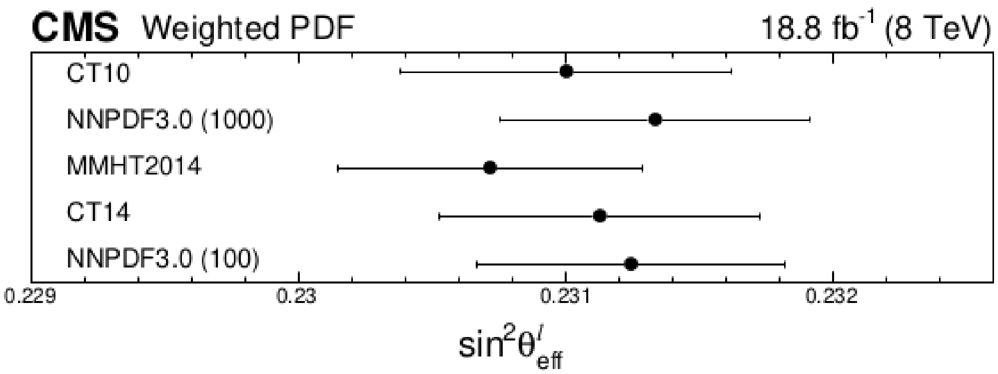
$$0.23140 \pm 0.00021\,(\text{stat.}) \pm 0.00024\,(\text{PDF}) \pm 0.00016\,(\text{syst.}),$$

PDF envelope 0.0028 – large, but driven by CT10. Outdated PDF sets in general...

Two slides on the weak mixing angle...

- In CMS





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

PDF envelope ~0.0006 (MMHT2014 – NNPDF3.0)

Summary

- The PDF dependence of measurements of fundamental parameters is nowadays typically comparable to the total measurement uncertainty (a fortiori the PDF uncertainty) – we should improve
  - Q : what is the significance of the difference between measurement results using the same data, but different PDF sets?
  - Disentangling effects of
    - Different data sets
    - Theory predictions
    - Parametrisation
    - Uncertainty treatment (tolerance or not?)

    on the PDF central fits and uncertainties is absolutely fundamental.
- An effort in this direction exists in the LHC EWWG, and very interesting discussion happen in this collaboration. Joint discussions would be extremely useful.

Back up

QCD corrections

- Reason :
  - "inconsistent" resummation of helicity cross sections in Resbos1
    - Resbos1 : all terms present at leading order are resummed (unpolarized; A4). Others left at fixed order
    - Resbos2 : all terms resummed consistently

$$A_i = \frac{\sigma_i}{\sigma_{\mathrm{unpol}}}, \qquad \frac{A_i^{\mathrm{ResBos2}}}{A_i^{\mathrm{ResBos1}}} = \frac{\sigma_i^{\mathrm{Res.}}/\sigma_{\mathrm{unpol.}}^{\mathrm{Res.}}}{\sigma_i^{\mathrm{F.O.}}/\sigma_{\mathrm{unpol.}}^{\mathrm{Res.}}} = \frac{\sigma_i^{\mathrm{Res.}}}{\sigma_i^{\mathrm{F.O.}}} = \frac{\sigma_{\mathrm{unpol.}}^{\mathrm{Res.}}}{\sigma_{\mathrm{unpol.}}^{\mathrm{F.O.}}},$$

$$A_i^{\mathrm{ResBos2}} = \frac{\sigma_i^{\mathrm{Res.}}}{\sigma_{\mathrm{unpol.}}^{\mathrm{Res.}}} = \frac{\sigma_i^{\mathrm{F.O.}}}{\sigma_{\mathrm{unpol.}}^{\mathrm{F.O..}}}.$$

QCD corrections

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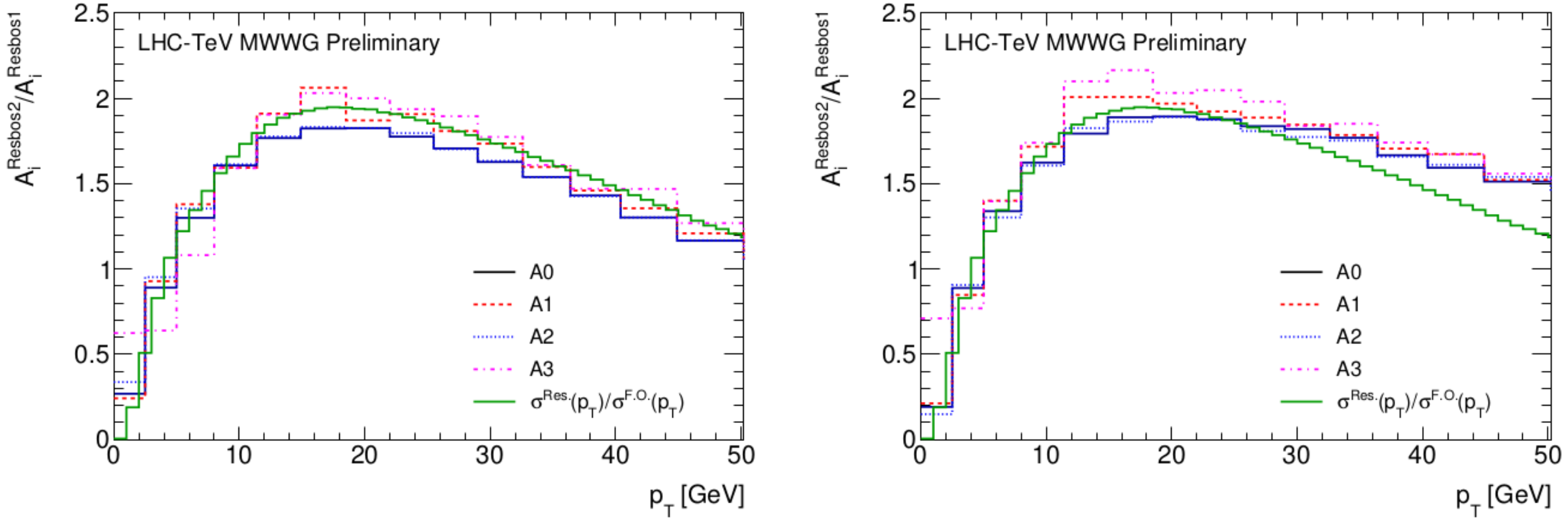
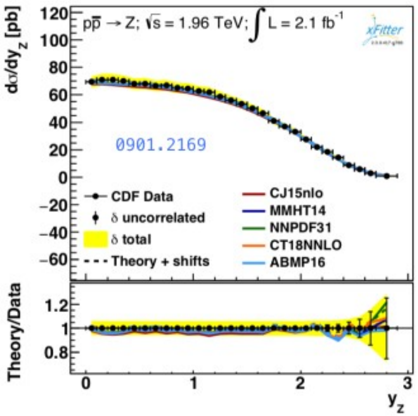
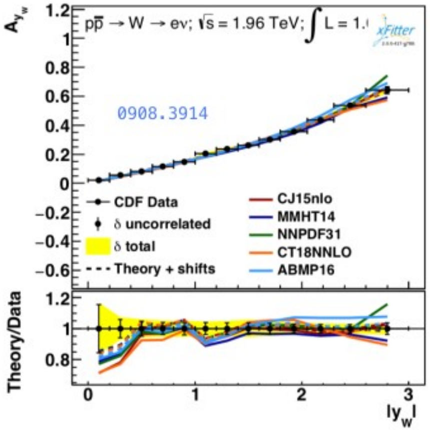
    - Resbos2 : all terms resummed consistently



Choice of target PDFs

- Comparisons between existing Drell-Yan data and "recent" NNLO PDFs
  - CDF





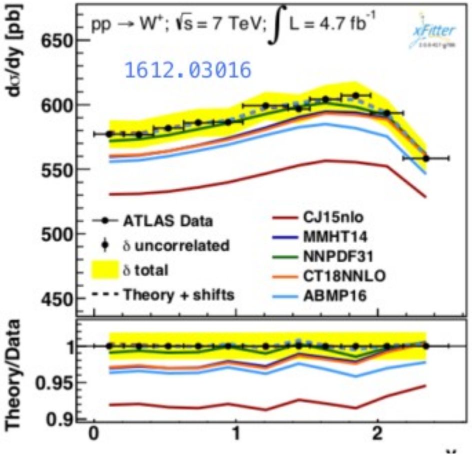
Dataset	CJ15nlo	MMHT14	NNPDF31	CT18NNLO	ABMP16
CDF W asymmetry 2009	18 / 13	12 / 13	11 / 13	13 / 13	17 / 13
Correlated χ^2	1.6	1.7	2.6	2.9	6.5
Log penalty χ^2	-0.00	-0.00	-0.00	-0.00	-0.00
Total χ^2 / dof	19 / 13	14 / 13	13 / 13	16 / 13	23 / 13
χ^2 p-value	0.11	0.37	0.43	0.25	0.04

Dataset	CJ15nlo	MMHT14	NNPDF31	CT18NNLO	ABMP16
CDF Z rapidity 2010	29 / 28	30 / 28	25 / 28	27 / 28	30 / 28
Correlated χ^2	1.5	0.99	1.7	0.49	0.69
Log penalty χ^2	-1.16	-0.63	-0.44	-0.60	-0.90
Total χ^2 / dof	30 / 28	30 / 28	26 / 28	27 / 28	30 / 28
χ^2 p-value	0.37	0.36	0.55	0.53	0.36

S.Amoroso

Choice of target PDFs

- Comparisons between existing Drell-Yan data and “recent” NNLO PDFs
  - ATLAS



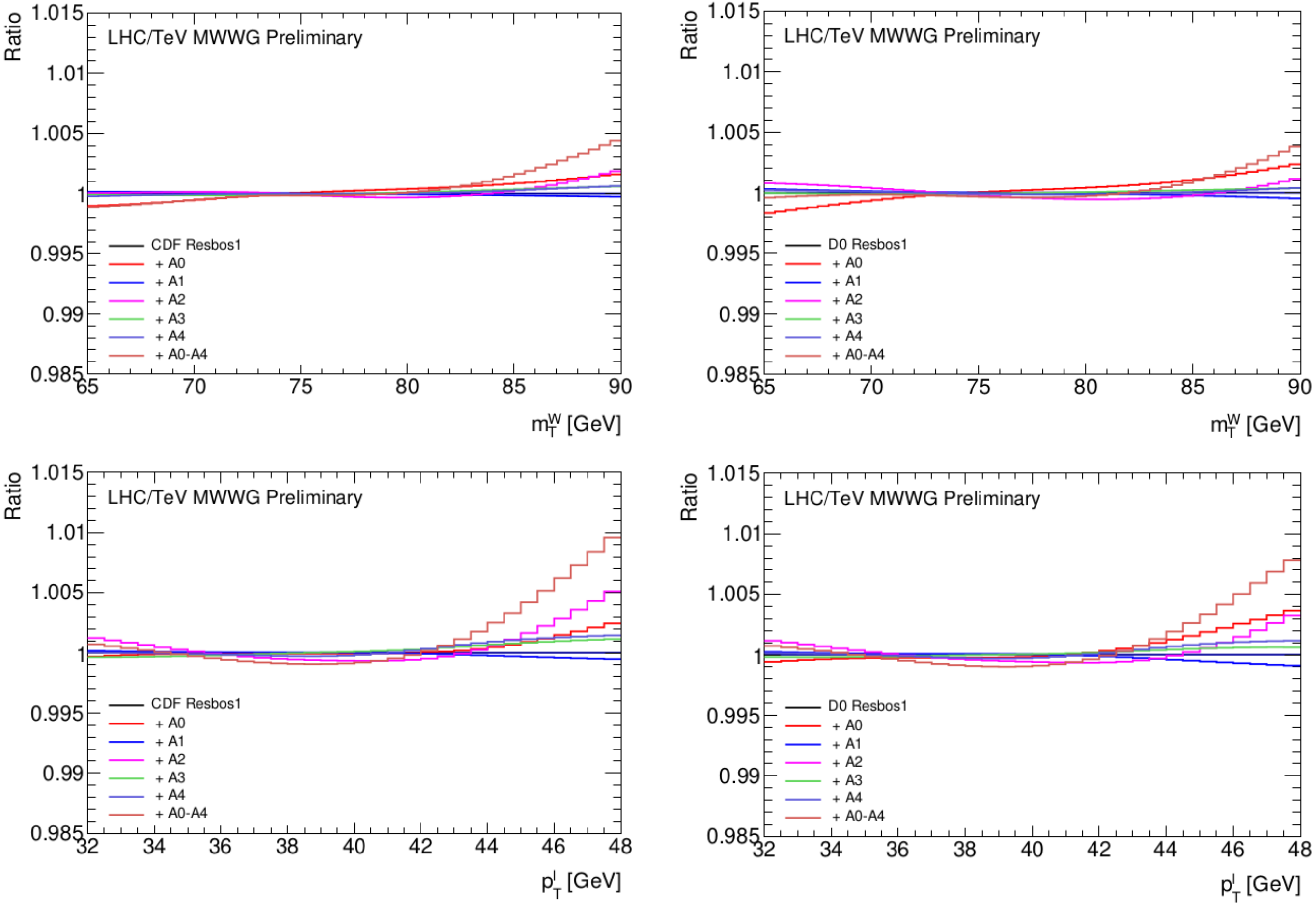
S.Amoroso

Dataset	CJ15nlo	MMHT14	NNPDF31	CT18NNLO	ABMP16
ATLAS low mass Z rapidity 2011	26 / 6	18 / 6	14 / 6	12 / 6	21 / 6
ATLAS peak CC Z rapidity 2011	52 / 12	21 / 12	12 / 12	16 / 12	24 / 12
ATLAS peak CF Z rapidity 2011	16 / 9	11 / 9	11 / 9	10 / 9	9.2 / 9
ATLAS high mass CC Z rapidity 2011	7.7 / 6	6.1 / 6	5.8 / 6	5.9 / 6	6.1 / 6
ATLAS high mass CF Z rapidity 2011	4.6 / 6	5.5 / 6	4.7 / 6	4.8 / 6	4.5 / 6
ATLAS W- lepton rapidity 2011	17 / 11	8.4 / 11	8.7 / 11	9.1 / 11	10 / 11
ATLAS W+ lepton rapidity 2011	16 / 11	11 / 11	11 / 11	10 / 11	13 / 11
Correlated χ^2	118	50	31	40	50
Log penalty χ^2	-9.09	-3.32	-2.45	-3.66	-4.22
Total χ^2 / dof	247 / 61	127 / 61	95 / 61	104 / 61	134 / 61
χ^2 p-value	0.00	0.00	0.00	0.00	0.00

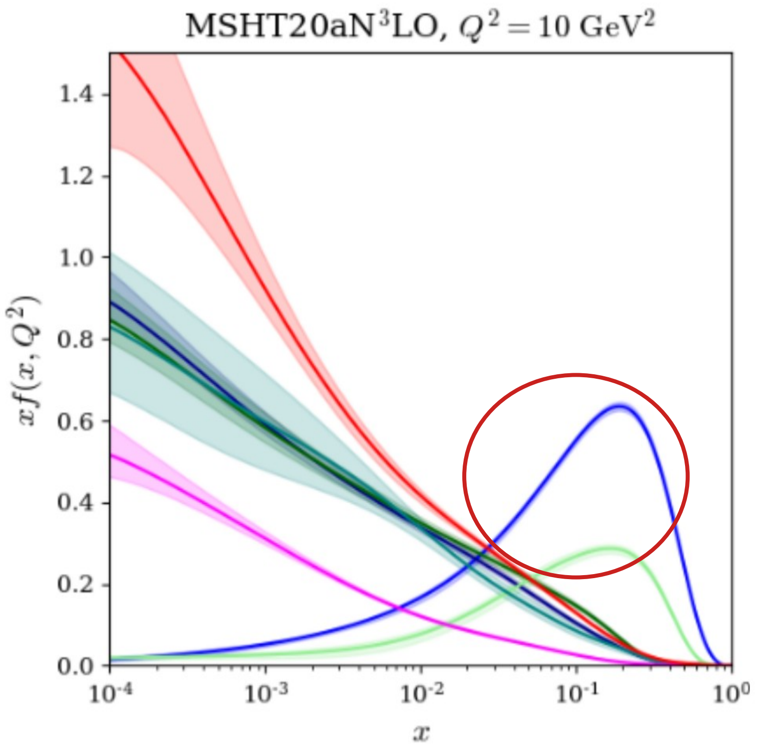
→ consider MMHT14, NNPDF3.1, CT18NNLO, ABMP16
→ best overall description of the data by NNPDF3.1, CT18NNLO
→ comparisons now extended to NNPDF4.0, MSHT20

QCD corrections

- Impact :
  - decomposition



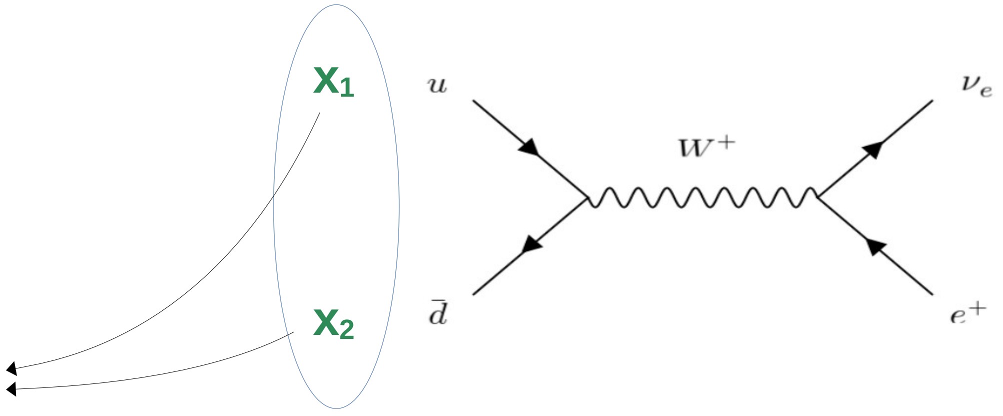
Rapidity distribution and PDFs



$m_W \sim 80$ GeV

$x_{1,2} = m/\sqrt{s}\, e^{\pm y}$

Tevatron	$\sqrt{s} \sim 2$TeV	$p\bar{p}$	$0<y<2$	$x_{1,2} \sim 10^{-2} – 10^{-1}$
ATLAS	$\sqrt{s} \sim 7$TeV	pp	$0<y<3$	$x_{1,2} \sim 10^{-3} – 10^{-1}$
LHCb	$\sqrt{s} \sim 13$TeV	pp	$y \sim 4$	$x_{1,2} \sim 10^{-4} – 10^{-1}$



Rapidity distribution and PDFs

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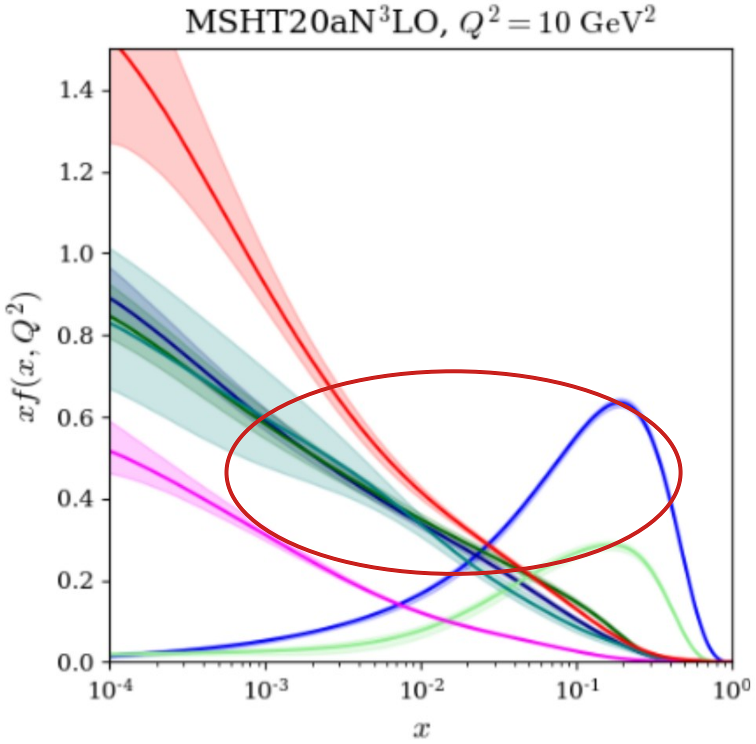
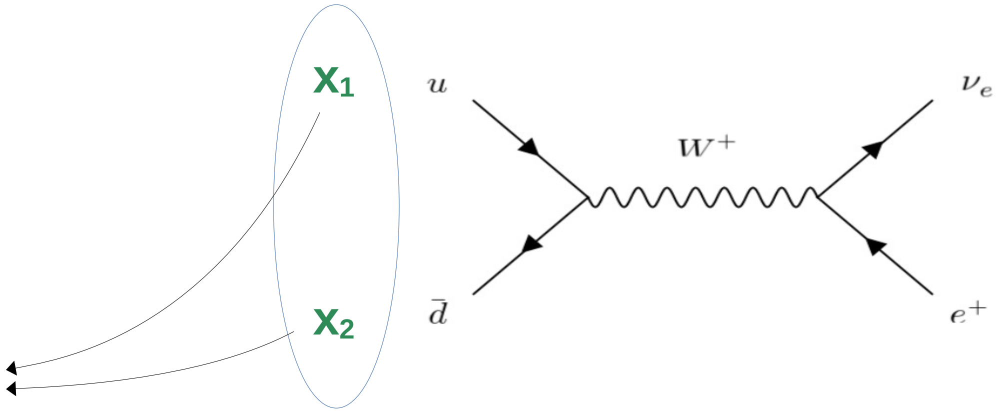
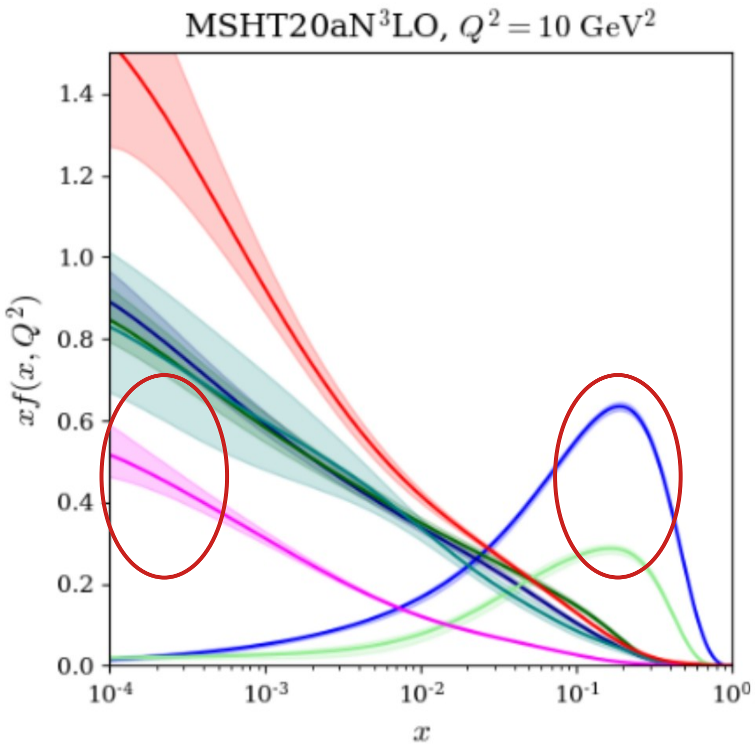




Rapidity distribution and PDFs



$m_W \sim 80$ GeV $\quad$ $x_{1,2} = m/\sqrt{s}\, e^{\pm y}$

Tevatron	√s~ 2TeV	$p\bar{p}$	0<y<2	$x_{1,2} \sim 10^{-2} - 10^{-1}$
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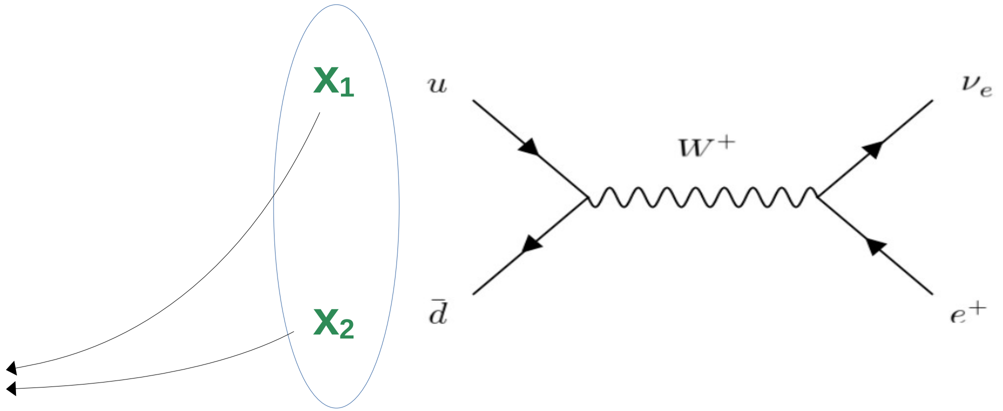
LHCb	√s~13TeV	pp	y~4	$x_{1,2} \sim 10^{-4} - 10^{-1}$



Emulation : D0

- Cross-checks on physics variations