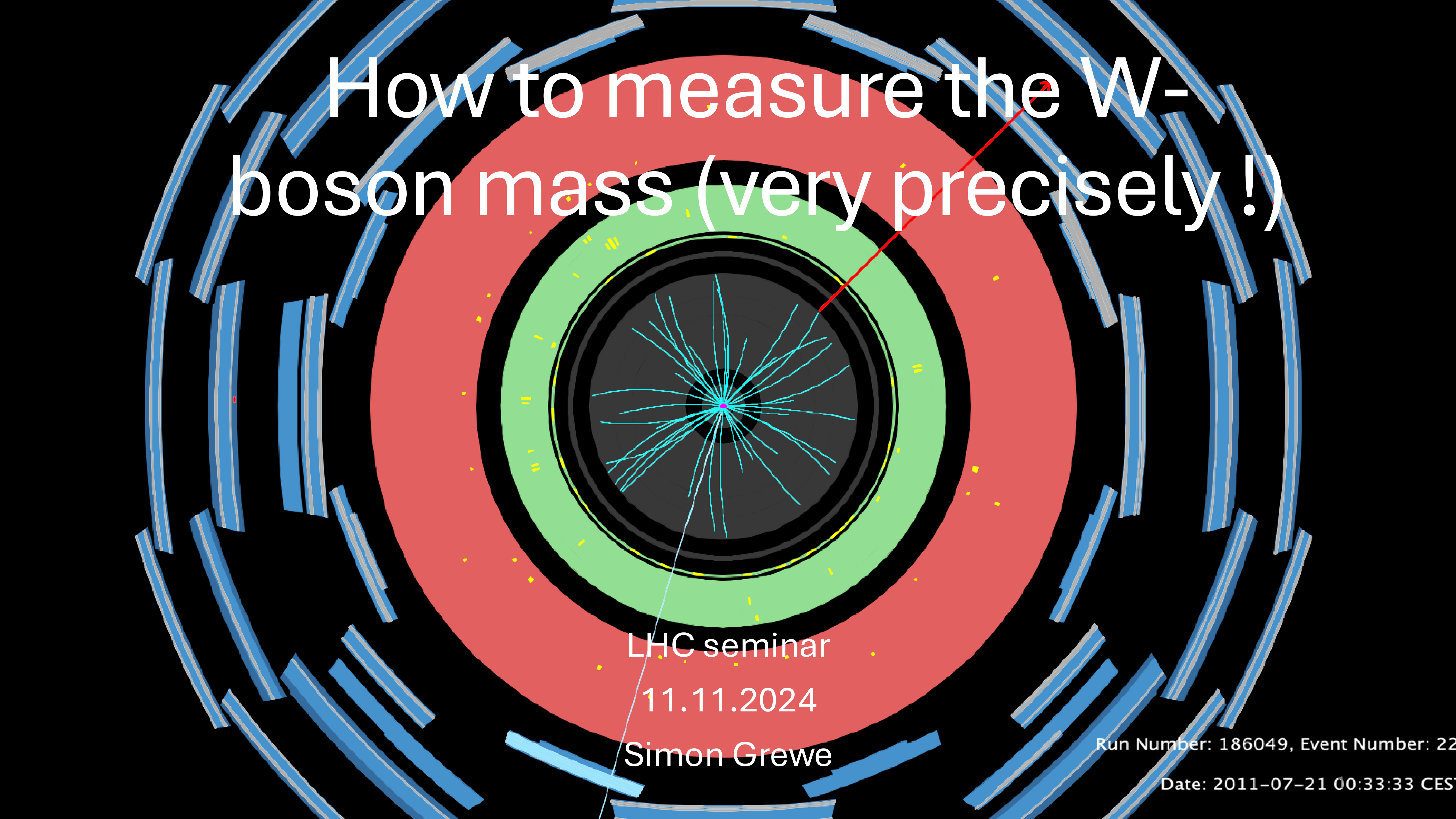
How to measure the W-boson mass (very precisely !)

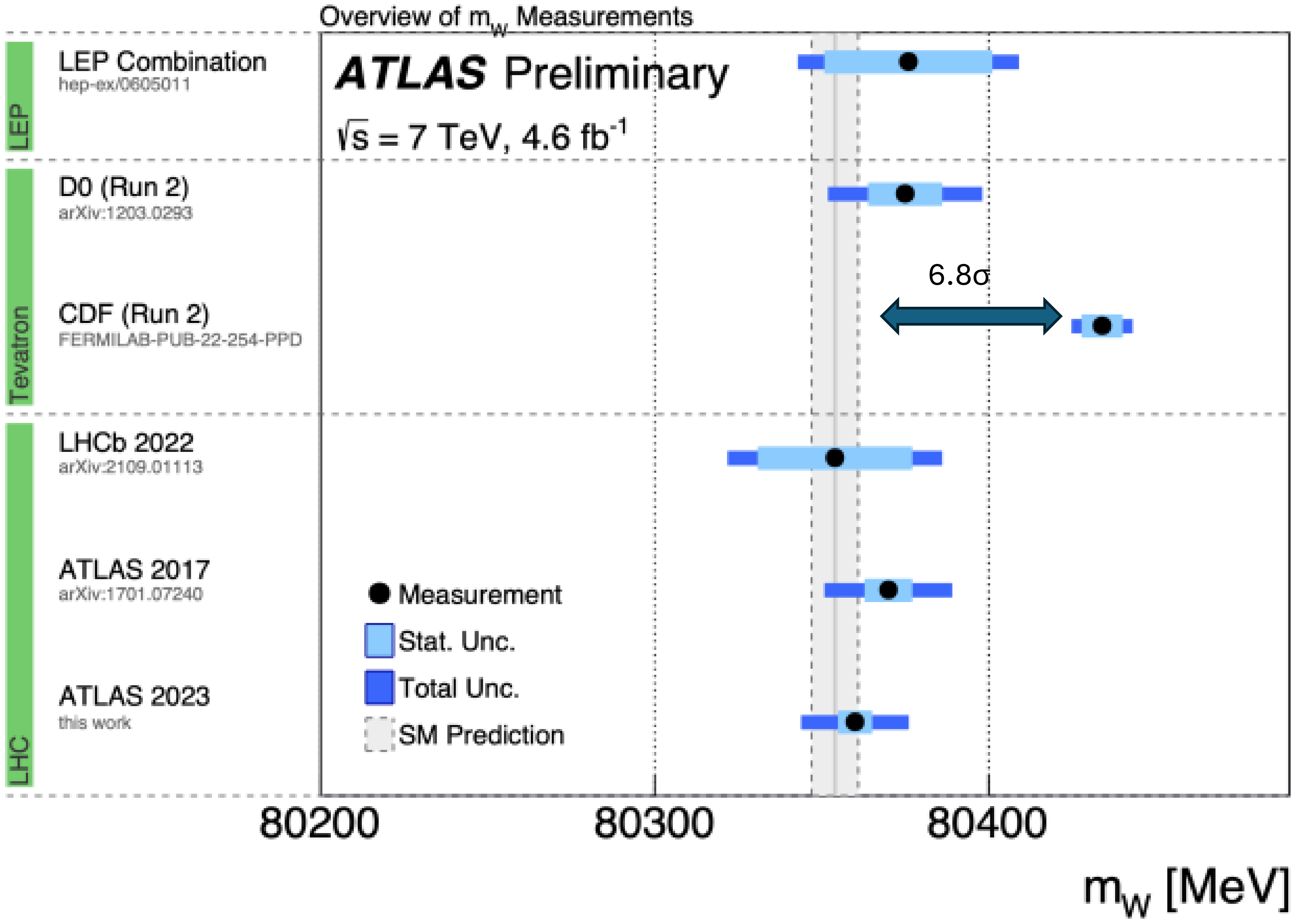
LHC seminar

11.11.2024

Simon Grewe



Measurement of the W-boson mass and width with the ATLAS detector using proton-proton collisions at $\sqrt{s}= 7$ TeV arxiv:2403.15085



Overview of m_W Measurements
ATLAS Preliminary
$\sqrt{s}$ = 7 TeV, 4.6 fb^{-1}
LEP
LEP Combination
hep-ex/0605011
Tevatron
D0 (Run 2)
arXiv:1203.0293
CDF (Run 2)
FERMILAB-PUB-22-254-PPD
6.8σ
LHC
LHCb 2022
arXiv:2109.01113
ATLAS 2017
arXiv:1701.07240
ATLAS 2023
this work
Measurement
Stat. Unc.
Total Unc.
SM Prediction
80200
80300
80400
m_W [MeV]

Why measure the W mass

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

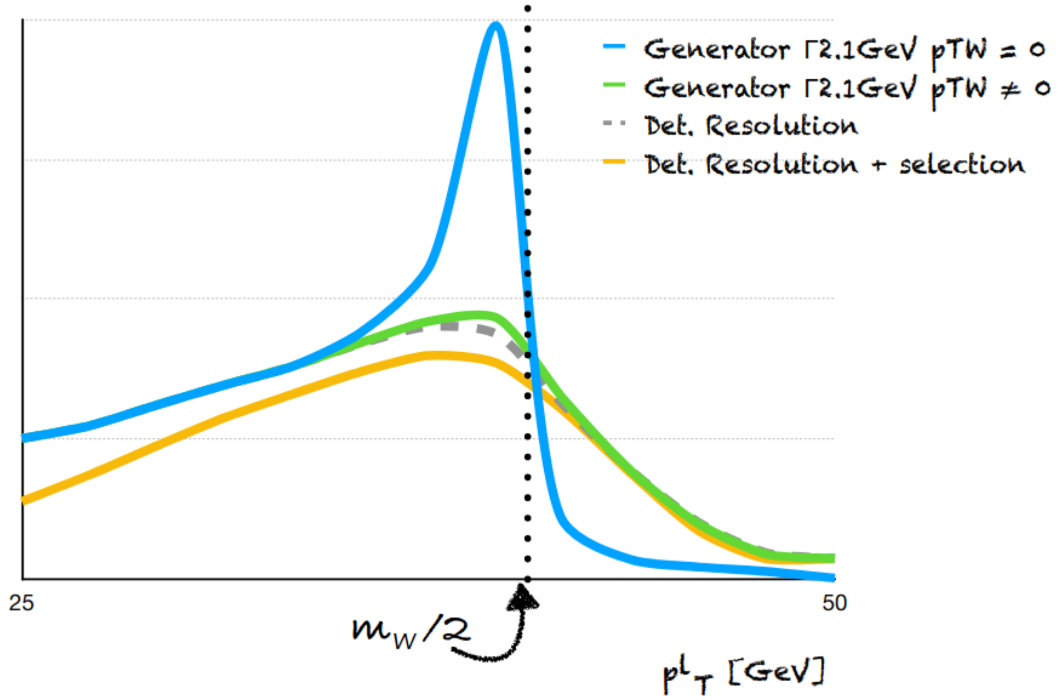
- Δ r: Loop corrections depending on m_{top} and m_{higgs} or potential BSM correction
- A very precise measurement is a powerful probe of the SM

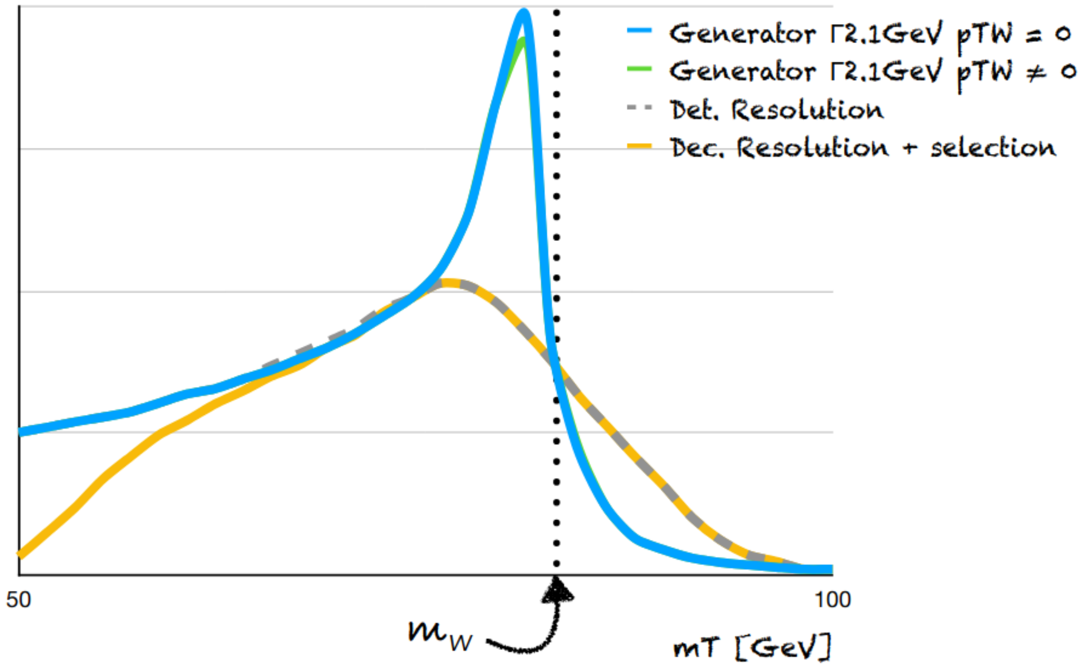
How to measure the W-boson mass

- W decays:
  - Hardonic decays: very "messy", low resolution (jet energy resolution~20% @ 30 GeV), pile-up
  - Leptonic decays: high resolution for both electrons and muons (e.g 1.6% mass resolution for the Z peak with muons) **but** neutrino can't be measured by ATLAS

We can't measure the W boson mass **directly** !

How to measure the W boson mass



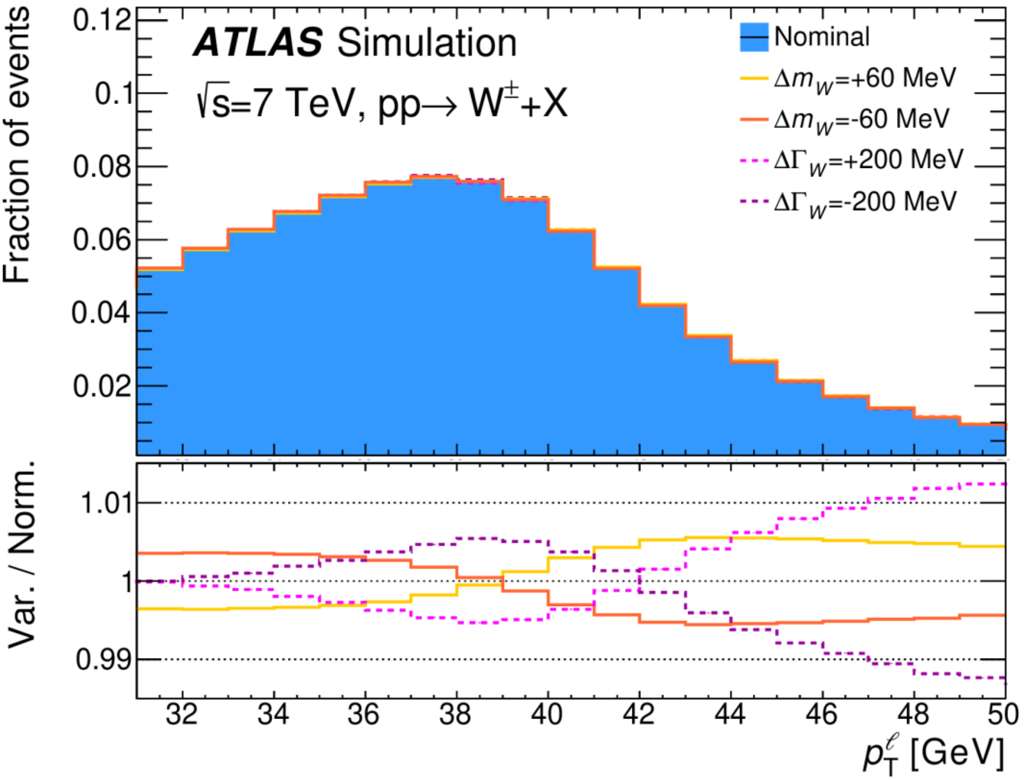


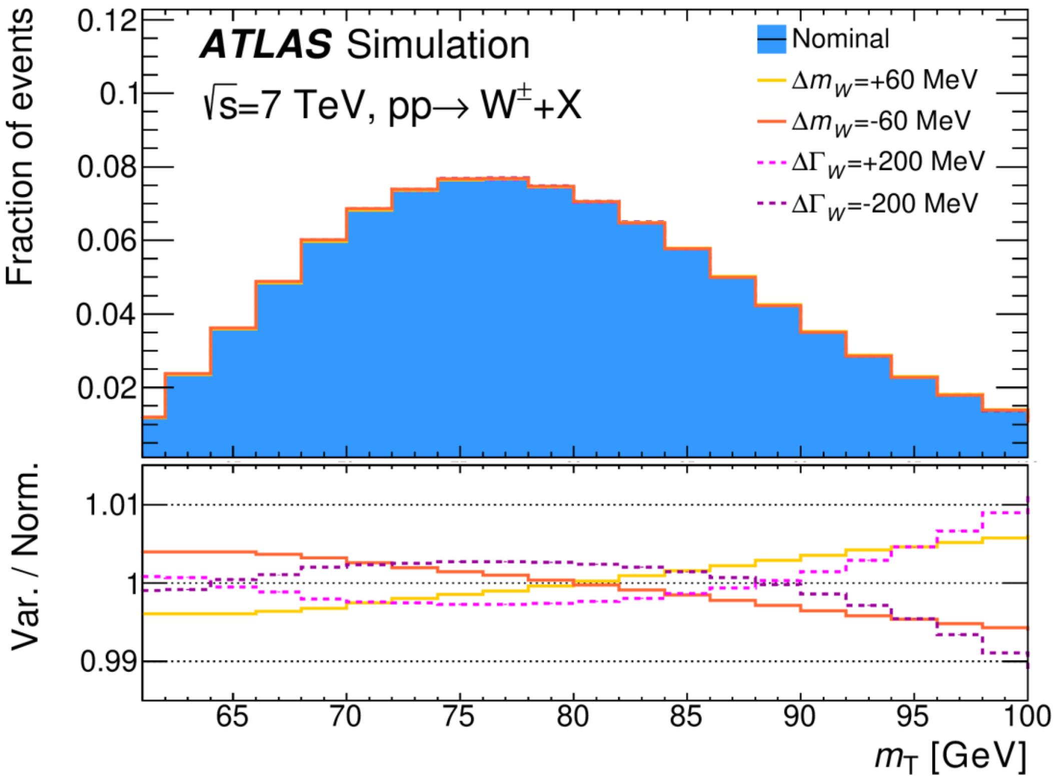
- The lepton transverse momentum and transvers mass are observables sensitive to the W mass
- The two observables are sensitive to different uncertainties/ modelling effects,
- In general: we need an excellent understanding of our detector and a precise knowledge of the modelling of our physics processes

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

Template fit

- Build different templates:
  - Simulate different mass hypothesis of the W boson
  - Check which templeate fits the data best

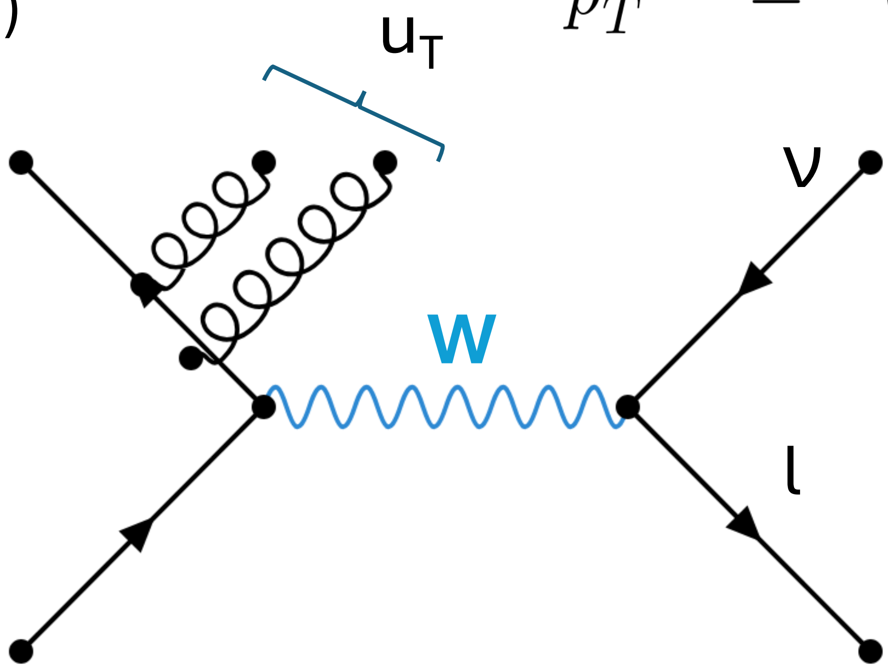




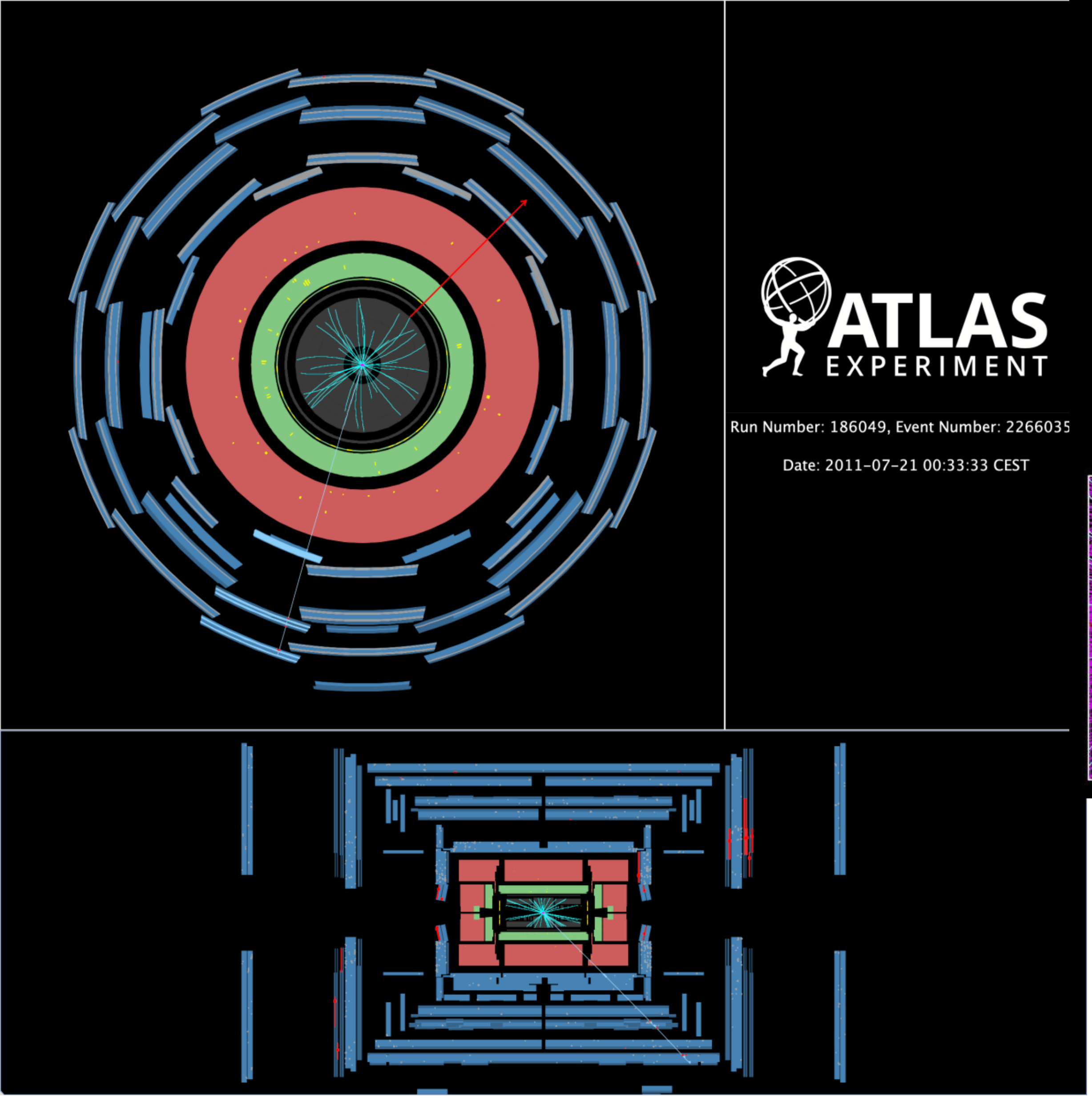
Analysis strategy

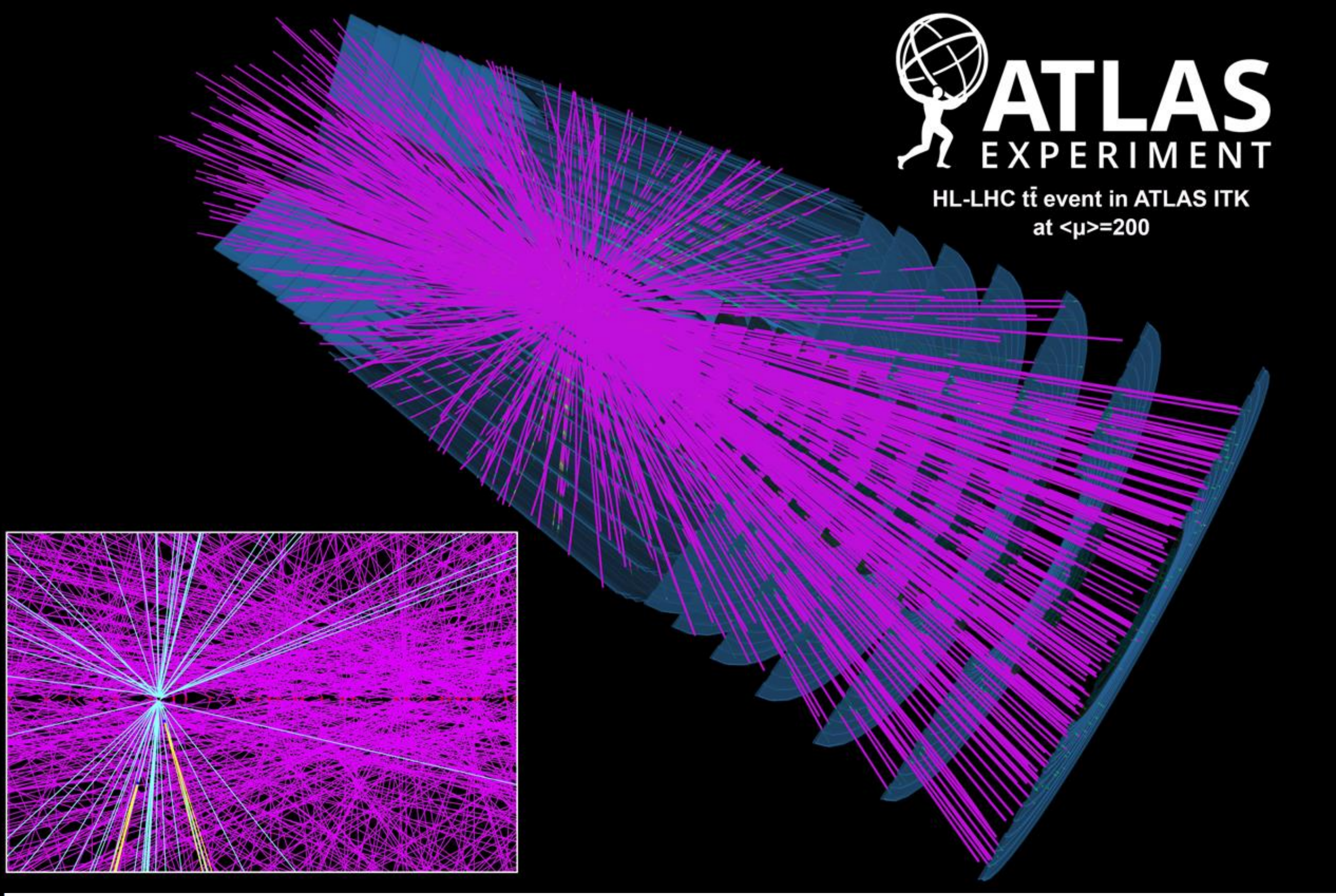
- Use the low μ ATLAS datatset @ 7 TeV recorded in 2007
  - Low pileup <μ>=9 is crucial to measure the measure the hadronic recoil precisely (% level resolution)
  - ~14 M W-> lν candidates
  - Split in 14 categories(charge, flavour,η)
- Select 1 lepton events:
  - p_T^l>30 GeV
  - p_T^{miss}>30 GeV
  - u_T<30GeV (recoil)
  - m_T>60 GeV

$$p_T^{miss} = -(p_T^l + u_T$$



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



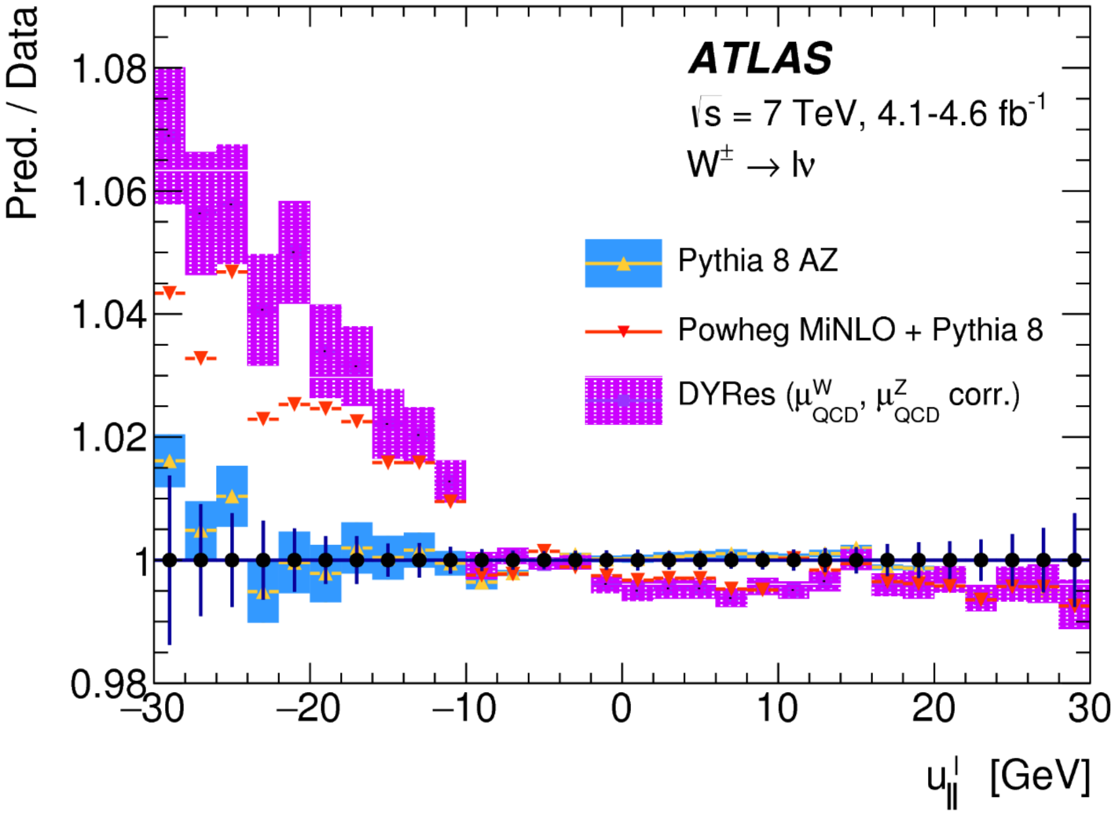


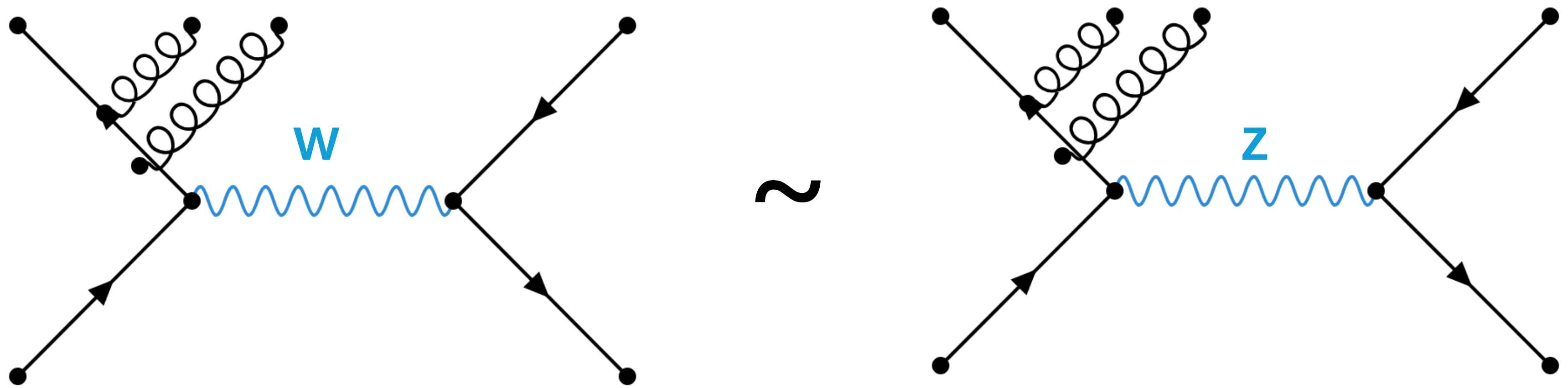
Simulated tt event at <μ> =200

W-> μ ν candidate at <μ> =9

Recoil modelling

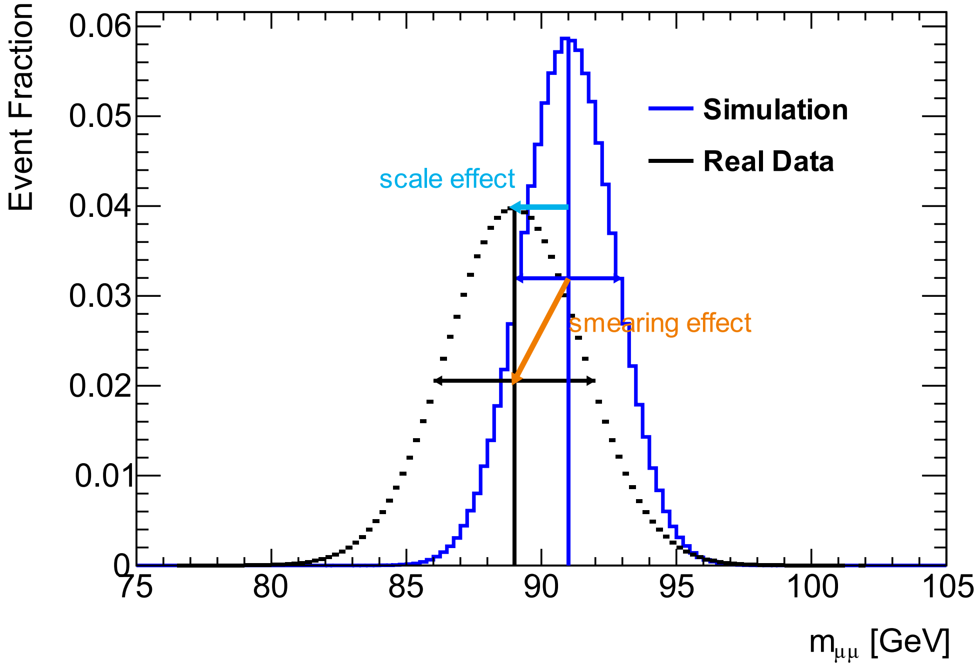
- The recoil/ W p_T is hard to model (by parton shower)
  - Non-perturbative QCD
  - Many scales
- Use Z samples to validate the recoil modelling and tune parameters to ensure a precise modelling
- PYTHIA AZN tune describes the W p_T very well





Excursion: Muon momentum calibration

- The Z boson is a very powerful "standard candle" allowing to calibration leptons to the per mill level
  - Similar the recoil can be calibrated by the considering the balance between p_T^Z and u_T



$$p_T^{Cor,Det} = \frac{p_T^{MC,Det} + s_0^{Det} + s_1^{Det} p_T^{MC,Det}}{1 + g_0 \Delta r_0^{Det} \frac{1}{p_T^{MC,Det}} + g_1 \Delta r_1^{Det} + g_2 \Delta r_2^{Det} p_T^{MC,Det}}$$

$s_i(\eta,\phi)$: Scale corrections

$\Delta r_i(\eta,\phi)$: Momentum smearing

g_i: random normally distributed variable

Profile likelihood fit

- Move from χ^2 fit to profile likelihood fit
  - Allows for (in situ) constrain experimental & modelling systematic uncertainties
- Maximize the likelihood function describing how compatible the data is with a hypothesis

Parameter of interest (mass)

Expected number of events under hypothesis

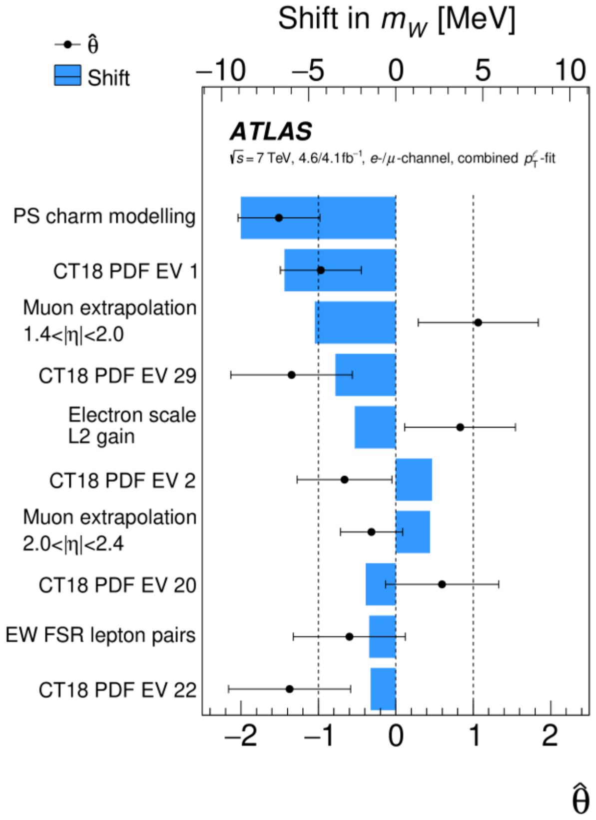
$$\mathcal{L}\left(\vec{n} \mid \mu, \vec{\theta}\right) = \prod_j \prod_i \mathrm{Poisson}\left(n_{ji} \mid \nu_{ji}(\mu, \vec{\theta})\right) \cdot \mathrm{Gauss}\left(\vec{\theta}\right)$$

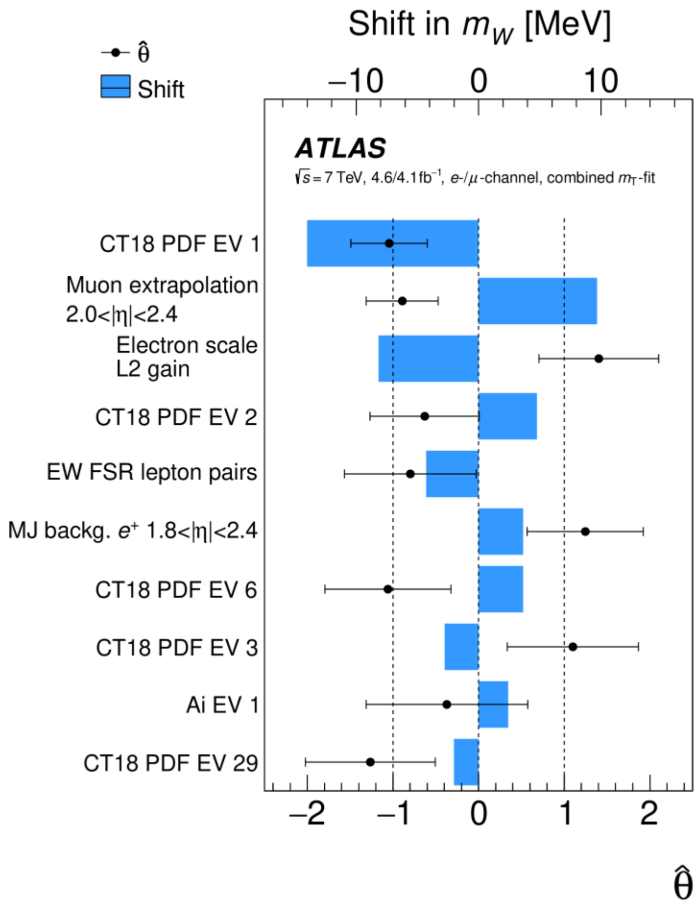
Measured data

Nuisances parameter/systematic uncertainty

Uncertainties

- Experimental uncertainties in the calibration of the recoil and lepton momentum
- Theorie uncertainties from the W modelling
  - PDF
  - Parton-shower (Recoil)
  - ...

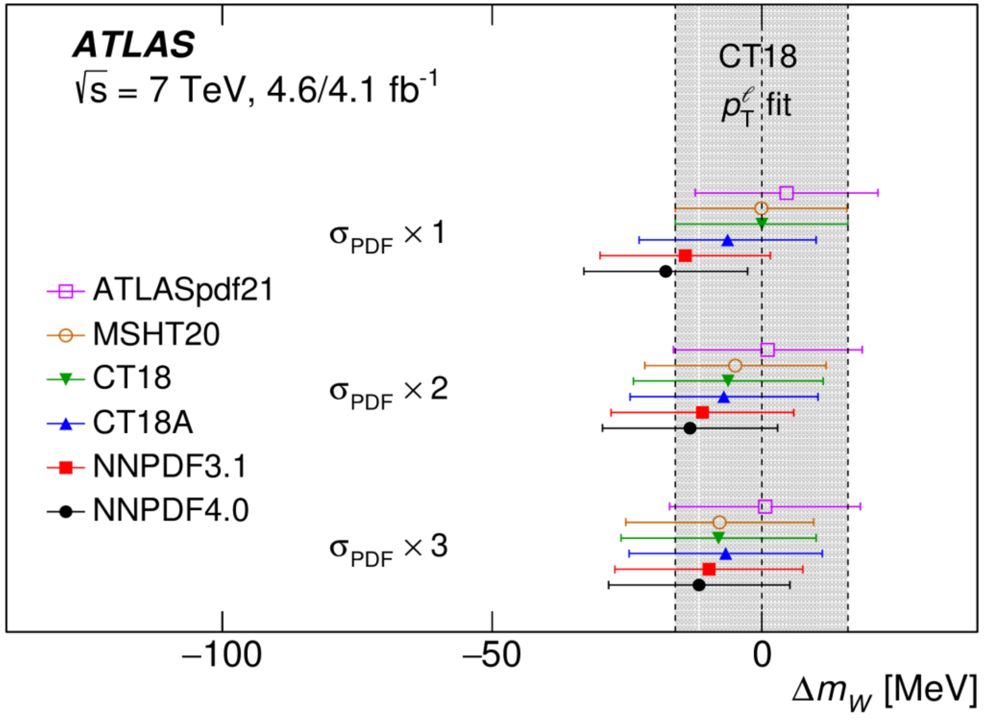


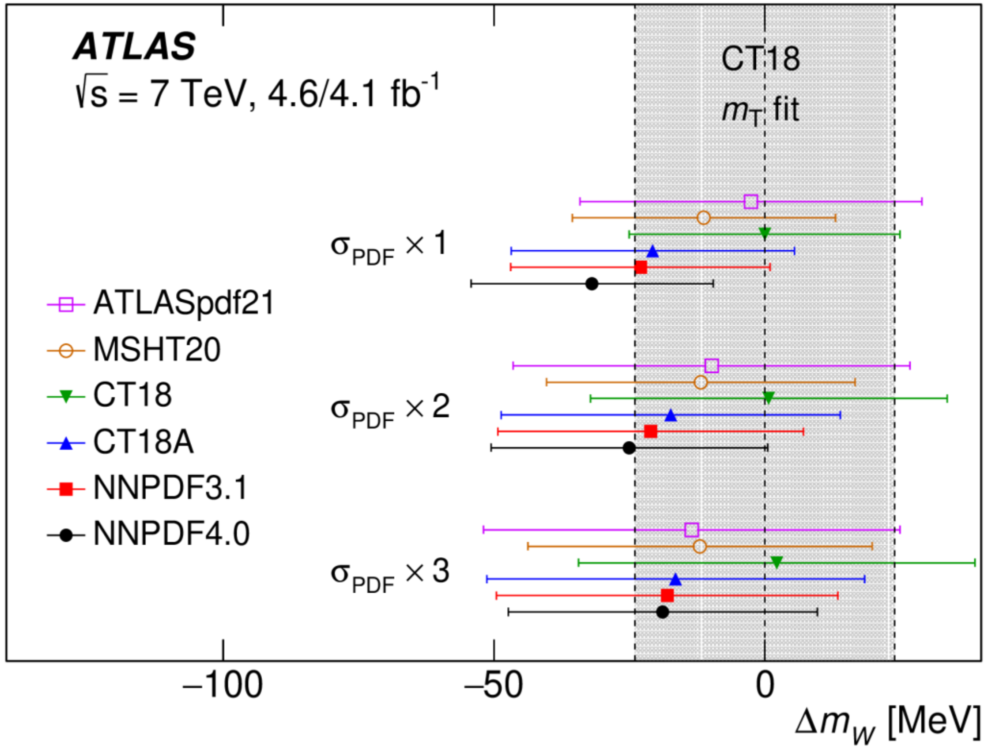


Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

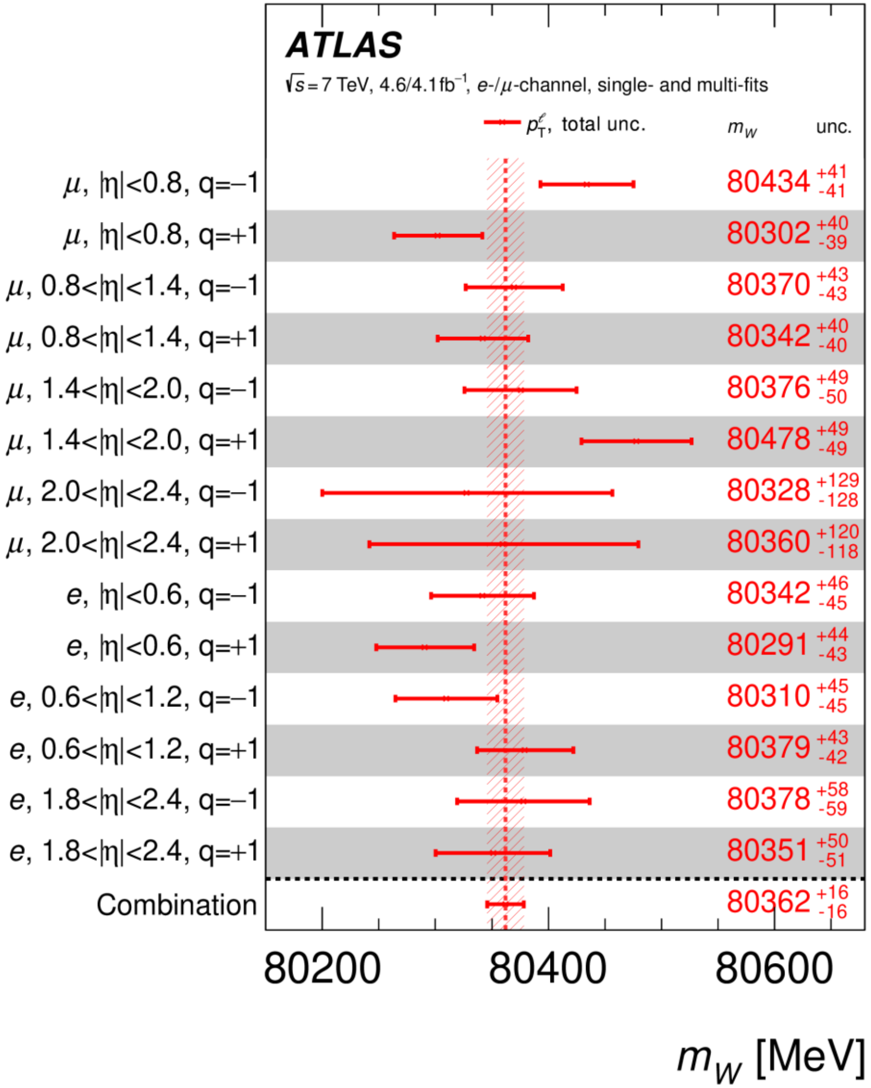
PDF uncertainties

- Due to difference between the u and d and valance and see quarks in different PDF sets yield to different rapidity distribution and difference in the acceptance in different regions

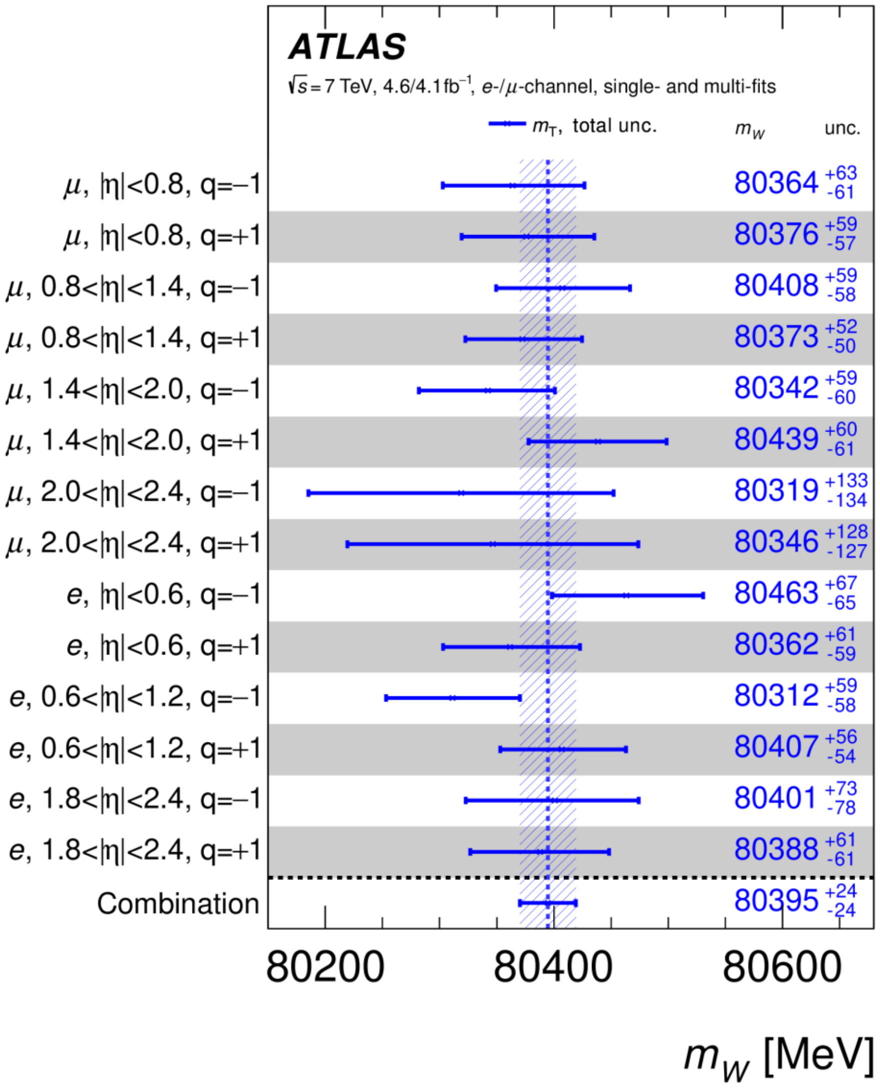




Results



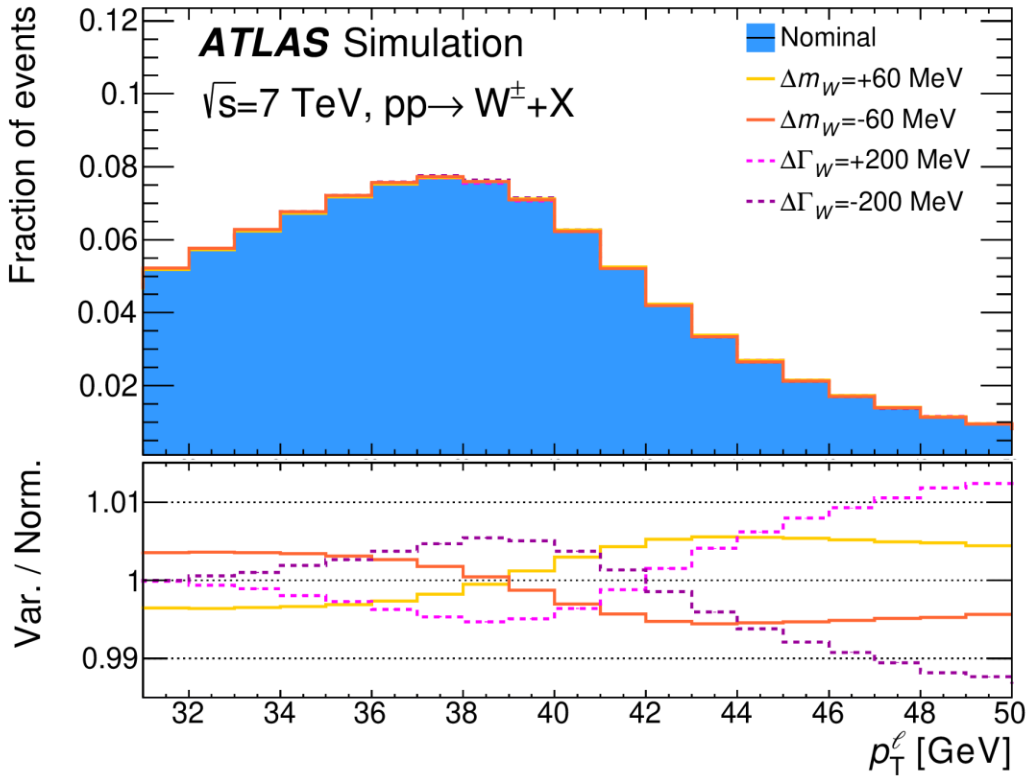
ATLAS
$\sqrt{s}$ = 7 TeV, 4.6/4.1 fb^{-1}, e-/μ-channel, single- and multi-fits
p_T^ℓ, total unc.
m_W
unc.
μ, |η|<0.8, q=–1 80434 +41 -41
μ, |η|<0.8, q=+1 80302 +40 -39
μ, 0.8<|η|<1.4, q=–1 80370 +43 -43
μ, 0.8<|η|<1.4, q=+1 80342 +40 -40
μ, 1.4<|η|<2.0, q=–1 80376 +49 -50
μ, 1.4<|η|<2.0, q=+1 80478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

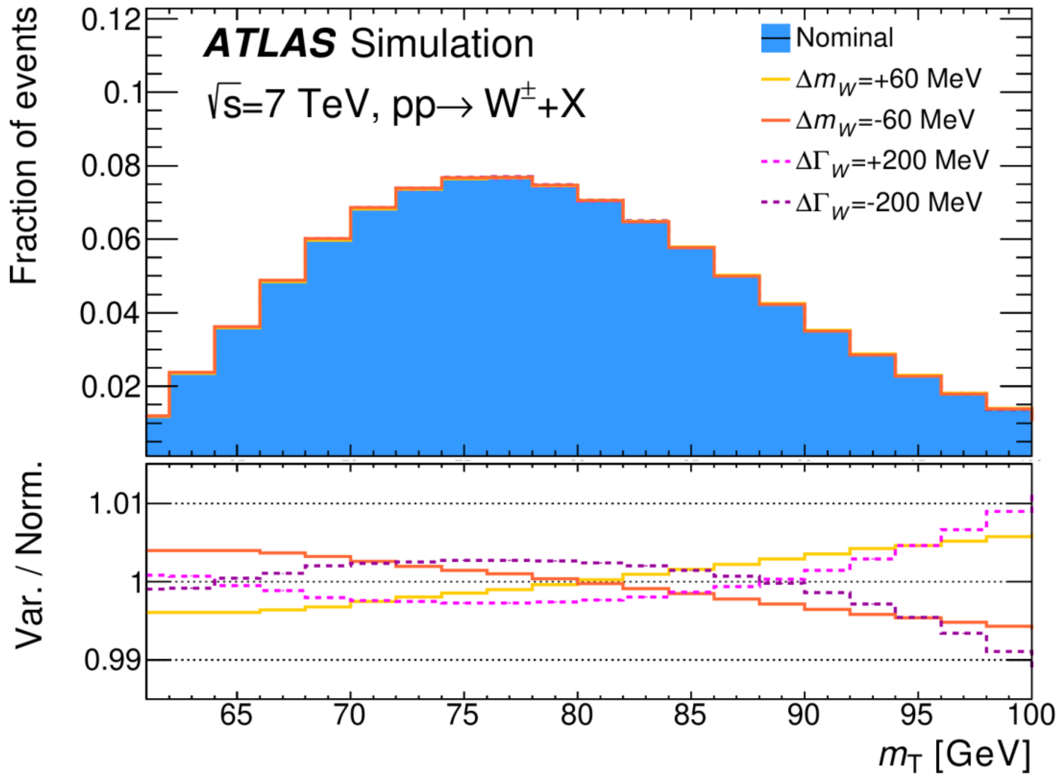


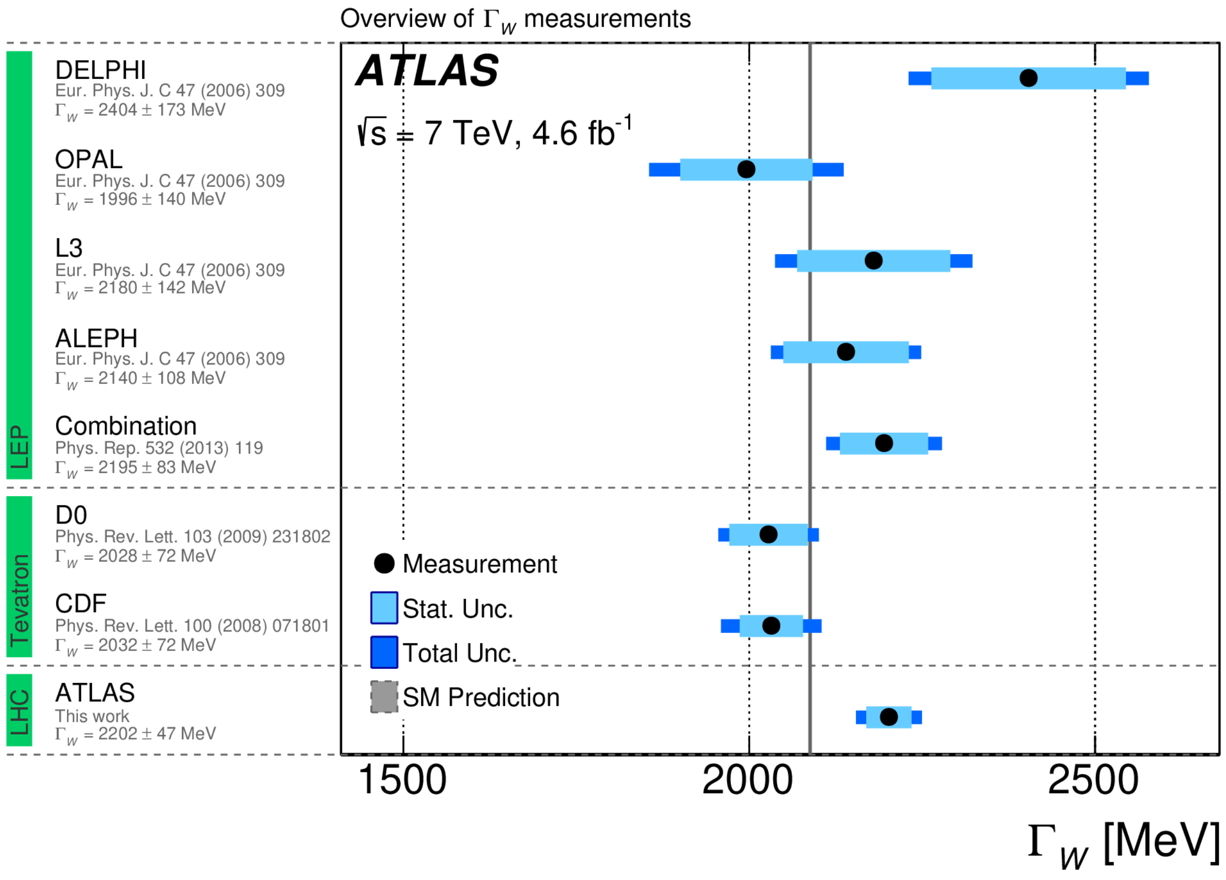
ATLAS
$\sqrt{s}$ = 7 TeV, 4.6/4.1 fb^{-1}, e-/μ-channel, single- and multi-fits
m_T, total unc.
m_W
unc.
μ, |η|<0.8, q=–1 80364 +63 -61
μ, |η|<0.8, q=+1 80376 +59 -57
μ, 0.8<|η|<1.4, q=–1 80408 +59 -58
μ, 0.8<|η|<1.4, q=+1 80373 +52 -50
μ, 1.4<|η|<2.0, q=–1 80342 +59 -60
μ, 1.4<|η|<2.0, q=+1 80439 +60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

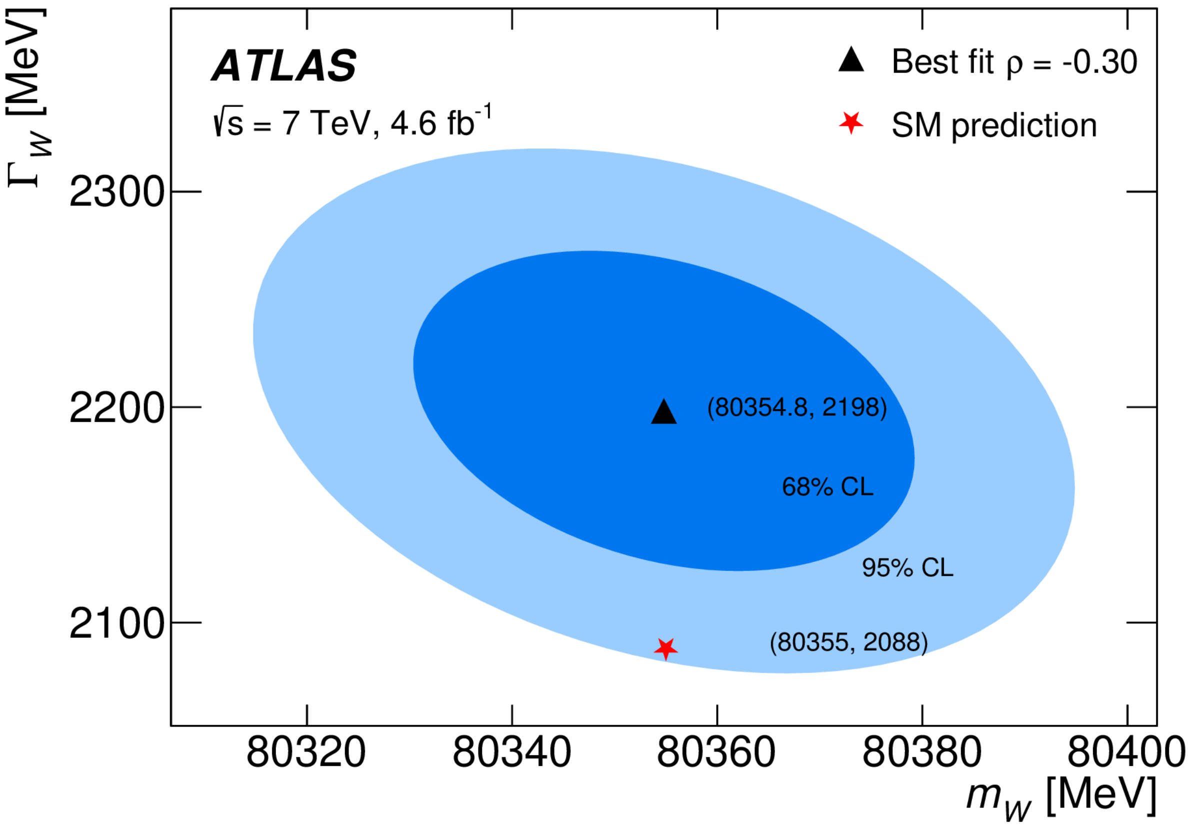
W boson width measurement

- The same procedure can be used to measure the W boson width






Overview of Γ_W measurements
ATLAS
$\sqrt{s}$ = 7 TeV, 4.6 fb^{-1}
DELPHI
Eur. Phys. J. C 47 (2006) 309
Γ_W = 2404 ± 173 MeV
OPAL
Eur. Phys. J. C 47 (2006) 309
Γ_W = 1996 ± 140 MeV
L3
Eur. Phys. J. C 47 (2006) 309
Γ_W = 2180 ± 142 MeV
ALEPH
Eur. Phys. J. C 47 (2006) 309
Γ_W = 2140 ± 108 MeV
Combination
Phys. Rep. 532 (2013) 119
Γ_W = 2195 ± 83 MeV
LEP
D0
Phys. Rev. Lett. 103 (2009) 231802
Γ_W = 2028 ± 72 MeV
CDF
Phys. Rev. Lett. 100 (2008) 071801
Γ_W = 2032 ± 72 MeV
Tevatron
ATLAS
This work
Γ_W = 2202 ± 47 MeV
LHC
Measurement
Stat. Unc.
Total Unc.
SM Prediction
1500
2000
2500
Γ_W [MeV]


ATLAS
$\sqrt{s}$ = 7 TeV, 4.6 fb^{-1}
Best fit ρ = -0.30
SM prediction
(80354.8, 2198)
68% CL
95% CL
(80355, 2088)
2300
2200
2100
80320
80340
80360
80380
80400
Γ_W [MeV]
m_W [MeV]

Conclusion

- W boson mass was measured with very high precision @ LHC
  - Dominated by lepton pT measurement
- m_W = 80366.5 ± 9.8 (stat.) ± 12.5 (syst.) MeV = 80366.5 ± 15.9 MeV
- Measurment is compatible with SM predictions and global fits