Precision measurements of Standard Model parameters at the ATLAS experiment at CERN

arXiv:1701.07240 [hep-ex]

arXiv:2403.15085 [hep-ex]

Nenad Vranješ,
Institute of Physics Belgrade

27. mart 2025.

*The more important fundamental laws and facts of Physical Science have all been discovered and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote...
Our future discoveries must be looked for in the sixth place of decimals.*

A Michelson (1894)

ВРЛО КРАТКА ИСТОРИЈА ЕКСПЕРИМЕНТА АТЛАС

ISBN 978-981-327-179-1

1984	Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne, Switzerland.
1987	Workshop on the Physics at Future Accelerators, La Thuile, Italy. The Rubbia "Long-Range Planning Committee" recommends the Large Hadron Collider as the right choice for CERN's future.
1990	LHC Workshop, Aachen, Germany (discussion of physics, technologies and detector design concepts).
1992	General Meeting on LHC Physics and Detectors, Evian-les-Bains, France (with four general-purpose experiment Expressions of Interest presented).
1993	Three Letters of Intent evaluated by the CERN peer review committee LHCC. ATLAS and CMS selected to proceed to a detailed technical proposal.
1994	The LHC accelerator approved for construction, initially in two stages.
1995	LHC Conceptual Design Report.
1996	ATLAS and CMS Technical Proposals approved.
1996	Approval for the construction of the 14 TeV LHC, to be completed in 2005.
1997	Formal approval for ATLAS and CMS to move to construction (materials cost ceiling of 475 MCHF).
1997	Construction of the experiments commences (after approval of detailed Technical Design Reports of detector subsystems).
2000	Assembly of experiments commences at CERN. The LEP accelerator is closed down to make way for the LHC.
2008	LHC experiments ready for pp collisions. LHC starts operation. An incident stops the LHC operation.
2009	LHC restarts operation, first pp collisions at 900 GeV recorded by the LHC detectors.
2010	LHC collides protons at high energy (centre of mass energy of 7 TeV).
2012	LHC operates at 8 TeV: announcement of the discovery of a Higgs-like boson.
2015	After a shutdown in 2013–2014 the LHC operates at 13 TeV for Run-2.

2018 : end of Run-2, start to LS2

2021: start of Run-3

ВРЛО КРАТКА ИСТОРИЈА ЕКСПЕРИМЕНТА АТЛАС

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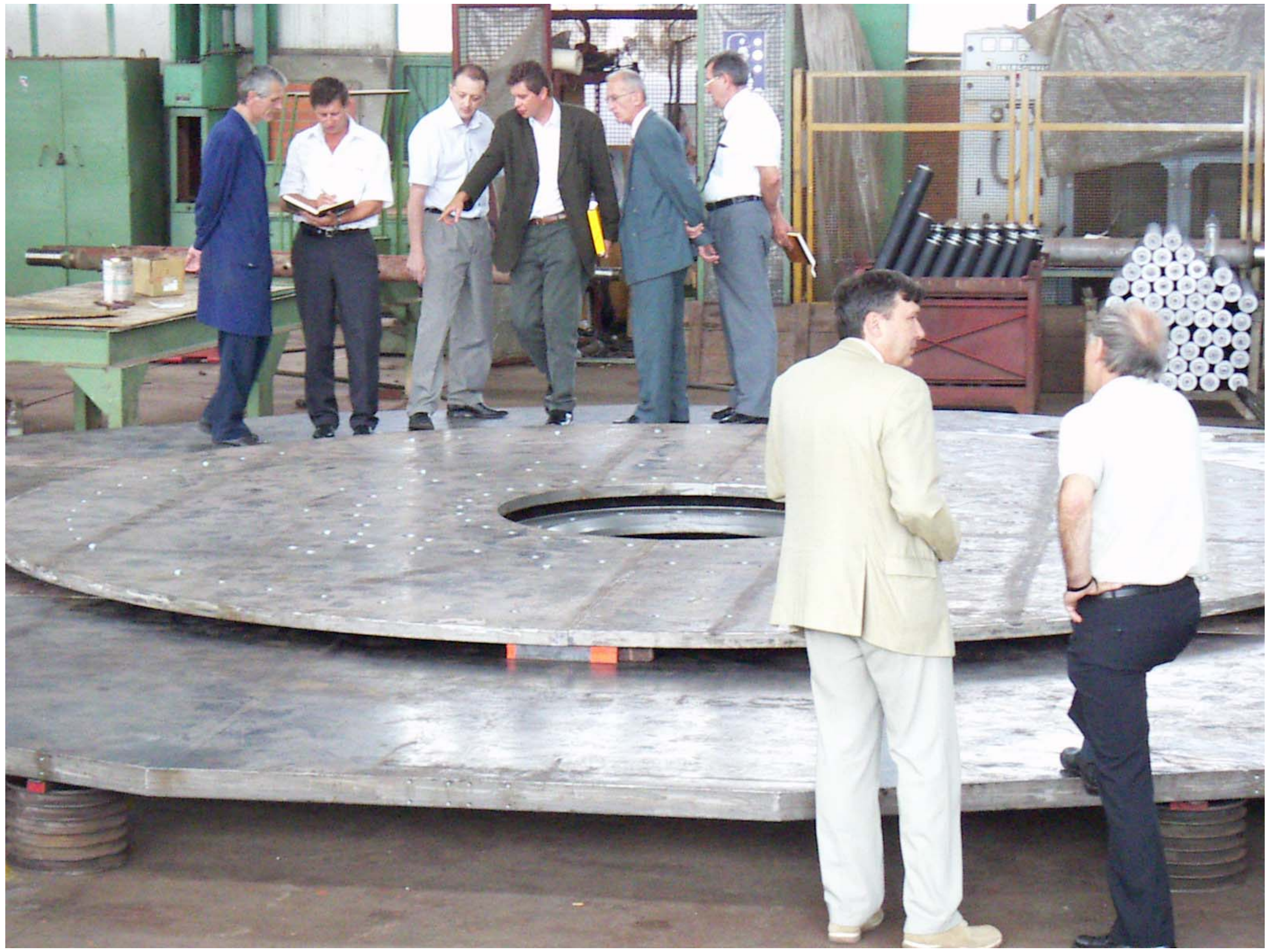
Fig. 3.1. First ATLAS Collaboration Week meeting outside CERN in Dubna, June 2000.

СРБИЈА И АТЛАС

- ИФ је дуго имао контакте са АТЛАС колаборацијом, прекидане током периода највећих криза у нашој земљи.
- У јуну 2001. ЦЕРН је потписао општи споразум о сарадњи са Србијом.
- У јануару 2003. Протокол о хардверском доприносу АТЛАС експерименту, потписан је од стране ЦЕРН-а, АТЛАС-а и Министарства науке Србије.
  - Тиме је ИФ постао члан АТЛАС колаборације.
- Наш допринос детектору АТЛАС су чинили заштитни дискови и предњи носачи дискова. Ови делови су имали основну вредност од 300 kCHF.
- У фебруару 2003. ИФ тим на челу са Драганом Поповићем имао је 6 физичара са докторатом и 3 студента. У то време неки чланови тима су већ били активни АТЛАС-у
- Током Драгановог руковођења групом (2003-2015.) одбрањене су
  - 3 докторске дисертације и 3 магистарска рада (и неколико дипломских радова)
  - 3 национална пројекта, (руководилац 2)
  - Изложбе, предавања
- Данас група броји 6 доктора наука и 2 студента.

НАША ГРУПА 2006.

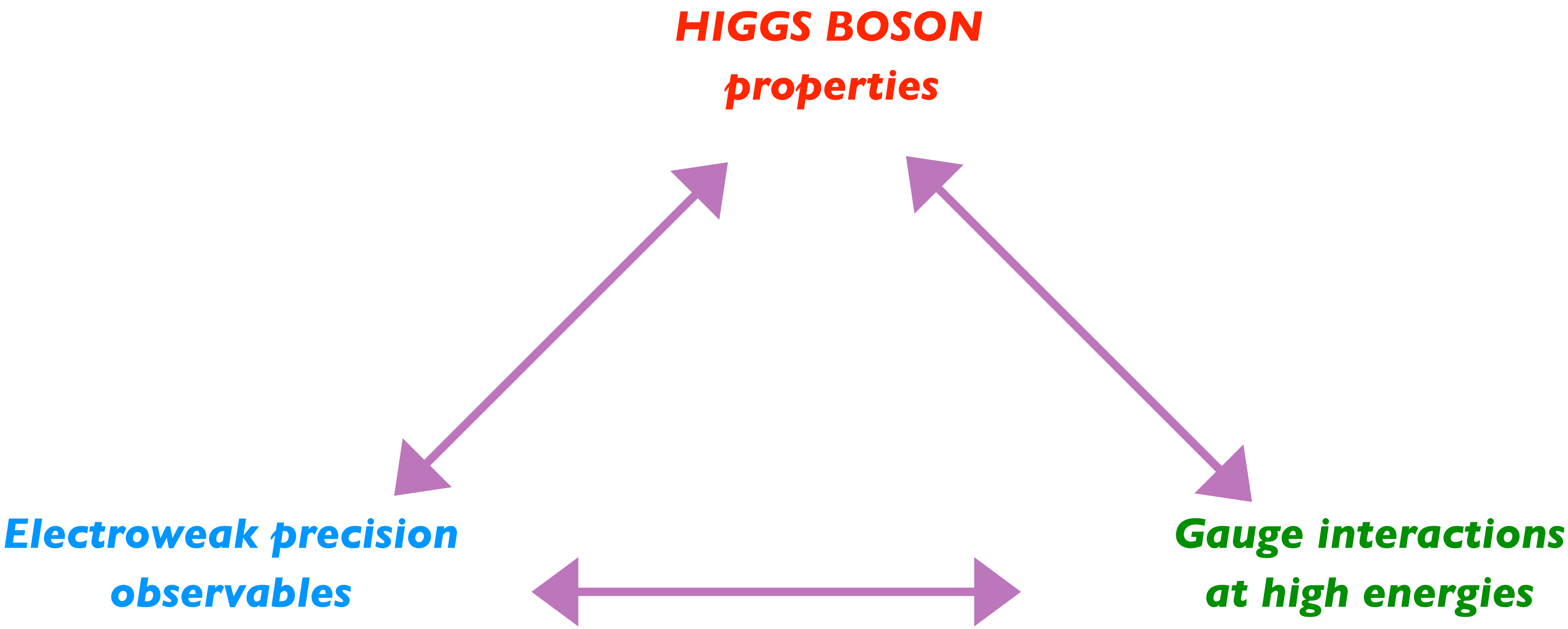
ДРАГАН И ЦЕРН



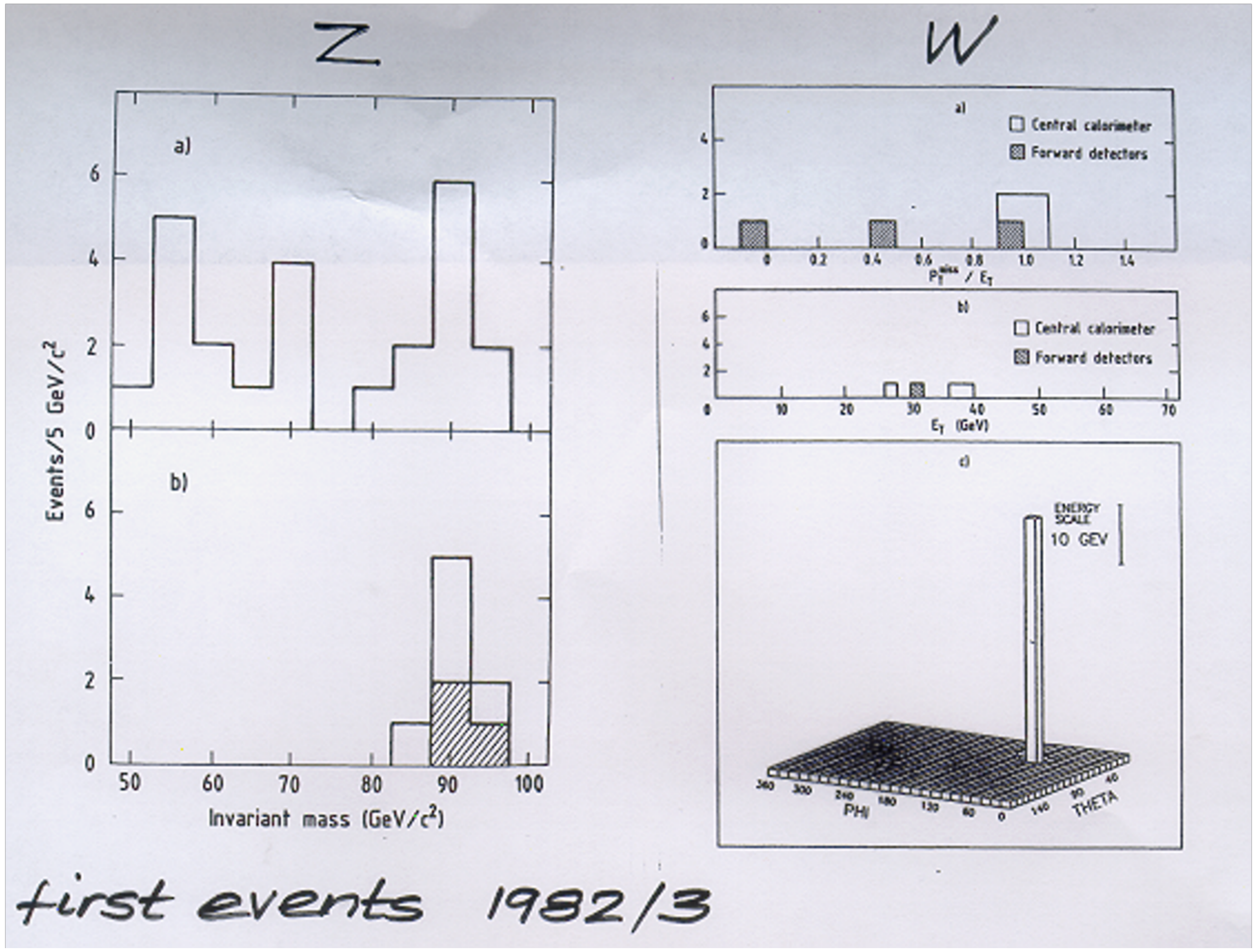
ДРАГАН И ЦЕРН

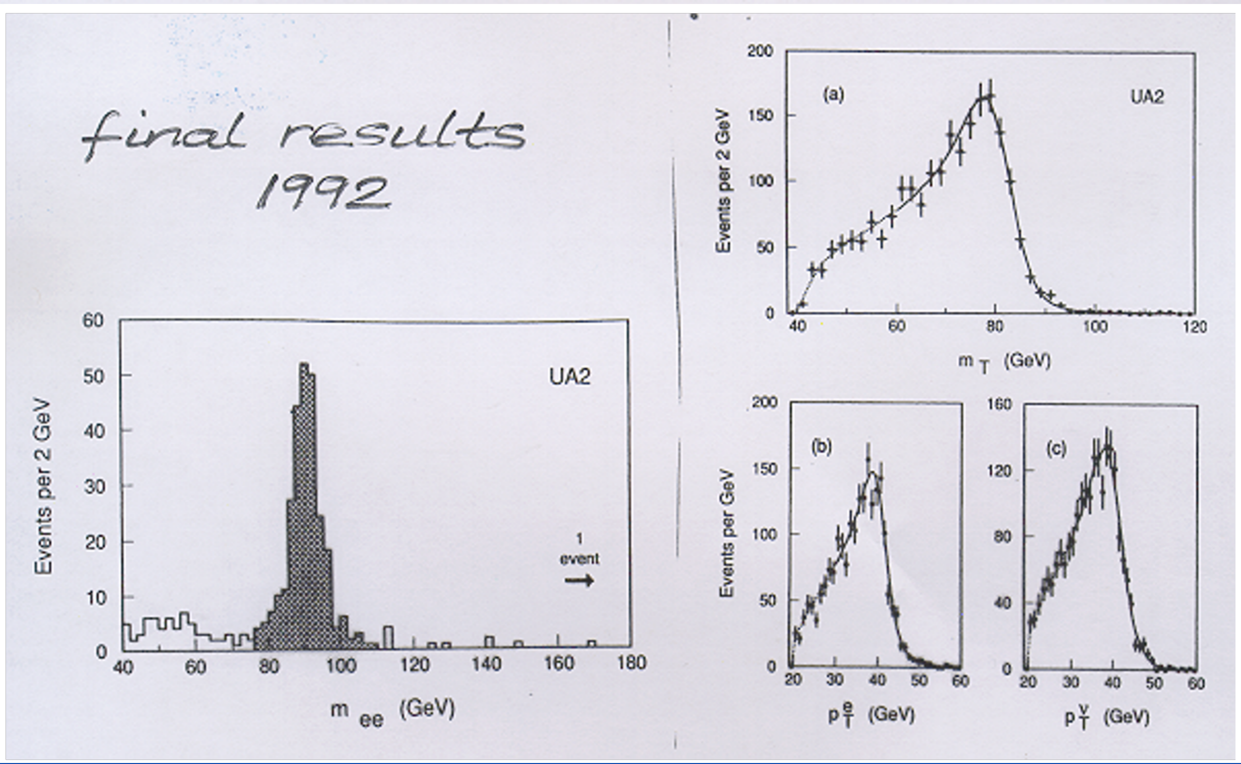
ДРАГАН И ЦЕРН

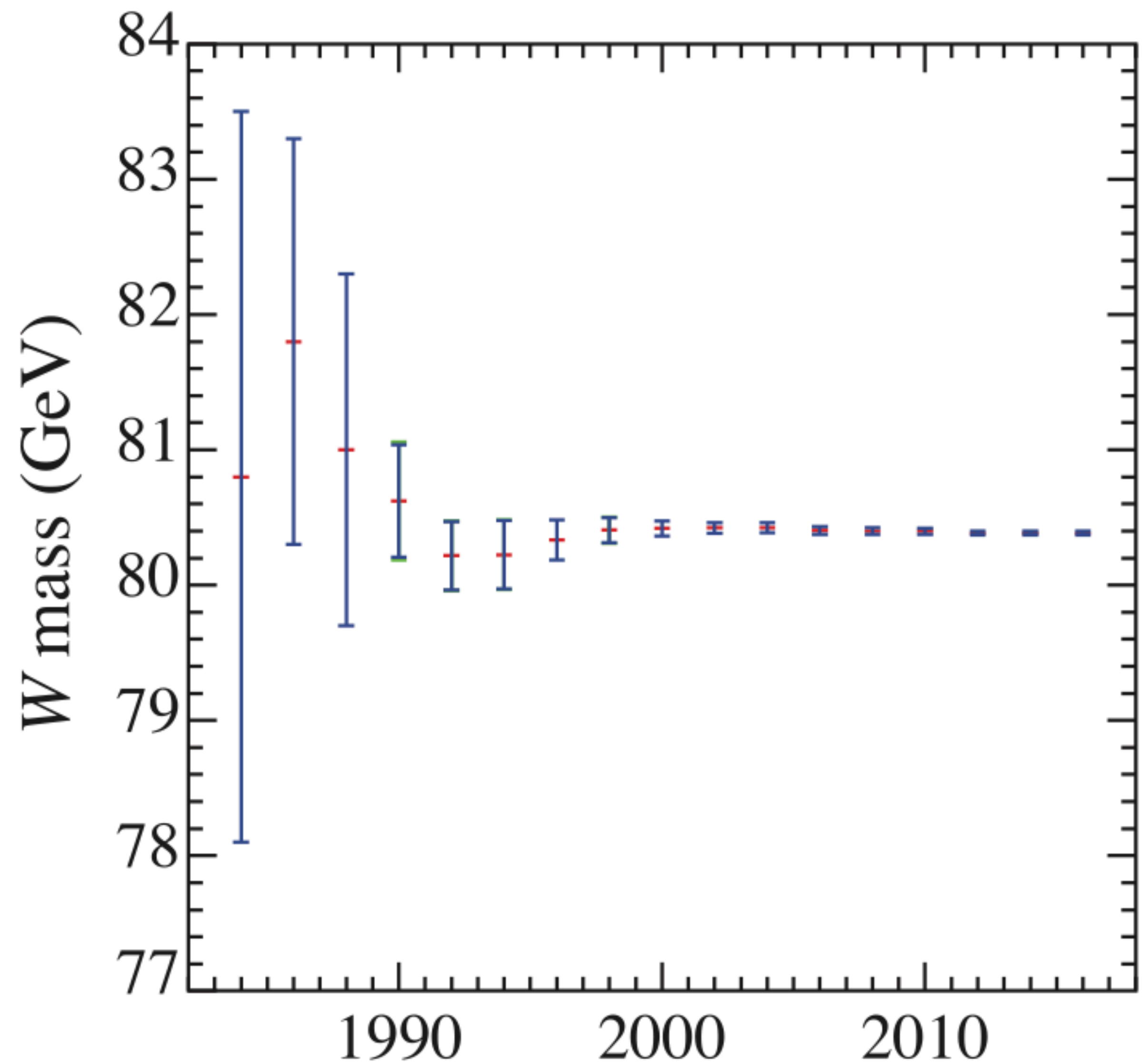
TEST OF THE ELECTROWEAK THEORY



W BOSON AND ITS PROPERTIES



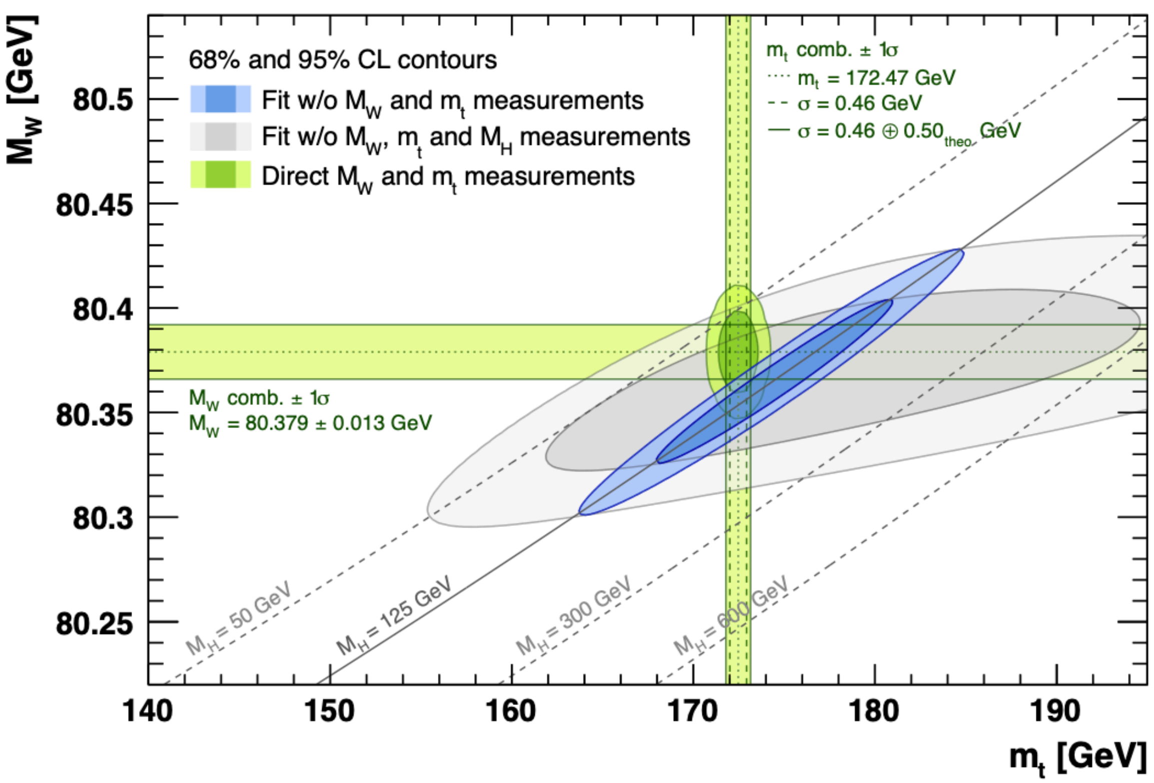


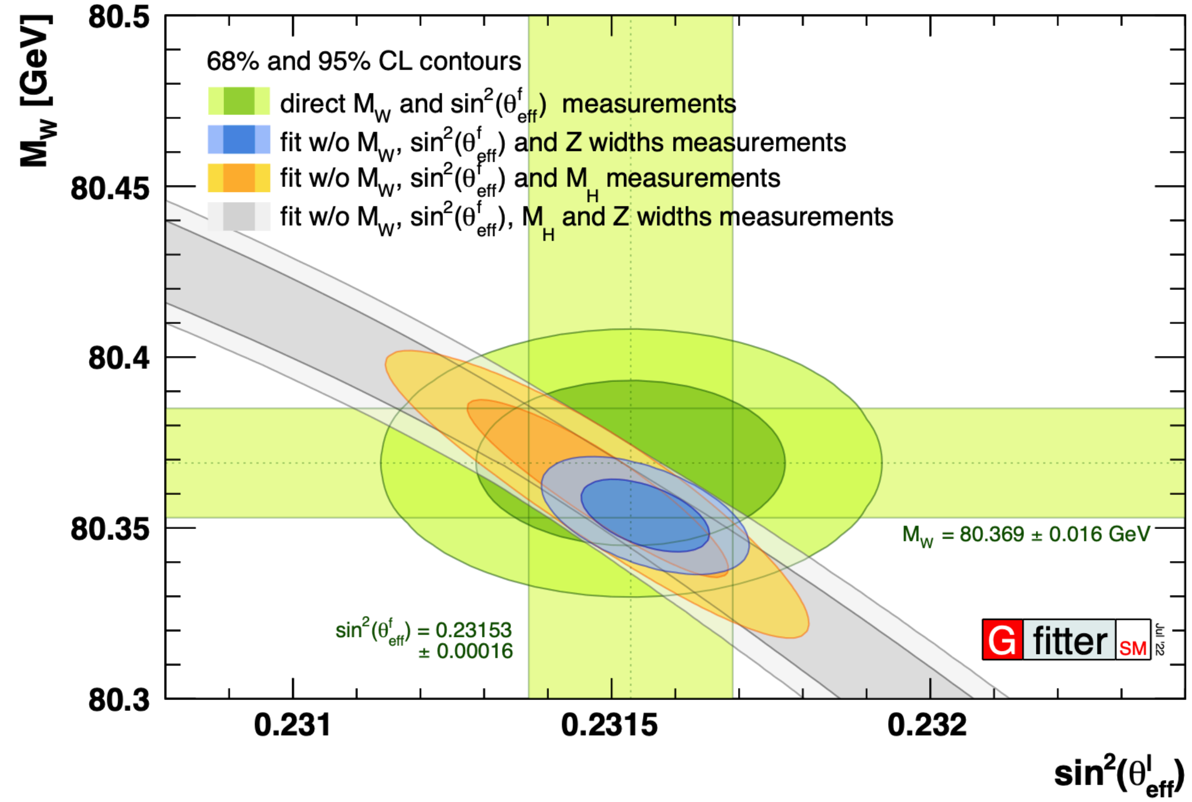


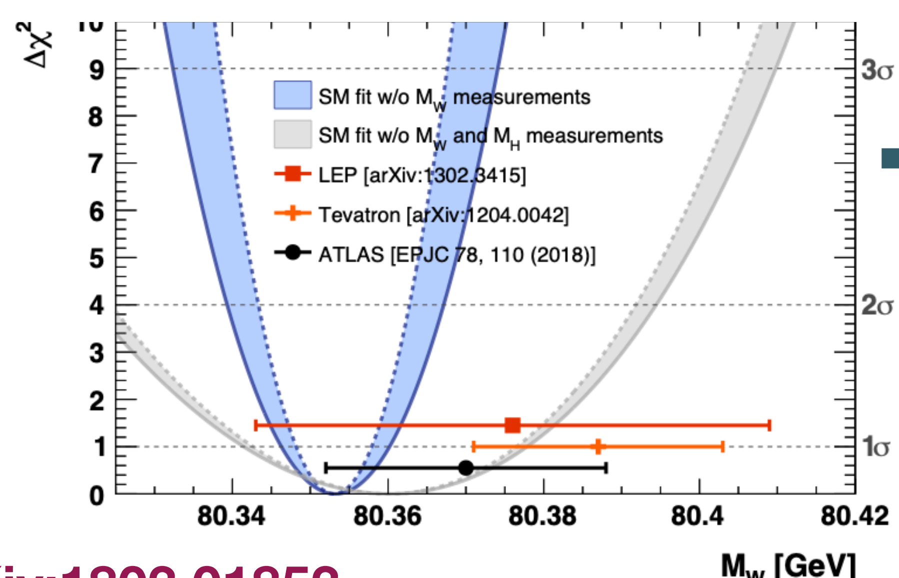
- Large steps, slow progress!

ELECTROWEAK PRECISION OBSERVABLES

- SM is overconstrained: W-boson mass, top quark mass and the Higgs mass
  - **m_W is the the prime SM consistency test!**
  - **… and a probe of BSM physics**







$$
\begin{aligned}
M_W &= 80.3535 \pm 0.0027_{m_t} \pm 0.0030_{\delta_{\rm theo} m_t} \pm 0.0026_{M_Z} \pm 0.0026_{\alpha_S} \\
&\qquad \pm 0.0024_{\Delta\alpha_{\rm had}} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\rm theo} M_W}\ {\rm GeV}\,, \\
&= 80.354 \pm 0.007_{\rm tot}\ {\rm GeV}\,,
\end{aligned}
$$

arXiv:1803.01853

Latest update: **80353 ± 6 MeV**, Phys. Rev. D 110, 030001

W-BOSON MASS

- EWK sector has 3 free parameters (+ Higgs mass)
- Three most precise measured values G_F, α, m_Z
- At LO m_W can be expressed as:

$G_F = 1.16637\ (1)\ \ 10^{-5}\ \mathrm{GeV}^{-2}$

$\alpha = 1\ /\ 1370359999679$

$m_Z = 91.1876\ (21)\ \mathrm{GeV}$

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}$$

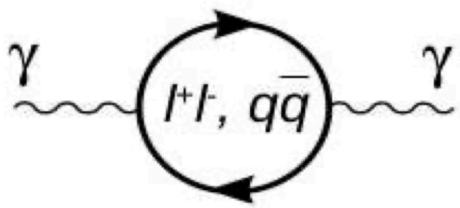
- This leads to : 80939 ± 3 MeV which is **~37σ** from the measurement !!!
    - **Is SM (so) wrong?**
- *No, it is not because we measure renormalised mass*, i.e:

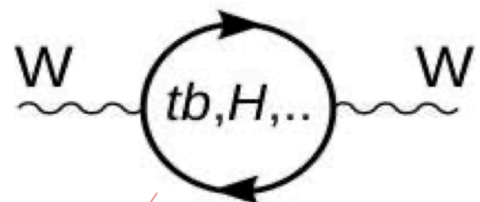
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

- m_W receives contributions from **radiative** corrections
    - incorporates higher-order corrections from the SM *and beyond*

QUANTUM CORRECTIONS

- Higher-order corrections, dominantly W and γ self-energies
- Mass depends on m^2_{top} and $\ln(m_H)$

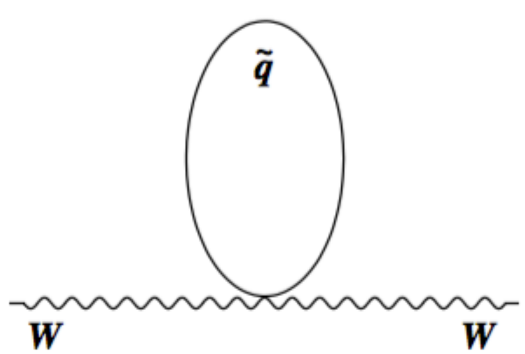


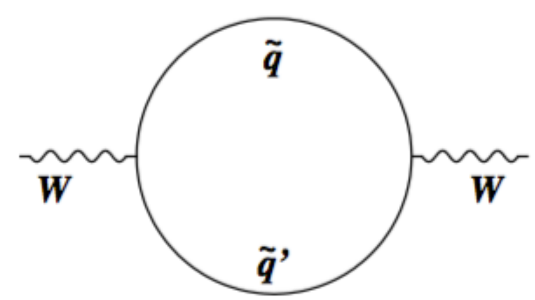


$$\Delta r = \Delta\alpha - \tan^2\theta_W \Delta\rho = \sim 0.059 - \frac{3G_\mu m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_{top}^2}{m_W^2}\cot^2\theta_W - \left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \dots\right]$$

$\alpha(0) \sim 1/137.. \rightarrow \alpha(m_Z) \sim 1/128.9$

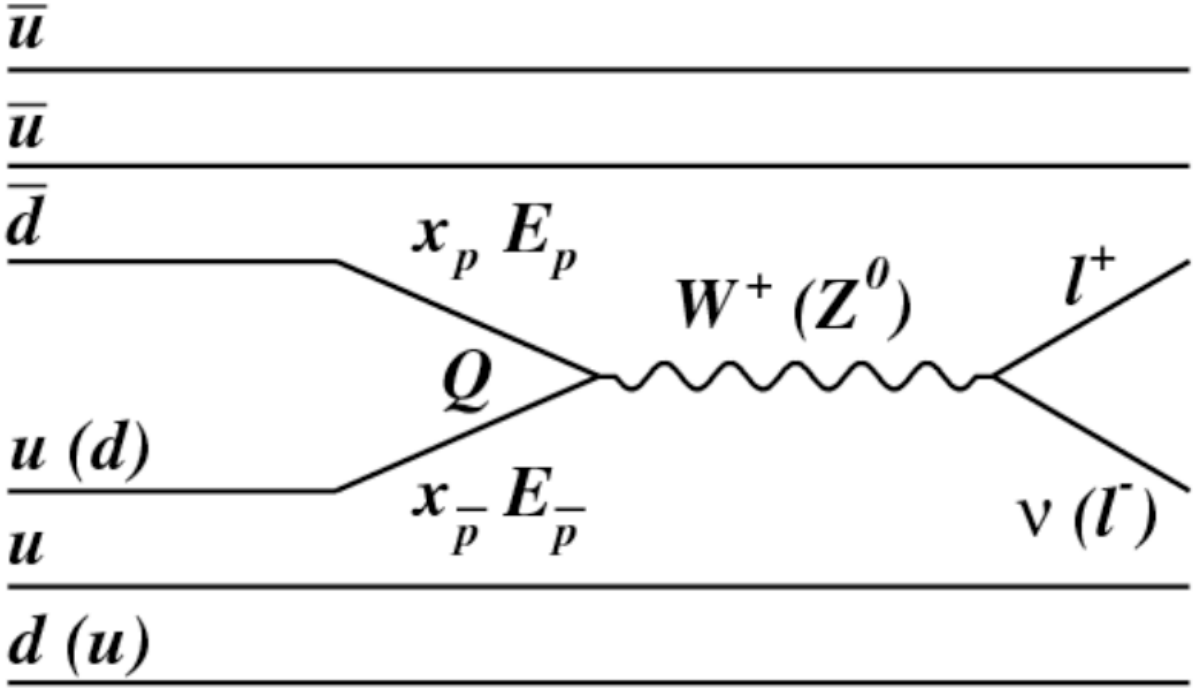
- m_W depends also on *any new particle* with weak charge



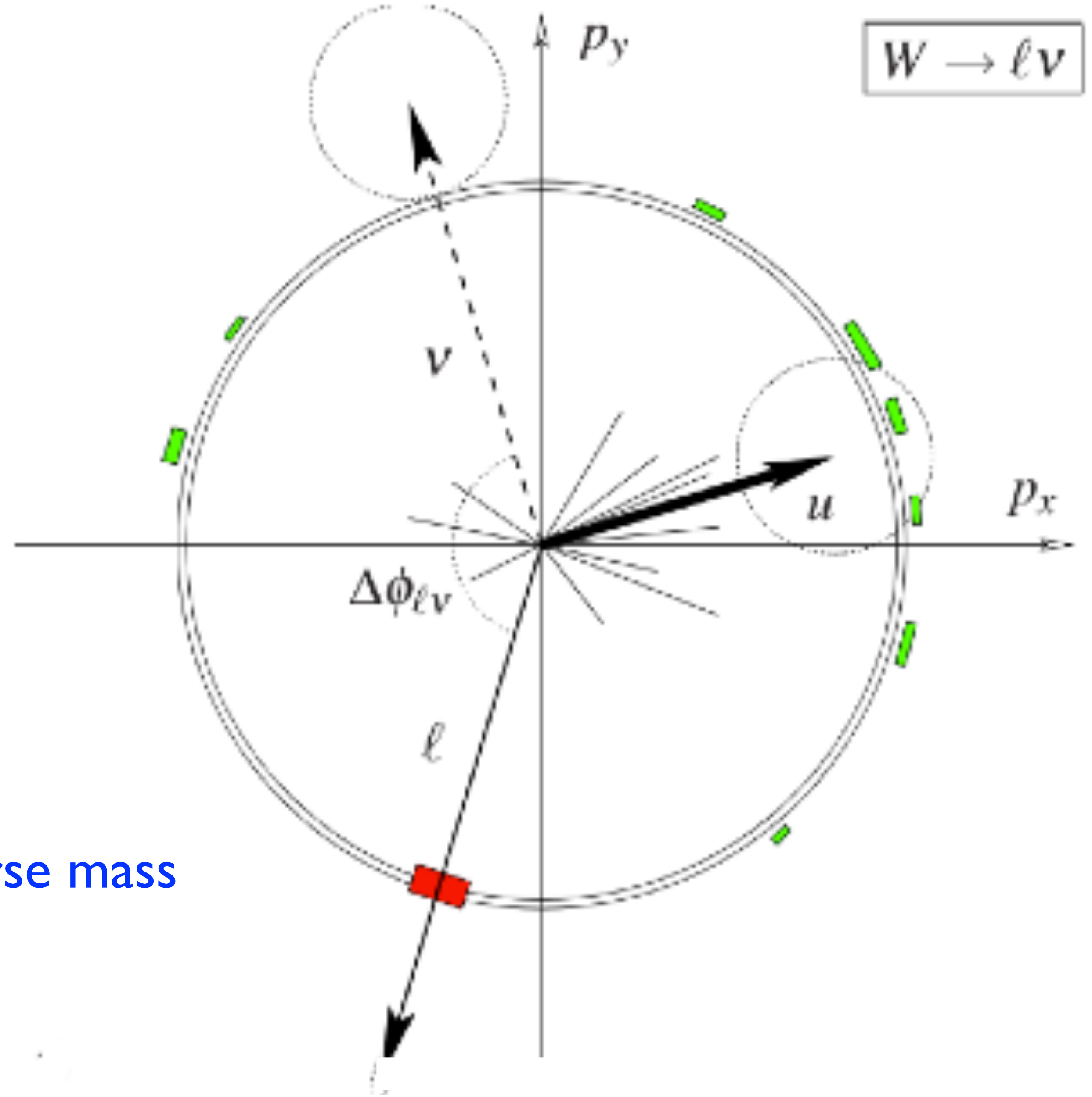


e.g. SUSY

HOW TO MEASURE W-BOSON MASS (HAD.COL.)



- Exploit leptonic channels (e and μ)
- Many components needed for m_W measurement: ***a very complex measurement***
- Three observables: lepton p_T, neutrino p_T, transverse mass



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

HOW TO MEASURE W-BOSON MASS (HAD.COL.)

$$p_T^\ell = \frac{m_W}{2}\sin\theta, \qquad {p_T^\ell}^2 = \frac{\hat{s}}{4}\sin^2\theta = \frac{\hat{s}}{4}(1-\cos^2\theta)$$

$$\hat{s} = (p_1^\mu + p_2^\mu)^2 = s x_1 x_2.$$

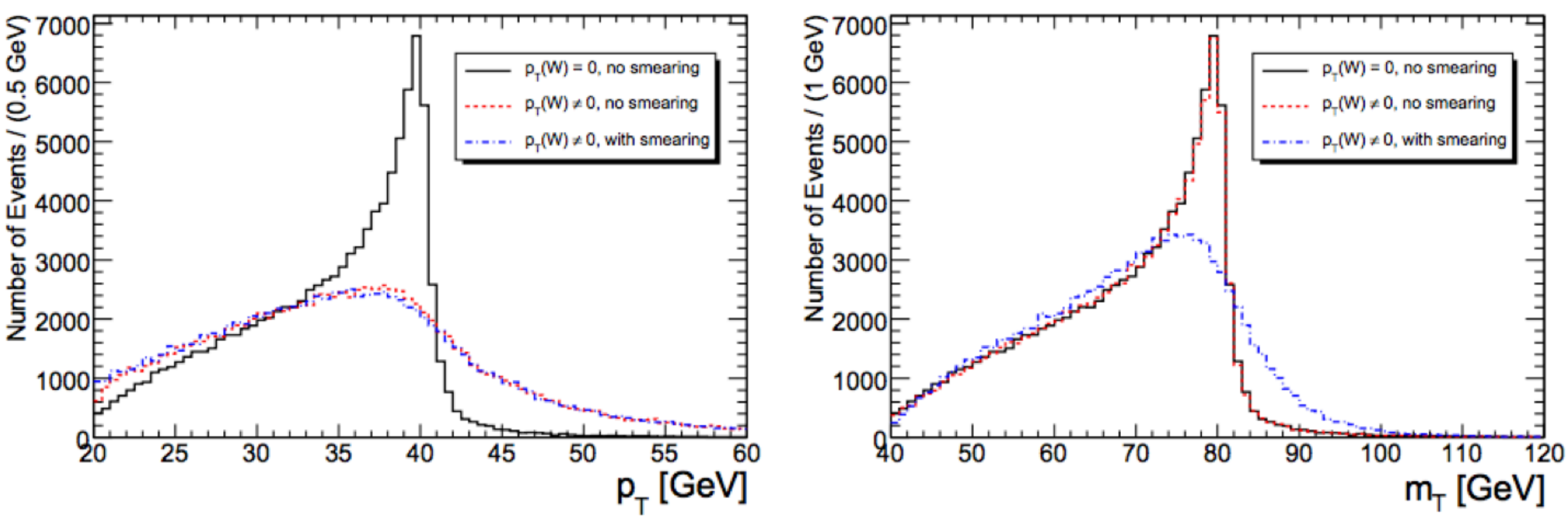
$$\frac{d\sigma}{dp_T^\ell} = \frac{d\sigma}{d\cos\theta}\frac{d\cos\theta}{dp_T^\ell}$$

$$\hat{s} = m_W^2$$

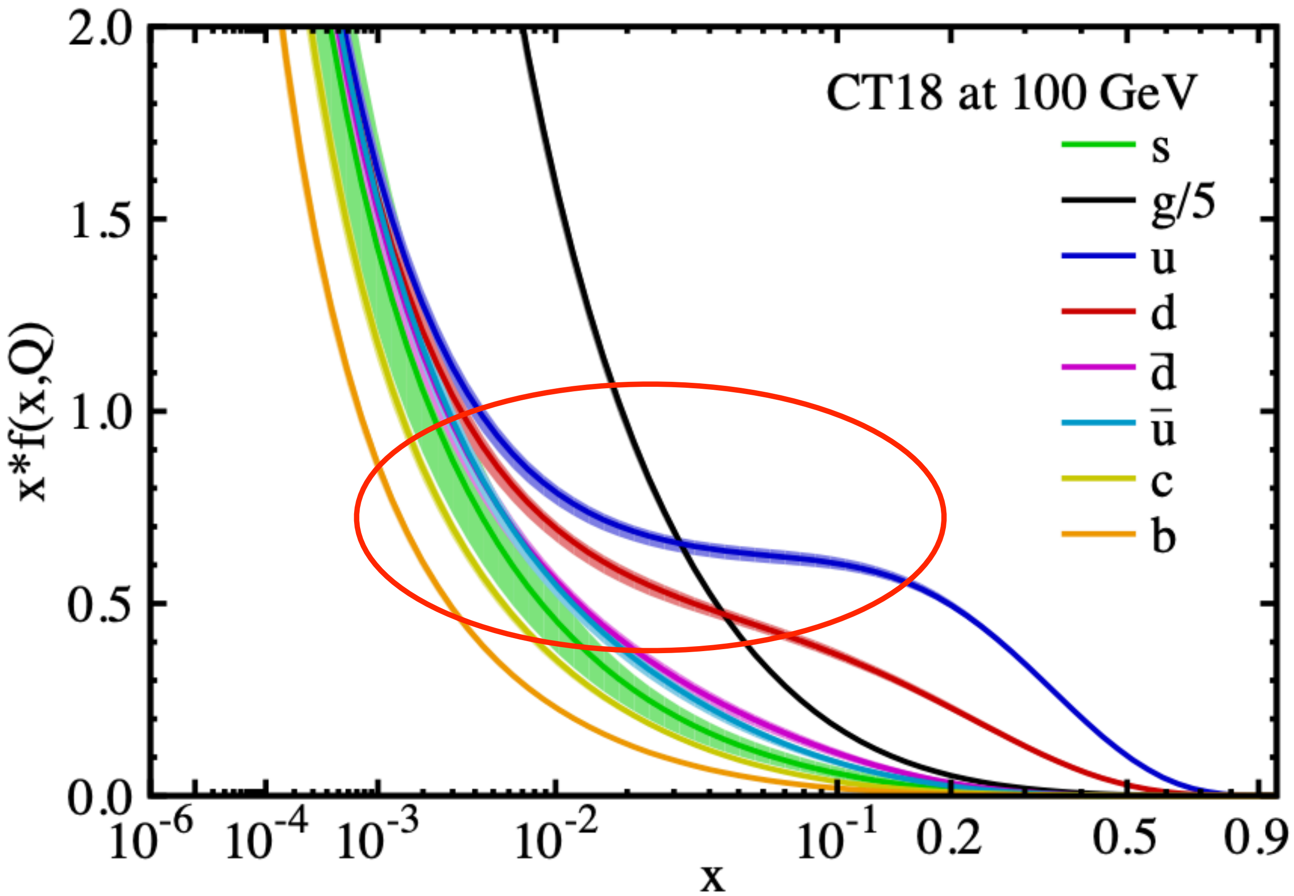
$$\frac{d\cos\theta}{dp_T^\ell} = \frac{4p_T^\ell}{\hat{s}}\left(1 - \frac{4p_T^\ell}{\hat{s}}\right)^{-1/2}$$

$$\hat{\sigma}(\hat{s}) \propto \left(\frac{G_F m_W^2}{\sqrt{2}}\right)^2 \frac{\hat{s}}{(\hat{s}-m_W^2)^2 - m_W^2\Gamma_W^2}$$

PhD Thesis of Aleksandra Dimitrievska, (FF, 2017): https://cds.cern.ch/record/2293638/



STRONG INTERACTION

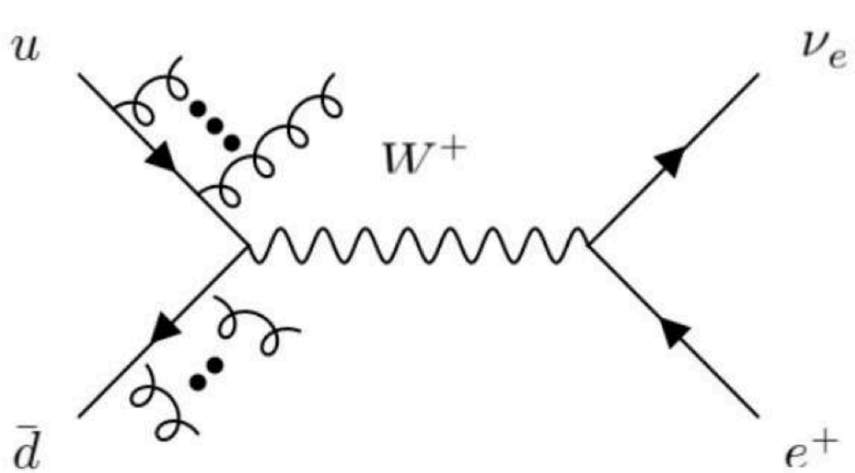


$x_{1,2}$ = m/√s exp(±y)

Tevatron √s~ 2TeV pp 0<y<2 $x_{1,2}$ ~ 10^{-2} – 10^{-1}

ATLAS √s~ 7TeV pp 0<y<3 $x_{1,2}$ ~ 10^{-3} – 10^{-1}

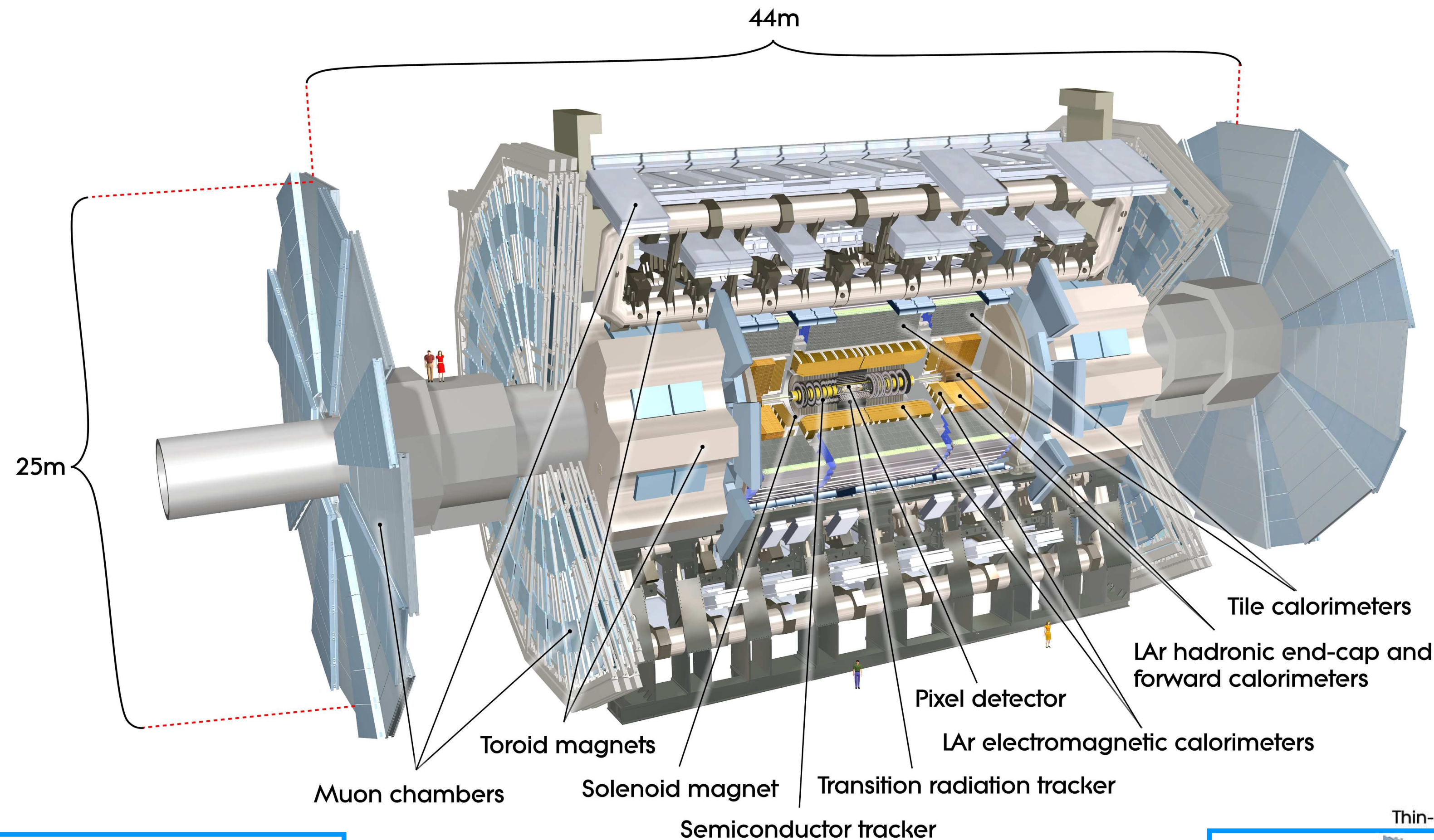
LHCb √s~13TeV pp y~4 $x_{1,2}$ ~ 10^{-4} – 10^{-1}



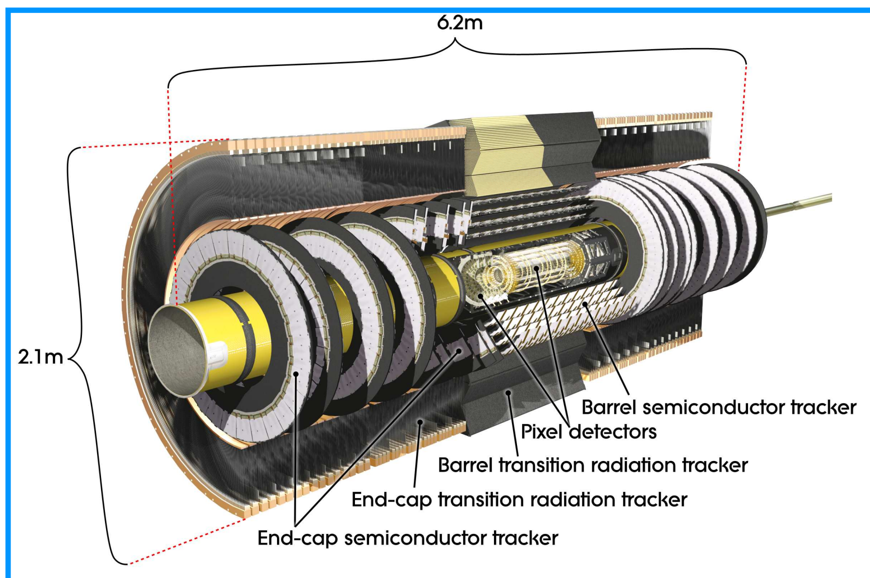
Transverse momentum distribution:

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

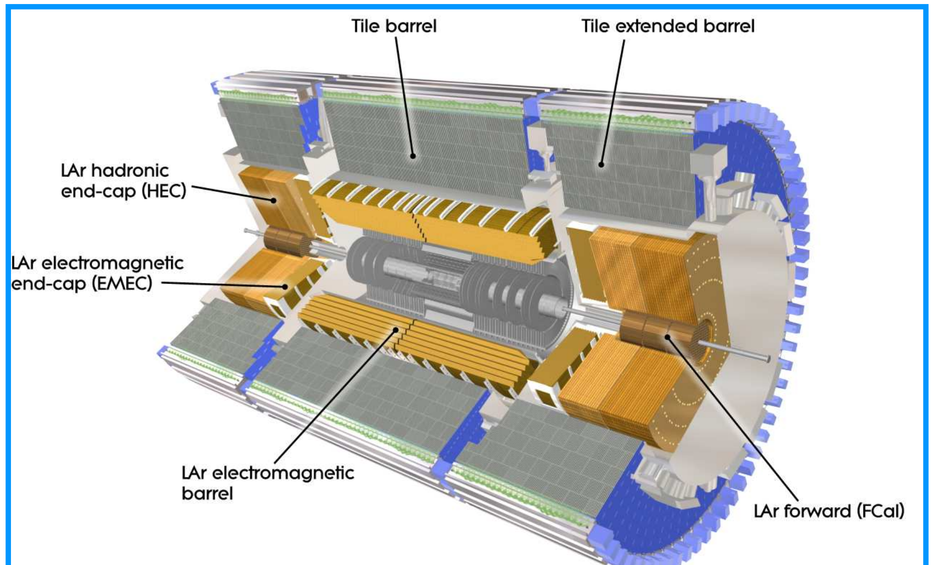
ATLAS DETECTOR



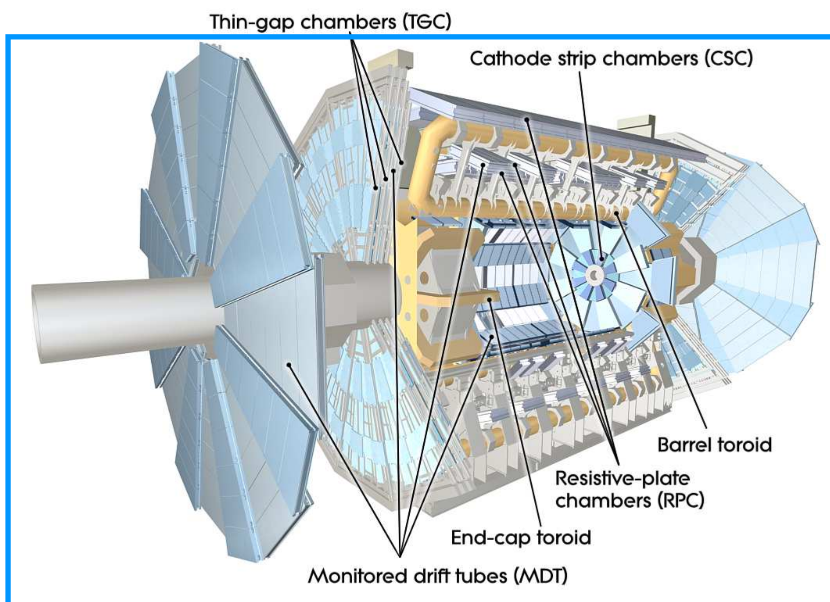
+ Trigger, computing resources, software infrastructure…



- **Inner detector: electrons, muons (kinematics)**

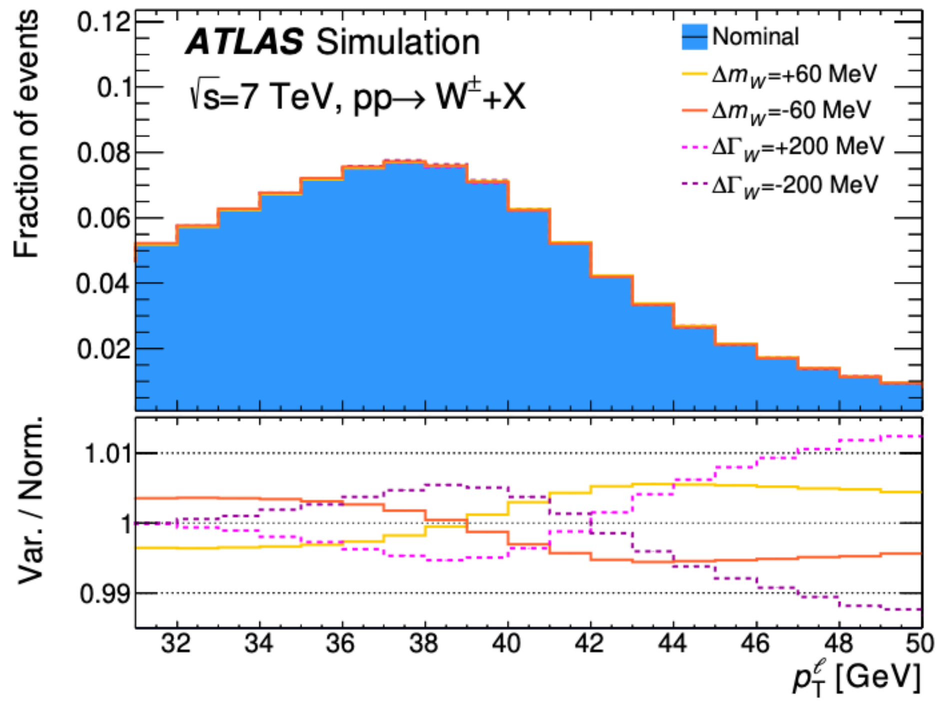


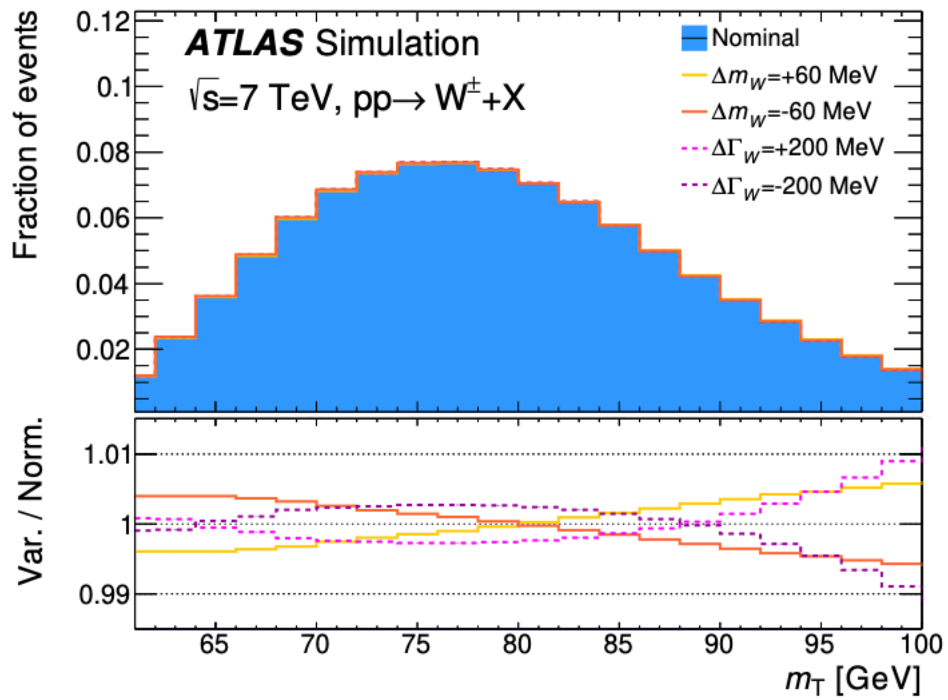
- **ECAL, HCAL: electrons, hadronic recoil**



- **Muon Systems: muons (identif.)**

HOW TO MEASURE W-BOSON MASS (HAD.COL.)





$$\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_V^2)^2 + m^4\Gamma_V^2/m_V^2},$$

Decay channel	$W \to e\nu$	$W \to \mu\nu$
Kinematic distributions	p_T^ℓ, m_T	p_T^ℓ, m_T
Charge categories	W^+, W^-	W^+, W^-
$\lvert\eta_\ell\rvert$ categories	[0, 0.6], [0.6, 1.2], [1.8, 2.4]	[0, 0.8], [0.8, 1.4], [1.4, 2.0], [2.0, 2.4]

- Parameter of interest (W-boson mass) obtained via minimisation X^2 minimisation
- Complementarity and gain in sensitivity
  - p_T vs m_T (theory), e vs μ (experimental)

SYSTEMATICS, SYSTEMATICS, SYSTEMATICS !

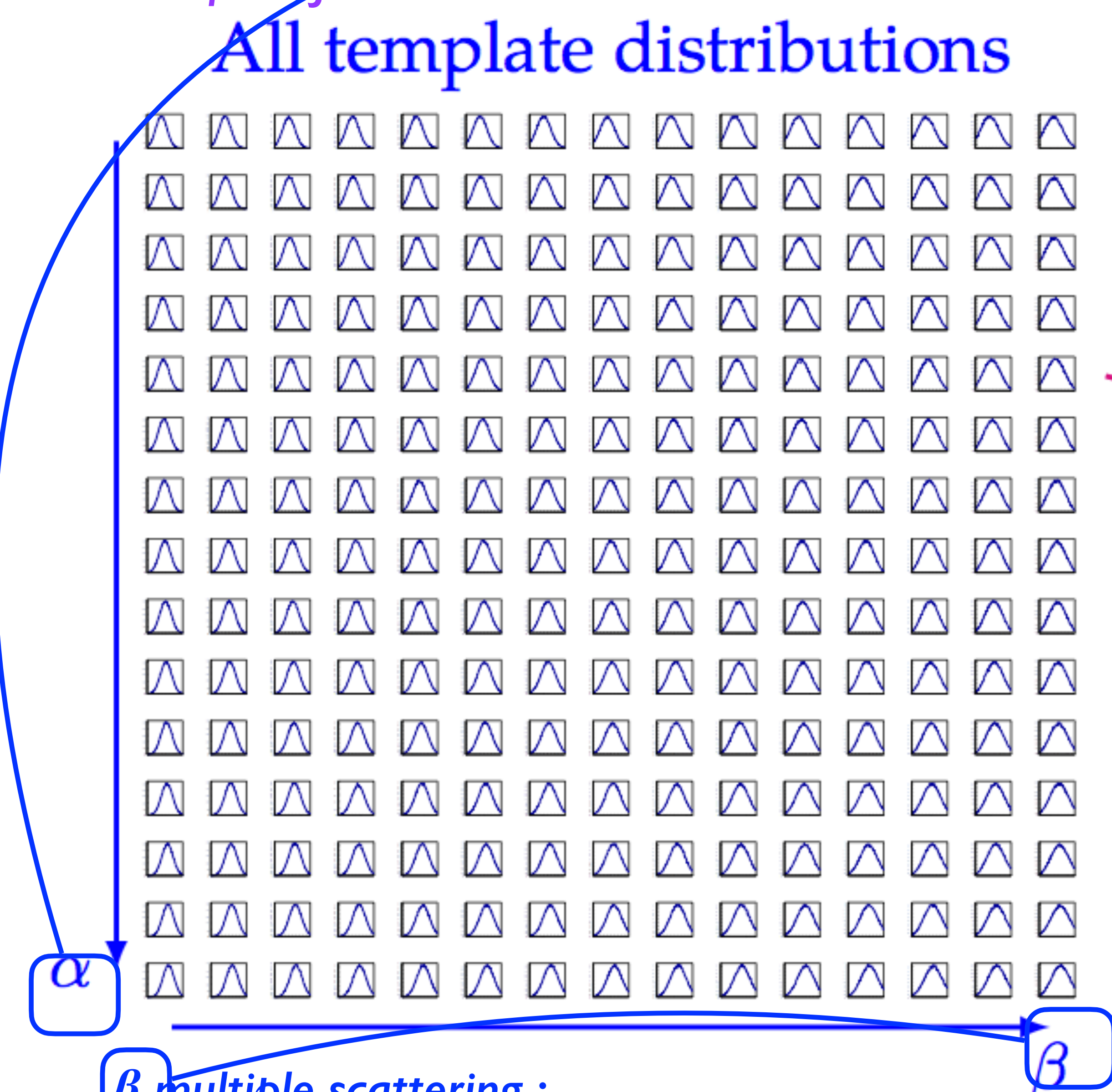
- **Experimental**
  - Leptons : electrons (e) and muons (μ)
    - Calibration: momentum scale and resolution,
      most critical δm/δα ~ 800 MeV/%, δm/δβ~8 MeV/%
    - Reconstruction, identification and trigger efficiency (most relevant vs p_T)
  - Hadronic recoil calibration: affects p_T^{miss} => m_T
  - Background : multijet production (poor prediction on rate, *but also the shape*) + others
- **Modeling** (Vector boson production and decay)
  - Electroweak : QED ISR, QED FSR, pure week and ISF and FSR interference
  - QCD :
    - Rapidity and transverse momentum distributions : fixed order predictions and parton shower. Parton distribution functions (PDFs)
    - Angular distributions
- Plus statistical uncertainty
  - Still not negligible

LEPTON CALIBRATION (MUONS)

- Find which distortion to apply on MC to match data (for instance a scale α) using **template method**
- X^2 test performed between data and each of the template distribution which gives a X^2 'valley', fitting parabola (or pol^n) gives α and dα.
- **We are fitting invariant mass distribution e.g. *J/ψ, Y, Z → μμ***
- A problem: resolution is biasing the scale, cf. backup.
- **As a solution 2D fits are performed (templates produced varying scale and resolution).**
- Get parameters from X^2 comparisons of data and references (2D plot on next page).
- No bias in α and additional smearing obtained.
- In each **category, e.g.** (η_i, η_j) calculate mass and get α_{ij} and $\beta_{ij:}$
- Solve system of equations to get scale factor (and residual smearing) for each bin (η, pT, phi, charge…)

LEPTON CALIBRATION (MUONS)

Cartoon from J-B. Blanchard - Thanks!



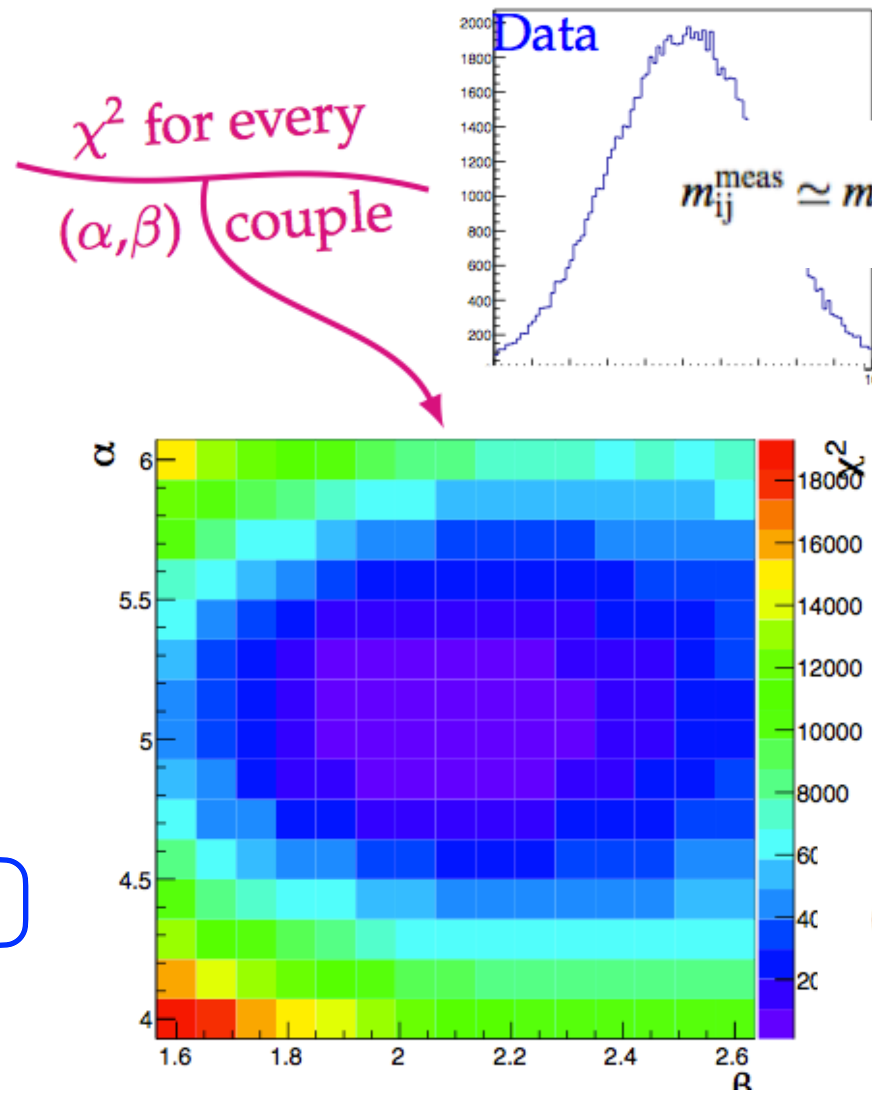
χ^2 comparison with data

$$\chi^2 = \sum_i \frac{(d_i - t_i)^2}{\sigma_{di}^2 + \sigma_{ti}^2}$$

$$m_{\ell\ell} = \sqrt{2E_1E_2(1-\cos(\theta_{12}))}$$

$$p_T^{meas} = p_T^{reco}(1+\alpha_i)$$

$$m_{ij}^{meas} \simeq m_{ij}^{reco}\left(1+\frac{\alpha_i+\alpha_j}{2}\right) = m_{ij}^{reco}\left(1+\frac{\alpha_{ij}}{2}\right)$$



$$B_i = \sum_{j=1}^{N} \frac{2\beta_{ij}}{(\delta\beta)_{ij}^2}$$

$$U_{ij} = \frac{1}{(\delta\beta)_{ij}^2} + \delta_{ij}\sum_{k=1}^{N}\frac{1}{(\delta\beta)_{ik}^2}$$

$$\alpha_i = \sum_{j=1}^{N} U_{ij}^{-1} B_j$$

$$(\delta\alpha)_i^2 = \sum_{j=1}^{N} (U_{ij}^{-1})^2 (\delta B)_j^2 \approx U_{ii}^{-1}$$

β multiple scattering :

$(q/pt)_{smear} = (q/pt)_{ini} + \beta_{mult} \times g \times (q/pt)_{ini}$

β intrinsic ('curvature') :

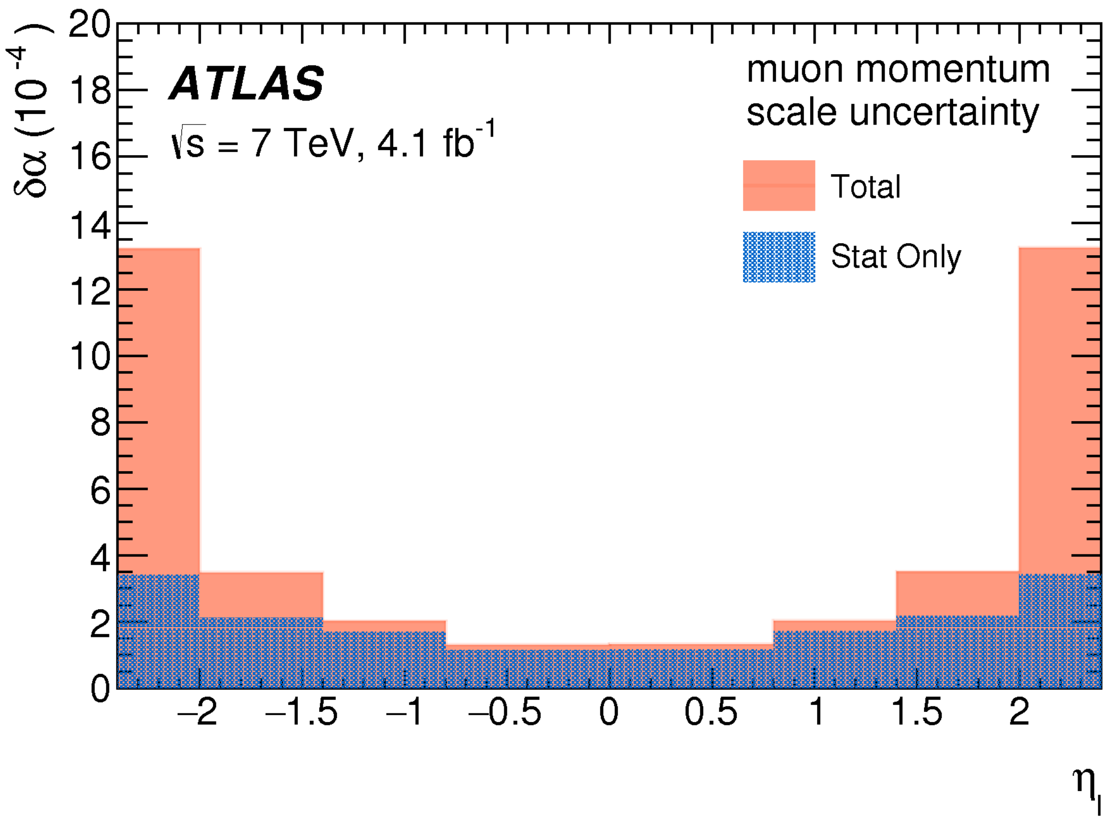
$(q/pt)_{smear} = (q/pt)_{ini} + \beta_{curv} \times g'$

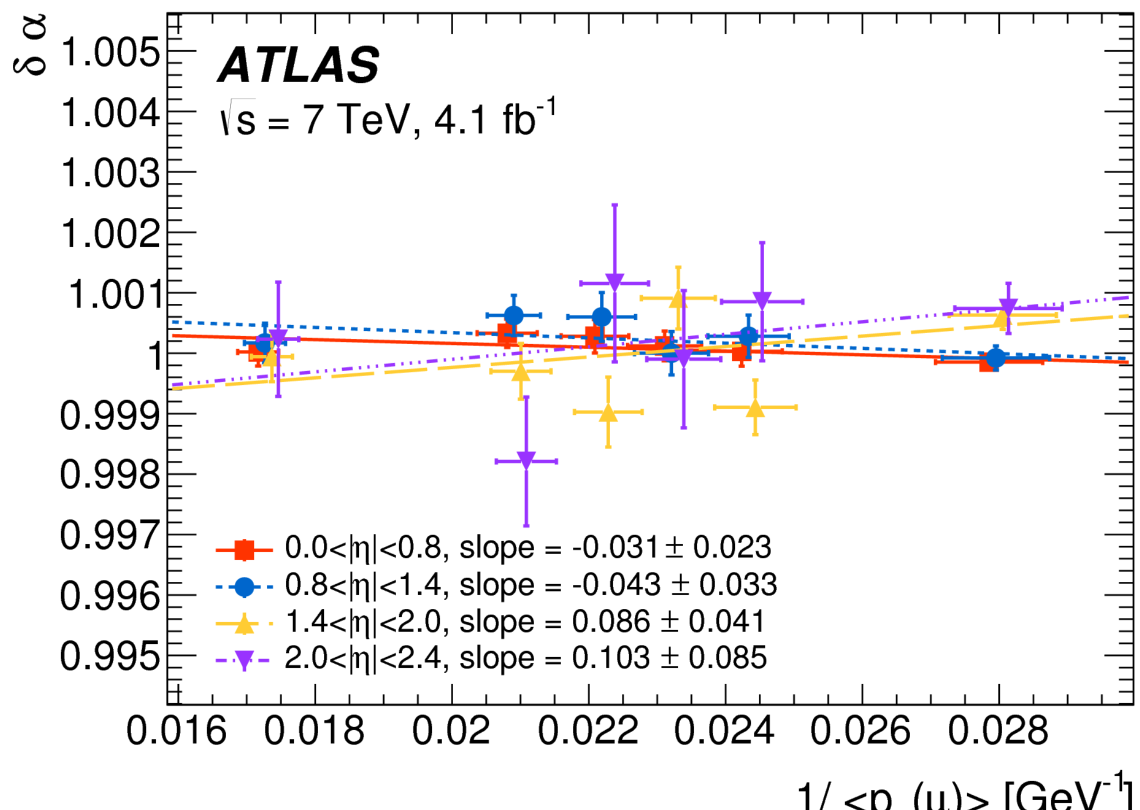
RADIAL BIAS

- ID kinematics used for the $W \to \mu\nu$ analysis, biased by resolution and position of the ID elements, magnetic field and material distribution
  - Radial scale along η (deformations along trajectory), intrinsic resolution
  - Correction parametrisation :

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

  - α and βcurv obtained from $Z \to \mu\mu$
    - Extrapolation *Z to W* by fitting vs <1/p_T>, uncer = max (p_1, $p_1$uncertainty)
    - Dominated by statistical uncertainty (+ exatrpolayion for |η|>2.0)



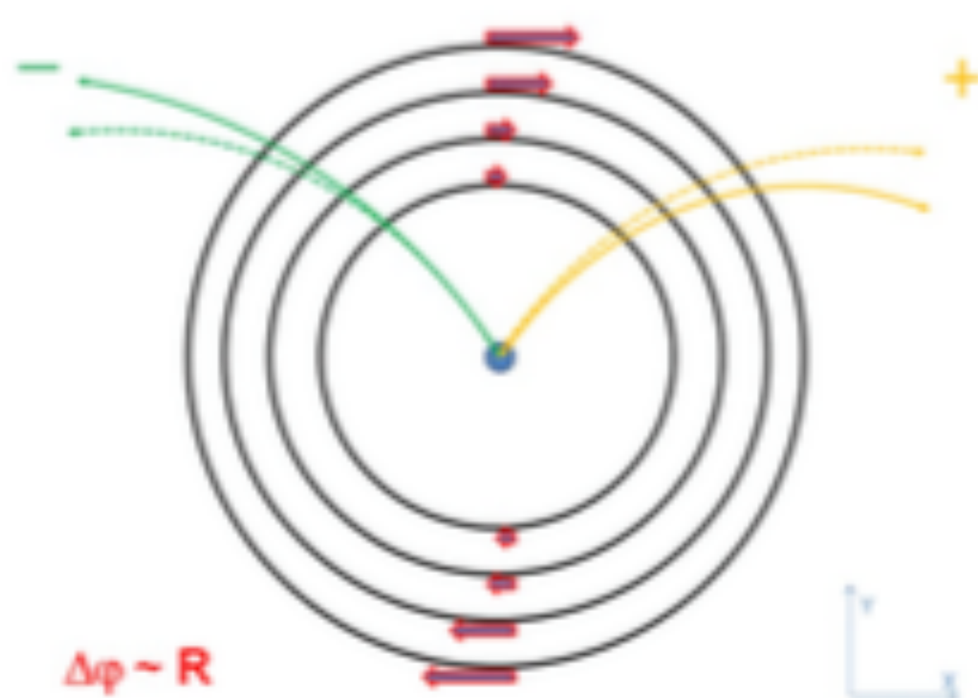


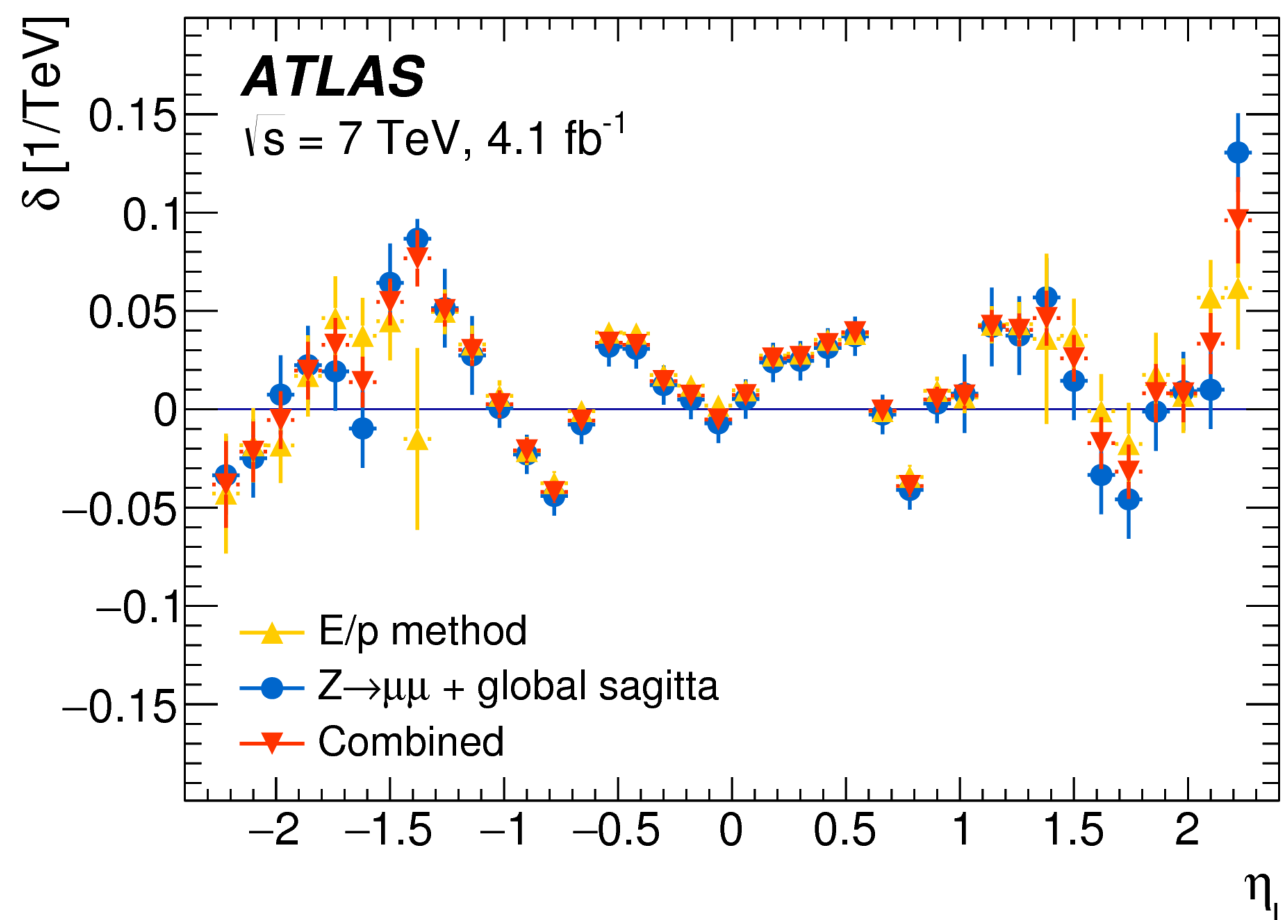
SAGITTA BIAS

- Twists and curls along z-axis : sagitta bias
  - Unlike radial scale - charge dependent very important **m_{W+}, m_{W-} consistency check**
  - Correction parametrisation :

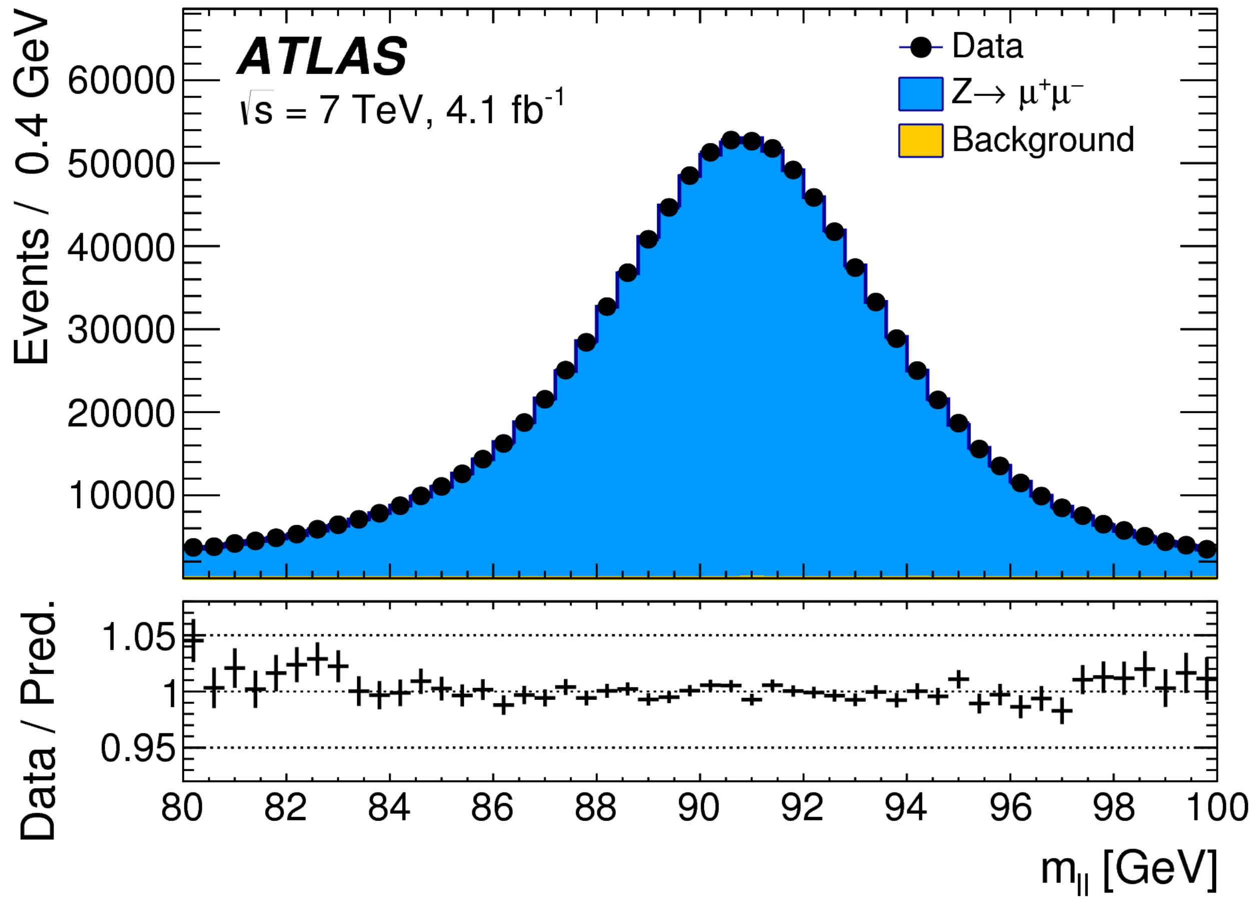
$$p_T^{\mathrm{data,corr}} = \frac{p_T^{\mathrm{data}}}{1 + q \cdot \delta(\eta, \phi) \cdot p_T^{\mathrm{data}}}$$

  - δ evaluated from $Z \to \mu\mu$ and E/p method (using $W \to e\nu$) events
    - *Z* and *E*/*p* agree up to global bias to which *Z* method is not sensitive.



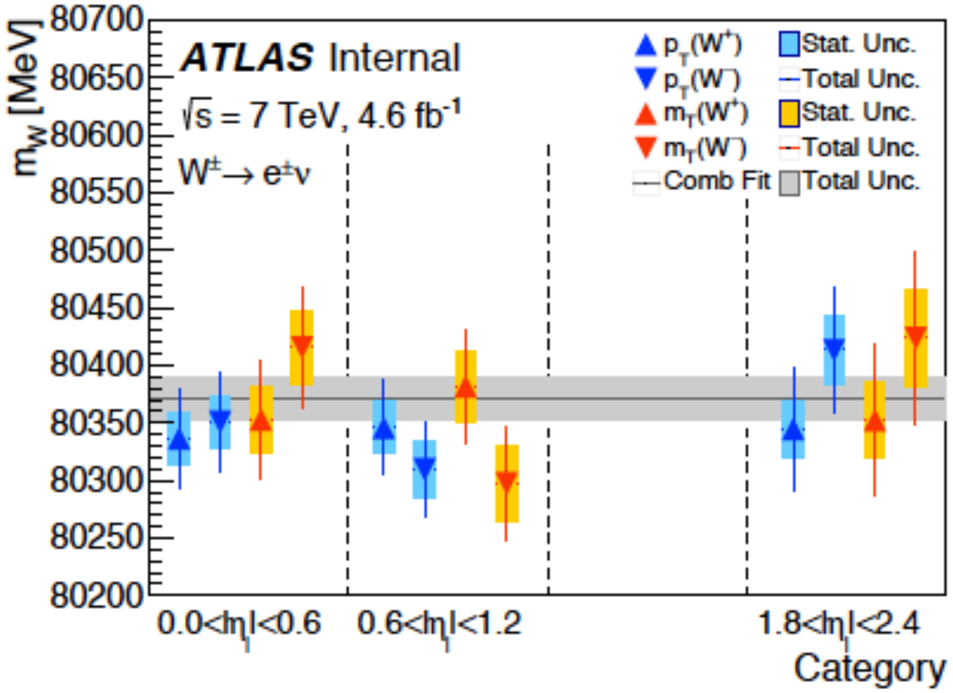


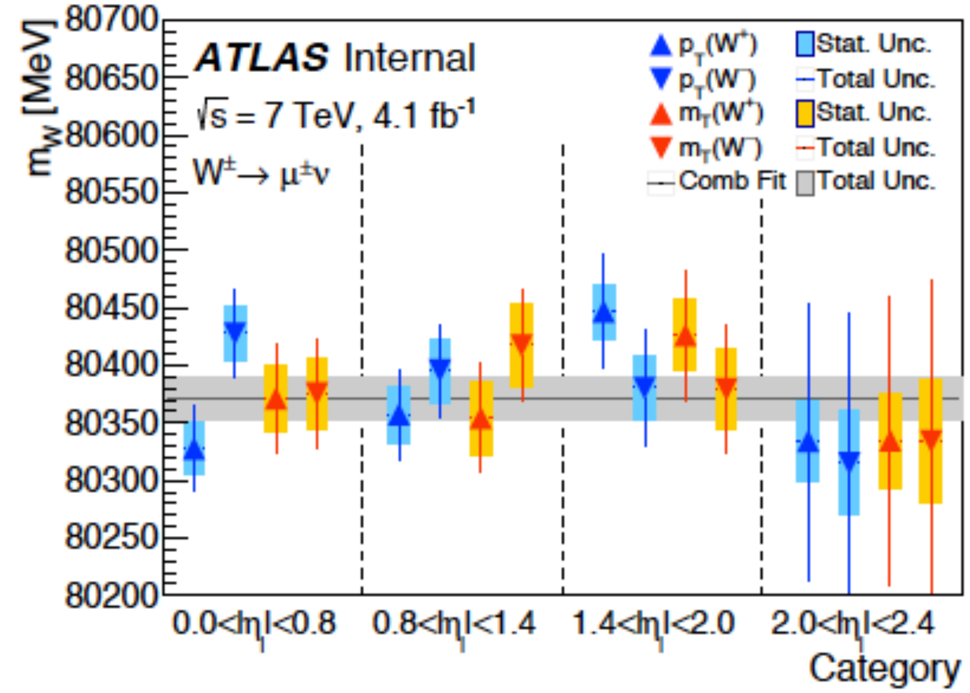
MUON MOMENTUM CALIBRATION - RESULTS

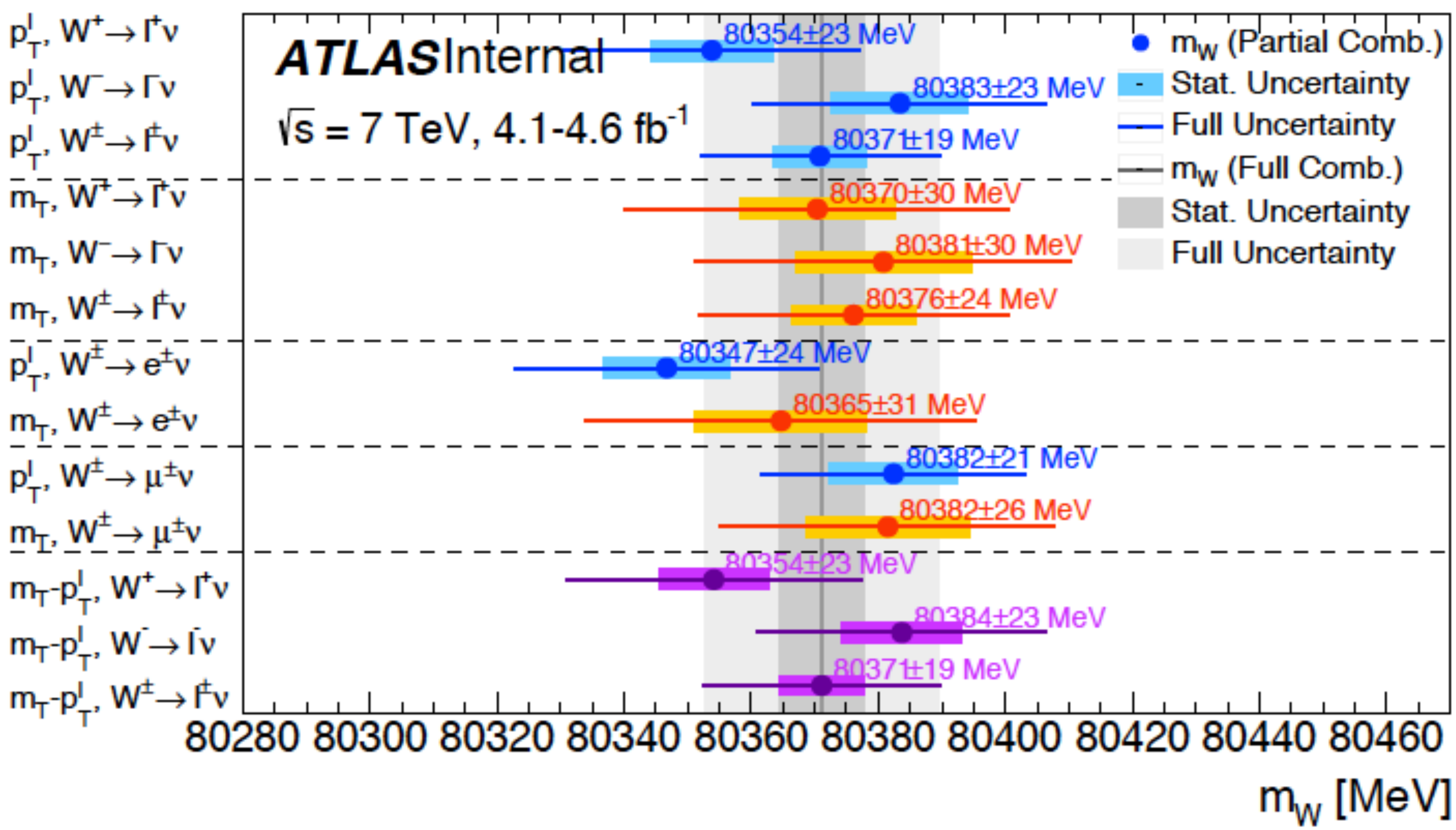


$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	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

MEASUREMENT CONSISTENCY

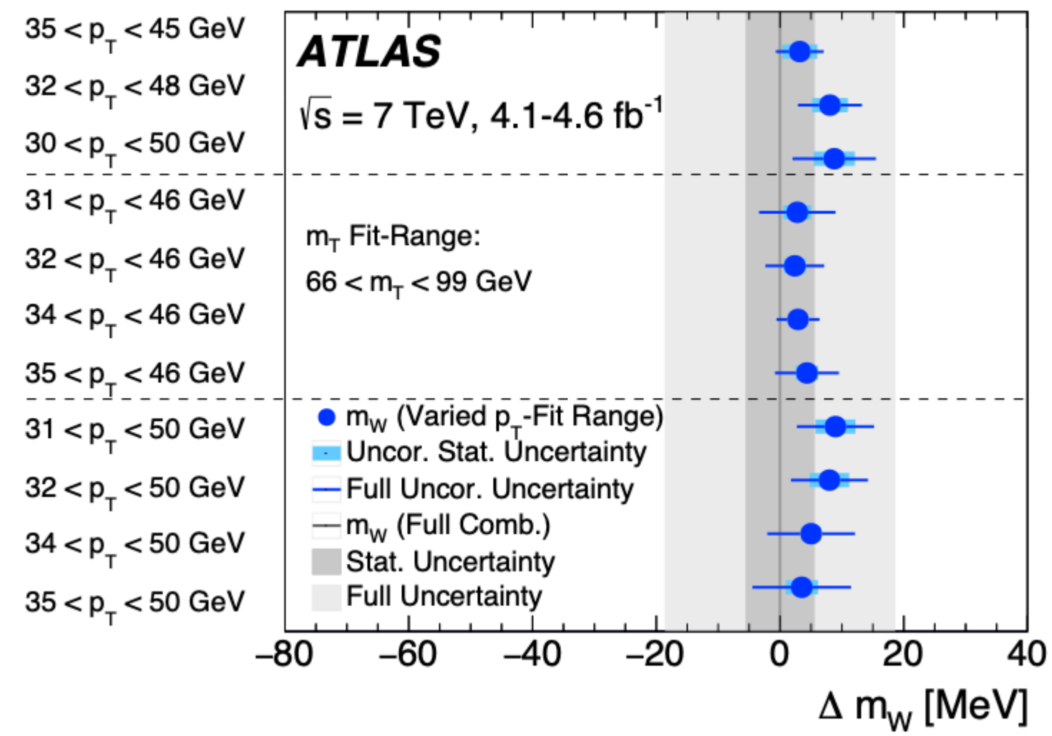


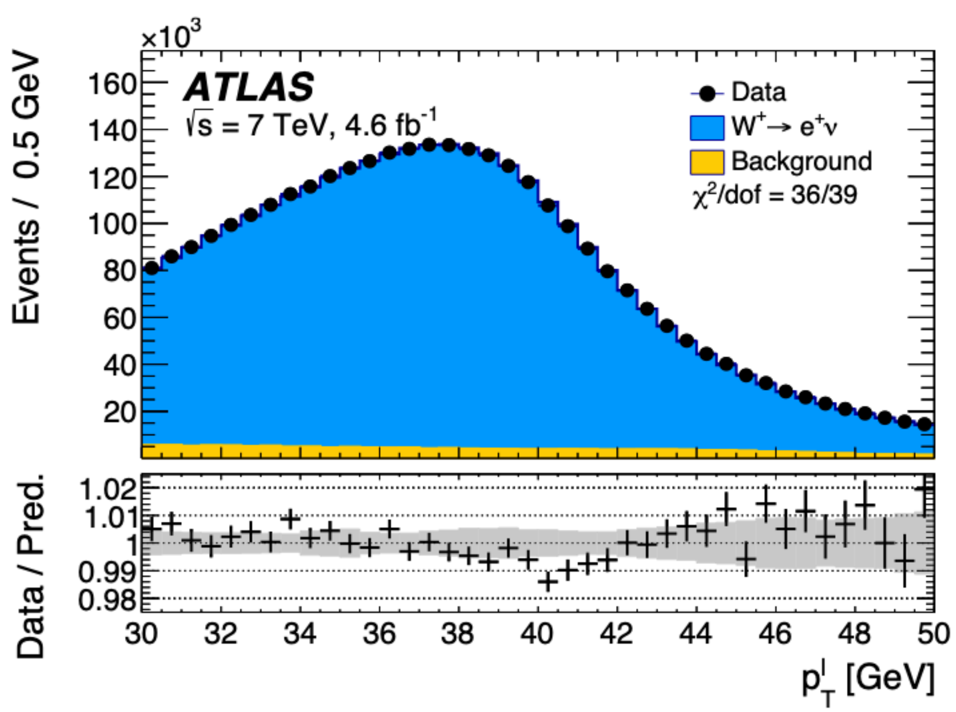


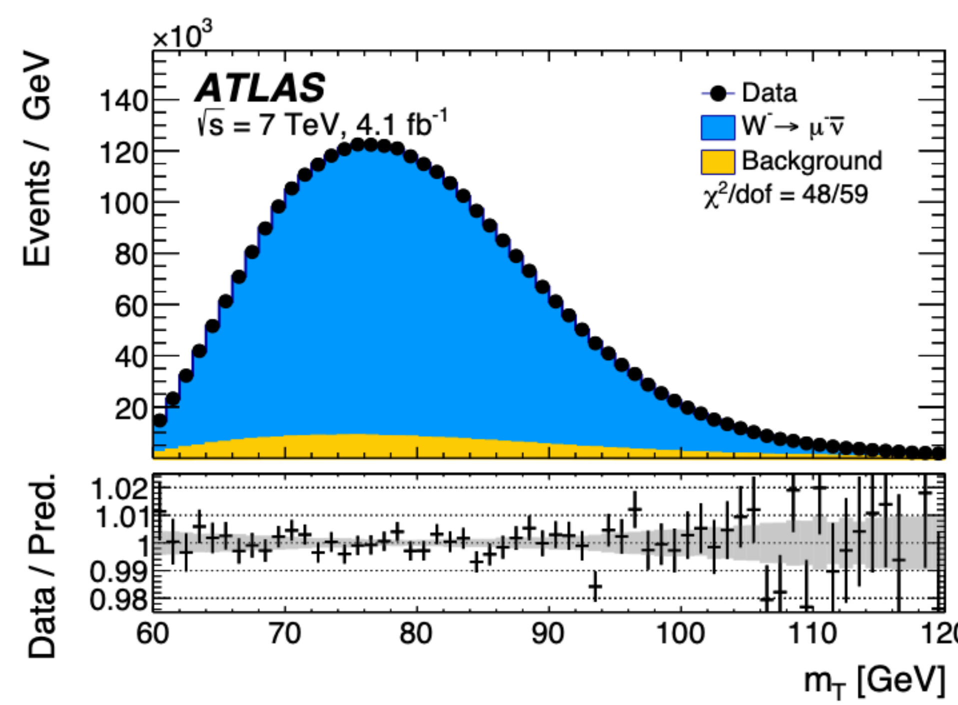


MEASUREMENT CONSISTENCY

Decay channel	$W \to e\nu$		$W \to \mu\nu$		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
Δm_W [MeV]						
$\langle\mu\rangle$ in [2.5, 6.5]	8 ± 14	14 ± 18	−21 ± 12	0 ± 16	−9 ± 9	6 ± 12
$\langle\mu\rangle$ in [6.5, 9.5]	−6 ± 16	6 ± 23	12 ± 15	−8 ± 22	4 ± 11	−1 ± 16
$\langle\mu\rangle$ in [9.5, 16]	−1 ± 16	3 ± 27	25 ± 16	35 ± 26	12 ± 11	20 ± 19
u_T in [0, 15] GeV	0 ± 11	−8 ± 13	5 ± 10	8 ± 12	3 ± 7	−1 ± 9
u_T in [15, 30] GeV	10 ± 15	0 ± 24	−4 ± 14	−18 ± 22	2 ± 10	−10 ± 16
$u_\parallel^\ell < 0$ GeV	8 ± 15	20 ± 17	3 ± 13	−1 ± 16	5 ± 10	9 ± 12
$u_\parallel^\ell > 0$ GeV	−9 ± 10	1 ± 14	−12 ± 10	10 ± 13	−11 ± 7	6 ± 10
No p_T^{miss}-cut	14 ± 9	−1 ± 13	10 ± 8	−6 ± 12	12 ± 6	−4 ± 9

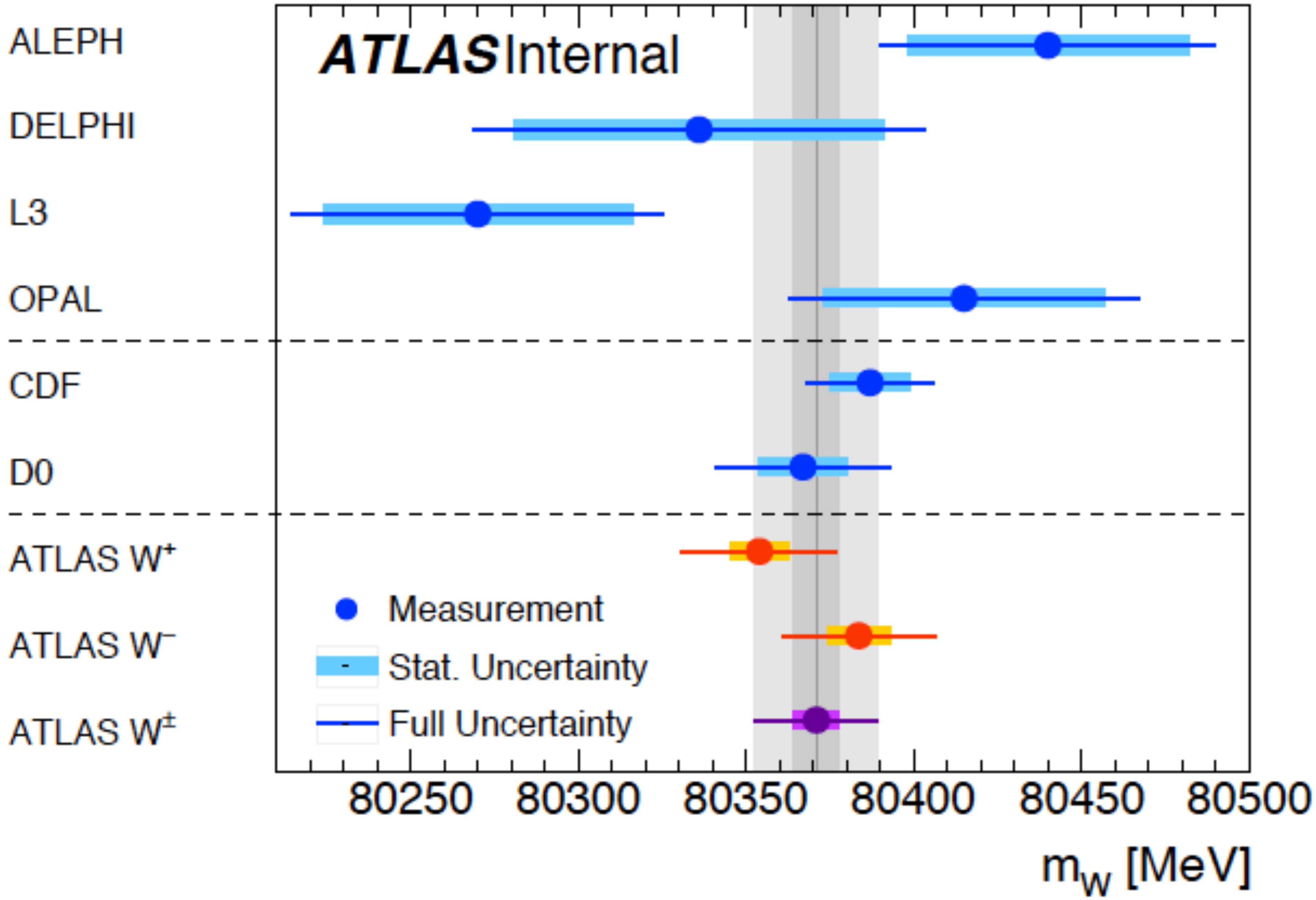






FIRST ATLAS RESULT

$$m_W = 80371 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14(\text{mod. syst.})\ \text{MeV}$$
$$= 80371 \pm 19\ \text{MeV},$$



$$m_{W^+} - m_{W^-} = -29.3 \pm 12.8\ \text{MeV}(\text{stat.}) \pm 5.4\ \text{MeV}(\text{exp. sys.}) \pm 23.9\ \text{MeV}(\text{mod. sys.})$$
$$= -29.3 \pm 27.6\ \text{MeV},$$

SAME ALL A LITTLE BIT DIFFERENT

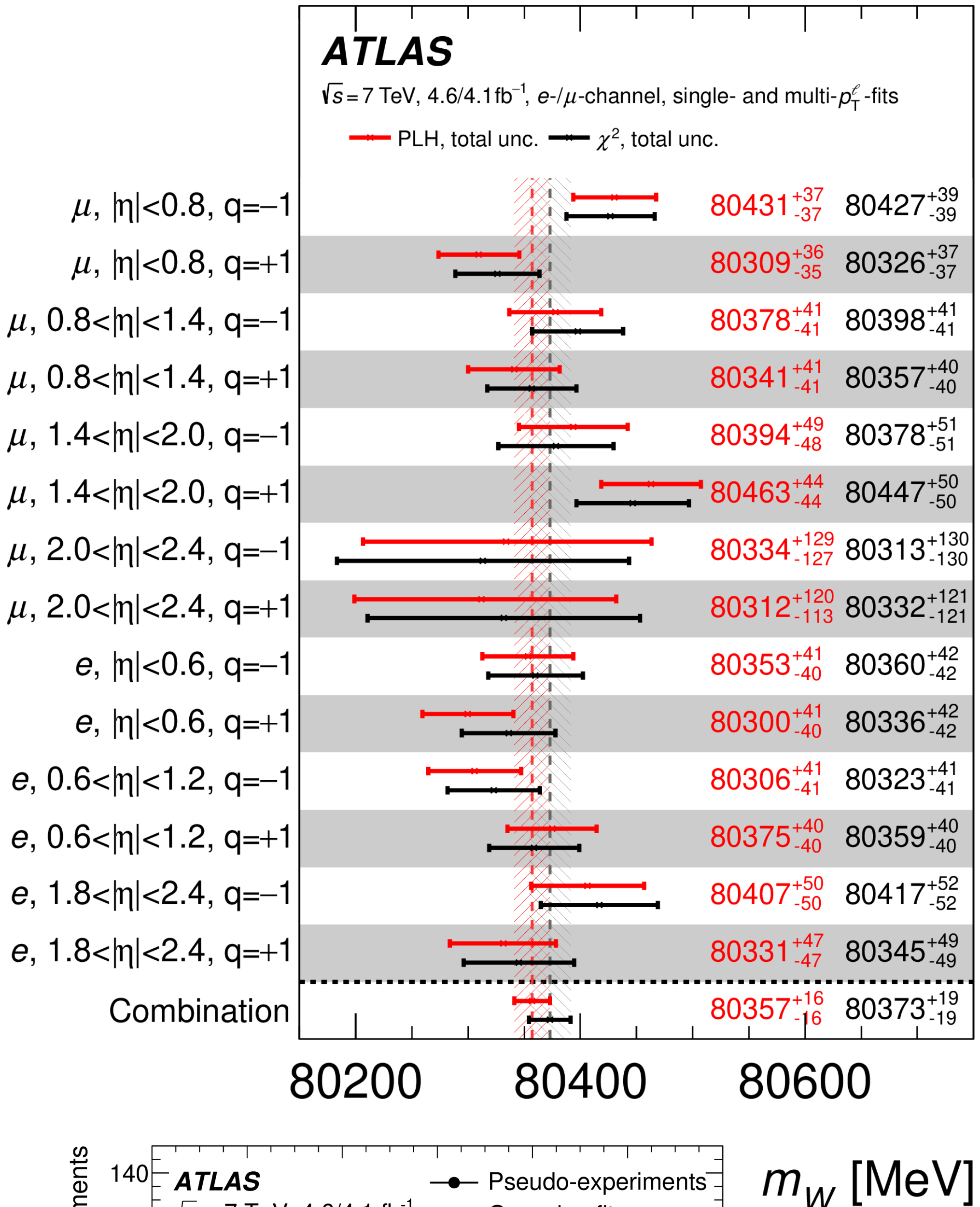
- **Profile likelihood fit**
  - The present analysis performs a simultaneous optimisation of POI and of **nuisance parameters** describing systematic uncertainties, through a global profile likelihood fit in all event categories for a given kinematic distribution.

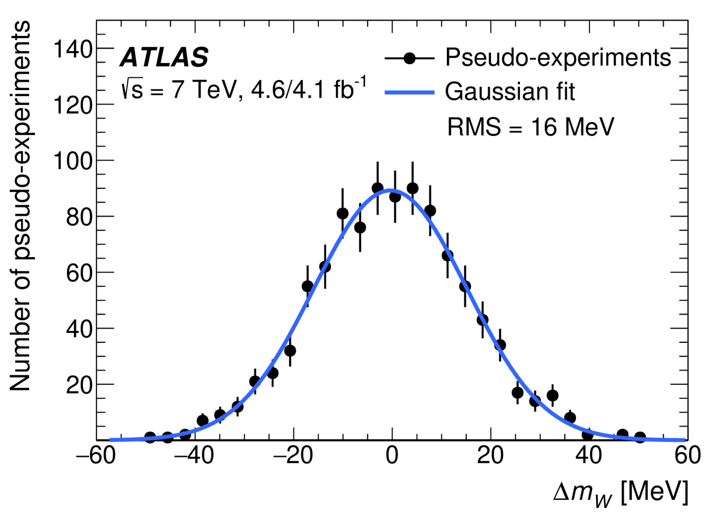
$$\mathcal{L}(\vec{\mu},\vec{\theta}) = \prod_{i=1}^{N} Poisson\left(n_i, \nu_i(\vec{\mu},\vec{\theta})\right) \times \prod_{i=1}^{M} Gaus(\theta_i)$$

$$\nu_i = \Phi \times \left(S_i^{\text{norm}} + \sum_{j=1}^{K}(S_i(\mu_j) - S_i^{\text{norm}})\right) + \sum_{j=1}^{M}\left(\theta_j \times (S_i^{\theta_j\ \text{var}} - S_i^{\text{norm}})\right) + B_i^{\text{norm}} + \sum_{j=1}^{M}\left(\theta_j \times (B_i^{\theta_j\ \text{var}} - B_i^{\text{norm}})\right)$$

- **POI: μ (mass, or width of the W-boson)**
  - NPS: O (100) for each pT and mT distributions.
  - Systematic uncertainties that yield differences smaller than 0.02% in the normalised distribution distribution are removed: factor of 2 reducing the number of shape systematic variations while central values change by less than 0.1 MeV. 1% in total uncertainty.
  - PCA used to transform variations in to a set of uncorrelated two-sided uncertainties, preserving the total uncertainty. This approach is used for the statistical uncertainties of the electron and muon efficiencies,

VALIDATION OF THE METHOD

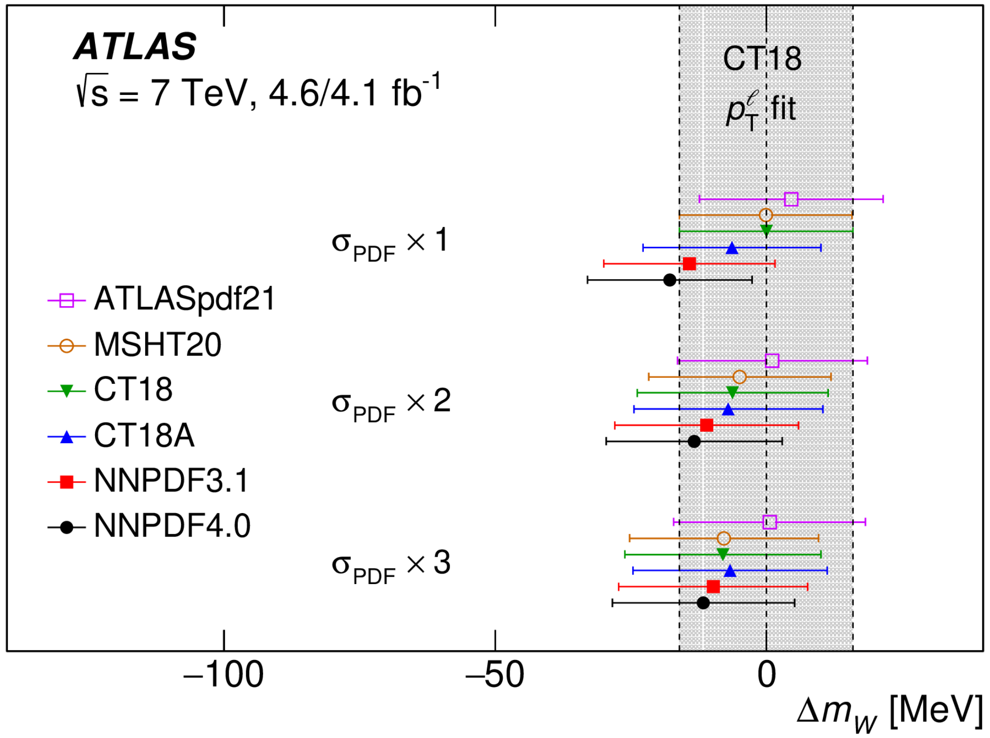




- **Improvements**
  - Electroweak corrections
    - Systematic estimated on reco-level instead of particle-level
  - MJ background
    - Re-evaluated both normalisation and shape calibration (20% increase of the MJ background in the electron channel)
    - Update the shape extrapolation, uncertainty reduced
  - Impact: central value shifted by 2.4 MeV (0.12σ of the published result)
- **Conisistency:** m_W PLH fitting result: 80357 ±16 MeV and 80388 ±24 MeV m_W shifted by -16 MeV and +3 MeV respectively
- Total uncertainty reduced by about 3 MeV as expected
  - **Within** 1sigma

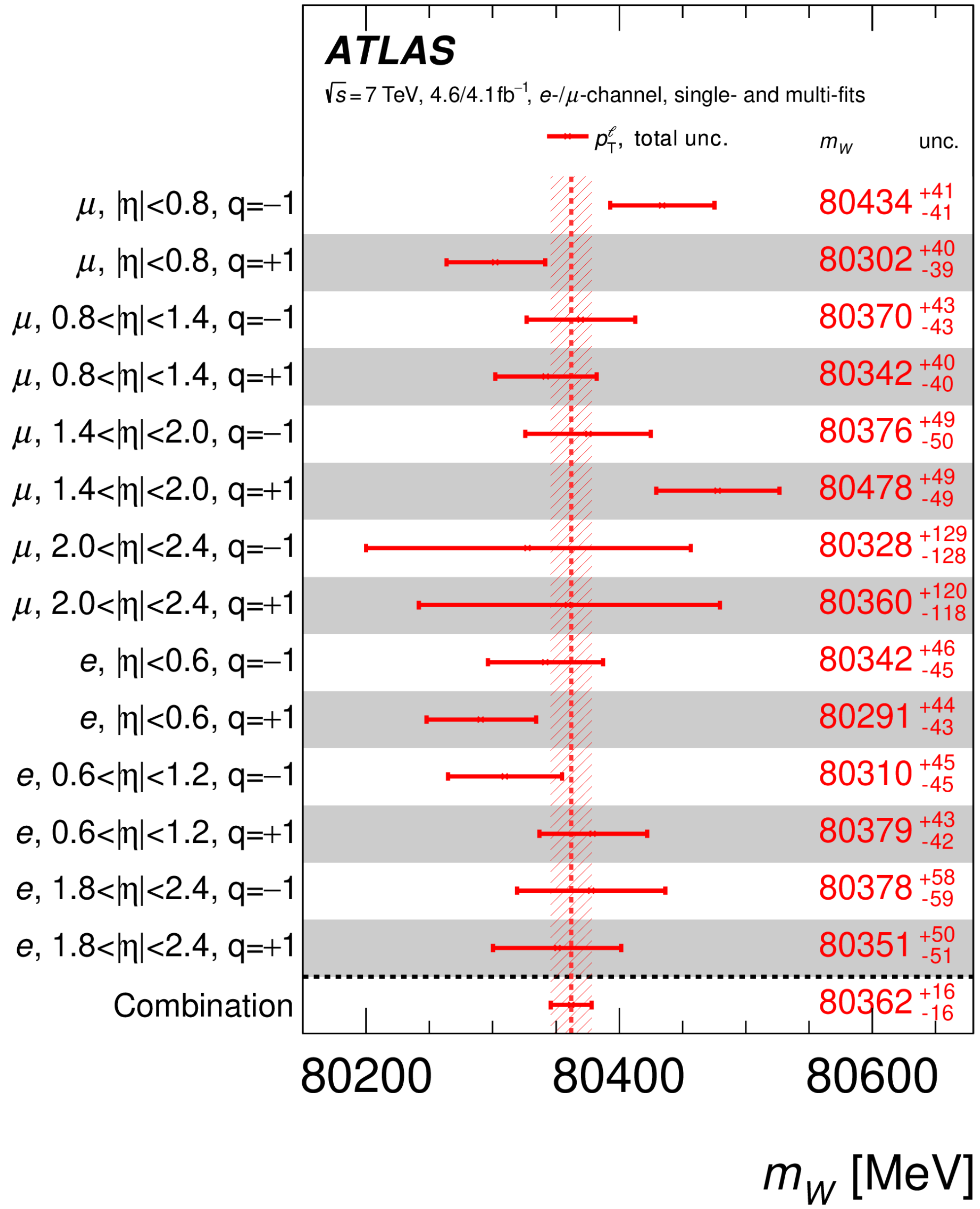
IMPACT DUE TO NEW PDFS

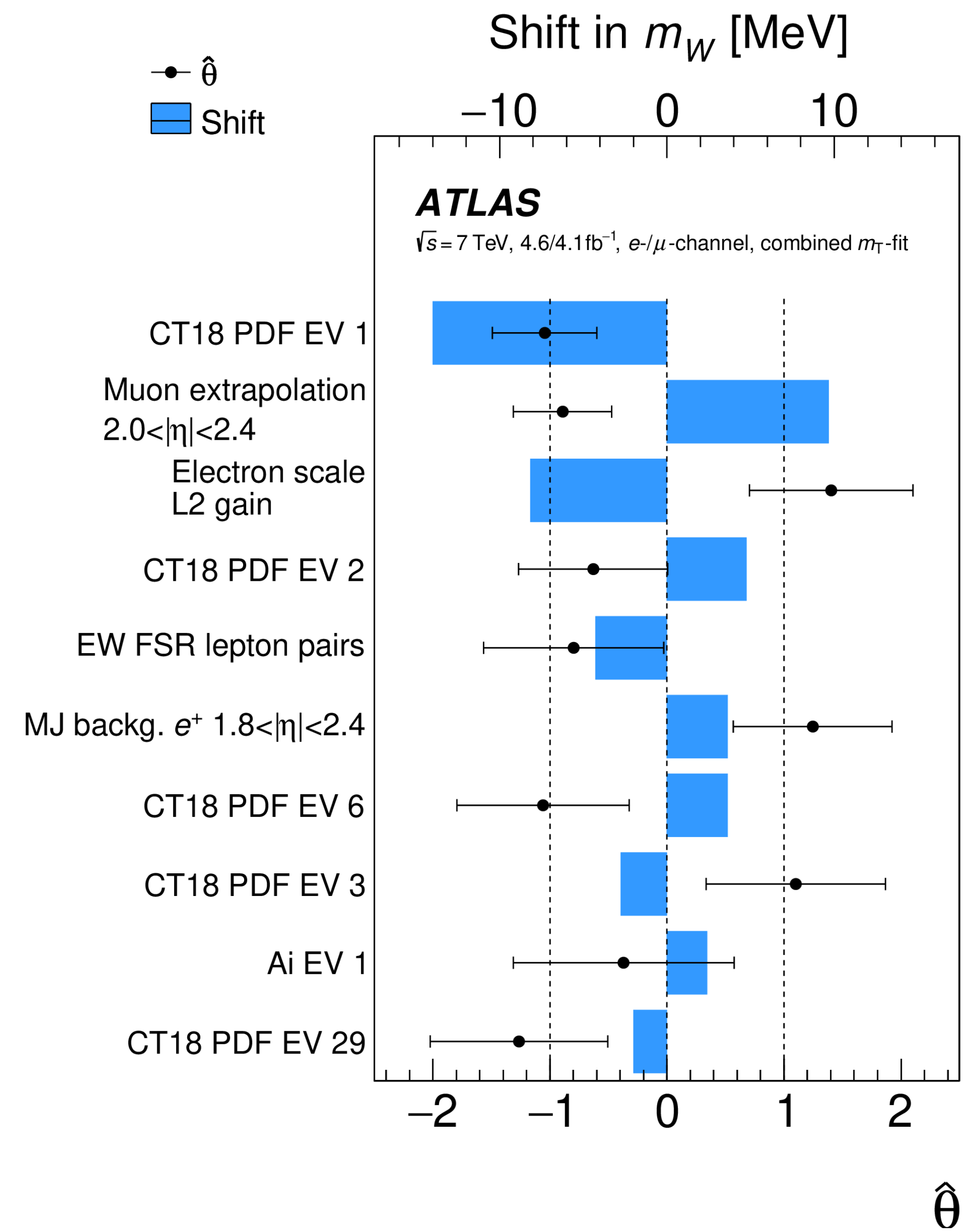
PDF set	p_T^ℓ fit				m_T fit			
	m_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.	m_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.
CT14	80358.3	$^{+16.1}_{-16.2}$	4.6	543.3/558	80401.3	$^{+24.3}_{-24.5}$	11.6	557.4/558
CT18	80362.0	$^{+16.2}_{-16.2}$	4.9	529.7/558	80394.9	$^{+24.3}_{-24.5}$	11.7	549.2/558
CT18A	80353.2	$^{+15.9}_{-15.8}$	4.8	525.3/558	80384.8	$^{+23.5}_{-23.8}$	10.9	548.4/558
MMHT2014	80361.6	$^{+16.0}_{-16.0}$	4.5	539.8/558	80399.1	$^{+23.2}_{-23.5}$	10.0	561.5/558
MSHT20	80359.0	$^{+13.8}_{-15.4}$	4.3	550.2/558	80391.4	$^{+23.6}_{-24.1}$	10.0	557.3/558
ATLASpdf21	80362.1	$^{+16.9}_{-16.9}$	4.2	526.9/558	80405.5	$^{+28.2}_{-27.7}$	13.2	544.9/558
NNPDF3.1	80347.5	$^{+15.2}_{-15.7}$	4.8	523.1/558	80368.9	$^{+22.7}_{-22.9}$	9.7	556.6/558
NNPDF4.0	80343.7	$^{+15.0}_{-15.0}$	4.2	539.2/558	80363.1	$^{+21.4}_{-22.1}$	7.7	558.8/558



- Span a range of about 18 MeV for the p_T fits and about 42 MeV for the m_T fits
  - Dominated by the NNPDF3.1 and NNPDF4.0 fits
  - The range spanned by the other sets: 9 MeV for p_T
  - T and 21 MeV for m_T
- The new baseline result: CT18
  - the most conservative uncertainty
  - the ATLAS 7 TeV precision W /Z data not included

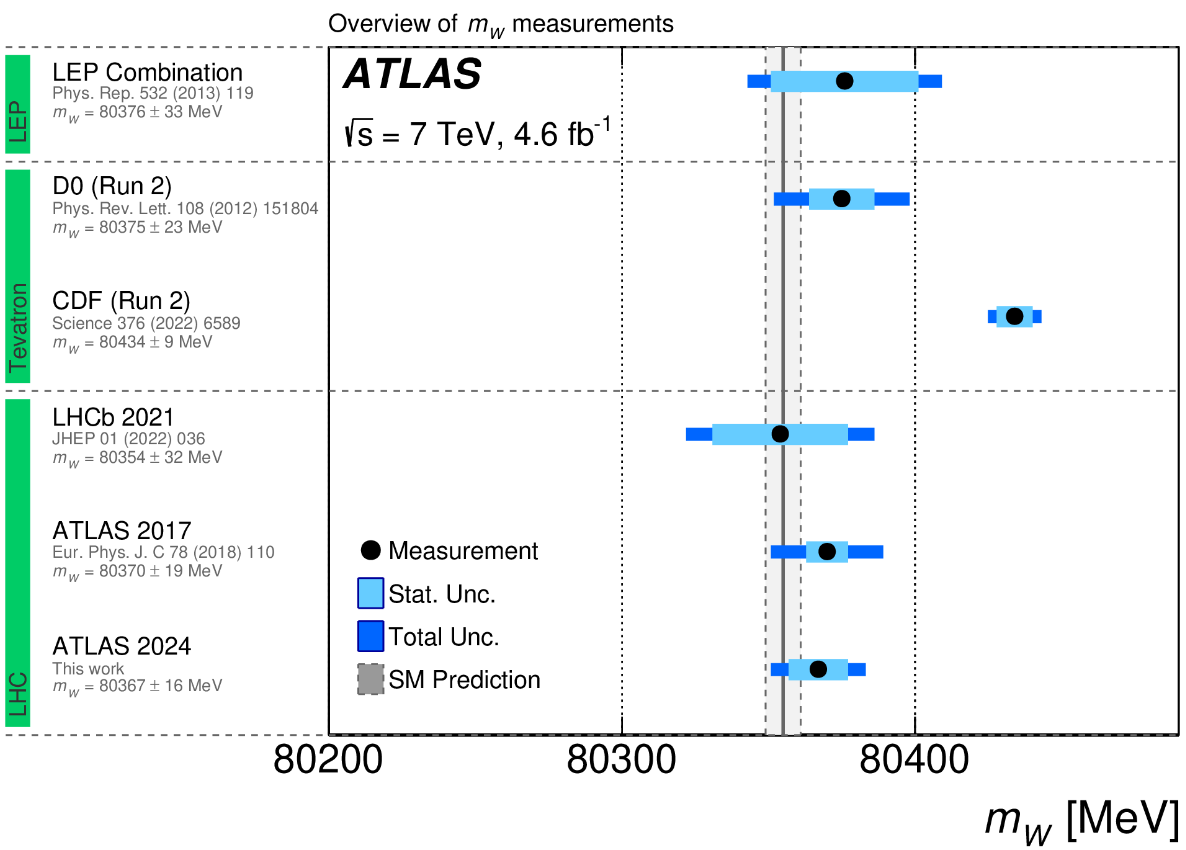
RESULTS

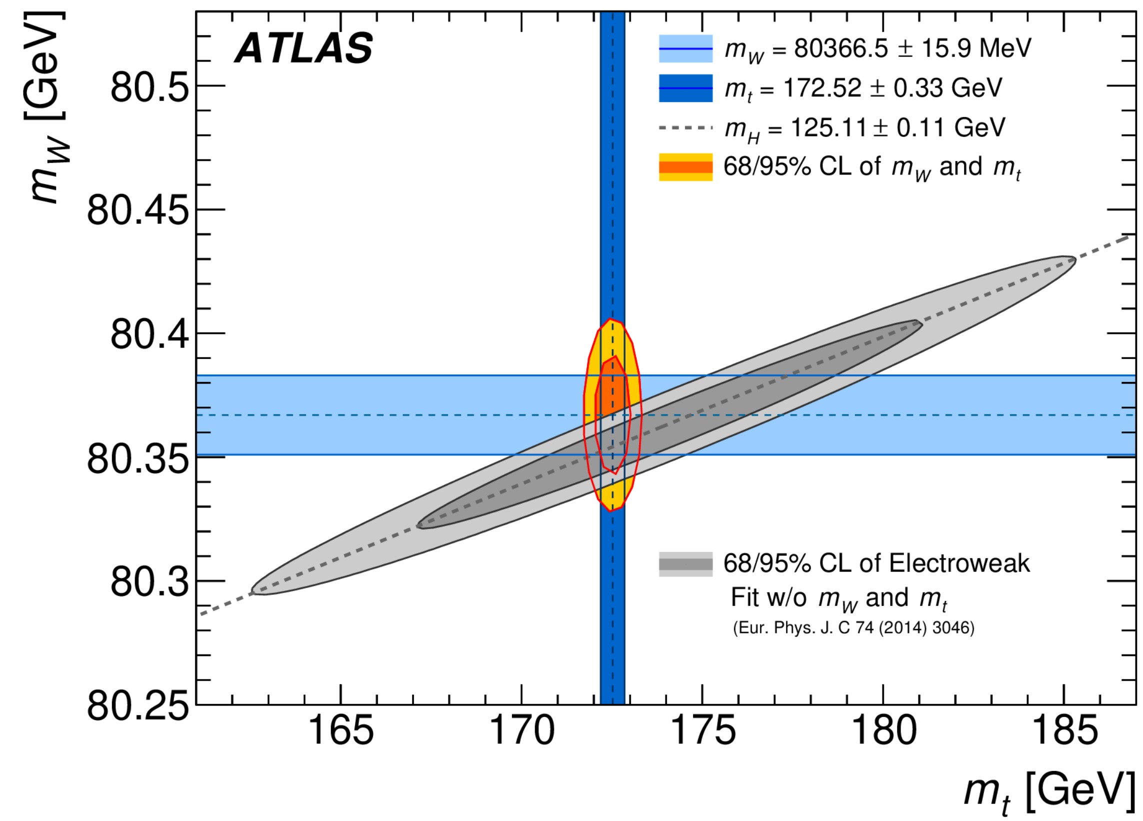




Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

RESULTS

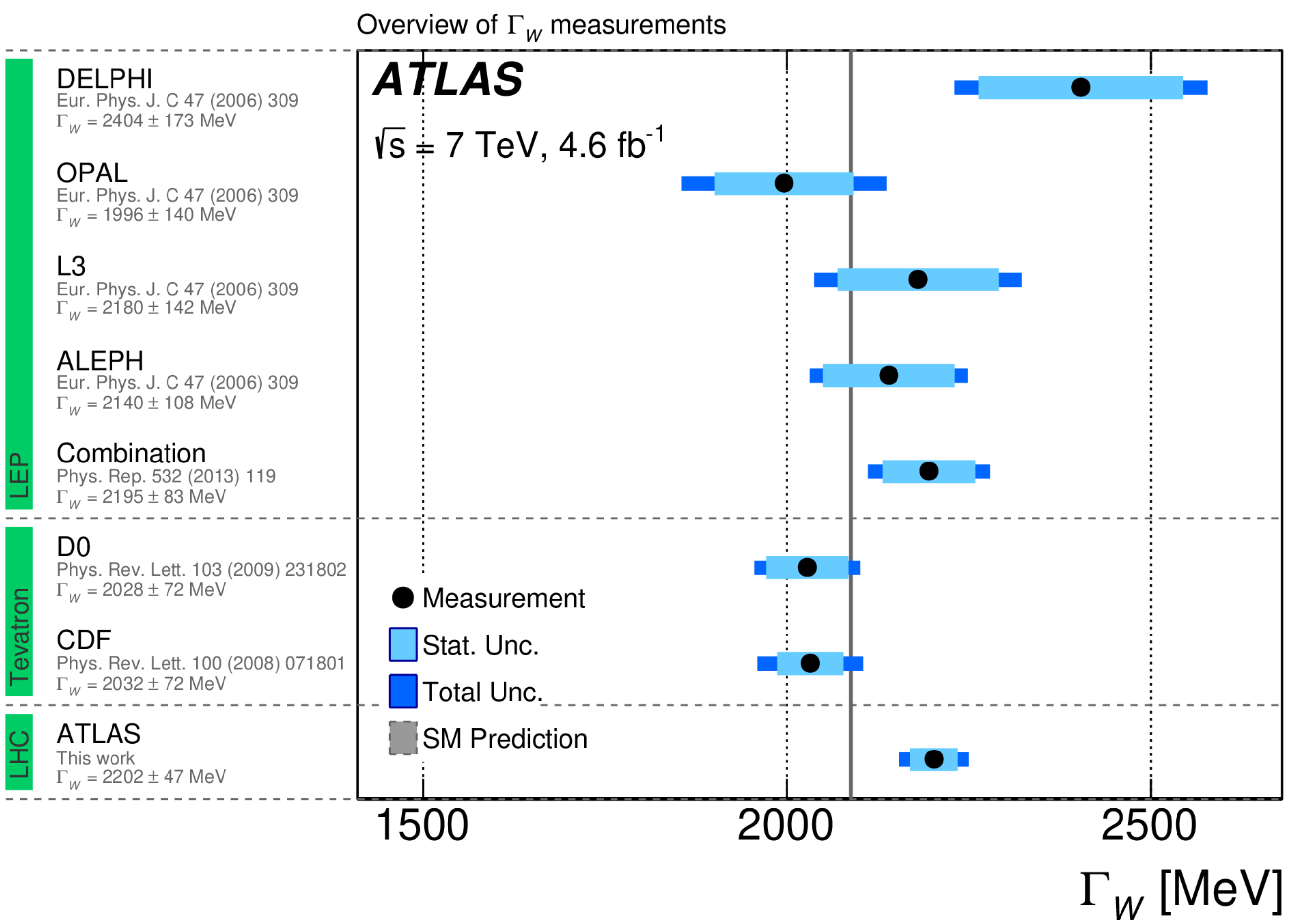


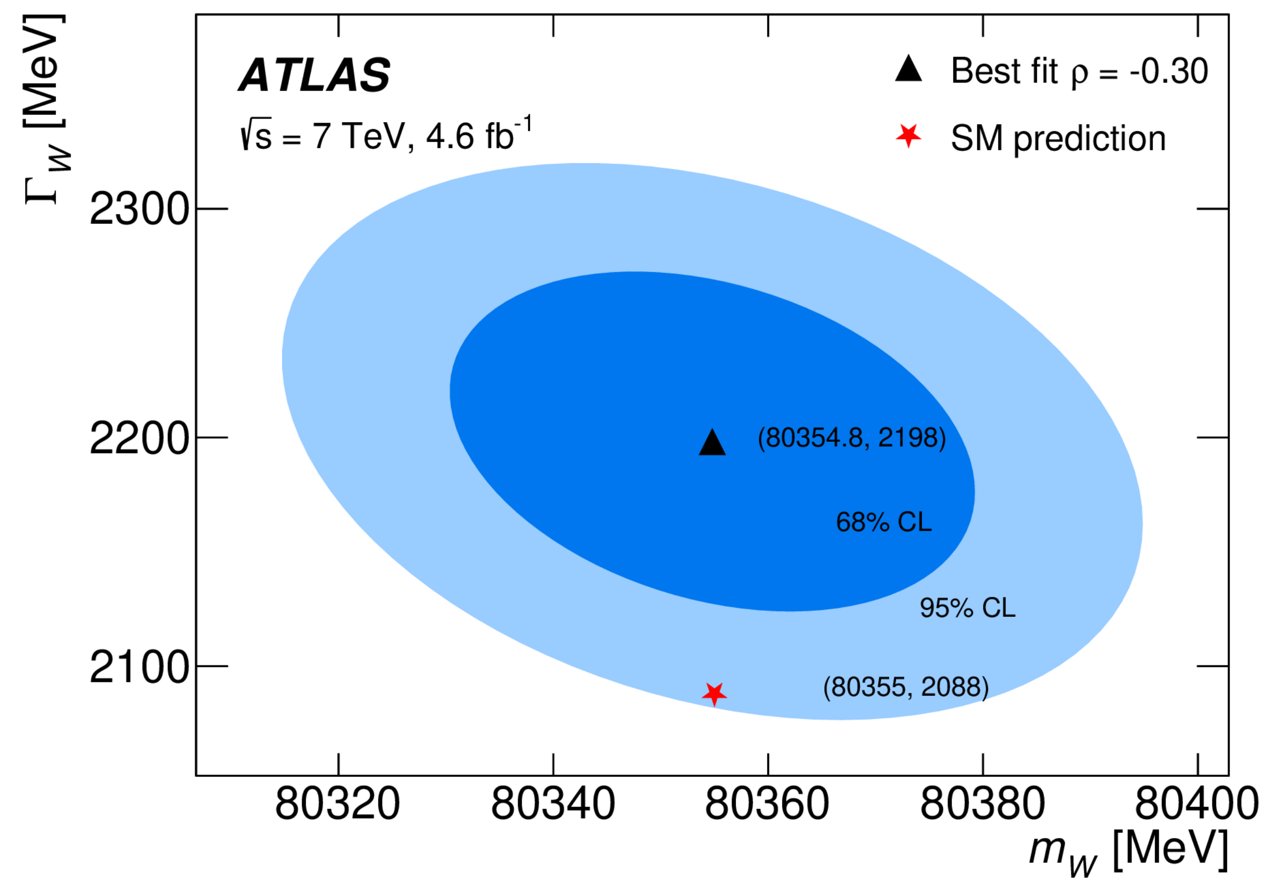


$$m_W = 80366.5 \pm 9.8\ (\text{stat.}) \pm 12.5\ (\text{syst.})\ \text{MeV} = 80366.5 \pm 15.9\ \text{MeV}$$

- Total uncertainty improved by 20% comparing to the previous measurement
- Increase in statistical uncertainty reflects larger number of parameters determined from the same d

BONUS: MEASUREMENT OF THE WIDTH





Γ_W = 2202 ±32(stat.) ±34(syst.) MeV = 2202 ±47 MeV

The most accurate measurement of the W-boson width to date!

Within ~2 standard deviations from SM prediction.

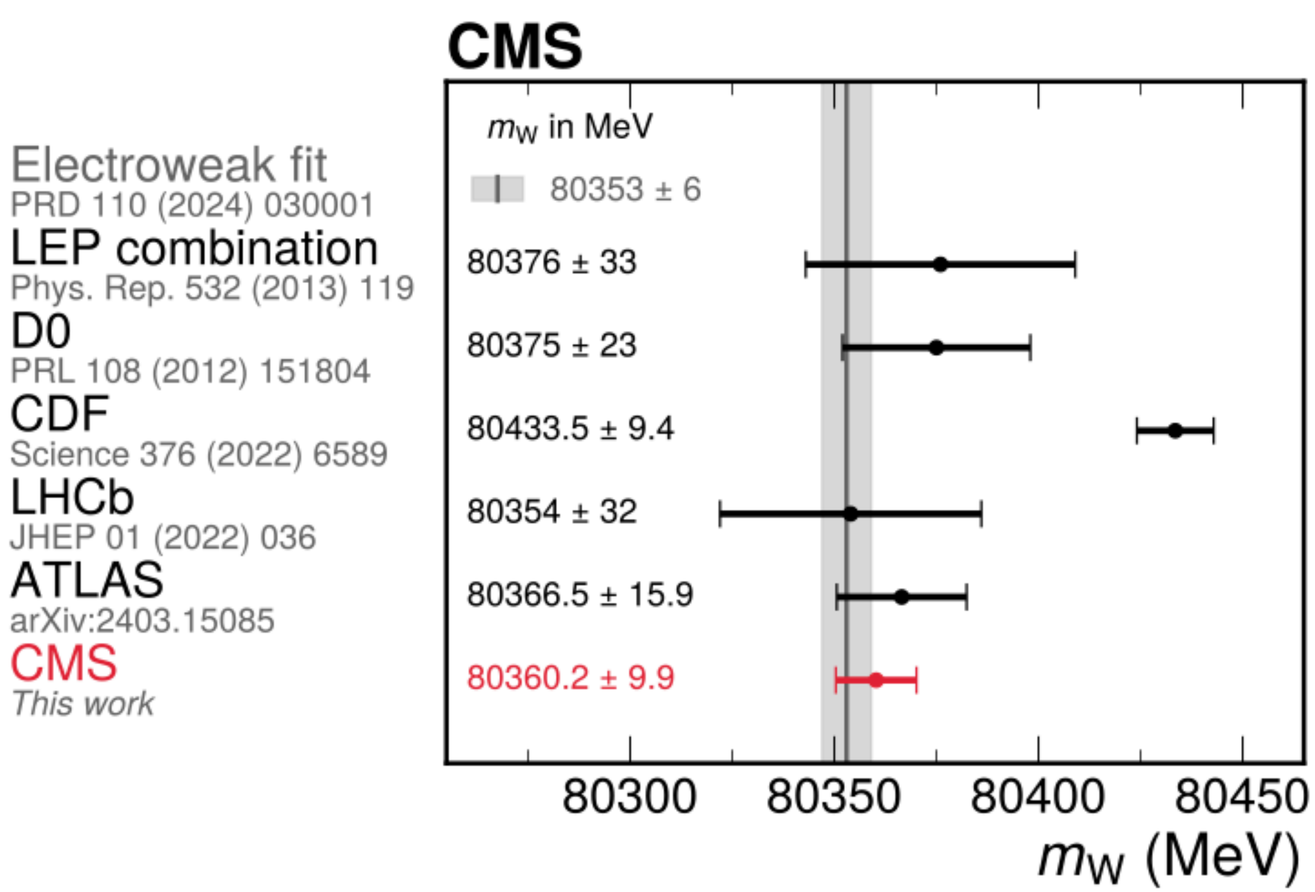
CURRENT EXPERIMENTAL STATUS

ATLAS 2024 m_W = 80366.5 ± 9.8 (stat.) ± 8.8 (exp.) ± 6.9 (theory) ± 5.7 (PDF)

LHCb 2021 m_W = 80354 ± 23 (stat.) ± 10 (exp.) ± 17 (theory) ± 9 (PDF)

CDF 2022 m_W = 80433.5 ± 6.4 (stat.) ± 4.5 (exp.) ± 3.5 (theory) ± 3.9 (PDF)

CMS 2024 m_W = 80360 ± 6.0 (stat.) ± 2.8 (exp) ± 3.5 (theory) ± 2.8 (PDF)

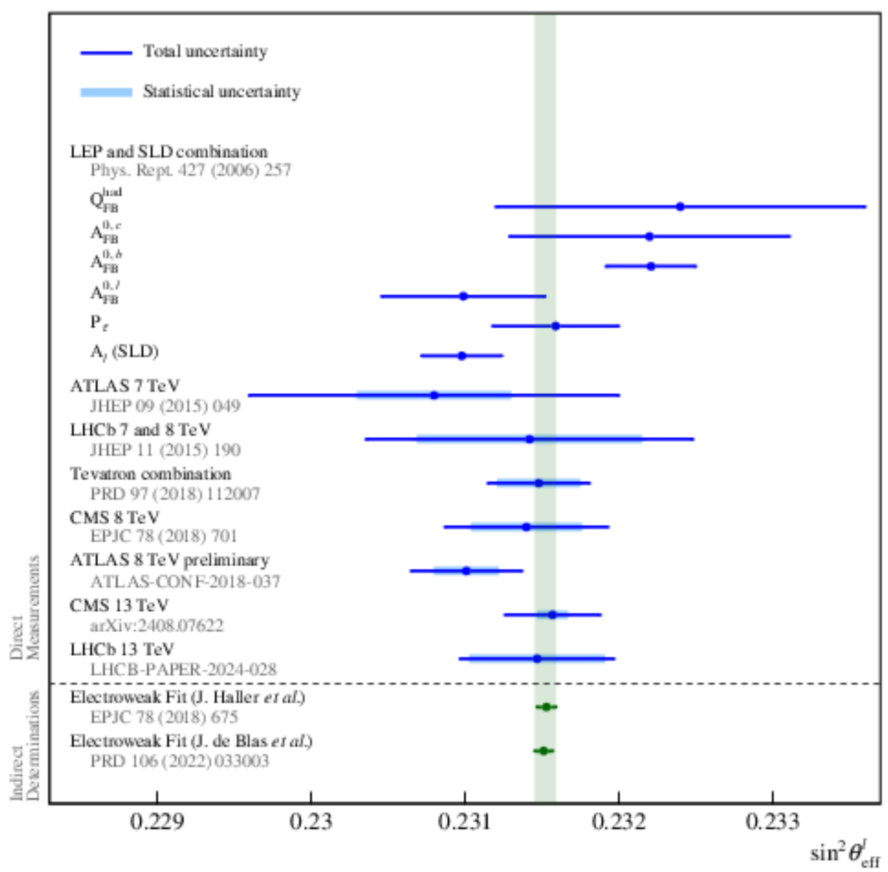


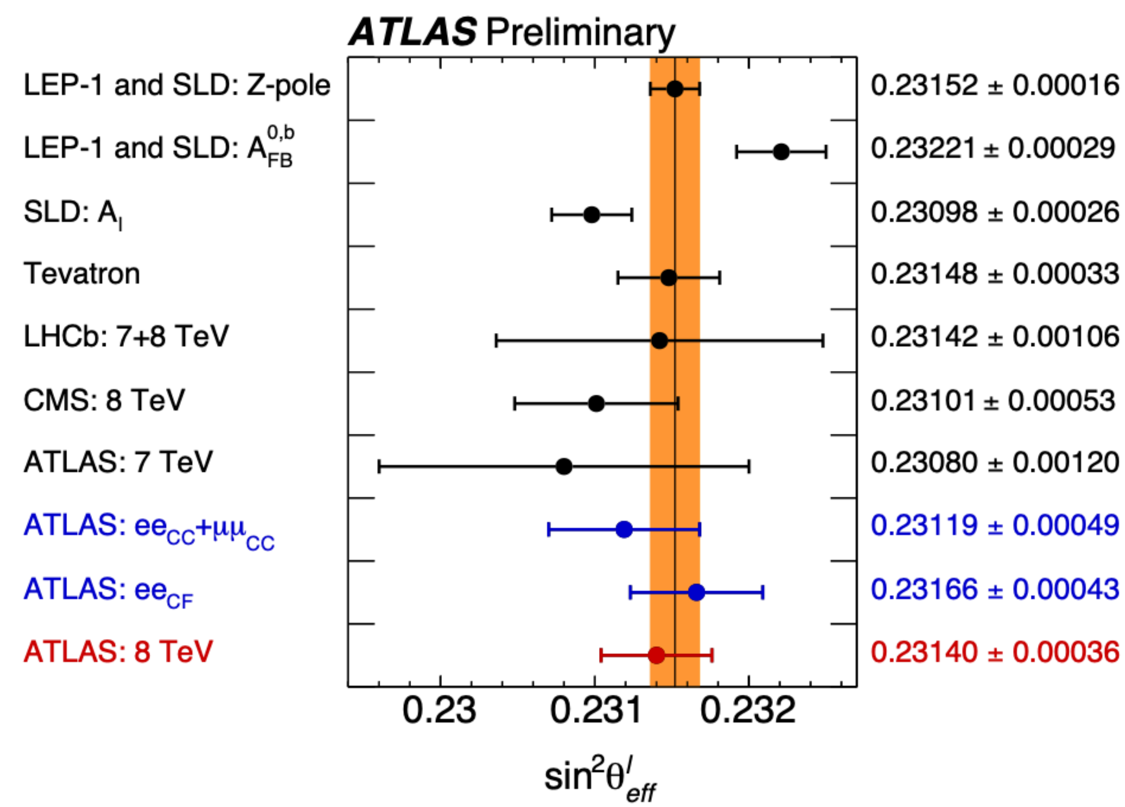
arXiv:2412.13872

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

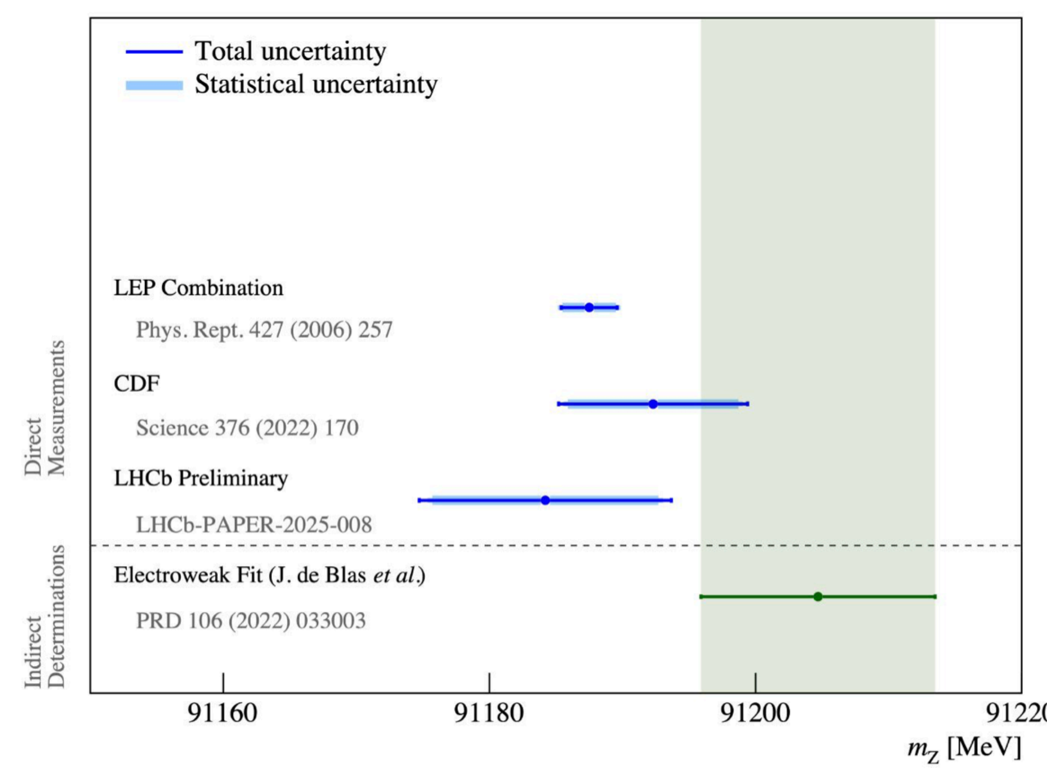
arXiv:2308.09417

MORE PRECISION MEASUREMENTS



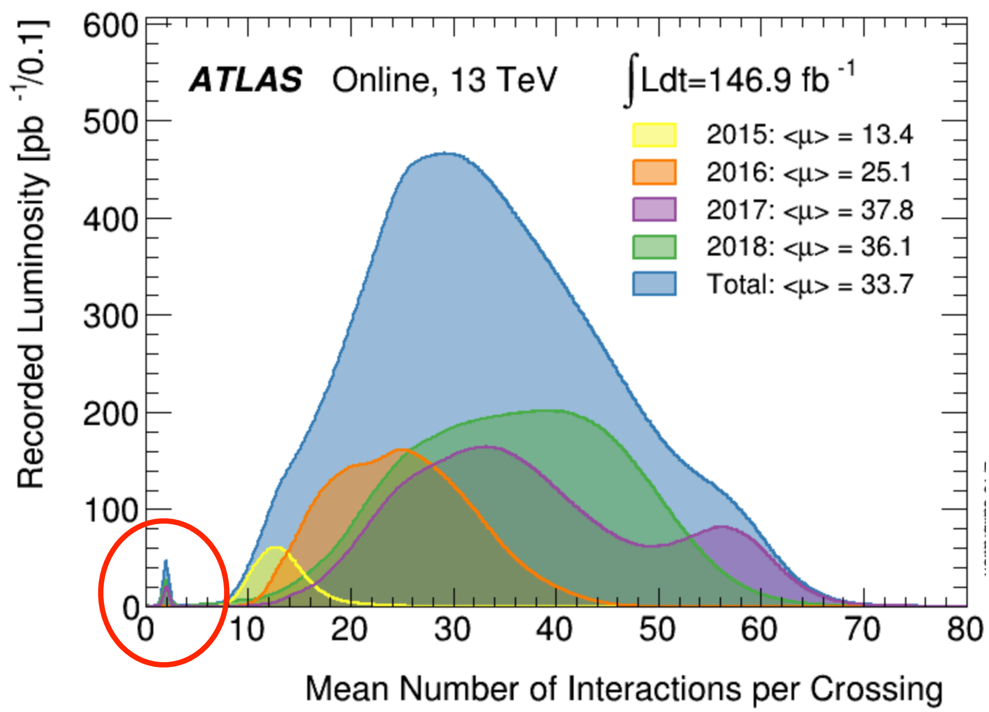


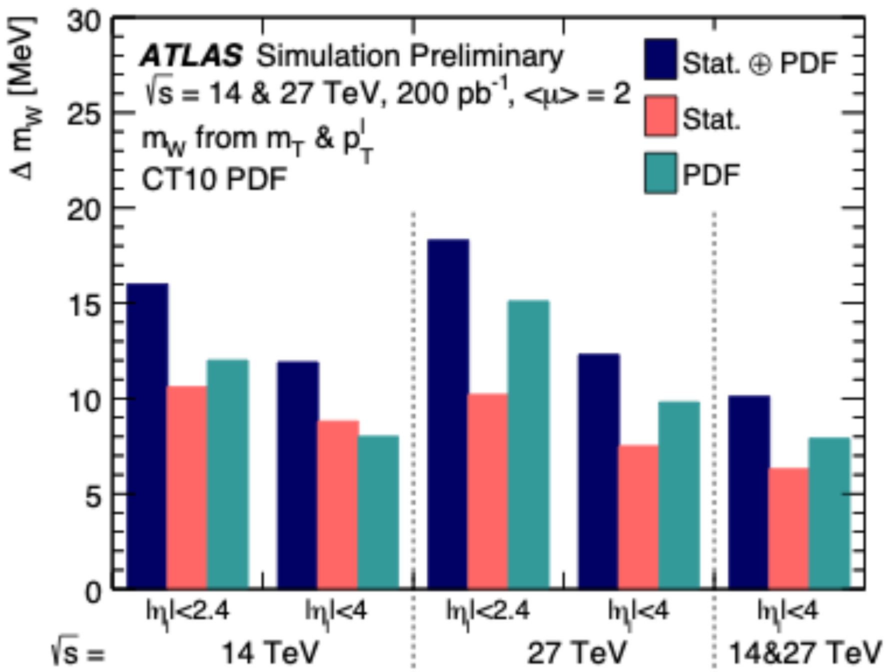
ATLAS-CONF-2018-037
CMS PAS SMP-22-010
LHCb-PAPER-2024-028
LHCb-PAPER-2025-008

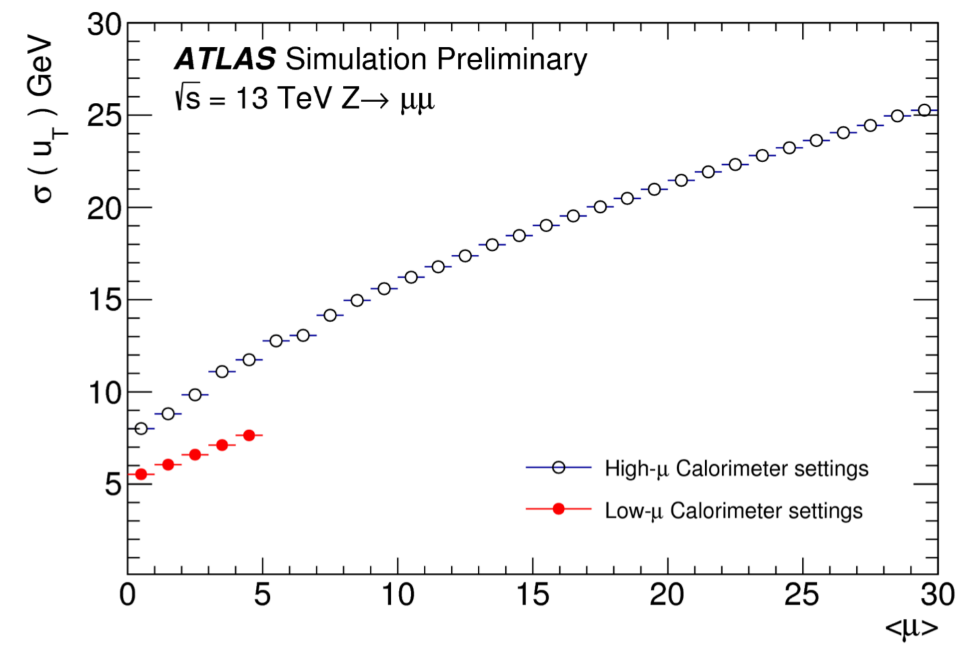


NEXT STEPS

- Measure p_{TW}: arXiv:2404.06204
- Measure using hadronic recoil not E_{Tmiss}, u_T
- Method sensitive to additional pile-up ⟨μ⟩ hadronic energy
- Measure using special dedicated low ⟨μ⟩ ~ 2 runs
- m_W measurement, stat uncertainty ~10 MeV





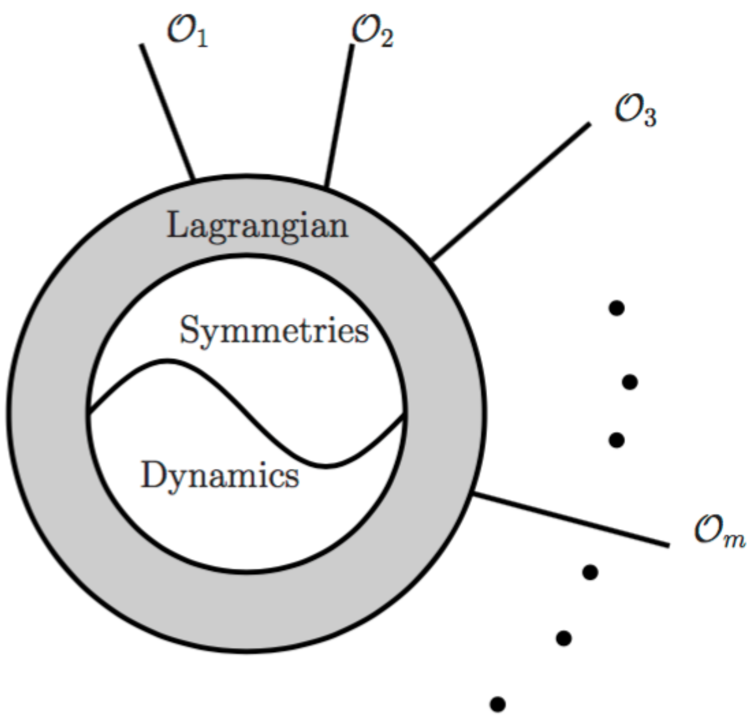


ATL-PHYS-PUB-2017-021

- Extended tracker for HL-LHC can improve sensitivity

DODACI

SM GLOBAL FITS (CONCEPT)



If there are n free parameters of the theory, and m computable and measurable observables, then we have $m - n$ predictions:

$$\mathcal{O}_1, \mathcal{O}_2, \cdots, \mathcal{O}_n$$

which can be computed from the n parameters P_i:

$$\mathcal{O}_i^{\text{expt}} = \mathcal{O}_i^{\text{th}}(P_1, P_2, \ldots, P_n)$$

the problem can be inverted and calculate param. from the obser.

$$P_i = F_i(\mathcal{O}_1^{\text{expt}}, \mathcal{O}_2^{\text{expt}}, \ldots, \mathcal{O}_n^{\text{expt}})$$

the remaining observables have the unambiguous predictions (based on other observables):

$$\mathcal{O}_{n+j}^{\text{th}} = \mathcal{O}_{n+j}^{\text{th}}(F_1(\vec{\mathcal{O}}^{\text{expt}}), F_2(\vec{\mathcal{O}}^{\text{expt}}), \ldots, F_n(\vec{\mathcal{O}}^{\text{expt}}))$$

$$\chi^2 = \sum_i \frac{(\mathcal{O}_i^{\text{expt}} - \mathcal{O}_i^{\text{th}}(\vec{P}))^2}{(\Delta\mathcal{O}_i^{\text{expt}})^2}$$

Test the predictions via chi2-minimisation

In the SM:

$$\vec{P} = \{m_H, m_t, \alpha_S, \alpha, \ldots\}$$

$$\mathcal{O}_i^{\text{expt}} = \{\hat{s}^2_{\text{eff}}, \hat{m}_W, \hat{\Gamma}_l, \hat{m}_t, \hat{\alpha}_S, \Delta\alpha^{(5)}_{\text{had}}, \ldots\}$$

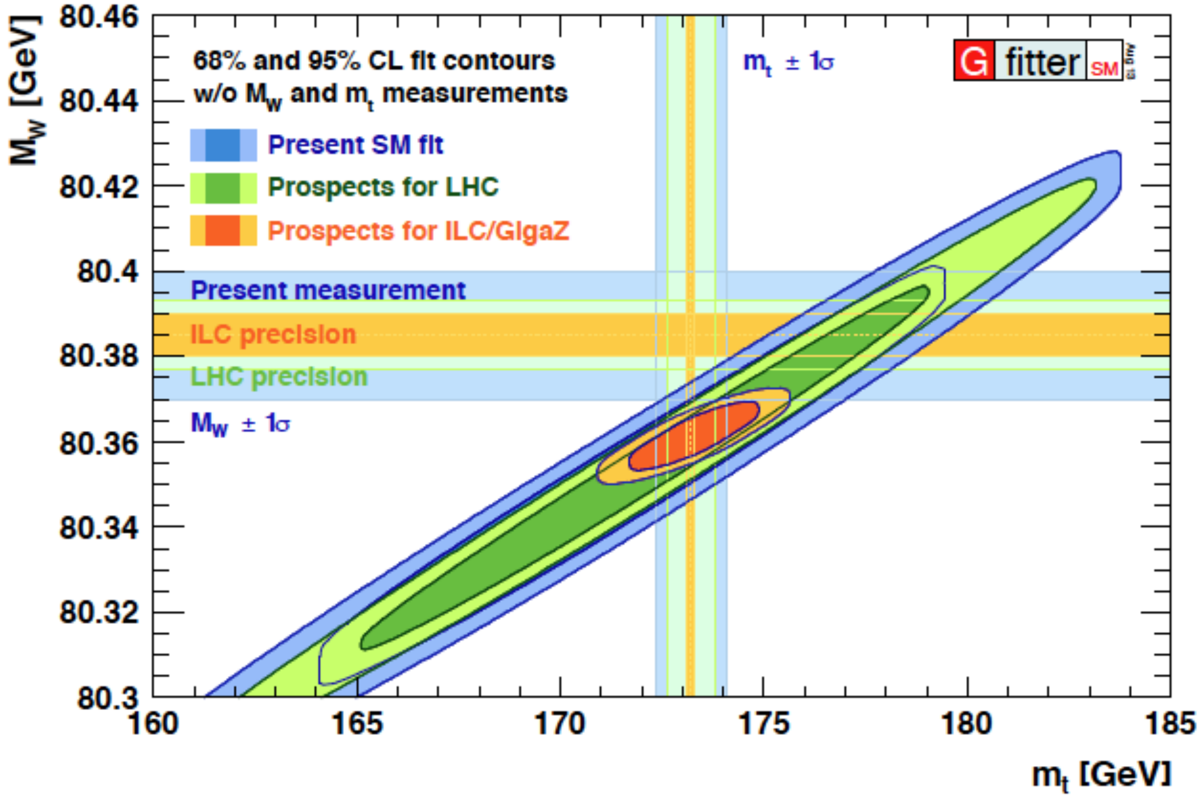
PROSPECTS

$$m_W = 80371 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14(\text{mod. syst.})\ \text{MeV}$$

O(1-2) MeV
Run-1+2015+2016,
negligible!

O(10M) of Z's, long way,
achievable,
could be negligible

Depends on Theory improvements:
PDFs and p_T^W (can we directly measure p_T^W)
(electroweak and polarisation expected to 'shrink')



+ CMS, experimental uncertainties uncorrelated

ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}$[fb^{-1}]	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

	LHC	LHC	ILC/GigaZ	ILC	ILC	ILC	TLEP	SM prediction
$\sqrt{s}$ [TeV]	14	14	0.091	0.161	0.161	0.250	0.161	-
$\mathcal{L}$[fb^{-1}]	300	3000		100	480	500	3000×4	-
ΔM_W [MeV]	8	5	-	4.1-4.5	2.3-2.9	2.8	< 1.2	4.2(3.0)
$\Delta \sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	36	21	1.3	-	-	-	0.3	3.0(2.6)

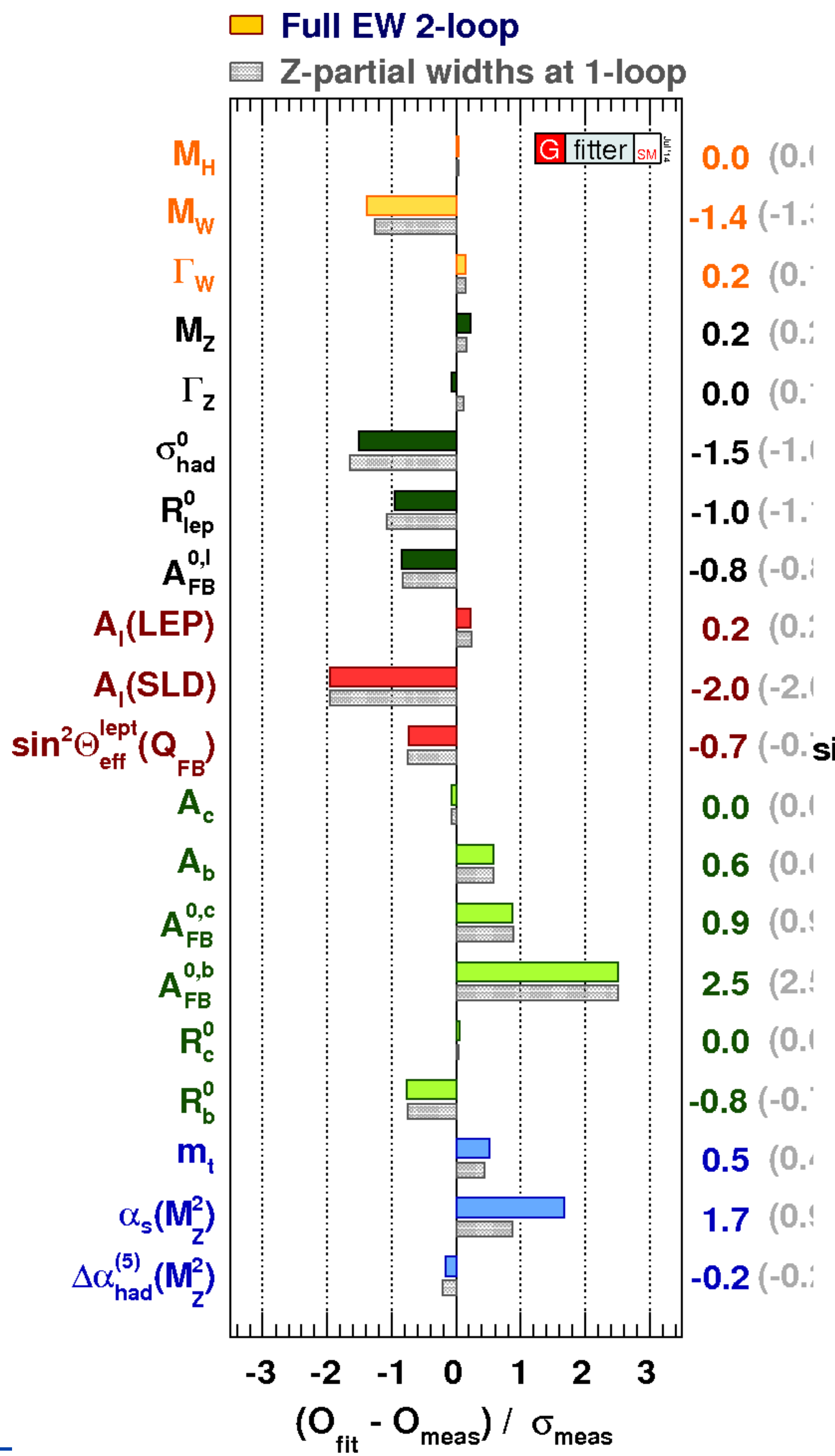
Table 1-12. *Target accuracies for the measurement of M_W and $\sin^2\theta^\ell_{eff}$ at the LHC, ILC and TLEP, also including estimated future theoretical uncertainties due to missing higher-order corrections, and theory uncertainties of their SM predictions. The uncertainties on the SM predictions are provided for $\Delta m_t = 0.5(0.1)$ GeV (see Table 1-3 for details). At present the measured values for M_W and $\sin^2\theta^\ell_{\rm eff}$ are: $M_W = 80.385 \pm 0.015$ GeV [112] and $\sin^2\theta^\ell_{\rm eff} = (23153 \pm 16) \times 10^{-5}$ [3] compared to their current SM predictions of Section 1.2.1: $M_W = 80.360 \pm 0.008$ GeV and $\sin^2\theta^\ell_{\rm eff} = (23127 \pm 7.3) \times 10^{-5}$.*

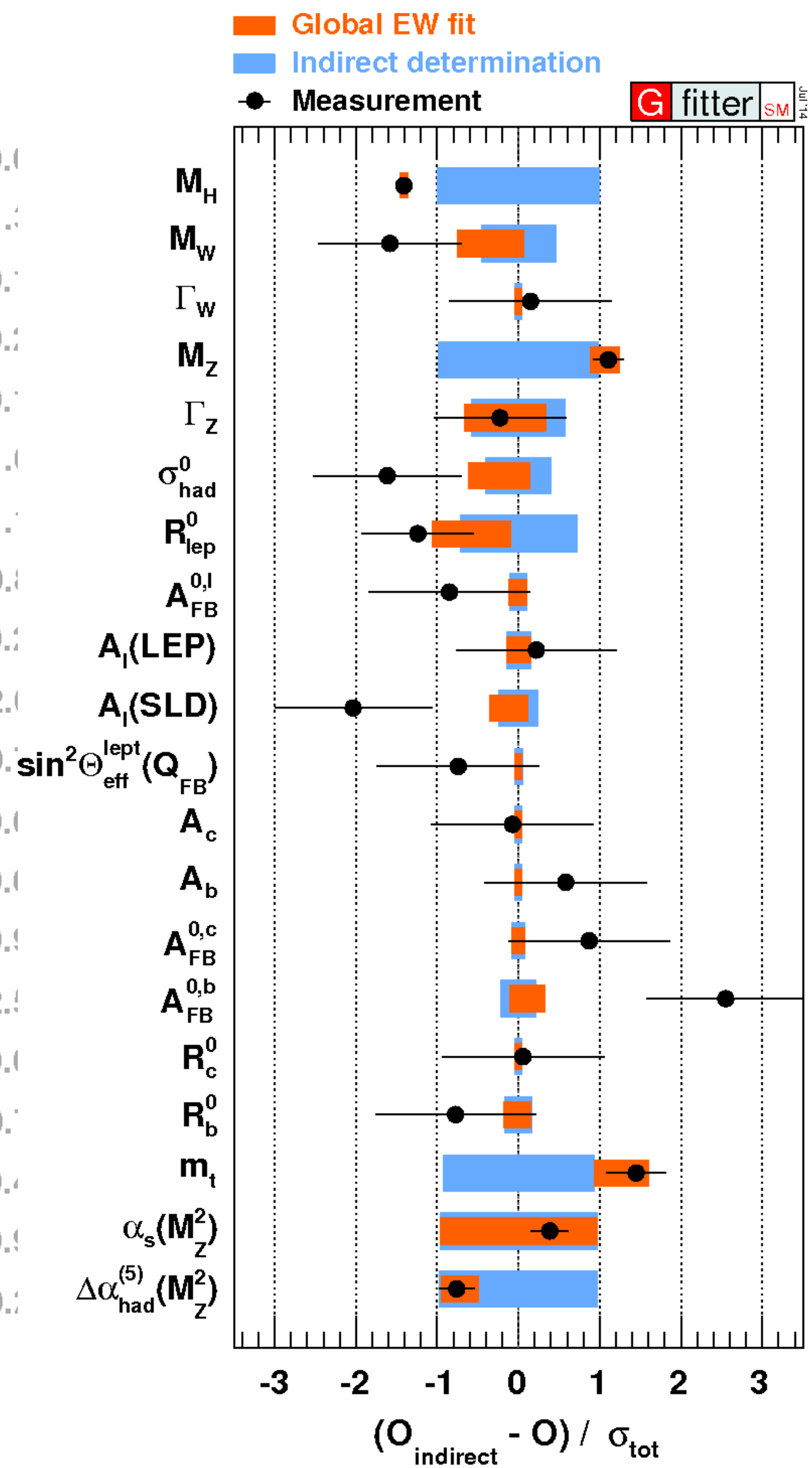
ELECTROWEAK FITS

- From the Gfitter Group, EPJC 72, 2205 (2012)
- Left: full fit incl. M_H
- Middle: not incl. M_H
- Right: fit incl M_H, not the row

Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV]$^\circ$	$125.7^{+0.4}_{-0.4}$	yes	$125.7^{+0.4}_{-0.4}$	94.7^{+25}_{-22}	94.7^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$	$80.367^{+0.006}_{-0.007}$	80.360 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1878 ± 0.0021	91.1978 ± 0.0114
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4954 ± 0.0014	2.4950 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014	41.471 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017	20.715 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$	$0.01626^{+0.0001}_{-0.0002}$	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007	–
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23149^{+0.00010}_{-0.00008}$	$0.23149^{+0.00010}_{-0.00008}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6679^{+0.00034}_{-0.00028}$	$0.6679^{+0.00034}_{-0.00028}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00005}_{-0.00007}$	$0.93464^{+0.00005}_{-0.00007}$	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004	0.0737 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005	0.1034 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21548 ± 0.00005	0.21548 ± 0.00005	0.21547 ± 0.00005
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.20 ± 0.87	yes	173.53 ± 0.82	173.53 ± 0.82	$176.11^{+2.88}_{-2.35}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2757 ± 10	yes	2755 ± 11	2755 ± 11	2718^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	$0.1190^{+0.0028}_{-0.0027}$	$0.1190^{+0.0028}_{-0.0027}$	0.1190 ± 0.0027
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-0.6	-0.5	–

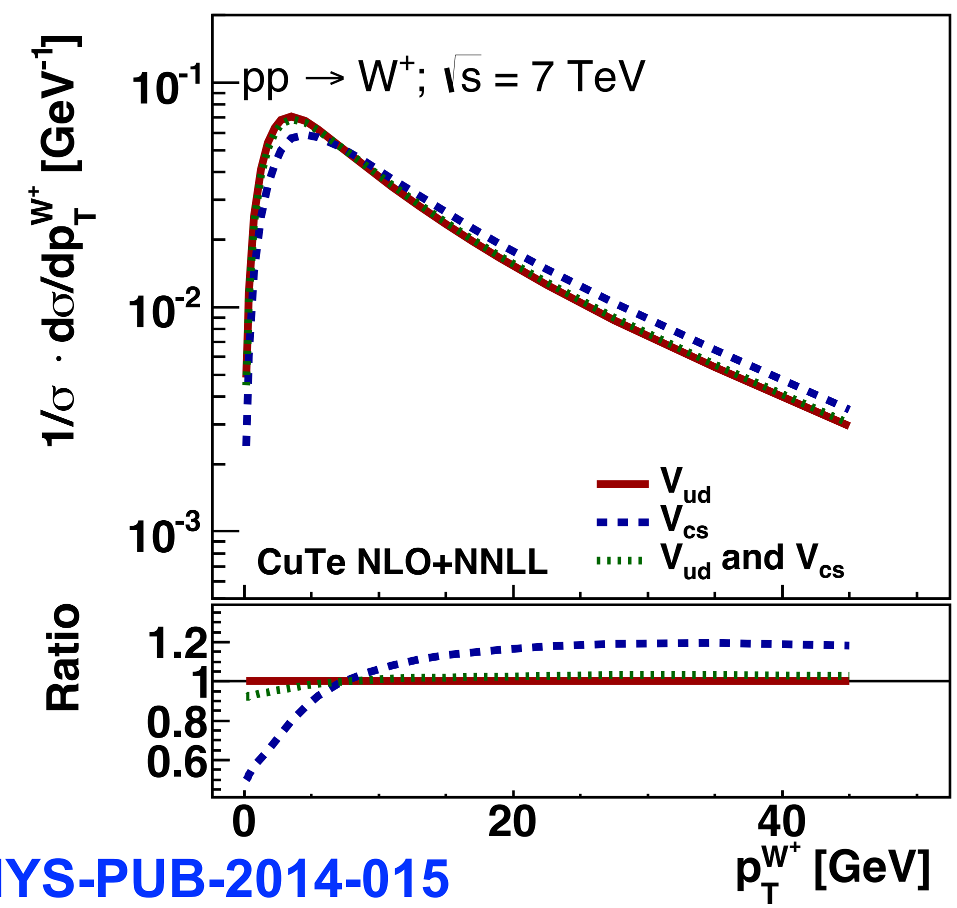
SM TESTS

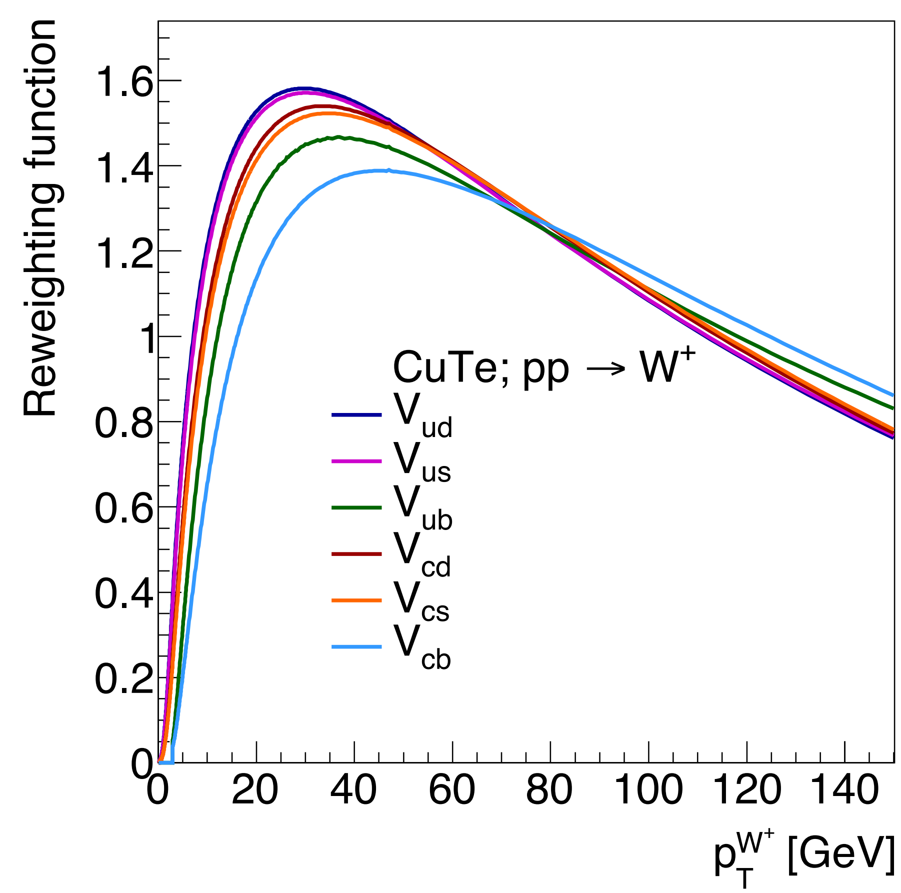

Full EW 2-loop
Z-partial widths at 1-loop
Gfitter SM
M_H 0.0
M_W -1.4
Γ_W 0.2
M_Z 0.2
Γ_Z 0.0
σ⁰_had -1.5
R⁰_lep -1.0
A^{0,l}_FB -0.8
A_l(LEP) 0.2
A_l(SLD) -2.0
sin²Θ^{lept}_eff(Q_FB) -0.7
A_c 0.0
A_b 0.6
A^{0,c}_FB 0.9
A^{0,b}_FB 2.5
R⁰_c 0.0
R⁰_b -0.8
m_t 0.5
α_s(M²_Z) 1.7
Δα^{(5)}_had(M²_Z) -0.2
-3 -2 -1 0 1 2 3
(O_fit - O_meas) / σ_meas


Global EW fit
Indirect determination
Measurement
Gfitter SM
M_H
M_W
Γ_W
M_Z
Γ_Z
σ⁰_had
R⁰_lep
A^{0,l}_FB
A_l(LEP)
A_l(SLD)
sin²Θ^{lept}_eff(Q_FB)
A_c
A_b
A^{0,c}_FB
A^{0,b}_FB
R⁰_c
R⁰_b
m_t
α_s(M²_Z)
Δα^{(5)}_had(M²_Z)
-3 -2 -1 0 1 2 3
(O_indirect - O) / σ_tot

PROTON PDF AND *W,Z* PRODUCTION

- Main production at LHC : $u\bar{d} \to W^+$ $d\bar{u} \to W^-$; $c\bar{s} \to W$ ~25%; *x* from 10^{-3} to 10^{-1}
- Similar for *W* and *Z*, BUT
  - The charm quark contribution significant to W production (~ ($V c\bar{s}$+$V c\bar{d}$+c.c.), smaller for Z production(~ $c\bar{c}$) and vice versa for the b-quark content, contributes to *Z* production (~ $b\bar{b}$), negligible to *W* production (~ ($V c\bar{b}$ +c.c.))
- Strange and charm production ~several times lager then in $p\bar{p}$ in Tevatron
  - Preliminary : 7-9 MeV uncertainty (including experimental effects)





ATL-PHYS-PUB-2014-015

PDF EFFECTS ON LEPTON PT AND W MT

- PDF uncertainties on Mw are dominated by the valence/sea ratio, and by 2nd generation
  - Transverse momentum distribution uncertainties due to uncertainties in the $p_T W$
    - Contributions from distribution heavy quark PDFs (+non-perturbative parameters)
  - Valence/sea PDF uncertainties
    - Determine the rapidity distribution => acceptance effects
    - Valence PDFs polarize the W decay along z-direction
- Uncertainty~10 MeV, differences between sets 20-30 MeV

arXiv:1501.05587v2 [hep-ph]

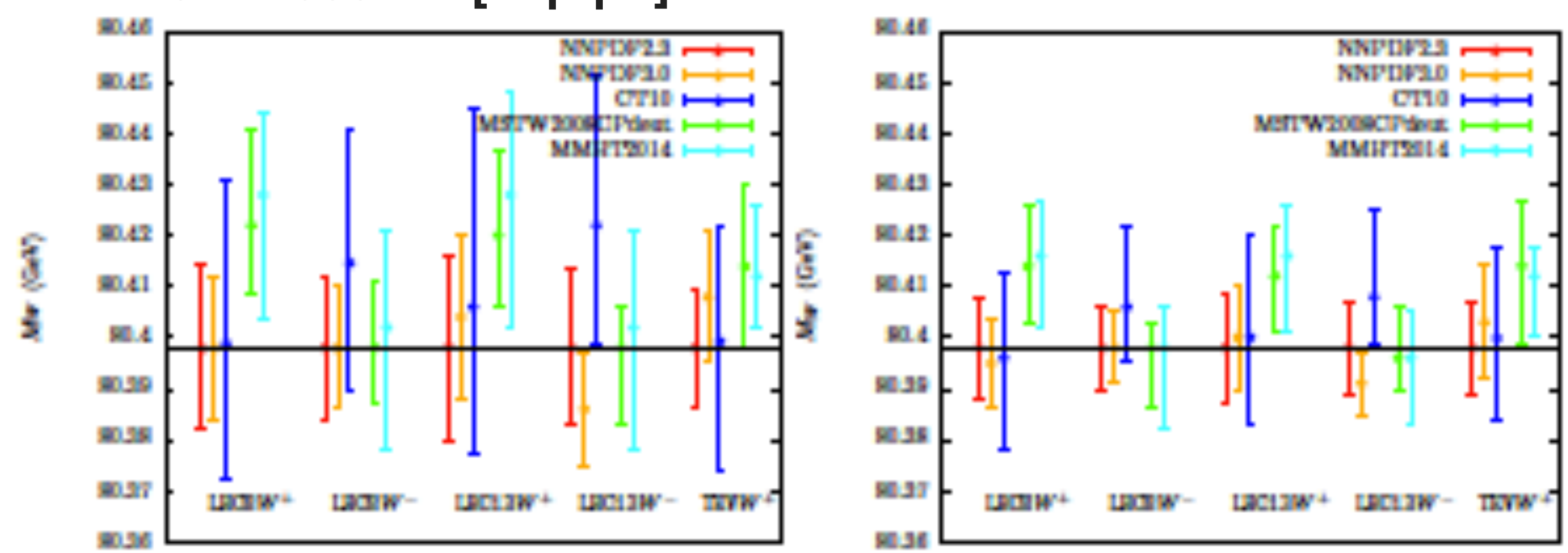
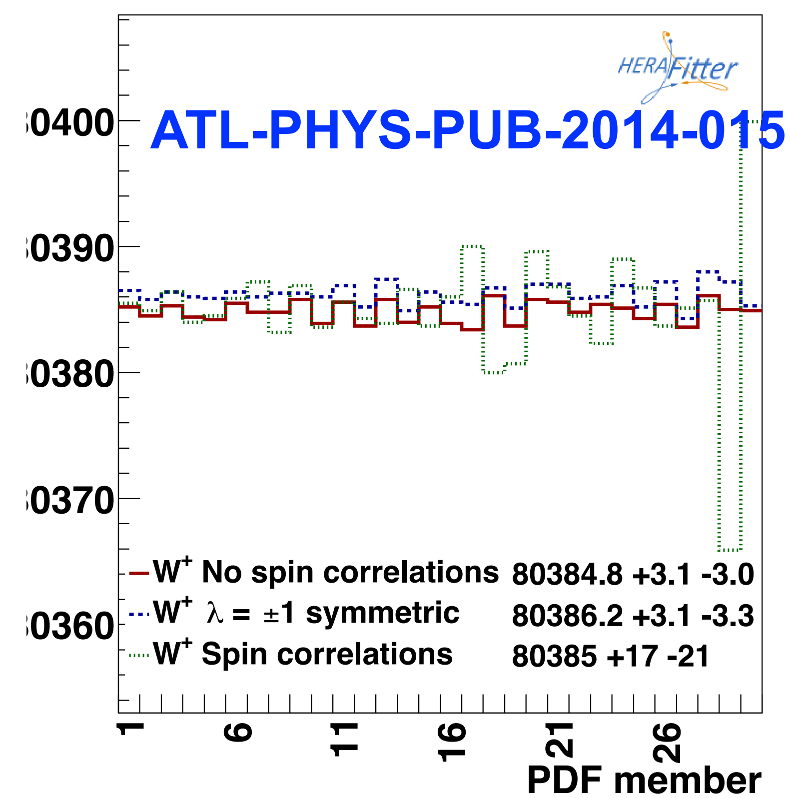
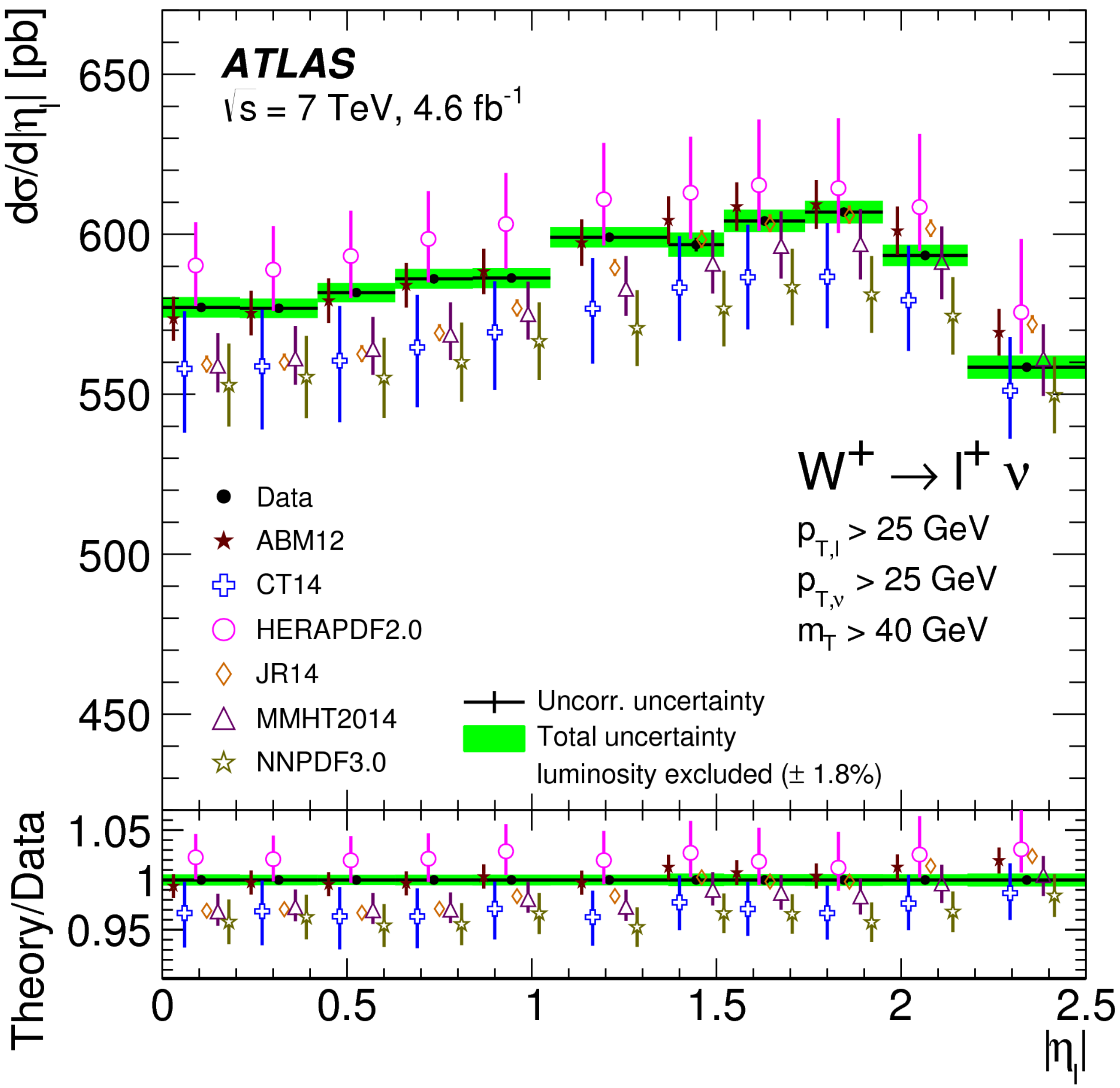
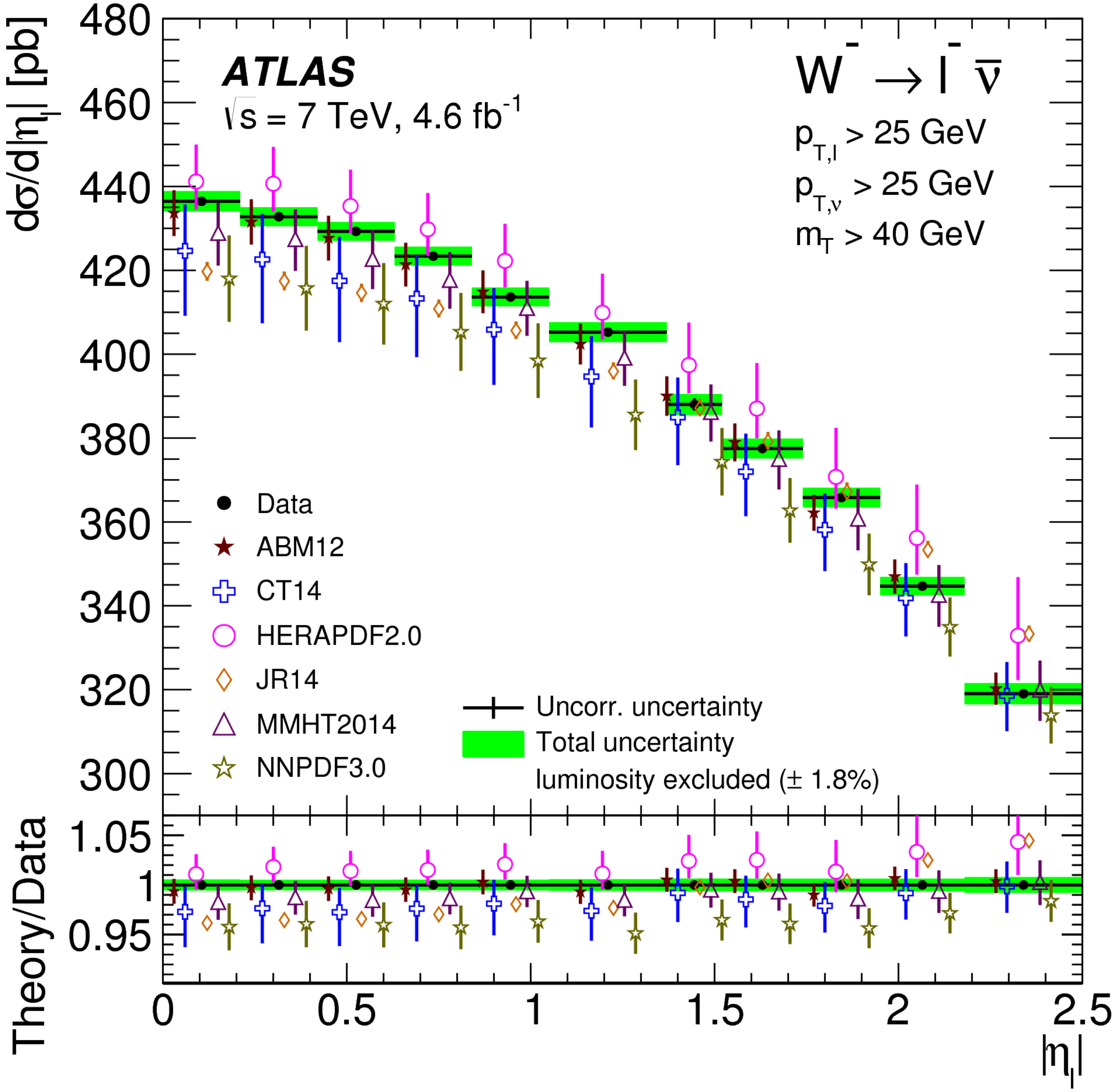


Figure 4: Summary of the PDF uncertainty on m_W computed with different PDF sets, colliders and final states. The basic acceptance criteria have been used in the left plot, while in the right plot an additional cut $p_\perp^W < 15$ GeV has been applied.



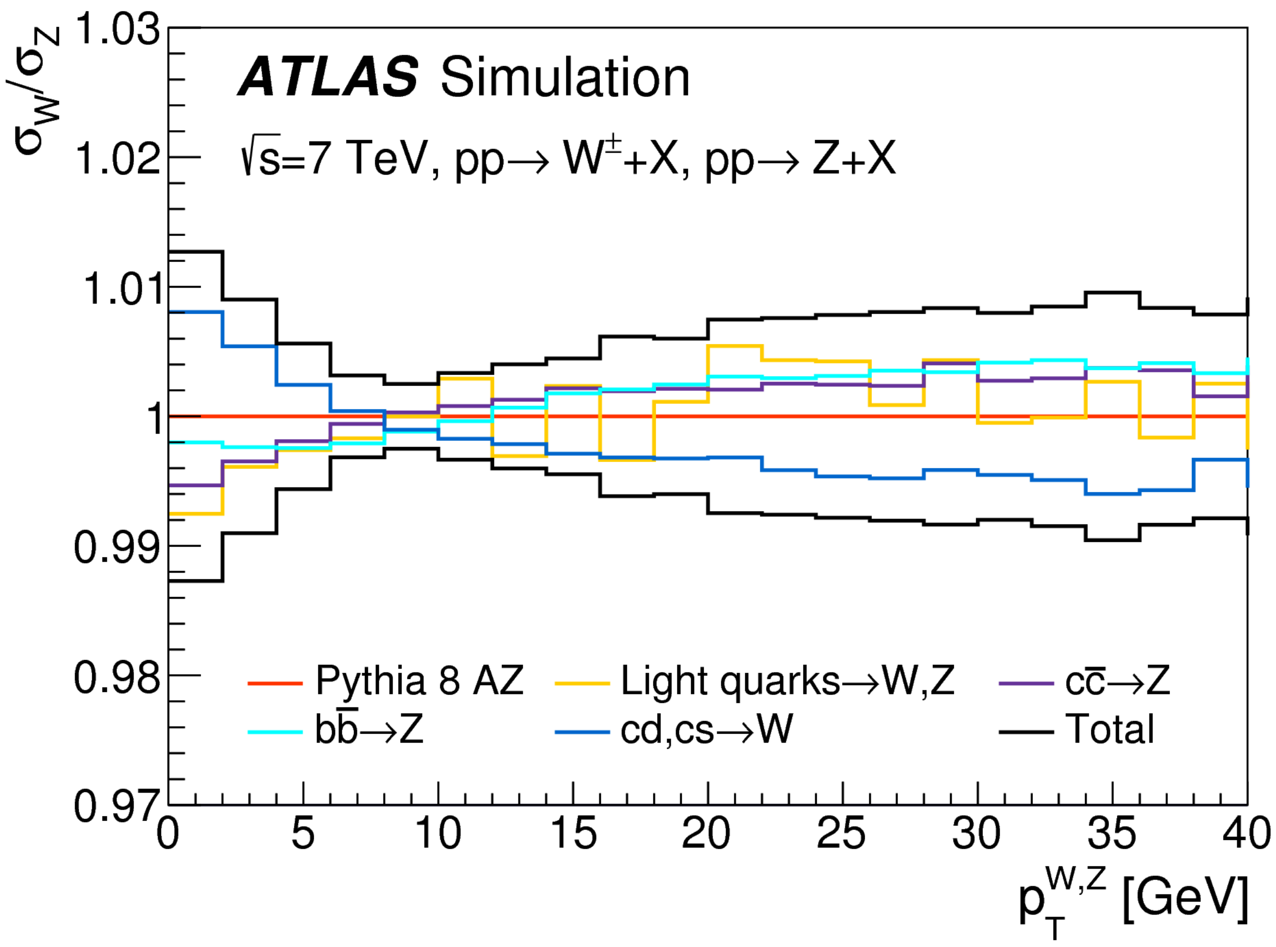
RAPIDITY DISTRIBUTIONS

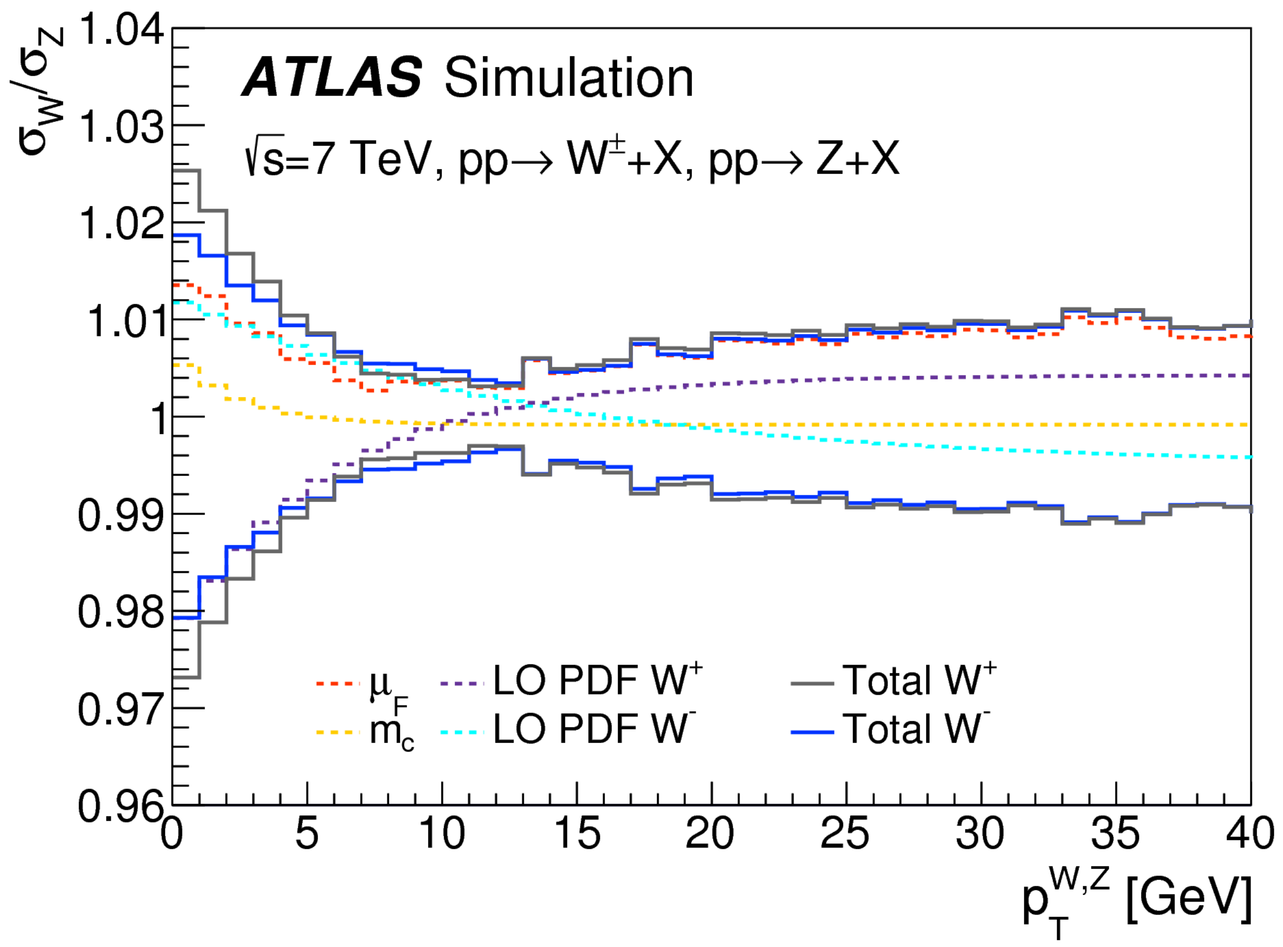




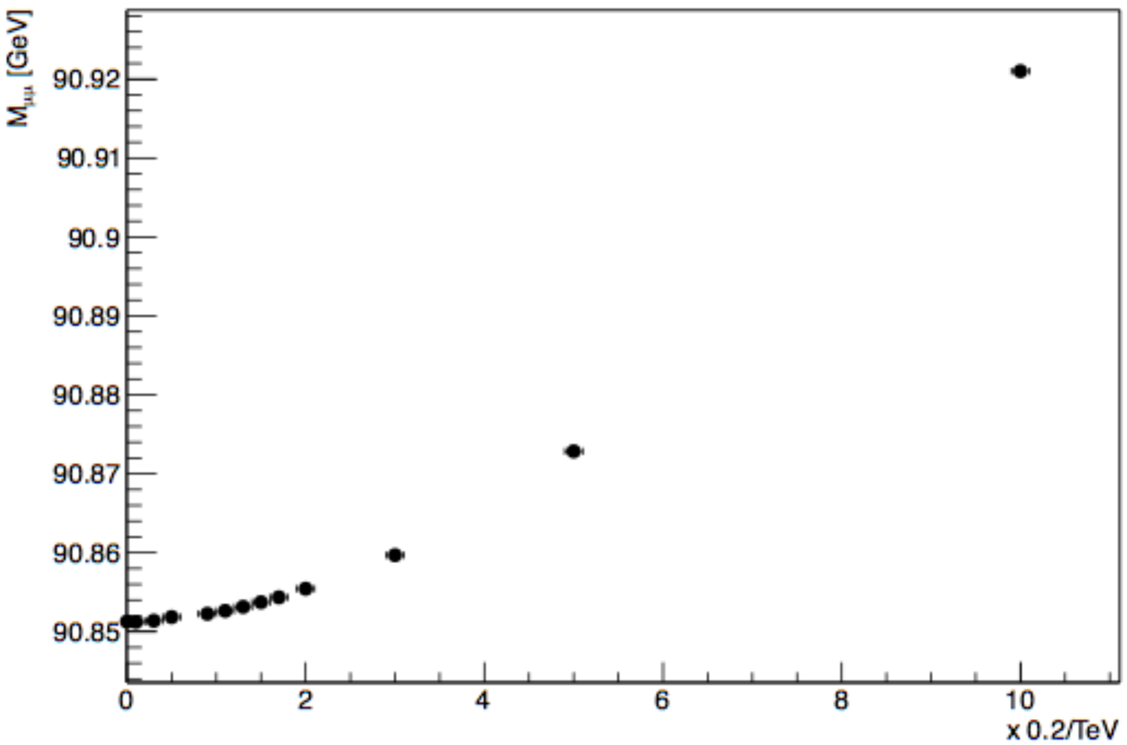
- Recent ATLAS results on W and Z cross section measurements arXiv:1612.03016
- Integrated and differential measurements with sub-% precision.
- High sensitivity to PDFs; critical to validate the predictions used for the m_W analysis.

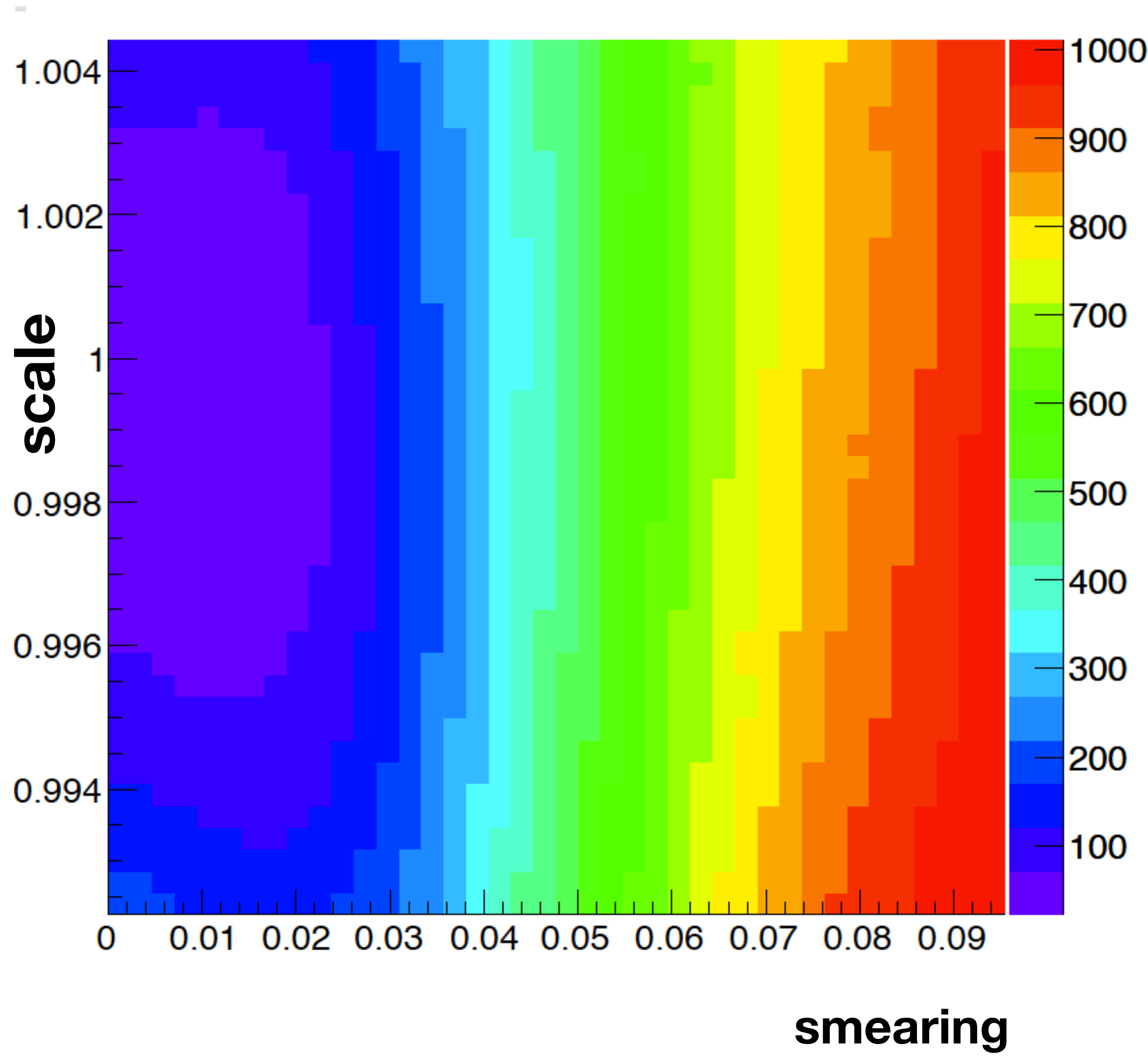
PTV R(W/Z) UNCERTAINTY





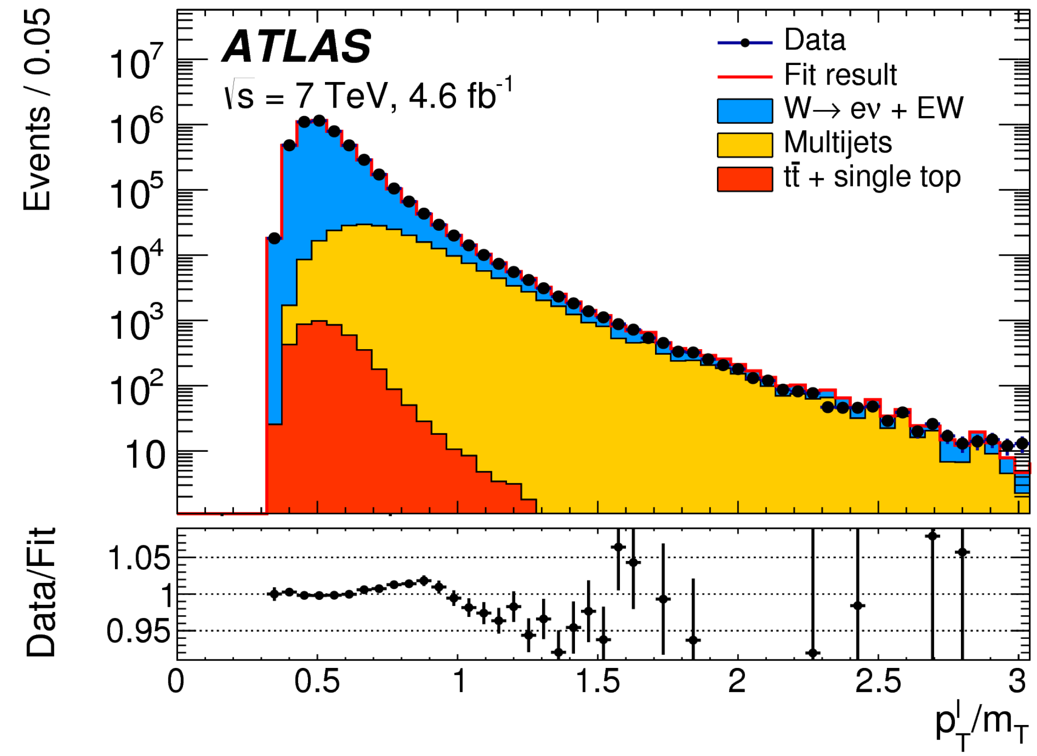
RESOLUTION BIAS ON THE SCALE

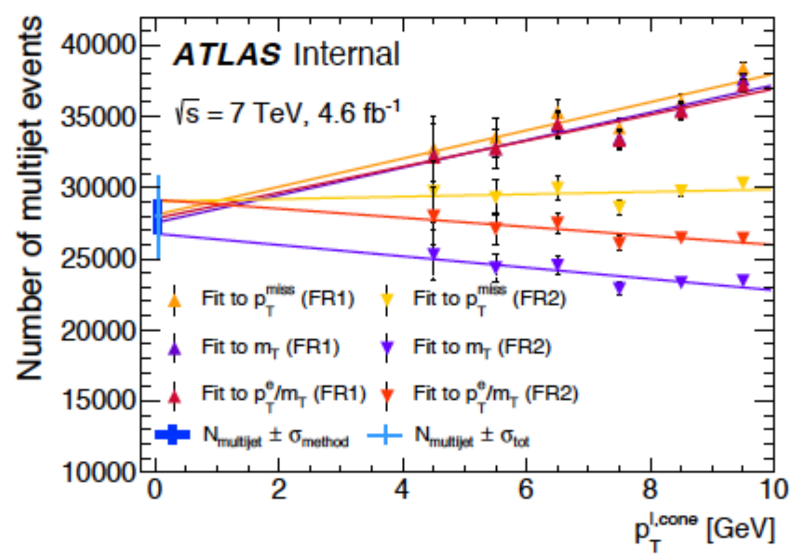


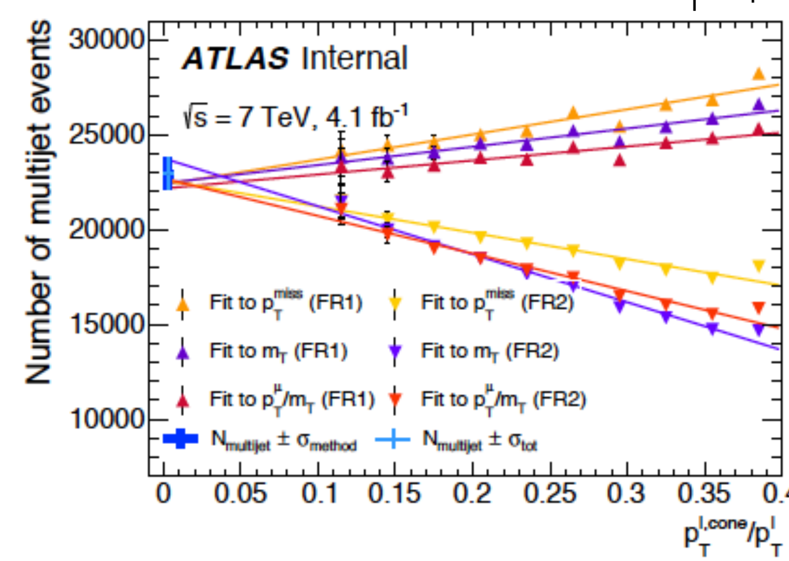


BACKGROUNDS

- Simulation : $Z \to \ell\ell, W \to \tau\nu$, top, dibosons
- Multijet (MJ) : data-driven, same procedure for $W \to e\nu$ and $W \to \mu\nu$
- Template fits to p_T^{miss}, m_T, p_T^l/p_T^{miss} in FR1 (no p_T^{miss} and m_T cuts) and FR2 (= FR1 + no u_T cut) using MJ templates obtained for several ranges of "anti-isolation" var.
  - The level of MJ corrected for different efficiencies in the signal region
  - Systematics: 1/2 of the largest difference between the results extrapolated to the signal region
- Corrections to the MJ shape
  - Parametrisation of the correction between signal and control region, extrapolated
  - Uncertainty dominated by the statistical uncertainty, propagated to m_W
- Normalisation uncertainty correlated, shapes uncorrelated between e/μ, W^+/W^-







BACKGROUNDS (2)

Background fractions [%]

$W \to \mu\nu$						
Category	$W \to \tau\nu$	$Z \to \mu\mu$	$Z \to \tau\tau$	Top	Dibosons	Multijet
$W^{\pm}$ $0.0 < \lvert\eta\rvert < 0.8$	1.04	2.83	0.12	0.16	0.08	0.72
$W^{\pm}$ $0.8 < \lvert\eta\rvert < 1.4$	1.01	4.44	0.11	0.12	0.07	0.57
$W^{\pm}$ $1.4 < \lvert\eta\rvert < 2.0$	0.99	6.78	0.11	0.07	0.06	0.51
$W^{\pm}$ $2.0 < \lvert\eta\rvert < 2.4$	1.00	8.50	0.10	0.04	0.05	0.50
$W^{\pm}$ all η bins	1.01	5.41	0.11	0.10	0.06	0.58
W^{+} all η bins	0.99	4.80	0.10	0.09	0.06	0.51
W^{-} all η bins	1.04	6.28	0.14	0.12	0.08	0.68

$W \to e\nu$						
Category	$W \to \tau\nu$	$Z \to ee$	$Z \to \tau\tau$	Top	Dibosons	Multijet
$W^{\pm}$ $0.0 < \lvert\eta\rvert < 0.6$	1.02	3.34	0.13	0.15	0.08	0.59
$W^{\pm}$ $0.6 < \lvert\eta\rvert < 1.2$	1.00	3.48	0.12	0.13	0.08	0.76
$W^{\pm}$ $1.8 < \lvert\eta\rvert < 2.4$	0.97	3.23	0.11	0.05	0.05	1.74
$W^{\pm}$ all η bins	1.00	3.37	0.12	0.12	0.07	1.00
W^{+} all η bins	0.98	2.92	0.10	0.11	0.06	0.84
W^{-} all η bins	1.04	3.98	0.14	0.13	0.08	1.21

Background uncertainties [MeV]

Kinematic distribution	p_T^ℓ				m_T			
Decay channel	$W \to e\nu$		$W \to \mu\nu$		$W \to e\nu$		$W \to \mu\nu$	
W-boson charge	W^+	W^-	W^+	W^-	W^+	W^-	W^+	W^-
δm_W [MeV]								
$W \to \tau\nu$ (fraction, shape)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
$Z \to ee$ (fraction, shape)	0.5	0.5	–	–	0.5	0.5	–	–
$Z \to \mu\mu$ (fraction, shape)	–	–	2.0	2.0	–	–	2.0	2.0
$Z \to \tau\tau$ (fraction, shape)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
WW, WZ, ZZ (fraction)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Top (fraction)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Multijet (fraction)	3.3	4.1	2.3	3.1	8.2	8.7	3.6	4.7
Multijet (shape)	5.6	7.3	2.1	2.8	8.0	11.4	2.5	3.5
Total	6.6	8.4	3.8	4.7	11.5	14.4	4.9	6.2

$M_{W+} - M_{W-}$

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	-29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	-28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	-29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

Improvement wrt PDG (±0.6 GeV)

28 CATEGORIES

Channel	m_W [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
m_T-Fit										
$W^+ \to \mu\nu, \lvert\eta\rvert < 0.8$	80371.3	29.2	12.4	0.0	15.2	8.1	9.9	3.4	28.4	47.1
$W^+ \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80354.1	32.1	19.3	0.0	13.0	6.8	9.6	3.4	23.3	47.6
$W^+ \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80426.3	30.2	35.1	0.0	14.3	7.2	9.3	3.4	27.2	56.9
$W^+ \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.6	40.9	112.4	0.0	14.4	9.0	8.4	3.4	32.8	125.5
$W^- \to \mu\nu, \lvert\eta\rvert < 0.8$	80375.5	30.6	11.6	0.0	13.1	8.5	9.5	3.4	30.6	48.5
$W^- \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80417.5	36.4	18.5	0.0	12.2	7.7	9.7	3.4	22.2	49.7
$W^- \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80379.4	35.6	33.9	0.0	10.5	8.1	9.7	3.4	23.1	56.9
$W^- \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.2	52.4	123.7	0.0	11.6	10.2	9.9	3.4	34.1	139.9
$W^+ \to e\nu, \lvert\eta\rvert < 0.6$	80352.9	29.4	0.0	19.5	13.1	15.3	9.9	3.4	28.5	50.8
$W^+ \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80381.5	30.4	0.0	21.4	15.1	13.2	9.6	3.4	23.5	49.4
$W^+ \to e\nu, 1,8 < \lvert\eta\rvert < 2.4$	80352.4	32.4	0.0	26.6	16.4	32.8	8.4	3.4	27.3	62.6
$W^- \to e\nu, \lvert\eta\rvert < 0.6$	80415.8	31.3	0.0	16.4	11.8	15.5	9.5	3.4	31.3	52.1
$W^- \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80297.5	33.0	0.0	18.7	11.2	12.8	9.7	3.4	23.9	49.0
$W^- \to e\nu, 1.8 < \lvert\eta\rvert < 2.4$	80423.8	42.8	0.0	33.2	12.8	35.1	9.9	3.4	28.1	72.3
p_T-Fit										
$W^+ \to \mu\nu, \lvert\eta\rvert < 0.8$	80327.7	22.1	12.2	0.0	2.6	5.1	9.0	6.0	24.7	37.3
$W^+ \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80357.3	25.1	19.1	0.0	2.5	4.7	8.9	6.0	20.6	39.5
$W^+ \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80446.9	23.9	33.1	0.0	2.5	4.9	8.2	6.0	25.2	49.3
$W^+ \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80334.1	34.5	110.1	0.0	2.5	6.4	6.7	6.0	31.8	120.2
$W^- \to \mu\nu, \lvert\eta\rvert < 0.8$	80427.8	23.3	11.6	0.0	2.6	5.8	8.1	6.0	26.4	39.0
$W^- \to \mu\nu, 0.8 < \lvert\eta\rvert < 1.4$	80395.6	27.9	18.3	0.0	2.5	5.6	8.0	6.0	19.8	40.5
$W^- \to \mu\nu, 1.4 < \lvert\eta\rvert < 2.0$	80380.6	28.1	35.2	0.0	2.6	5.6	8.0	6.0	20.6	50.9
$W^- \to \mu\nu, 2.0 < \lvert\eta\rvert < 2.4$	80315.2	45.5	116.1	0.0	2.6	7.6	8.3	6.0	32.7	129.6
$W^+ \to e\nu, \lvert\eta\rvert < 0.6$	80336.5	22.2	0.0	20.1	2.5	6.4	9.0	5.3	24.5	40.7
$W^+ \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80345.8	22.8	0.0	21.4	2.6	6.7	8.9	5.3	20.5	39.4
$W^+ \to e\nu, 1,8 < \lvert\eta\rvert < 2.4$	80344.7	24.0	0.0	30.8	2.6	11.9	6.7	5.3	24.1	48.2
$W^- \to e\nu, \lvert\eta\rvert < 0.6$	80351.0	23.1	0.0	19.8	2.6	7.2	8.1	5.3	26.6	42.2
$W^- \to e\nu, 0.6 < \lvert\eta\rvert < 1.2$	80309.8	24.9	0.0	19.7	2.7	7.3	8.0	5.3	20.9	39.9
$W^- \to e\nu, 1.8 < \lvert\eta\rvert < 2.4$	80413.4	30.1	0.0	30.7	2.7	11.5	8.3	5.3	22.7	51.0

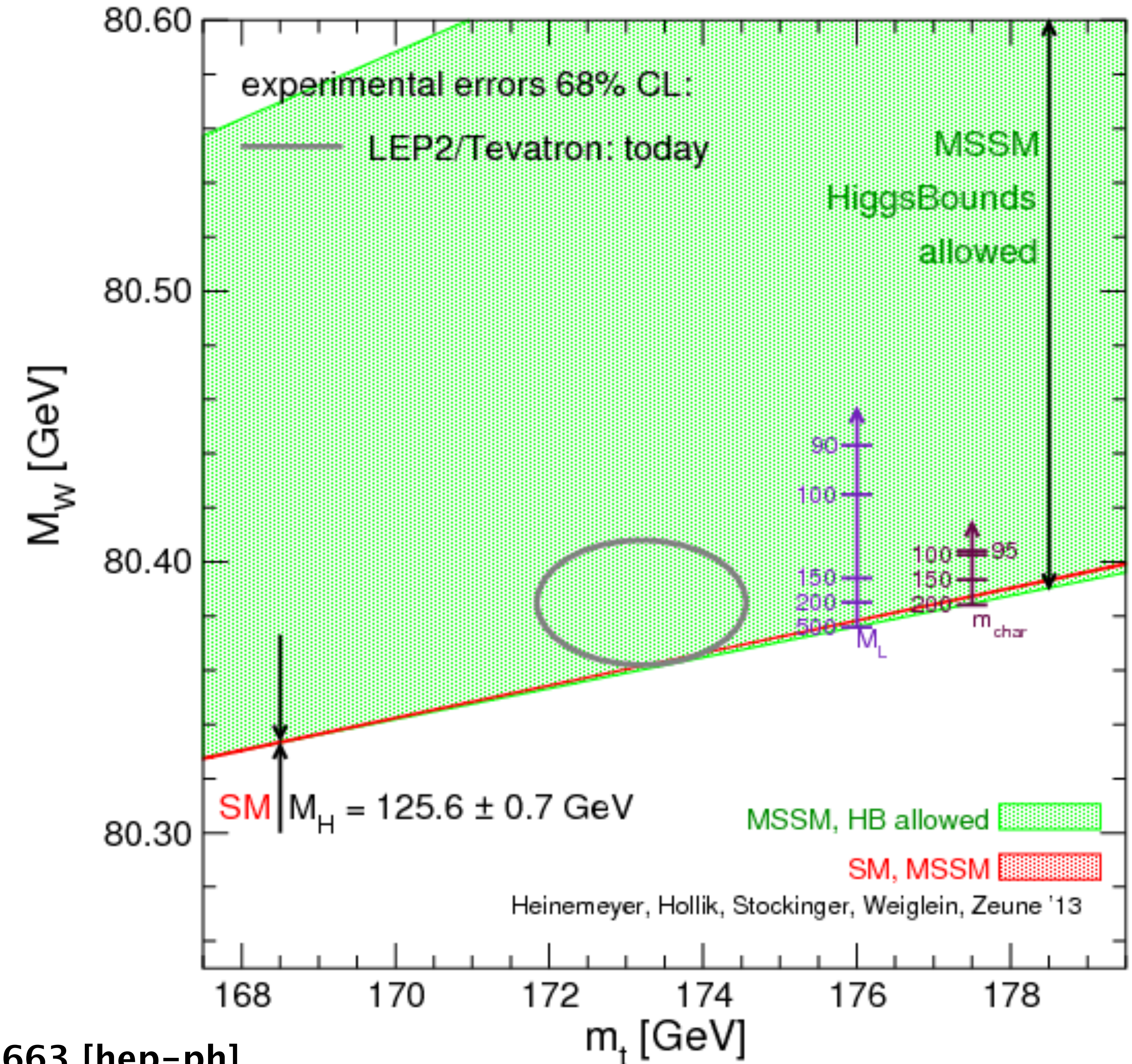
|η| comb e → ~15 MeV
μ → ~11 MeV

Strongly correlated

Strongly correlated

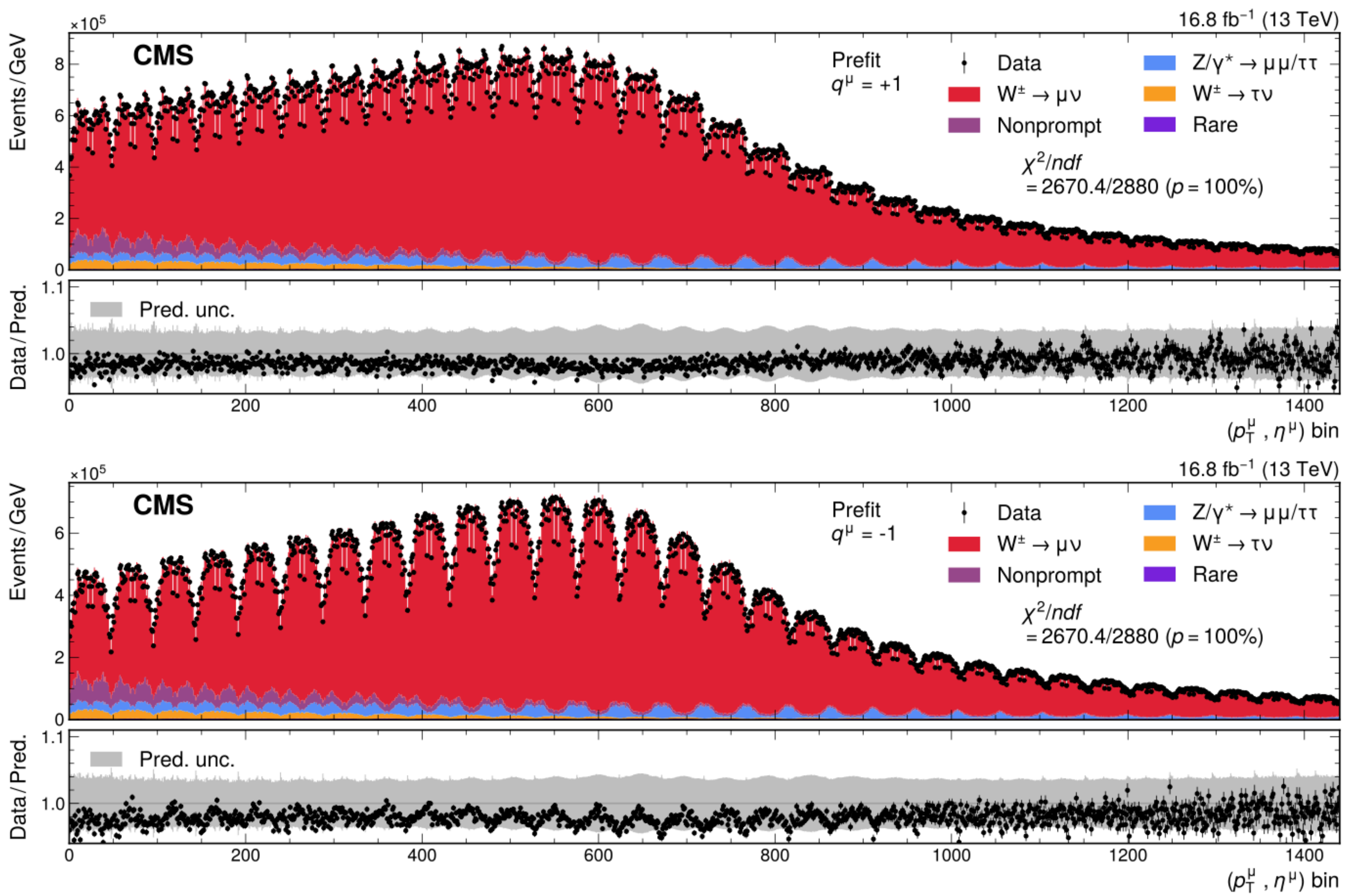
|η| comb. → ~14 MeV
W+/W- comb → ~8 MeV

IMPACT OF MW ON MSSM



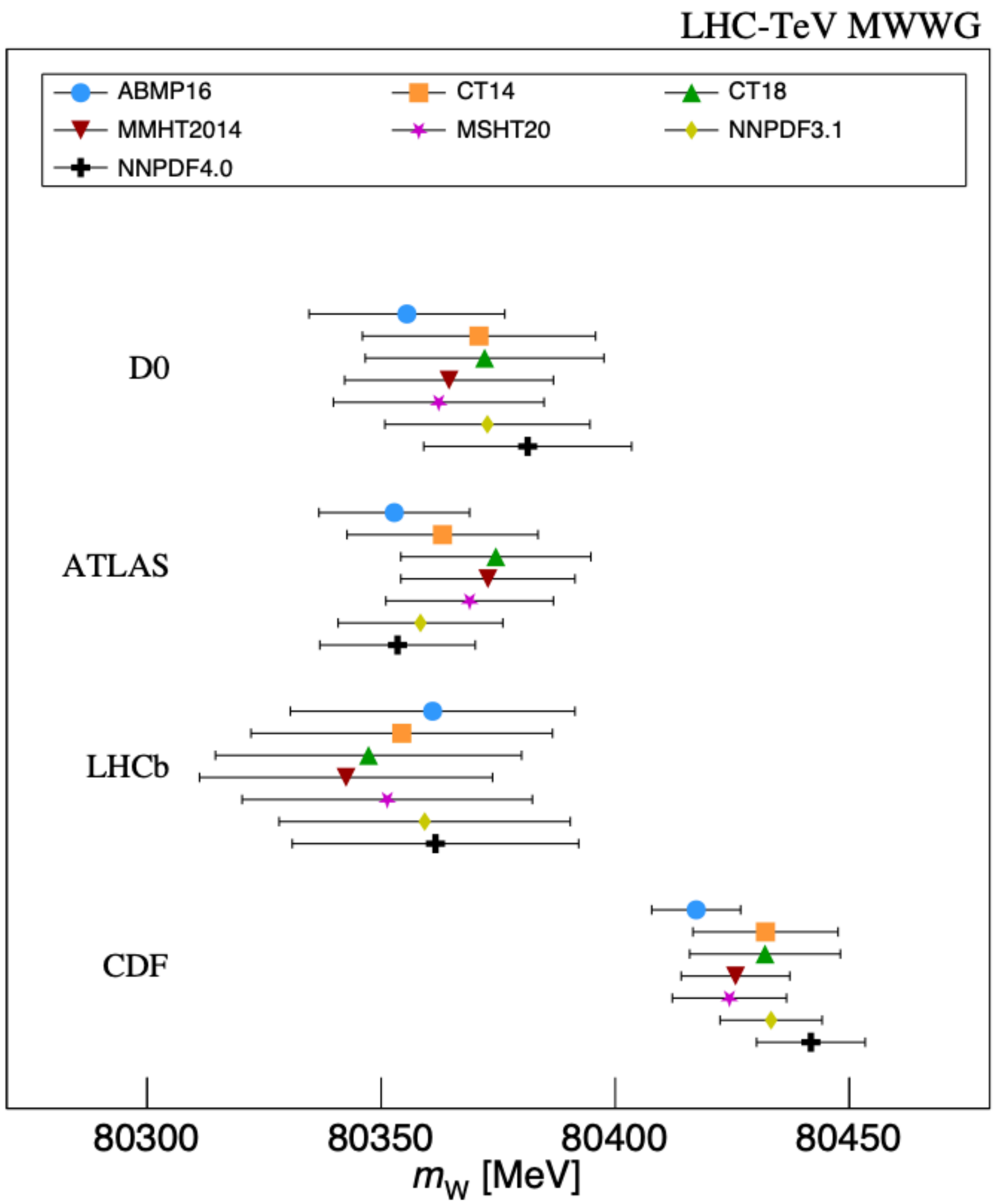
arXiv:1311.1663 [hep-ph]

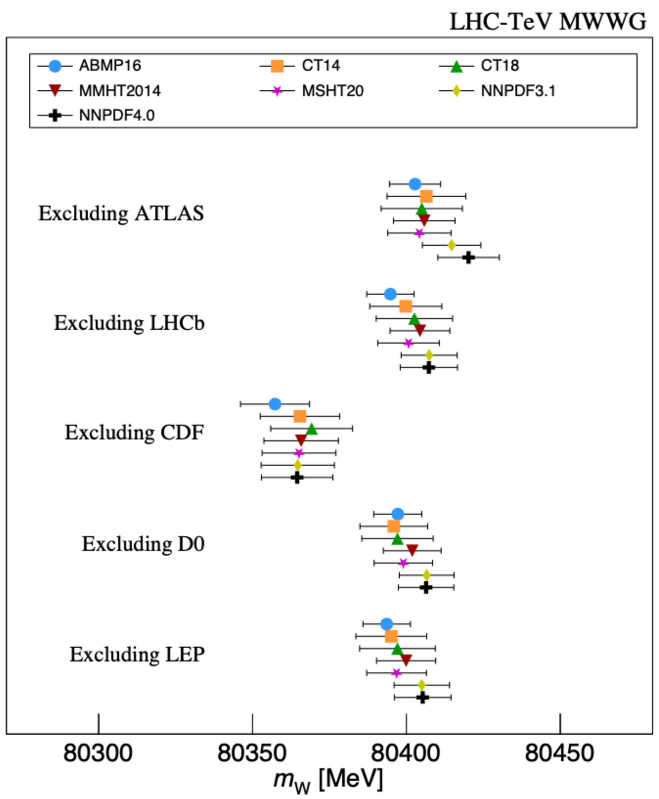
CMS MEASUREMENT

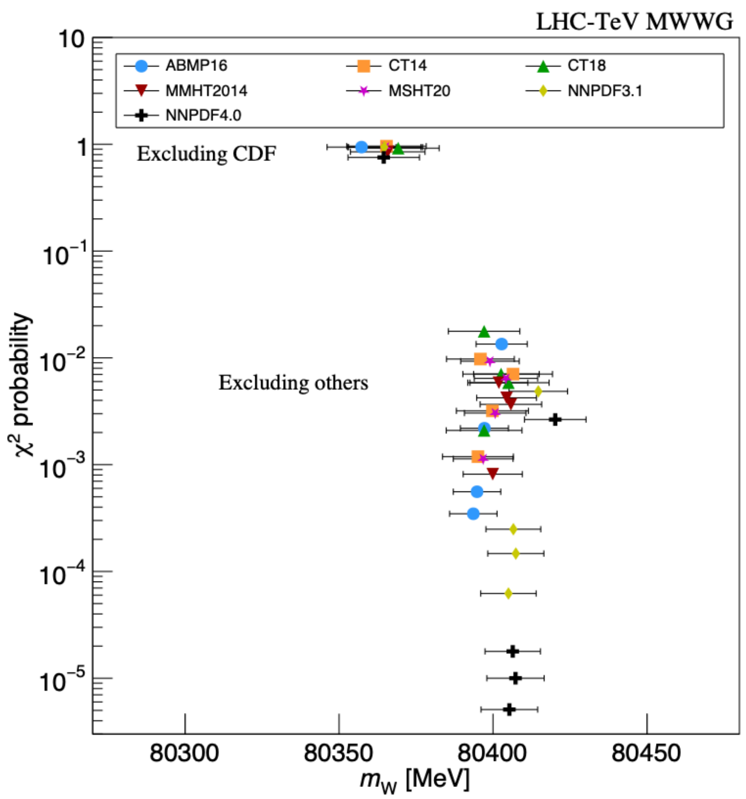


arXiv:2412.13872 [hep-ex]

W MASS COMBINATION

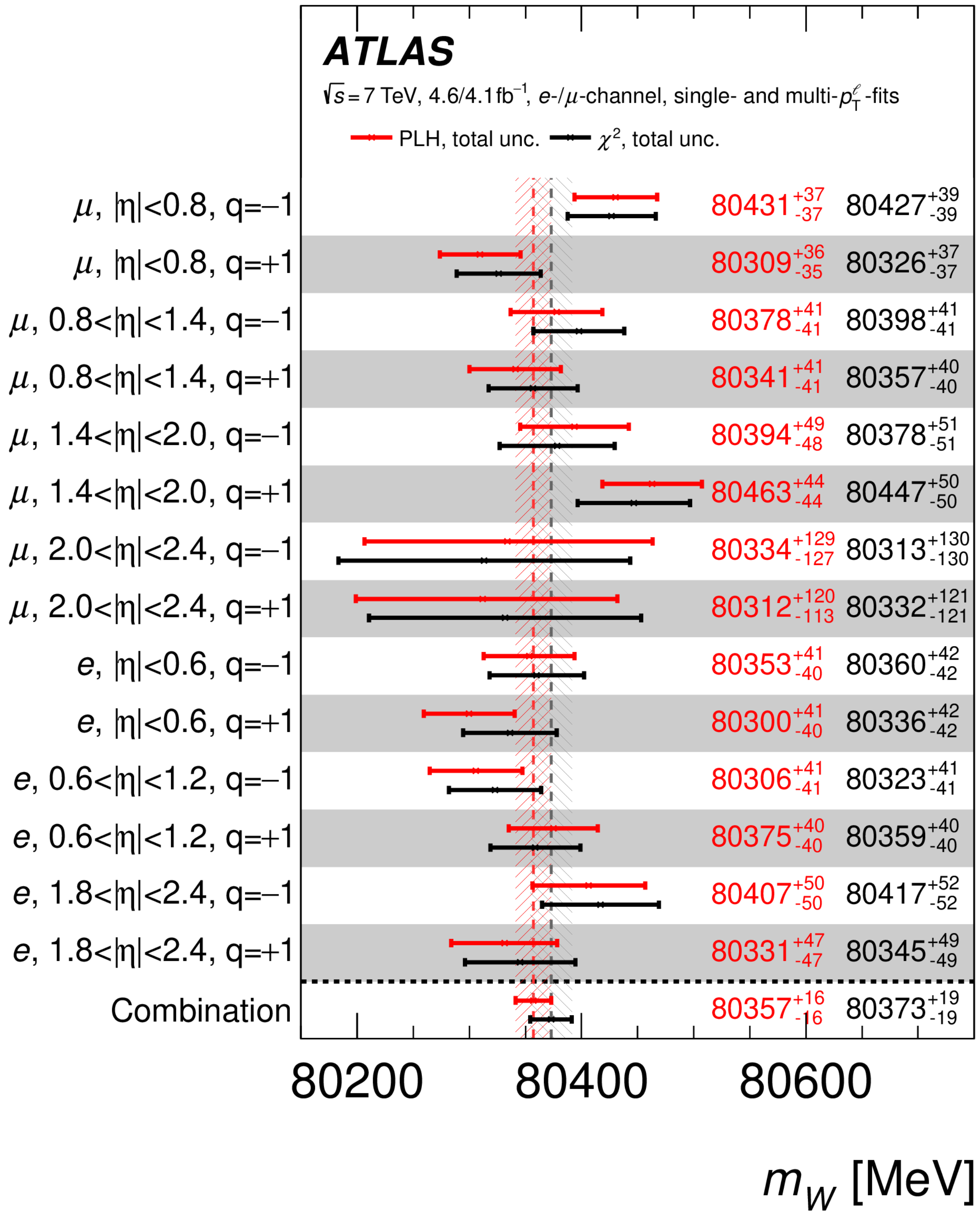


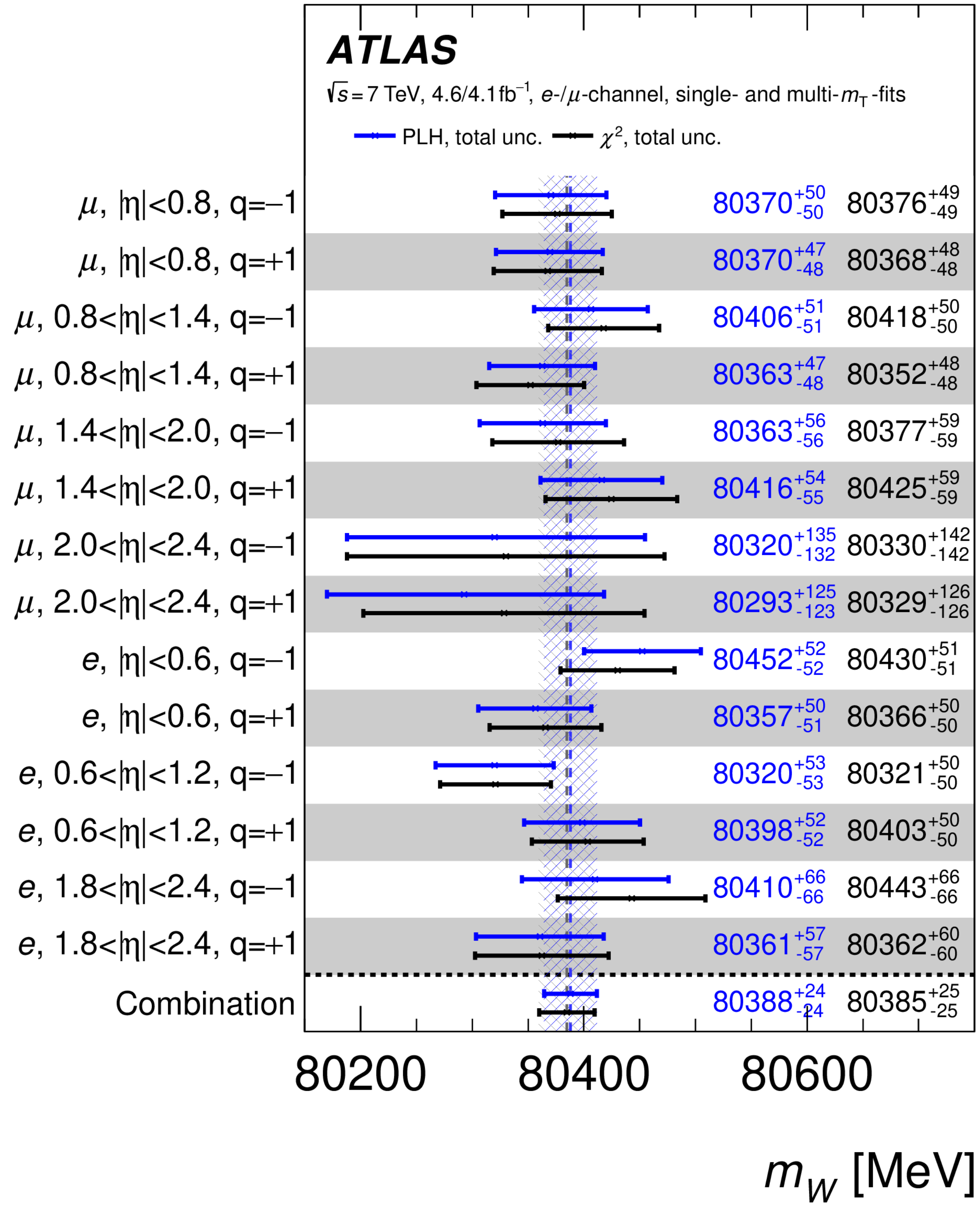




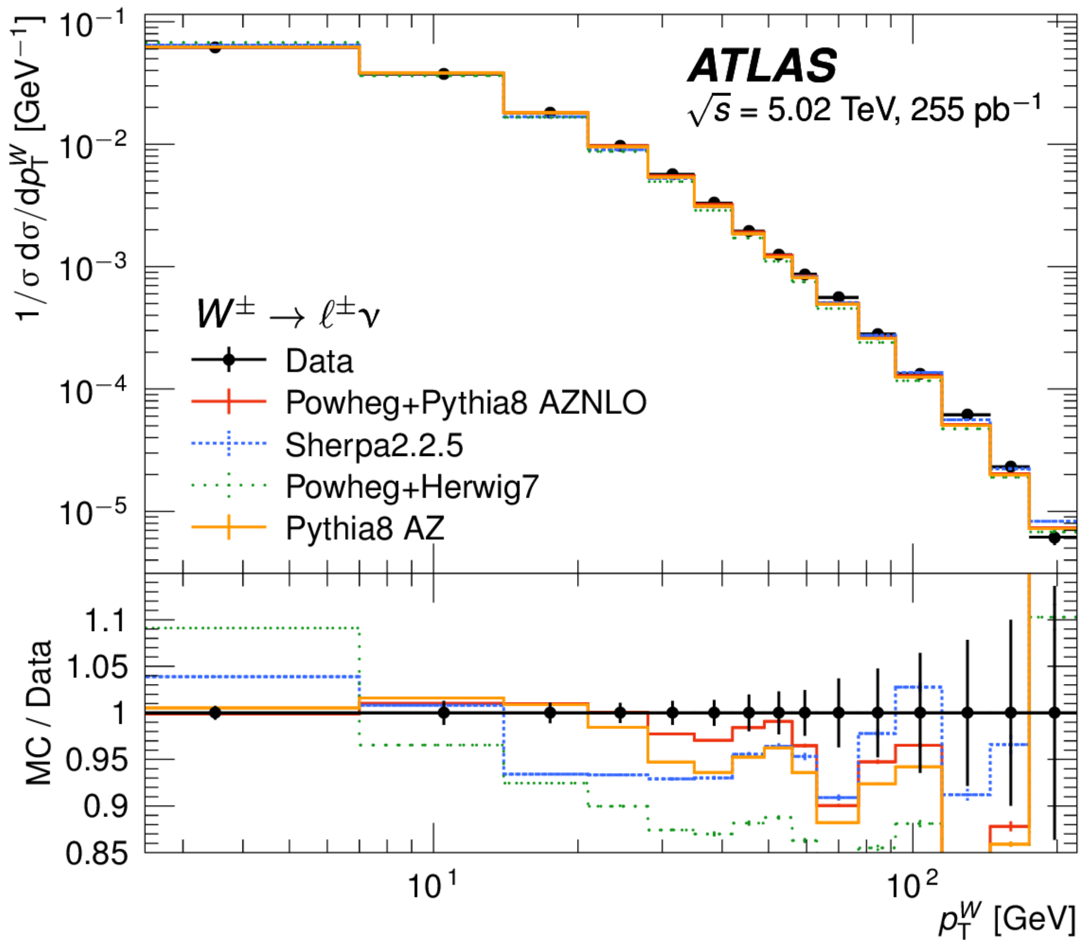
https://arxiv.org/pdf/2308.09417

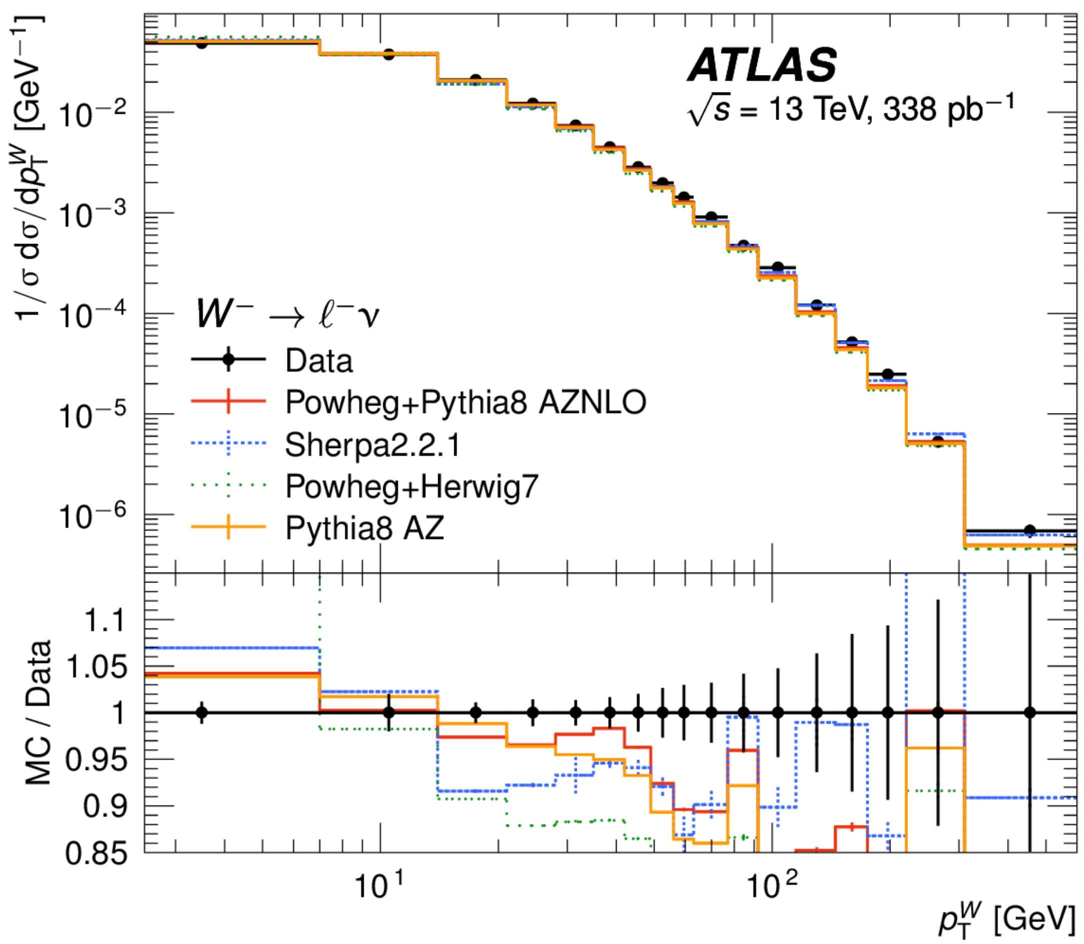
PLH VALIDATION



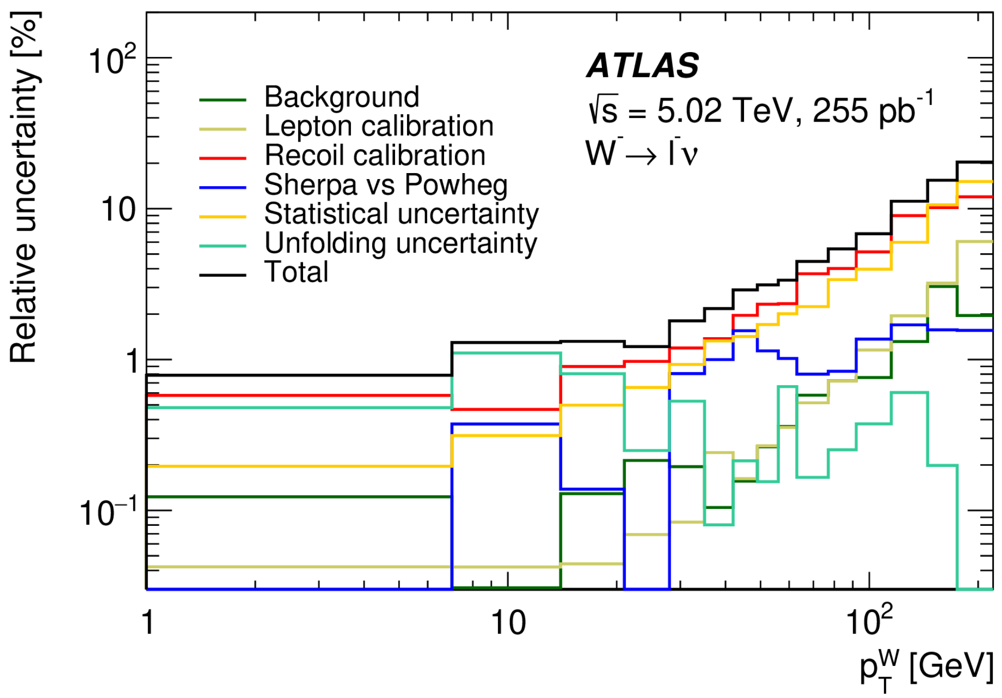


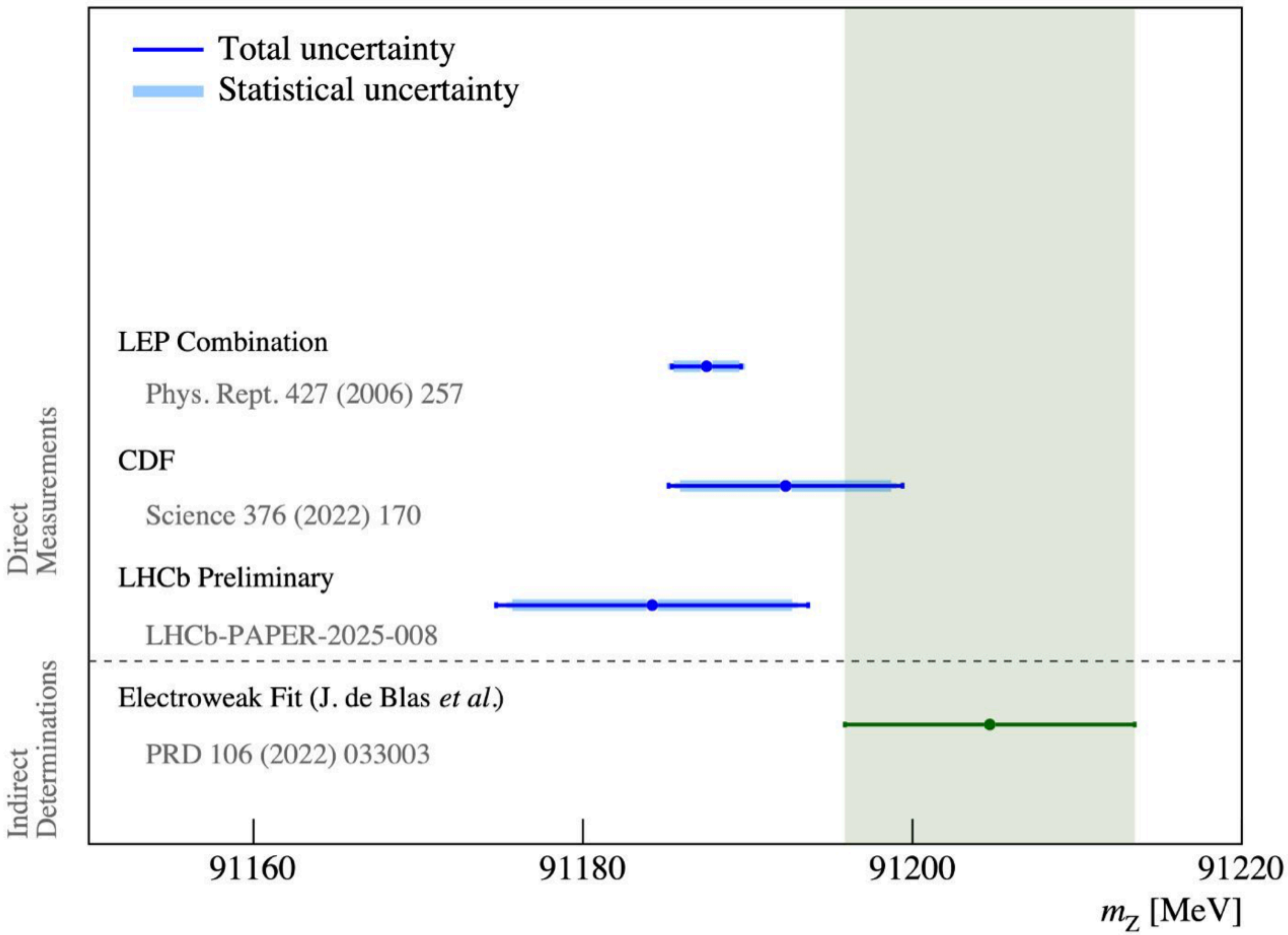
PTW AT LOW MU





e-print [arXiv:2404.06204]





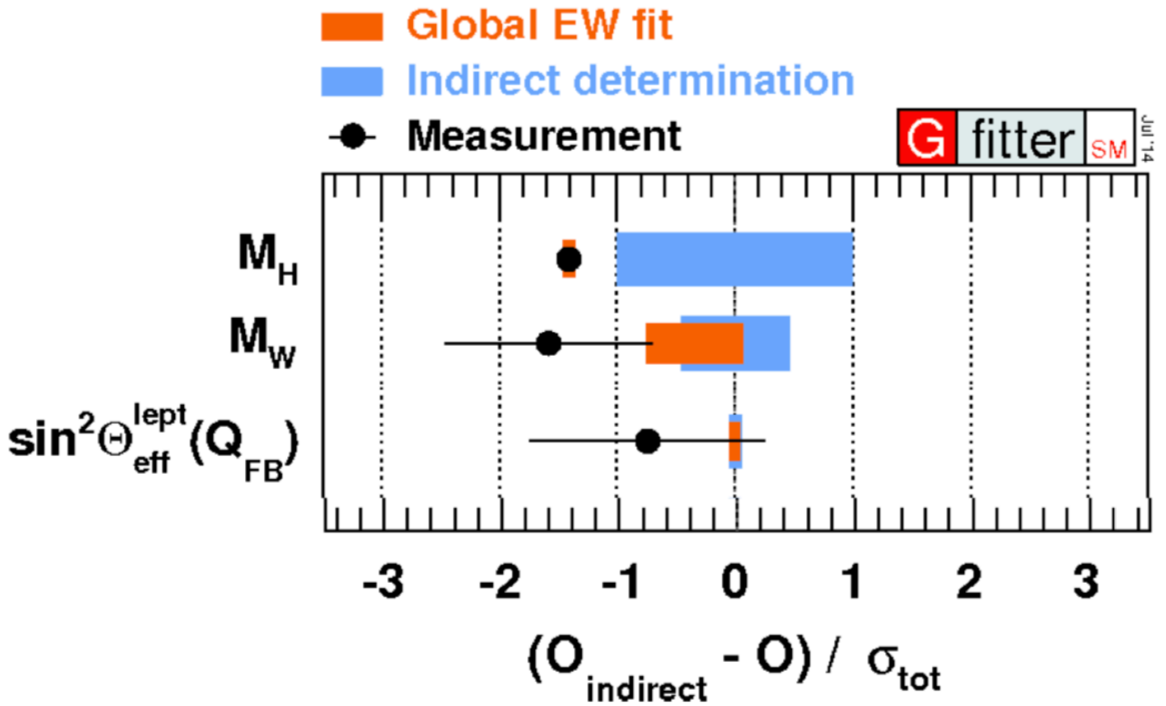
Total uncertainty
Statistical uncertainty
LEP Combination
Phys. Rept. 427 (2006) 257
CDF
Science 376 (2022) 170
LHCb Preliminary
LHCb-PAPER-2025-008
Electroweak Fit (J. de Blas *et al.*)
PRD 106 (2022) 033003
Direct Measurements
Indirect Determinations
91160
91180
91200
91220
m_Z [MeV]

WEAK MIXING ANGLE

- The measurement of $\sin^2\theta_W$ tests this relation: tree level, other EW parameters can be expressed as

$$\sin^2_{\rm eff}\,\theta_W \quad = \quad \left(1 - \frac{m_W^2}{m_Z^2}\right)\kappa$$

- We measure effective weak mixing angle (leptonic one) - absorb radiative corrections
  - It is proportional to the $\sin^2\theta_W$
- Indirect determination of m_W and $\sin^2\theta^{eff}_W$ more precise then the experimental measurement
- This call for a precise direct measurement
- Stringent test of the self consistency of the SM!



VECTOR BOSON PRODUCTION AND DECAY

- Powheg+Pythia8 MC for W and Z is reweighted to include HO QCD corrections, EW corrections, and according to measured distributions
  - Agreement to data improved
- Physics corrections to the final state distributions are based on the ansatz of the factorisation of the cross section

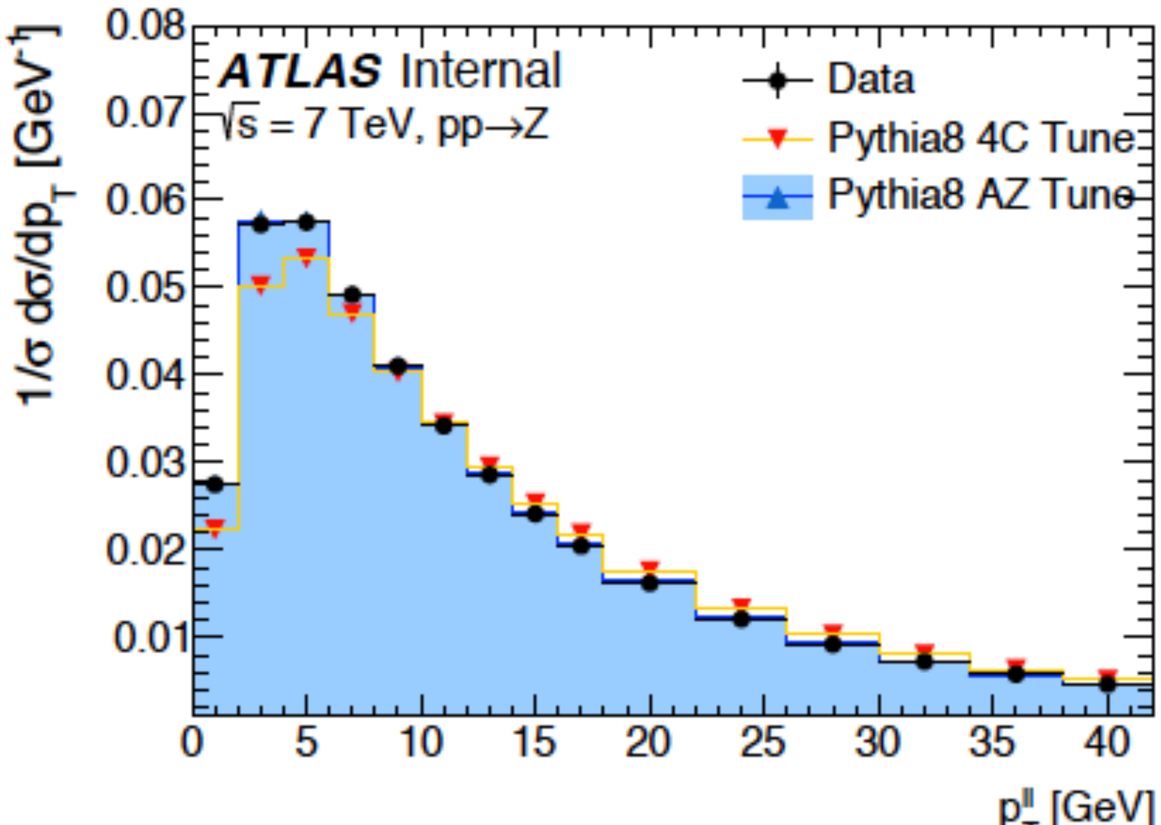
$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

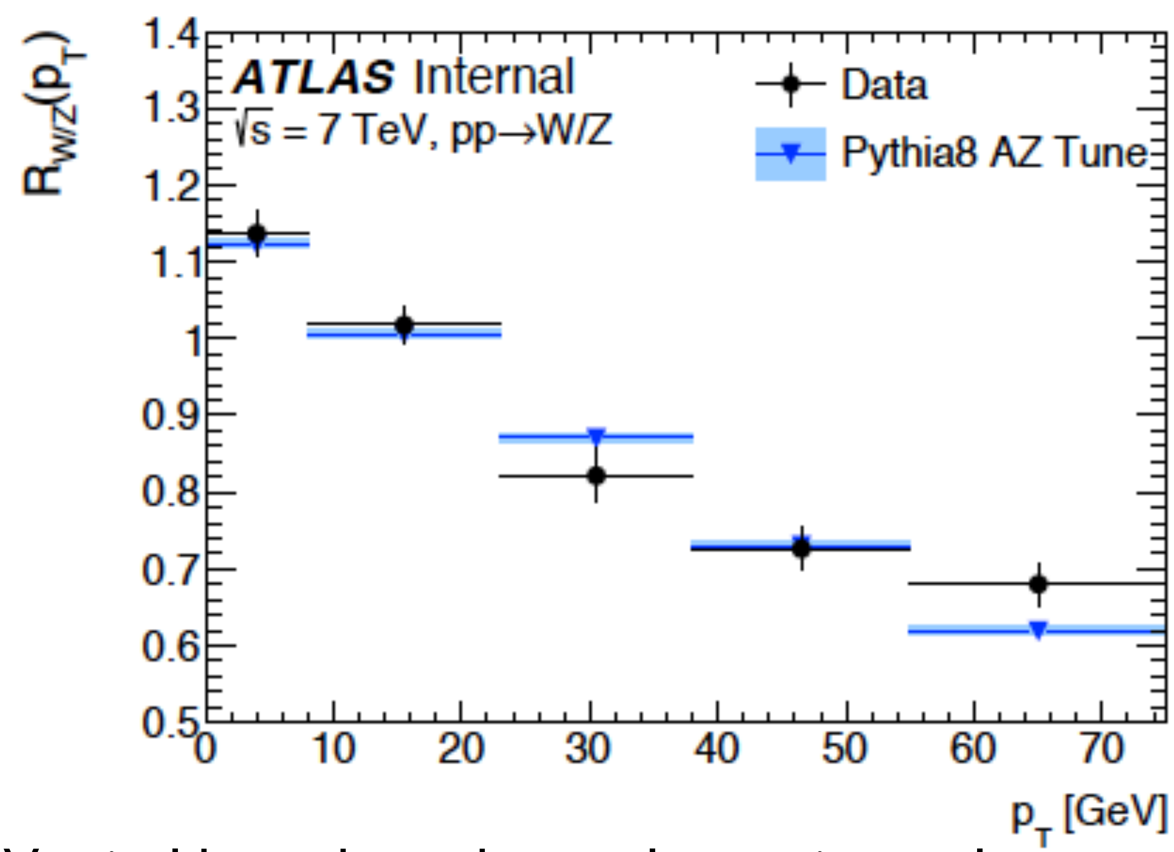
BW parametrisation (Z boson running α_{EM})	Pythia 8 Parton Shower	Perturbative QCD fixed order predictions (NNLO)

- Ancillary measurement of W and Z production used to validate and constrain the modelling
  - W&Z cross section, **arXiv: 1606.00689 [hep-ex], arXiv: 1211.6899 [hep-ex]. 1406.3660 [hep-ex] arXiv: 1108.6308 [hep-ex]**
- Model applied through event-by-event reweighting
  - y rwgt based on NNLO → p_T^W rwgt to Py8 AZ (at given y) → Ai rwgt: $w = \frac{1+\cos^2\theta + \sum_i A_i' P_i(\cos\theta,\phi)}{1+\cos^2\theta + \sum_i A_i P_i(\cos\theta,\phi)}$,
- Validity of the procedure is tested by comparing Z and W cross sections vs y_Z and lepton eta
  - The agreement between data and predictions yields **χ^2/dof=45/34**
- Validity of Ai is tested by comparing prediction with $\sqrt{s}$=8 TeV measurement

$P_T V$, V=Z,W

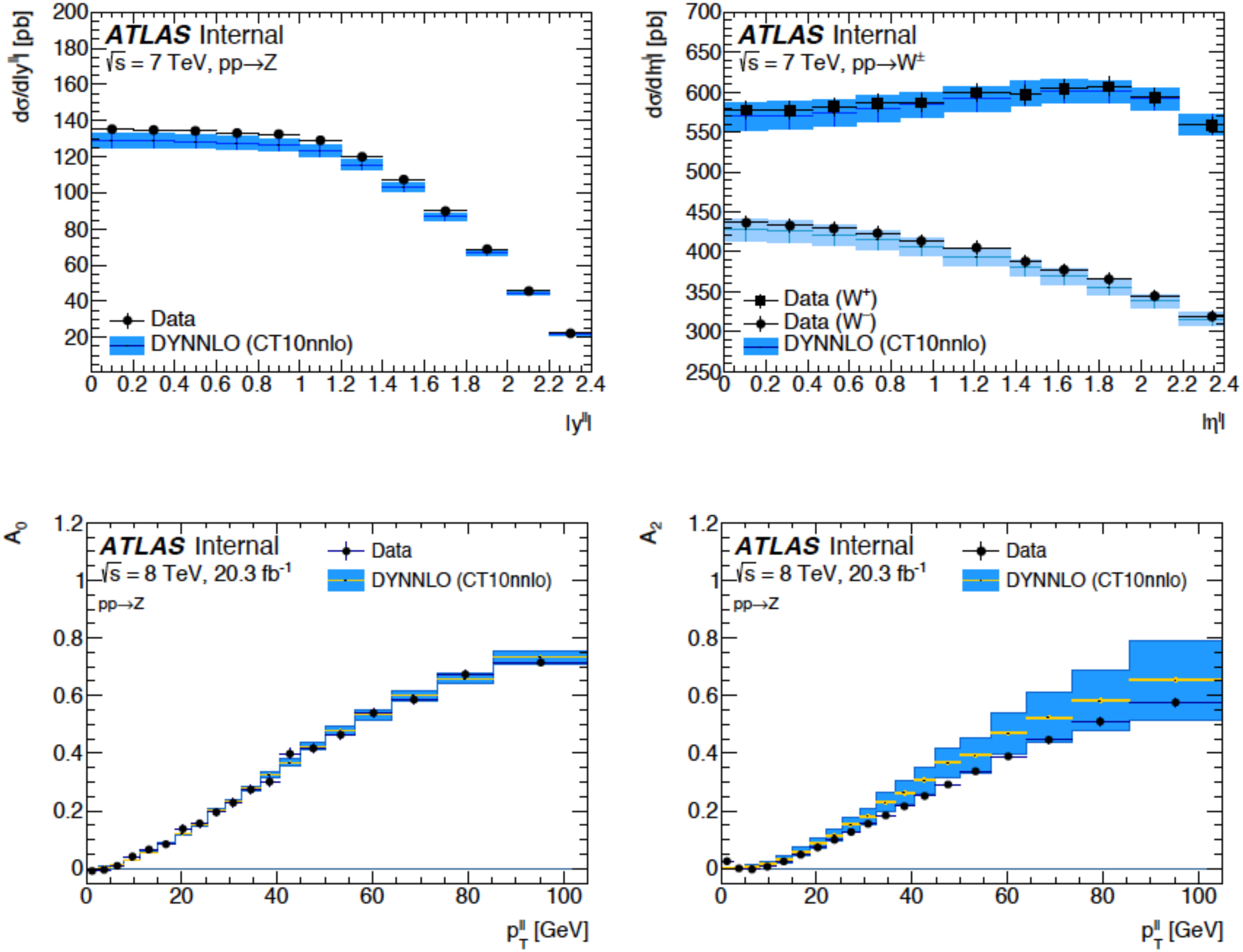
- Primary approach is to use the well-measured *Z* p_T and extrapolate to *W* p_T :uncertainties are on possible differences between *W* and *Z* : **$R_{W/Z}$ (p_T)**
- The optimal values QCD parameters in Pythia 8 from the ATLAS $p_T Z$ 7 TeV measurement
  - intrinsic p_T of the colliding partons, $\alpha_s(M_Z)$, ISR infrared cut-off = **AZ tune**
- W boson p_T cannot rely on the fixed-order perturbative QCD - large logs need to be resummed for low p_T region
  - Non-perturbative effects: Parton Shower or by analytical resummation
- P**redictions based on several state-of-the-art-programs (DYRES, RESBOS, Powheg MinLo) predicted harder value of R (wrt data) and are excluded by comparing $u_{||}$ distribution in *W* events, and discarded**





Vertical bars show the total experimental uncertainties.

QCD PREDICTIONS



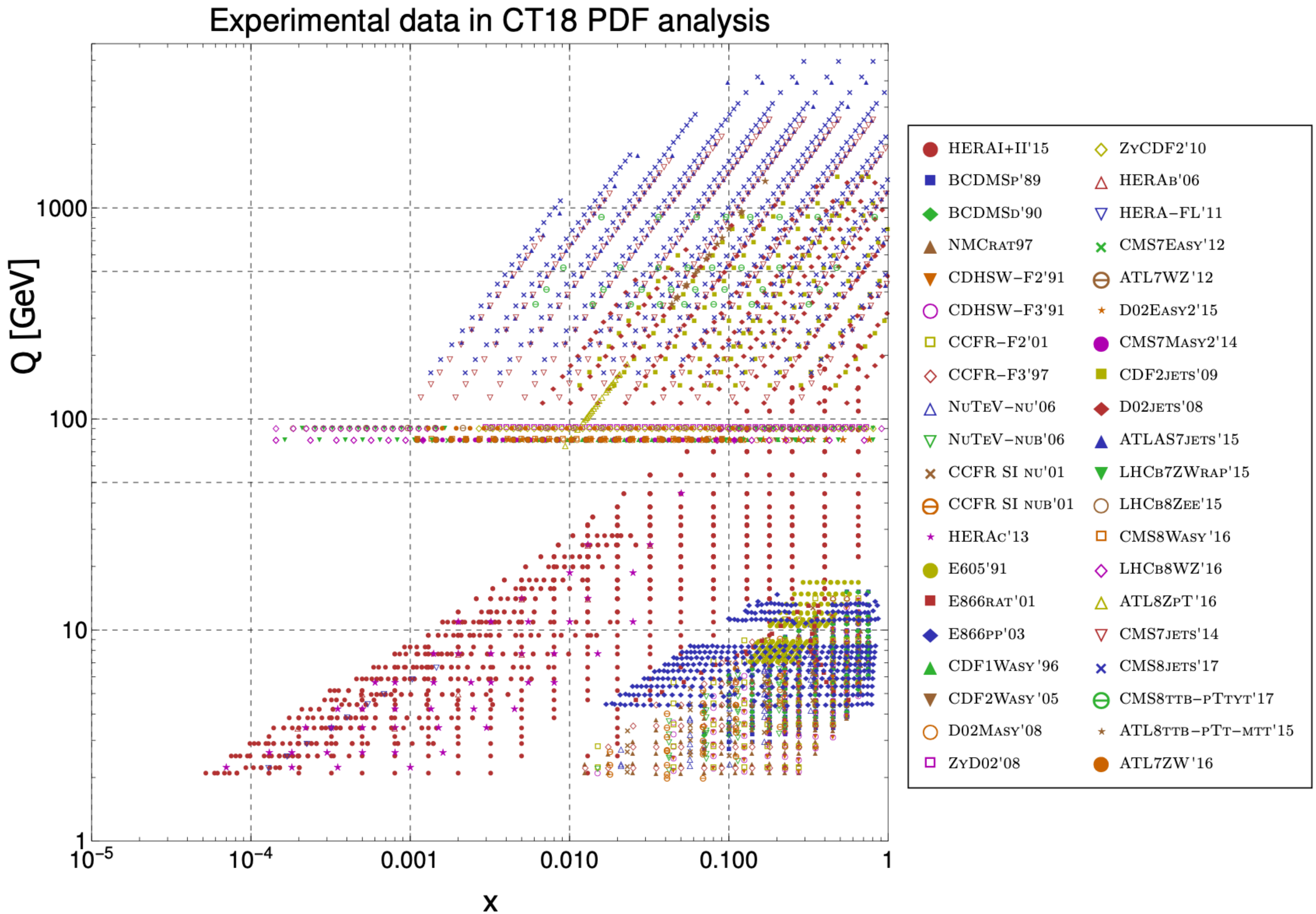
- dσ/dy and *Ai* are modelled with fixed-order perturbative QCD predictions at $O(\alpha^2 s)$
  - The study is performed using DYNNLO program with CT10nnlo PDF

PHYSICS MODELLING 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

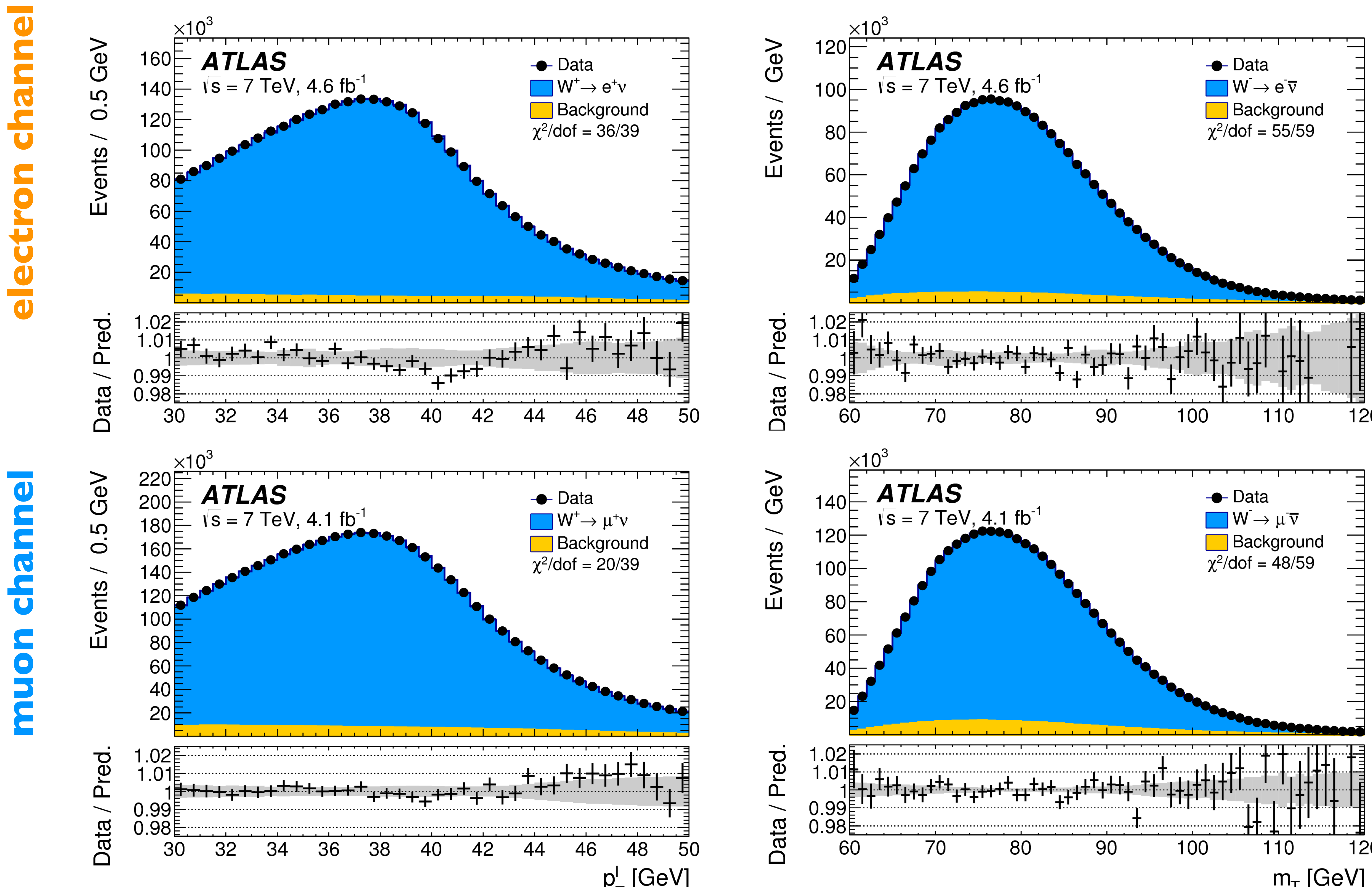
- The PDF uncertainties are the dominant uncertainties in the physics modelling.
- However they are strongly anticorrelated between W^+ *and* W^-, and a significant reduction is achieved from the combination of positive- and negative-charge categories.

CT18 PDFS

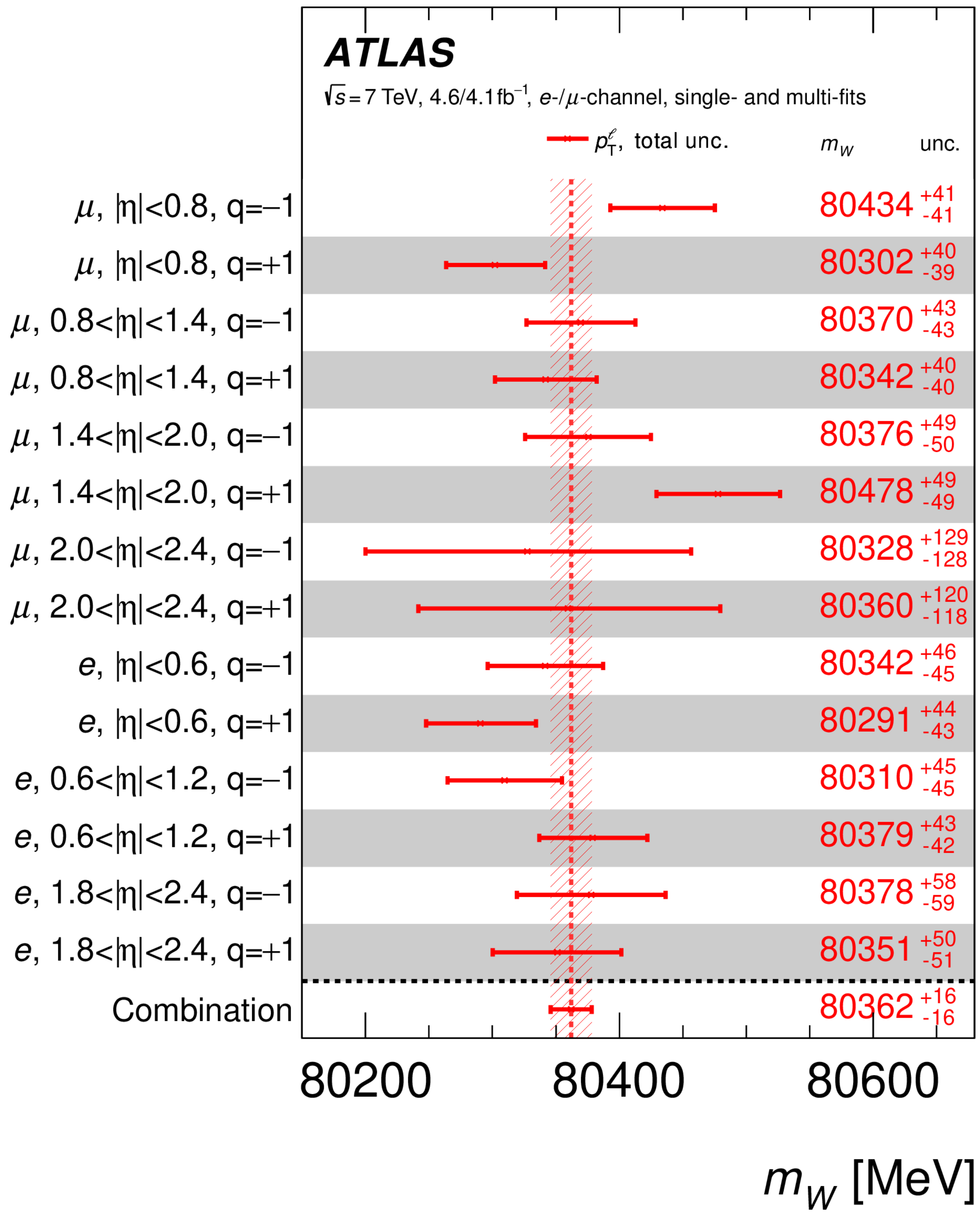


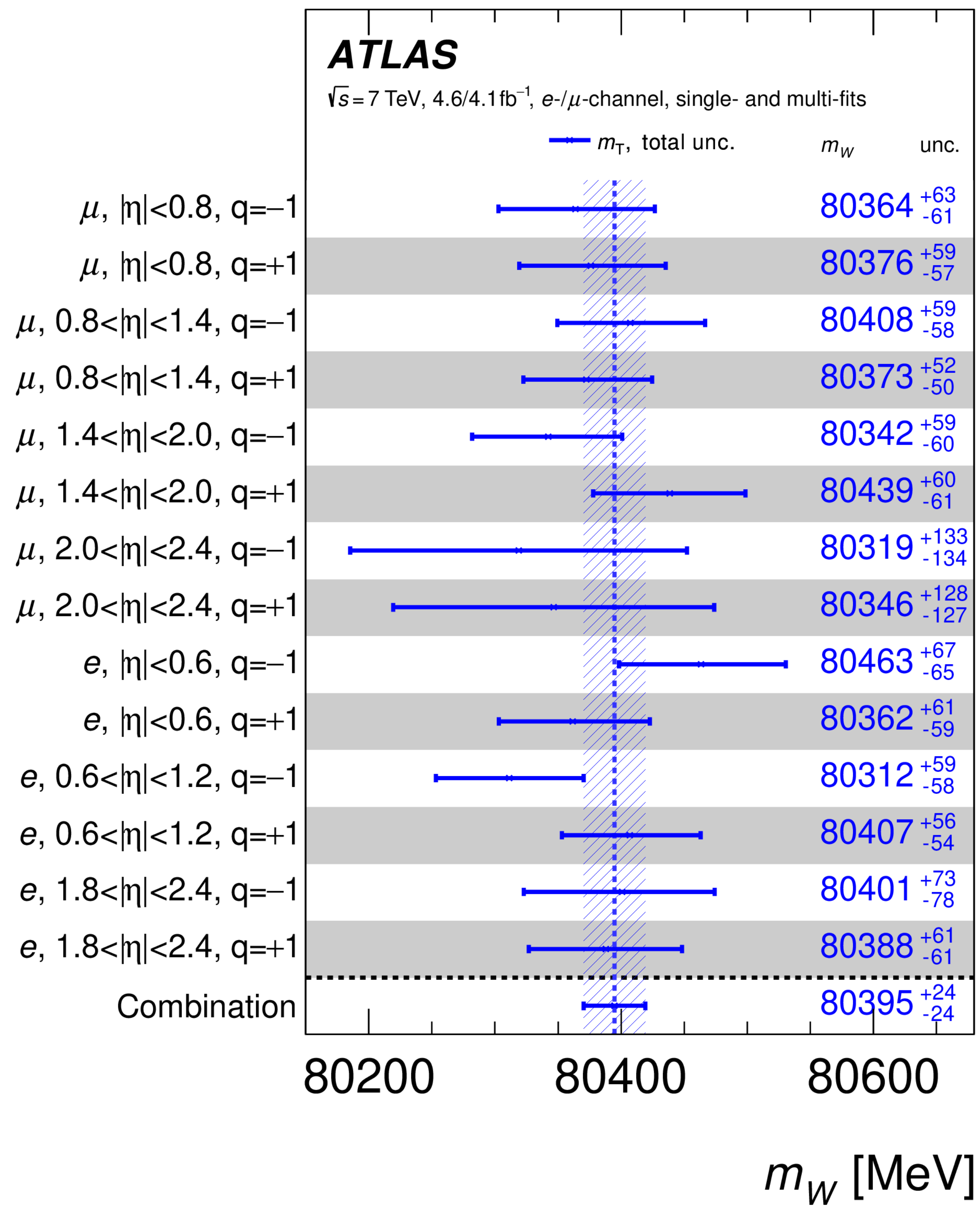
Experimental data in CT18 PDF analysis
Q [GeV]
x
1000
100
10
1
10^-5
10^-4
0.001
0.010
0.100
1
HERAI+II'15
BCDMSp'89
BCDMSd'90
NMCRat97
CDHSW-F2'91
CDHSW-F3'91
CCFR-F2'01
CCFR-F3'97
NuTeV-nu'06
NuTeV-nub'06
CCFR SI nu'01
CCFR SI nub'01
HERAc'13
E605'91
E866rat'01
E866pp'03
CDF1Wasy'96
CDF2Wasy'05
D02Masy'08
ZyD02'08
ZyCDF2'10
HERAb'06
HERA-FL'11
CMS7Easy'12
ATL7WZ'12
D02Easy2'15
CMS7Masy2'14
CDF2jets'09
D02jets'08
ATLAS7jets'15
LHCb7ZWrap'15
LHCb8Zee'15
CMS8Wasy'16
LHCb8WZ'16
ATL8ZpT'16
CMS7jets'14
CMS8jets'17
CMS8ttb-pTtyt'17
ATL8ttb-pTt-mtt'15
ATL7ZW'16

MASS SENSITIVE VARIABLES

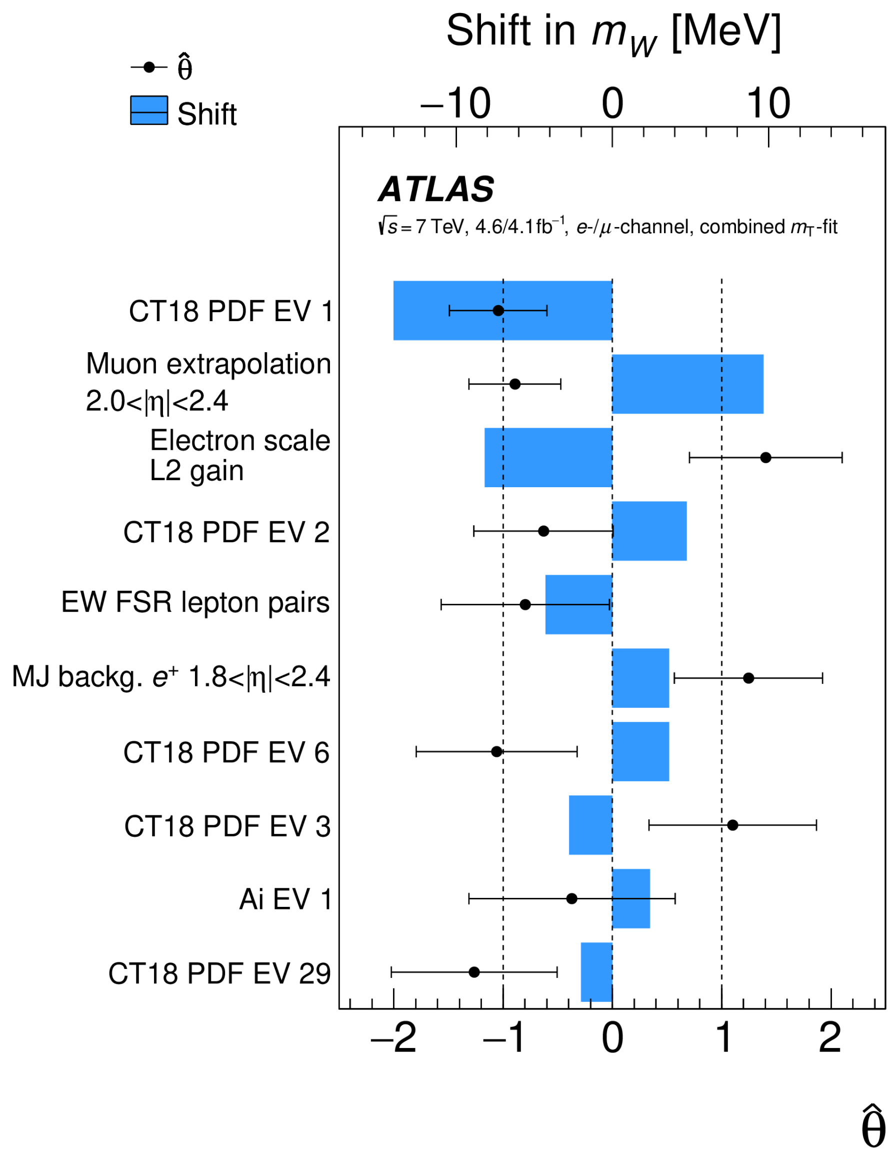


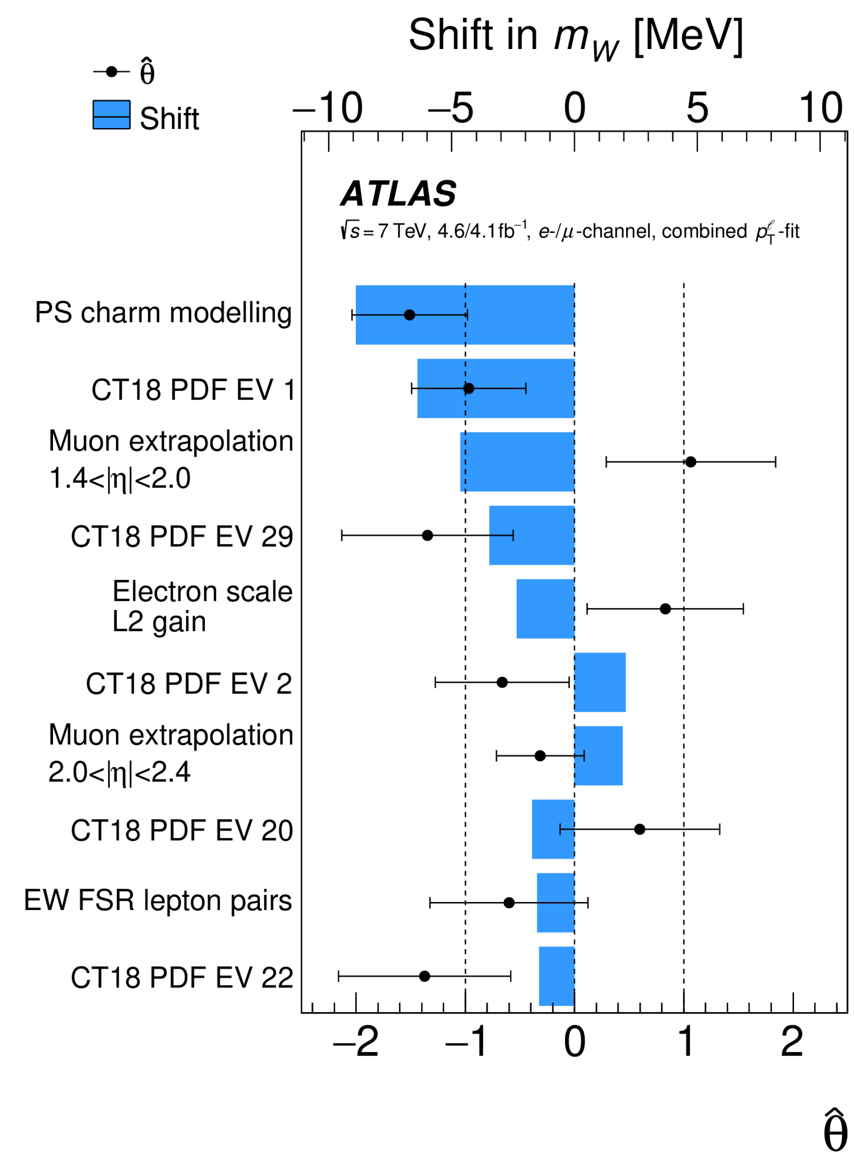
PLH FITS


ATLAS
√s = 7 TeV, 4.6/4.1 fb⁻¹, e-/μ-channel, single- and multi-fits
p_T^ℓ, total unc.
m_W
unc.
μ, |η|<0.8, q=–1
μ, |η|<0.8, q=+1
μ, 0.8<|η|<1.4, q=–1
μ, 0.8<|η|<1.4, q=+1
μ, 1.4<|η|<2.0, q=–1
μ, 1.4<|η|<2.0, q=+1
μ, 2.0<|η|<2.4, q=–1
μ, 2.0<|η|<2.4, q=+1
e, |η|<0.6, q=–1
e, |η|<0.6, q=+1
e, 0.6<|η|<1.2, q=–1
e, 0.6<|η|<1.2, q=+1
e, 1.8<|η|<2.4, q=–1
e, 1.8<|η|<2.4, q=+1
Combination
80434 +41 -41
80302 +40 -39
80370 +43 -43
80342 +40 -40
80376 +49 -50
80478 +49 -49
80328 +129 -128
80360 +120 -118
80342 +46 -45
80291 +44 -43
80310 +45 -45
80379 +43 -42
80378 +58 -59
80351 +50 -51
80362 +16 -16
80200
80400
80600
m_W [MeV]


ATLAS
√s = 7 TeV, 4.6/4.1 fb⁻¹, e-/μ-channel, single- and multi-fits
m_T, total unc.
m_W
unc.
μ, |η|<0.8, q=–1
μ, |η|<0.8, q=+1
μ, 0.8<|η|<1.4, q=–1
μ, 0.8<|η|<1.4, q=+1
μ, 1.4<|η|<2.0, q=–1
μ, 1.4<|η|<2.0, q=+1
μ, 2.0<|η|<2.4, q=–1
μ, 2.0<|η|<2.4, q=+1
e, |η|<0.6, q=–1
e, |η|<0.6, q=+1
e, 0.6<|η|<1.2, q=–1
e, 0.6<|η|<1.2, q=+1
e, 1.8<|η|<2.4, q=–1
e, 1.8<|η|<2.4, q=+1
Combination
80364 +63 -61
80376 +59 -57
80408 +59 -58
80373 +52 -50
80342 +59 -60
80439 +60 -61
80319 +133 -134
80346 +128 -127
80463 +67 -65
80362 +61 -59
80312 +59 -58
80407 +56 -54
80401 +73 -78
80388 +61 -61
80395 +24 -24
80200
80400
80600
m_W [MeV]

PLH FITS PULLS





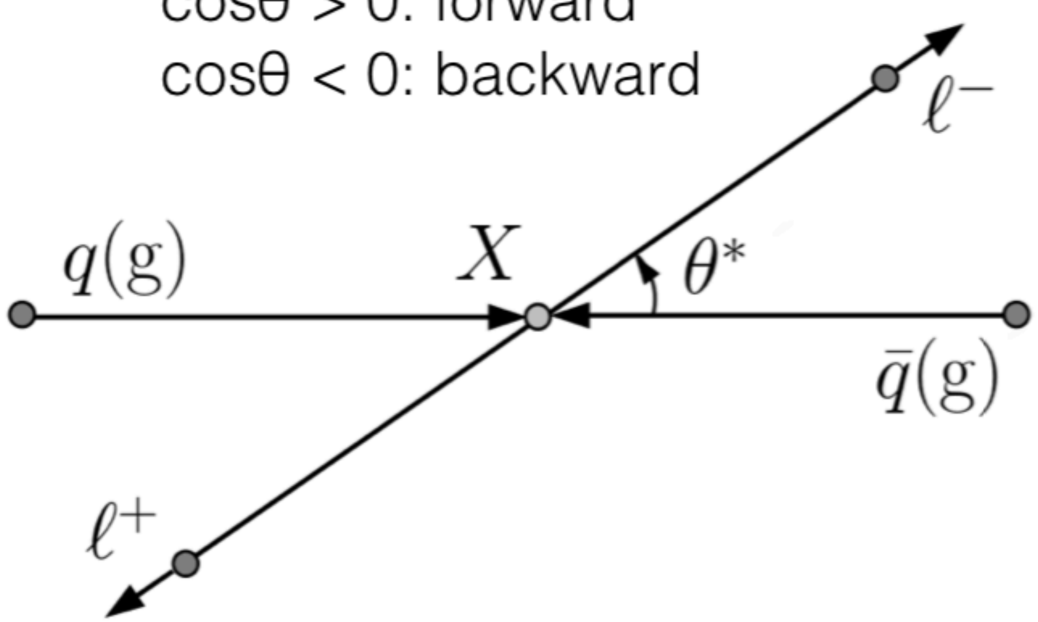
WEAK MIXING ANGLE METHODOLOGY

- The Drell-Yan production cross section as function of the scattering angle θ

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{4\pi\alpha^2}{3s}\left[\frac{3}{8}(A(1+\cos^2\theta) + B\cos\theta\right]$$

- Linear term gives rise to the non-vanishing Forward-Backward asymmetry
- Since the asymmetry depends directly on the vector and axial-vector couplings, it is sensitive to
  the weak mixing angle which relates the two.

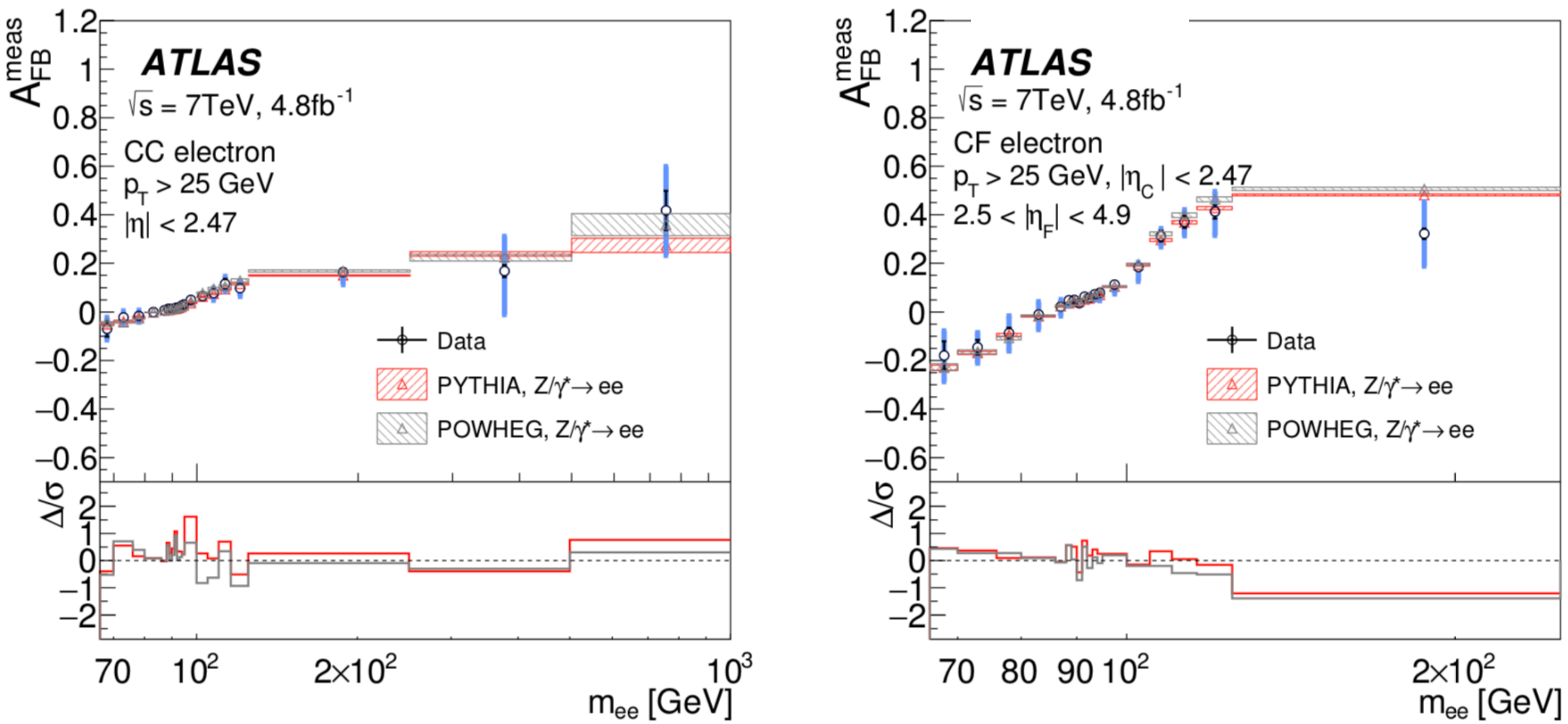
cosθ > 0: forward
cosθ < 0: backward



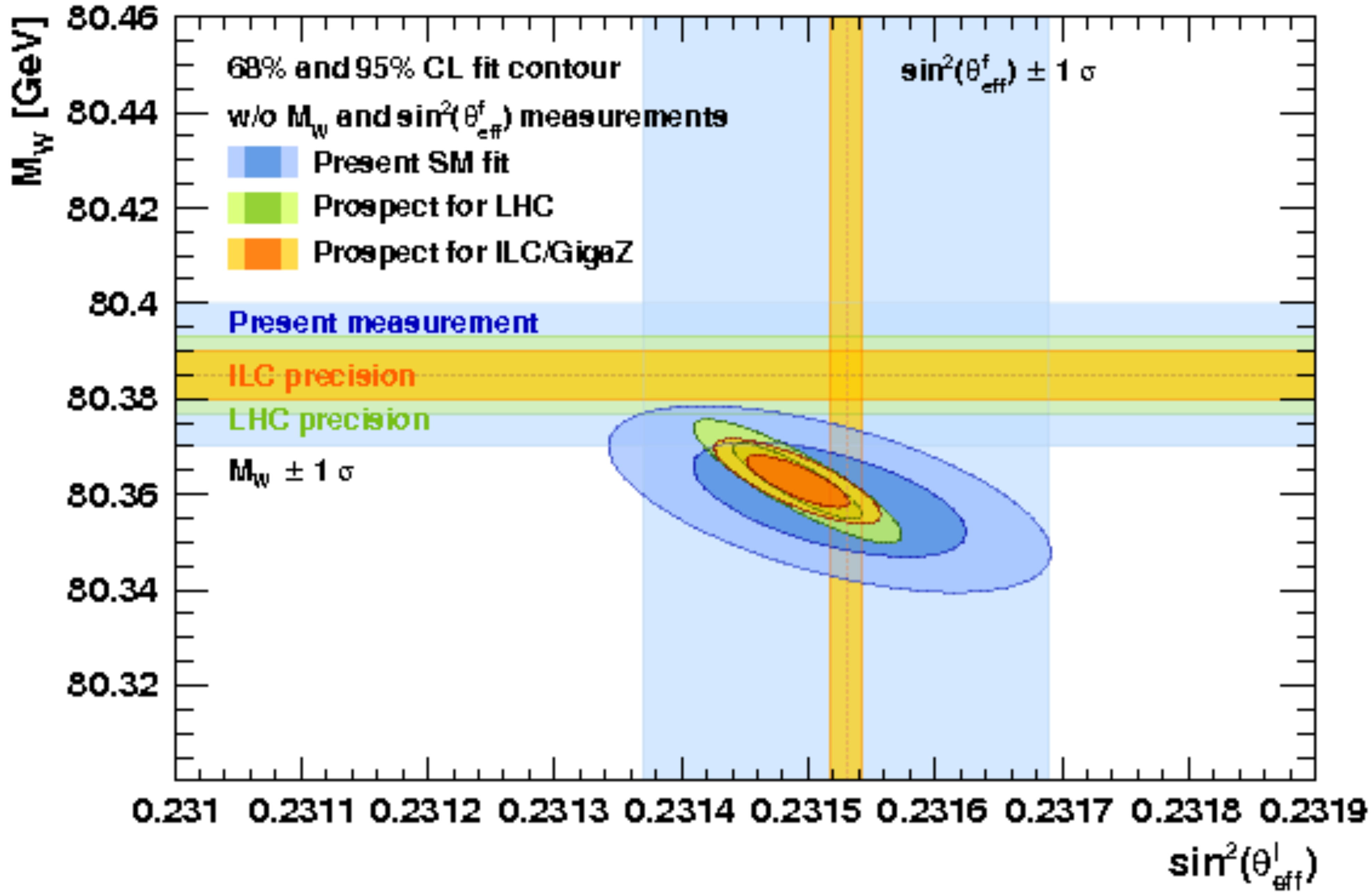
$$A_{\mathrm{FB}} = \frac{N_{\cos\theta^*_{\mathrm{CS}}\geq 0} - N_{\cos\theta^*_{\mathrm{CS}}<0}}{N_{\cos\theta^*_{\mathrm{CS}}\geq 0} + N_{\cos\theta^*_{\mathrm{CS}}<0}}.$$

COMPLICATION AT THE LHC

- There is a complication at the LHC: as this is pp collider we don't know what is te direction of the antiquark
- This is called *dilution* and it is incorporated in *our simulation* (MC modelling)
  - But of course with uncertainty!
- Dilution is smaller if we go more forward
- HL-LHC - we extend our detector more forced so we measure we higher precision



PROSPECTS FOR WEAK MIXING ANGLE



- With HL-LHC upgrade, and installation of new detector we expect signifiernt improvement
  - **LEP precisions (20 x 10^-5) is achiavable**

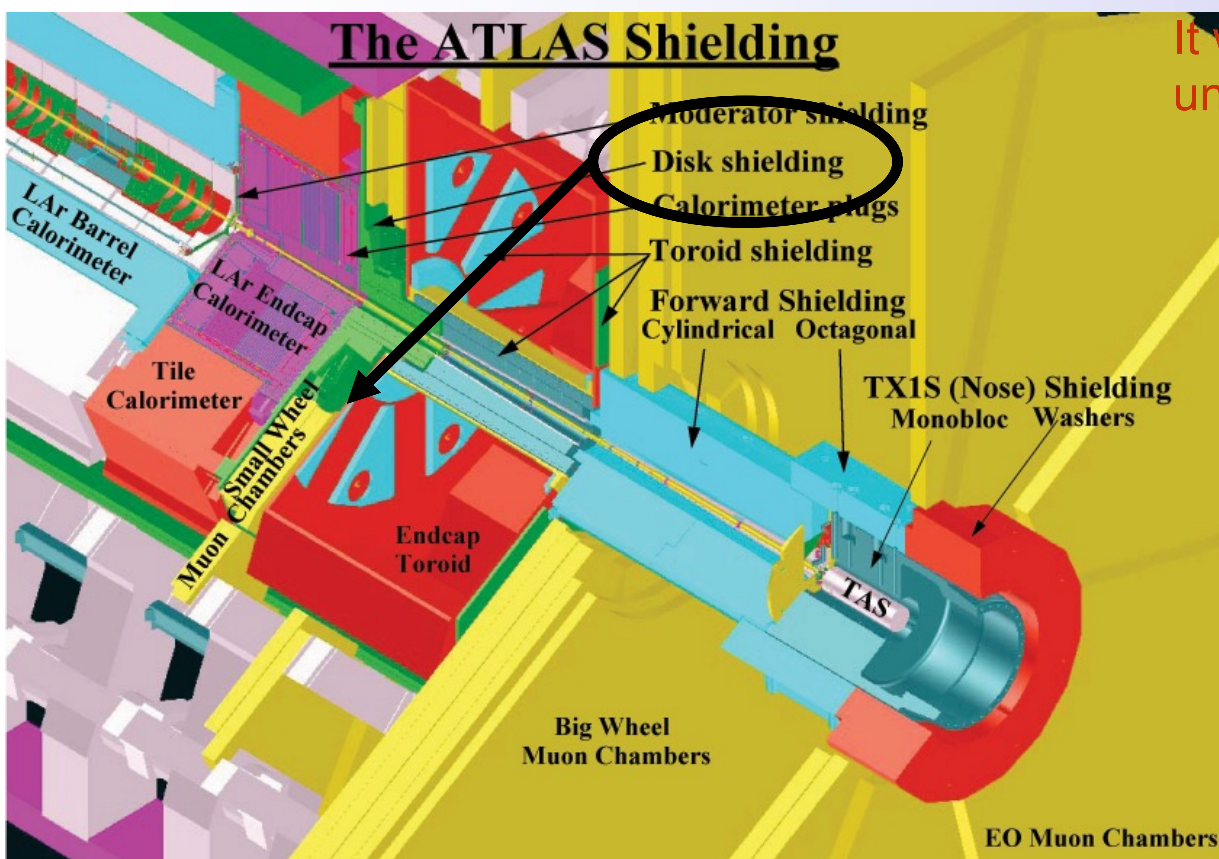
Hardware Contribution

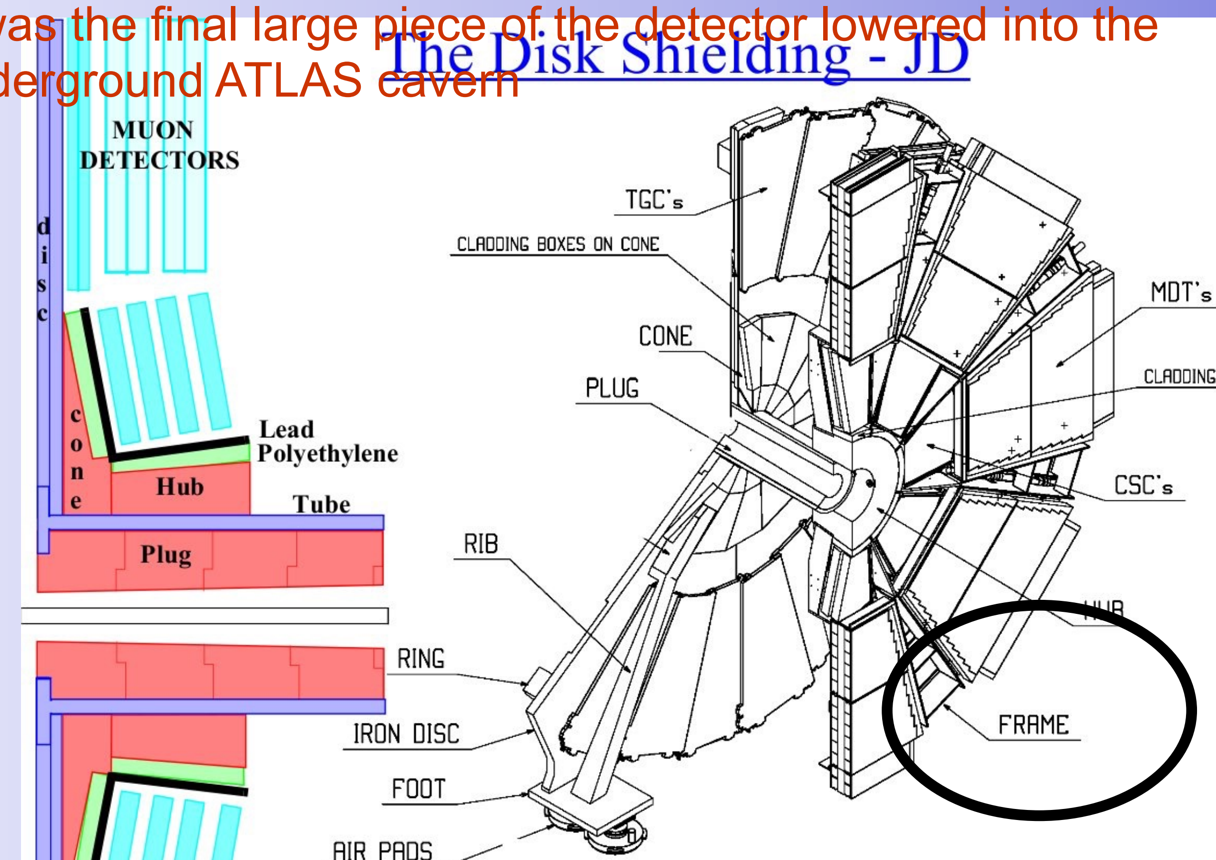
- IPB's in-kind contribution to the Shielding System are the *Disk Shielding* (JD) and *A-frame supports* for the forward shielding (JF).

- Two stainless steel shielding disks, 87 tons each, were produced by Lola Corporation, Železnik, Serbia. The disks and supports (produced by Kryooprema, Belgrade) were transported to CERN in December 2004, and successfully installed. The last peace was installed in February 2008.

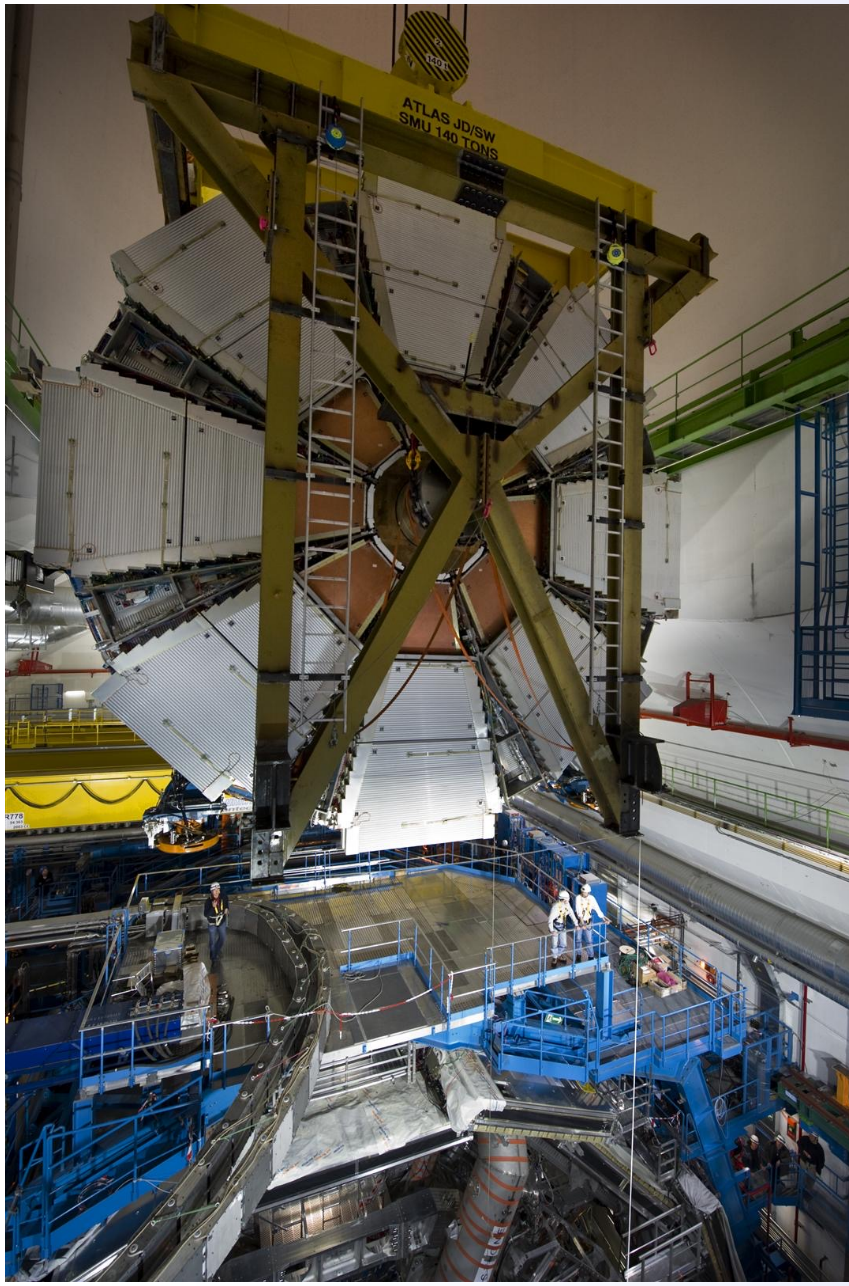
- Together with forward muon chambers, shielding disks make the part of the detector called the *Small Wheel*.

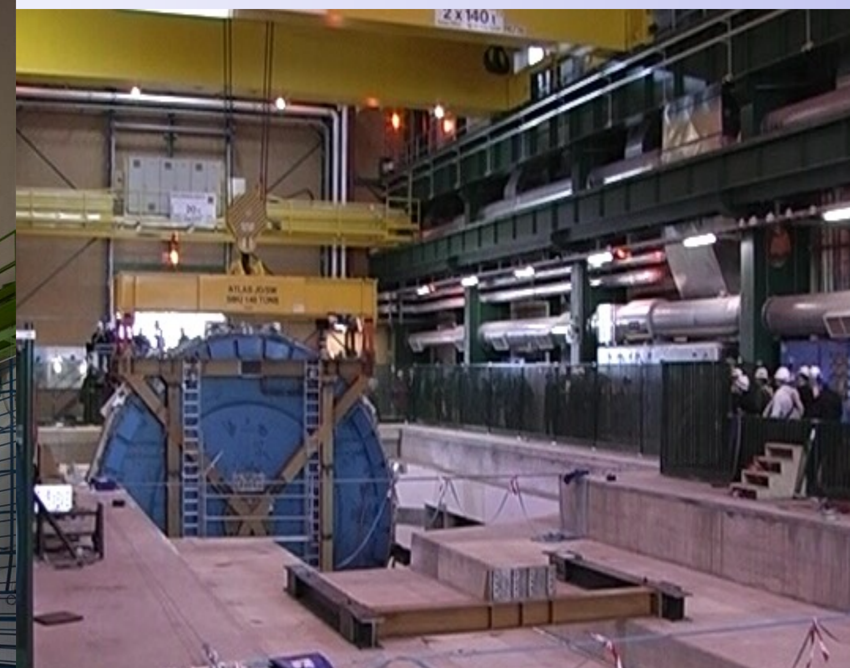
The shielding disks are a part of the ATLAS muon spectrometer known as the “small wheels which were assembled on the surface and then transported slowly to the ATLAS cavern at Point 1. It was the final large piece of the detector lowered into the underground ATLAS cavern

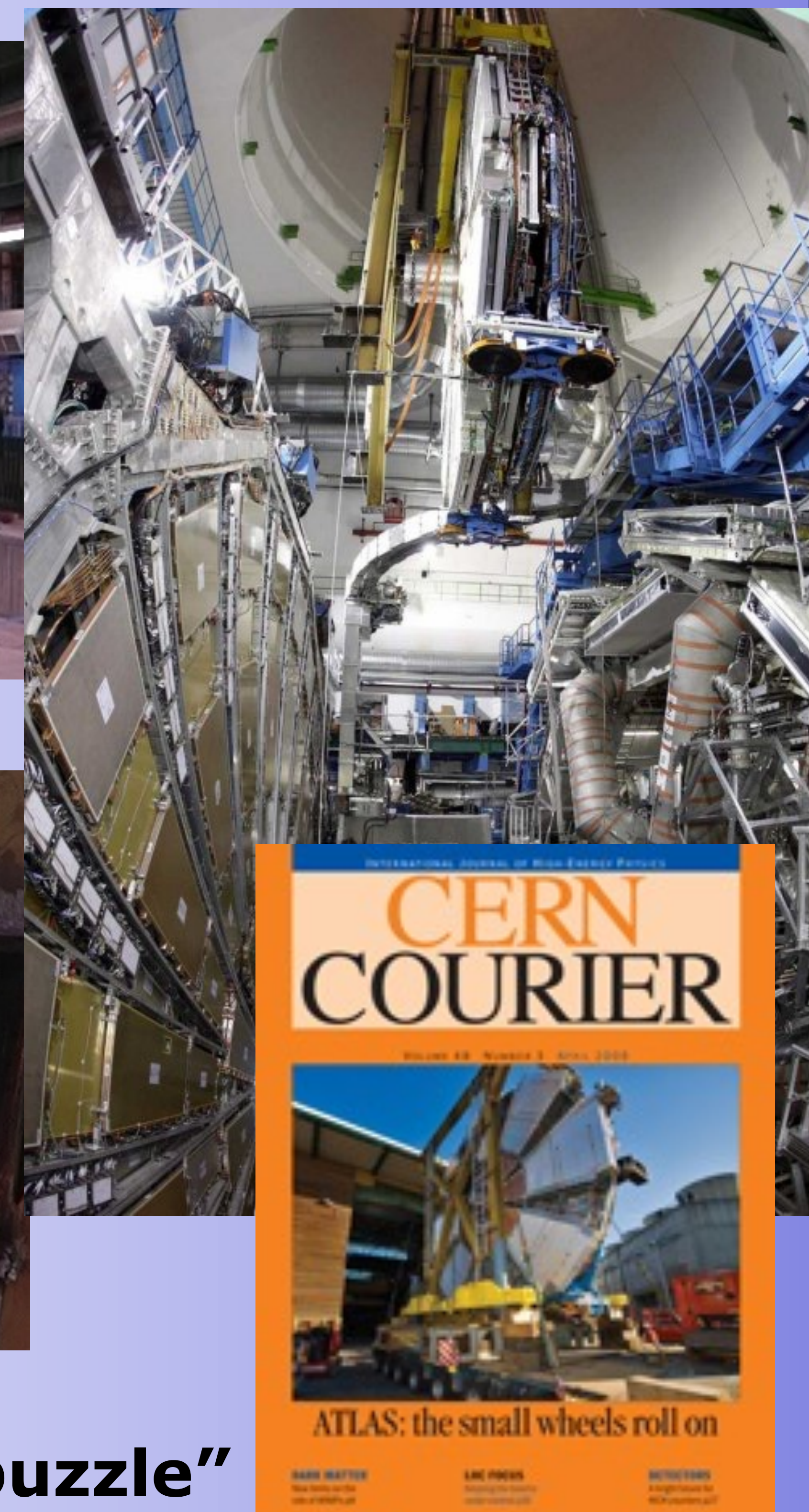




Hardware Contribution: Lowering of the Small Wheel to the ATLAS cavern







April 2008: "ATLAS puts last piece in puzzle"