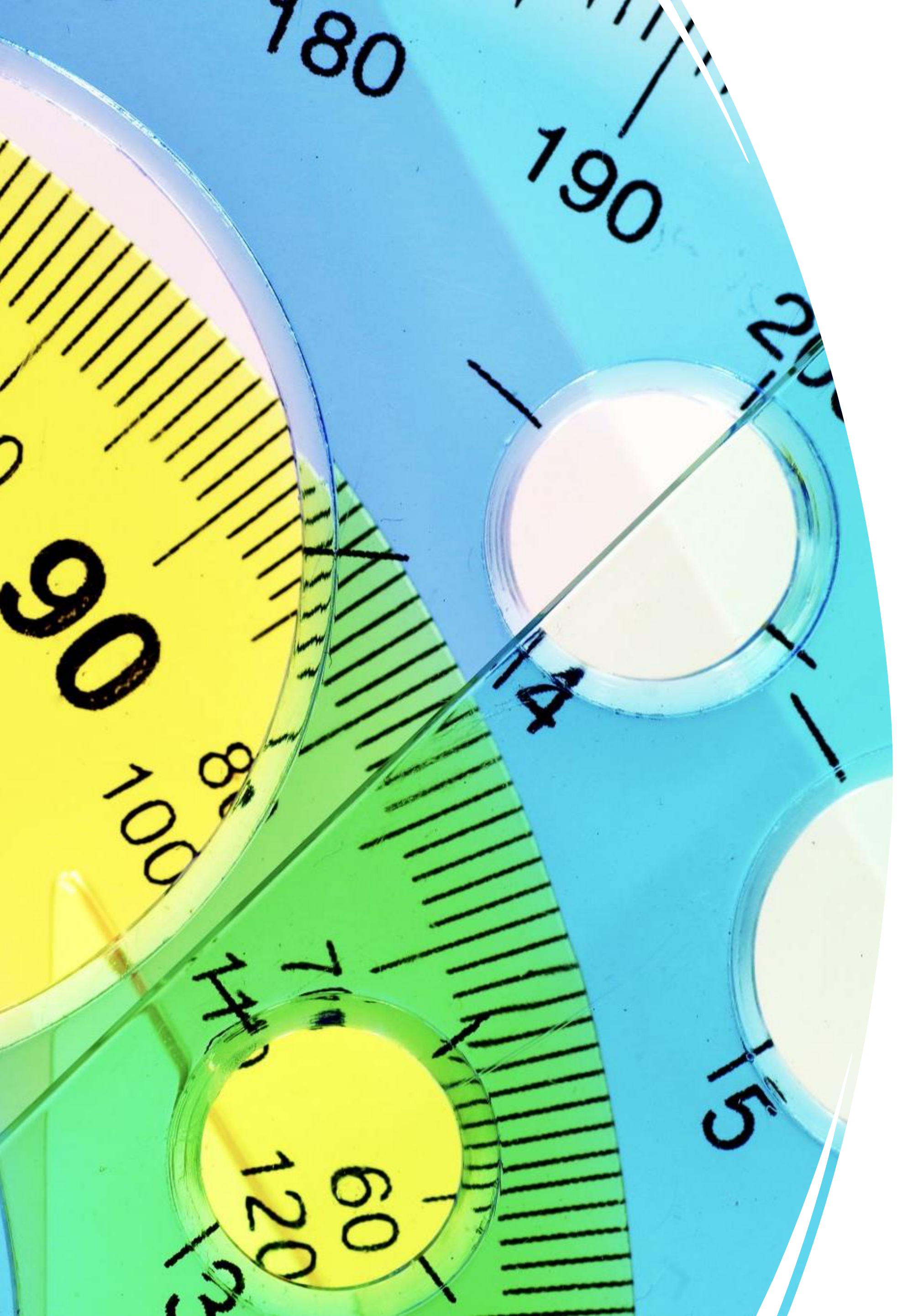


Progress in the precision measurements of W mass, V pT, and α_s

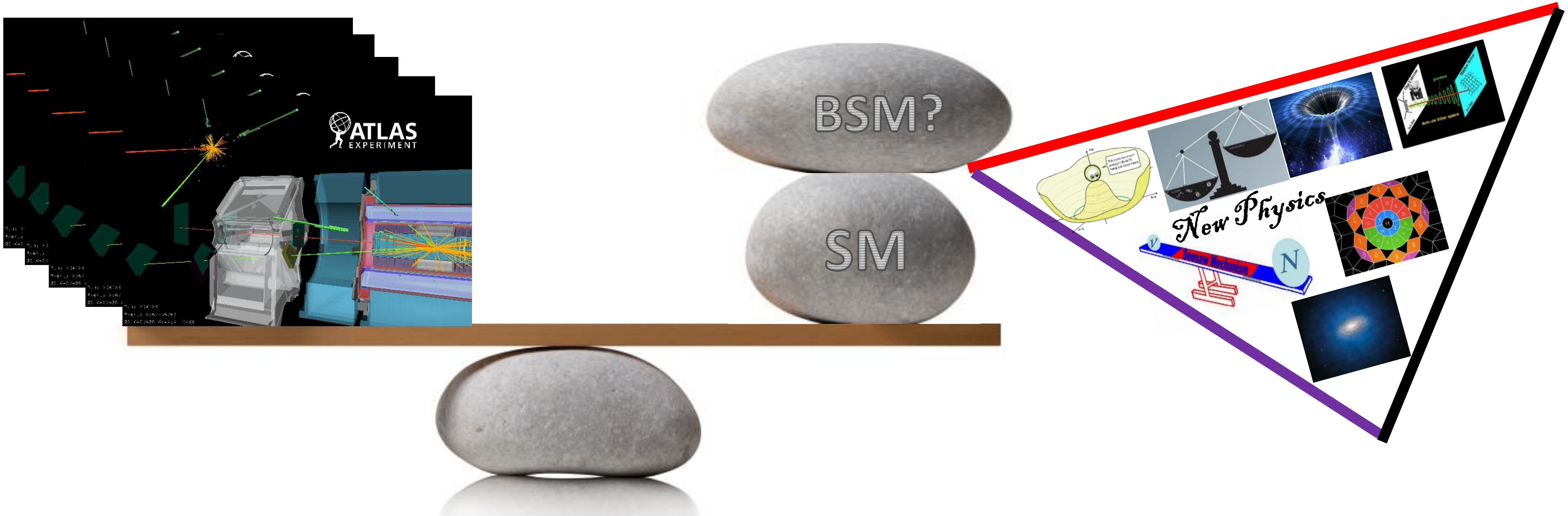
Yusheng Wu

University of Science and Technology of China

For ATLAS and CMS collaborations

WIN2023, Zhuhai, July 3 – July 8, 2023

Measurement of phenomena at smallest scales



Collider endeavors on precision comparisons between observations and predictions:

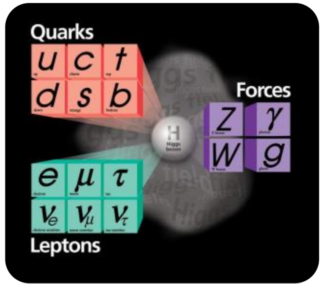
>> **precisely test the Standard Model (cross-sections, parameters, …)**

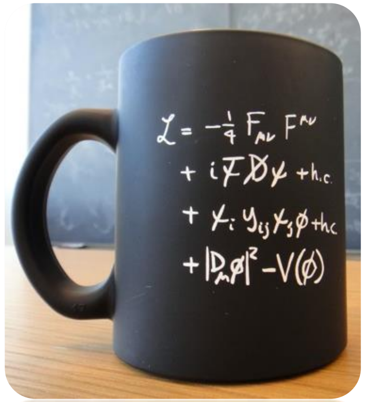
>> **search for new physics phenomena (resonances, deviations)**

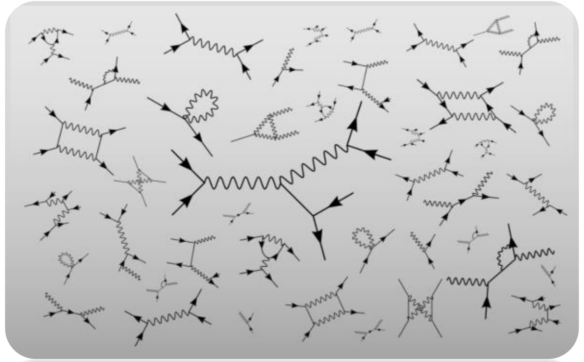
>>> **knock on the door to potentially answer outstanding questions**

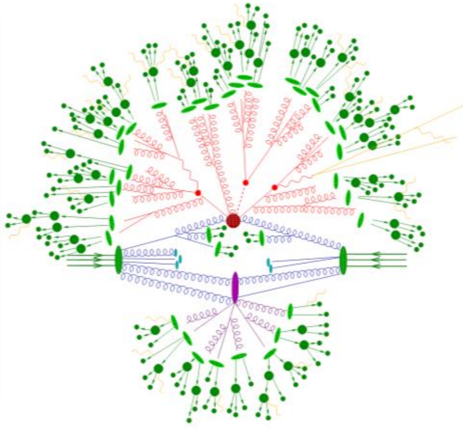
(dark matter, matter-anti-matter asymmetry, ν masses, hierarchies, …)

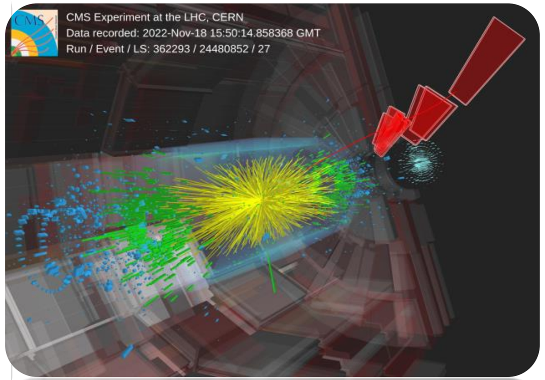
Predictions and measurements





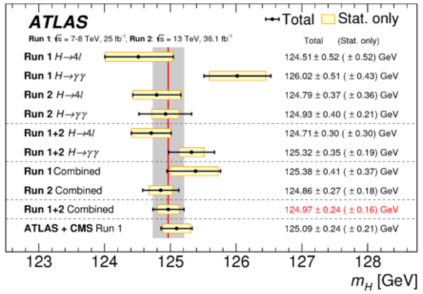


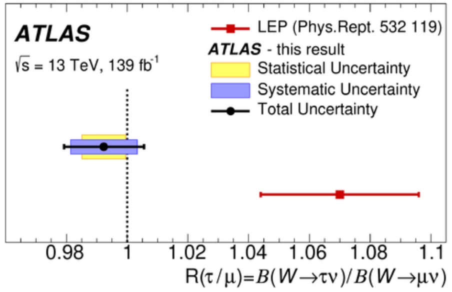




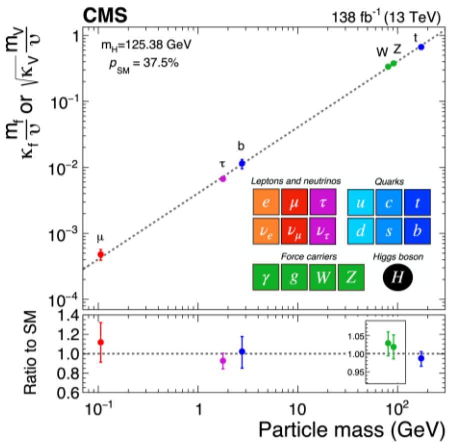
Predictions

Measurements

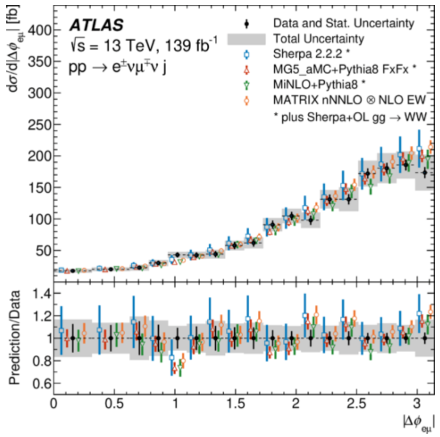




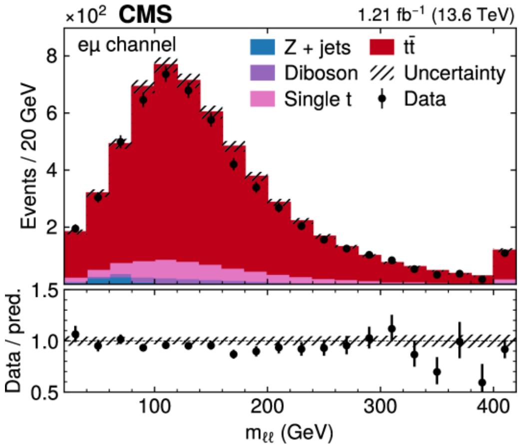
Quantum field structures, symmetries and intrinsic properties, model parameters



Couplings, interactions



Cross-sections



Detector observables

SM parameters

19 free parameters

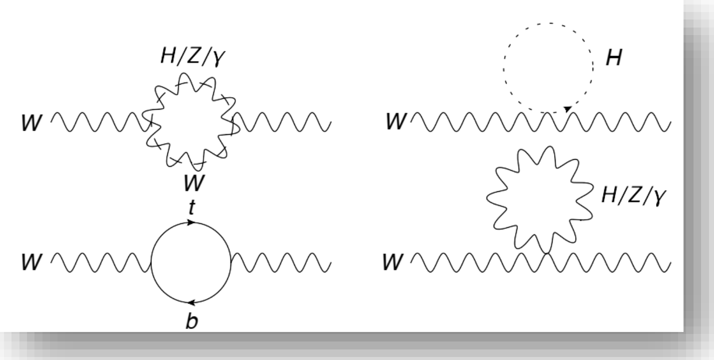
or 26 parameters (including neutrino sector with masses)

Parameters	Relative Error (PDG)
α, $\sin^2\theta_W$, α_S	10^{-10}, 10^{-4}, 10^{-2}
m_W (m_Z), m_H	10^{-4} (10^{-5}), 10^{-3}
m_u, m_d, m_s	10^{-1}, 10^{-1}, 10^{-1}
m_e, m_μ, m_τ	10^{-10}, 10^{-8}, 10^{-4}
m_c, m_b, m_t	10^{-2}, 10^{-2}, 10^{-2}
CKM 3 mixing angles & 1 CP-violating phase	10^{-4} - 10^{-2}
Strong CP violating phase	$< 10^{-9}$

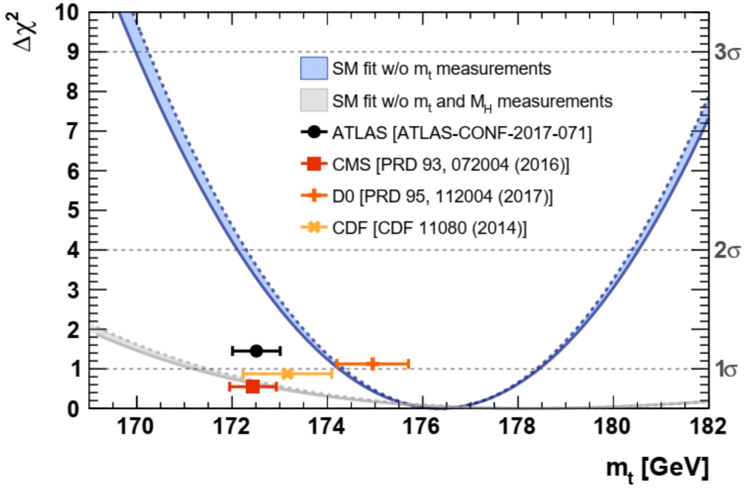
Those sensitive for EW & TeV scale colliders to measure are marked in red

Measuring these parameters at different exp. offers

- stringent test of SM internal consistency
- high sensitivity to new physics
- probe of running nature of fundamental couplings



Example of other particles in loops that impact W boson propagator and its mass



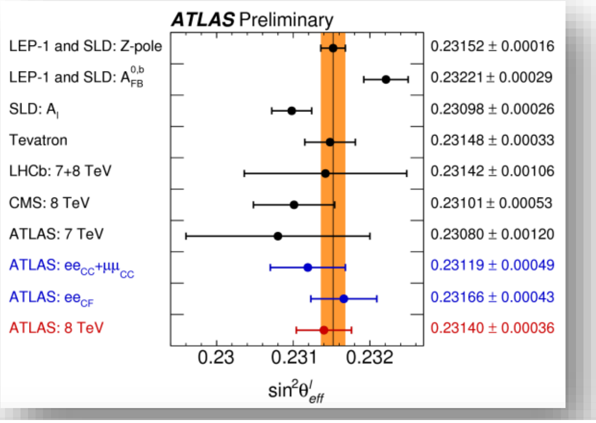
Example of EW fit on m_t vs measured values

EPJC 78, 675 (2018)

LHC measurements

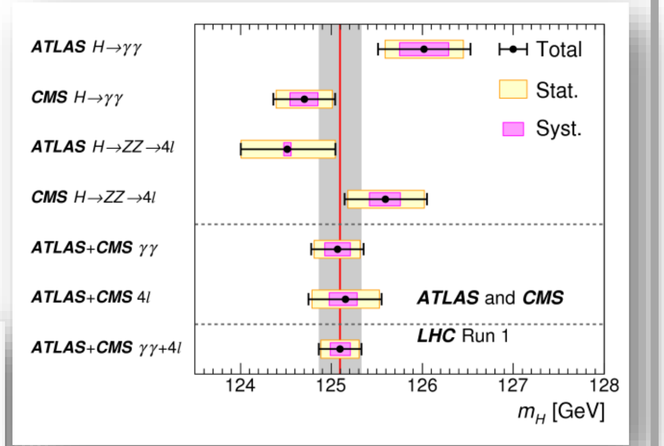
ATLAS-CONF-2018-037

$\sin^2\theta_W$

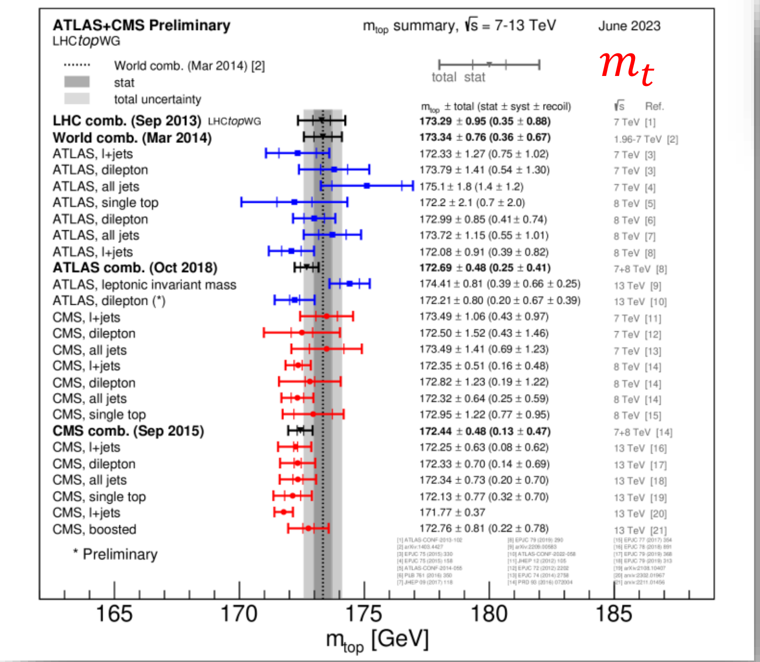


PRL 114 (2015) 191803

m_H



m_t

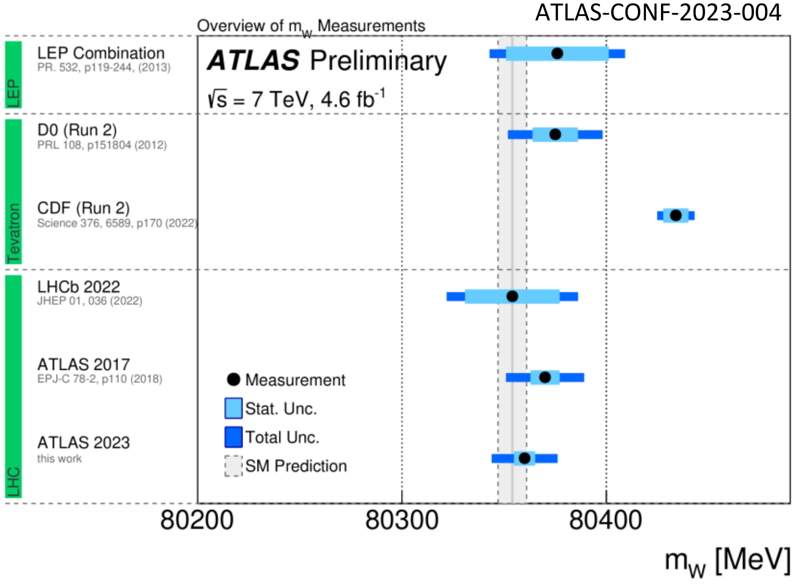


ATL-PHYS-PUB-2023-015

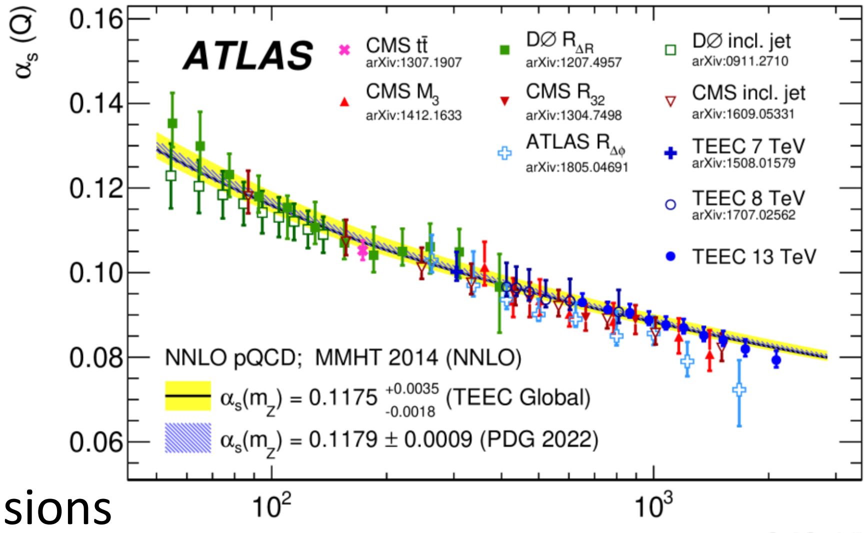
Not covered in this talk

ATLAS-CONF-2023-004

m_W



α_S



arXiv:2301.09351

Already providing competitive/
most precise precisions

Covered measurements relevant to m_W and α_S from ATLAS and CMS

ATLAS: W mass measurement with 7 TeV pp collision data
ATLAS-CONF-2023-004 improved upon original result in EPJC 78 (2018) 110

ATLAS: Measurement of W/Z pT with low pile-up data at 5 and 13 TeV
ATLAS-CONF-2023-028

ATLAS: Measurement of Z pT at 8 TeV
ATLAS-CONF-2023-013

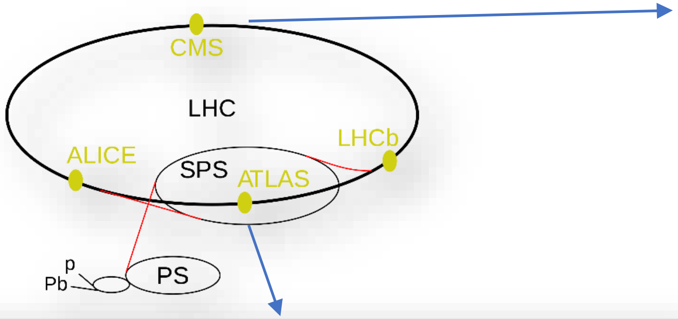
CMS: Measurement of Z pT at 13 TeV
arXiv:2205.04897

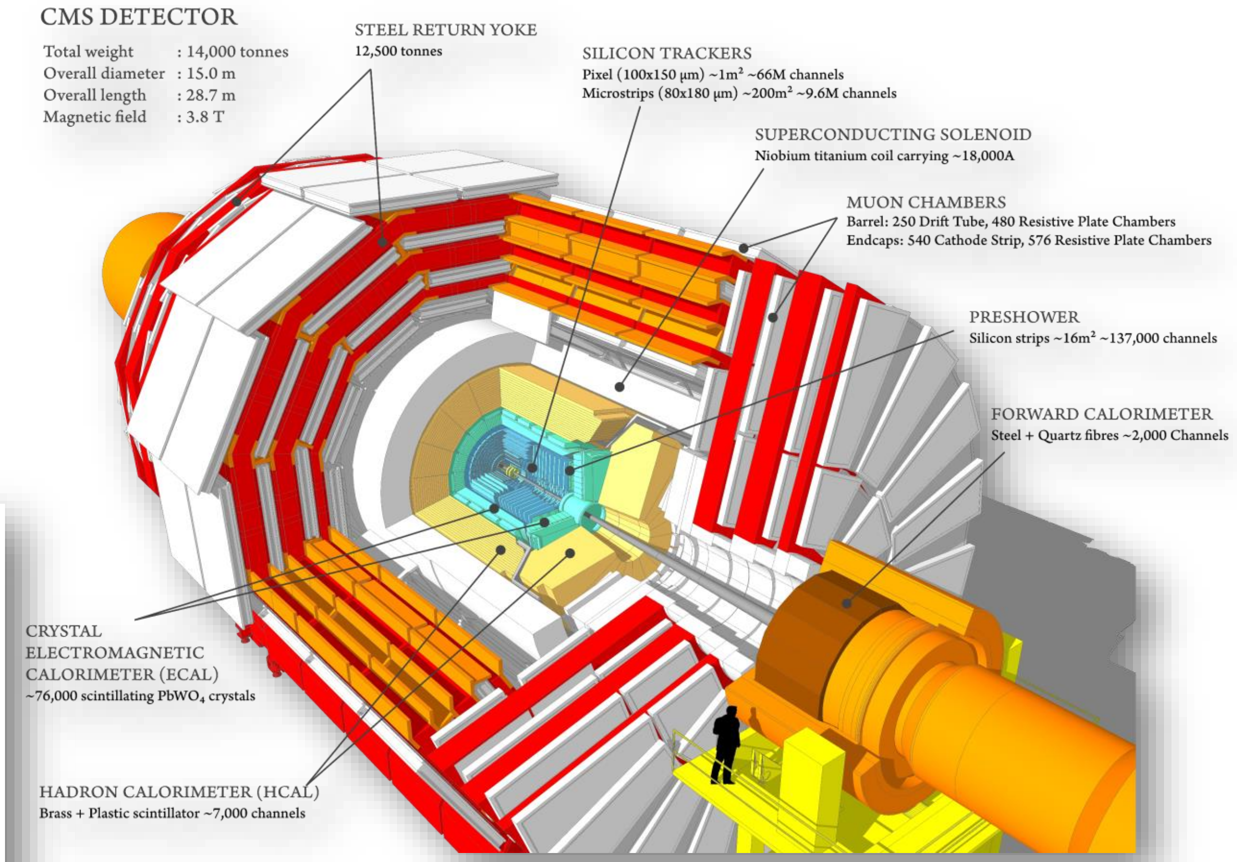
CMS: α_S measurement with inclusive jet cross-sections at 13 TeV
JHEP 02 (2022) 142

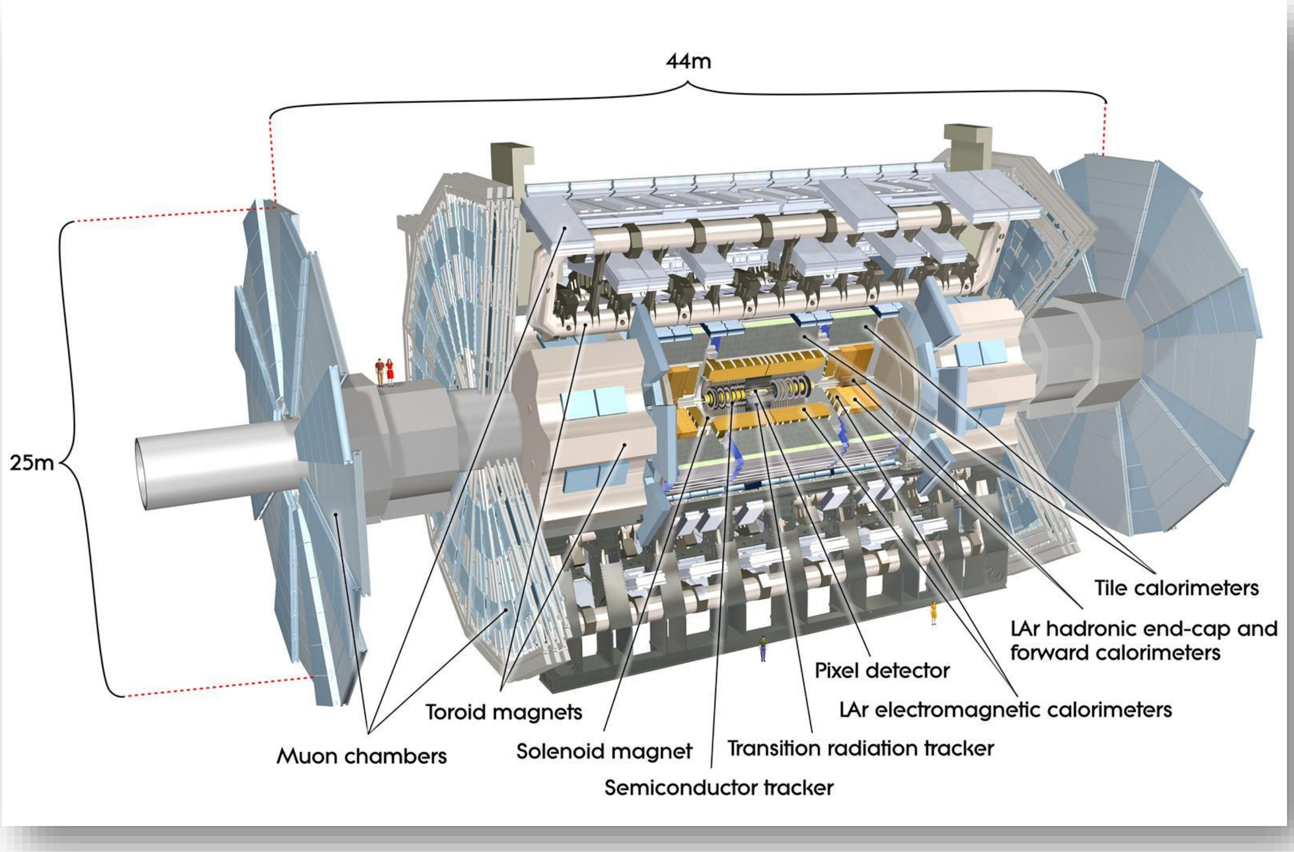
ATLAS: α_S measurement with multi-jets at 13 TeV
arXiv:2301.09351

ATLAS: α_S measurement with Z pT at 13 TeV
ATLAS-CONF-2023-015

LHC, ATLAS and CMS







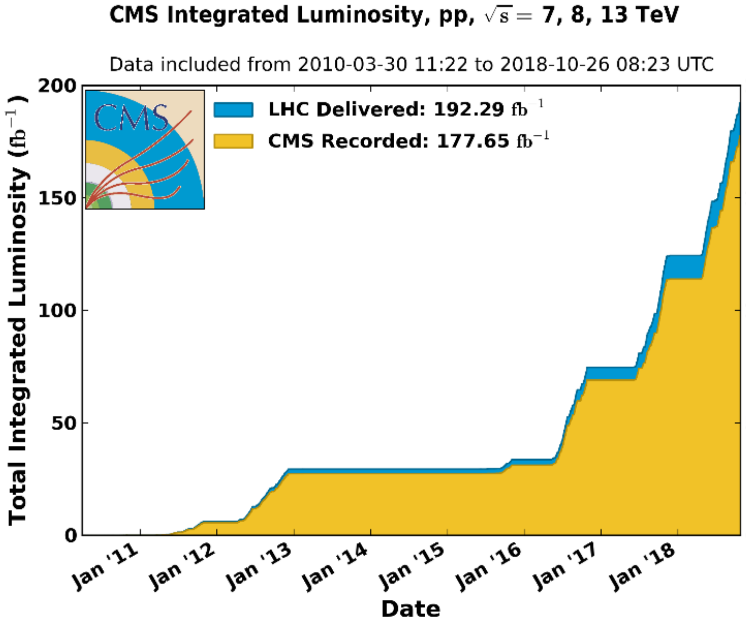
Two general-purpose detectors with excellent performance and broad physics potentials:

Higgs and other SM measurements, direct search for new physics at EW and TeV scales, …

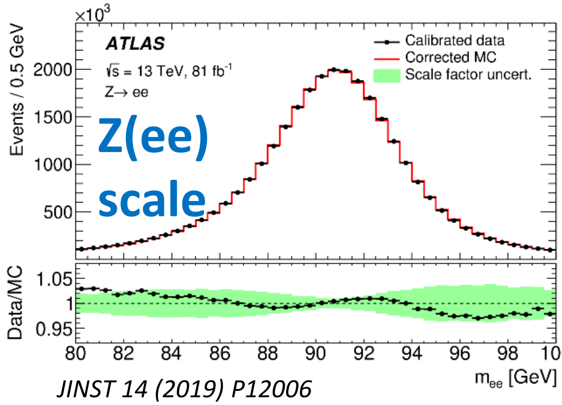
Data taking and processing

Physics successes owing to precise understanding of e, μ, jets, E_T^{miss}, and tagging of heavy-flavor jets

Per-mil to percentage precision achieved in many

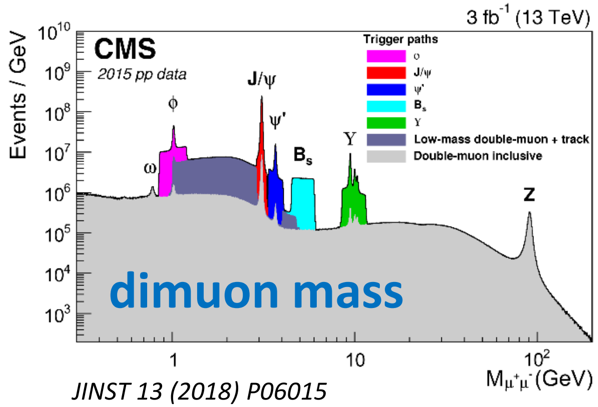


Tremendous efforts from LHC, detector teams to make the data collection smooth



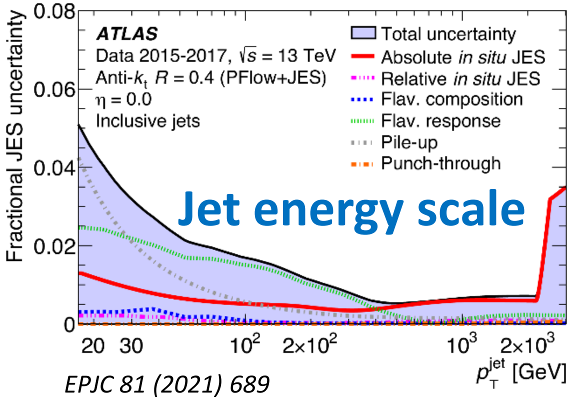
Z(ee) scale

JINST 14 (2019) P12006



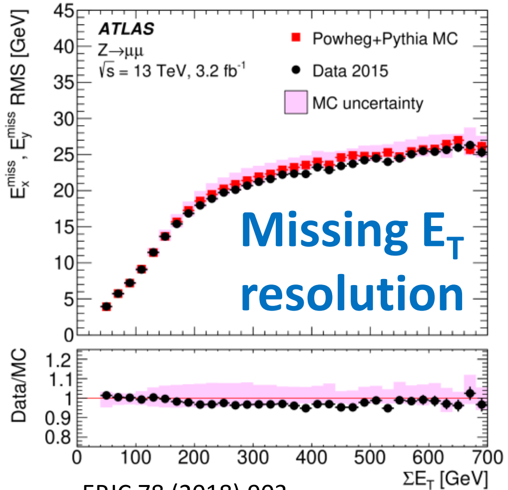
dimuon mass

JINST 13 (2018) P06015



Jet energy scale

EPJC 81 (2021) 689



Missing E_T resolution

EPJC 78 (2018) 903

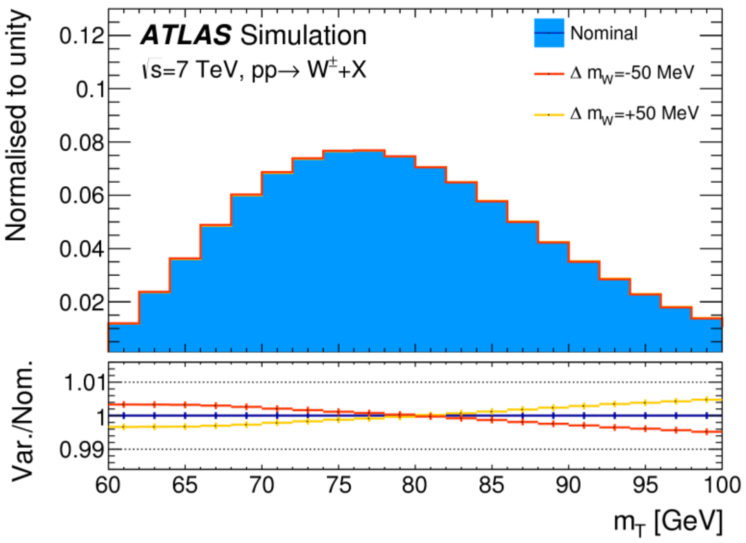
W mass measurement

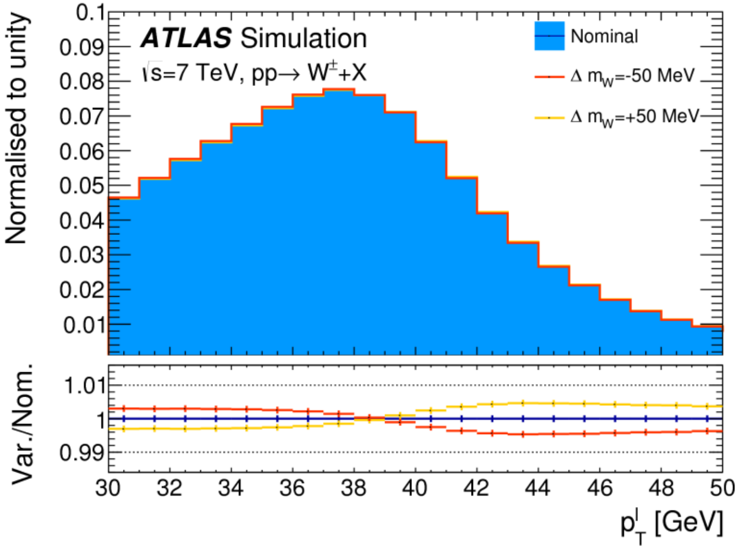
EPJC 78 (2018) 110 ATLAS-CONF-2023-004

←

Walk through the methodology in the
original paper and flash through the updates

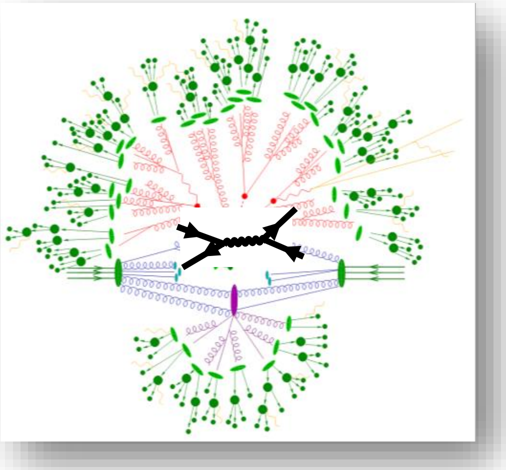
Story of being precise …





- ✓ **Abundant and clean W →eν and μν events (> 10M)**
- ✓ **Sensitive variables p_T^{lepton} and m_TW to measure mW**
  - ○ Templates with varying mW fit to data
- ✓ **Target of O(10) MeV precision requires per-mil precision in predicting and measuring p_T^l and m_T**
  - ○ Correcting MC simulation to start-of-art predictions
  - ○ Calibrating physics objects to best possible precisions
- ✓ **Z events for calibrations and verifying corrections and methodology**
  - ○ more precise mZ, and similar process to W

Modelling and Corrections



Needs precise modelling upon all corners:

from matrix-element all the way to final state particles

W, Z process initially modelled with Powheg+Pythia8:

NLO QCD + QED final state radiation + LL QCD resummation

Correct to start-of-art predictions based on **Drell-Yan factorisation formula**

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

Differential σ for final states
$\otimes$ detector response
➔ Detector-level templates

Breit-Wigner mass distribution,
vary as mW
(uncertainty on width considered)

Rapidity distribution:
Correct to perturbative
NNLO via DYNNLO

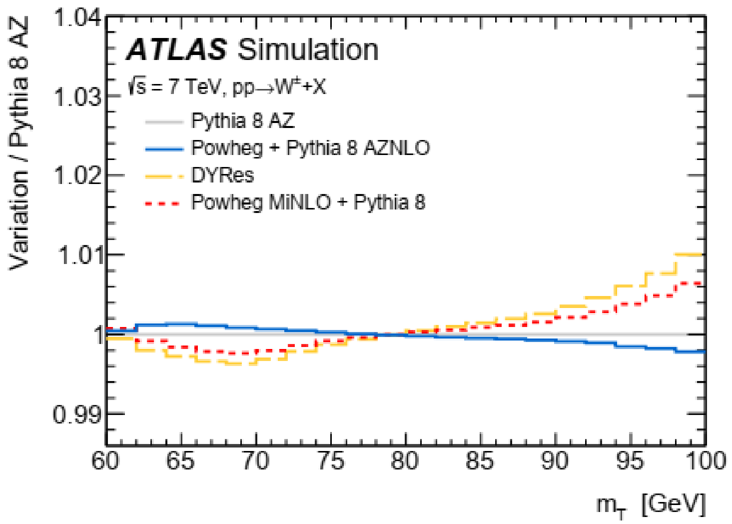
Helicity σ and A_i:
Correct to perturbative
NNLO via DYNNLO

$p_T(V)$: sensitive in small p_T, subject to large uncertainties
Correct to Pythia 8 tuned with data — AZ tunes
(approximately NLO QCD + NLL resummation accuracies)

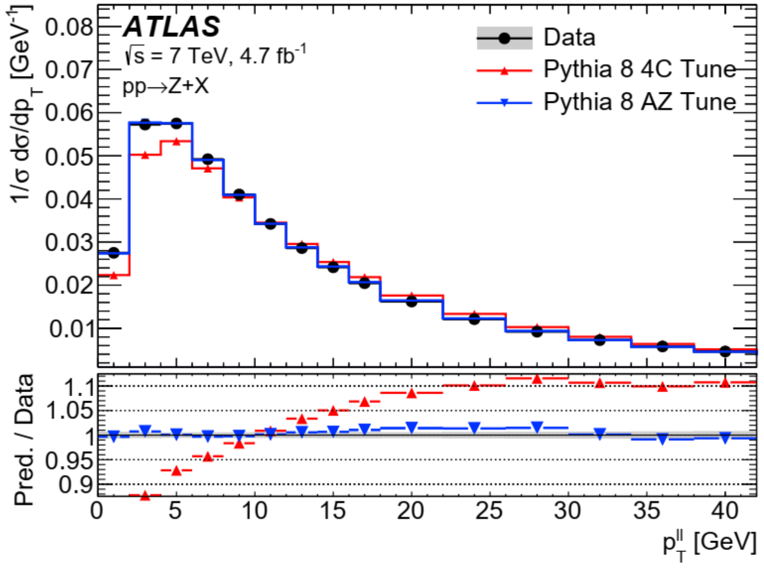
Corrections on variables insensitive to mW ➔ reliable modelling, minimum biases to mW

Improved modelling

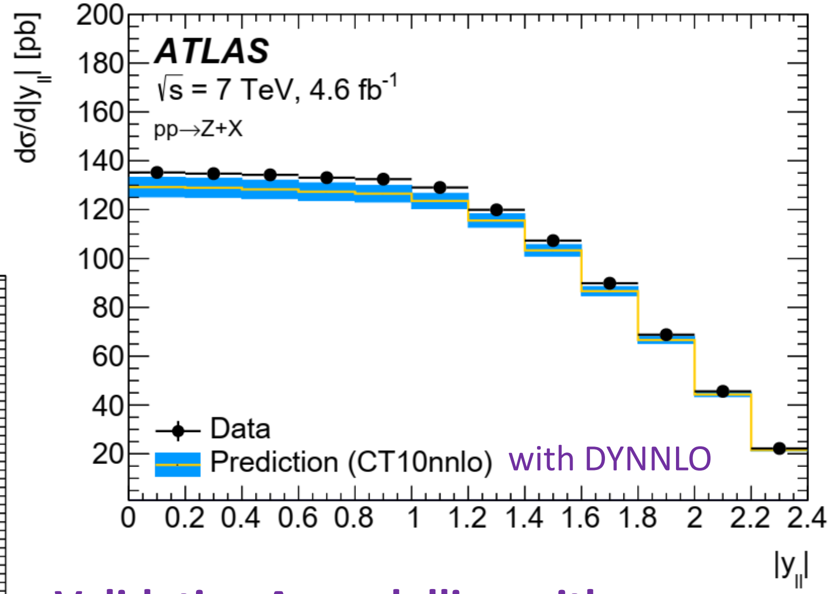
Modelling variation in m_TW under control



pT(V) greatly improved

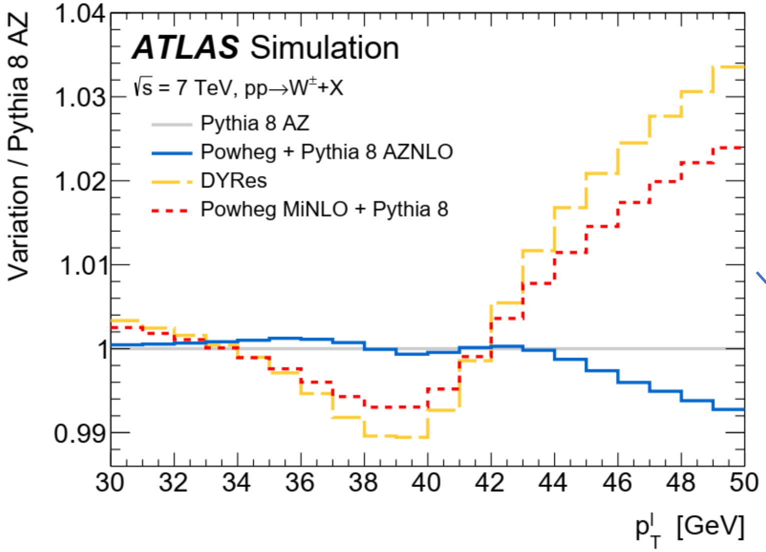


Validating y modelling with measurement



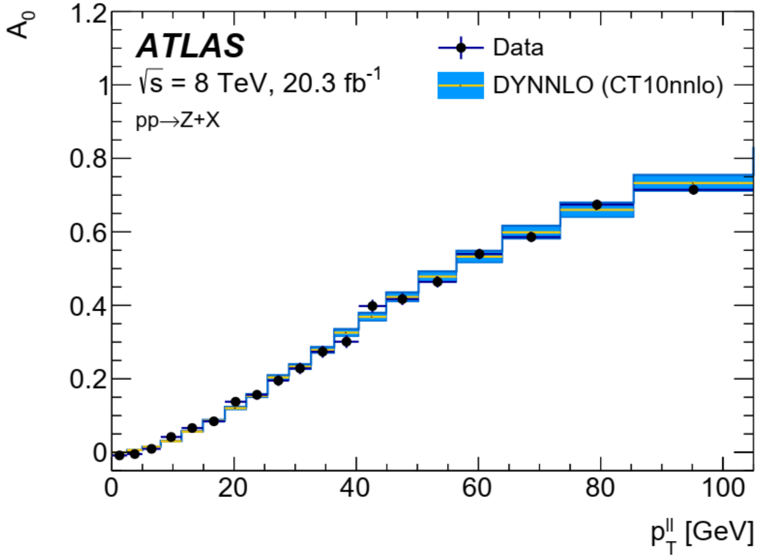
with DYNNLO

Modelling variation in p_T^l under control



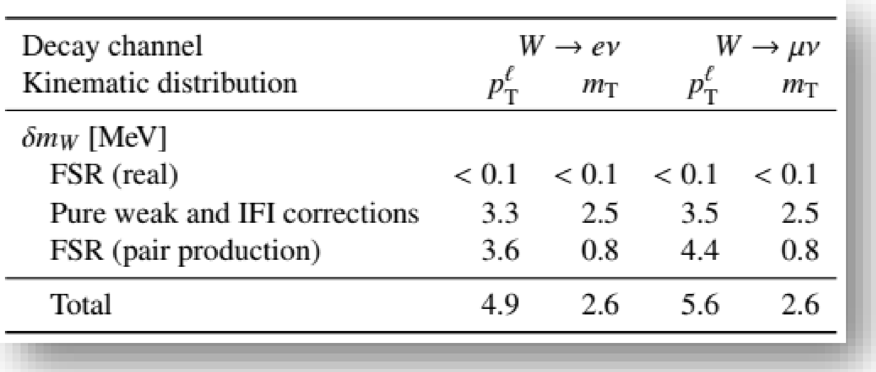
Avoid larger uncertainty ranges: Narrower range p_T and m_T used for measurement

Validating A_i modelling with measurement



Modelling uncertainties

Demonstrating the impact on mW measurement directly

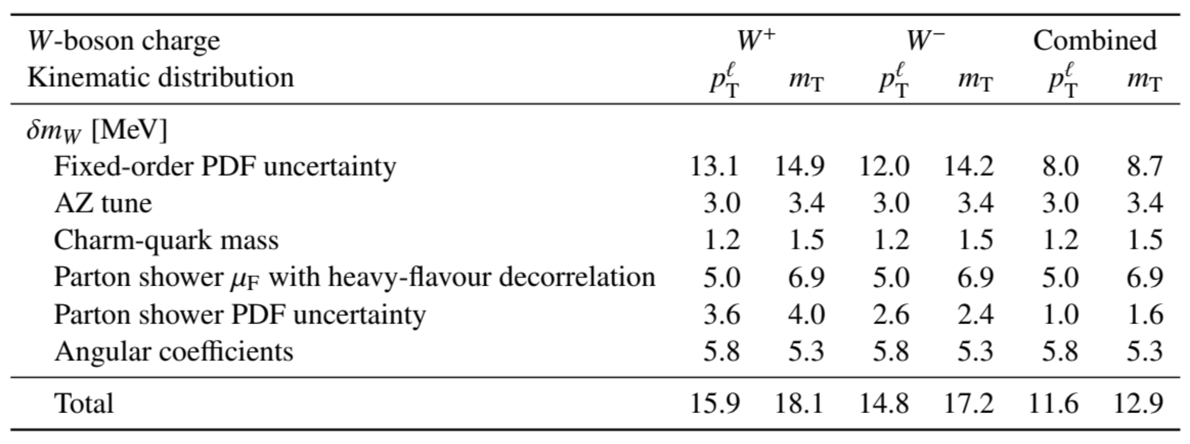


Decay channel Kinematic distribution	$W \to e\nu$ p_{T}^{ℓ}	 m_{T}	$W \to \mu\nu$ p_{T}^{ℓ}	 m_{T}
δm_W [MeV]				
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

Higher-order electroweak (with WINHAC and SANC)

Real FSR included in simulation → negligible unc.

Loop, interference (ISR-FSR), FSR pair production not included in simulation → full size evaluated and assigned unc.



W-boson charge Kinematic distribution	W^+ p_{T}^{ℓ}	 m_{T}	W^- p_{T}^{ℓ}	 m_{T}	Combined 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

QCD

PDF unc. dominates

→ CT10nnlo internal errors, alternative sets

Parton shower unc. important

→ affect pT modelling; uncertainty reduction in ratios

(Z_{data}* W_{MC} / Z_{MC})

Angular coefficients Ai also important

→ Rely on Z measurement errors/discrepancies

QCD scale variation in matrix element negligible

Detector response

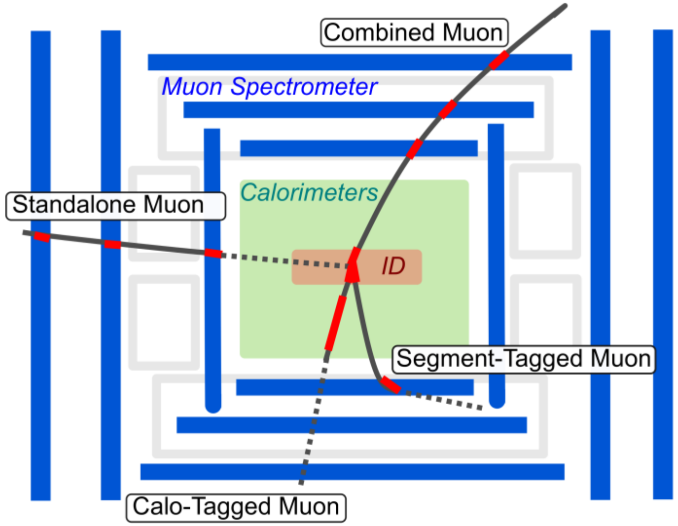
Key observables are p_T^l and m_T

$$m_T = \sqrt{2 p_T^{\ell} p_T^{\text{miss}} (1 - \cos \Delta\phi)}$$

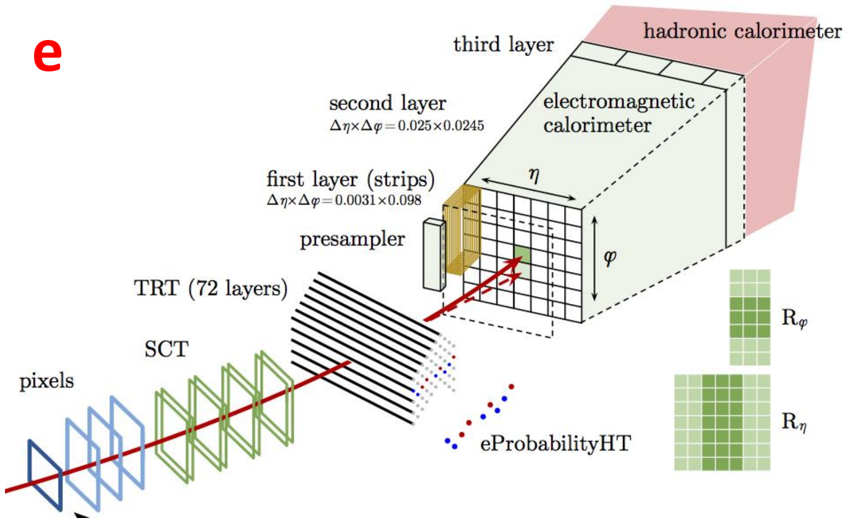
$$\vec{p}_T^{\,\text{miss}} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right)$$

- Rely on precise measurement or response to $\mathbf{p_T^l}$ and $\mathbf{p_T^{miss}}$
- Calorimeter clusters used to reconstruct **recoiling energy $\mathbf{u_T}$** to improve $\mathbf{p_T^{miss}}$ resolution

μ

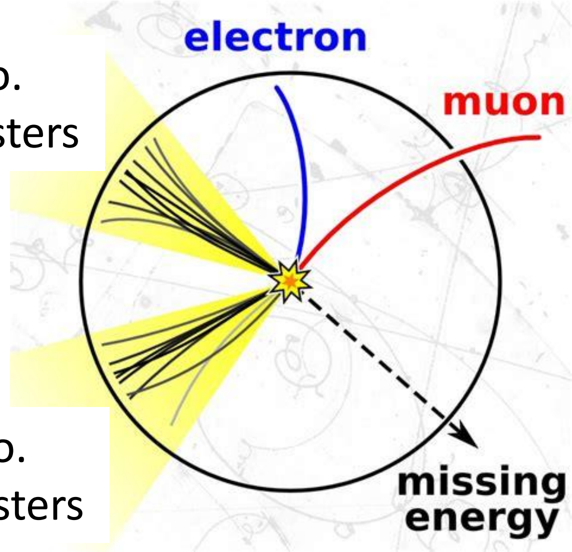


e



u_T

Calo. Clusters



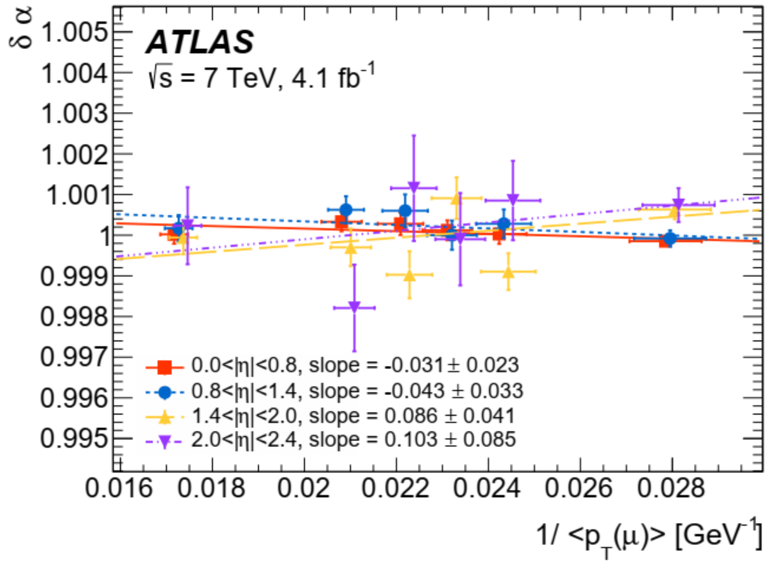
Calo. Clusters

Lepton p, E scale and resolution, efficiencies, determined via Tag & Probe method in **Z** events, corrected in simulation

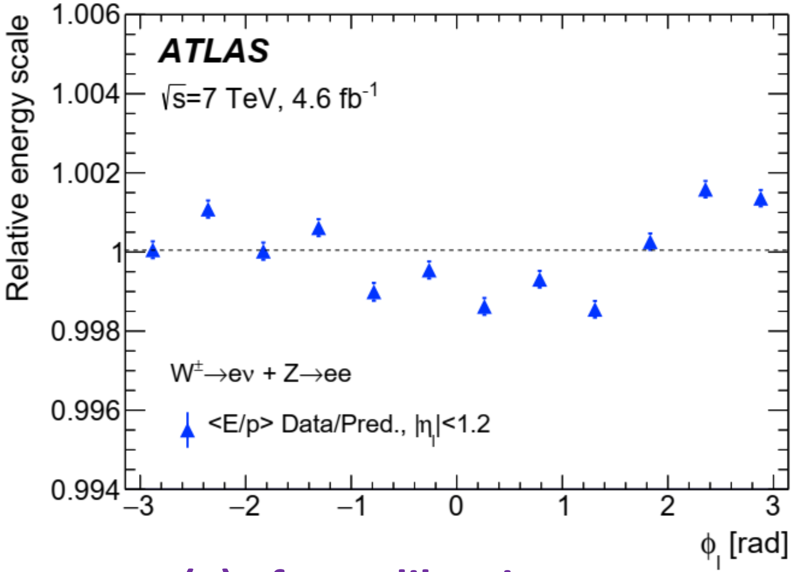
Calibrated activities along-side **Z** events

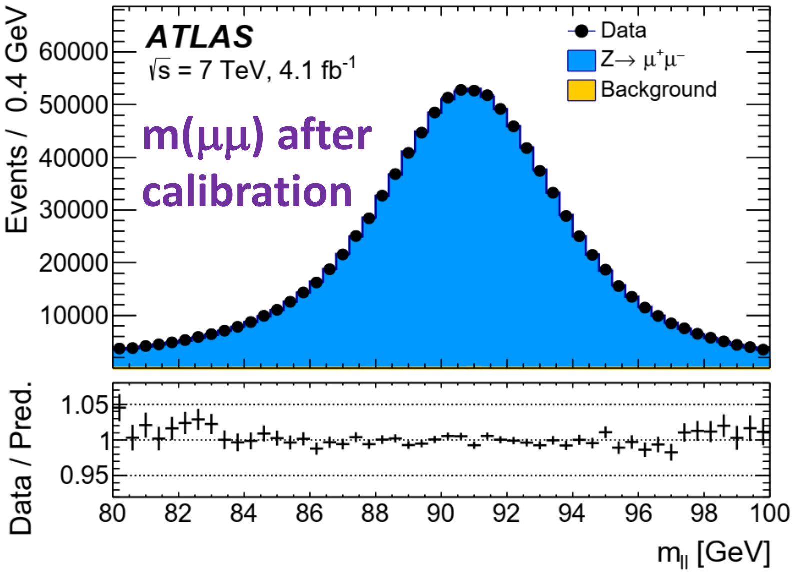
Calibrated e, μ

μ scale correction to simulation



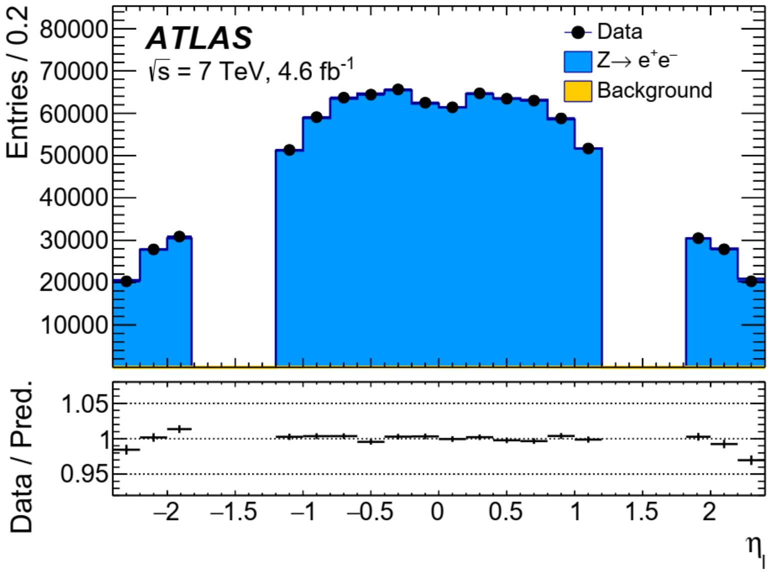
electron energy scale





m($\mu\mu$) after calibration

η(e) after calibration



Corrections (in p_T, η, ϕ) validated in Z data

➔ Small uncertainties compatible to statistical error of Z data (per-mil)

➔ Impact on mW could be O(10) MeV

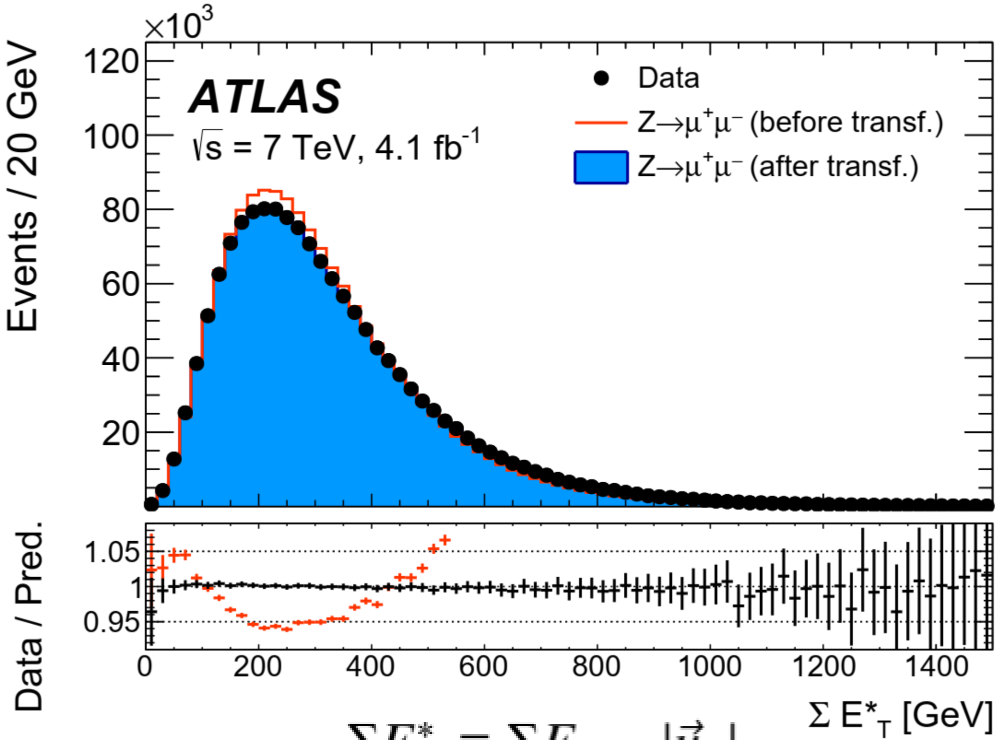
Benefit from larger samples in the future

Calibrated u_T

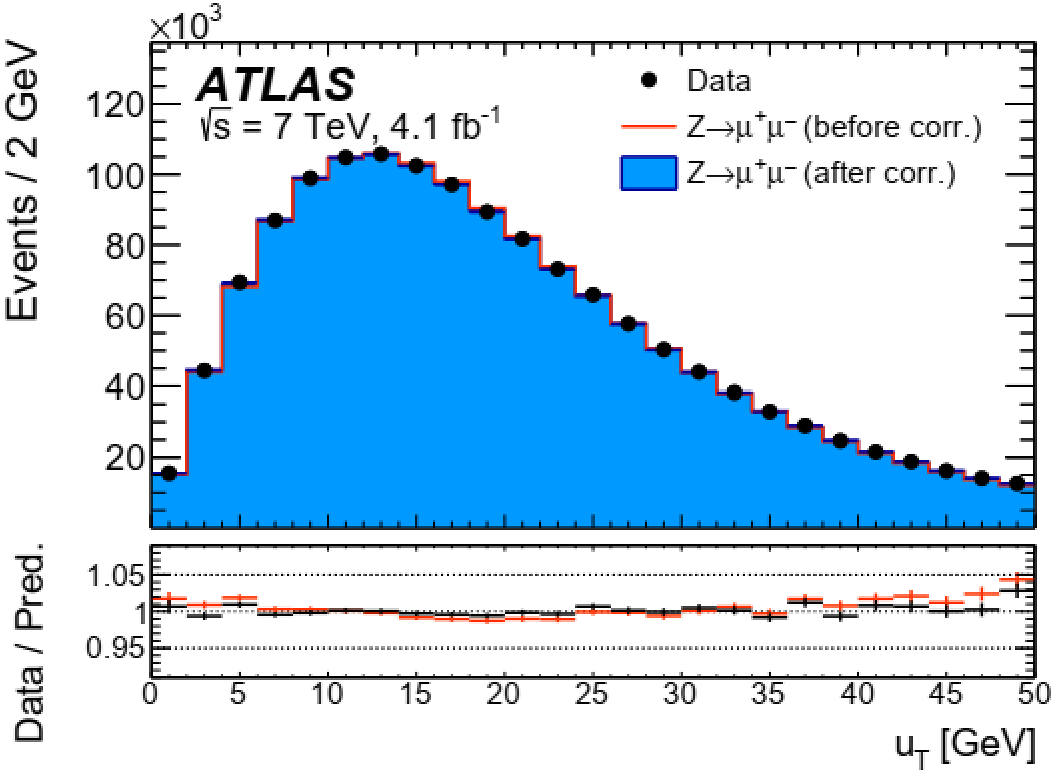
u_T sensitive to effects of extra pp collisions (pile-up)

➔ Prefer to work in low pile-up environment

➔ Use Z events to correct for event activities and then for **u_T** energy scale and resolution



$$\Sigma E_T^* \equiv \Sigma E_T - |\vec{u}_T|$$



u_T modelling affects mW measured from m_T

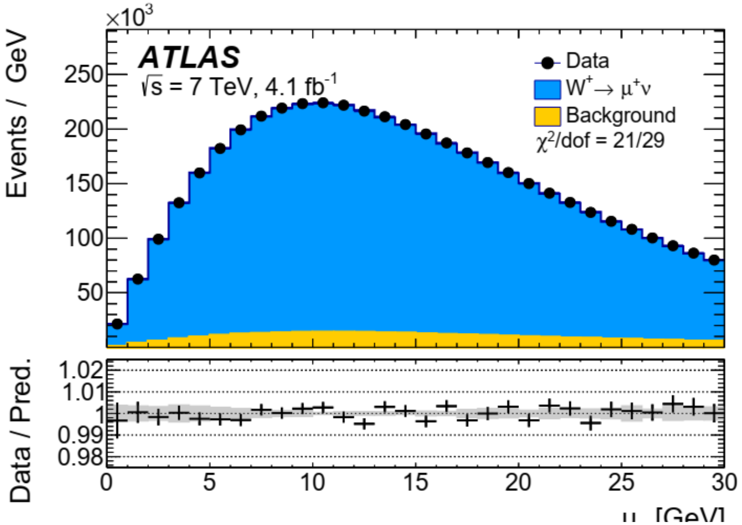
O(10) MeV due to event activity correction, and Z→W extrapolation

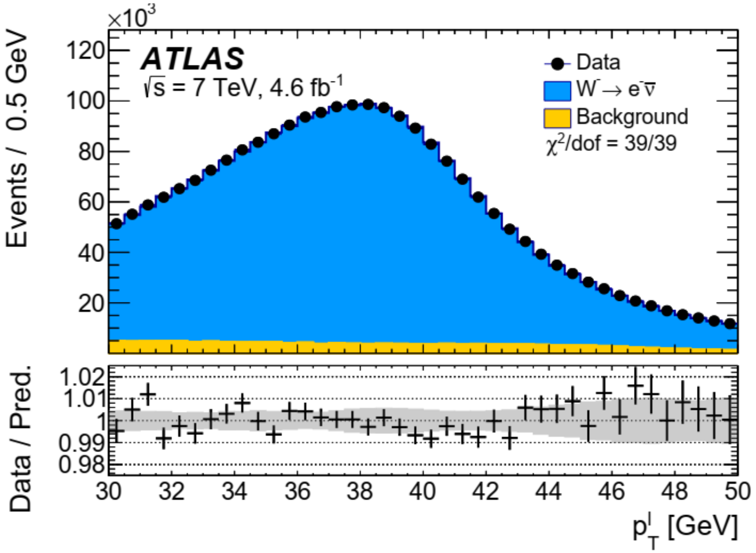
Measurement Regions

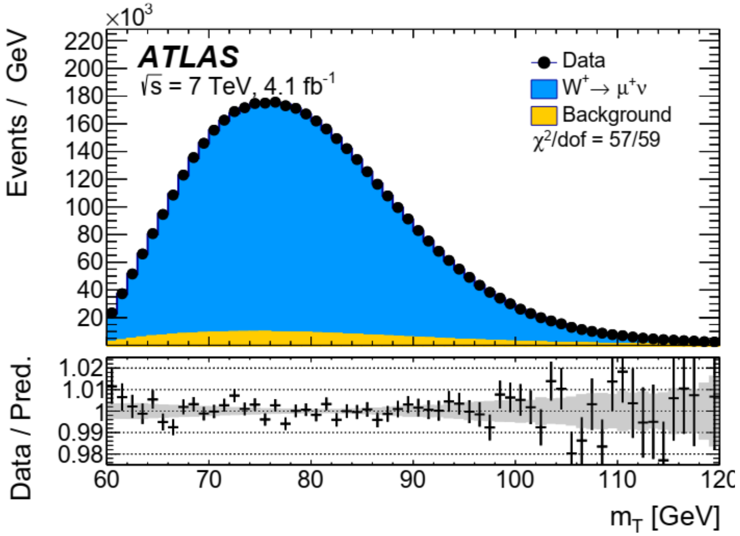
Full procedure validated with Z events (treated one lepton missing) – see backup

Data and predictions for W events after all corrections

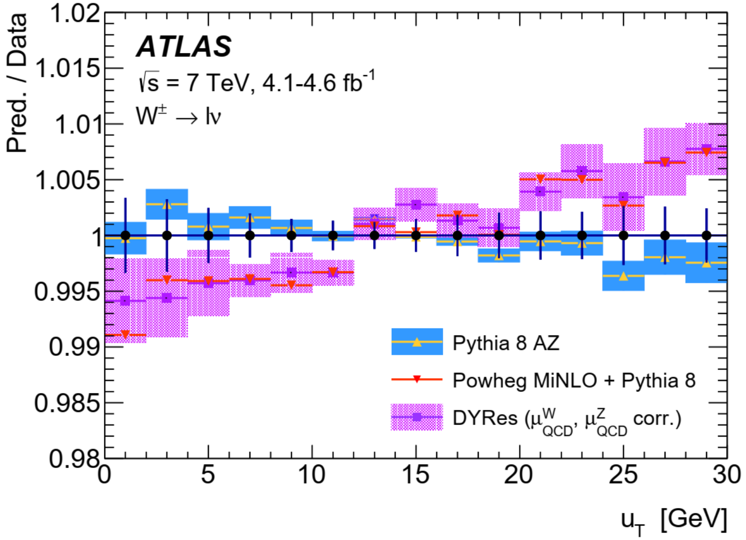
Backgrounds mainly Z, multijet (data-driven) → imposing 5-10 MeV unc. to mT







pT(W) modelling examined with u_T

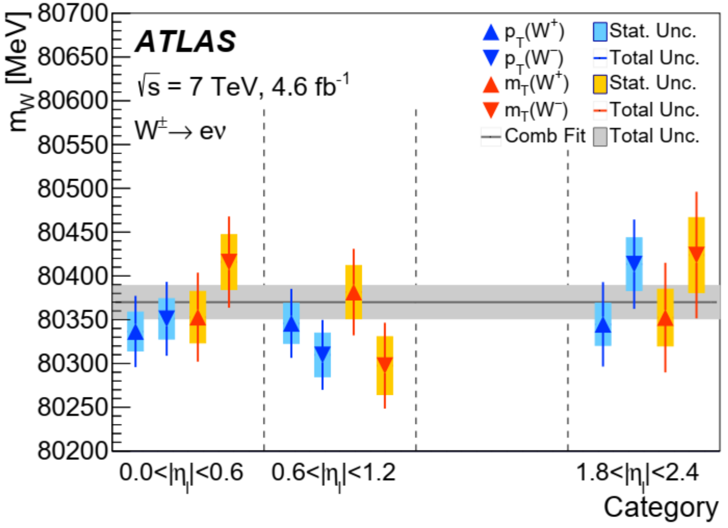


All ingredients in place to perform final measurements:

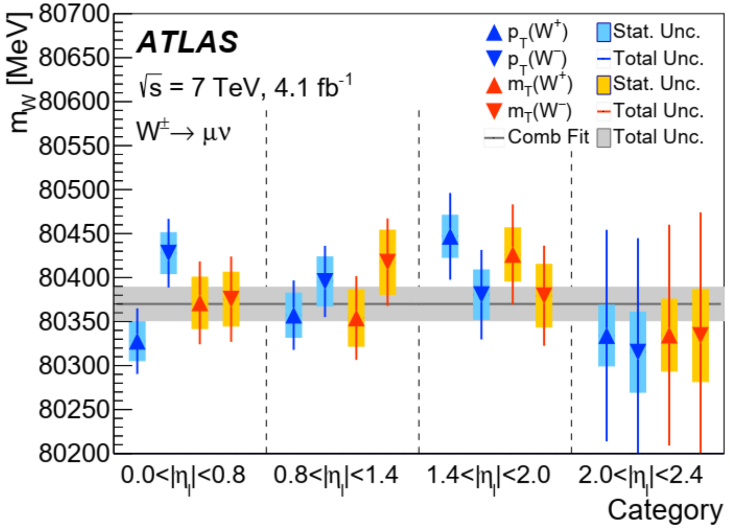
Chi2 fit with varying mW templates to data, performed in various bins, variables (consistency check) and combined

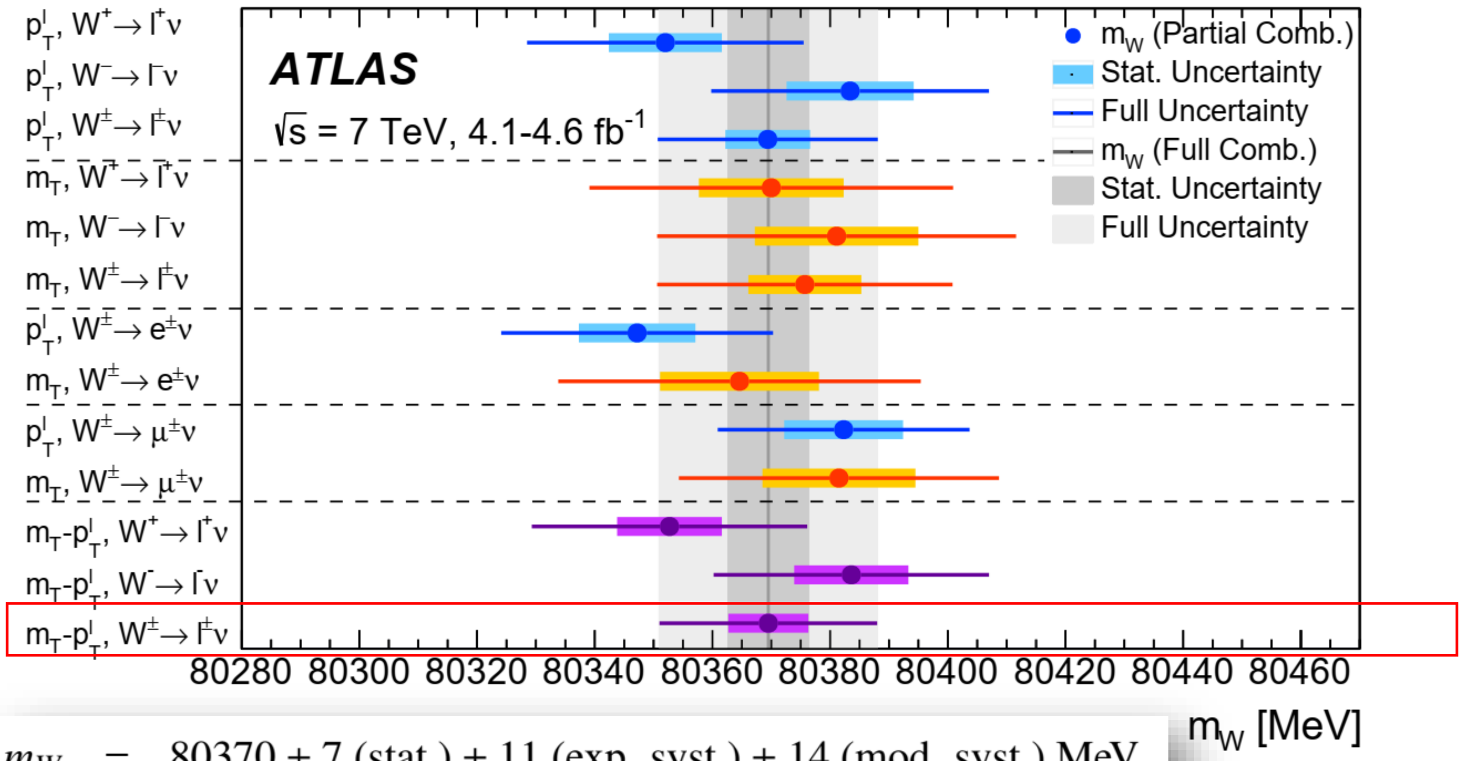
Measured W mass

e



μ





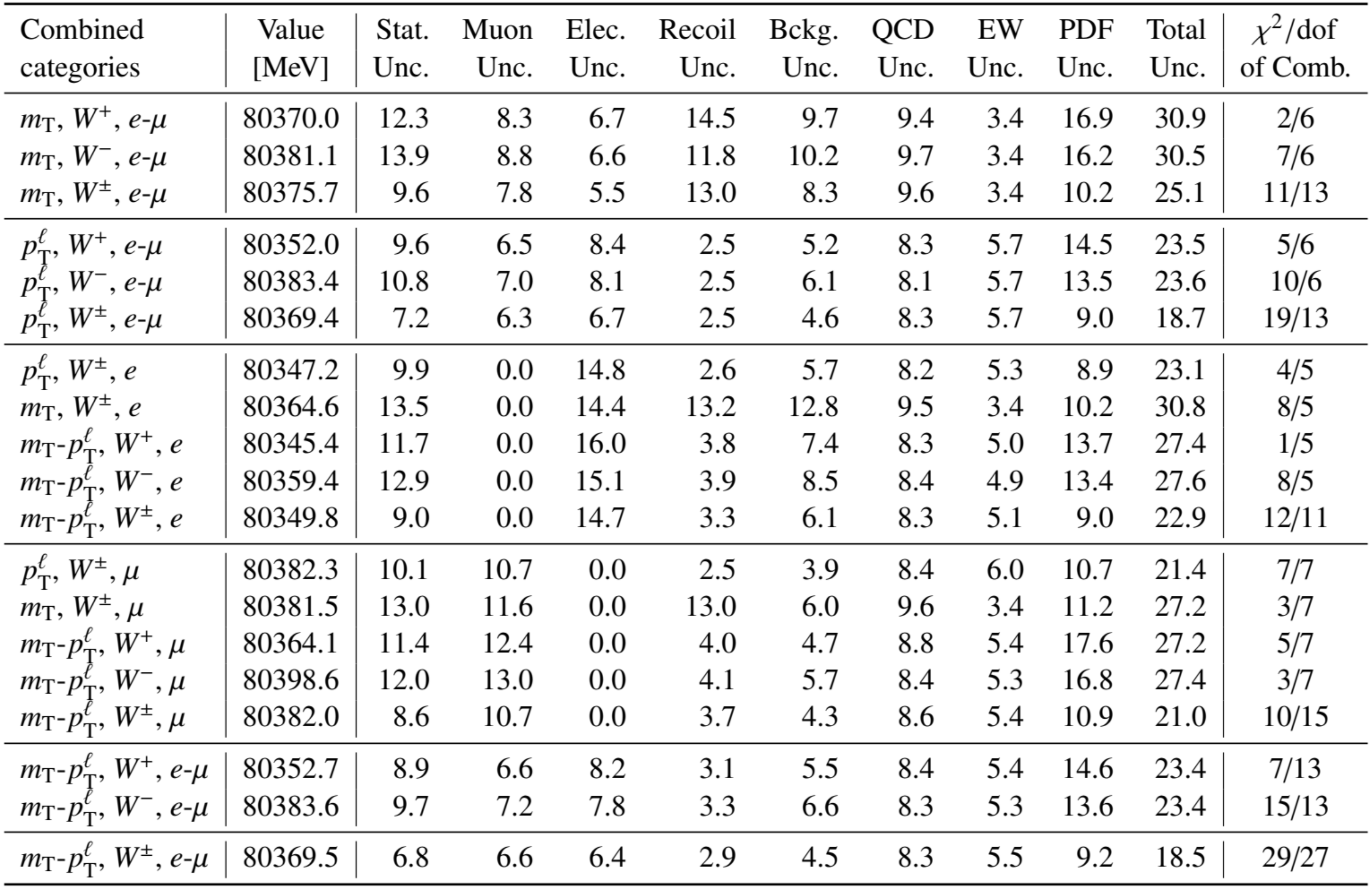
$$\begin{aligned} m_W &= 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV} \\ &= 80370 \pm 19\ \text{MeV}, \end{aligned}$$

Final results given by combined m_T and p_T^l fits

→ Stat. improvement, syst. cancellation w.r.t. individual fit

Extensive test of stability, consistency has been performed

Systematics in a nutshell



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, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_T, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_T, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_T^ℓ, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_T^ℓ, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_T^ℓ, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_T^ℓ, $W^\pm$, e	80347.2	9.9	0.0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_T, $W^\pm$, e	80364.6	13.5	0.0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_T-p_T^ℓ, W^+, e	80345.4	11.7	0.0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_T-p_T^ℓ, W^-, e	80359.4	12.9	0.0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_T-p_T^ℓ, $W^\pm$, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_T^ℓ, $W^\pm$, μ	80382.3	10.1	10.7	0.0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, $W^\pm$, μ	80381.5	13.0	11.6	0.0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
m_T-p_T^ℓ, W^+, μ	80364.1	11.4	12.4	0.0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_T-p_T^ℓ, W^-, μ	80398.6	12.0	13.0	0.0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_T-p_T^ℓ, $W^\pm$, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
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

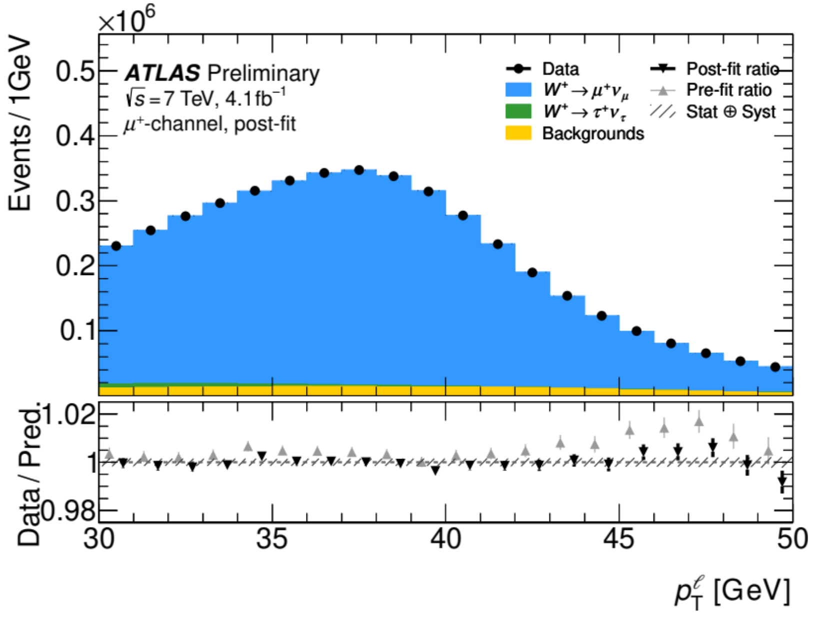
Cannot miss any corners of potential effects

Updated W mass NEW!

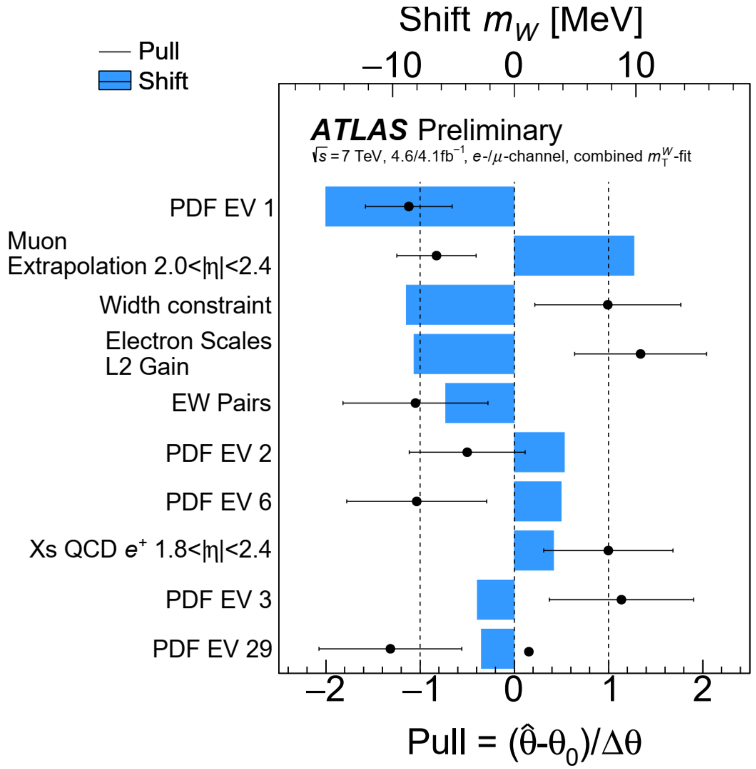
Chi2 fit method don't exploit data directly to improve modelling of systematics

- ➔ **Change to likelihood fit method**
- ➔ **Same modelling as in original paper, except for updated PDF to CT18NNLO**

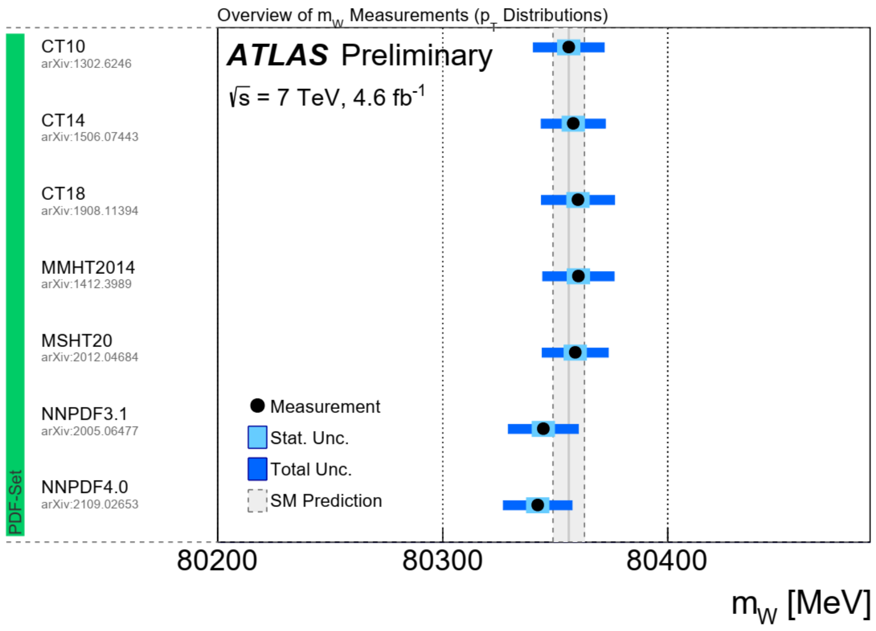
$$L\left(\mu,\vec{\theta}|\vec{n}\right)=\prod_{j}\prod_{i}\text{Poisson}\left(n_{ji}|\nu_{ji}(\mu,\vec{\theta})\right)\cdot\text{Gauss}\left(\vec{\theta}\right)$$



Can visualize post/pre-fit behaviors



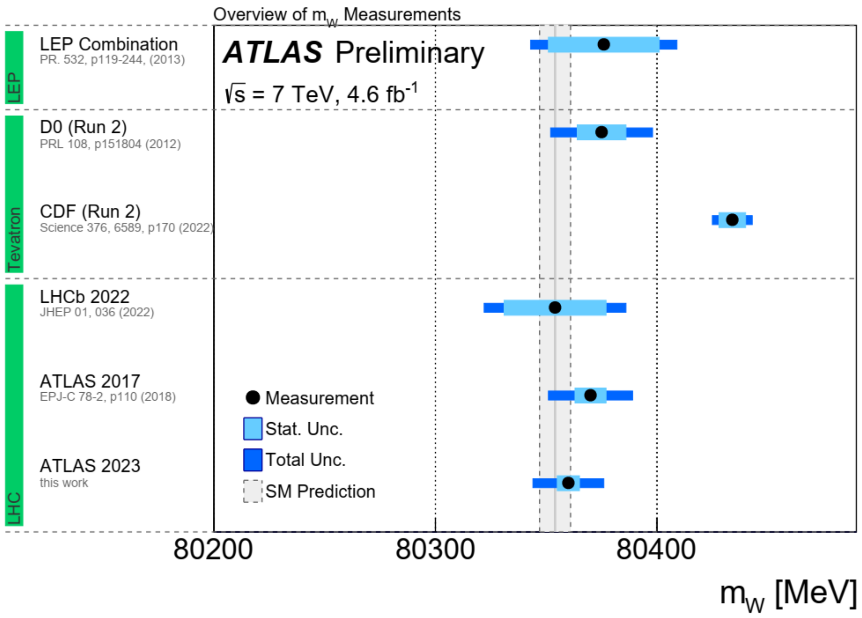
Statistical interplays start to happen

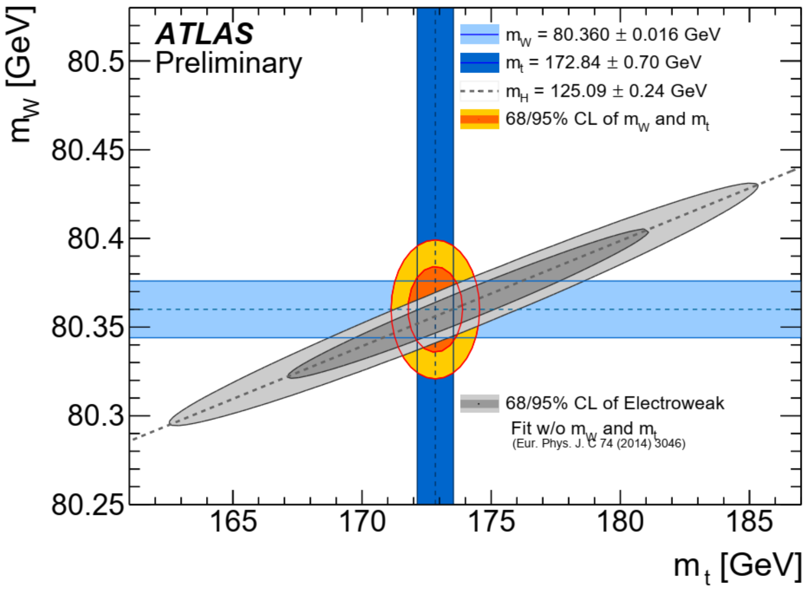


Check PDFs on the markets

Updated W mass NEW!

Statistical combination of pT and mT fits, pT dominates the precision





$$m_W = 80360 \pm 5(\text{stat.}) \pm 15(\text{syst.}) = 80360 \pm 16 \text{ MeV}$$

Updated mW measured to have lower mass, and 3 MeV smaller unc.

Better consistency with electroweak fit prediction

FUTURE:

more precise, independent measurements from ATLAS, CMS, LHCb will be desired (in view of discrepancies w.r.t. CDF results) ➔ more precise calibrations (with more data), better pT modelling (more precise V pT measurements), better PDF modelling (more relevant PDF measurements at the LHC)

V pT measurements

ATLAS-CONF-2023-028 ATLAS-CONF-2023-013 arXiv:2205.04897

Flash through new measurement results

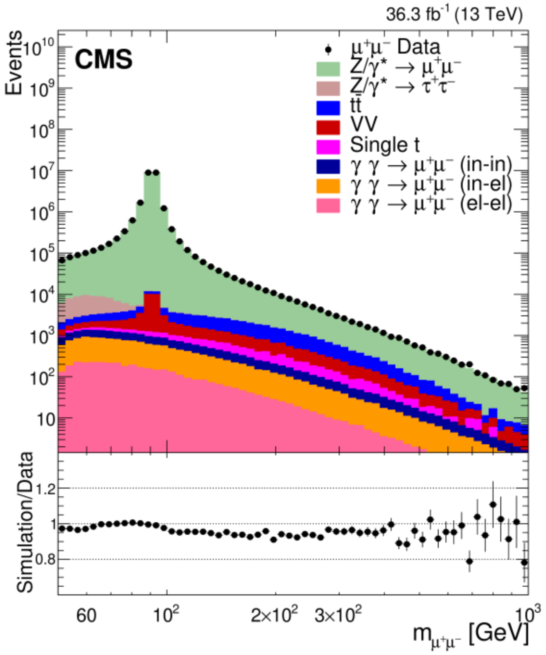
arXiv:2205.04897

V pT measurements

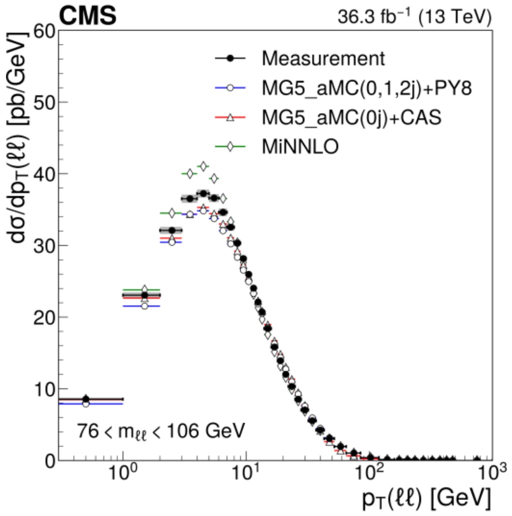
Or precision differential measurements of W or Z:

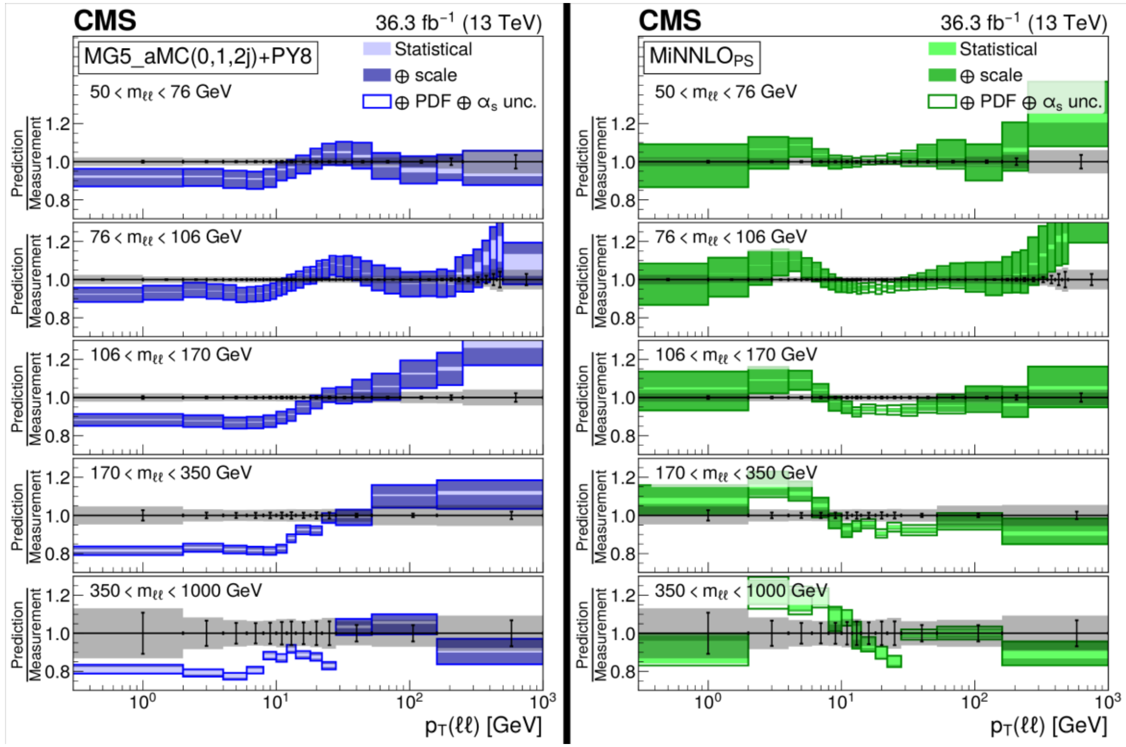
- Parameter determination (e.g., W mass and α_S); Understanding of QCD (V+jets); Search for new physics, study of Higgs physics, …

Clean, abundant Z samples



1% measurement precision provides great inputs to latest MC algorithms (NLO multi-leg, NNLO + PS, NNLL resummation, TMD, …)

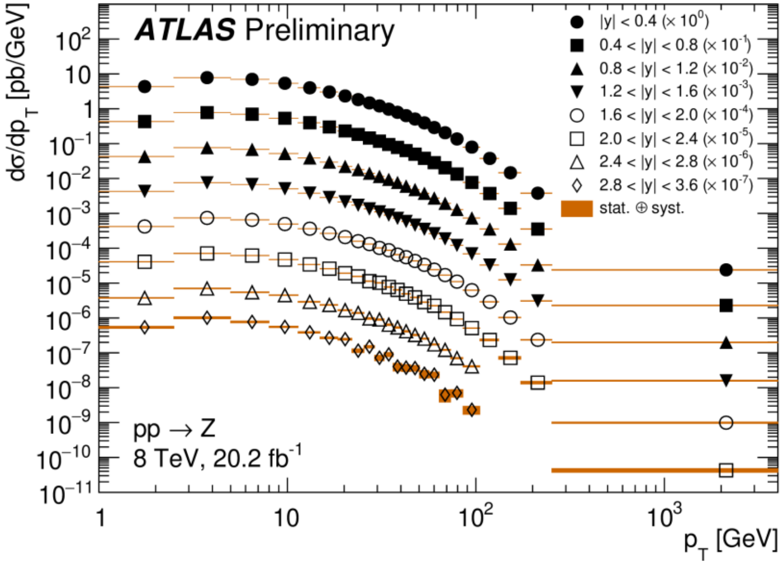




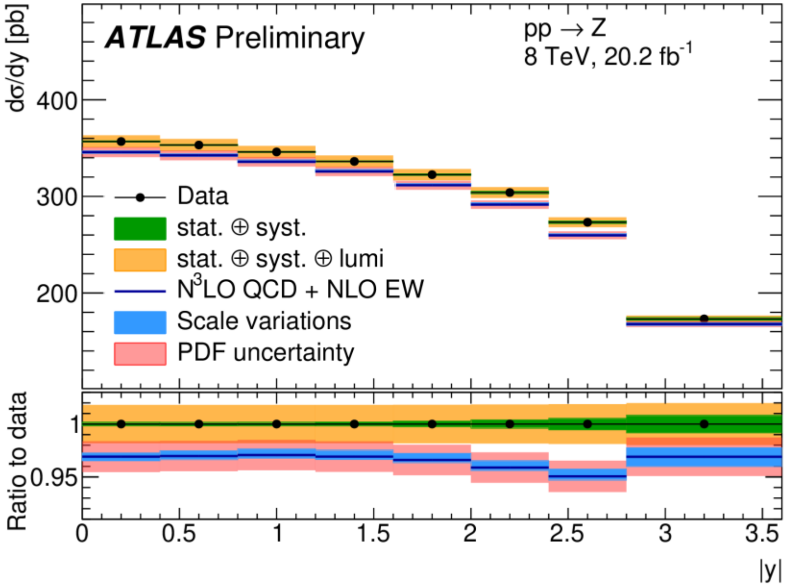
Z pT measurements

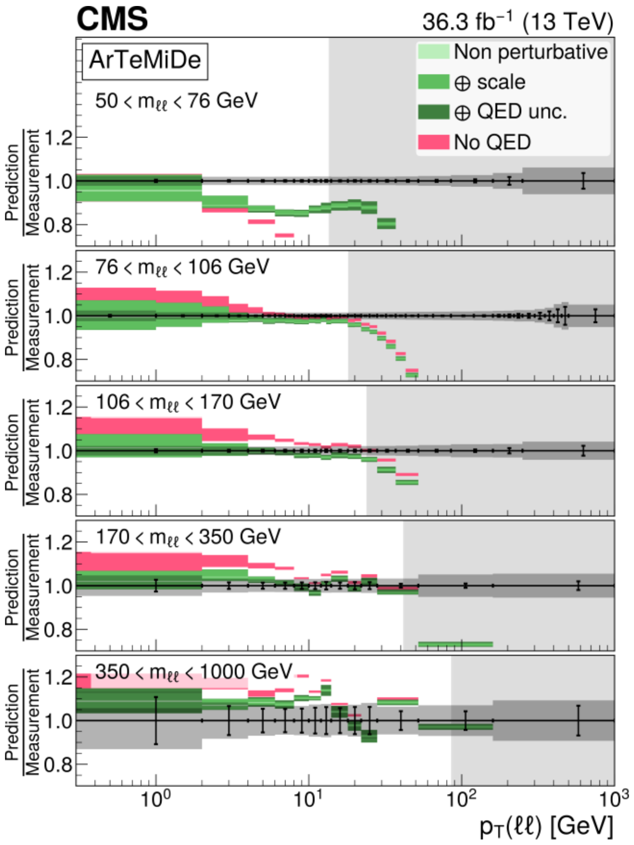
ATLAS-CONF-2023-013 arXiv:2205.04897

Broad coverage of phase spaces

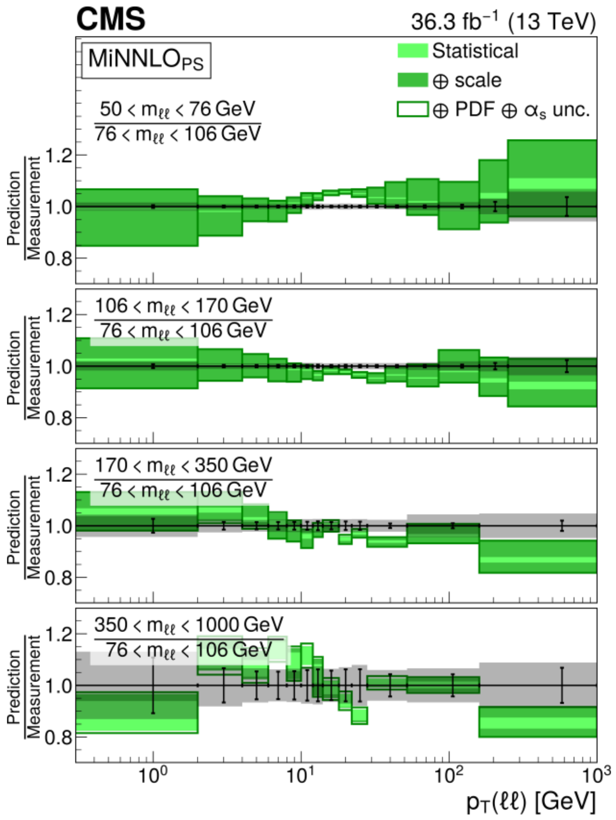


Not only pT: constraining high-order perturbative





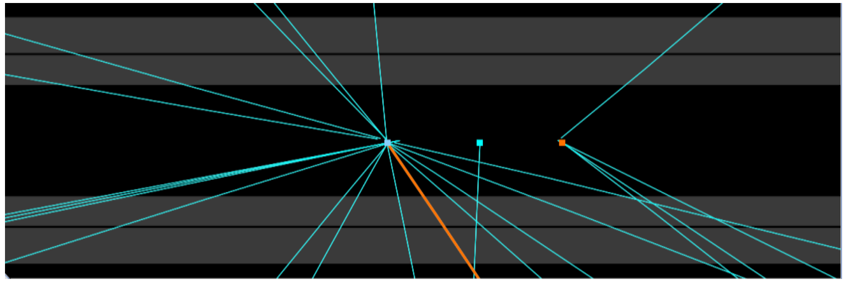
Constraining TMD (from ArTemiDe and from parton branching TMD from CASCADE), resummation effects



Ratio measurement to explore more precision and constraining powers

ATLAS-CONF-2023-028

Low pile-up pT(V) measurements



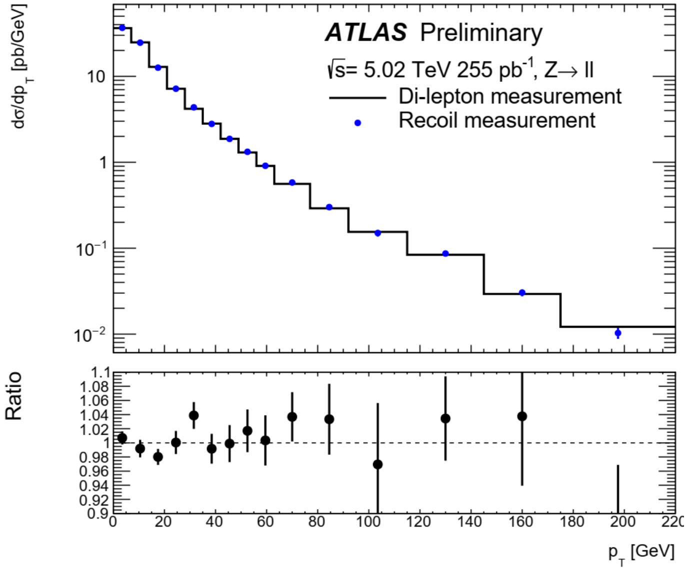
Low pile-up gives smaller but sufficient data sets and clean collision environment

Ideal to gain precision knowledge for pT(W) modelling at lower end

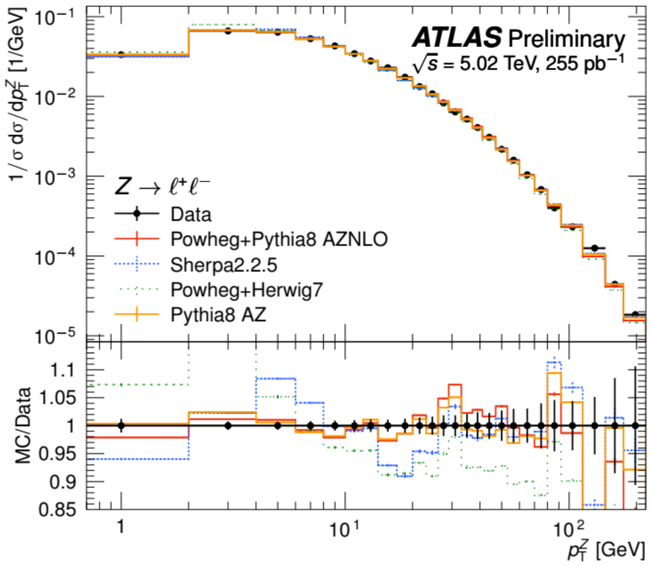
$$\vec{p}_{\mathrm{T}}^{\,W} = \vec{p}_{\mathrm{T}}^{\,\ell} + \vec{p}_{\mathrm{T}}^{\,\nu} = -\vec{u}_{\mathrm{T}}$$

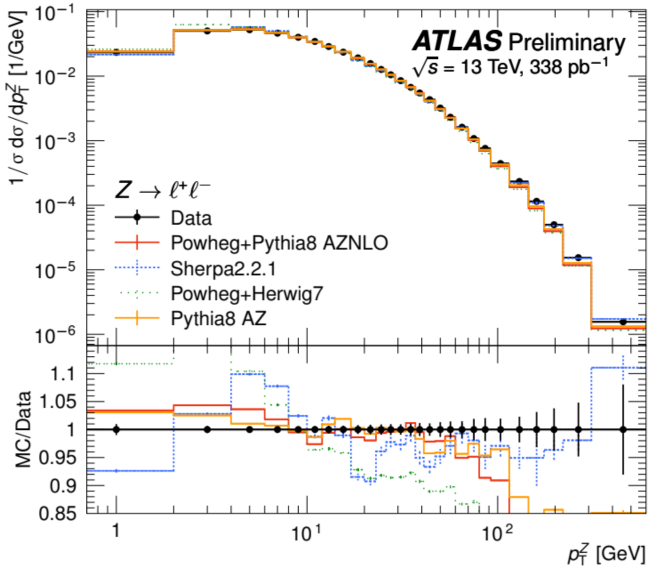
$$\vec{p}_{\mathrm{T}}^{\,Z} = \vec{p}_{\mathrm{T}}^{\,\ell+} + \vec{p}_{\mathrm{T}}^{\,\ell-} = -\vec{u}_{\mathrm{T}}$$

u_{T} after correction (derived from Z events) is equivalent to pT



Worked on Z events, to validate that pT-u_{T} equivalence





Two collision-energy points measurement for pT(Z)

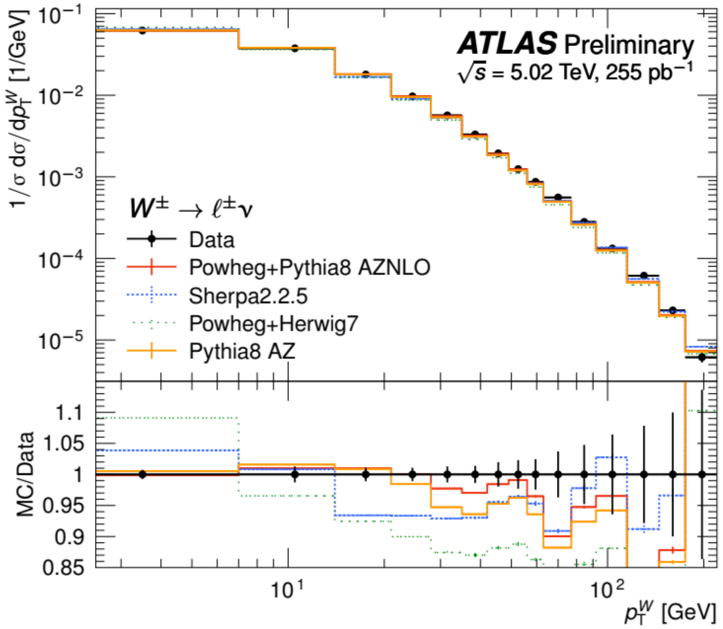
Pythia with tunes excels at lower energy

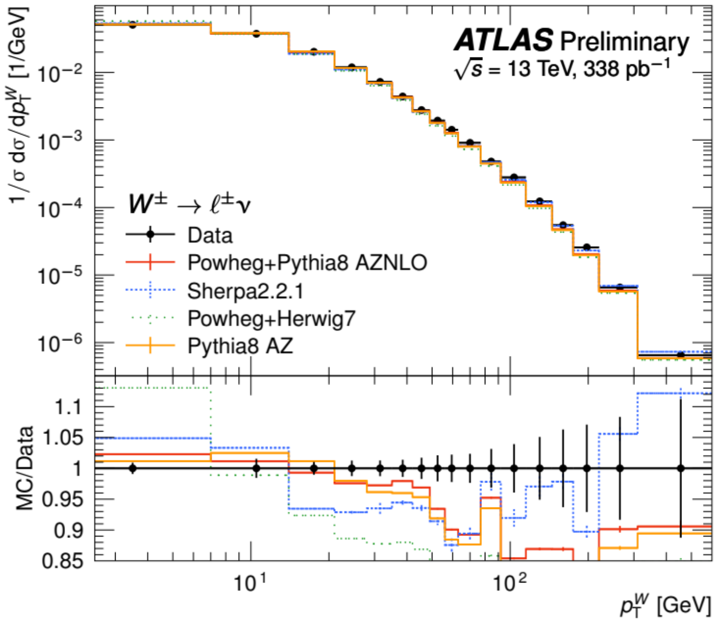
ATLAS-CONF-2023-028

Low pile-up pT(V) measurements

Presentation of pT(W) modelling vs measurement

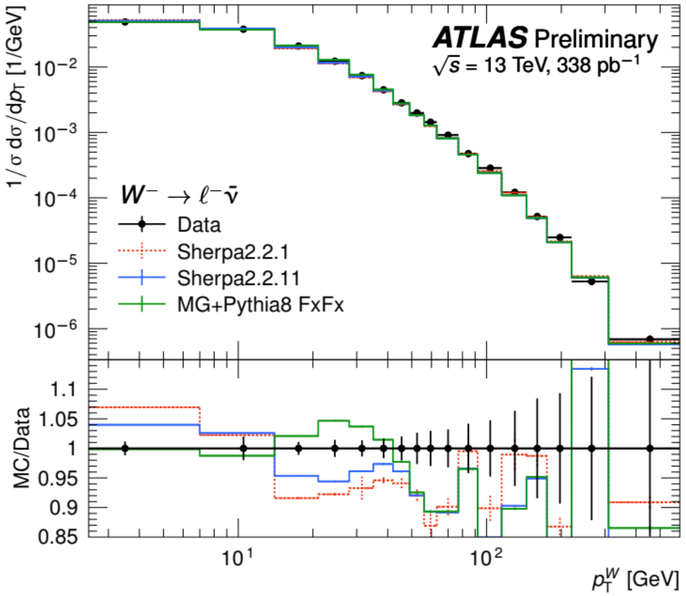
Excellence of <1% precision in low pT(W)!





Evidence that 13 TeV, intermediate pT need further care

Comparisons also to NLO + multi-leg predictions



FUTURE:

New generation of precision inputs

➔ Better modelling of pT(V) lower range

➔ Reduction of mW uncertainties due to pT (currently ~10 MeV)

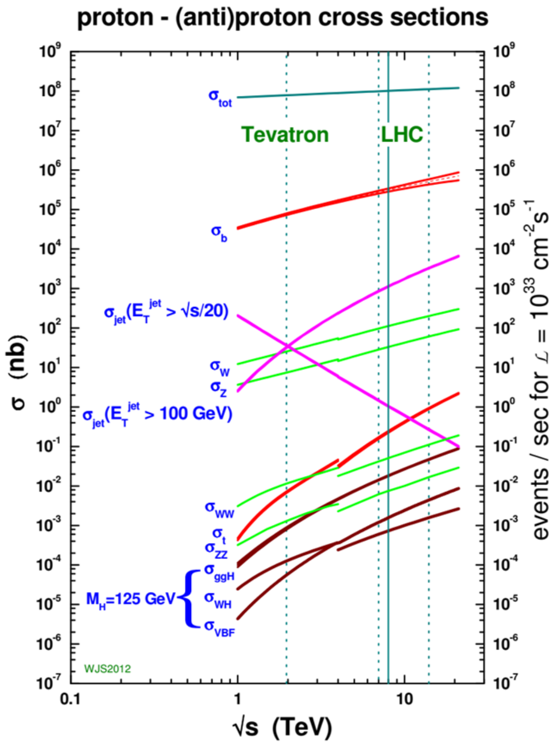
α_S measurements

JHEP 02 (2022) 142 arXiv:2301.09351 ATLAS-CONF-2023-015

α_S affects everything

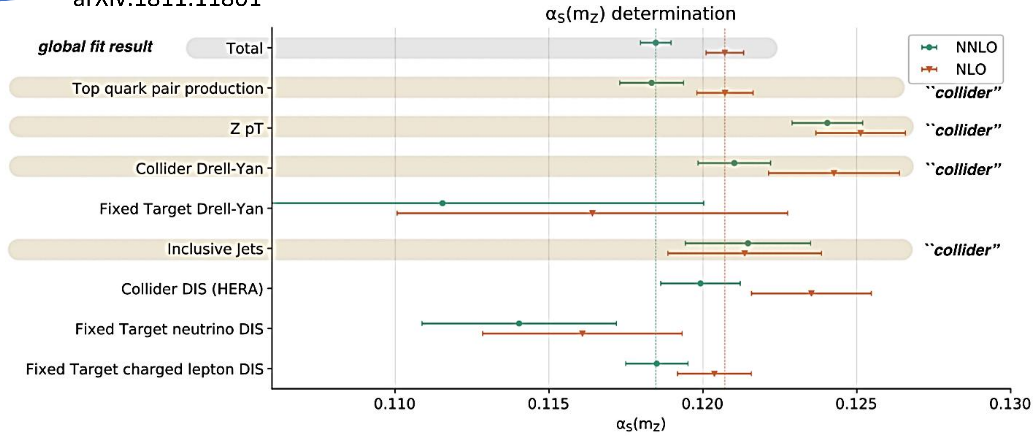
LHC measurements unique to test the α_S running to electroweak scale and TeV

Many different methodologies, relevant examples below

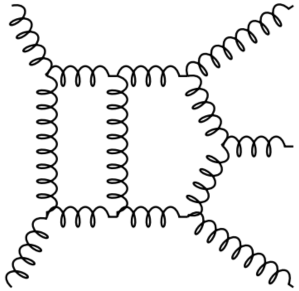


Utilize the abundant production of jets and V+jets

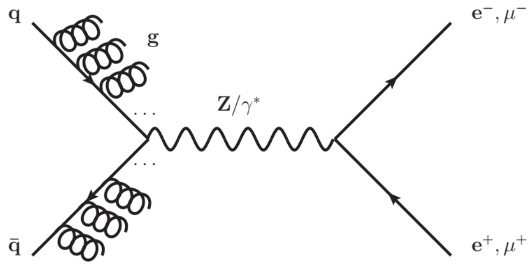
arXiv:1811.11801



PDF fit with collider results (e.g., inclusive jet) can give constraint to α_S (sensitivity from parton σ and DGLAP scaling)



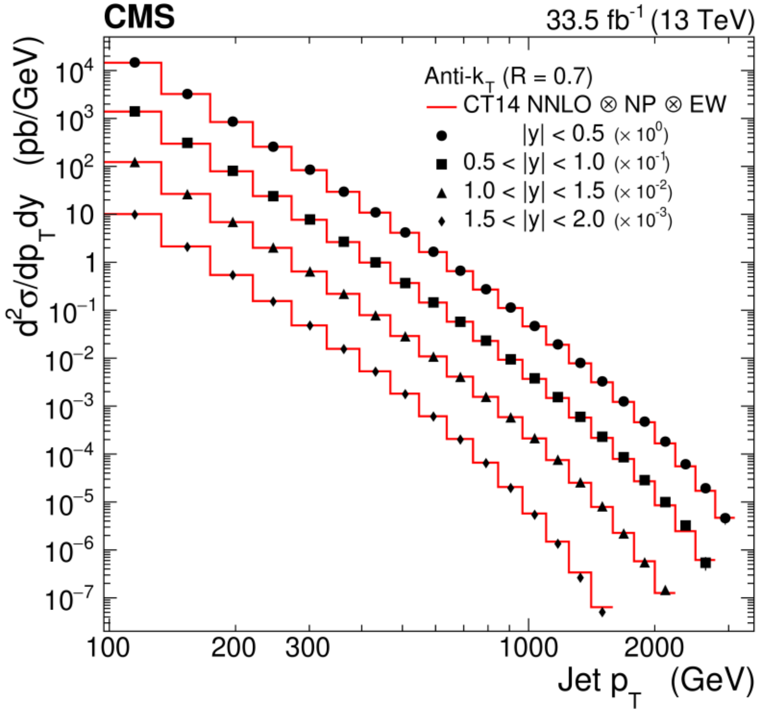
Transverse energy-energy correlation (TEEC)
dated back to e+e-, to explore multi-jet FSR correlation affected by α_S



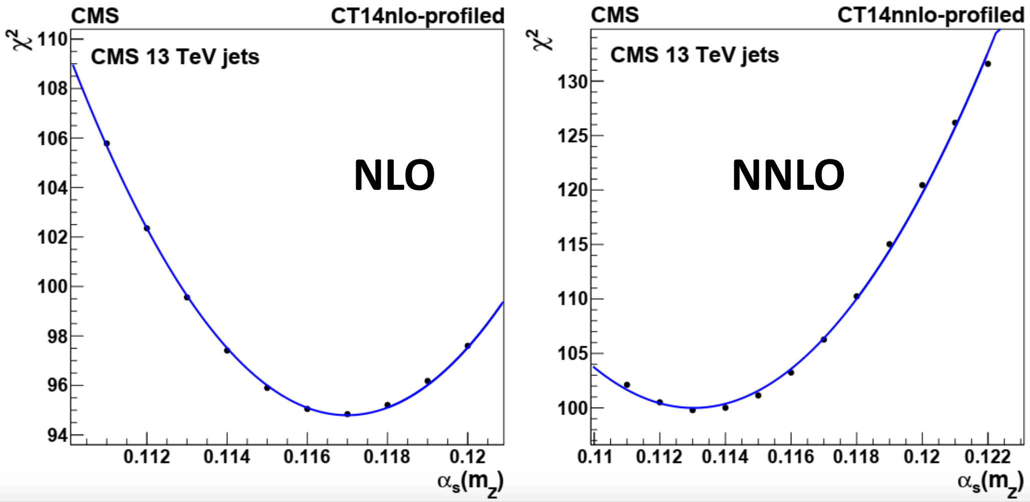
α_S modifies the strength of ISR, and therefore affects p_T(Z)
⇔ p_T(Z) is one of most precisely measured distribution at LHC

JHEP 02 (2022) 142

Inclusive jets → α_s

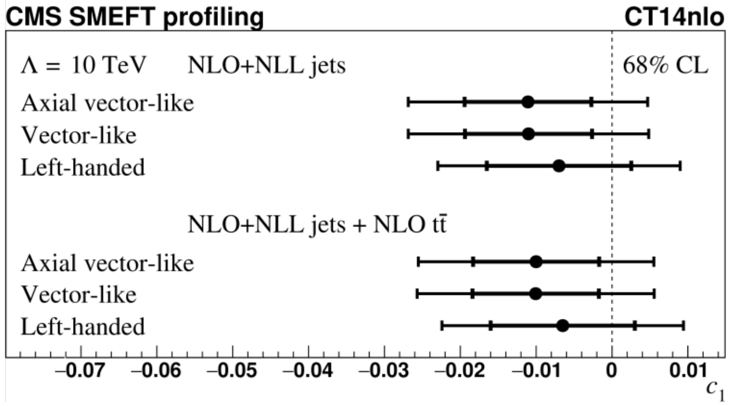


Beautiful jet measurements input to
a PDF fit, including CT14nlo/nnlo
and CMS ttbar data

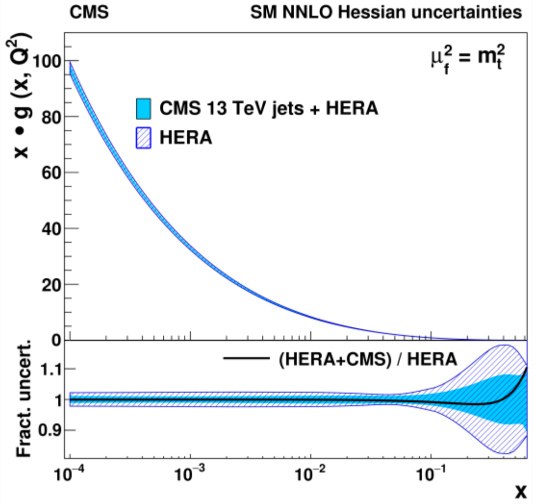


$$\alpha_S(m_Z) = 0.1170 \pm 0.0014\,(\text{fit}) \pm 0.0007\,(\text{model}) \pm 0.0008\,(\text{scale}) \pm 0.0001\,(\text{param.})$$

1.5% precision achieved, hitting most precise regime



Constraints to EFT parameters



Constraints to gluon PDF

arXiv:2301.09351

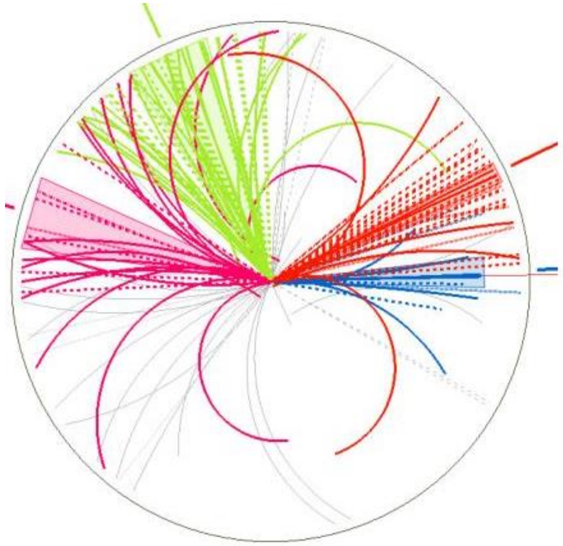
TEEC in multi-jets → α_S

TEEC

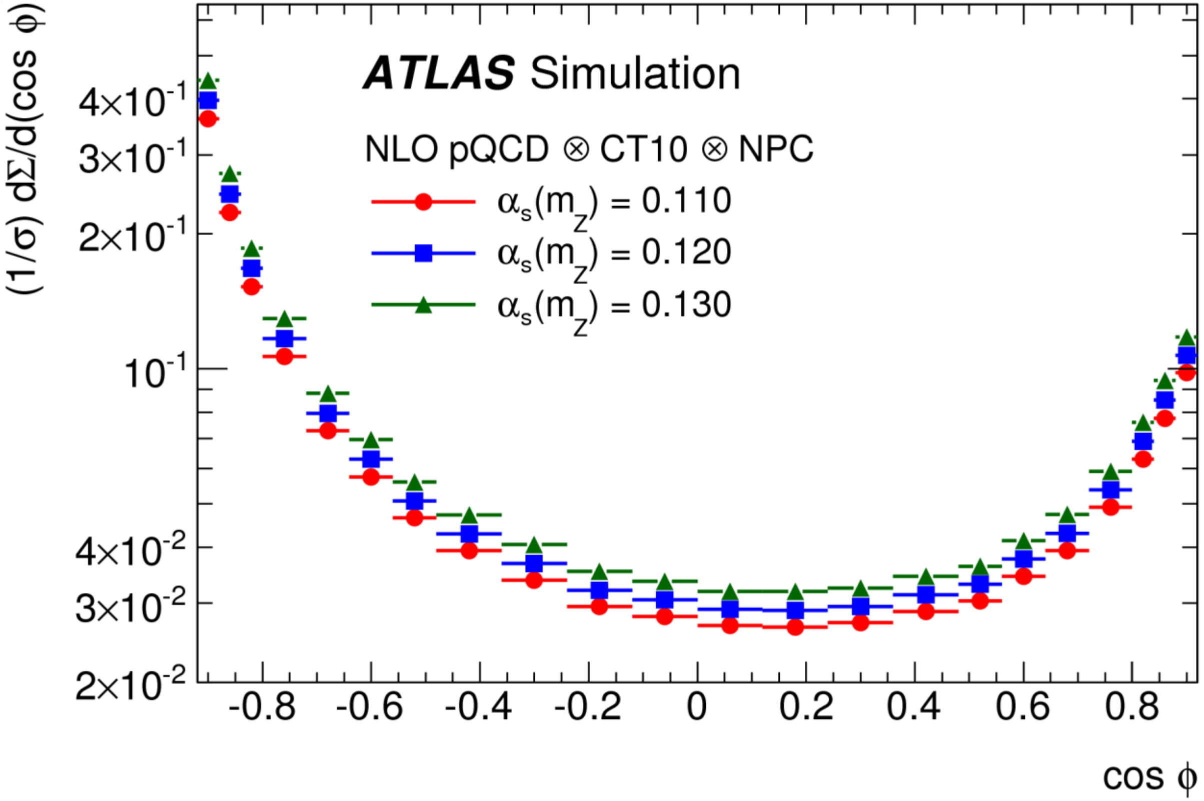
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d\cos\phi}x_{Ti}x_{Tj}dx_{Ti}dx_{Tj} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^{A}E_{Tj}^{A}}{\left(\sum_k E_{Tk}^{A}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$$

ATEEC

$$\frac{1}{\sigma}\frac{d\Sigma^{\text{asym}}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$



In short: **energy-weighted jet pair azimuth distribution**

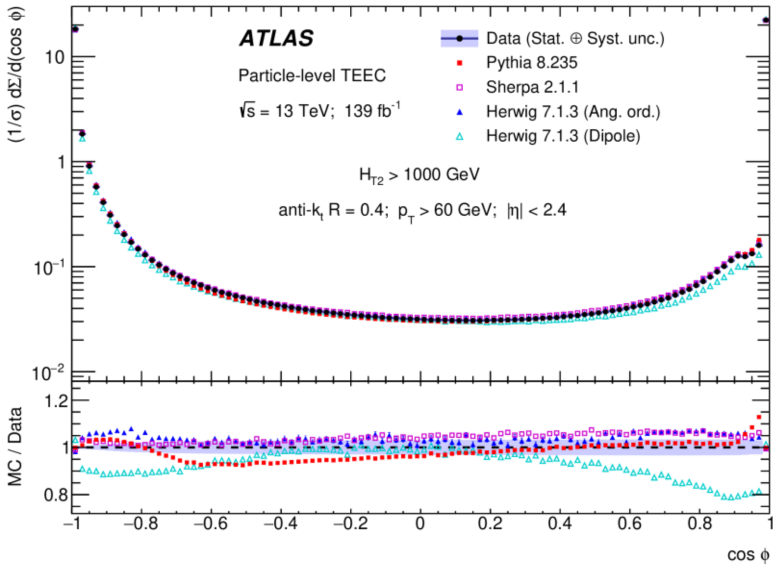


Older simulation results from
PLB 750 (2015) 427

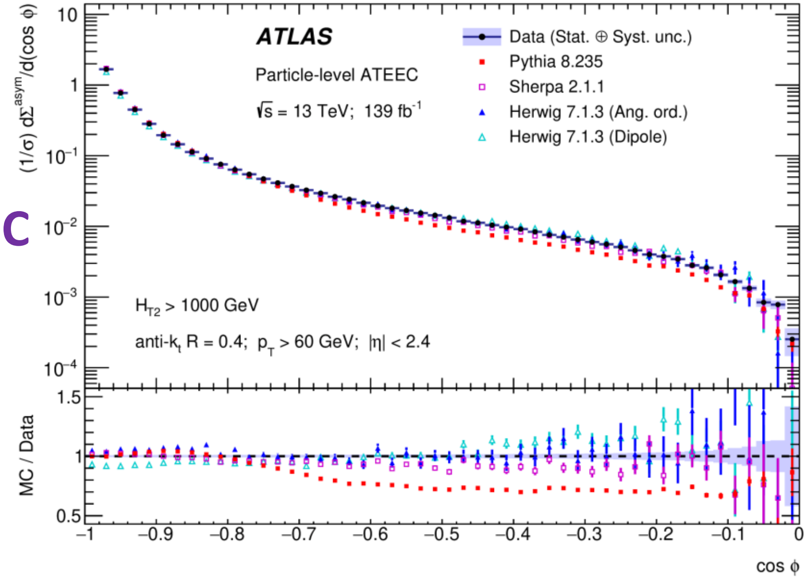
The more precise the measurement is, the better sensitivity to α_S

TEEC in multi-jets → α_S

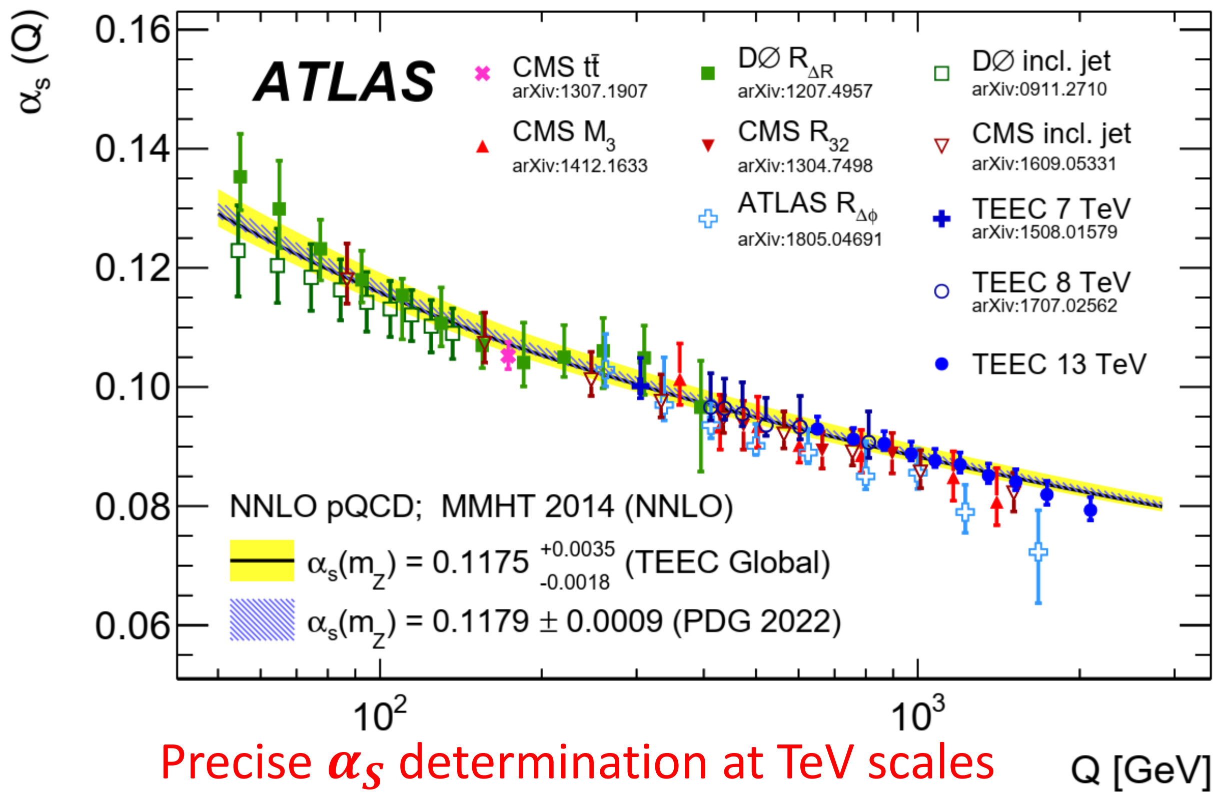
TEEC



ATEEC



Chi2 template fits with varying α_S at different energy scales



Precise α_S determination at TeV scales

ATTEC fit (with MMHT PDF) gives global value

$$\alpha_s(m_Z) = 0.1185 \pm 0.0009\,(\text{exp.})^{+0.0025}_{-0.0012}\,(\text{theo.})$$

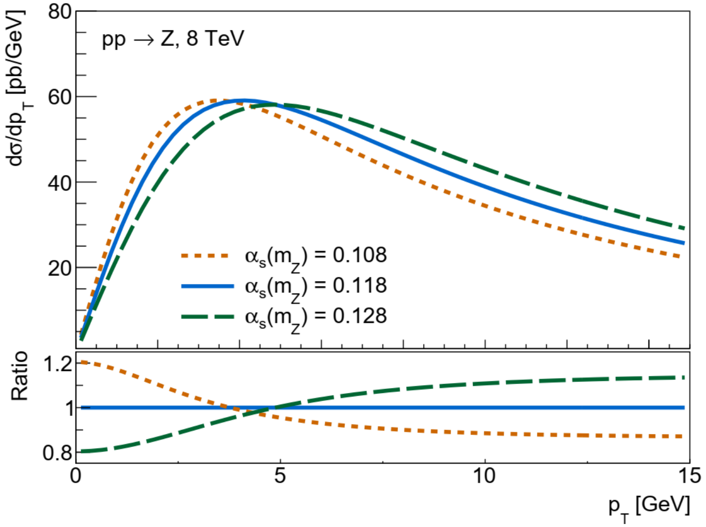
2% precision

TEEC, ATTEEC similar precision, correlation ~ 86%

ATLAS-CONF-2023-015

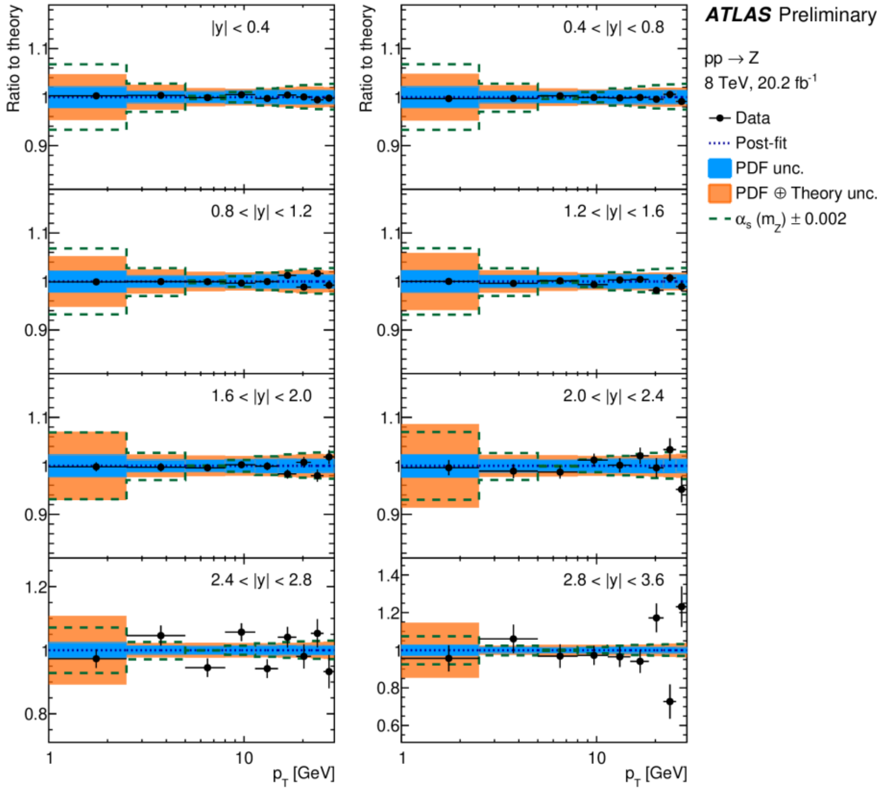
Z pT → α_S

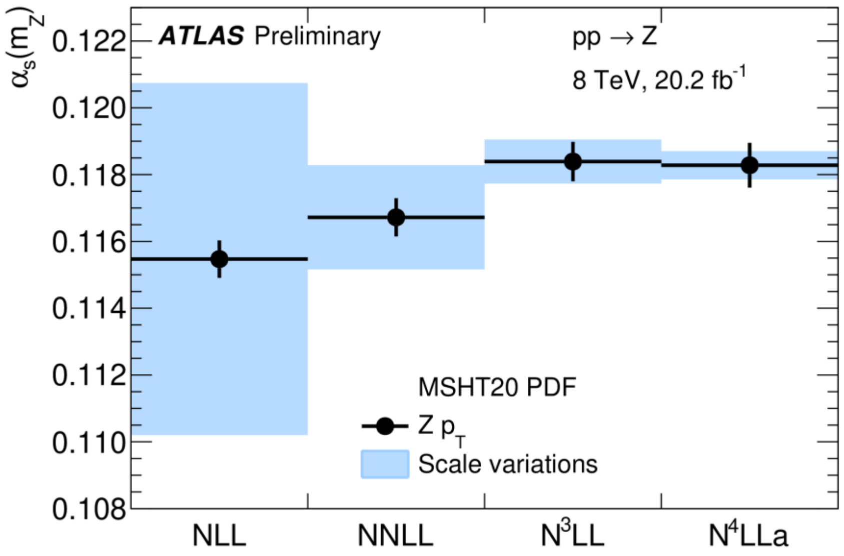
Demonstration of ZpT and α_S relationship



State of art prediction:
DYTurbo: **N^{4}LL** resummation
+ a**N^{3}LO** perturbative
with **N^{3}LO** MSHT20 PDF

Z pT measurement being very precise matching to precise modelling prediction can yield great precision in α_S

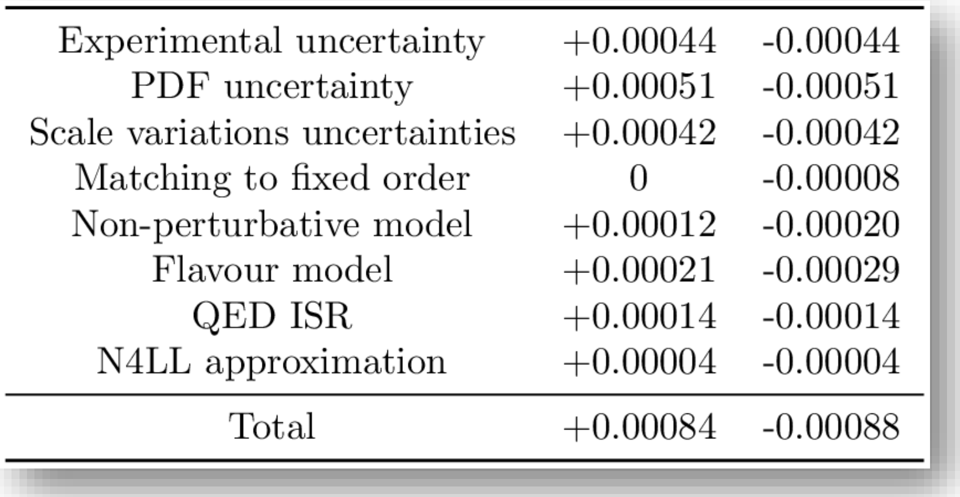




Evolution of measured α_S precision v.s. increased accuracies of prediction (improving accuracies and good convergence of results)

ATLAS-CONF-2023-015

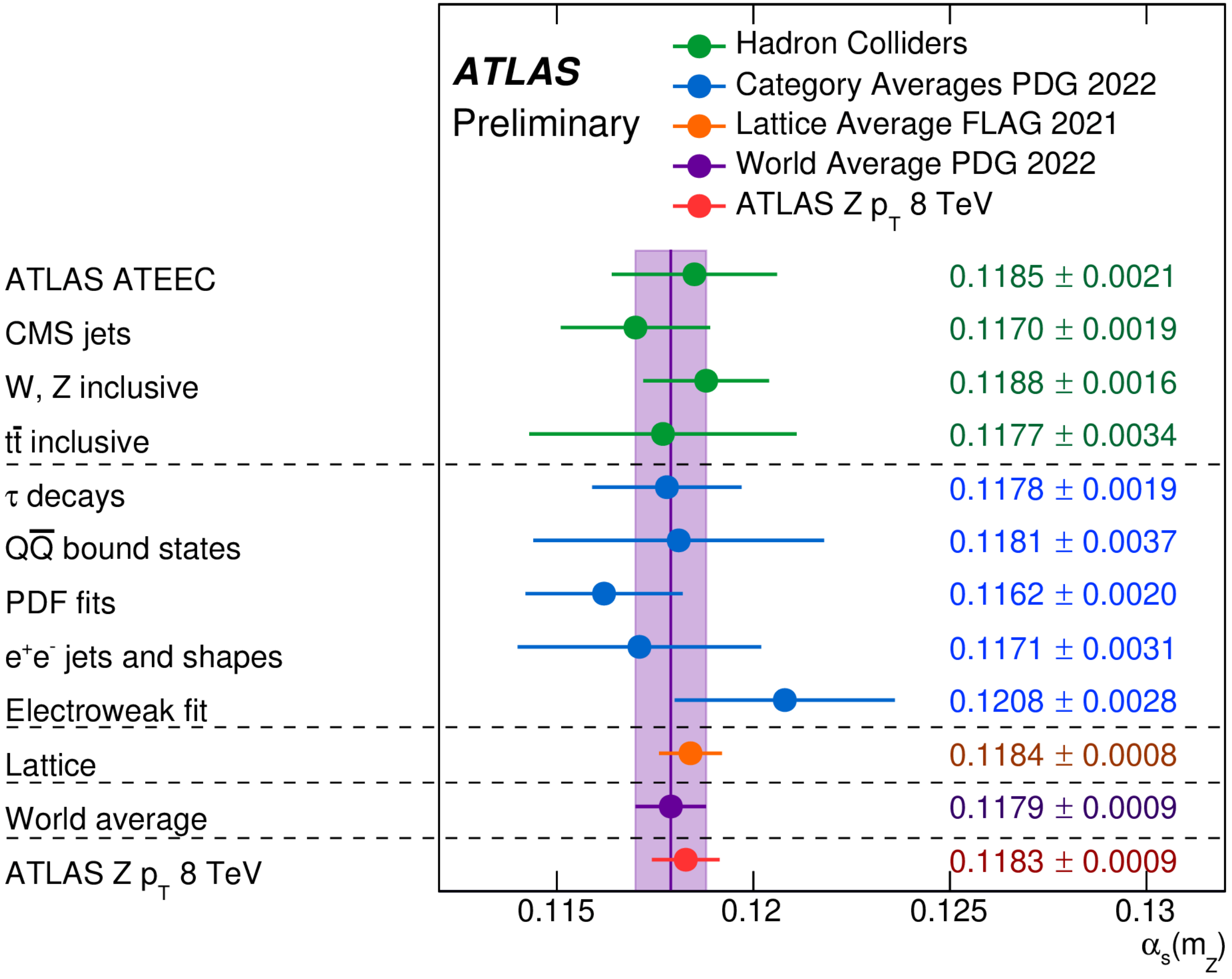
Z pT → α_S



Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

Uncertainty break-down for α_S
➔ Dominate by modelling uncertainty

A single best precision measurement so far
0.8% precision in α_S



Summary

Discussed selected topics and recent progress relating to **mW** and $\boldsymbol{\alpha_S}$

⇒ Full exploitation of abundant process at the LHC: W, Z, jets leads to great precision

⇒ Careful detector calibration is indispensable

⇒ State-of-art predictions are indispensable

⇒ LHC already at the leading precision of measuring relevant fundamental parameters

⇒ Triumph of both experimental and theoretical communities

⇒ More sensitive to find potential anomalies relating to long-sought new physics

NEXT:

⇒ **Rely on even larger, cleaner data sets to improve both experimental and theoretical precision**

NO easy tasks but rewarding!

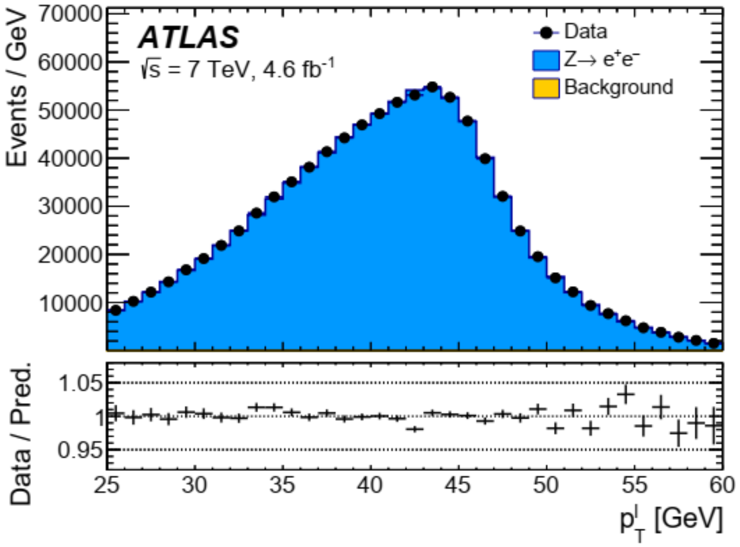
Thank you for your attention!

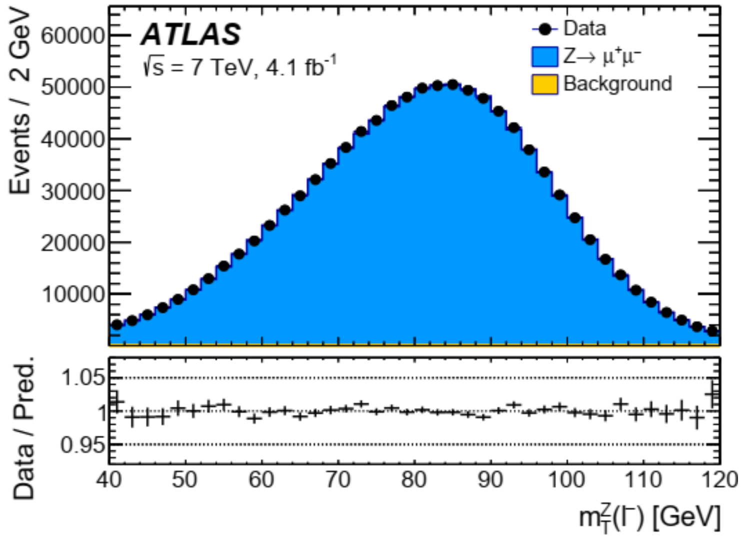
Backup

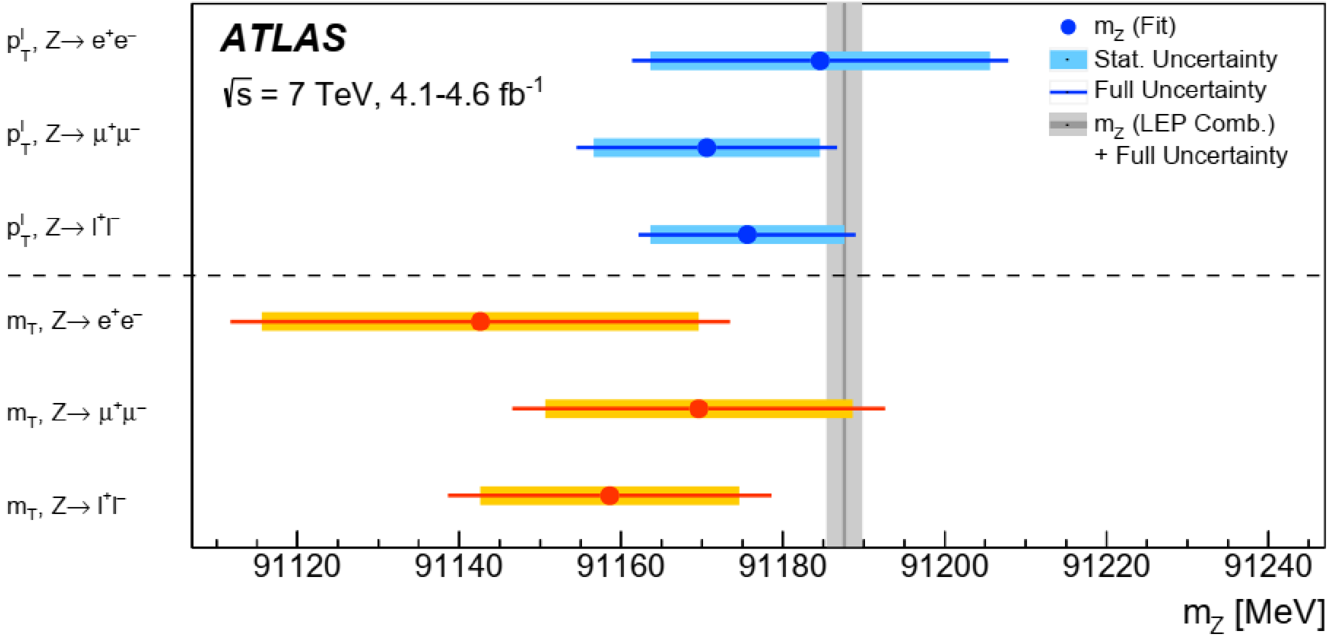
Consistency Test with Z

Treat one lepton from Z as missing to mimic W events

All previous corrections applied ➔







Measured Z mass agrees with reference value ➔ validation of methodology

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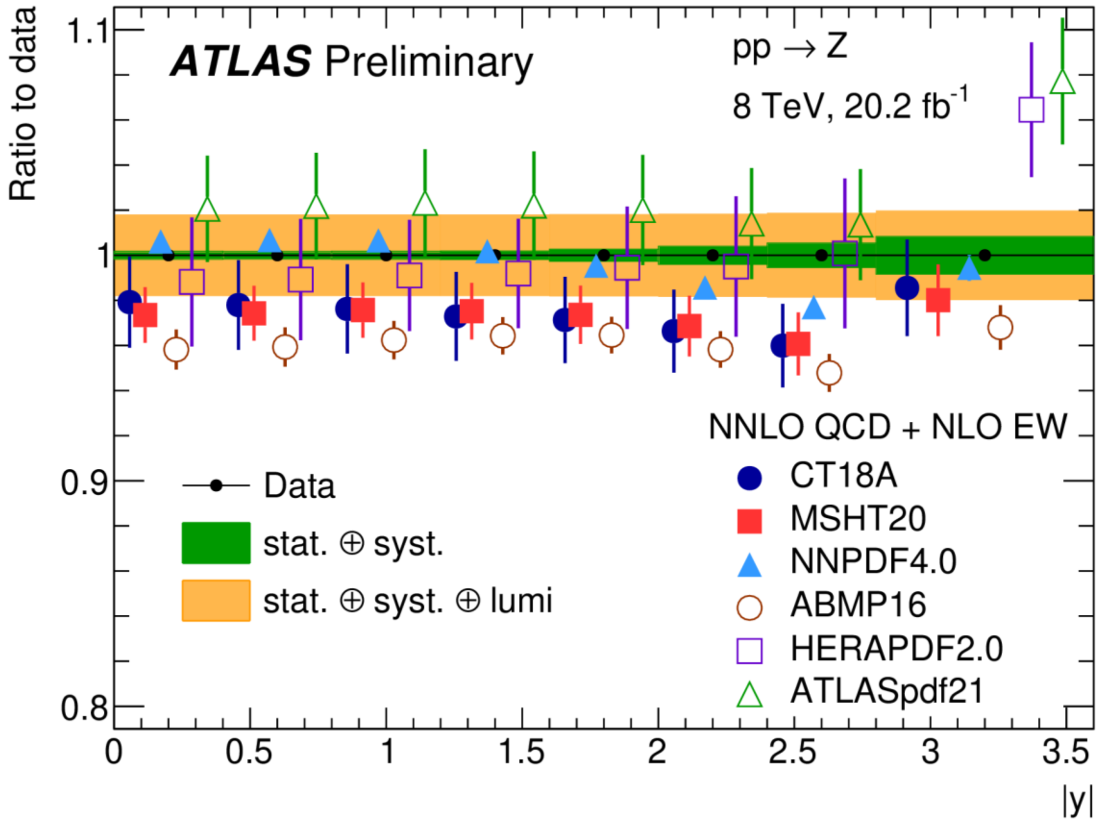
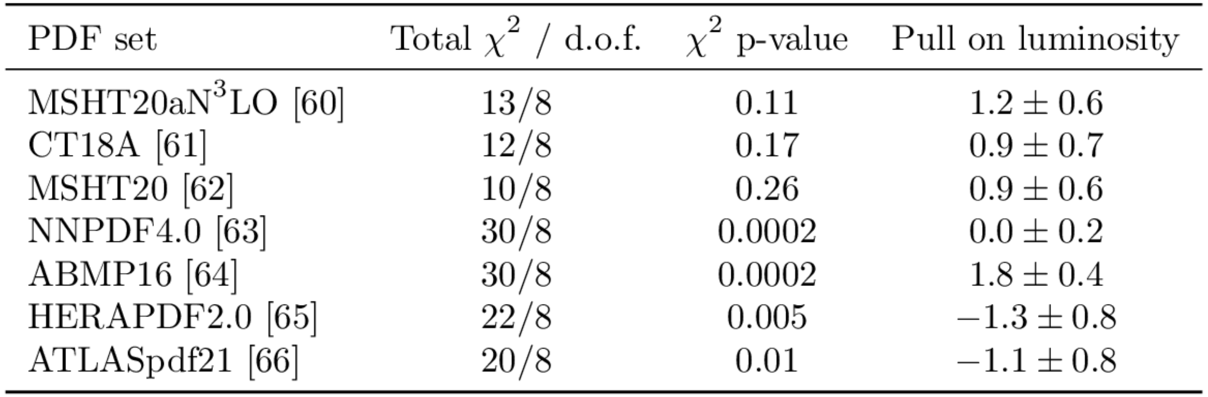
More on ZpT 8 TeV ATLAS





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

Comparison between high precision data to various PDF sets

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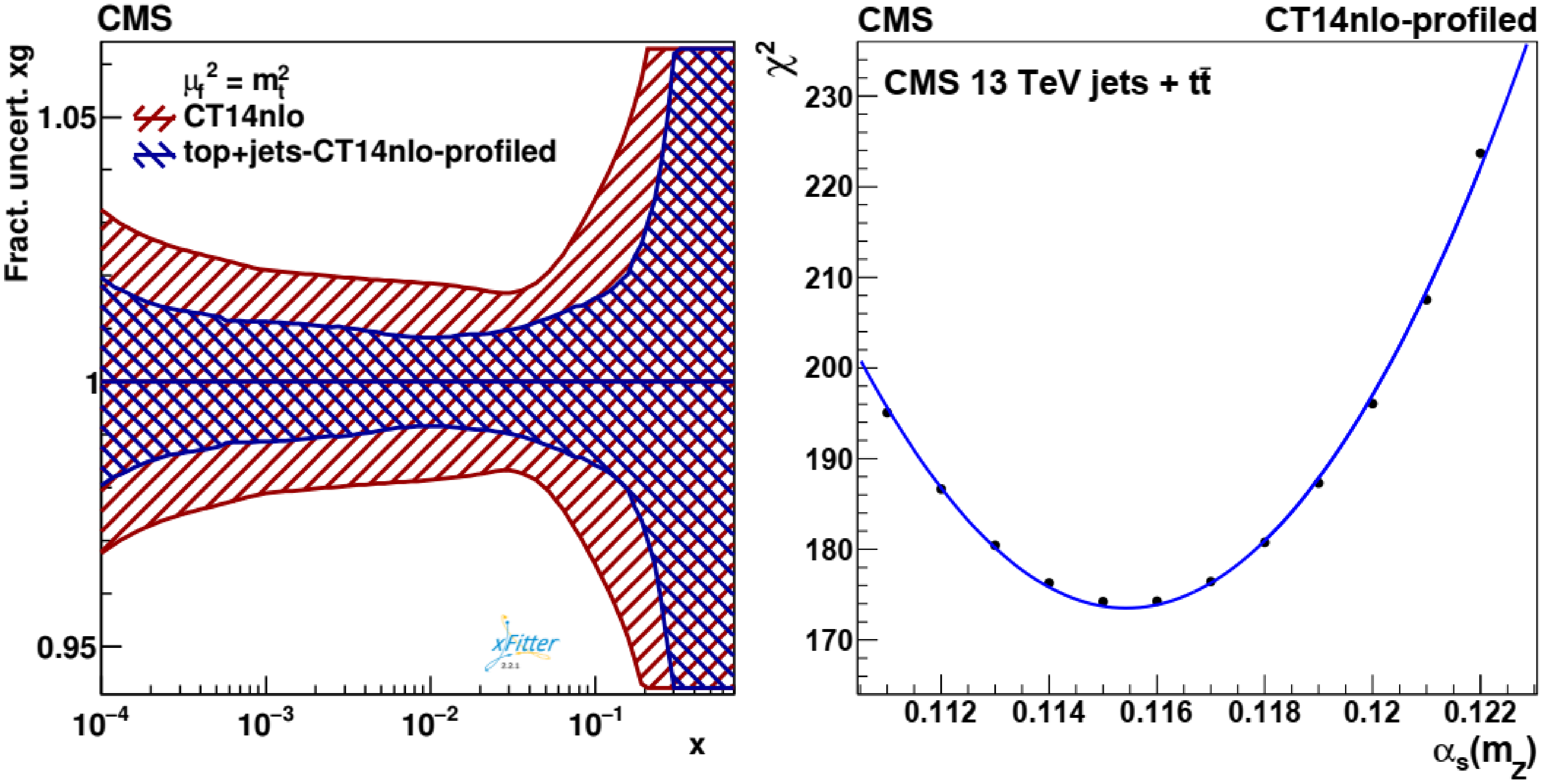
More on inclusive jets CMS



Constraints including both jet data and ttbar data

More on pileup dependence of U_T

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