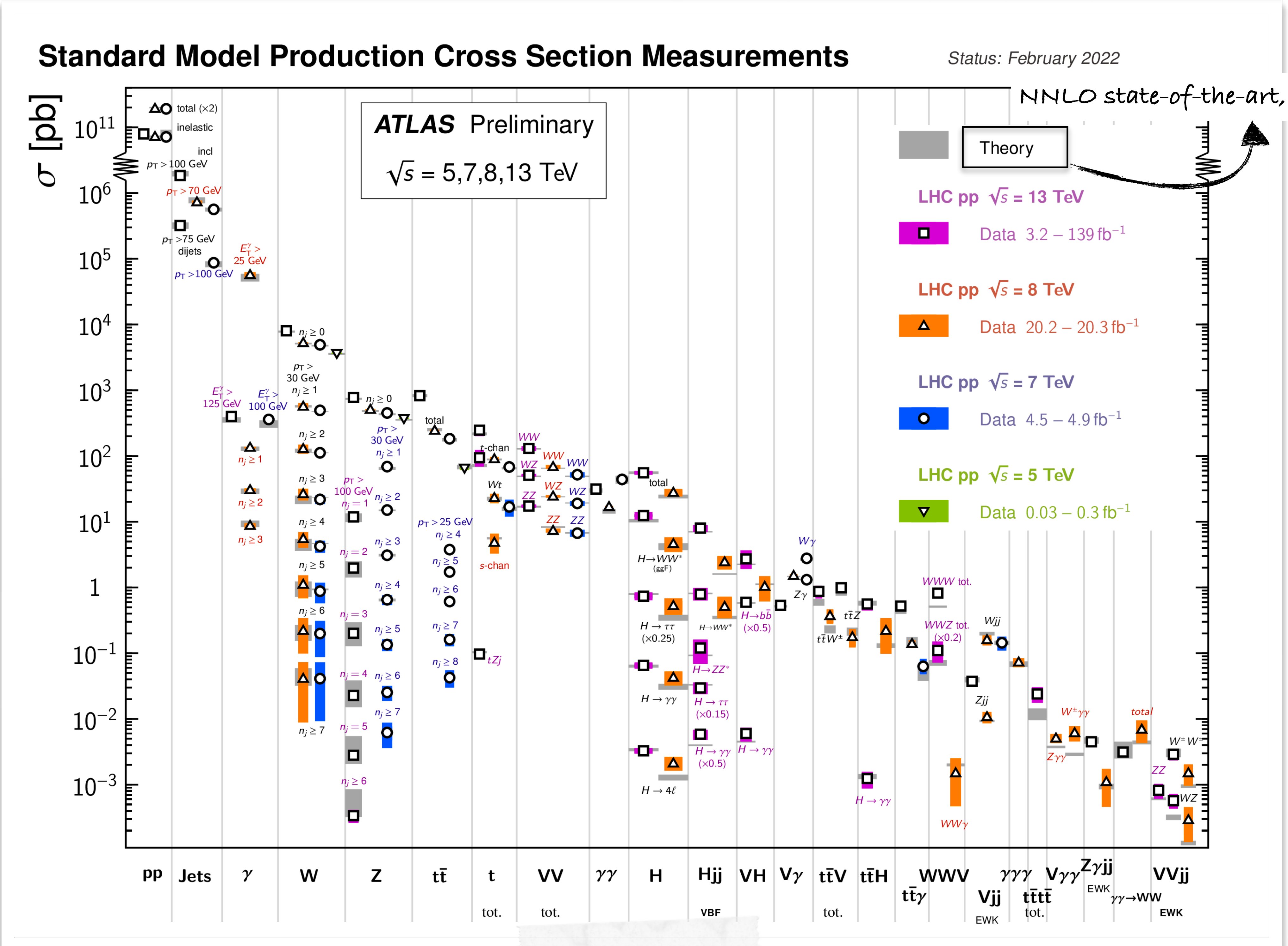
How to precisely measure the W boson properties: The most recent ATLAS results

- *Improved W boson Mass Measurement using √s = 7 TeV Proton-Proton Collisions with the ATLAS Detector*
  ATLAS-CONF-2023-004 (Briefing W-Mass-Measurement)
- *Precise measurements of W and Z transverse momentum spectra with the ATLAS detector at √s = 5.02 TeV and 13 TeV*
  ATLAS-CONF-2023-028/ (Briefing WZ-properties-milestone)

LHC Seminar - ATLAS - July 11

L. Aperio Bella on behalf of the ATLAS Collaboration

The SM of particle physics @LHC



NNLO state-of-the-art, rising to N3LO

Some (not so-obvious) observations:

A. Theory agrees with measurements across wide range of processes and cross sections ...

B. Often data precision challenges the theory predictions...

40 years from the W and Z discovery

20 Jan 1983 UA1 seminar on W discovery; corresponding UA2 seminar (similarly packed) on 21 Jan 1983

4 July 2012 seminars: Higgs boson discovery by ATLAS and CMS

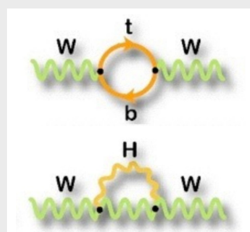
40 years after their discovery the **W** and **Z** bosons play still a central role in the LHC physic program:

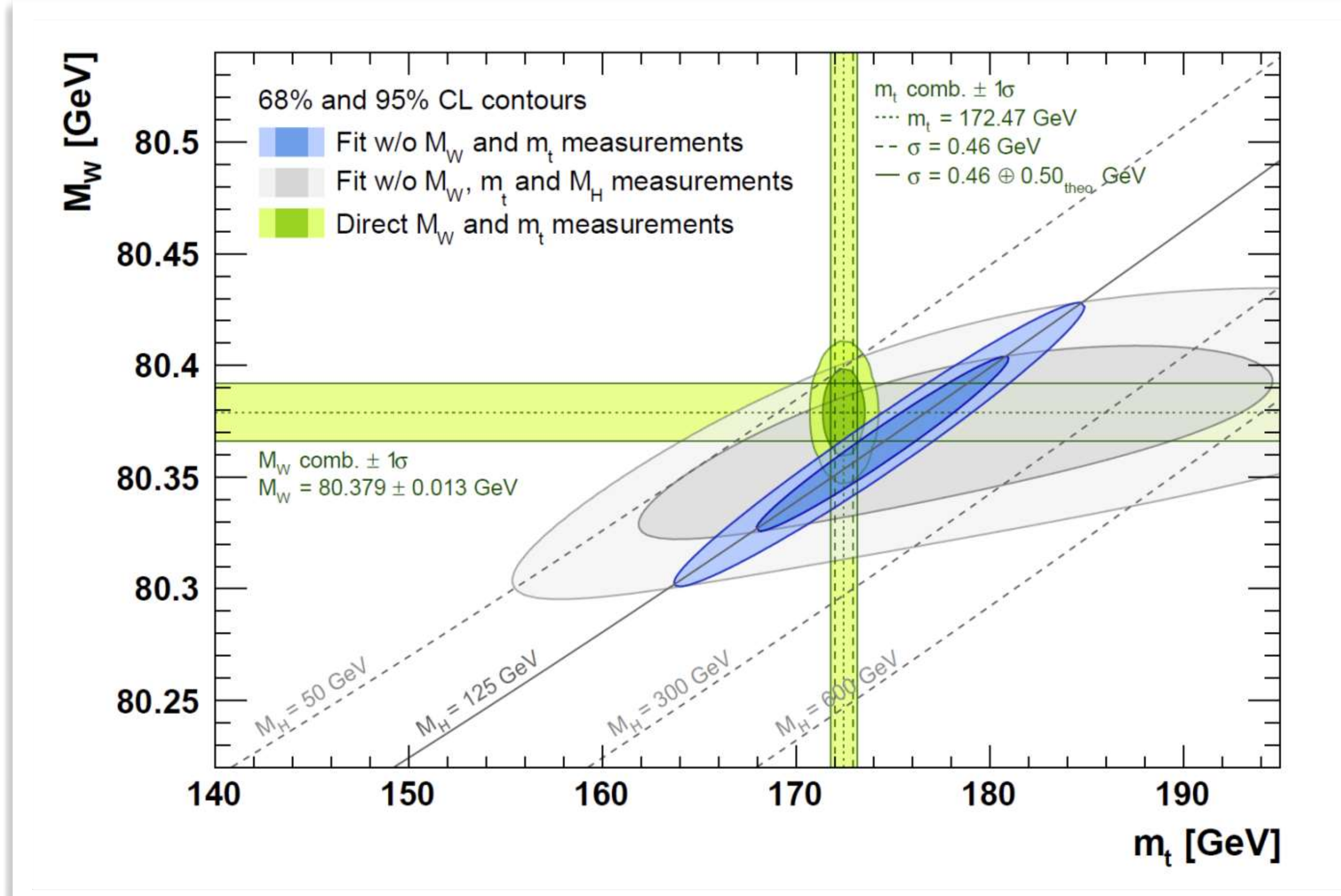
- Their **clean signatures** allow to search for/discover new processes and particles
- They provide standard candles to **calibrate the detector** performance
- Their properties and couplings with other particles allows to **test the Standard Model**

The EW sector: m_t m_W and m_H

$$M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\,\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$

In SM, Δr reflects loop corrections and depends on m_t^2 and $\ln(m_H)$





- The m_W relation together with $\sin^2\vartheta^{eff}_W$ and g^V, $g^{A\text{-}V}$ couplings represent a powerful test of SM:
  - The **global EW fit** allowed to constrain the masses of the top quark and Higgs boson before their discovery
  - While $\mathbf{m_H}$ is sufficiently well known (δm_H ~ 0.2 GeV), also improving the precision on $\mathbf{m_t}$ has little impact on precision of global EW fit (δm_t ~0.5/0.4 GeV fit precision 5-6 times worse than that of direct measurement)
  - Both m_W and $\sin^2\vartheta^{eff}_W$ are more **precisely** determined by SM fit then experimentally…

The EW sector: m_t m_W and m_H

$$M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\,\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$

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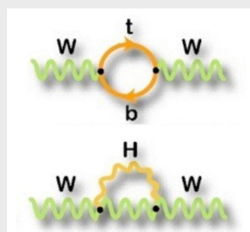
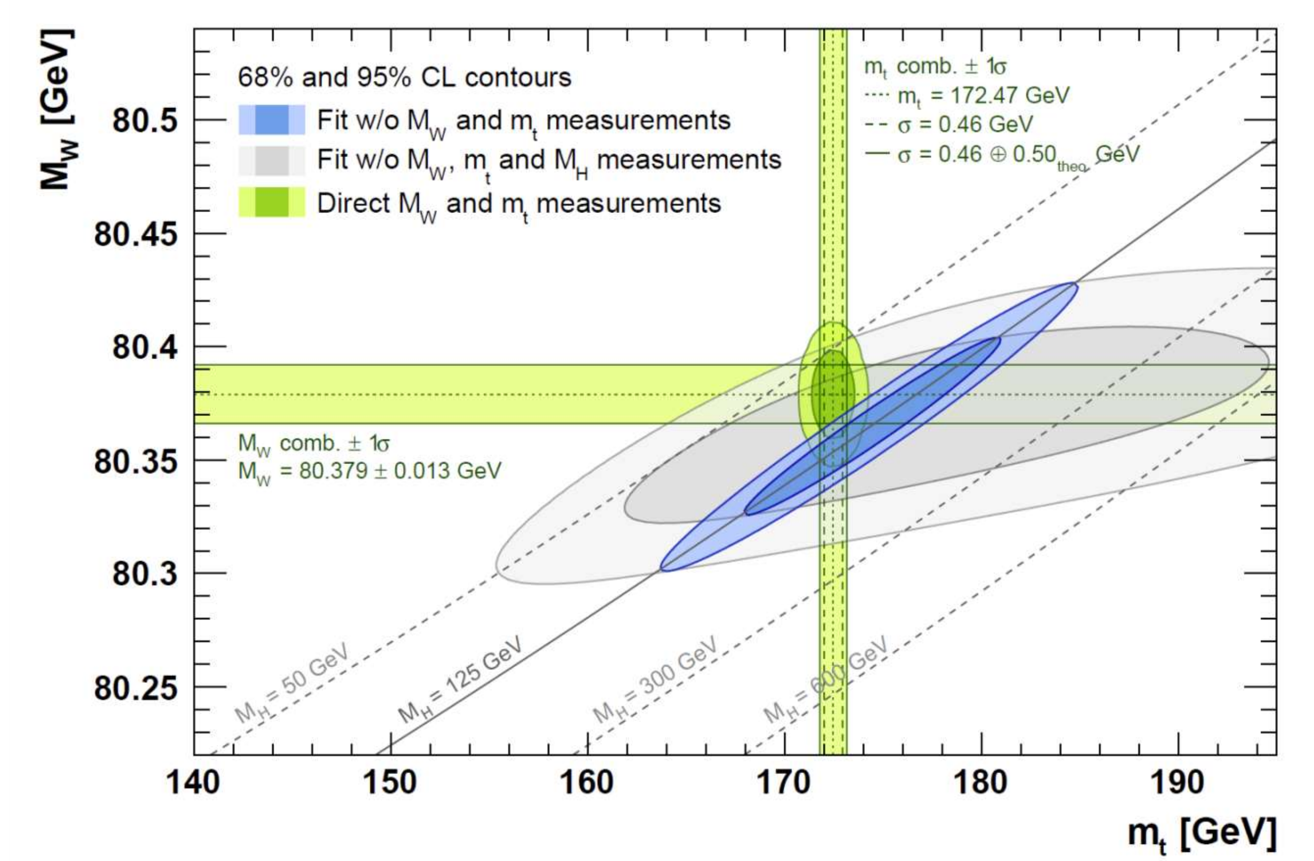




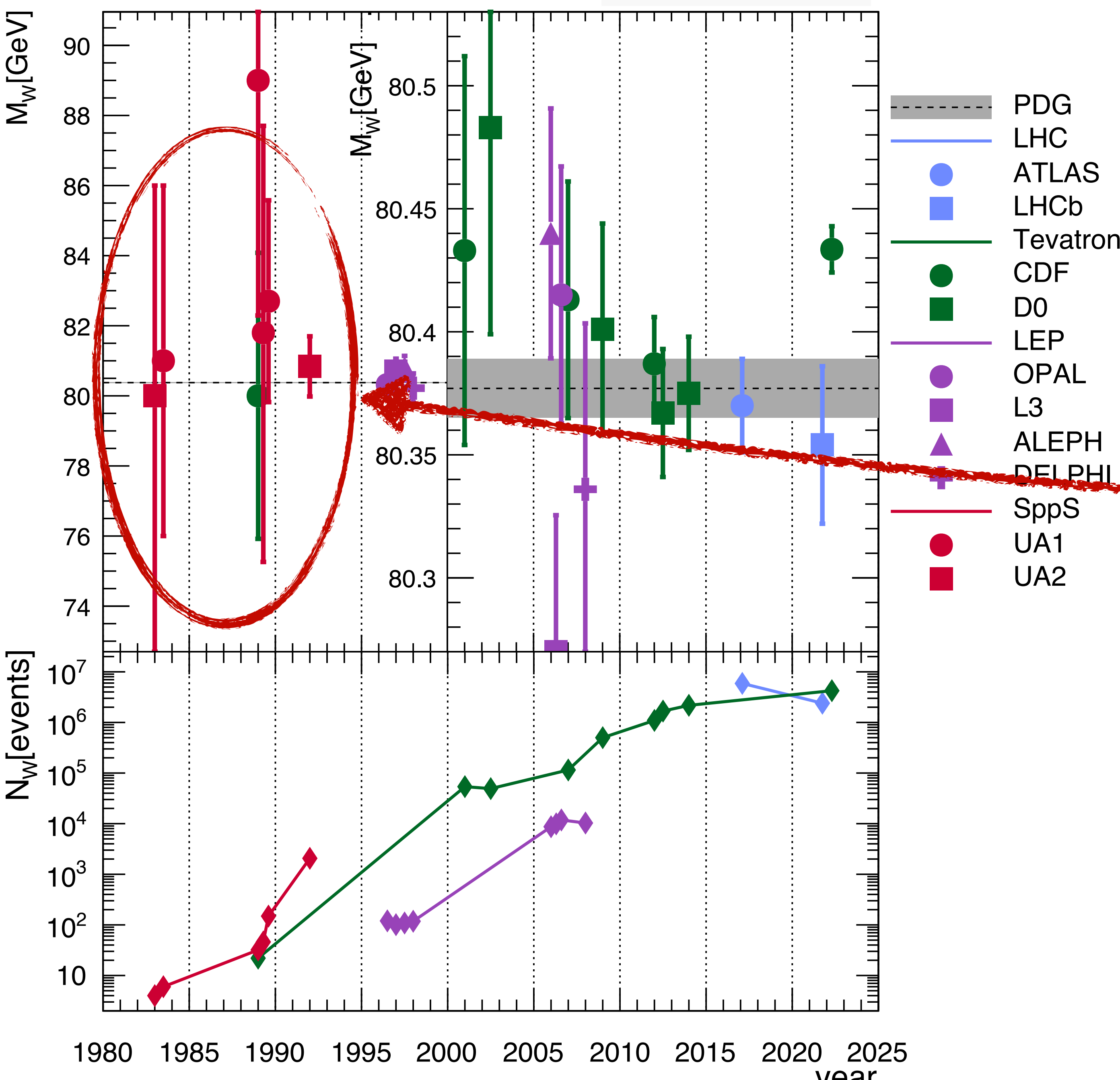
from SM EW-fit

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

40 years of measurements

reading PDG live

credit to S. Camarda



very first **UA1** measurement $m_W = 81 \pm 5$ GeV

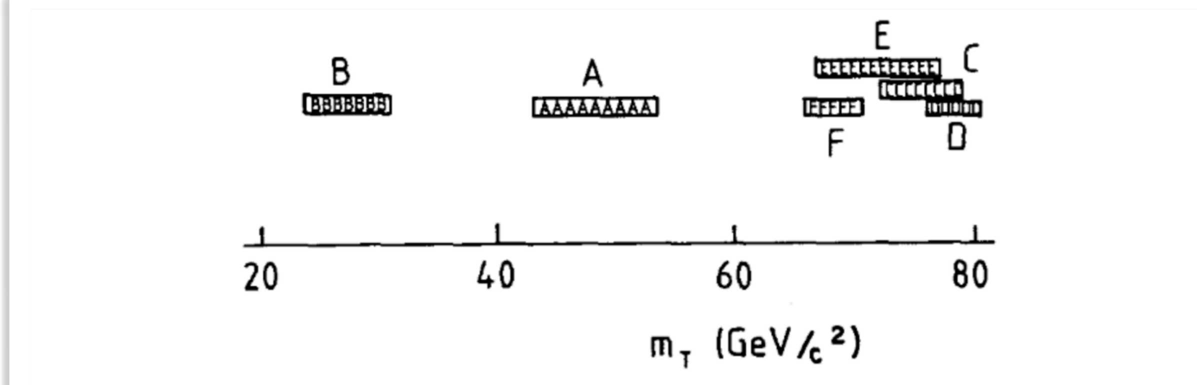
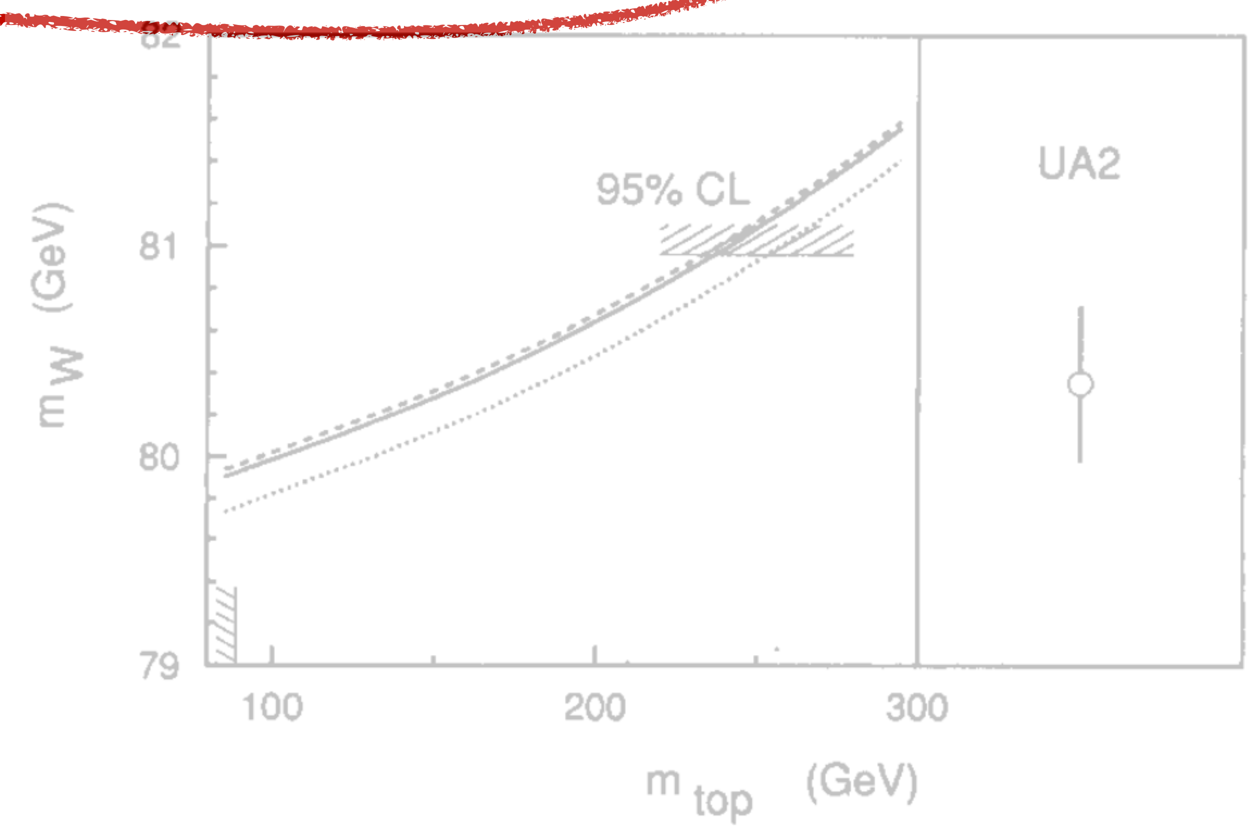


Figure 1: The transverse mass m_T of the first six candidate W events recorded by UA1 [6], labeled A-F, with the horizontal error bar indicating the precision of the m_T measurement for each event.



40 years of measurements

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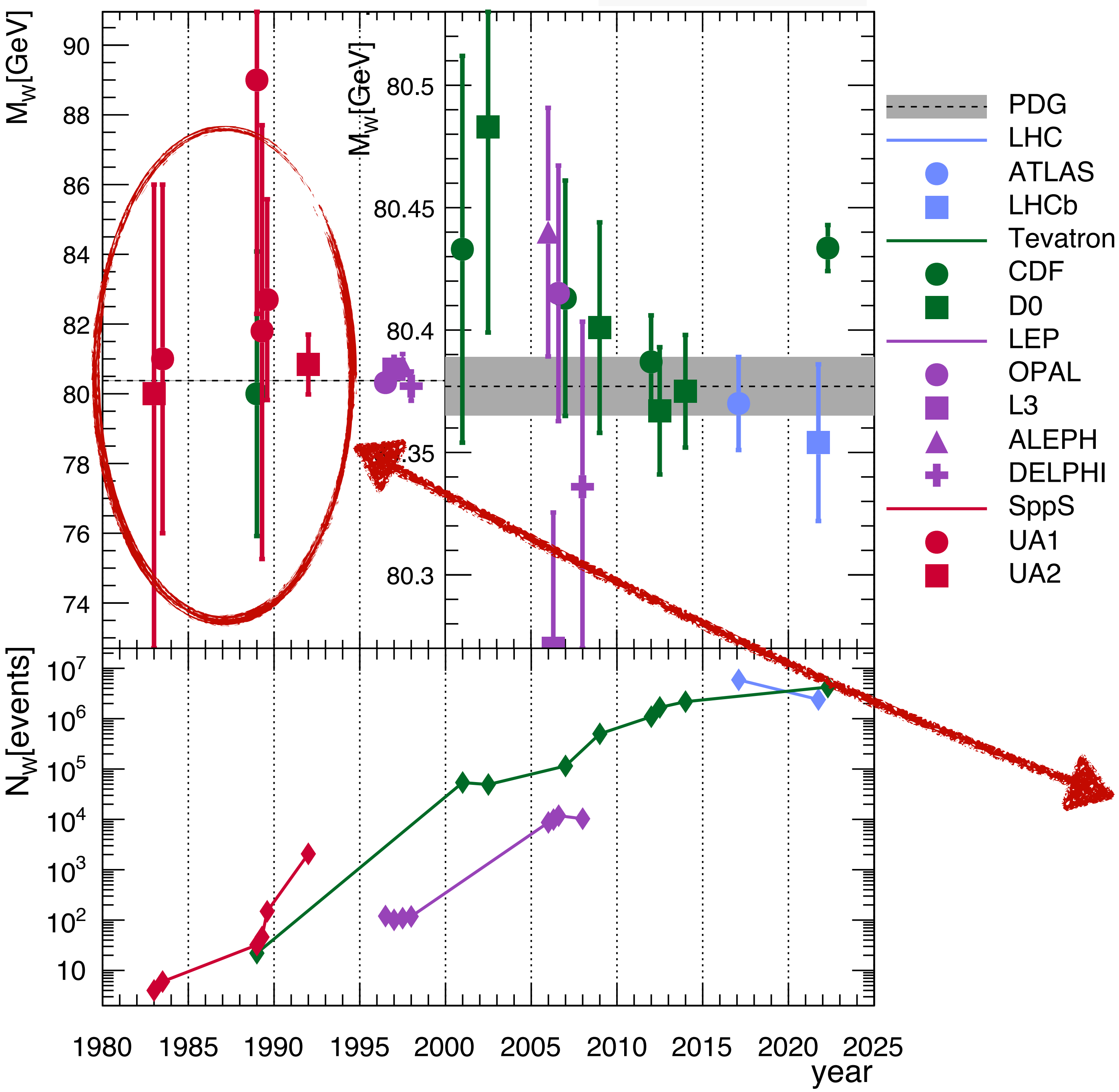

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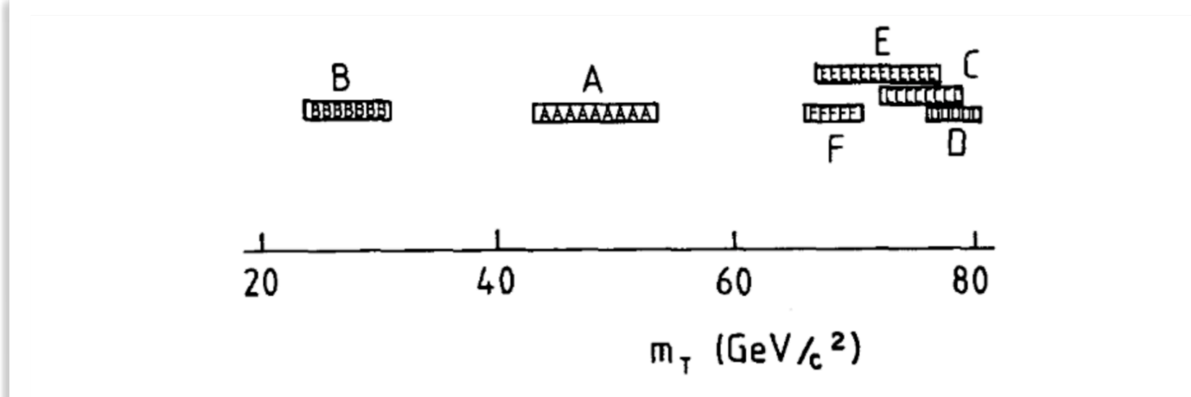
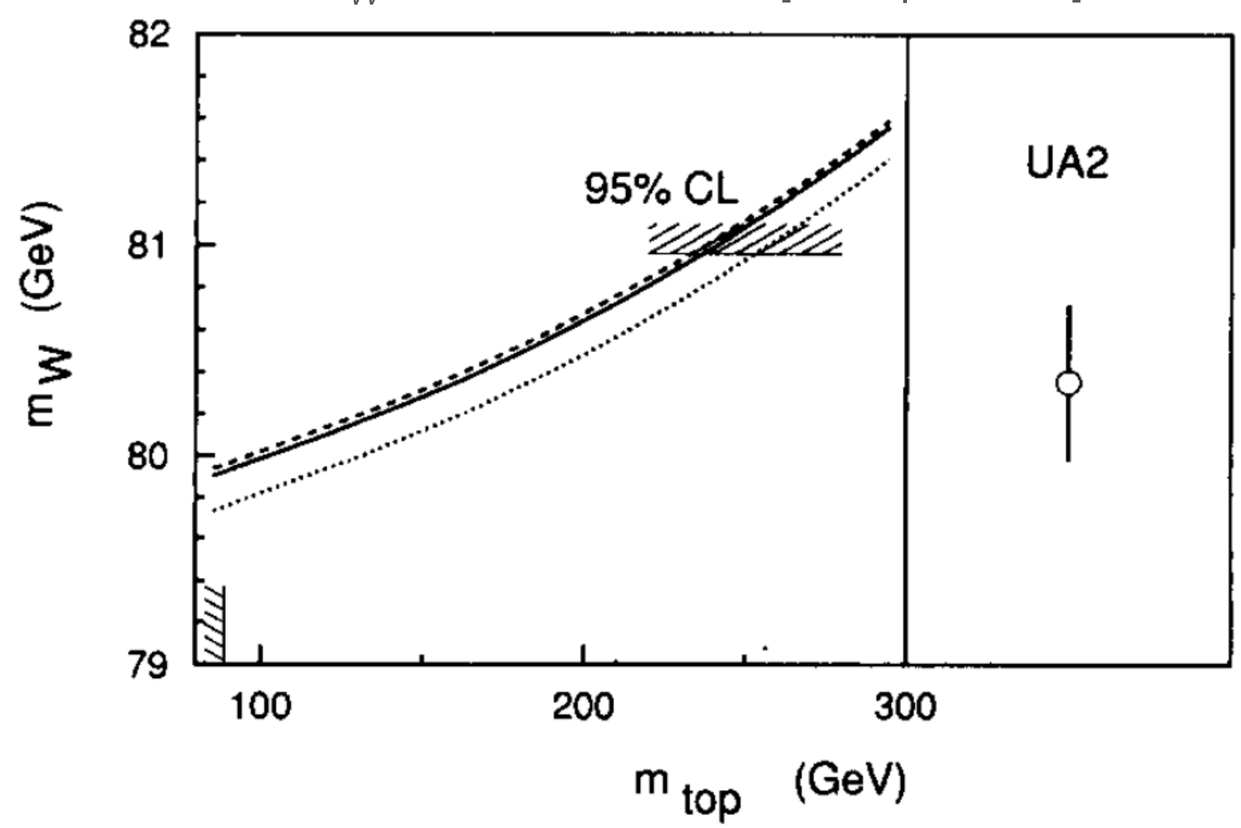


Figure 1: The transverse mass m_T of the first six candidate W events recorded by UA1 [6], labeled A-F, with the horizontal error bar indicating the precision of the m_T measurement for each event.

10 years later the best **UA2** measurement using LEP Zmass measurement

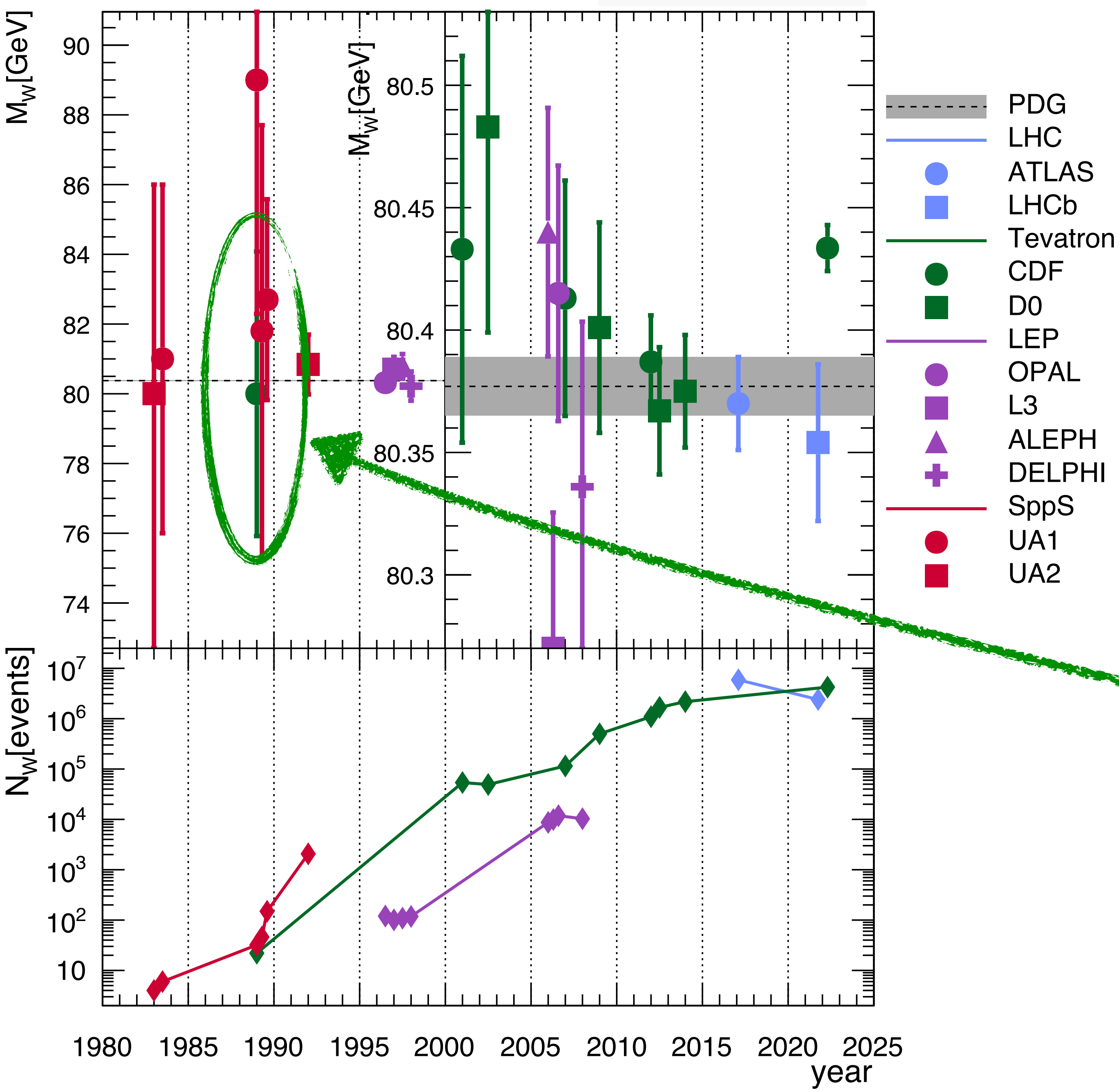
$m_W = 80.35 \pm 0.37$ GeV [0.5% precision]



40 years of measurements

[reading](#) [PDG live](#)

credit to S. Camarda



very first UA1 measurement m_W = 81 ± 5 GeV. 10 years later the best **UA2** measurement m_W = 80.79 ± 0.37 GeV [0.5% precision]

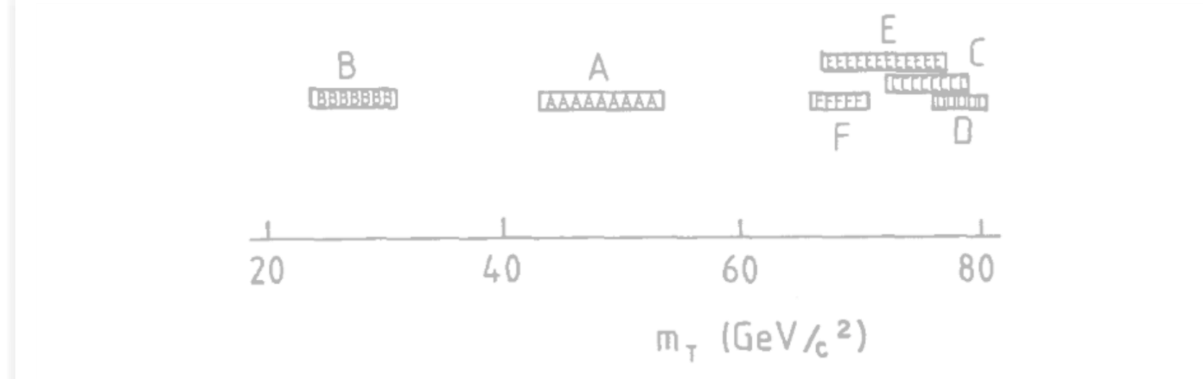


Figure 1: The transverse mass m_T of the first six candidate W events recorded by UA1 [6], labeled A-F, with the horizontal error bar indicating the precision of the m_T measurement for each event.

the first Tevatron measurement

CDF m_W 80.0 ± 4.1 GeV

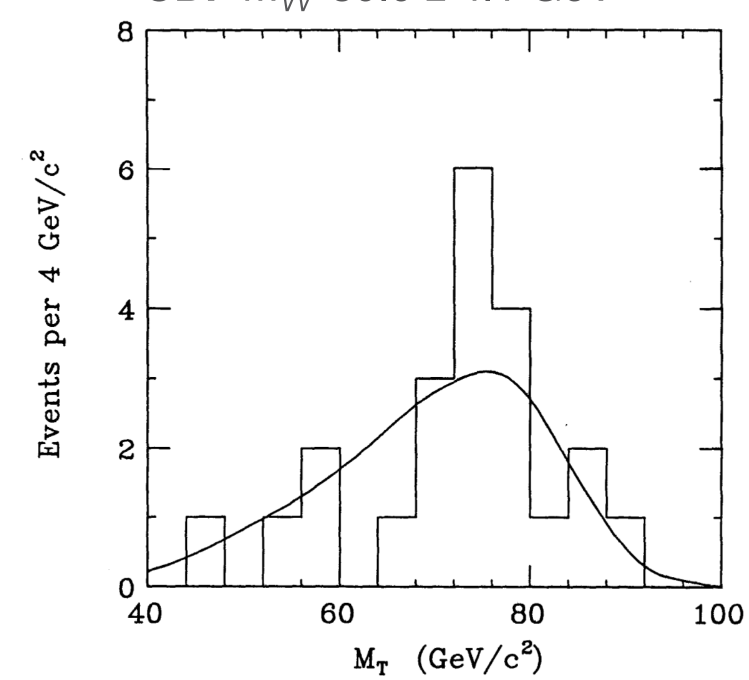


Fig. 2

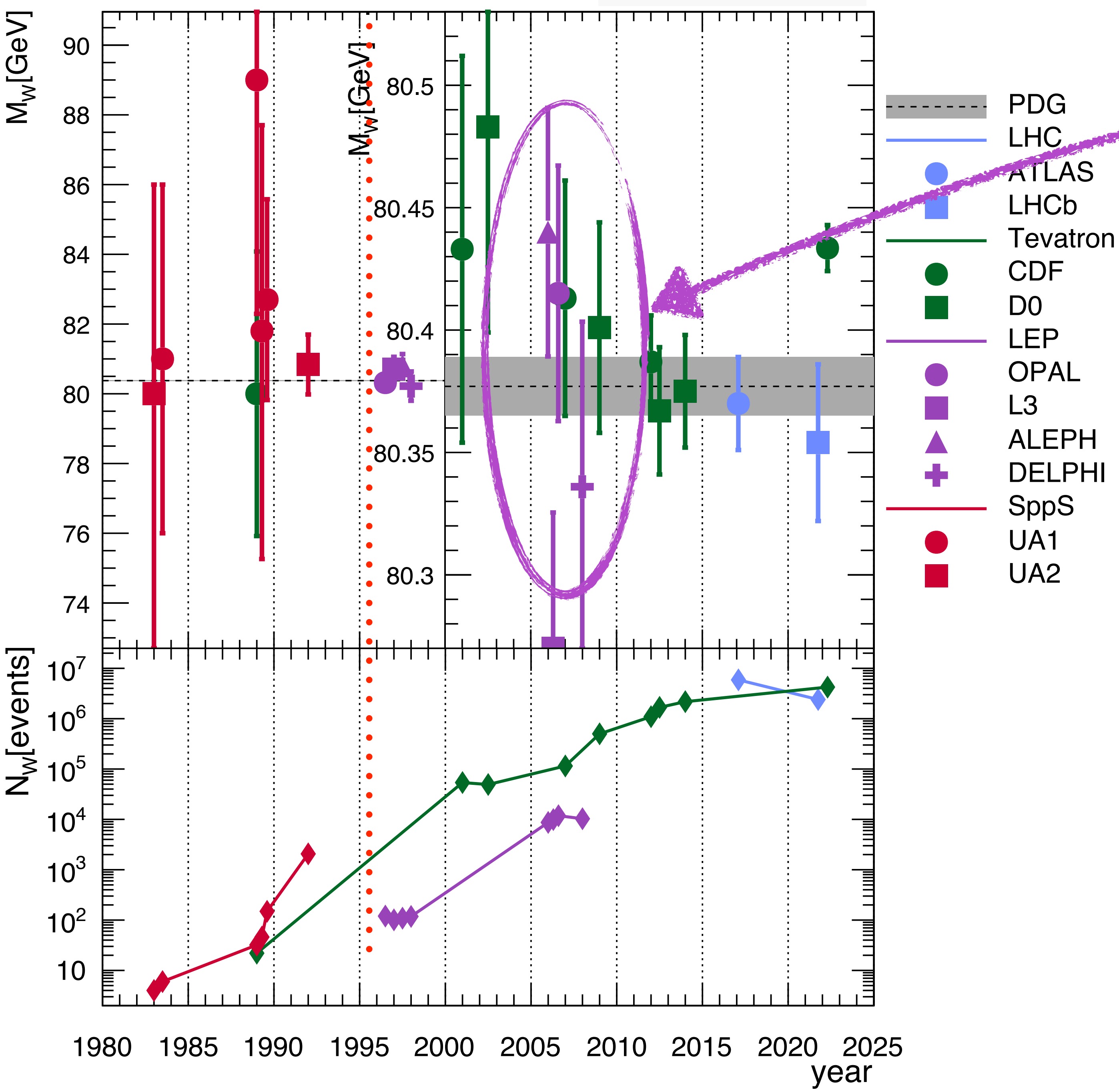
40 years of measurements

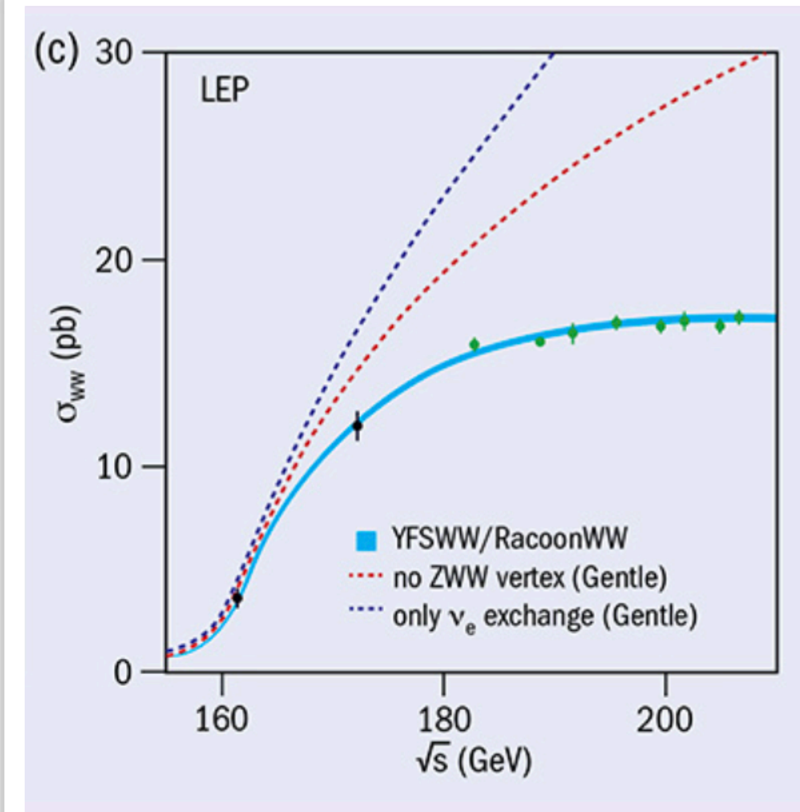
reading PDG live

combined LEP W-mass measurement:

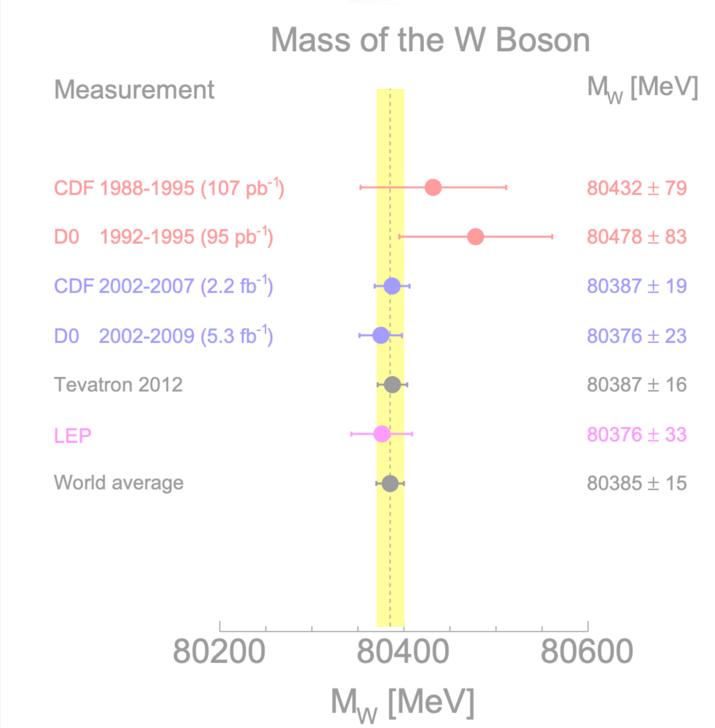
$m_W = 80376 \pm 33$ MeV

credit to S. Camarda





LEP upgrade sqrt(s) crossing the energy threshold for W-pair production



Tevatron RunI+RunII combination:

$m_W = 80387 \pm 16$ MeV

40 years of measurements

reading PDG live

credit to S. Camarda

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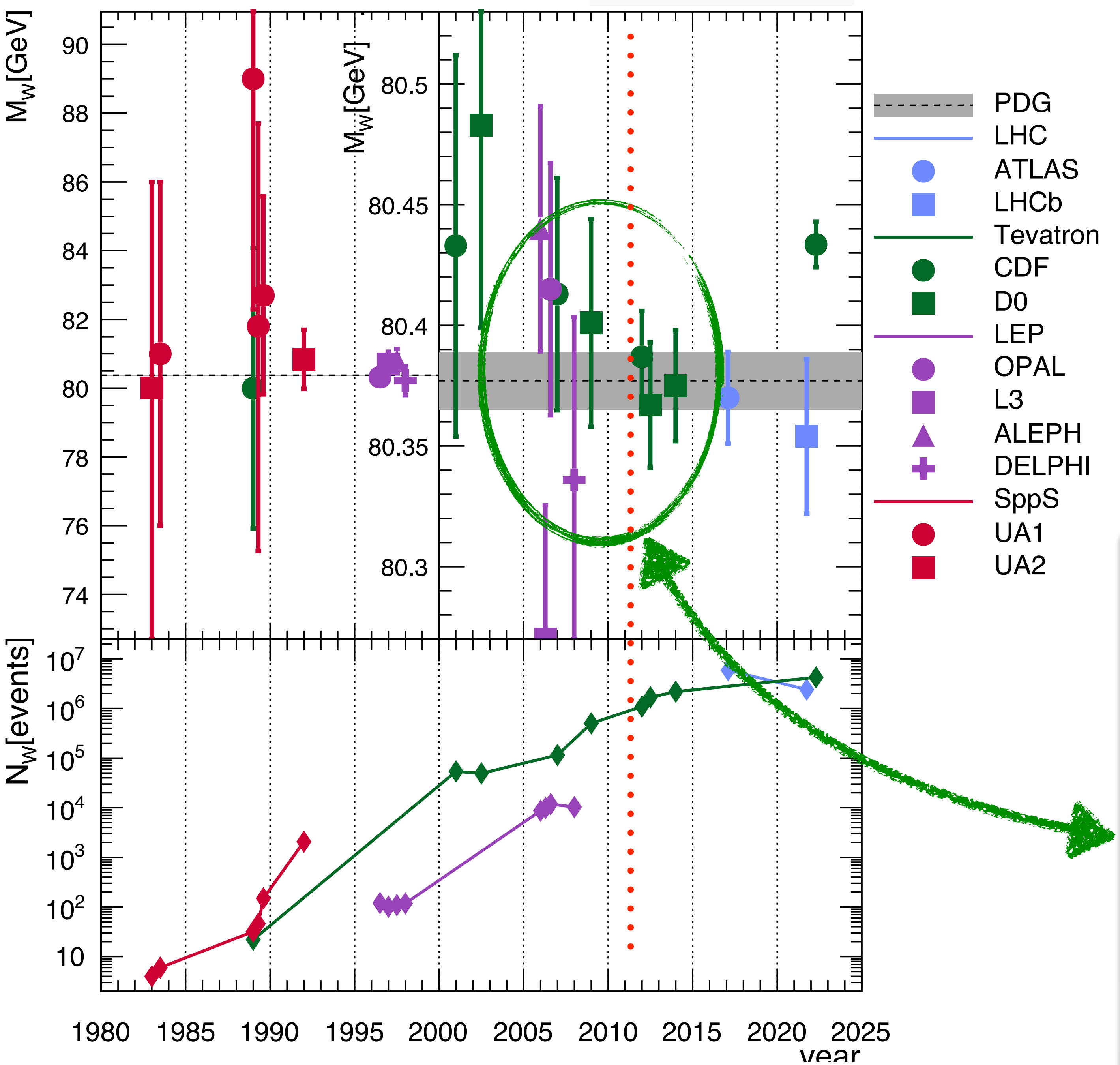
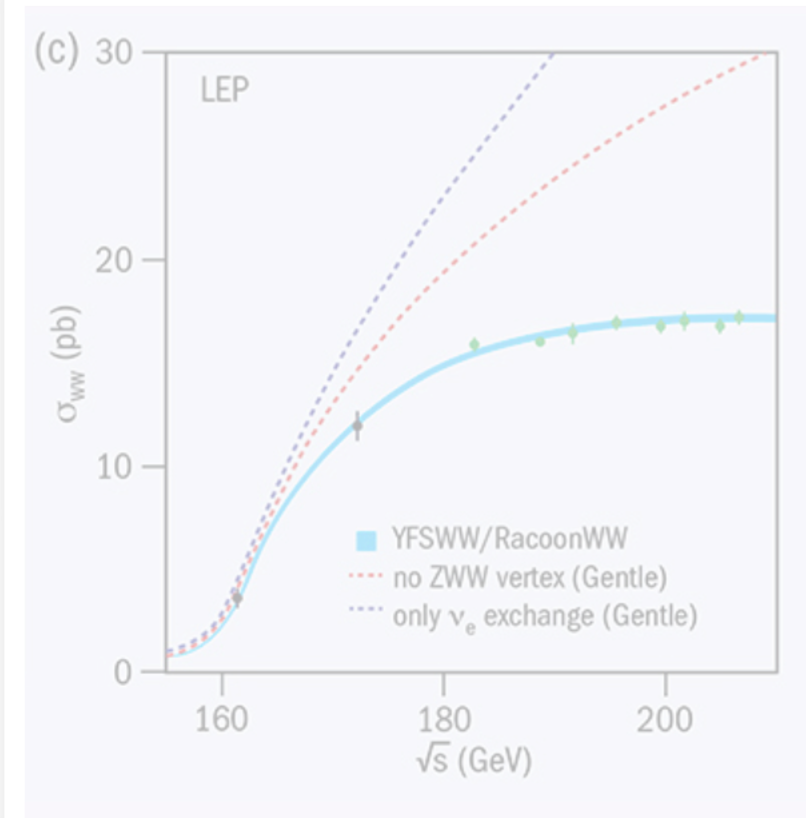
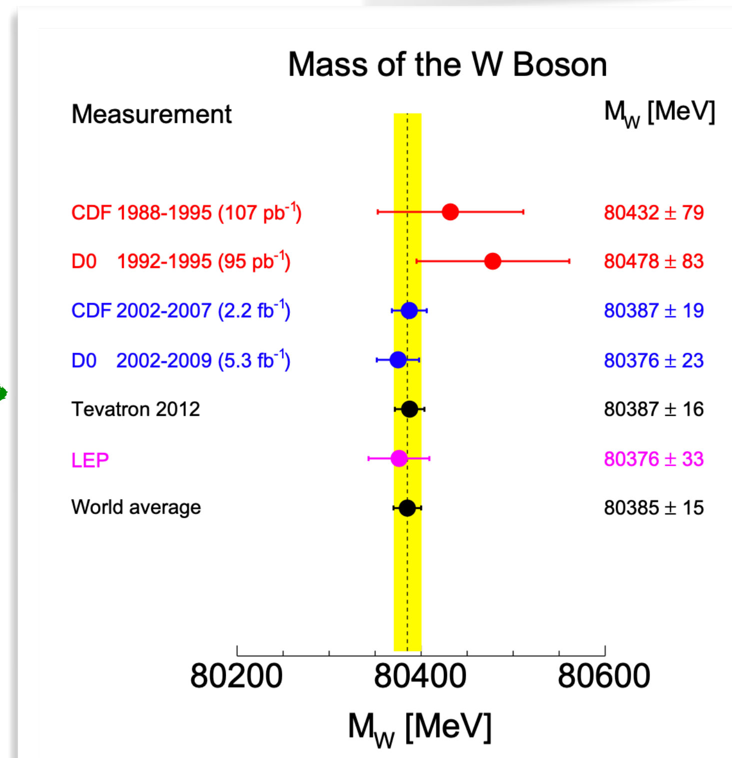


Higgs boson mass discovery mH 125 GeV. Indirect prediction W-mass 80'357 ± 7 MeV [better than 0.1 per mille precision]





Tevatron RunI+RunII combination:

$m_W = 80387 \pm 16$ MeV

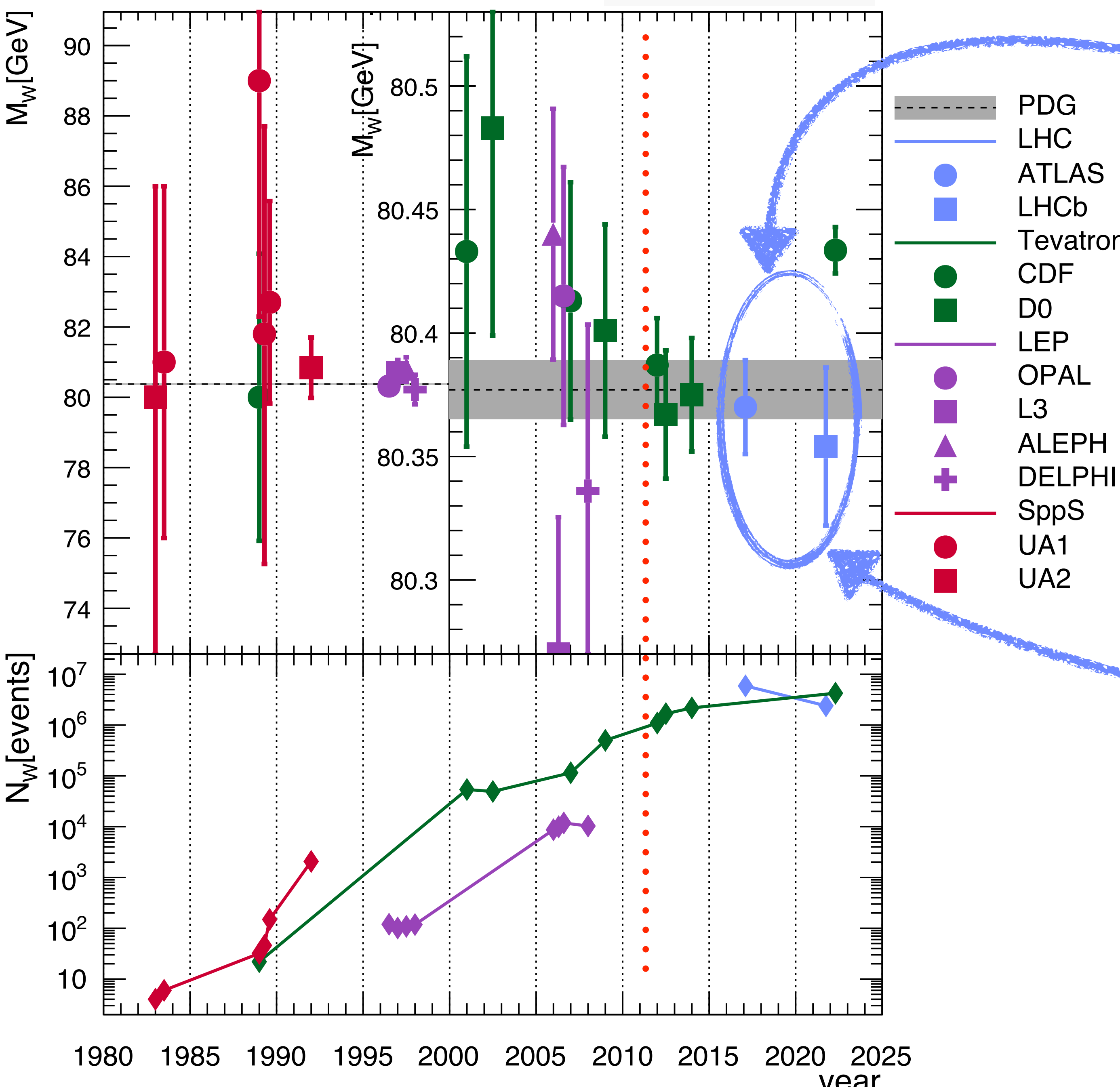
40 years of measurements

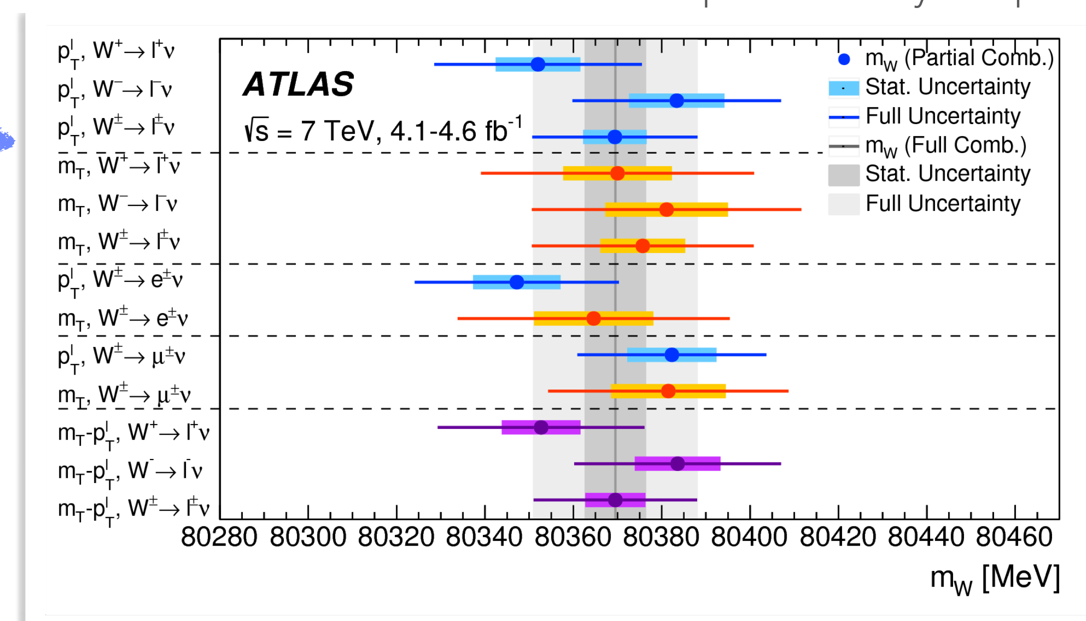
reading PDG live

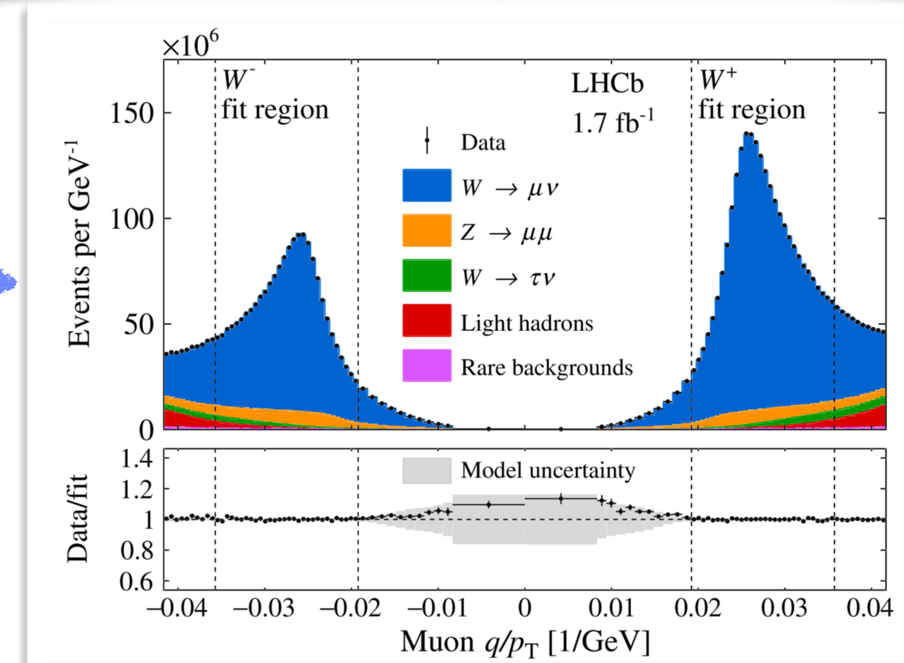
First LHC measurement: **ATLAS**

$m(W)_{ATLAS}$ 80370±19 MeV (7_{stat} ± 11_{exp} ± 10_{theory} ± 9_{pdf})

credit to S. Camarda







Higgs boson mass discovery mH 125 GeV. Indirect prediction W-mass 80'357 ± 7 MeV [better than 0.1 per mille precision]

recent **LHCb** measurement performed in the fwd region

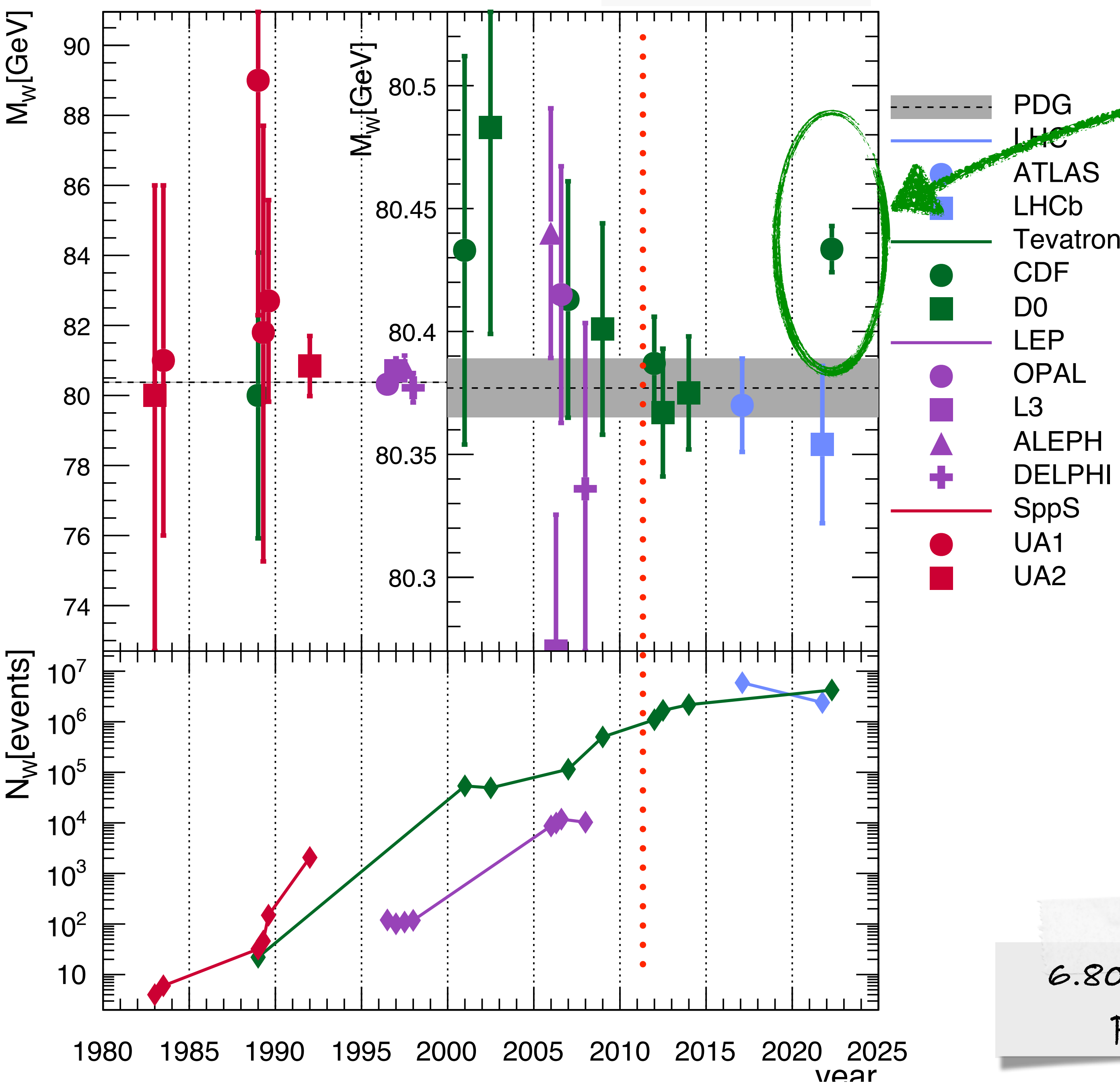
$m(W)_{LHCb}$ 80354±32 MeV (23_{stat} ± 10_{exp} ± 17_{theory} ± 9_{pdf})

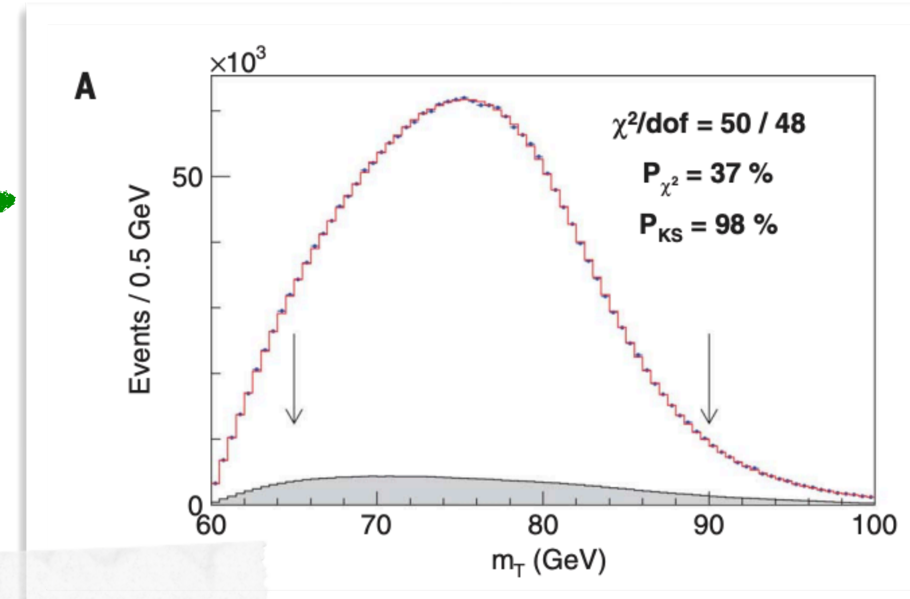
40 years of measurements

reading PDG live

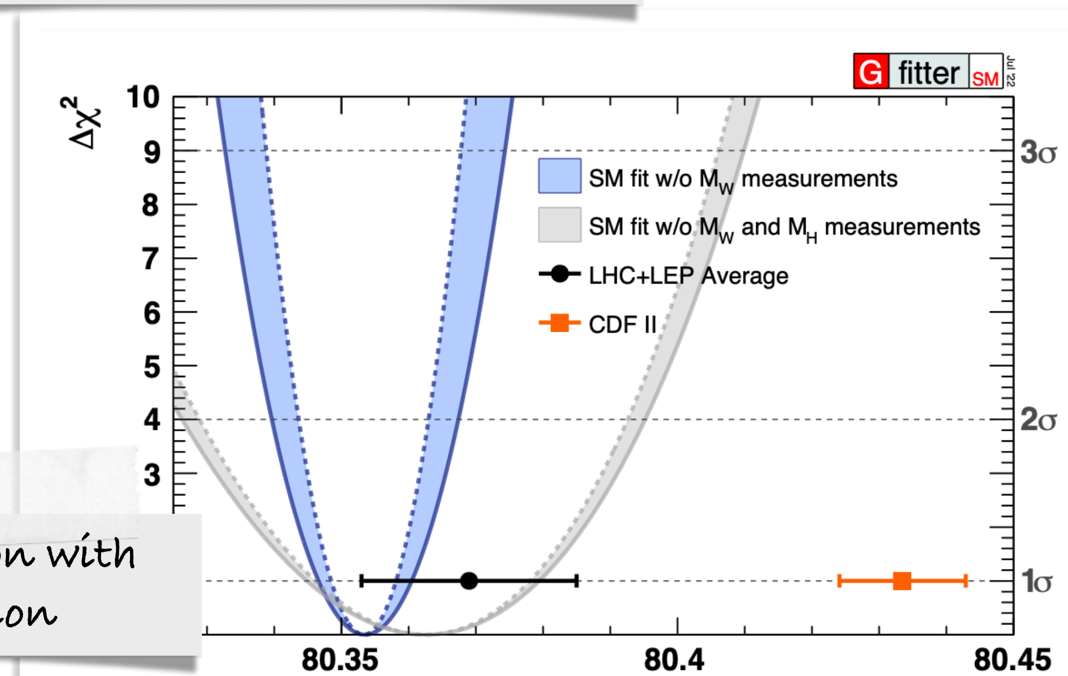
to… **the latest CDF** result m_W 80.433 ± 0.009 GeV

credit to S. Camarda





3σ tension with ATLAS measurement



6.8σ tension with prediction

Higgs boson mass discovery mH 125 GeV. Indirect prediction W-mass 80'357 ± 7 MeV [better than 0.1 per mille precision]

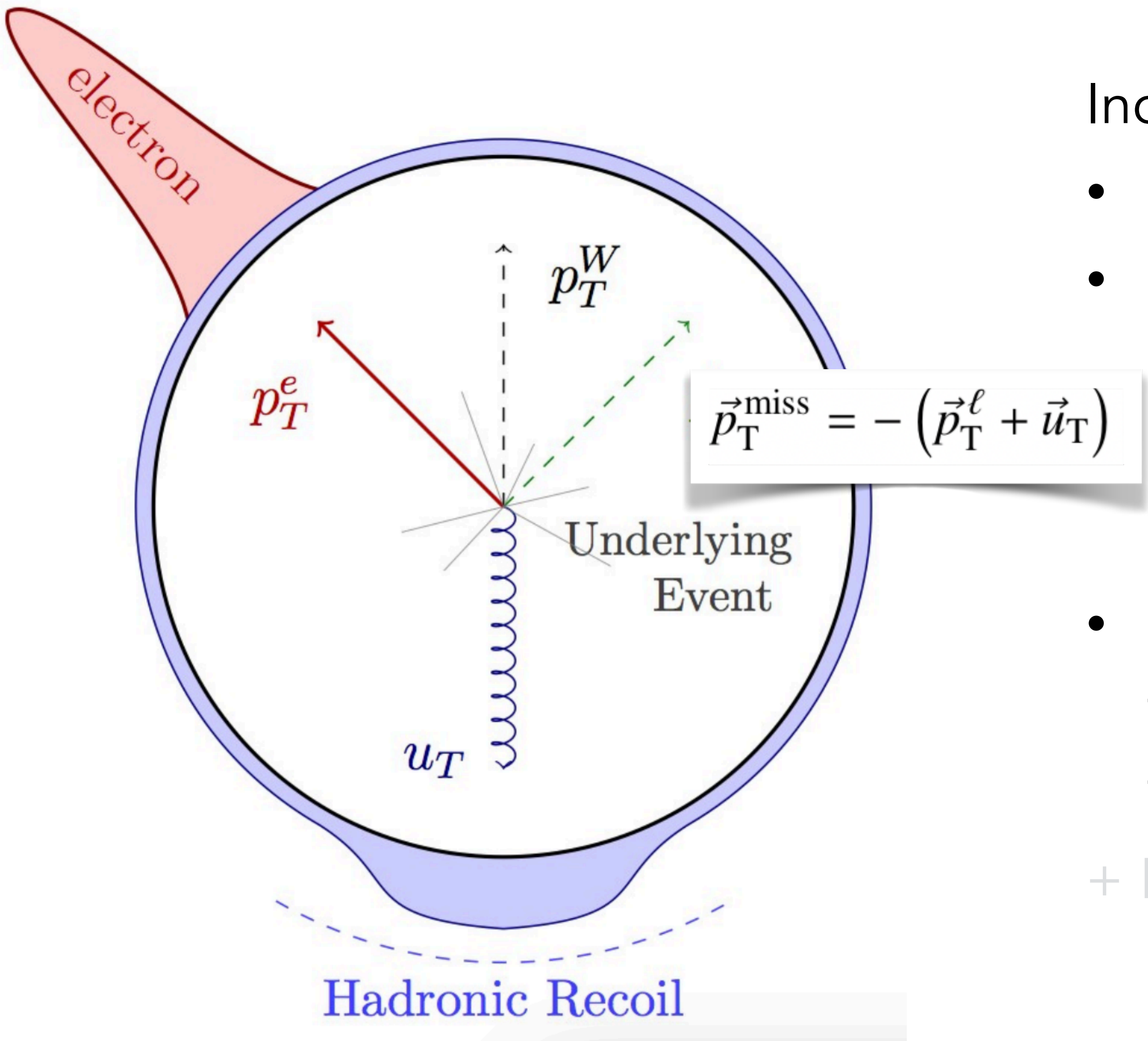
R.Kogler ICHEP2022

A **new** and improved W boson mass measurement

The important ingredients of the improved m_W measurement:

- consolidation of the experimental analysis
- solid and reliable physics modelling
- benefit from recent progress on statistical fitting framework

W boson signature



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

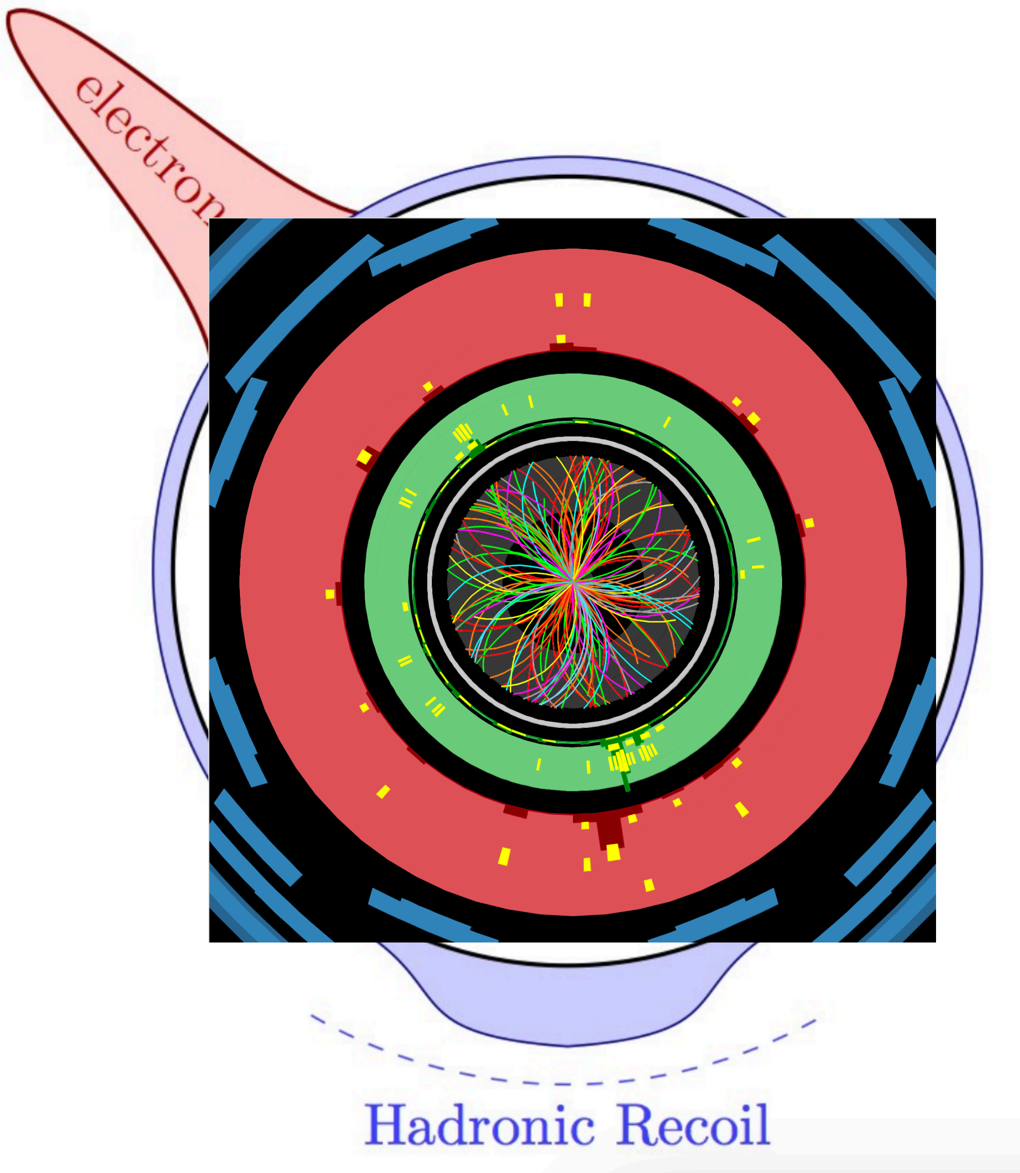
Incomplete kinematics (missing **neutrino**):

- no invariant mass
- measured quantities
  - Prompt and isolated **lepton** (e or μ)
  - *Hadronic*-**Recoil** (u_T): sum of "everything else" reconstructed in the calorimeters;
- exploit momentum conservation in the transverse plane to reconstruct p_T^{miss} and transverse mass (m_T)

+ Pileup …

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

W boson signature



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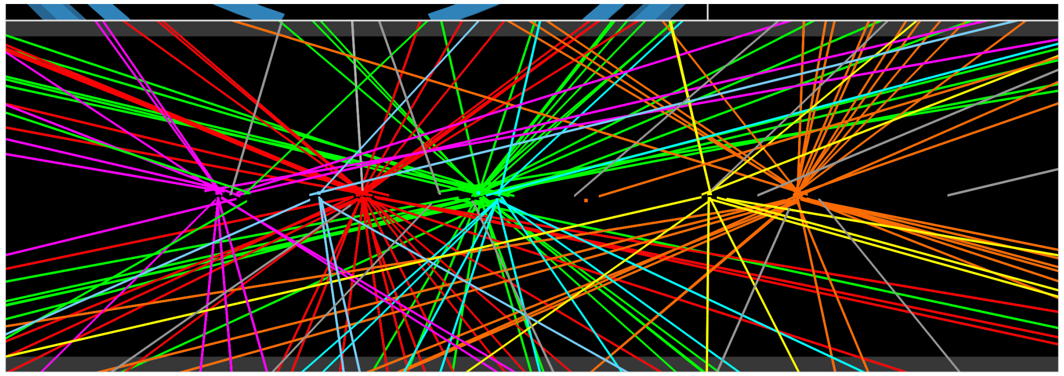
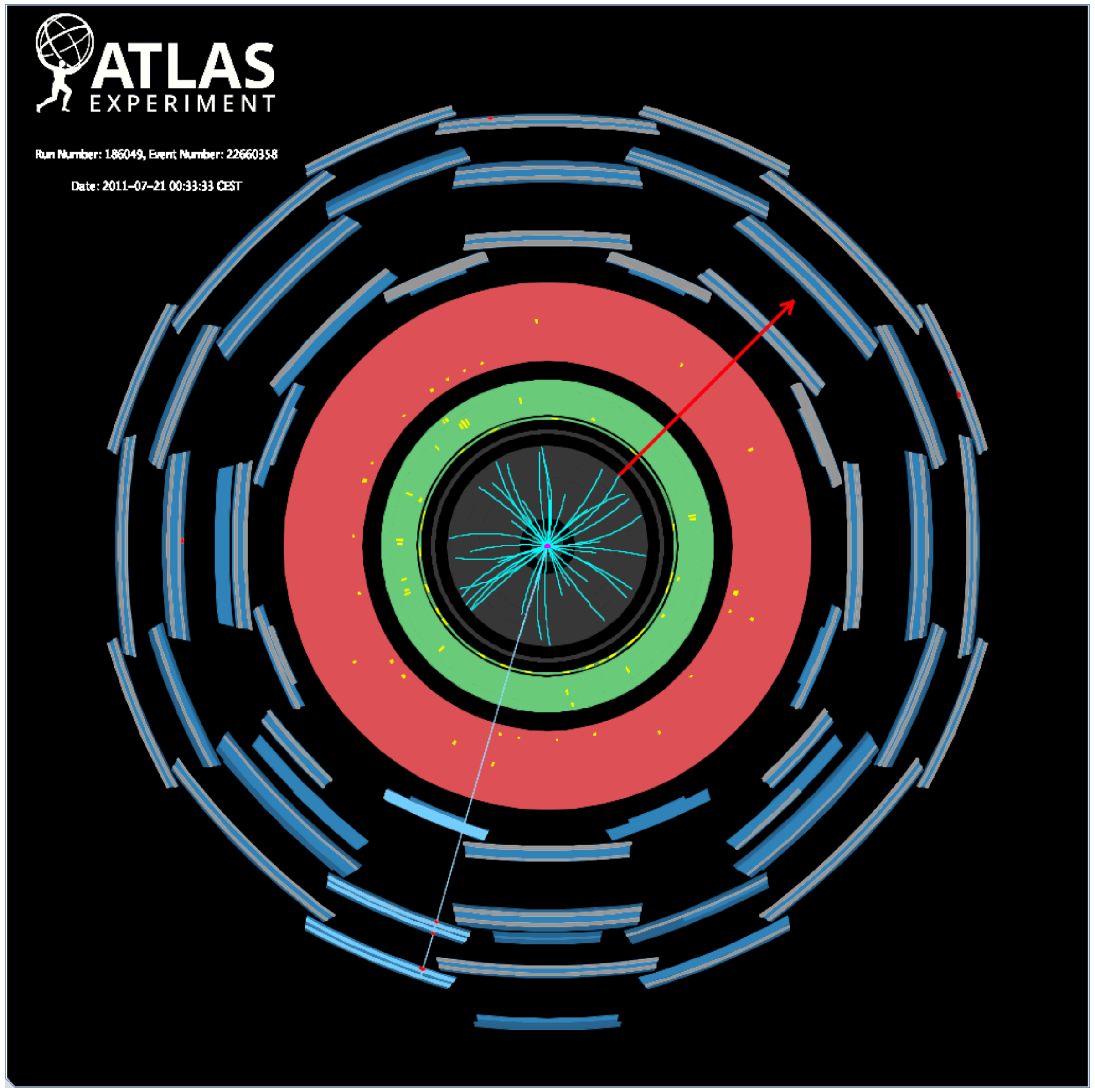


W boson signature



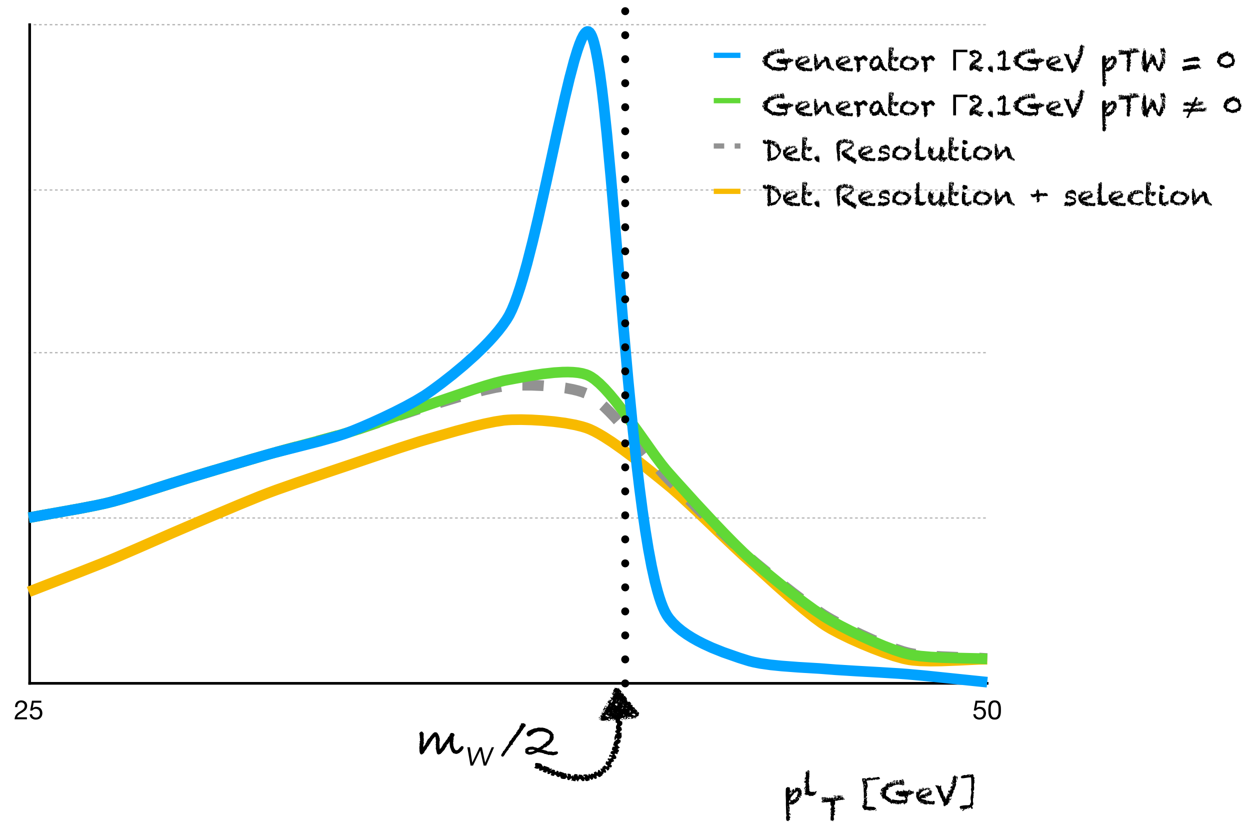
ATLAS m_W measurement done with 4.7 fb^{-1} at $\sqrt{s}$ =7TeV with **<μ>~9**

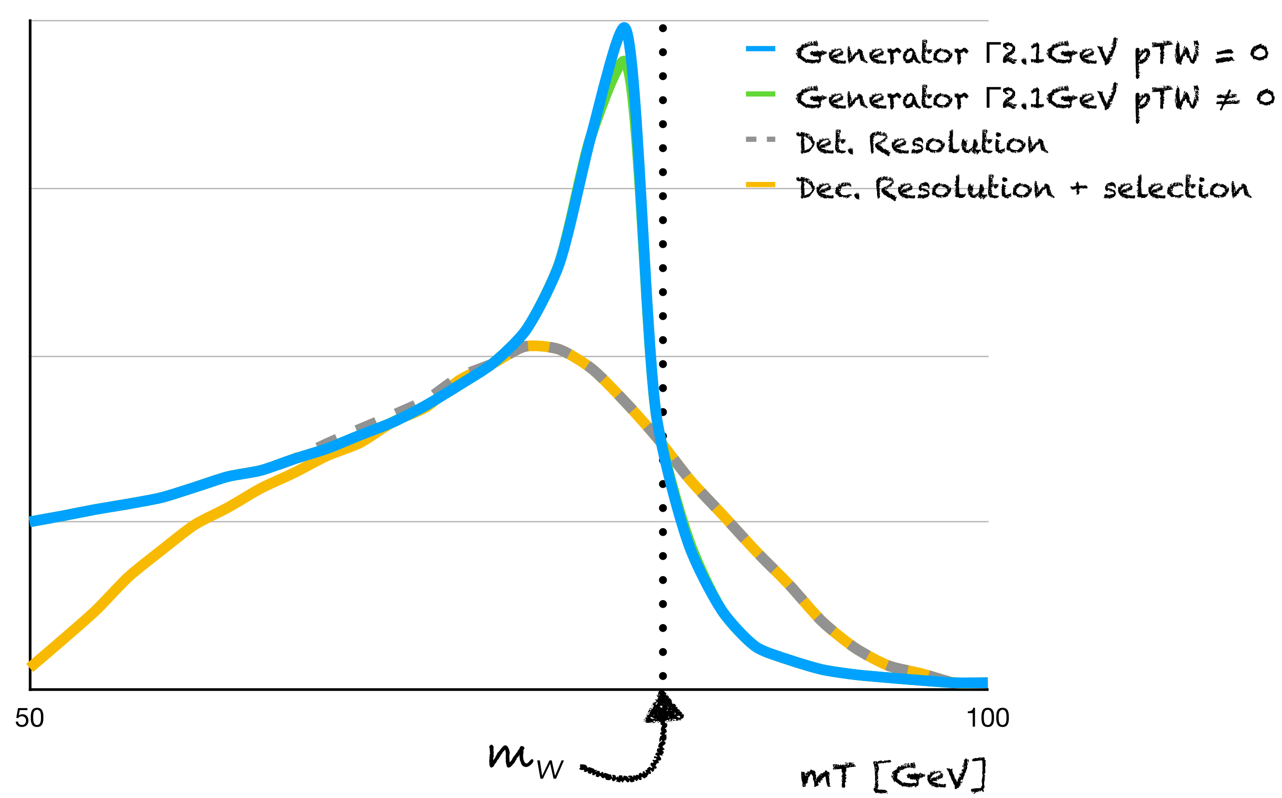
- ~14M candidates in $W \rightarrow \ell\nu$ (ℓ= e,μ) (Background: 5% (6.5%) for μ(e))
- ~2M of $Z \rightarrow \ell\ell$ for calibration

Observable sensitive to m_W

(A) Identify observables sensitive to m_W :

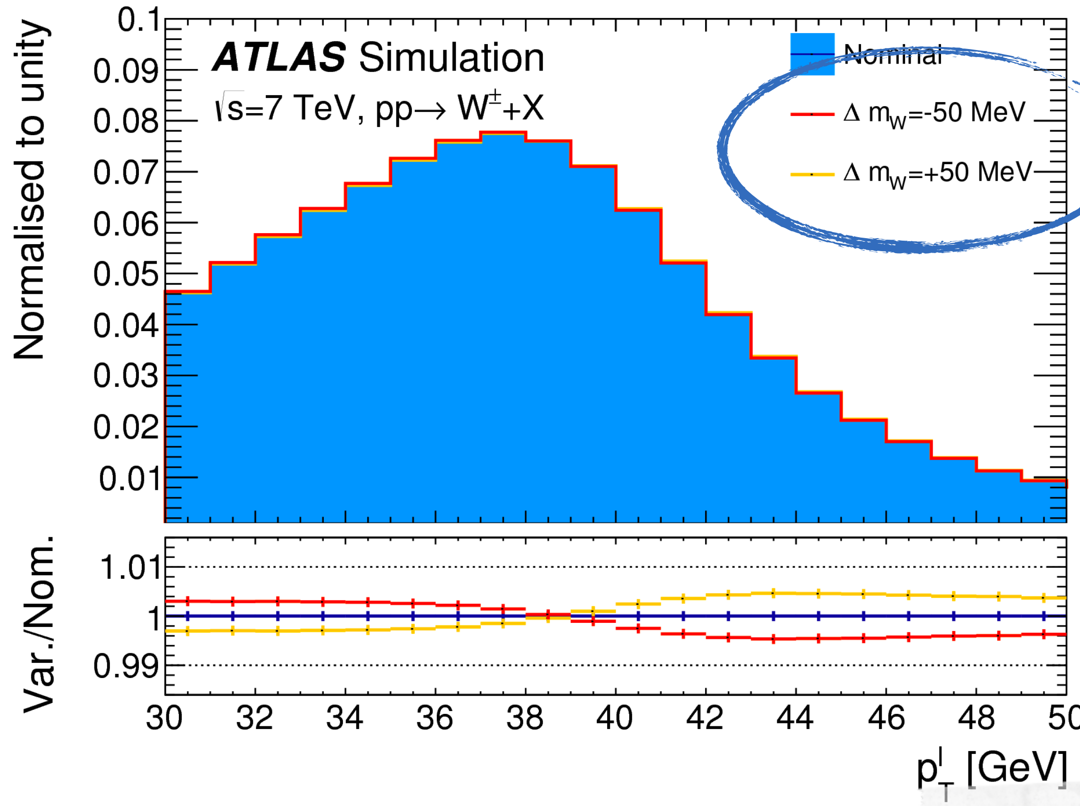
- ☆ lepton transverse momenta ($\mathbf{p^l_T}$) has a Jacobian peak at $m_W/2$
- ☆ transverse mass ($\mathbf{m_T}$) has an endpoint at m_W

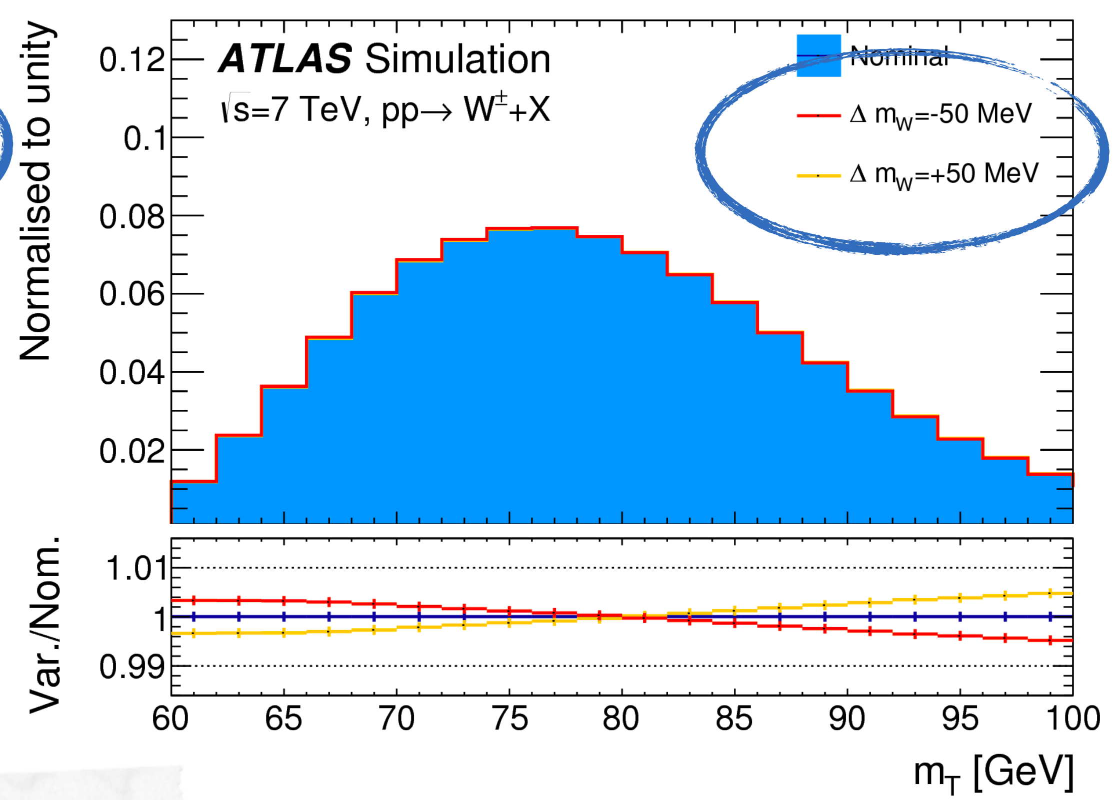




Building m_W templates

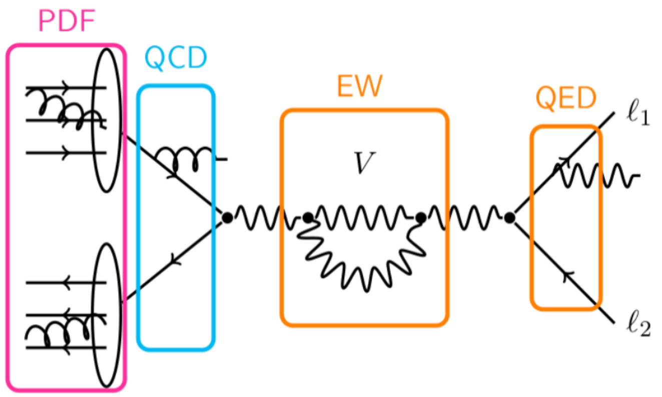
(B) Produce models ("templates") with different m_W-hypotheses and compare to **data** in 28 categories (e/μ, η regions, W^+W^-, $p^l_T m_T$)



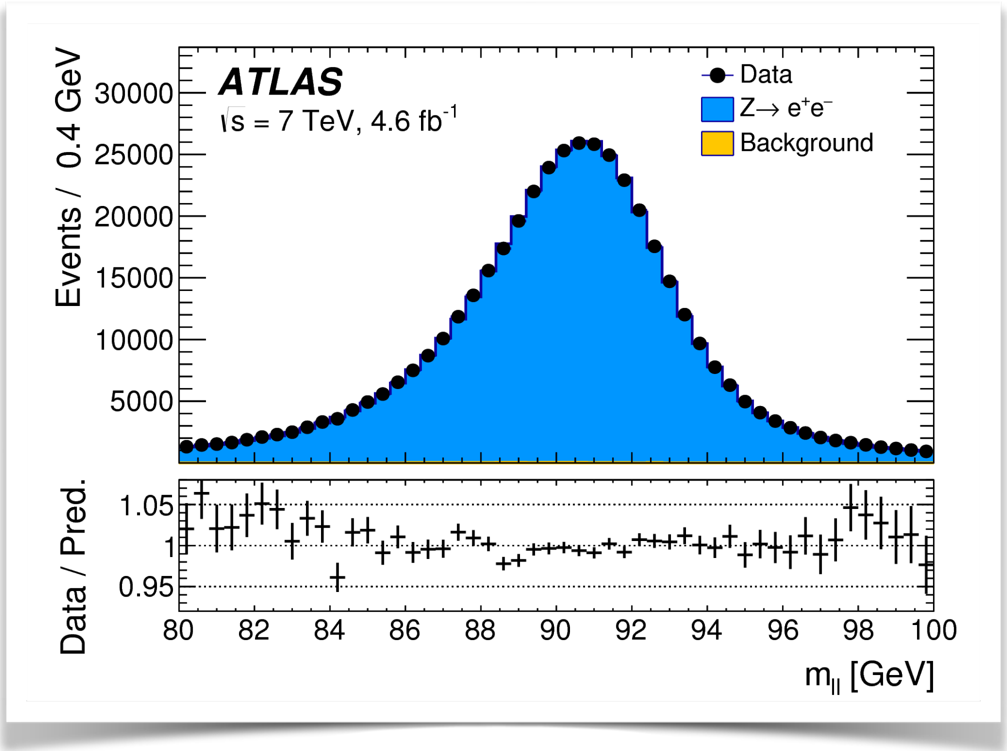


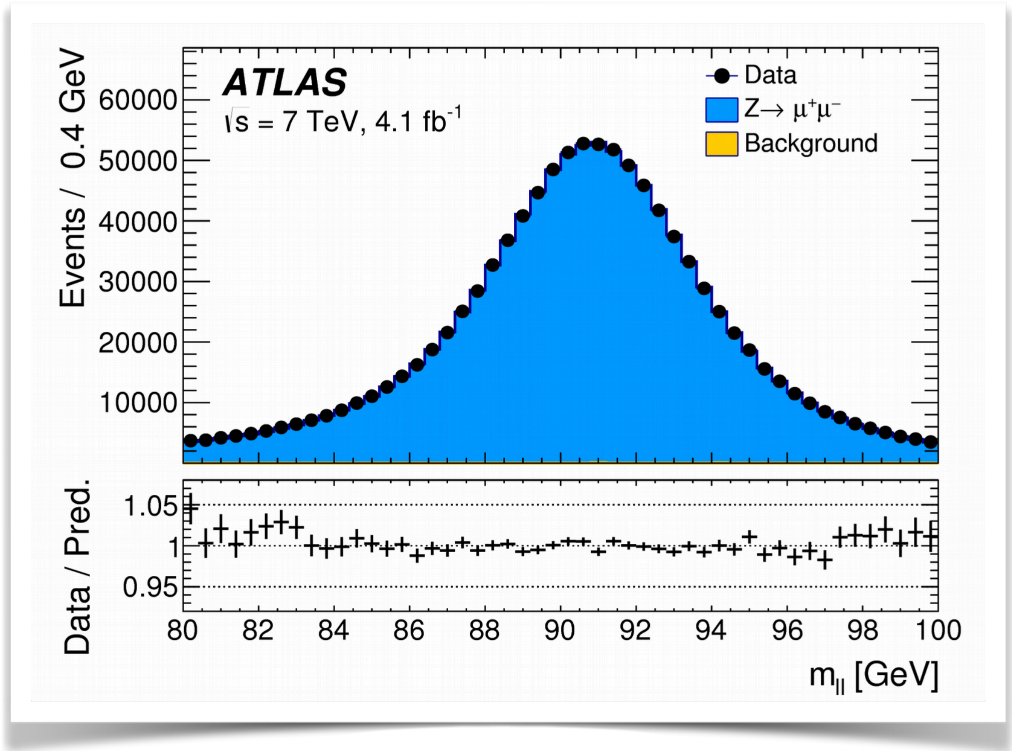
Δm_W = 15 MeV ⇒ ~0.1-0.2% variation in the kinematics of the W production

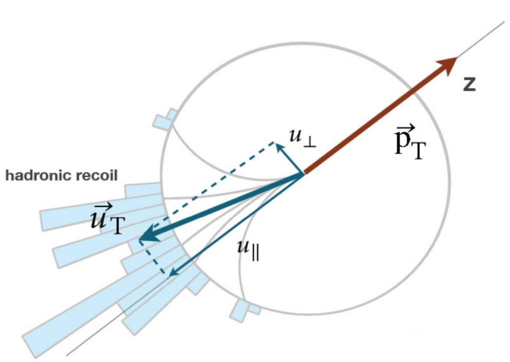
- p^l_T and m_T distributions are sensitive to:
  - ➡Leptons and Recoil calibration
  - ➡Modelling effects:



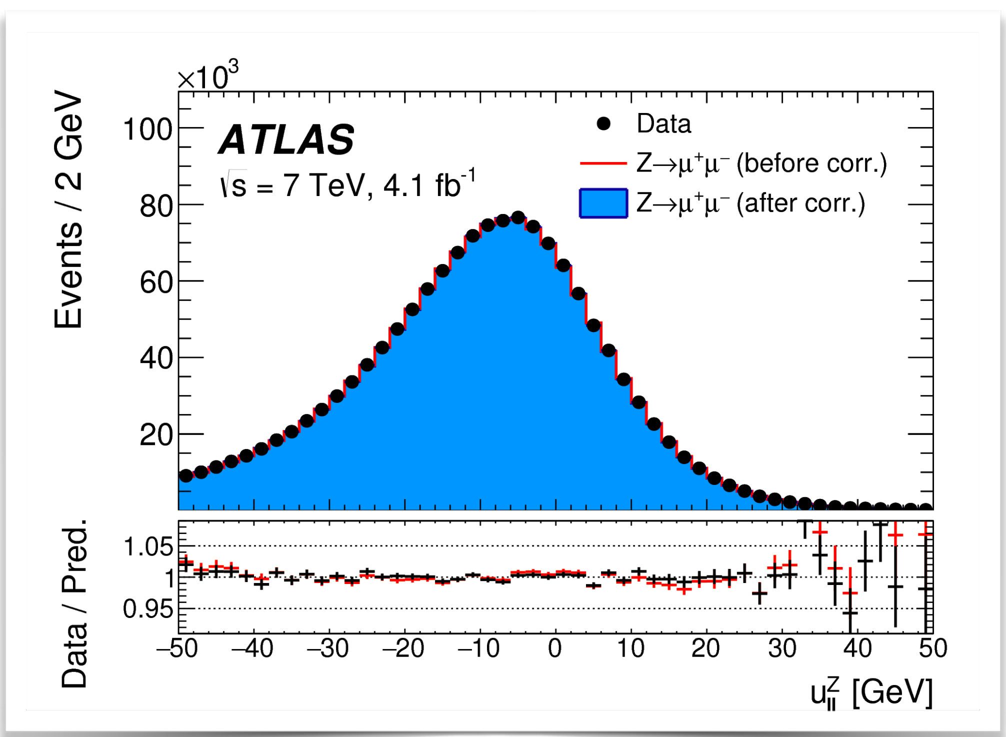
Experimental precision







Hadronic recoil response calibration used the p^Z_T balance in Z boson events



- Z boson events are used to derive detector calibrations.
- **Outstanding experimental precision :**
  - Lepton performances at sub-‰ level ⇒ $\delta m_W \sim 7\text{-}10$ MeV
  - Hadronic Recoil calibration at % level ⇒ $\delta m_W \sim 12$ MeV

The physics modelling

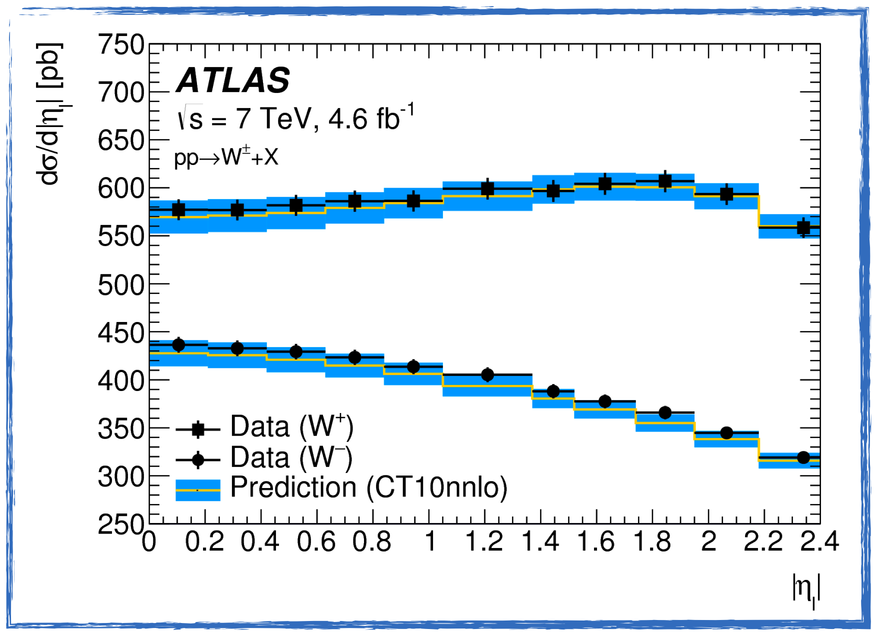
- W mass physics modelling is described using a **composite model** :
  - Start Powheg+Pythia8 [NLO+LL (PS)] and apply corrections ⇒ NNLO pQCD accuracy

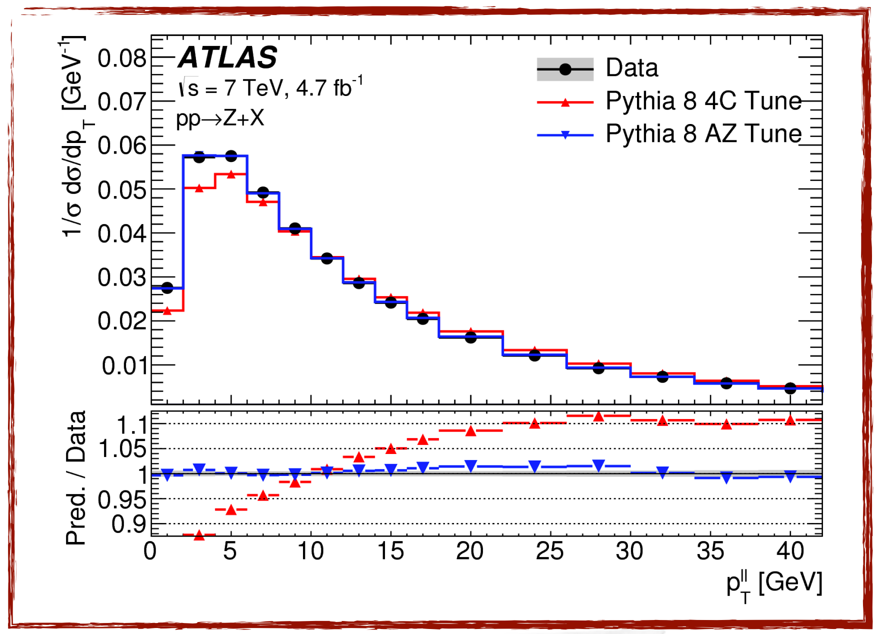
$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y)P_i(\cos\theta, \phi)\right]$$

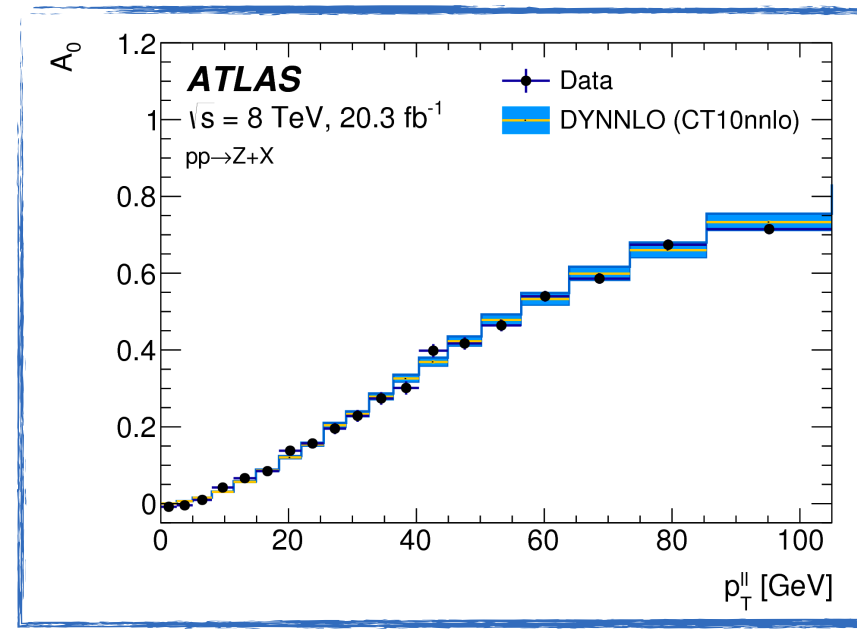
Breit-Wigner

NNLO pQCD

Parton Shower





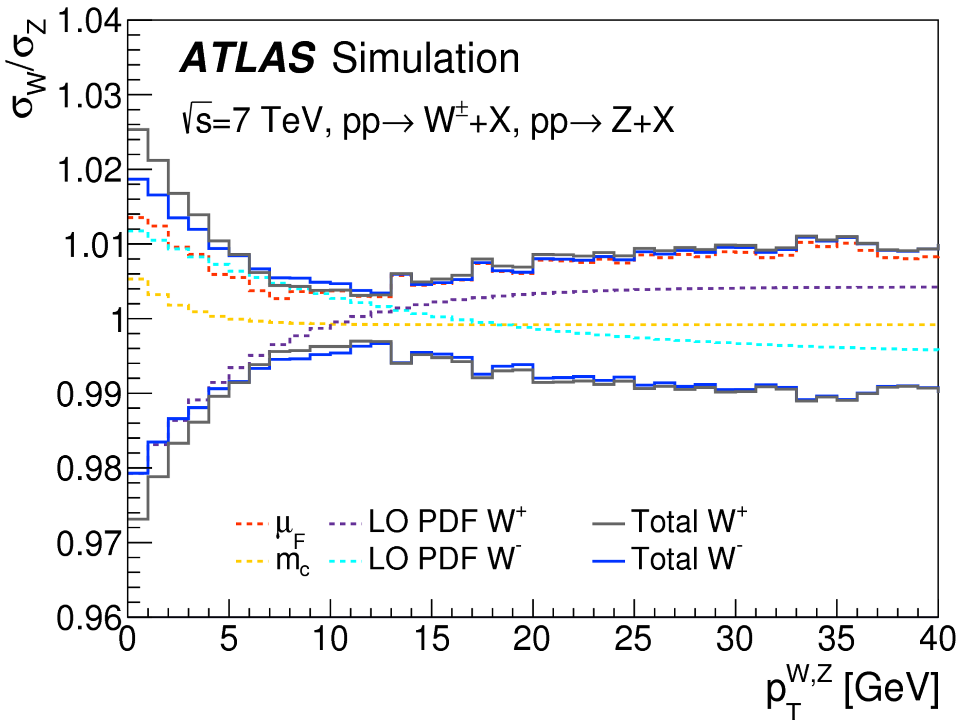


Key role of ancillary measurements : used to validate (and tune) the model and assess systematic uncertainties.

The p^W_T modelling

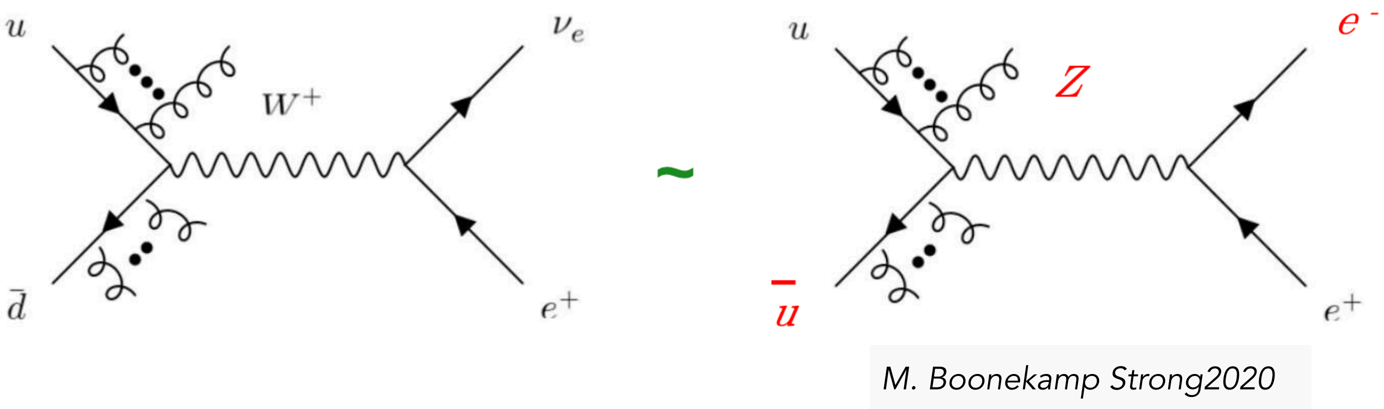
m_W $d\sigma/dp_T$ modelling uses **Pythia parton shower**

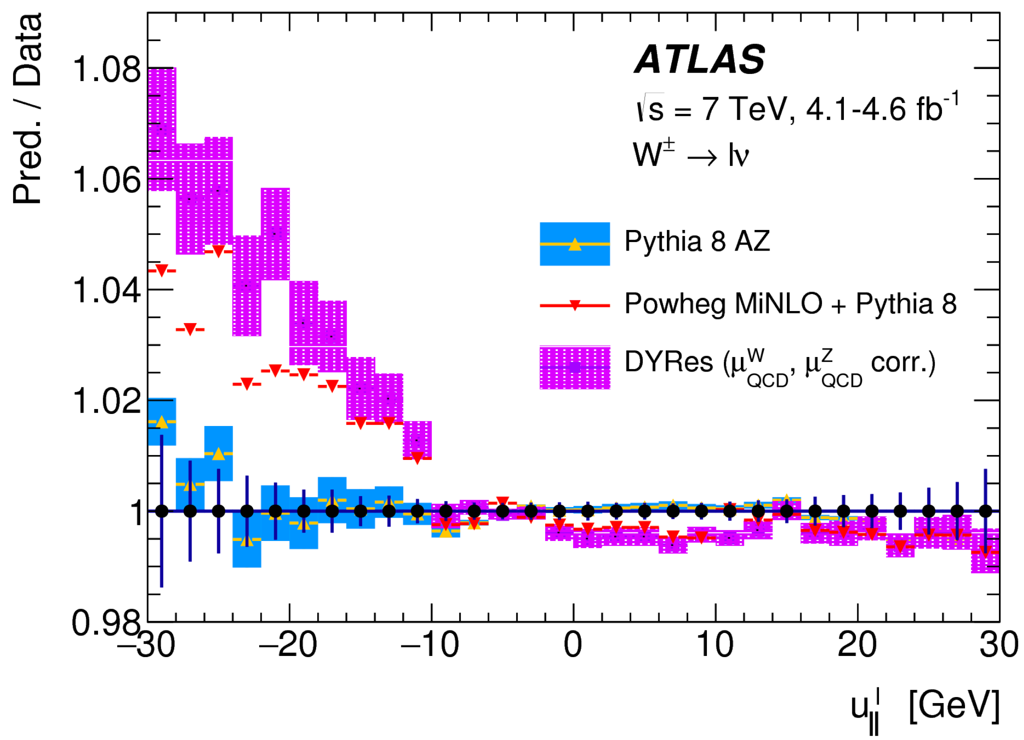
- PS parameters tune on 7TeV p^Z_T data (*AZ tune*)
- Fairly good modelling of the W-data, **but hard to improve on uncertainties** (mostly related to model limitations)



Addressing the difficulties of $p^W{}_T$ modelling

- **$p_T{}^W$ modelling is a challenge for QCD theory** (resummation, heavy flavour, multiple scale, no pQCD)
  - Experimentally very precise $p_T{}^Z$ measurement (W limited by recoil resolution)
- **Approach: adjust model parameters using Z events → extrapolate to W production**





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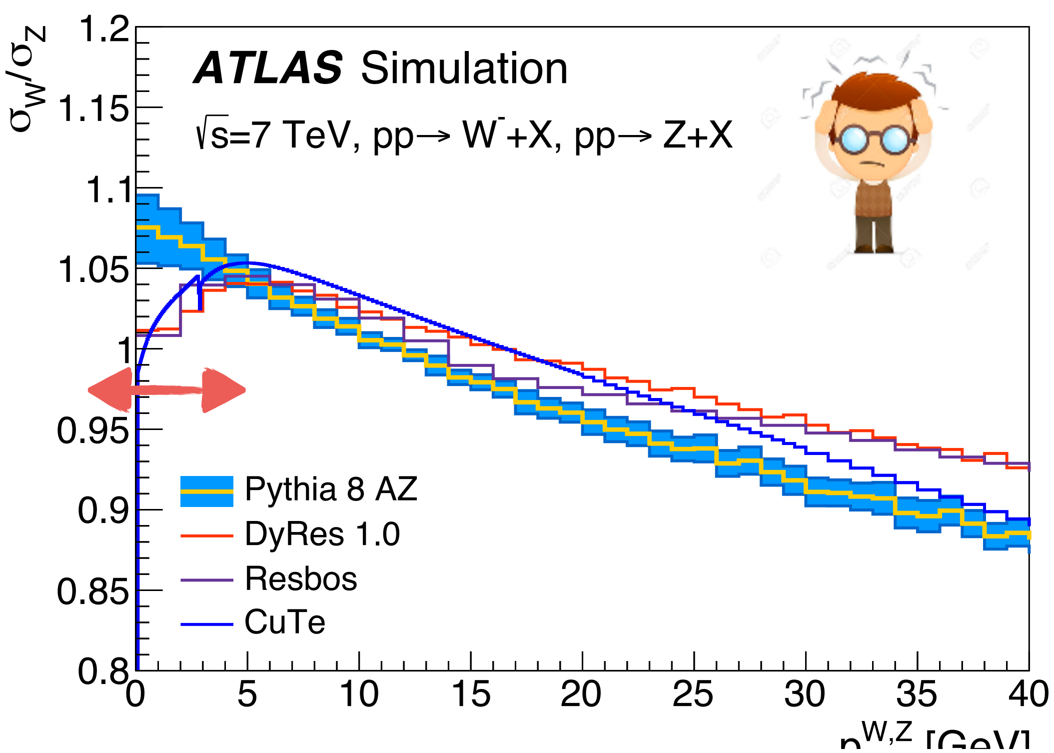
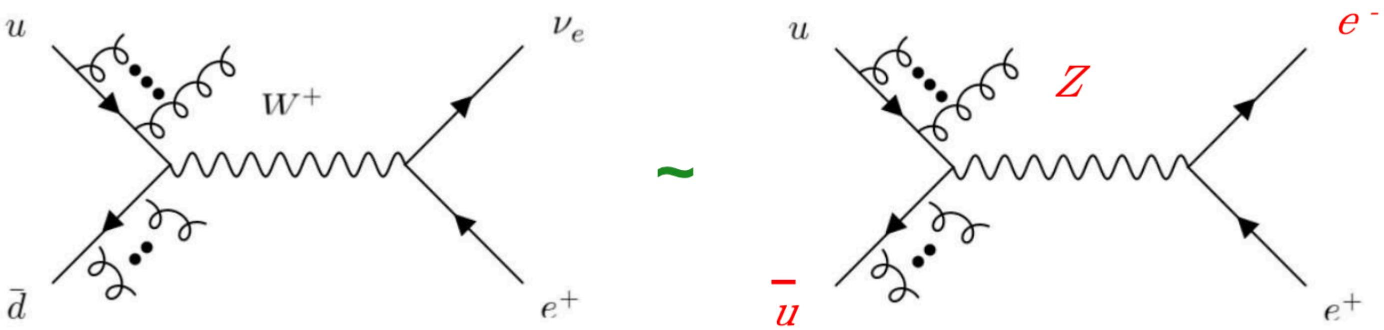


@time of the first measurement: analytic resummed predictions were **strongly disfavoured** by the recoil distribution in data.

@time of the first measurement: low p_T W/Z ratio very different between analytic resummed predictions and PS tuning.

The p^{W}_{T} modelling validation

- p_T^W modelling is a challenge for QCD (resummation, heavy flavour, multiple scale, no pQCD)
  - Experimentally very precise p_T^Z measurement (W limited by recoil resolution)
- **Approach: adjust model parameters using Z events → extrapolate to W production**



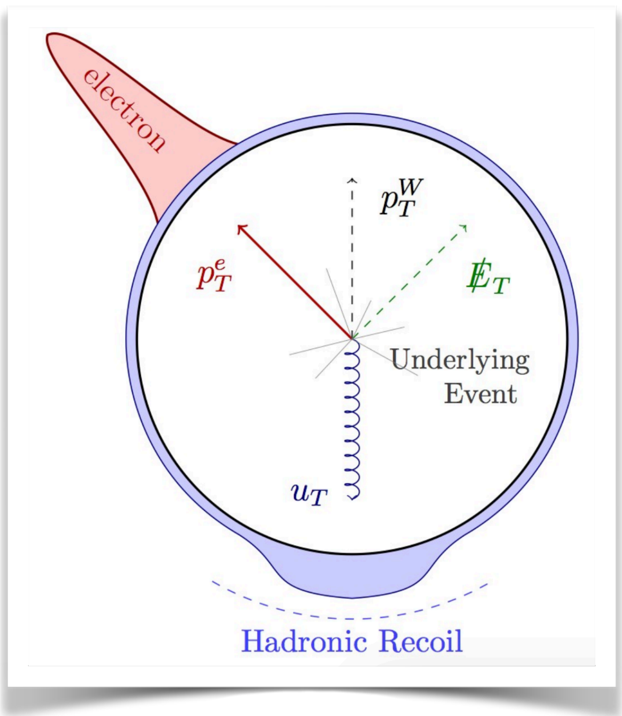
M. Boonekamp Strong2020

A **measurement** able to resolve low p^{W}_{T} spectra with 1% uncertainty would validate the p^{W}_{T} modelling for the m_W analysis
→ crucial experimental input to any future m_W measurement

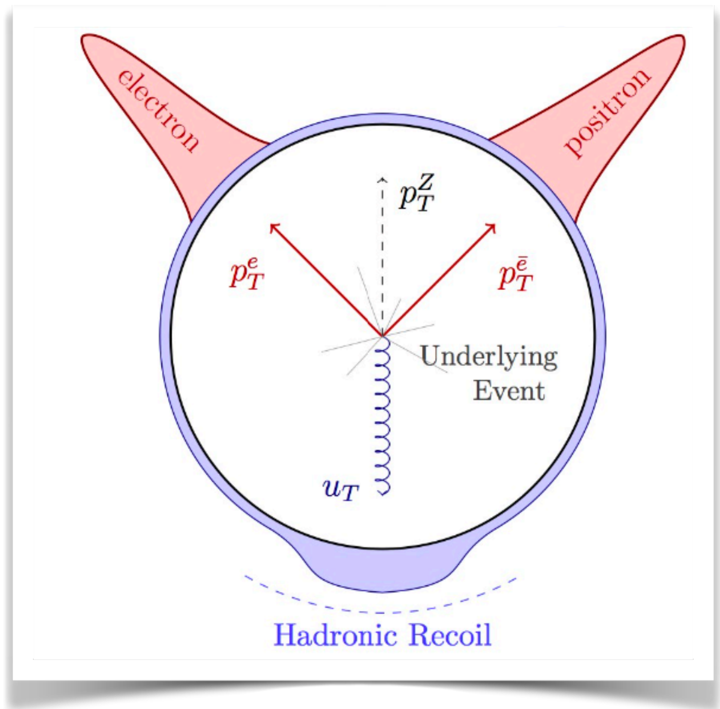
NB To resolve W p_T with ⊢O(5GeV)⊣ in data hadronic recoil resolution need same order.

Hadronic recoil resolution

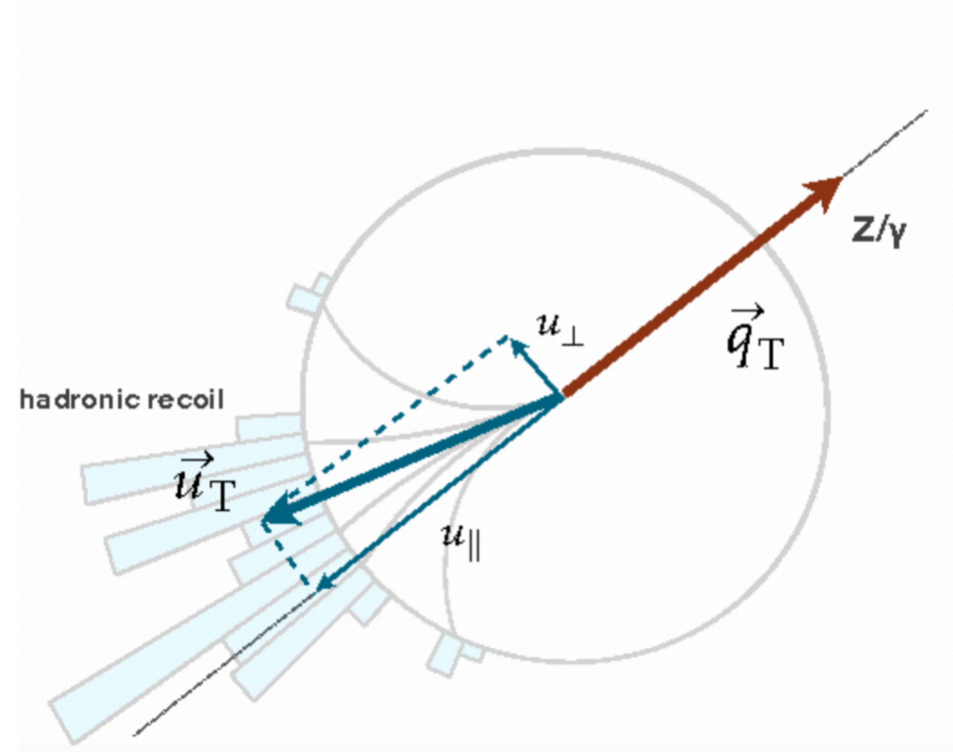
- some basics concepts :



in W events the Hadronic recoil (u_T) is the measurement of "everything else" reconstructed in the calorimeters



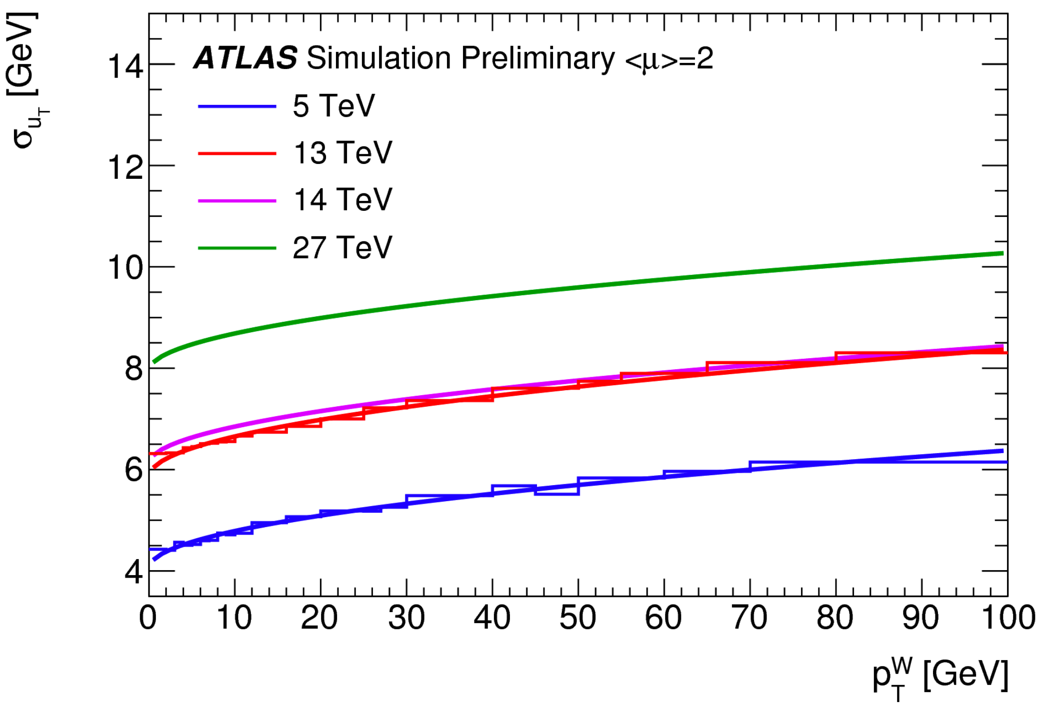
The response of u_T is measured in data using the p^Z_T balance in Z events

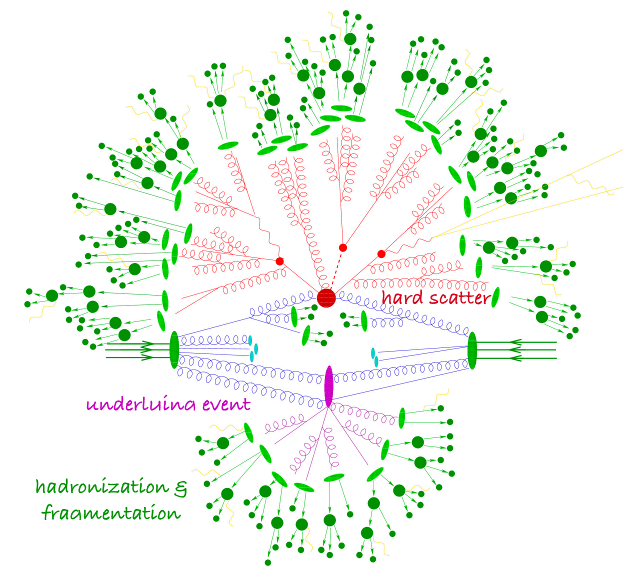


u_T scale and resolution are characterise by the // and ⊥ projection of the recoil into the p^Z_T axis

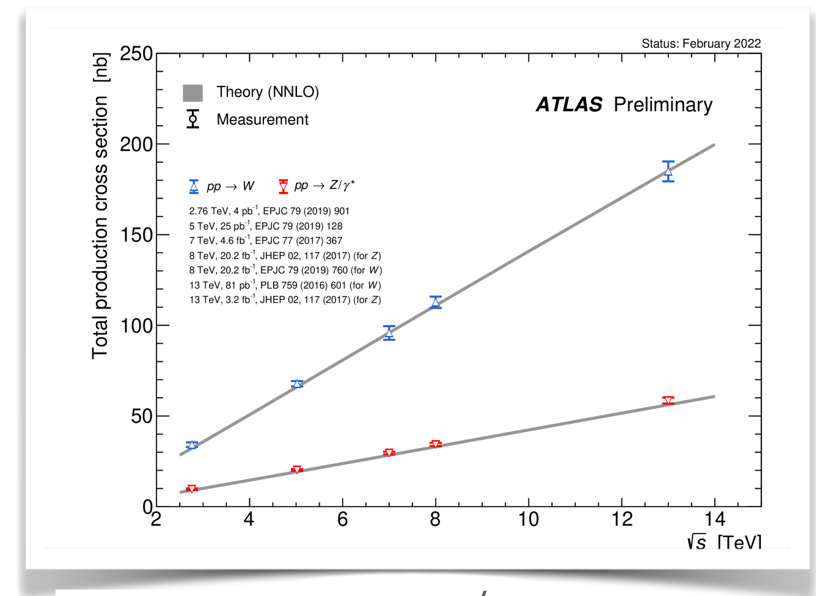
- **u_T resolution** strongly depends on **ΣE_T** (~ total event activity)
  - At low p_T^W, <u>underlying event</u> & <u>pileup</u> contribute to deterioration of the recoil resolution

Underlying event and Pileup contribtuion to the recoil

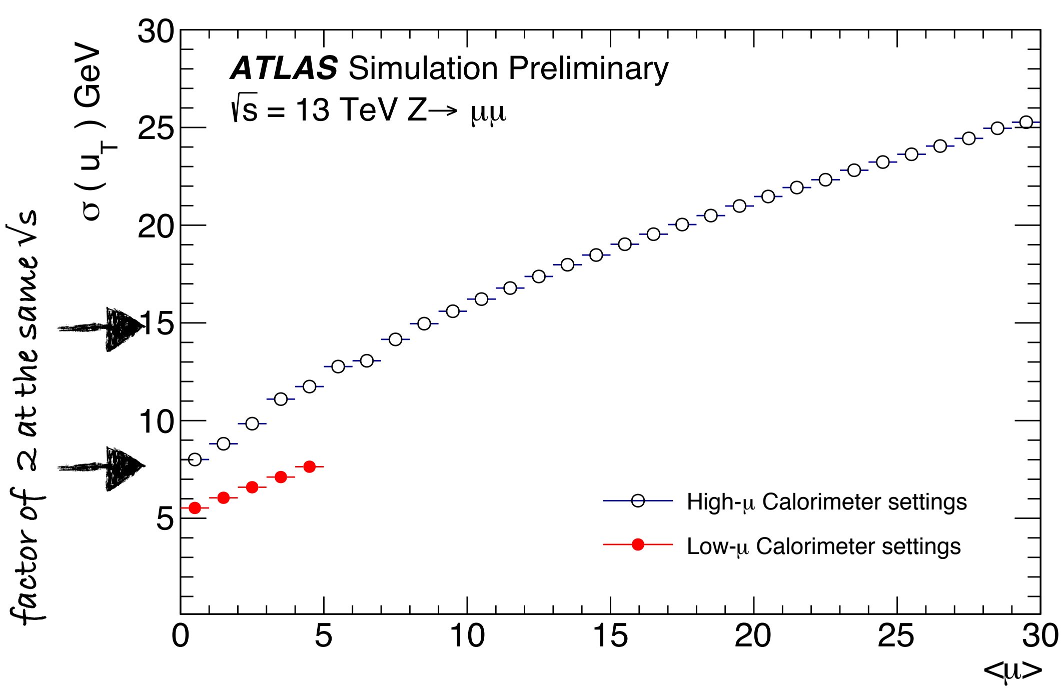


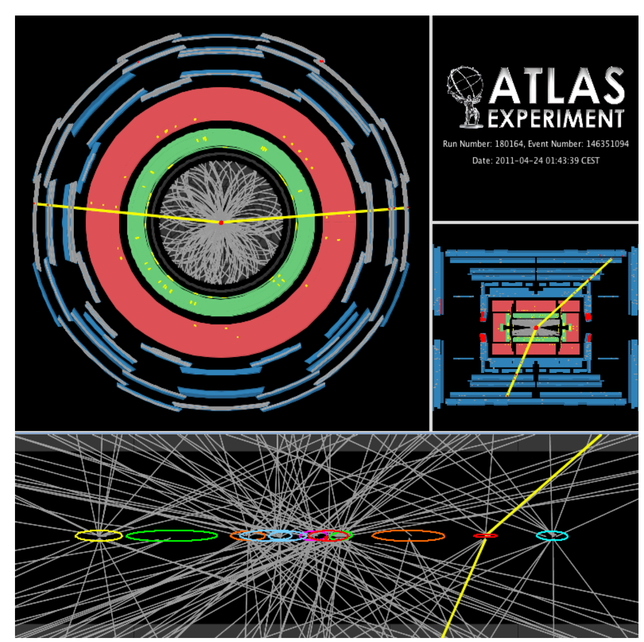


underlying events grows with √s

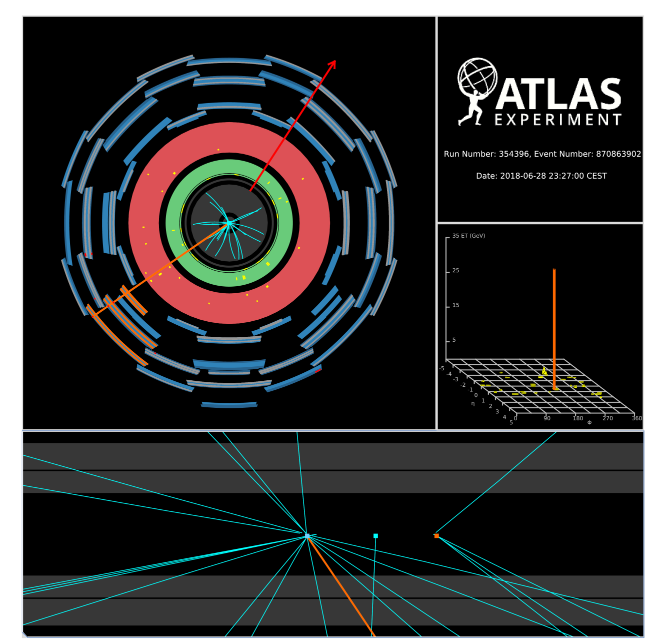


X-section grows with √s





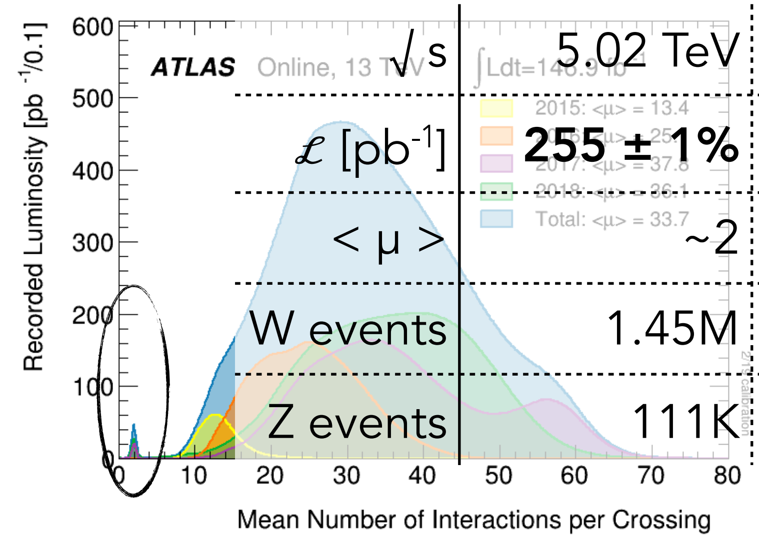
9 additional reconstructed vertices



2 additional reconstructed vertices

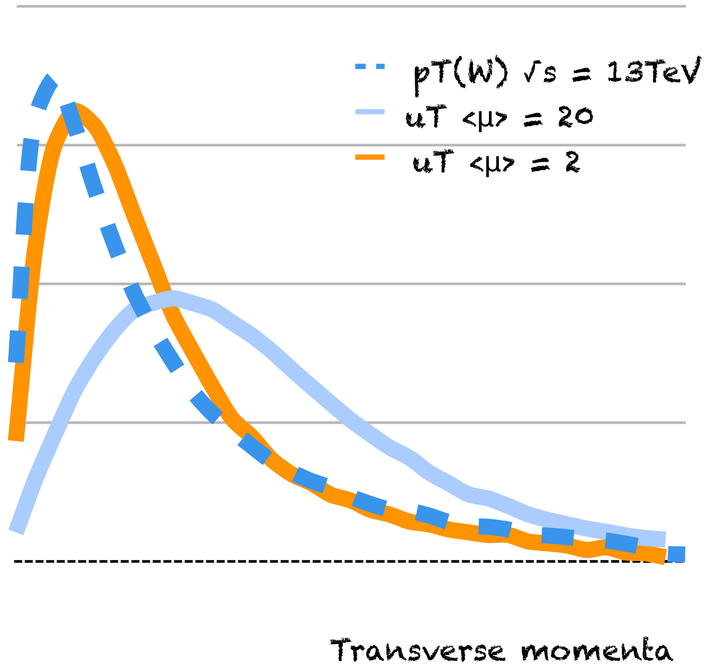
Low-μ dataset

In Run-2 ATLAS collected ~ 500 pb^{-1} at <μ> ~ 2
fantastic opportunity for W precision physics!



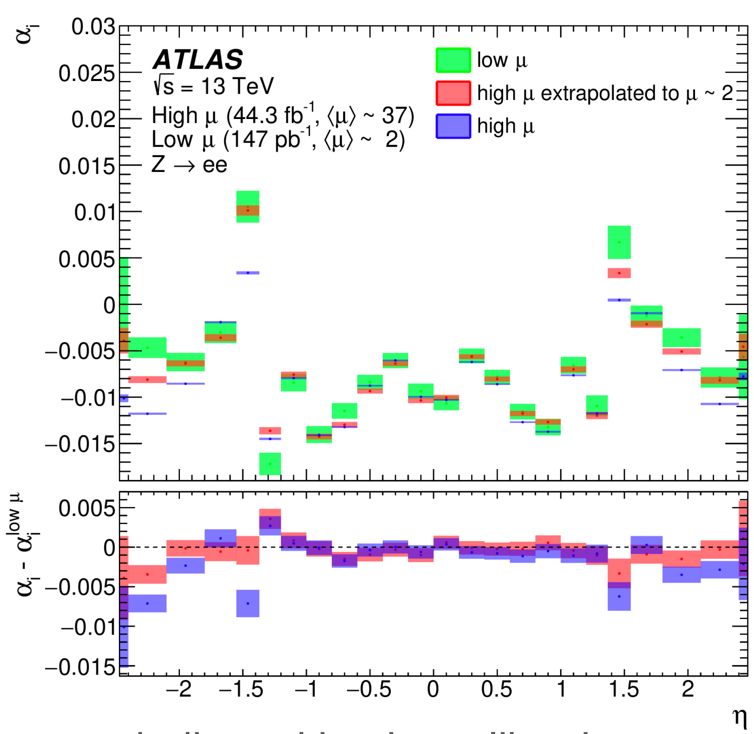
$\sqrt{s}$	5.02 TeV	13 TeV
$\mathcal{L}$ [pb^{-1}]	**255 ± 1%**	**338 ± 0.92%**
< μ >	~2	2 (levelled)
W events	1.45M	4.36M
Z events	111K	366K

Run2-luminosity

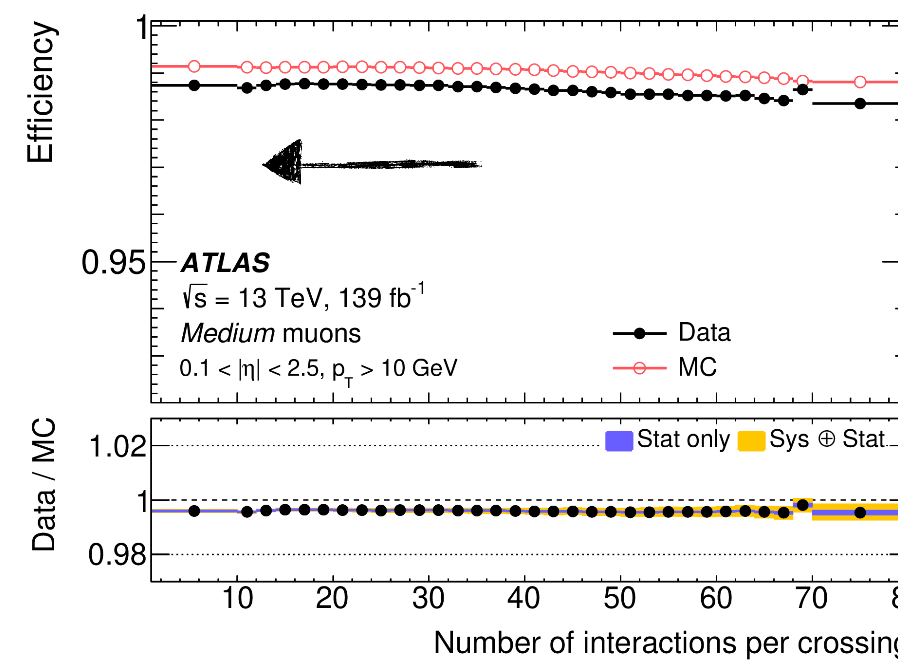


- *Unique* recoil resolution
- Benefit from ***super precise* luminosity** uncertainty
- *Dedicated* set of detector calibration and performances

leptons performance accuracy limited by the Z sample statistic



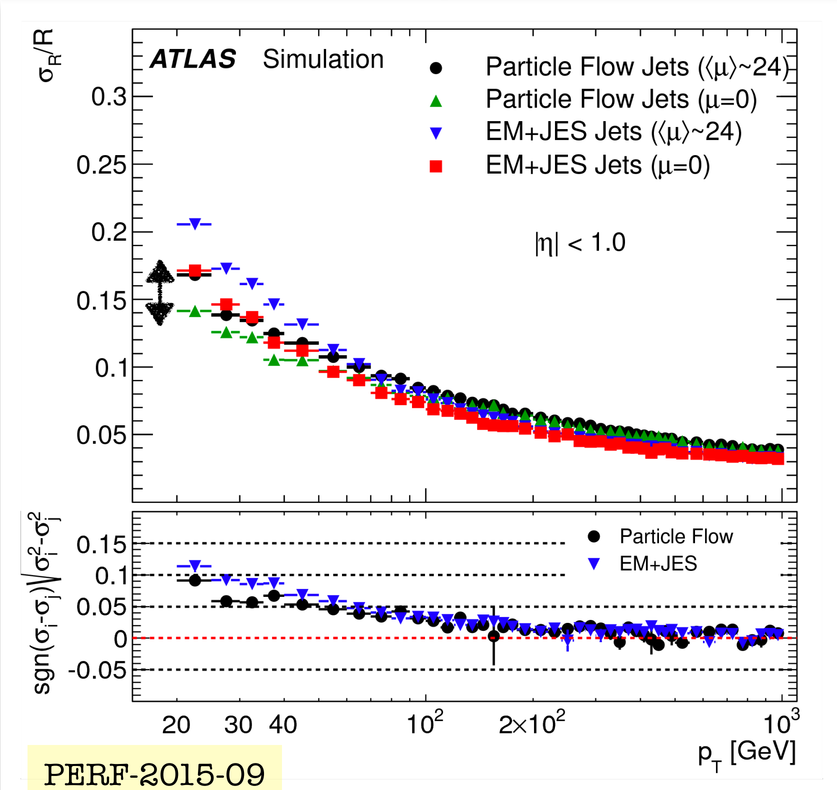
dedicated in-situ calibrations

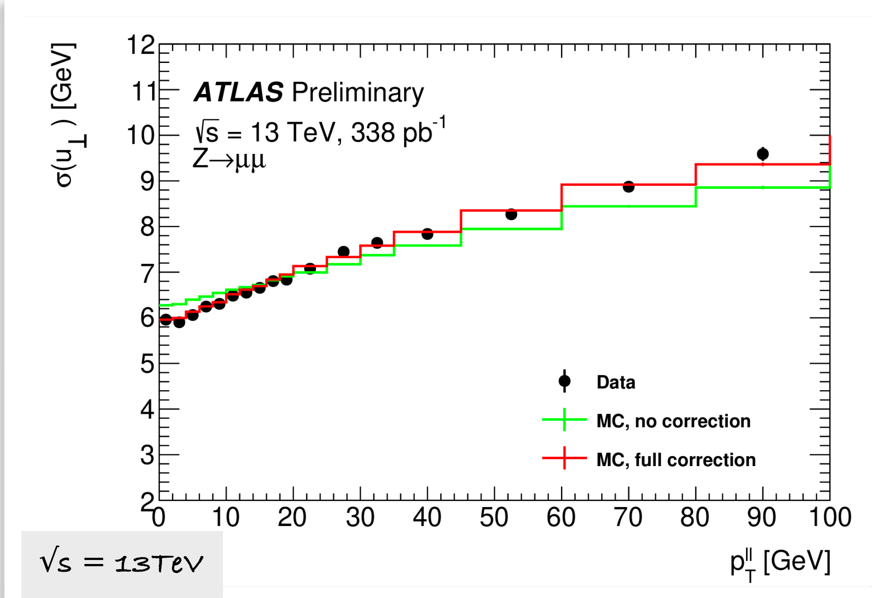


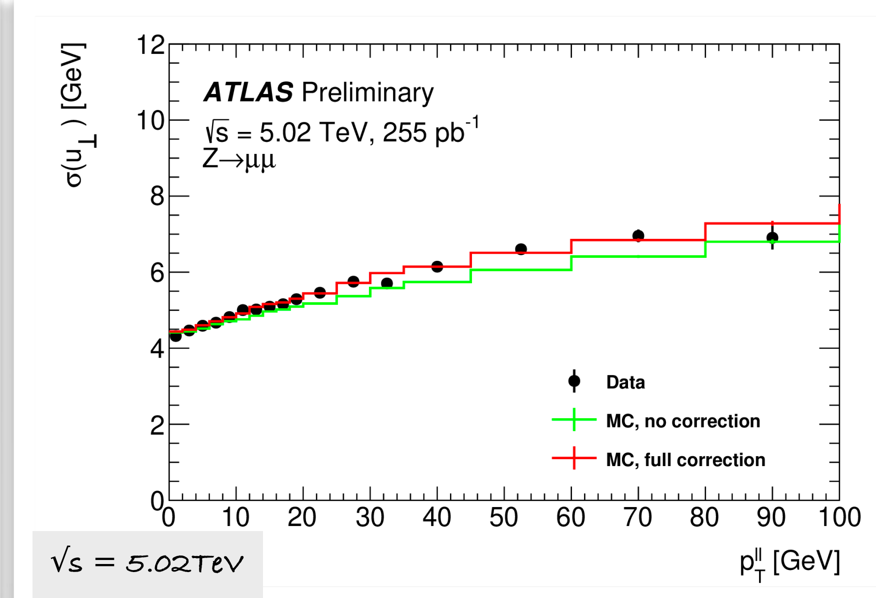
wherever possible extrapolated high-μ to low-μ conditions

Hadronic recoil performances

A) Particle flow objects (**PFOs**) for recoil **reconstruction** *up to 5% improvement in resolution*







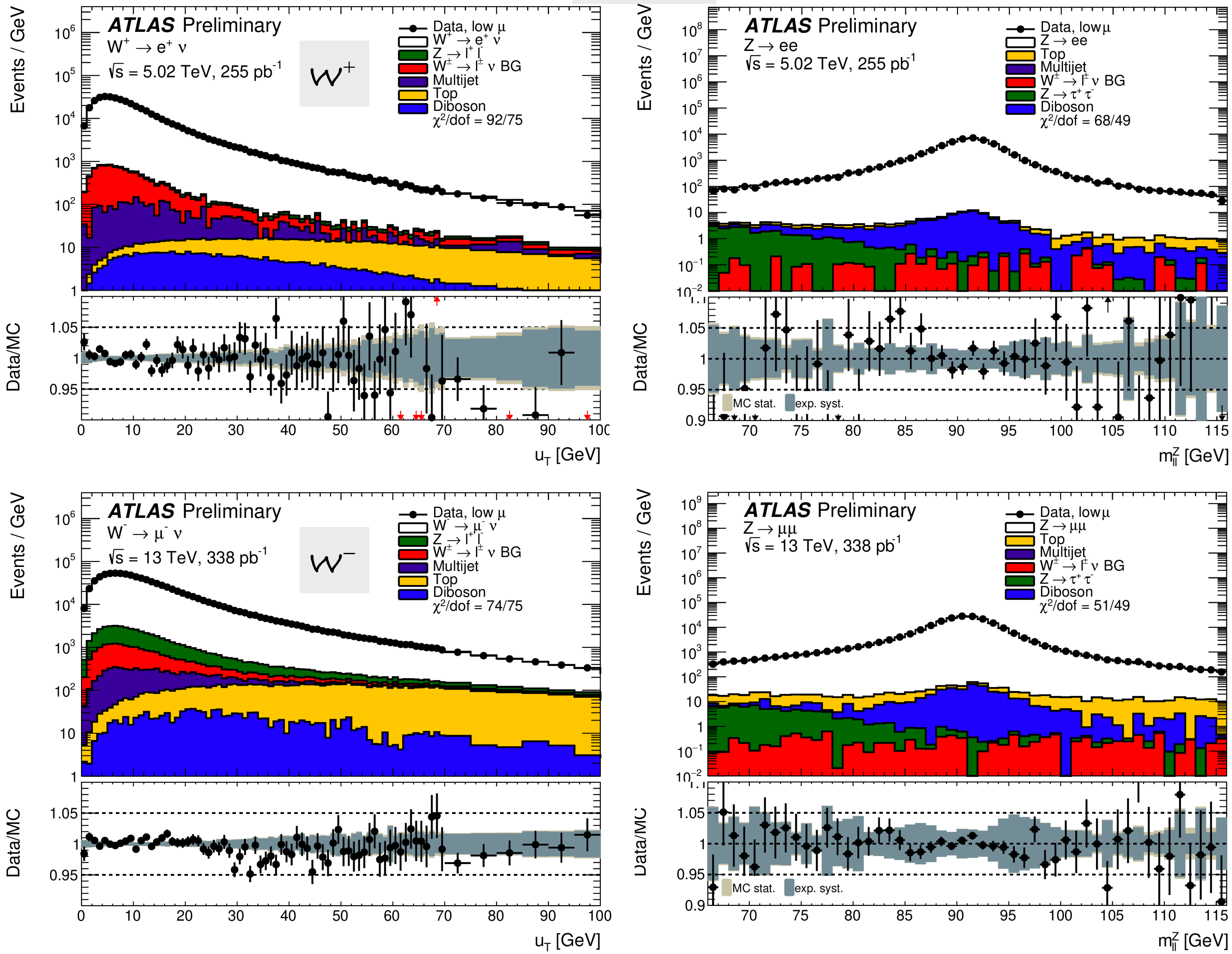
B) in-situ in $Z\rightarrow\ell\ell$ events used to **Calibrate** the recoil response:

- Modelling of underlying activity from data
- Correcting response non-uniformity in the calorimeter (beam displacement, beam-crossing angle. azimuthal angle)
- Equalising response and resolution differences between data/MC
- Correcting for residual non-Gaussian tails in the response

Hadronic-recoil uncertainties have sub-percent level impact on p_T^W < 50 GeV (@ 5TeV limited stat of the Z samples is the dominant source)

Detector level distributions

√s = 5.02TeV

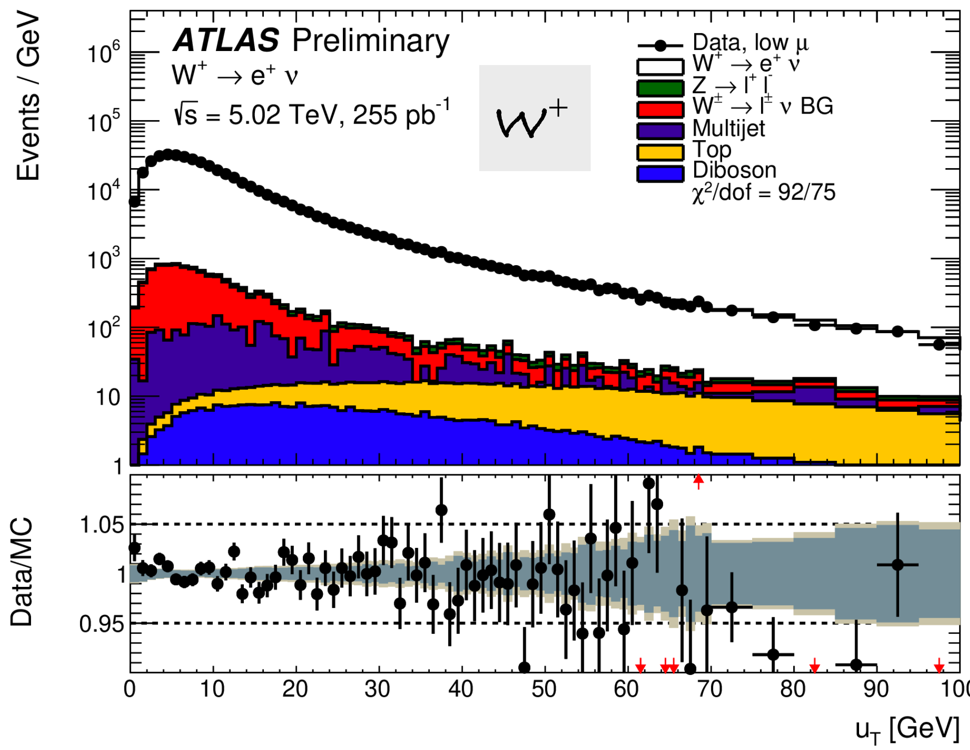


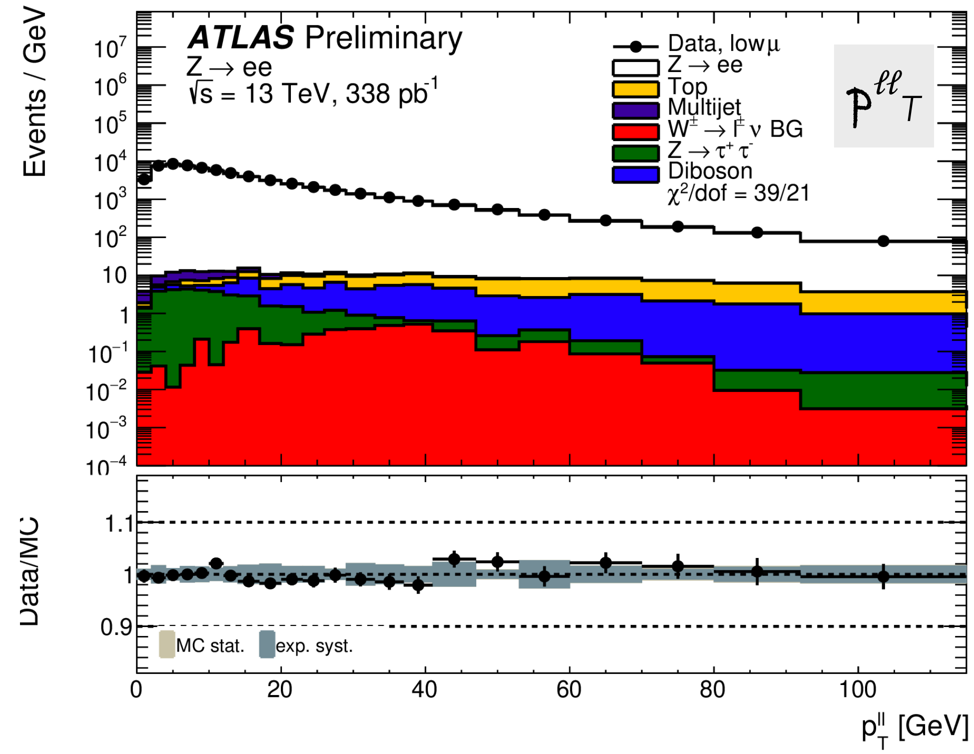
√s = 13TeV

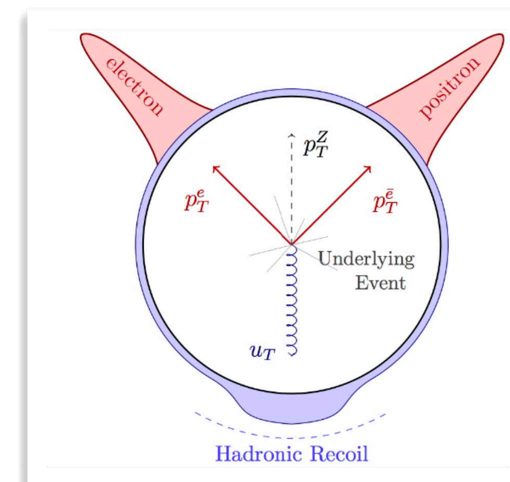
Excellent data/MC agreement

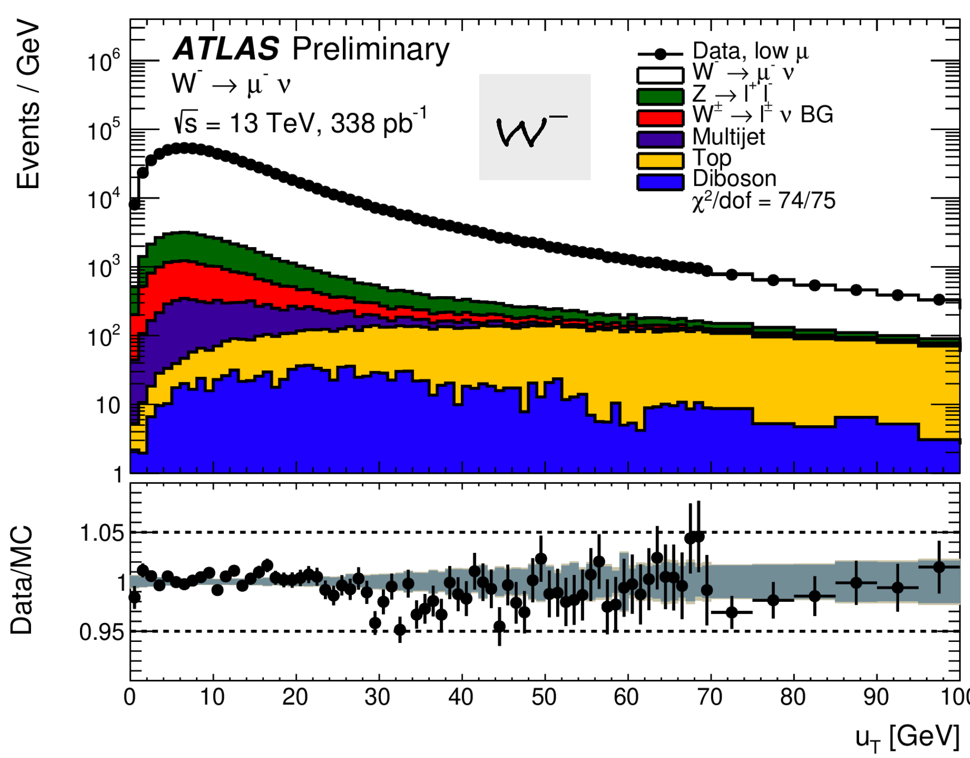
- Multijet background estimated with data-driven improved method
- use experimental sensitivity to optimise the agreement between data and MC for the reconstructed u_T distribution

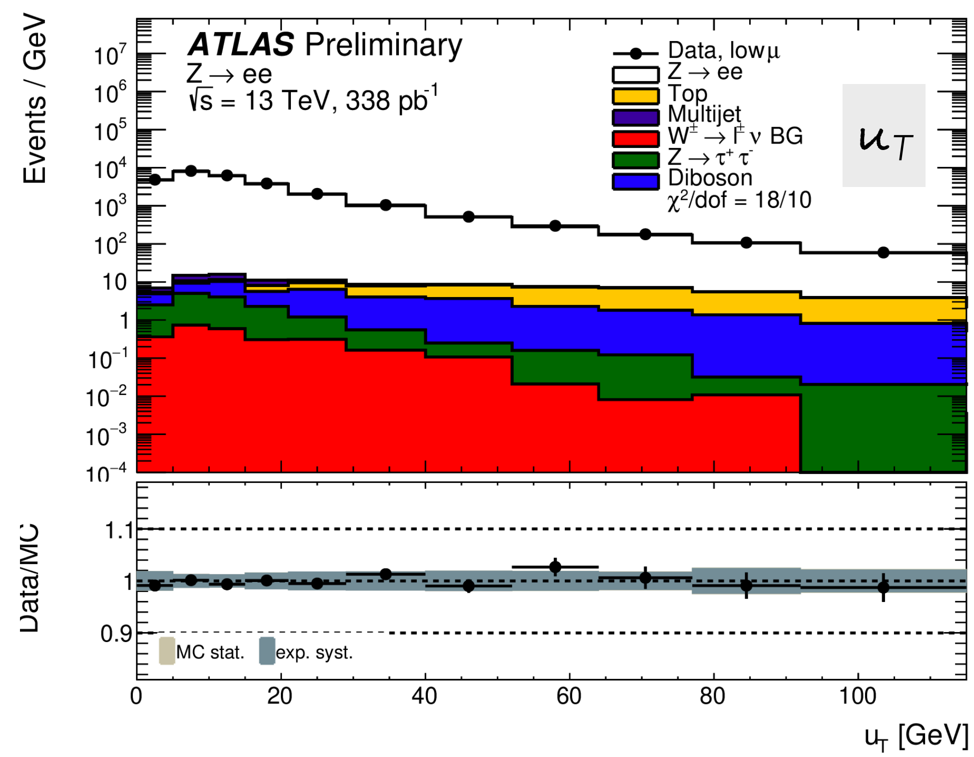
The role of Z sample







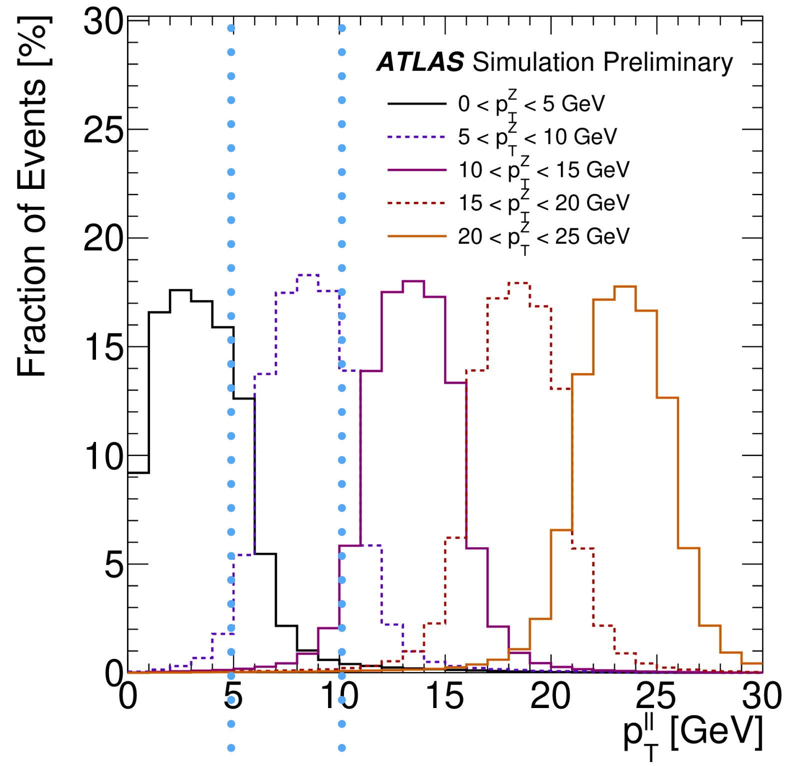


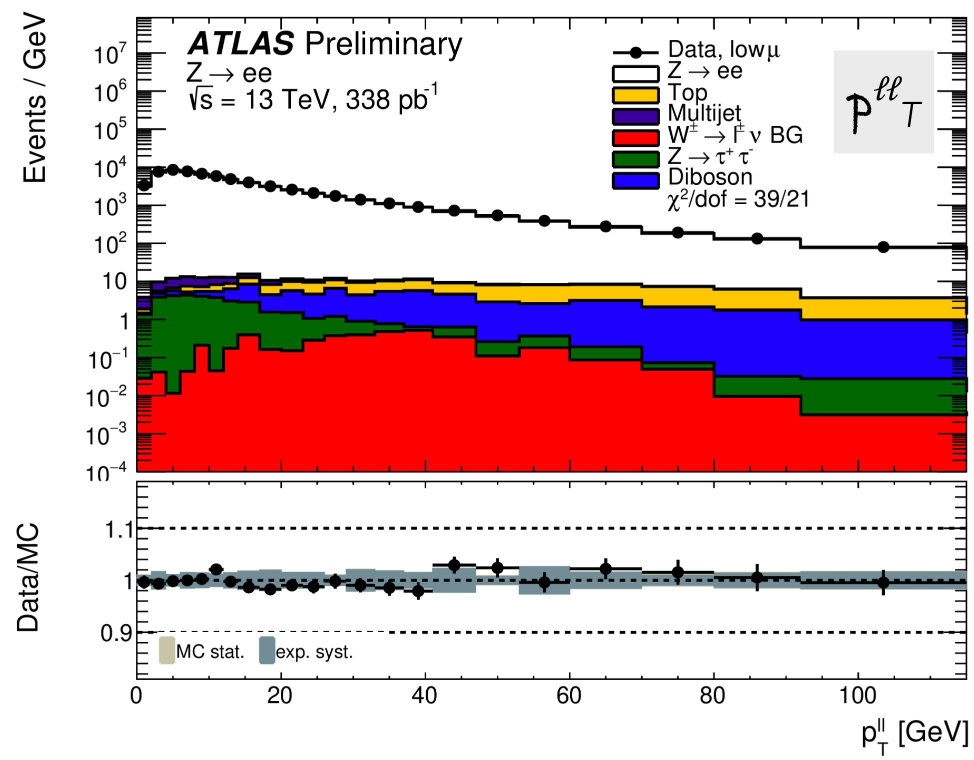


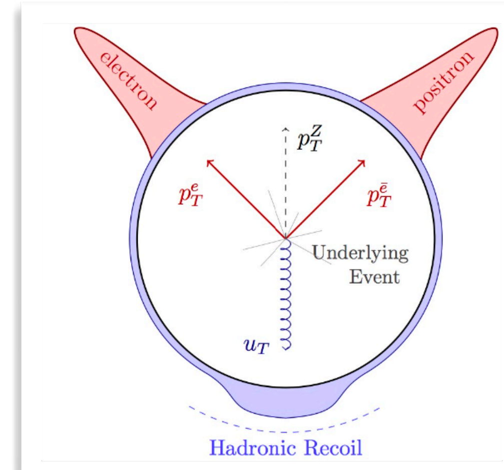
Z boson decay powerful tool to validate measurement of p_T^W

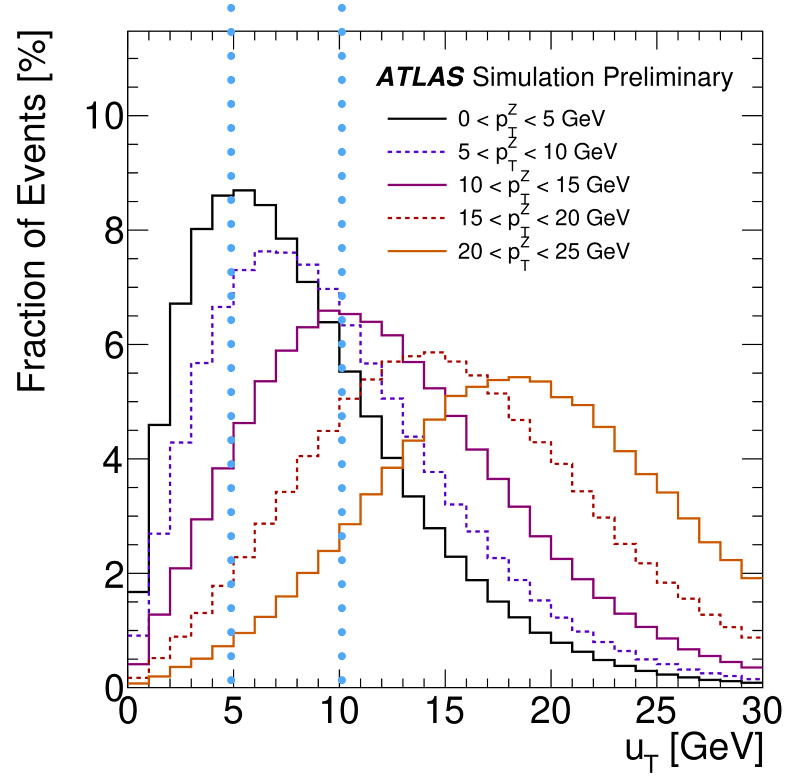
p_T^Z measured either from $p_T(\ell\ell)$ or u_T

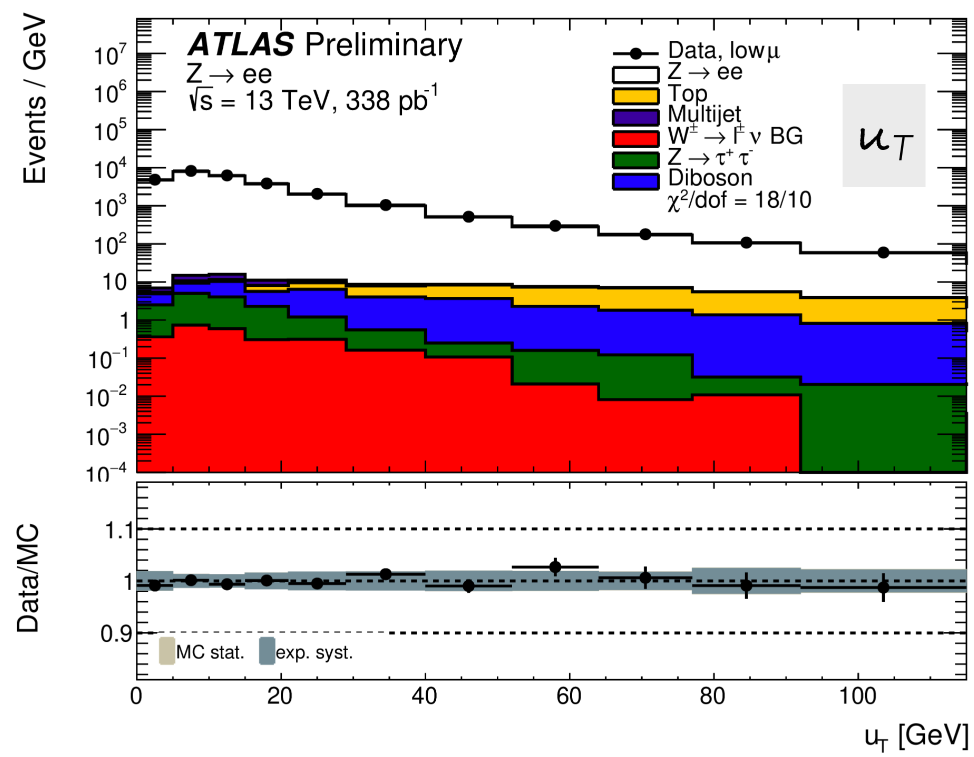
u_T measurement: the challenge











The hadronic recoil resolution leads to significant migrations in u_T
⇒challenges for the unfolding

The measurements

Detector level distributions unfolded at particle level in fiducial volume:

lepton $p_T > 25$ GeV
lepton $|\eta| < 2.5$
W : $p^{\nu}_T > 25$ GeV ; $m_T > 50$ GeV
Z : $66 < m_{\ell\ell} < 116$ GeV

- **Bayesian unfolding** of u_T(W) ; $p^{\ell\ell}_T$ (Z) , separately for e/μ channels
  - Bin width/iterations **optimise to reduce uncertainty of unfolding prior bias**
  - 9 (25) iterations, ⊢7GeV⊣ bin at low p_T^W at 5.02 (13) TeV
  - 2 iterations, ⊢2GeV⊣ bin width at low p_T^Z
- electron and muon channels combined with BLUE, all giving good $\chi 2$

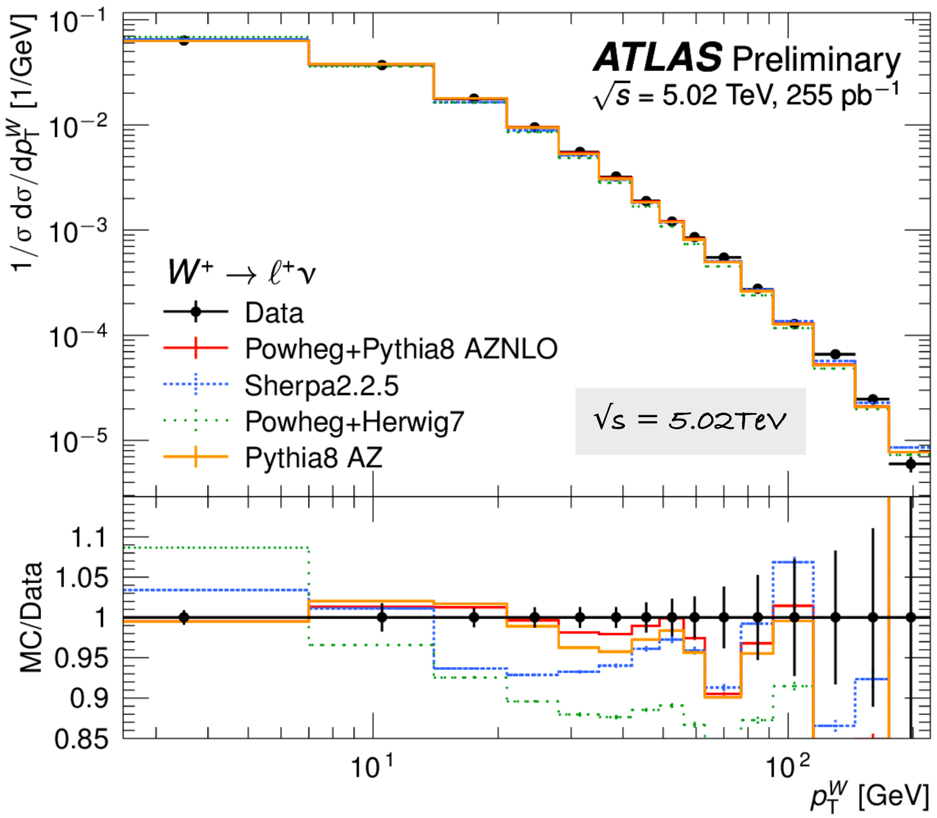
Most precise integrated fiducial measurement of the W± and Z boson @ 5.02 and 13 TeV:

Process	Cross section at $\sqrt{s} = 5.02$ TeV [pb]	Cross section at $\sqrt{s} = 13$ TeV [pb]
$W^- \to \ell\nu$	1385 ± 2 (stat.) ± 5 (sys.) ± 15 (lumi.)	3486 ± 3 (stat.) ± 18 (sys.) ± 34 (lumi.)
$W^+ \to \ell\nu$	2228 ± 3 (stat.) ± 8 (sys.) ± 23 (lumi.)	4571 ± 3 (stat.) ± 21 (sys.) ± 44 (lumi.)
$Z \to \ell\ell$	333.0 ± 1.2 (stat.) ± 2.2 (sys.) ± 3.3 (lumi.)	780.3 ± 2.6 (stat.) ± 7.1 (sys.) ± 7.1 (lumi.)

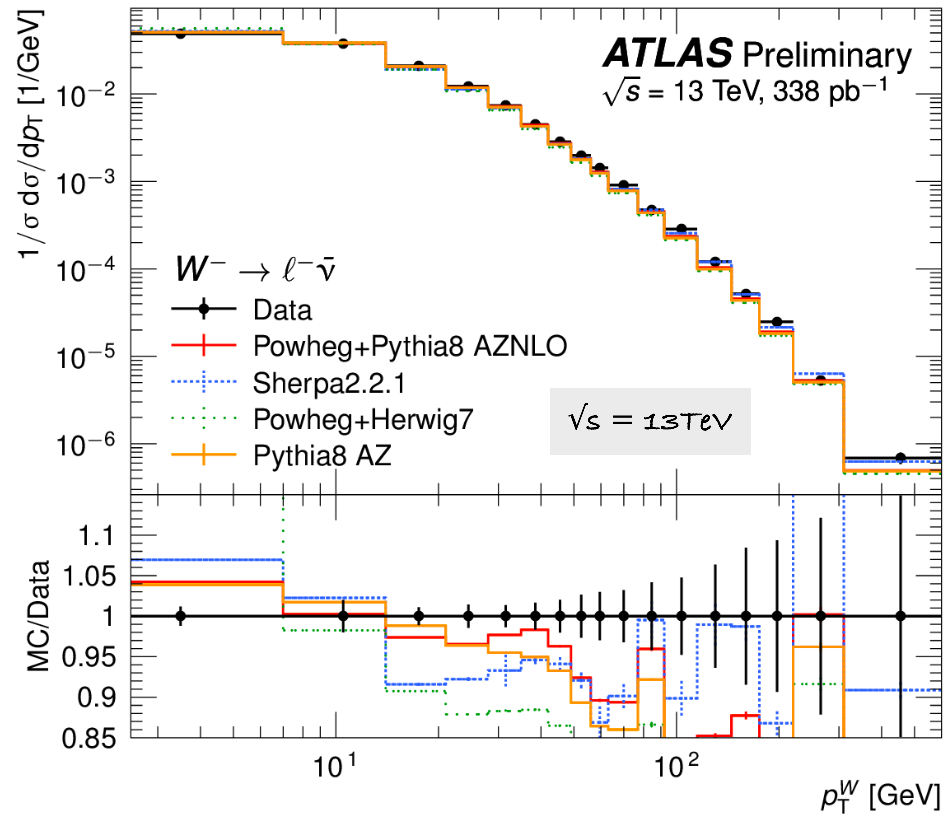
experimental accuracy 0.4 - 0.5 % with 1% lumi
factor of 2 (3.5) better then previous W X-section at 5.02 (13TeV)
good agreement with DYTURBO [NNLO+NNLL] prediction with 3 different PDF sets

W+ and W- transverse momentum measurement

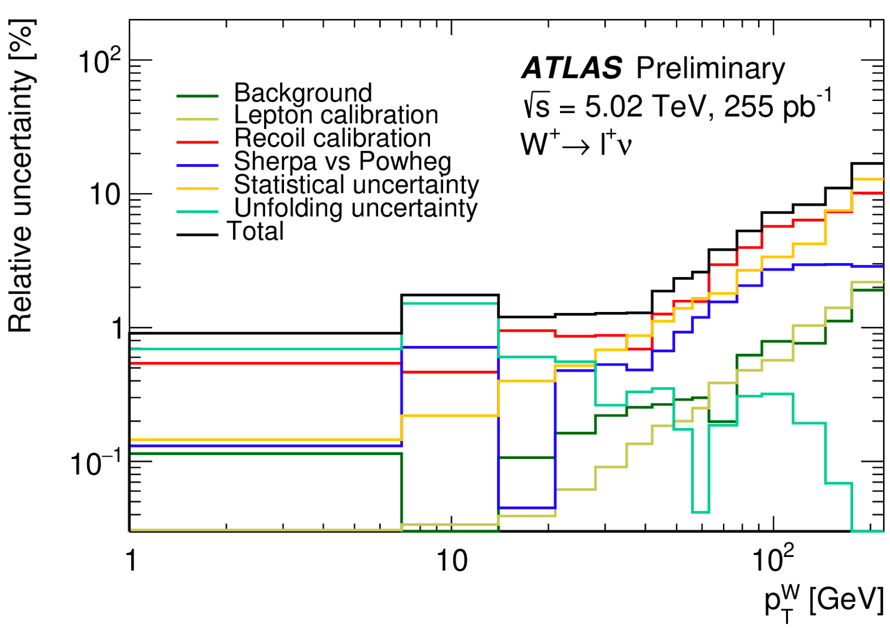
W^+

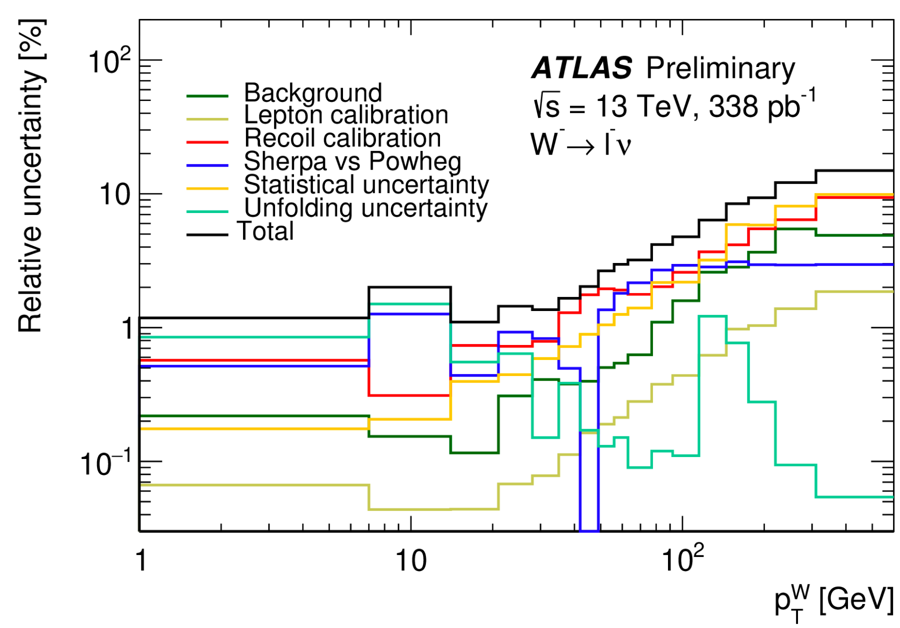


W^-



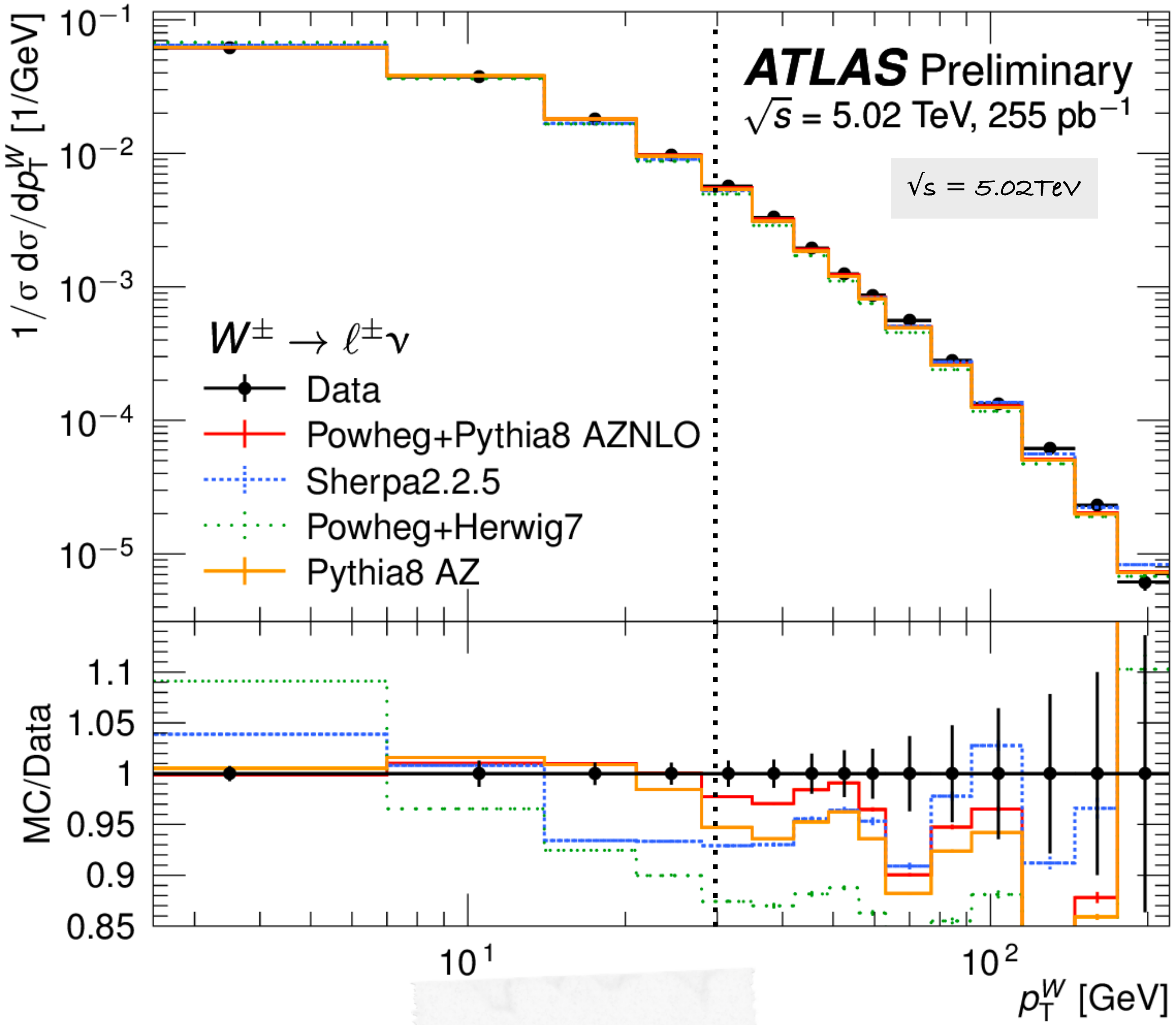
- Normalised differential distributions in data are compared to several predictions



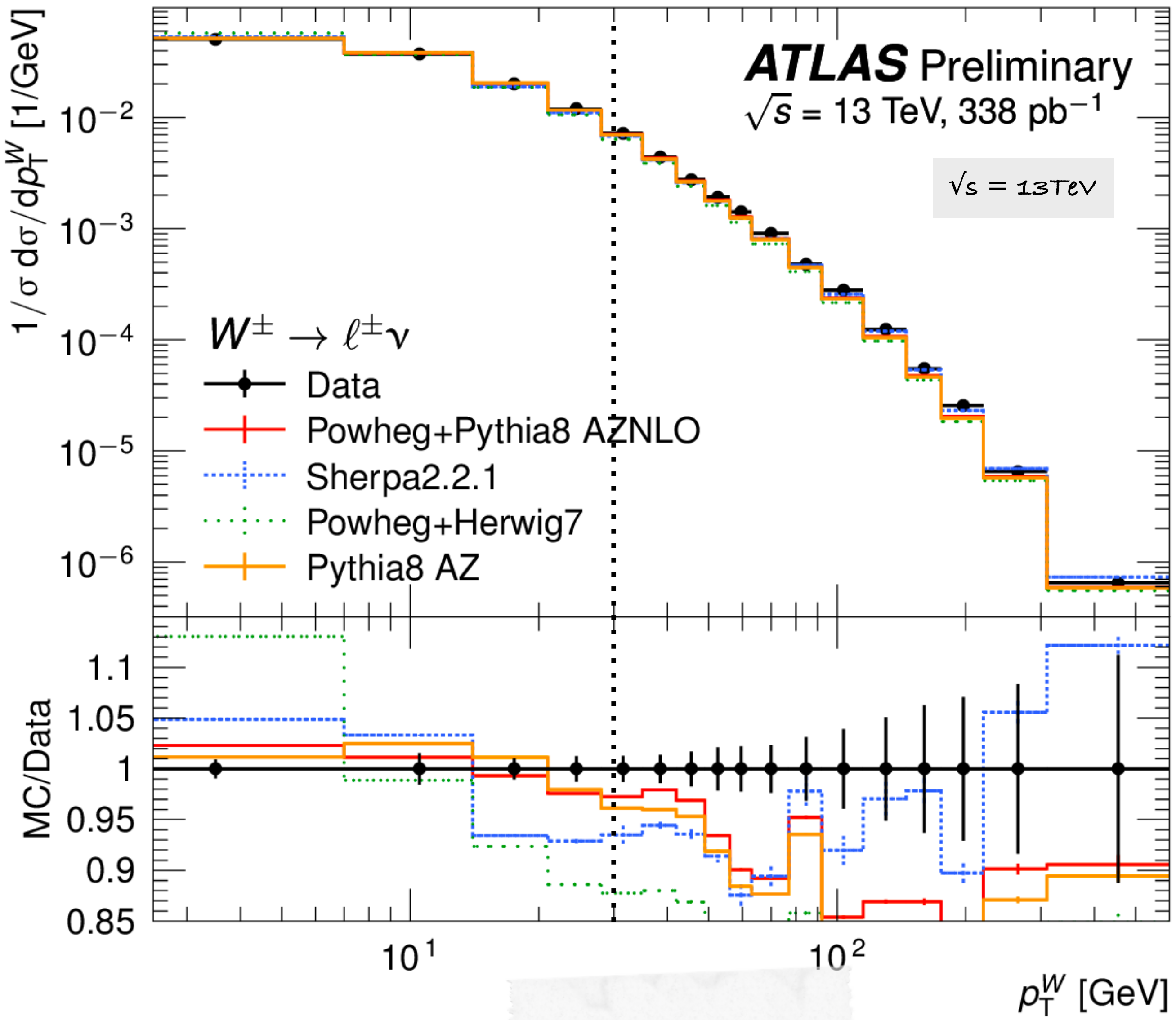


overall data precision:
~ 1% at low pT,
~ 10% towards the end of the spectrum.

Validation of the m_W physic modelling

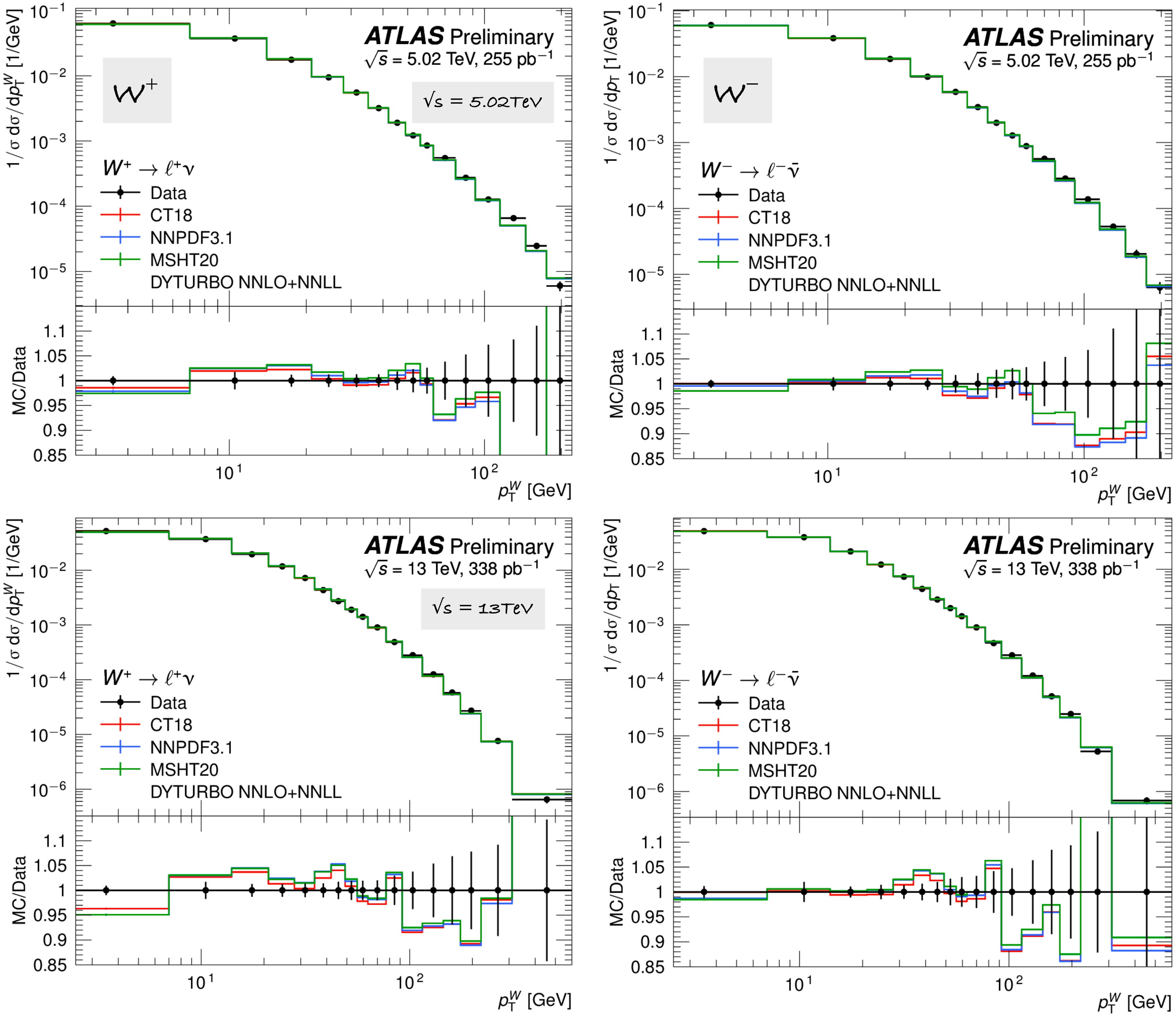


W mass pTW physics modelling [Powheg+Pythia 8 AZNLO ; Pythia 8 AZ] describe well the data in the low-pT region @5TeV



W mass pTW physics modelling [Powheg+Pythia 8 AZNLO ; Pythia 8 AZ] a bit worst agreement @13TeV ⇒ PS retuning needed.

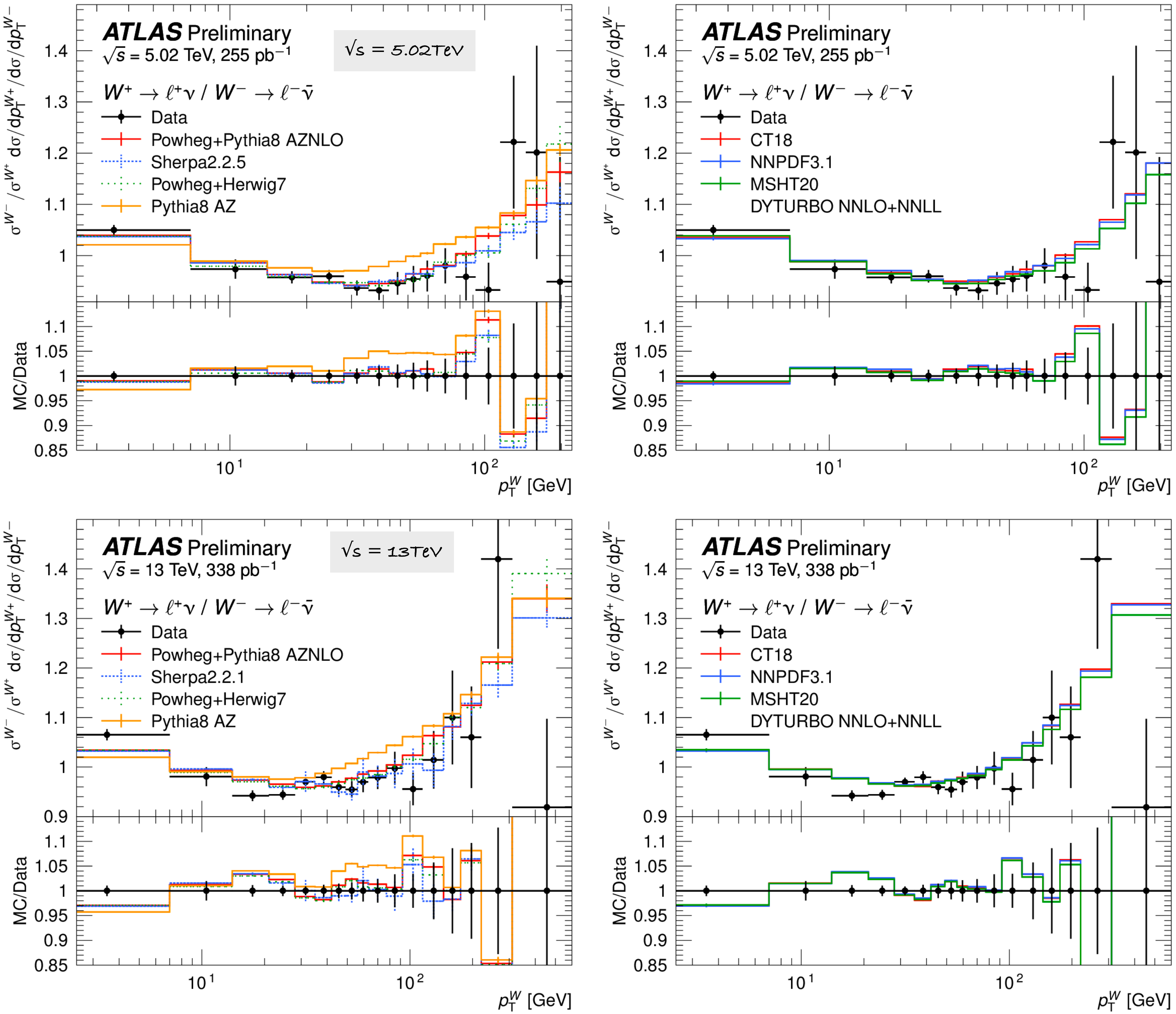
W+ and W- transverse momentum measurement



- Data distributions are compared with DYTURBO predictions [NNLO + NNLL]
  - Effect of PDF estimate comparing 3 recent PDF sets

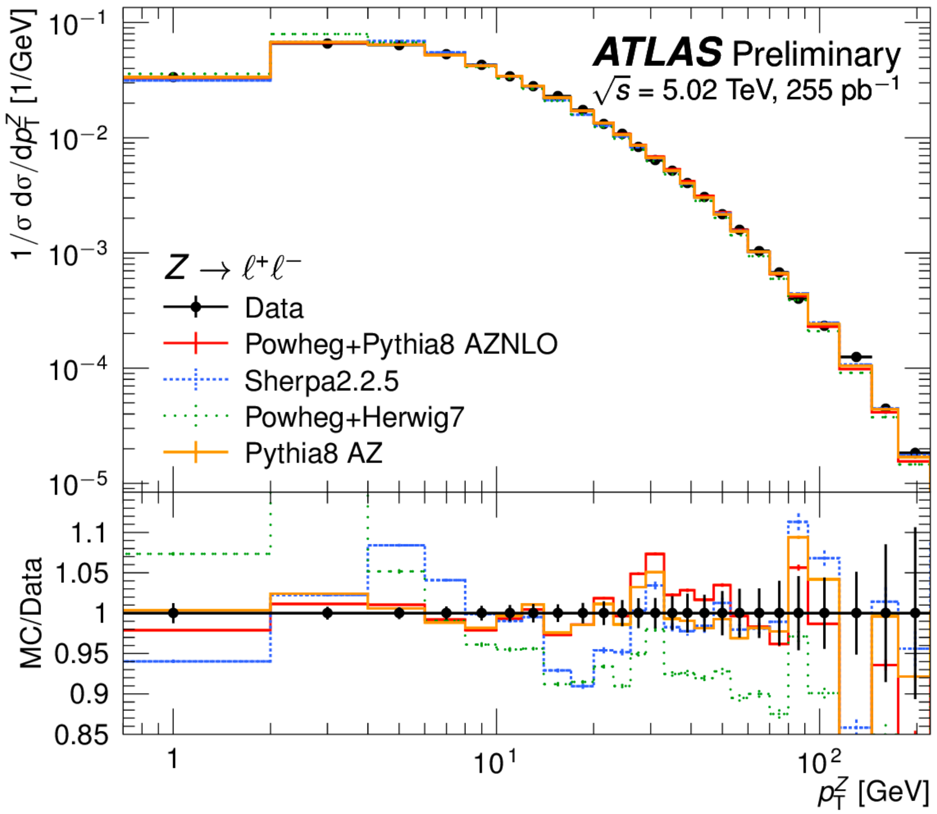
reasonable good agreement in the whole spectra
→showing the improvements on analytic resummation programs!

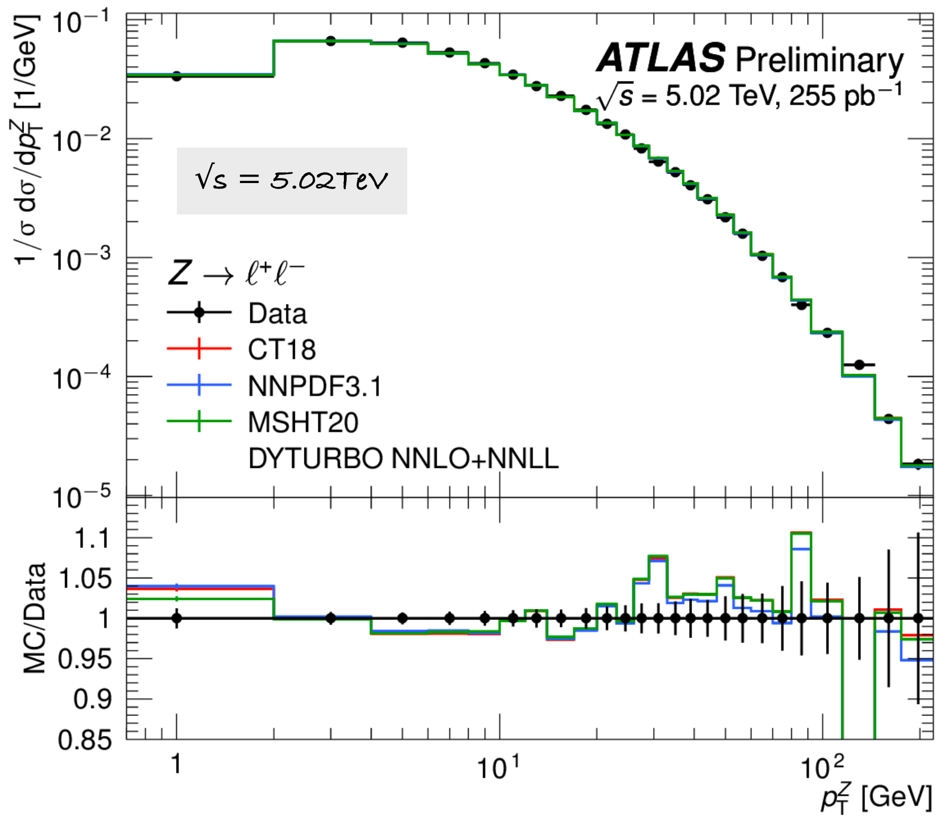
W^+/W^- ratio

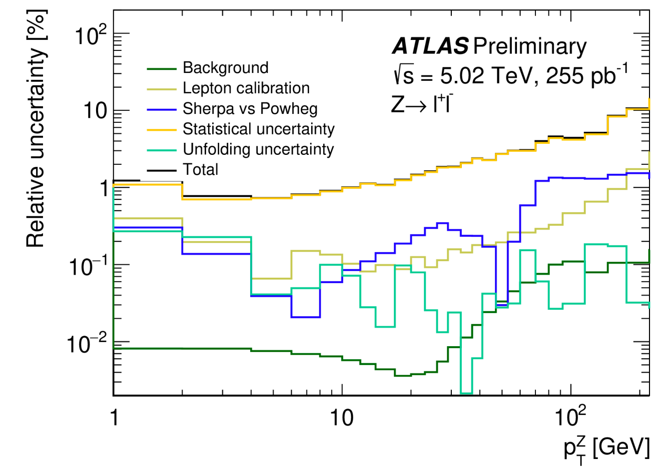


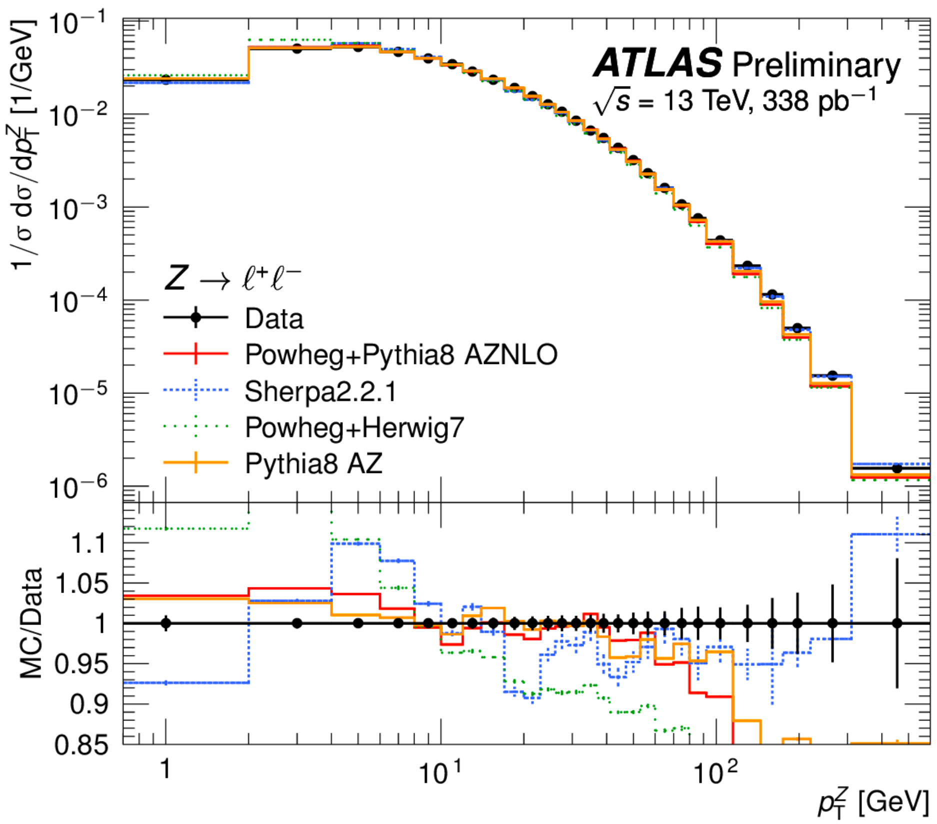
The W+ /W− ratio is expected to be relatively insensitive to universal resummation effects, but the low-pT range is sensitive to the different initial quark flavours. Exp precision ~ 1%

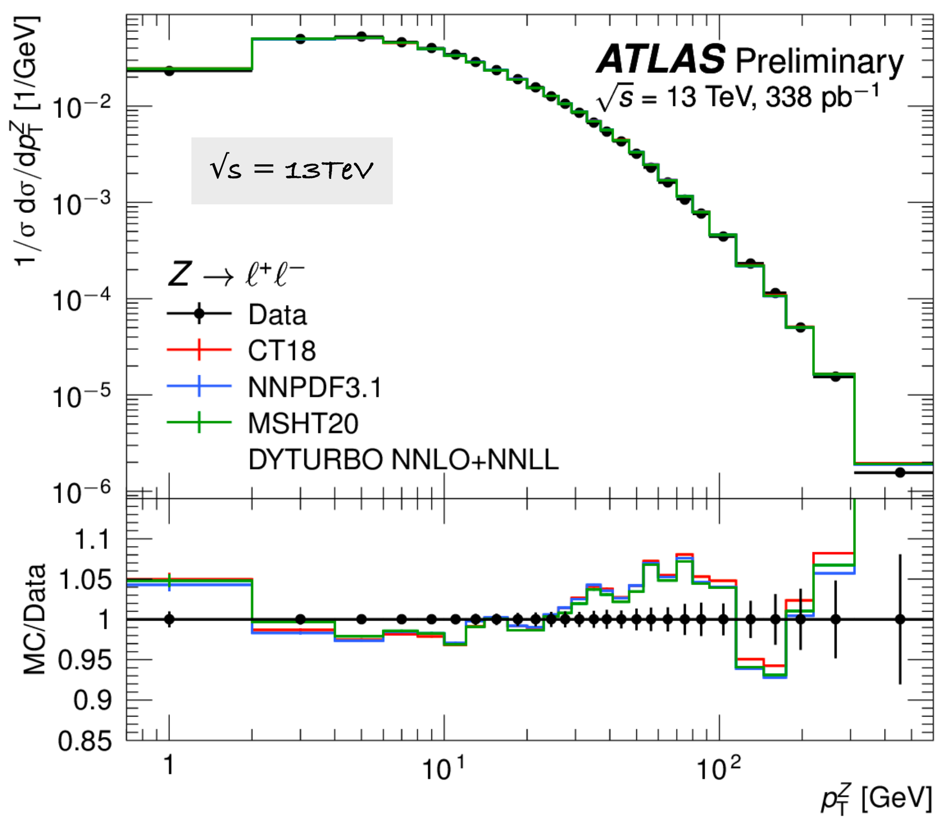
Z transverse momentum differential measurement

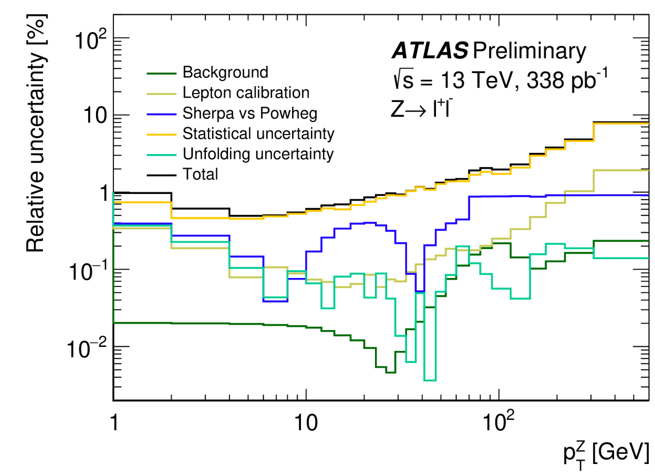












The comparison to MC sample/resummed predictions shows a variety of deficiencies most of which are common for all vector bosons. The agreement is better at $\sqrt{s}$ = 5.02 TeV

The "new" m_W physics modelling

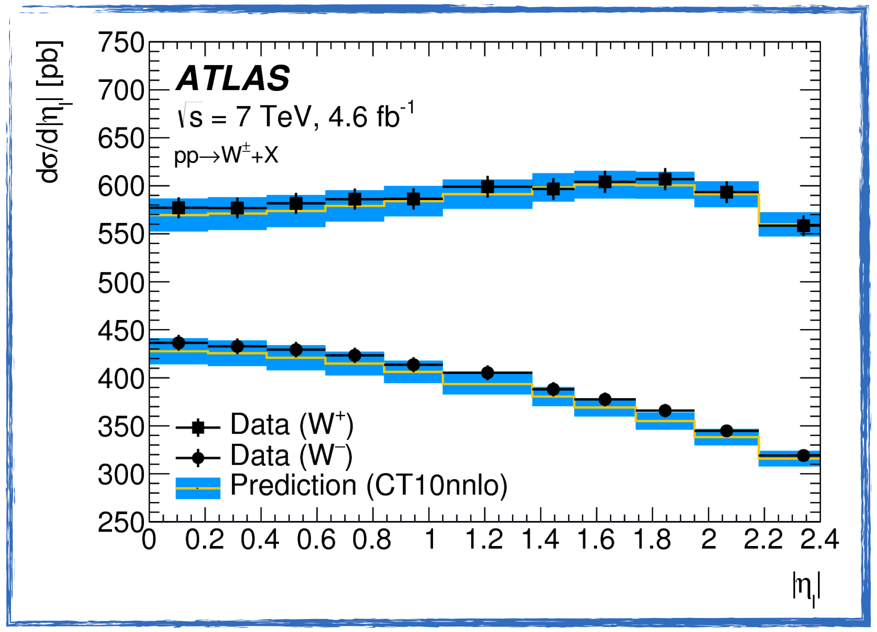
- Recent Unique set of high-precision $d\sigma/dp_T^W$ cross section at $\sqrt{s}$ = 5.02 and 13TeV **validate** the "week point" of the m_W physics modelling

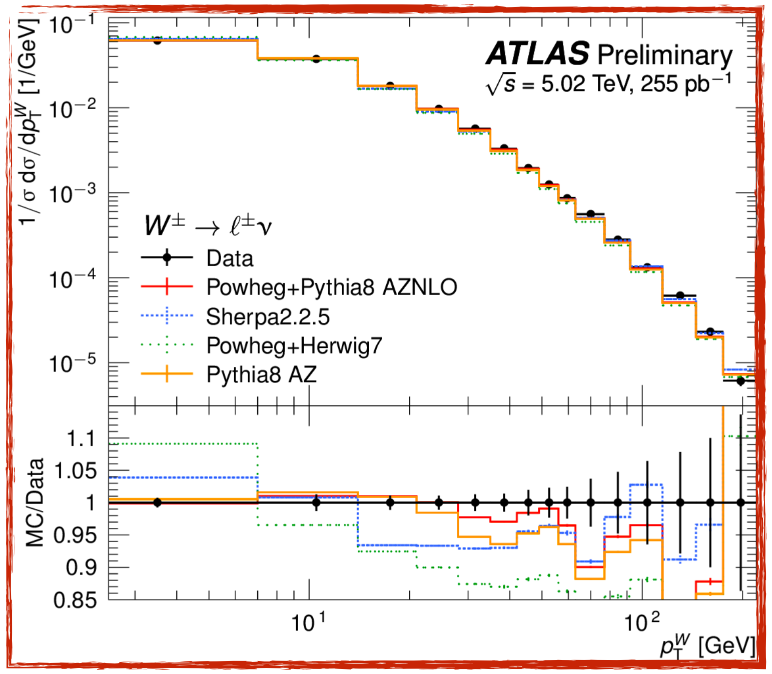
$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

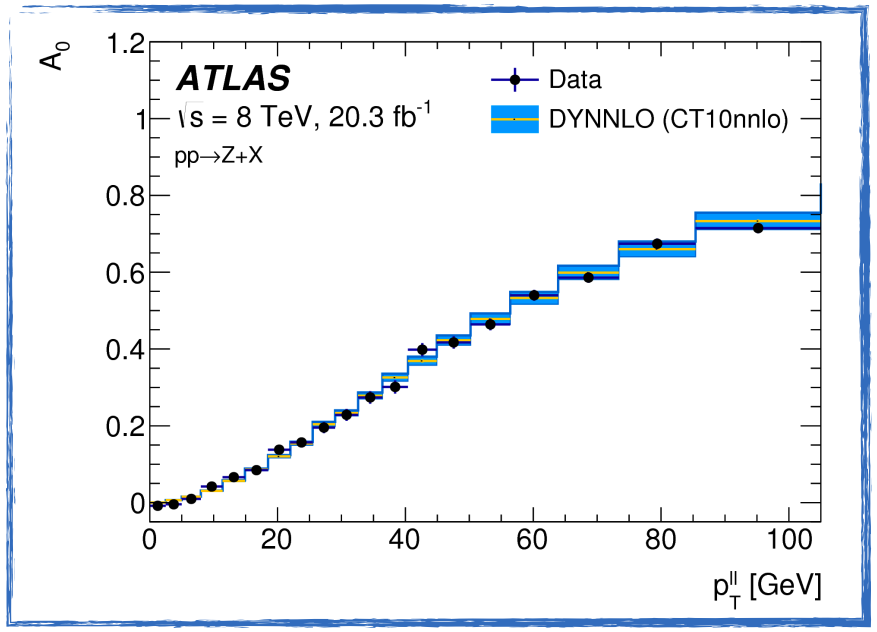
Breit-Wigner

NNLO pQCD

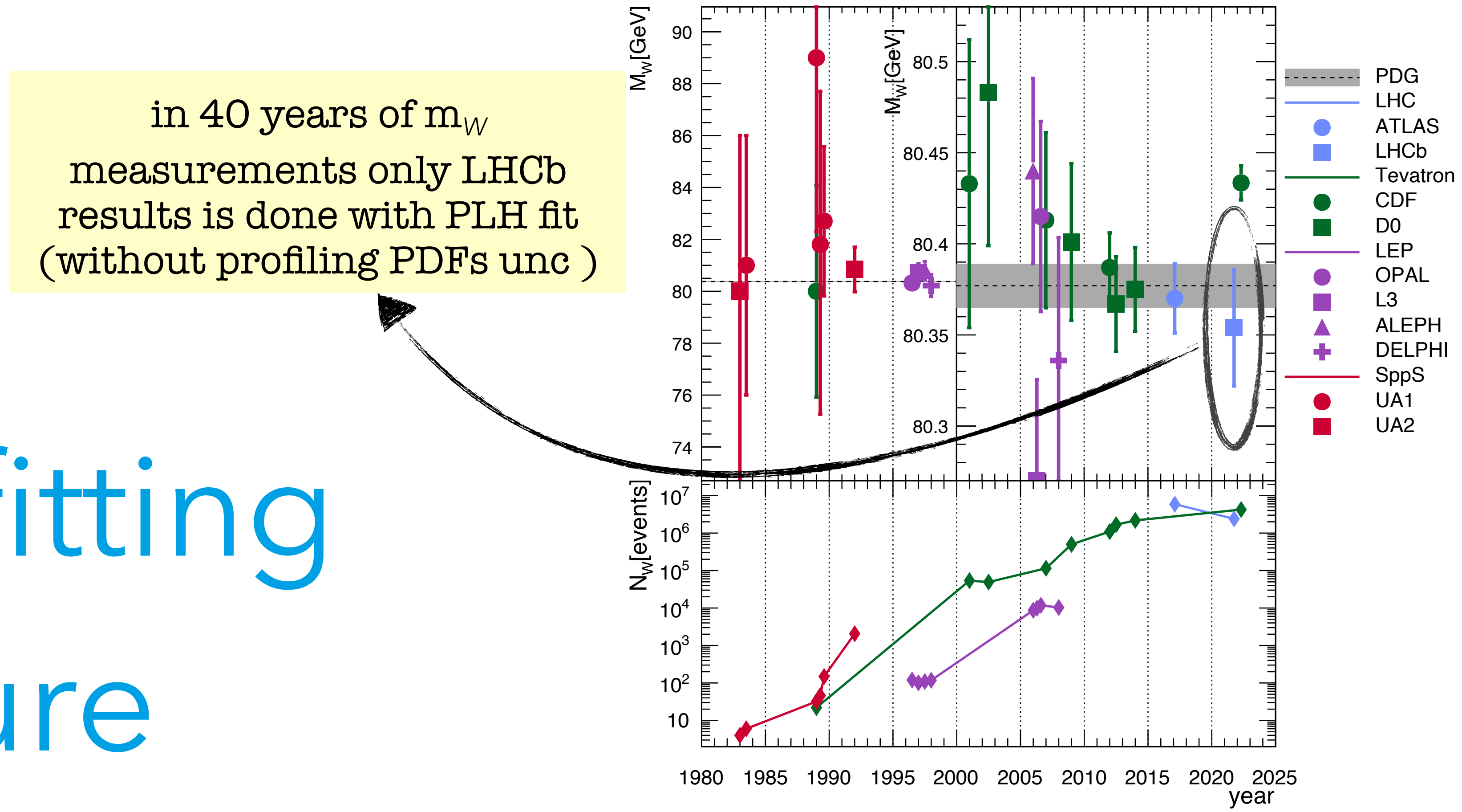
Parton Shower







p_T^W in data measured with 1% precision



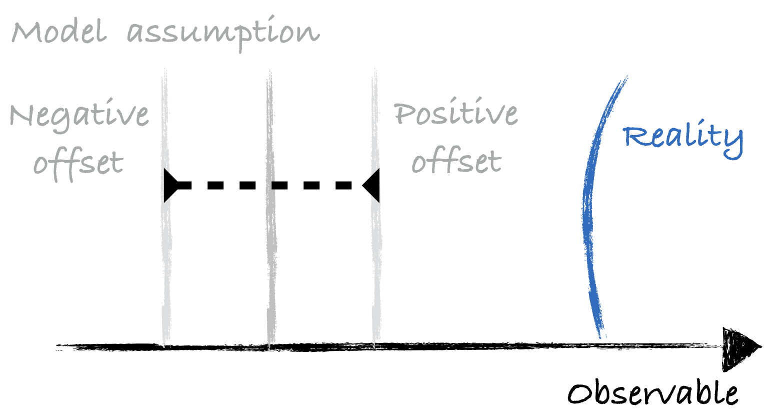
Improved fitting procedure

Revisit ATLAS measurement with profile likelihood (PLH) fitting

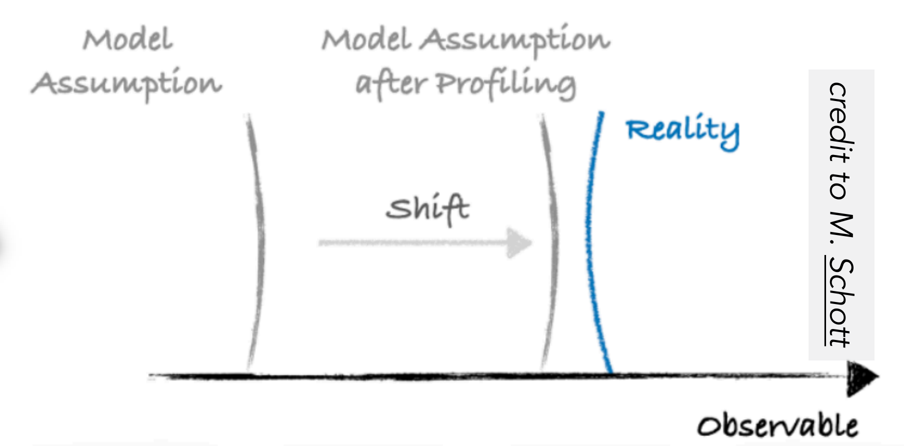
- Advantage:
  - (in situ) constrain experimental & modelling systematic uncertainties
  - + adding modern PDF sets
- Disadvantage:
  - Computational expensive
  - Several 1000 Nuisance Parameter (NP) → robust systematic model

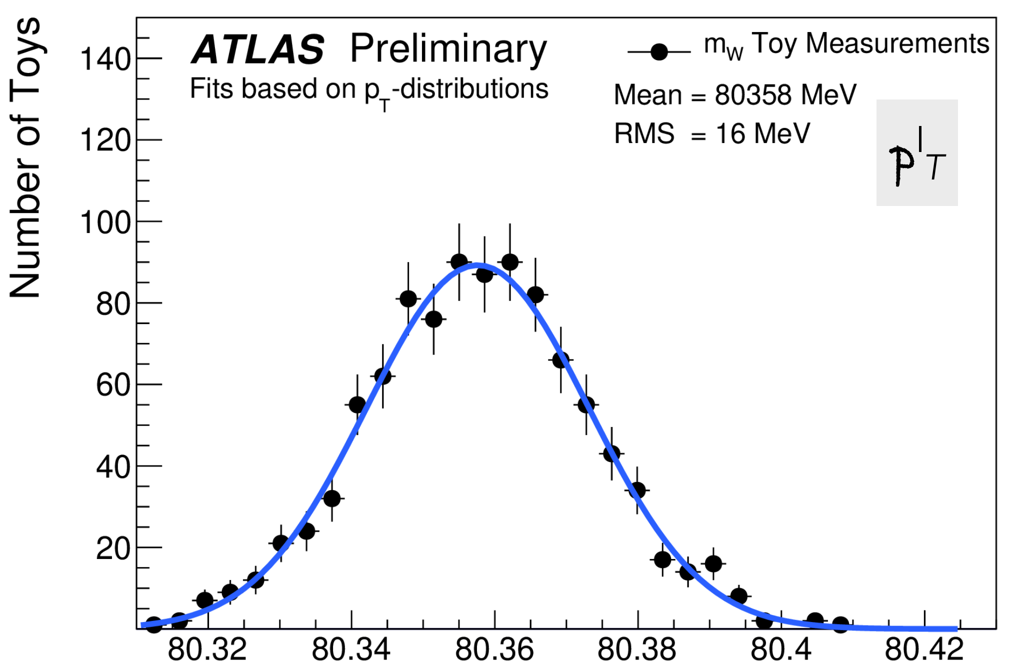
The improvement of the analysis

χ^2 offset fit

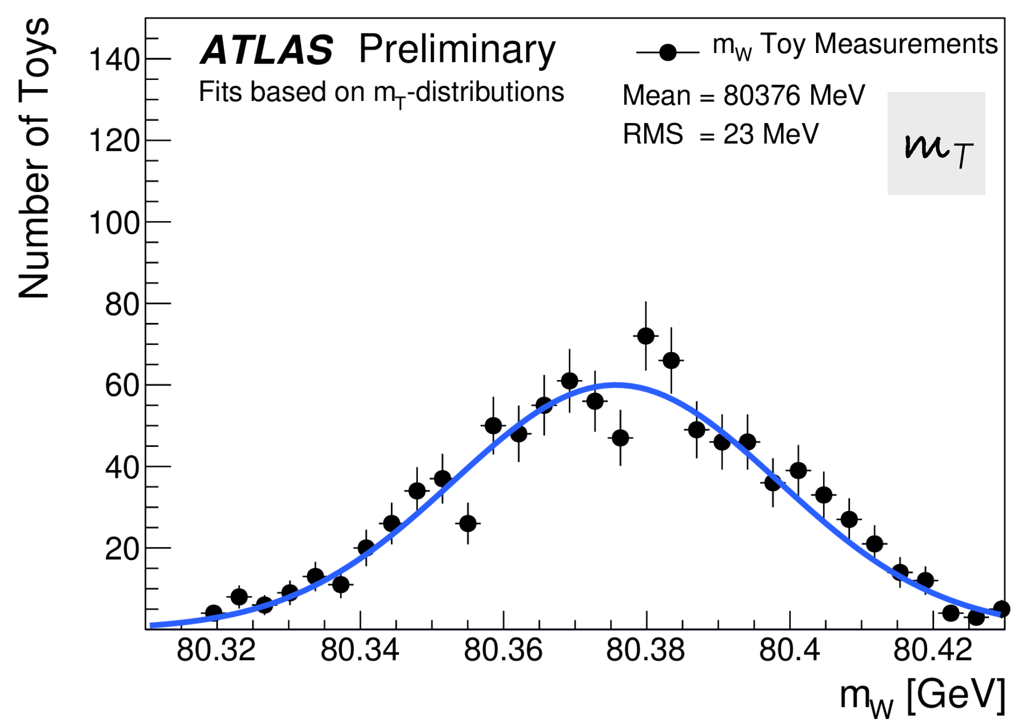


Profiled Likelihood fit





MC Toy study of sys. spread using CT10 PDFs



PLH allows simultaneous determination of POI together with NP taking account correlation in each category

expected allowed shift m_W ±16 (±23) MeV for p^l_T (m_T)

Rigorous review of the analysis

- New data-driven multijet Background estimation
  - Δm_W =1.9 MeV and reduction unc. by 2 MeV
- Better evaluation of EW uncertainties
  - Increase of 1-2 MeV unc.
- Recovering data in the electron channel
  - Increase statistics by 1.5%
- Add parametric uncertainty on $\Gamma(W)$

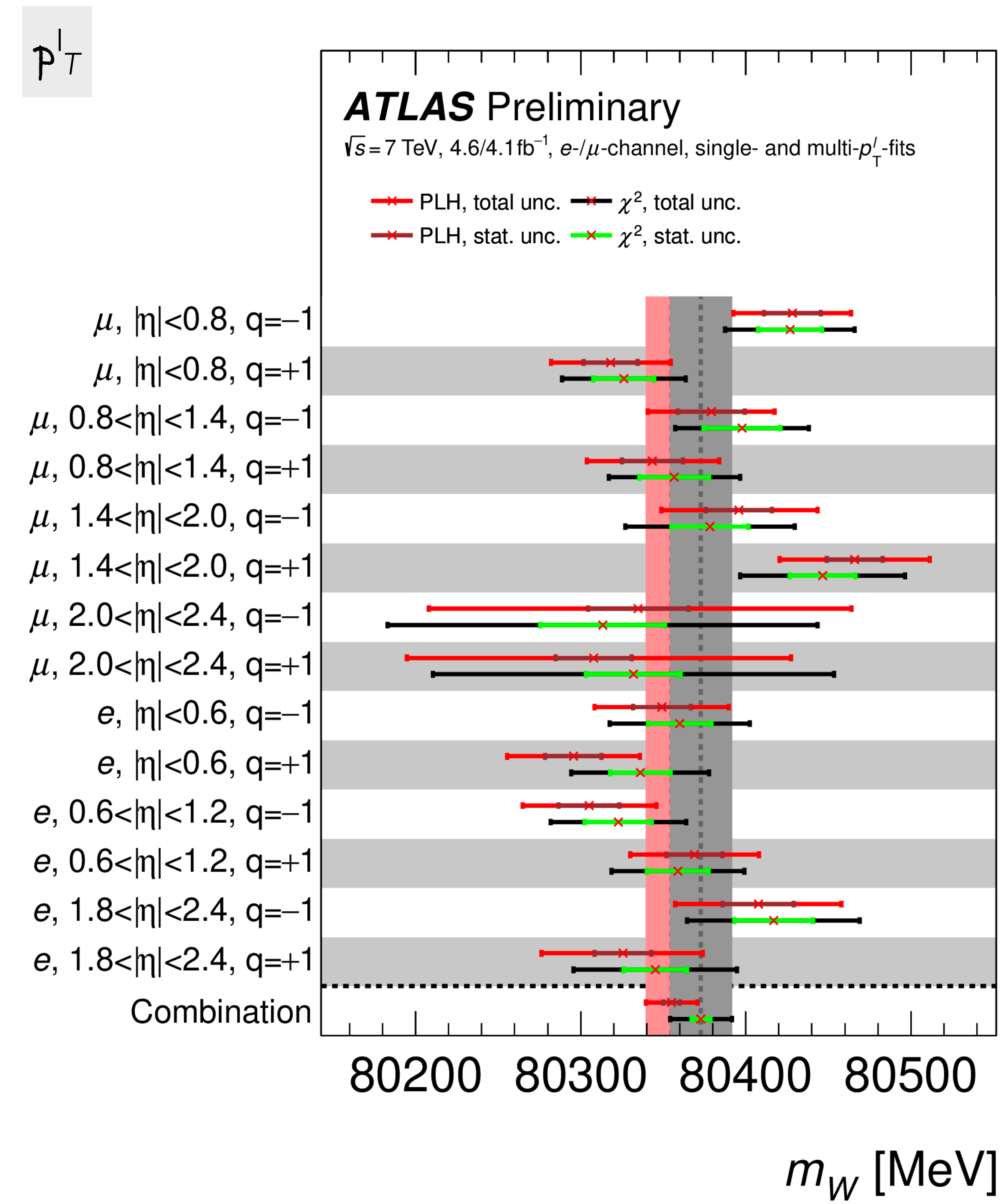
Overall fixes/improvements result in only ~ 2 MeV impact on m_W

Test consistency PLH fit

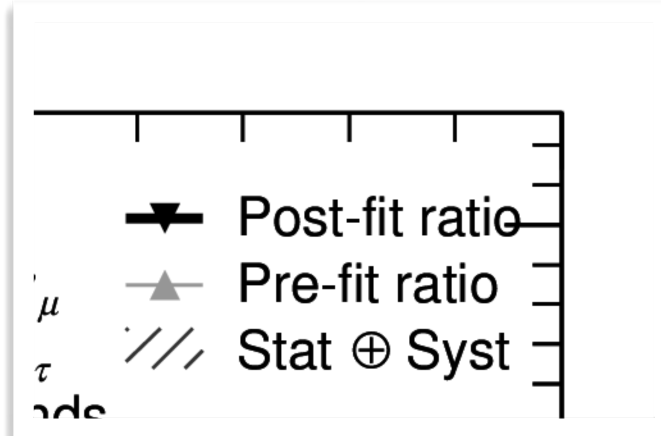
- PLH fit **m_W = 80355.1 ± 15.6 MeV** (CT10nnlo PDF)
  - Δm_W = -14.4 MeV (**m_W^{2017} = 80369.5 ± 18.5 MeV)**
  - Profiling of systematic uncertainties reduce δm_W by 15%

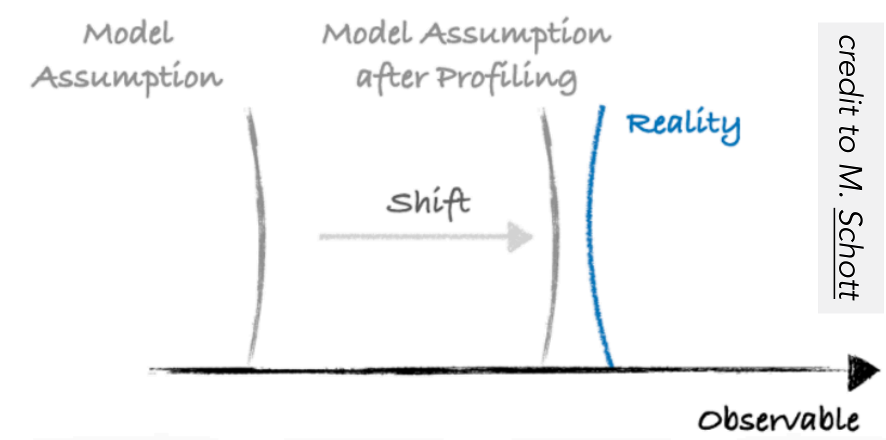
Δ(m_W) well within the expectation from Toys studies.

PLH fit validation using CT10 PDFs

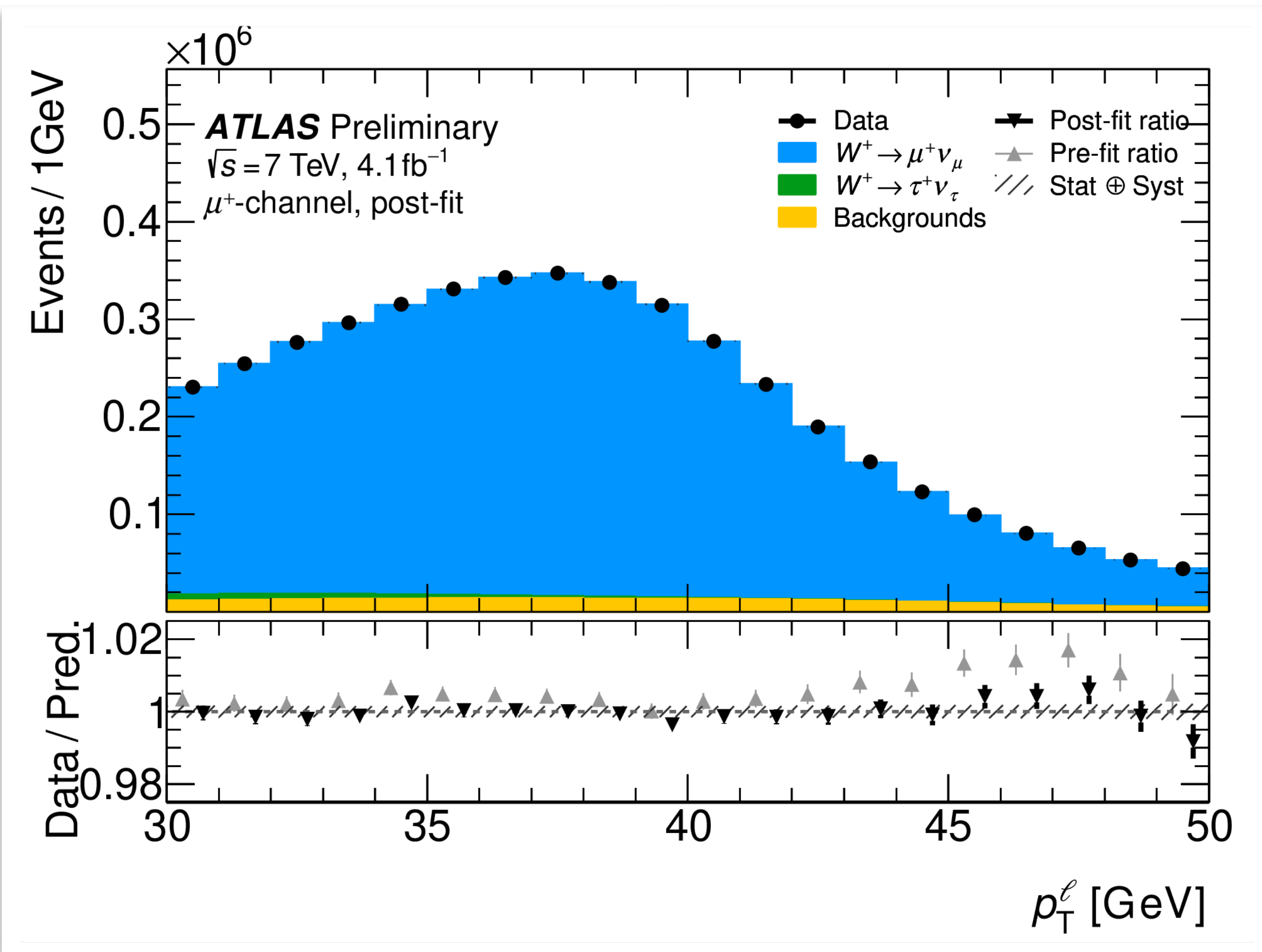


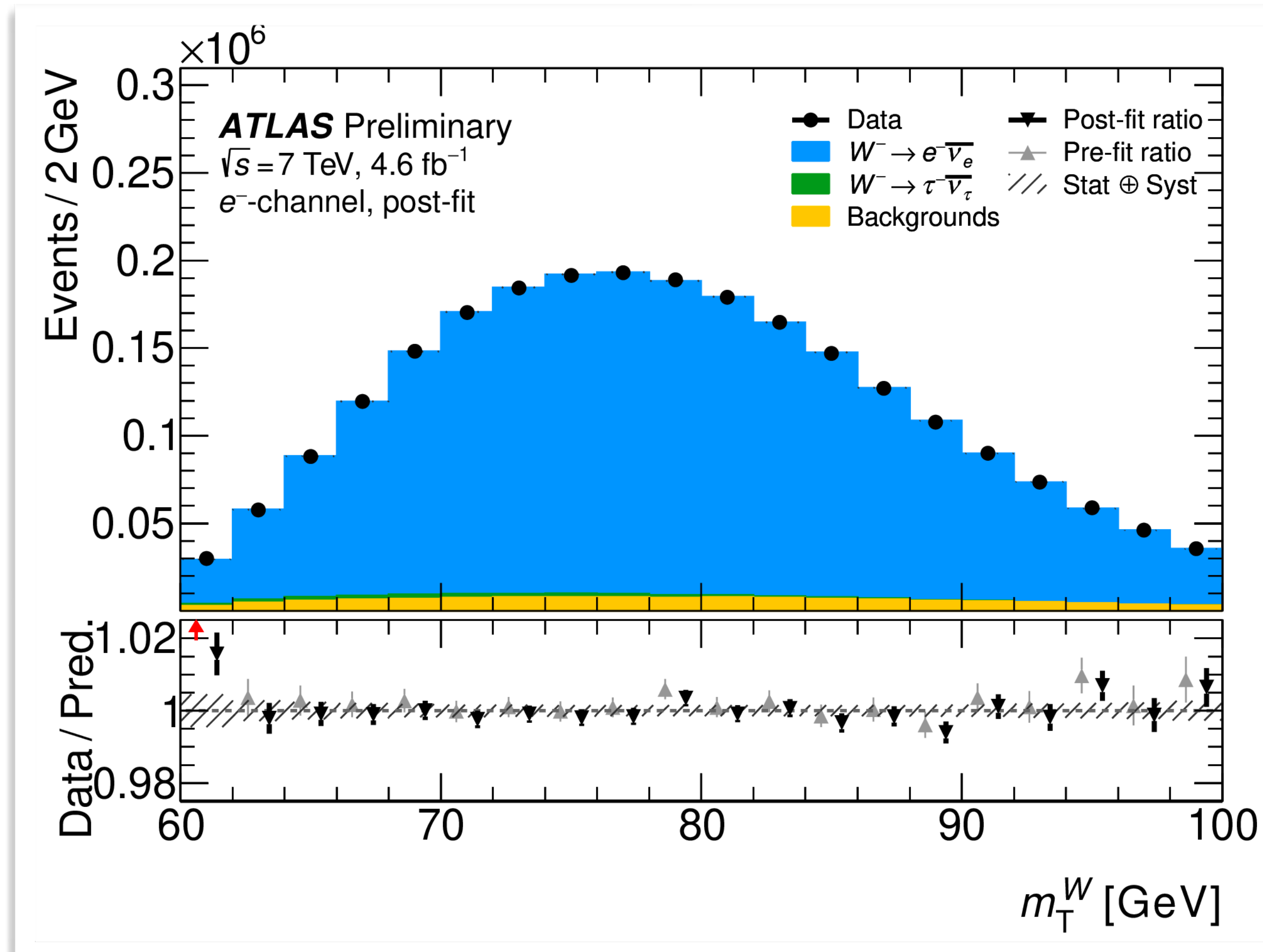
Post fit PLH observable





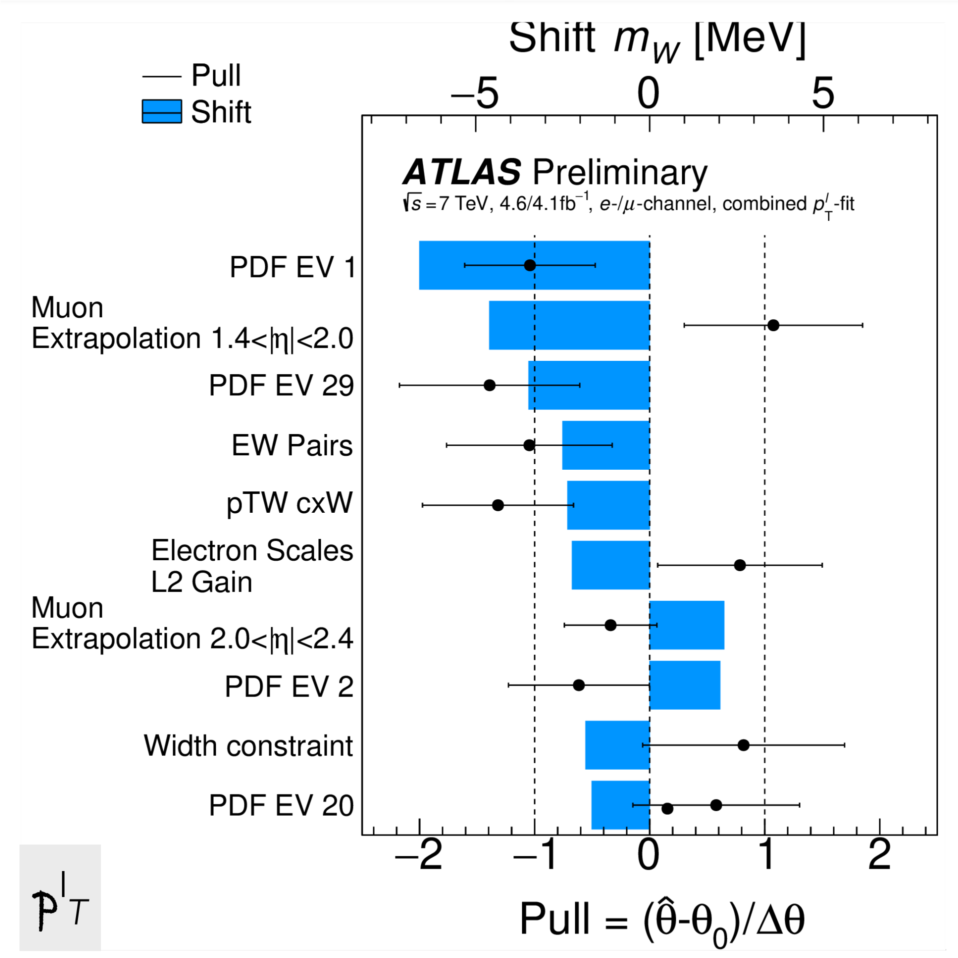
post-fit value estimated with CT18 PDFs

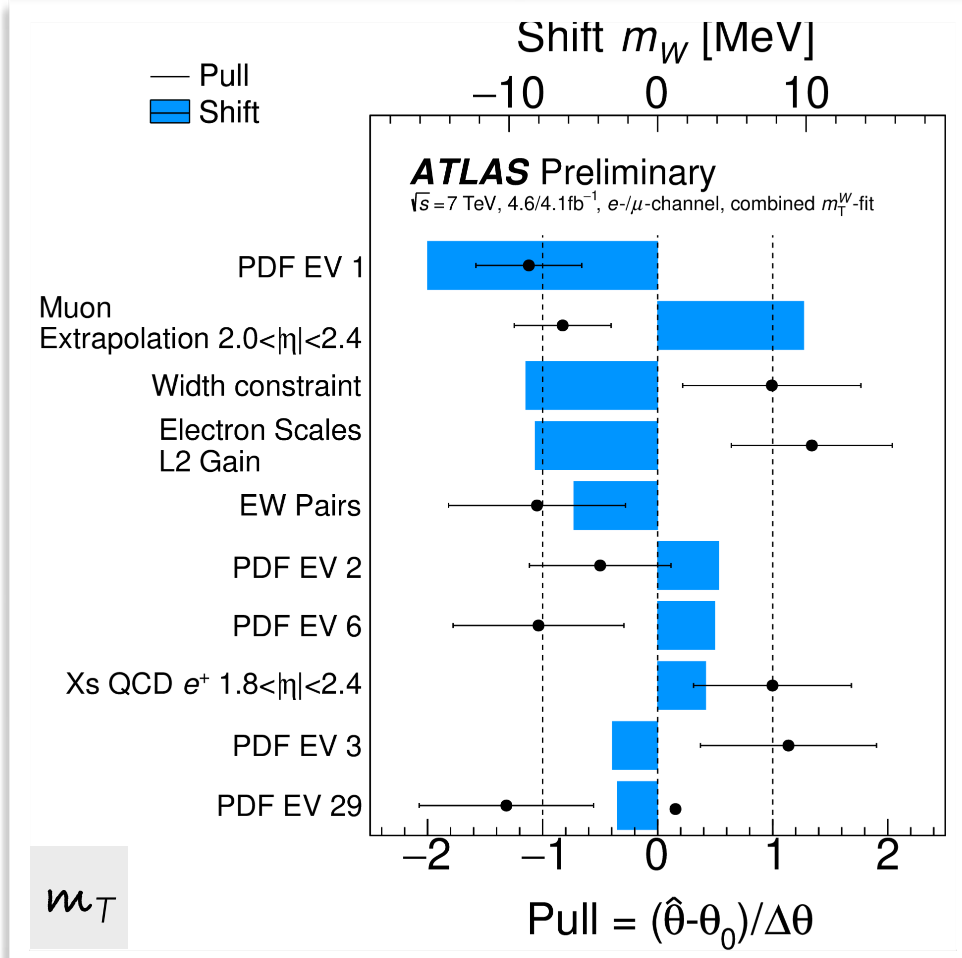


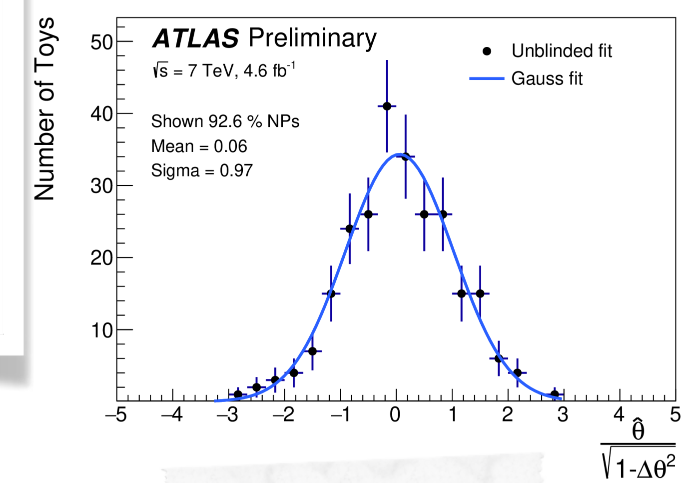


PLH and NP constraint

NP Ranking with CT18 PDFs





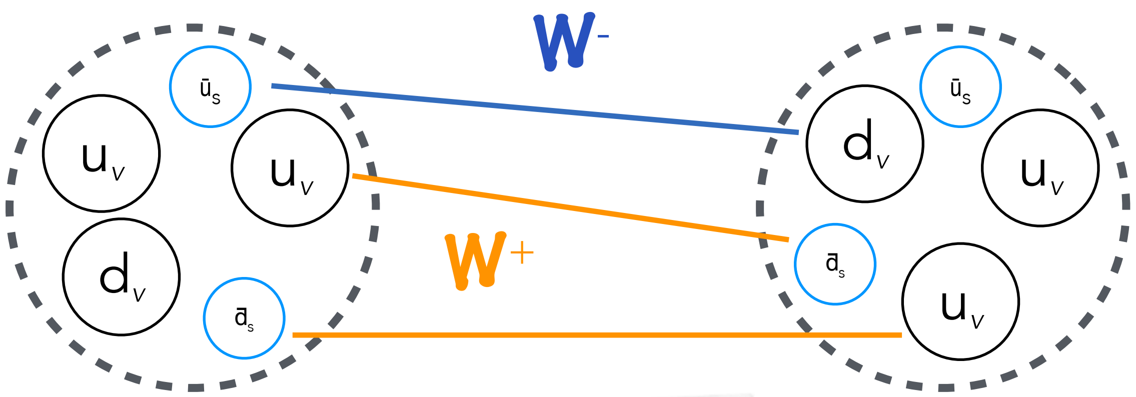


The largest NPs **pulls** are related to

- eigenvector of the PDF set
- muon momentum scale extrapolation uncertainty
- modelling uncertainty of charm-induced production for p^W_T
- missing higher-order EW final state radiation corrections.

Normal distribution for nuisance parameter pulls: overall correct estimation of the pre-fit uncertainties.

W mass analysis and in situ PDF constraint



In pp collision: different cross section for W+ and W- and different dynamics.

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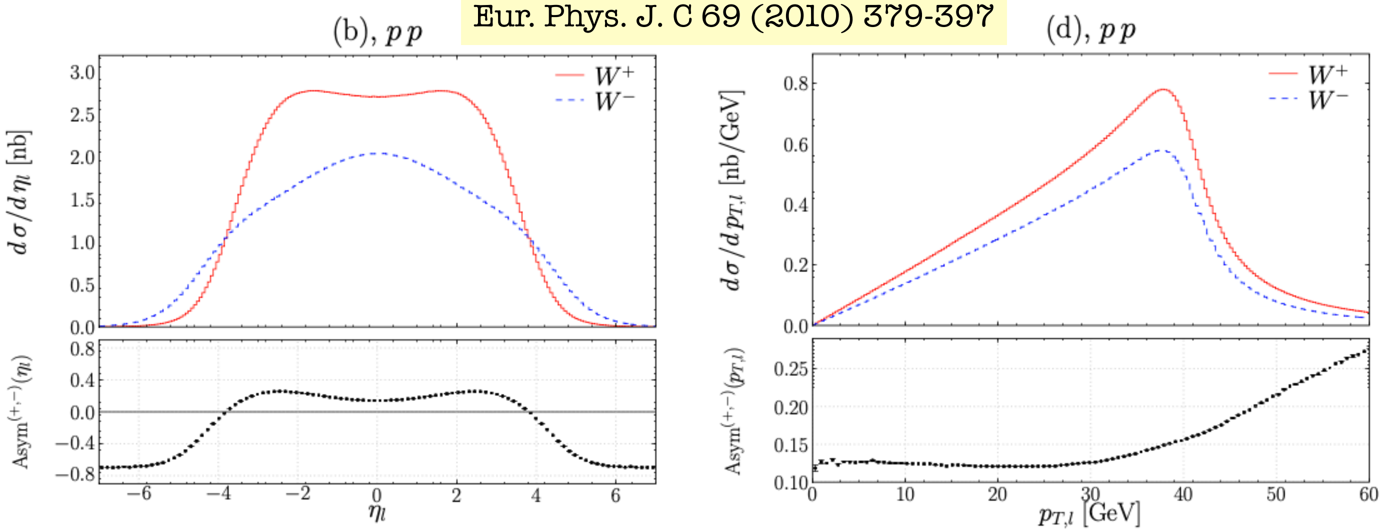
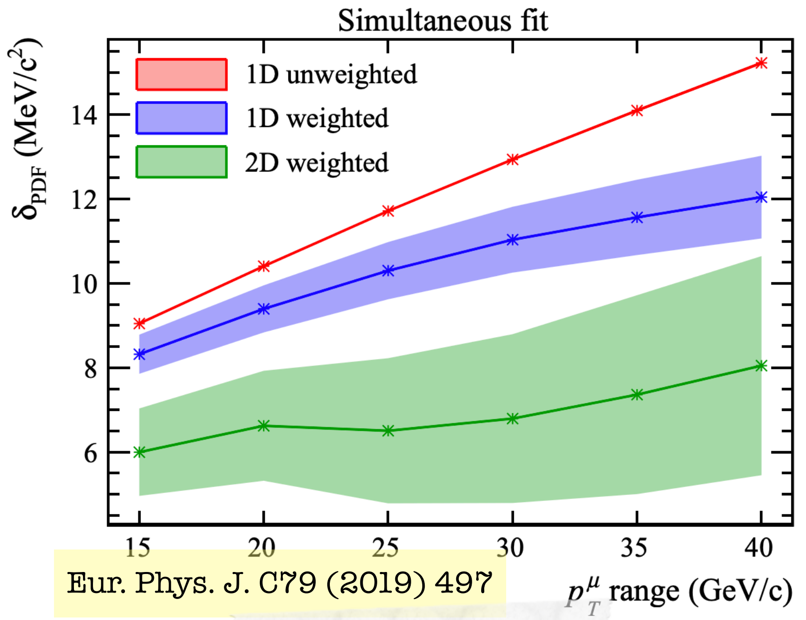


- Difference between u,d valence and the see distributions determine the W-boson rapidity distributions → affects acceptance and fiducial volume
  - kinematic distributions & signal yields in the different categories have additional constraining power on the PDFs unc. (*in situ constraint*)
- With profiling of PDF uncertainty it is expected :
  - **reduction** of **Δm_W PDFs envelope**
  - **reduction** impact of PDF uncertainties
    (*previous measurement* $\delta^{(PDF)} m_W$ ± *9-10 MeV*)



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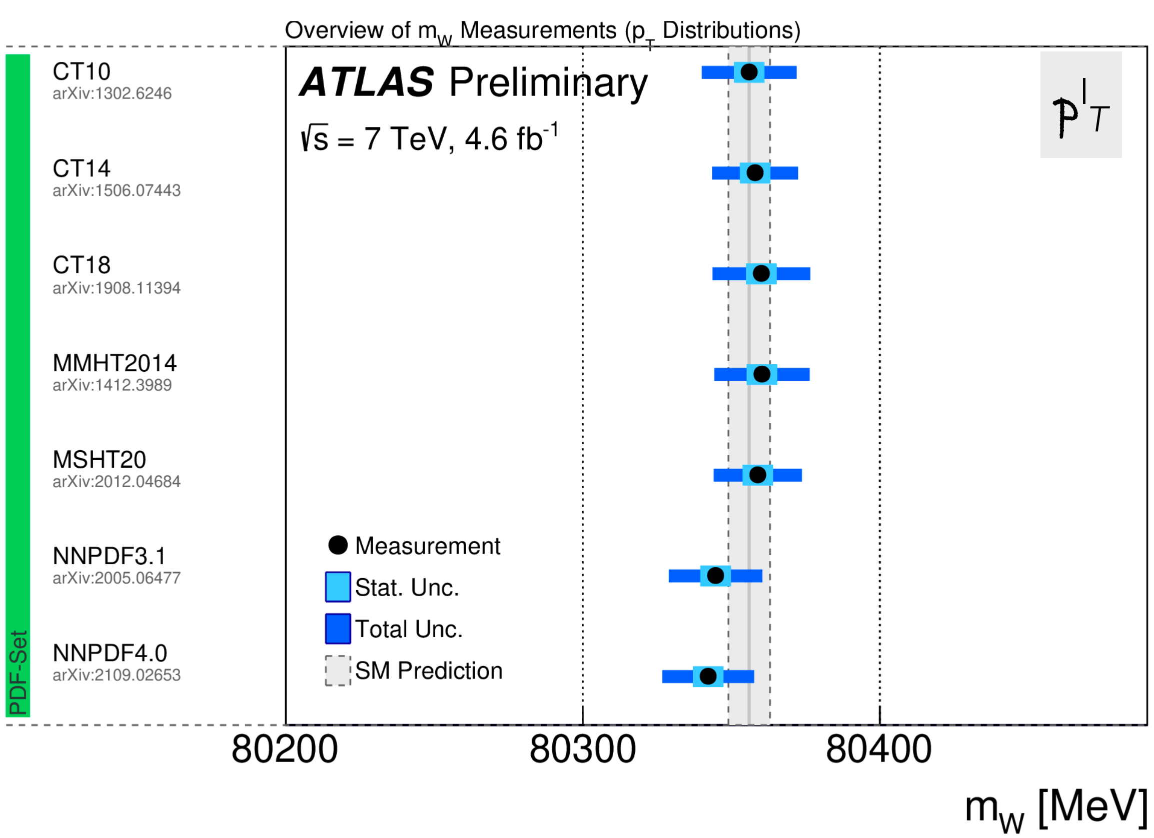
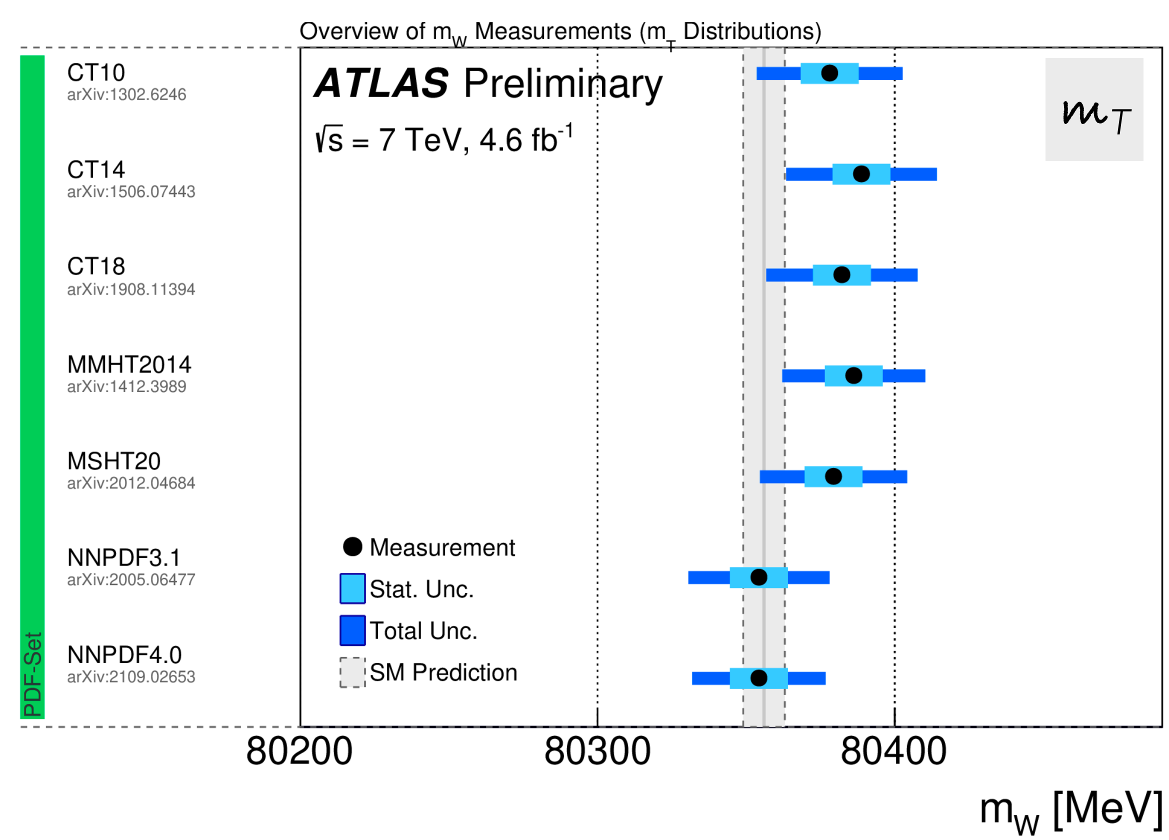
PDF in situ constraint the proof of principle with LHCb kinematics

PDFs constraint

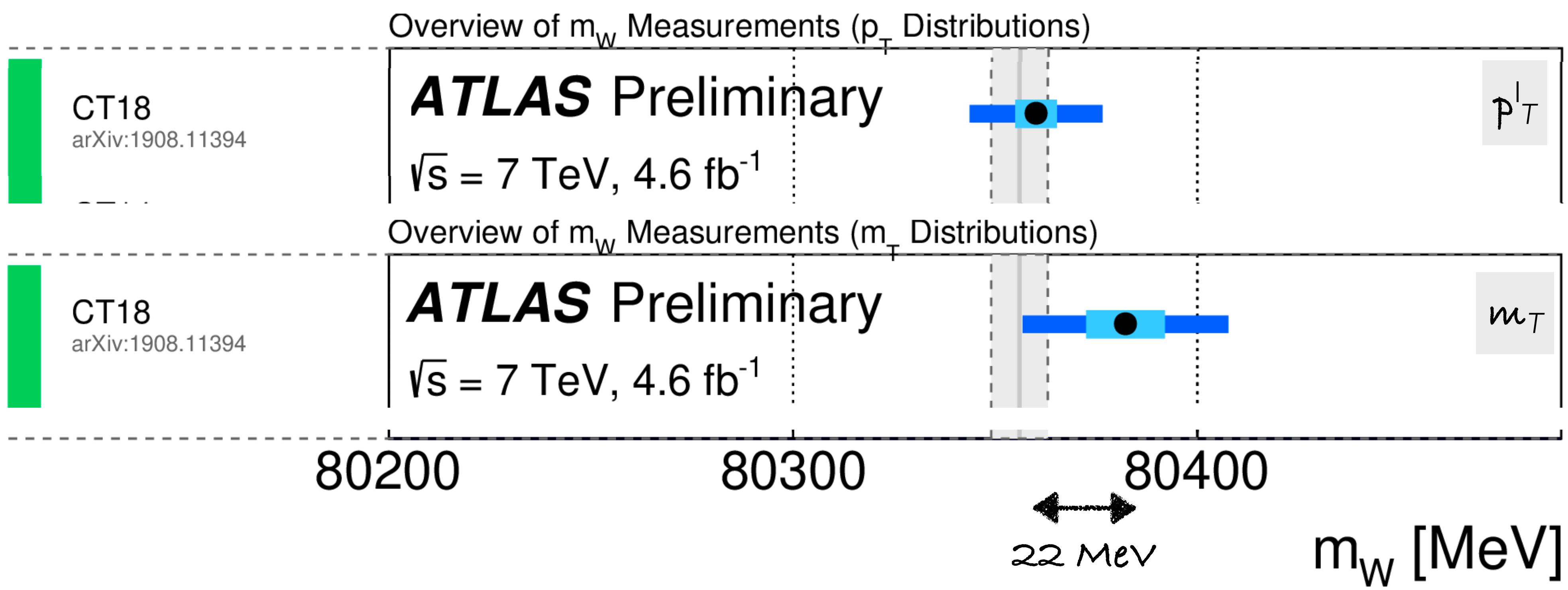
- Profiling **reduces the Δm_W spread of PDFs:** methodological PDF unc. ±14 MeV → ±9MeV
- **CT18 PDF** set **new baseline**: yields *most conservative* uncertainties $\delta^{(PDF)} m_W = 7.7$ MeV
  - cover the central values of CT10, CT14, MMHT2014 and MSHT20, but not of NNPDF3.1 and NNPDF4.0

PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
MSHT20	$80358.9^{+13.0}_{-16.3}$	$80379.4^{+24.6}_{-25.1}$	$80356.3^{+14.6}_{-14.6}$
NNPDF3.1	$80344.7^{+15.6}_{-15.5}$	$80354.3^{+23.6}_{-23.7}$	$80345.0^{+15.5}_{-15.5}$
NNPDF4.0	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$





The new W boson mass



- p^l_T and m_T measurement are compatible at 1.2σ level
  - correlation between the 2 measurements ρ = 0.63

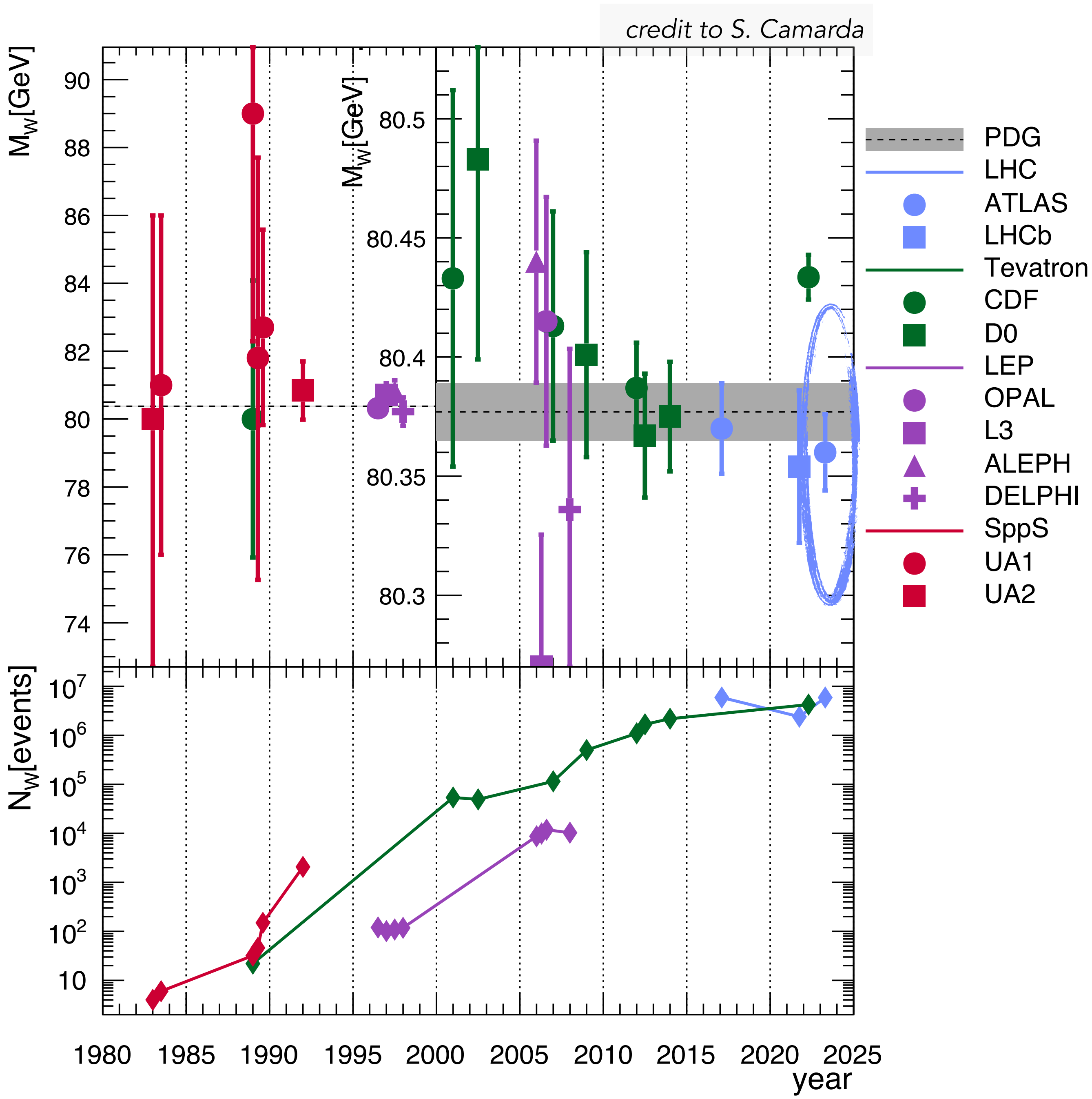
Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3

$\Delta m_W(p^l_T) > \Delta m_W(m_T)$ due to impact of PDF/p_T^W sys profiling

BLUE Combination for p^l_T and m_T results $m_W = 80360 \pm 5(\text{stat.}) \pm 15(\text{syst.}) = 80360 \pm 16$ MeV

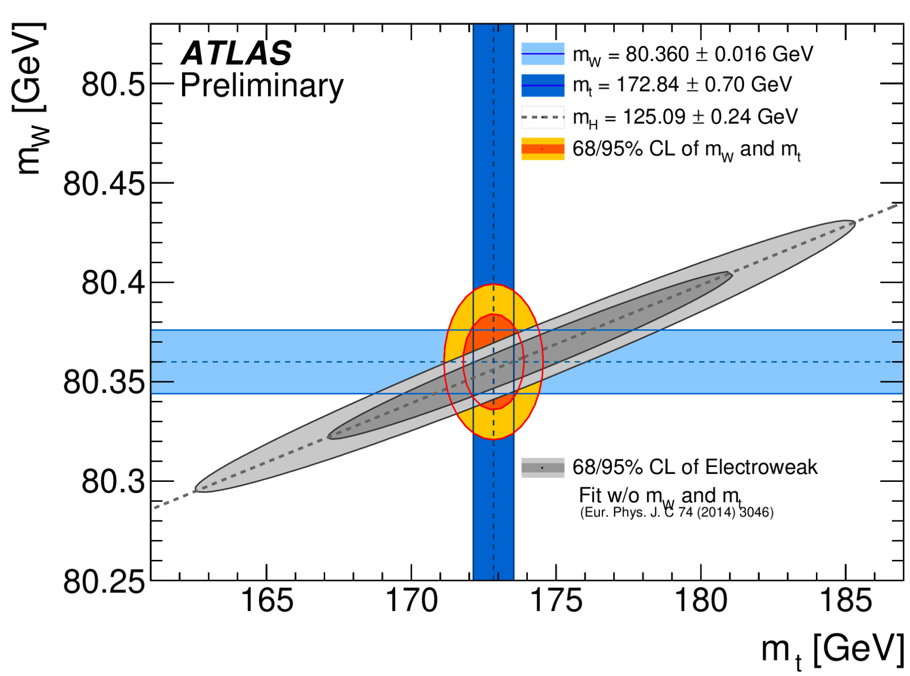
- The p^l_T fit largely dominates the final result (95% weight)

Conclusion



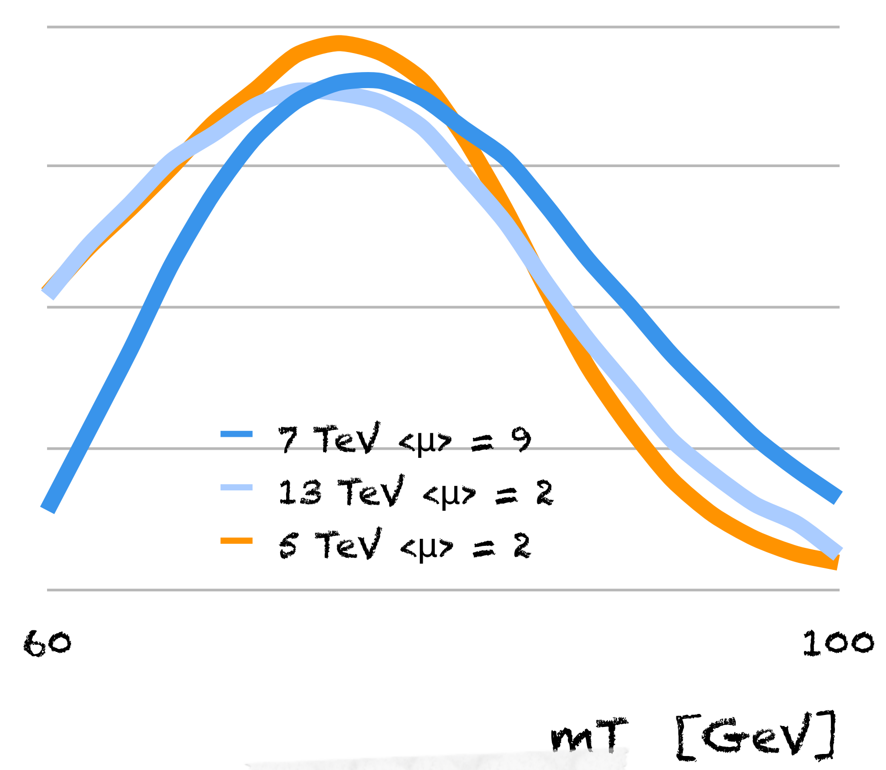
New set of high-precision ATLAS results show that it is possible to **very precisely measure W boson properties** @LHC:

- ☆ Unique set of high-precision Wp_T spectra measured at $\sqrt{s}$= 5.02 and 13TeV **validate modelling used m_W**
- ☆ Re-analysis of 7TeV data with new fitting technique confirms previous ATLAS results and improves precision by **3 MeV** to m_W = 80360 ± 16 MeV which is compatible with the SM



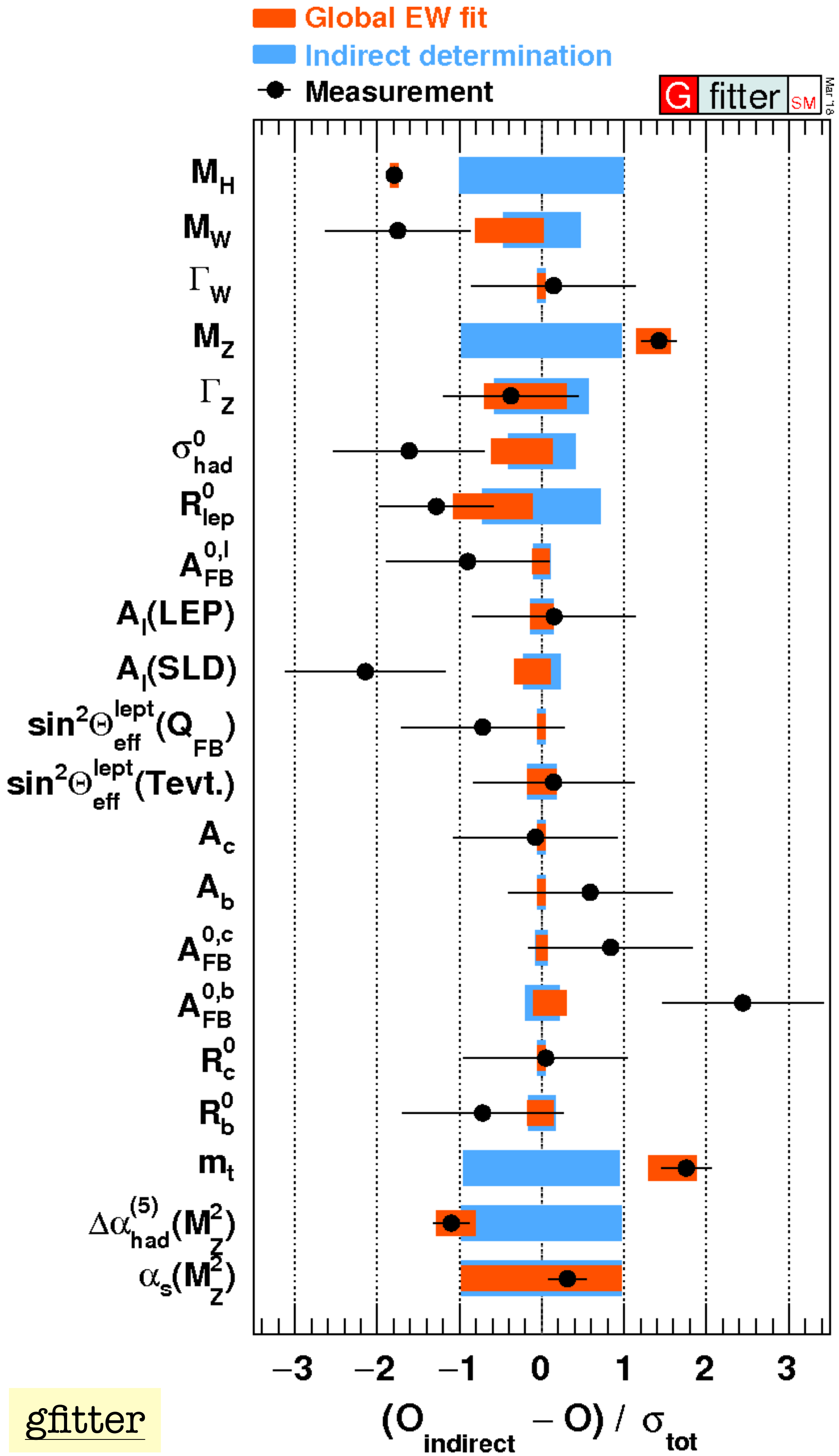
what next ?

- **ATLAS results reaches an outstanding experimental precision**
  - significant progress has been made in the statistical framework: PLH test statistics adopt for m_W measurement
- The **W boson physics modelling** stays the **most difficult aspect** to challenge the current theoretical precision of 7MeV on **the W-mass**
  - Recently make public an unique measurement to validated the modelling of low-p_T^W
  - data can be used to test and constrain most recent state of the art prediction:
    - PDF uncertainties
    - p_T^W modelling

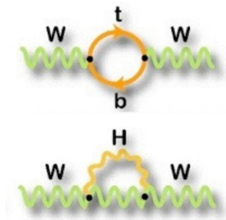


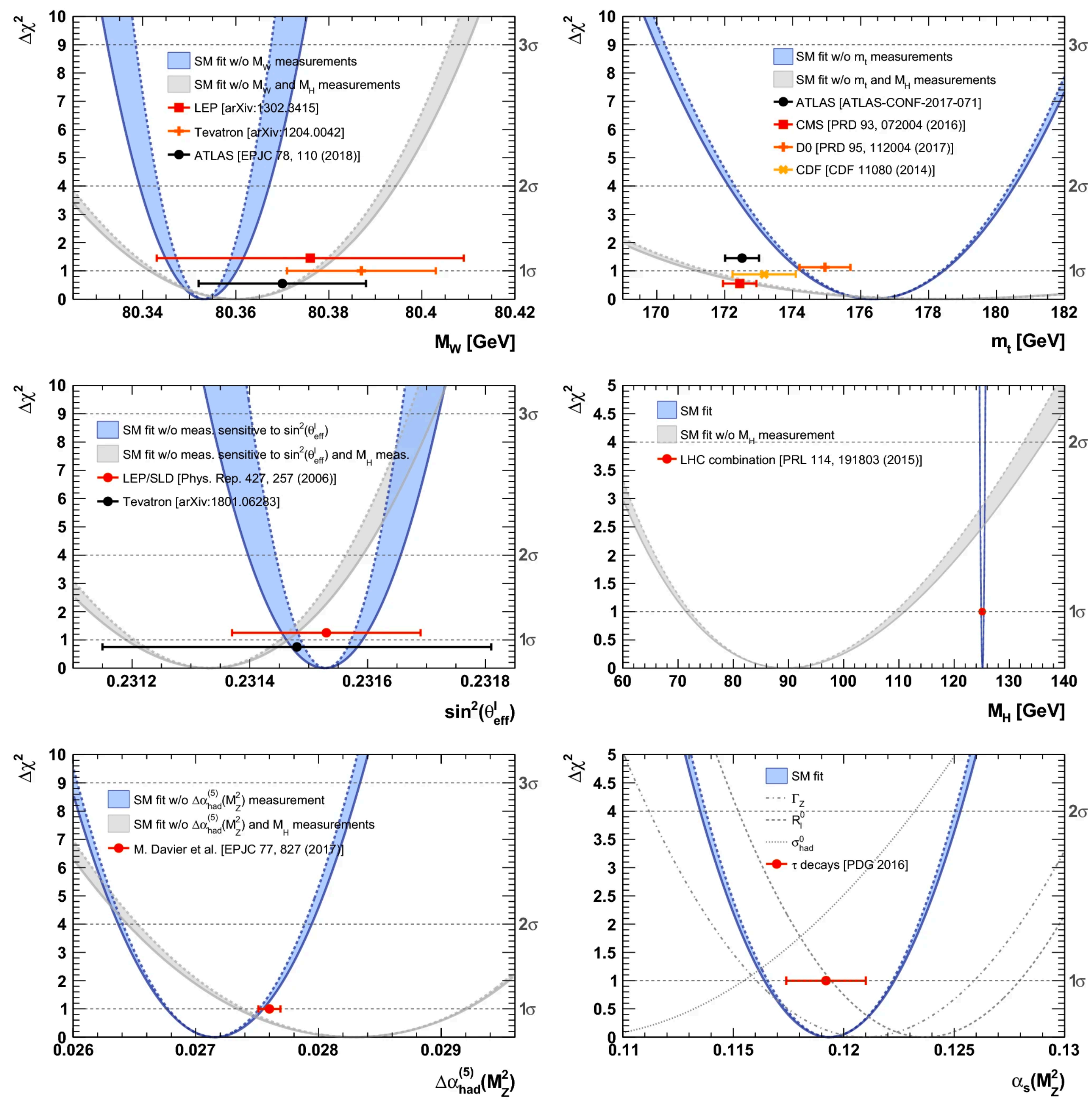
And ... Prospect for a new and orthogonal W mass measurement additional slides

the EW Fit



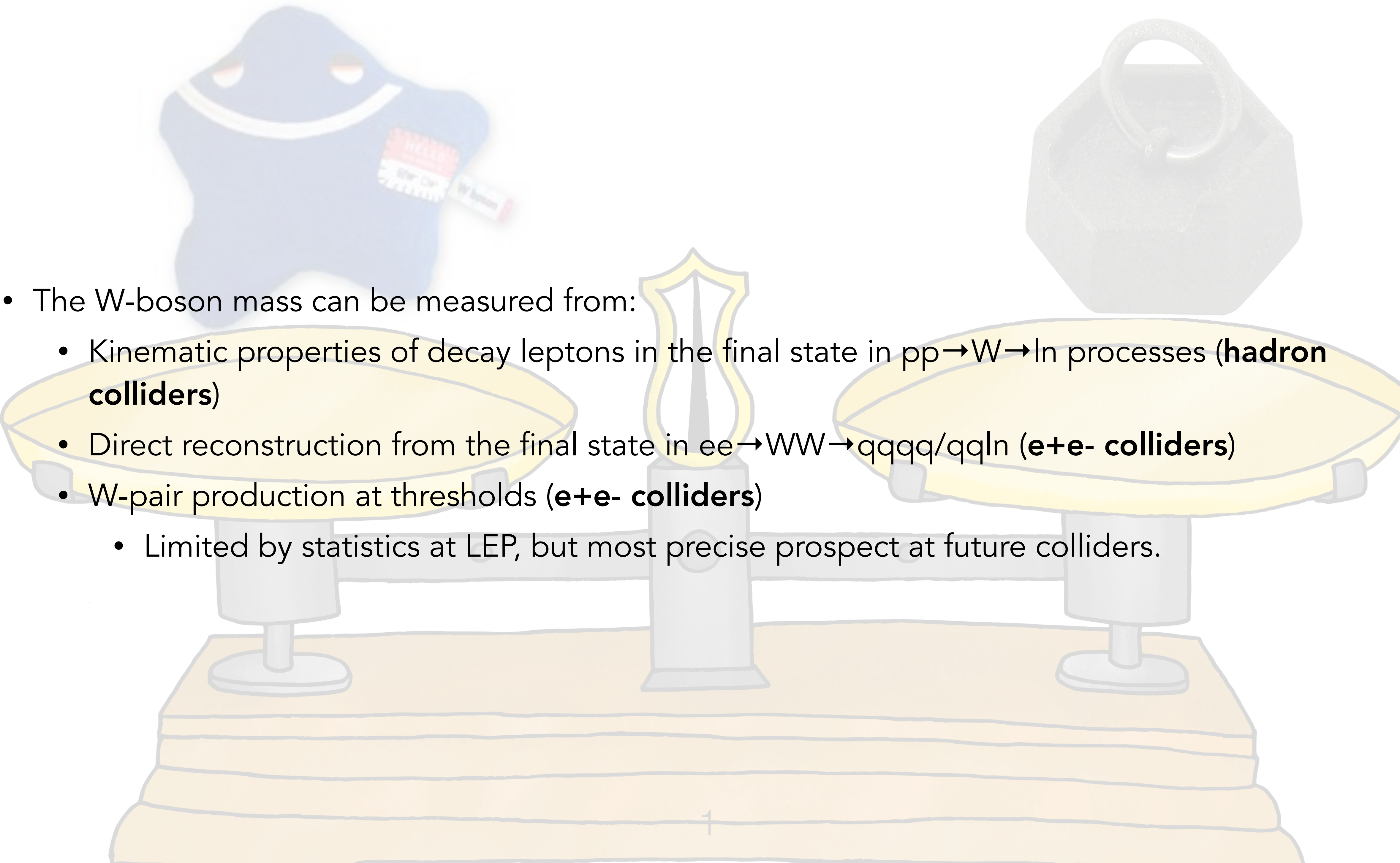
$$M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\,\pi\alpha(1-\Delta r)}{G_F M_Z^2}}\right)$$





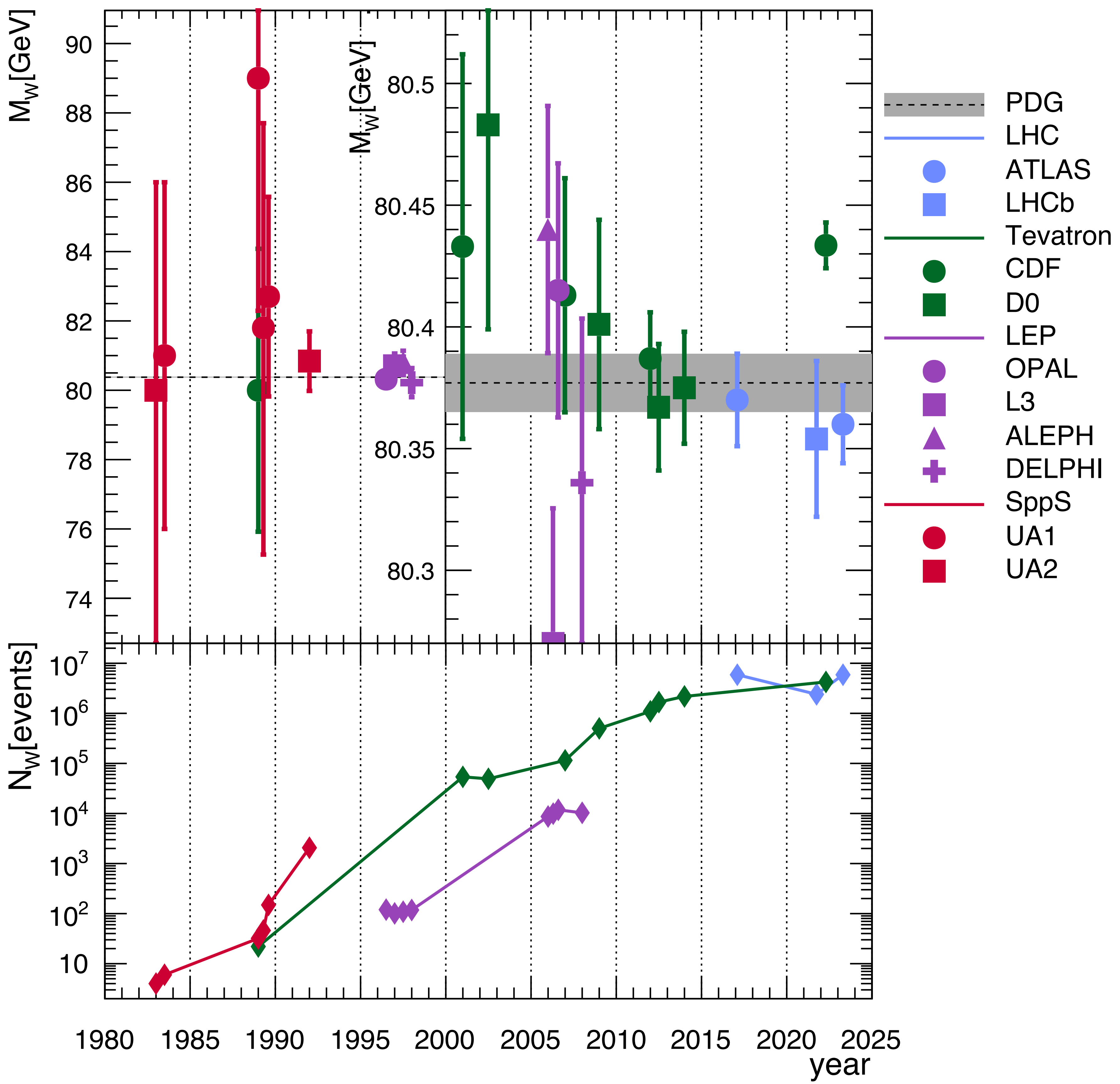
gfitter

How to measure m_W ?



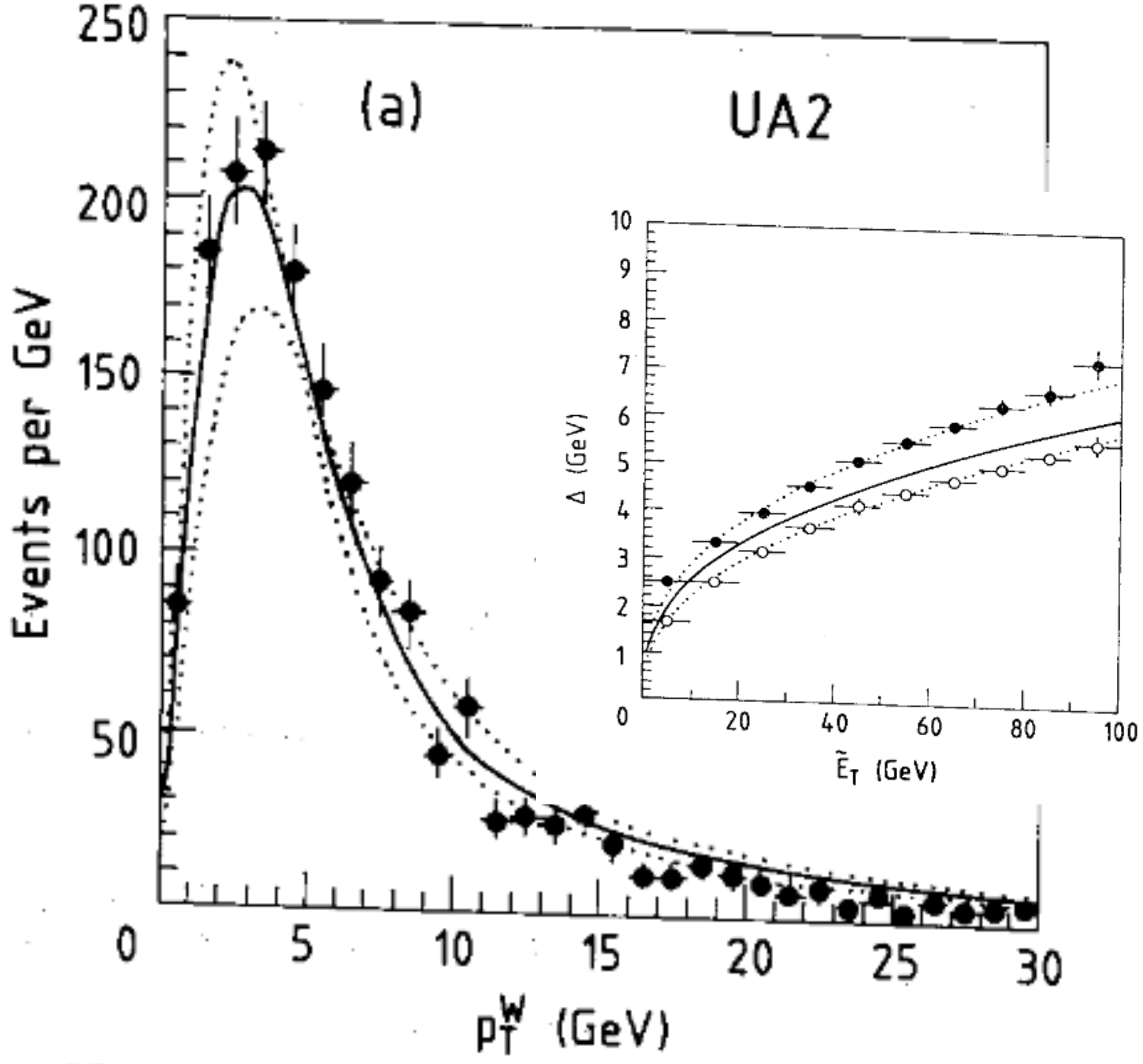
- The W-boson mass can be measured from:
  - Kinematic properties of decay leptons in the final state in pp→W→ln processes (**hadron colliders**)
  - Direct reconstruction from the final state in ee→WW→qqqq/qqln (**e+e- colliders**)
  - W-pair production at thresholds (**e+e- colliders**)
    - Limited by statistics at LEP, but most precise prospect at future colliders.

40 years of measurements

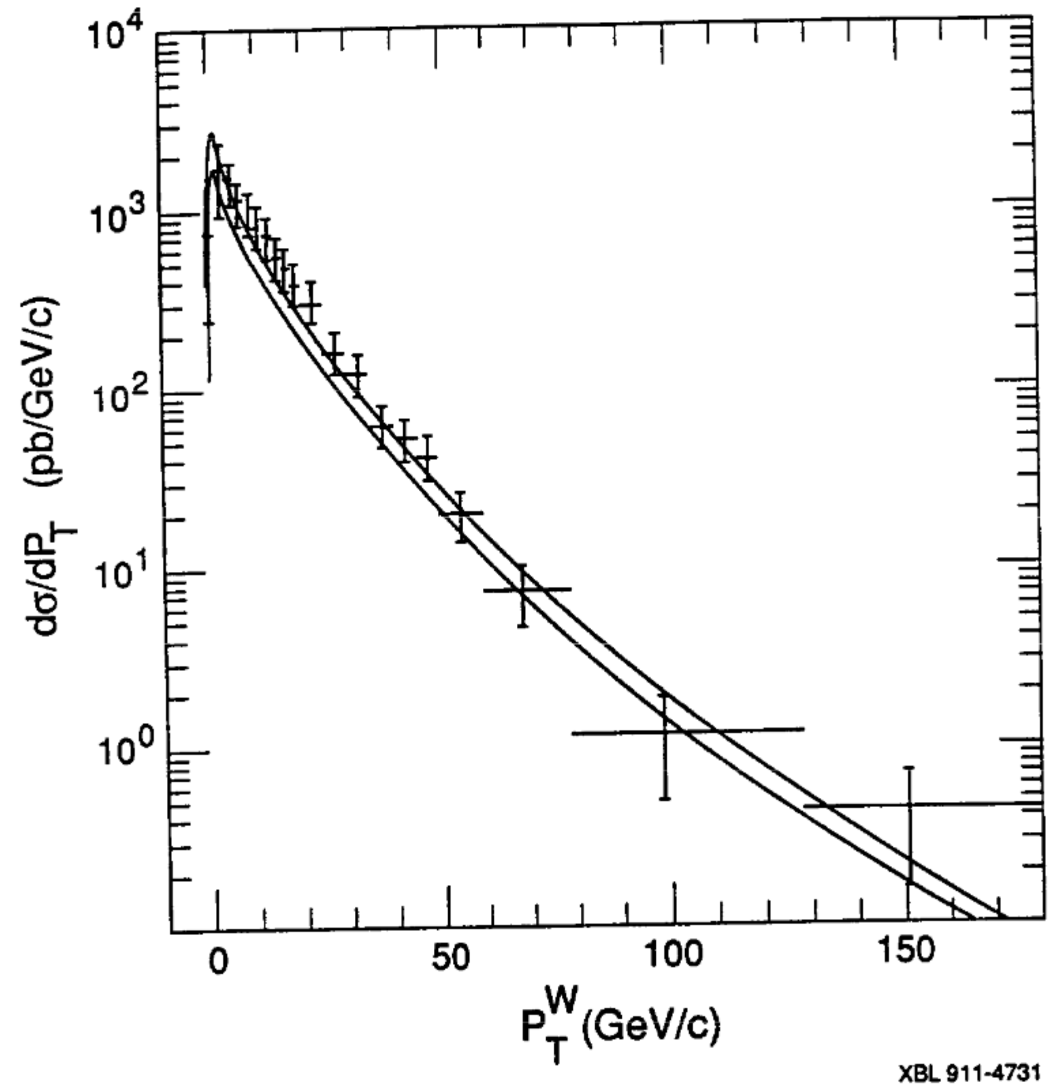


L. Aperio Bella

$p\overline{p}$ W p_T spectra

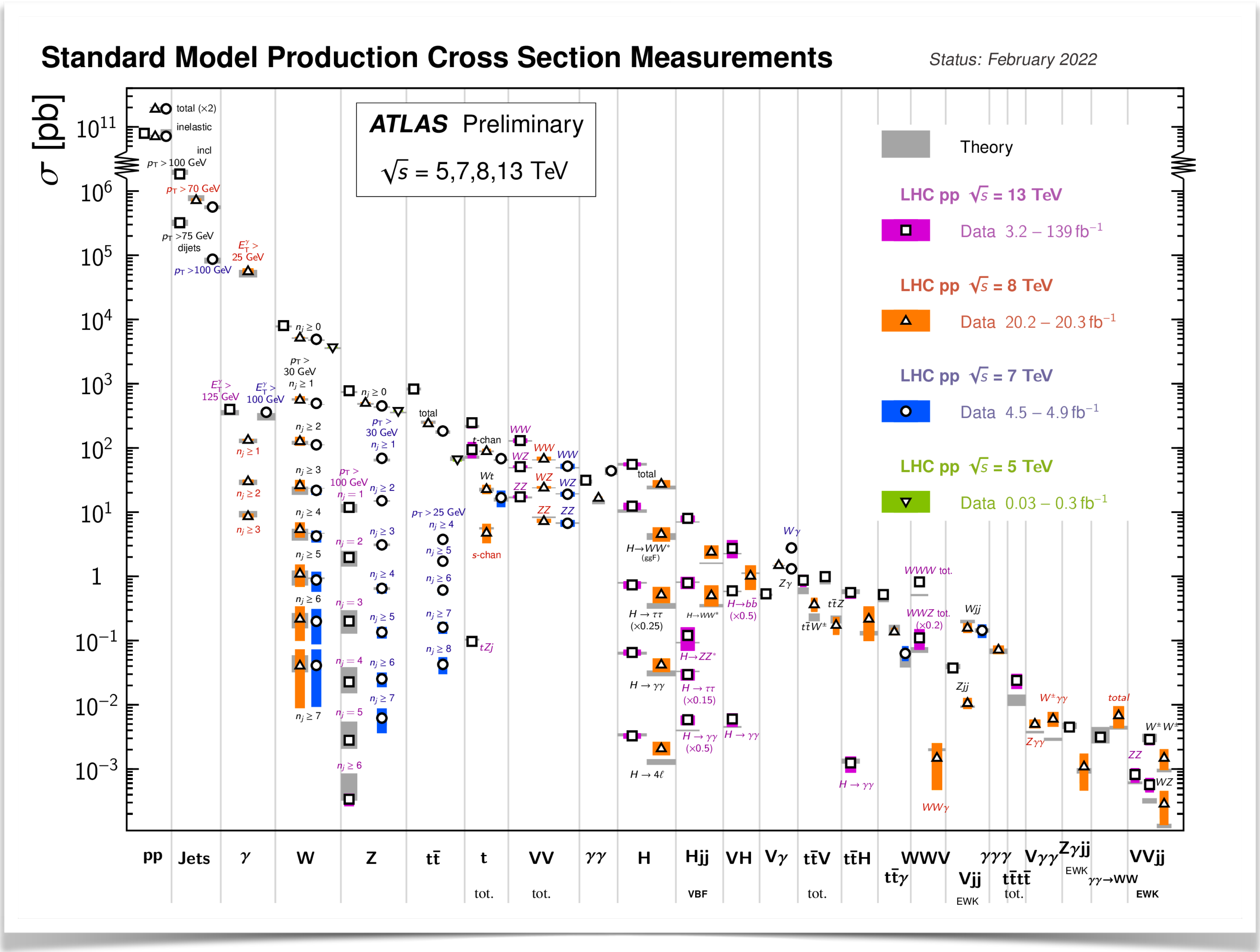


UA2 (1990)
$p\overline{p}$, $\sqrt{s}$ = 630 GeV
⟝1GeV⟞



CDF: (1991)
$p\overline{p}$ $\sqrt{s}$ =1.8 TeV
⟝ 2GeV ⟞

The SM of particle physics @LHC



- In our days the ***LHC experiments*** have in their hands the richest hadron collision data sample ever recorded
- Vast and reach program at High energy frontier.
  - testing self consistency of the SM
  - *1st observation of very rare processes*
  - *exploring new physics via direct and* ***indirect measurements***

Observable sensitive to m_W

ATLAS m_W measurement done with 4.7 fb^{-1}@7TeV **<μ>~9**

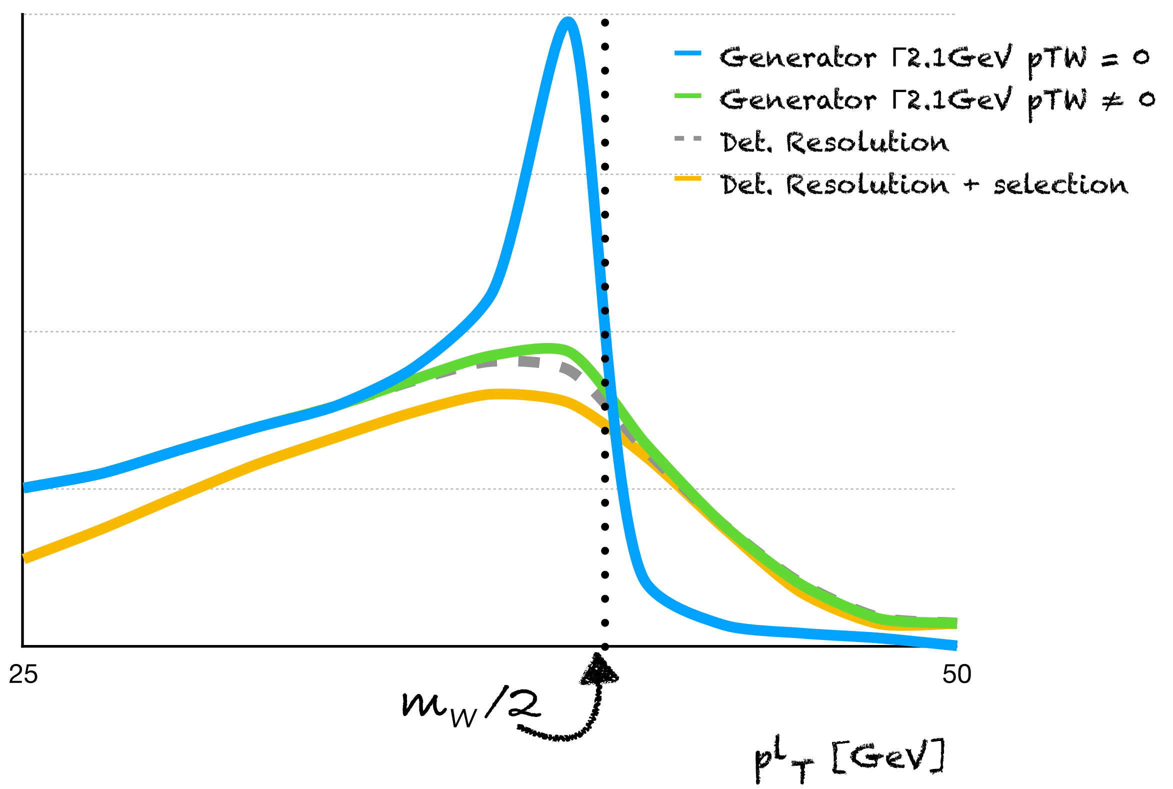
~14M candidates in $W \to e\nu$ and $W \to \mu\nu$ channels (Background: 5% (6.5%) for μ(e)-channel)

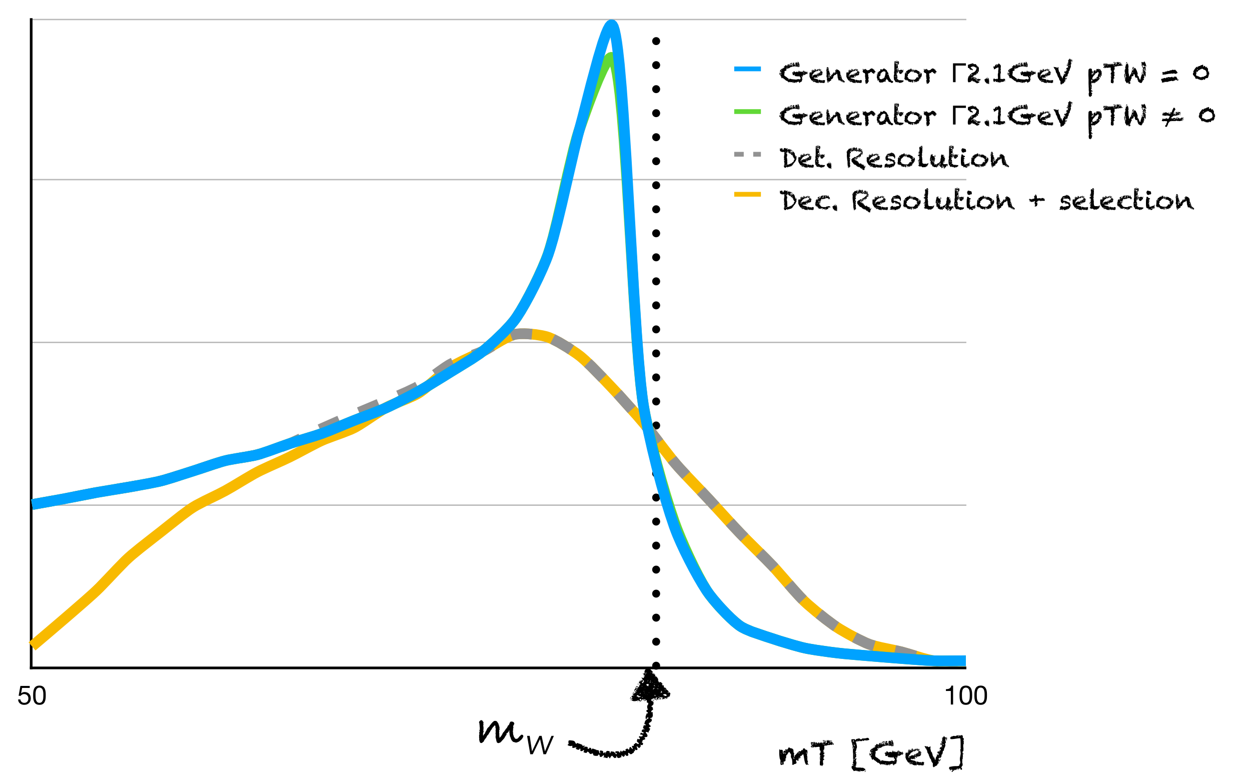
Total of ~2M of $Z \to \ell\ell$ for calibration

(A) Identify observables sensitive to m_W :

☆ lepton transverse momenta ($\mathbf{p^l_T}$) has a Jacobian peak at $m_W/2$

☆ transverse mass ($\mathbf{m_T}$) has an endpoint at m_W





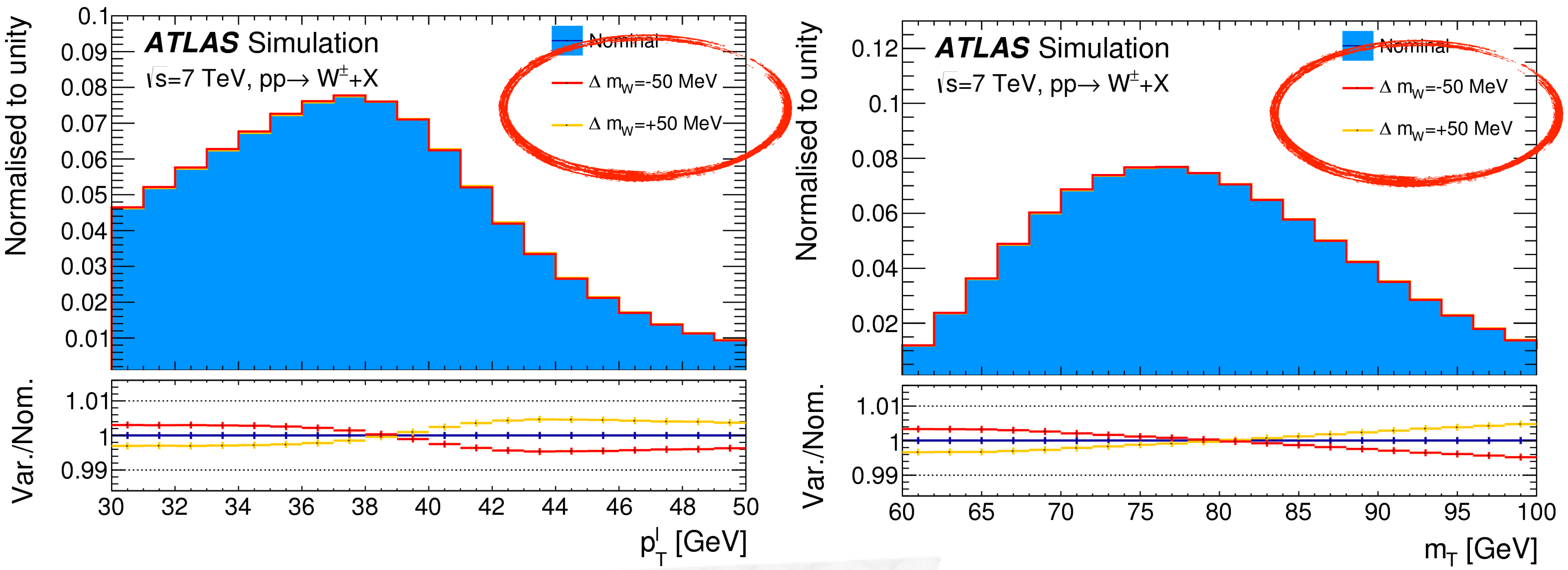
Building mW templates

ATLAS m_W measurement done with 4.7 fb^{-1}@7TeV **<μ>~9**

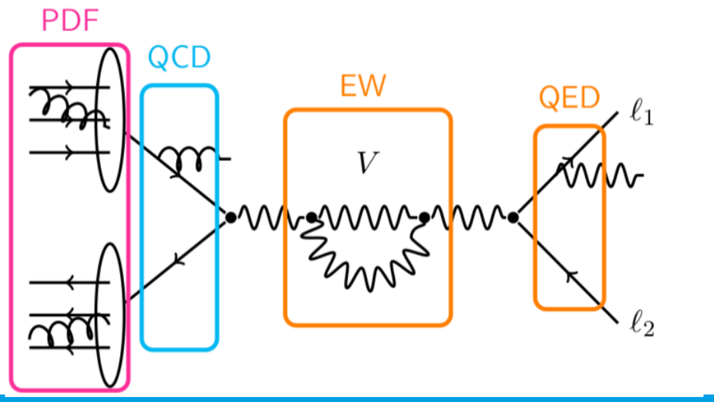
~14M candidates in W→eν and W→μν channels (Background: 5% (6.5%) for μ(e)-channel)

Total of ~2M of Z→ℓℓ for calibration

(B) Produce models ("templates") with different m_W-hypotheses and compare to **data** in 28 categories (e/μ, η regions, W^+W^-, p^l_T m_T)



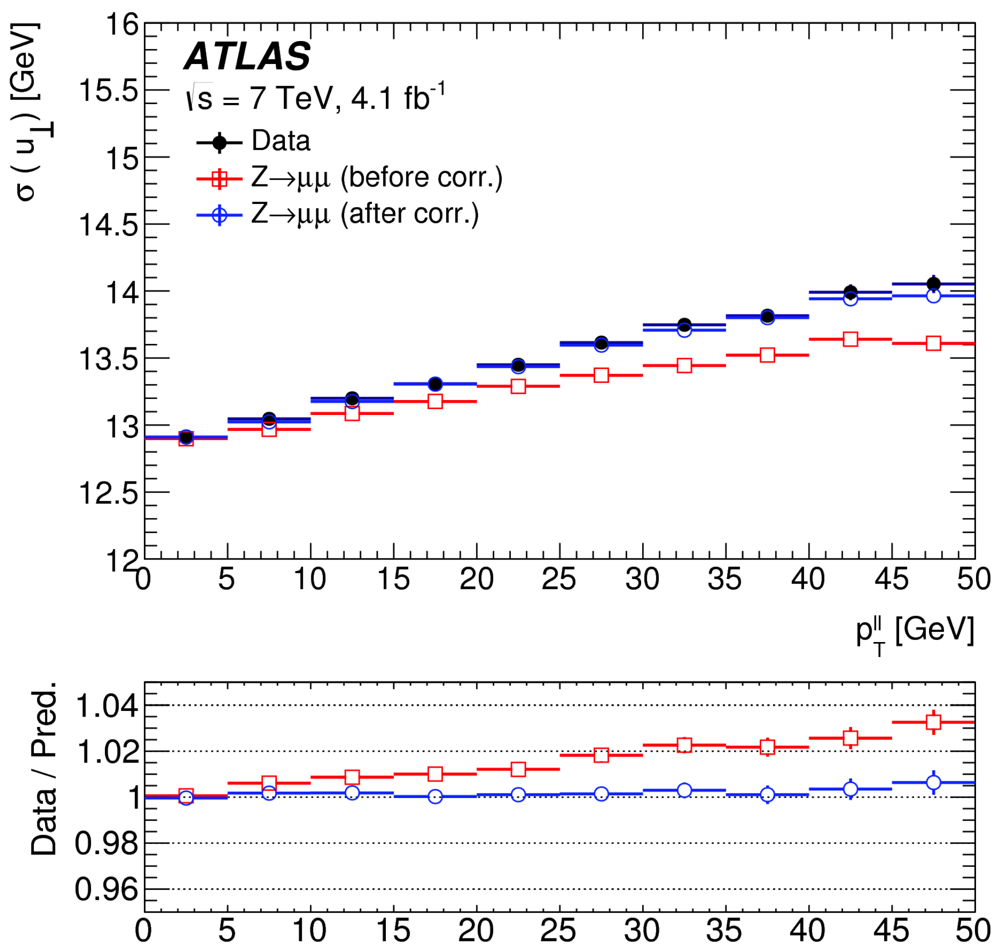
- p^l_T and m_T distributions are sensitive to:
  - ➡Leptons and Recoil calibration
  - ➡Modelling effects:



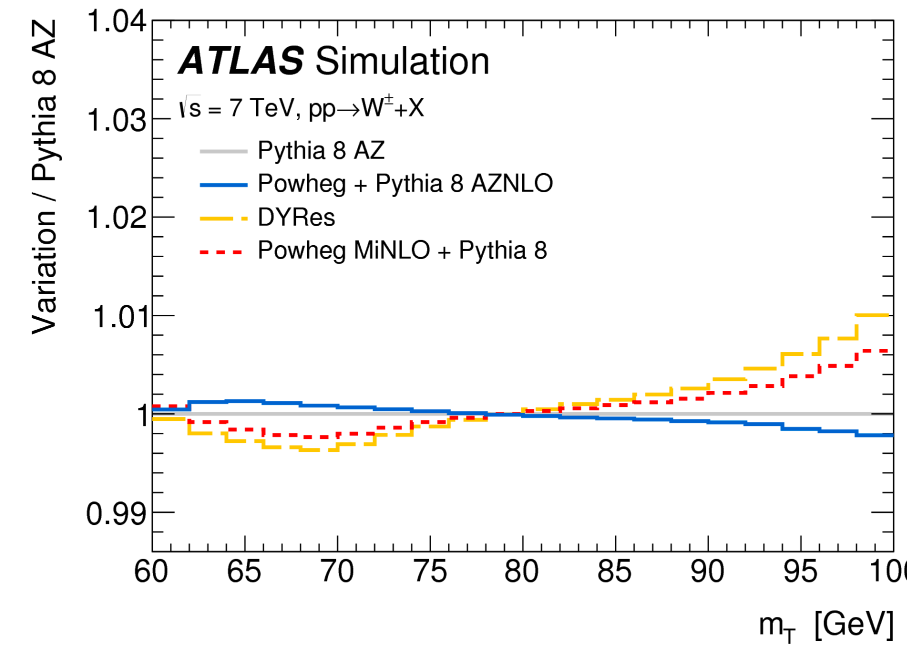
A 15 MeV variation in m_W corresponds to ~0.1-0.2% variation in the kinematics of the W production

m_W ATLAS legacy

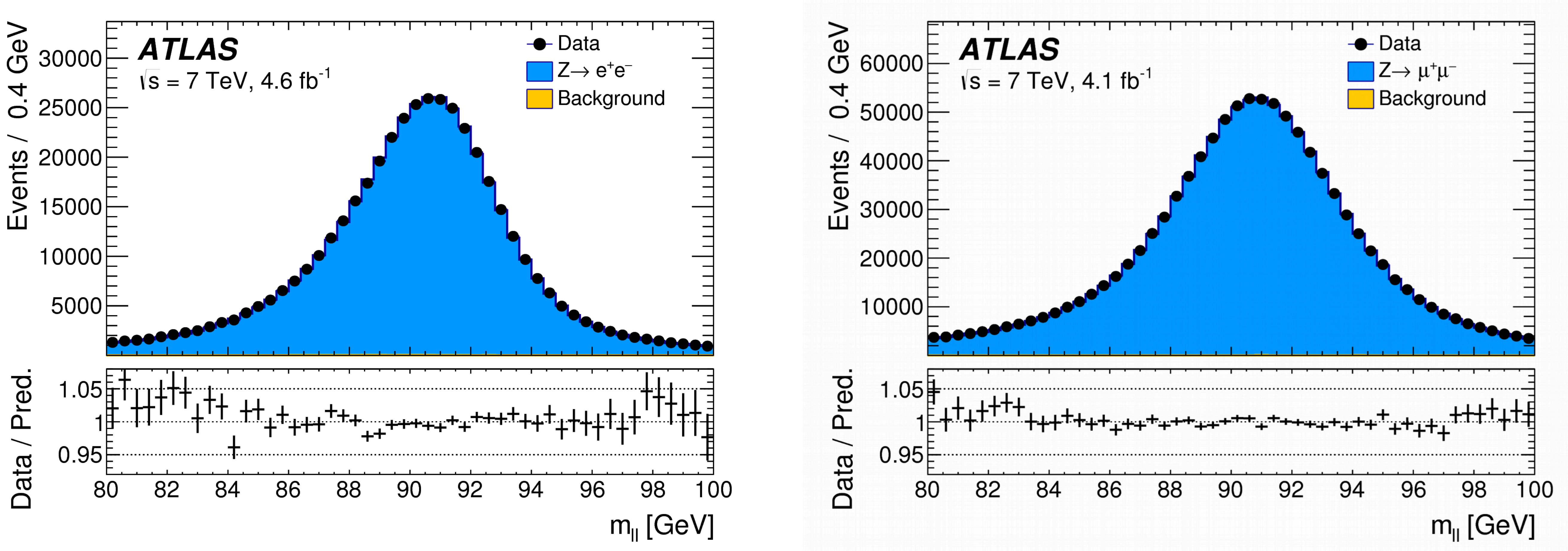
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
p_T^{ℓ}, $W^{\pm}$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
m_T, $W^{\pm}$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13



Combination	Weight
Electrons	0.427
Muons	0.573
m_T	0.144
p_T^{ℓ}	0.856
W^+	0.519
W^-	0.481

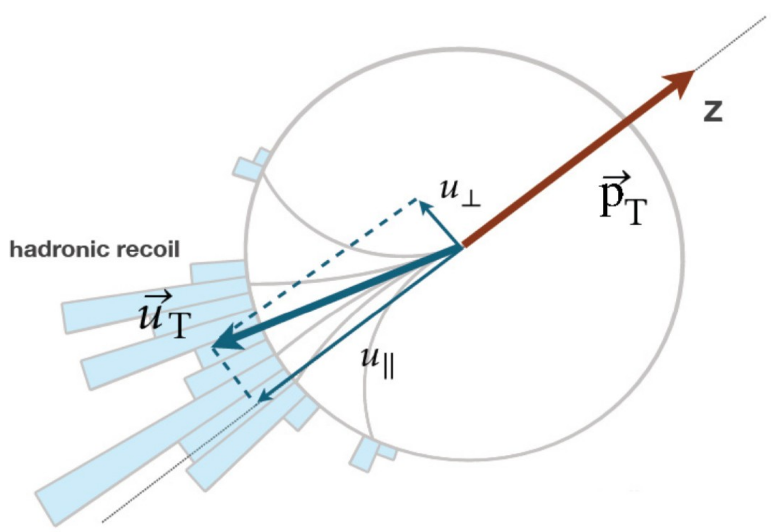


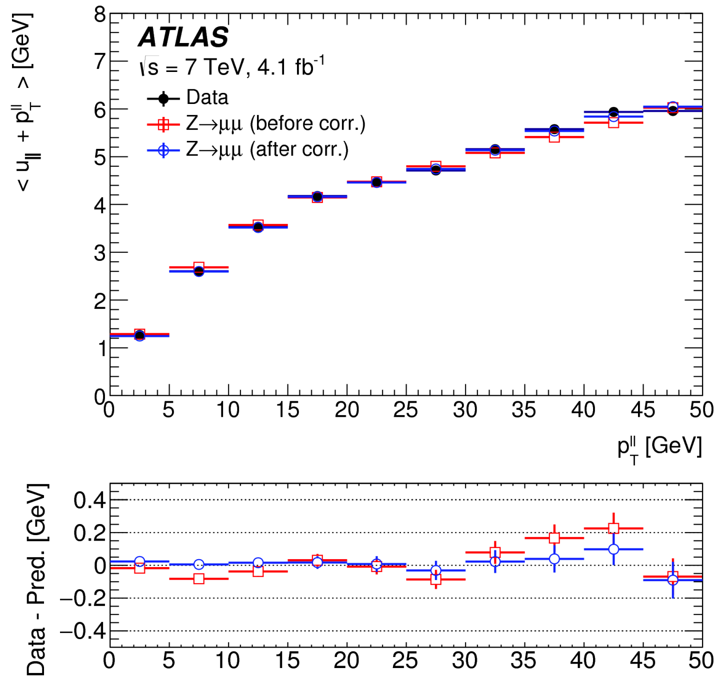
lepton calibration

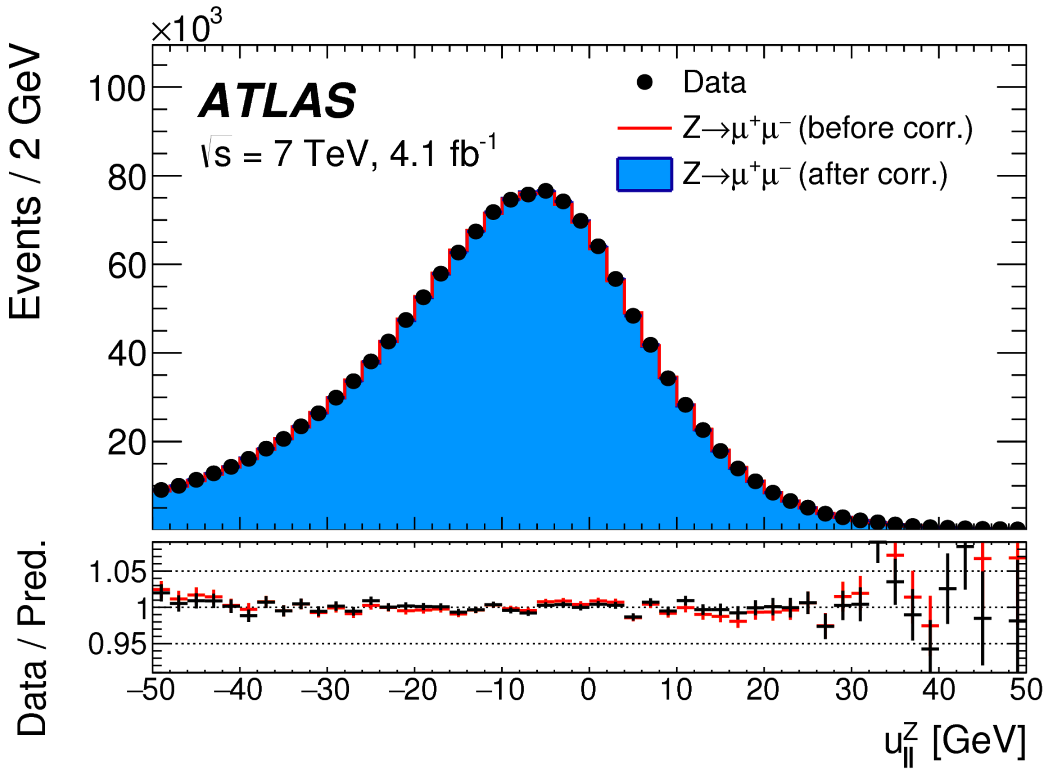


- **Leptons momentum scales** are measured using Z->ll and events and corrected in MC
  - Scale known better than **~2x10^{-4}** (except for muons at highest rapidity)
  - Translates into an uncertainty on m_W of approx. **8-9 MeV**
- Reconstruction, identification and trigger efficiency studied from Z sample, small effects for muon, of similar size as the energy scale for electrons.

recoil calibration







- The reconstruction of the **hadronic recoil** depends strongly on the total ΣE_T in the event, three corrections are needed:
  1. Pileup distribution: data/MC equalisation.
  2. Correction of residual differences in the total ΣE_T distribution (activity mis-modeling)
  3. Derive scale and resolution corrections from the p_T balance in Z events [**precision at % level**]

Uncertainty on m_W **~ 13 MeV** for mT fits (smaller for p_T^{ℓ}), dominated by the total ΣE_T correction.

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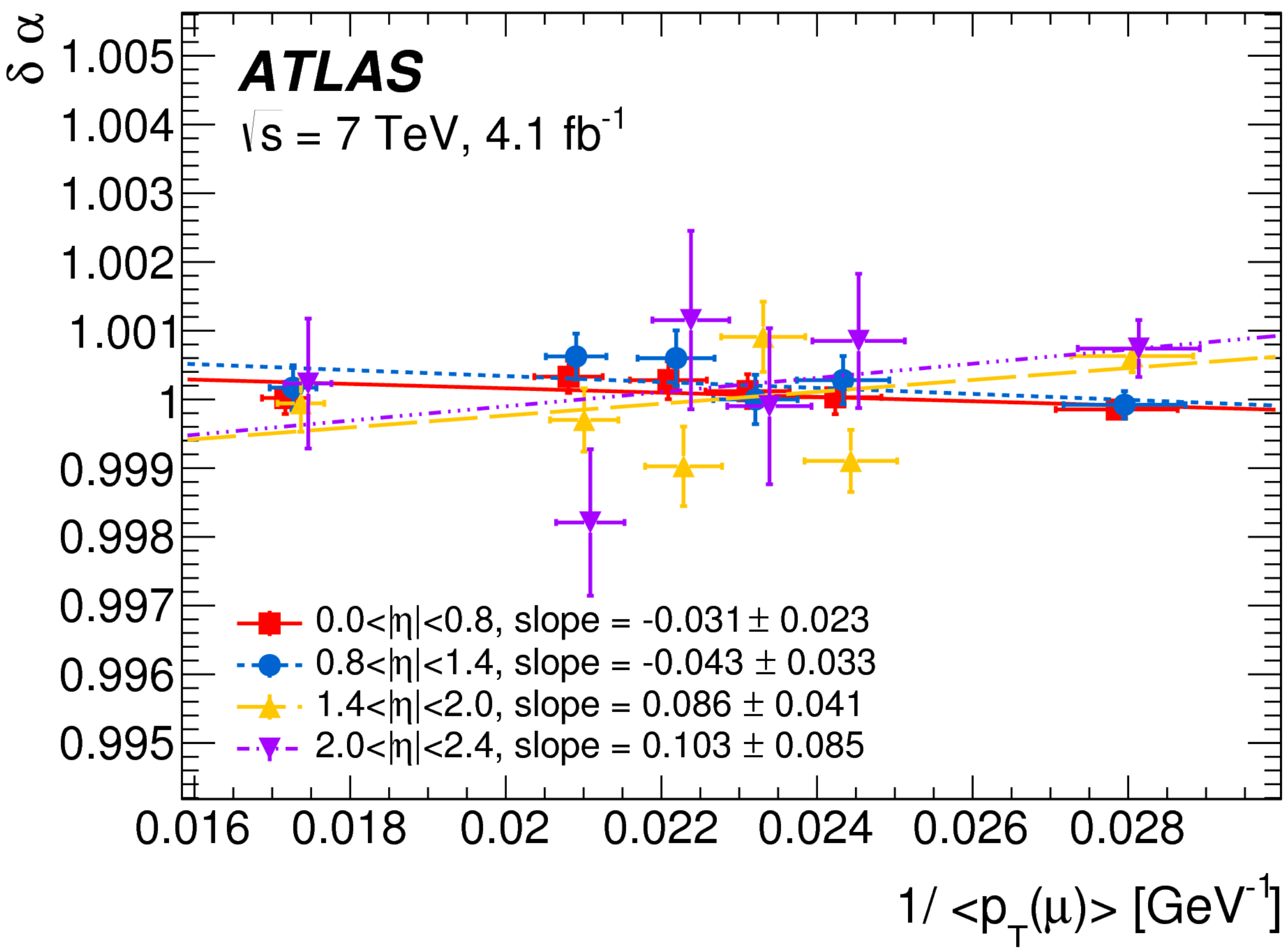


The systematic uncertainty in the muon momentum scale due to the extrapolation from the $Z \rightarrow \mu\mu$ momentum range to the $W \rightarrow \mu\nu$ momentum range is estimated by evaluating momentum-scale corrections as a function of 1/pT for muons in various |η| ranges. The extrapolation uncertainty **δα** is parameterised as

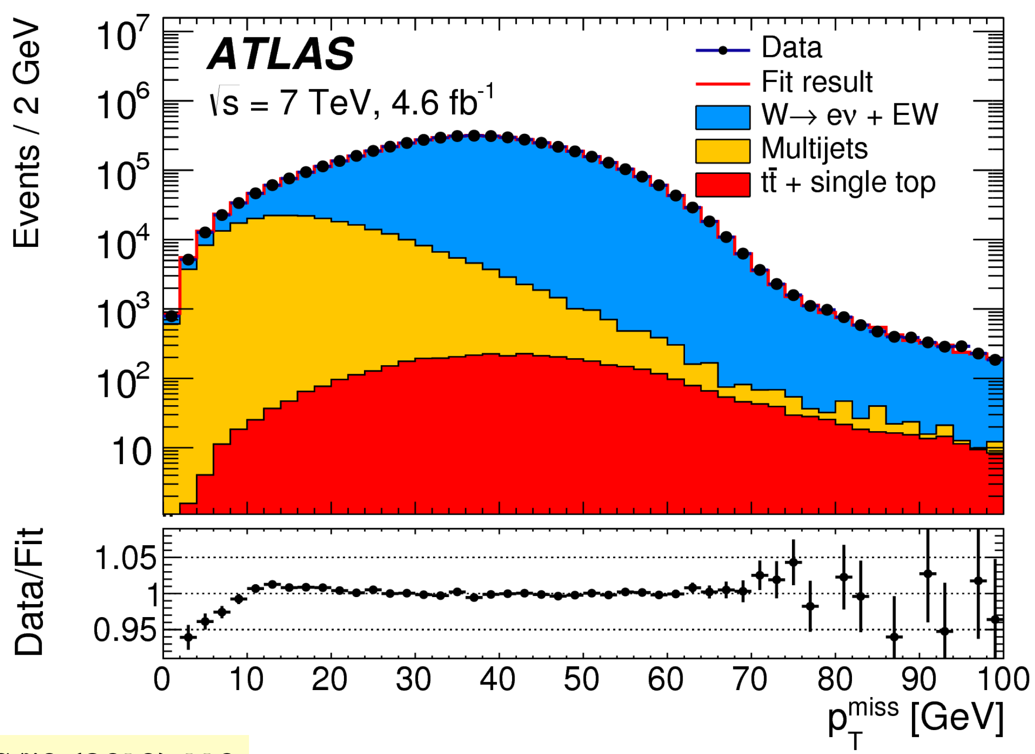
$$\delta\alpha = p_0 + \frac{p_1}{\langle p_{\mathrm{T}}^{\ell}(W)\rangle},$$

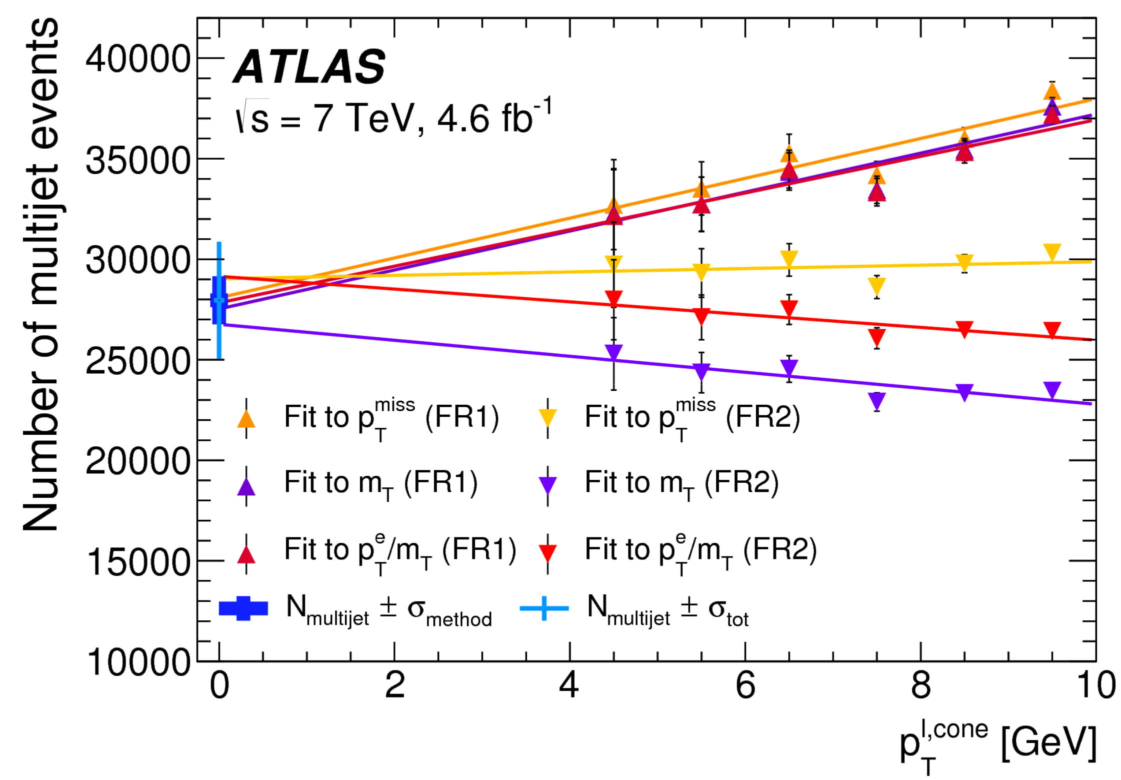
follows:

If the momentum-scale corrections are independent of 1/pT, the fitting parameters are expected to be p0 = 1 and p1 = 0. Deviations of p1 from zero indicate a possible momentum dependence. The fitted values of **δα** are shown in Figure 5(a), and are consistent with one, within two standard deviations of the statistical error.

- **General method:**
  - Define a background dominated fit region with relaxed kinematic cut(s)
    - Signal distribution from MC
    - mj templates from control region with inverted lepton isolation cut (large activity around leptons)
    - The multijet background is normalized with fraction fit
- Variations:
  - 3 observables(p_T^{miss},m_T,p_T^l/m_T); 2 fitting regions
  - try different isolation criteria,
  - extrapolate to the signal region
- Uncertainty: ~ 4 MeV (μ); ~ 8 MeV (e)

MJ / fakes kinematic distribution are affected by the activity around the "fake" leptons





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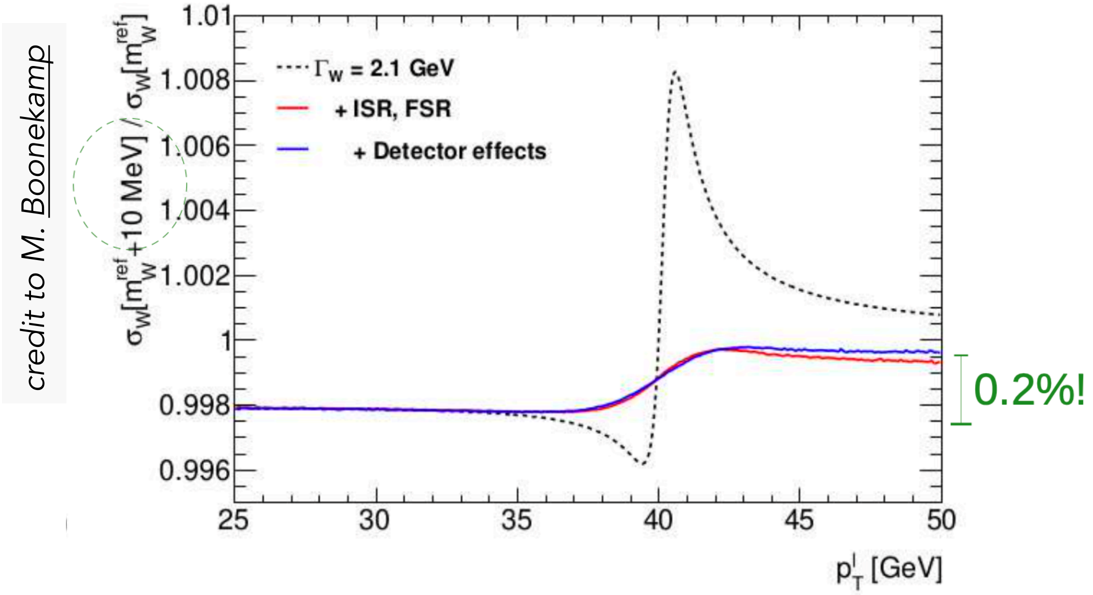
Complexity of the physics modelling



- **10 MeV precisions required ~0.1-0.2% control on the kinematics of the W production**
- sub-percent accuracy of predictions for PDF ; $p_T W$ modelling and W polarisation (Ai) is extreme challenge for QCD theory!

- @LHC W mass physics modelling is described using a **composite model** :
- Start from the NLO generators + LL parton-shower (Powheg+Pythia8) and apply corrections to reach the state of the art accuracy.
  - Use **<u>ancillary measurements</u>** of Drell-Yan processes to validate (and tune) the model and assess systematic uncertainties.

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

Breit-Wigner

NNLO pQCD

Parton Shower

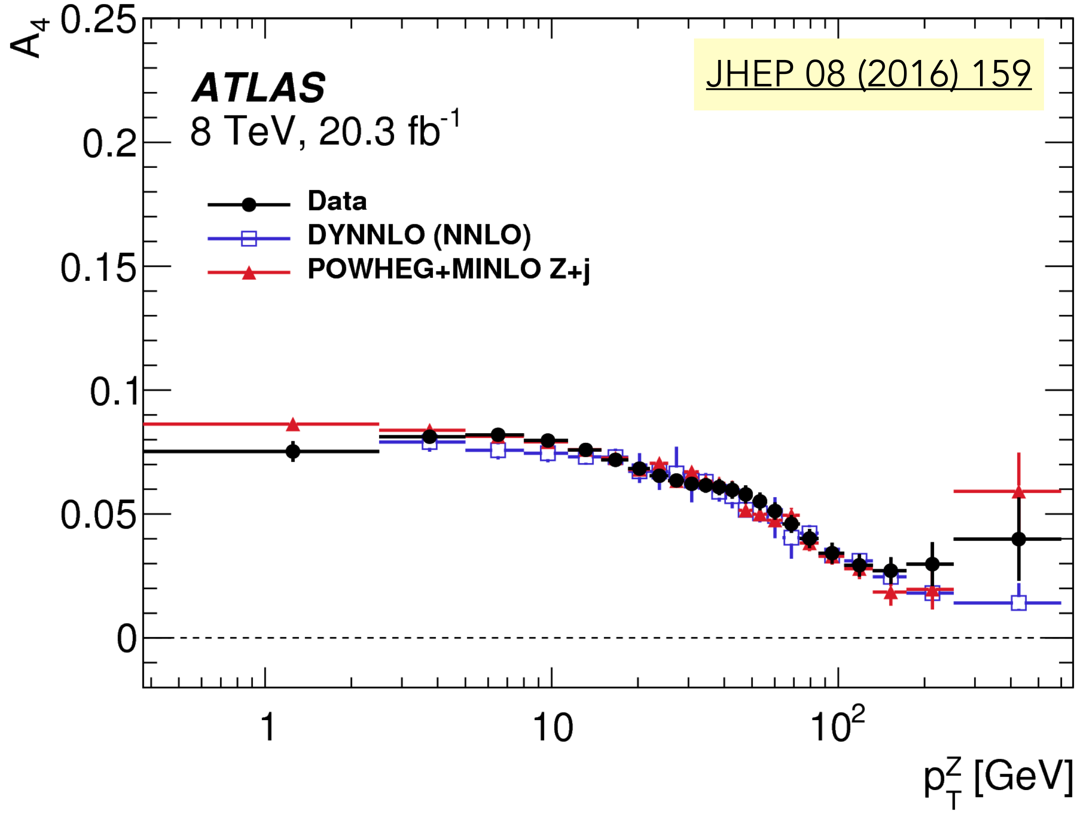
The Drell-Yan cross-section can be decomposed by factorising the dynamic of the boson production and the kinematic of the boson decay.

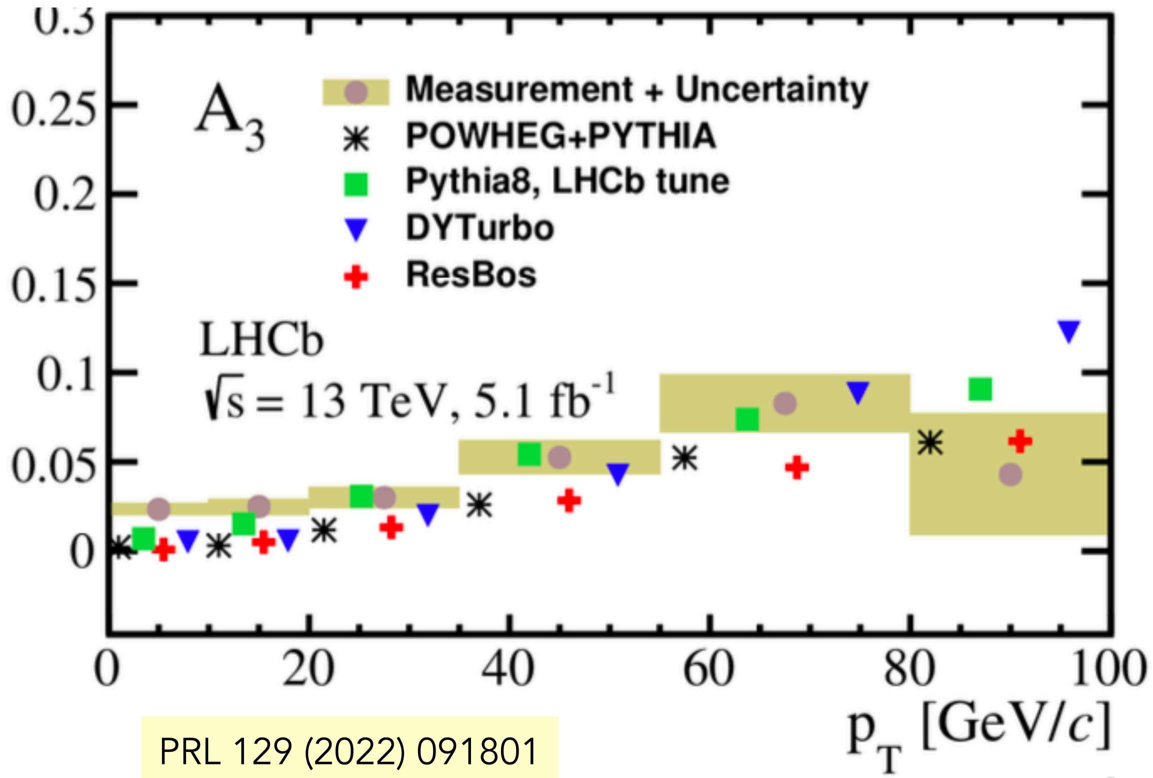
W mass: Angular coefficients

- The DY cross section can be reorganised by factorising the dynamic of the boson production, and the kinematic of the boson decay

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

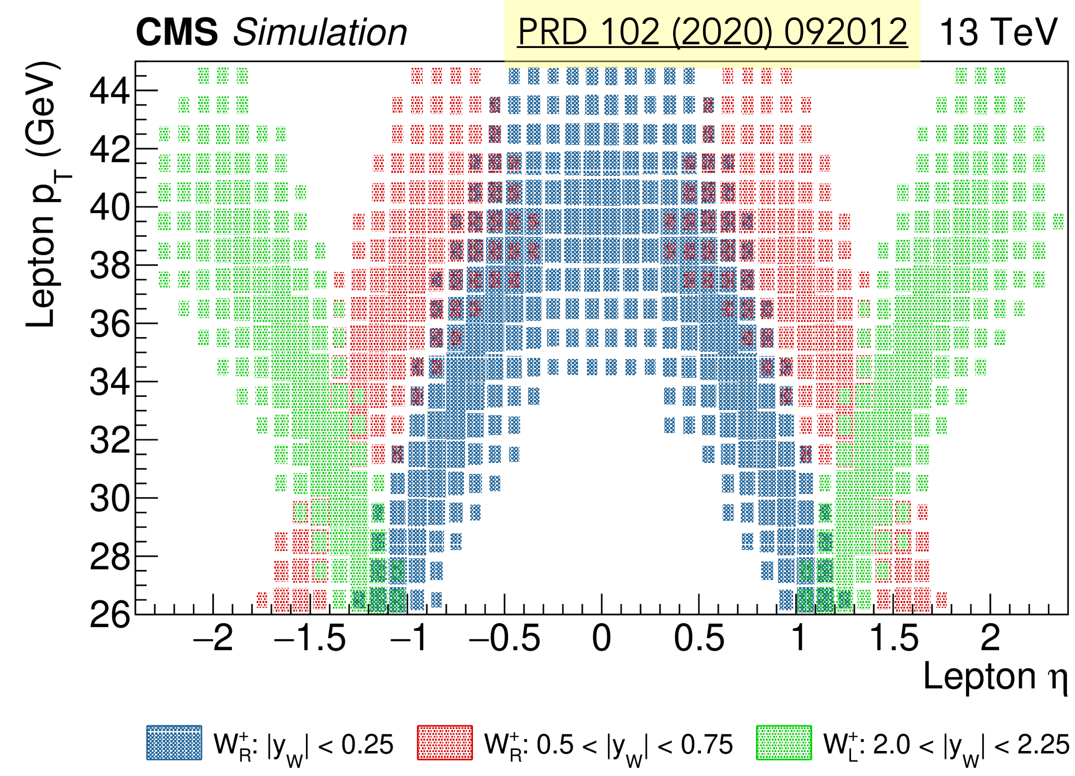
- Current m_W physics modelling has the angular coefficients (Ai) modelled with fixed order perturbative QCD at NNLO
- Ai predictions are validated by comparisons to the Z measurement
  - **Suboptimal for A4: fixed order prediction down to low pT** ?
    - Nowadays A4 can be predicted including resummation effects
  - LHCb m_W measurement accounts for A3 data/prediction discrepancy [cf. Recent LHCb measurement of Ai in $Z\rightarrow\ell\ell$]

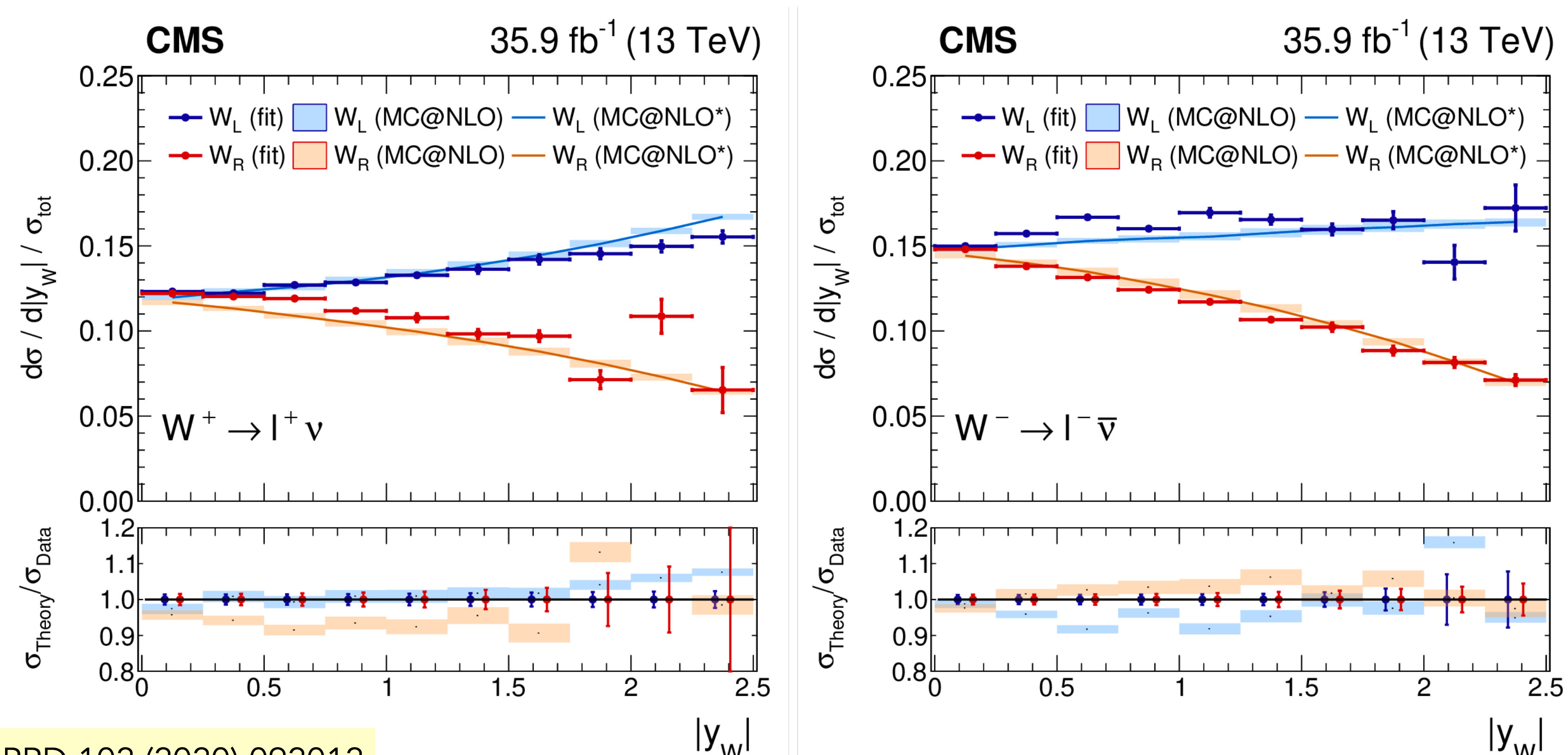




CMS approach: PDF constraint from Helicity X-section

- Idea: Lepton kinematic (pT:η) retain information on the W-boson rapidity and helicity states.
- From a **multi-differential measurement of lepton pT:η** extract the W boson rapidity and helicity cross-section
  - charge asymmetry are also measured as functions of the charged lepton transverse momentum and pseudorapidity.
    - **Large sensitivity** (and constraints) on valence-quark **PDFs**.





PRD 102 (2020) 092012

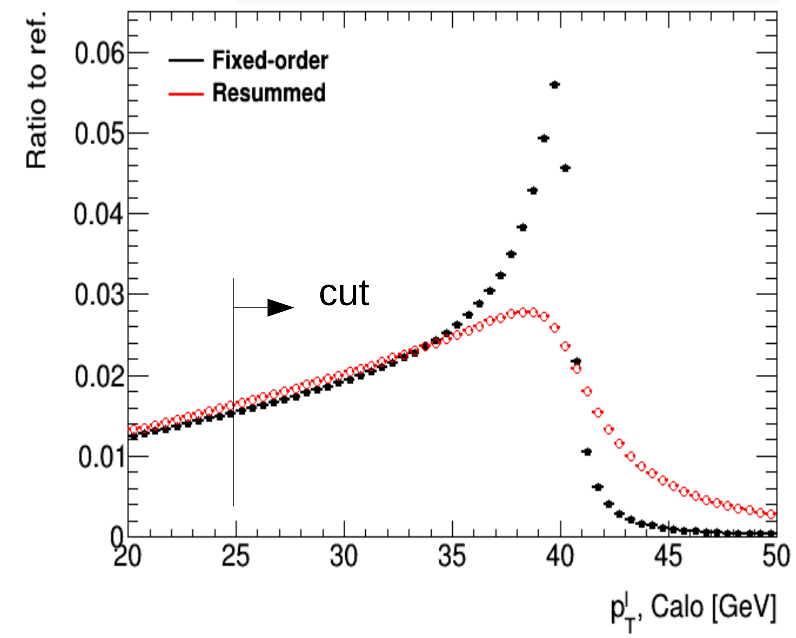
Future strategy for m_W at CMS?

- *Exploit fully available information from lepton distribution (pT:η)*
- *Minimal theoretical assumptions on W vs Z uncertainties*
- *Reduction of uncertainties through in-situ constraints*

Exploit PDF constraint power of ancillary measurements

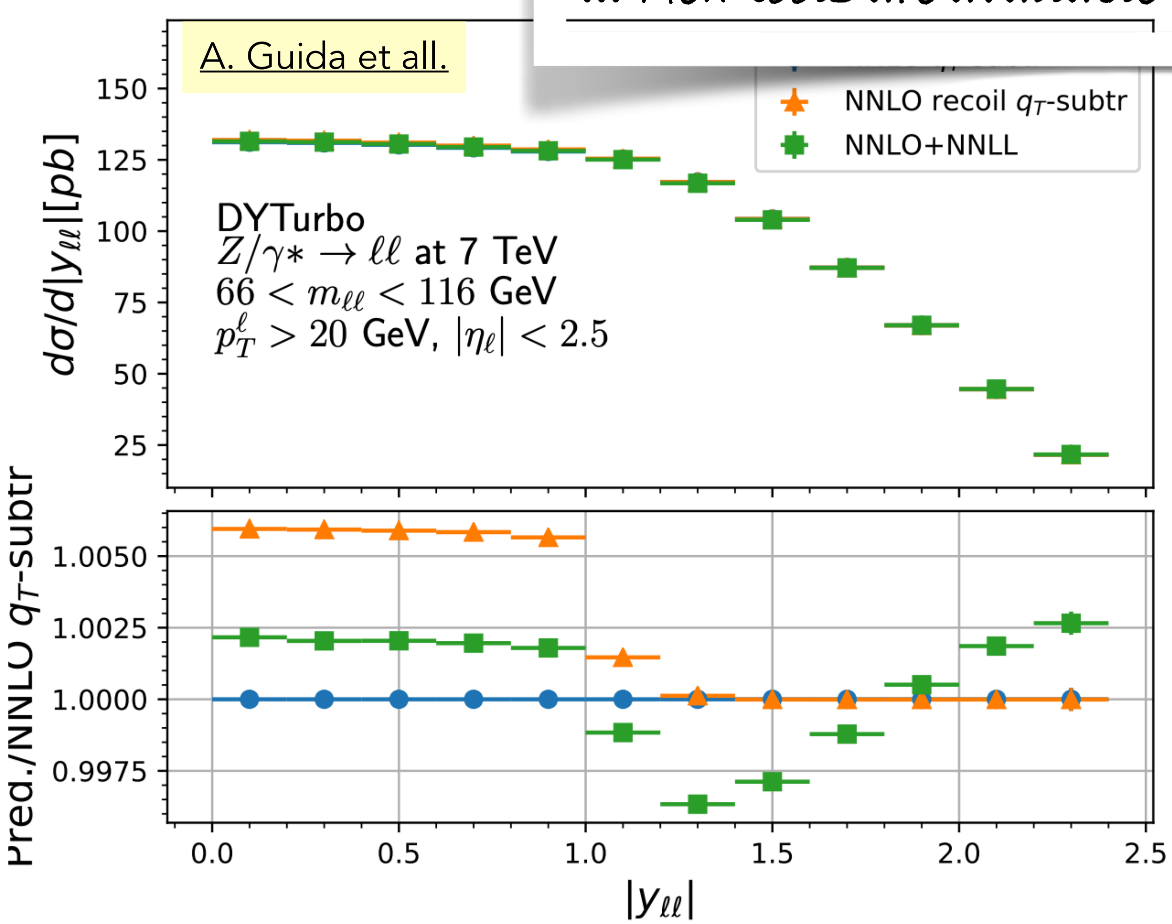
- Current m_W physics modelling uses fixed order calculation for **dσ/dy**
- OK for lepton-inclusive phase space but has known problems for fiducial x-section *[arXiv:2006.11382]*
  - Recoil q_T-subtraction scheme *[arXiv:2102.08039]* and resummation effects affect the lepton pT distributions → the acceptance of fiducial cuts
  - *This leads to a small inconsistency when interpreting fiducial cross section measurements in terms of PDFs fits, which typically use fixed-order predictions*

M.Boonekamp, LHCEWWG meeting



... New tools are available to fix this issue:

A. Guida et all.



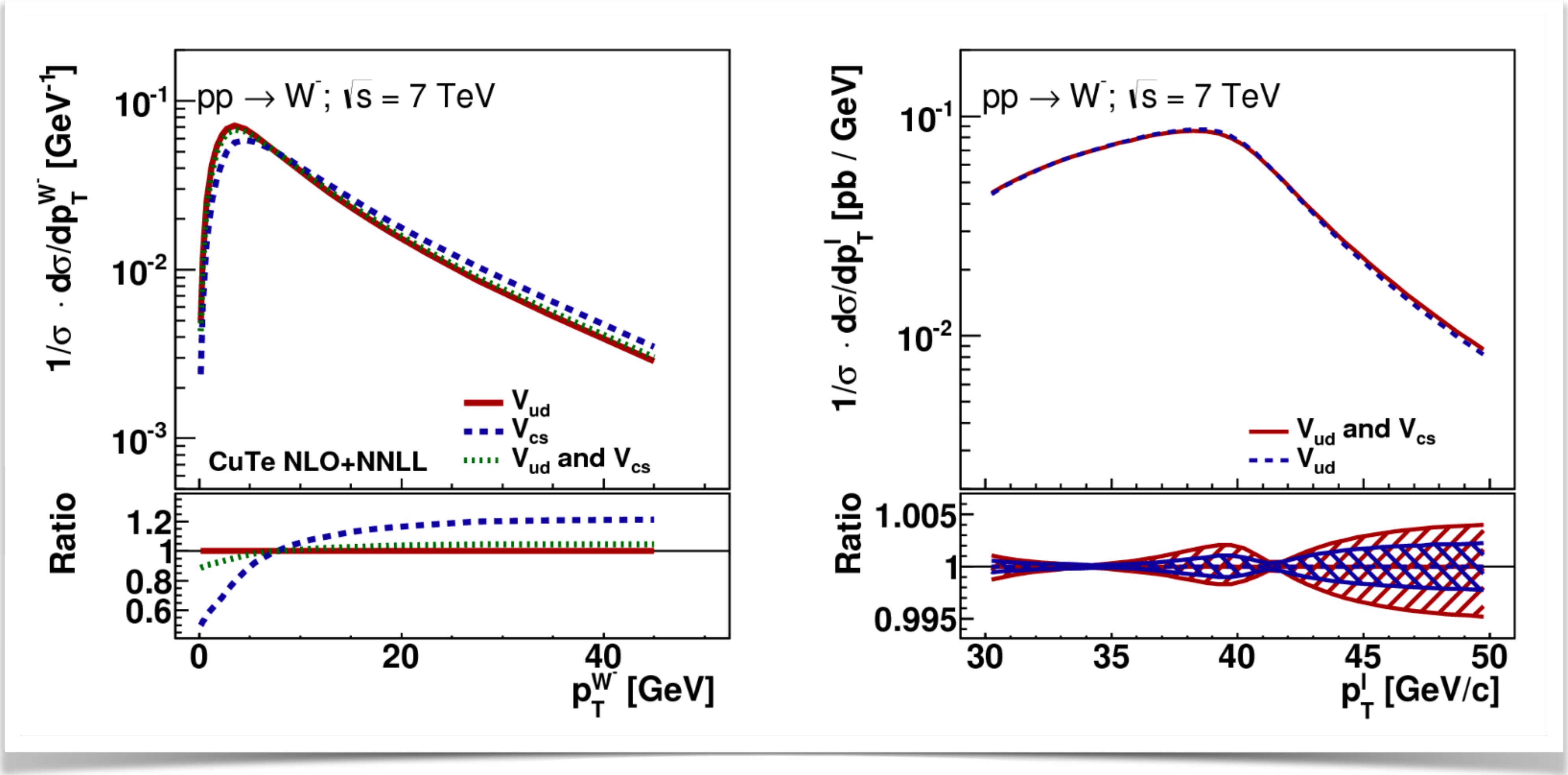
CT14nnlo 68%CL

Dataset	NNLO q_T-subtr.	NNLO recoil q_T-subtr.	NNLO+ NNLL
ATLAS W+ lepton rapidity	9.4 / 11	8.8 / 11	8.8 / 11
ATLAS W- lepton rapidity	8.2 / 11	8.7 / 11	8.2 / 11
ATLAS low mass Z rapidity	11 / 6 →	7.2 / 6 →	7.5 / 6
ATLAS peak CC Z rapidity	15 / 12 →	10 / 12 →	7.7 / 12
ATLAS peak CF Z rapidity	9.6 / 9	5.3 / 9	6.4 / 9
ATLAS high mass CC Z rapidity	6.0 / 6	6.5 / 6	5.8 / 6
ATLAS high mass CF Z rapidity	5.2 / 6	5.6 / 6	5.3 / 6
Correlated χ^2	39 →	40 →	32
Log penalty χ^2	-4.33	-3.39	-4.20
Total χ^2 / dof	99 / 61 →	88 / 61 →	77 / 61
χ^2 p-value	0.00	0.01	0.08

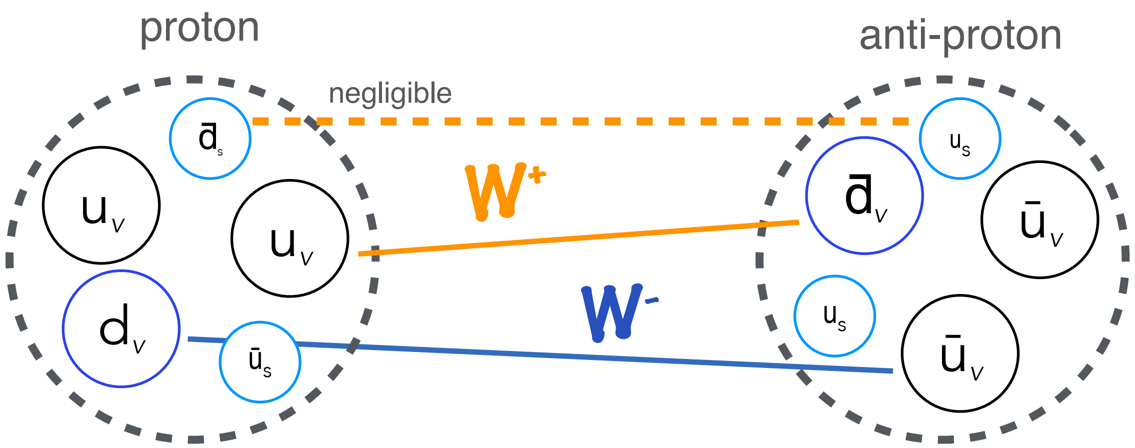
W mass @LHC (eg pp collision)

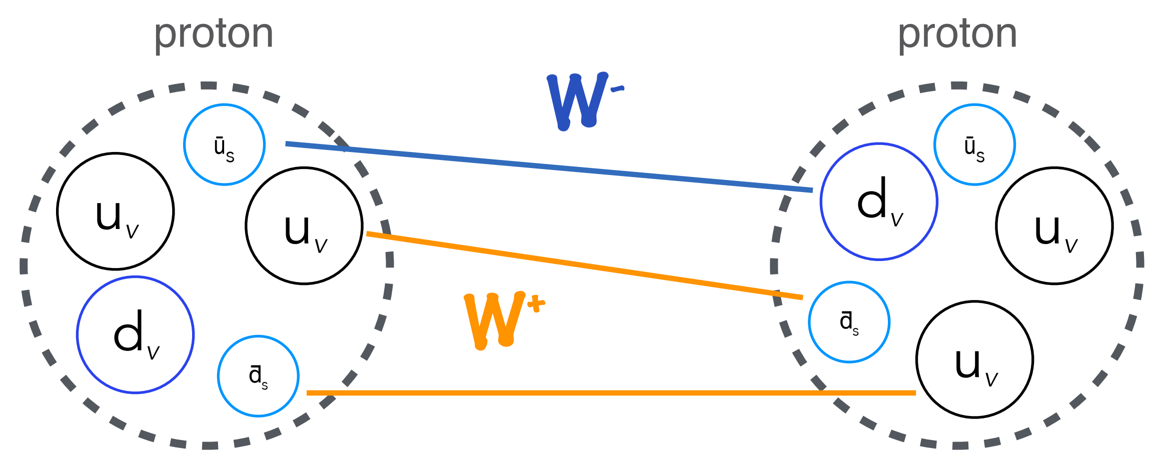
A *pp* collider is the most challenging environment to measure m_W, worse compared to e^+e^- and $p\bar{p}$

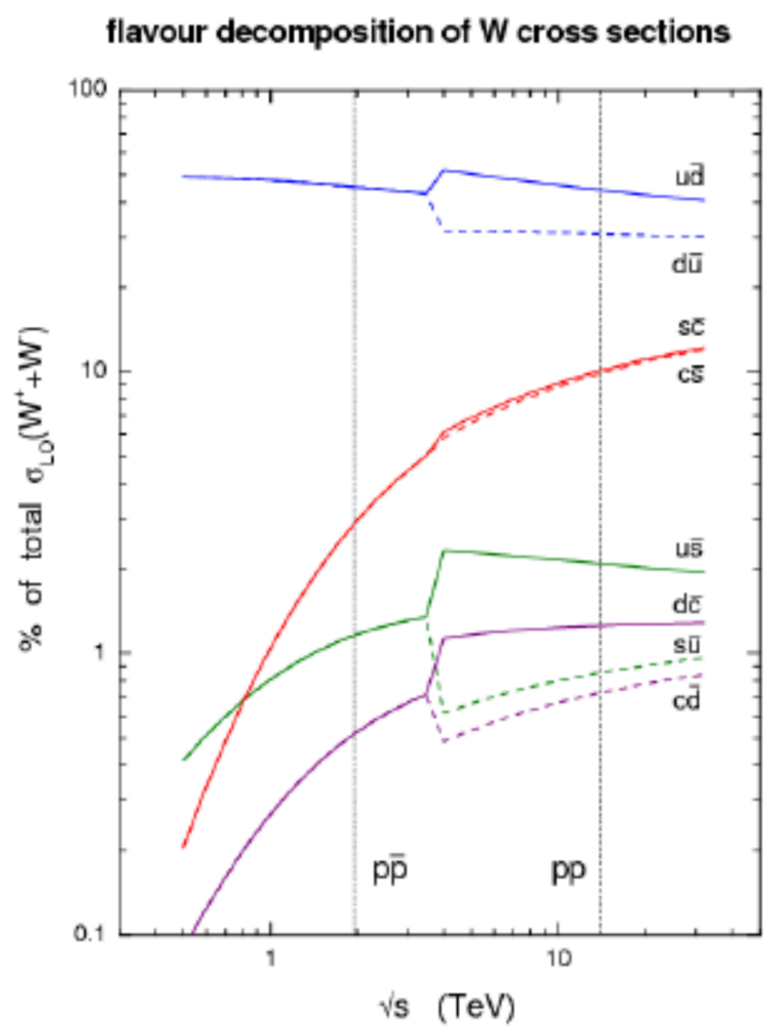
- In $p\bar{p}$ collisions W bosons are mostly produced in the same helicity state but in *pp* collision instead the W polarisation is determined by the difference between the u,d valence and sea densities
  - Large PDF-induced W-polarisation uncertainty affecting the p^l_T distribution
- W^+/W^- production is asymmetric→ charge-dependent analysis
- Second generation quark PDFs play a larger role at the LHC *(25% of the W* boson production is induced by at least one second generation quark s or c not the case for the Z boson). The amount of heavy-quark- initiated production has implications for the W-boson transverse-momentum distribution and for the W polarisation.

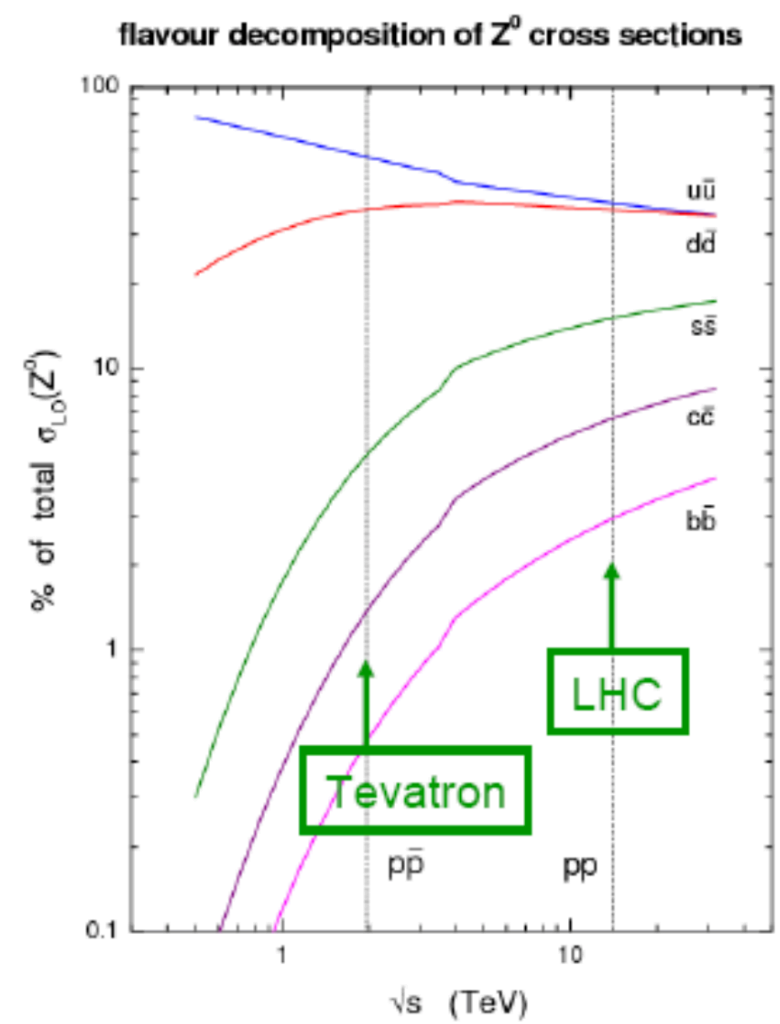


challenge of W production @LHC









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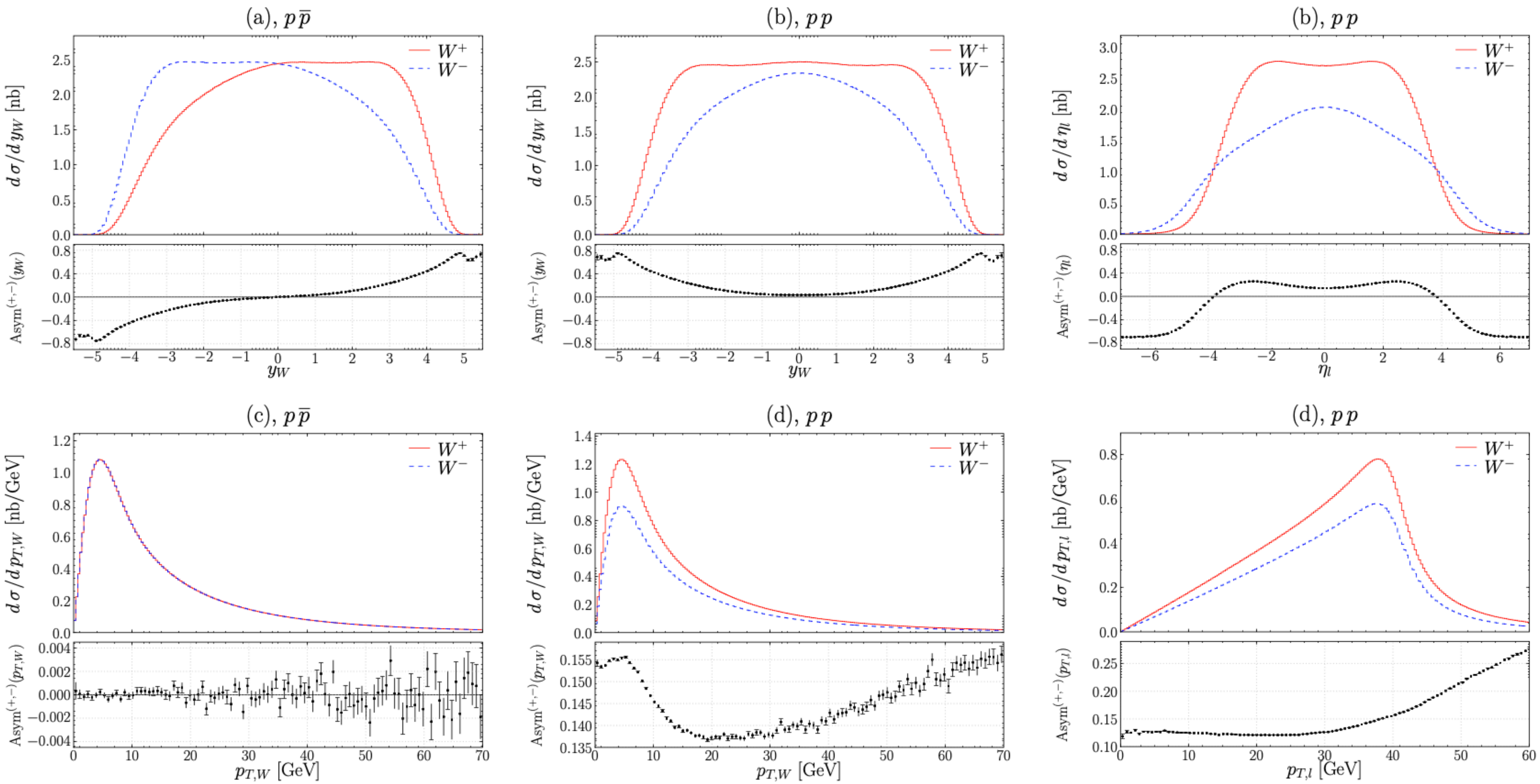
challenge of W production @LHC

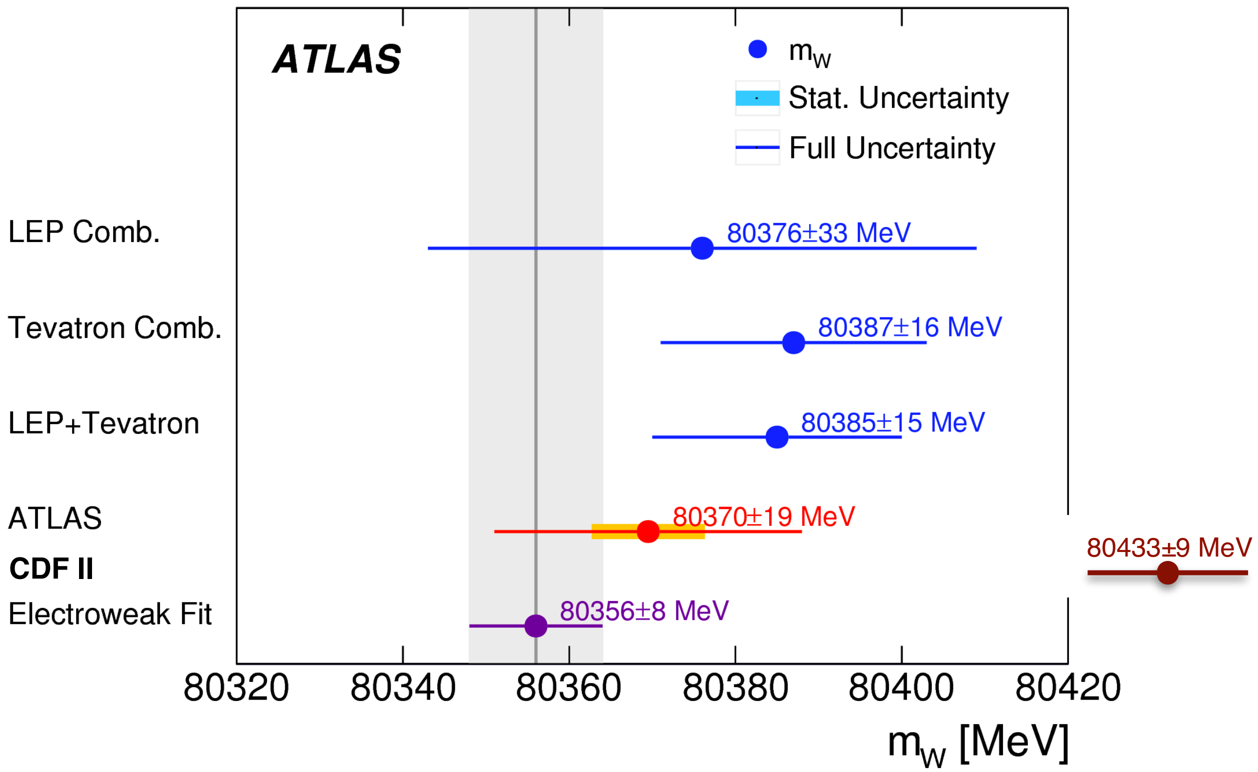
Eur. Phys. J. C 69 (2010) 379-397



7TeV w_m re-analysis

💡 The idea is to revisit ATLAS measurement with profile likelihood (PLH) fitting

- Advantage:
  - Rigorous review of the analysis
  - (in situ) constrain experimental & modelling systematic uncertainties
  - + adding modern PDF sets
- Disadvantage:
  - Computational expensive
  - Several 1000 Nuisance Parameter (NP) → robust systematic model



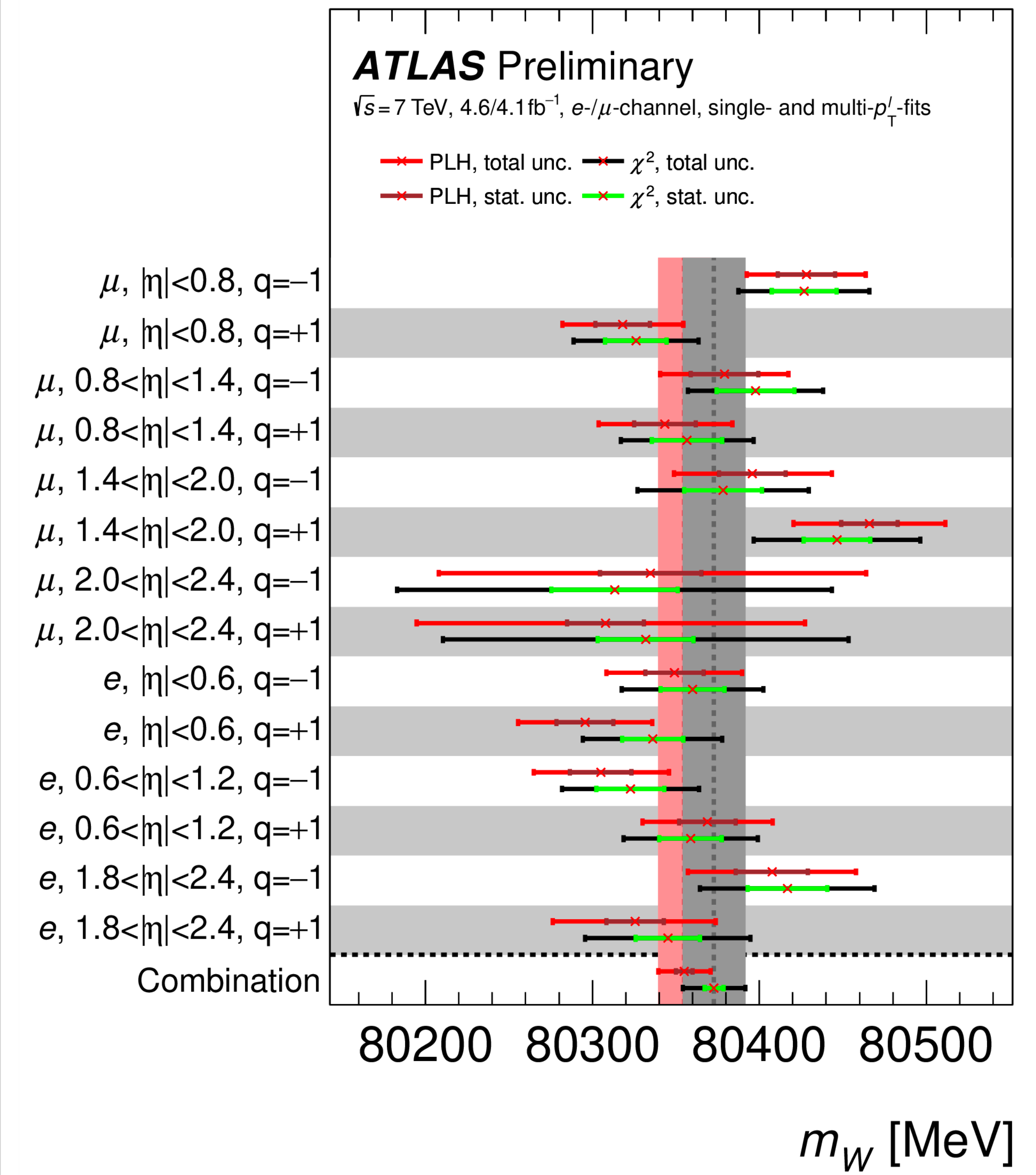
The analysis improvements

- **Improvement of the analysis:**
  - Multijet Background Estimation (Δm_W =1.9 MeV)
    - Systematic shape variation using PCA (principal component analysis)
    - New transform function form CR to SR
    - Reduction of 2 MeV uncertainty
  - EW unc. are evaluated at detector level
    - increase of 1-2 MeV uncertainty
  - Recovering data in the electron channel
    - Increase statistics by 1.5%
  - Add ΓW as NP parameter

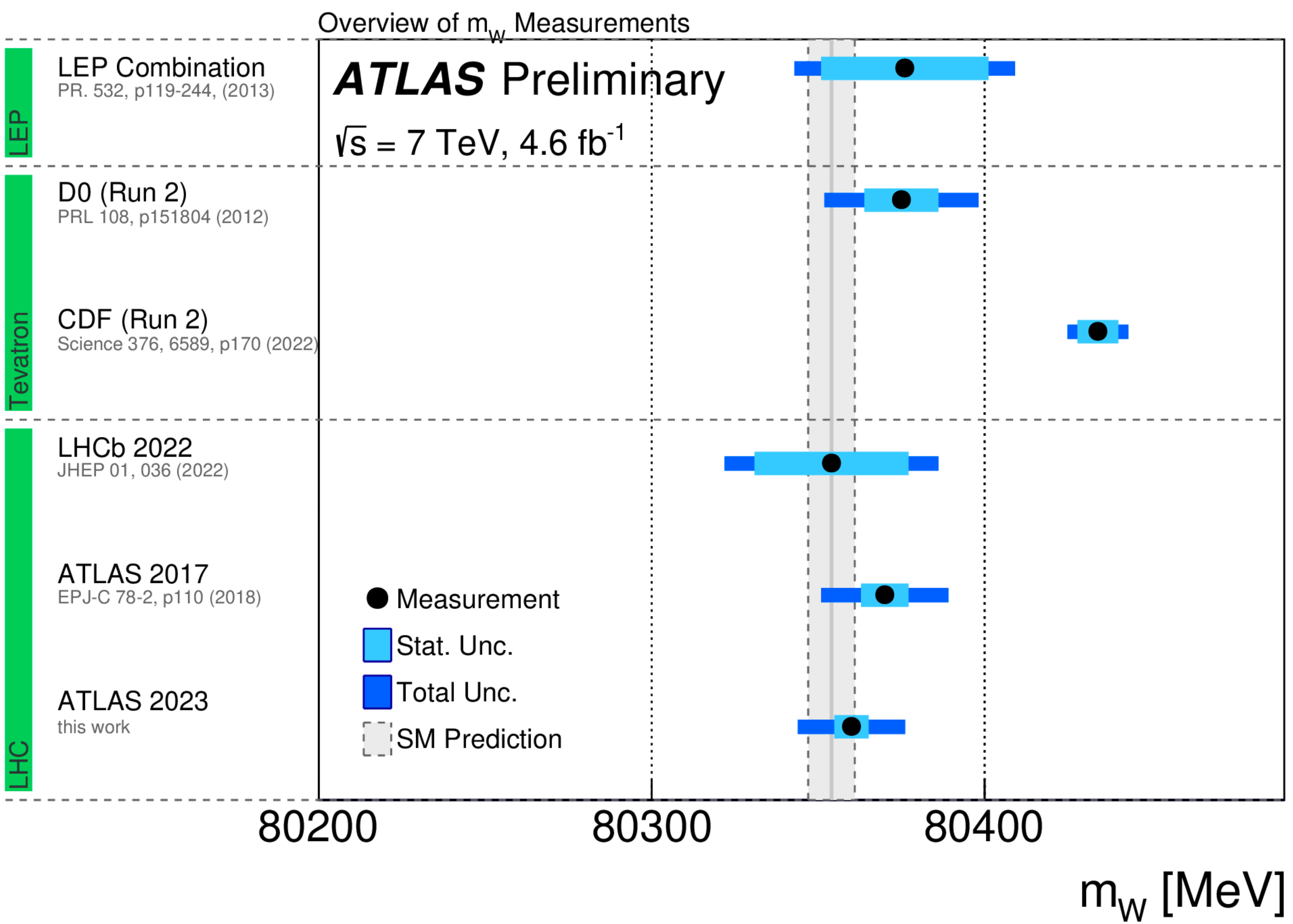
The PLH fit result using all categories yields a value of **m_W = 80355.1 ± 15.6 MeV** with the CT10nnlo PDF

Overall m_W 14.4 MeV lower compared to the legacy (80369.5 ± 18.5 MeV)
Profiling of systematic uncertainties has an impact of −16.3 MeV

PLH fit validation using CT10 PDFs



New Measurement



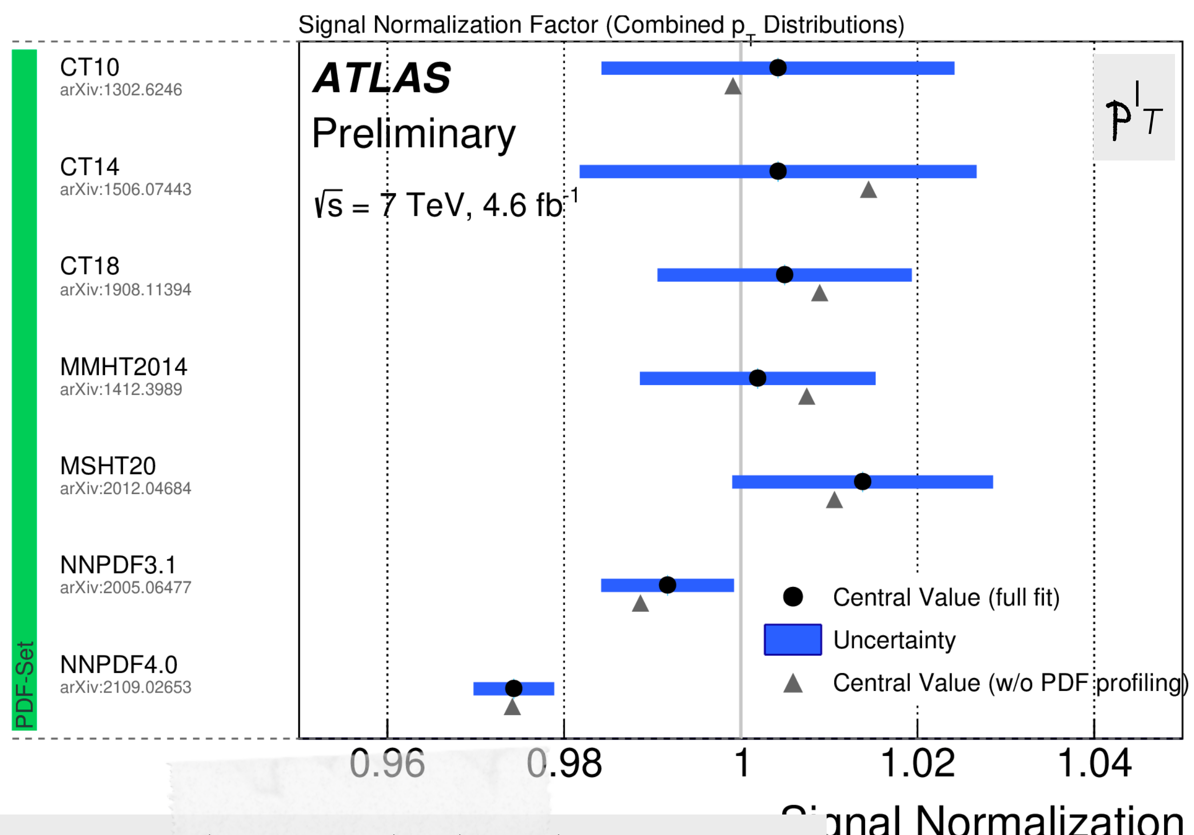
ATLAS re-analysis PDF Normalisation factor

- Profiling reduces the spread of PDFs from 28 to 18 MeV
- **CT18 PDF Set chosen as new baseline**: yields most conservative uncertainties
- CT18 PDF uncertainties of 7.7 MeV cover the central values of CT10, CT14, MMHT2014 and MSHT20, but **not** of NNPDF3.1 and NNPDF4.0
- Normalization of NNPDF4.0 **far away from other PDFs sets** (NNPDF4.0 and 3.1 are not overlapping even within their own systematics)

PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
MSHT20	$80358.9^{+13.0}_{-16.3}$	$80379.4^{+24.6}_{-25.1}$	$80356.3^{+14.6}_{-14.6}$
NNPDF3.1	$80344.7^{+15.6}_{-15.5}$	$80354.3^{+23.6}_{-23.7}$	$80345.0^{+15.5}_{-15.5}$
NNPDF4.0	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$

$$v_{ji}(\mu,\theta) = \Phi\times[S_{ji}^{nom}+\mu\times(S_{ji}^{\mu}-S_{ji}^{nom})] + \sum(\theta_k\times(S_{ji}^{k}-S_{ji}^{nom})) + B_{ji}^{nom}+\sum(\theta_t\times(B_{ji}^{t}-B_{ji}^{nom}))$$

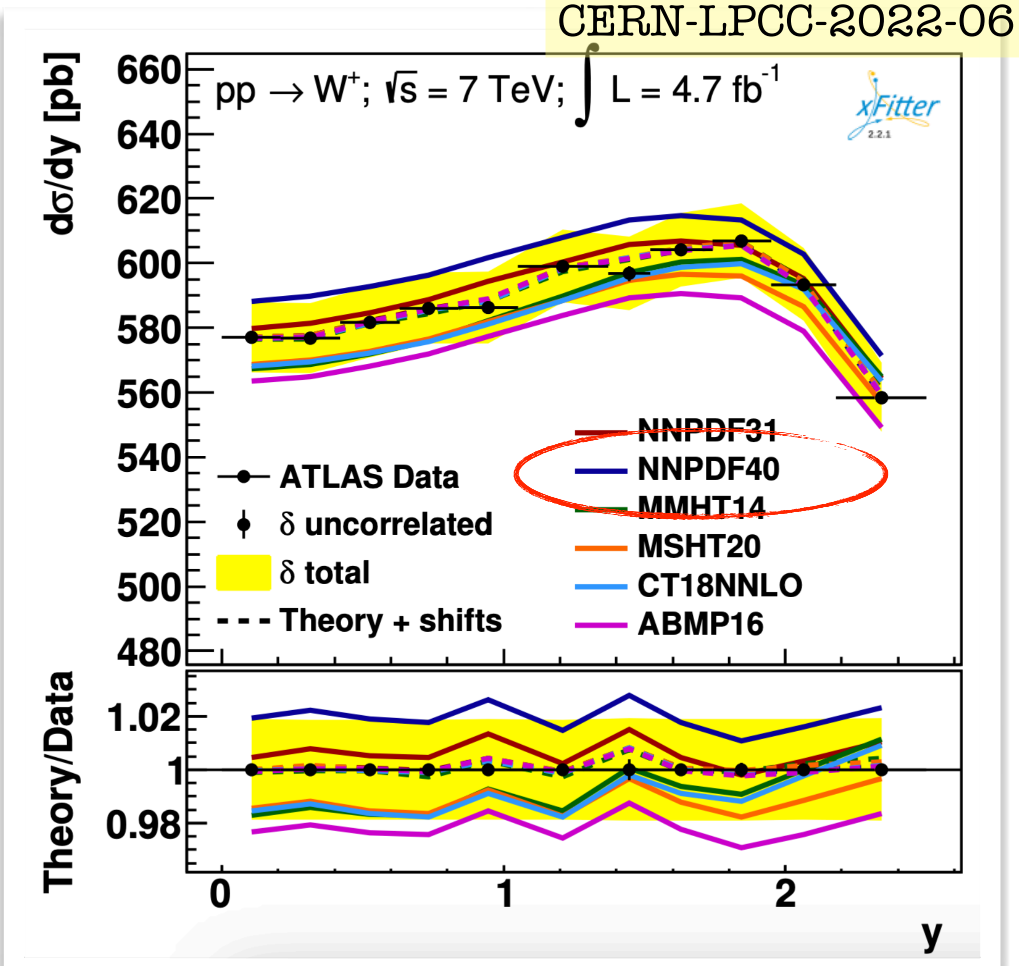
The signal normalisation factors (fitted in the LH model) obtained from the combined PLH fits indicate the quality of the description of the W-boson cross sections at $\sqrt{s} = 7$ TeV by the different PDF sets.



~2% of lumi unc missing in the plot !

(compatibility of NNPDF4.0 with other ATLAS measurement)

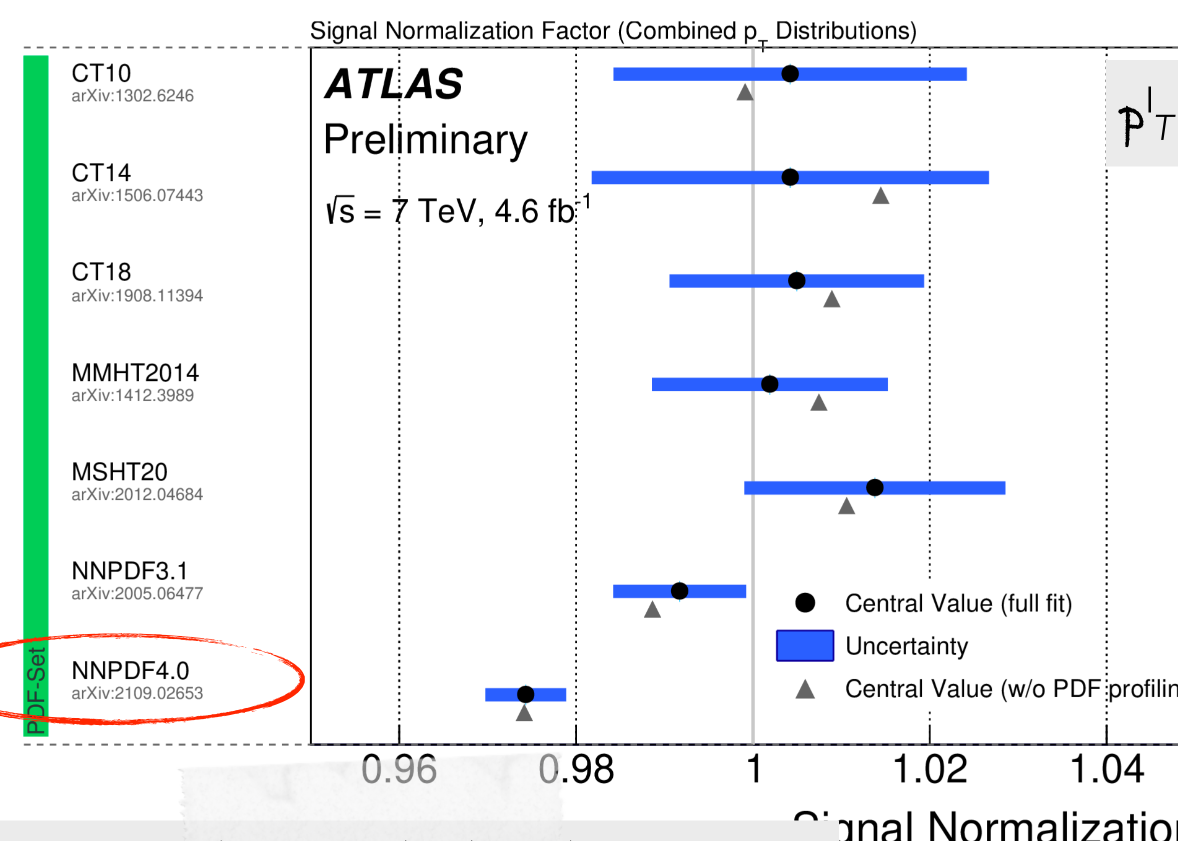
CERN-LPCC-2022-06



Compatibility test between 8TeV ATLAS full phacespace $Z\to\ell\ell\ d\sigma/dy$ measurements and predictions obtained from DYTURBO using different PDF sets.

PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN^{3}LO [60]	13/8	0.11	1.2 ± 0.6
CT18A [61]	12/8	0.17	0.9 ± 0.7
MSHT20 [62]	10/8	0.26	0.9 ± 0.6
NNPDF4.0 [63]	30/8	0.0002	0.0 ± 0.2
ABMP16 [64]	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0 [65]	22/8	0.005	-1.3 ± 0.8
ATLASpdf21 [66]	20/8	0.01	-1.1 ± 0.8

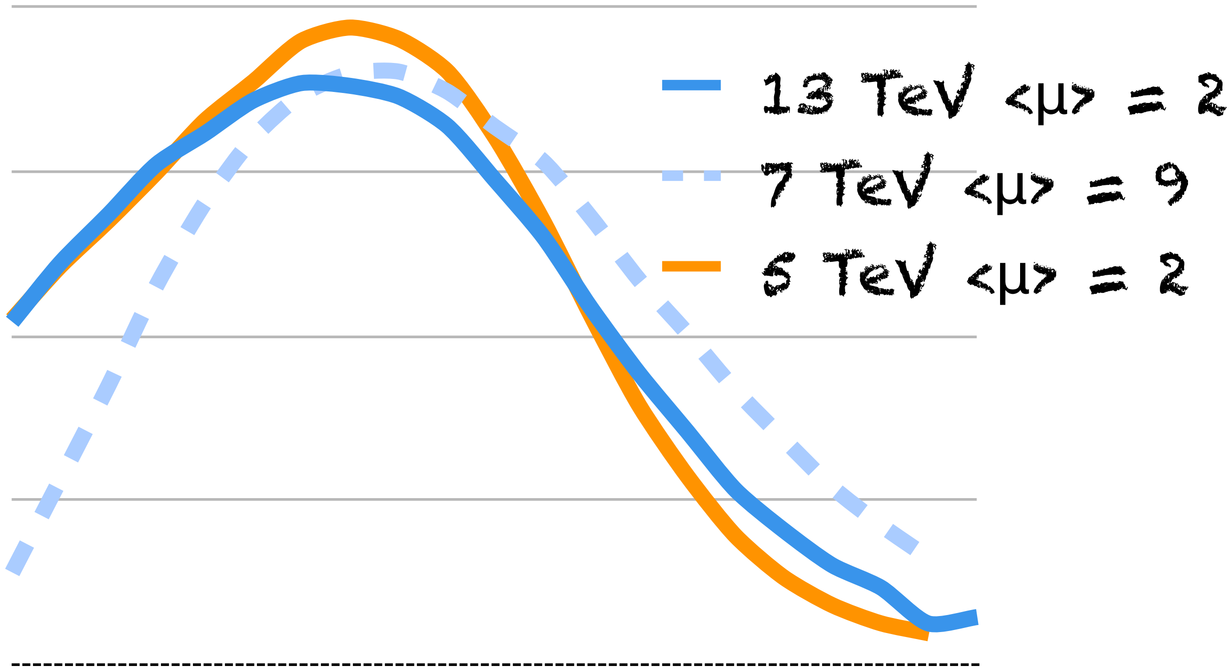
ATLAS-CONF-2023-013



more recent NNPDF PDF set is appeared to be slightly disfavour by ATLAS data

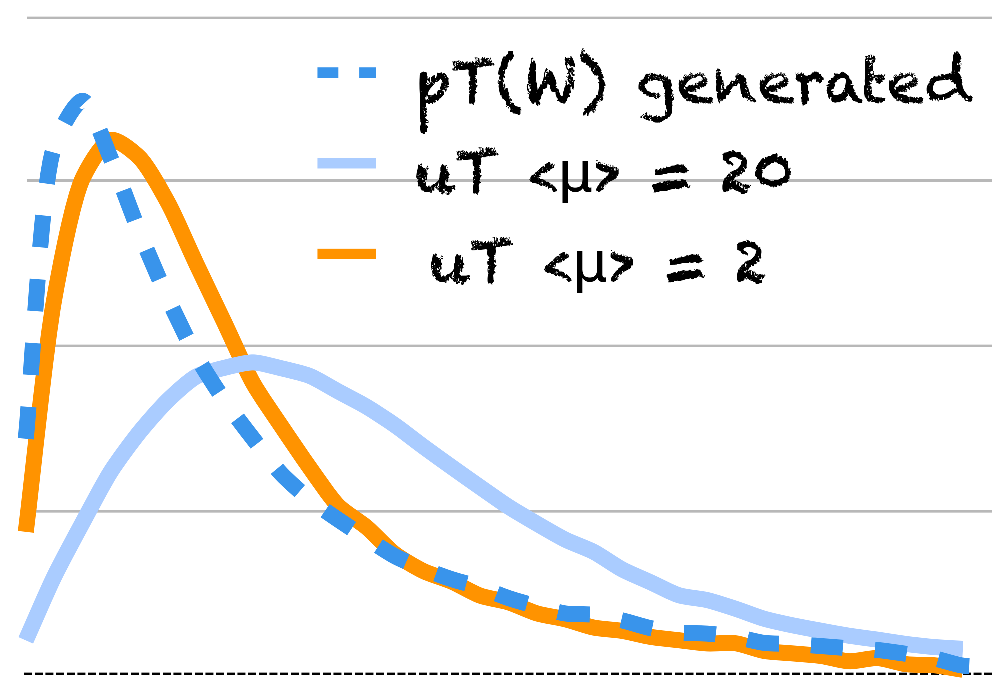
~2% of lumi unc missing in the plot !

low mu benefit



Transverse mass W

Combination	Weight
Electrons	0.427
Muons	0.573
m_{T}	0.144
p_{T}^{ℓ}	0.856
W^{+}	0.519
W^{-}	0.481

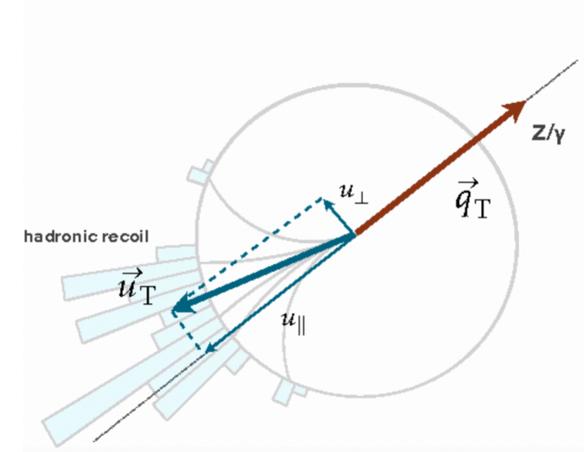


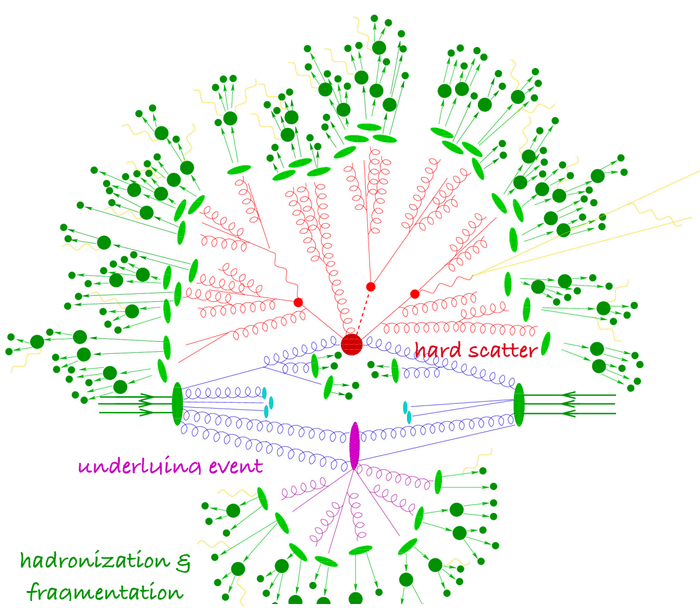
Transverse momenta W

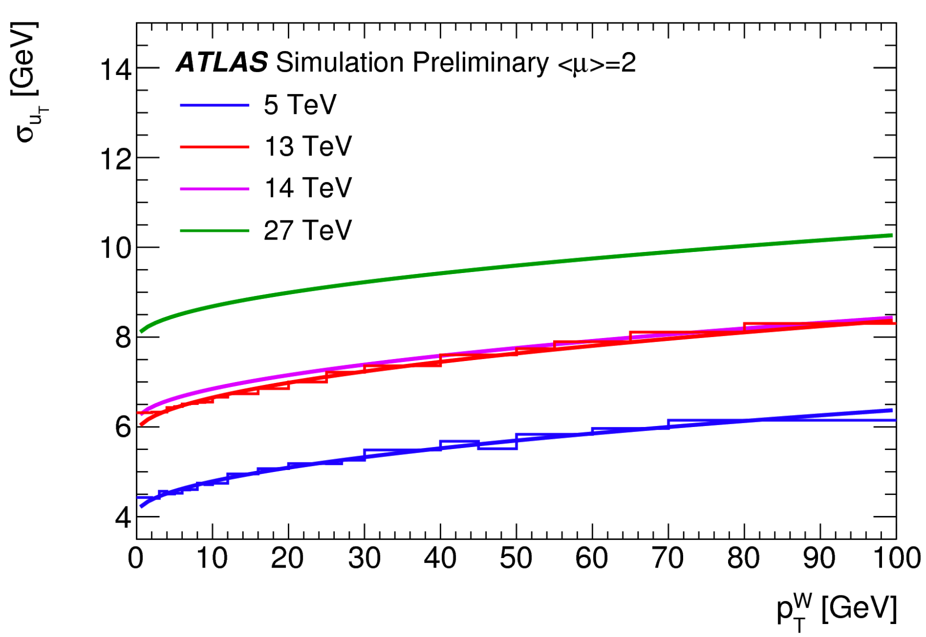
Underlying event

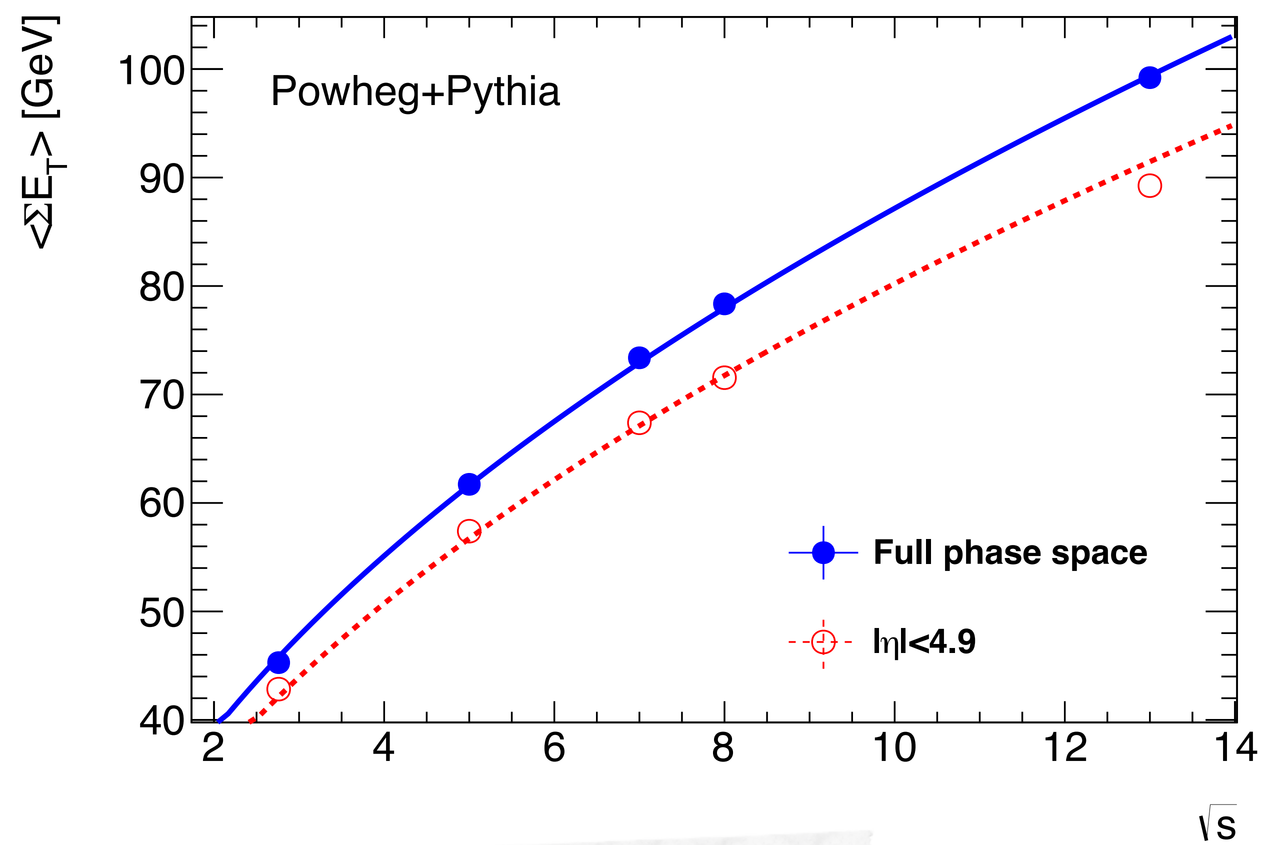
In order to resolve p_T^W at 5 GeV we need to achieve a hadronic recoil resolution of the same order.

- The resolution of the hadronic recoil strongly depends on **ΣE_T** (the scalar sum of the transverse energy deposited in the detector that represents the total event activity)
  - At low p_T^W, two sources largely contribute to ΣE_T and to the deterioration of the recoil resolution: **A) underlying event** and B) pileup









The underlying event grows as expected with √s as well as recoil resolution

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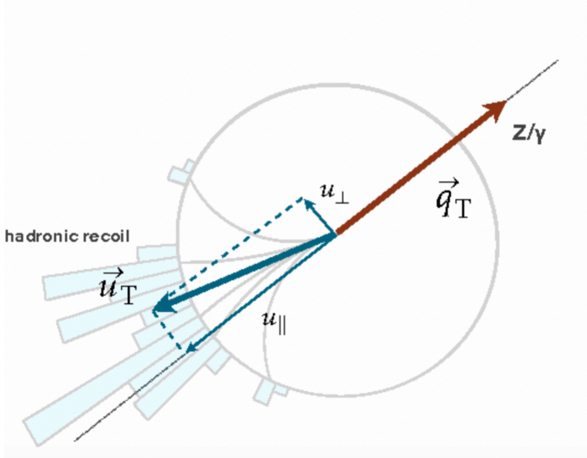
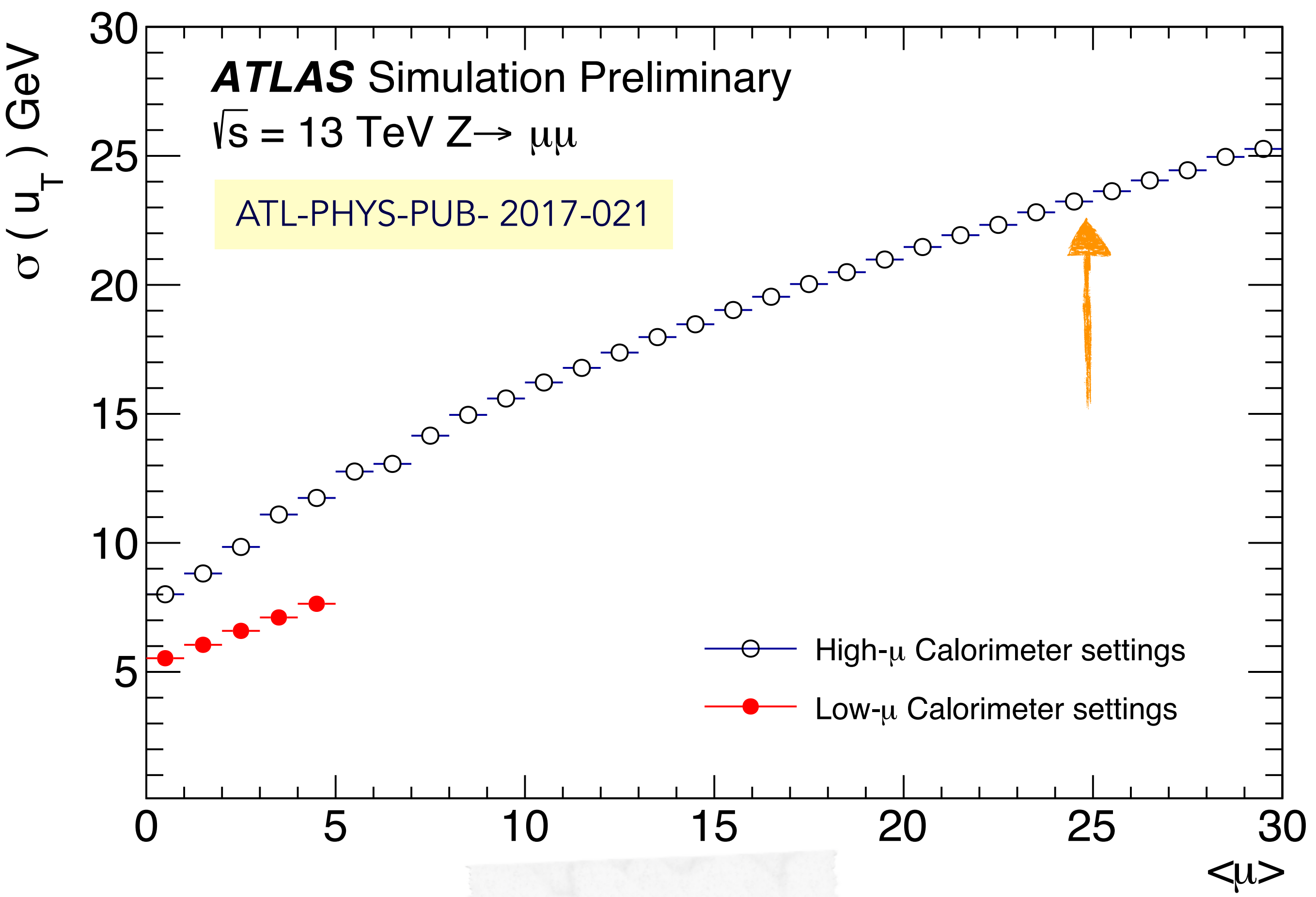
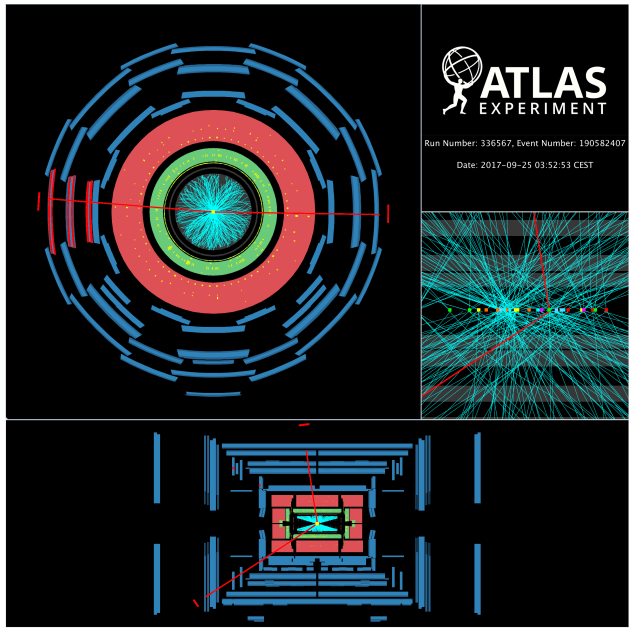
A) underlying event and **B) pileup**







24 additionally reconstructed vertices

$\langle\Sigma E_T\rangle$ increases ~linearly with pileup: about 20 GeV per additional pileup interaction.
At low $\langle\mu\rangle$, the resolution, σu_T increases by ~12% per each additional pileup interaction

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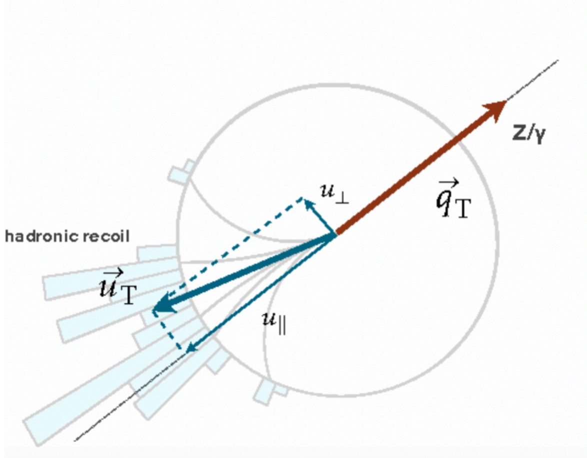
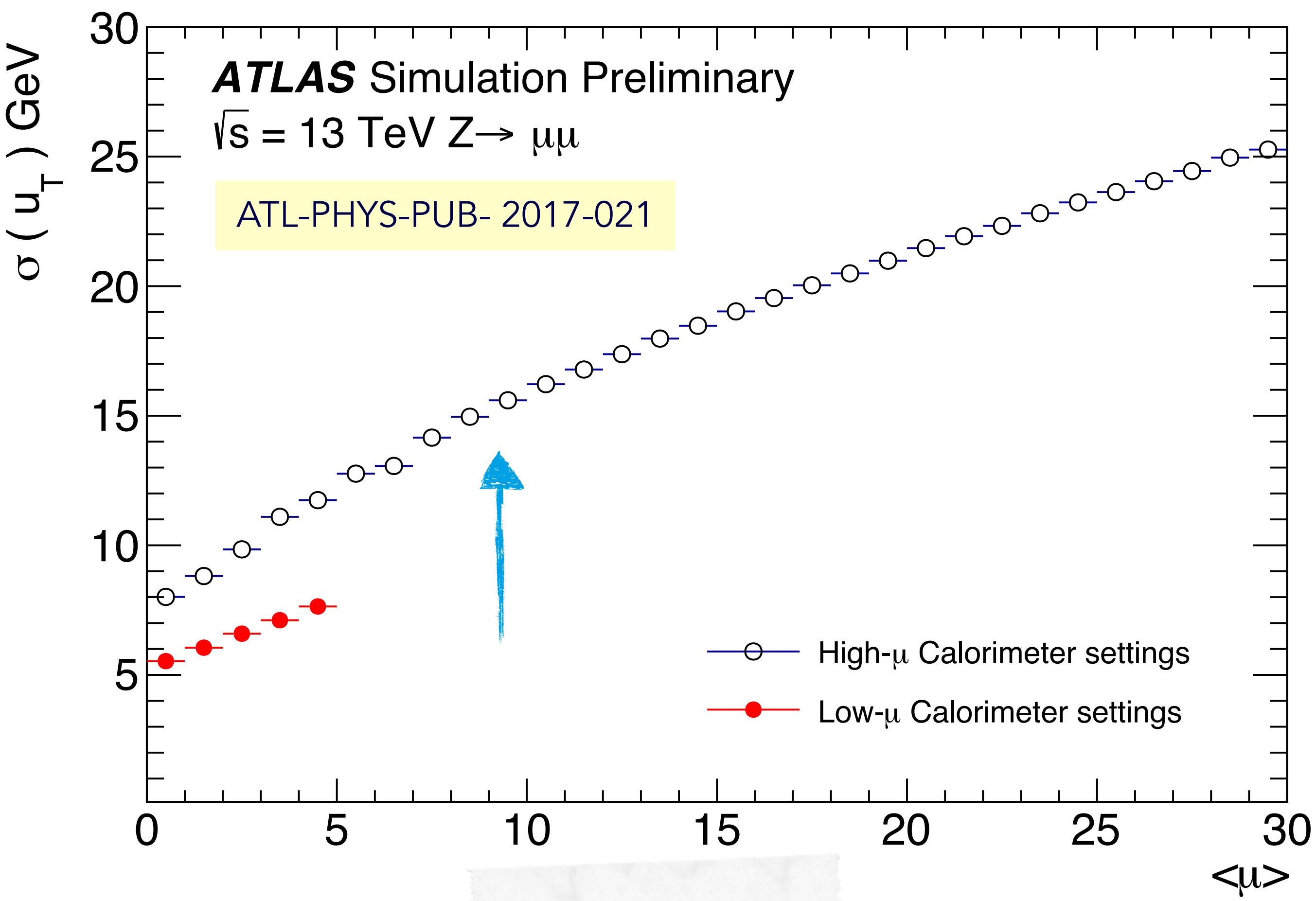
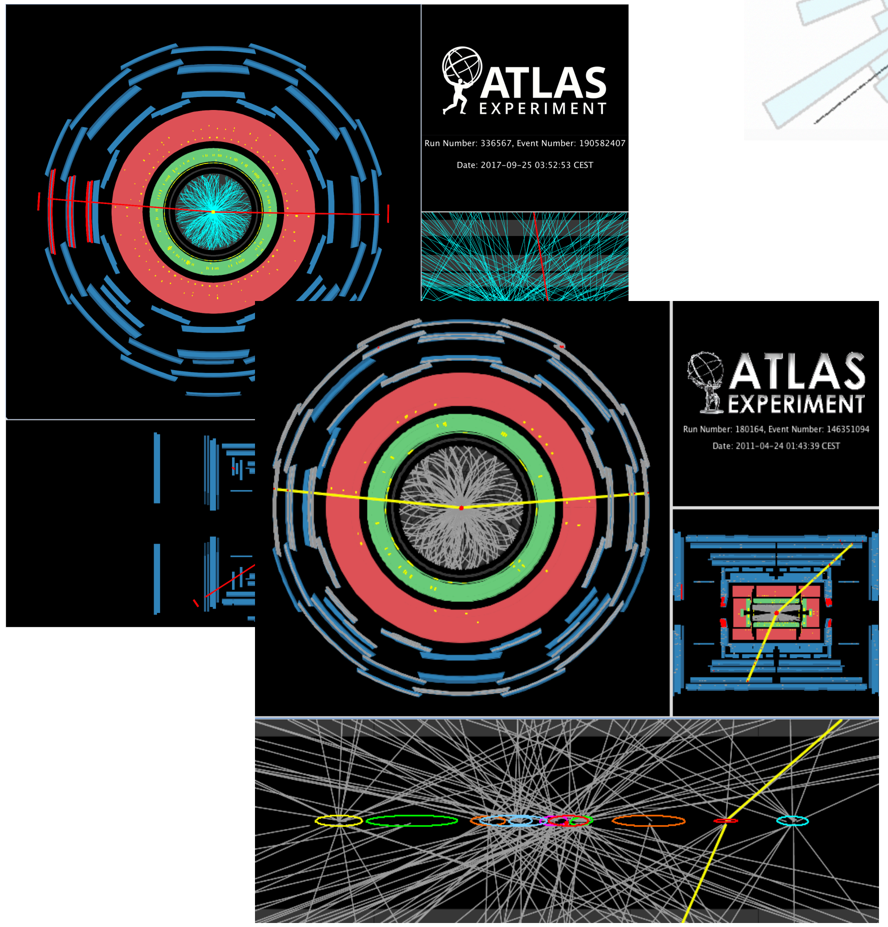


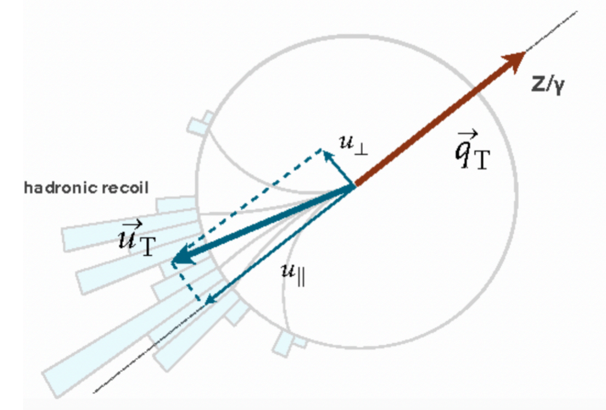




9 additionally reconstructed vertices

$\langle\Sigma E_T\rangle$ increases ~linearly with pileup: about 20 GeV per additional pileup interaction.
At low $\langle\mu\rangle$, the resolution, σu_T increases by ~12% per each additional pileup interaction

How to get 1% measurement of the p^W_T spectrum?



In order to resolve p_T^W at 5 GeV we need to achieve a hadronic recoil resolution of the same order.
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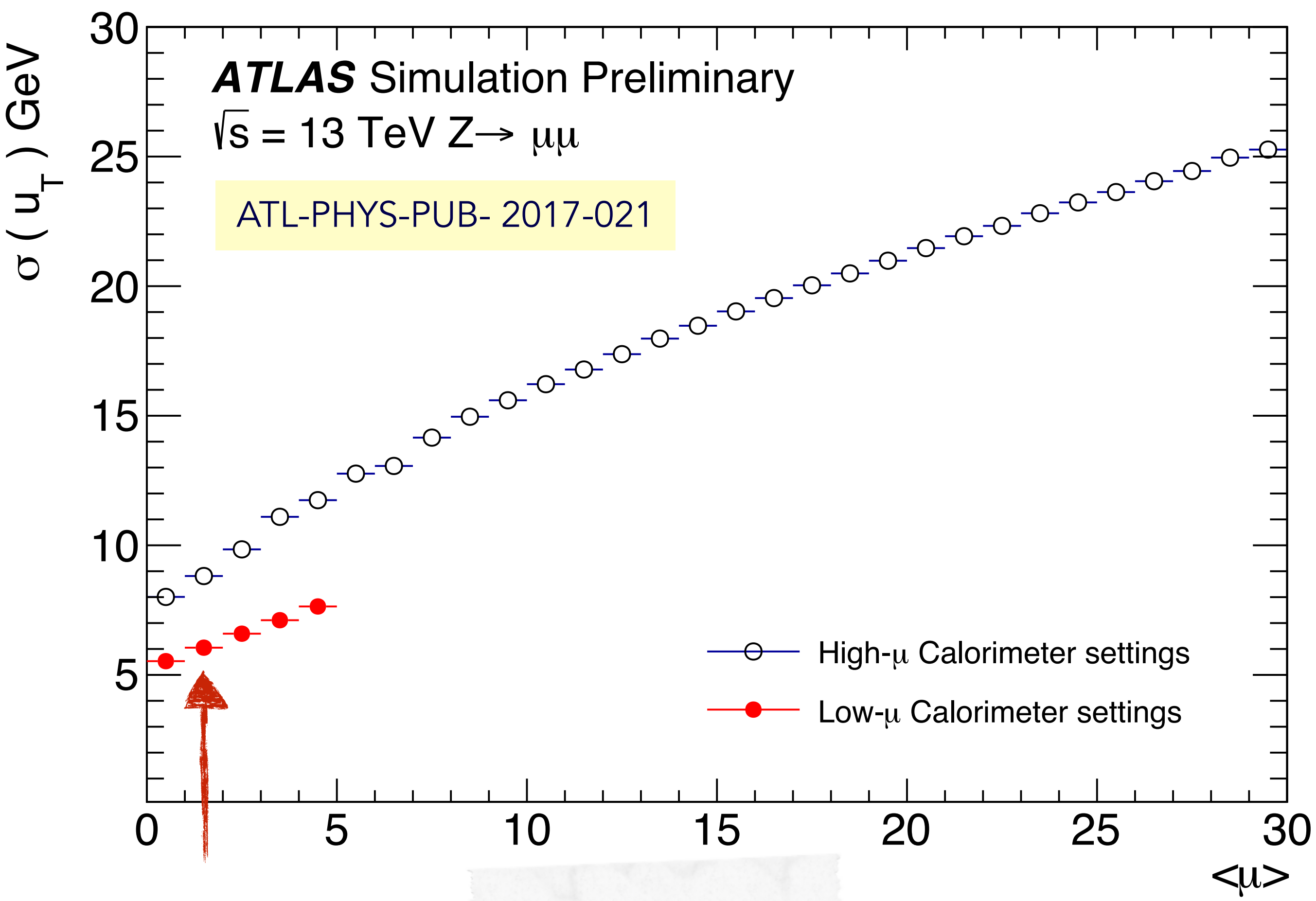
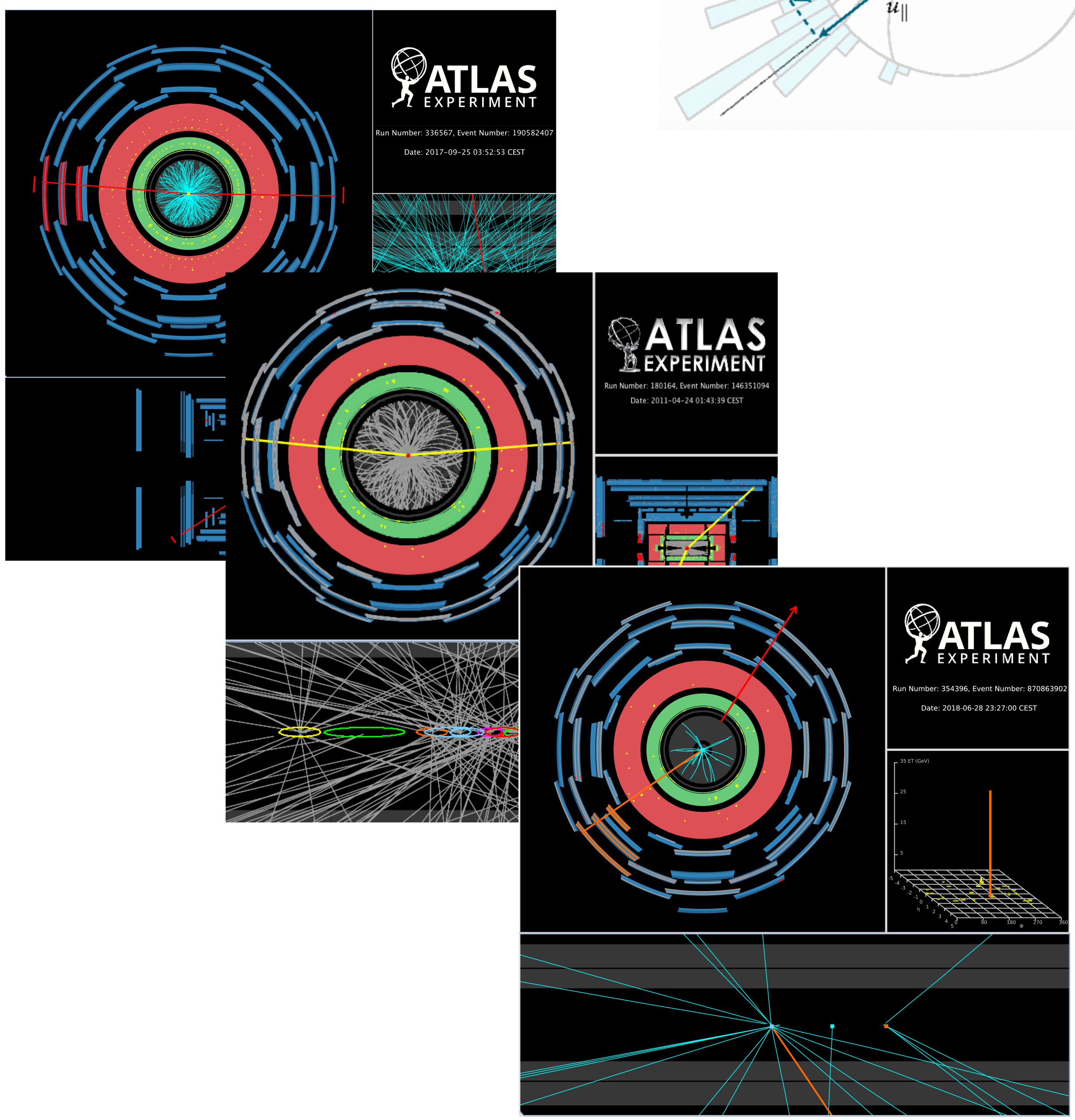
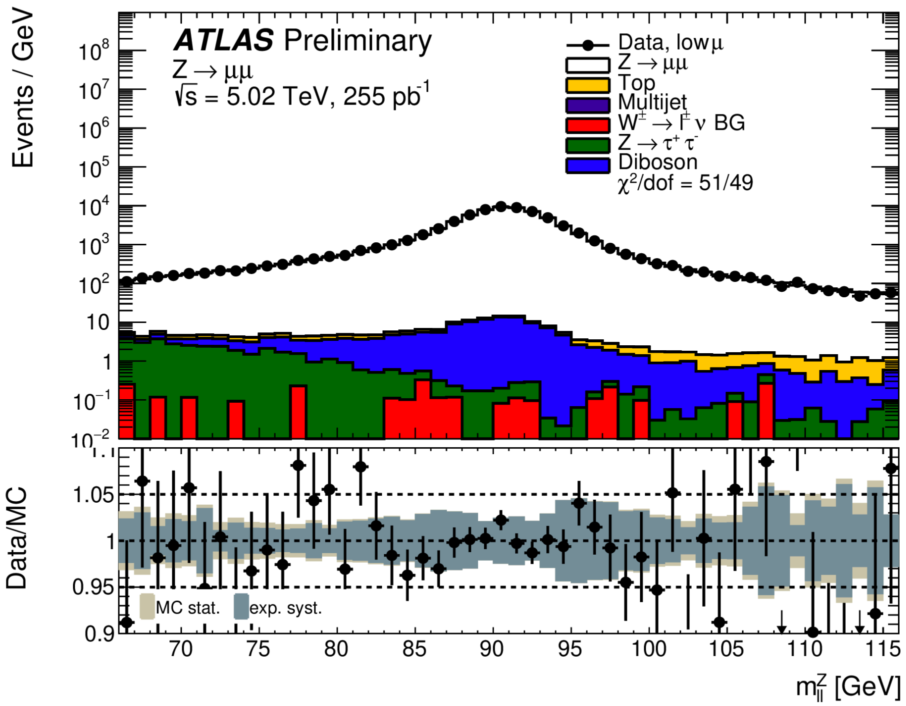


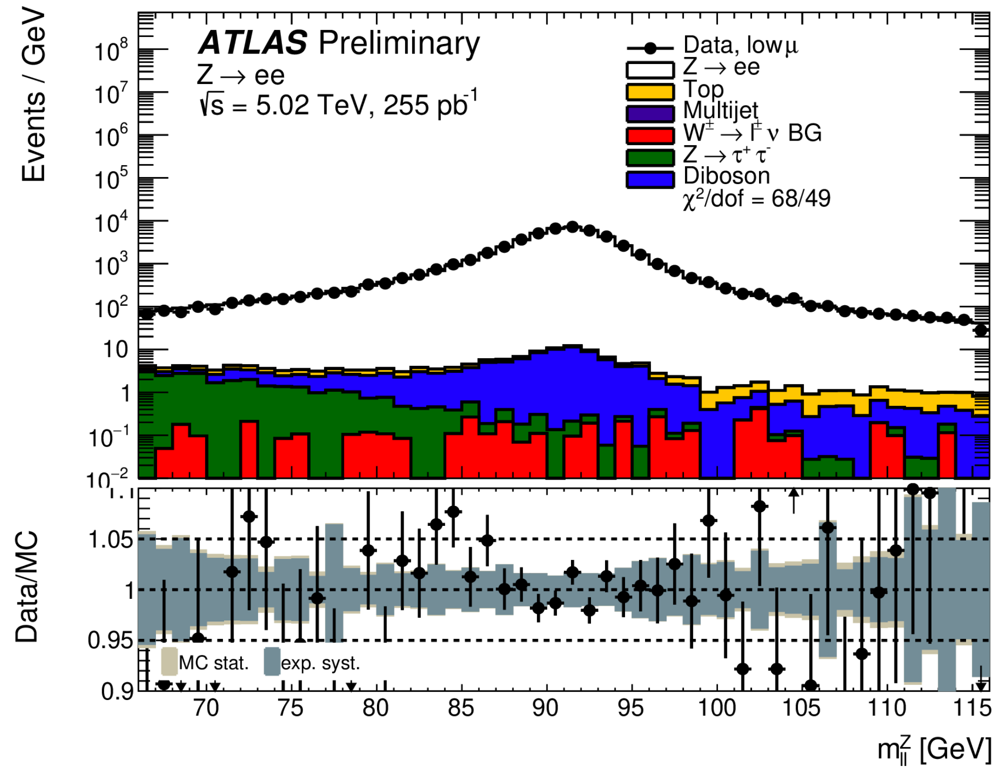


2 additionally reconstructed vertices

$<\Sigma E_T>$ increases ~linearly with pileup: about 20 GeV per additional pileup interaction.
At low $<\mu>$, the resolution, σu_T increases by ~12% per each additional pileup interaction

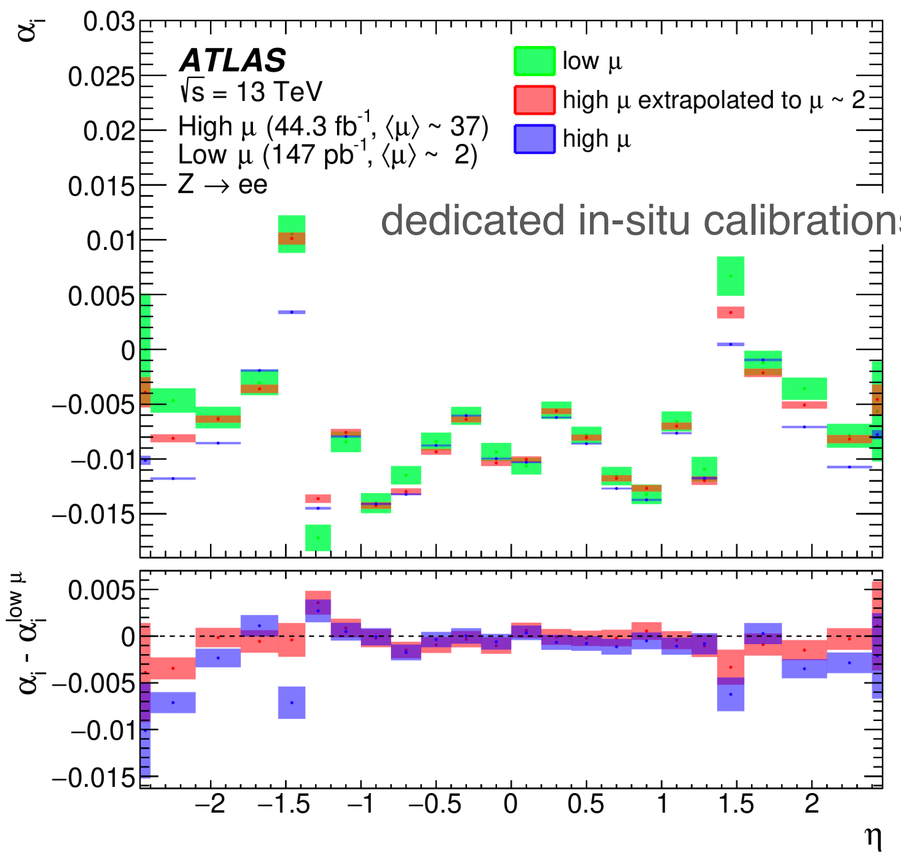
leptons performances



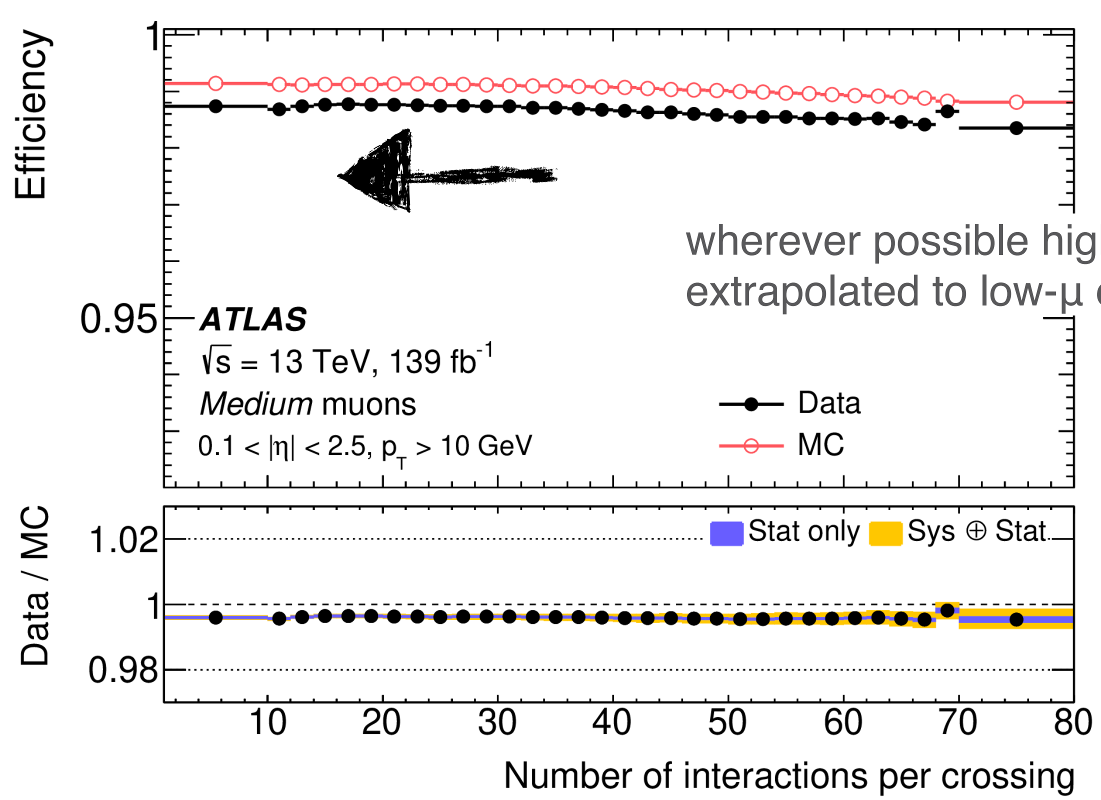


leptons performance accuracy limited by the Z sample statistic

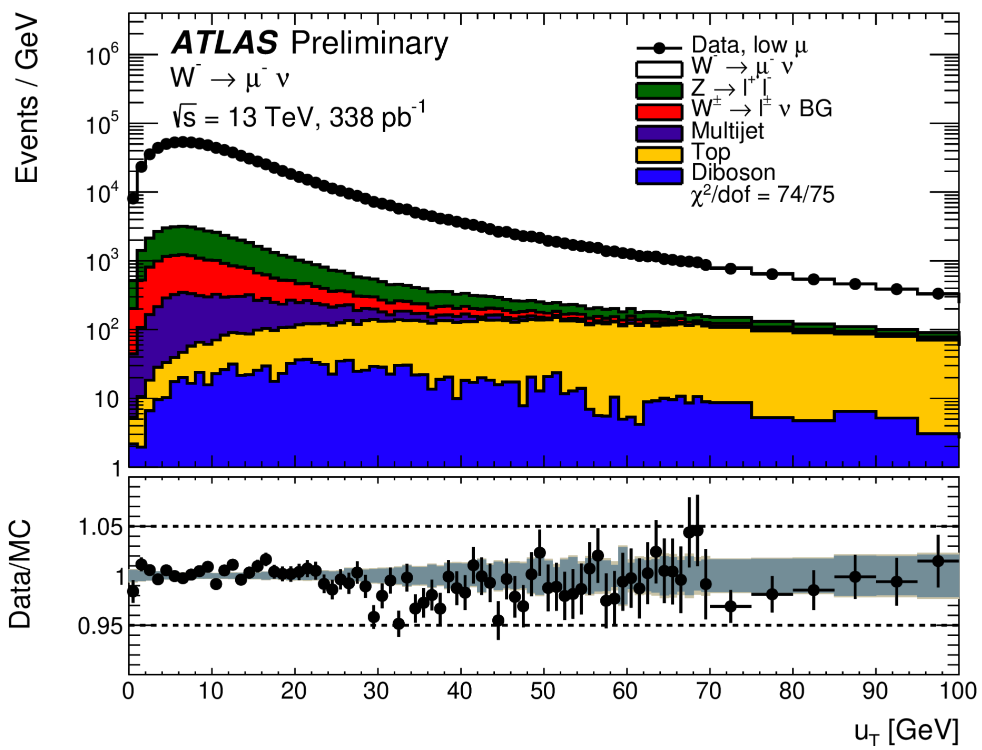
dedicated in-situ calibrations

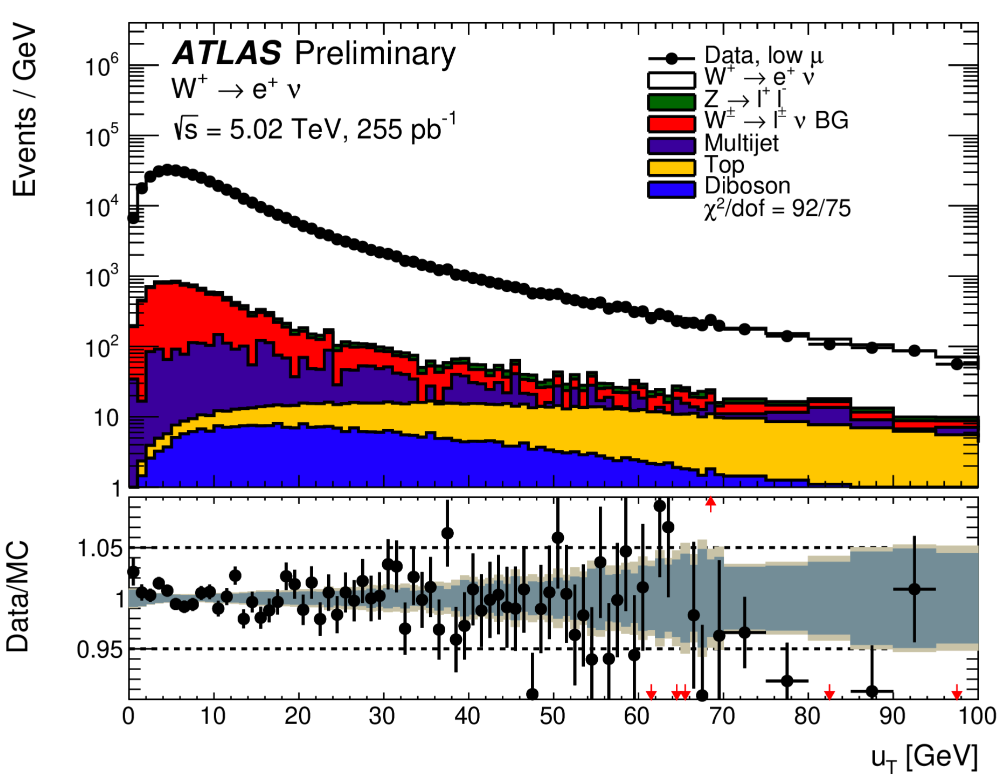


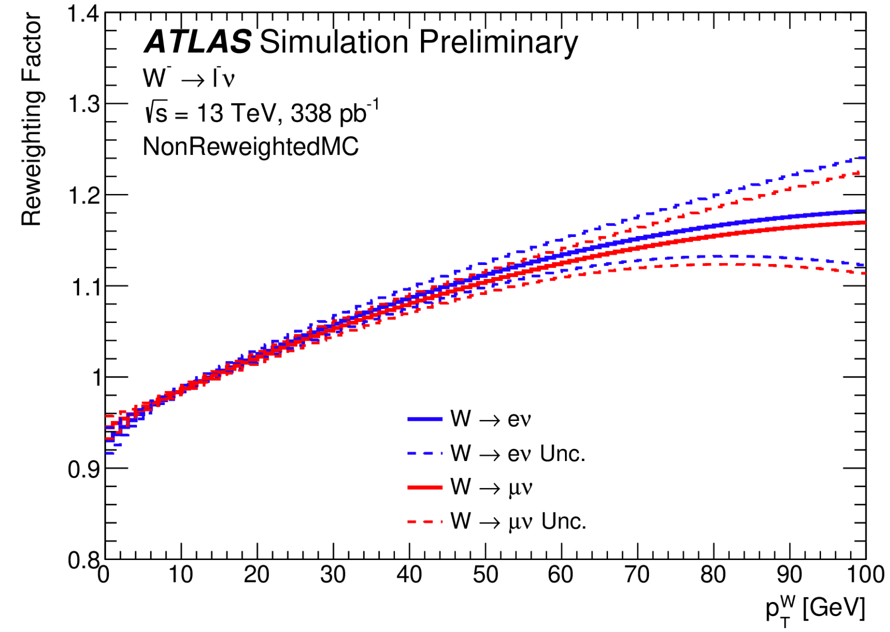
wherever possible high-μ data extrapolated to low-μ conditions

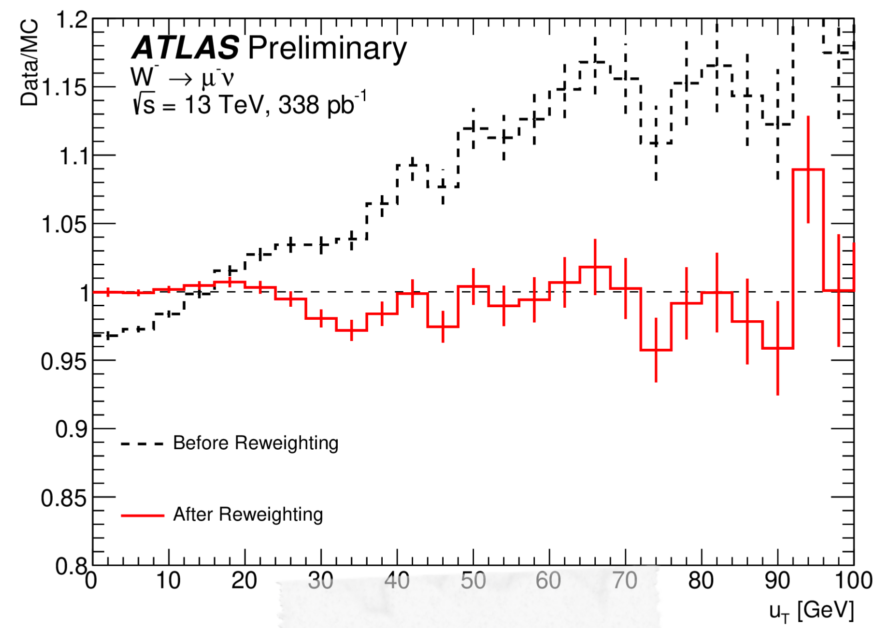


W,Z transverse momentum differential measurement









$$\chi^2 = \sum_{ij} \Delta_i^T \, (C^{-1})_{ij} \, \Delta_j \,,$$

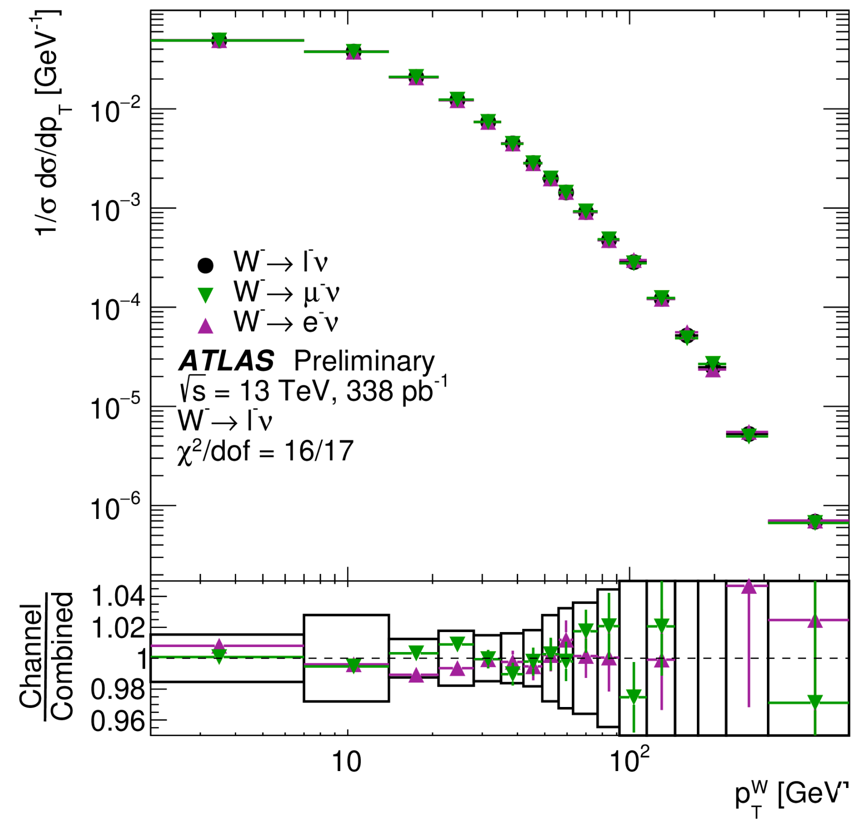
$$\Delta_i = (D_i - B_i) - \sum_k T_{ik} \times w_k \,.$$

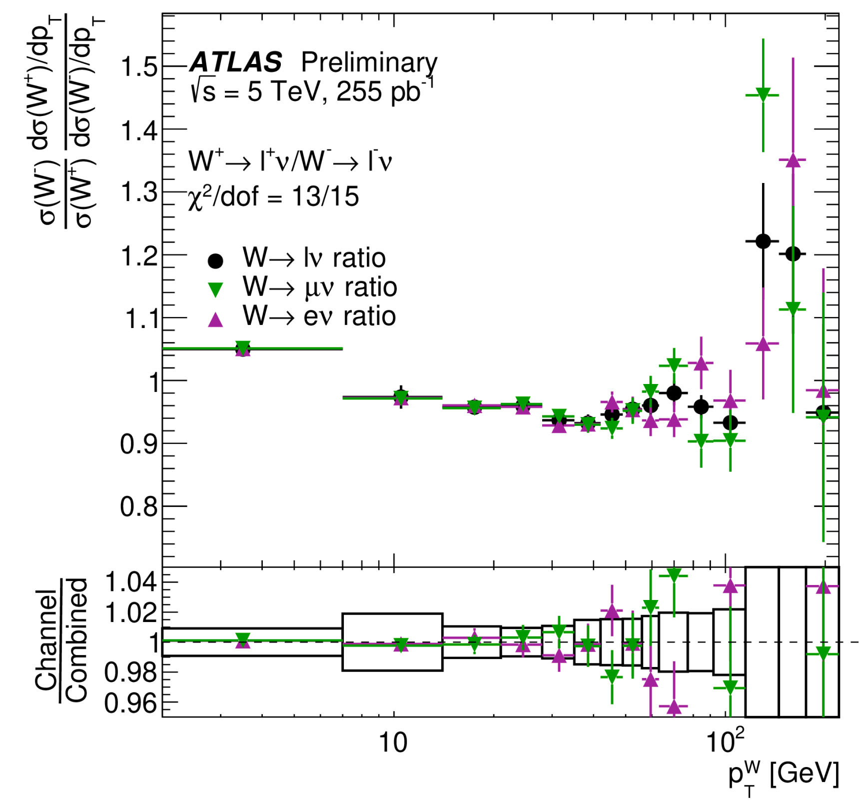
Multijet background estimated with data-driven improved m_W method

use experimental sensitivity to optimise the agreement between data and MC for the reconstructed uT distribution

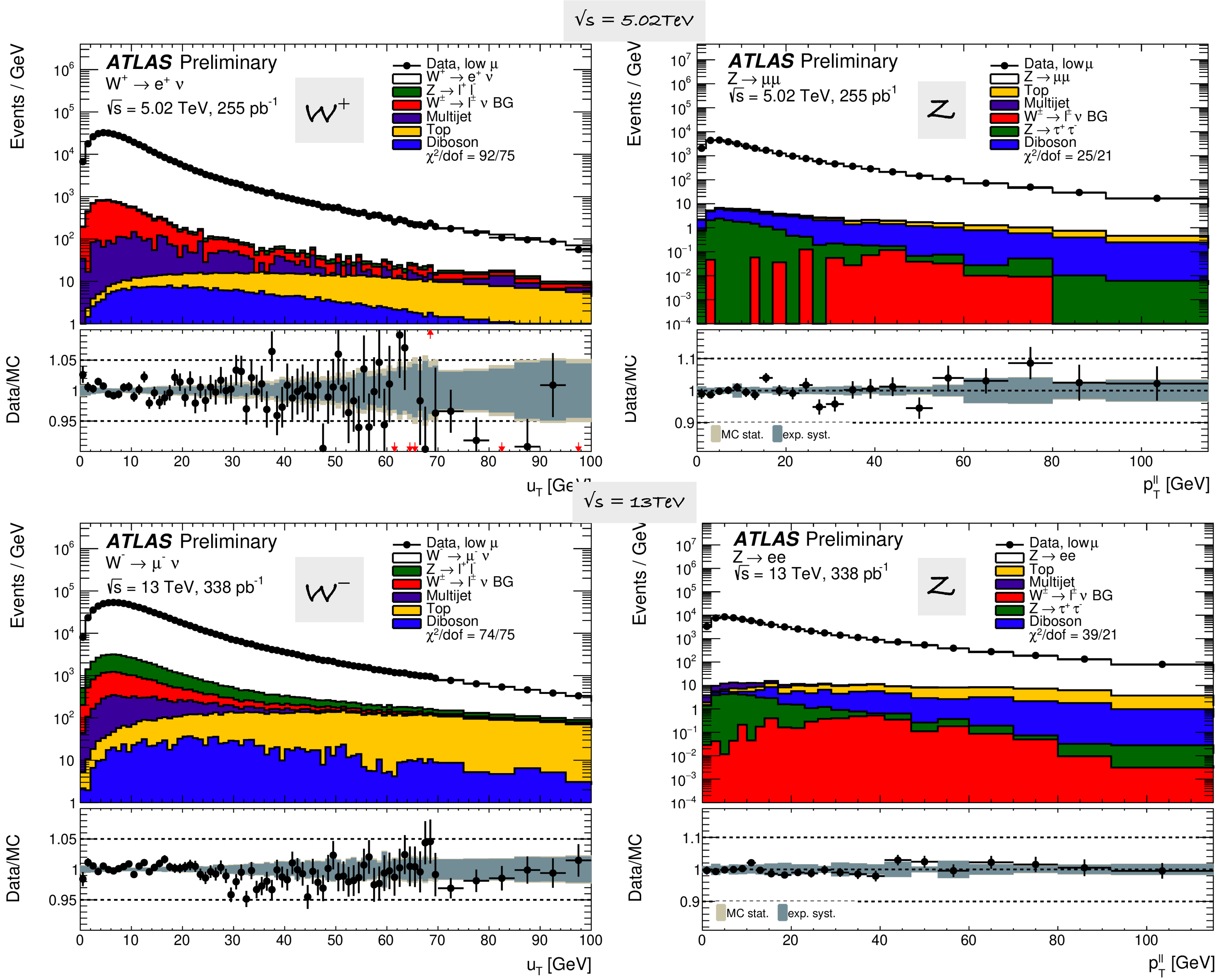
low mu data results channel compatibility

Channel	χ^2/dof
5.02 TeV	
$W^- \to \ell^- \nu$	14.6/15
$W^+ \to \ell^+ \nu$	14.5/15
$W \to \ell \nu$	12.1/15
$Z \to \ell\ell$	13.7/26
$W^+ \to \ell^+ \nu\ /\ W^- \to \ell^- \nu$	13.0/15
$W \to \ell\nu / Z \to \ell\ell$	16.3/15
13 TeV	
$W^- \to \ell^- \nu$	16.0/17
$W^+ \to \ell^+ \nu$	17.6/17
$W \to \ell \nu$	22.1/17
$Z \to \ell\ell$	21.4/27
$W^+ \to \ell^+ \nu\ /\ W^- \to \ell^- \nu$	11.3/17
$W \to \ell\nu / Z \to \ell\ell$	17.1/17
Ratio 13 TeV/5.02 TeV	
$W^- \to \ell^- \nu$	11.5/15
$W^+ \to \ell^+ \nu$	9.3/15
$W \to \ell \nu$	7.3/15
$Z \to \ell\ell$	14.2/25





Detector level distributions

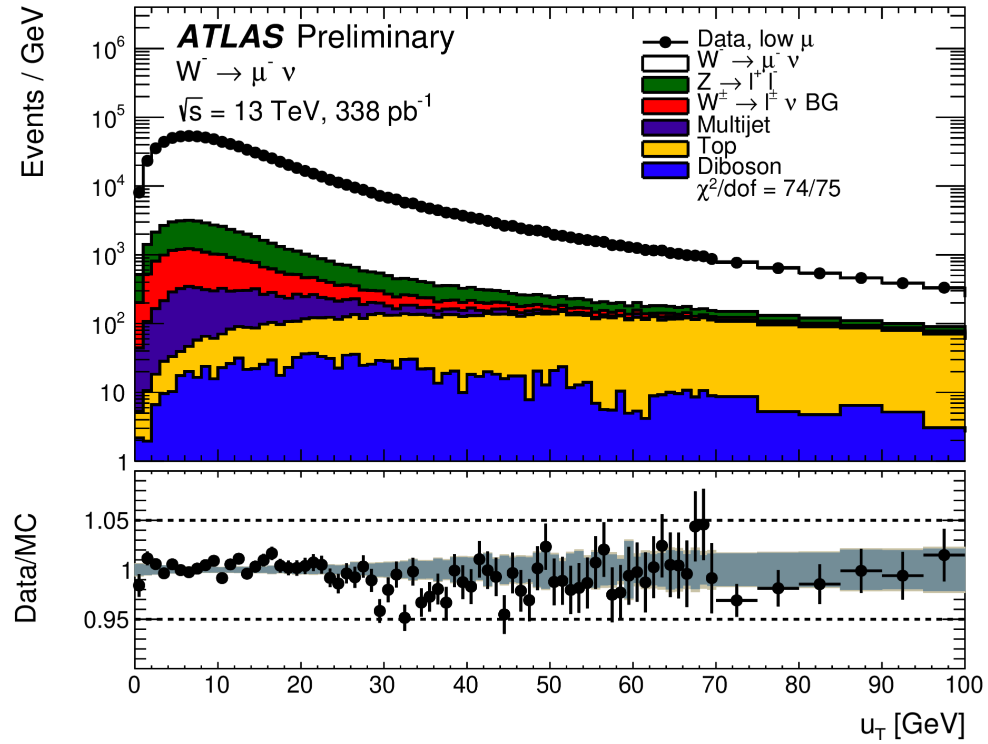


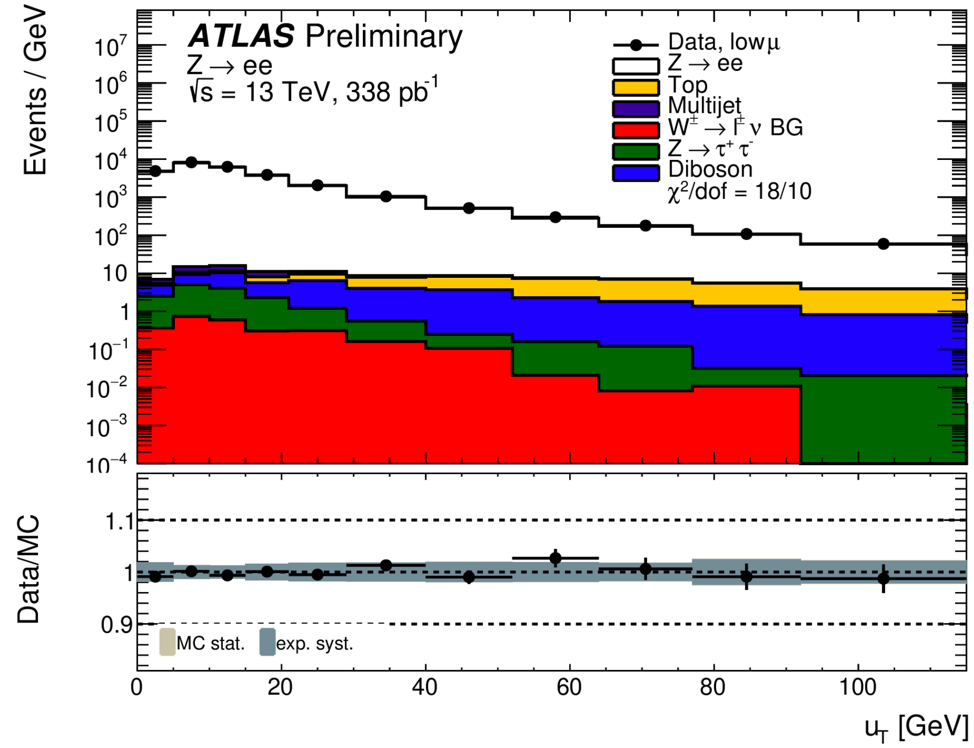
Multijet background estimated with data-driven improved method

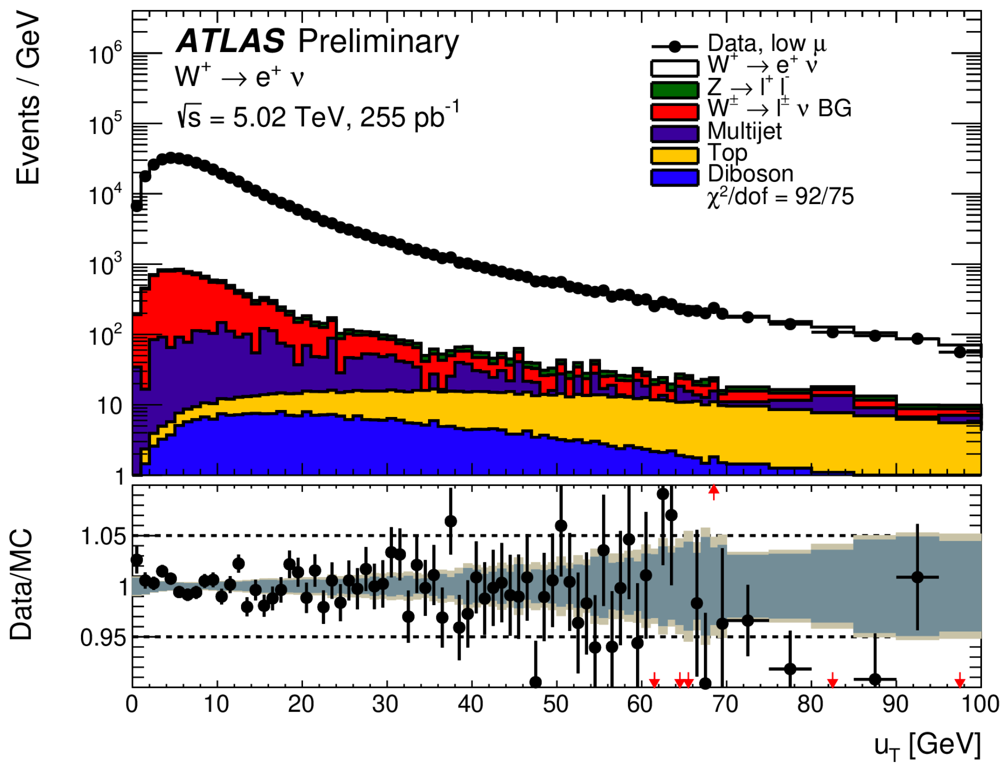
Excellent data/MC agreement

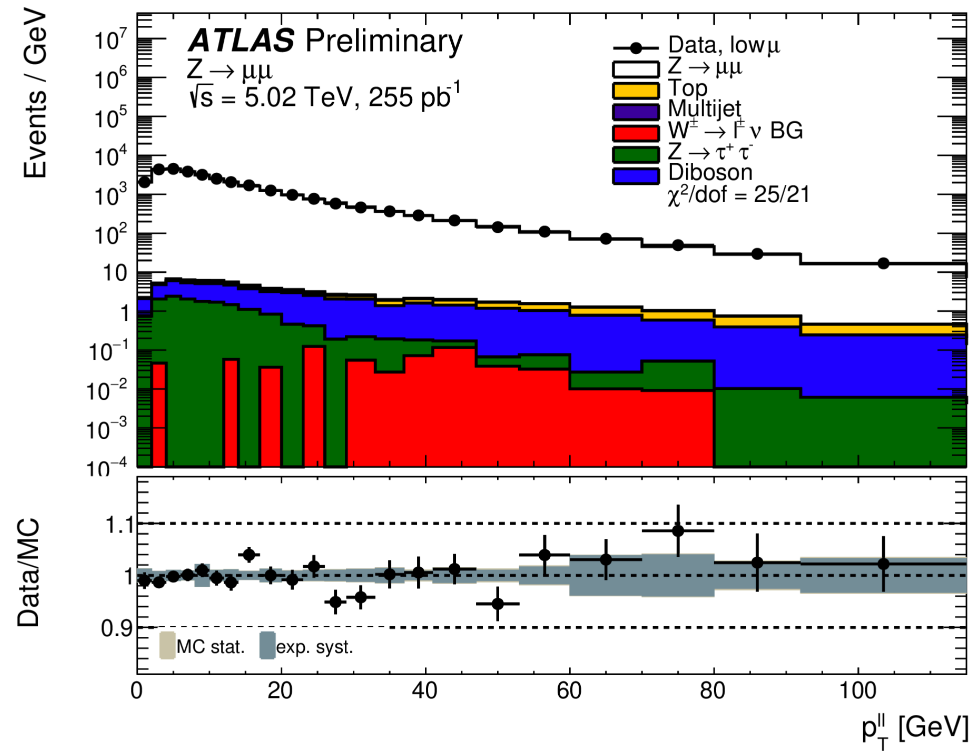
- Multijet background estimated with data-driven improved method
- use experimental sensitivity to optimise the agreement between data and MC for the reconstructed u_T distribution

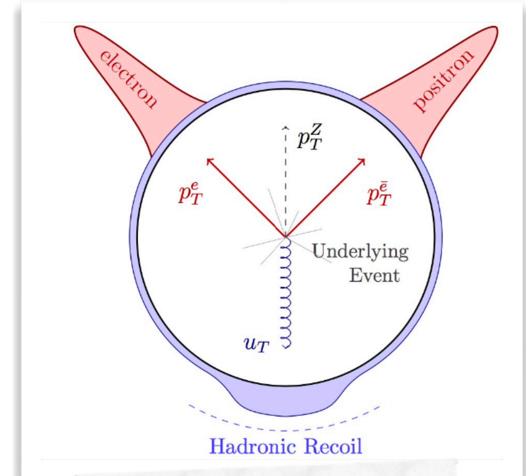
p_T^Z to validate p_T^W







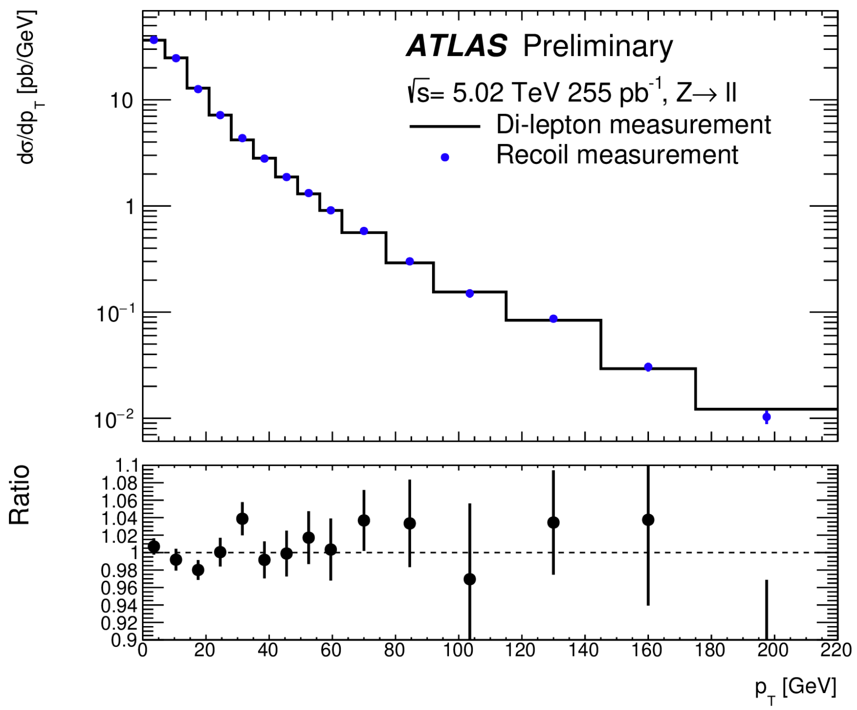


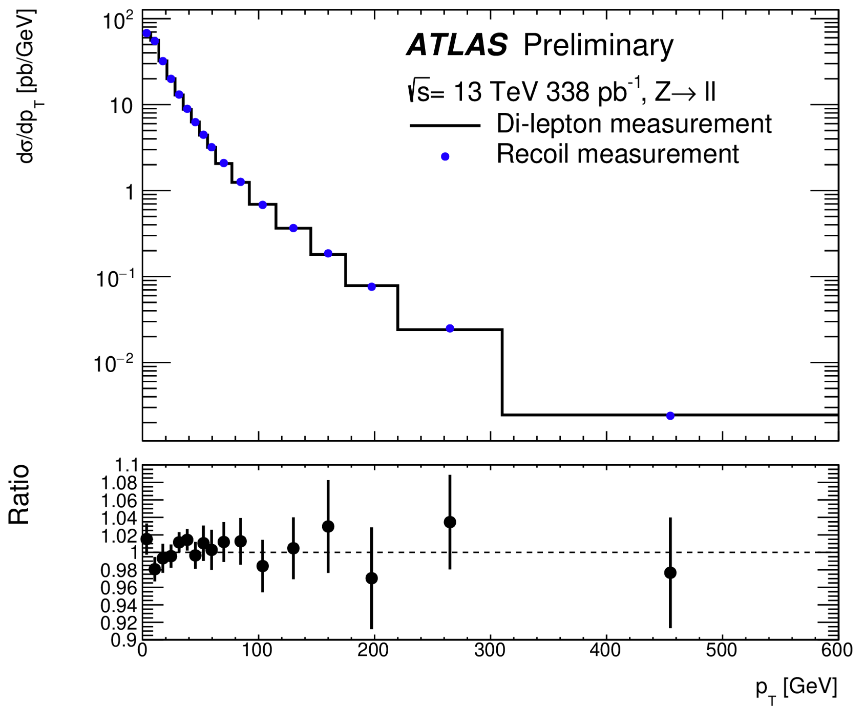


Z boson decay powerful tool to validate p_T^W measurement: In $Z \to \ell\ell$ events the transverse momentum spectra can be inferred either from the $p_T(\ell\ell)$ or from the u_T distributions

compatibility check

The Measurements: fiducial **differential** measurement of the $W^{\pm}$ and Z boson transverse momenta at 13 and 5.02 TeV





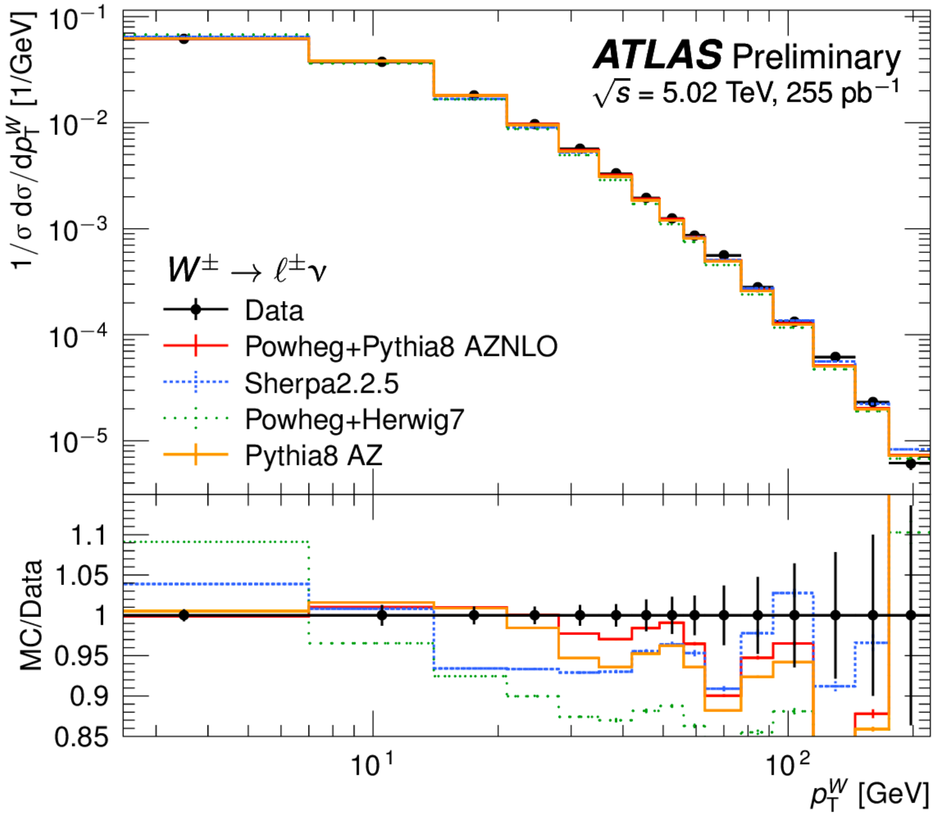
- **Bayesian unfolding** of u_T in the W and $p_T(\ell\ell)$ in the Z, separately in electron and muon channels
  - Binning and number of iterations optimised to minimise total uncertainty in the low p_T^W region
  - 9 (25) iterations, 7 GeV bin width at low p_T^W for the W at 5.02 (13) TeV
  - 2 iterations, 2 GeV bin width at low p_T^Z for the Z
- electron and muon channels combined with BLUE, all giving good $\chi 2$

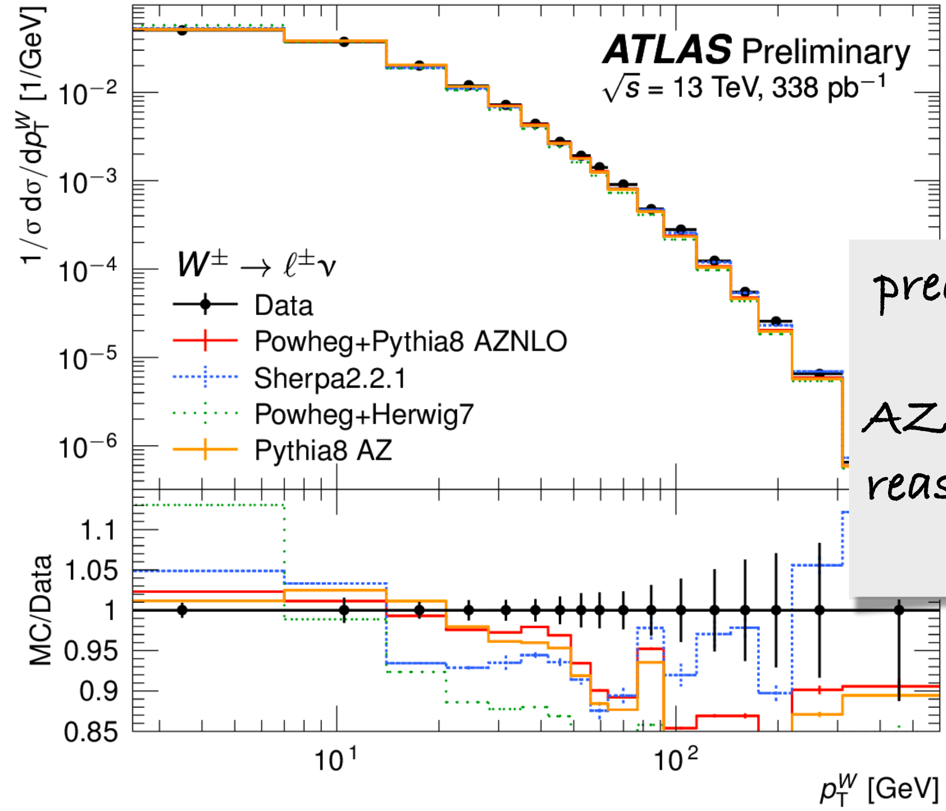
excellent compatibility between the p_T^Z measured with the u_T or $p_T(\ell\ell)$ spectra

$\chi^2/dof = 14.9/14$ 5.02 TeV

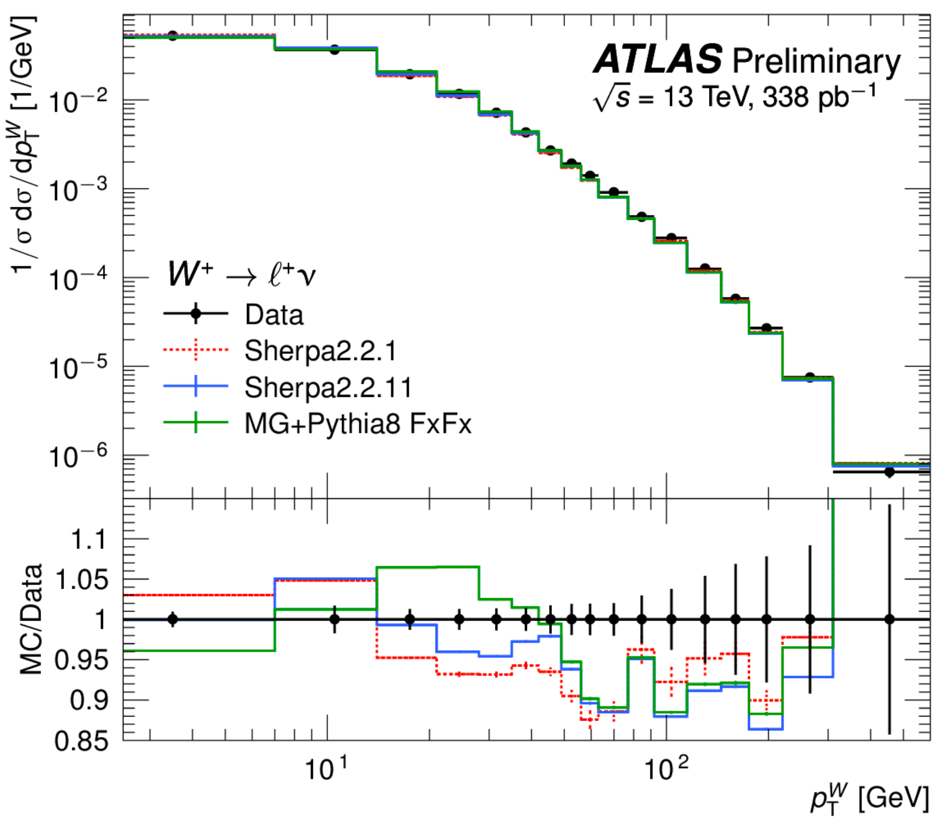
$\chi^2/dof = 8.7/16$ 13 TeV

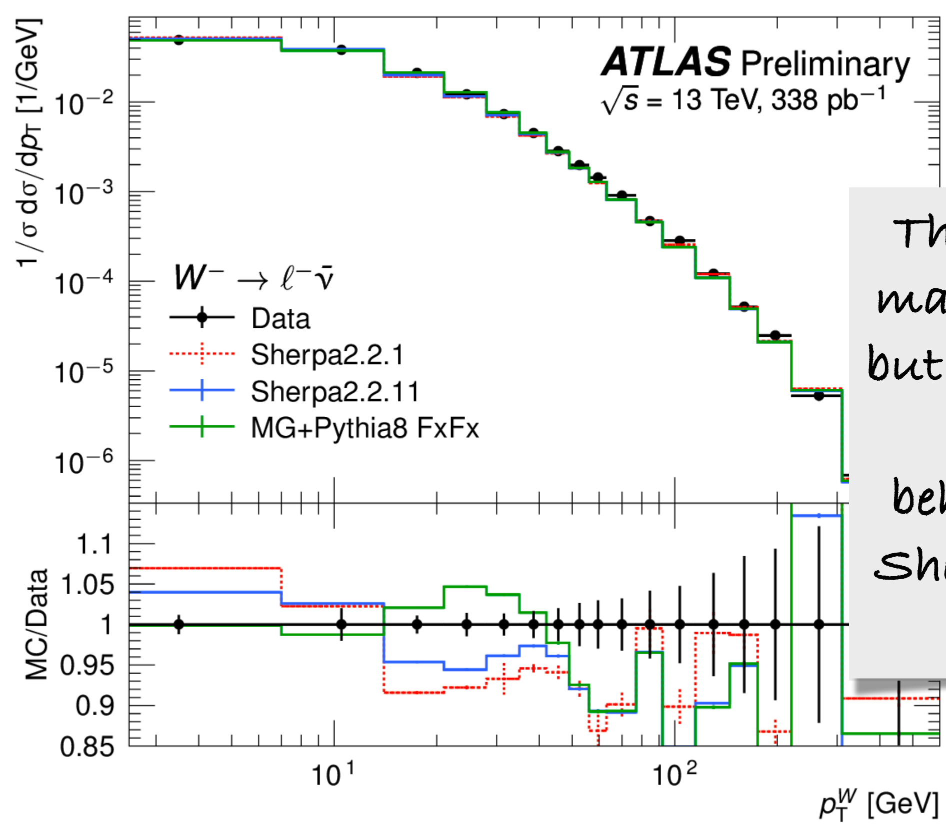
W transverse momentum differential measurement





predictions tuned to $\sqrt{s} = 7$ TeV data [Powheg+Pythia 8 AZNLO ; Pythia 8 AZ] describe reasonably well the low-pT region @5TeV





The Sherpa 2.2.1/5 predictions match the data best at higher pT, but they deviate significantly in the region pT < 20 GeV, a behaviour that was improved in Sherpa 2.2.11 by optimising the matching conditions

The results

<u>The Measurements:</u> integrated fiducial measurement for $W^{\pm}$ and for Z boson at 13,5.02 TeV and their ratios

PDF set	$W^- \to \ell\nu$	$W^+ \to \ell\nu$	$Z \to \ell\ell$
Cross-section at 5.02 TeV [pb]			
CT18	1364	2199	320.9
MSHT20	1351	2185	324.3
NNPDF3.1	1381	2232	329.8
Data	1384 ± 16	2228 ± 25	333.0 ± 4.1
Cross-section at 13 TeV [pb]			
CT18	3410	4462	749.8
MSHT20	3397	4457	766.1
NNPDF3.1	3452	4513	771.4
Data	3486 ± 38	4571 ± 49	780.3 ± 10.4

~2/3% PDF unc. expected

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