The W-boson mass : status and perspectives

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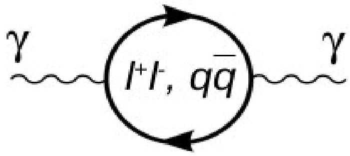
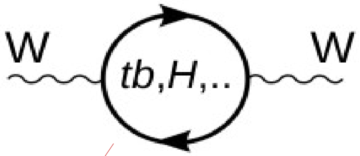
Prediction of m_W in the SM – a snapshot

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-4\frac{\pi\alpha}{\sqrt{2}\,G_\mu m_Z^2}\frac{1}{1-\Delta r}}\right)$$

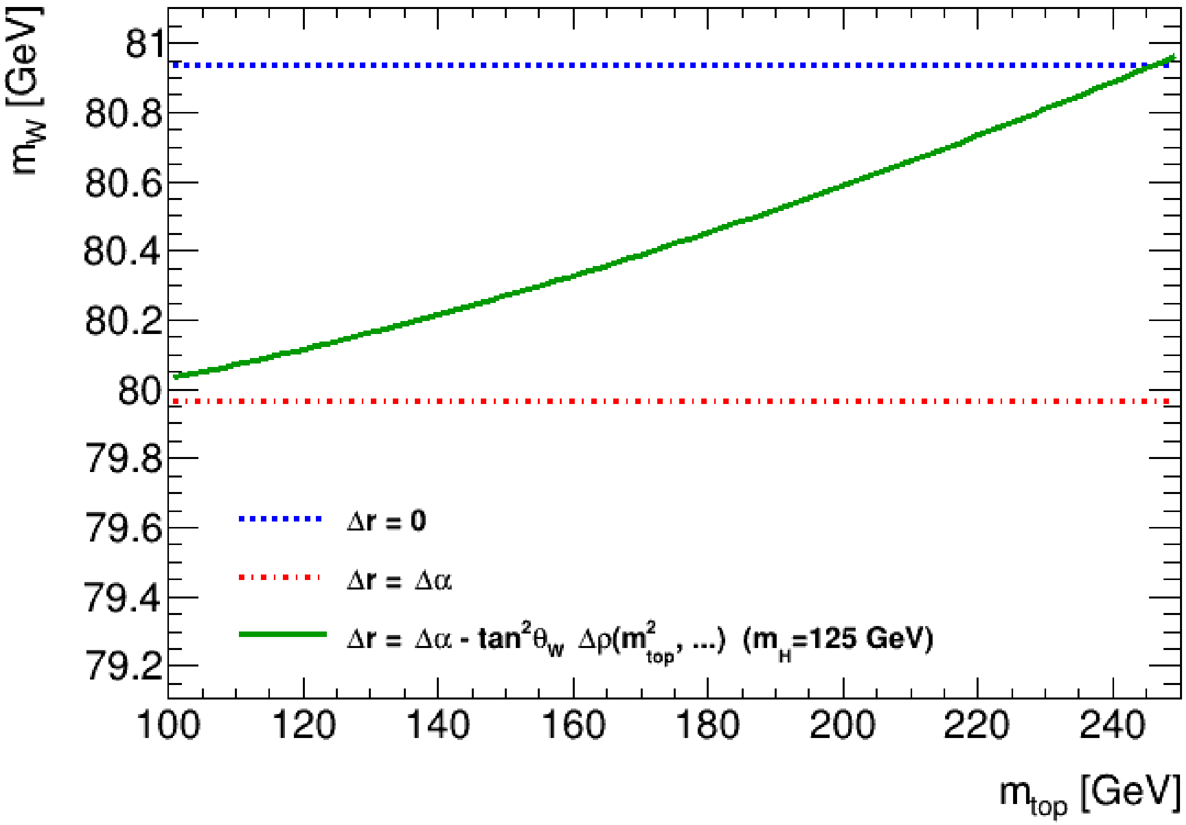




$$\Delta r = \Delta\alpha - \tan^2\theta_W \Delta\rho = \sim 0.059 - \frac{3G_\mu m_W^2}{8\sqrt{2}\,\pi^2}\left[\frac{m_{top}^2}{m_W^2}\cot^2\theta_W - \left(\ln\frac{m_H^2}{m_W^2}-\frac{5}{6}\right)+\dots\right]$$

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

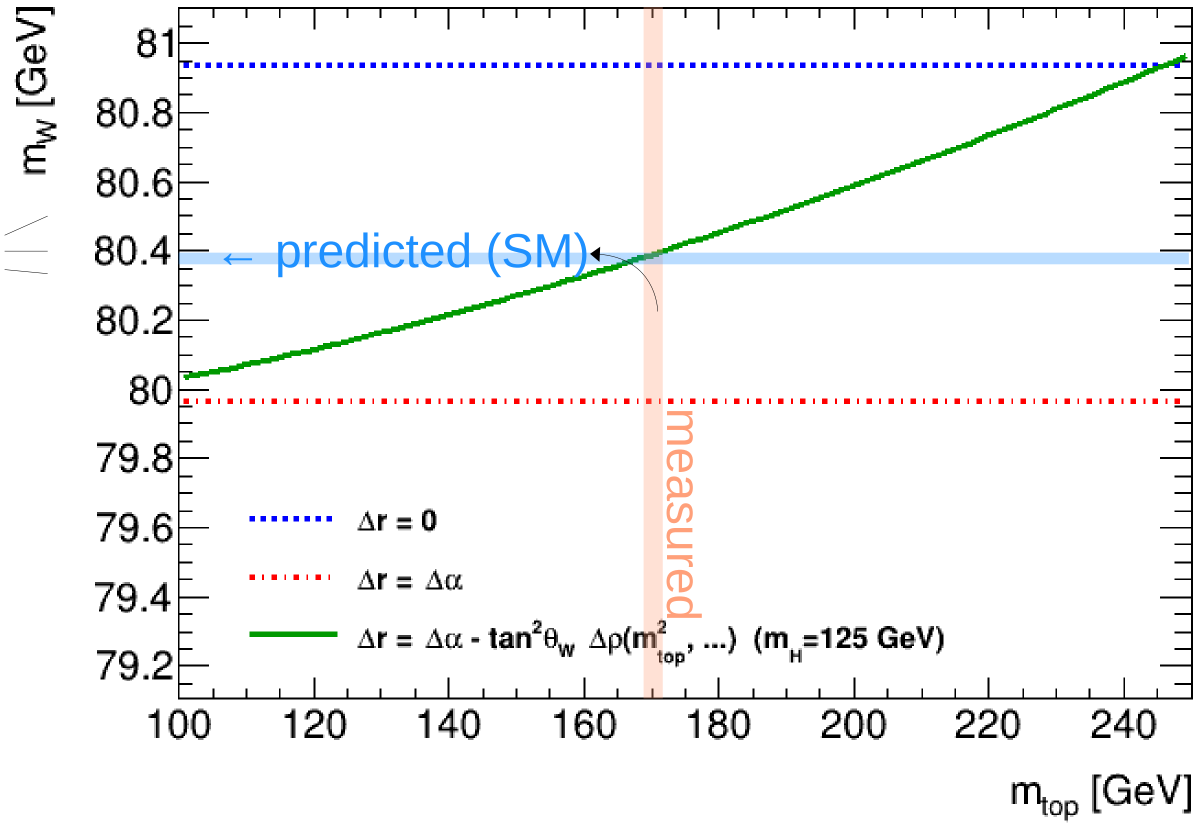
Prediction of m_W in the SM – a snapshot



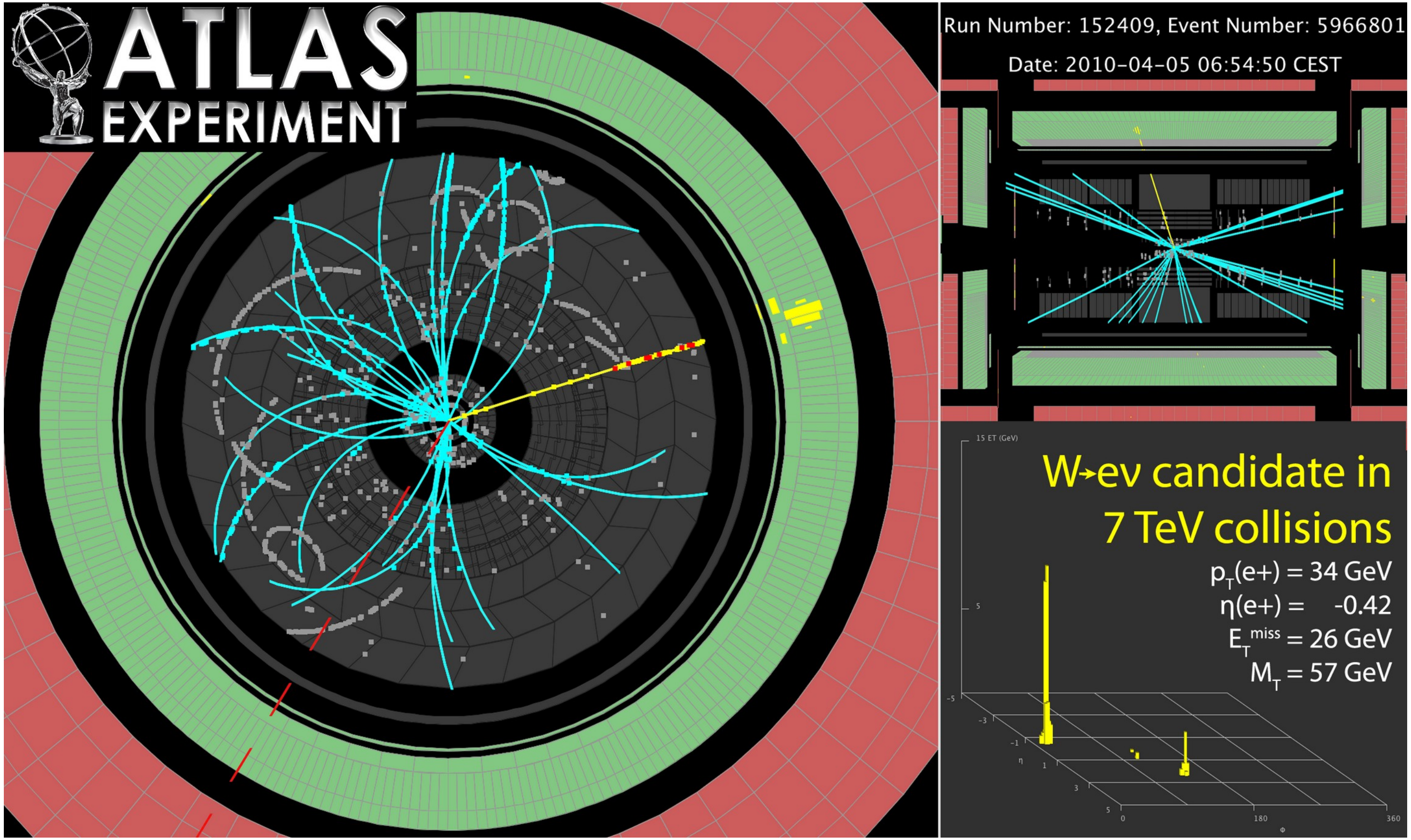
Prediction of m_W in the SM – a snapshot

Today

Measurement?



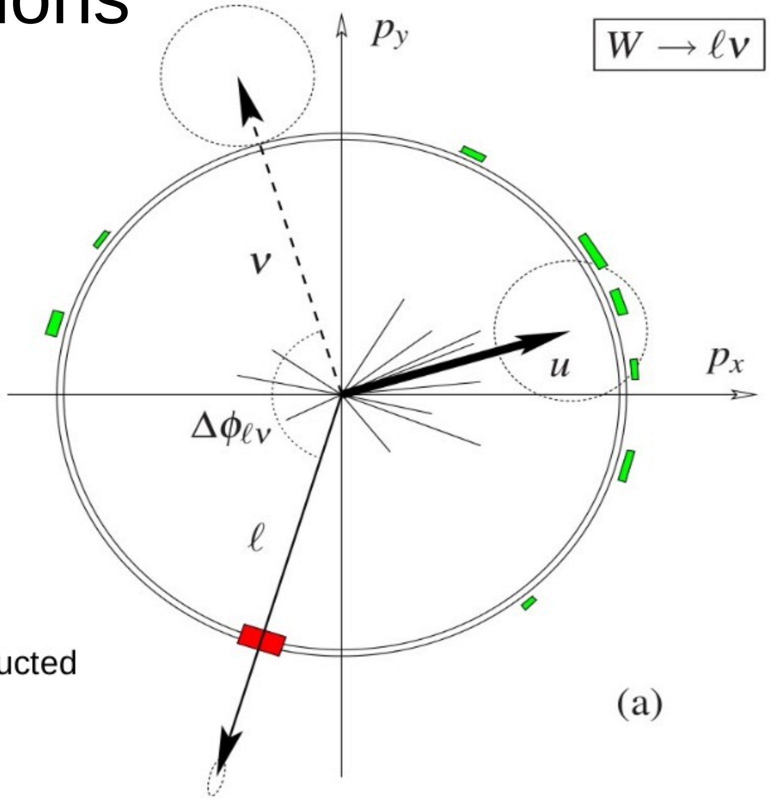
The W boson mass in proton collisions



The W boson mass in proton collisions

- Incomplete kinematics (missing neutrino!)
  → no invariant mass
  → rely on measured quantities, and exploit momentum conservation in the transverse plane

- Event representation :



- Main signature :
  single electron or muon $\vec{p}_T^{\,l}$

- Recoil : sum of "everything else" reconstructed in the calorimeters; a measure of $p_T^{W,Z}$

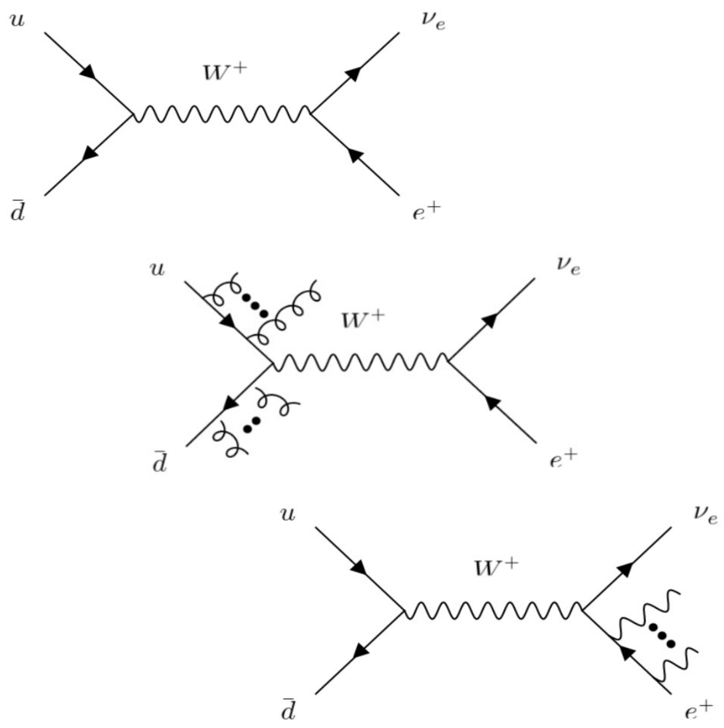
$$\vec{u}_T = \sum_i \vec{E}_{T,i}$$

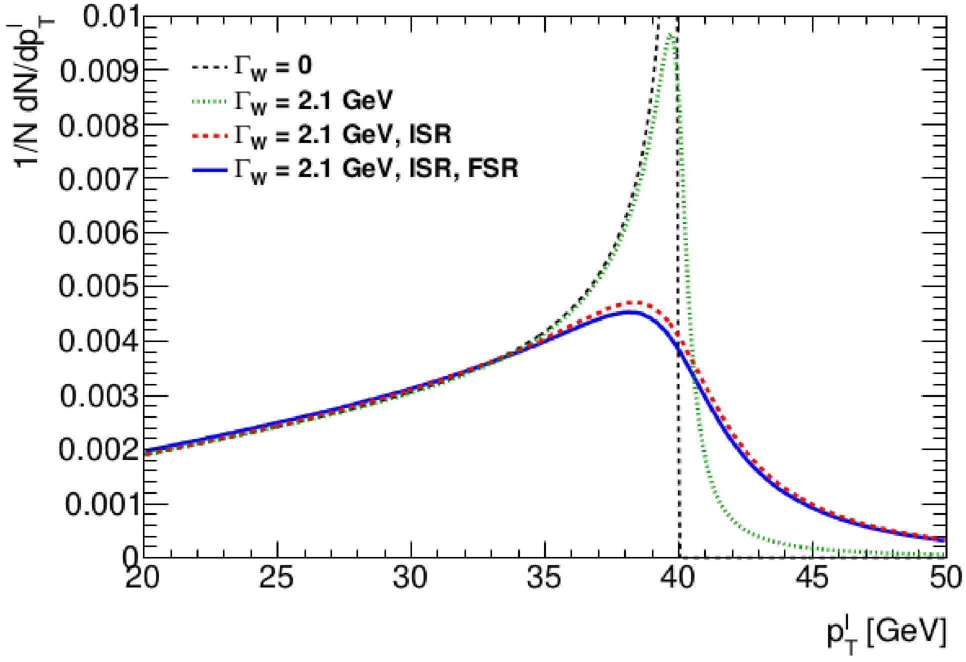
- Derived quantities : $\vec{p}_T^{\,miss} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right)$ $\quad m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos\Delta\phi)}$

The W boson mass in proton collisions

- Physics corrections : W width; QCD and QED ISR and FSR, PDFs, ...

  → all carry uncertainties to be quantified!





The W boson mass in proton collisions

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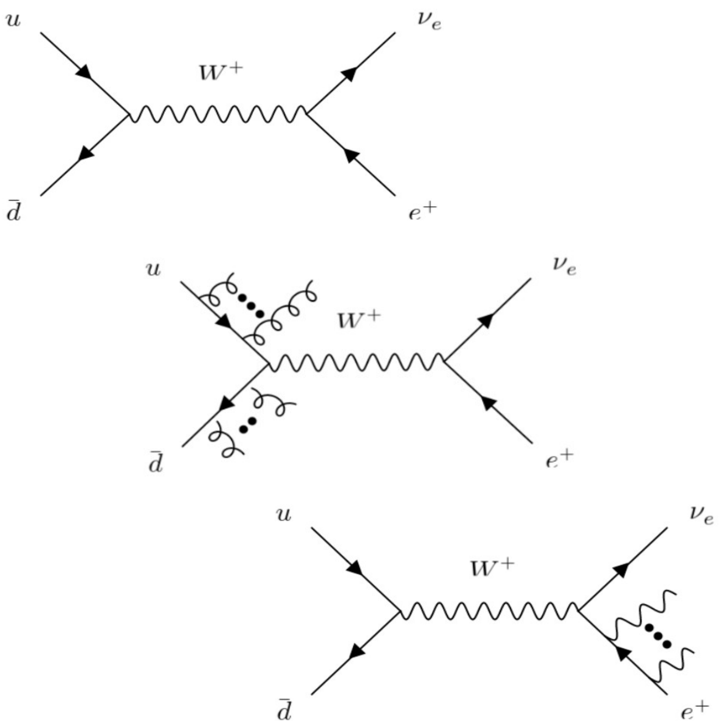
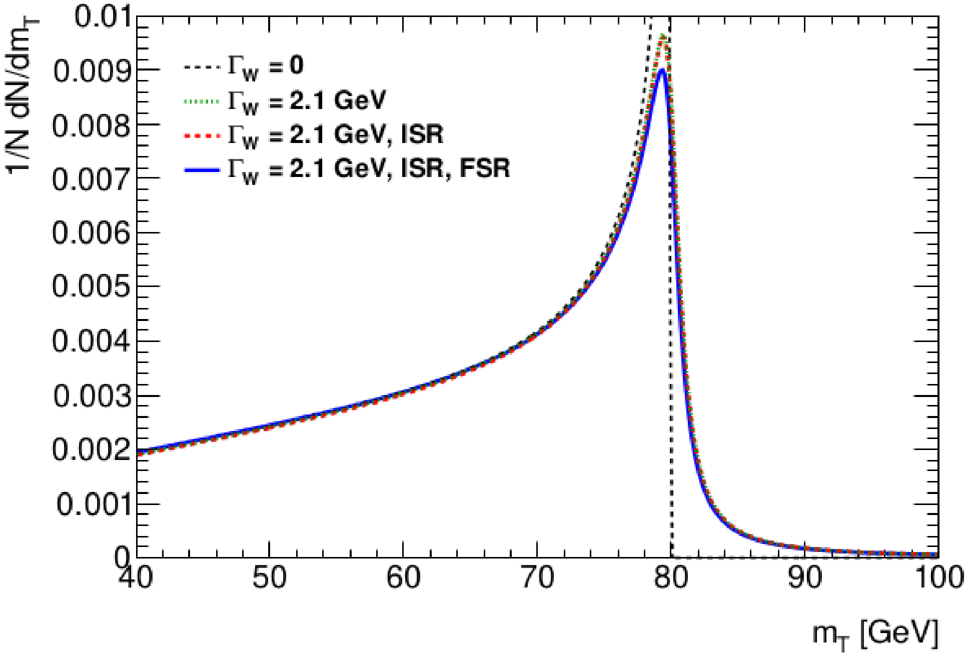
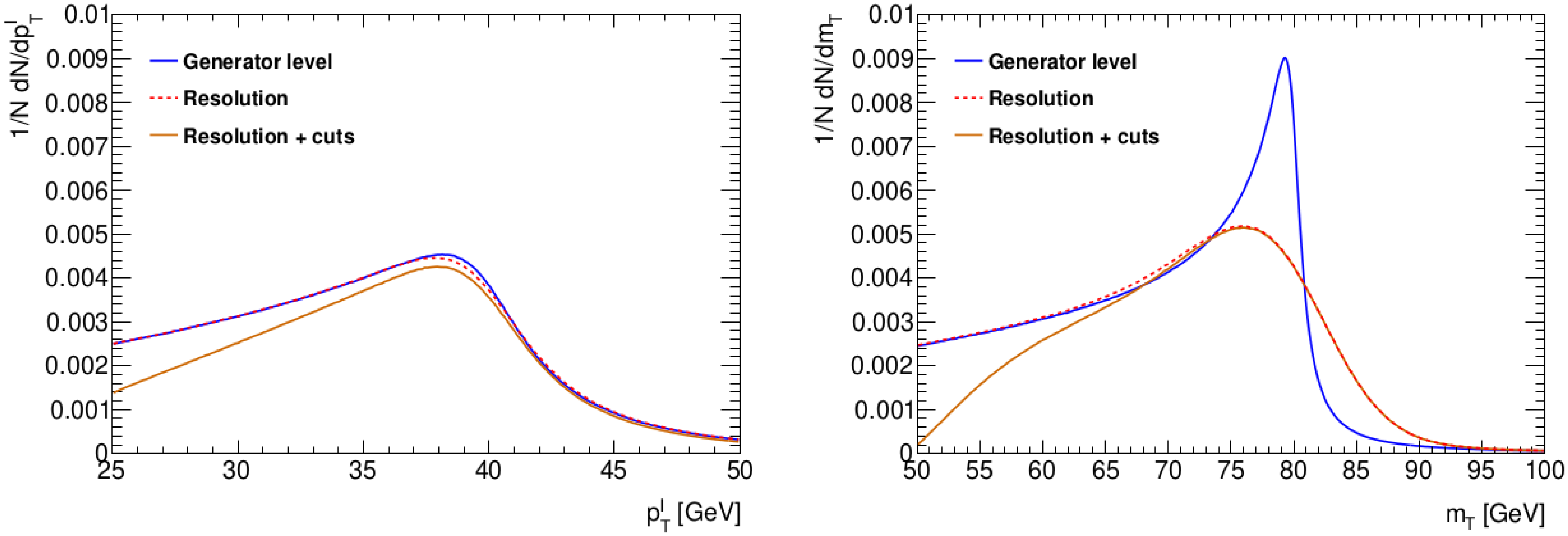




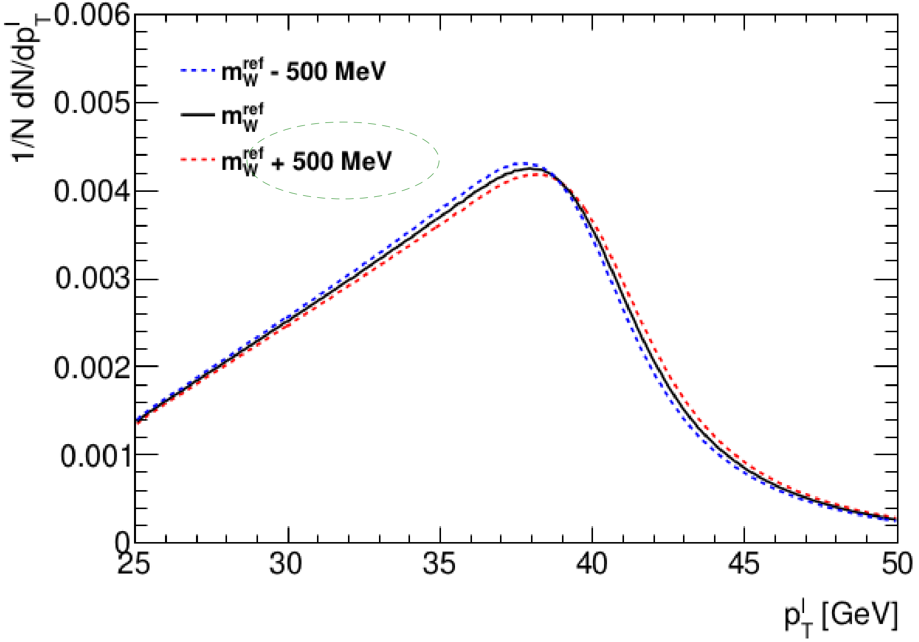
The W boson mass in proton collisions

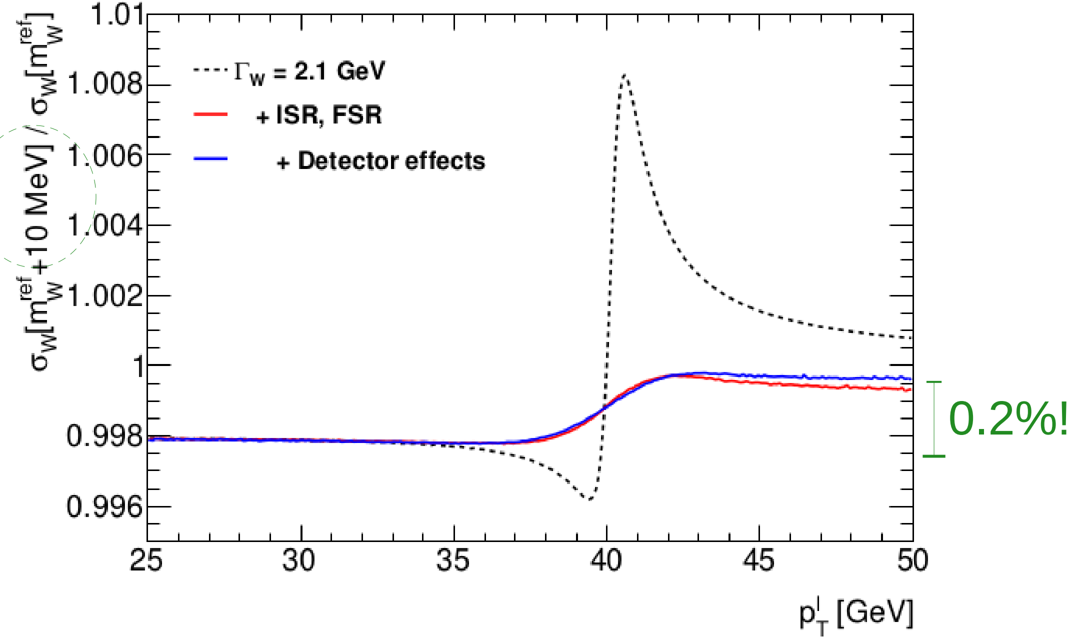
- Detector effects, also with uncertainties :
  - Lepton calibration and resolution;   Missing E_T resolution ~ 5 – 15 GeV
  - Efficiencies and acceptance ~15% (with non-trivial kinematic dependence!)



The W boson mass in proton collisions

- Mass measurement : produce models (“templates”) of the final state distributions for different mass hypotheses; compare to data





Two slides on calibration

- Leptons calibration from “perfectly known” resonances

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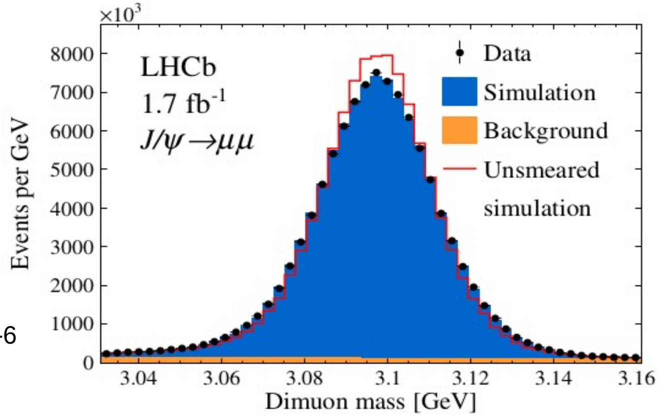
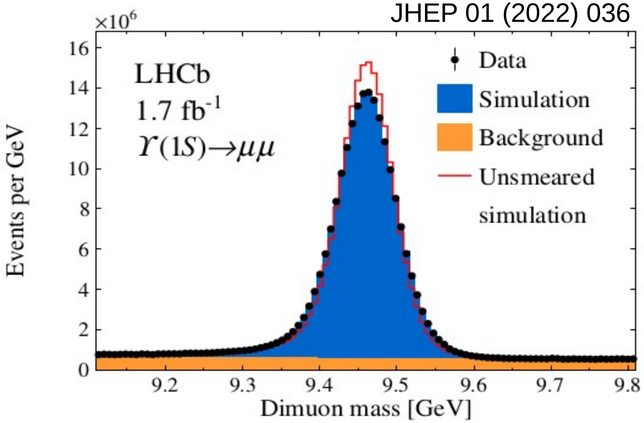
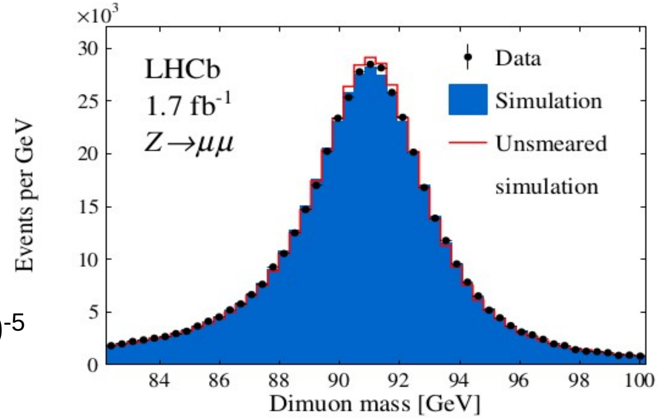




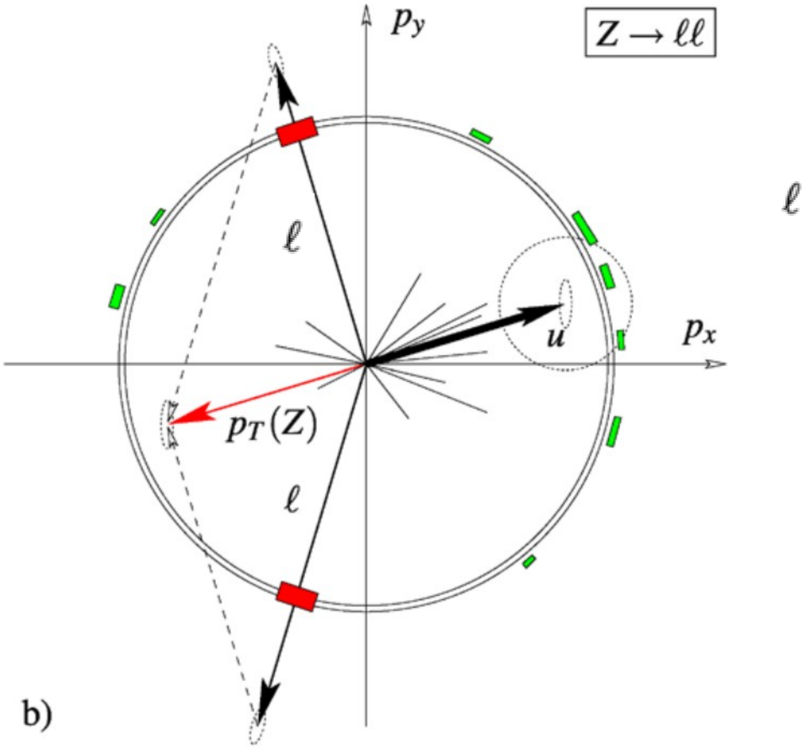
$\delta m_{J/psi} / m_{J/psi} \sim 10^{-6}$

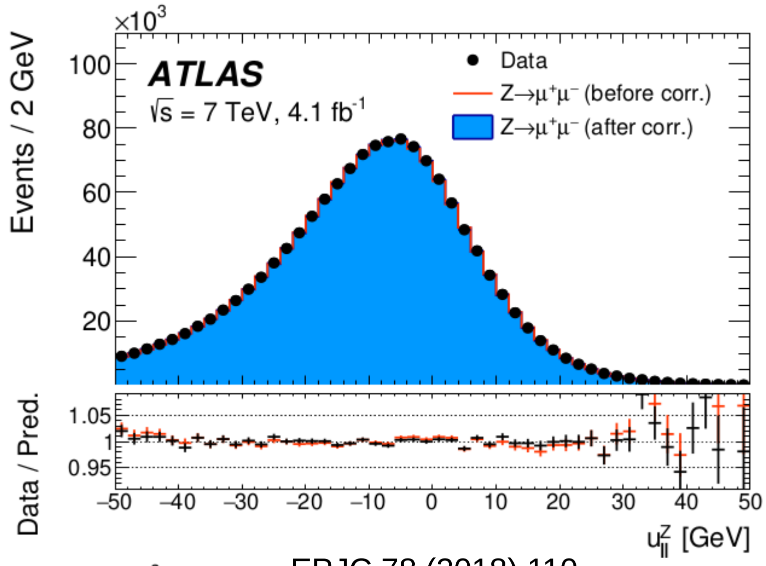


$\delta m_Z / m_Z \sim 2.10^{-5}$

Two slides on calibration

- Recoil response & resolution calibrated using over-constrained kinematics in Z events





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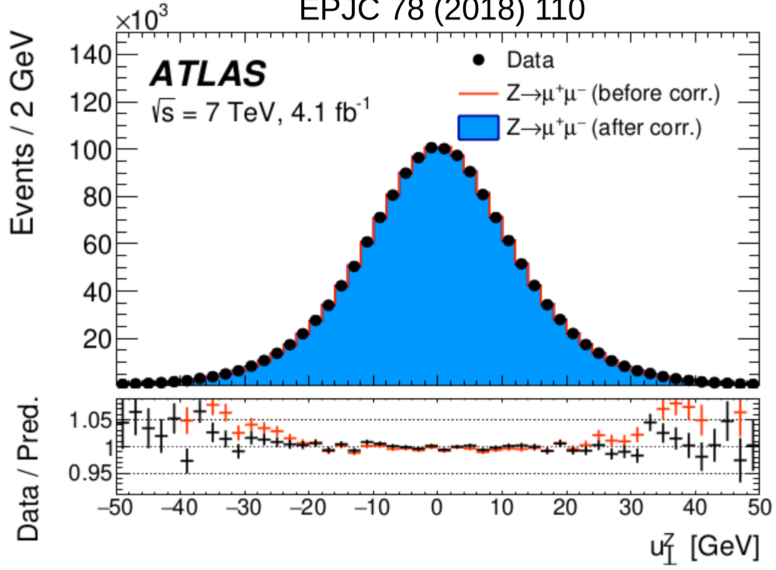
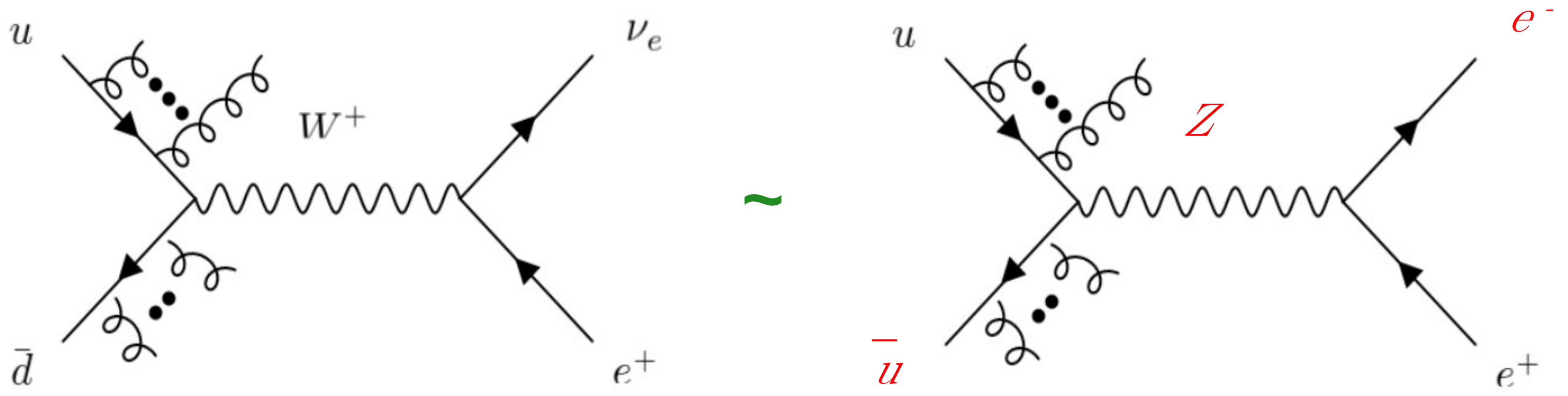


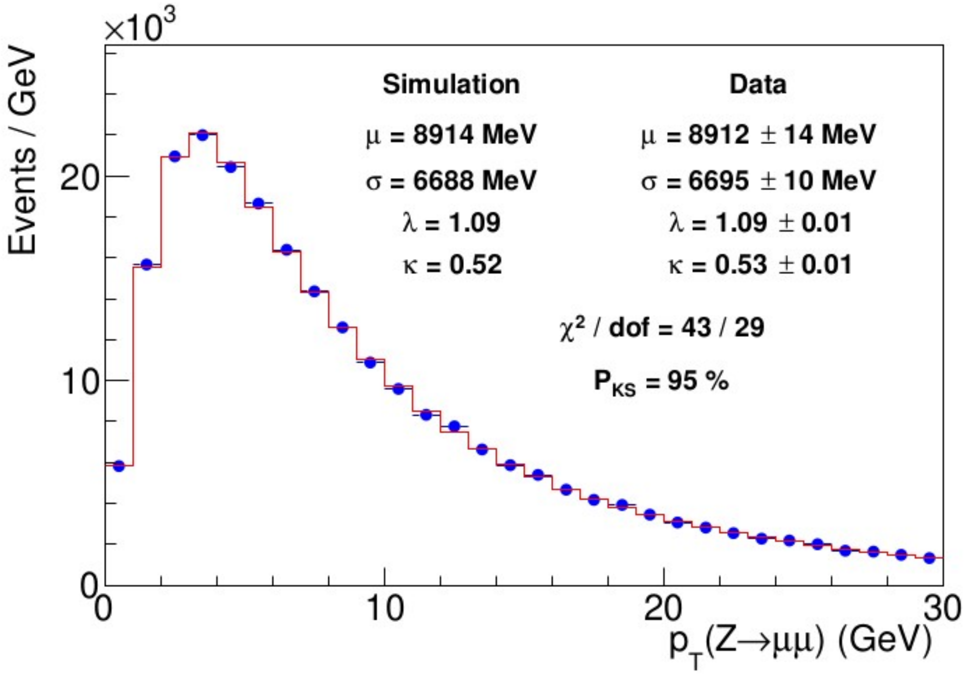
Transverse momentum distribution

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

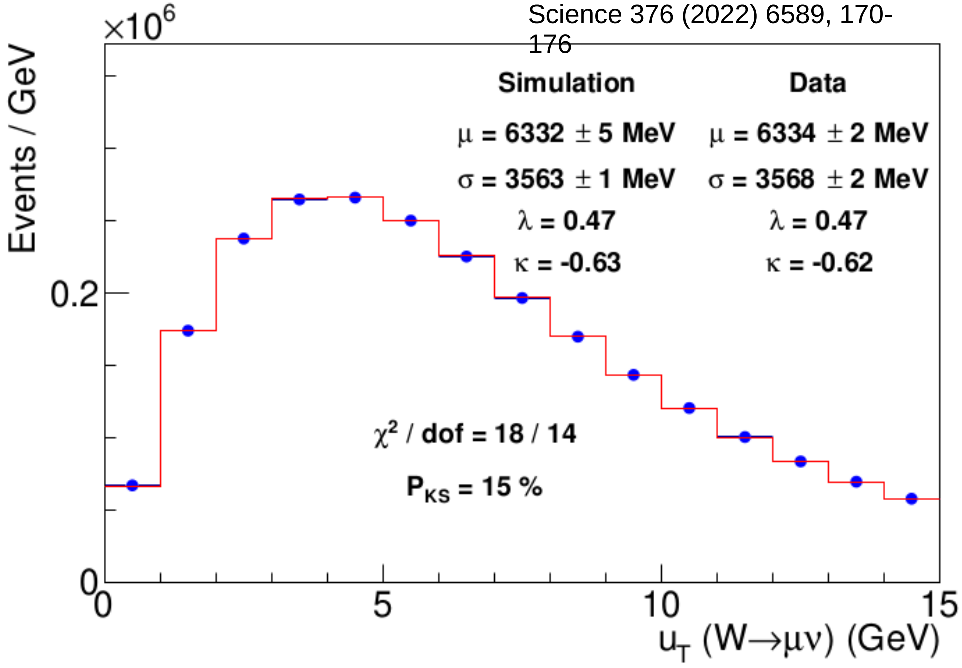


Transverse momentum distribution

- **Tevatron** : Z-based model tuning (Resbos); no extrapolation uncertainties, but validation with W events



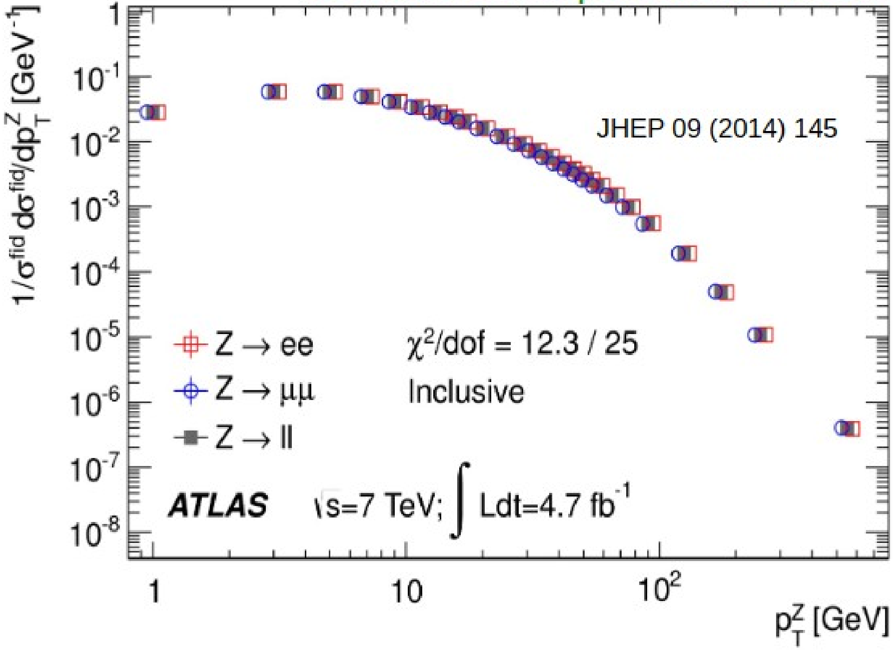
Science 376 (2022) 6589, 170-176

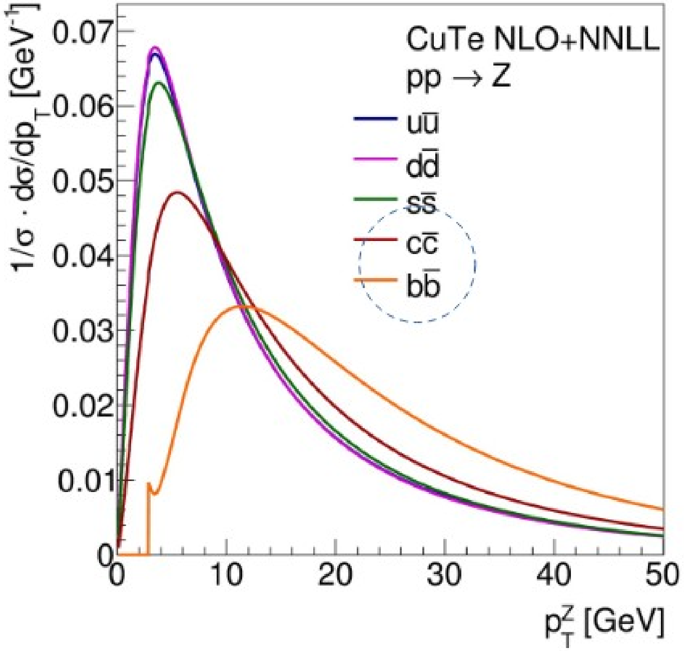


Transverse momentum distribution

- **ATLAS** : Z-based model tuning + Z → W extrapolation. Corresponding uncertainties :
  - Treatment of HQ mass and thresholds;
  - HQ PDFs

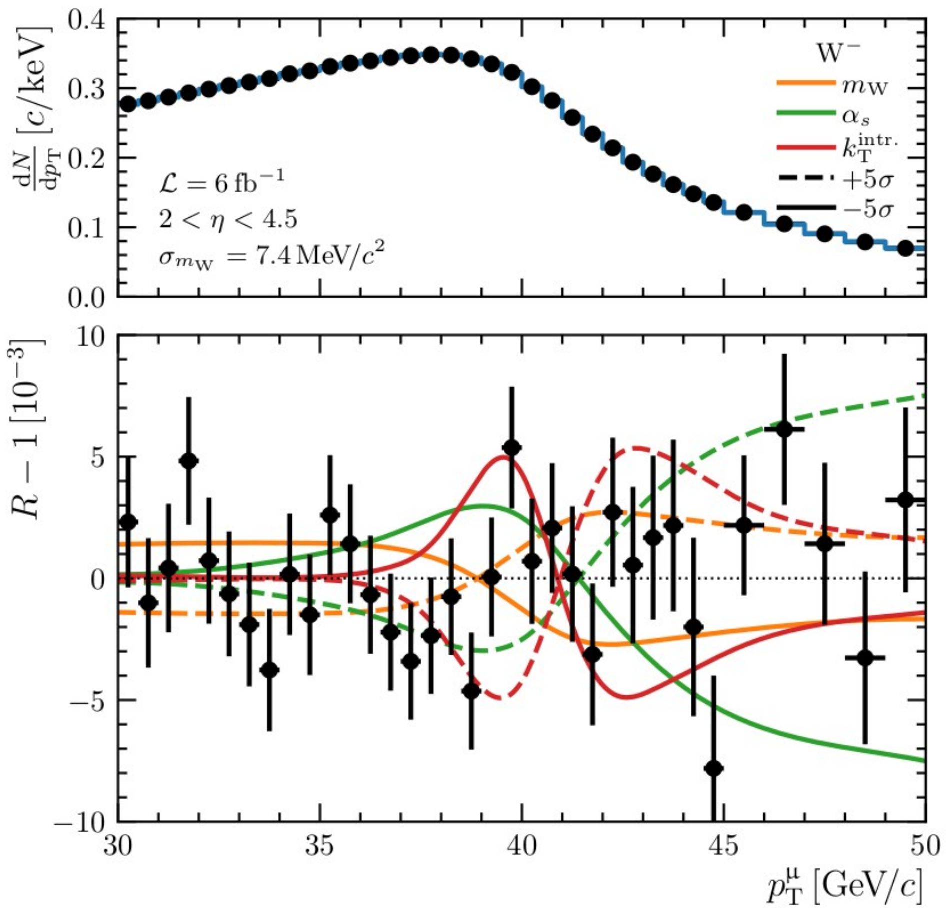
Measurement precision ~0.5%





Transverse momentum distribution

- **LHCb** :
  - Z data
  - simultaneous fits to mW and pTW in W events
  - repeated for different theoretical models



Transverse momentum distribution

- Analytical resummation – now at approximate N4LO+N4LL

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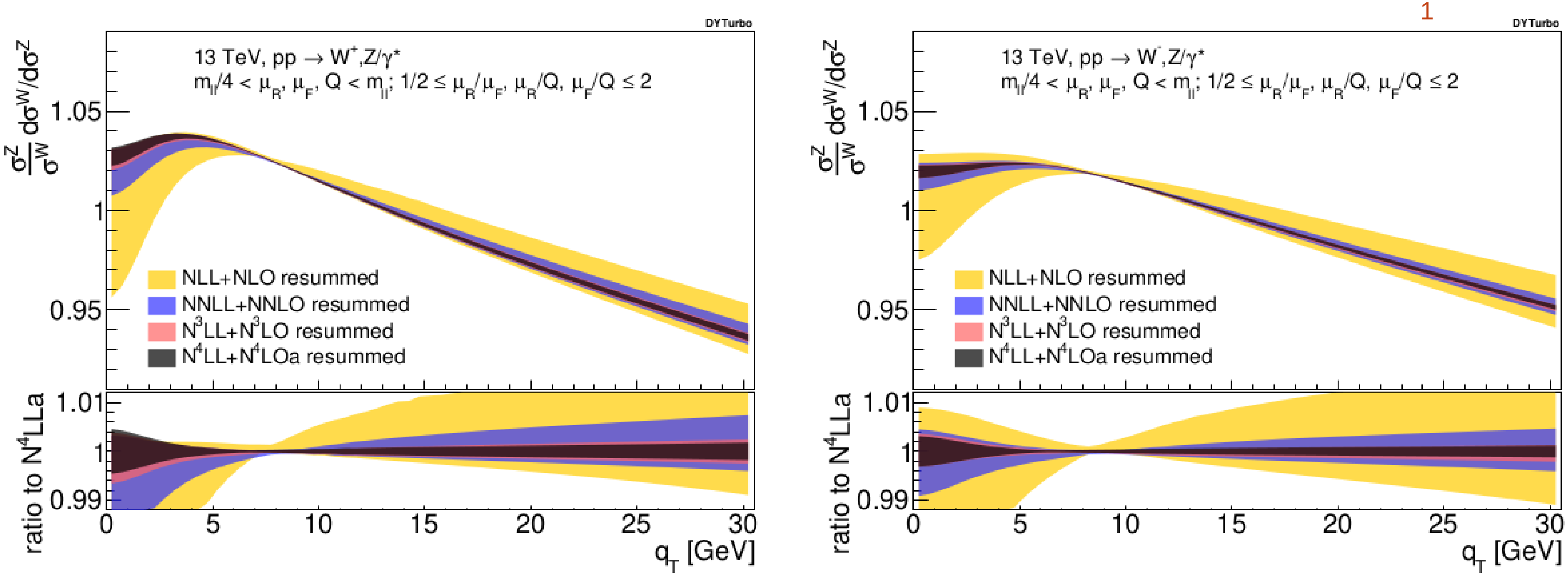
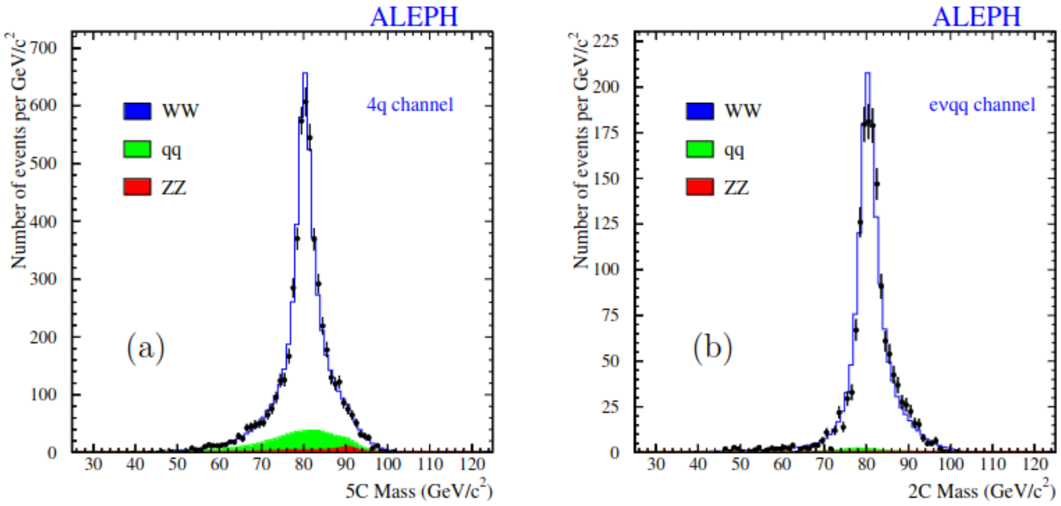


  - Essentially removing any uncertainty in the W/Z pT distribution ratio
  - However, analysis is not complete : flavour-dependent intrinsic kT; heavy-quark mass effects; process-dependent EWK effects… are not (yet) addressed

Published results

- LEP

~35k $e^+e^- \to W^+W^-$ candidate events



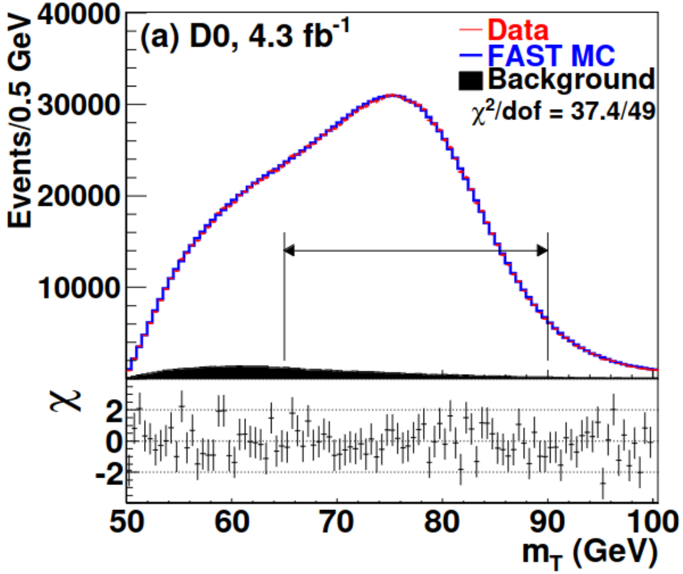
Source	Systematic Uncertainty in MeV			
	on m_W			on Γ_W
	$q\bar{q}\ell\nu_\ell$	$q\bar{q}q\bar{q}$	Combined	
ISR/FSR	8	5	7	6
Hadronisation	13	19	14	40
Detector effects	10	8	9	23
LEP energy	9	9	9	5
Colour reconnection	–	35	8	27
Bose-Einstein Correlations	–	7	2	3
Other	3	10	3	12
Total systematic	21	44	22	55
Statistical	30	40	25	63
Statistical in absence of systematics	30	31	22	48
Total	36	59	34	83

$$m_W = 80.376 \pm 0.025(\text{stat.}) \pm 0.022(\text{syst.})\ \text{GeV}.$$

Published results

- Tevatron – D0

~1.68M W → eν candidate events

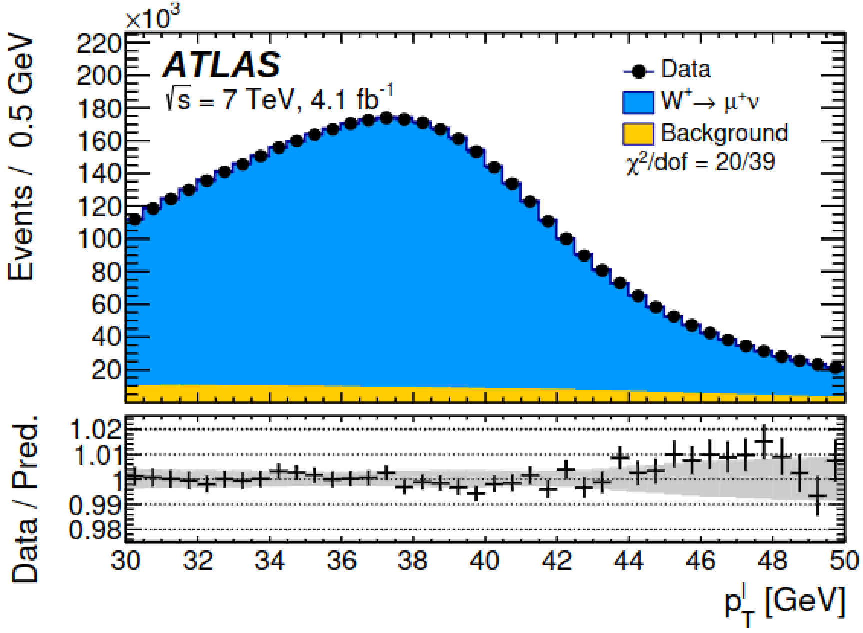


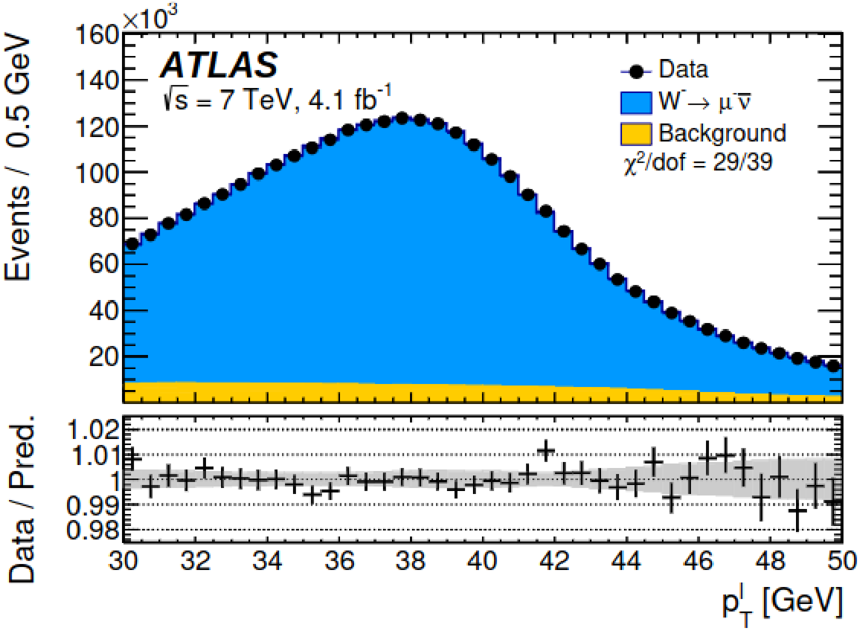
$$M_W = 80.375 \pm 0.011\ (\text{stat.}) \pm 0.020\ (\text{syst.})\ \text{GeV}$$
$$= 80.375 \pm 0.023\ \text{GeV}.$$

	ΔM_W (MeV)		
Source	m_T	p_T^e	$\not{E}_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	13	14	17
Total	22	24	29

Published results

- LHC – ATLAS 7 TeV ~15M W → eν, μν candidates

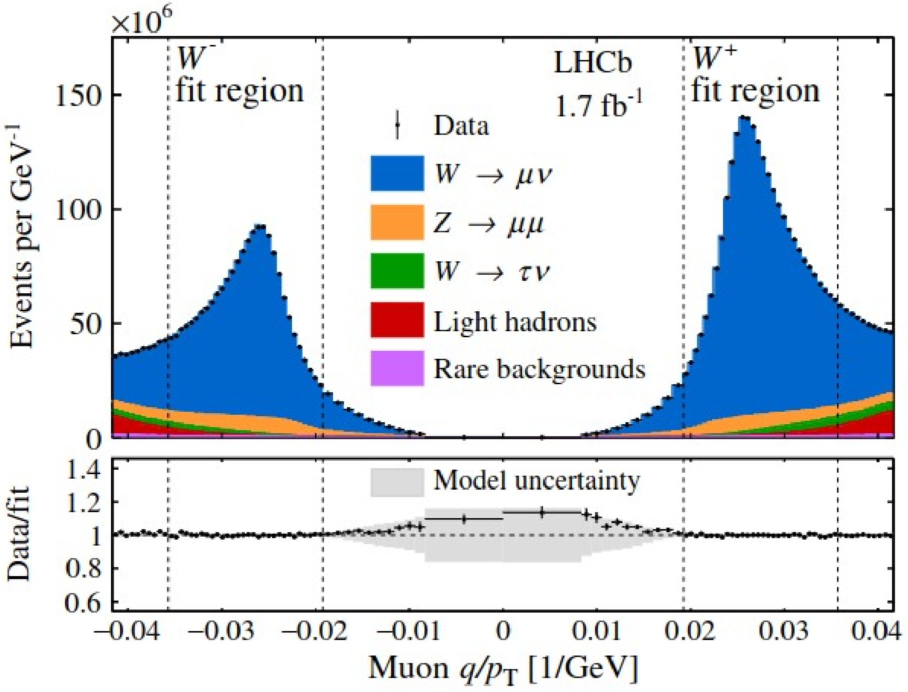




m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Published results

- LHC – LHCb 13 TeV ~2.4M W → μν candidates



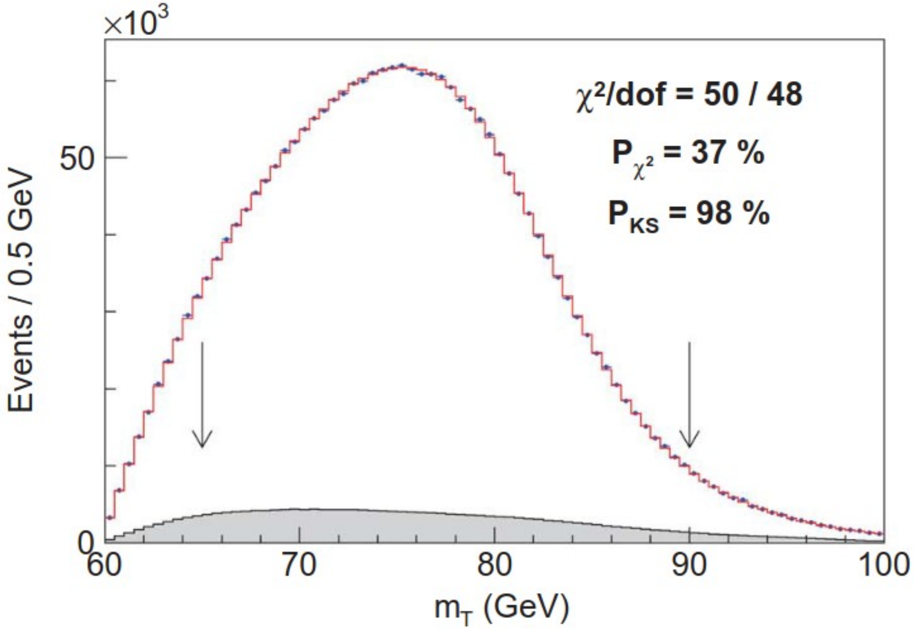
$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}.$$

Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

Published results

- Tevatron – CDF

~4M W $\rightarrow$ eν, $\mu\nu$ candidates



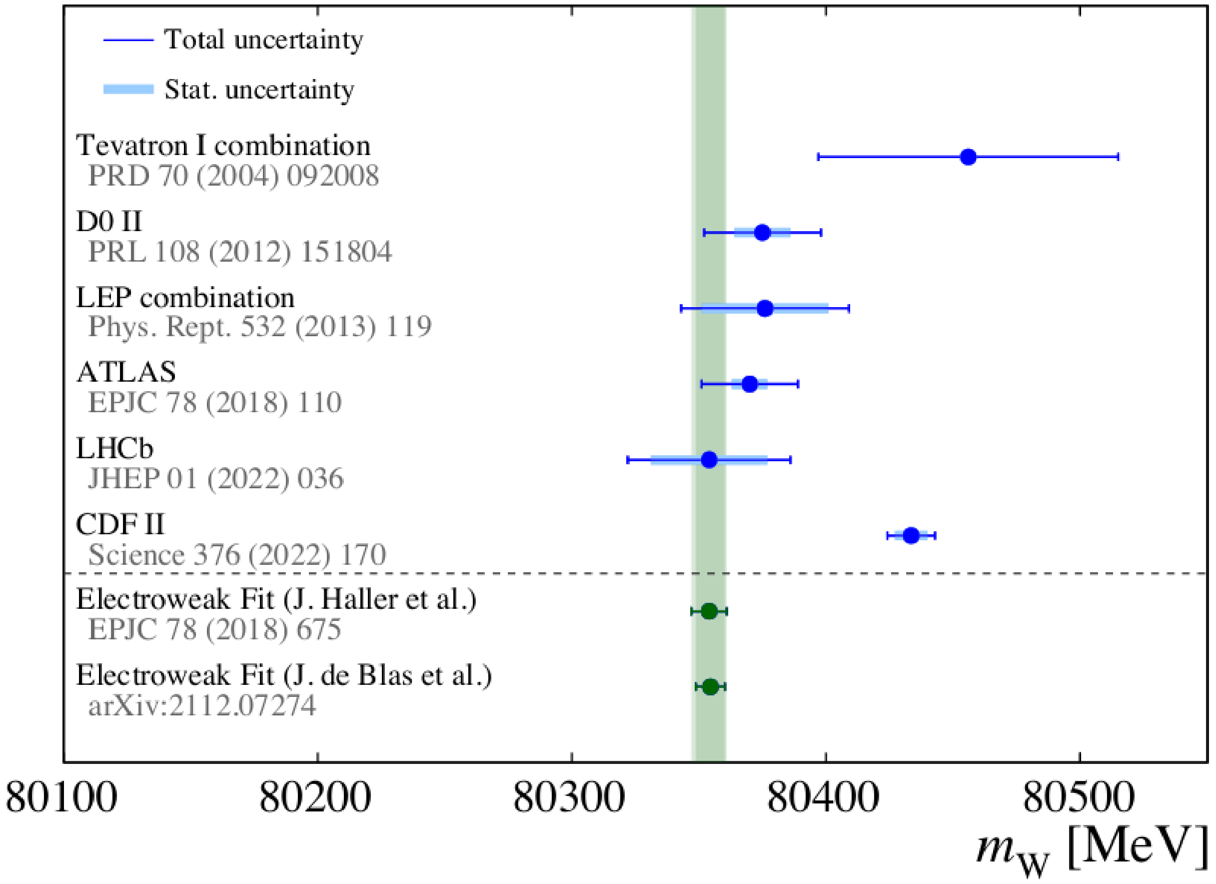
$$M_W = 80{,}433.5 \pm 9.4\,\mathrm{MeV}$$

7σ from the SM, but….

Table 2. Uncertainties on the combined M_W result.

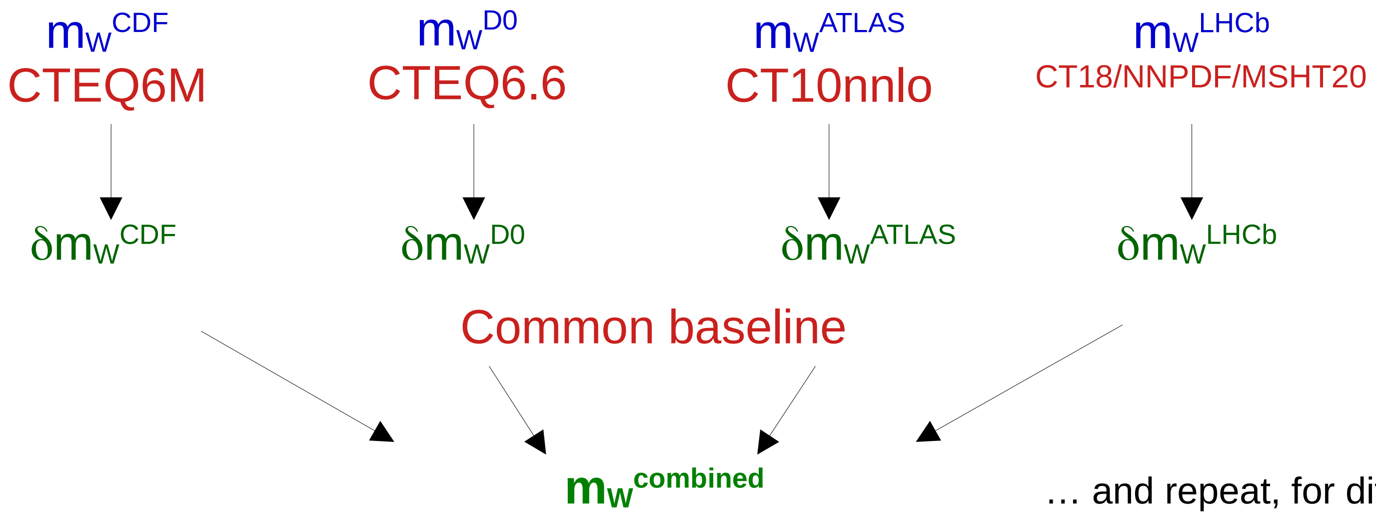
Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

Overall picture



Combination

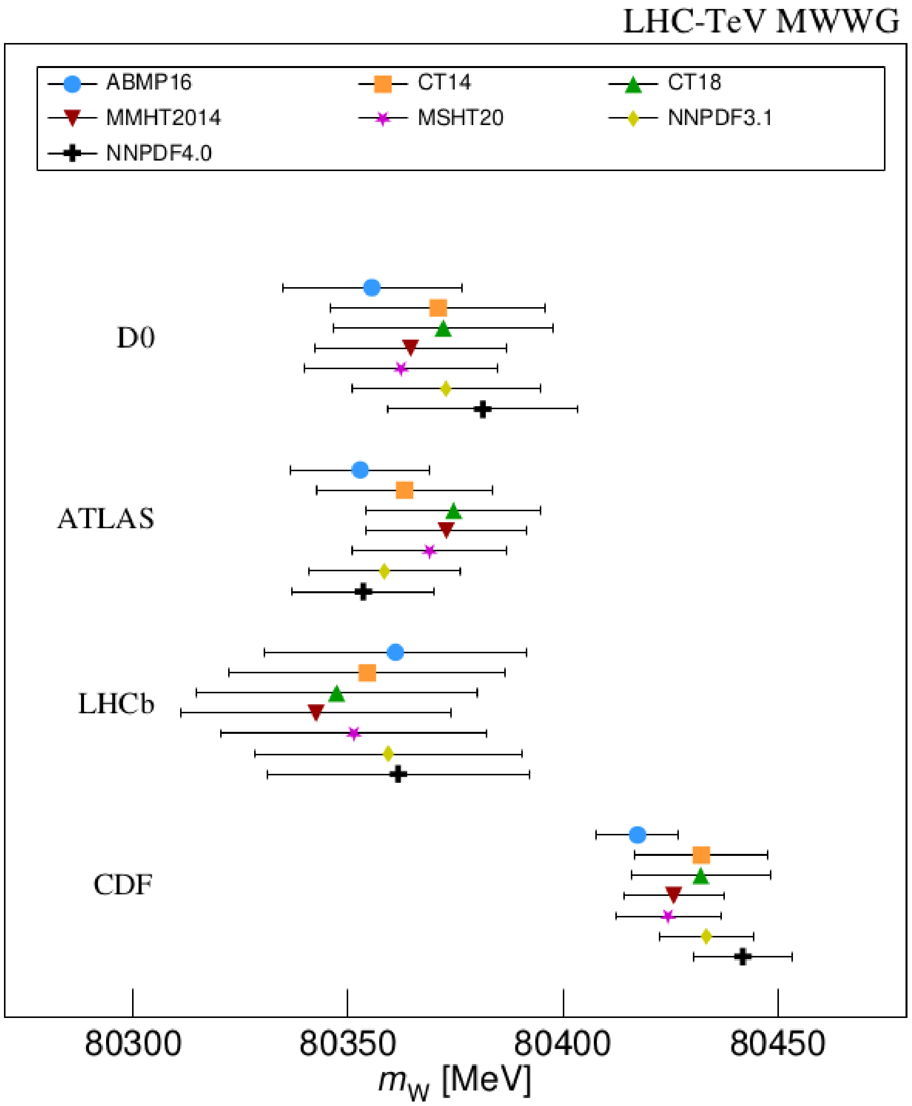
- Measurements performed at different times, using different baseline PDFs and QCD tools : existing result extrapolated to a common baseline
- Two-step procedure :
  - correct to common theory and modelling
  - combine including correlations (proton structure)



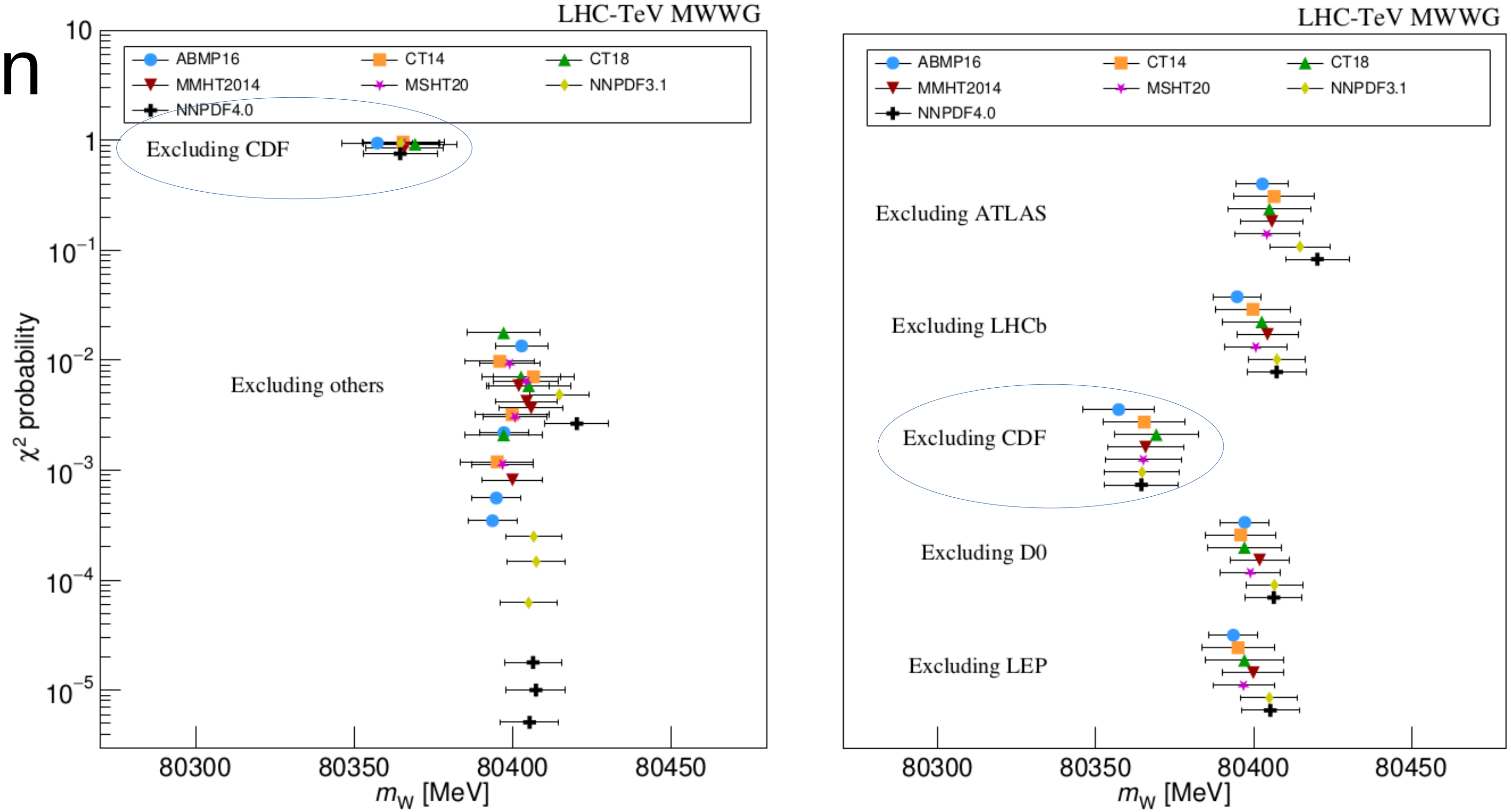
… and repeat, for different PDFs

Combination

- PDF extrapolations
  - Large effects on separate experiments
  - Opposite trends stabilize combination



Combination



Full world average $P(\chi^2) = <0.5\%$ $m_W^{CDF} - m_W^{Others} \sim 4\sigma$

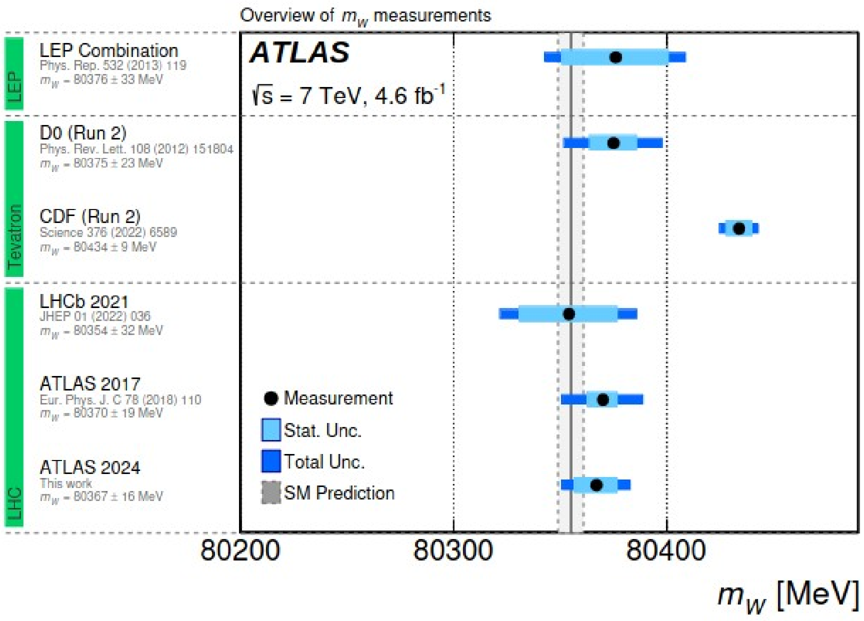
Average w/o CDF $P(\chi^2) = 91\%$ $m_W = 80369.2 \pm 13.3$ MeV

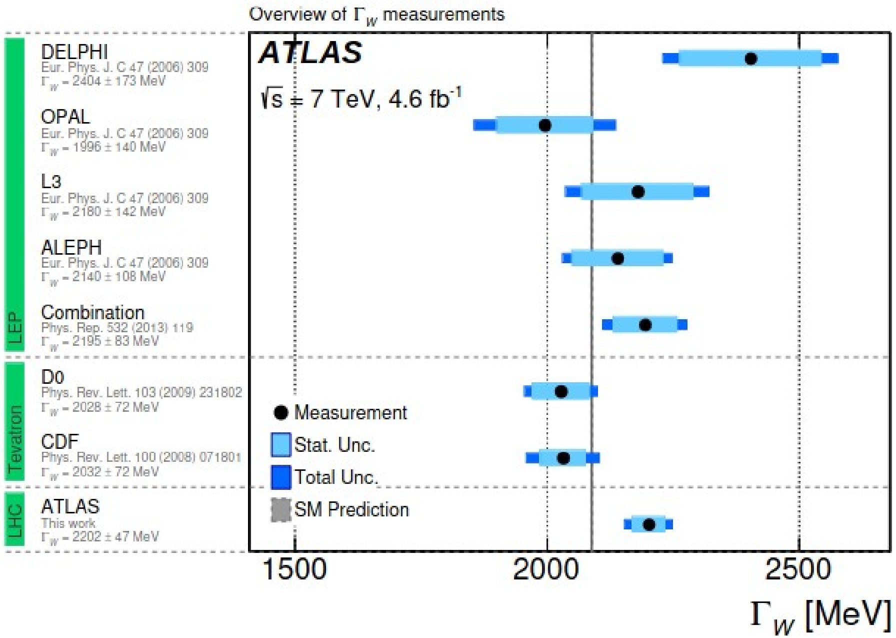
This average and the published CDF result considered on equal footing but incompatible

Updates and prospects

- ATLAS : re-analysis of 7 TeV data
  - extend study of PDF dependence of $m_{W;}$ W-boson width; Improved statistical method

… everything else unchanged (or almost)





Updates and prospects

(Miguel Ramos Pernas, Orsay, '23

- LHCb

Analysis strategy for the full Run 2 result

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

Include 2017 + 2018 data

New strategies/tools

Inputs from the theory community

The overall strategy remains the same as for the 2016 analysis:

- Calibration using J/ψ, Υ(1S) and Z decays:
  - Dedicated alignment and momentum scaling
  - Momentum smearing and selection efficiencies
- Reweighting the simulation at generator level in 5 dimensions
- Template fit to the muon transverse momentum using a Beeston-Barlow method in the minimization

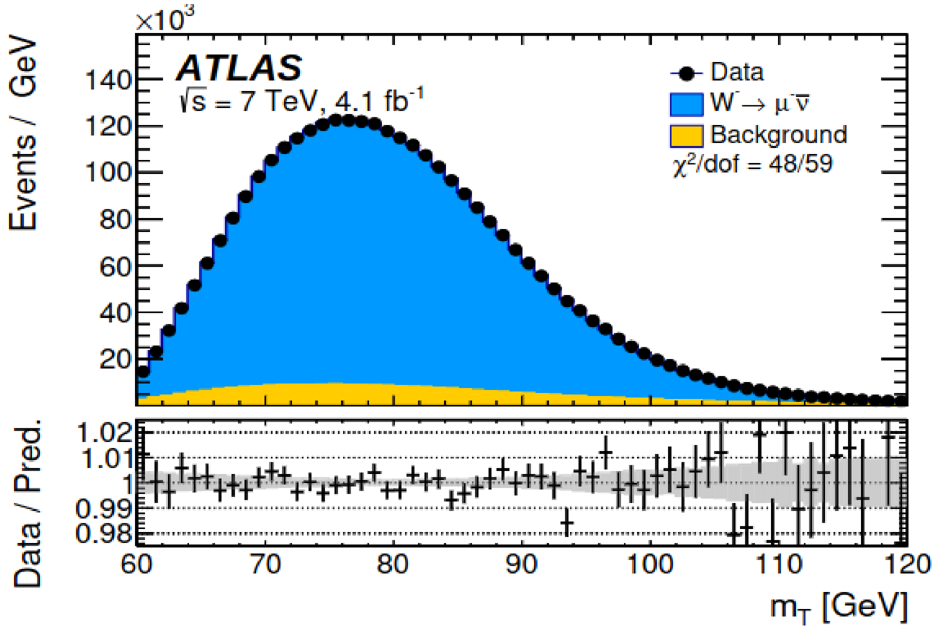
Target sensitivity:

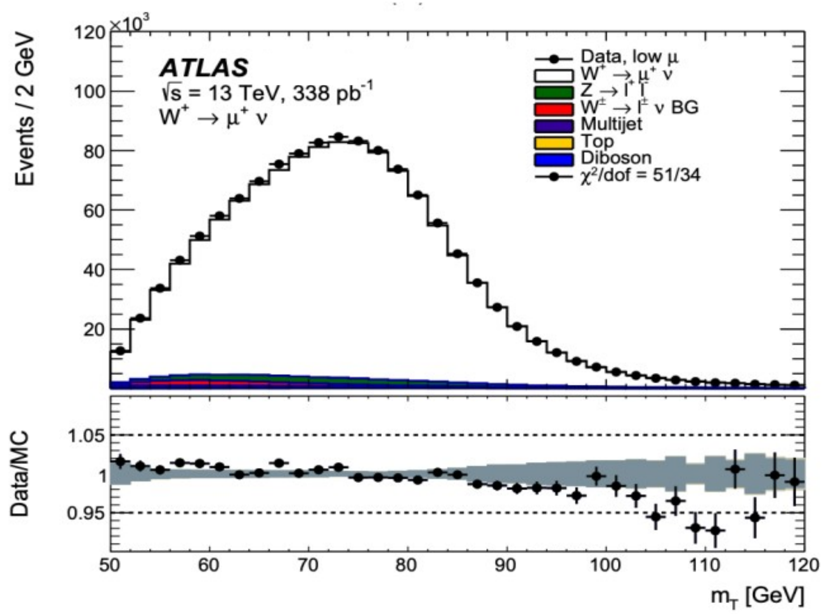
$$\sigma^{\text{Run 2}}_{\text{stat.}} \sim 14\,\text{MeV}$$

$$\sigma^{\text{Run 2}}_{\text{total}} \sim 20\,\text{MeV}$$

Updates and prospects

- Low-pile-up data in ATLAS : compared to 7 TeV, the loss in statistics (/7) is good part compensated by the sensitivity per event (x3)
- 1 fb^{-1} of such data would be an extremely good investment in this respect





Updates and prospects

- CMS

Updates and prospects

- CDF

A look back..

- Final measurement by UA2 :

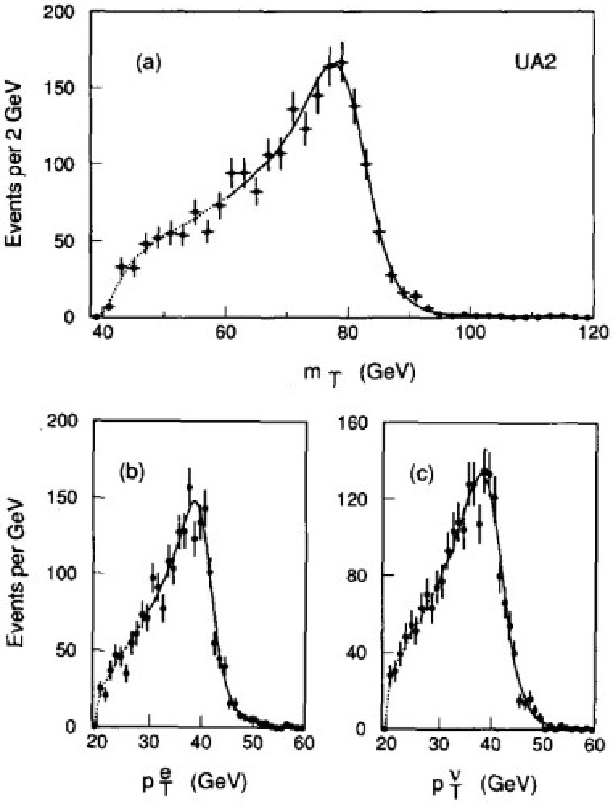


Table 3
The size (in MeV) of the systematic uncertainties in measuring m_W and m_Z.

	$\delta m_W(m_T)$	$\delta m_W(p_T^e)$	$\delta m_W(p_T^\nu)$	δm_Z(central)	$\delta m_Z(p_T\text{-con})$
structure function	85	135	105	–	–
electron energy resolution	75	100	75	35	35
neutrino scale	70	–	140	–	–
p_T^W and p_T^{had}	60	120	90	–	–
underlying event	30	50	–	50	50
fitting procedure	30	40	40	–	–
radiative decays	30	50	20	50	50
electron efficiency versus p_T^e	30	40	30	–	–
$u_\parallel$ effect	25	95	350	–	–
p_T constraint	–	–	–	–	100
total systematic uncertainties	160	240	420	80	130

In combination with the m_Z measurement from LEP, this gives

$$m_W = 80.35 \pm 0.33\,(\text{stat.}) \pm 0.17\,(\text{syst.})\ \text{GeV}. \qquad (9)$$

Conclusions

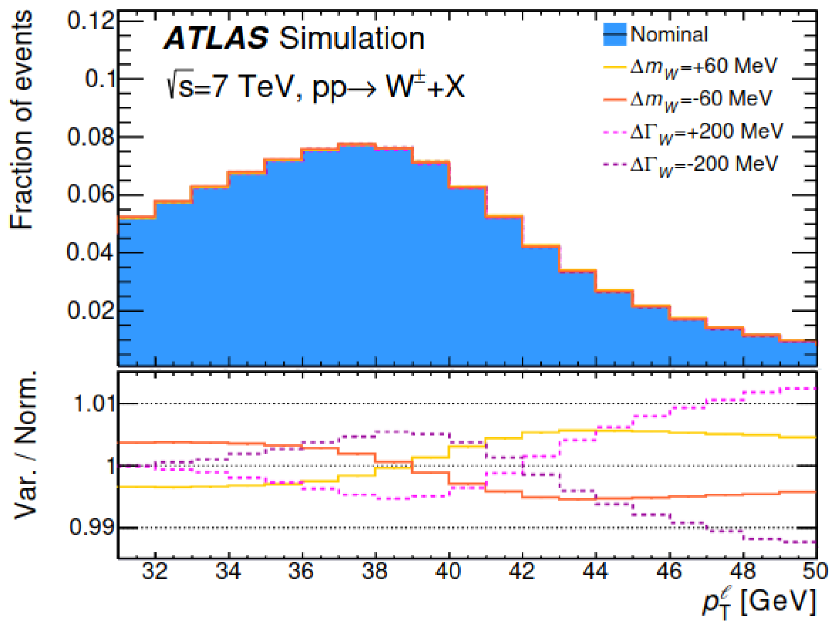
- m_W now an active field at the LHC… progress is still slow
- ~<10 MeV sensitivity per experiment not an unrealistic goal; ~5 MeV combined?
- Main challenge : theoretical and modelling accuracy of W production and decay
  - Perturbative accuracy keeps improving (→ A.Vicini's presentation Sat.)
  - measurements require a fully exclusive description of the final state (QCD and QED showers, underlying event) : MC's!
  - Proton structure uncertainties difficult to quantify (and discussions with the PDF groups do not progress very much…)
- The experimental situation is presently confused; forthcoming measurements will hopefully clarify the situation.

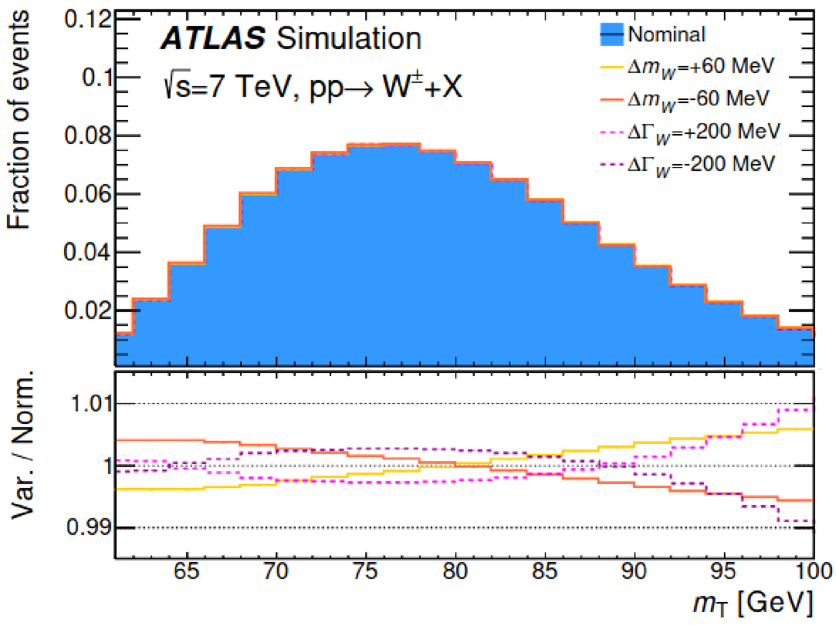
Thank you!

overflow

Updates and prospects

- ATLAS : re-analysis of 7 TeV data
- Sensitivity to the width :

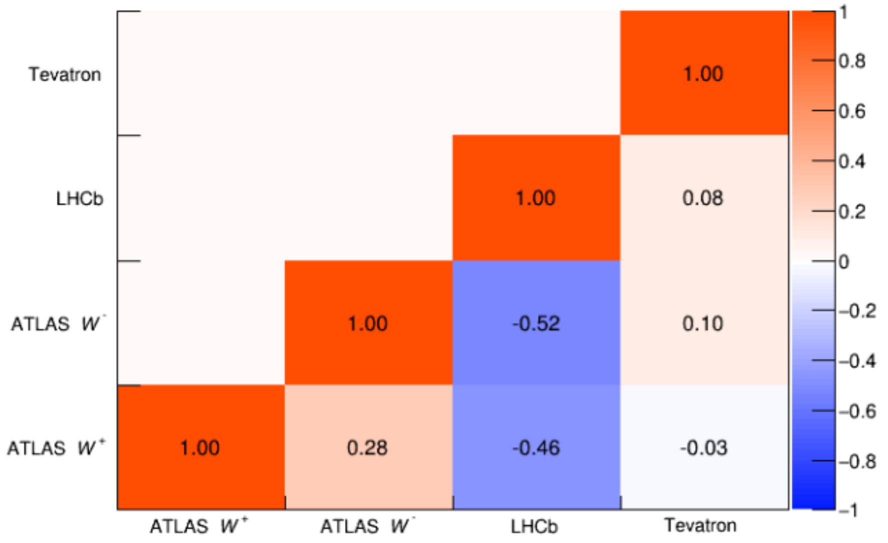




Combination

- PDF uncertainties and correlations :

PDF set	D0	CDF	ATLAS	LHCb
CTEQ6	–	14.1	–	–
CTEQ6.6	15.1	–	–	–
CT10	–	–	9.2	–
CT14	13.8	12.4	11.4	10.8
CT18	14.9	13.4	10.0	12.2
ABMP16	4.5	3.9	4.0	3.0
MMHT2014	8.8	7.7	8.8	8.0
MSHT20	9.4	8.5	7.8	6.8
NNPDF3.1	7.7	6.6	7.4	7.0
NNPDF4.0	8.6	7.7	5.3	4.1

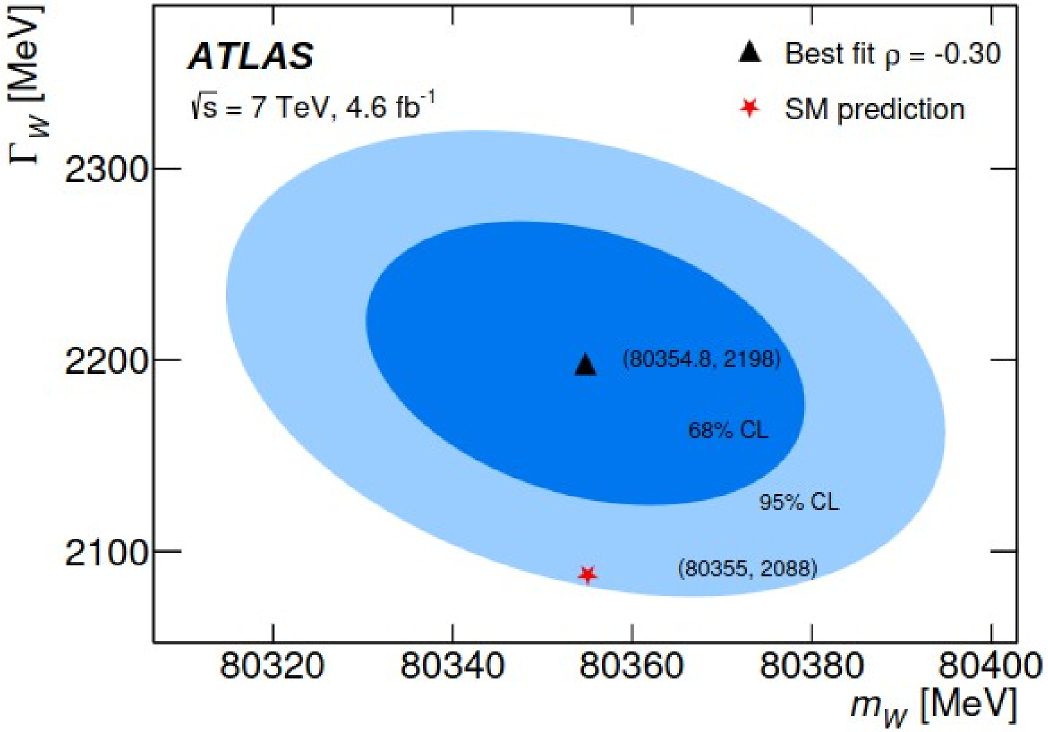


CT18

Sometime partial or negative correlations → stabilizes PDF effects on combinations

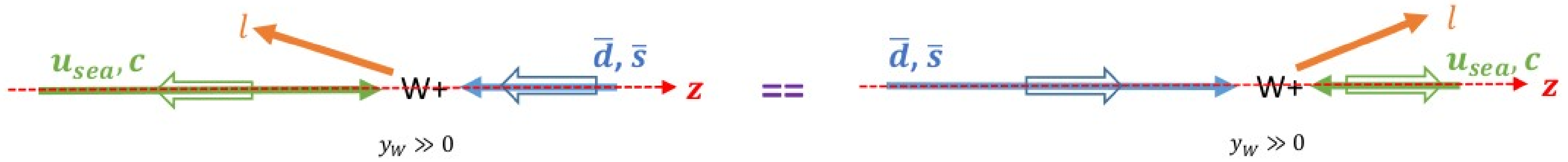
Updates and prospects

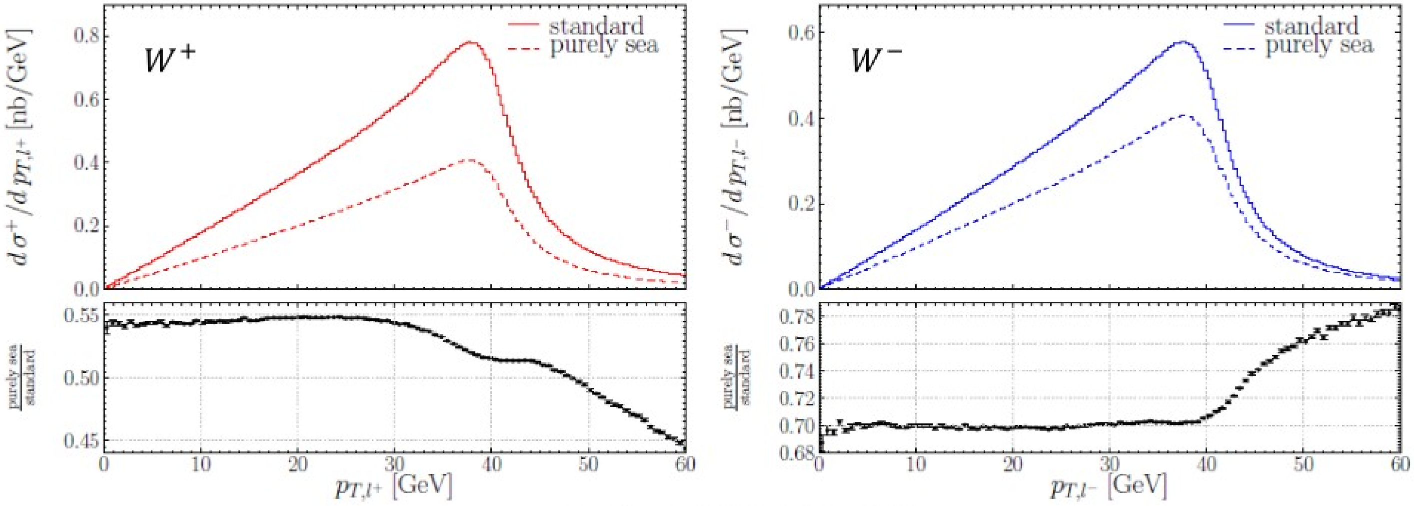
- ATLAS : re-analysis of 7 TeV data
- Results :



The W boson mass in proton collisions

- Polarization





Sea: symmetric, unpolarized

Including u_V, d_V leads to an overall polarization along z

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