中国科学院高能物理研究所
Institute of High Energy Physics
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ATLAS
EXPERIMENT

Towards a more precise m_W measurement in ATLAS

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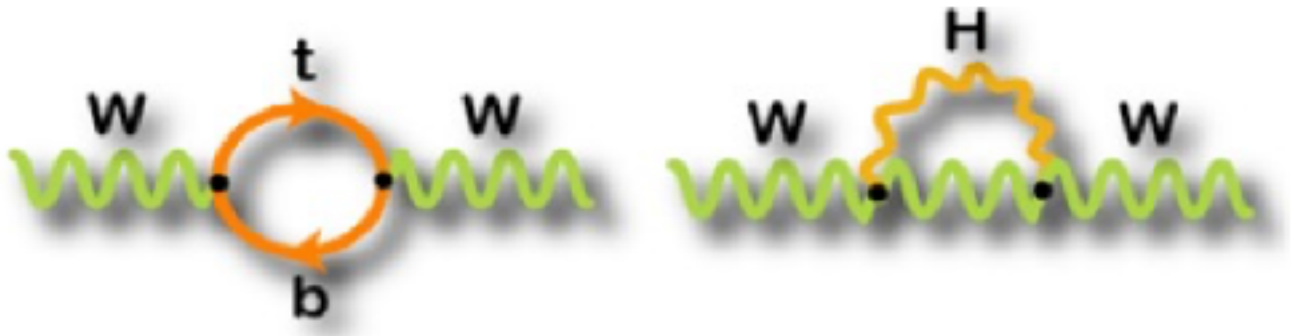
2024/11/15
CLHCP2024
第十届中国LHC物理会议

Outline

- Motivation
- W signature and measurement strategy
- Precision W, Z transverse momentum measurement
- Next ATLAS m_W measurement
  - Uncertainty components
  - Prospects

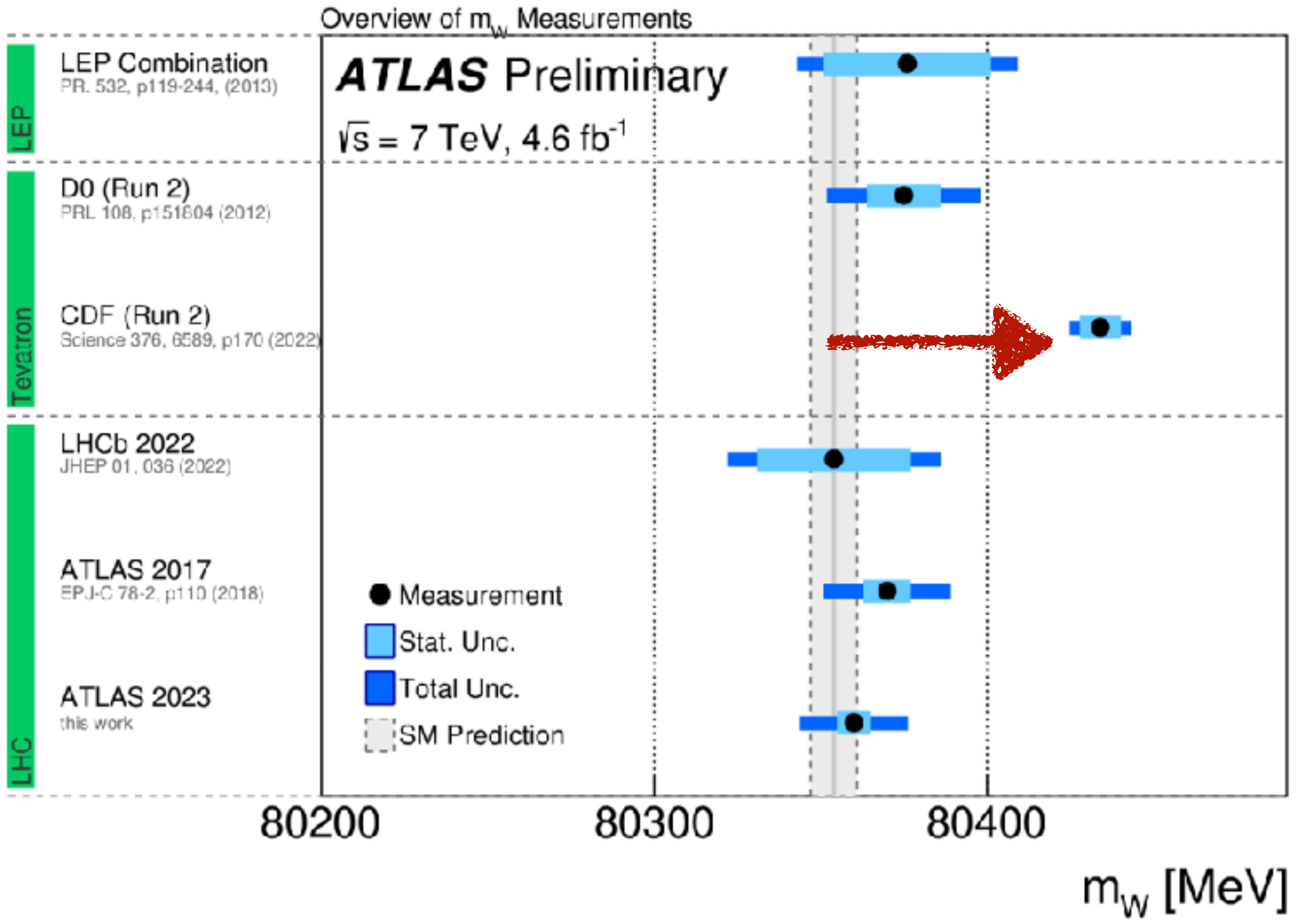
W mass measurement: motivation

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$



Dominated by top quark and Higgs, also affected by new physics contribution

- Fundamental parameter in Standard model
- Precision limit the constraints on physics BSM
- CDF measurement 7 sigma deviation from SM
- Latest ATLAS measurement: re-analysis of 7 TeV data



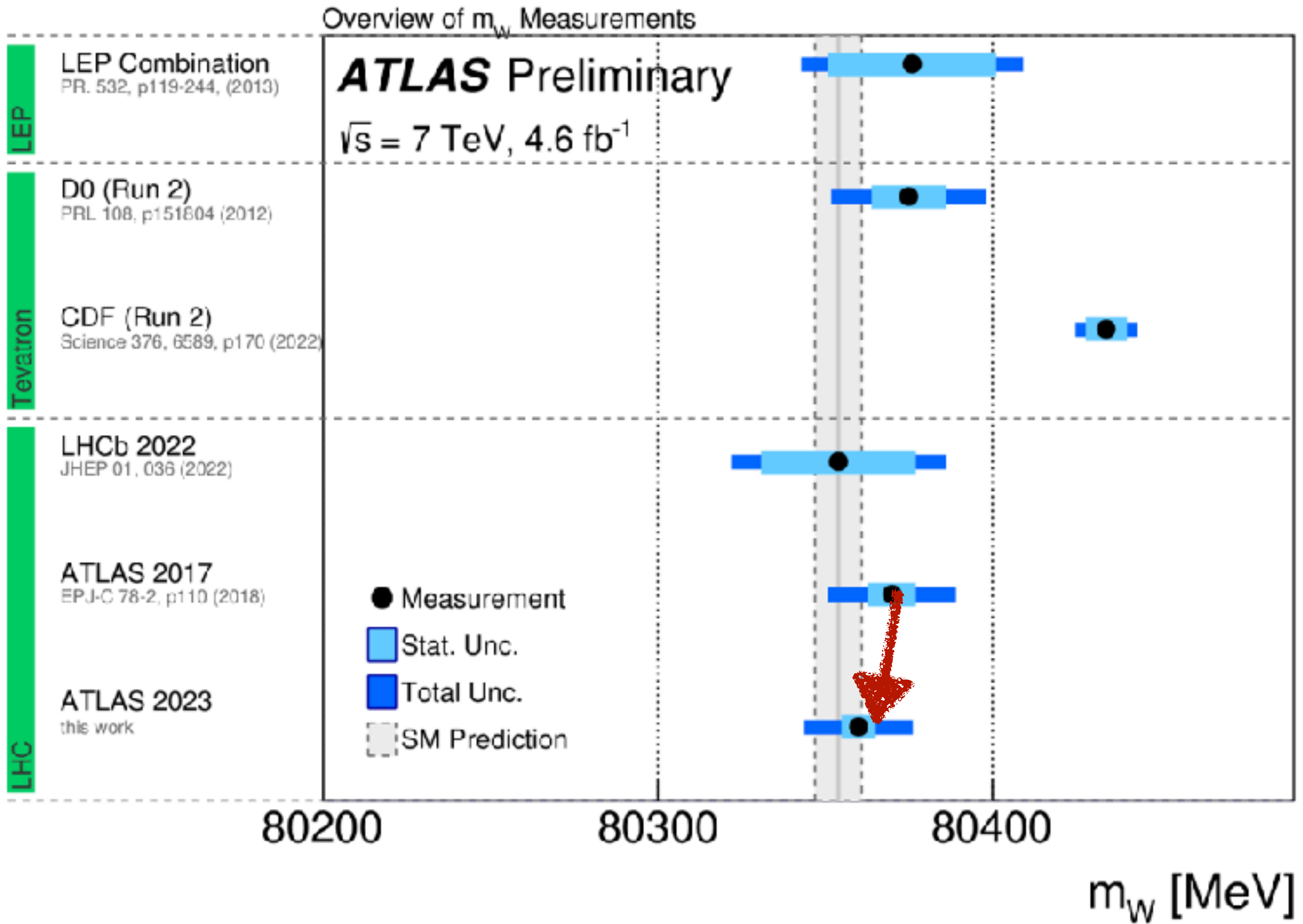
Improvements in 7 TeV re-analysis

Revisit of 2016, 7 TeV measurement with profile likelihood fit and modern physics model

- Profile likelihood fit: constrains on systematic uncertainties
- New PDF uncertainty
  - Extrapolated from CT10 to new PDF set CT18
  - Uncertainty cover central values from CT10, CT14, MMHT2014 and MSHT20
- Multijet background uncertainty
  - New systematic shape variation
  - New shape extrapolation from CR to SR
  - Reduction of 2 MeV uncertainty
- EW uncertainty evaluated at detector level
  - Increase 1-2 MeV uncertainty
- Add W width as NP parameter

Previous: 80370 ± 19 MeV

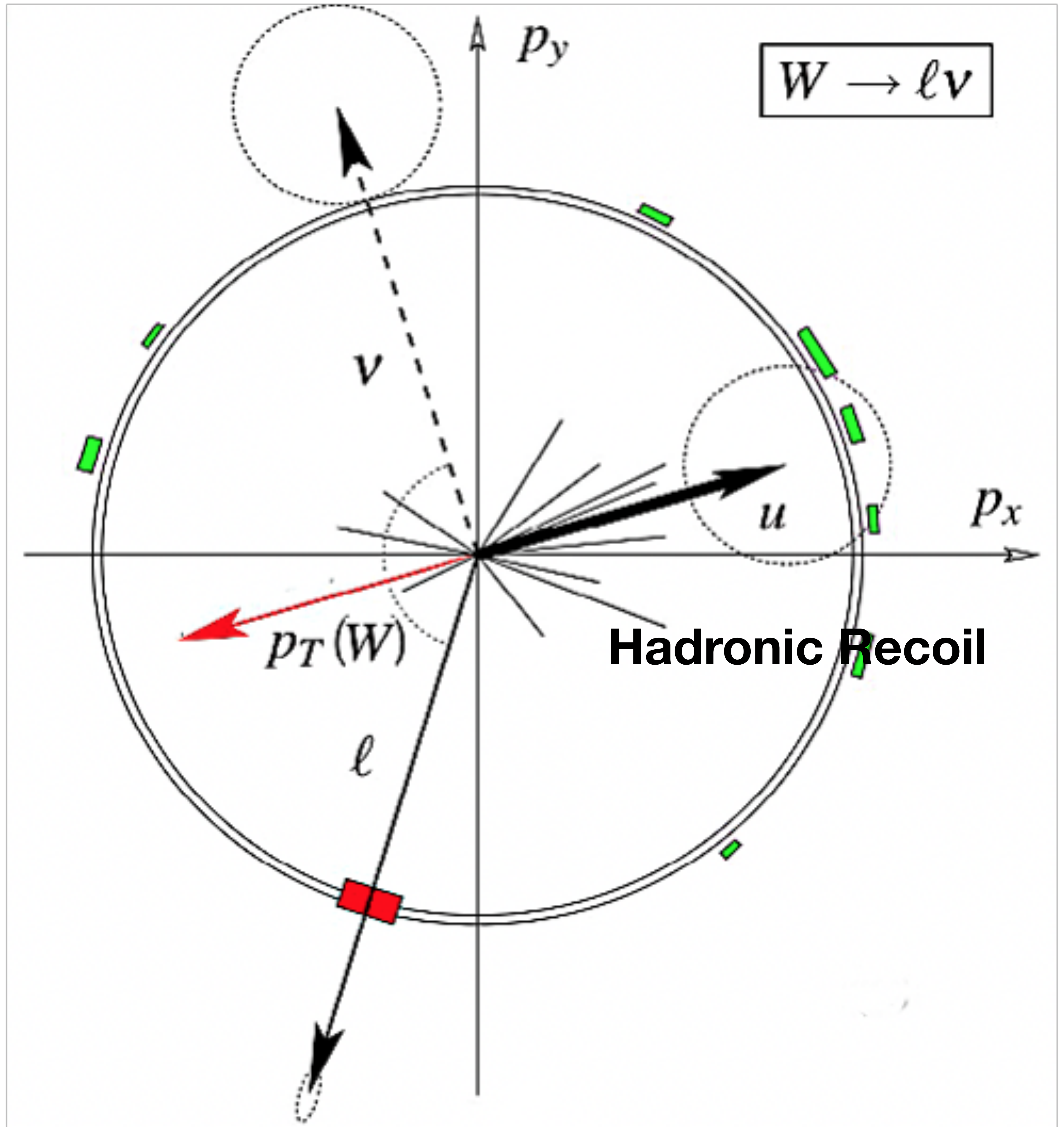
Re-analysis: 80360.4 ± 16 MeV



Closer to Standard Model prediction

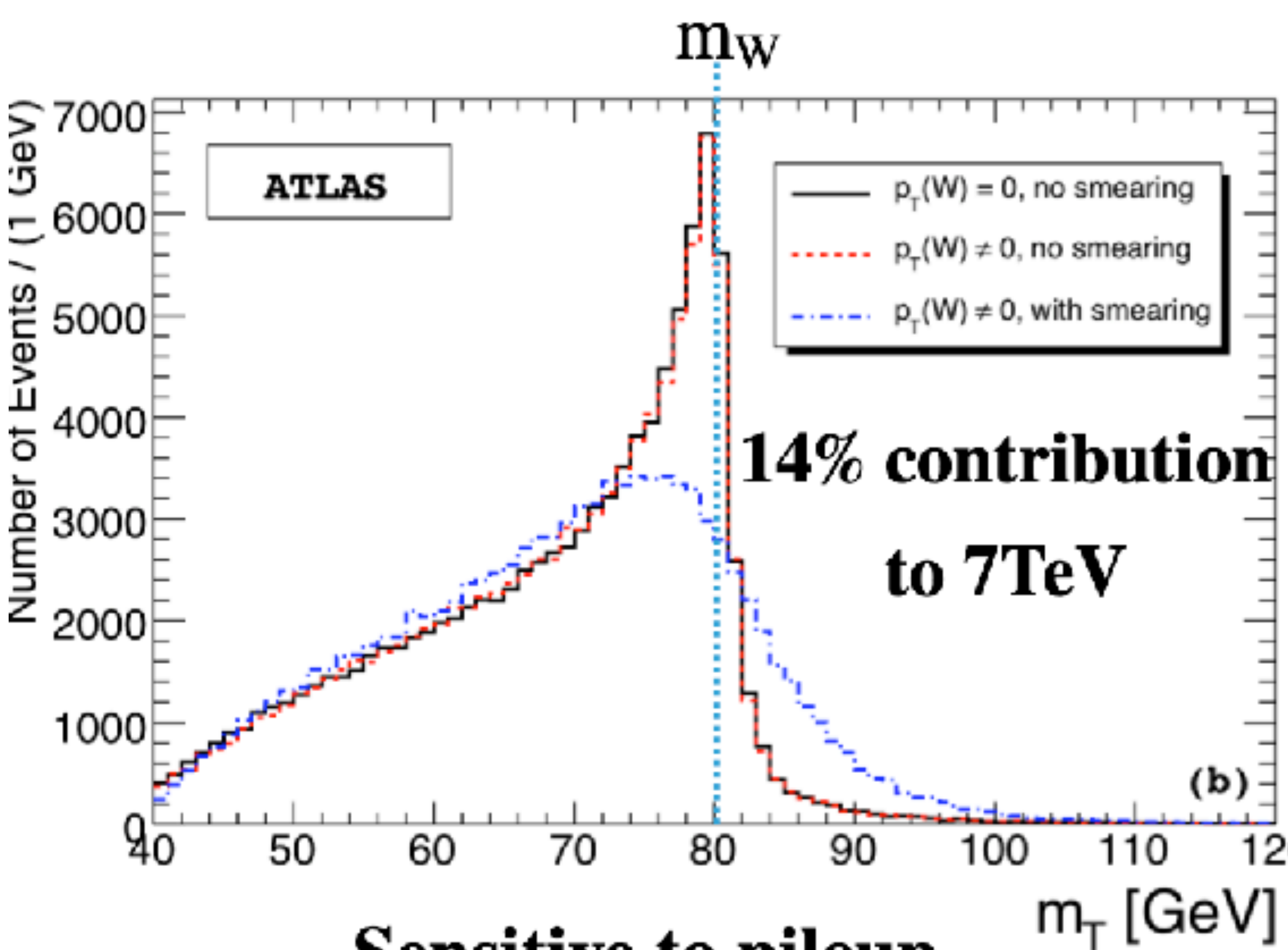
W signature and measurement strategy

W mass extracted from m_T and p_T^l spectrum - Jacobian peak



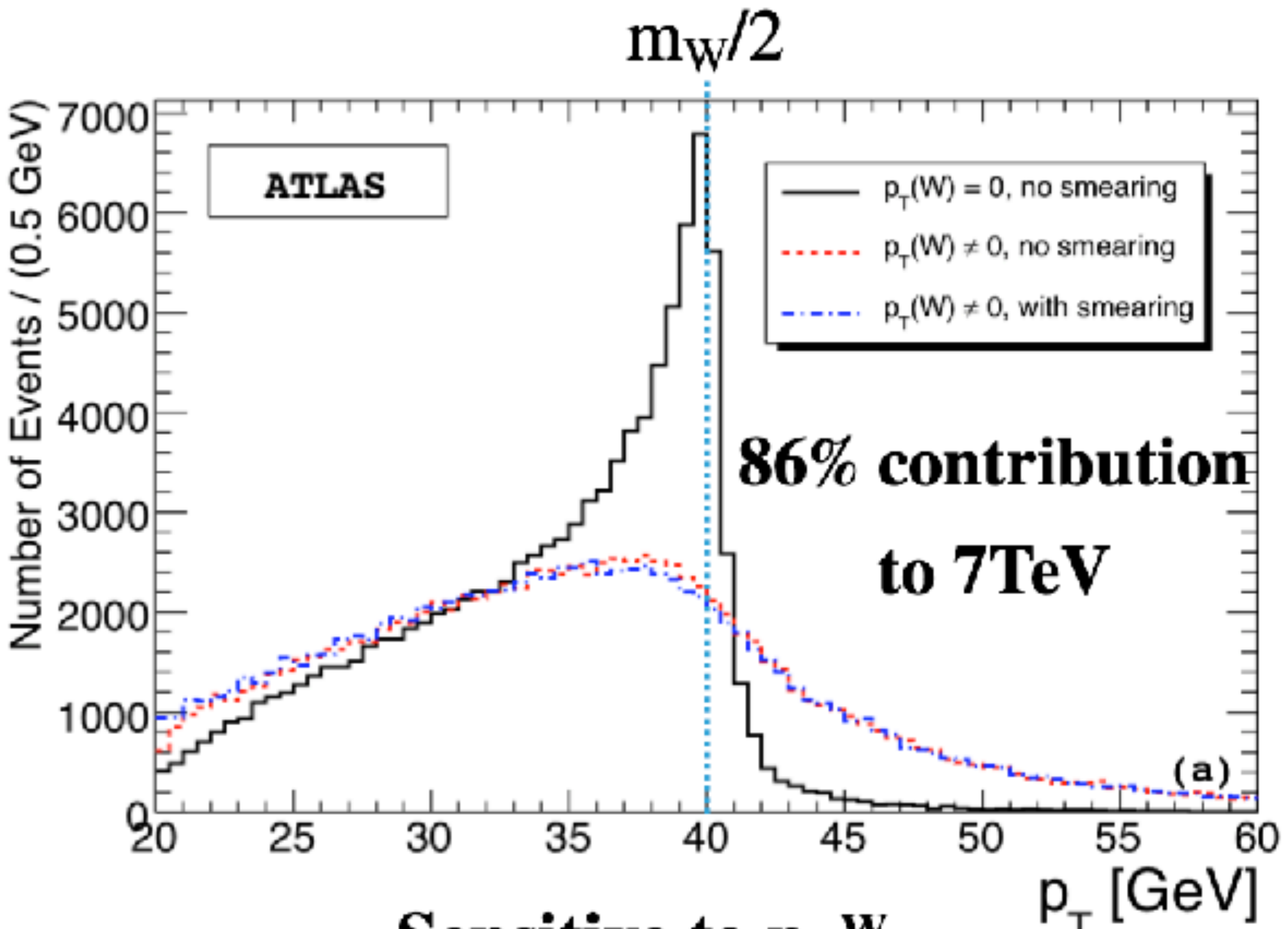
$$m_T = \sqrt{2p_T^l p_T^{miss}(1 - cos\Delta\phi)}$$

$$\vec{p}_T^{\,\nu} = -\vec{p}_T^{\,l} - \vec{u}_T \qquad \vec{u}_T = \sum_i \overrightarrow{E_{T,i}}$$



14% contribution to 7TeV

Sensitive to pileup

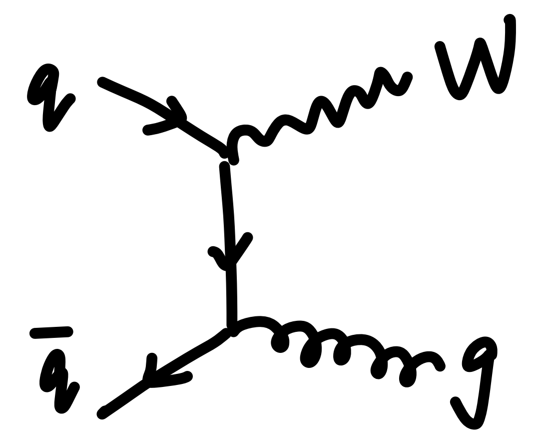


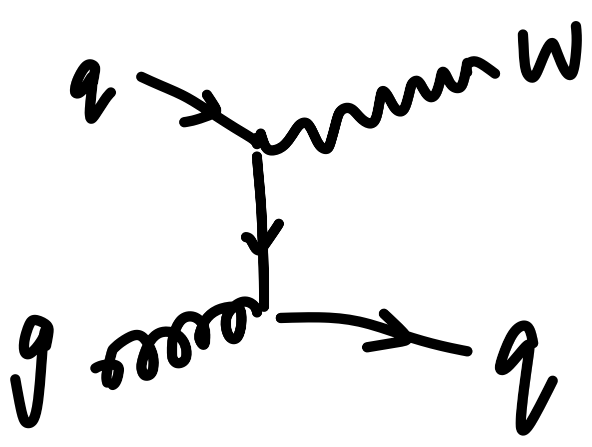
86% contribution to 7TeV

Sensitive to p_T^W

Tevatron vs LHC

- Tevatron: $p\bar{p}$ collision
  - valence quark(~80%), less theoretical uncertainty
- LHC: pp collision
  - W events larger by than one order of magnitude
  - gluon and sea quark are important, less precise than valence quark PDF, more sensitive to proton PDF
  - ATLAS, CMS and LHCb have a partially anti-correlation in PDF uncertainty, overall better precision.





	8.8 fb^{-1} **CDF**	4.1-4.6 fb^{-1} **7 TeV**
Stat	6.4	6.8
PDF	<u>3.9</u>	<u>9.2</u>
Bkg	3.3	4.5
EW	2.7	5.5
e	3.3	6.4
mu		6.6
recoil	2.5	2.9
QCD	2.2	8.3
Total	**9**	**19**

First ATLAS m_W measurement

High pile-up, $< \mu > = 9.1$

m_T have bad resolution given the high pile-up

$\boxed{p_T^W}$ predicted from p_T^Z, not precise. p_T^l have large theoretical uncertainties.

First step:

Precision W, Z transverse momentum measurement using low pile-up data

W and Z pT with low-pileup data

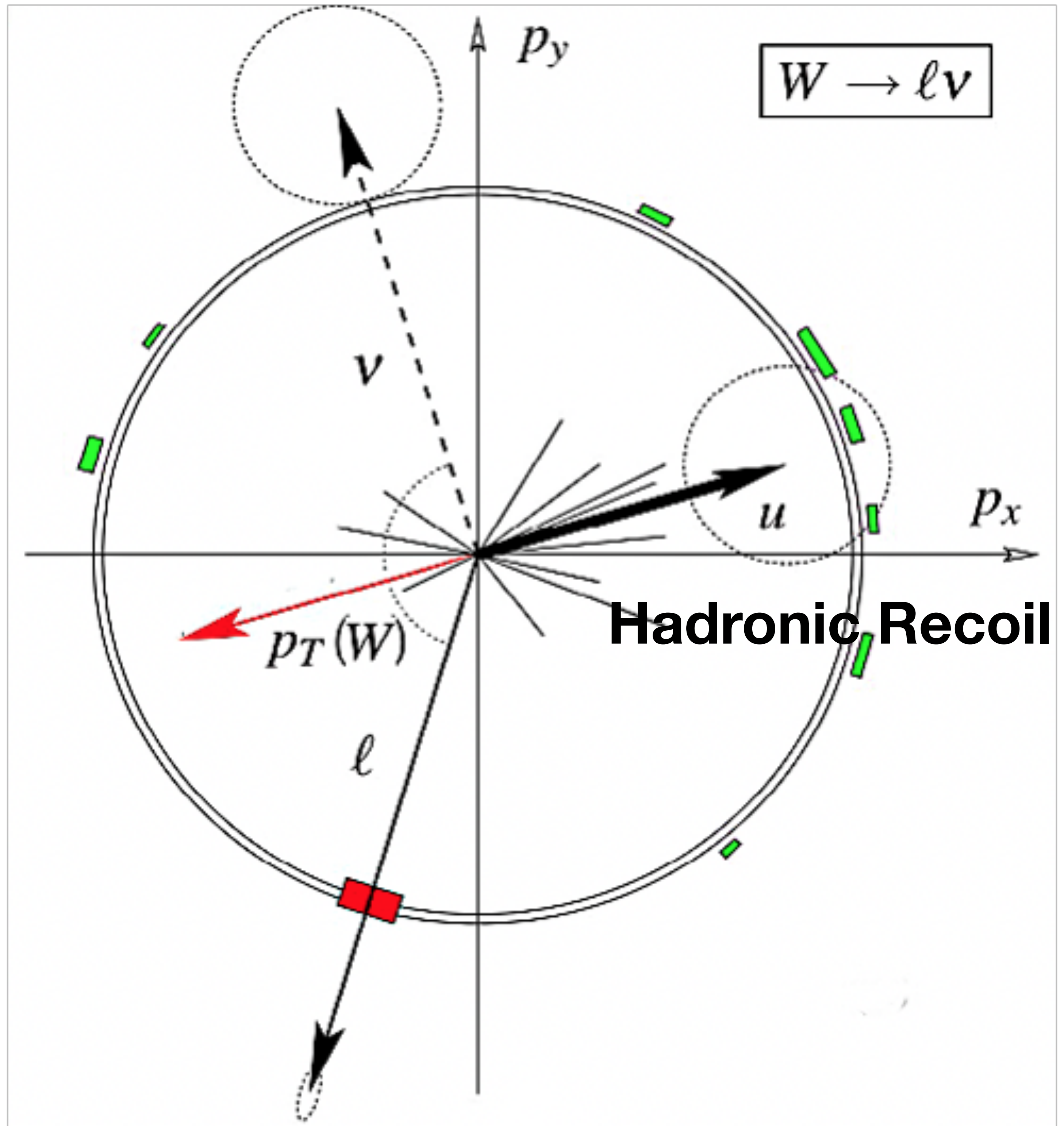
Submitted to EPJC
https://arxiv.org/abs/2404.06204

Low pile-up data:

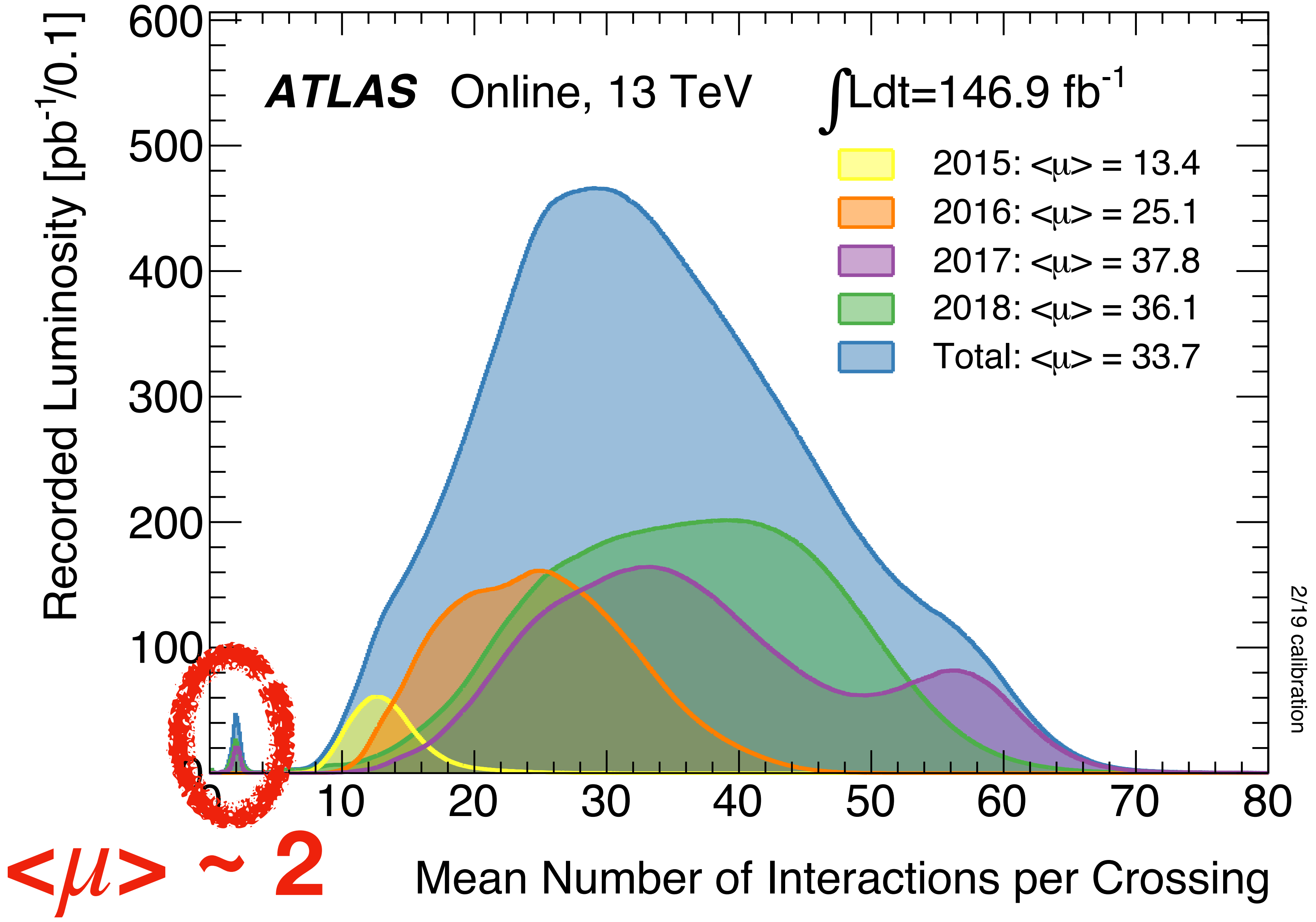
- $\sqrt{s}$= 5.02 TeV: Nov 2017, 255 ± 1% pb^{-1}
- $\sqrt{s}$= 13 TeV: Nov 2017 + Jun 2018, 335 ± 0.92% pb^{-1}
- Standard W and Z selection

  1.45 M (5 TeV) and 4.35 M (13 TeV) W events

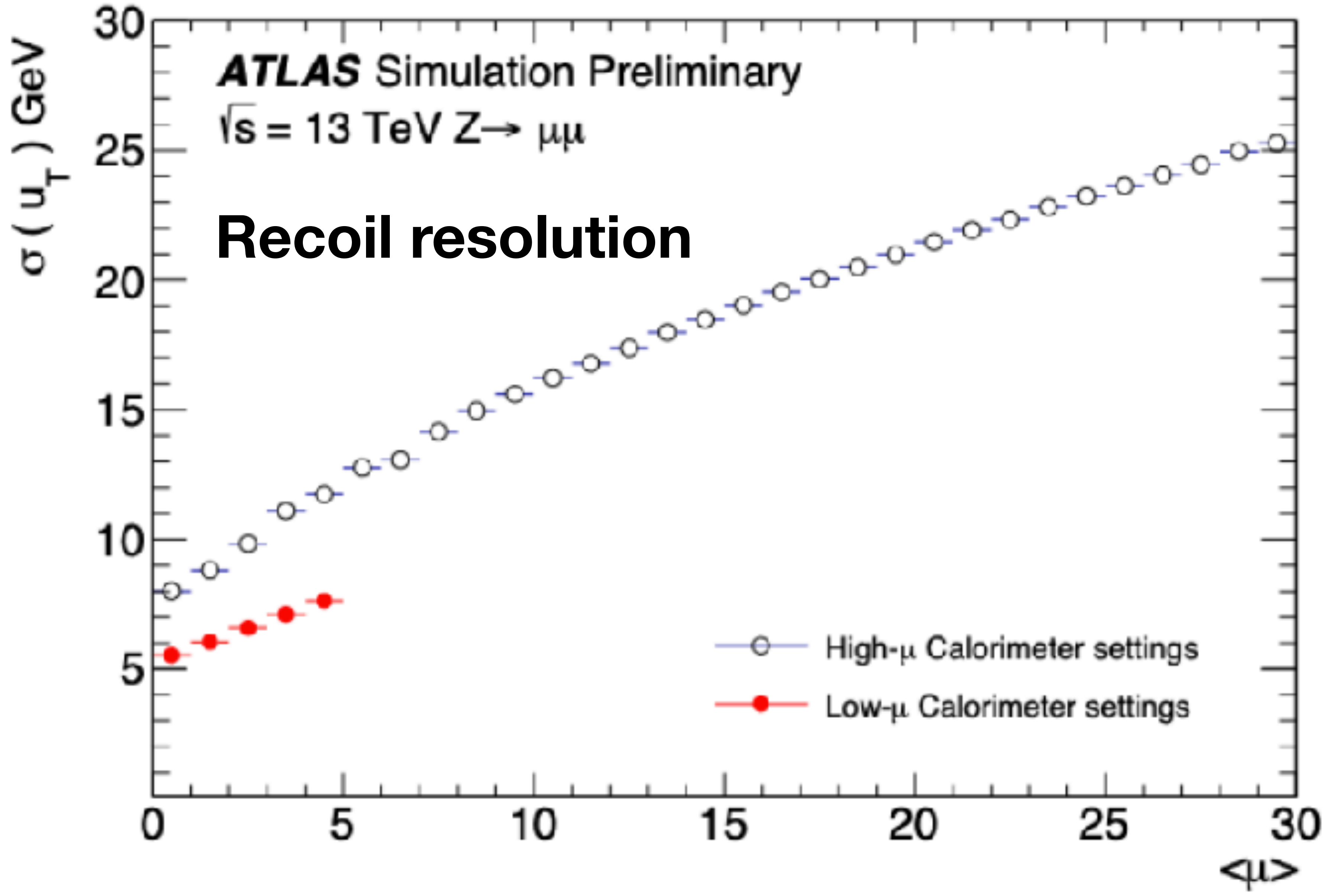
  111 K (5 TeV) and 366 K (13 TeV) Z events

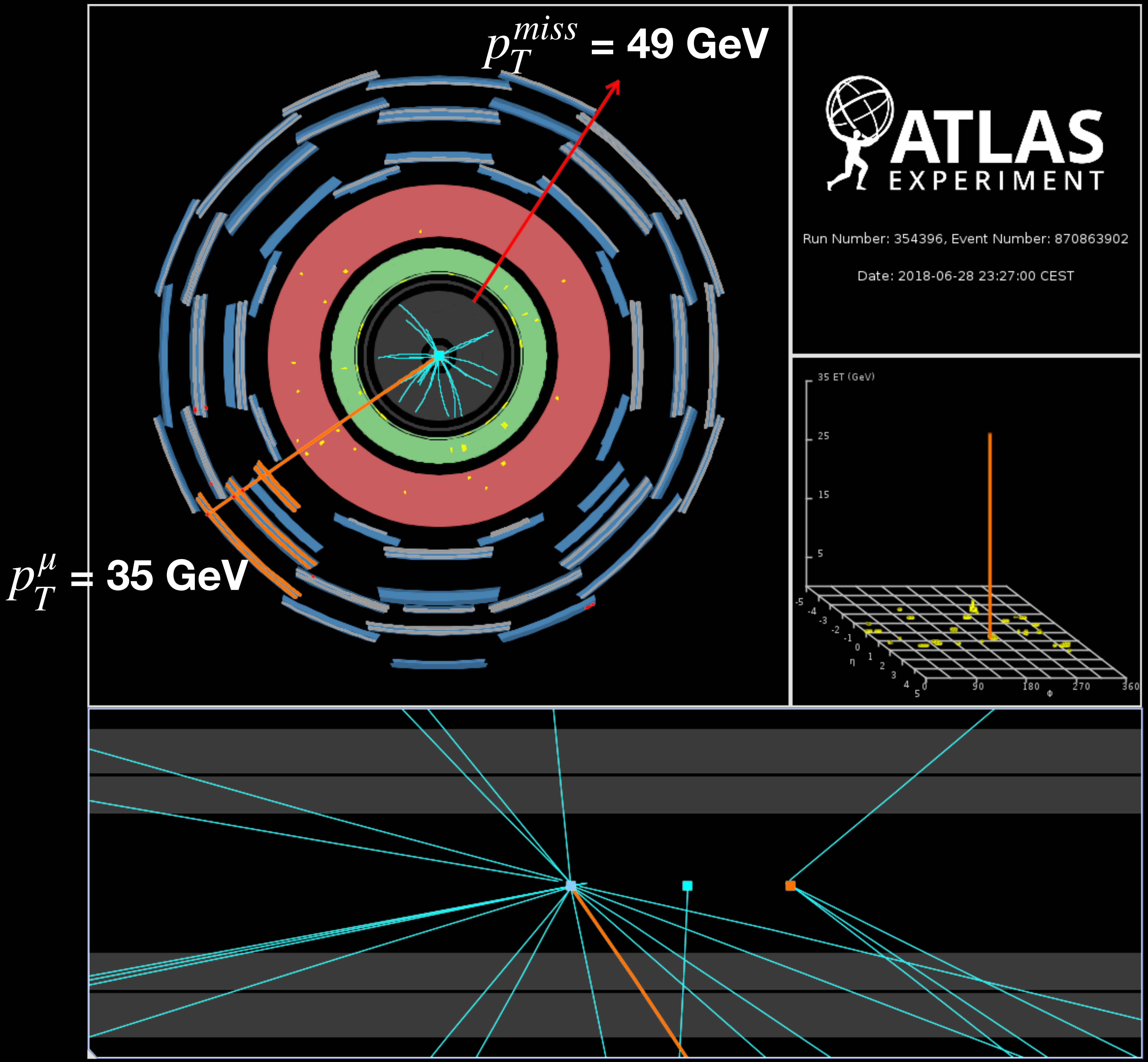


Boson transverse momentum reconstruction



$<\mu>$ ~ 2





13 TeV W—>$\mu\nu$ candidate

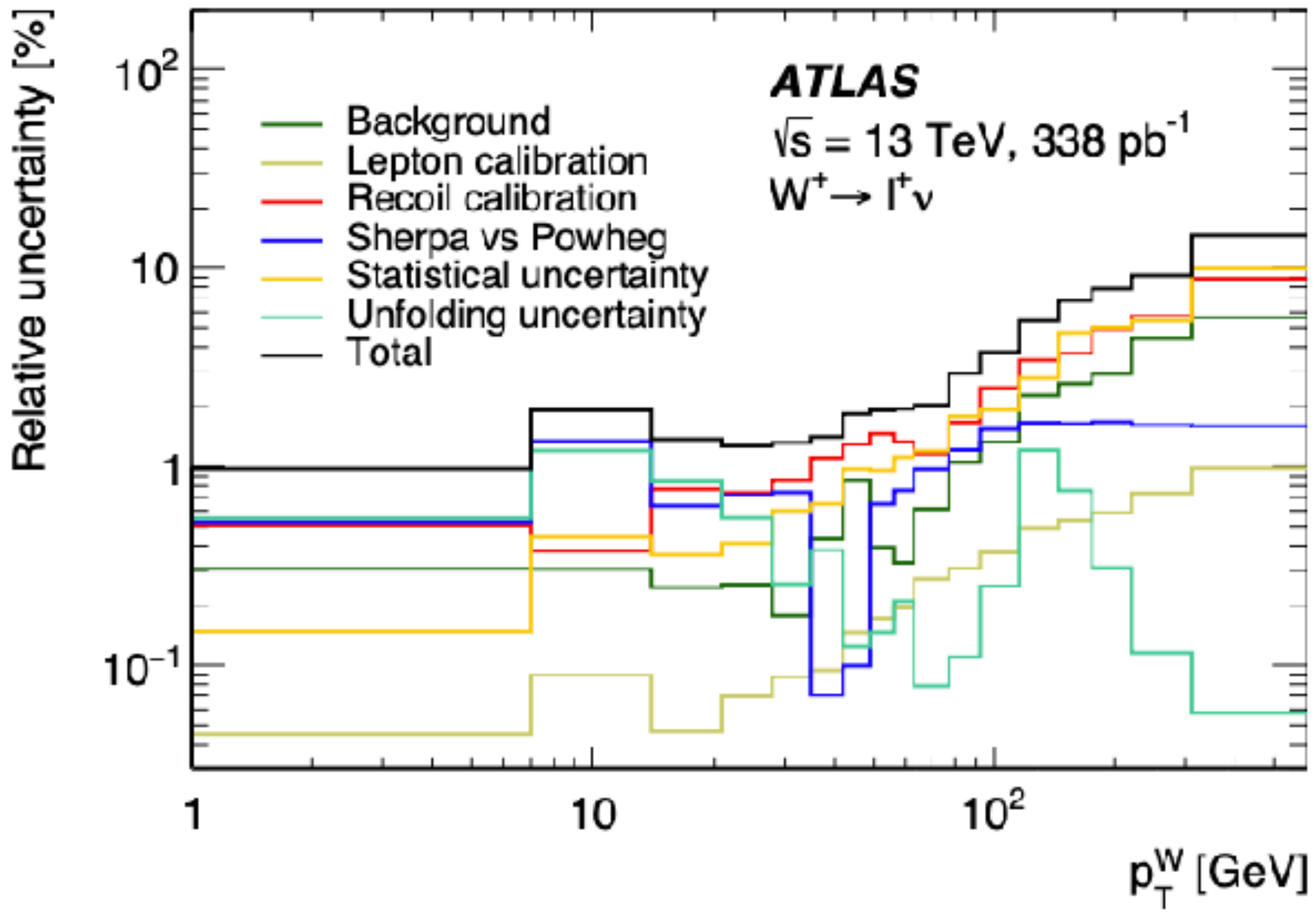
m_T = 77 GeV

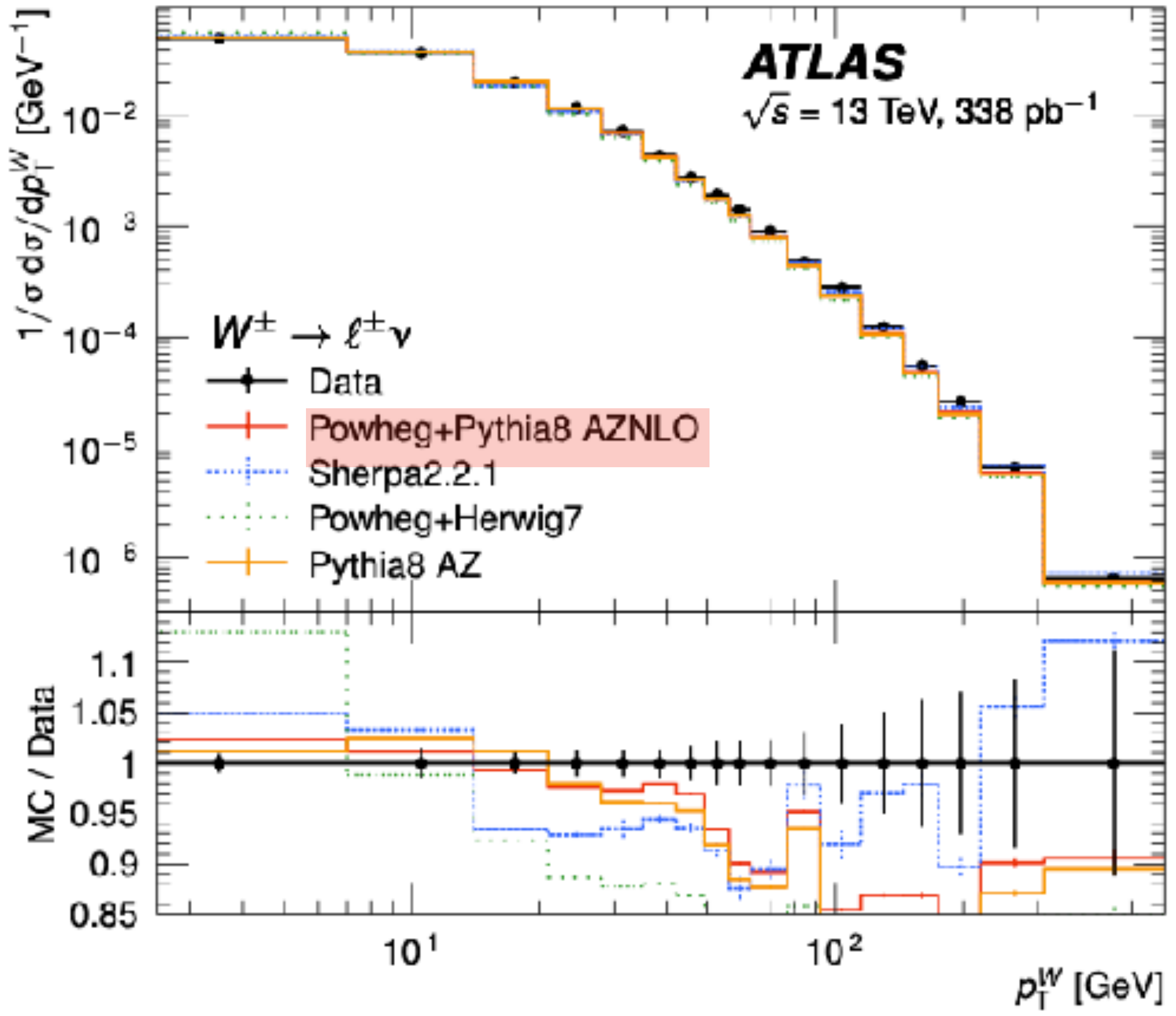
u_T = 16 GeV

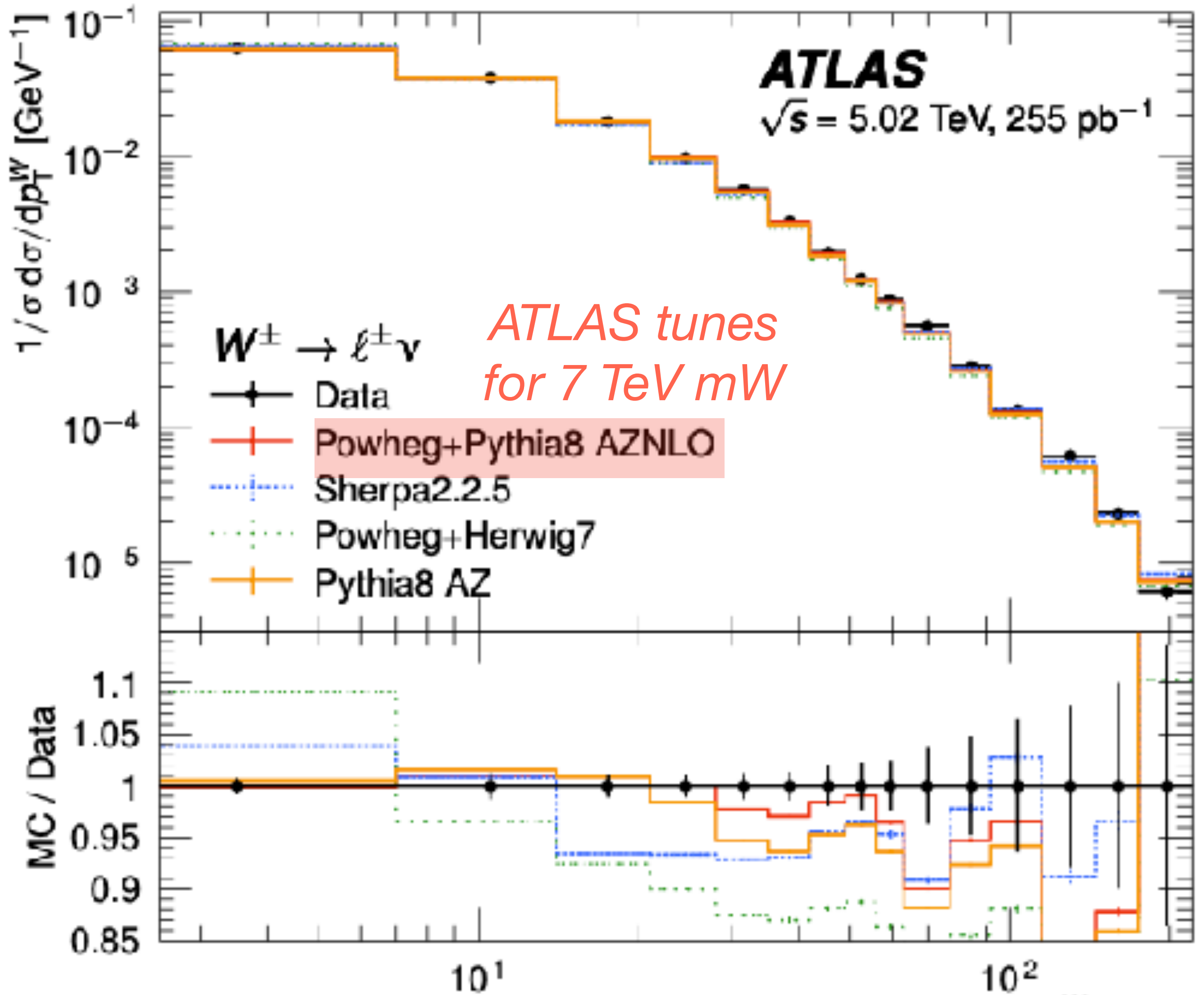
W and Z pT with low-pileup data

- Lepton and recoil calibration and MC dedicated to low-μ conditions
  - Signal: Powheg+Pythia8 AZNLO using CT10, interfaced to PHOTOS++
  - Top quark pair, single top: Powheg+Pythia8.Diboson: Sherpa
- Use Z events to calibrate recoil
- Standard background:
  - EW and top estimated from MC, Multijet using data-driven method
- Bayesian unfolding of u_T in the W and $p_T(\ell\ell)$ in the Z
- Electron and muon channels combined with BLUE, good χ^2

~1 % unc at low p_T^W region







ATLAS tunes for 7 TeV mW

➡ General agree with prediction
  - Further validation of the AZNLO

➡ Provide test and constrains for theory

➡ *Milestone for future next ATLAS low pile-up W mass measurement

  ➡ Save extrapolate p_T^W from Z. Reduce modelling uncertainty

Next: Low-μ m_W measurement

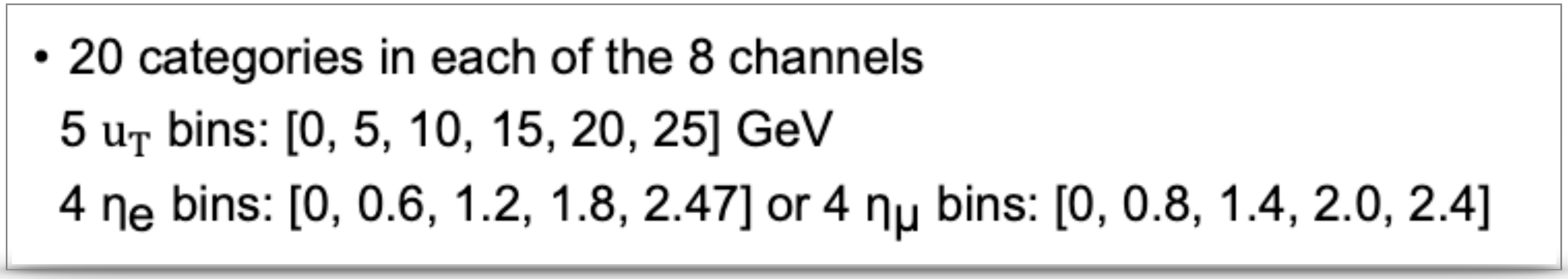
- Based on low-μ p_T measurement
  - lepton and recoil calibration
- Lessons from reanalysis:
  - eg. Profile likelihood fit to further constrain systematics
- Update to latest PDF sets, CT18
- Improved physics modeling

High-μ reanalysis

	7 TeV	7 TeV re-analysis
Stat	6.8	9.8
PDF	9.2	**5.7**
Bkg	4.5	2.0
EW	5.5	5.4
e	6.4	6.0
mu	6.6	5.4
recoil	2.9	2.3
QCD	8.3	**4.4**

W mass extraction: Profile likelihood fit

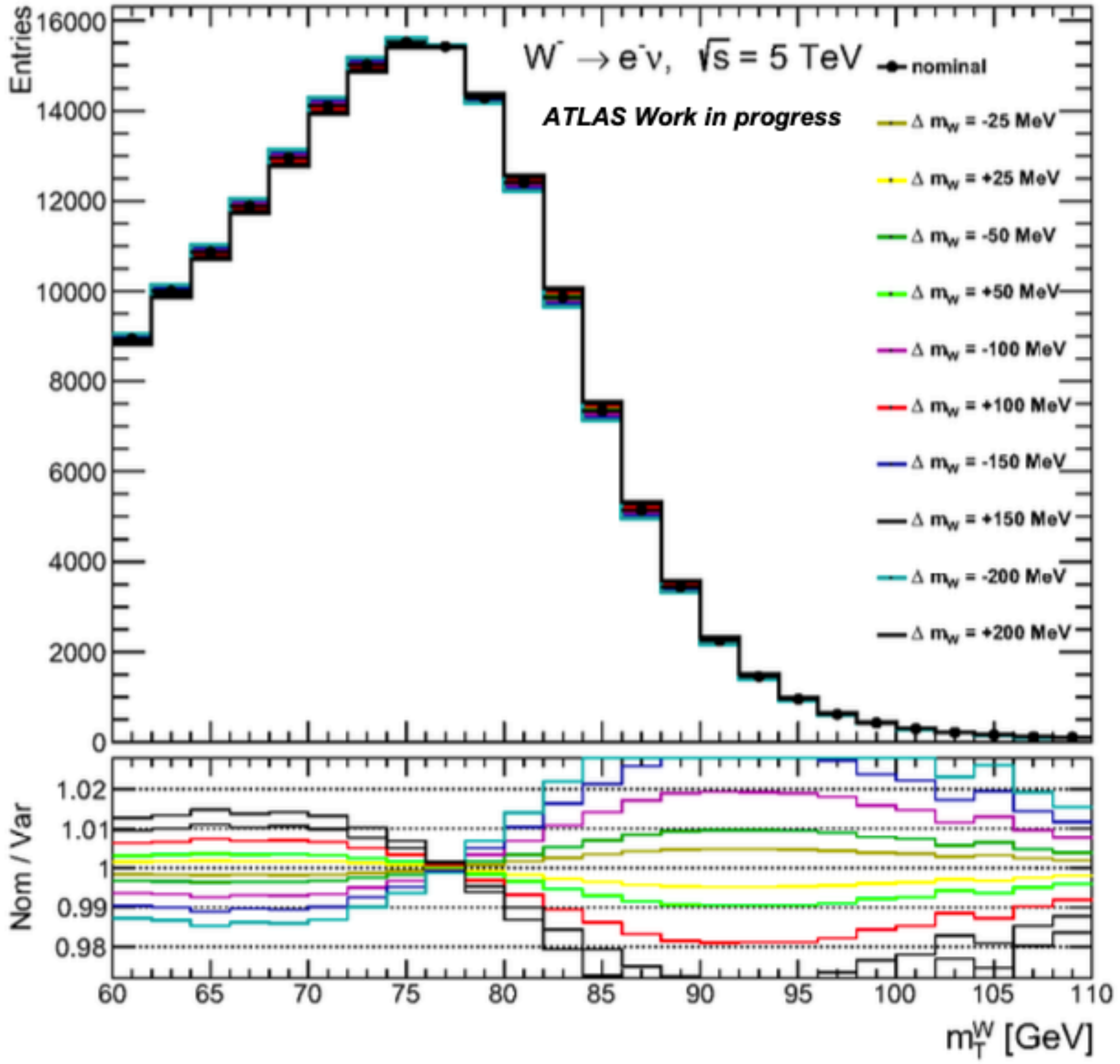
- W mass determined from fit experimental distributions to predictions with different values of W mass - **template**
- Final global fit will be done in 5.02 and 13 TeV, electron and muon channels, charge(W+, W-), and p_T^W, lepton eta categories



- 20 categories in each of the 8 channels

5 u_T bins: [0, 5, 10, 15, 20, 25] GeV

4 η_e bins: [0, 0.6, 1.2, 1.8, 2.47] or 4 η_μ bins: [0, 0.8, 1.4, 2.0, 2.4]



Kinematic distributions with different m_W predictions are obtained from reweighting the resonance of the baseline simulation.

Profile likelihood fit for m_W

- Profile likelihood fit: simultaneous fit POI (mW) and NP.
- Systematic considered in the fit, further constrain systematics

$$L\left(\underset{\text{POI}}{\mu}, \underset{\text{NP}}{\theta} | N^{obs}\right) = \prod_{j=1}^{channels} \prod_{i=1}^{n_j^{bins}} \text{Pois}\left(n_{ji}^{obs} | \nu_{ji}(\mu, \theta)\right) \cdot \underset{\text{NP constraints}}{C(\theta)},$$

ϕ: float global normalization factor, cross-section independent

$$\nu_{\text{ji}}(\mu, \theta) = \Phi \times \left[S_{\text{ji}}^{\text{nom}} + \mu \times \left(S_{\text{ji}}^{\text{BW}} - S_{\text{ji}}^{\text{nom}}\right)\right] + \sum_{p} \theta_p \times \left(S_{\text{ji}}^{p} - S_{\text{ji}}^{\text{nom}}\right)$$

$$+ B_{\text{ji}}^{\text{nom}} + \sum_{p'} \theta_{p'} \times \left(B_{\text{ji}}^{p'} - B_{\text{ji}}^{\text{nom}}\right)$$

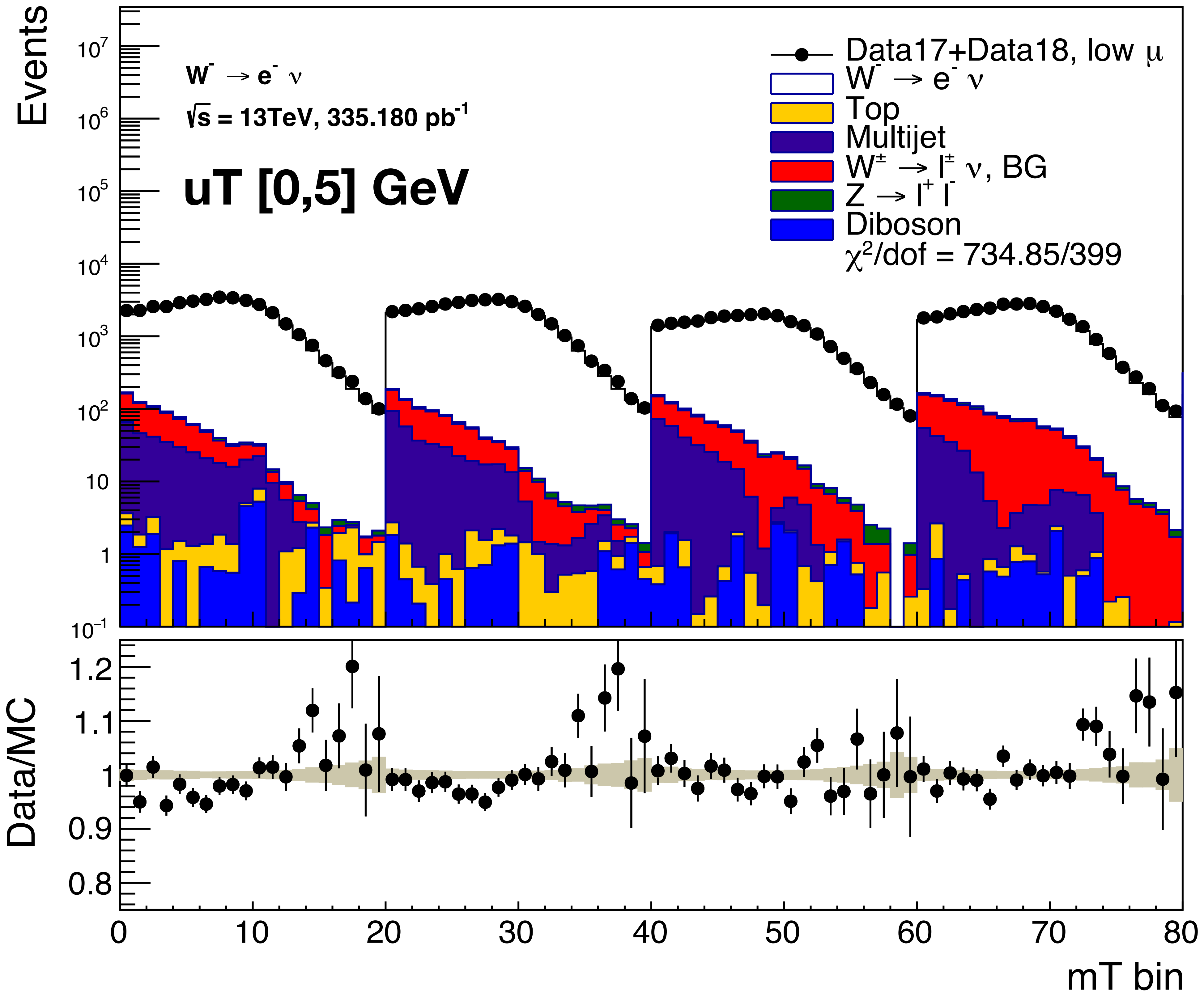
$$+ MJ_{\text{ji}}^{\text{nom}} + \sum_{p''} \theta_{p''} \times \left(MJ_{\text{ji}}^{p''} - MJ_{\text{ji}}^{\text{nom}}\right),$$

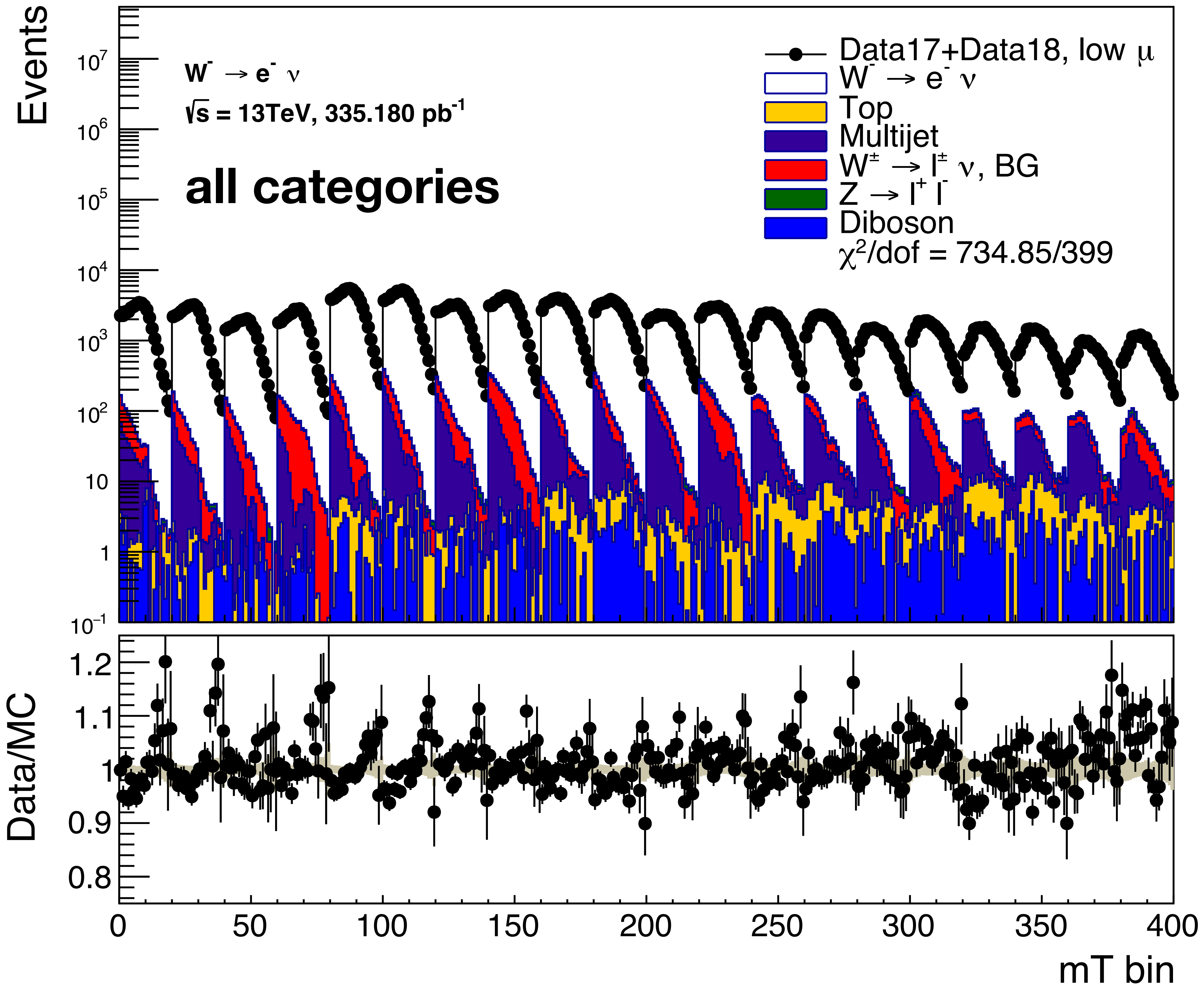
Control plots for unrolled distribution

- 20 categories in each of the 8 channels

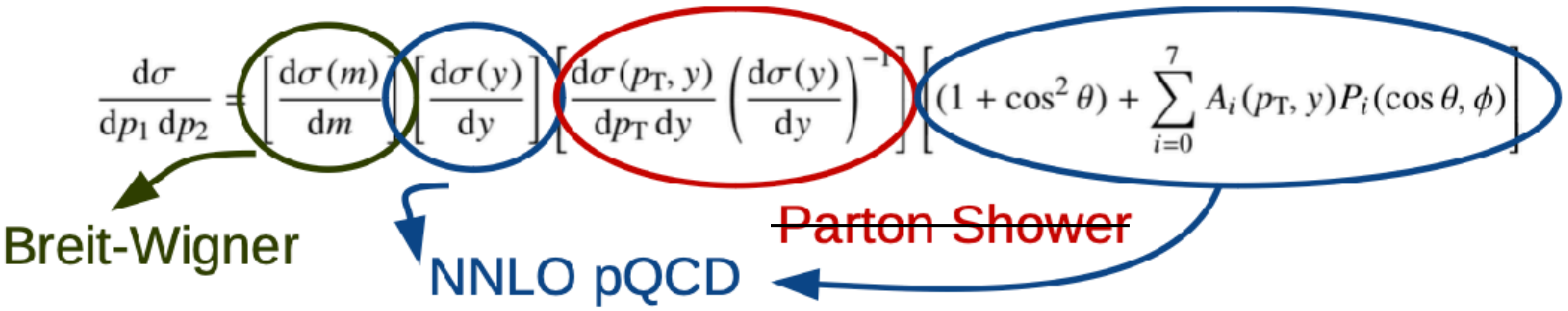
  5 u_T bins: [0, 5, 10, 15, 20, 25] GeV

  4 η_e bins: [0, 0.6, 1.2, 1.8, 2.47] or 4 η_μ bins: [0, 0.8, 1.4, 2.0, 2.4]





Physics Modeling: QCD



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

Breit-Wigner

NNLO pQCD

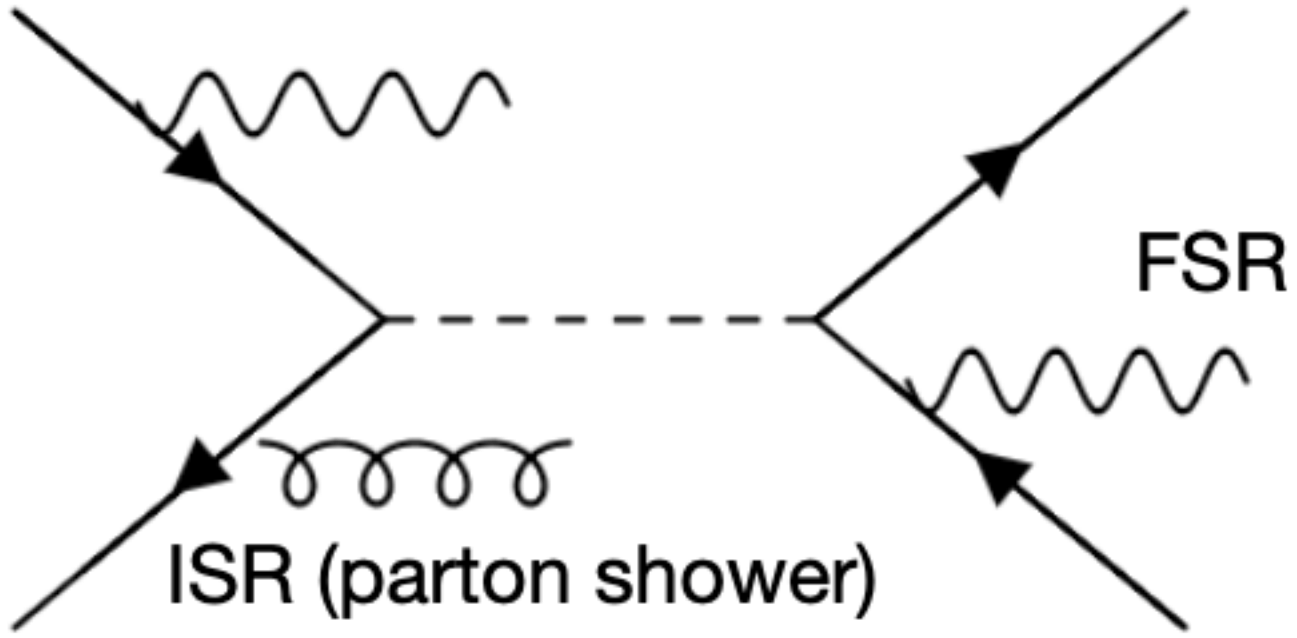
~~Parton Shower~~

- Modeled with fix order pQCD at NNLO using CT18 PDF set
  - vary model parameters to assess uncertainty
- Validated and constrained by ancillary DY measurements
  - a new W angular coefficient (Ai) measurements on-going
- p_T^W modeling
  - Joint fit with W, Z ratios with model variations in DYTURBO
  - First time in ATLAS

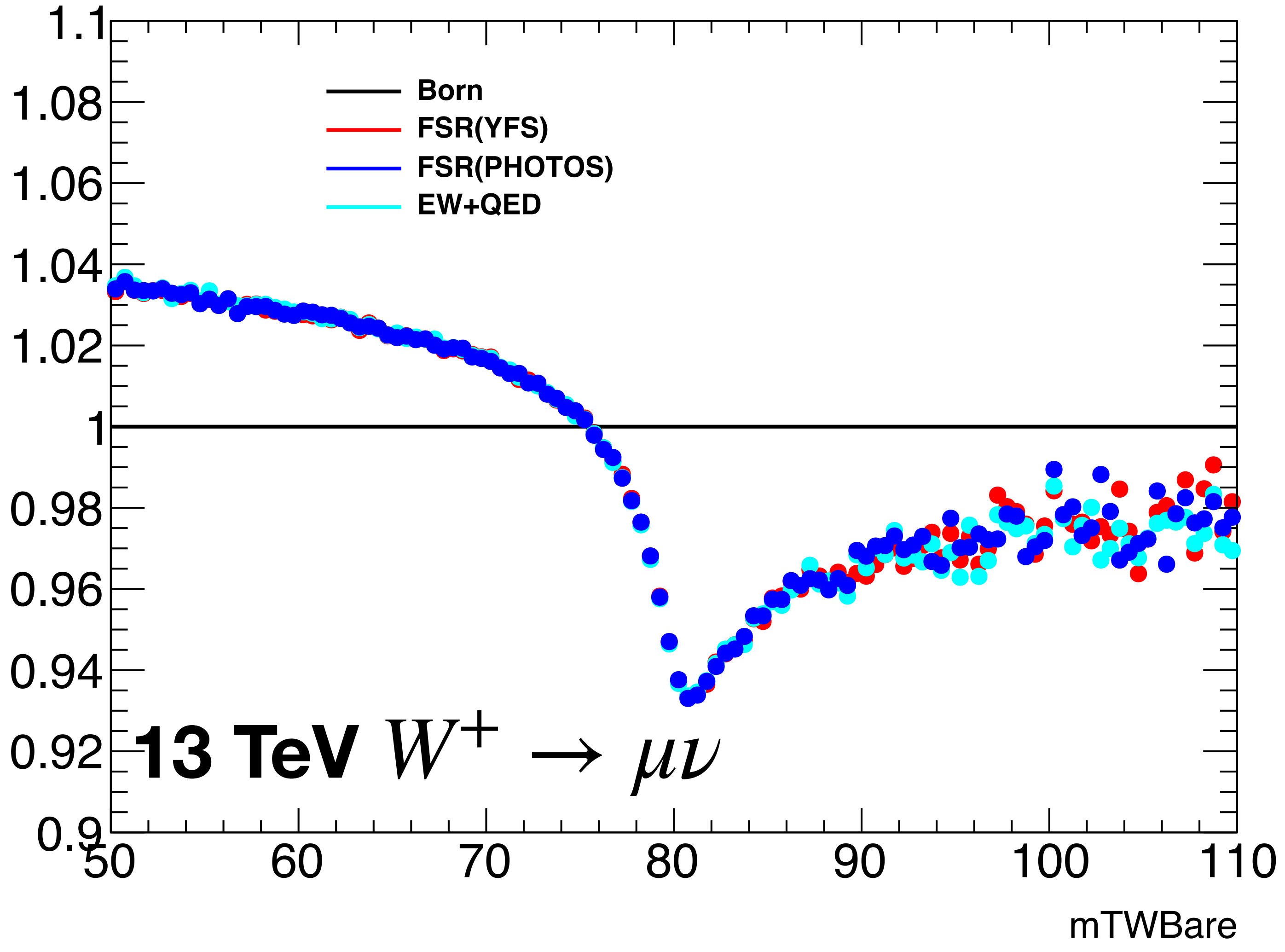
Physics Modeling: Electroweak

Electroweak corrections and uncertainty:

- Pythia ISR, PHOTOS QED FSR included in sample
- QED FSR modeling: Validated by PHOTOS and YFS comparison
- Most important: Missing higher order considered into systematics (pure weak, IFI)
  - Evaluated at detector level
  - Less than 5 MeV impact
- Further compare with other generator

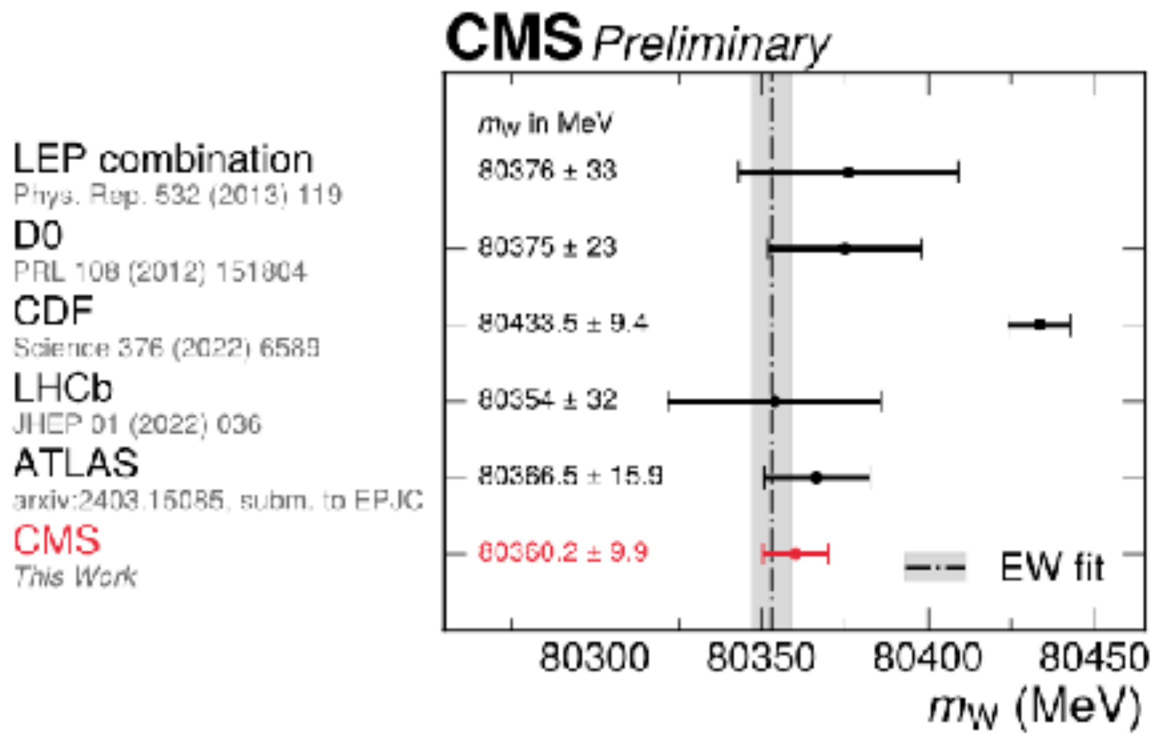


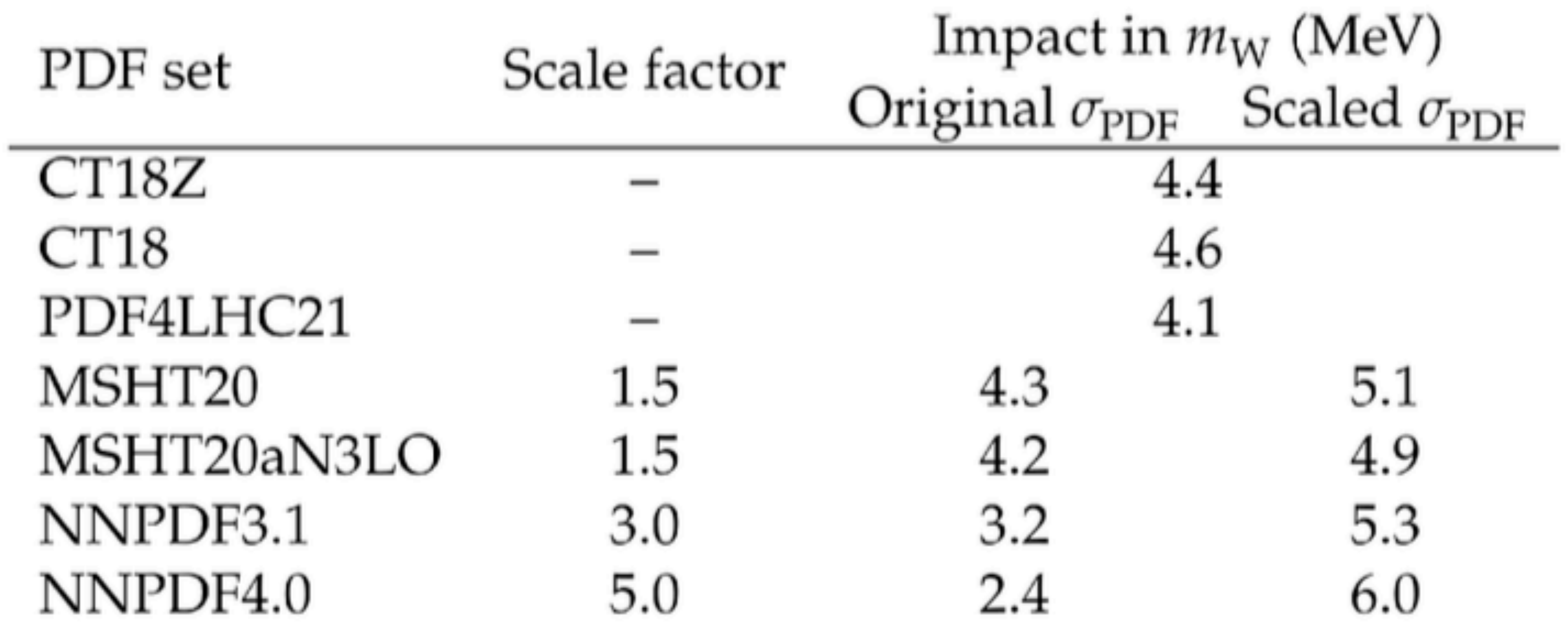
Higher order electroweak corrections impact [MeV]					
	13 TeV $W^+ \to \mu\nu$	13 TeV $W^+ \to e\nu$	13 TeV $W^- \to \mu\nu$	13 TeV $W^- \to e\nu$	channel average
m_T fit	-3.3 ± 0.19	-2.7 ± 0.20	-2.8 ± 0.11	-3.1 ± 0.10	-2.98 ± 0.15
p_T^l fit	-3.3 ± 0.24	-3.9 ± 0.29	-1.3 ± 0.18	-2.2 ± 0.18	-2.68 ± 0.22
	5 TeV $W^+ \to \mu\nu$	5 TeV $W^+ \to e\nu$	5 TeV $W^- \to \mu\nu$	5 TeV $W^- \to e\nu$	channel average
m_T fit	-0.2 ± 0.18	-0.0 ± 0.17	-1.3 ± 0.14	-1.0 ± 0.31	-0.63 ± 0.20
p_T^l fit	-3.1 ± 0.17	-3.9 ± 0.17	-2.4 ± 0.16	-3.2 ± 0.35	-3.15 ± 0.21



First CMS W mass

- Muon only, p_T^l only
- Large statistics
- Agree well with SM prediction
- p_T^W modeling and PDF uncertainties are strongly constrained in-situ by the data
- Scale prefit PDF uncertainties to ensure consistency between sets for measured W mass





PDF set	Scale factor	Impact in m_W (MeV)	
		Original σ_{PDF}	Scaled σ_{PDF}
CT18Z	–	4.4	
CT18	–	4.6	
PDF4LHC21	–	4.1	
MSHT20	1.5	4.3	5.1
MSHT20aN3LO	1.5	4.2	4.9
NNPDF3.1	3.0	3.2	5.3
NNPDF4.0	5.0	2.4	6.0

	7 TeV re-analysis	CMS
Stat	9.8	7.1
PDF	5.7	2.8
Bkg	2.0	1.7
EW	5.4	1.9
e	6.0	-
mu	5.4	5.0
recoil	2.3	-
QCD	4.4	3.1

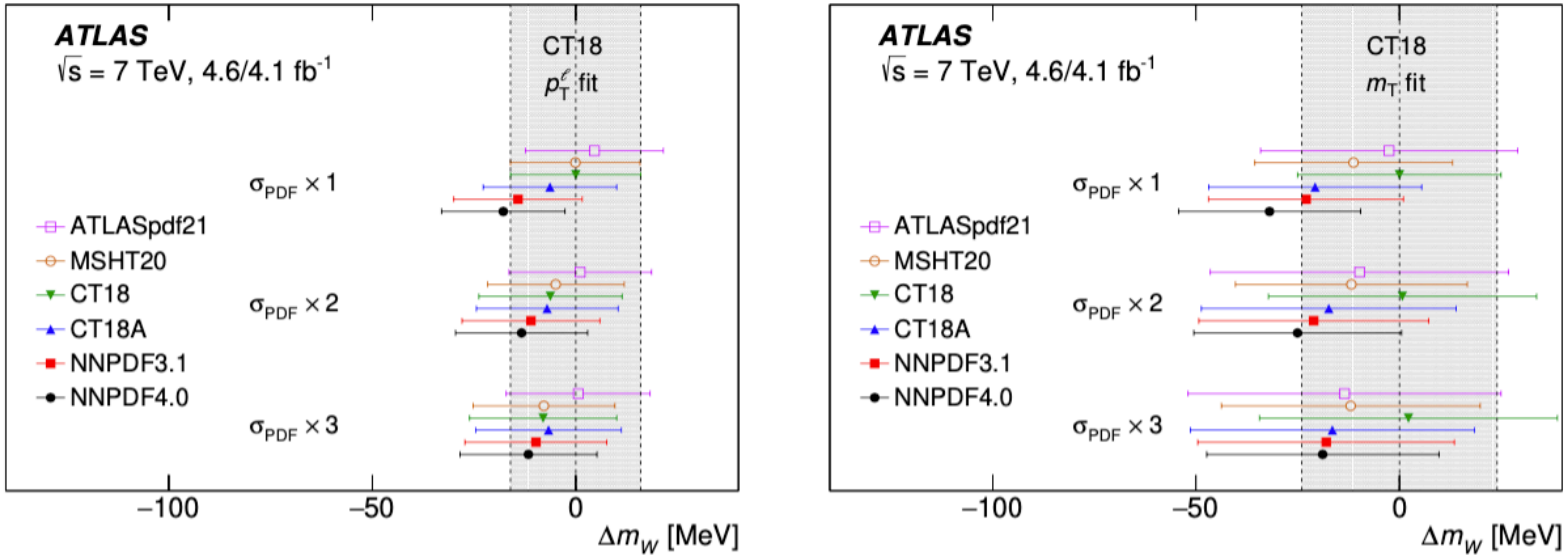
strong in-situ constrain

Prospect

- Potential improvement in calibrations and modeling
- Preliminary joint fit of p_T^l and m_T at 5.02 and 13 TeV
- Precision around 15 MeV, statistical dominant
- Combination with 7 TeV will gain better precision (around 10 MeV)

	4.1-4.6 fb^{-1}	16.8 fb^{-1}	255 pb^{-1}, 335 pb^{-1}
	7 TeV re-analysis	**CMS**	**Low-mu Preliminary**
Stat	9.8	7.1	12
PDF	5.7	2.8	3.2
Bkg	2.0	1.7	2.1
EW	5.4	1.9	~3
e	6.0	-	5.4
mu	5.4	5.0	2.6
recoil	2.3	-	2.4
QCD	4.4	3.1	3-4 p_T^W 1.5 Ai not available yet
	16 MeV	**9.9 MeV**	**~15 MeV**

Back-up



(a)

(b)

Figure 5: Variation of the fitted value of m_W with the PDF set used in the fit, for the (a) p_T^ℓ and (b) m_T distributions and different scalings of the pre-fit PDF uncertainties. The reference value is defined by the CT18 PDF set.

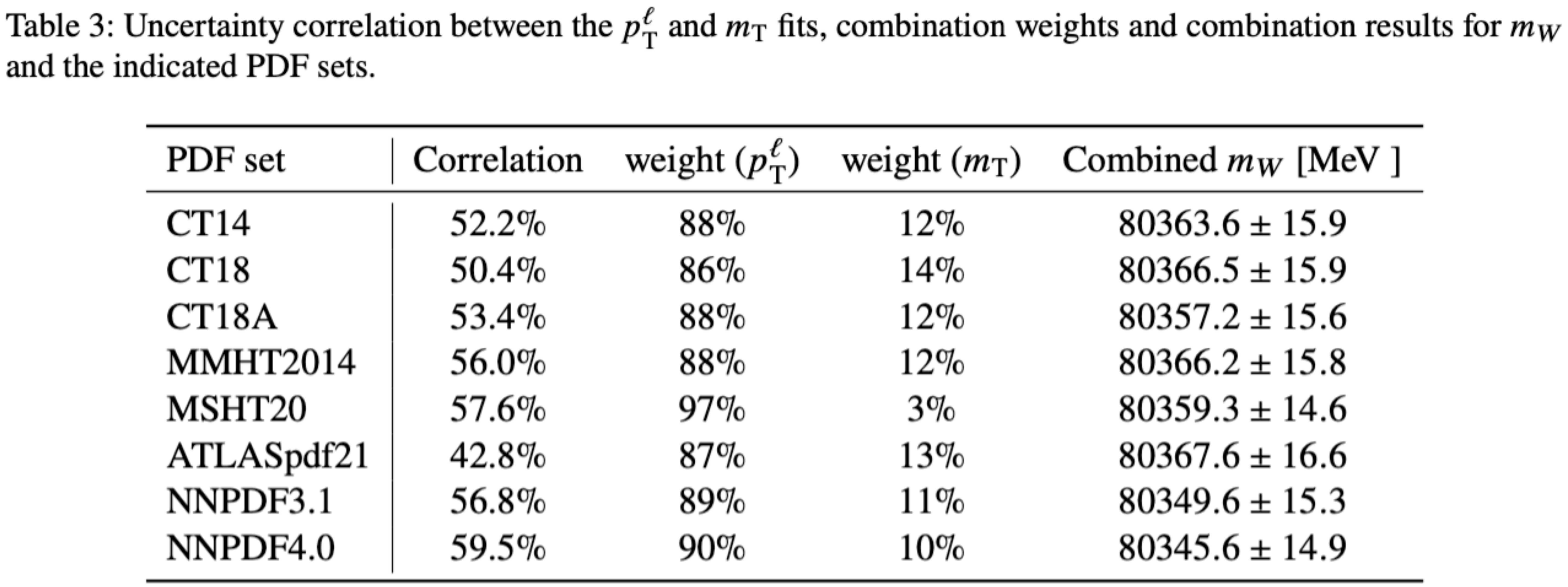


Table 3: Uncertainty correlation between the p_{T}^{ℓ} and m_{T} fits, combination weights and combination results for m_W and the indicated PDF sets.

PDF set	Correlation	weight (p_{T}^{ℓ})	weight (m_{T})	Combined m_W [MeV]
CT14	52.2%	88%	12%	80363.6 ± 15.9
CT18	50.4%	86%	14%	80366.5 ± 15.9
CT18A	53.4%	88%	12%	80357.2 ± 15.6
MMHT2014	56.0%	88%	12%	80366.2 ± 15.8
MSHT20	57.6%	97%	3%	80359.3 ± 14.6
ATLASpdf21	42.8%	87%	13%	80367.6 ± 16.6
NNPDF3.1	56.8%	89%	11%	80349.6 ± 15.3
NNPDF4.0	59.5%	90%	10%	80345.6 ± 14.9

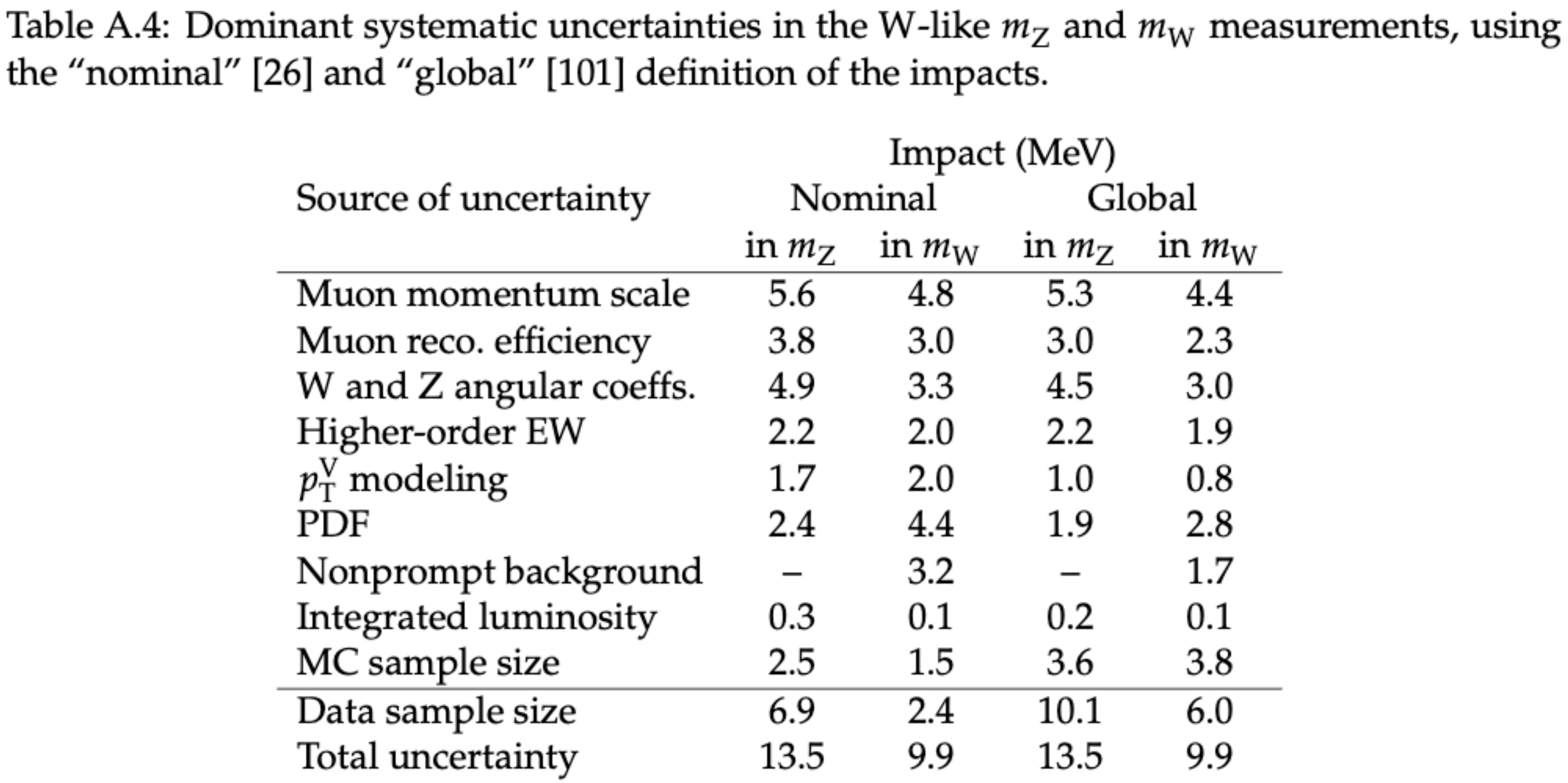
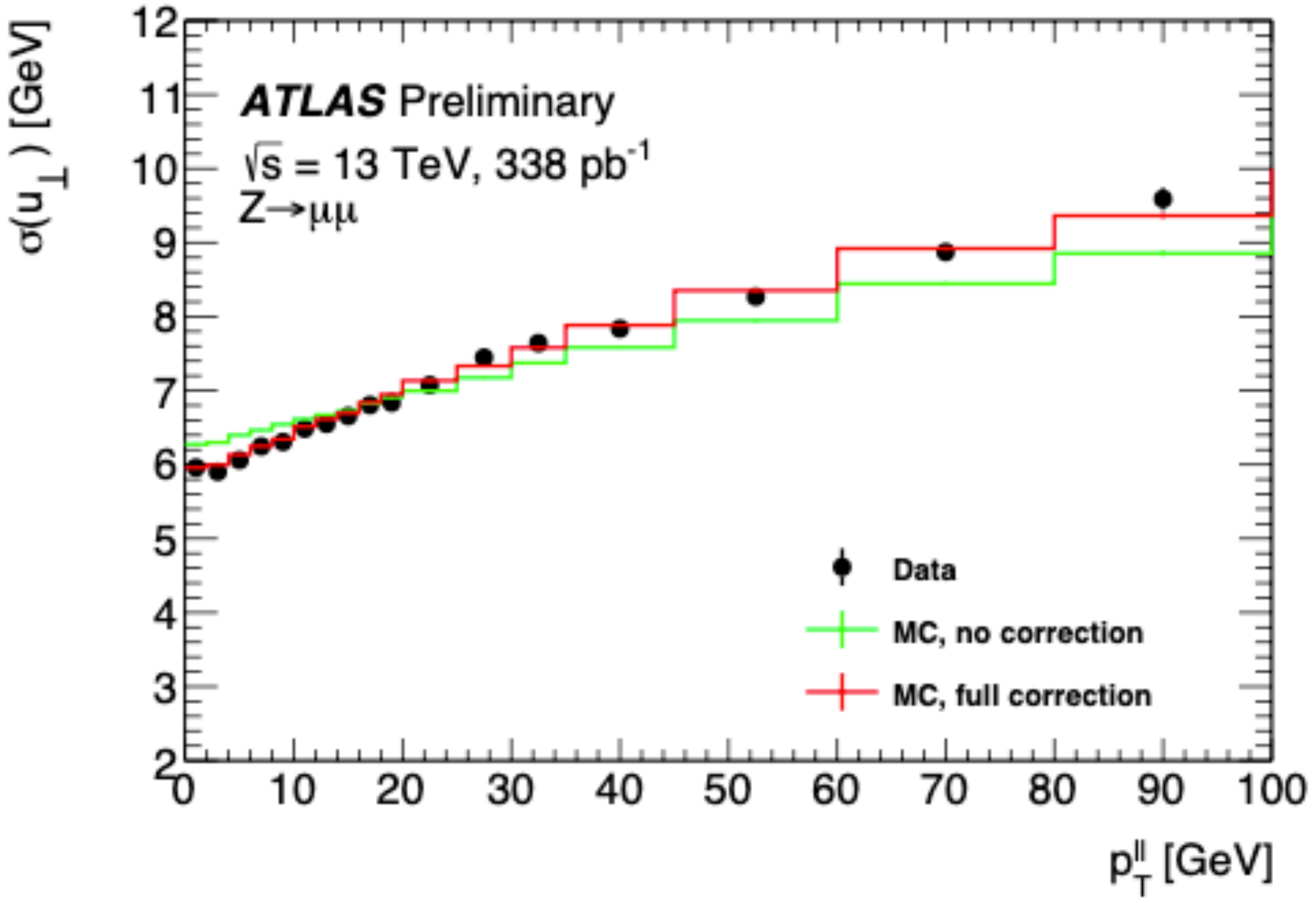


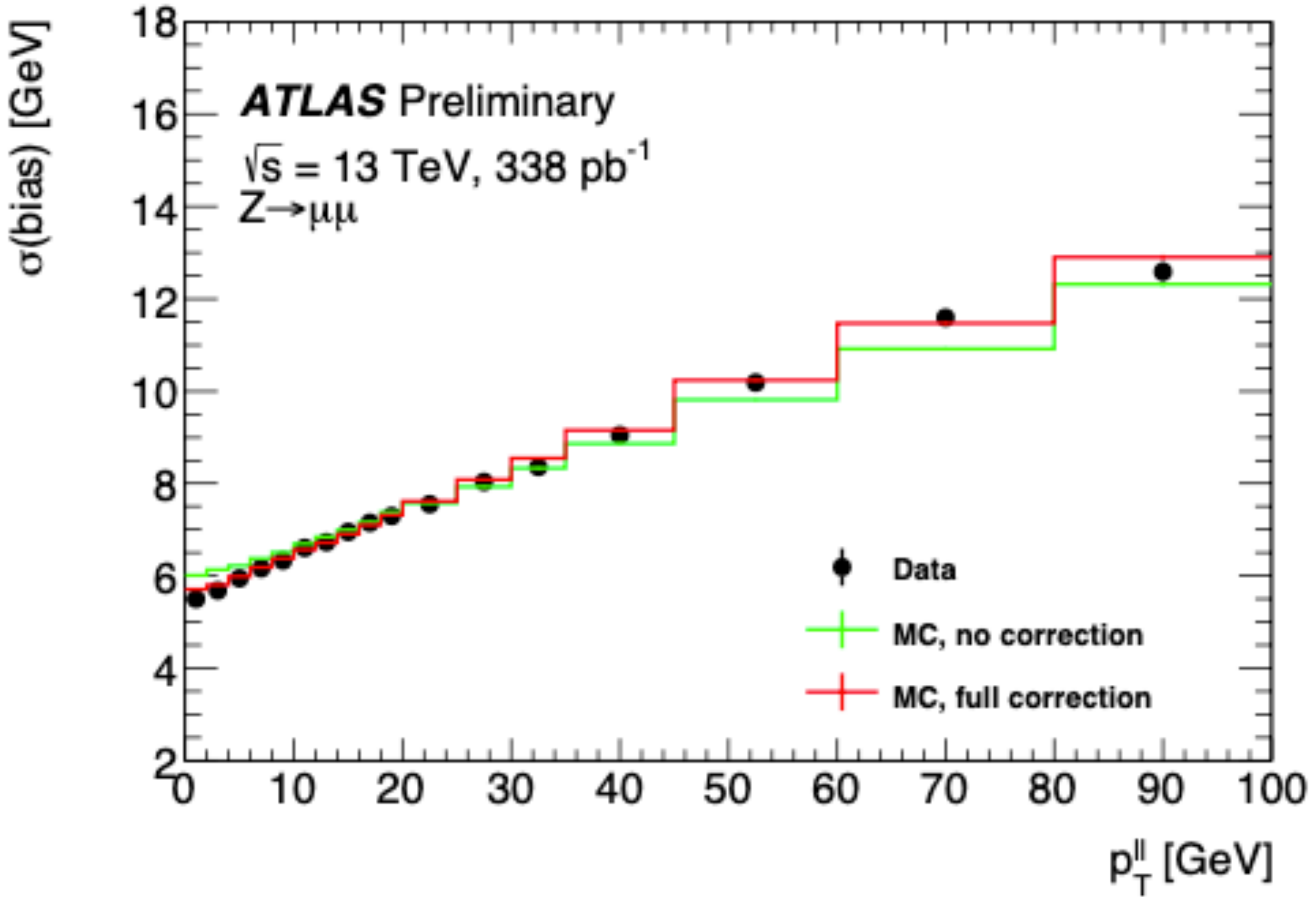
Table A.4: Dominant systematic uncertainties in the W-like m_Z and m_W measurements, using the “nominal” [26] and “global” [101] definition of the impacts.

	Impact (MeV)			
Source of uncertainty	Nominal		Global	
	in m_Z	in m_W	in m_Z	in m_W
Muon momentum scale	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt background	–	3.2	–	1.7
Integrated luminosity	0.3	0.1	0.2	0.1
MC sample size	2.5	1.5	3.6	3.8
Data sample size	6.9	2.4	10.1	6.0
Total uncertainty	13.5	9.9	13.5	9.9

Detector calibration

- **Lepton calibration** uses standard high-pileup data extrapolate to low-pileup wherever possible, otherwise in-situ calibrations with Z events.
- **Hadronic recoil:**
  - Reconstructed with particle flow objects(PFOs), improve resolution by 3%-15%
  - Calibrated with in-situ Z events
    - Modeling of underlying events, response and resolution correction, azimuthal angle and non-Gaussian tails also addressed





Event Selection

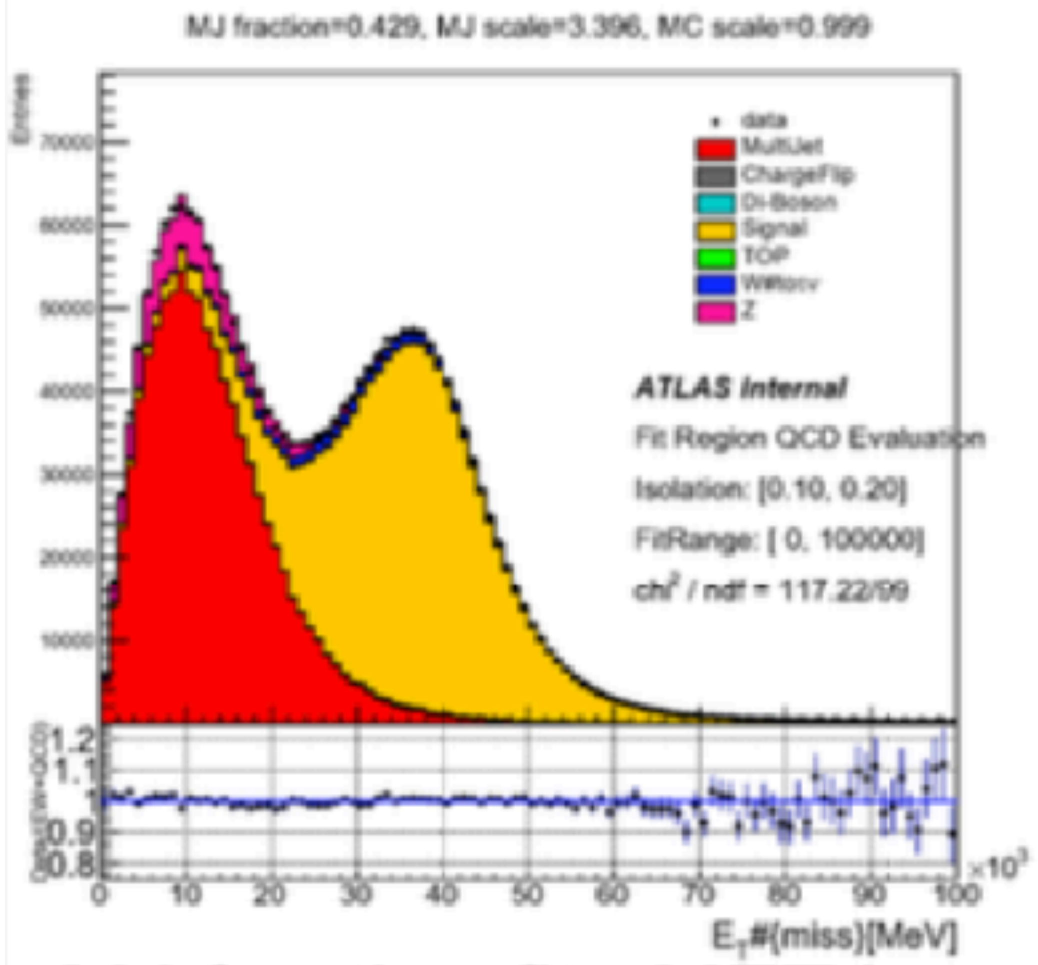
Standard W selection:

- Exactly one identified and isolated electron or muon
- Lepton trigger matched (loose electron E_T >15 GeV or medium muon E_T >14 GeV)
- Isolation: Ptcone20/Min(p_T^l, 50 GeV) $<$ 0.1
- Kinematics: $p_T^l >$ 25 GeV $E_T^{miss} >$ 25 GeV, $m_T >$ 50 GeV

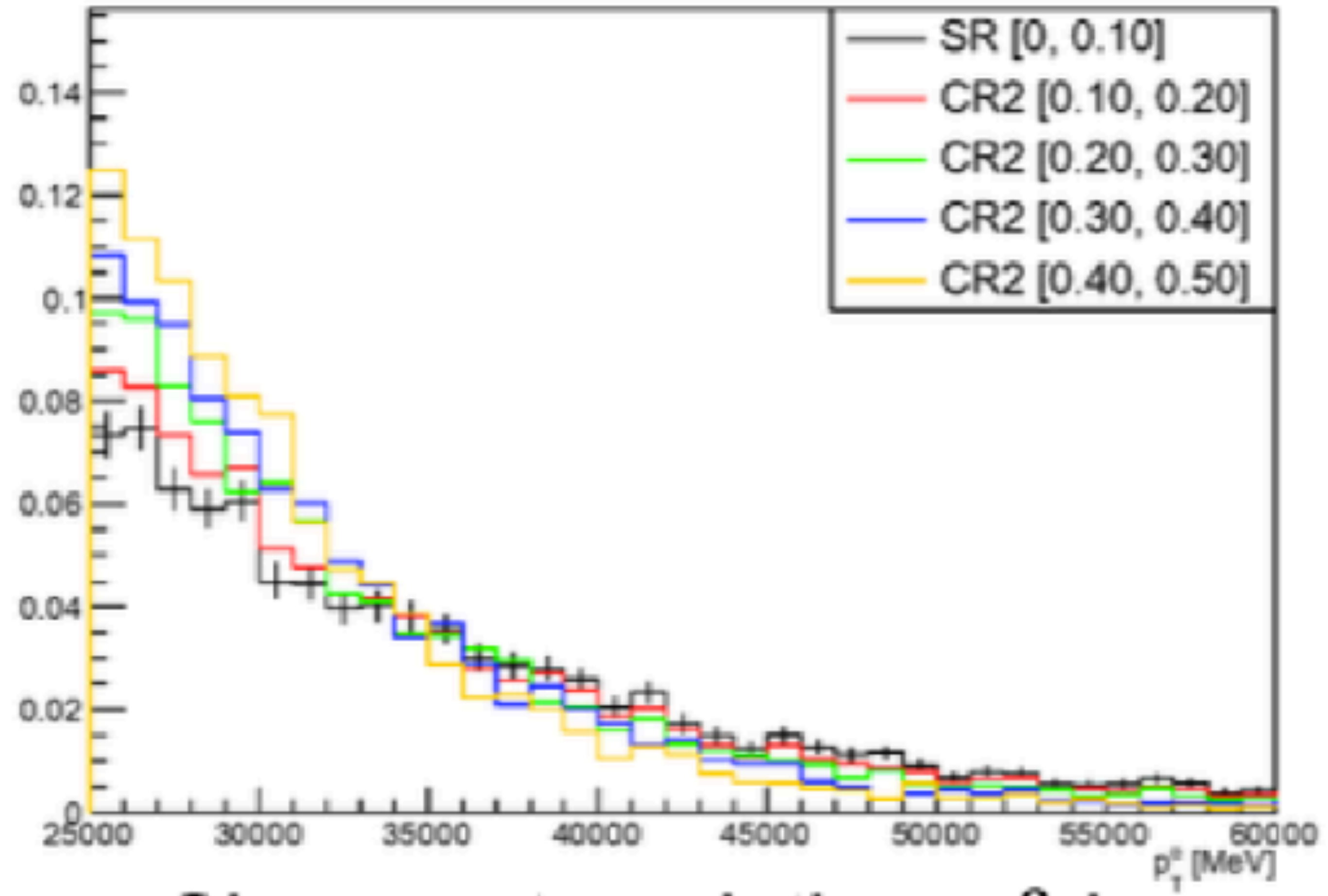
	5.02 TeV	13 TeV
Lumi	255 pb-1	338 pb-1
W events	1.45 M	4.36 M

Background estimation

- Backgrounds from electroweak and top related are estimated from MC samples
- Multijet estimated with data-driven method
  - Yield by fraction fit extrapolating to signal region
  - Shape extrapolation from CR2
  - Uncertainty propagated into profile

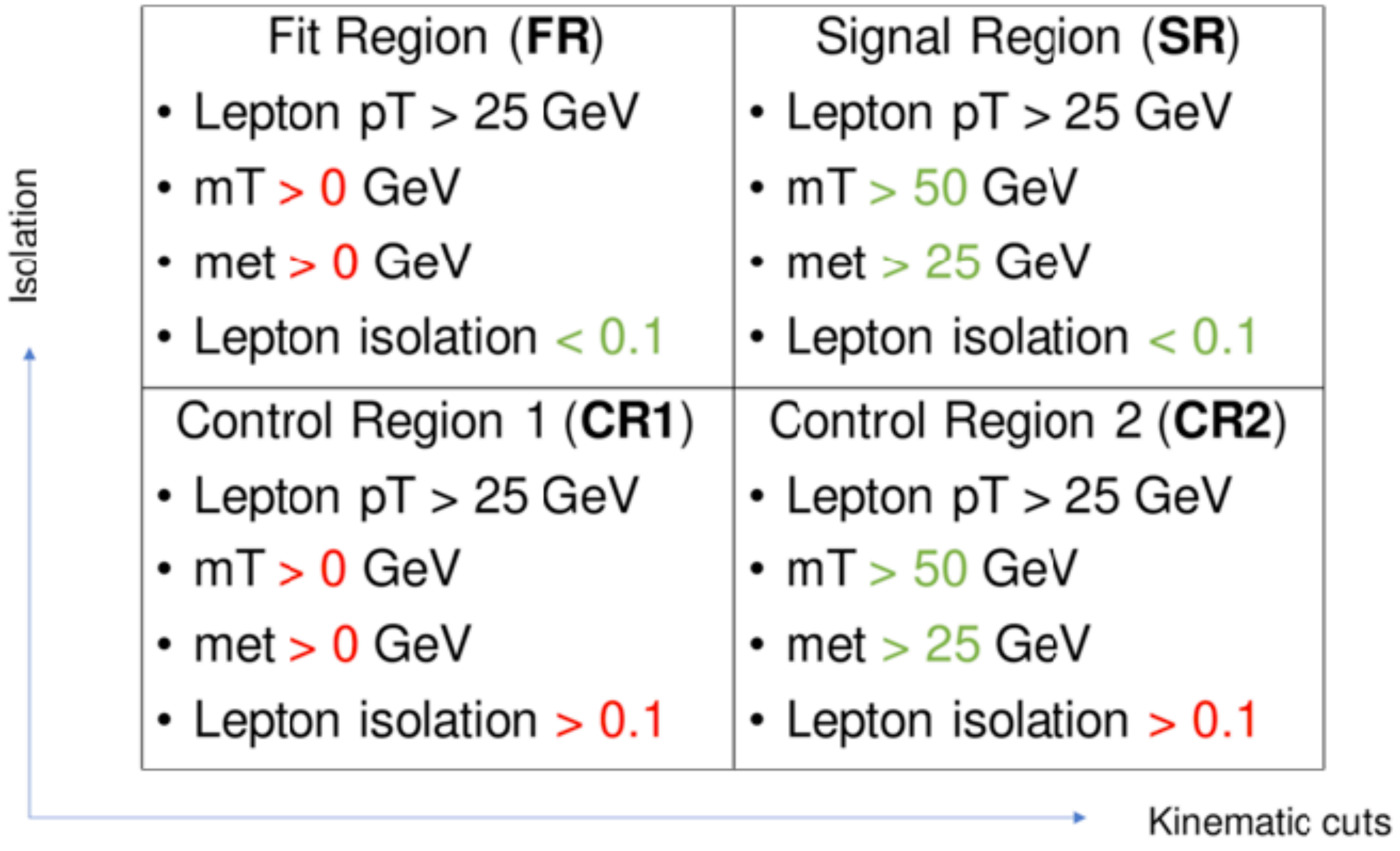


MJ fraction fit : MET in 13 TeV $W^{-}\rightarrow ev$ channel.



Shape extrapolation: p_T^e in 13 TeV $W^{-}\rightarrow ev$ channel.

ABCD method



Fit Region (**FR**) • Lepton pT > 25 GeV • mT > 0 GeV • met > 0 GeV • Lepton isolation < 0.1	Signal Region (**SR**) • Lepton pT > 25 GeV • mT > 50 GeV • met > 25 GeV • Lepton isolation < 0.1
Control Region 1 (**CR1**) • Lepton pT > 25 GeV • mT > 0 GeV • met > 0 GeV • Lepton isolation > 0.1	Control Region 2 (**CR2**) • Lepton pT > 25 GeV • mT > 50 GeV • met > 25 GeV • Lepton isolation > 0.1