Precise QCD measurements from LHC to future colliders

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on behalf of
ATLAS, CMS, LHCb

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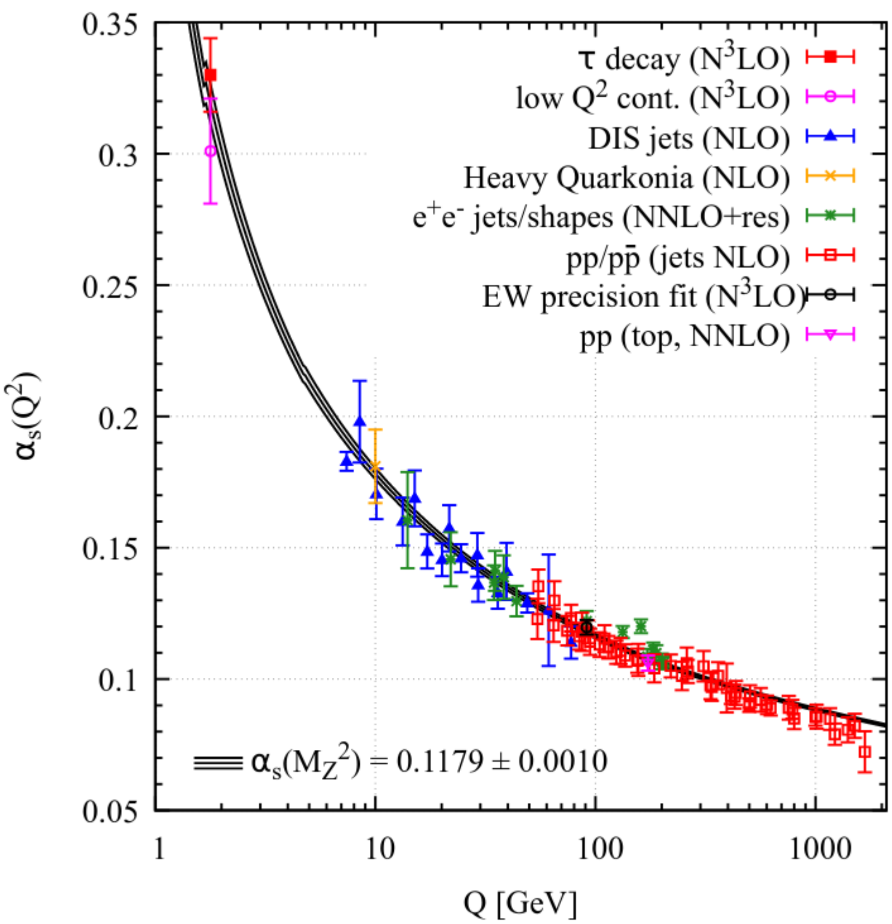
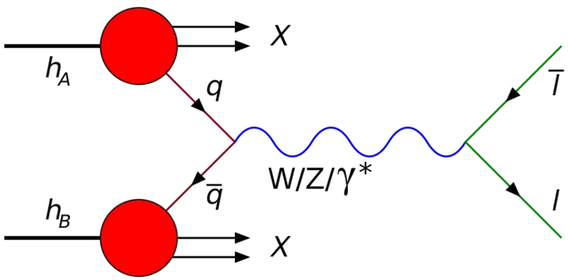
Precise QCD measurements

- Understanding QCD is critical for physics at hadron colliders
- Focus on precision:
  - Interplay between QCD and electroweak precision measurements
  - Precise QCD measurements leading to determination of $\alpha_s(m_Z)$, PDFs
- Topics:
  - QCD measurements of the Drell-Yan process
  - Measurements of $\alpha_s(m_Z)$ with jets and top at the LHC, and at future coliders

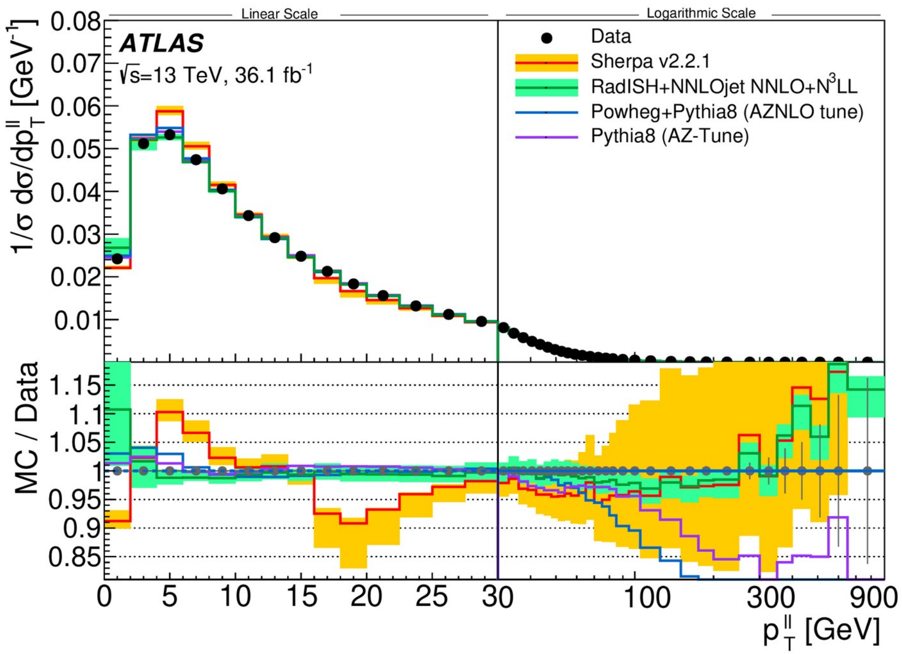


Drell-Yan QCD measurements

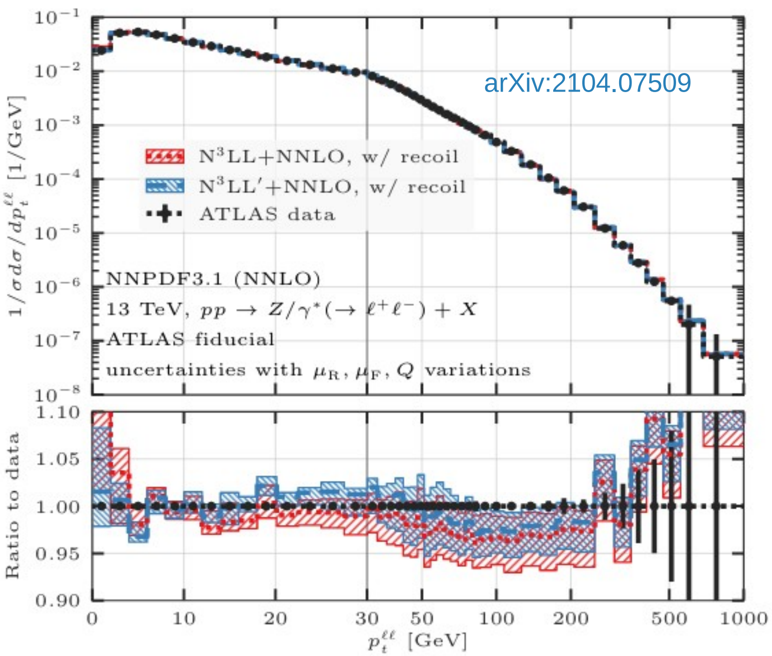


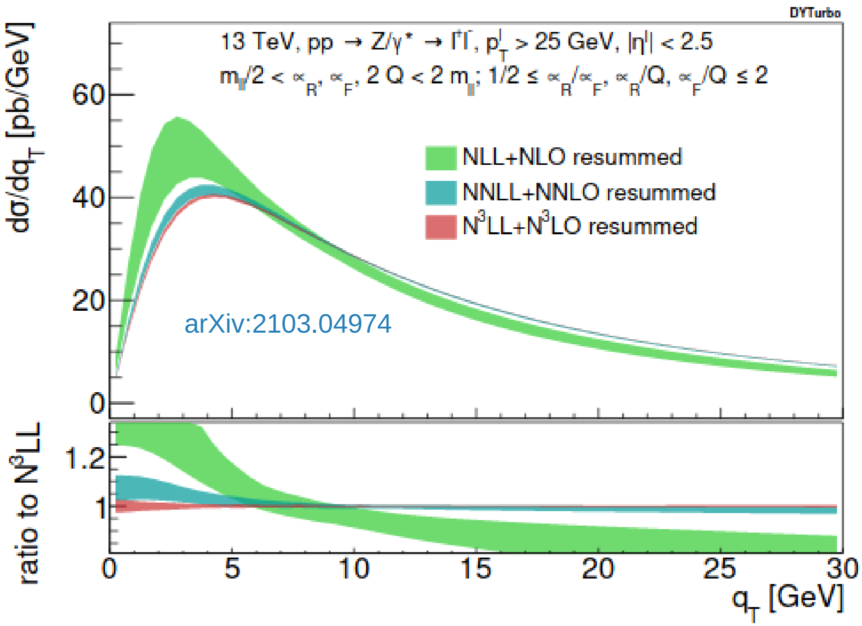
- The Drell-Yan mechanism was proposed and observed in 1970. It was a milestone in the building of QCD as the theory of the strong interation. After 45 years, why is this process still of interest for QCD and what can we learn from it?
- The Drell-Yan process at the LHC provides an extremely clear experimental signature: high resolution in the electron and muon channels, and small background contamination
- Measurements have reached permille level accuracy, QCD predictions are at 3 orders beyond LO → ideal framework for precision tests of QCD
  - $d\sigma/dpt$ allows probing of the transverse dynamic of non-perturbative and perturbative QCD
  - $d\sigma/dy$ allows probing of the longitudinal dynamic (PDFs)
  - The angular coefficients allow testing of the QCD and EW helicity structure
- QCD issues in these measurements are tightly connected to precision measurements of m_W and $\sin^2\theta_W$

Measurement of Z-boson transverse momentum

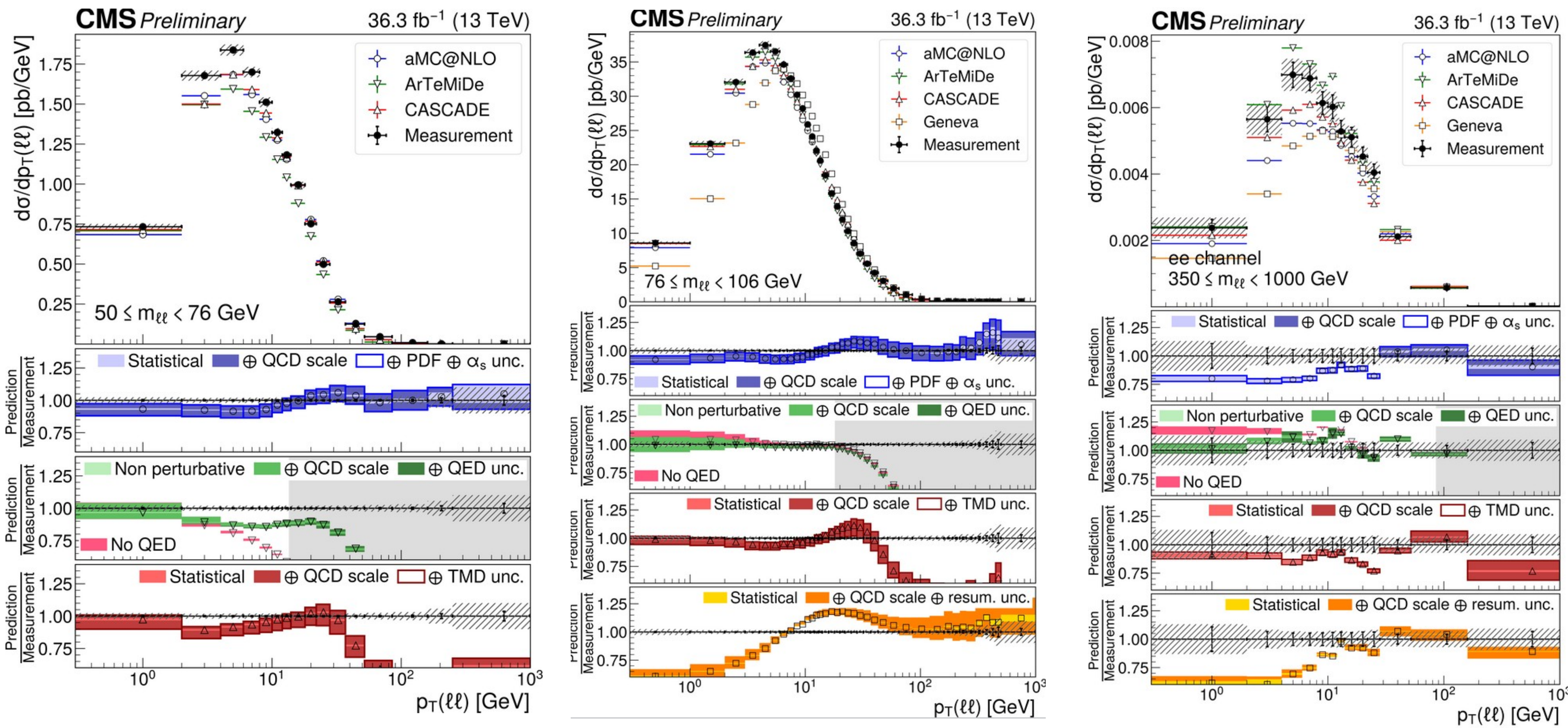


- Measurements have reached an accuracy of a few permille in the region below 100 GeV
- QCD predictions at N3LO+N3LL
- Excellent test of perturbative and non-perturbative QCD





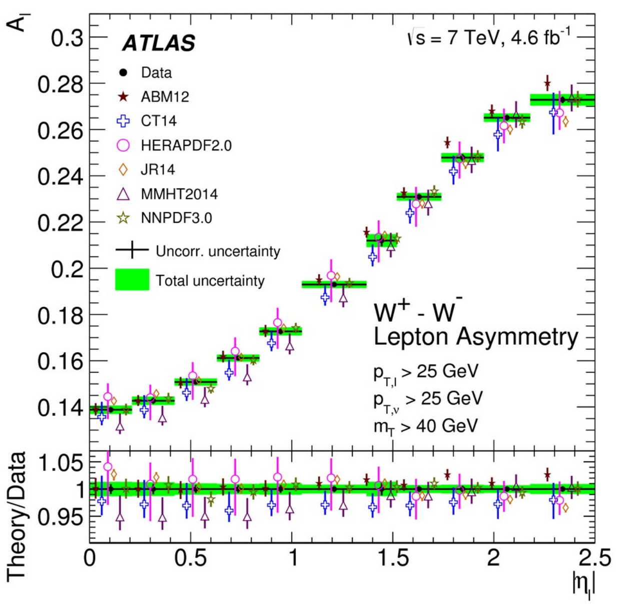
Measurement of Z-boson transverse momentum

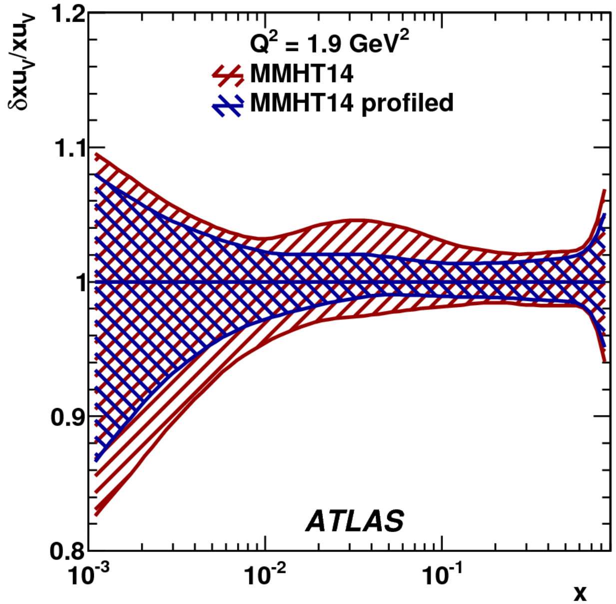


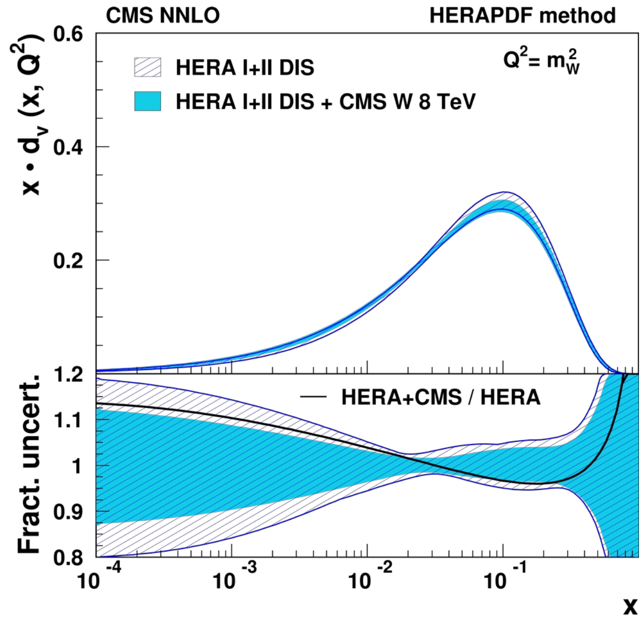
- Measurements differential in invariant mass, allows disentaglement of perturbative and non perturbative effects, and of different initial flavour compositions

W, Z rapidity cross section measurements

- W asymmetry and Z rapidity measurements at the LHC directly constrain valence and sea PDFs



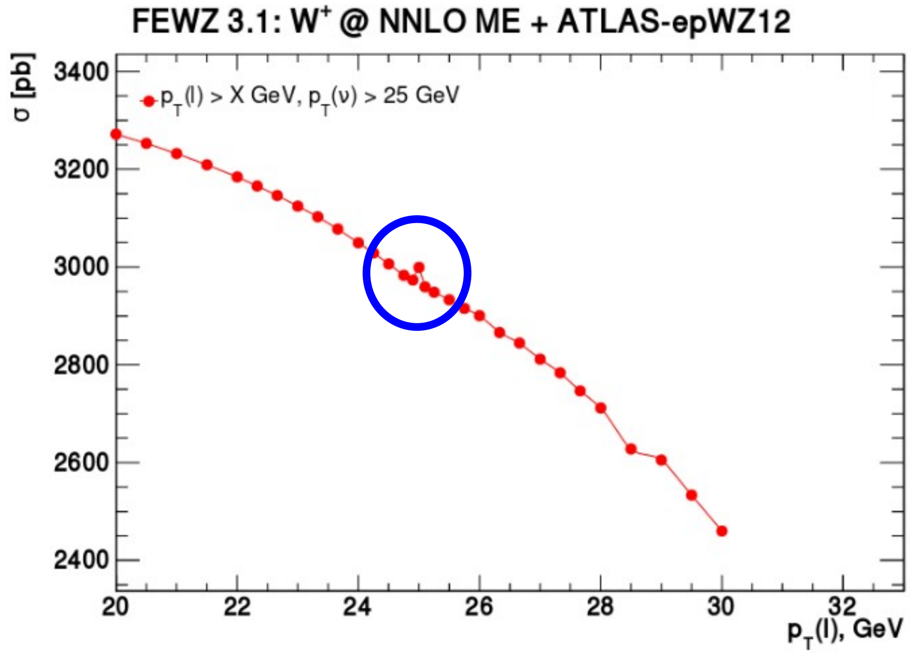


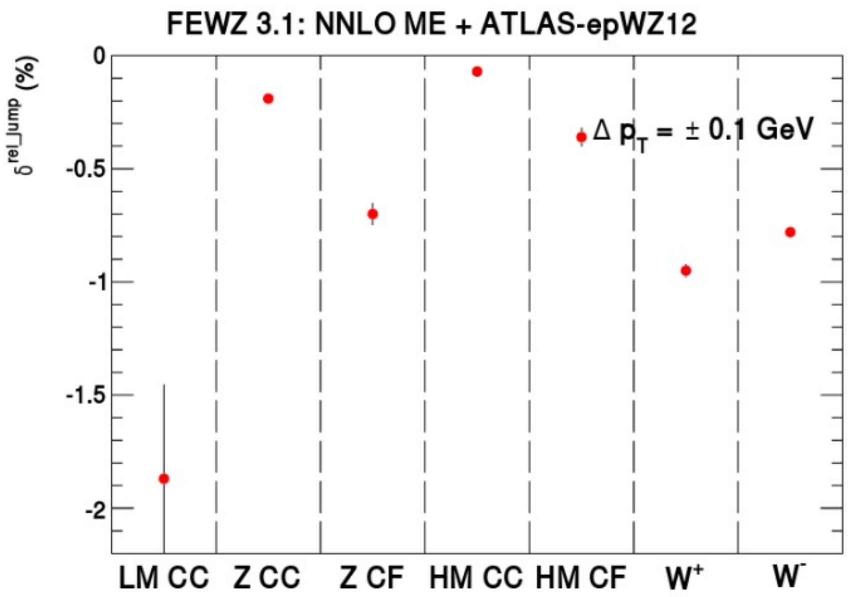


- These measurements are systematics limited already in Run 1
- New experimental methodology are needed to fully exploit the potential of the full LHC data sample
- With enough statistics, low pile up data can also be used to perform measurements with smaller systematic uncertainties

Fiducial power corrections

- The usage of W asymmetry and Z rapidity measurements to reduce PDF uncertainties is currently limited by symmetric fiducial cuts
- Perturbative calculations are be affected by enhanced logarithms, connected to the linear dependence of acceptance on the boson p_T. When approaching the limit $p_{T,2} \rightarrow p_{T,1}$ they become unreliable
- The effect is larger when p_T is closer $m_{ll}/2$, and at large values of $\cos(\theta)$, as in the central-forward (CF) kinematic region
- Need to resum fiducial power corrections in order to get a meaningful predictions, either with parton shower or with analytic resummation





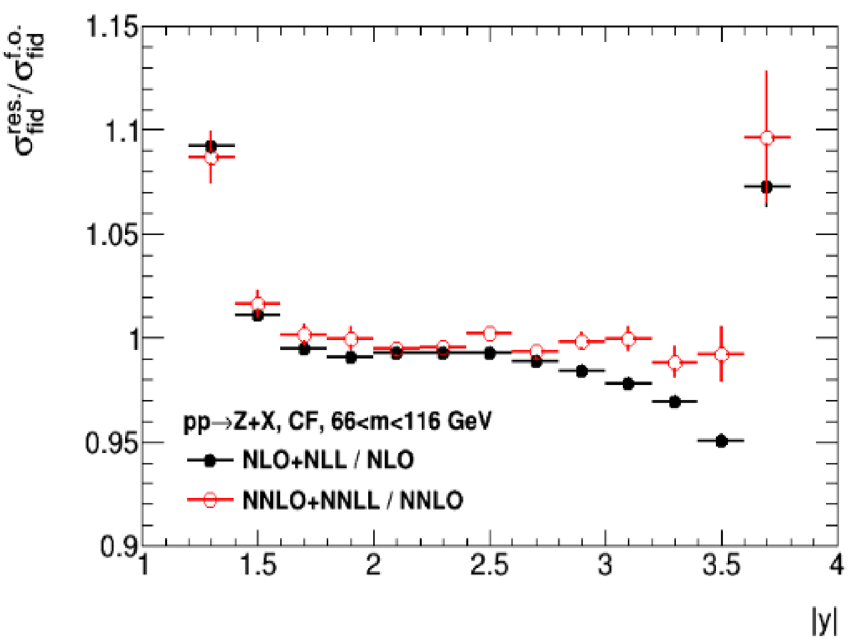
Recent studies on this topic with alternative solutions

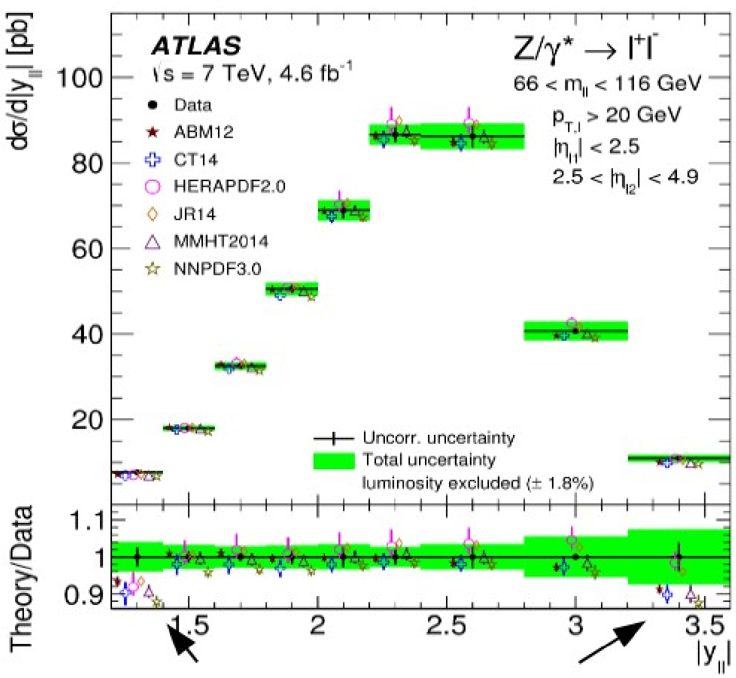
- arXiv:2106.08329 Salam, Slade
- arXiv:2104.02400 Alekhin et al.
- arXiv:2006.11382 Ebert et al.
- arXiv:2001.02933 Glazov

Fiducial power corrections

- Preliminary study, including q_T-resummation with a recoil prescription in PDF fits to ATLAS W,Z rapidity measurements
- Corrections are significant compared to the experimental accuracy, and gives large improvement in χ^2
- Striking example is the Z central-forward configuration, with 10% corrections in the first and last bins

Dataset	CT14 published	CT14 NNLL
ATLAS low mass Z rapidity 2011	11 / 6 →	8.7 / 6
ATLAS peak CC Z rapidity 2011	16 / 12 →	10 / 12
ATLAS peak CF Z rapidity 2011	10 / 9 →	5.6 / 9
ATLAS high mass CC Z rapidity 2011	6.3 / 6	6.3 / 6
ATLAS high mass CF Z rapidity 2011	5.1 / 6	5.4 / 6
ATLAS W- lepton rapidity 2011	8.9 / 11	8.8 / 11
ATLAS W+ lepton rapidity 2011	10 / 11	10 / 11
Correlated χ^2	39 →	35
Log penalty χ^2	-4.11	-3.60
Total χ^2 / dof	103 / 61 →	86 / 61
χ^2 p-value	0.00	0.02

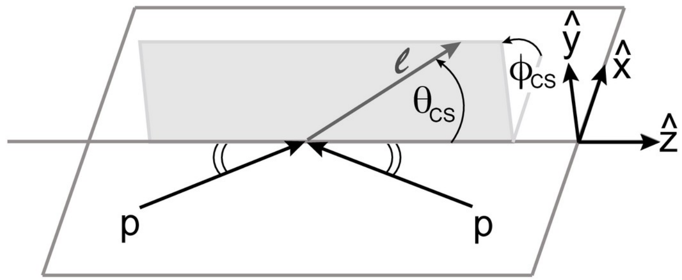


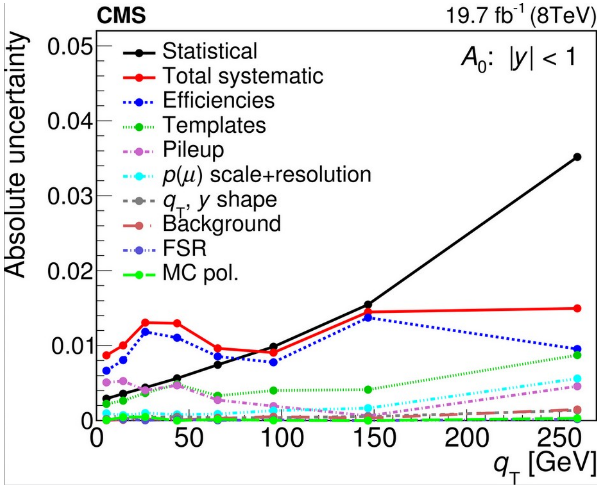


Z-boson angular coefficients

- The angular coefficients provide a powerful framework to describe asymmetries of the DY cross section as the azimuthal (A2) and the forward-backward (A4). The decomposition holds at all order in QCD

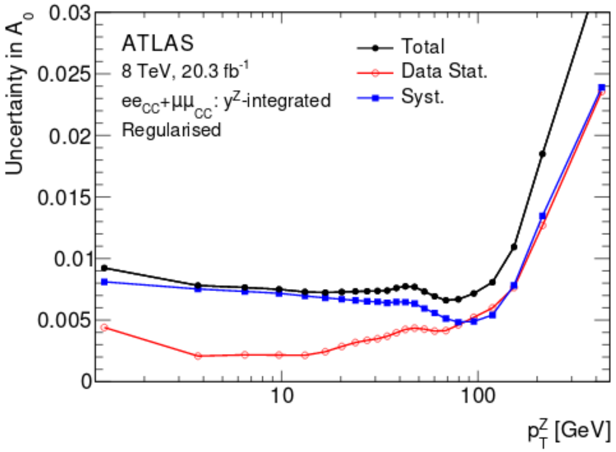
$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma}{dp_T dy dm} \sum_i A_i(y, p_T, m) P_i(\cos\theta, \phi)$$





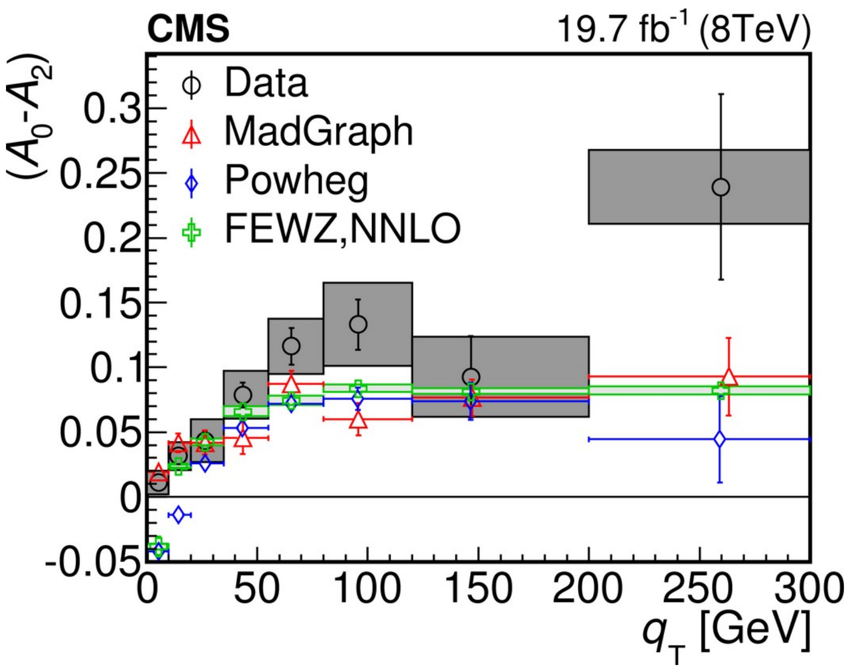
- Coefficients defined in the Collins-Soper frame

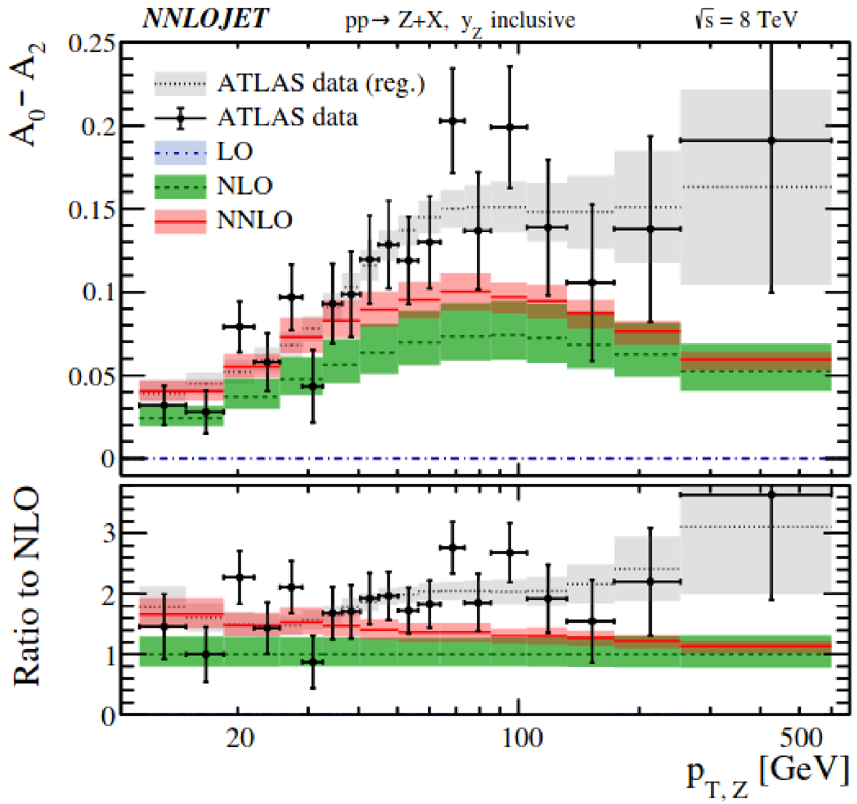
- Percent-level measurements from ATLAS and CMS at 8 TeV, as well as accurate perturbative QCD predictions at O(α_s^3) are available

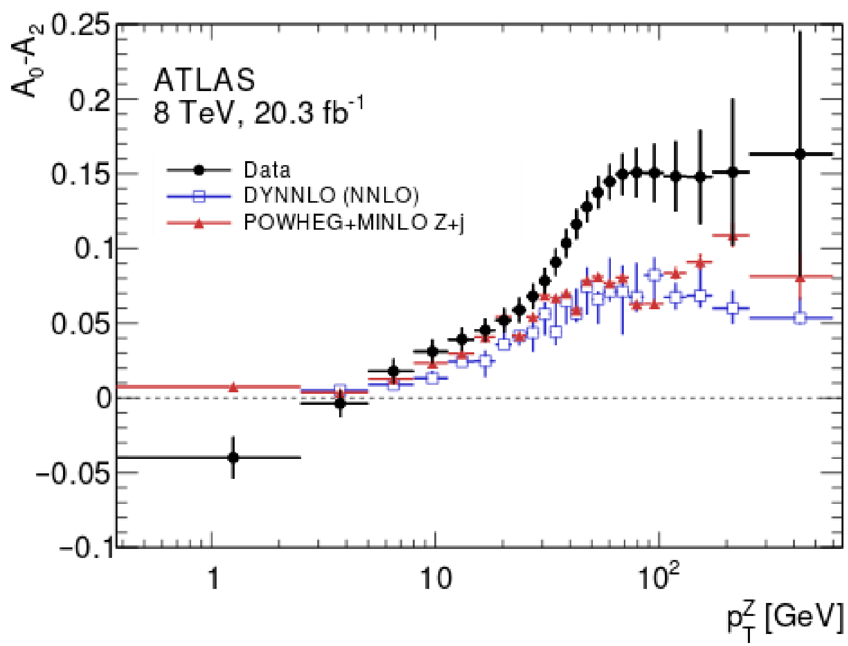


Z-boson angular coefficients

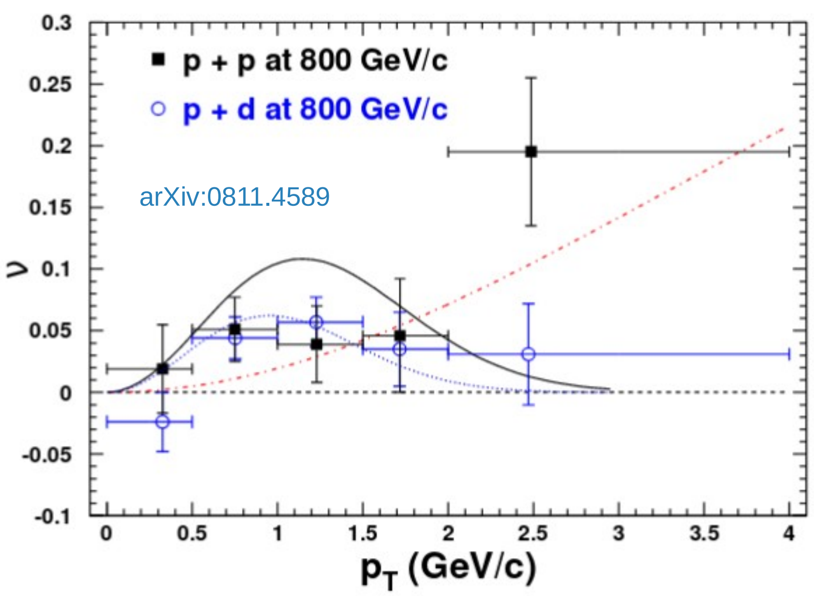
- Interesting violation of the The Lam-Tung relation A0-A2 = 0 in excess with respect to perturbative QCD predictions
- Tension mildly reduced at O(α_s^3)



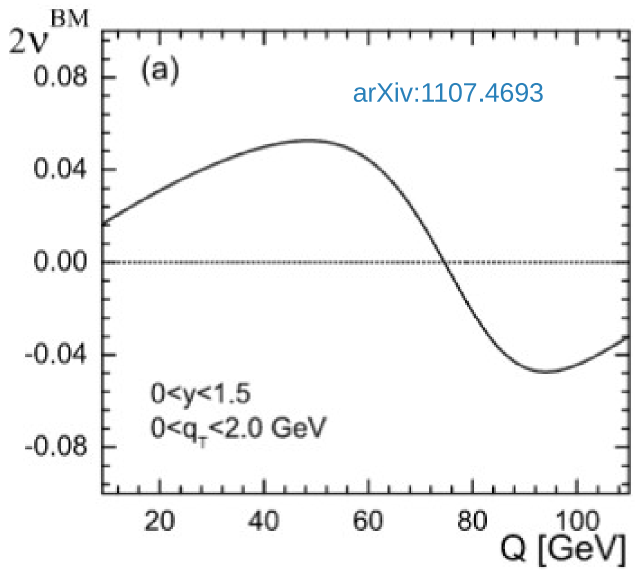




Angular coefficients in the non perturbative regime

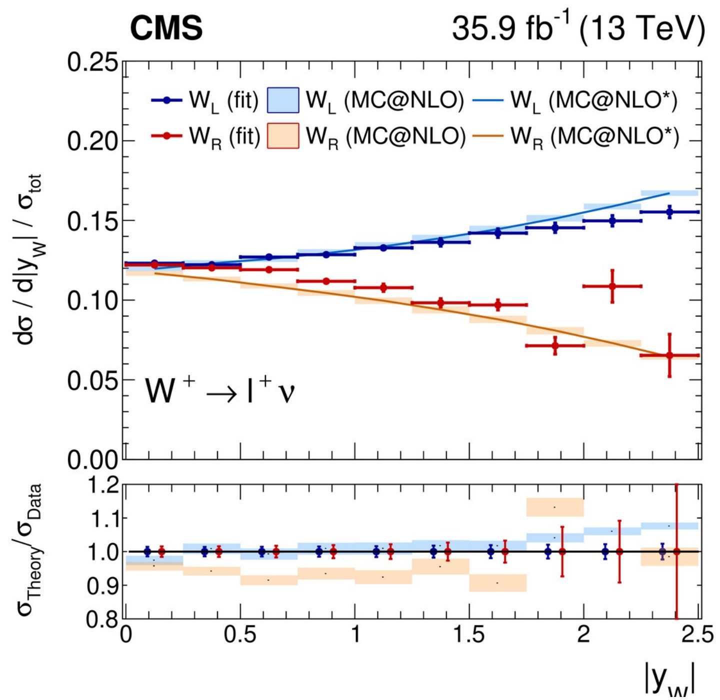


- cos(2ϕ) (A2) asymmetries in the non perturbative regime were observed in fixed target Drell-Yan experiments (NA10, E866)
- They are well described by Boer-Mulder TMD functions



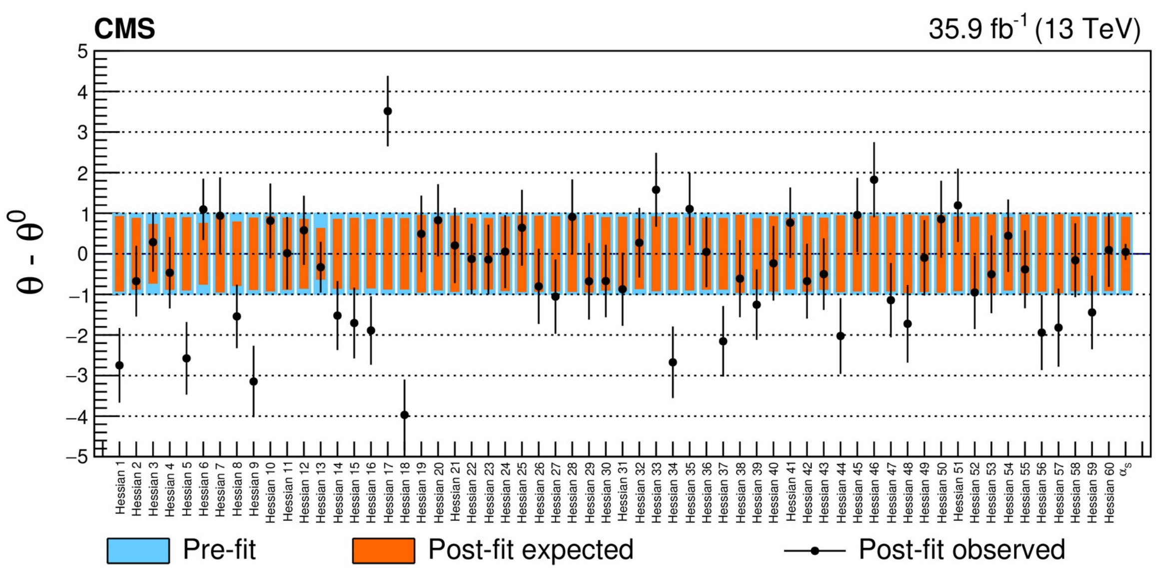
- The non-perturbative contribution to A2 at small q_T is expected to change sign between γ^* and Z exchange
- Is such an asymmetry expected also in W? The measurement of m_W could be sensitive to such non-perturbative QCD asymmetries, it may be necessary to quantify it precisely for future measurements

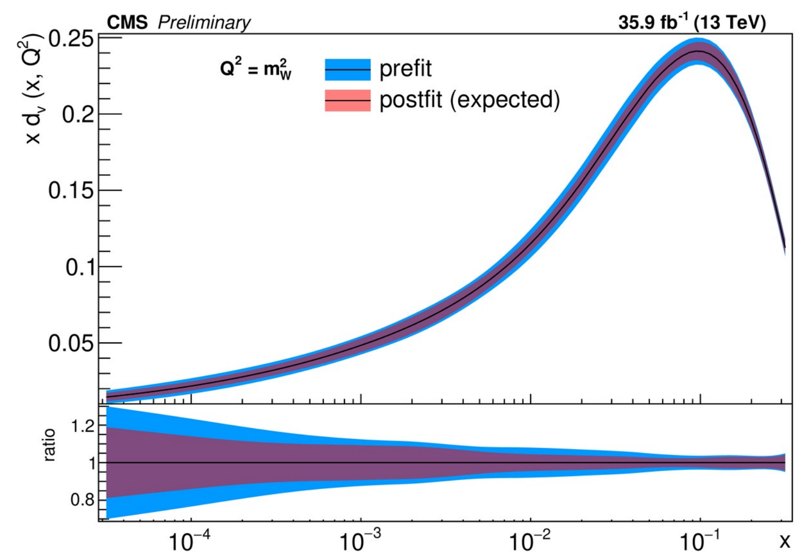
CMS W polarisation



arXiv:2008.04174

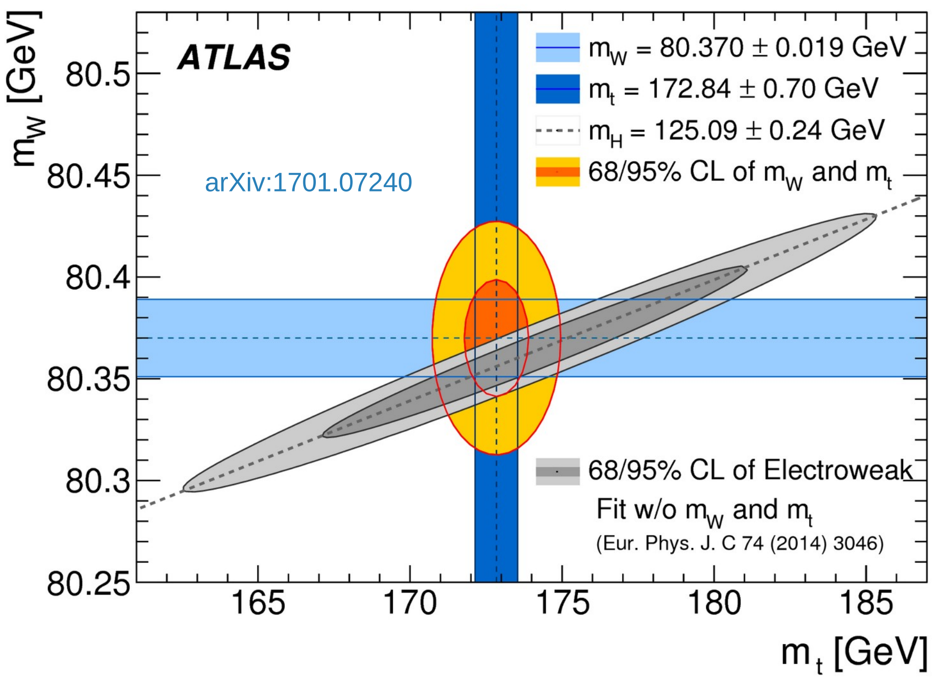
- New measurement of W helicity fractions, essentially a measurement of forward-backward asymmetry in W
- Together with the standard W charge asymmetry provides an interesting constraint on PDFs

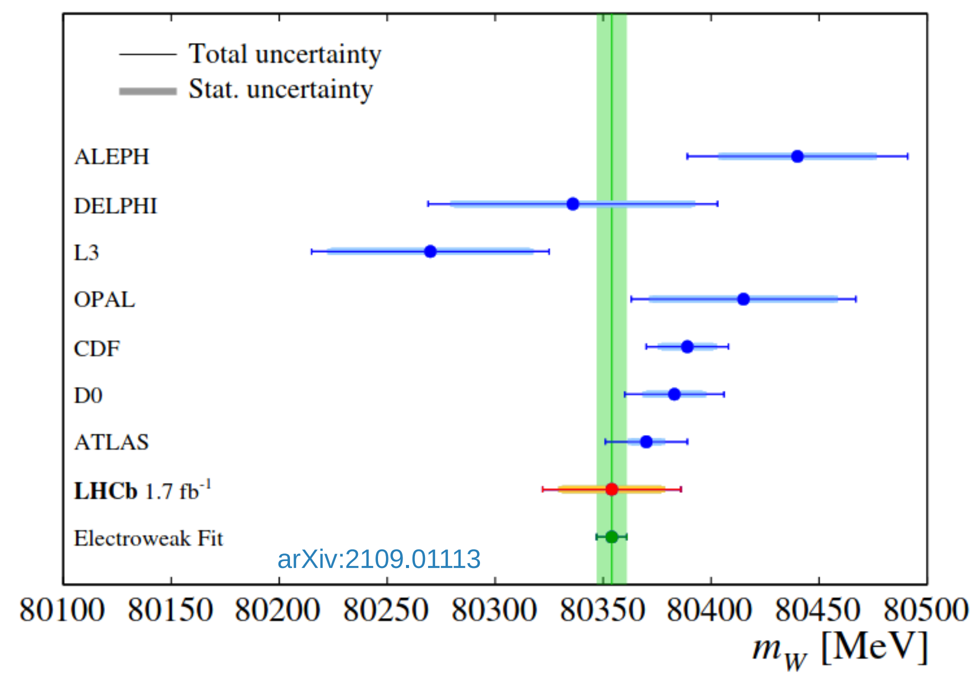




QCD issues in the measurement of m_W at the LHC

- The measurement of m_W at the LHC is extremely sensitive to QCD effects
- They affect all aspects of the measurement: detector calibration, transfer from Z to W, PDF uncertainties, W polarisation, modelling of p_T W
- The measurement of m_W provides a great occasion to understand QCD, recent examples are the ATLAS and LHCb measurements





ATLAS and LHCb results for m_W

ATLAS

M_W = 80369.5 ± 6.8 (stat) ± 10.6 (exp.syst.) ± 13.6 (model.syst.) MeV

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

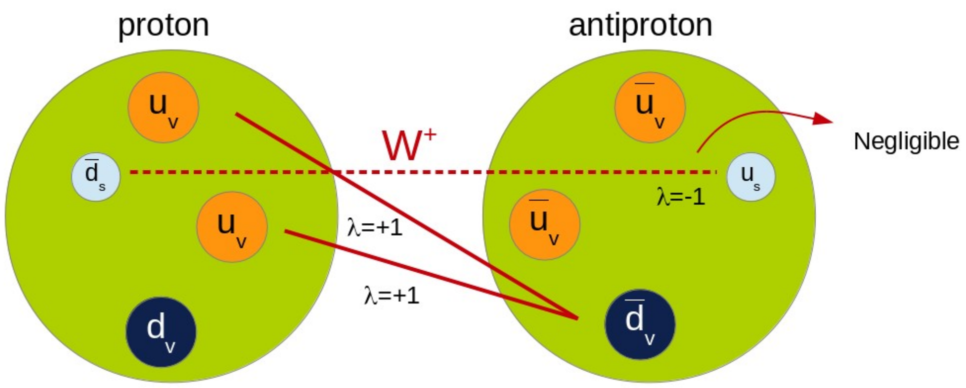
LHCb

M_W = 80354
± 23 (stat)
± 10 (exp)
± 17 (theory)
± 9 (PDF)
MeV

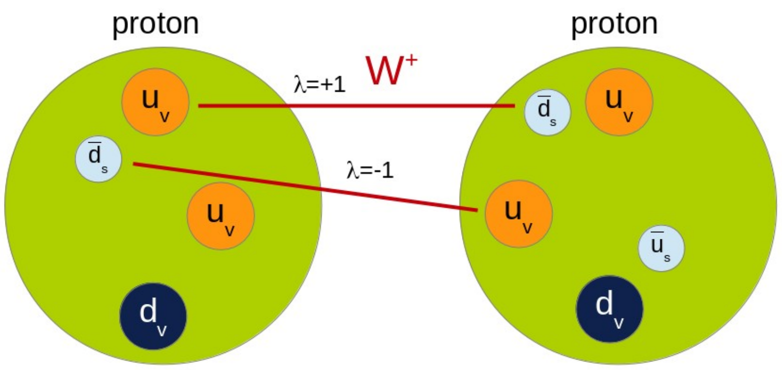
Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

- The dominant uncertainty is due to the physics modelling (theory)
- The largest contributions are from QCD/PDFs

A proton-proton collider is the most challenging environment to measure m_W, worse compared to e+e- and proton-antiproton



In $p\bar{p}$ collisions W bosons are mostly produced in the same helicity state



In pp collisions they are equally distributed between positive and negative helicity states

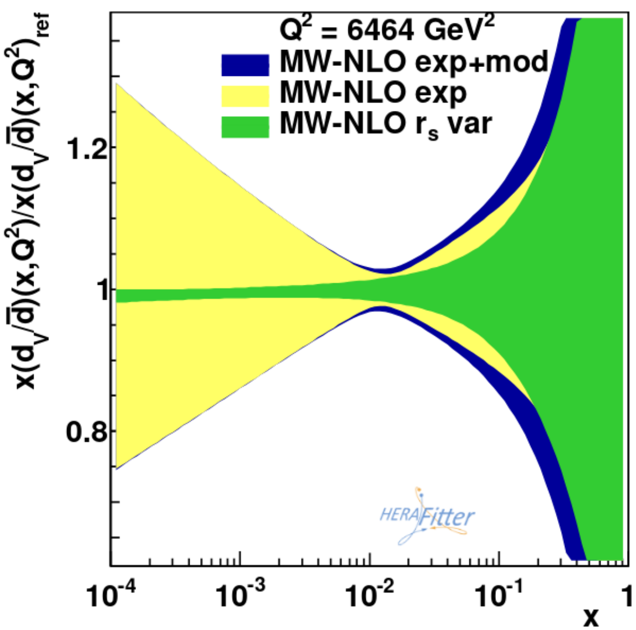
Further QCD complications

- Heavy-flavour-initiated processes
- W+, W- and Z are produced by different light flavour fractions
- Larger gluon-induced W production

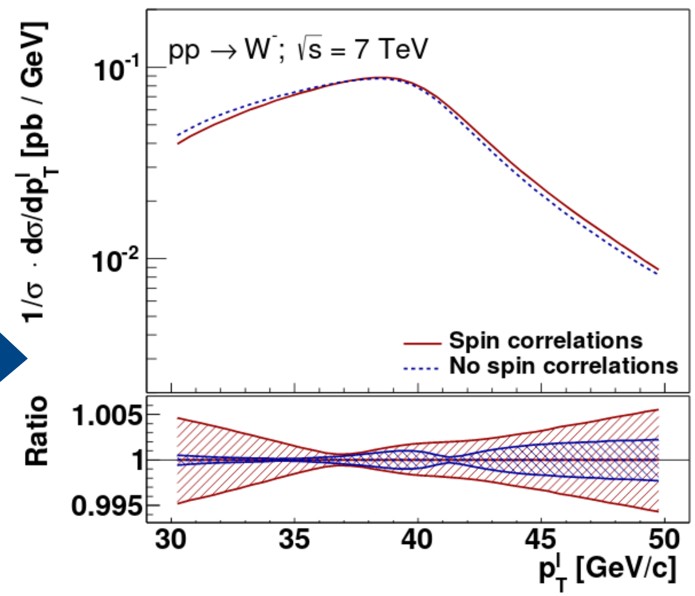
Large PDF-induced W-polarisation uncertainty affecting the p_T lepton distribution

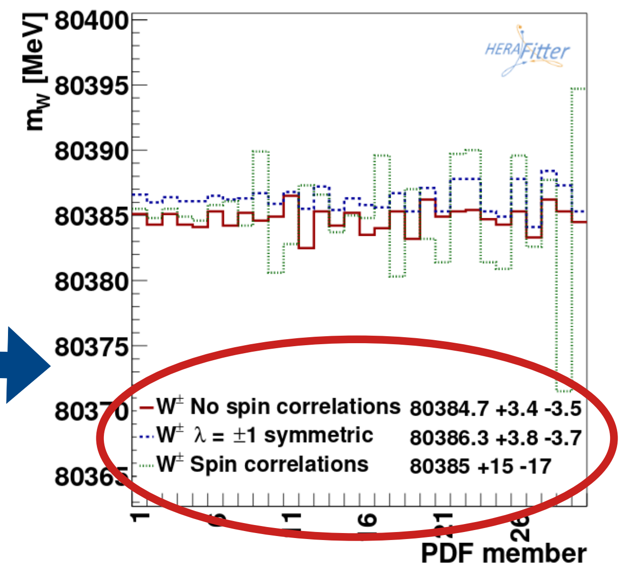
PDF uncertainties

- PDF uncertainties are currently the largest uncertainty at the LHC, and they are expected to remain dominant in future measurements
- The main mechanism which gives rise to large PDF uncertainties is: valence/sea → W helicity → p_T lepton → m_W



ATL-PHYS-PUB-2014-015





~80% of the PDF uncertainty on m_W is longitudinal-polarisation induced

Physics modelling for m_W

- The physics modelling comprises the theoretical prediction used to extract the W mass from the observed distributions in data, and the way theory uncertainties are addressed.
- The DY cross section can be reorganised by factorising the dynamic of the boson production, and the kinematic of the boson decay:

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

Breit-Wigner

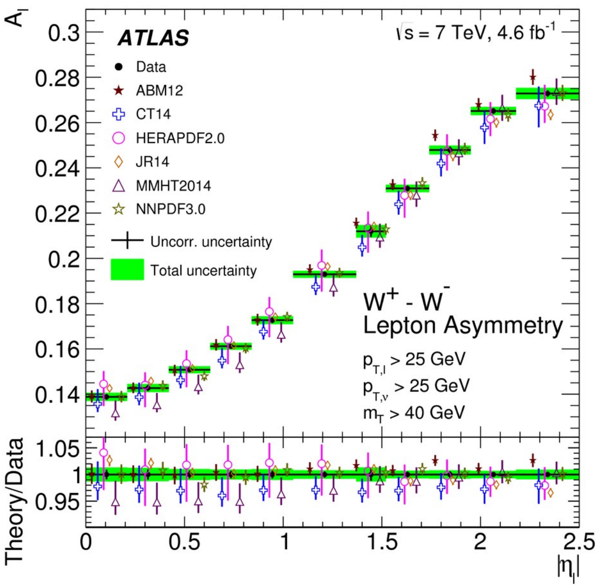
NNLO pQCD

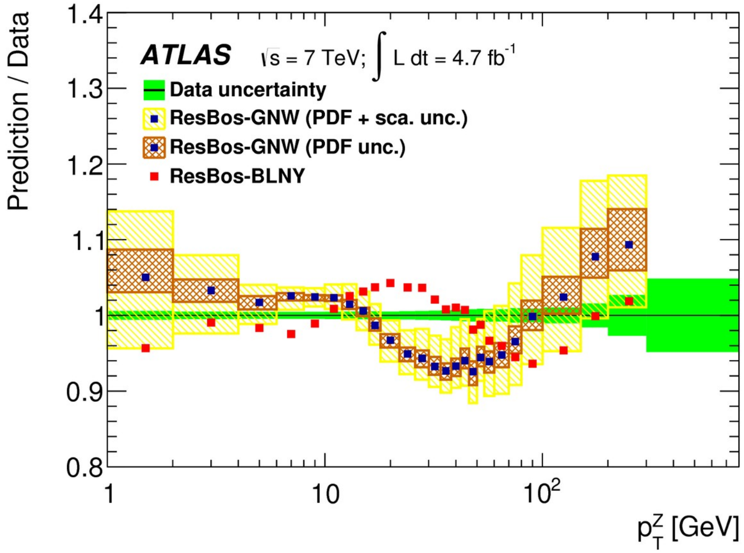
Parton Shower

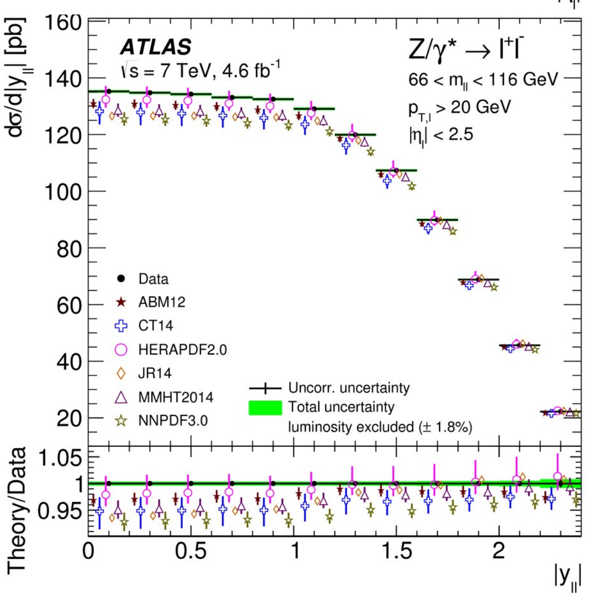
- This factorization allows building a composite model, and using the most appropriate or accurate model for each term.
- Precise QCD is essential for modelling of dσ/dy, dσ/dpt and of the angular coefficients. The physics modelling strategy is based on QCD predictions and auxiliary DY measurements.

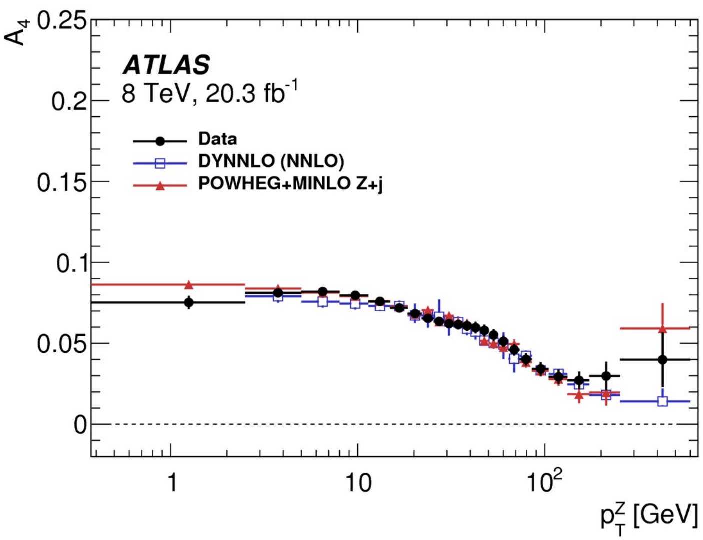
Physics modelling – DY ancillary measurements

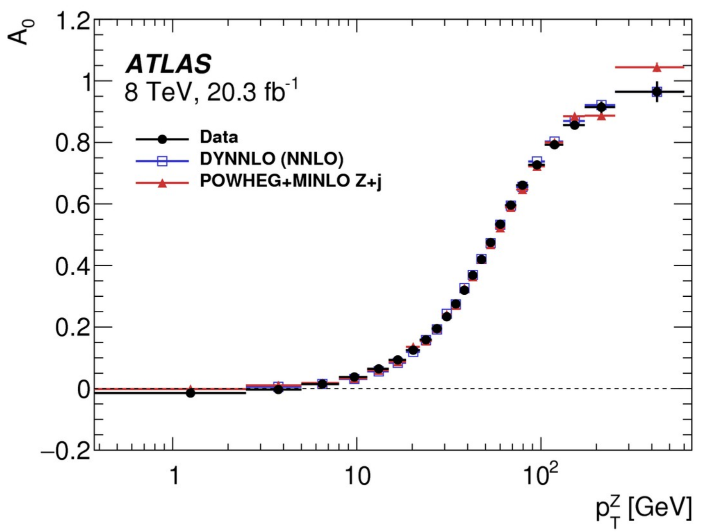
$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y) P_i(\cos\theta, \phi)\right]$$





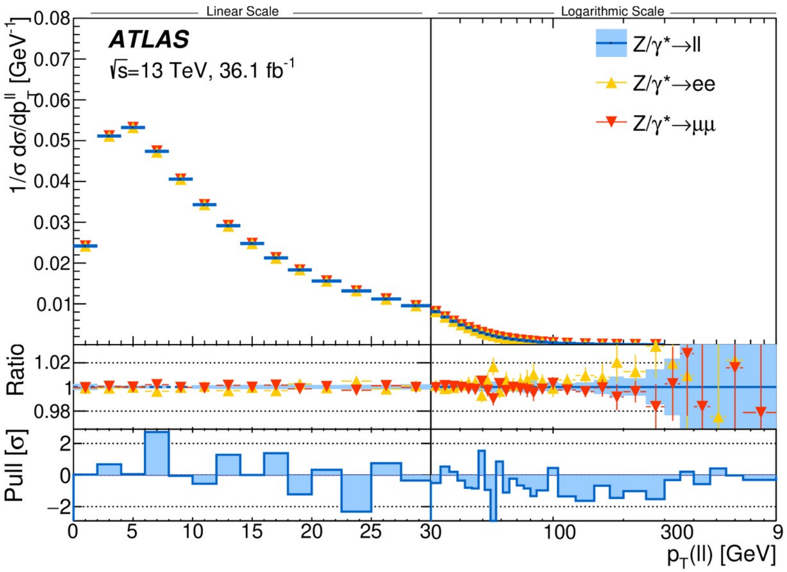


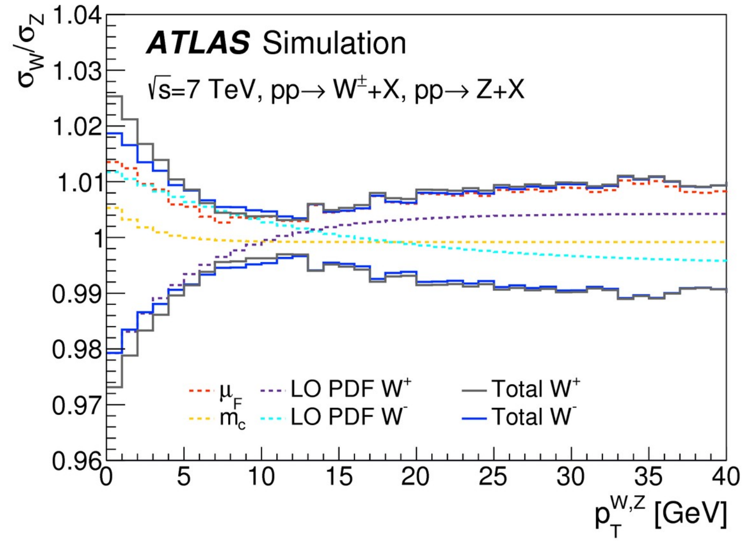


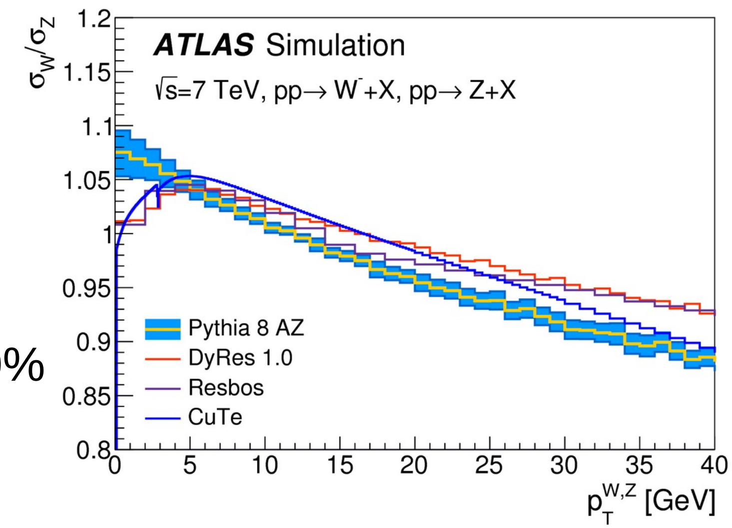


Modelling of p_T W

- The p_T W modelling is based on precise measurements of p_T Z and accurate predictions of the W/Z p_T ratio





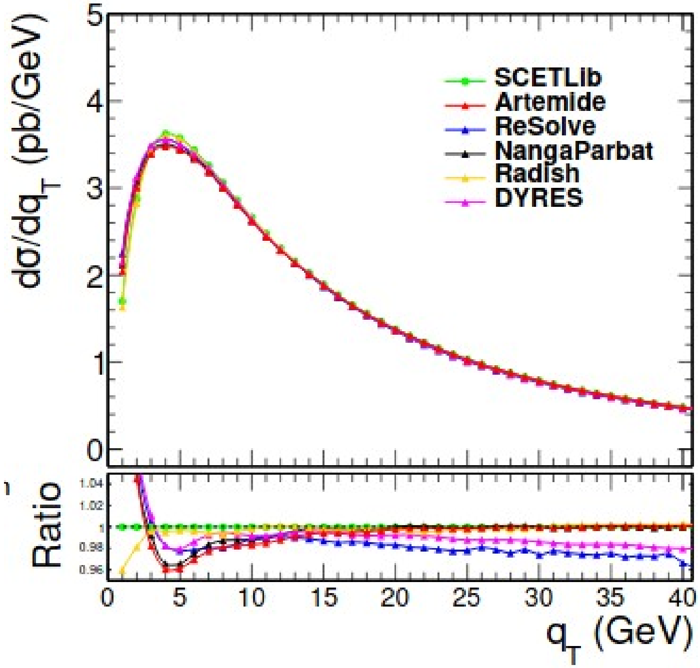


- The p_T Z distribution is measured at permille accuracy
- The WZ p_T ratio is currently known with 2-3% uncertainty
- Large spread of W/Z p_T ratio predictions at the level of 5-10%

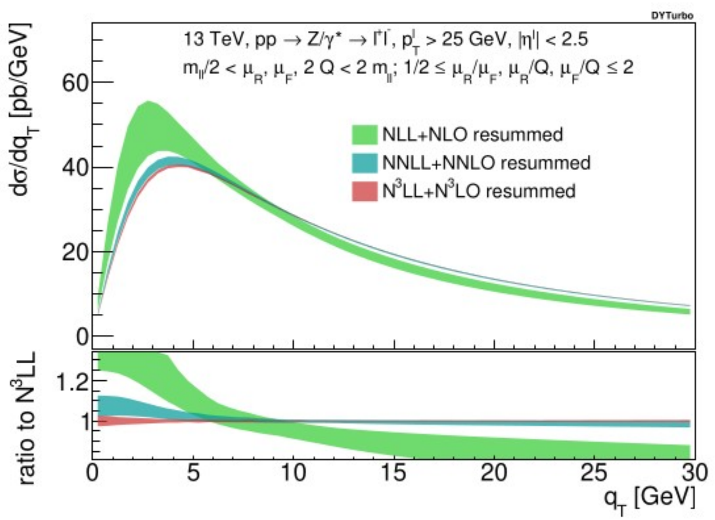
→ Require great control of:

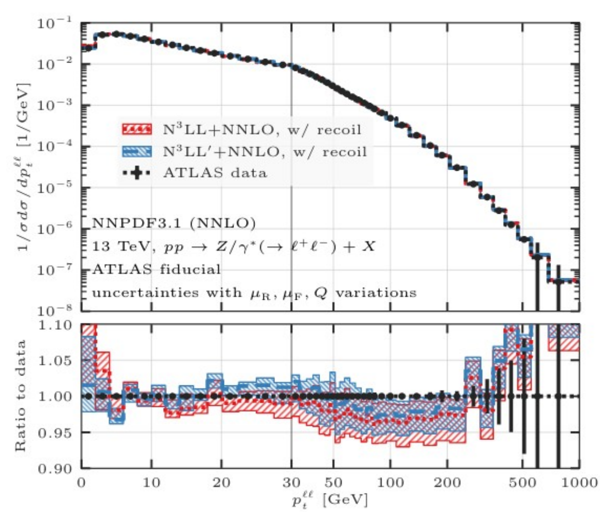
- non-perturbative QCD
- q_T-resummation
- heavy-flavour-initiated production

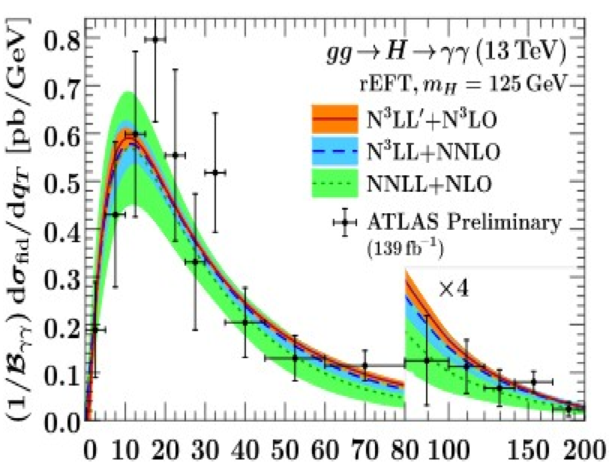
Modelling of p_T W



- Ongoing effort in the LPCC EW working group to benchmark various different predictions of the W/Z p_T ratio, aimed at
  - Define a common baseline where all predictions agree
  - Allow using the prediction which is best suited to derive each particular correction and/or uncertainty on top of the baseline
- Recently q_T-resummation predictions have reached N3LL' accuracy
- However high-order perturbative accuracy alone is not sufficient for a precise prediction of the W/Z pT ratio

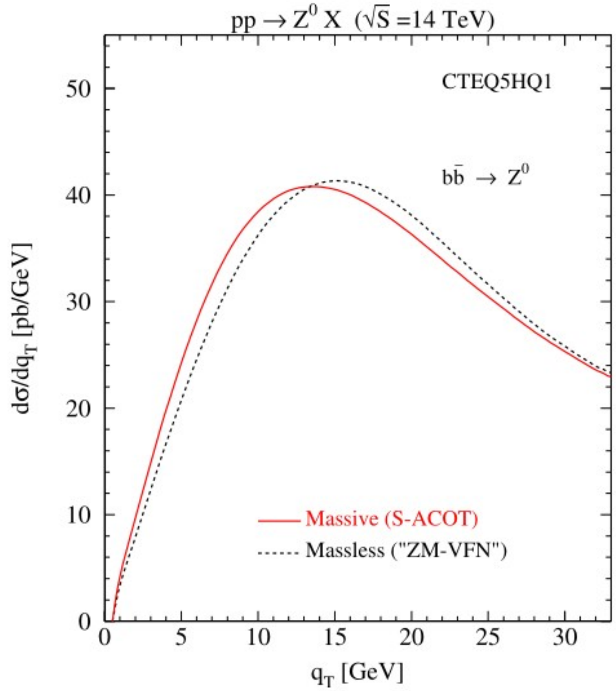






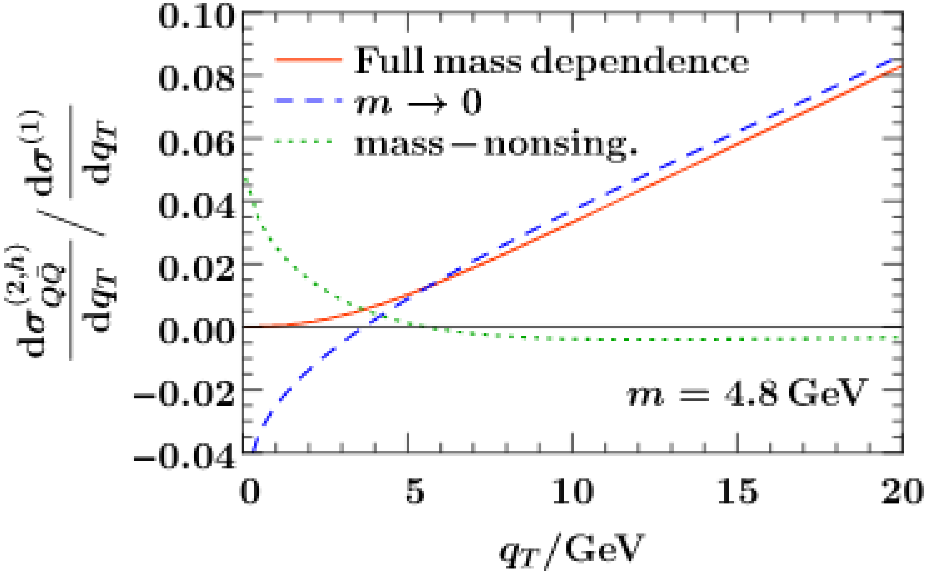
Modelling of p_T W

hep-ph/0509023



- Heavy flavours initiated production with ACOT VFN scheme for Drell-Yan

arXiv:1703.09702

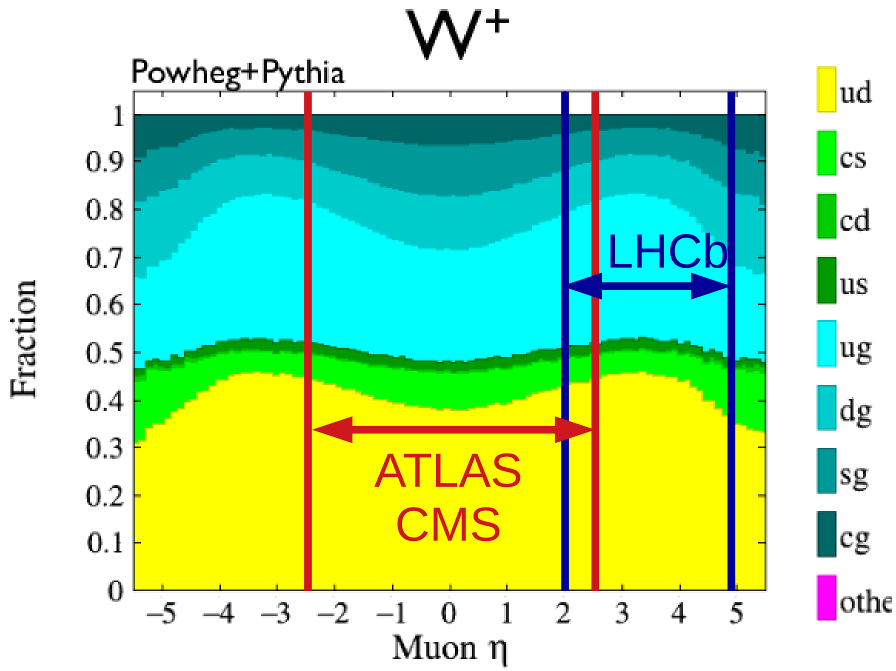


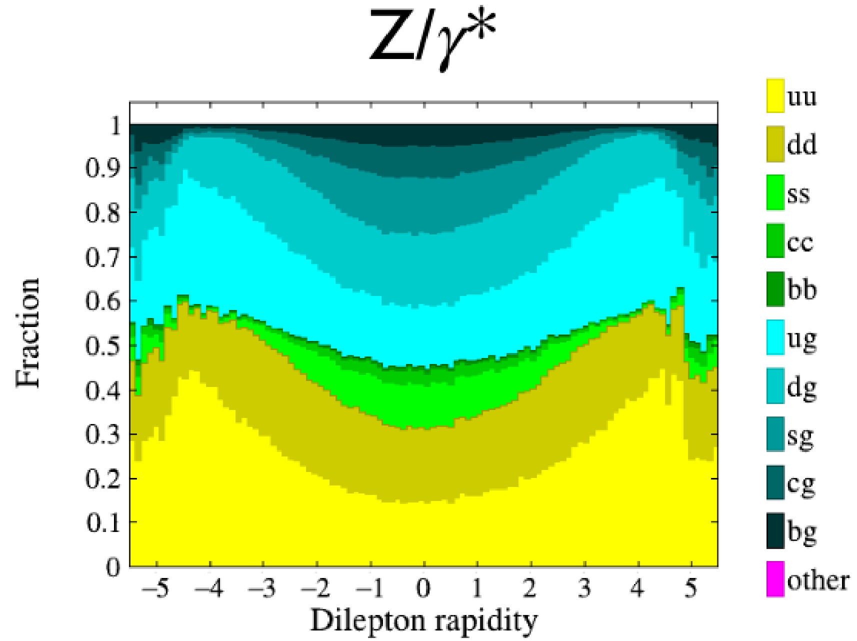
- SCET-based approach for q_T-resummation with massive quark effects

Further open issues

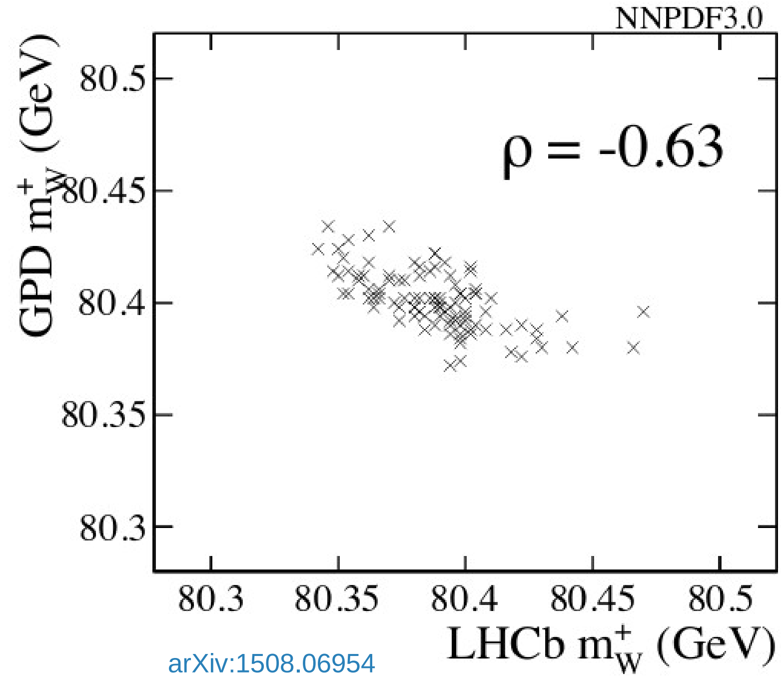
- Non perturbative models, TMD
- Prescription for the IR Landau Pole
- BFKL

LHCb m_W

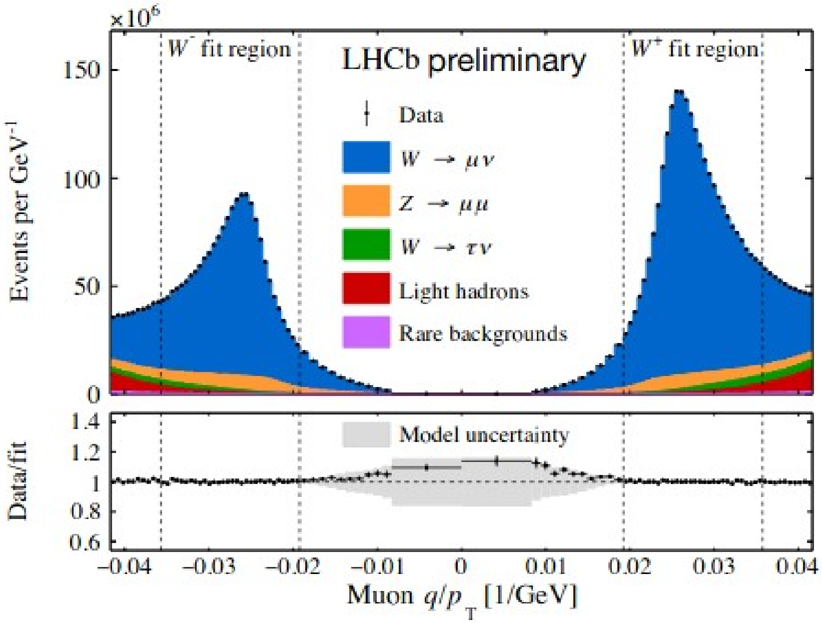


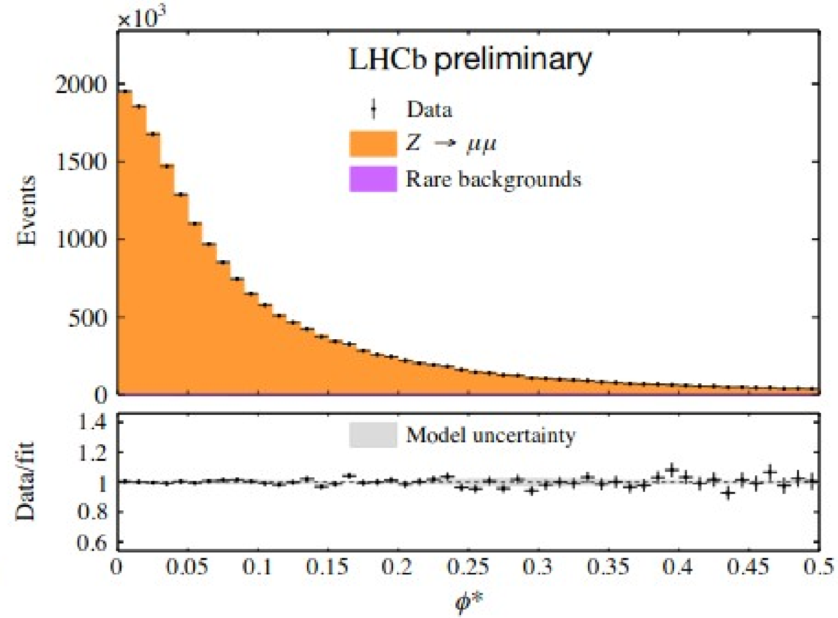


- LHCb acceptance is highly complementary to ATLAS and CMS
- W production at LHCb has a different flavour decomposition with respect to ATLAS and CMS
- PDF uncertainty are largely uncorrelated or anti-correlated between ATLAS-CMS and LHCb, and the corresponding uncertainty will be largely reduced in the combination



LHCb physics modelling





Floating parameter	Postfit value
Fraction of $W^+ \to \mu^+\nu$	0.5293 ± 0.0006
Fraction of $W^- \to \mu^-\nu$	0.3510 ± 0.0005
Fraction of hadron background	0.0151 ± 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	0.979 ± 0.026

$$\chi^2/\mathrm{ndf} = 105/102$$

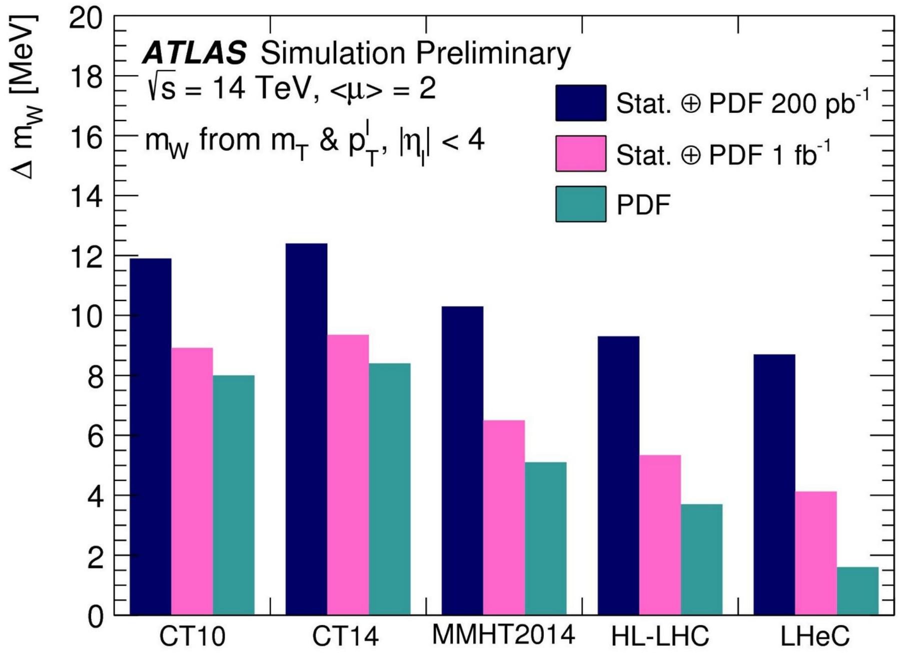
$$\sigma_{\mathrm{stat}}(m_W) = 23\ \mathrm{MeV}$$

(Fit value is still blinded)

- Additional freedom in the W/Z p_T ratio through independent $\alpha_s(m_Z)$ values
- Normalisation of A3 coefficient is left free in the fit

- LHC measurements would greatly benefit from understanding such issues from first principles

Prospects for m_W at the HL-LHC with low pileup data



ATL-PHYS-PUB-2018-026

- Increased acceptance provided by the new inner detector in ATLAS, (ITk) extends the coverage up to $|\eta| < 4$
- → Allows further constraints on PDFs from cross section measurements
- With 1fb^{-1} of low pileup data ($<\mu>\sim2$) likely to reach ~ 6 MeV of stat+PDF uncertainty
- LHeC ep collisions would largely reduce PDF uncertainties (< 2 MeV)

W mass at future colliders

- The ultimate precision on m_W can be achieved at e^+e^- colliders through an energy scan of the WW production threshold

- Near threshold, the WW cross section is proportional to the non-relativistic W velocity

$$\sigma(WW) \propto \beta_W$$

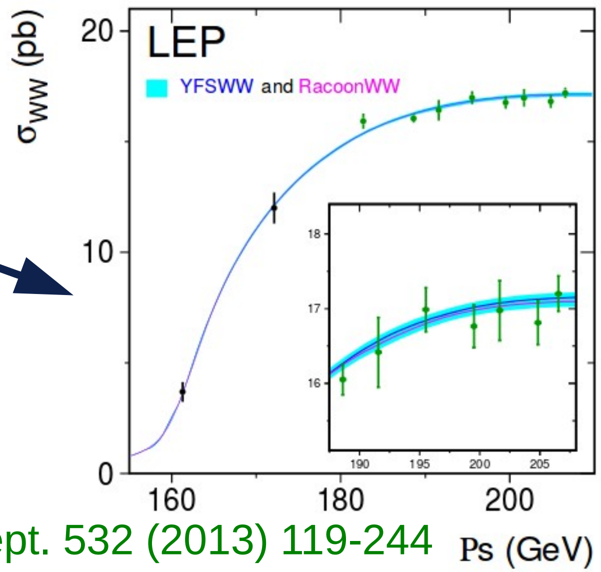
arXiv:1306.6352

ILC Giga-Z program
- Energy scan 160 to 170 GeV
- δM_W = 6-7 MeV

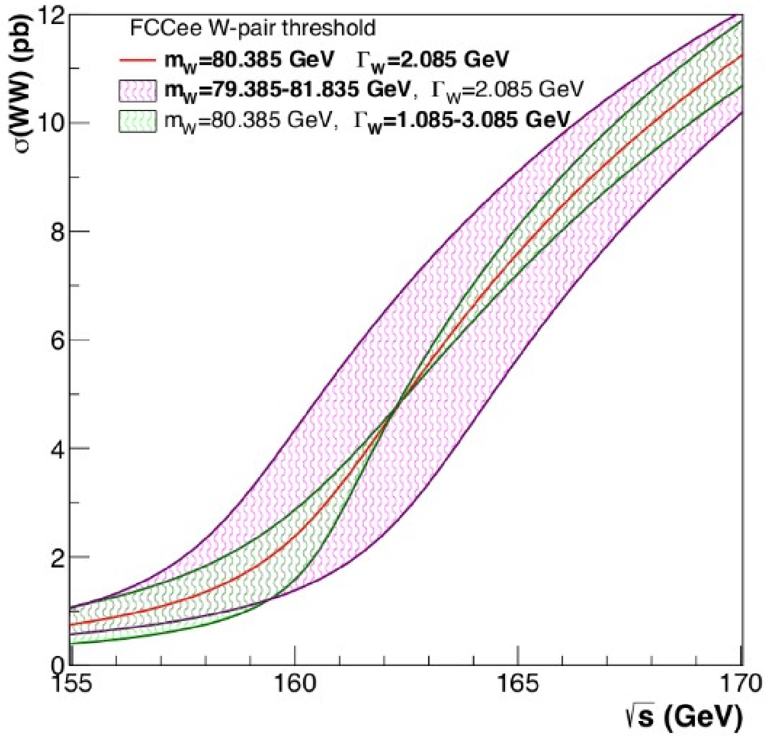
FCC-ee WW program
- δM_W = 0.5 MeV
  → dominated by statistical uncertainty

Dominant theory uncertainties
- Initial state QED corrections
- Parametrization of cross section near threshold

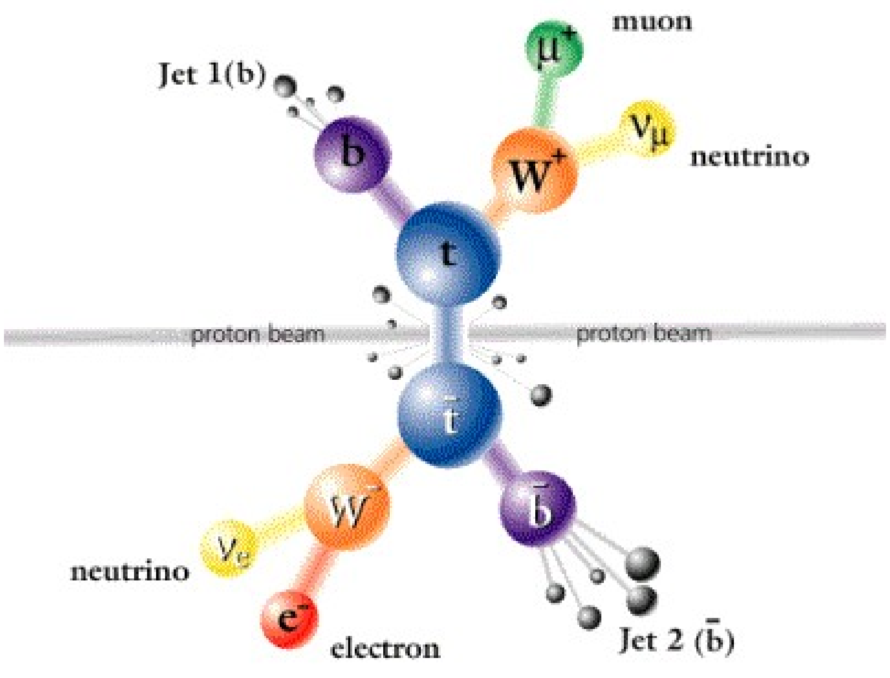
QCD not an issue!



Phys.Rept. 532 (2013) 119-244

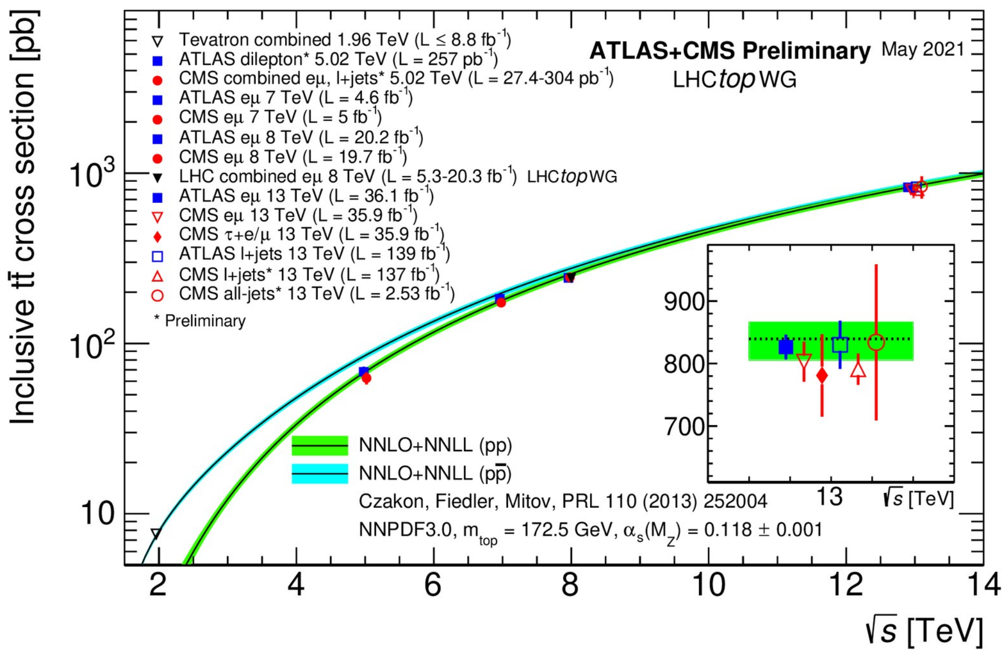


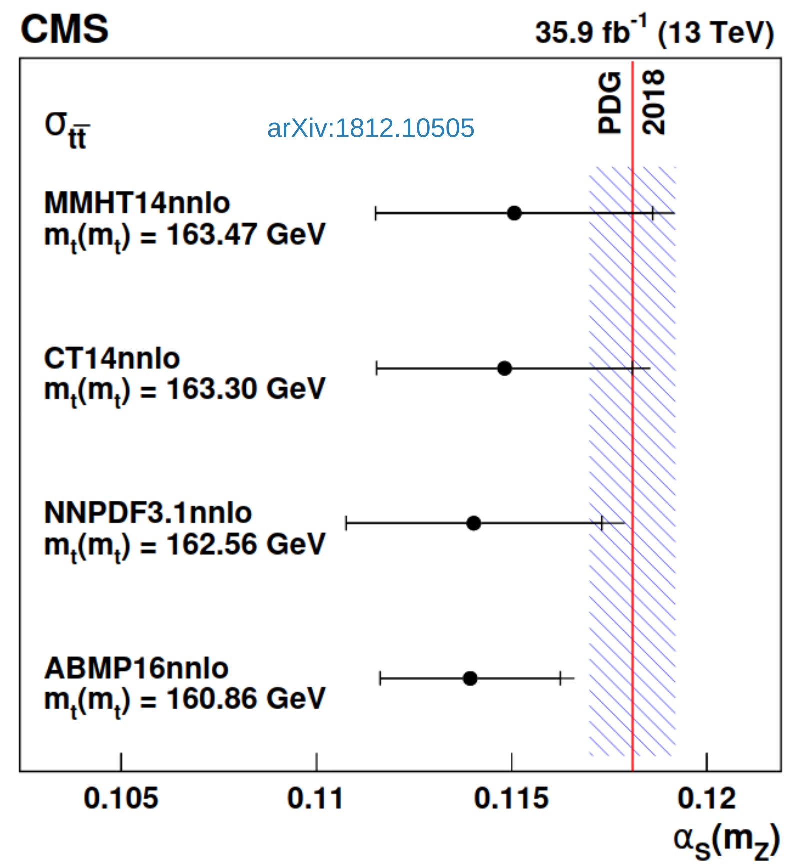
Top quark QCD measurements



- Top quark production cross-section measurements at the LHC have reached percent-level accuracy
- Focus on measurements and QCD analyses leading to the determination of PDFs and $\alpha_s(m_Z)$
  - Inclusive top quark production
  - Differential partonic $t\bar{t}$ cross sections
  - Differential leptonic $t\bar{t}$ cross sections

Top quark production inclusive cross section

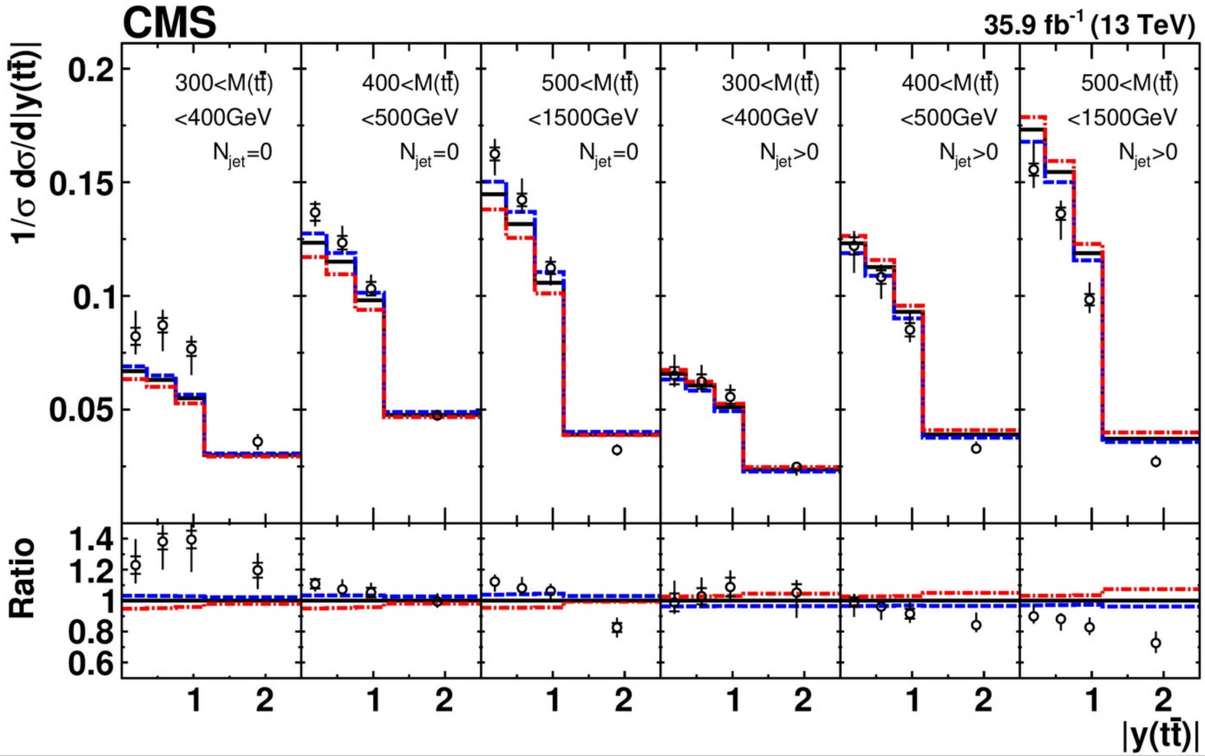


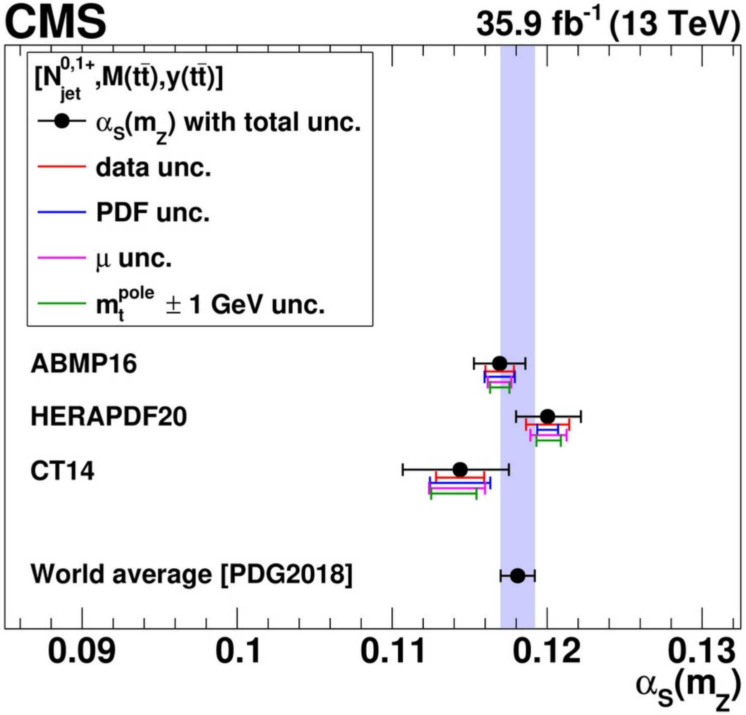


- Inclusive cross section is sensitive to PDFs, $a_s(m_Z)$ and top mass
- Allows determination of $a_s(m_Z)$ with a NNLO QCD analysis

PDF set	$\alpha_S(m_Z)$
ABMP16	0.1139 ± 0.0023 (fit + PDF) $^{+0.0014}_{-0.0001}$ (scale)
NNPDF3.1	0.1140 ± 0.0033 (fit + PDF) $^{+0.0021}_{-0.0002}$ (scale)
CT14	0.1148 ± 0.0032 (fit + PDF) $^{+0.0018}_{-0.0002}$ (scale)
MMHT14	0.1151 ± 0.0035 (fit + PDF) $^{+0.0020}_{-0.0002}$ (scale)

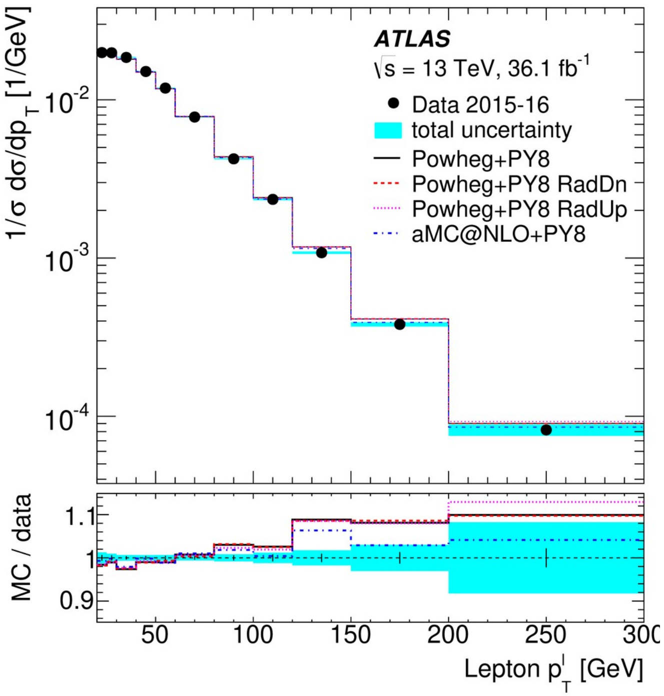
QCD analysis of top production

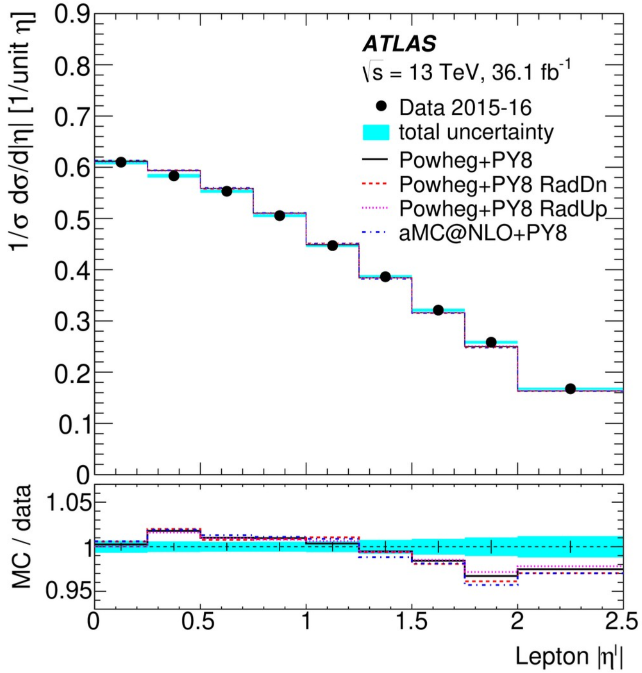




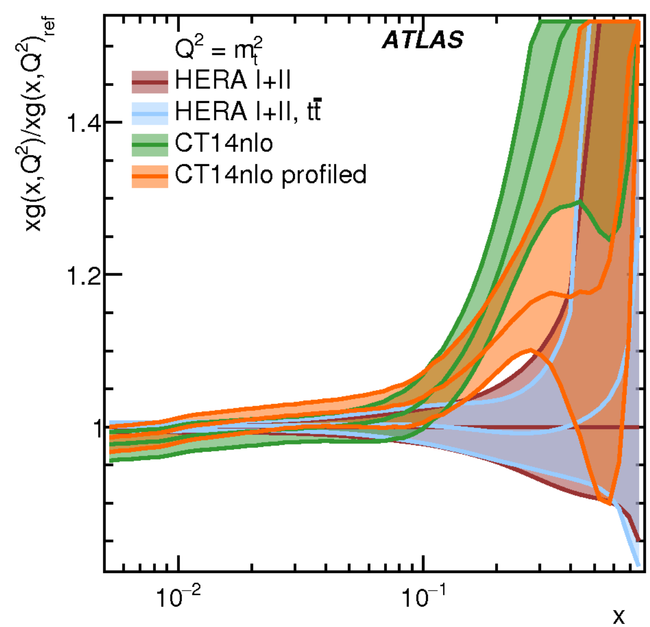
- QCD analysis of top production differential cross sections as functions of (m_{tt}, y_{tt}, N_{jets})
- Simultaneous fit of m_{top}, $\alpha_s(m_Z)$, PDFs

Leptonic top production cross sections

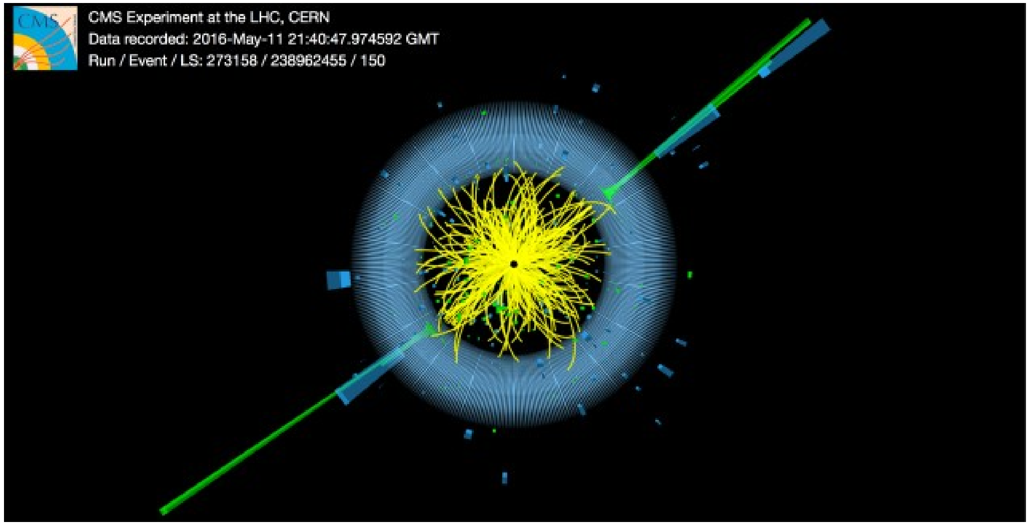




- Measurements of leptonic differential cross sections in top production at 8 and 13 TeV have reached subpercent accuracy
- Measurement at 8 TeV was used for PDFs and m_{top} determination

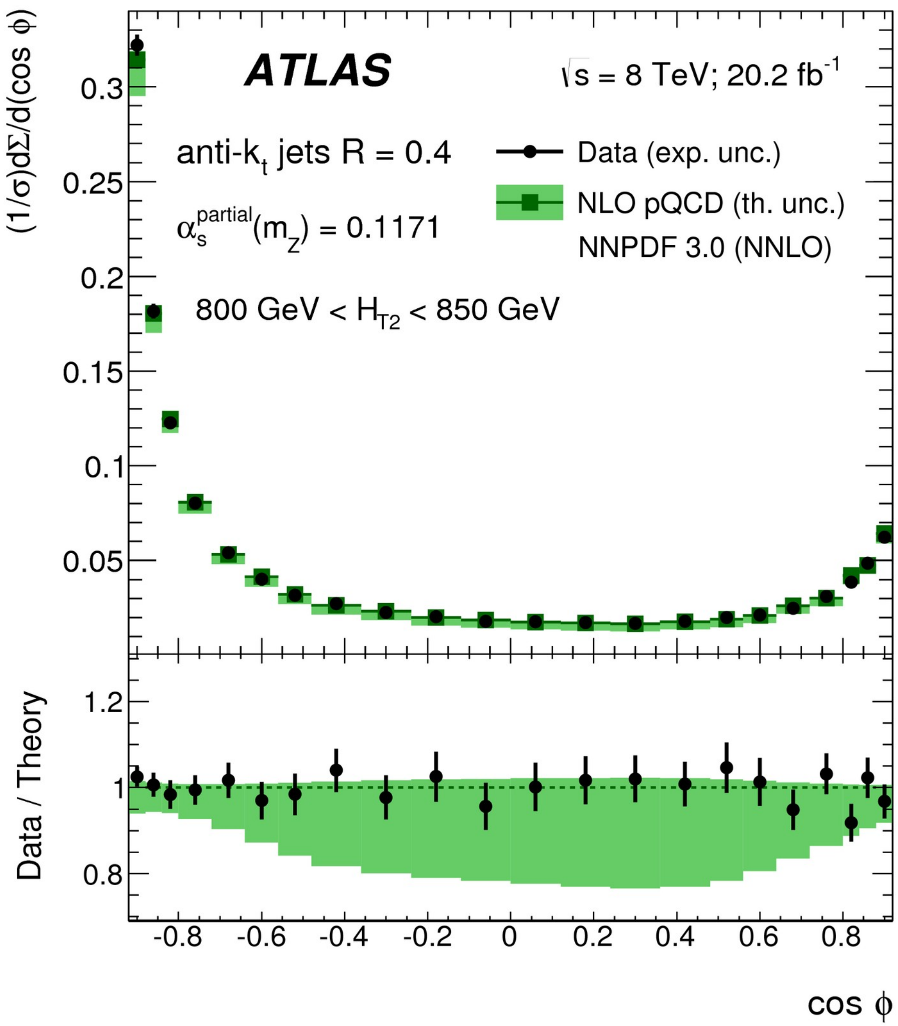


Strong-coupling constant from jets measurements



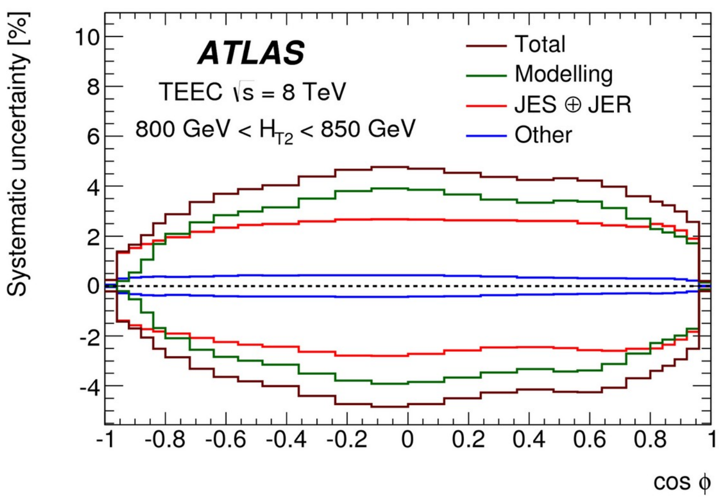
- Measurements with highest experimental sensitivity:
  - TEEC (ATLAS)
  - Inclusive jet cross sections (CMS)
- Other measurements not discussed here: dijets, 3-jet mass, R_{32} cross-section ratios

Transverse energy-energy correlations

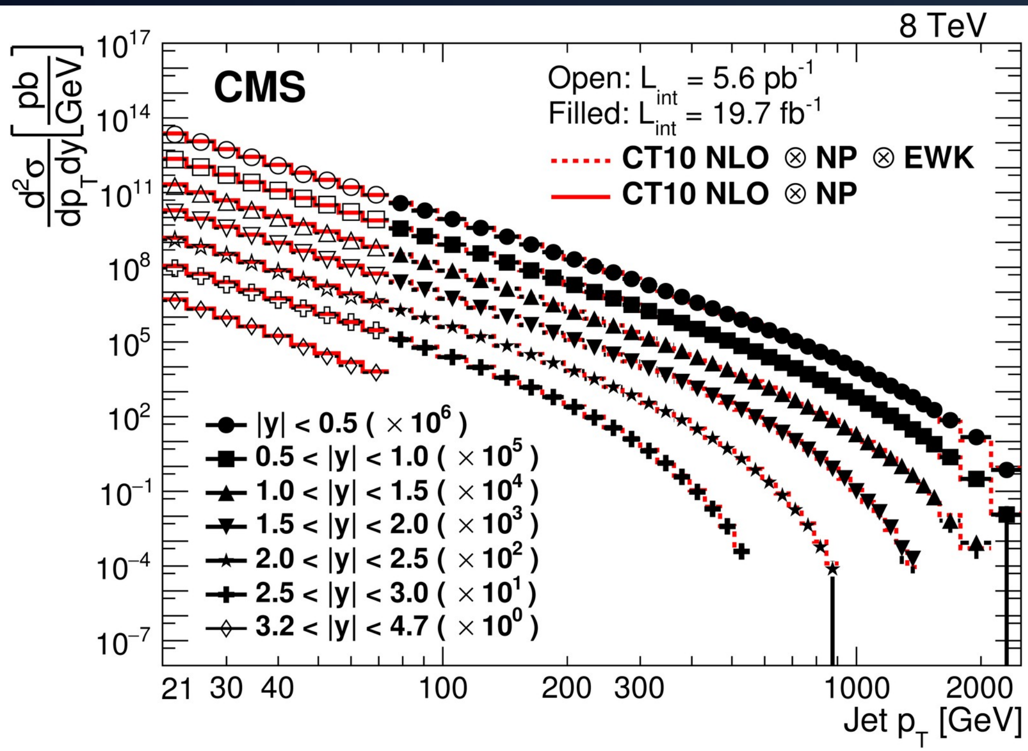


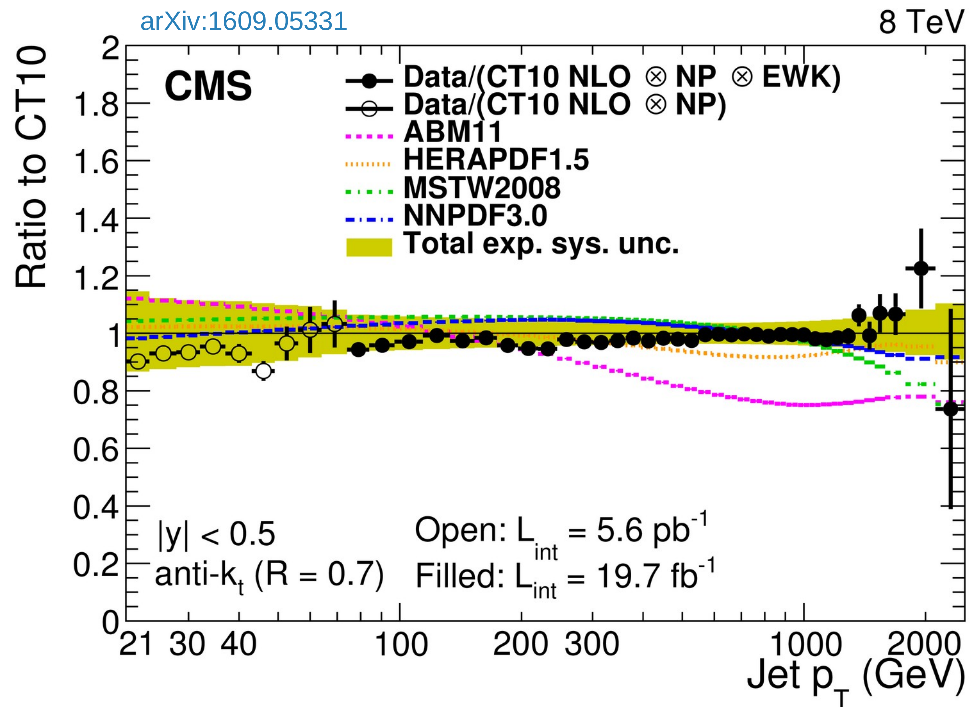
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi-\cos\phi_{ij})$$

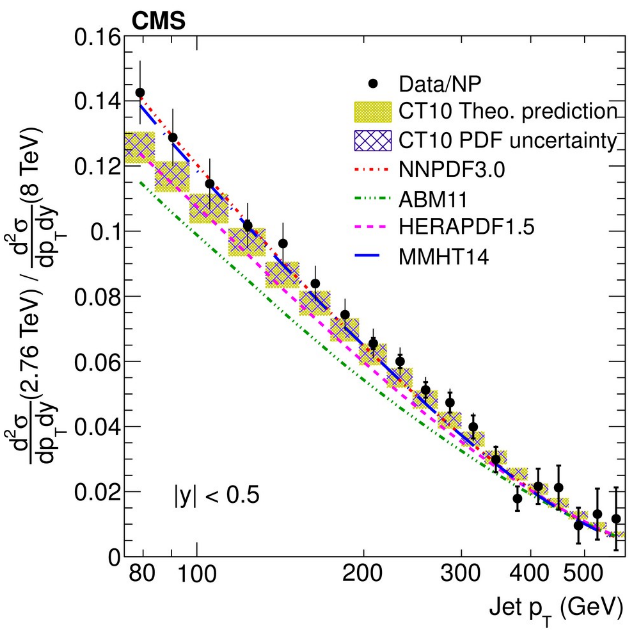
- Transverse energy-energy correlations (TEECs) are the transverse energy-weighted angular distribution of jet pairs
- TEECs provide a measurement of $\alpha_s(m_Z)=0.1162\pm0.0011(\mathrm{exp.})+0.0084-0.0070(\mathrm{theo.})$
- High experimental sensitivity <1%, experimental uncertainties dominated by jet modeling and JES/JER
- Large theory uncertainties dominated by scale variations



CMS inclusive jet production at 2.76, 7 and 8 TeV

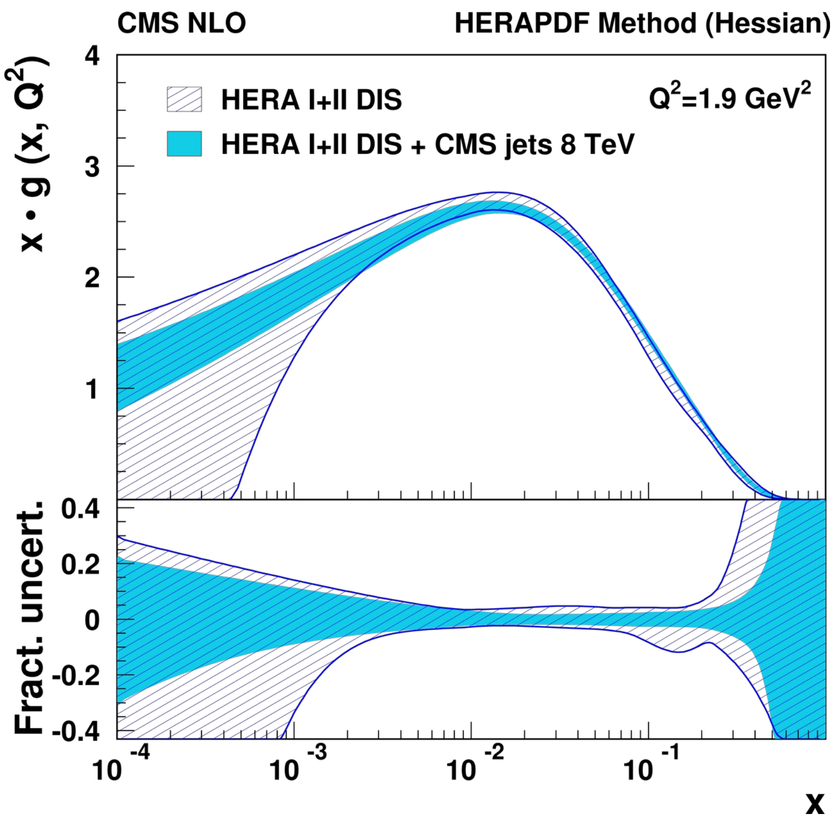


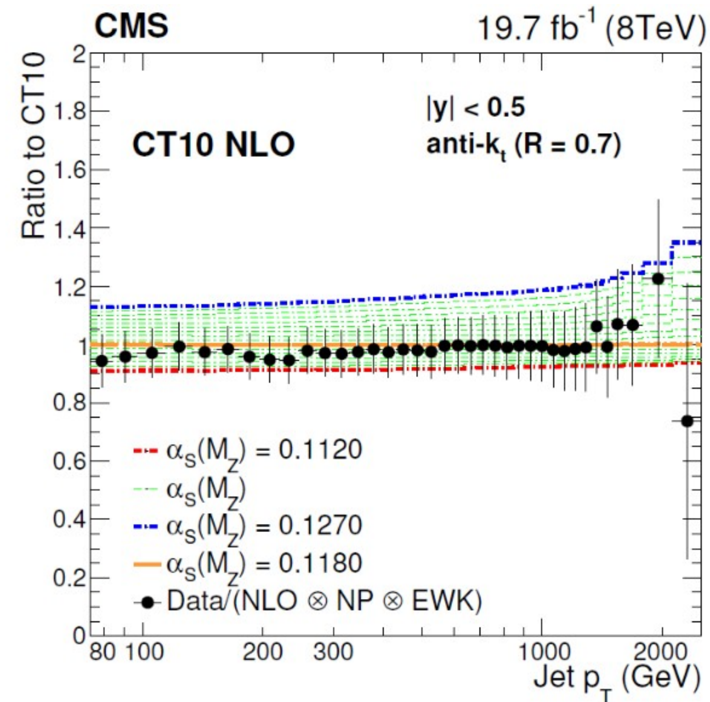




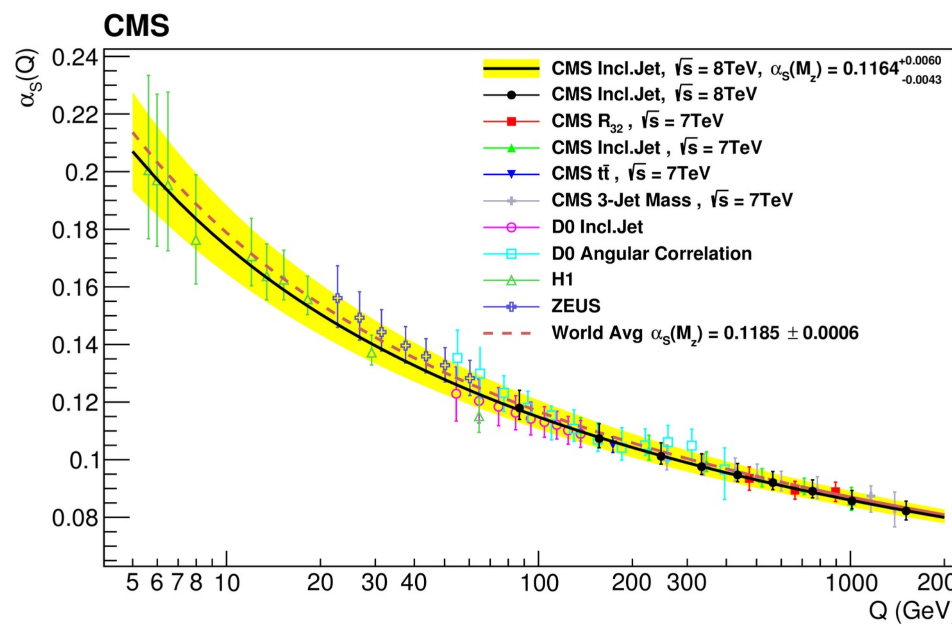
- The measurement is sensitive to the gluon PDF
- Cross-section ratios at 8, 7, and 2.76 TeV improve the sensitivity to PDFs

CMS inclusive jets



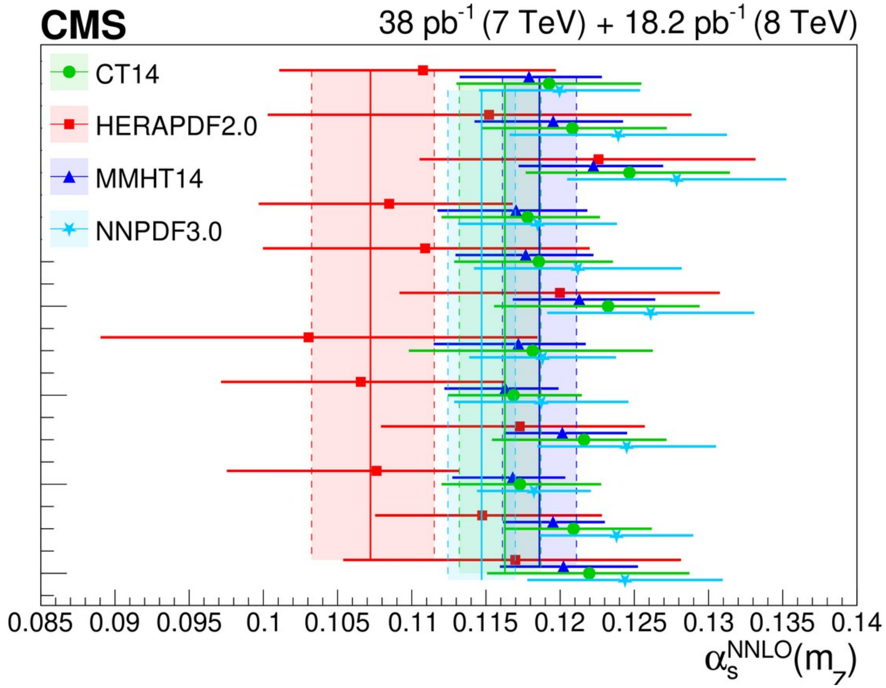


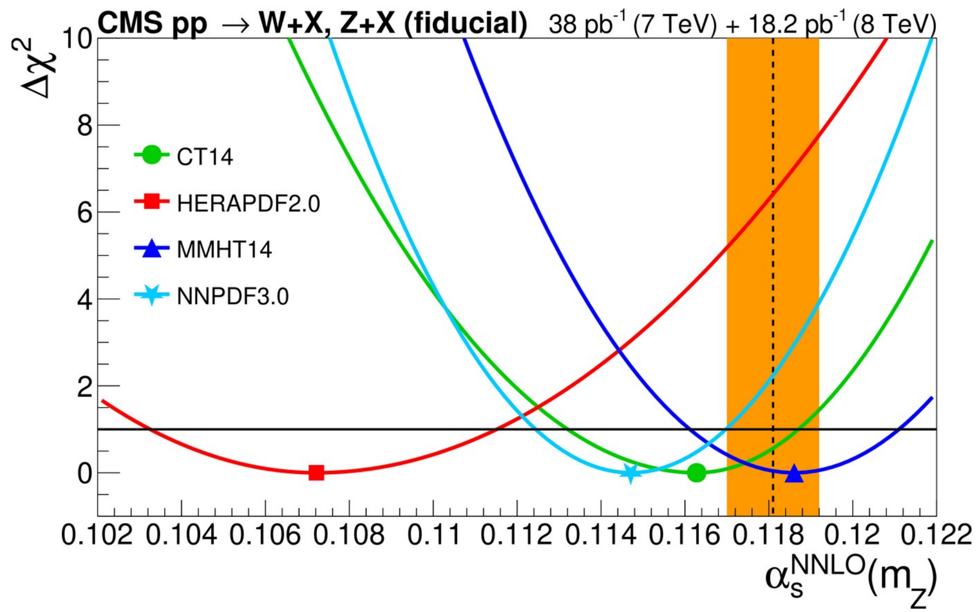
arXiv:1609.05331



- Strong reduction of the gluon PDF uncertainty, especially at high-x
- The measurement is used to determine $\alpha_s(m_Z)=0.1164\pm0.0015(\text{exp.})\ {}^{+0.0058}_{-0.0040}(\text{theo.})$
- Dominated by scale variations and PDFs
- The running of α_s is probed up to 1.5 TeV

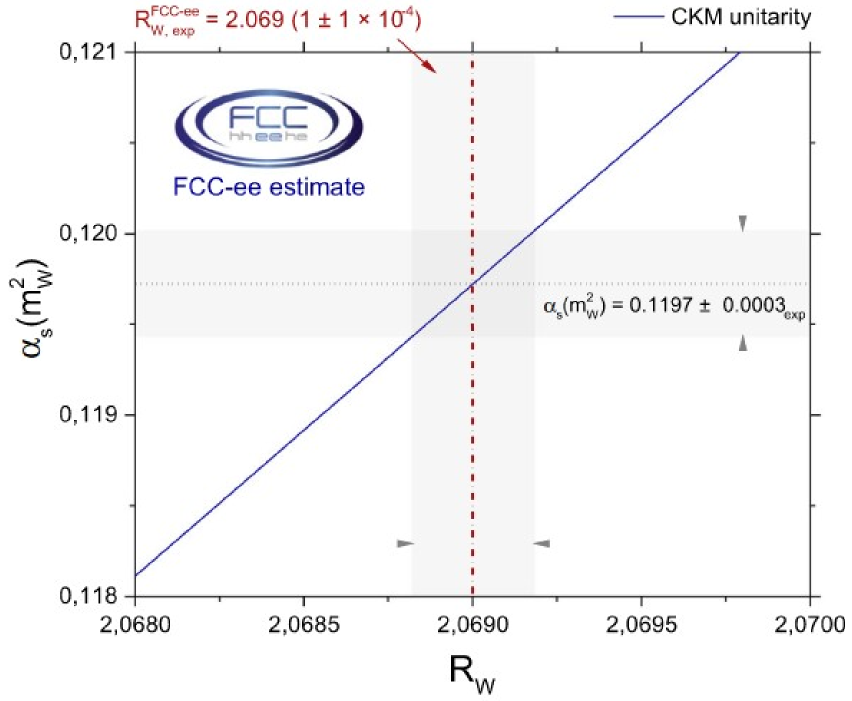
Strong-coupling constant from W,Z cross section

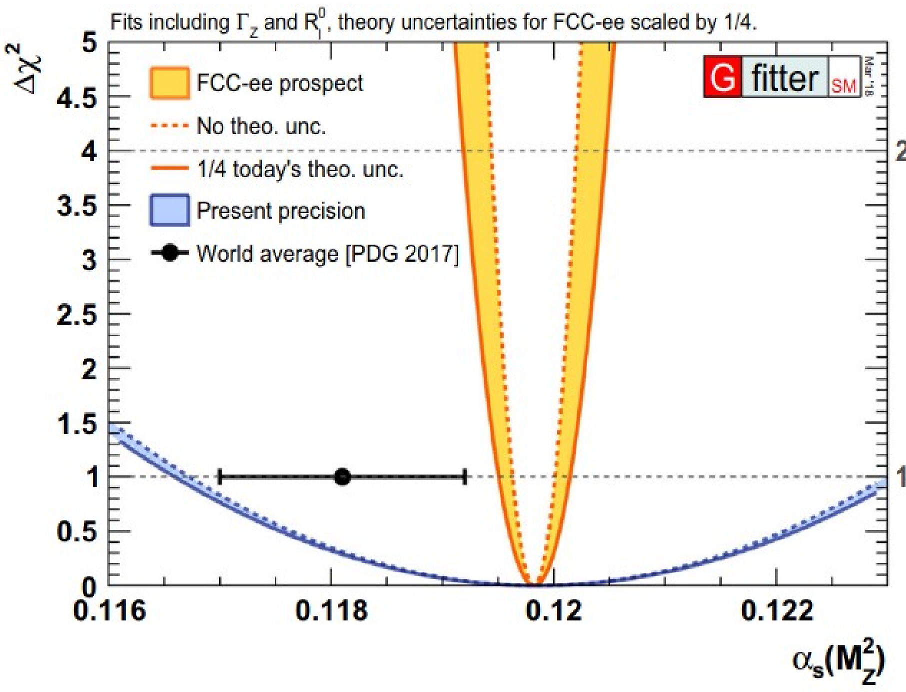




- First determination of $\alpha_s(m_Z)$ with the DY process
- Result compatible with the PDG world average: $\alpha_s(m_Z) = 0.1175{+0.0025}{-0.0028}$
- Measurement dominated by PDF and luminosity uncertainties

$\alpha_s(m_Z)$ from R_W and at R_Z FCC-ee





- Prospects for measuring $\alpha_s(m_Z)$ at permille level precision from the hadronic/leptonic Z and W decay ratios (R_Z, R_W) at the FCC-ee

Summary

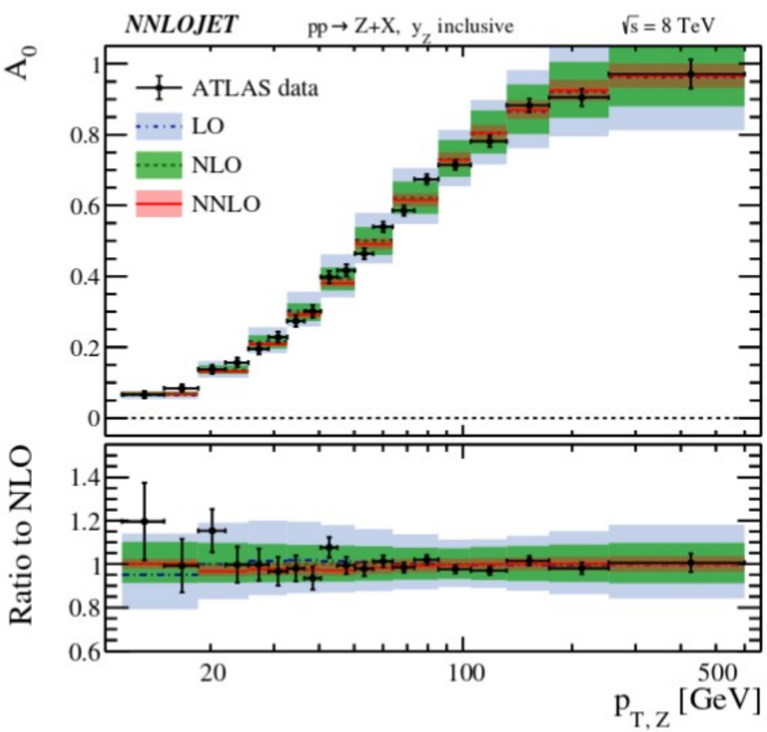
- Understanding of QCD is critical for all aspects of the LHC physics program: many analyses limited by PDFs, α_s, and QCD modelling
- QCD is entering a new precision era, with several LHC measurements at percent or permille level precision, and QCD predictions at two and three loops
- Permille level accuracy is expected for tests of QCD at future colliders, and in particular a determination of the strong-coupling constant at 0.1% accuracy

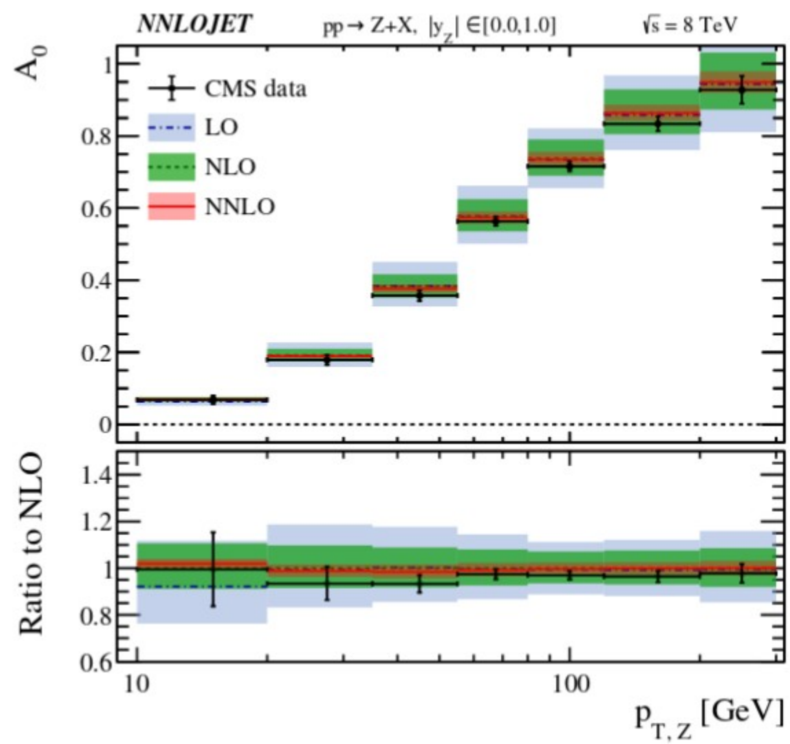
BACKUP

Angular coefficients A_i

- The angular coefficients provide a powerful framework to describe asymmetries of the DY cross section as the azimuthal (A2) and the forward-backward (A4). The decomposition holds at all order in QCD

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma}{dp_T dy dm} \sum_i A_i(y, p_T, m) P_i(\cos\theta, \phi)$$

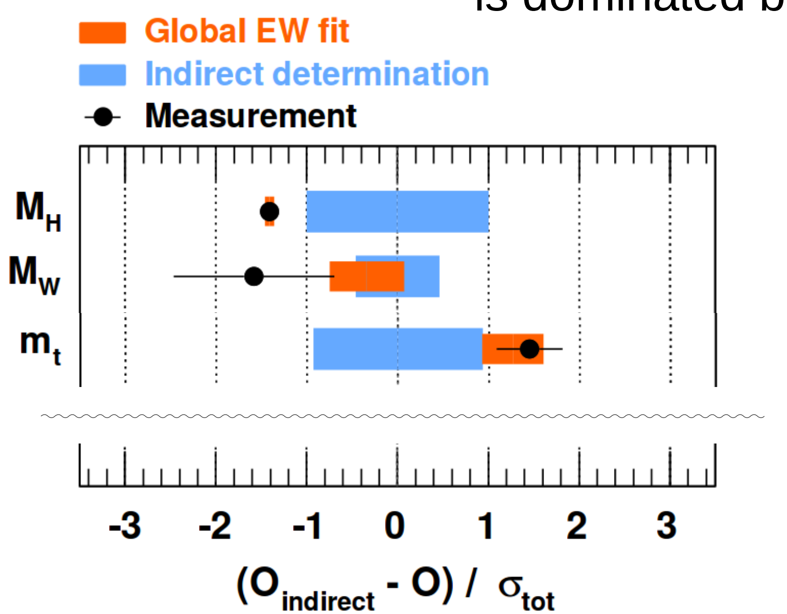




- Precise measurements from ATLAS and CMS as well as accurate perturbative QCD predictions at $O(\alpha_s^3)$ are available

Motivation for m_W

The global fit of the electroweak observables is dominated by the measurement of m_W



	Measurement	SM Prediction (*)
m_H	**125.09 ± 0.24**	**100.6 ± 23.6**
m_t	**173.1 ± 0.6**	**176.1 ± 2.2**
m_W	**80.379 ± 0.012**	**80.360 ± 0.007**

(*) arXiv:1710.05402

The measurements of the Higgs and top-quark masses are currently more precise than their indirect determination from the global fit of the electroweak observables → Improving precision will not increase sensitivity to new physics

Indirect determination of m_W (±7 MeV) is more precise than the experimental measurement → Call for $\delta m_W^{exp} \sim 5$ MeV

The W mass is nowadays the crucial measurement to improve the sensitivity of the global EW fits to new physics

Measurements of SM parameters at the LHC

Various SM parameters can be measured at the LHC with a precision competitive with previous determinations

m_H	125.09 ± 0.24 GeV (ATLAS+CMS Run 1) arXiv:1503.07589	Uniquely measured at the LHC	Higgs
m_t	172.69 ± 0.48 GeV (ATLAS) arXiv:1810.01772 172.44 ± 0.49 GeV (CMS) arXiv:1509.04044	Most precise measurements	QCD
$\alpha_s(m_Z)$	0.1164 ± 0.0052 (CMS jets) arXiv:1609.05331 0.1151 ± 0.0028 (CMS $t\bar{t}$) arXiv:1307.1907 0.1173 ± 0.0046 (ATLAS TEEC) arXiv:1508.01579	Currently dominated by large theory uncertainty (MHO, PDFs)	QCD
m_W	80.370 ± 0.019 GeV (ATLAS) arXiv:1701.07240	Competing with Tevatron precision	Electroweak
$\sin^2\theta_W$	0.23140 ± 0.00036 (ATLAS) ATLAS-CONF-2018-037 0.23101 ± 0.00053 (CMS) arXiv:1806.00863 0.2314 ± 0.0011 (LHCb) arXiv:1509.07645	Not yet competitive with LEP and SLD	Electroweak
Γ_W	2144 ± 62 MeV (CMS) arXiv:1107.4789	From W/Z cross section ratio	Electroweak

Experimental measurements at colliders

The W-boson mass can be measured from:

- Kinematic properties of decay leptons in the final state in $pp \rightarrow W \rightarrow l\nu$ processes (hadron colliders)

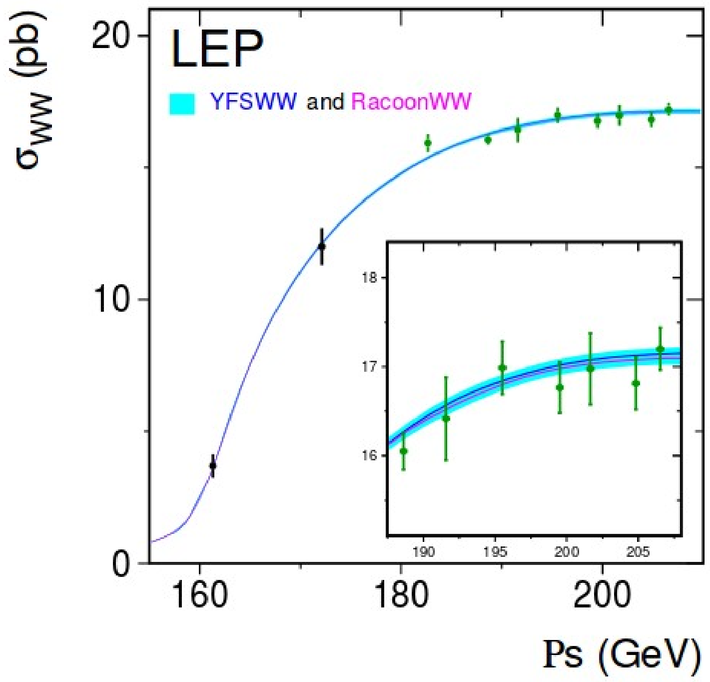
SPS, Tevatron, LHC

- Direct reconstruction from the final state in $ee \rightarrow WW \rightarrow qqqq/qql\nu$ (e+e- colliders)

LEP best measurements

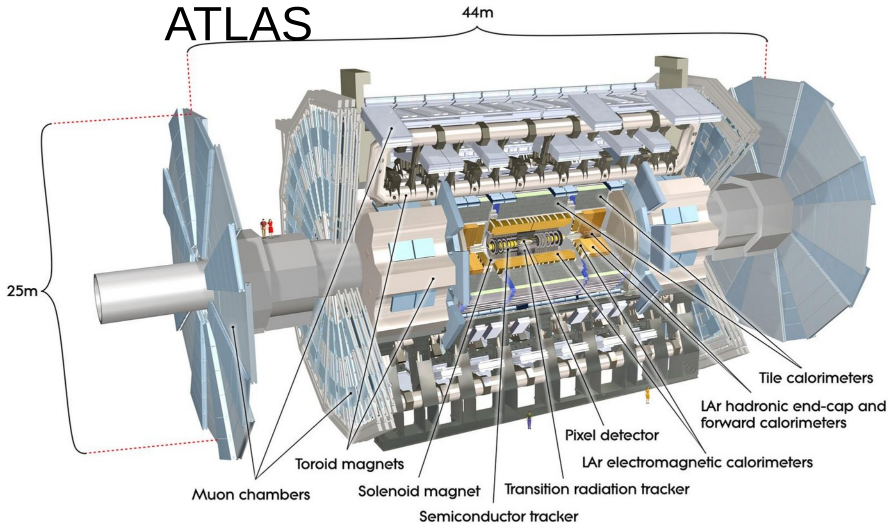
- W-pair production at thresholds (e+e- colliders)

Limited by statistics at LEP, but most precise prospect at future colliders

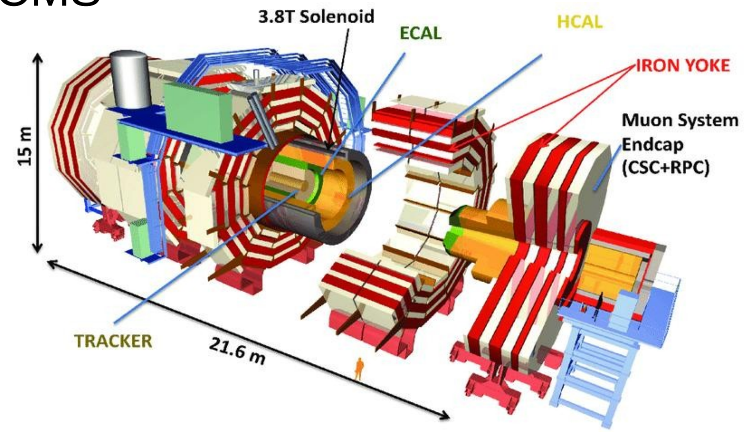


LHC experiments

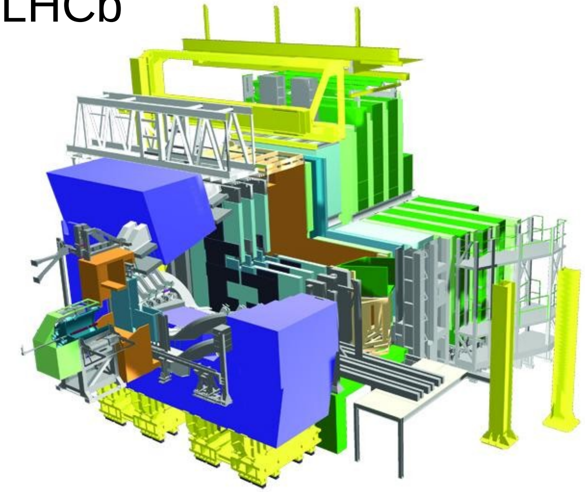
ATLAS



CMS

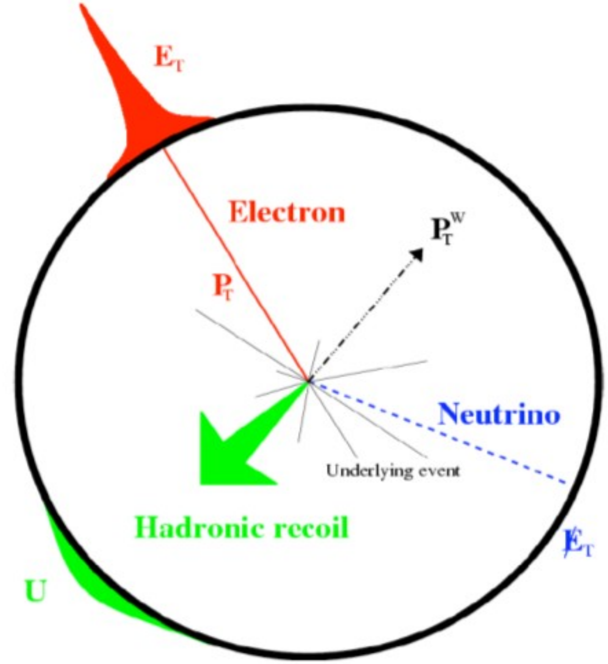


LHCb



W mass at the LHC

$$pp \to W \to \ell\nu$$



- Main signature: final state prompt and isolated charged lepton (electron or muon)
- The neutrino momentum can be reconstructed from momentum imbalance in the transverse plane: p_T^{miss}
- The transverse mass m_T is defined from variables measured in the transverse plane

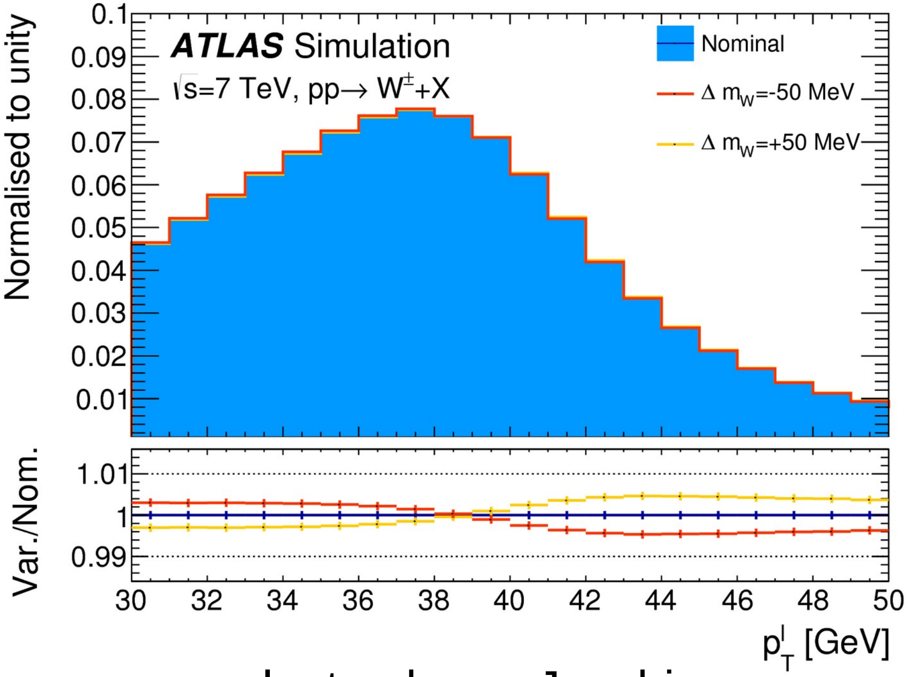
Observables sensitive to m_W are

Lepton transverse momentum p_T^ℓ	Good detector resolution, pileup robust	Very sensitive to theory uncertainties (PDF, p_TW)
Transverse mass $m_T = \sqrt{2p_T^\ell p_T^\nu(1-\cos\Delta\phi(\ell,\nu))}$	Poor detector resolution, sensitive to recoil calibration, degrades at high pileup	Less sensitive to theory uncertainties

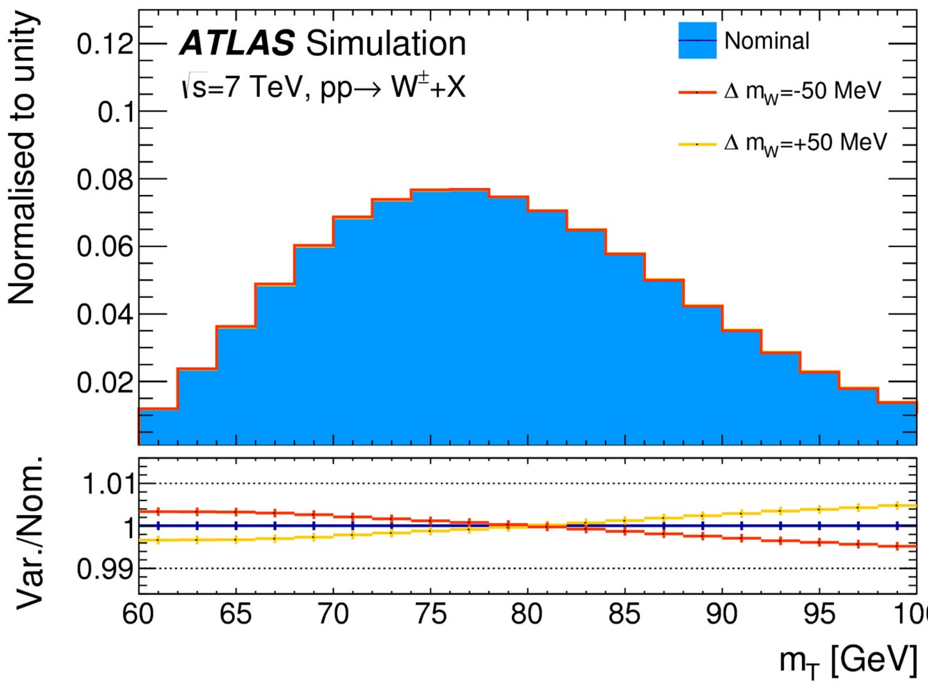
W mass – Measurement strategy

m_W extracted from the p_T lepton and transverse mass (m_T) distributions

arXiv:1701.07240



p_T lepton has a Jacobian edge at $m_W/2$



m_T has a Jacobian edge at m_W

Template-fit approach:

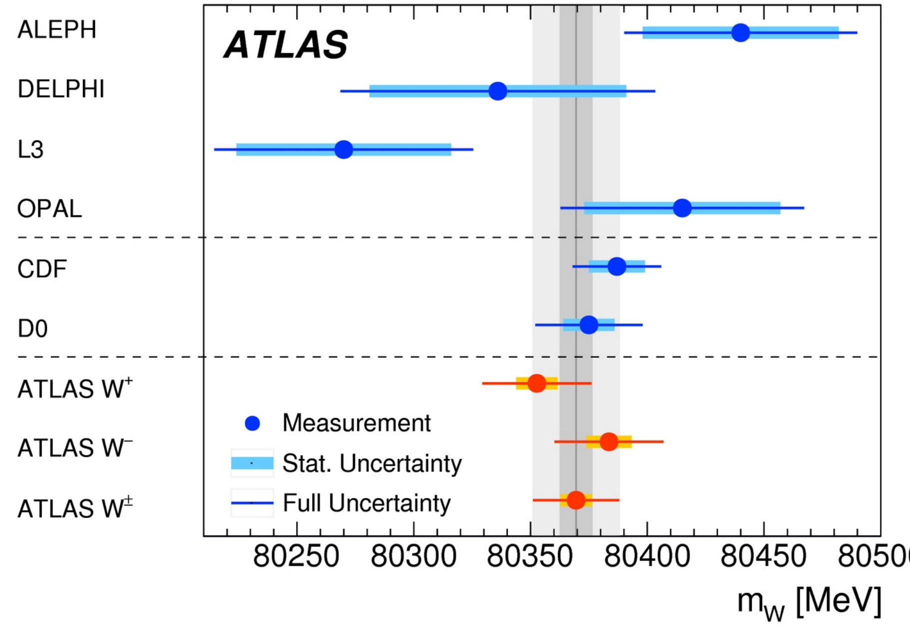
- Vary the W-boson mass values in the theory prediction, and predict the p_T lepton and m_T distributions
- Compare to data, and determine the W mass by χ^2 minimization

Challenges:

- Ultra-precise detector calibration ~ 10^{-4}
- Accurate theory predictions

ATLAS – 7 TeV result for m_W

The ATLAS result equals in precision the previous single-experiment best measurement of CDF



$$M_W = 80369.5 \pm 18.5 \text{ MeV}$$

$$M_W = 80369.5 \pm 6.8 \text{ (stat)} \pm 10.6 \text{ (exp.syst.)} \pm 13.6 \text{ (model.syst.)} \text{ MeV}$$

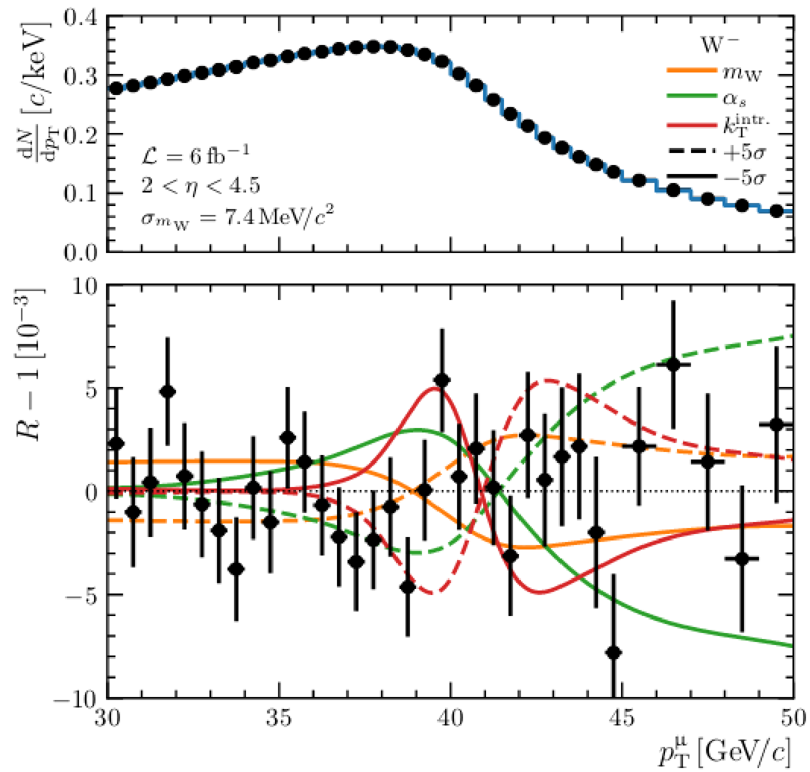
The dominant uncertainty is due to the physics modelling

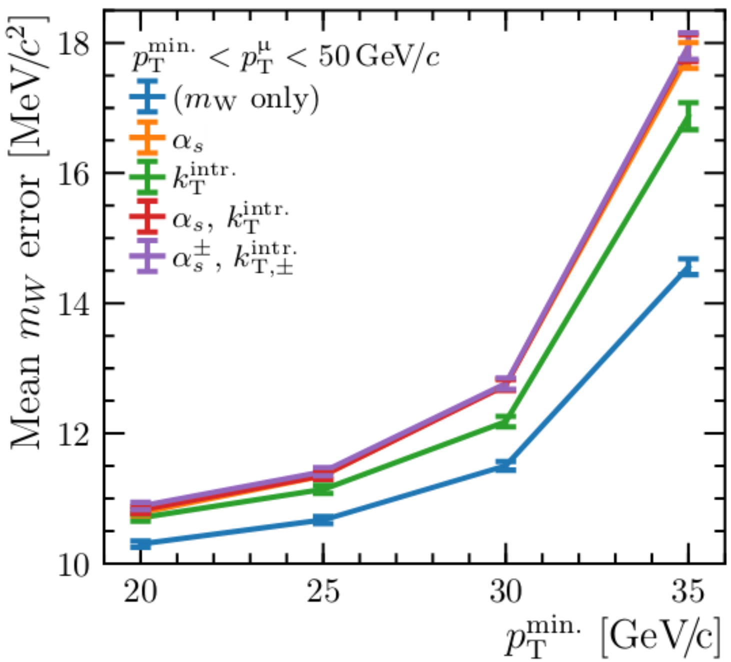
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

and the largest contributions are from QCD/PDF

LHCb – Prospects for m_W

- Run 1 + 2 allows reaching ~10 MeV statistical uncertainty
- LHCb analysis plans to exploit the sensitivity of the p_T lepton distribution to the W mass and to all components of the p_T W uncertainty
- Simultaneous fit to W mass and p_T W nuisance parameters





- When the fit range is large enough it is possible to determine all parameters with a relatively small loss in the precision of the W mass

Prospects for future measurements

Two paths for future measurements at ATLAS and CMS

	High pileup	Low pileup
Most sensitive observable	p_T lepton	m_T
Theory challenge	W/Z p_T ratio, PDFs	PDFs
Experimental challenge	p_T lepton calibration	Recoil calibration
Dominant uncertainties	Physics modelling, PDFs	Recoil, stat, PDFs

High pileup:
- Only option at LHCb
- Can benefit from very high stat of the HL-LHC program

Low pileup:
- Requires dedicated runs
- Provides measurement and data-driven modelling of p_T W

- Orthogonal approaches with different dominant uncertainties
- Should be both pursued, will benefit from the combination

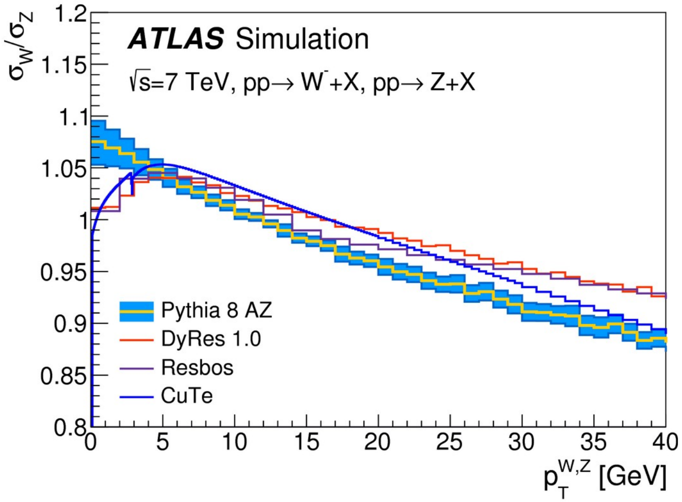
Physics modelling – Summary of QCD uncertainties

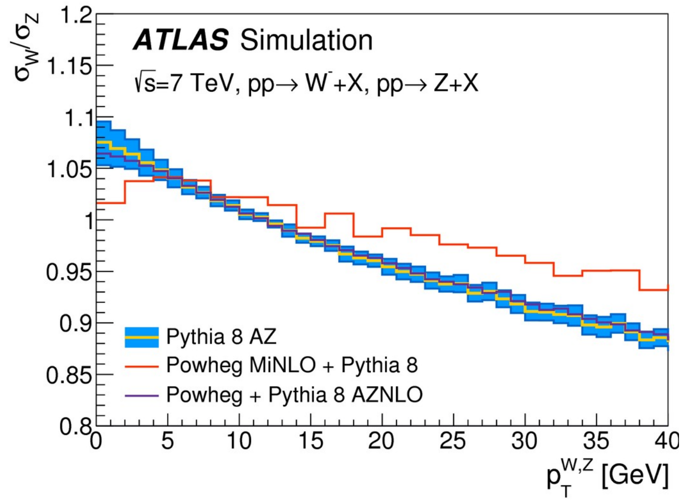
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	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

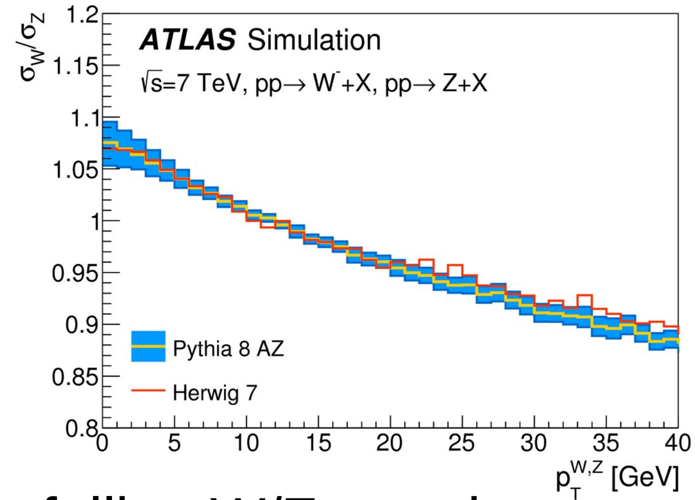
- PDFs are the dominant uncertainty, followed by p_T W uncertainty due to heavy-flavour-initiated production
- PDF uncertainties are partially anti-correlated between W+ and W-, and significantly reduced by the combination of these two categories.
- p_T W uncertainties are similar for m_W extracted from p_T lepton and from m_T

Models for p_T W

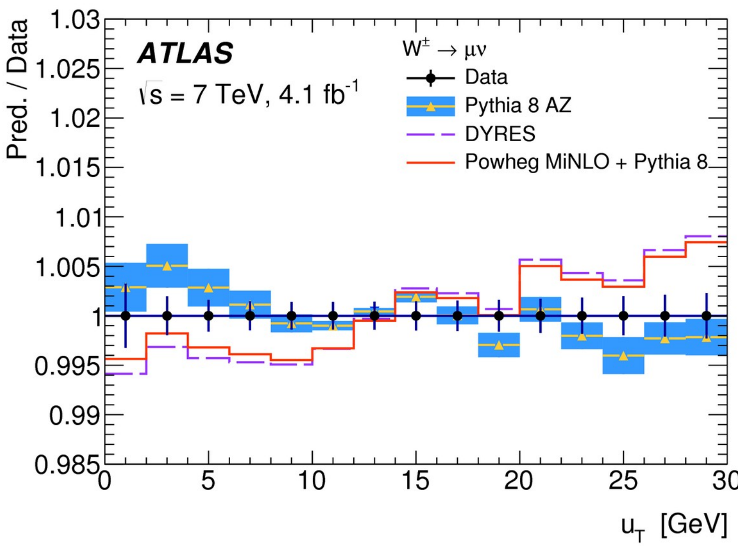
Since the p_T Z distribution is very well measured, the relevant theoretical uncertainties are those which affect the W/Z p_T distribution

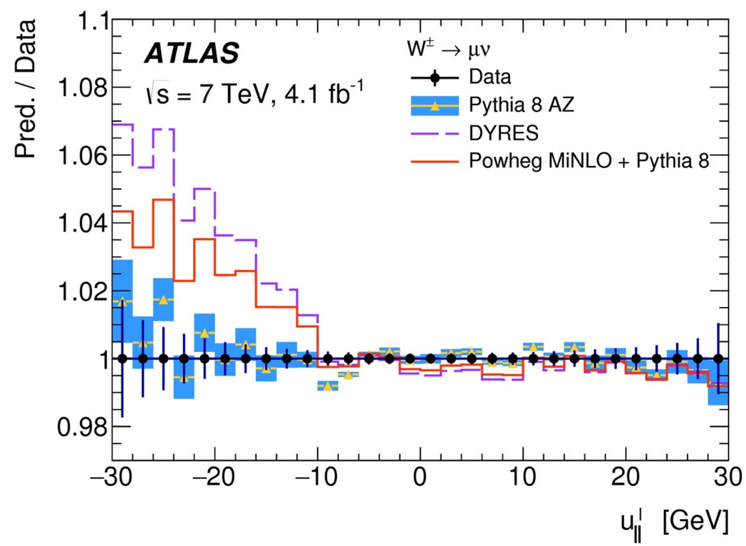






Only Herwig, Pythia, and Powheg predict a monotonic falling W/Z pt ratio



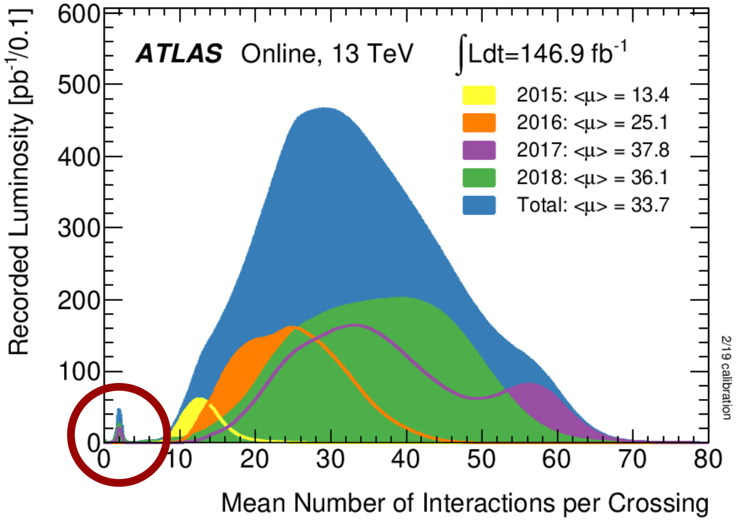


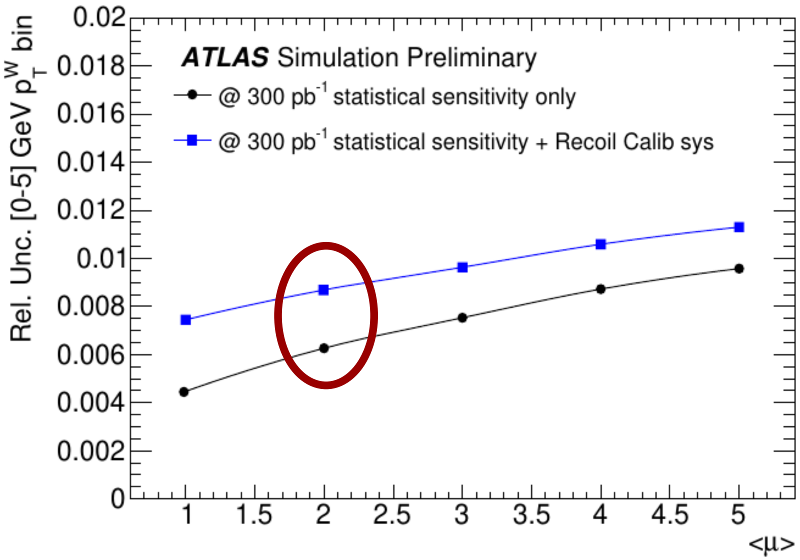
MINLO and NNLL analytic resummed predictions as Resbos, Cute, and DyRes are strongly disfavoured by the recoil distribution in data

Modelling of p_T W

- The modelling of p_T W is crucial for the measurement of m_W, especially when using p_T lepton

- ~300 pb^{-1} already collected at $\langle\mu\rangle$ = 2 by ATLAS and CMS can provide a new ~1% measurement of p_T W and significantly reduce the associated uncertainty



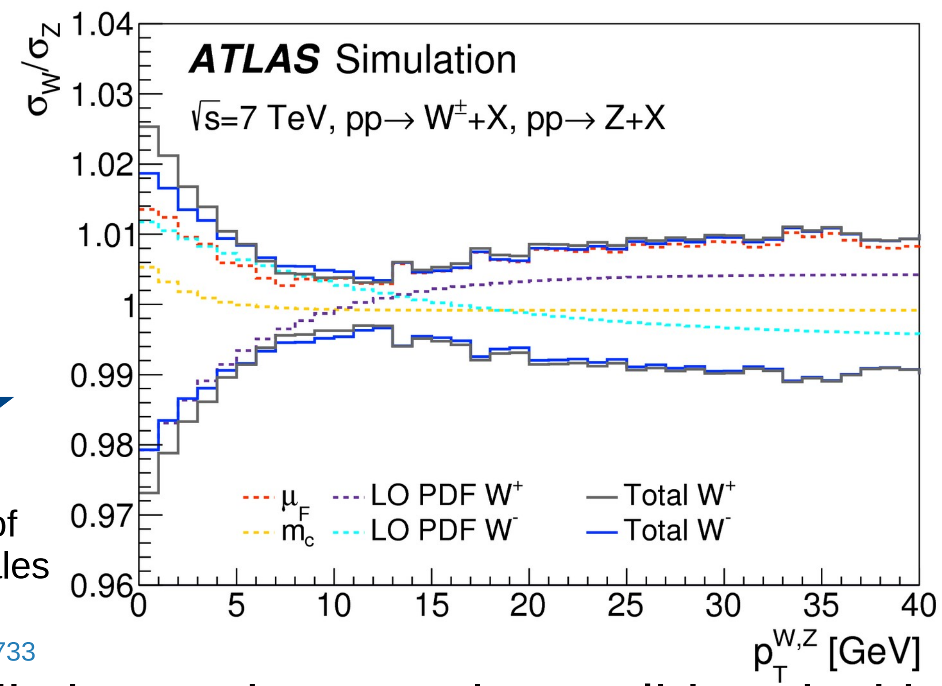


- The expected resolution at $\langle\mu\rangle$ = 2 is ~5 GeV

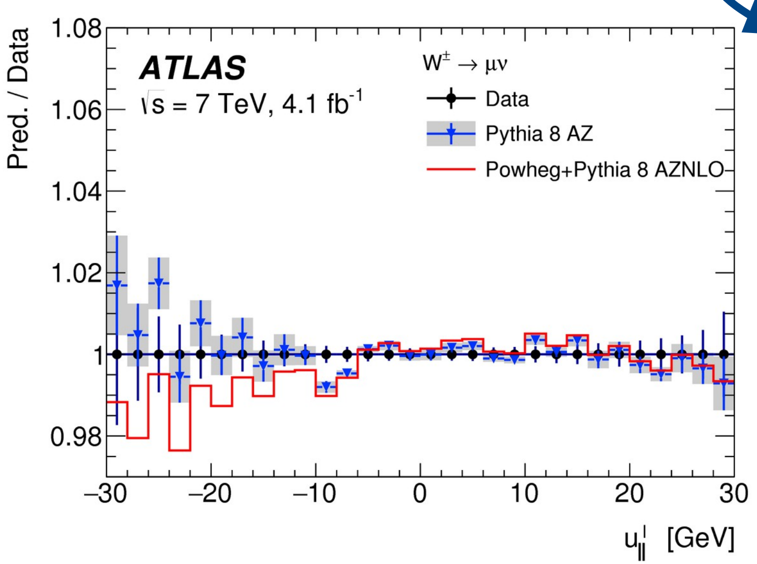
Uncertainties in the p_T W modelling

- Heavy-flavour-initiated (HFI) production introduce differences between Z and W production
- HFI production determines a harder boson p_T spectrum, $cc \rightarrow Z$ and $bb \rightarrow Z$ are 6% and 3% of Z production, $cs \rightarrow W$ is ~20% of W production
- HFI addressed with charm-quark mass variations, and by decorrelating the PS μ_F between light and HFI processes

p_T W theory uncertainties are evaluated as the sum of experimental Z p_T unc. and theory unc. on the W/Z p_T ratio



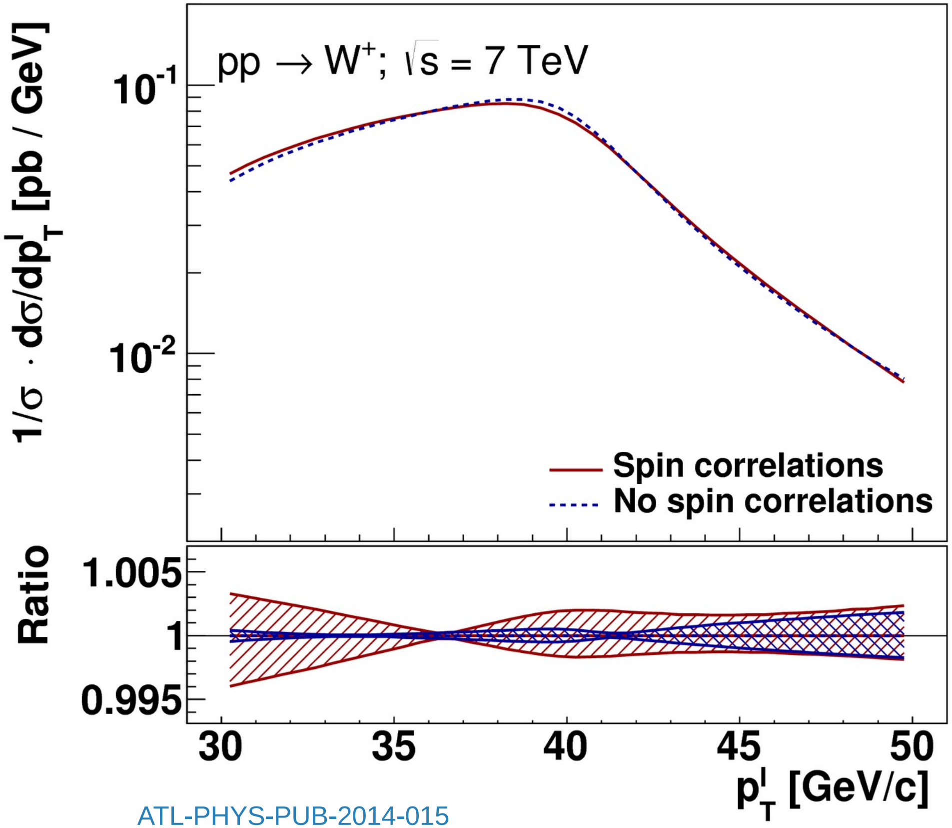
This procedure is a proxy for variations of the HF matching scales in the PDFs, see arXiv:1605.01733



Central prediction and uncertainty validated with the recoil distribution → when using the data to constrain the model we end up with compatible central value and similar uncertainties

W mass at the LHC

- A large fraction of W production at the LHC is inititiated by sea quarks
- The W polarisation at the LHC is more influenced by PDF uncertainties, implying larger uncertainties on the lepton p_T distribution
- The valence-sea difference, as well as the amount of sea quarks with u and d flavour, must be known with better precision than needed at the Tevatron



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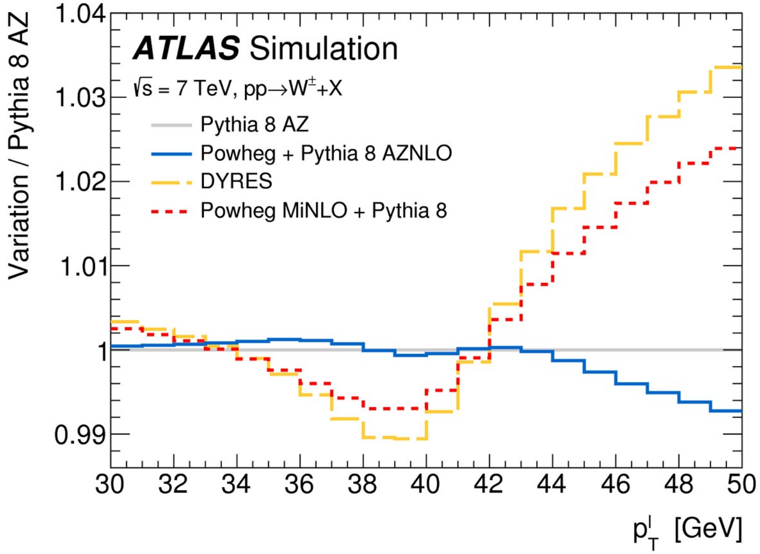
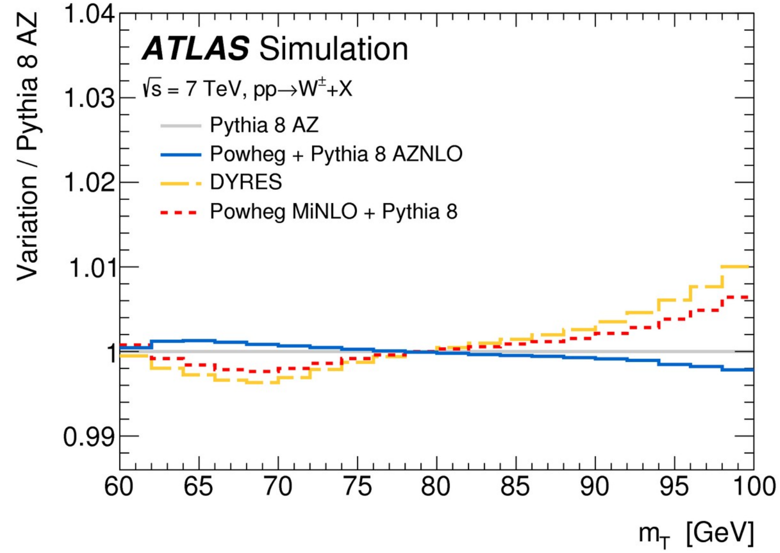
- The effect can be isolated by switching off spin correlations
- O(10-20) MeV effect for m_W extracted from the p_T lepton distribution

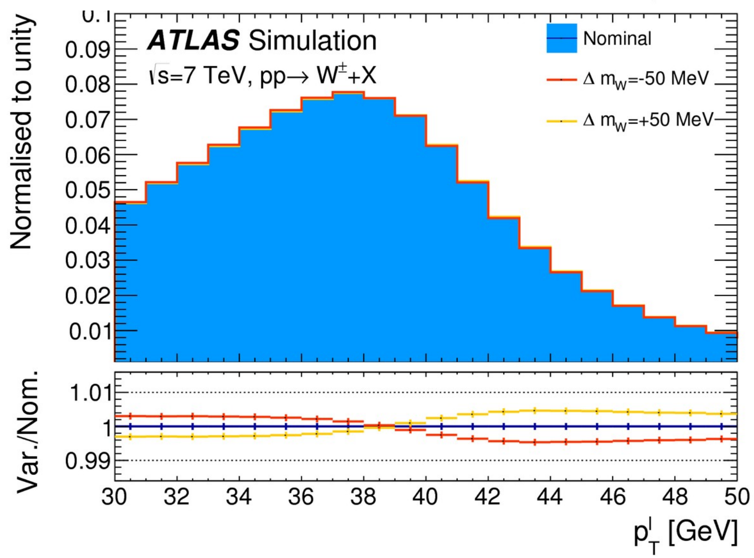
Large reduction of PDF uncertainties near the Jacobian peak

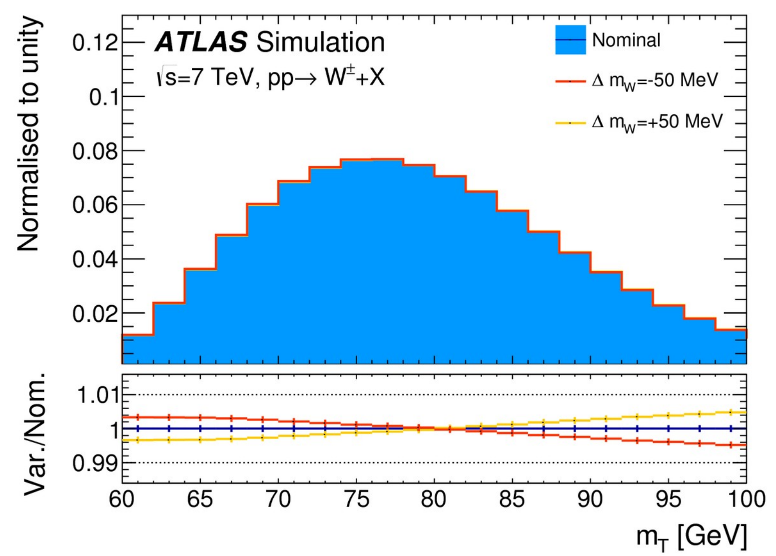
p_T W uncertainties on p_T lepton and m_T

p_T W uncertainties are similar for m_W extracted from p_T lepton and from m_T









→ m_T is less sensitive to p_T W, but p_T W variations on m_T are less distinguishable from m_W variations