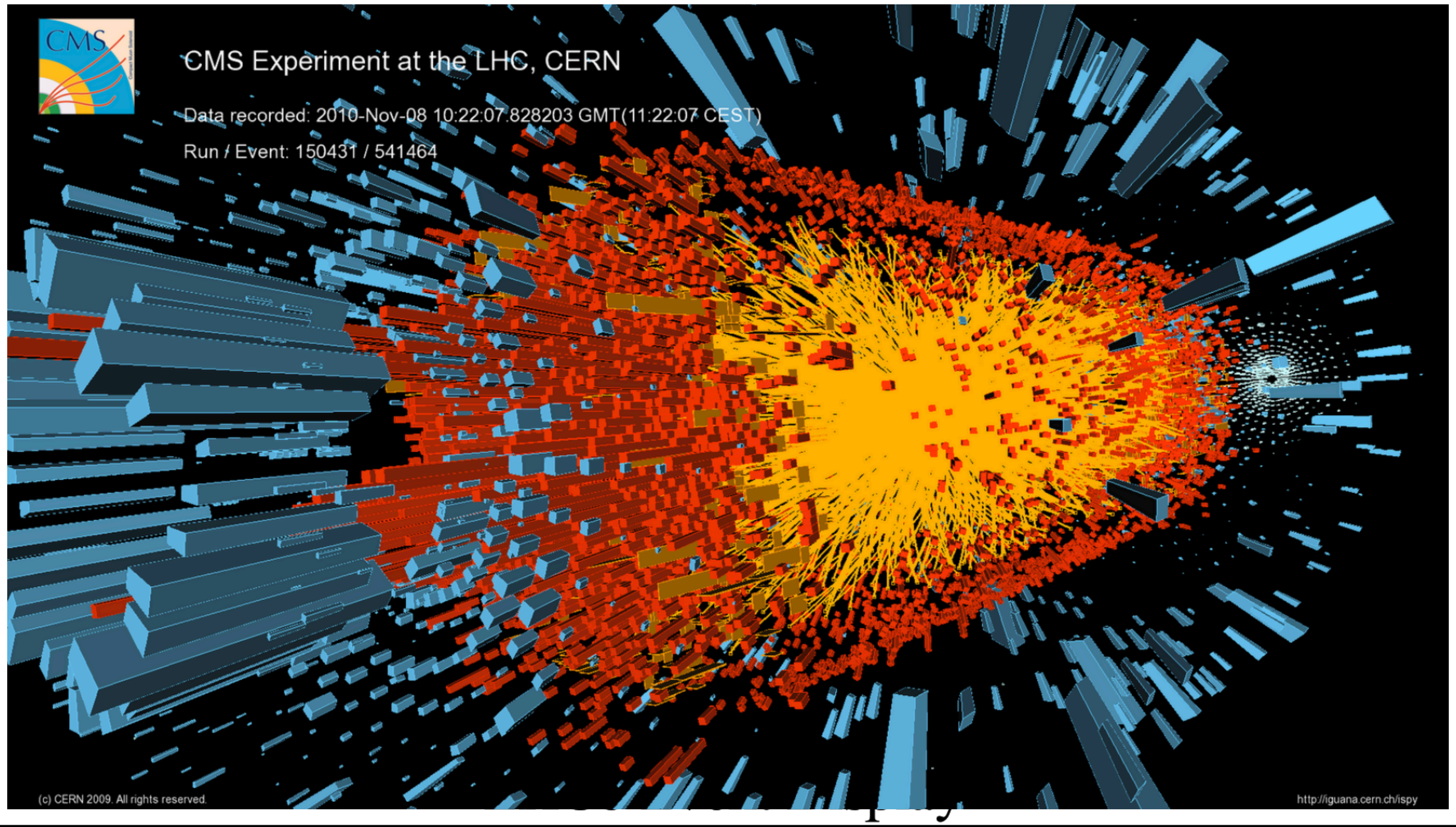
W mass measurement at LHC

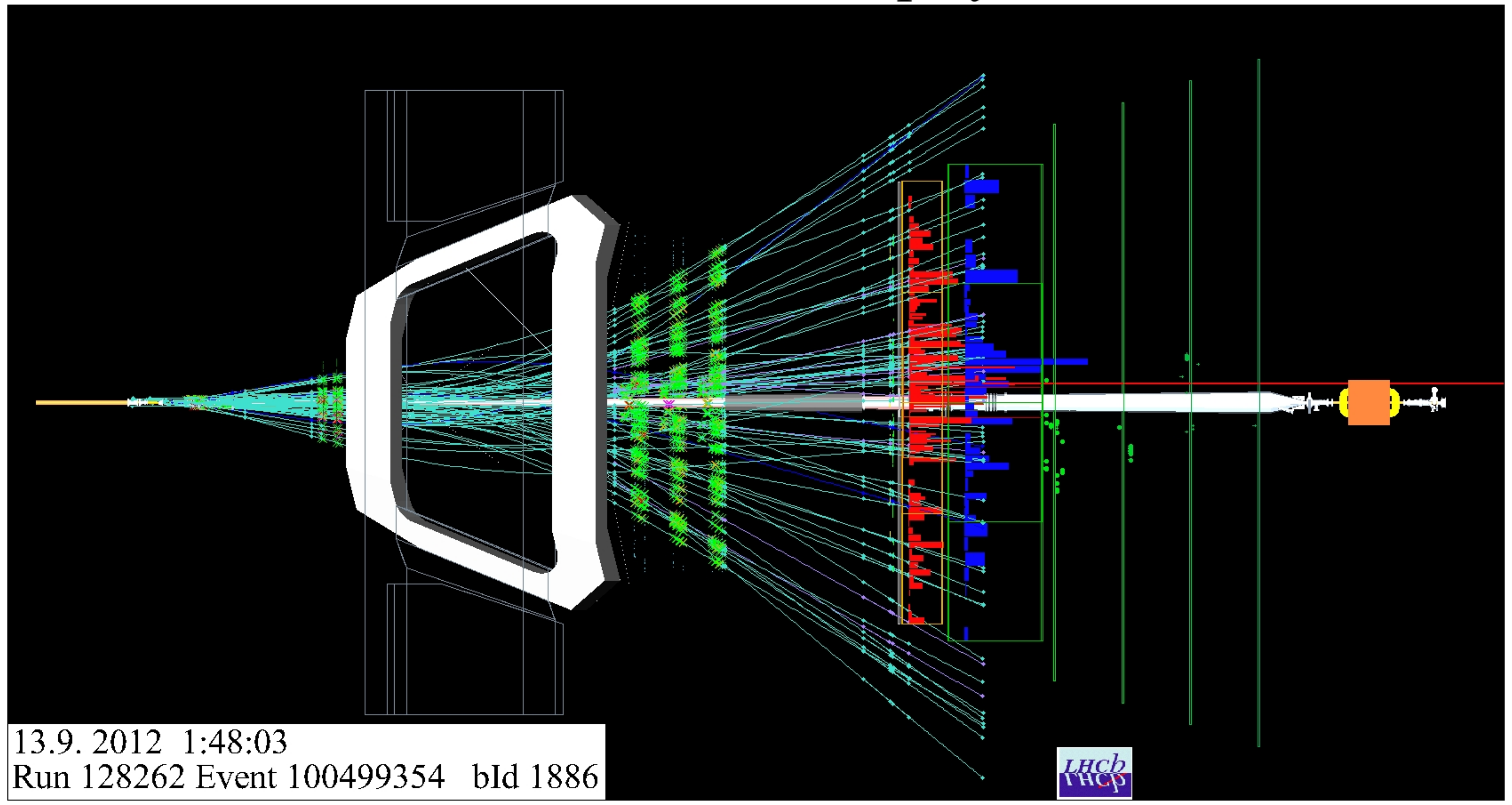
Lorenzo Sestini - INFN Padova

Misura della massa della W a CDF - Dipartimento di Fisica G. Galilei e INFN - Padova - 9/5/2022

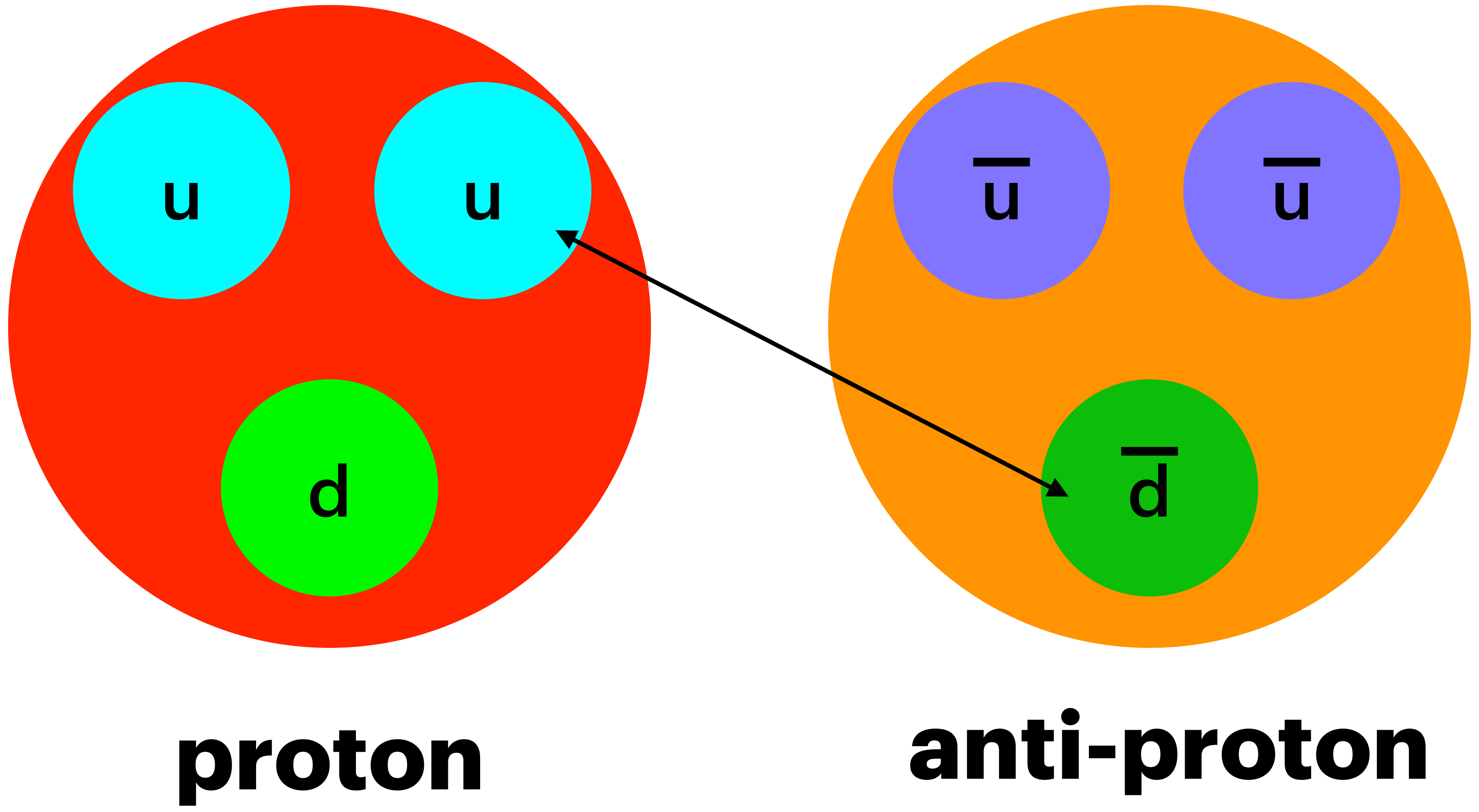
W mass measurement with *pp* collisions

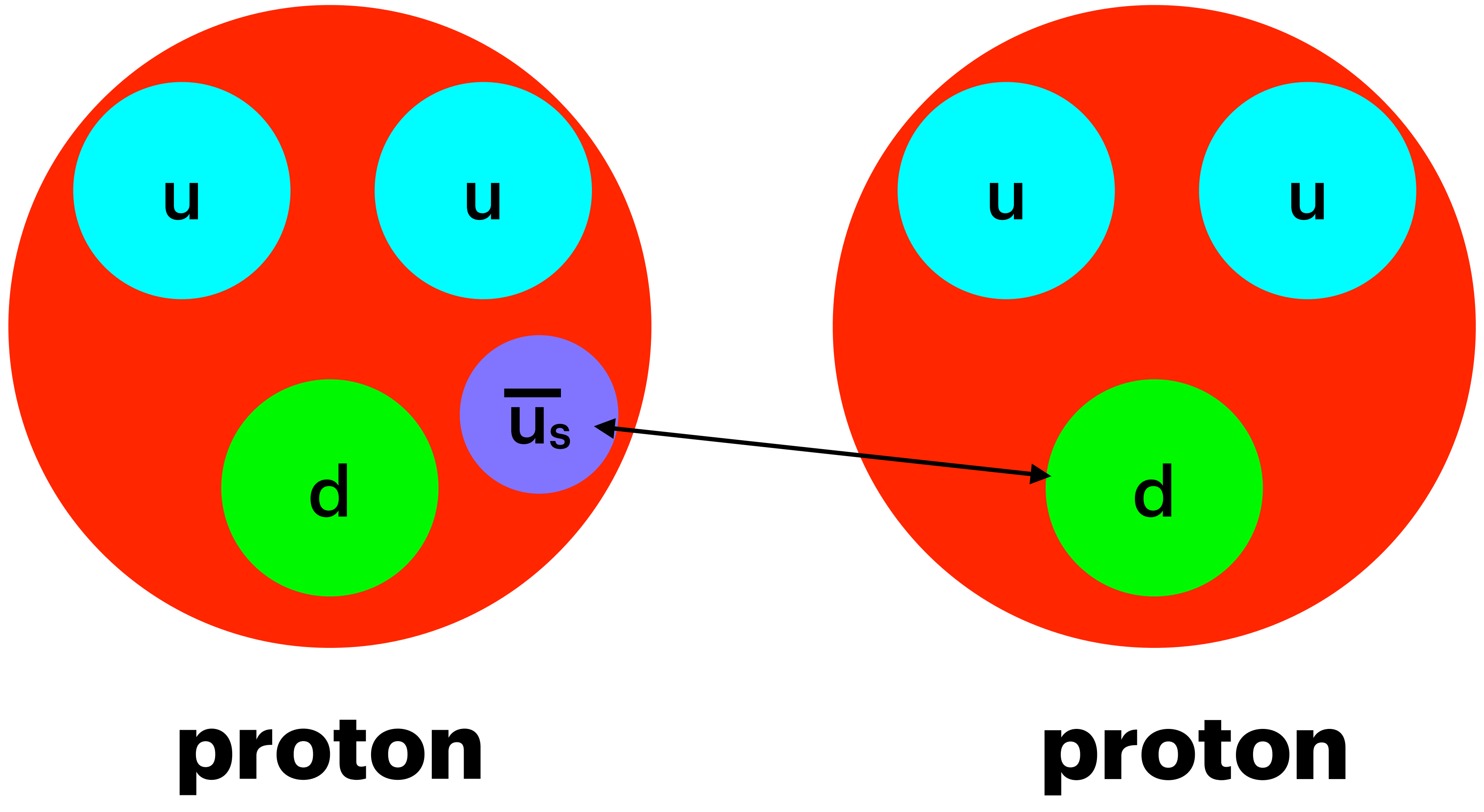
- The environment of proton-proton colliders is probably the **most challenging** for the W boson mass measurement
- Experimental conditions are not as clean as at lepton colliders
- The W boson production modeling is more under control at proton-anti-proton colliders
- Nevertheless LHC experiments are collecting an incredible amount of collision data
- Millions of W bosons can be analyzed to extract the W boson mass measurements
- **ATLAS, CMS and LHCb have already accepted the challenge!**





Proton-anti-proton vs proton-proton

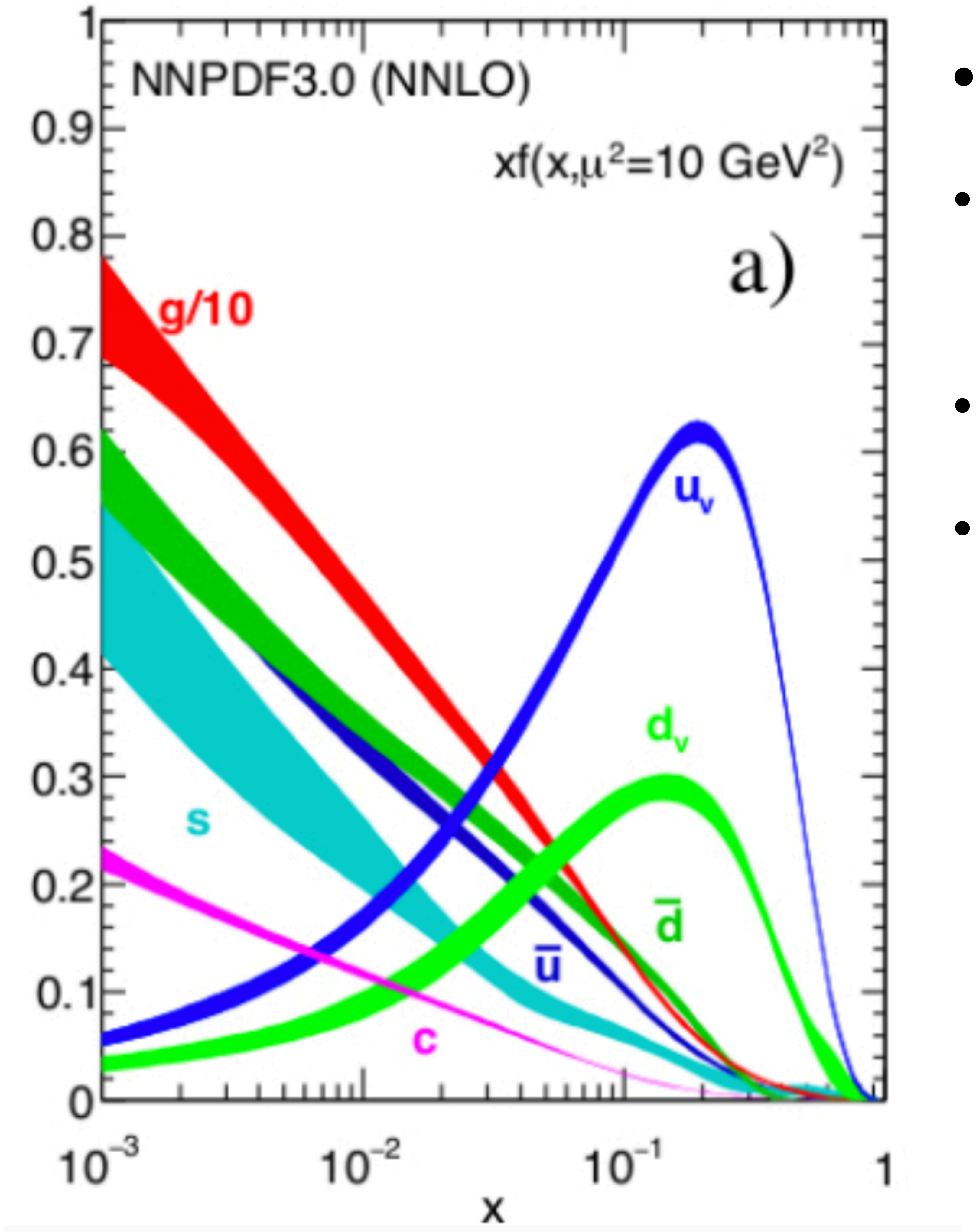




- At Tevatron W boson is mainly produced via valence quark interactions
- At LHC mainly through valence-sea quarks interaction

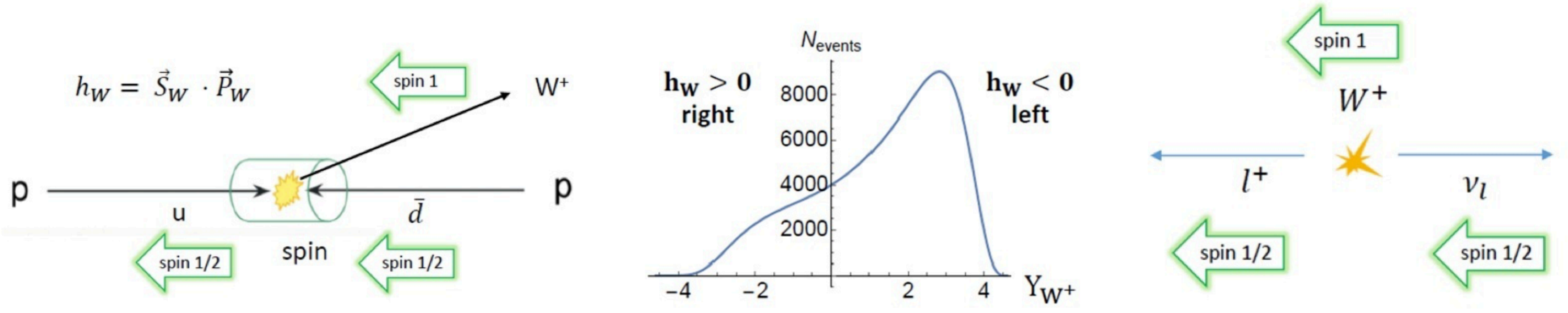
Knowledge of Parton Distribution Functions is fundamental for modeling the W boson production

Parton distribution functions



x = fraction of proton momentum taken by the parton

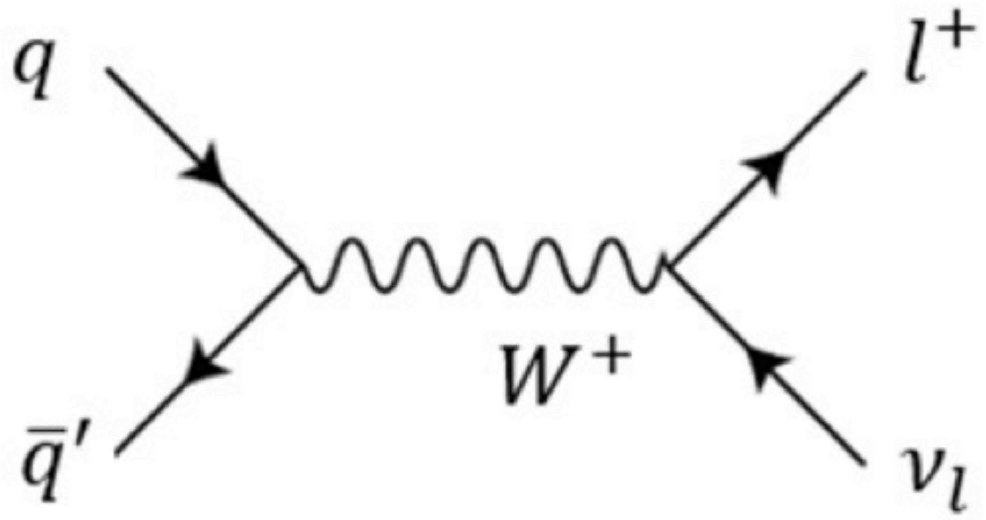
- **Larger uncertainties for sea quarks PDFs**
- At LHC 20% of W bosons are produced by heavy quarks from the sea (just 5% at CDF)
- At LHC W bosons are mainly produced with negative helicity
- PDFs uncertainties propagate in the model through the helicity-dependent cross-sections

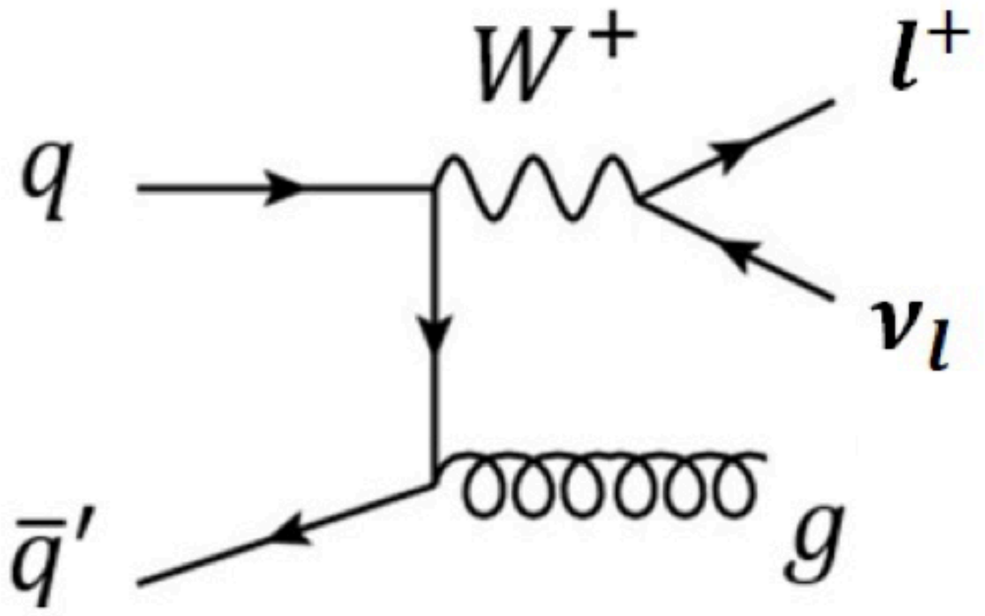


https://www.roma1.infn.it/exp/cms/tesiPHD/tesi_phd_completate/cipriani.pdf

W boson cross section

leading diagrams





$P_T(W)=0$

$P_T(W)>0$

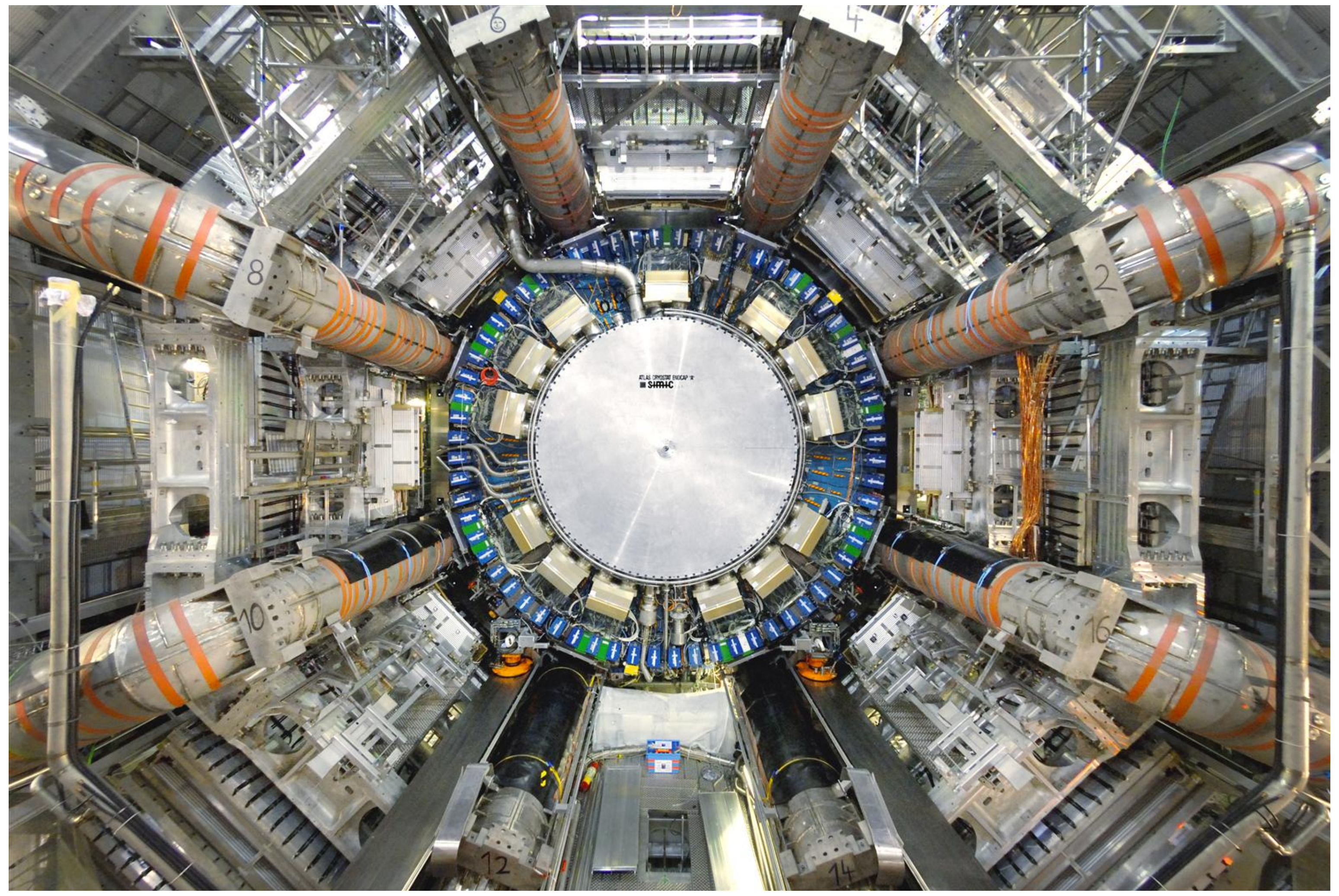
A_i = angular coefficients: ratio between helicity dependent and unpolarized cross-sections

Angular-integrated cross-section

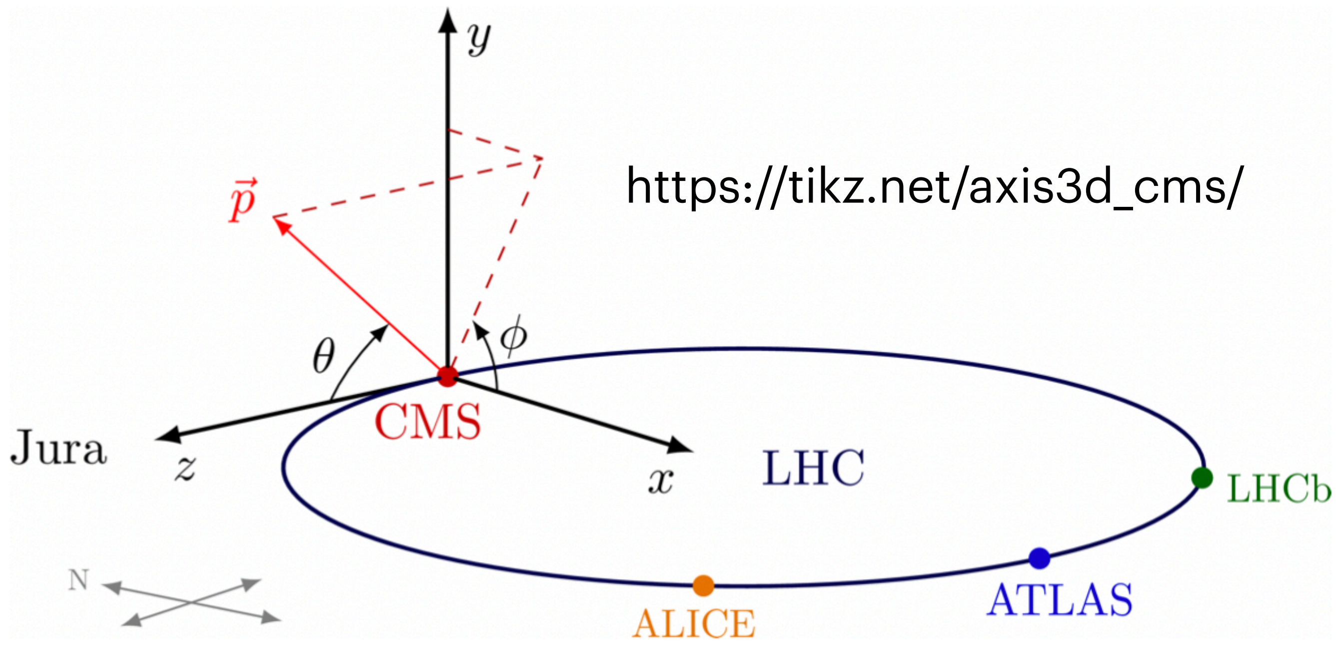
$$\frac{d\sigma}{dp_T^2\, dy\, dm\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma}{dp_T^2\, dy\, dm} \times [(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta)$$
$$+ A_1 \sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta$$
$$+ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi].$$

Experiments

ATLAS

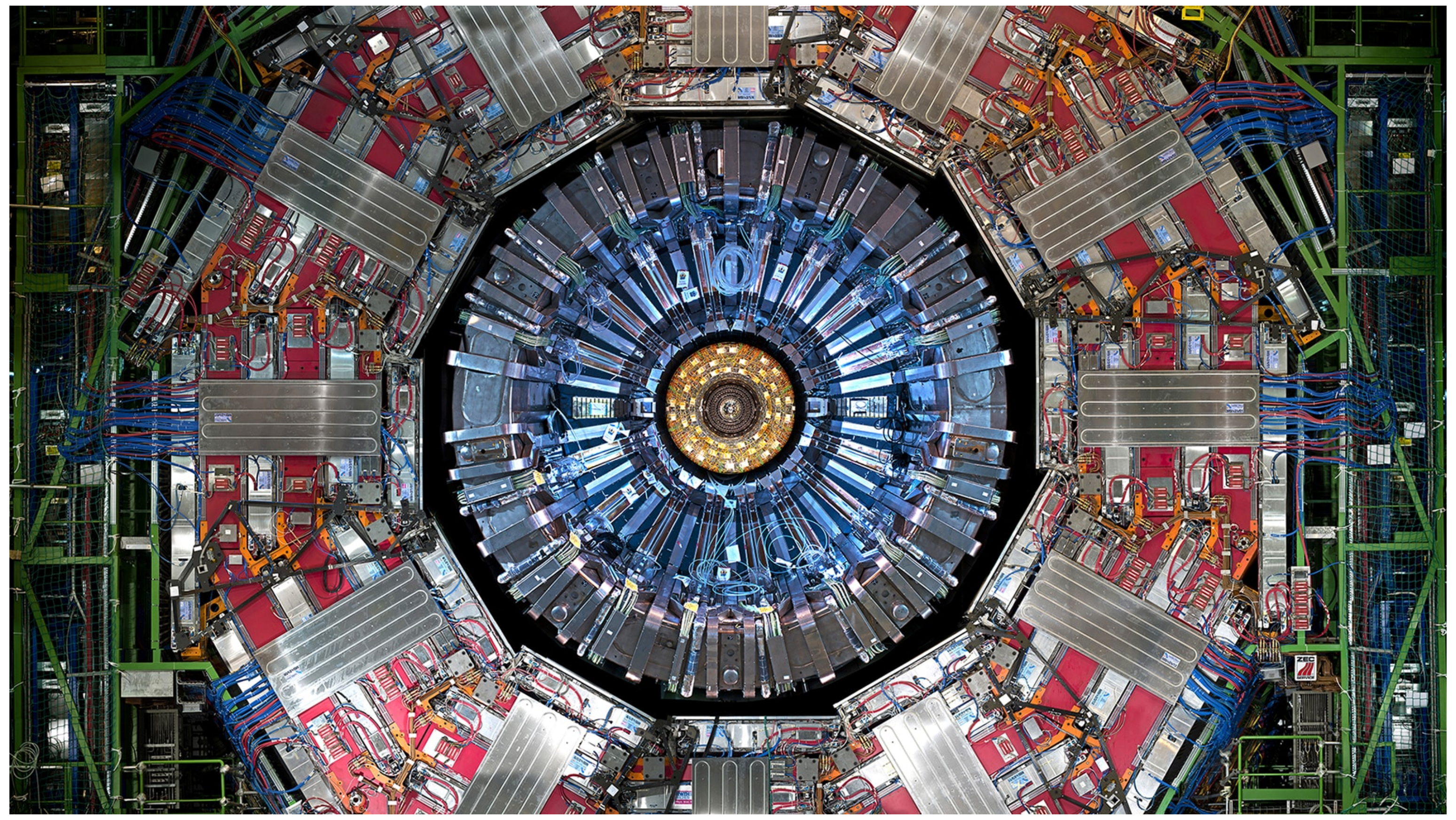


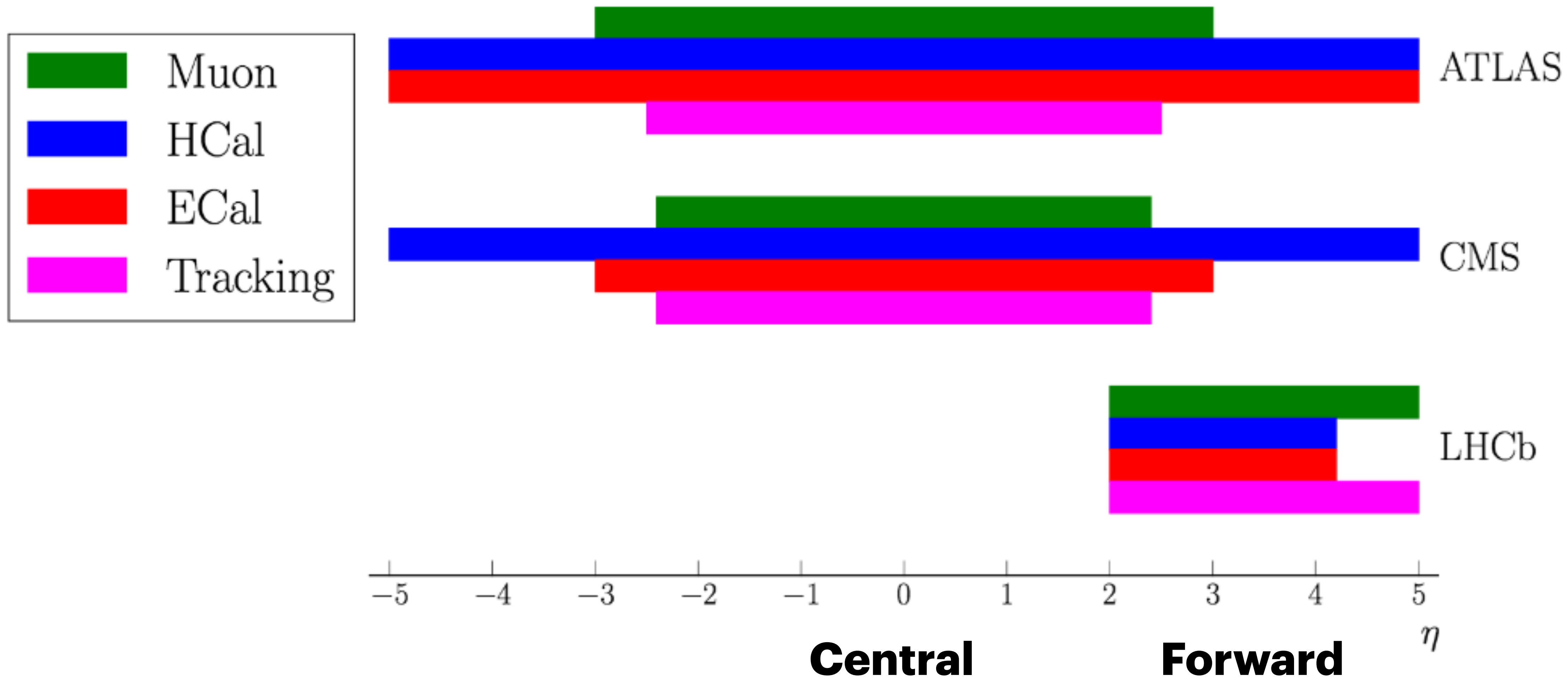
LHCb



https://tikz.net/axis3d_cms/

CMS

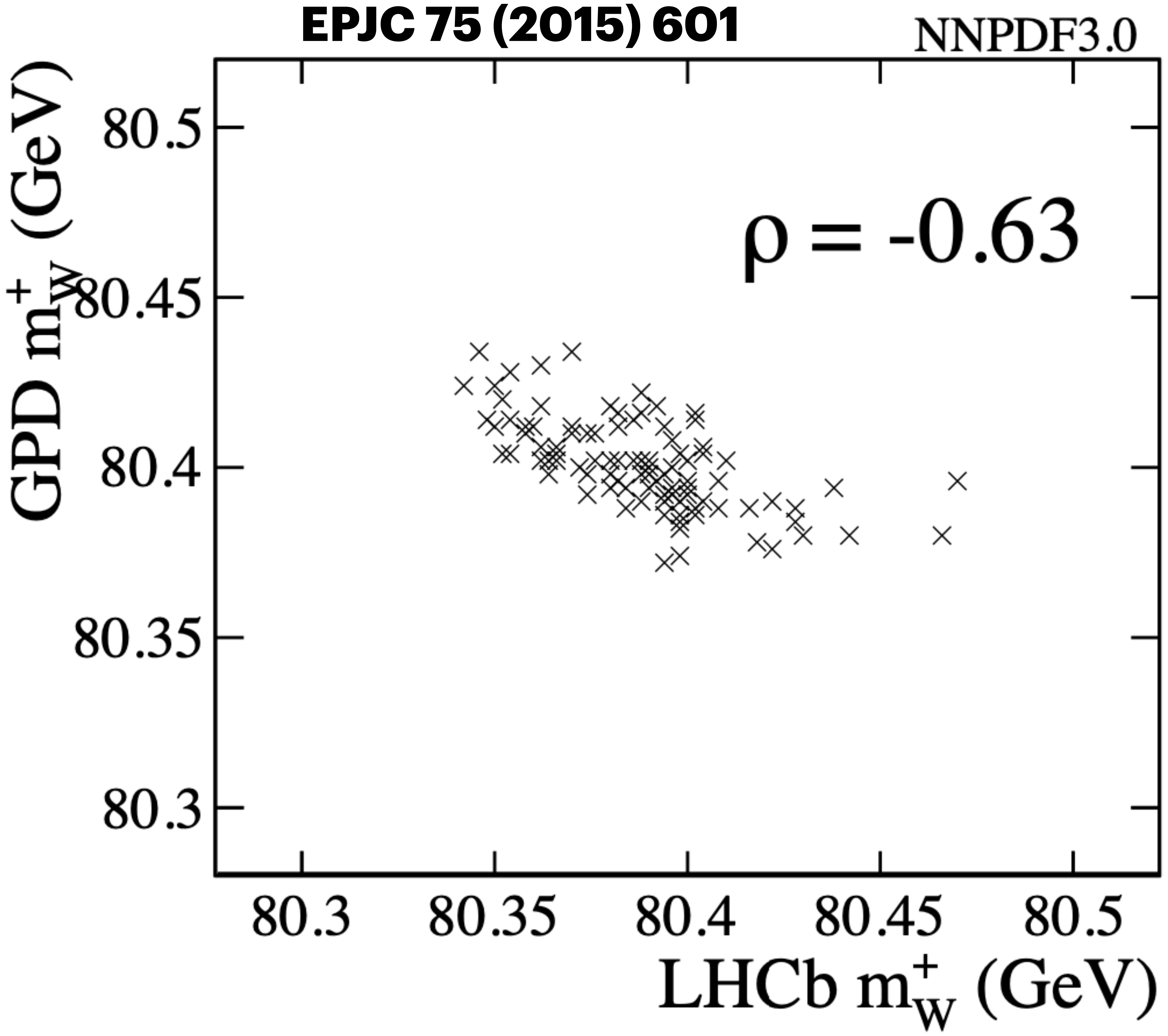




$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Complementarity

EPJC 75 (2015) 601



GPD = General Purpose Detector = ATLAS/CMS

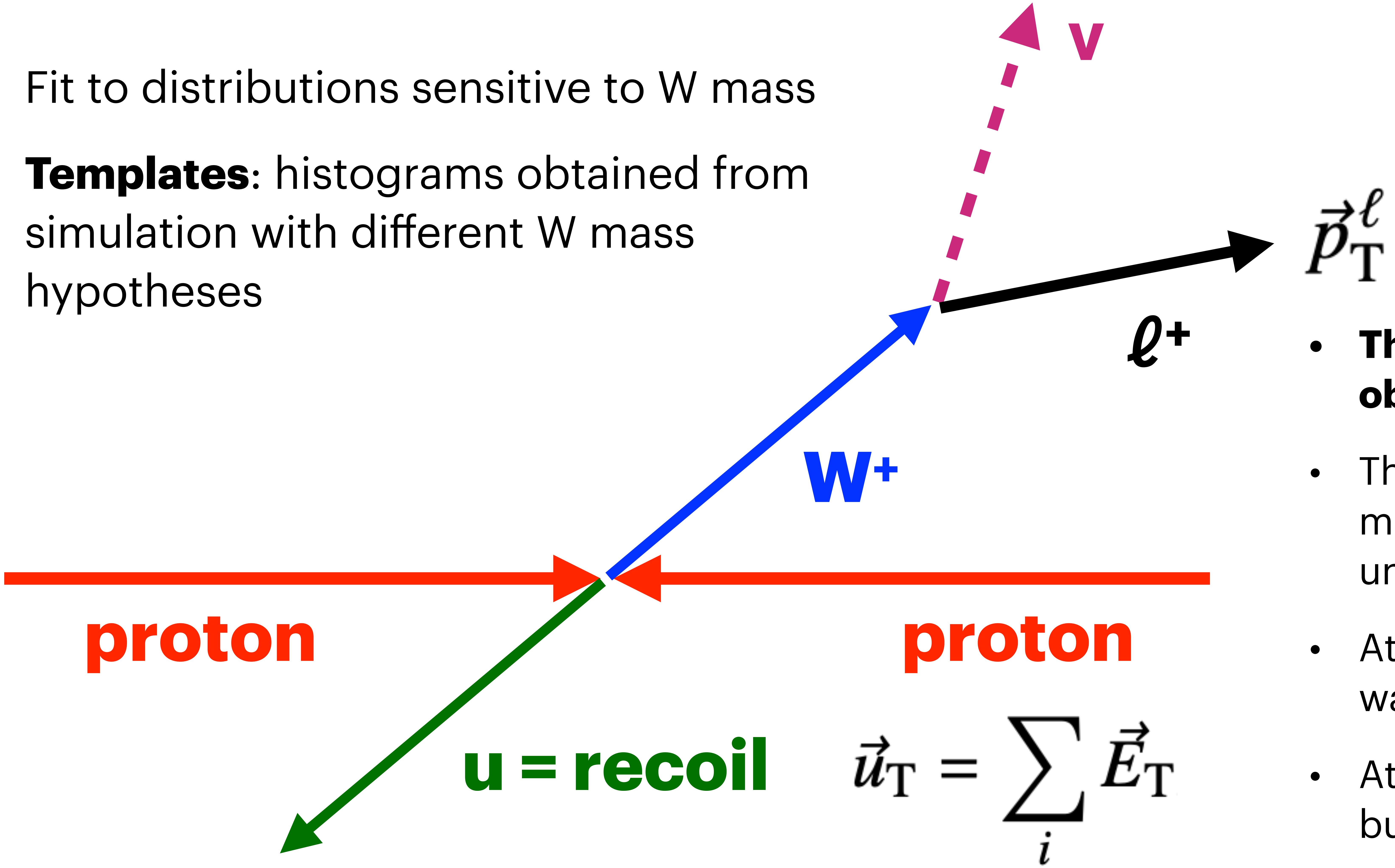
- PDFs uncertainties in the W mass measurement are anti-correlated between the central and forward region
- Combining ATLAS/CMS+LHCb can reduce the PDFs uncertainty
- All the three experiments can significantly contribute in a LHC-wide average
- **The overall average is ultimately the quantity that matters**

Analysis techniques

- Fit to distributions sensitive to W mass
- **Templates**: histograms obtained from simulation with different W mass hypotheses

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right)$$

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$$

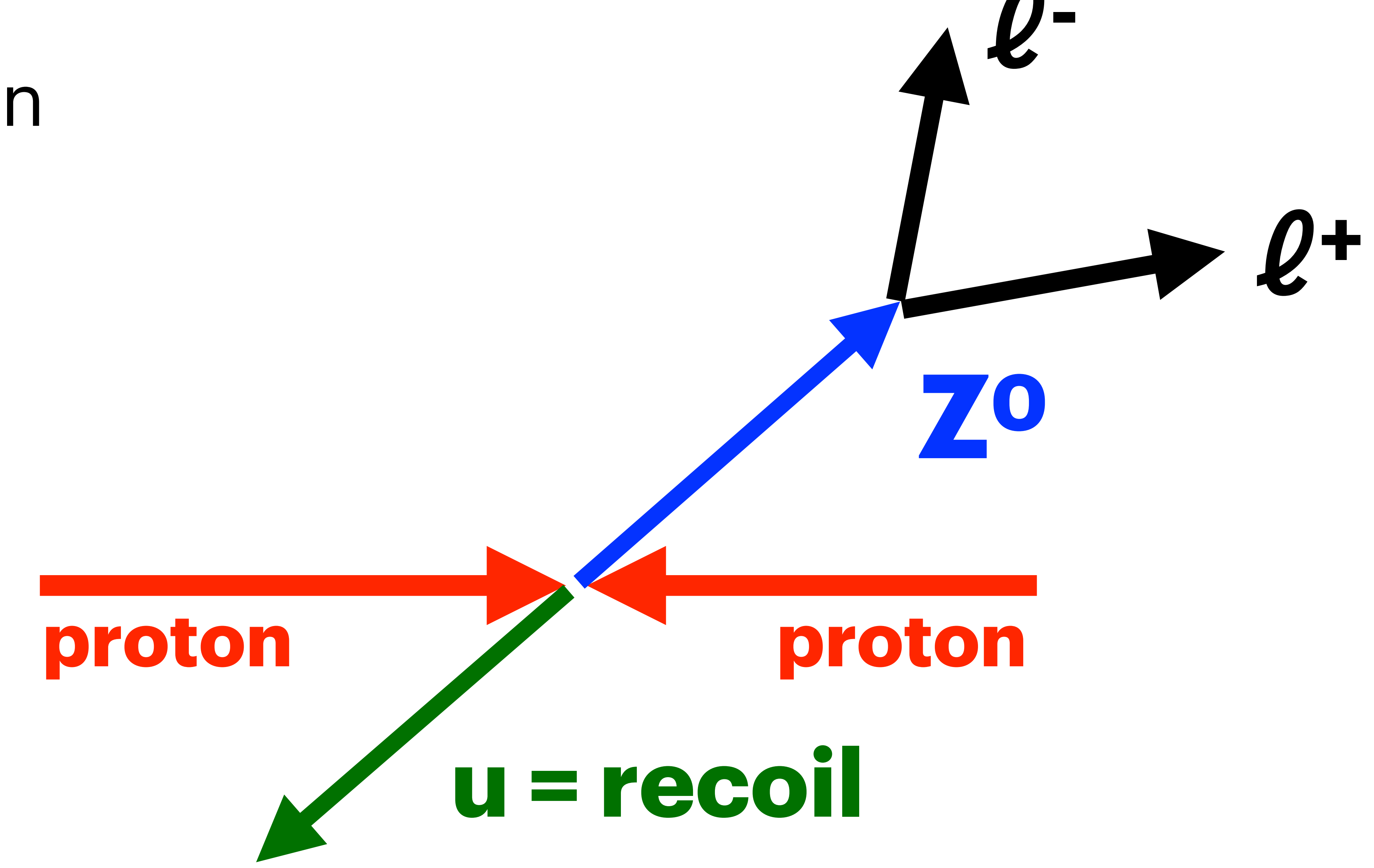


$$\vec{u}_{\mathrm{T}} = \sum_i \vec{E}_{\mathrm{T}}$$

- **The recoil is the most difficult observable to model at LHC**
- The recoil measurement is affected by multiple *pp* interactions (pile-up), underlying event
- At ATLAS/CMS in Run 1-2 the pile-up was ~25-50, at CDF ~1
- At LHCb in Run 1-2 the pile-up was ~1 but recoil not available

Analysis techniques

- Large samples of $Z^0 \to \ell^+\ell^-$ for tuning and validation
- Z^0 fully reconstructed
- energy scale and resolution can be determined by comparing Z^0 data and simulation
- Tag & Probe technique to measure lepton efficiencies in data



- Templates depend from the W boson production model, should be corrected for data/simulation differences

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

Inv. mass: Breit Wigner

Rapidity: fixed order pQCD

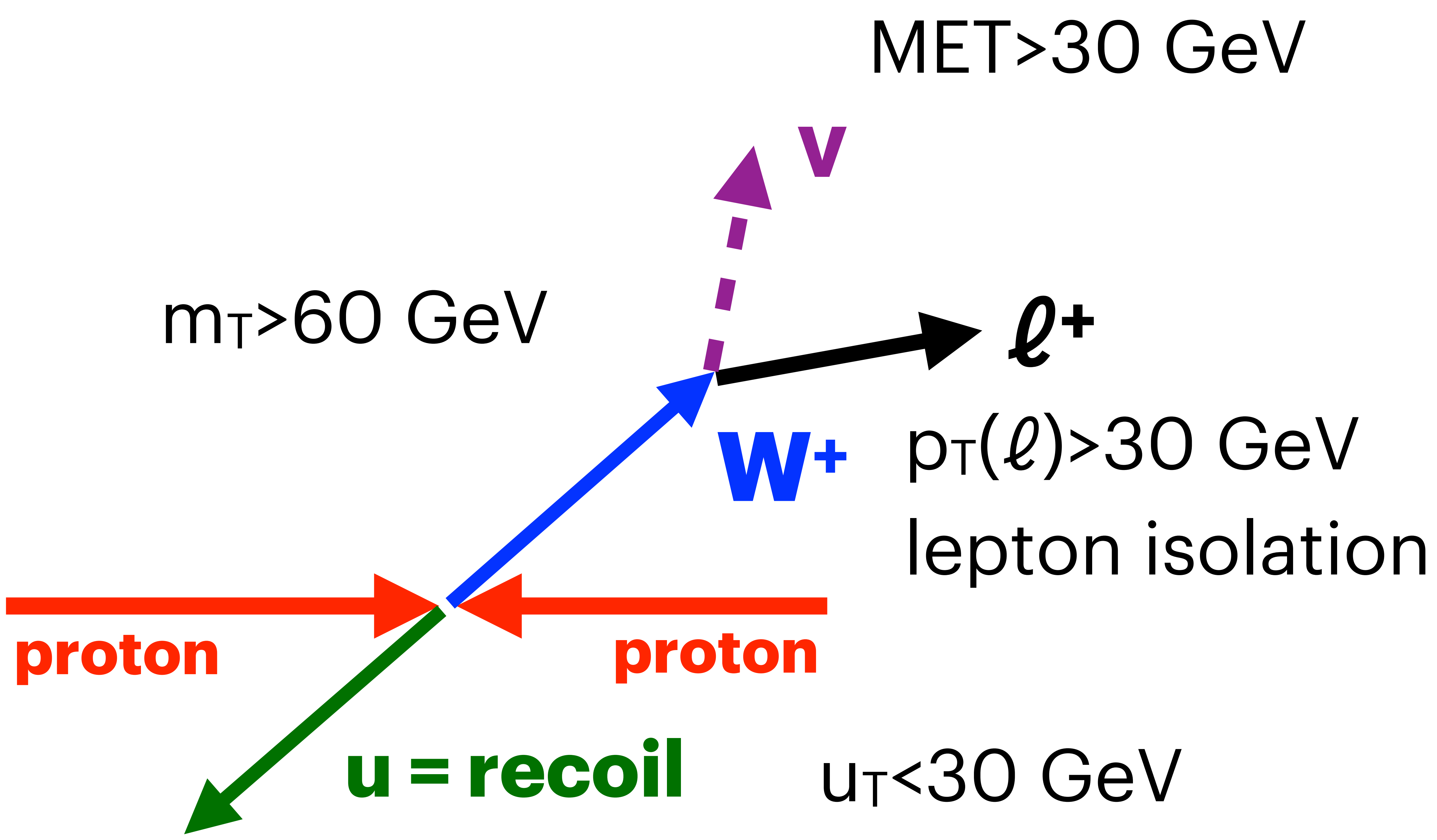
p_T: parton shower

Angular coefficients: fixed order pQCD

ATLAS W mass measurement

Eur. Phys. J. C 78 (2018) 110

- Collisions at 7 TeV, integrated luminosity 4.6 fb^{-1}



8M/6M W bosons are selected in muon/electron final state

$\|\eta_\ell\|$ range	0–0.8	0.8–1.4	1.4–2.0	2.0–2.4	Inclusive
$W^+ \to \mu^+\nu$	1 283 332	1 063 131	1 377 773	885 582	4 609 818
$W^- \to \mu^-\bar{\nu}$	1 001 592	769 876	916 163	547 329	3 234 960
$\|\eta_\ell\|$ range	0–0.6	0.6–1.2		1.8–2.4	Inclusive
$W^+ \to e^+\nu$	1 233 960	1 207 136		956 620	3 397 716
$W^- \to e^-\bar{\nu}$	969 170	908 327		610 028	2 487 525

Fit to $p_T(\ell)$ and m_T distributions

Baseline simulation: Powheg+Pythia

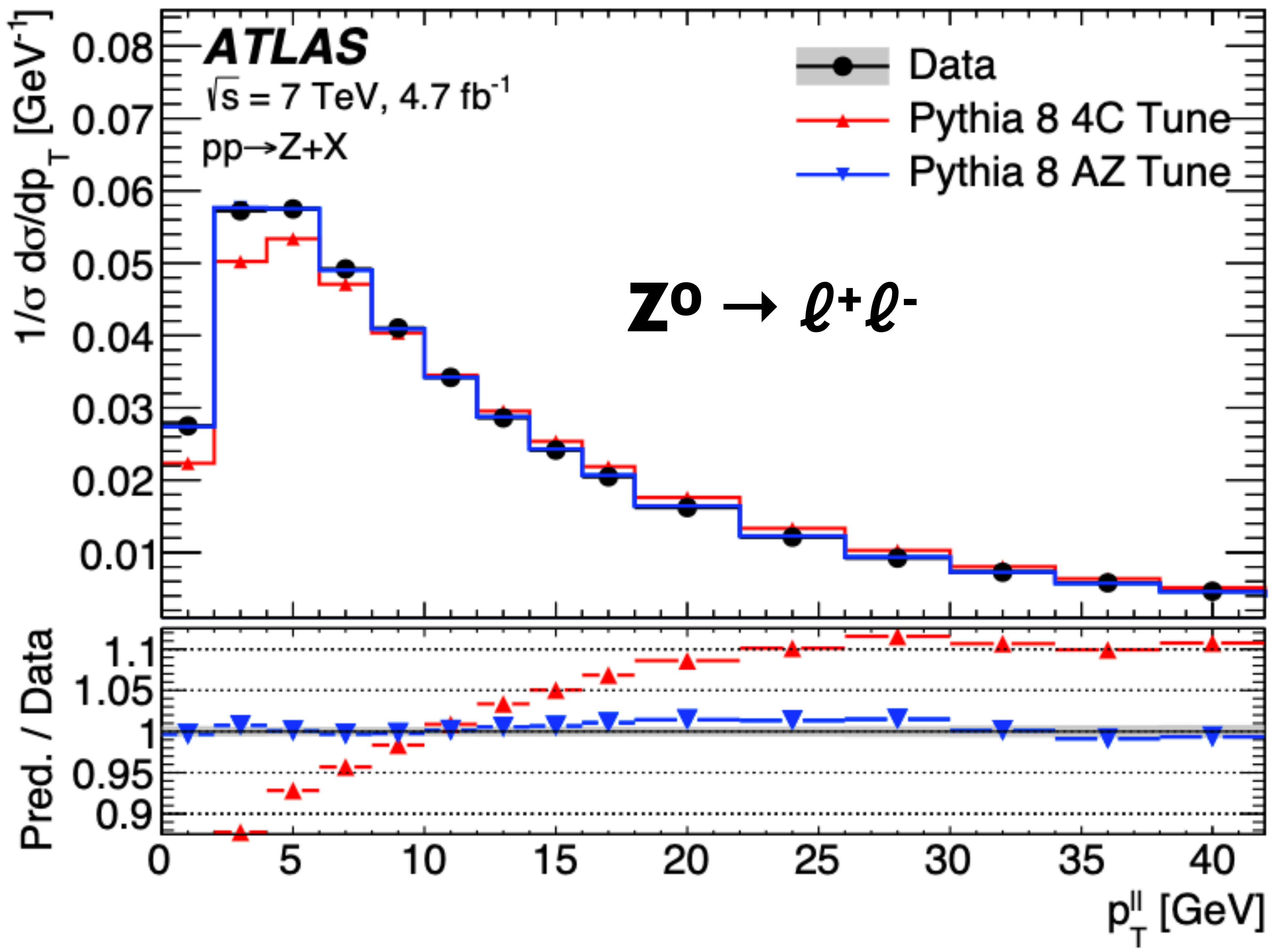
But corrections are applied

ATLAS: $p_T(W)$ model

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

p_T: parton shower

- At a given rapidity $p_T(W)$ model depends from Pythia 8
- **Most W bosons have p_T<30 GeV**, not-perturbative effects should be included
- Pythia 8 QCD parameters are fitted to match data/MC distributions in $p_T(Z^0)$



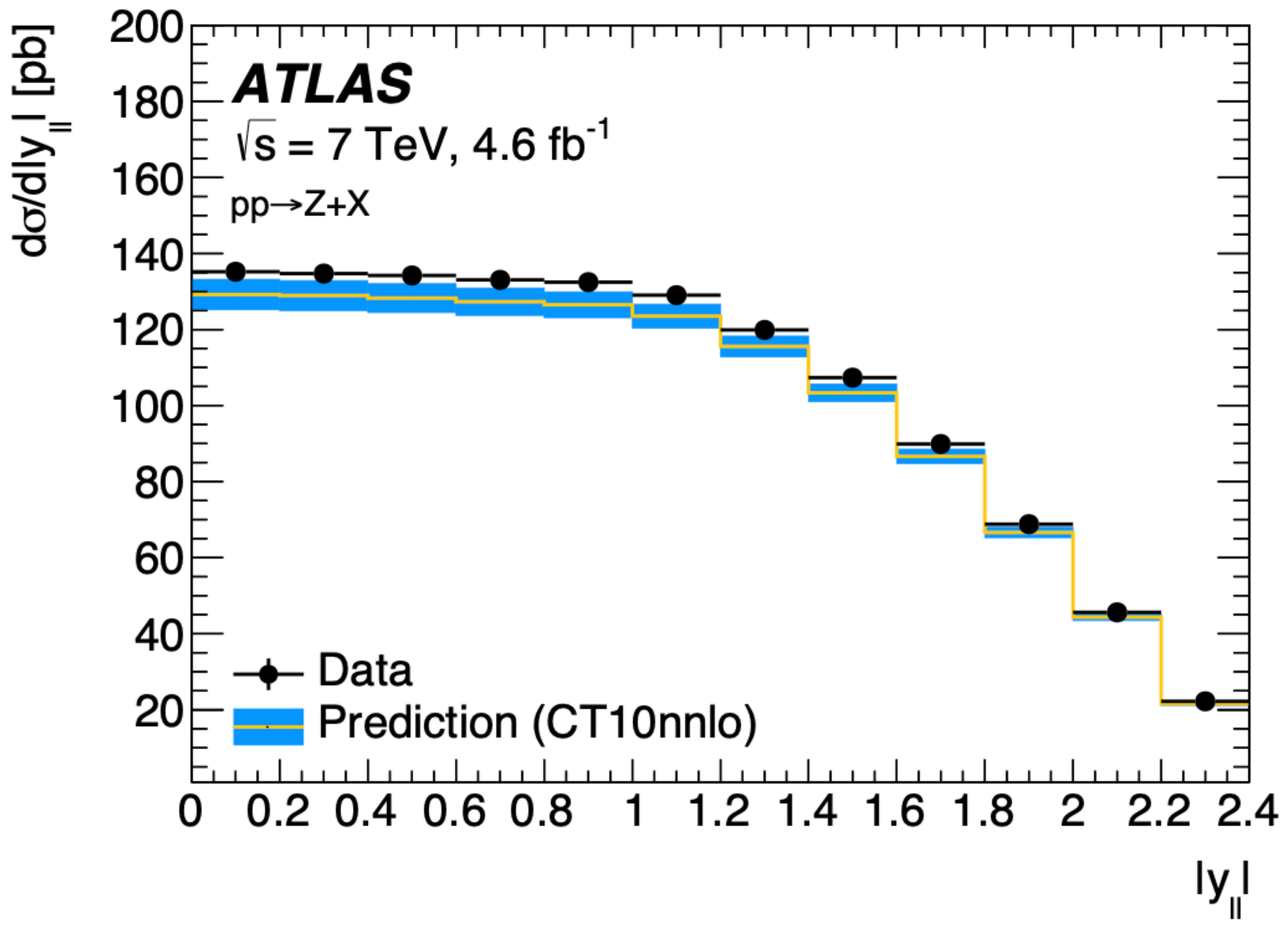
ATLAS: W rapidity and angles

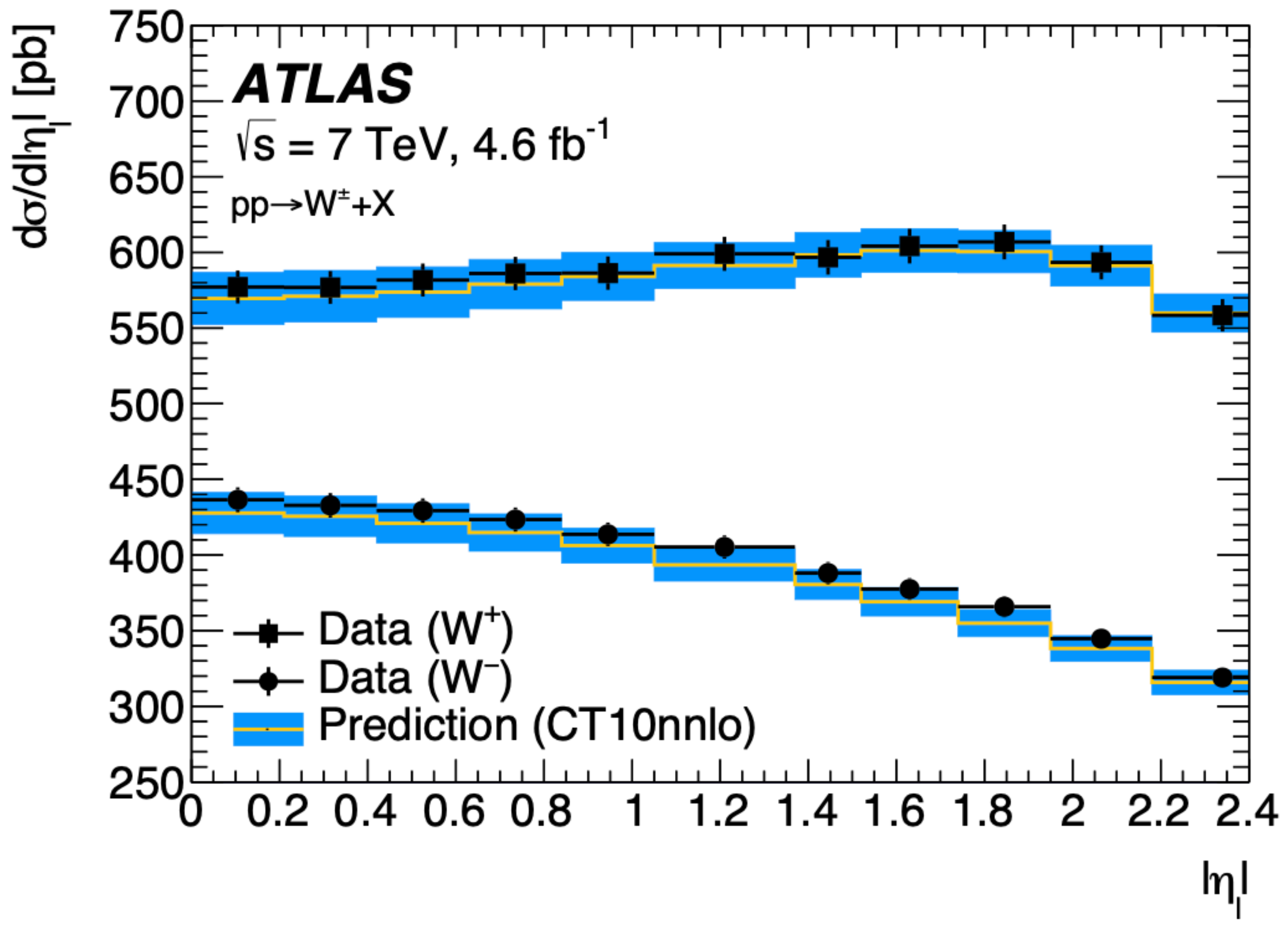
$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

Rapidity: fixed order pQCD

Angular coefficients: fixed order pQCD

- Inclusive rapidity reweight according to NNLO QCD predictions evaluated with DYNNLO
- Angular part reweighted for A'_i evaluated at $O(\alpha_s^2)$:



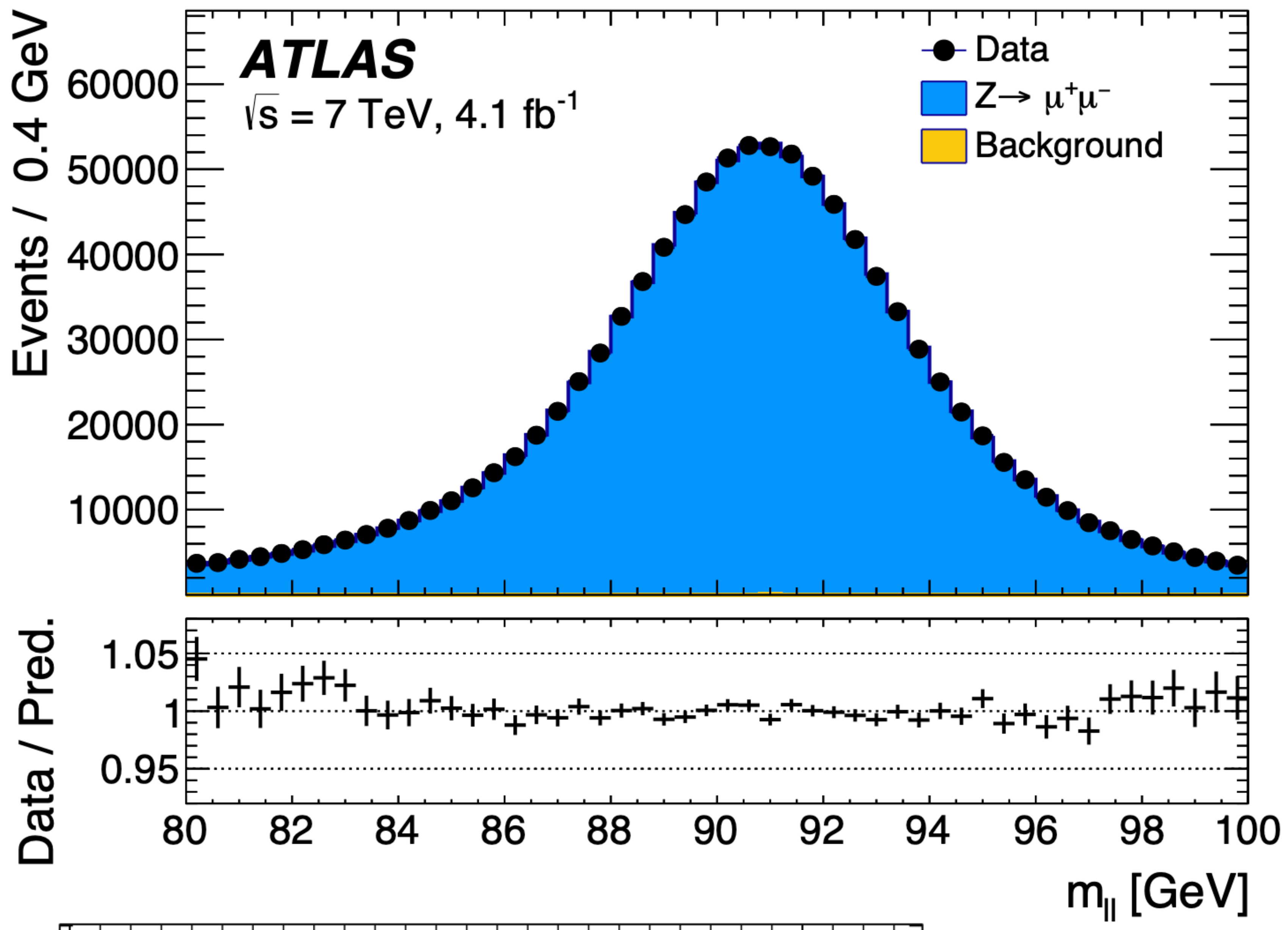


Model uncertainties

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

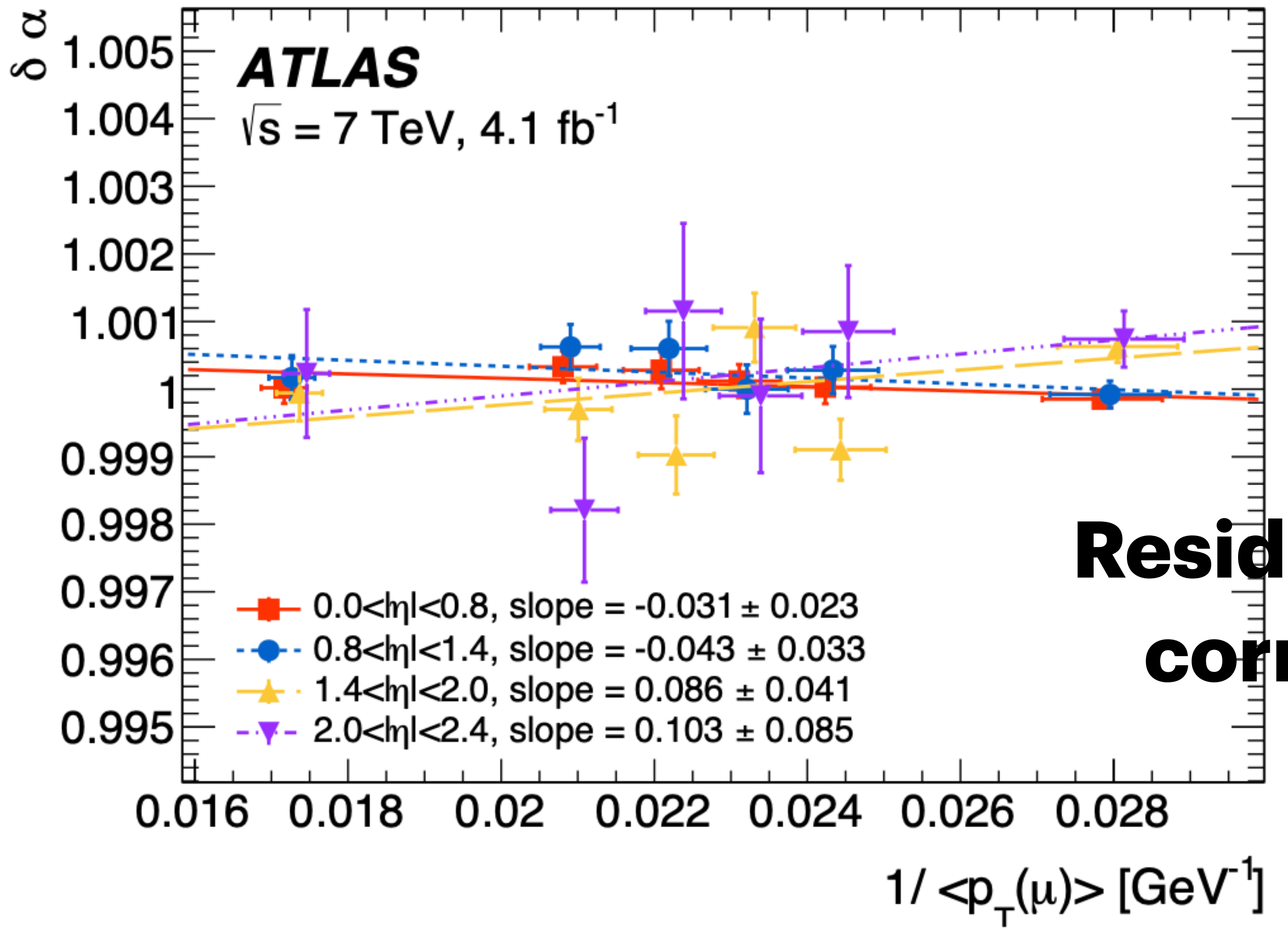
ATLAS: muon reconstruction

- Muon momentum scale and resolution obtained by comparing the invariant mass distribution in $Z^0 \to \mu^+\mu^-$ data/simulation
- Efficiencies with tag & probe $Z^0 \to \mu^+\mu^-$
- Uncertainties on m_W mainly due to the scaling from Z^0 to W (different p_T distributions)



Momentum scale: ratio btw reconstructed momentum in data and simulation

$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	1.2
Sagitta bias	0.7	0.8	1.7	1.7	3.1	3.1	4.5	4.3	0.6	0.6
Reconstruction and isolation efficiencies	4.0	3.6	5.1	3.7	4.7	3.5	6.4	5.5	2.7	2.2
Trigger efficiency	5.6	5.0	7.1	5.0	11.8	9.1	12.1	9.9	4.1	3.2
Total	11.4	11.4	16.9	17.0	30.4	31.0	112.0	116.1	9.8	9.7

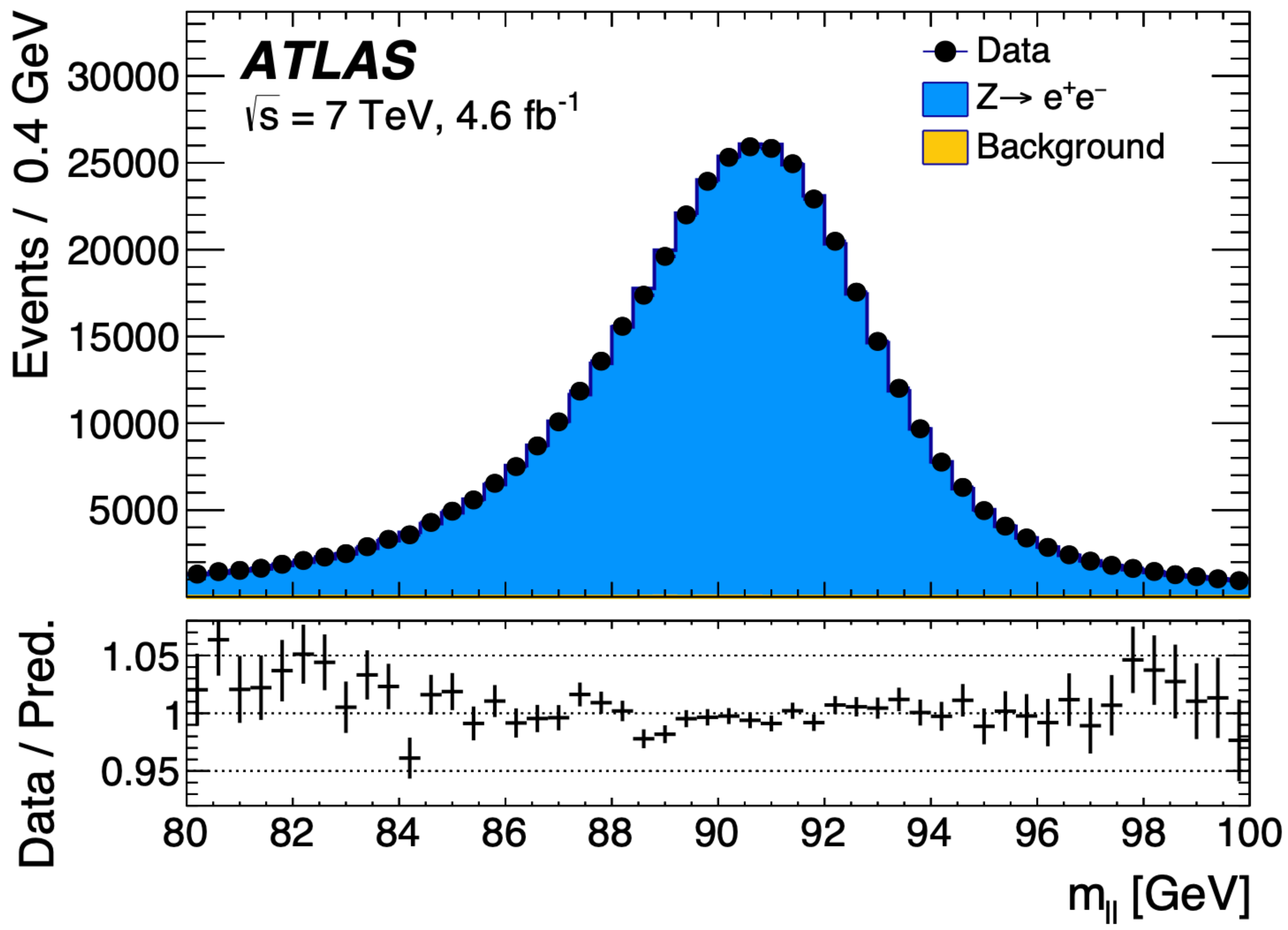


Residual scale correction

ATLAS: electron reconstruction

- Electron energy scale and resolution correction from $Z^0 \to e^+e^-$
- Efficiencies with $Z^0 \to e^+e^-$ tag & probe

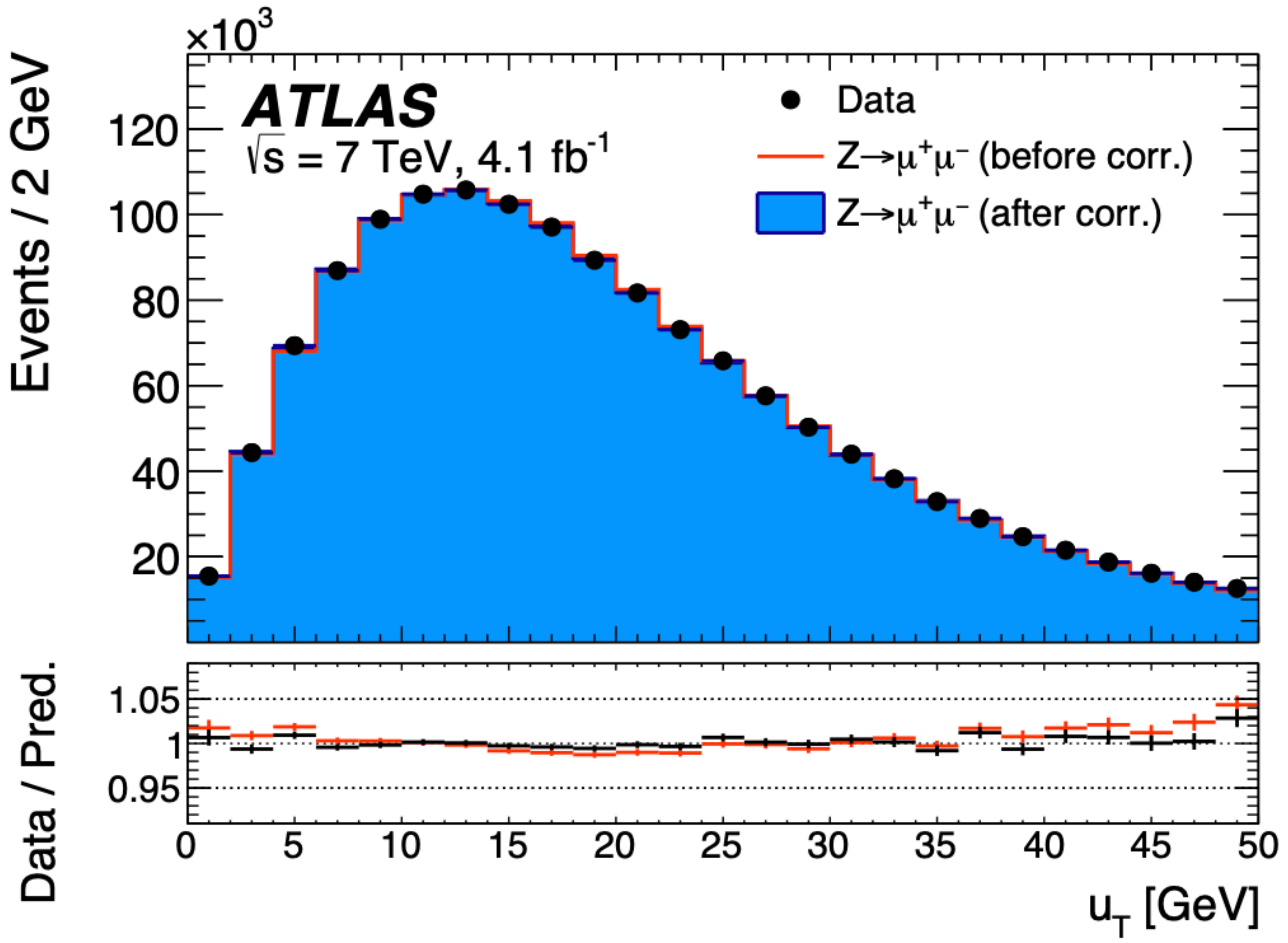
$\lvert\eta_\ell\rvert$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
Energy tails	2.3	3.3	2.3	3.3	2.3	3.3	2.3	3.3
Reconstruction efficiency	10.5	8.8	9.9	7.8	14.5	11.0	7.2	6.0
Identification efficiency	10.4	7.7	11.7	8.8	16.7	12.1	7.3	5.6
Trigger and isolation efficiencies	0.2	0.5	0.3	0.5	2.0	2.2	0.8	0.9
Charge mismeasurement	0.2	0.2	0.2	0.2	1.5	1.5	0.1	0.1
Total	19.0	17.5	21.1	19.4	30.7	30.5	14.2	14.3



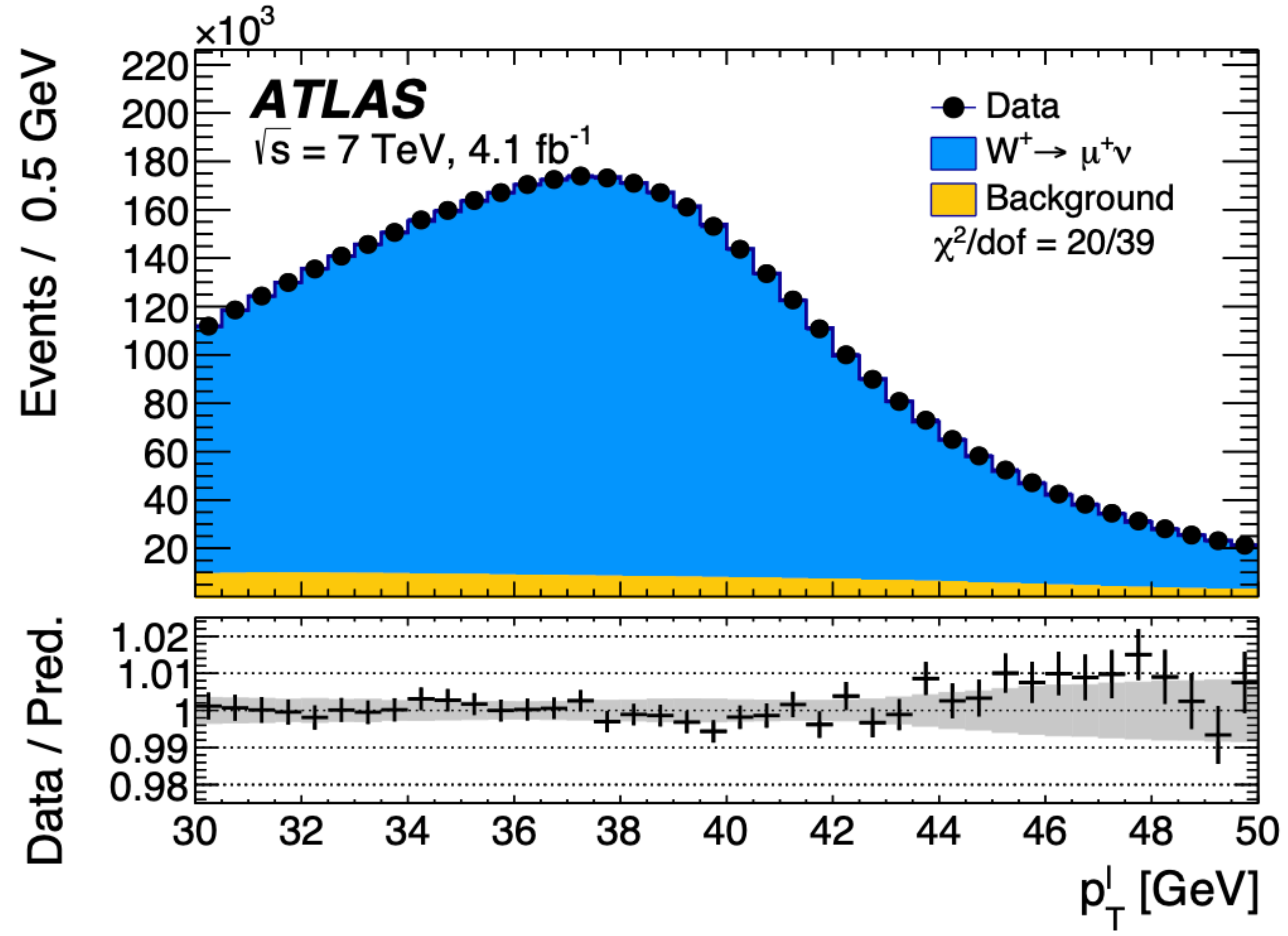
ATLAS: recoil calibration

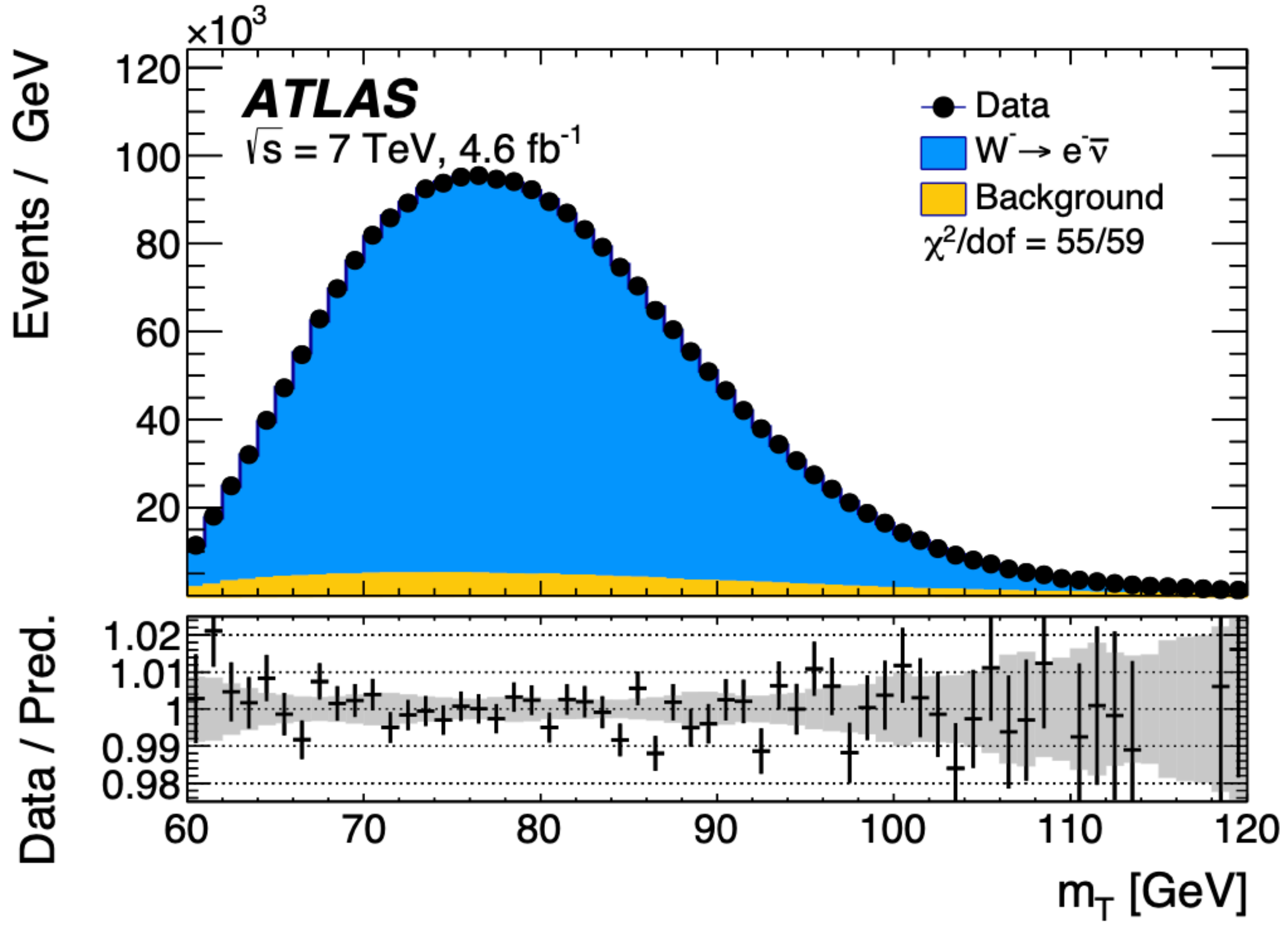
- Corrections obtained with $Z^0 \to \mu^+\mu^-$
- **Event activity correction**
- Transfer from Z^0 to W: assuming the same p_T-dependence of data/MC differences

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]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
ΣE_T^* correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

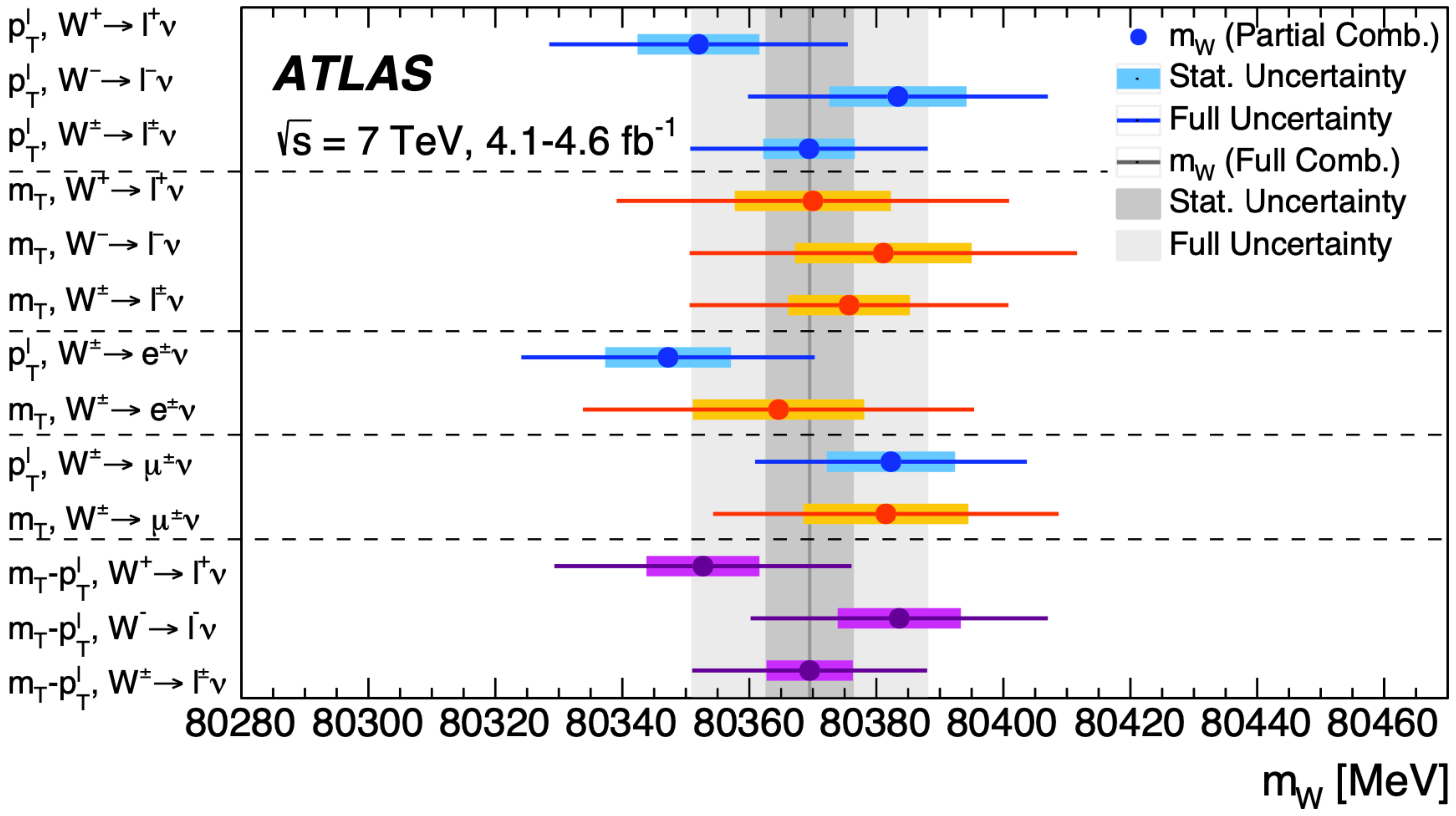


ATLAS: W mass results





Compatibility between different categories



The pseudo-W measurement of Z^0 boson mass is also performed as cross-check

Final result:

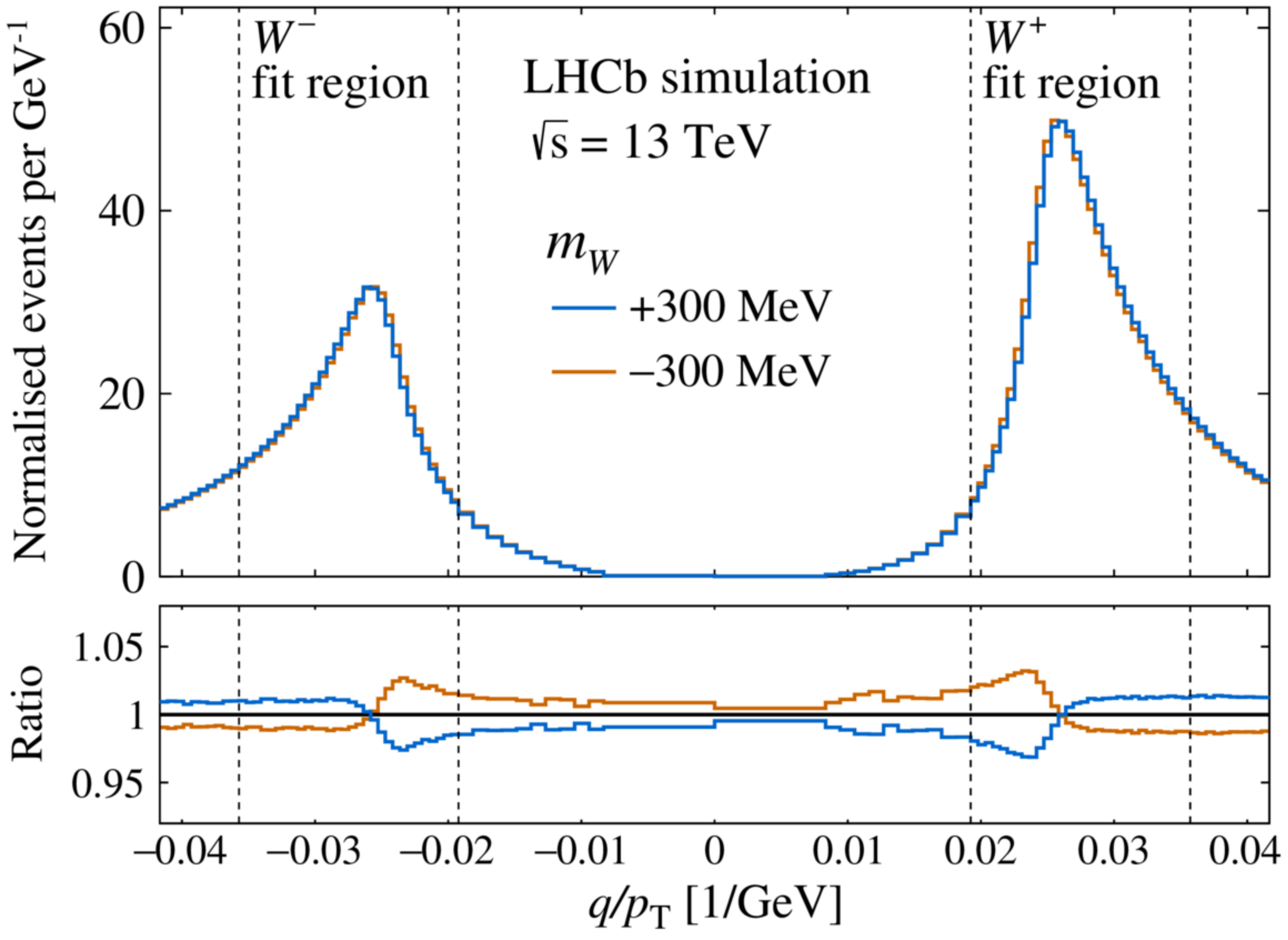
$$m_W = 80369.5 \pm 6.8\ \text{MeV(stat.)} \pm 10.6\ \text{MeV(exp. syst.)} \pm 13.6\ \text{MeV(mod. syst.)}$$
$$= 80369.5 \pm 18.5\ \text{MeV},$$

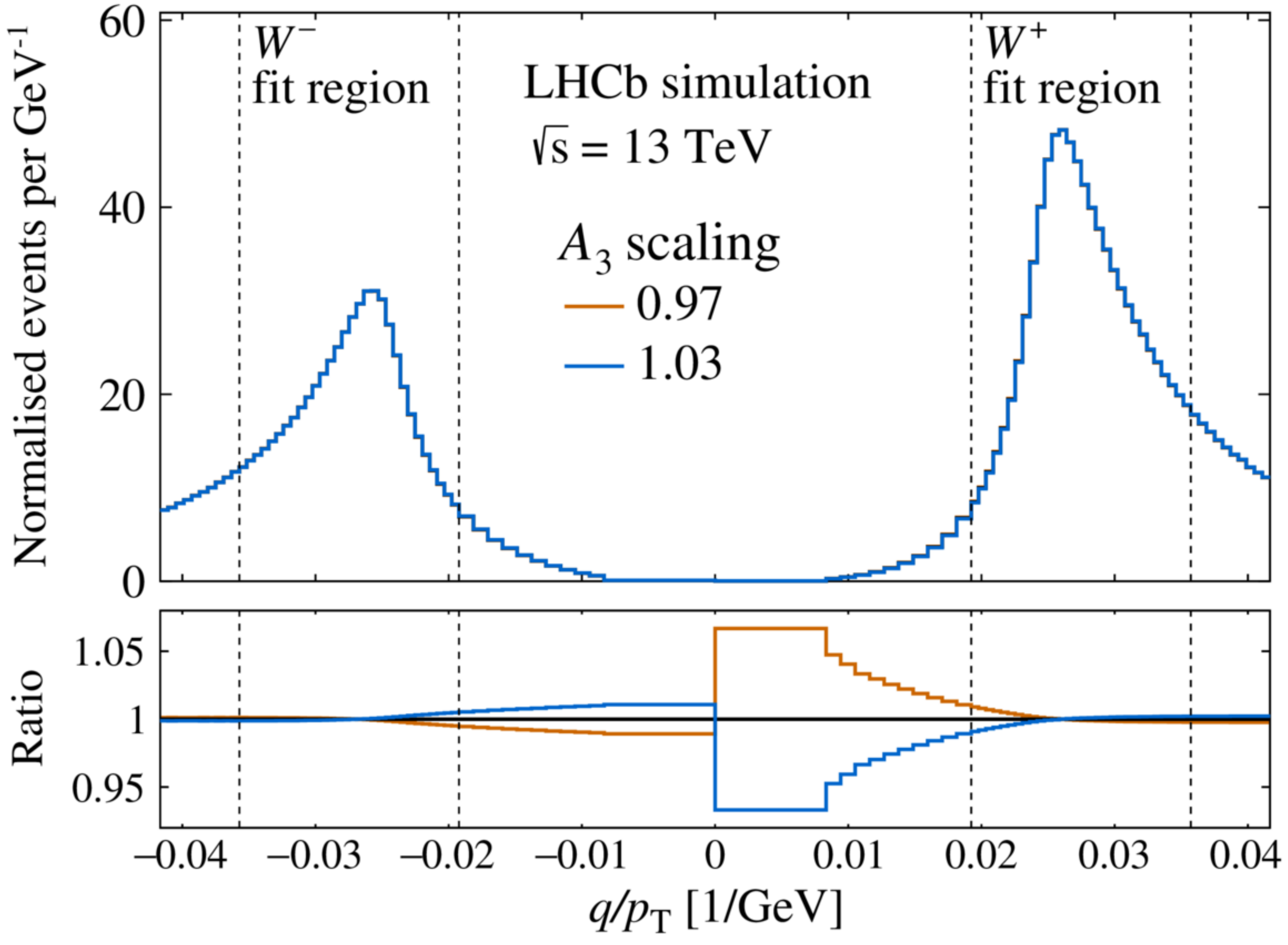
W mass measurement at LHCb

JHEP 01 (2022) 036

- Measurement with muon final state, just a part of the Run 2 dataset has been used (1.7 fb^{-1})
- Simultaneous fit to W boson q/p_T and $Z^0 \to \mu^+\mu^-$ boson ϕ^*
- $28 < p_T(\mu) < 52$ GeV is the optimal range for the fit: **2.4M W candidates**

$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T^Z}{M}$$





LHCb: modeling

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

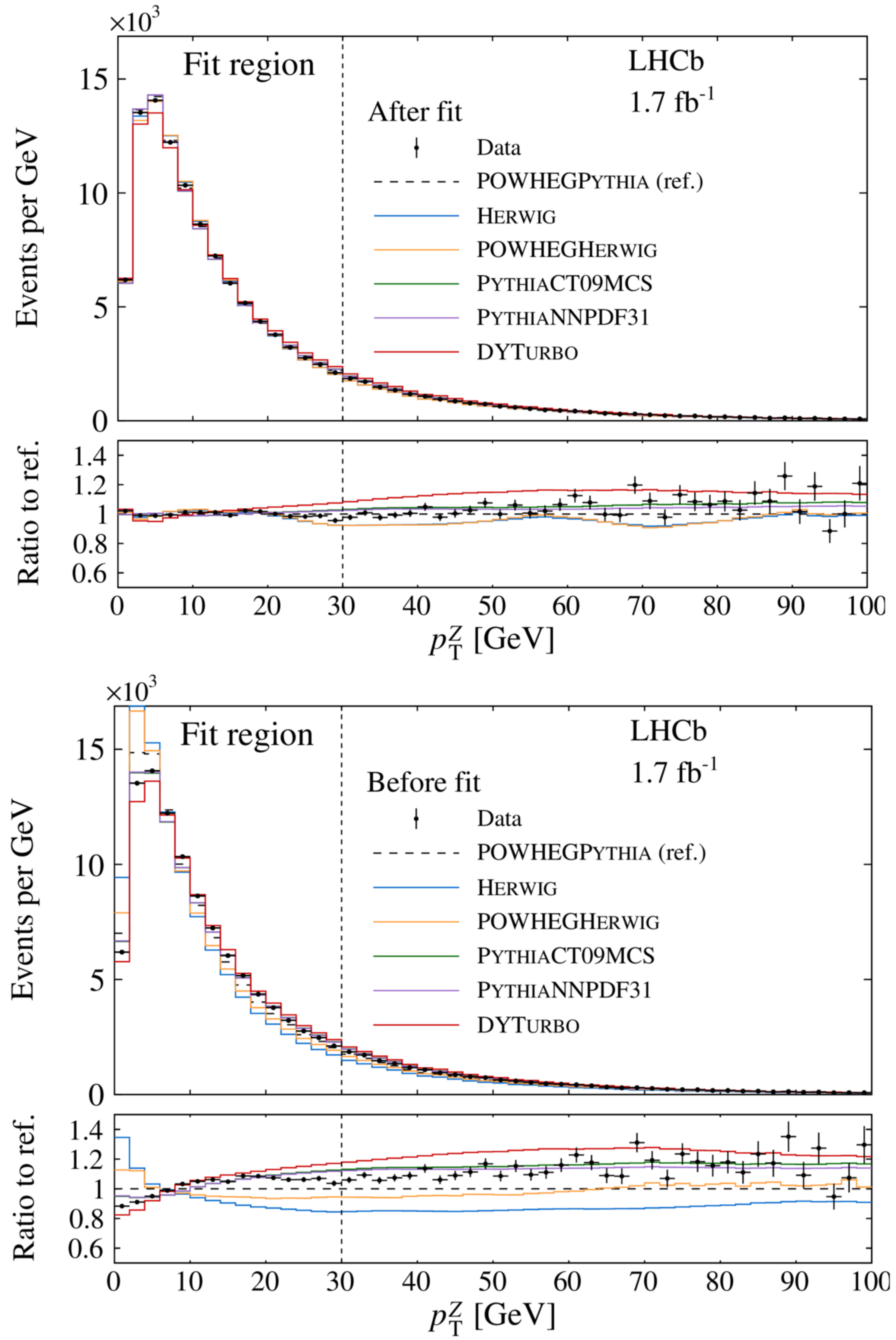
Inv. mass: Breit Wigner

Rapidity: fixed order pQCD

p_T: parton shower

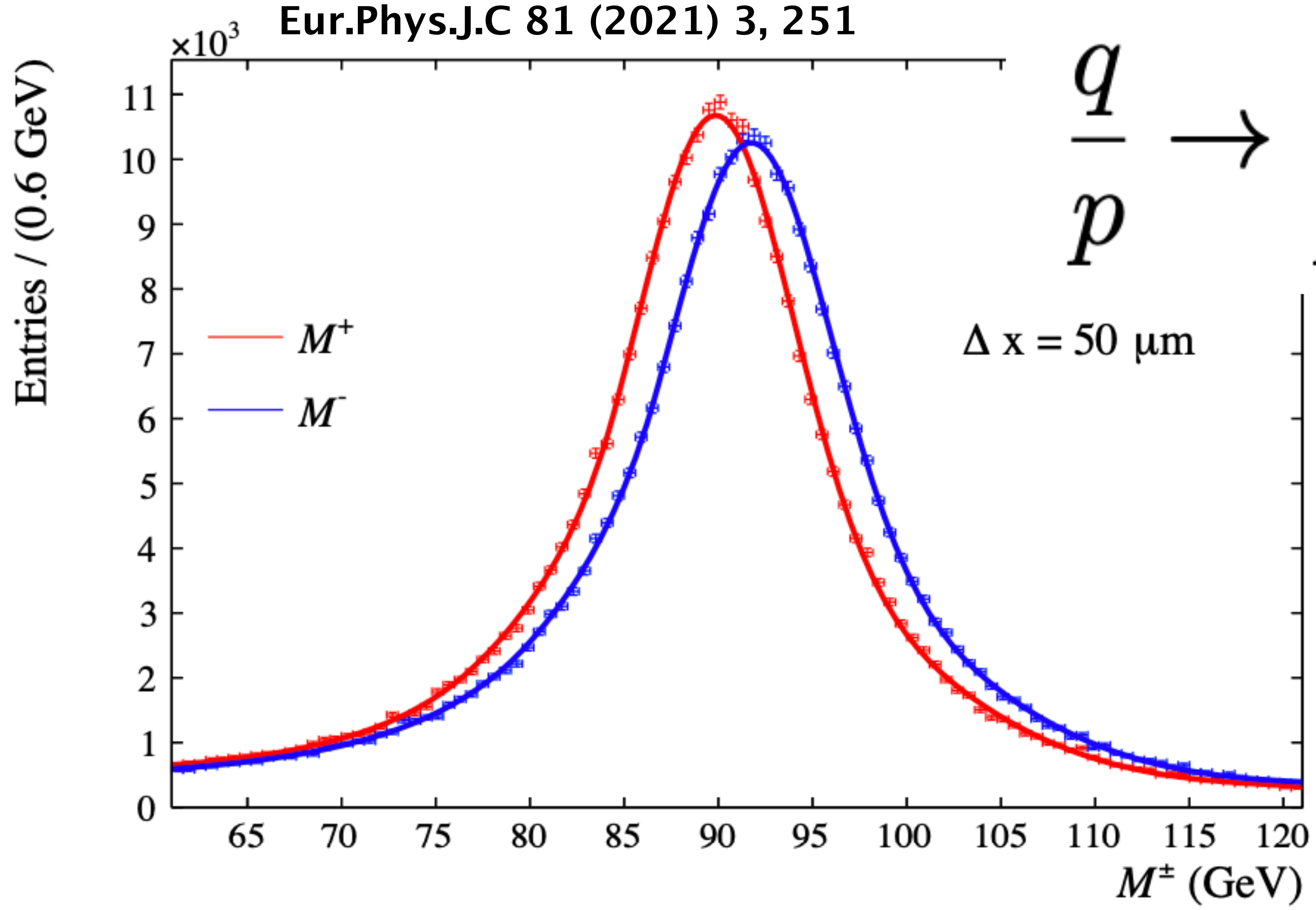
Angular coefficients: fixed order pQCD

- As for ATLAS, Powheg+Pythia is used as baseline simulation
- QCD parameters of parton shower are fitted to match the $p_T(Z^0 \rightarrow \mu^+\mu^-)$ distribution
- Templates reweighted also to match DYTurbo
- Pythia, Photos, Herwig for QED description
- Three different PDFs sets: NNPDF3.1, CT18, MSHT20



LHCb: muon curvature bias

Eur.Phys.J.C 81 (2021) 3, 251

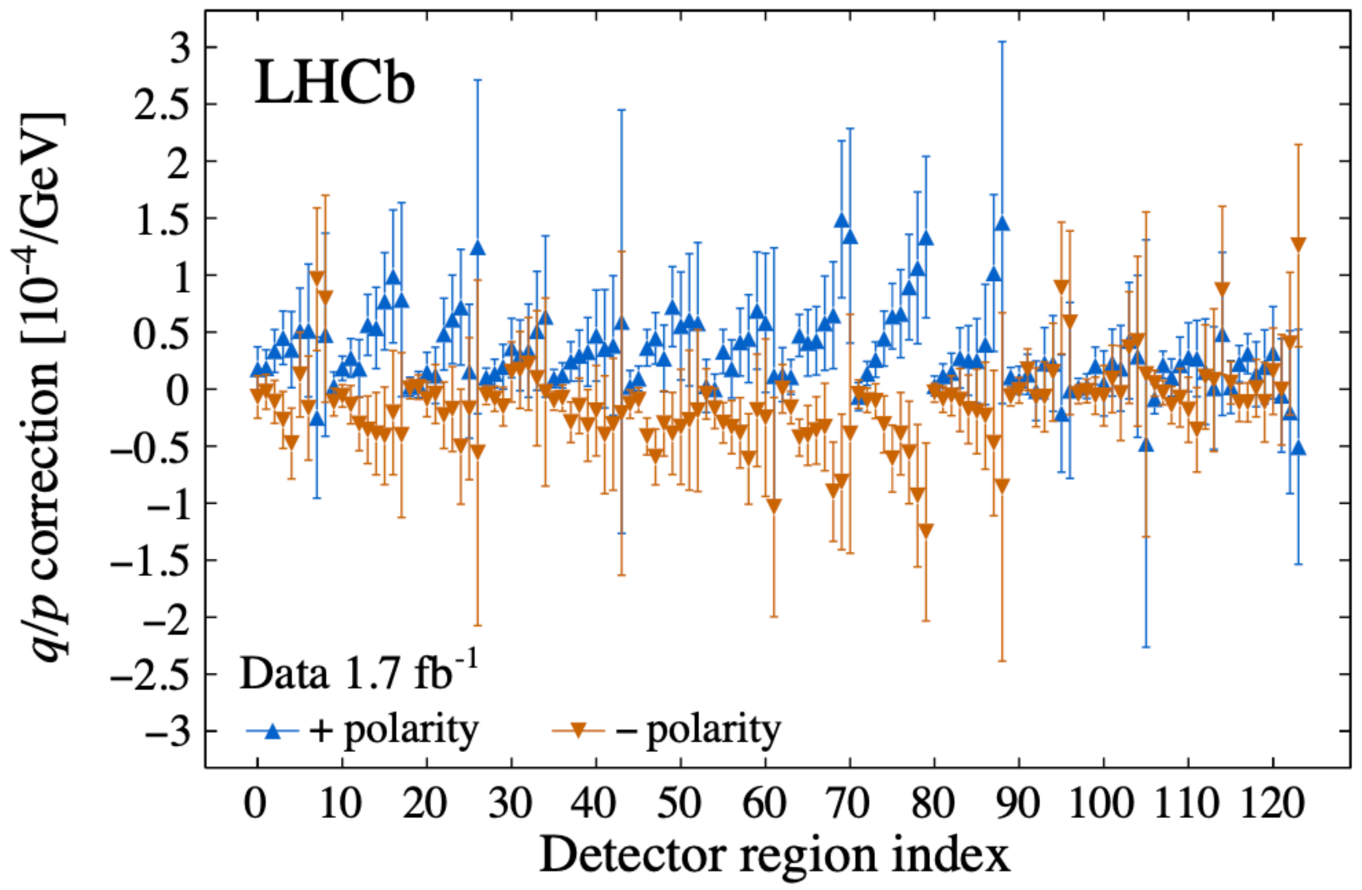


$$\frac{q}{p} \rightarrow \frac{q}{p} + \delta$$

- ATLAS determined the curvature bias (δ) in E/p calibration for electrons: usable only if muon and electron reconstruction has a comparable performance
- Due to saturation effects in ECAL, at LHCb electrons are not usable for this purpose
- **Pseudo-mass method applied to $Z^0 \rightarrow \mu^+\mu^-$**: does not depend from the magnitude of the momentum

$$\mathcal{M}^{\pm} = \sqrt{2p^{\pm}p_{\mathrm{T}}^{\pm}\frac{p^{\mp}}{p_{\mathrm{T}}^{\mp}}(1-\cos\theta)}$$

$$\delta \approx A\frac{<\frac{1}{p^+}> + <\frac{1}{p^-}>}{2}$$

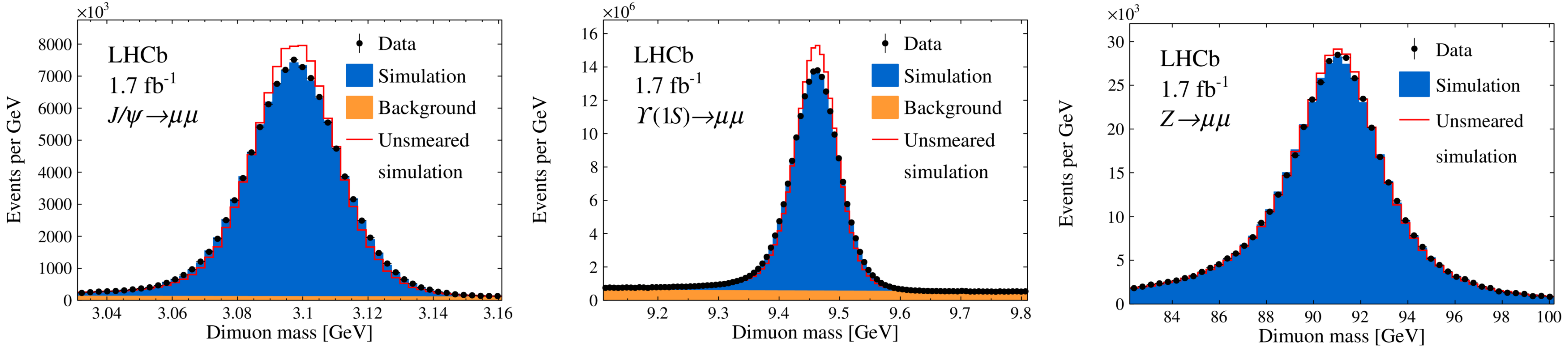


LHCb: muon momentum

- Muon momentum scale and resolution obtained with several dimuon resonances samples
- Reconstruction efficiencies with tag & probe $\mathbf{Z^0 \rightarrow \mu^+\mu^-}$

$$\frac{q}{p} \rightarrow \frac{q}{p \cdot \mathcal{N}(1+\alpha, \sigma_{\mathrm{MS}})} + \mathcal{N}\left(\delta, \frac{\sigma_\delta}{\cosh\eta}\right)$$

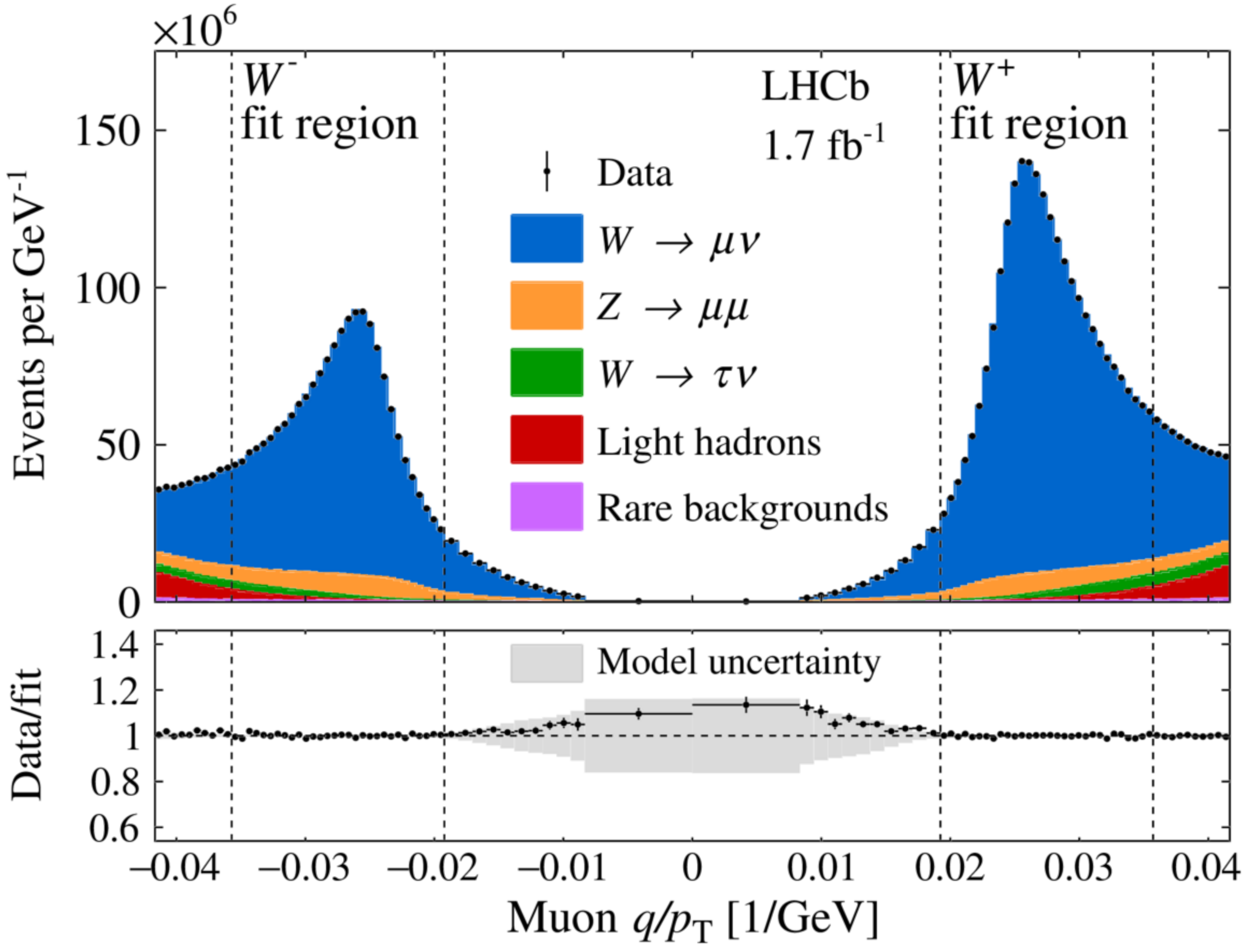
scale smearing bias

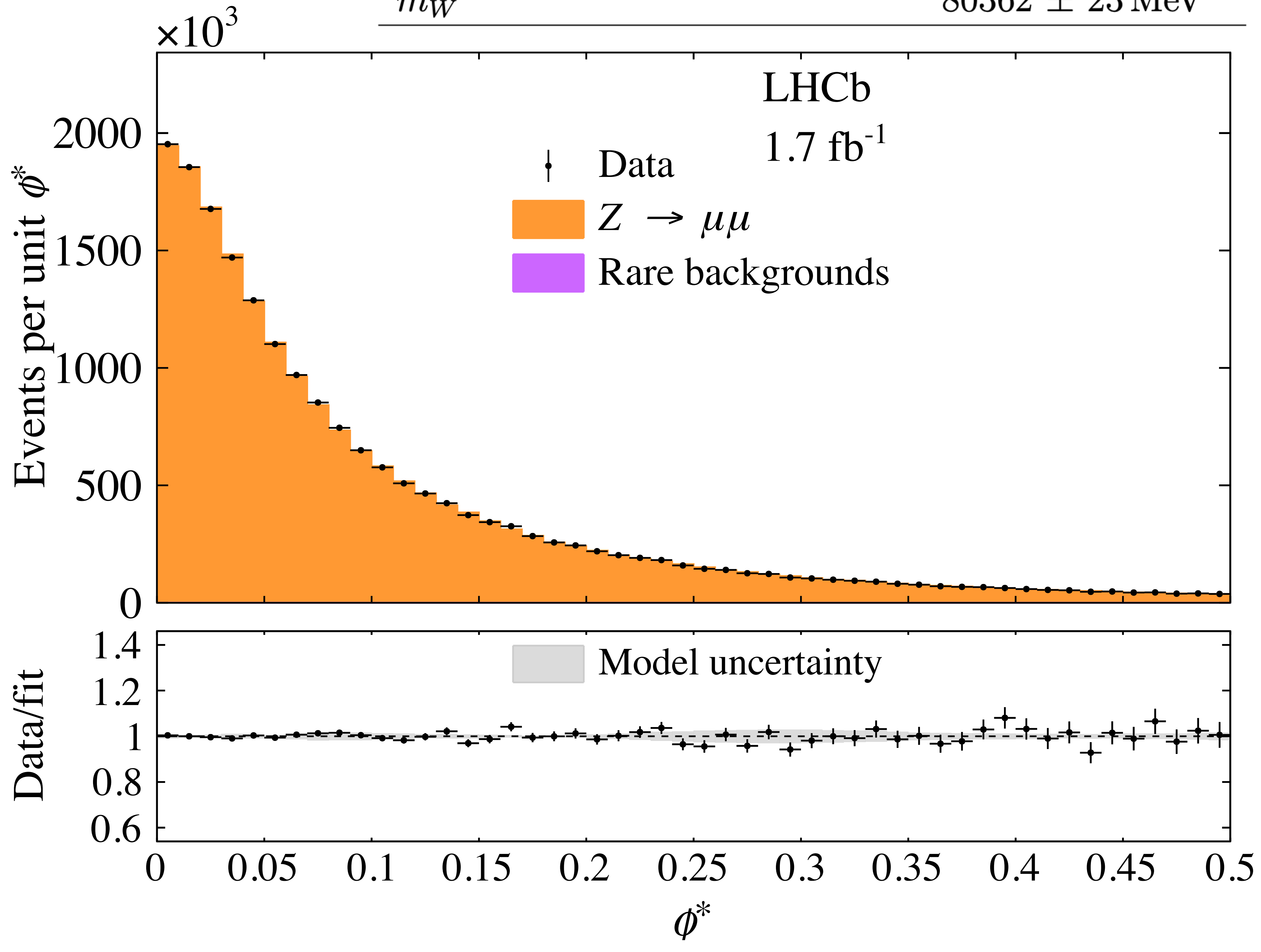


LHCb: W mass fit result

- Several QCD parameters and A_3 scaling are also extracted from the m_W template fit

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





LHCb: systematics and cross-checks

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

Statistical uncertainty still large: with the full Run 2 dataset a total uncertainty < 20 MeV is already possible

Cross checks:

- W-like measurement of Z^0 boson mass
- Consistency of orthogonal subsets: muon charge, magnet polarities, ϕ, η
- Fit p_T range
- Fit model freedom
- NNLO vs NLO PDFs

$m_W = 80362 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ MeV, **NNPDF3.1**

$m_W = 80350 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 12_{\text{PDF}}$ MeV, **CT18**

$m_W = 80351 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 7_{\text{PDF}}$ MeV, **MSHT20**

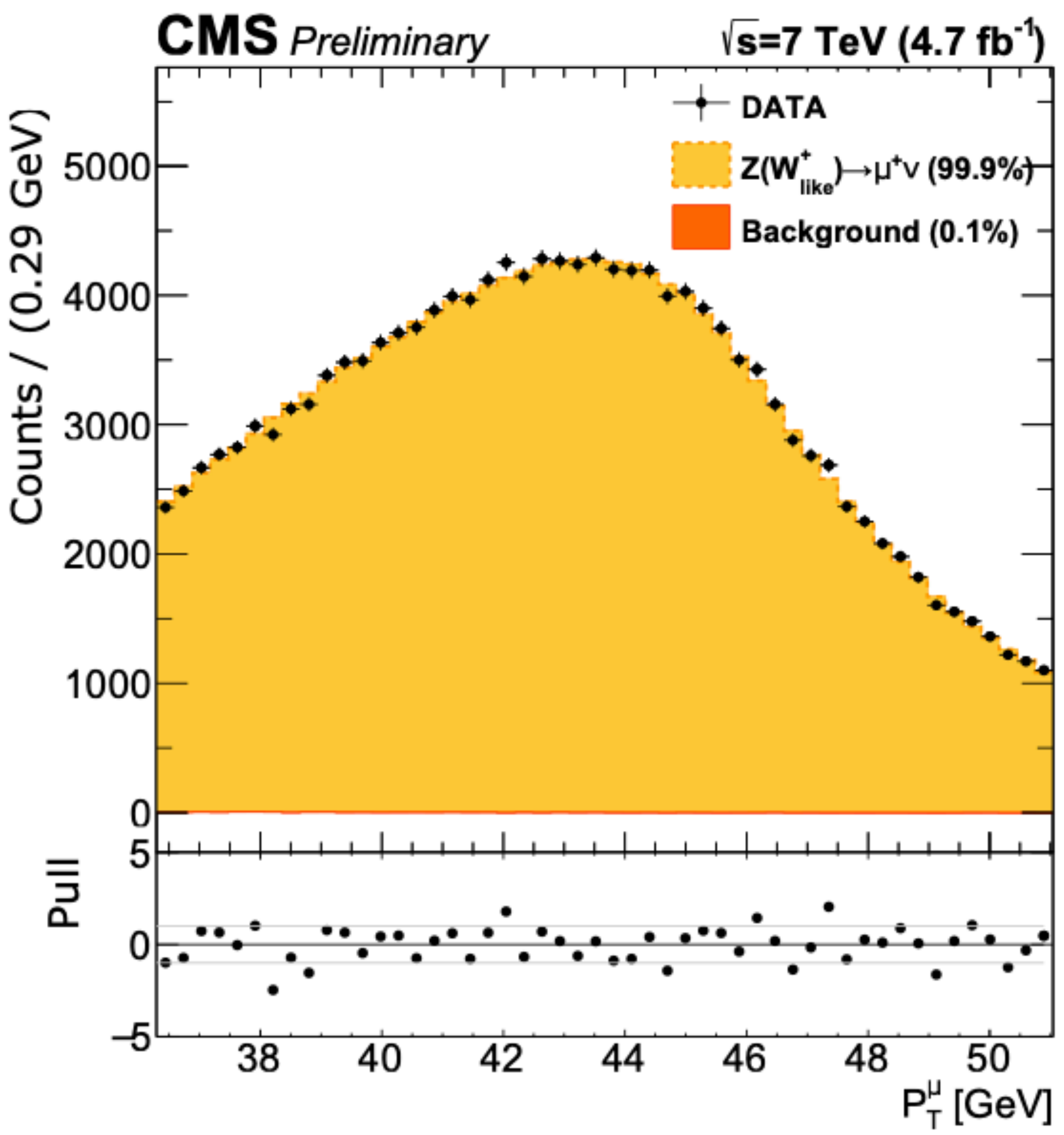
Final result:

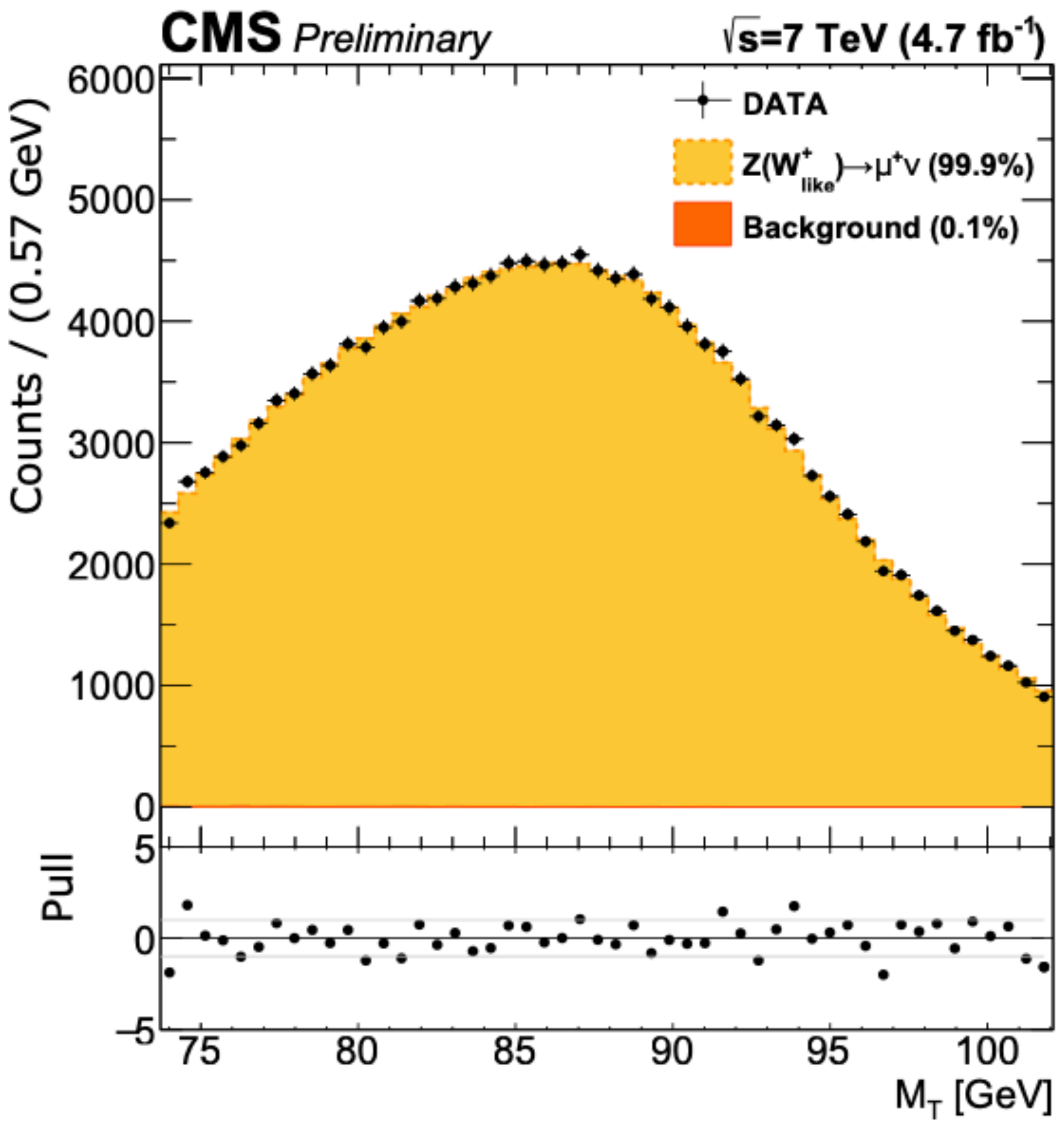
$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

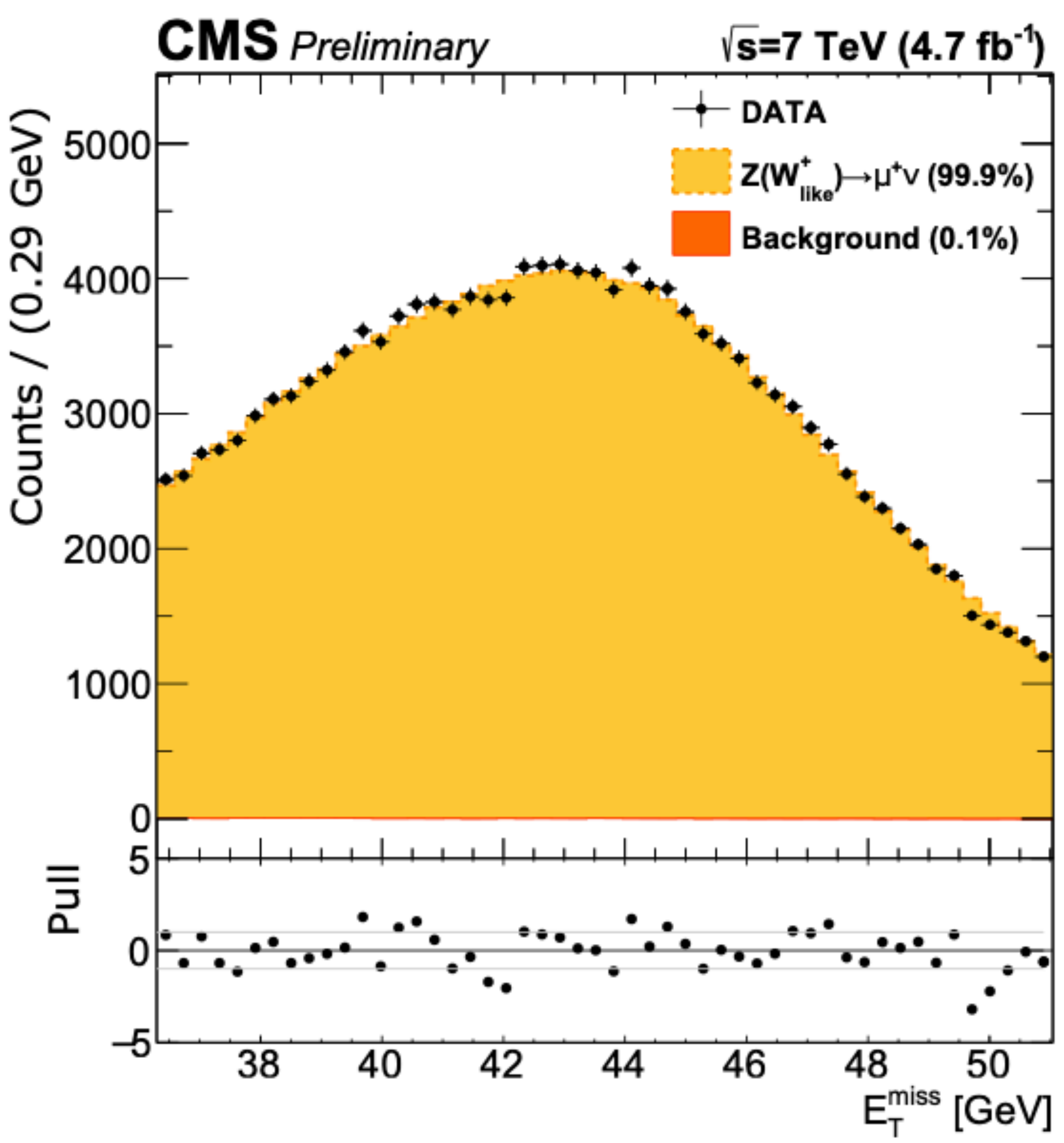
CMS: W-like measurement of Z^0 mass

CMS-PAS-SMP-14-007

- *pp* collisions at 7 TeV, 4.7 fb^{-1} of integrated luminosity
- Muon dataset is used
- Experimental technique similar to ATLAS analysis: template fit of $p_T(\mu)$, m_T and E_T^{miss}

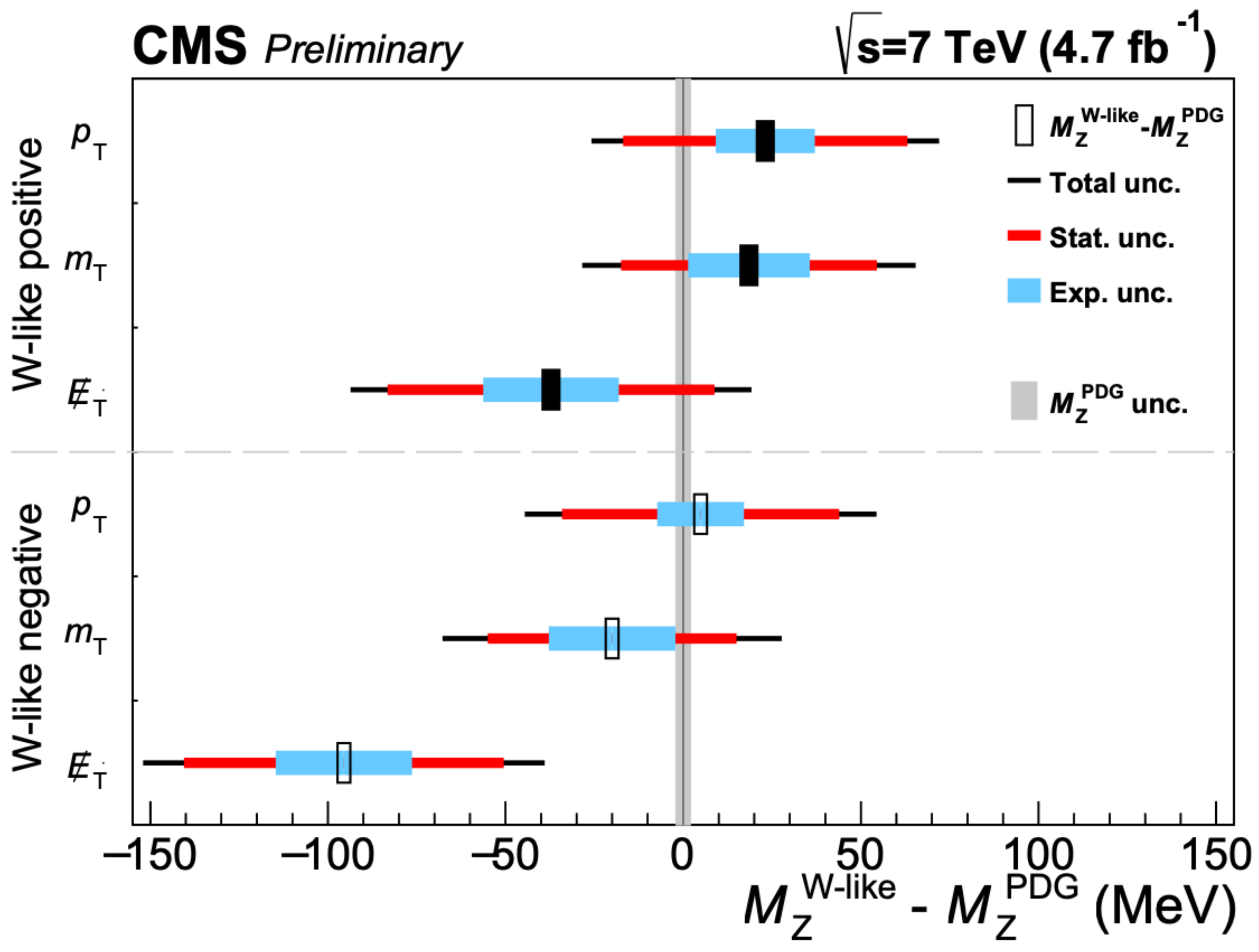






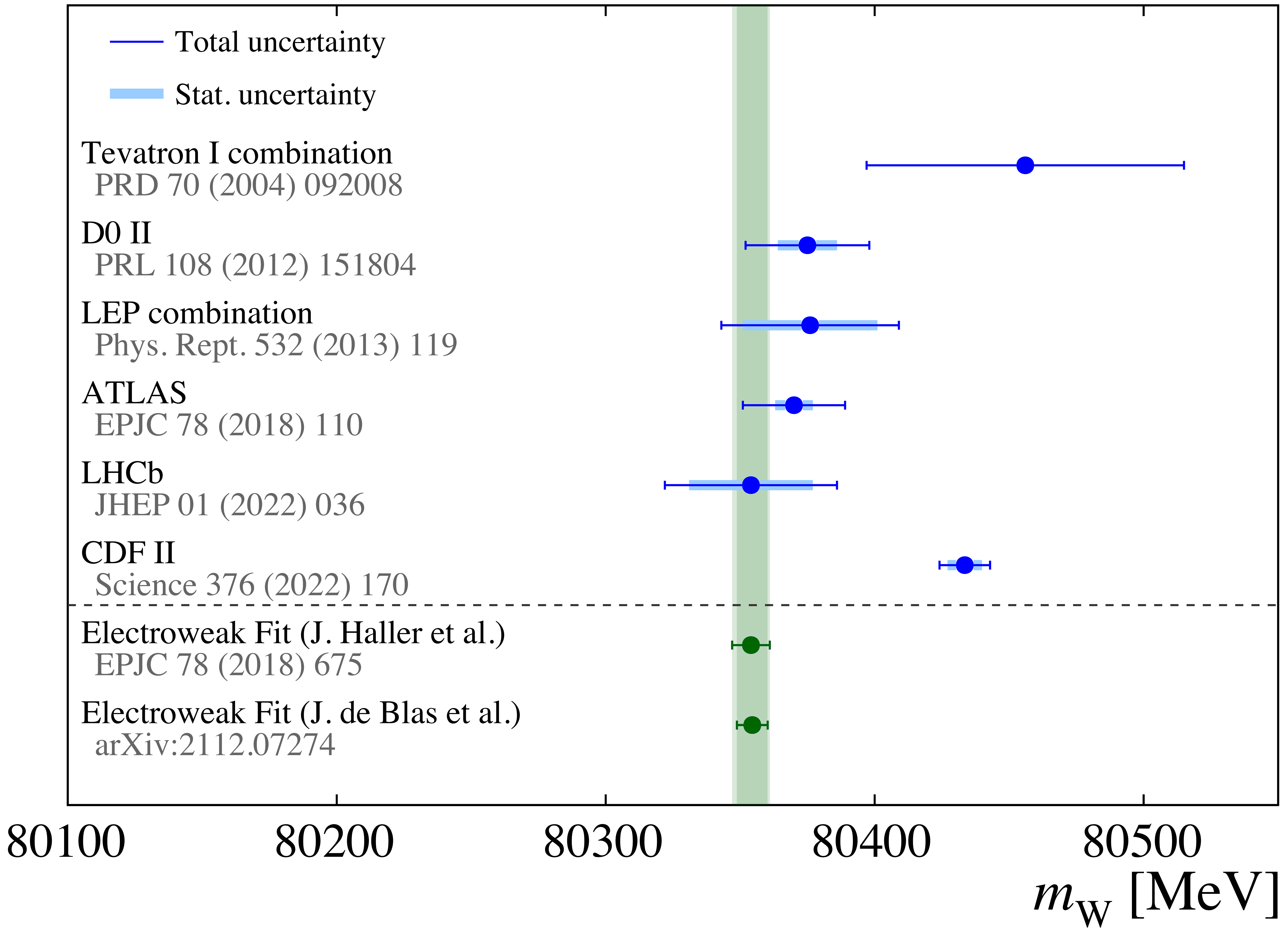
CMS: results and systematics

- Proof-of-principles and validation of experimental techniques
- W mass measurement at CMS currently on-going, new ideas to reduce model systematics (discussed later)



Sources of uncertainty	$M_Z^{\mathrm{Wlike}+}$ p_T	$M_Z^{\mathrm{Wlike}+}$ m_T	$M_Z^{\mathrm{Wlike}+}$ $\not{E}_T$	$M_Z^{\mathrm{Wlike}-}$ p_T	$M_Z^{\mathrm{Wlike}-}$ m_T	$M_Z^{\mathrm{Wlike}-}$ $\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57

Comparison with CDF



- Significant displacement between new CDF II measurement and other most precise measurements
- LHC measurements are closer to the Electroweak Fit prediction with respect to CDF II
- However precision of CDF II measurement is much better

Comparison with CDF

Uncertainties (in MeV)

	CDF	ATLAS	LHCb
Statistical	6.4	6.8	23
Lepton energy/ momentum scale	2 (μ) + 6 (e)	7* (μ) + 7* (e)	7 (μ)
PDFs	4	7*	9
Model (excl. PDFs)	3.5	8*	17
Total	9.4	18.5	31.4

Modeling

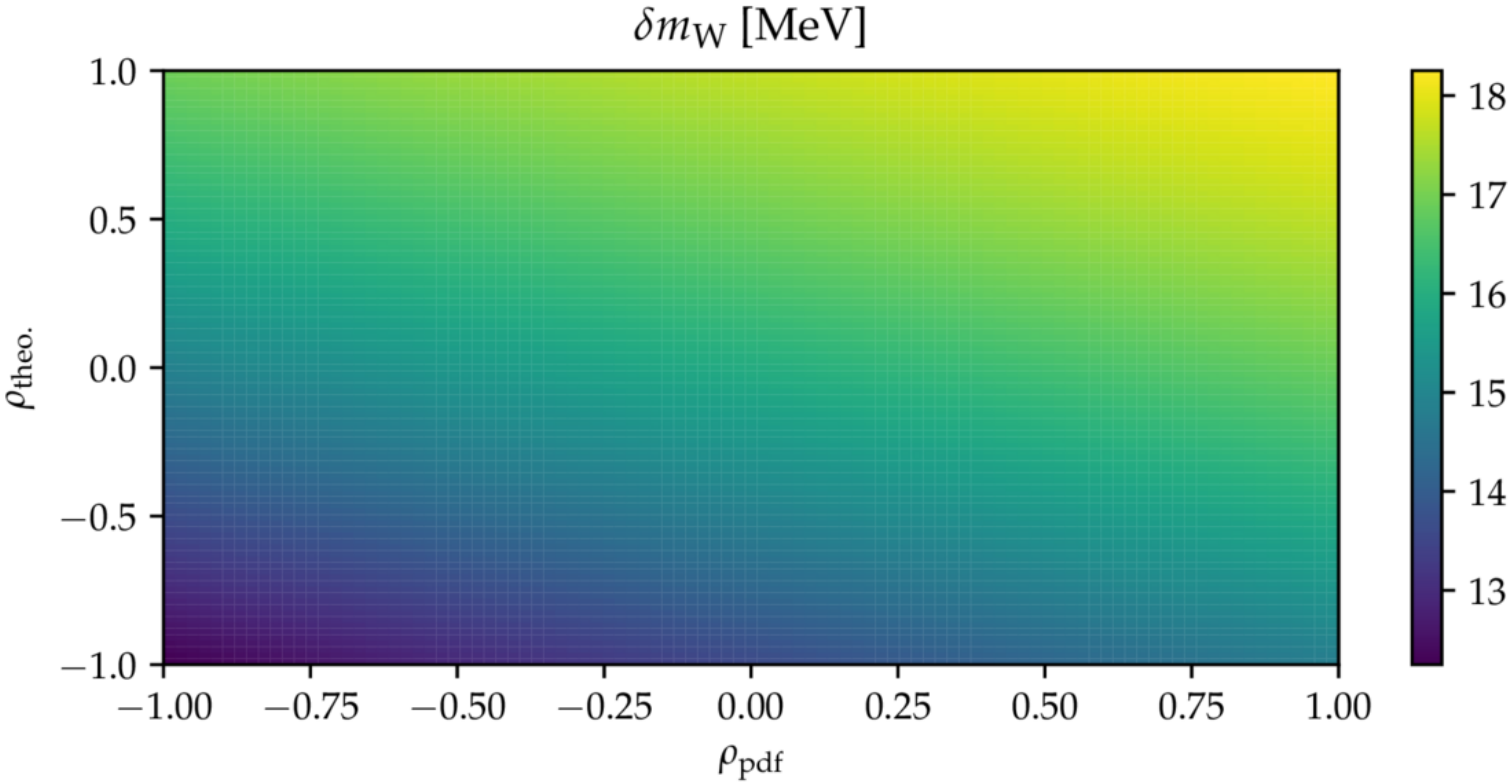
	CDF	ATLAS	LHCb
Baseline	RESBOS	Powheg+Pythia	Powheg+Pythia
Reweight	-	DYNNLO	DYTURBO
Parton shower	data-driven	data-driven	data-driven
QED	PHOTOS+HORACE	PHOTOS	Pythia+PHOTOS+Herwig

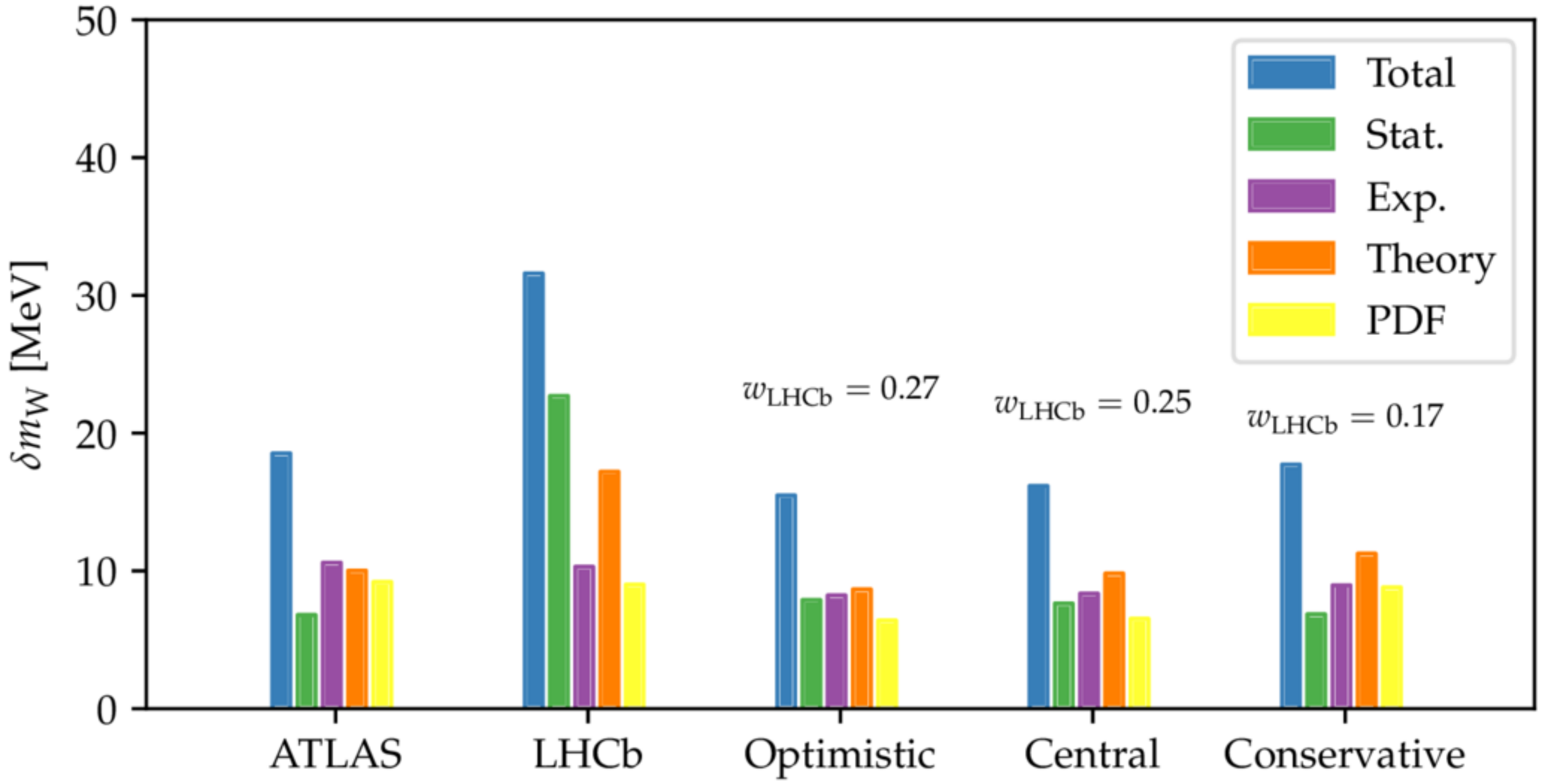
*given separately for p_T and m_T fits, combined assuming 50% correlation

Notice: CDF measurement took profit of the PDFs determination at LHC

LHC combination

- LHC measurements combination is not trivial, it depends on several correlations
- A naive expectation on **ATLAS+LHCb combination** is given

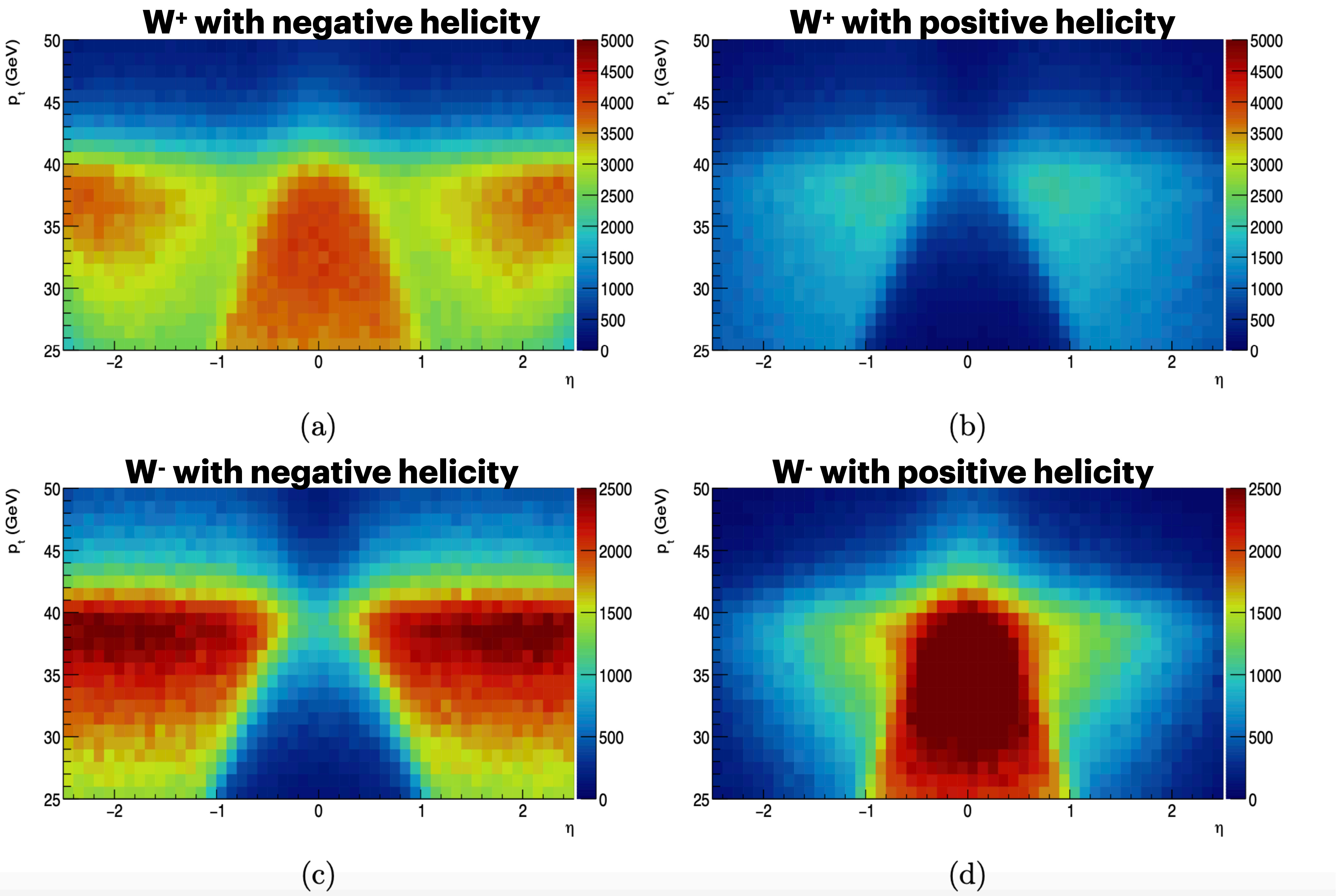




PDFs uncertainty correlation is expected to be negative

Future prospects at LHC

- The W boson differential cross sections contain information on the model
- In order to reduce the model uncertainty (including PDFs) m_W should be simultaneously fitted with the W differential cross section (p_T-η)
- **Model-agnostic approach: the model systematic uncertainty is traded for statistical uncertainty**
- This technique has been already tested for the measurement of W polarization: Phys. Rev. D 102 (2020) 092012



Future prospects at LHC

EPJC 75 (2015) 601

Scenario	Experiments	δm_W (MeV) Tot	Exp	PDF
Default	2×GPD + LHCb	9.0	4.7	7.7
Default	1×GPD + LHCb	10.1	6.5	7.7
Default	2×GPD	12.0	5.8	10.5
PDF4LHC(3-sets)	2×GPD + LHCb	13.6	4.8	12.7
PDF4LHC(3-sets)	1×GPD + LHCb	14.6	7.3	12.7
PDF4LHC(3-sets)	2×GPD	17.7	5.5	16.9
$\delta_{exp}^{LHCb} = 0$	2×GPD + LHCb	8.7	4.0	7.7
$\delta_{exp}^{LHCb} = 0$	1×GPD + LHCb	9.8	5.9	7.9
$\delta_{exp}^{LHCb} = 0$	2×GPD	12.0	5.8	10.5
$\delta_{exp}^{GPD} = 0$	2×GPD + LHCb	7.9	1.9	7.7
$\delta_{exp}^{GPD} = 0$	1×GPD + LHCb	7.9	1.9	7.7
$\delta_{exp}^{GPD} = 0$	2×GPD	10.5	0.1	10.5
$\delta_{PDF} = 0$	2×GPD + LHCb	4.6	4.6	0.0
$\delta_{PDF} = 0$	1×GPD + LHCb	5.8	5.8	0.0
$\delta_{PDF} = 0$	2×GPD	5.5	5.5	0.0

GPD = General Purpose Detector = ATLAS/CMS

- Not a precise extrapolation, just a way to visualize the contribution of the three experiments to the m_W combination
- Only the PDF uncertainty is considered for the model
- Statistical uncertainty not included

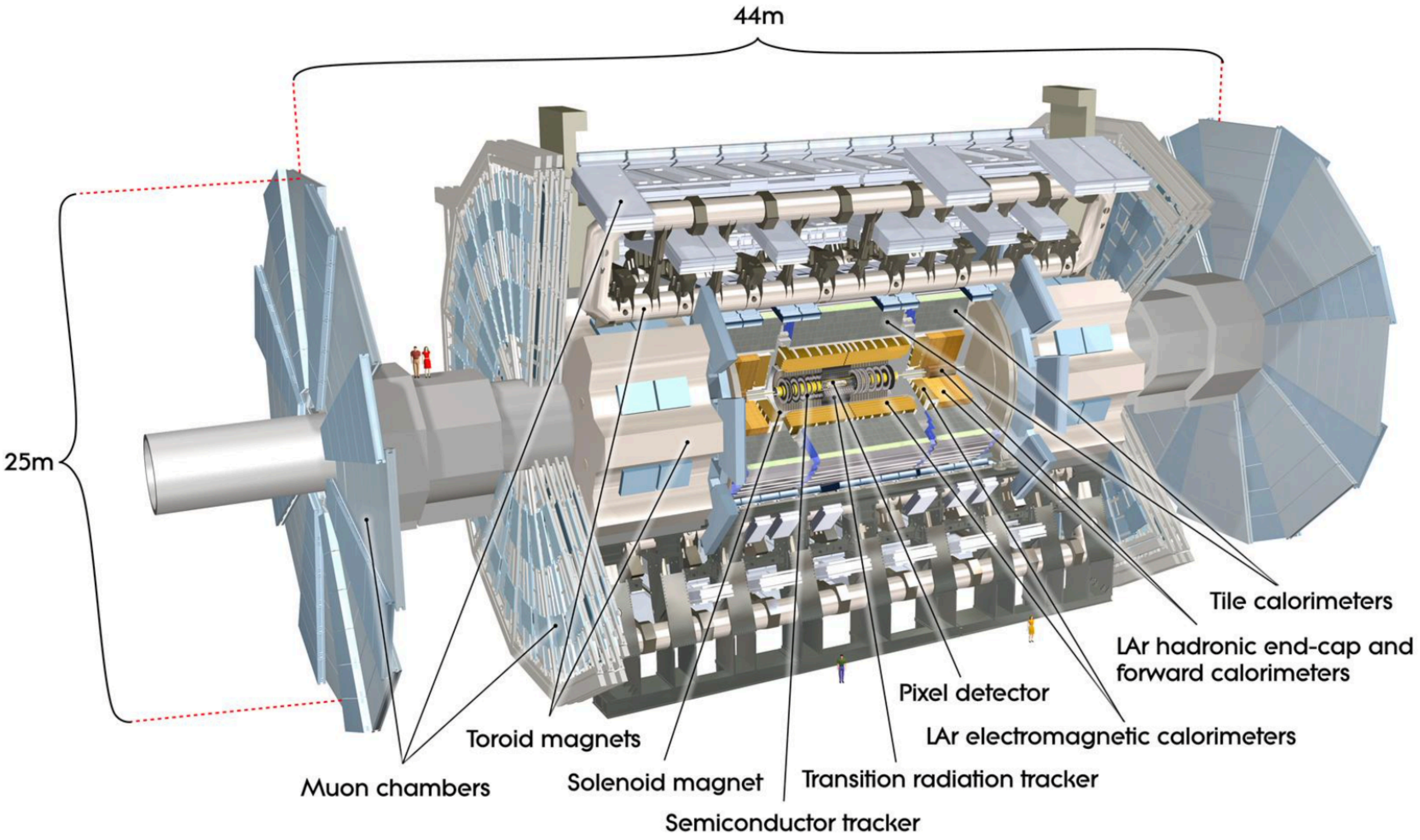
Conclusions

- ATLAS and LHCb have already performed a W mass boson measurement, CMS is on its way
- The precision obtained is not yet at the level of CDF II measurement
- There are few ideas to improve the modeling systematic uncertainty
- **The combination of the measurements from the three experiments is fundamental to obtain the final precision at LHC**
- **We have many years before the next lepton collider, LHC could be the the only way to confirm CDF result in the short period**

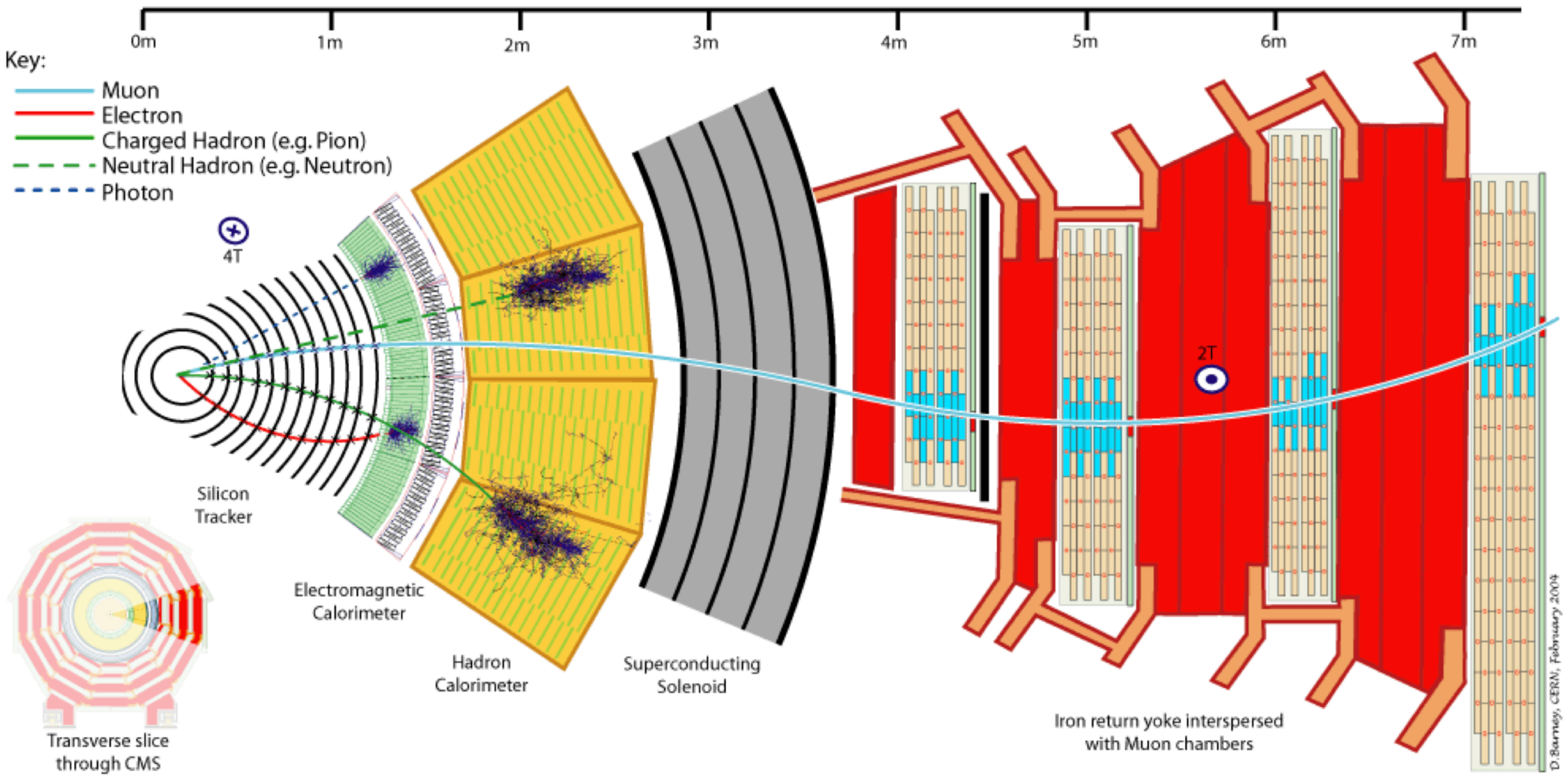
Thanks for your attention!

Backup

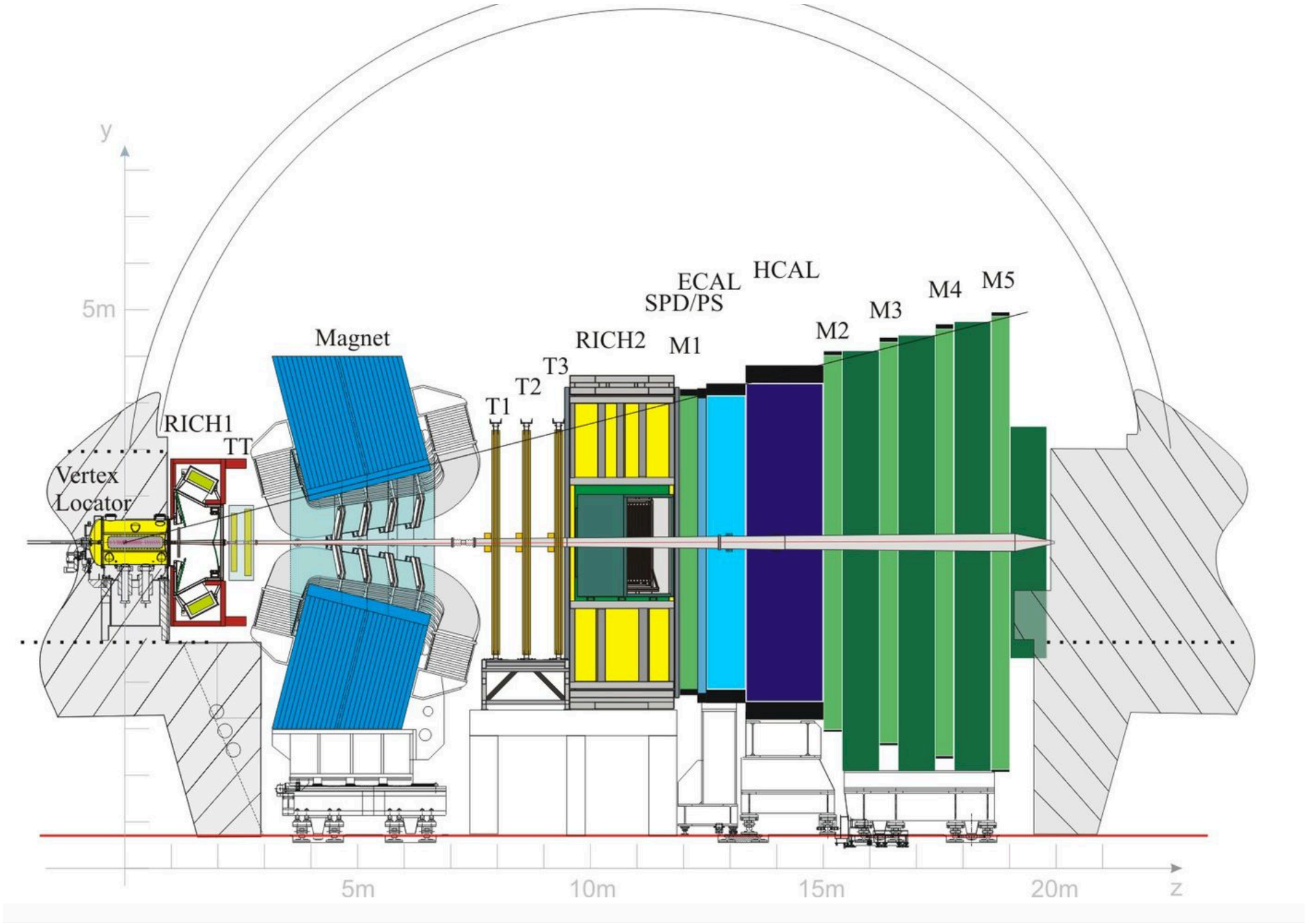
ATLAS detector



CMS detector



LHCb detector



Uncertainties

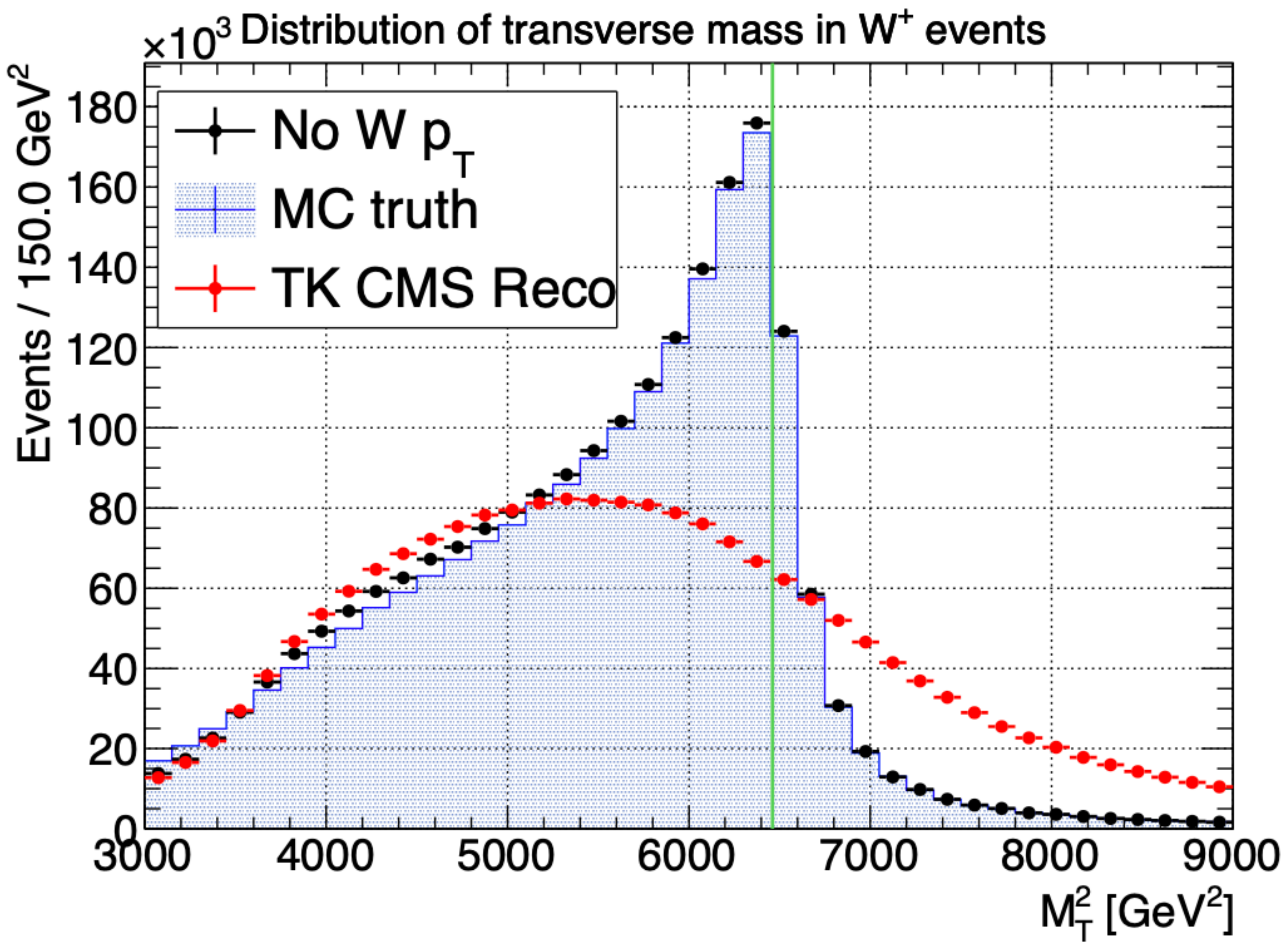
Experimental uncertainties

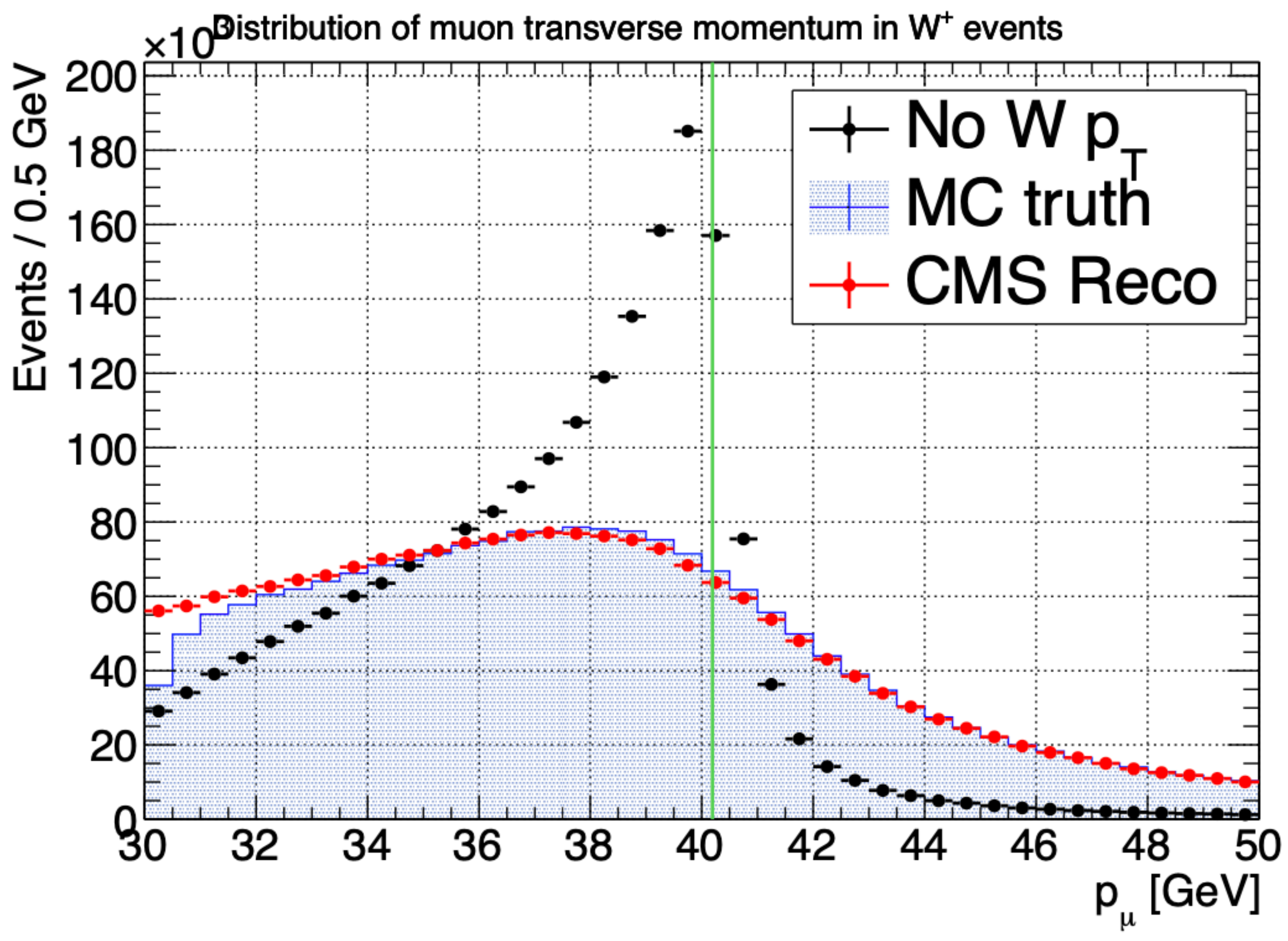
- Lepton momentum calibration and scale
- Recoil resolution and energy scale
- Background processes
- Differences between data and simulation for lepton efficiencies

Theoretical uncertainties

- Parton Distribution Functions
- Modeling of $p_T(W)$
- Modeling of angular coefficients A_i
- Modeling of QED radiation

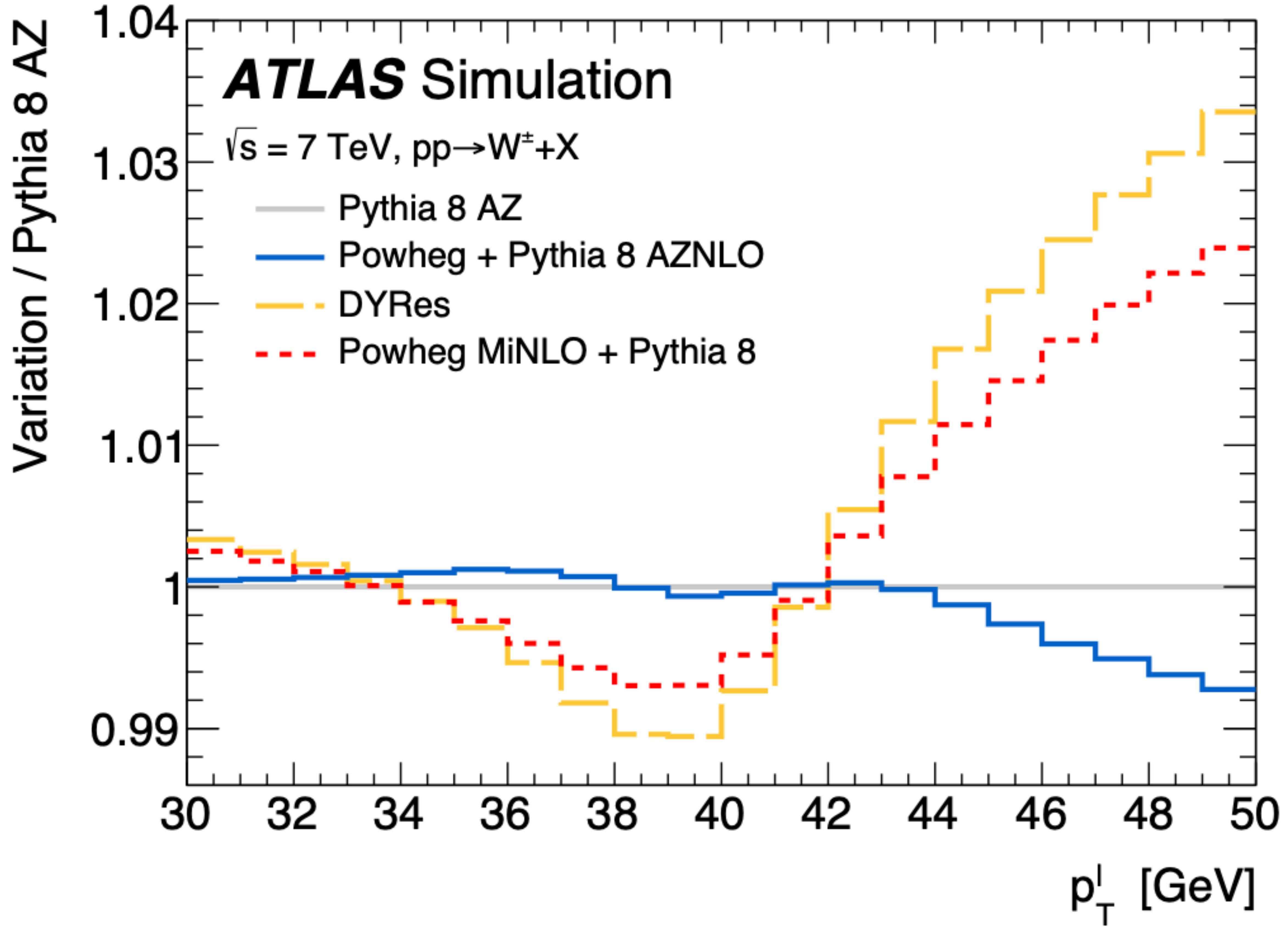
Experimental techniques

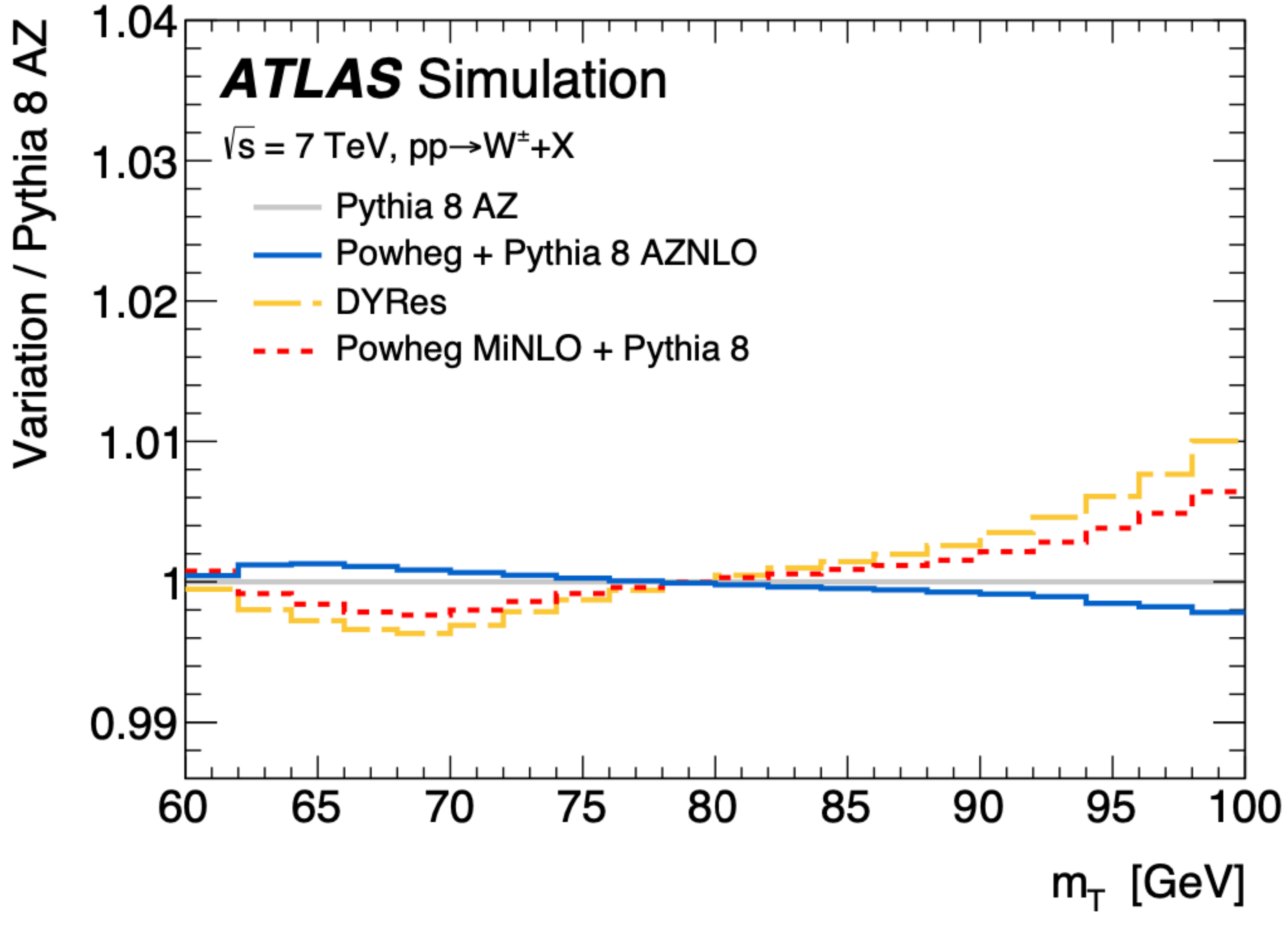




https://cds.cern.ch/record/2285935/files/CERN-THESIS-2017-157.pdf

ATLAS: p_T model



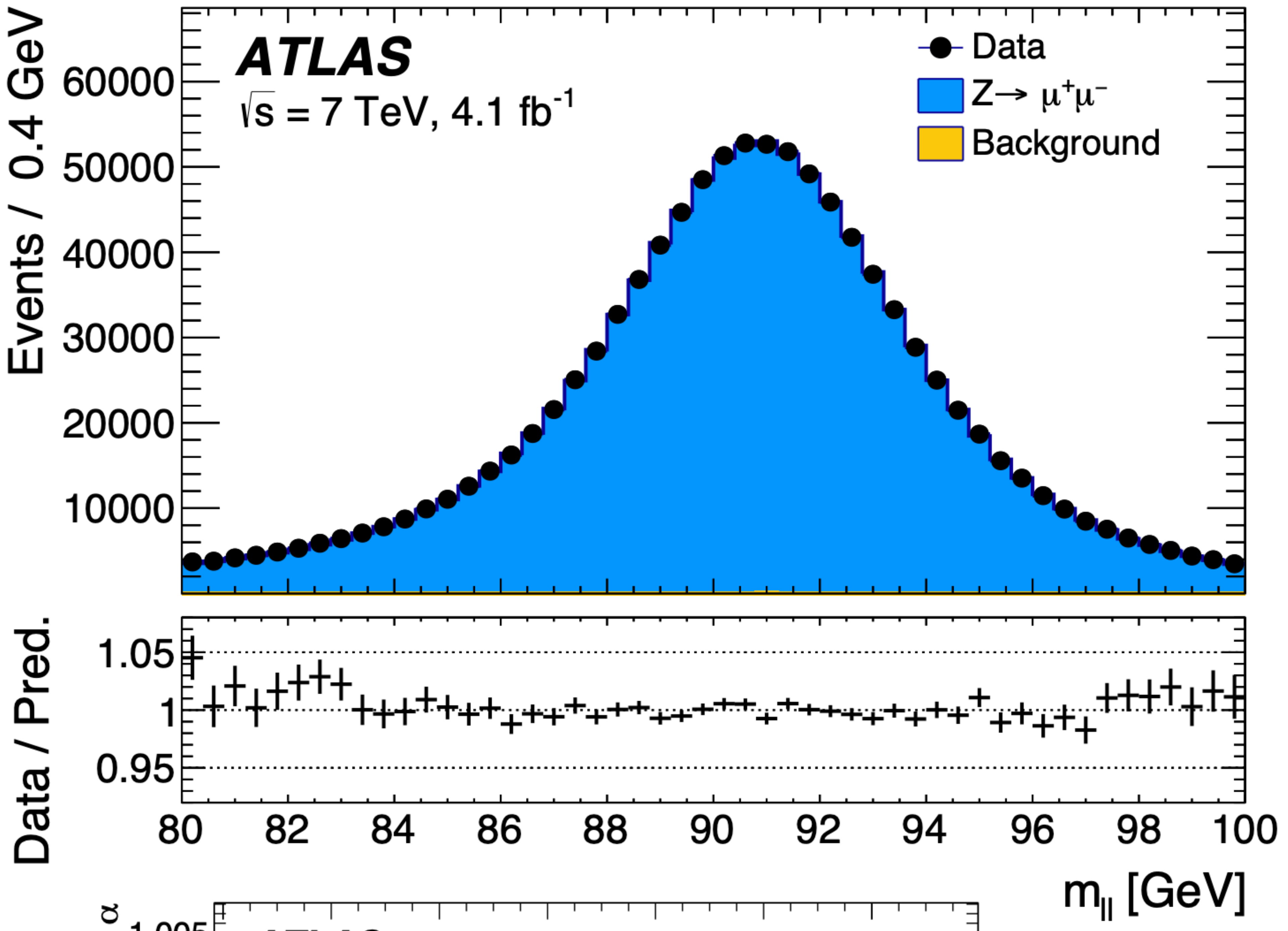


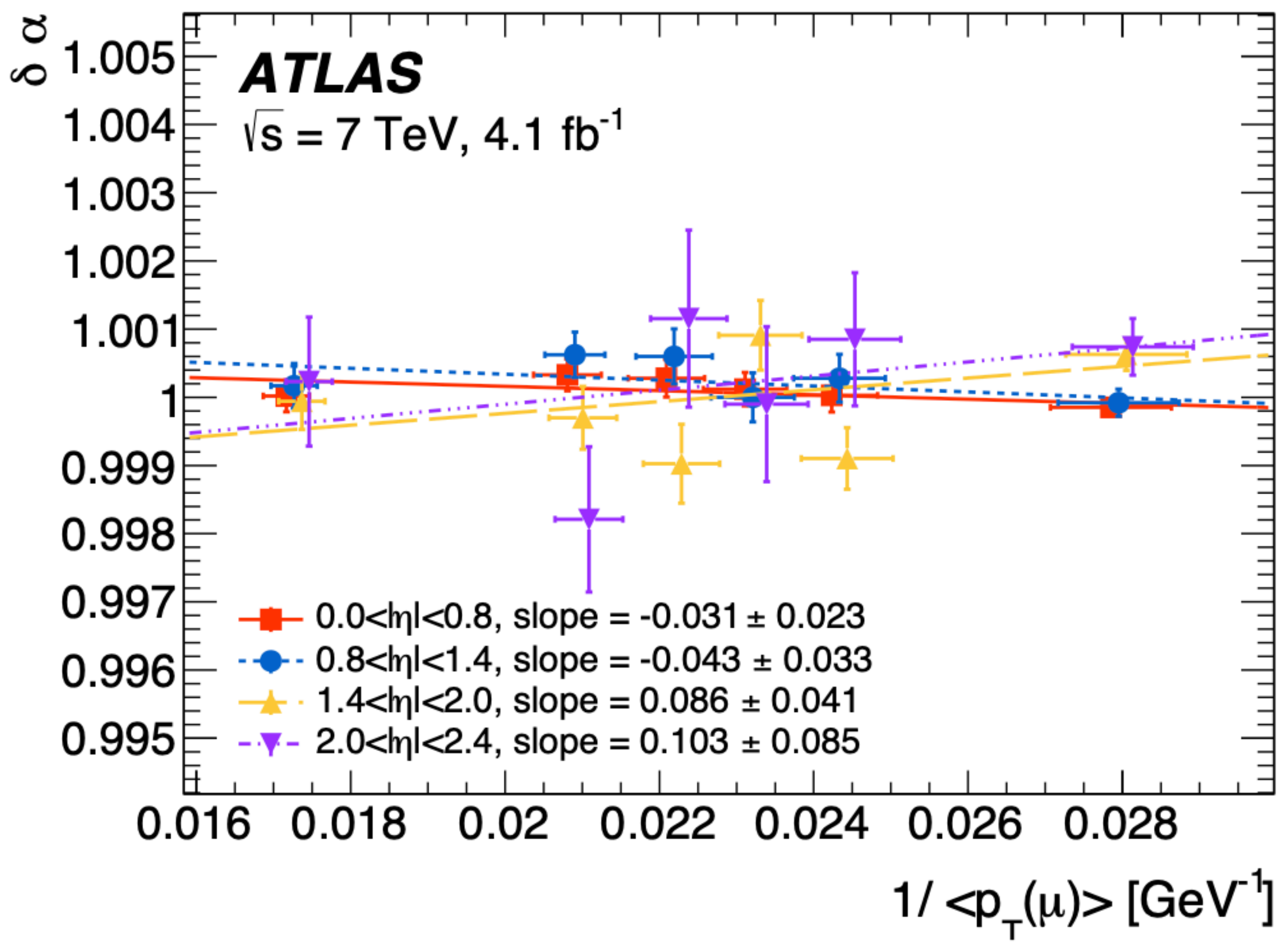
ATLAS: muon reconstruction

$$p_T^{\text{MC,corr}} = p_T^{\text{MC}} \times [1 + \alpha(\eta, \phi)] \times \left[1 + \beta_{\text{curv}}(\eta) \cdot G(0,1) \cdot p_T^{\text{MC}}\right],$$

$$p_T^{\text{data,corr}} = \frac{p_T^{\text{data}}}{1 + q \cdot \delta(\eta, \phi) \cdot p_T^{\text{data}}},$$

$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	1.2
Sagitta bias	0.7	0.8	1.7	1.7	3.1	3.1	4.5	4.3	0.6	0.6
Reconstruction and isolation efficiencies	4.0	3.6	5.1	3.7	4.7	3.5	6.4	5.5	2.7	2.2
Trigger efficiency	5.6	5.0	7.1	5.0	11.8	9.1	12.1	9.9	4.1	3.2
Total	11.4	11.4	16.9	17.0	30.4	31.0	112.0	116.1	9.8	9.7

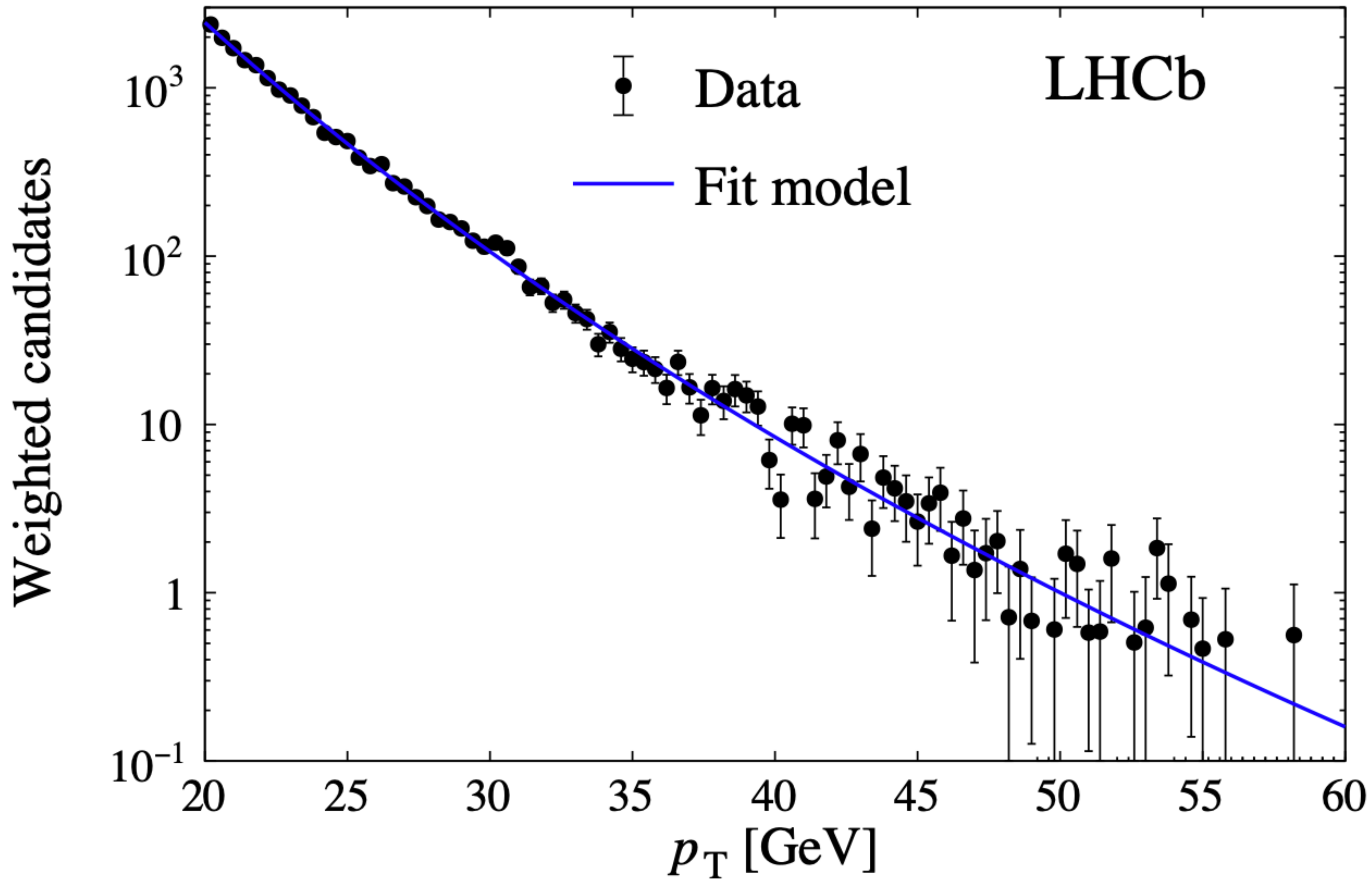




$$\delta\alpha = p_0 + \frac{p_1}{\left\langle p_T^\ell(W)\right\rangle},$$

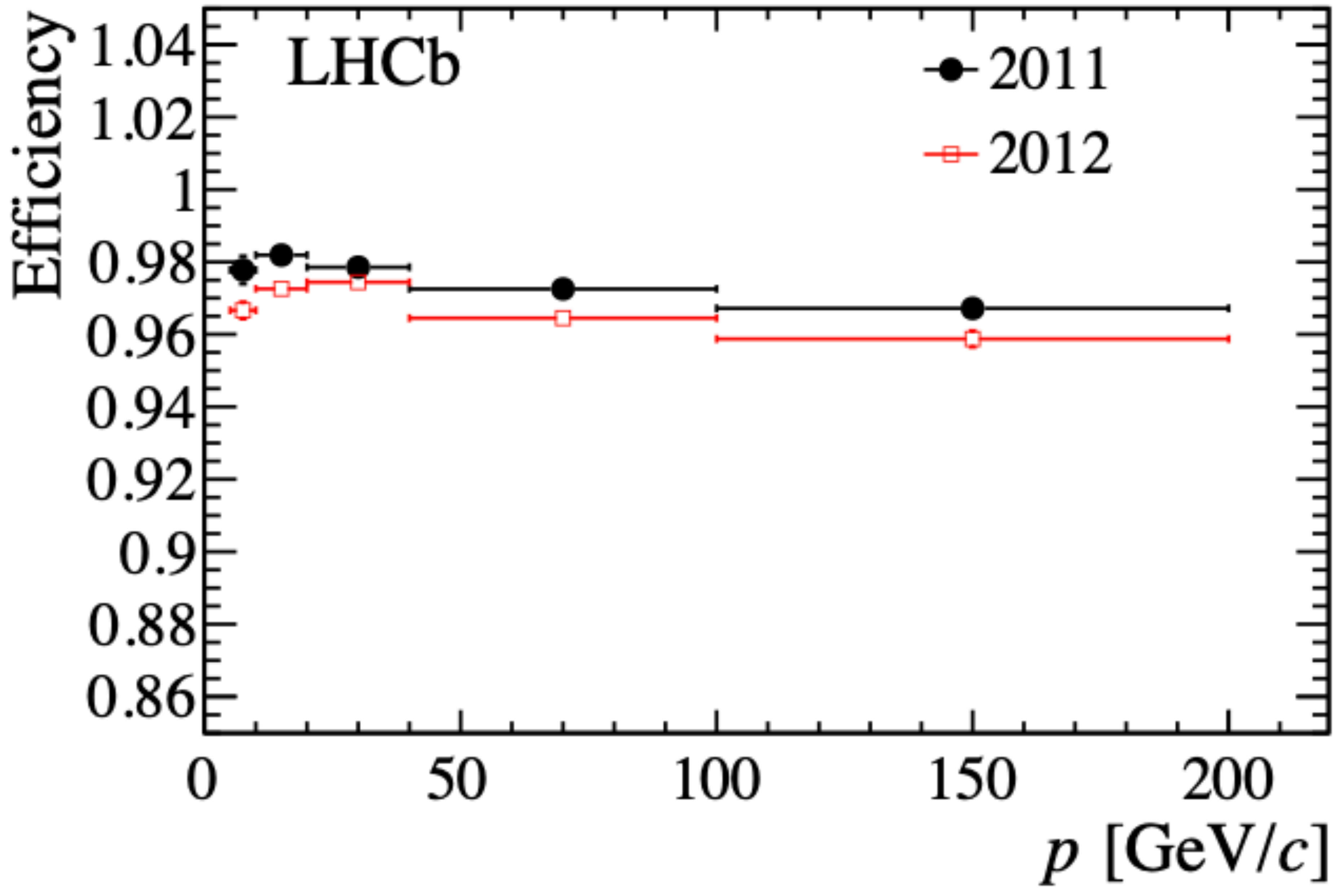
LHCb: background

- Most of backgrounds are modeled with simulated samples: single-top, quark/anti-quark (t, b, c), Z/W decays, Drell-Yan
- QCD background (decays-in-flight) has been obtained with a data-driven technique, by inverting the muon identification cuts (i.e. impact parameter)
- This model (Hagedorn distribution) accurately described the region of the Jacobian peak



LHCb performance

Int. J. Mod. Phys. A 30, 1530022 (2015)



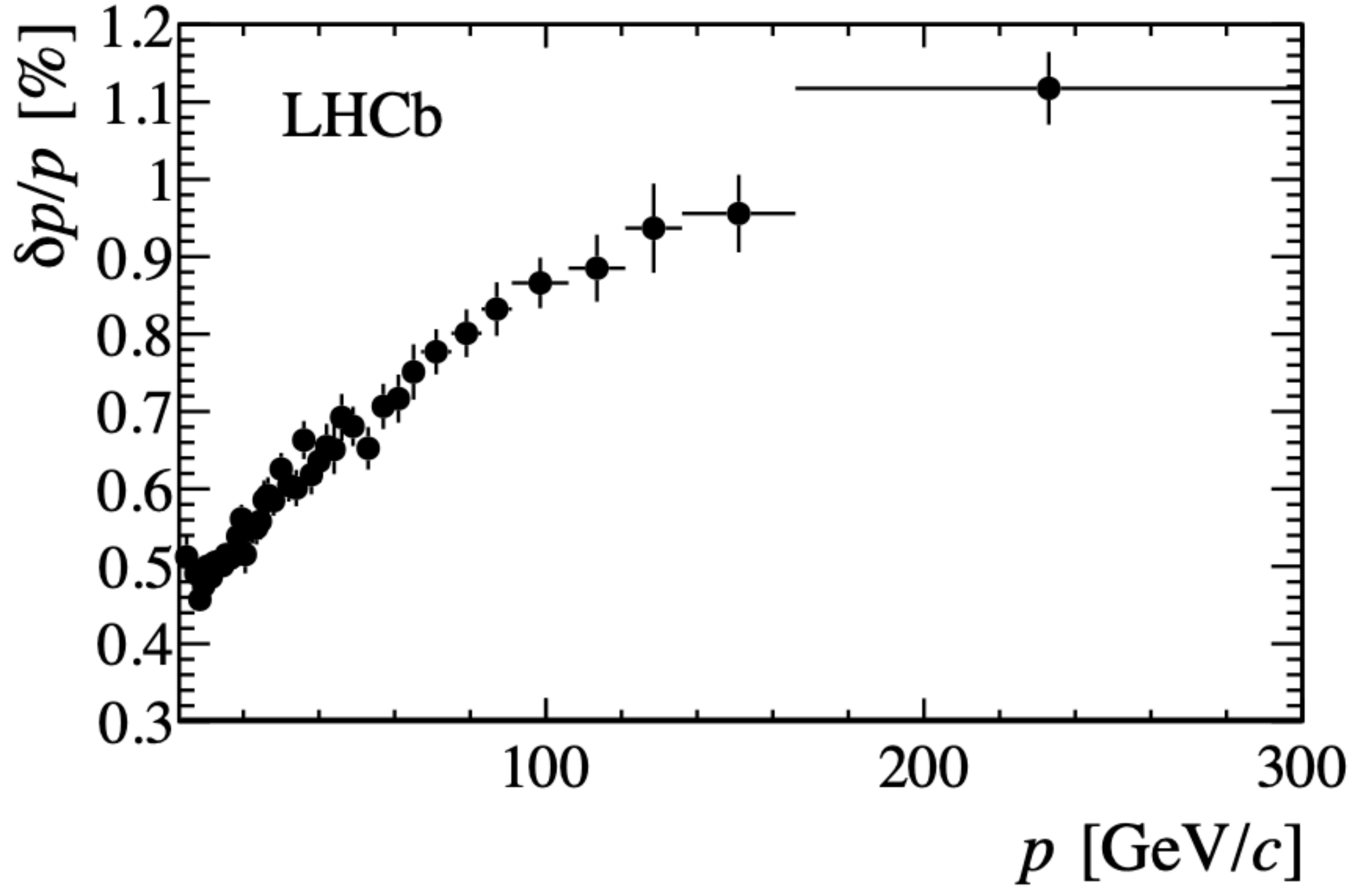
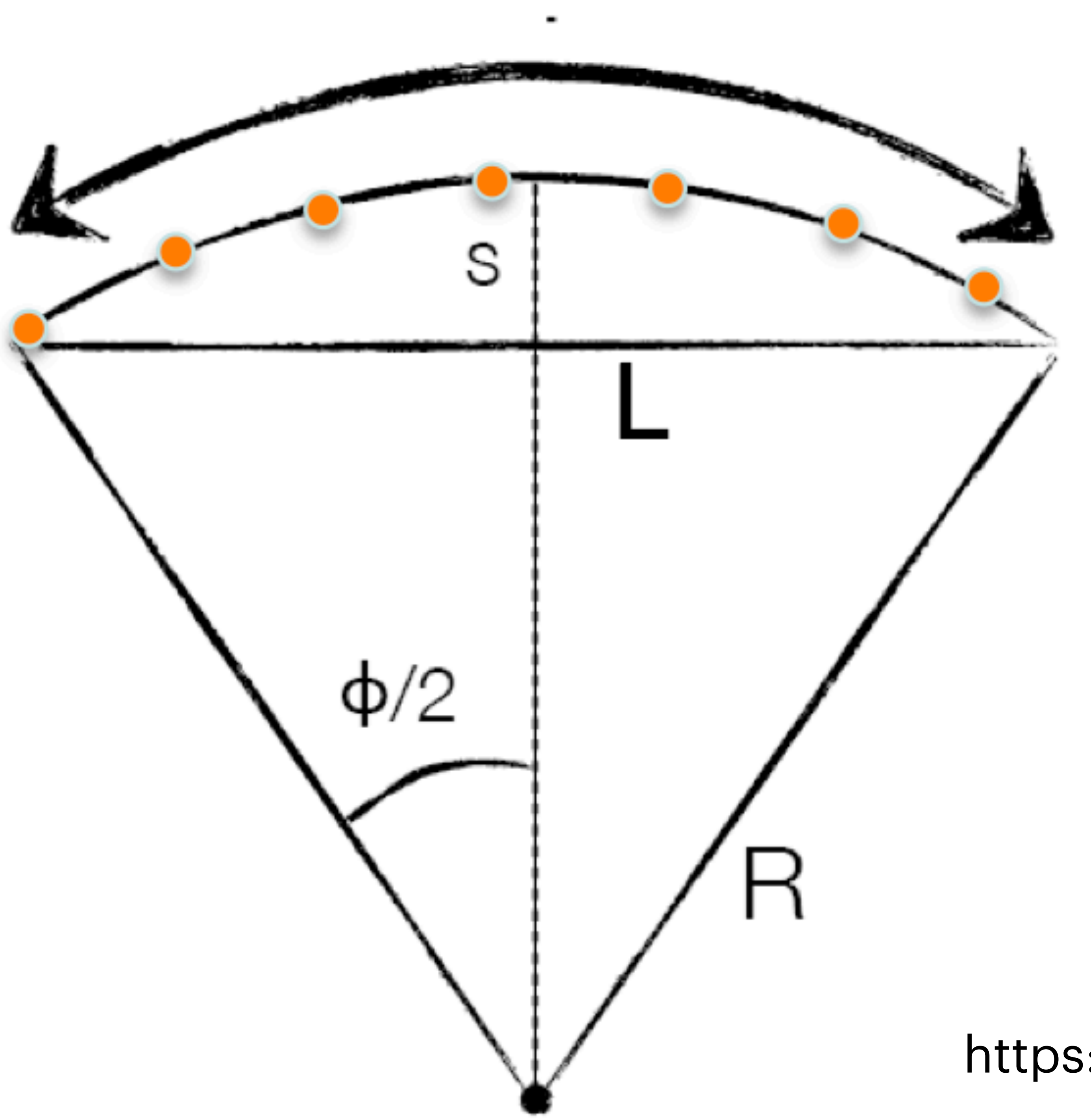


Figure 17: Relative momentum resolution versus momentum for long tracks in data obtained using J/ψ decays.

Tracking



$$p\left[\frac{GeV}{c}\right] = 0.3\ \mathrm{B[T]\ R[m]}$$

$$R = \frac{L^2}{8s}$$

$$\frac{q}{p} \to \frac{q}{p \cdot \mathcal{N}(1+\alpha, \sigma_{\mathrm{MS}})} + \mathcal{N}\left(\delta, \frac{\sigma_\delta}{\cosh\eta}\right)$$

scale **smearing** **bias**

https://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/L9_Tracking.pdf