The W-boson mass at the ~~$Sp\bar{p}S$~~
~~LEP~~
~~Tevatron~~
LHC

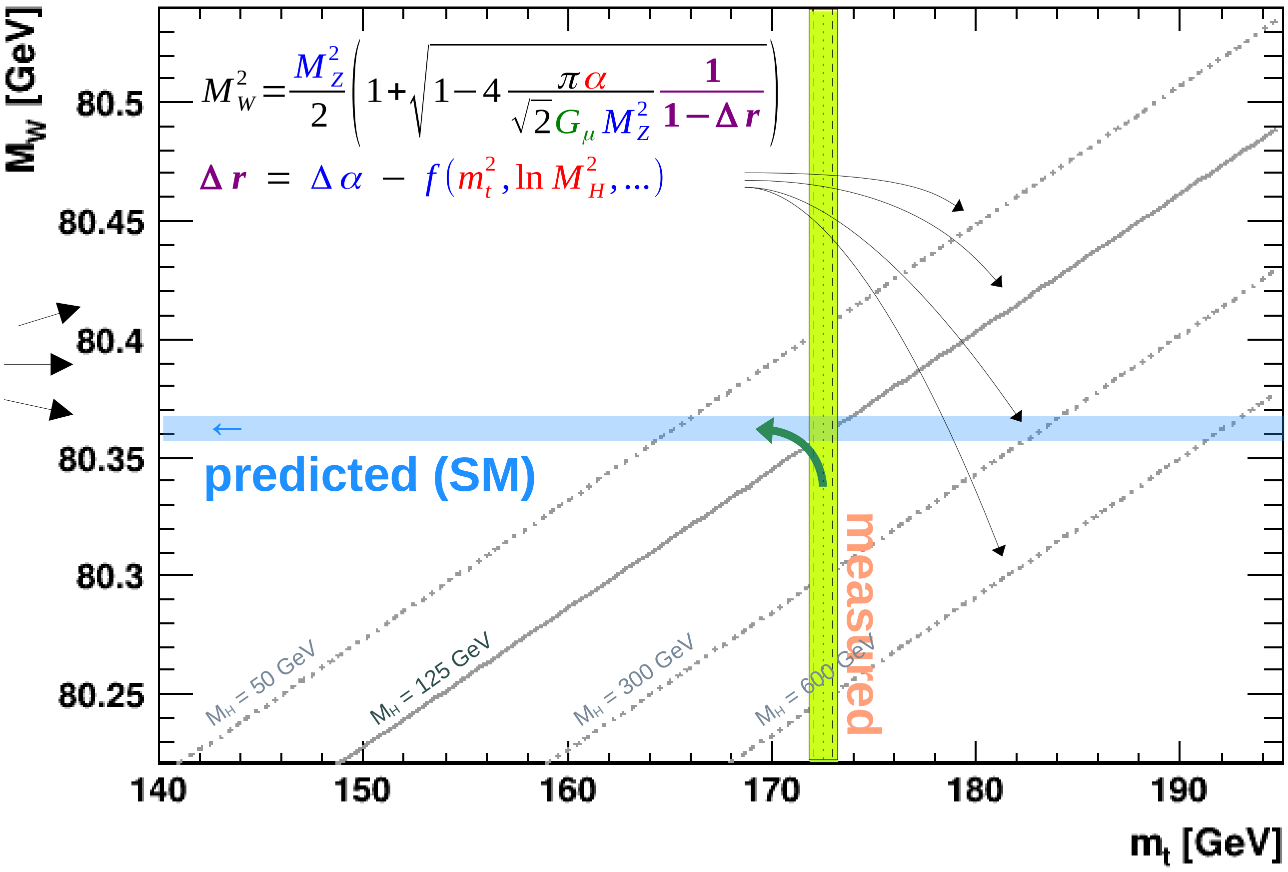
- Motivation
- W-boson production and decay
- Precision tags
- Present experimental situation
- Future

Maarten Boonekamp

Motivation

Eur. Phys. J. C78, 675 (2018)

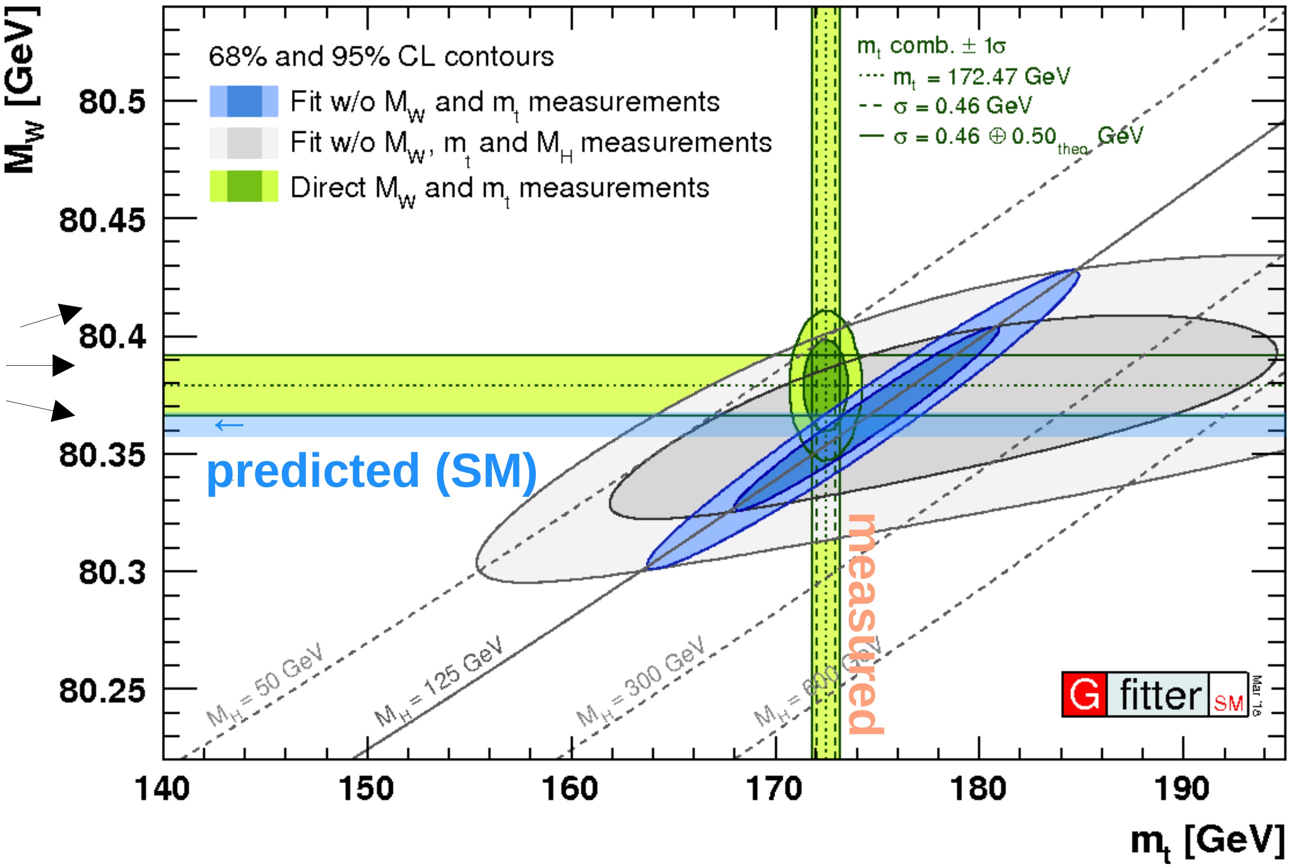
Measurement?



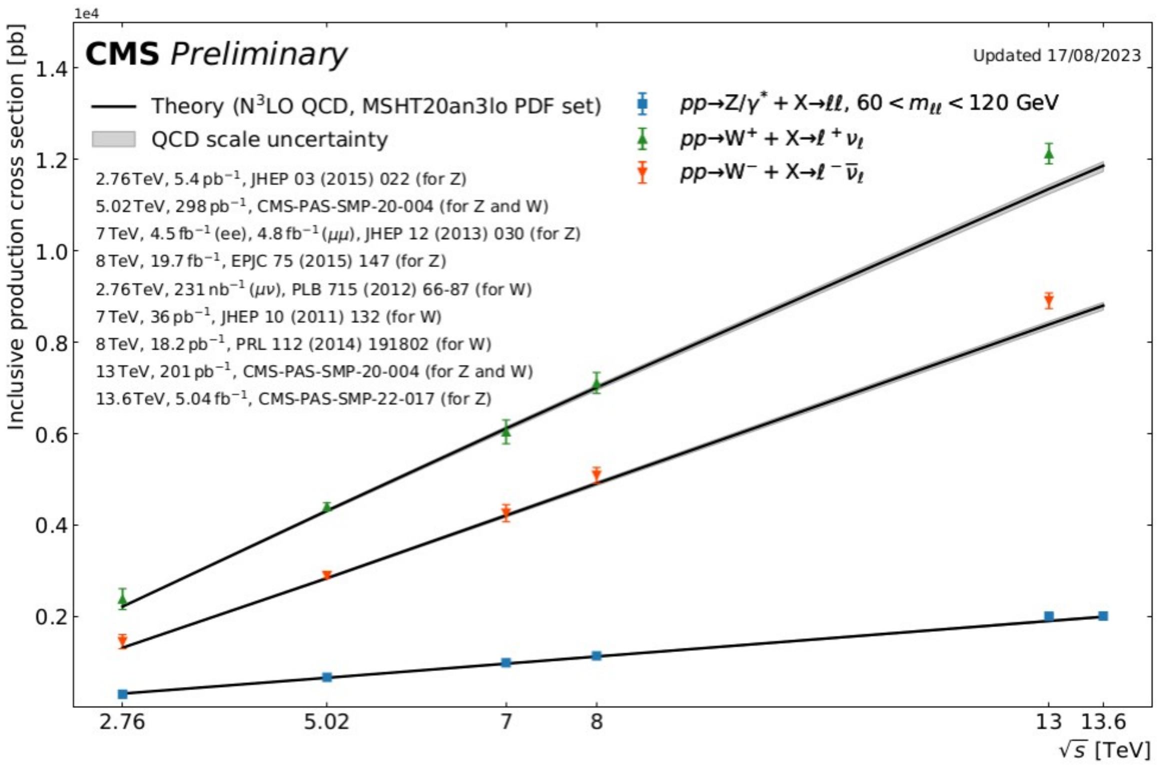
Motivation

Eur. Phys. J. C78, 675 (2018)

Measurement?



Motivation / Goals



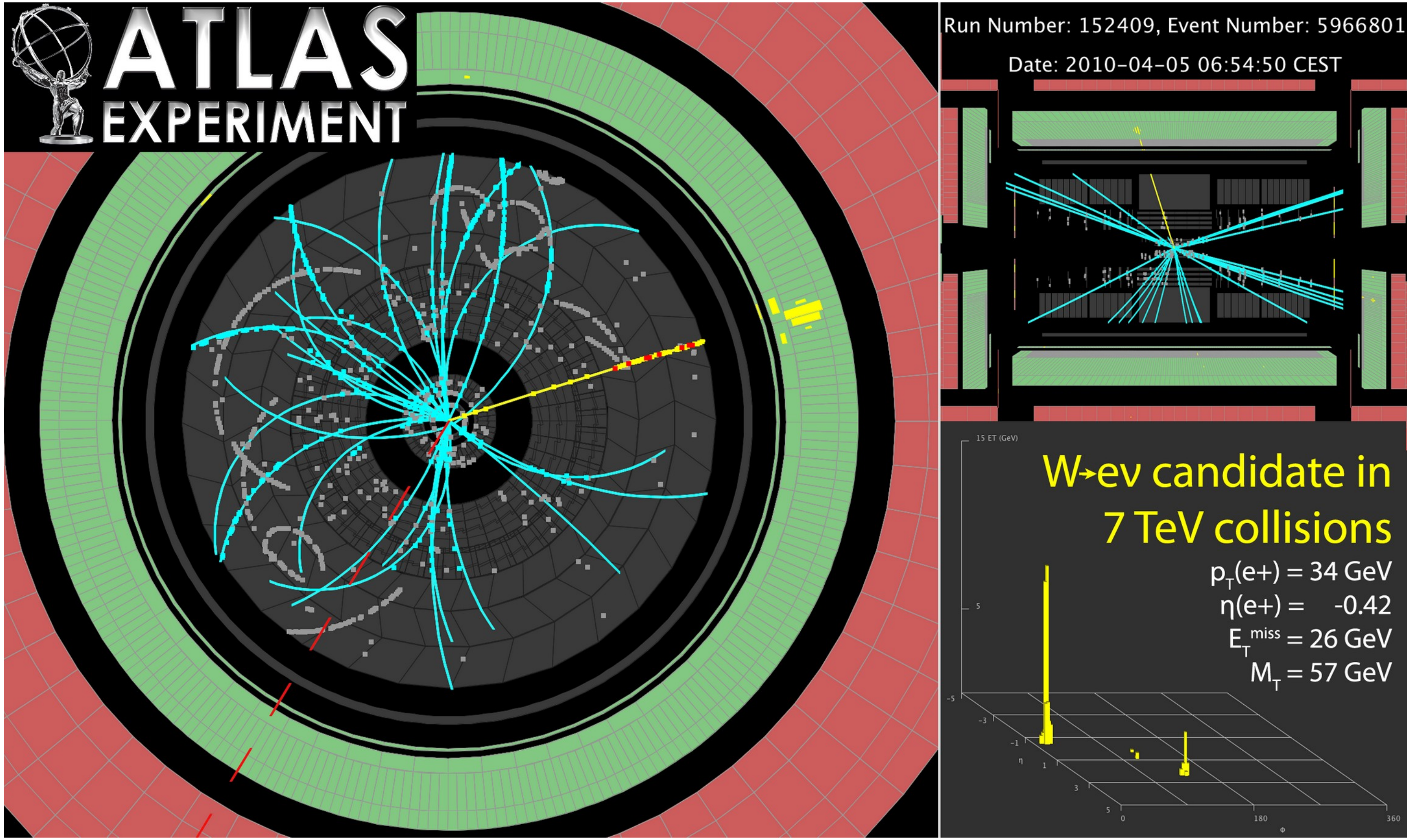
- Sensitivity

$\sigma(W \rightarrow l\nu)$	~10 nb
Acceptance	~0.1
L_{int}	~10 fb^{-1}
RMS(m_T, p_T^l)	~20 GeV

→ σ_{stat} ~ 5 MeV, ~0.005%

→ Aim for 0.01%, incl. Systematics
→ δm_W < 10 MeV

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

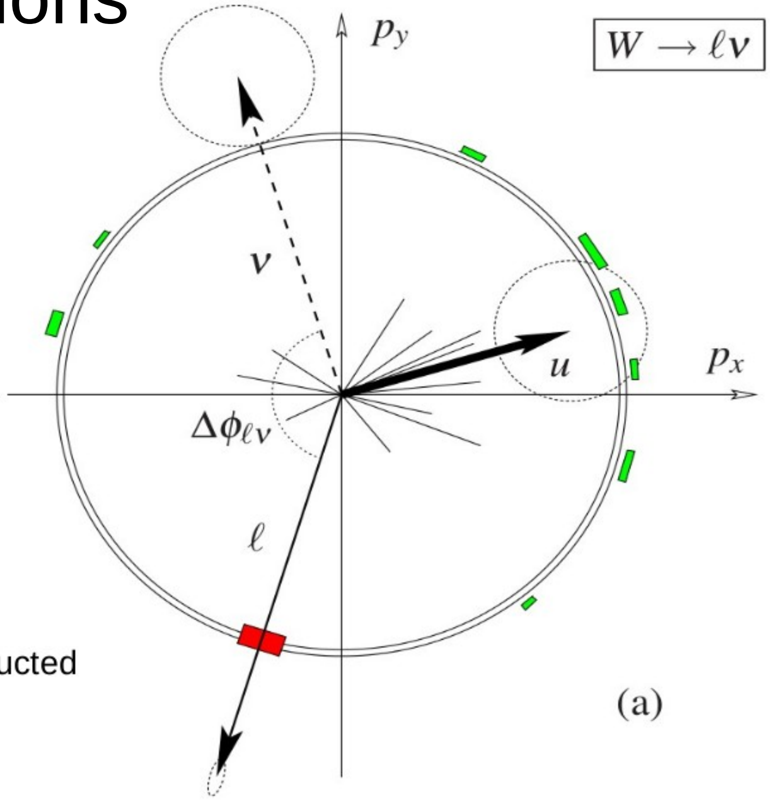
- Event representation :

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

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

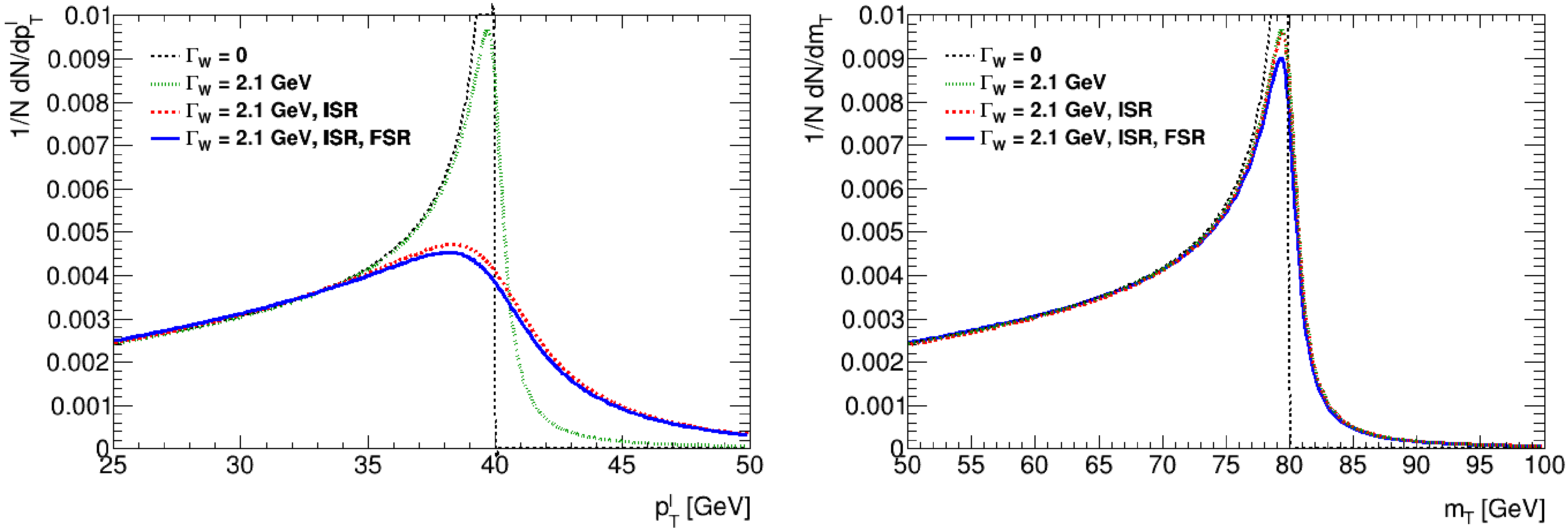
    $$\vec{u}_T = \sum_i \vec{E}_{T,i}$$

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



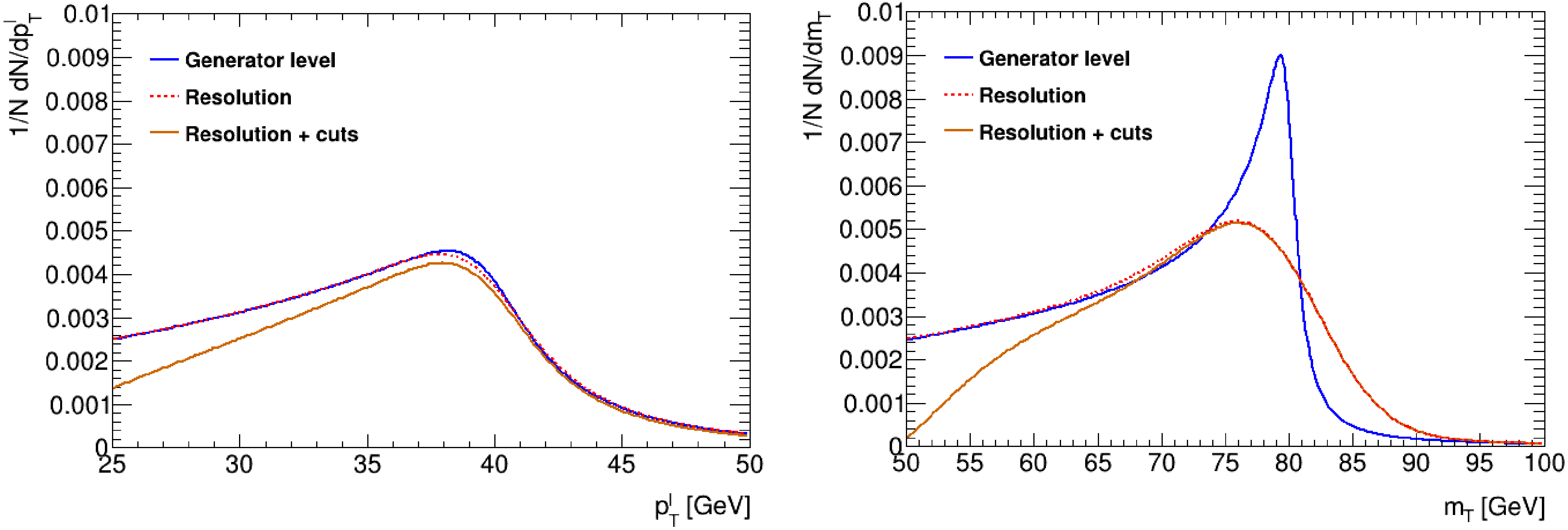
Kinematic distributions

- QCD & QED effects – all with uncertainties, to be quantified



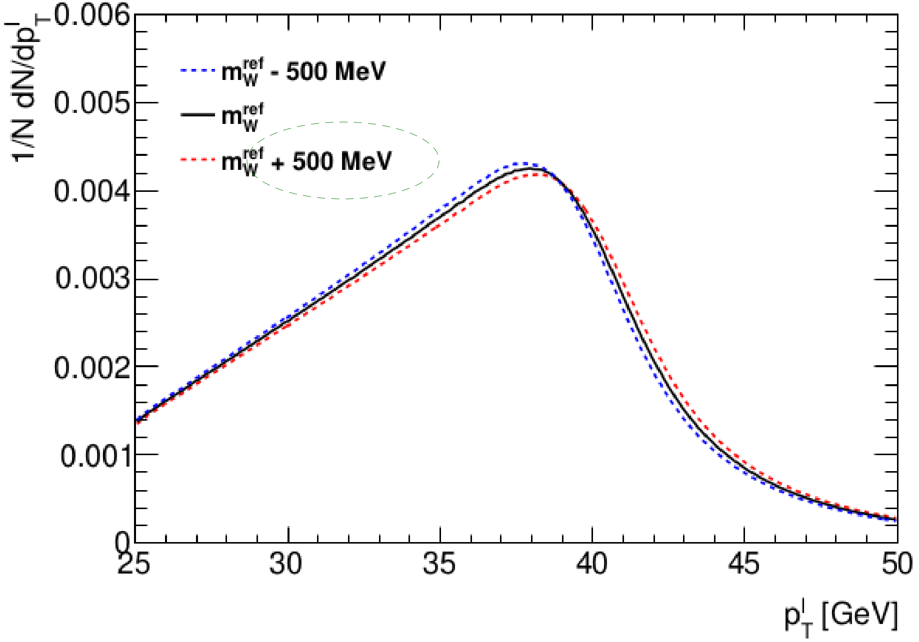
Kinematic distributions

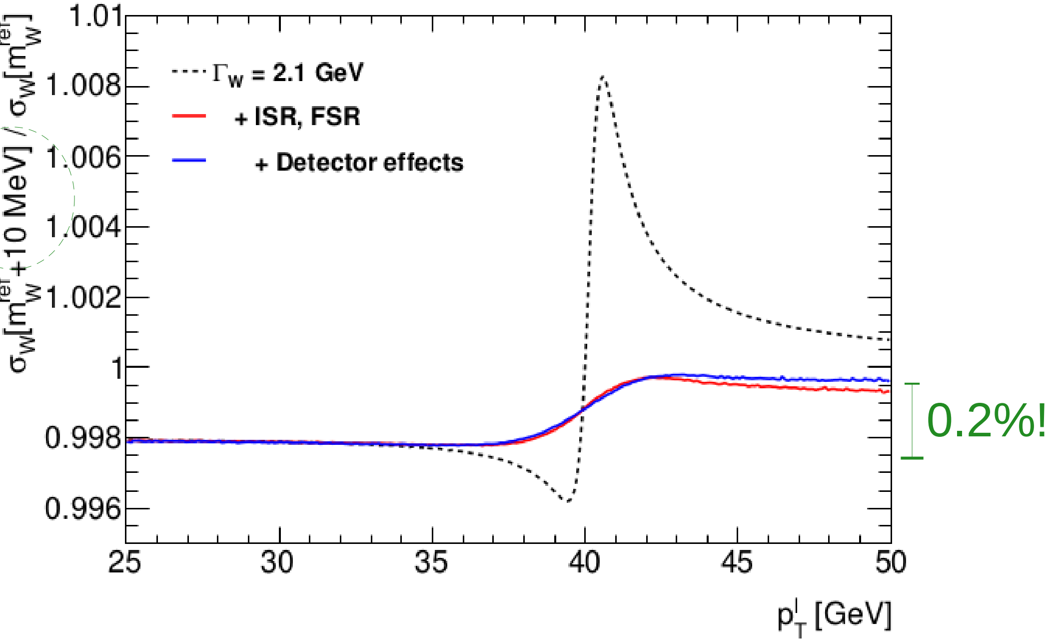
- QCD & QED effects – all with uncertainties, to be quantified
- Detector effects, also with uncertainties :
  - Lepton calibration ~10^{-4}; Recoil resolution ~ 5 – 15 GeV; acceptance ~15%



Sensitivity to m_W

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





Lepton calibration

- Leptons calibration from "perfectly known" resonances

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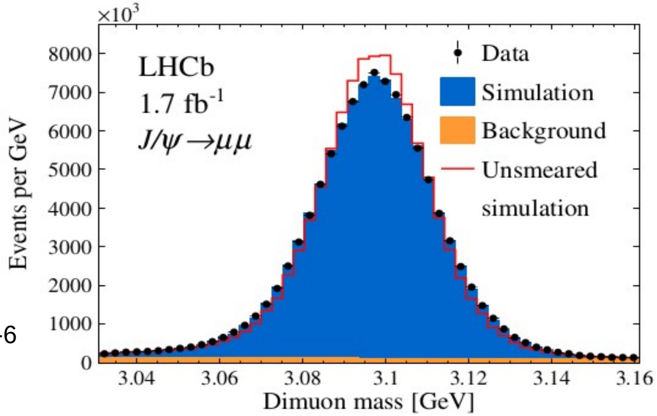
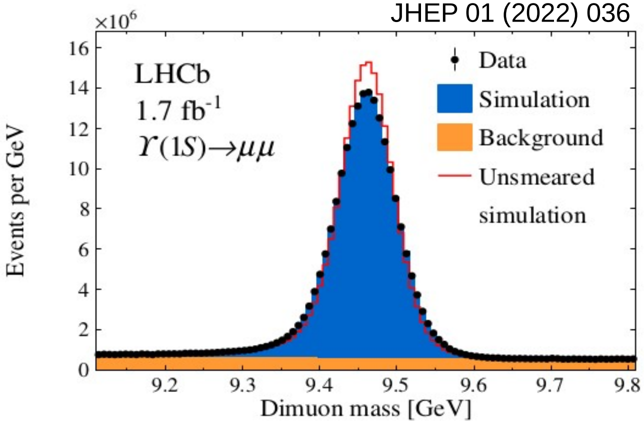
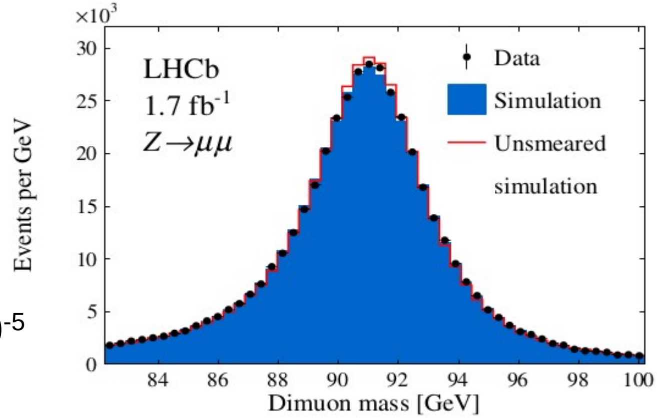


$\delta m_{J/psi} / m_{J/psi} \sim 10^{-6}$

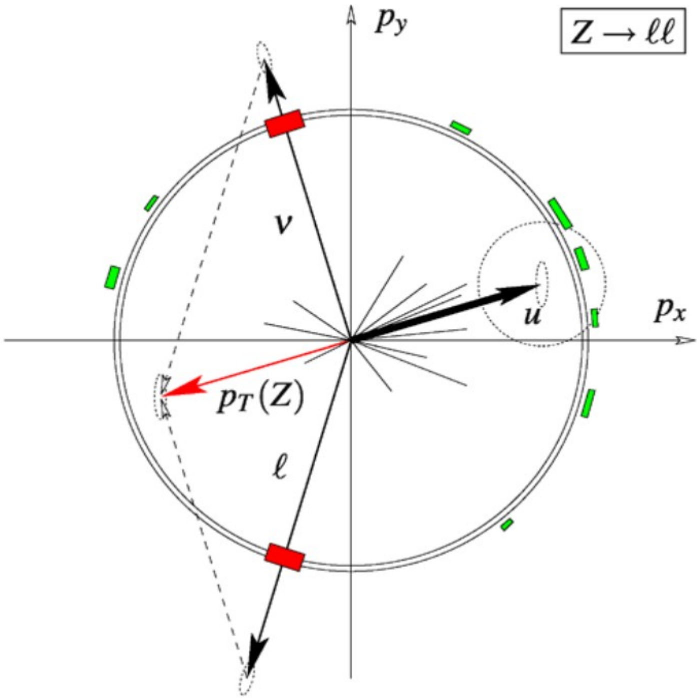


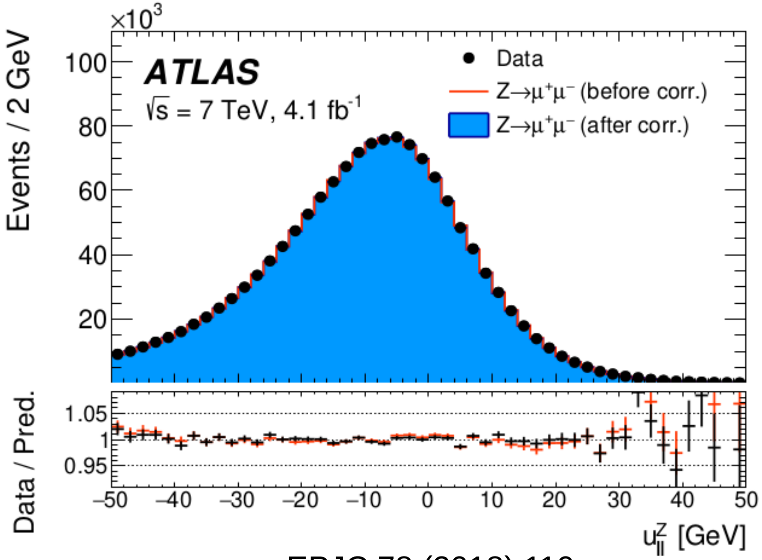


$\delta m_Z / m_Z \sim 2.10^{-5}$

Recoil calibration

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





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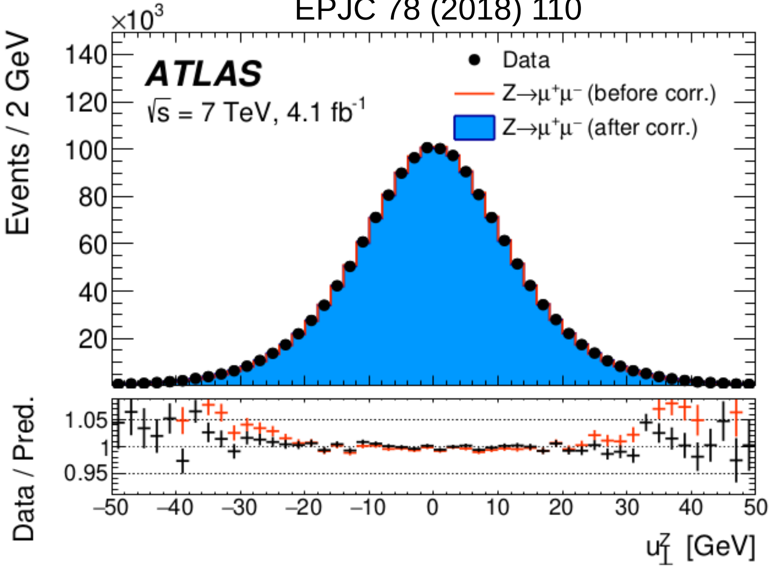
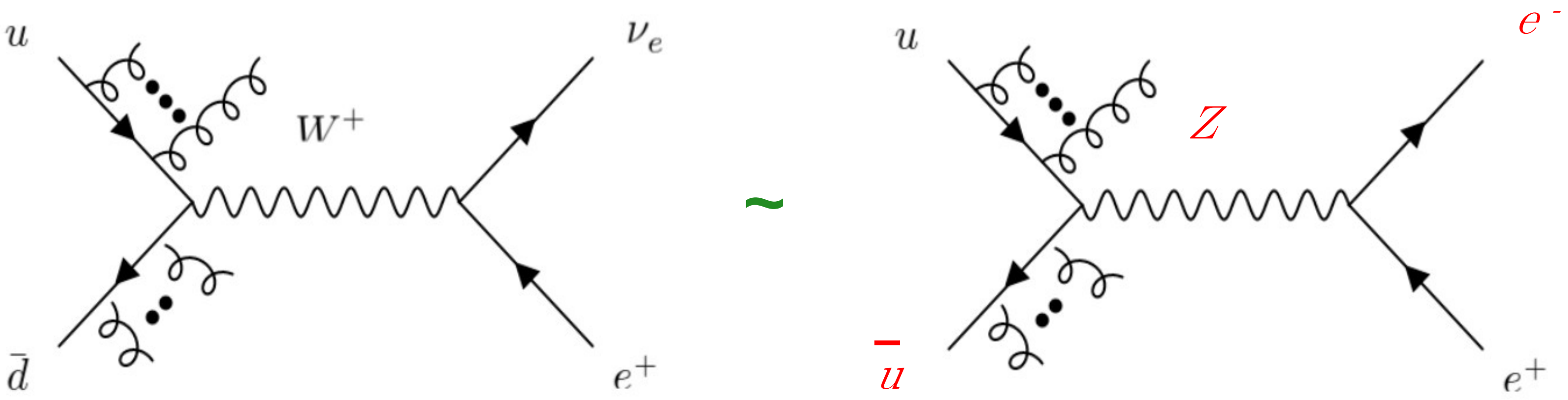


Transverse momentum distribution

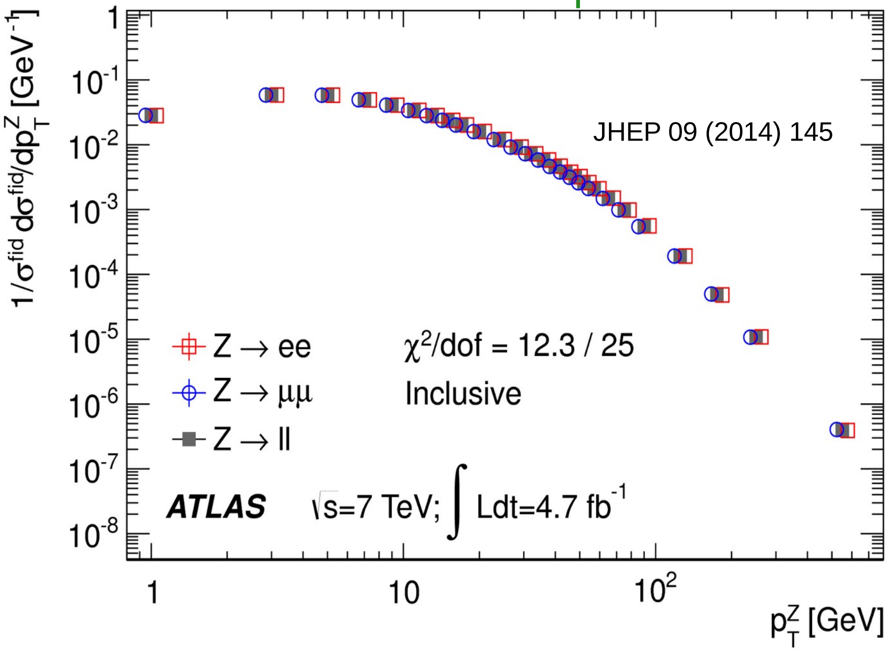
- Initial state radiation involves large corrections, and is in part non-perturbative. W events are only partly measured (neutrino!)
- Approach : adjust model parameters using Z events, which are close to W's and can be measured precisely; extrapolate to W production

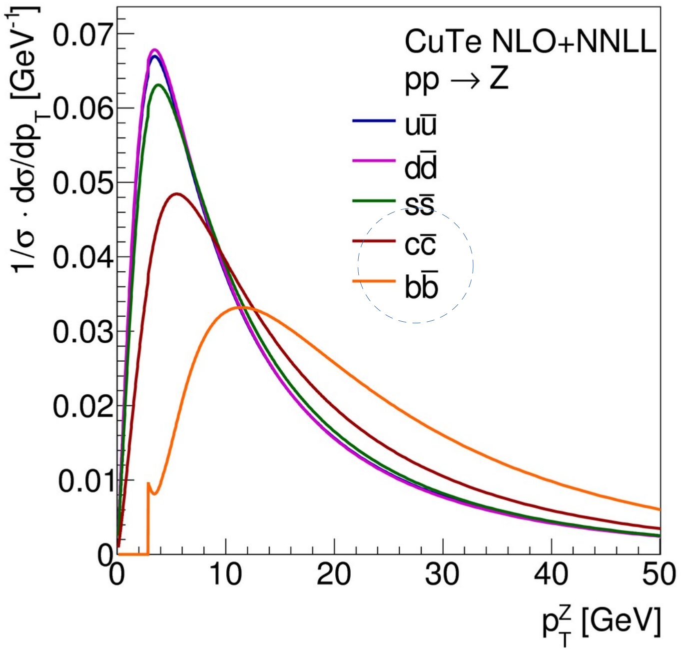


Transverse momentum distribution

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

Measurement precision ~0.5%





ATLAS measurement : $\sqrt{s}$=7 TeV; ~4.6 fb^{-1}

- Lepton distributions:

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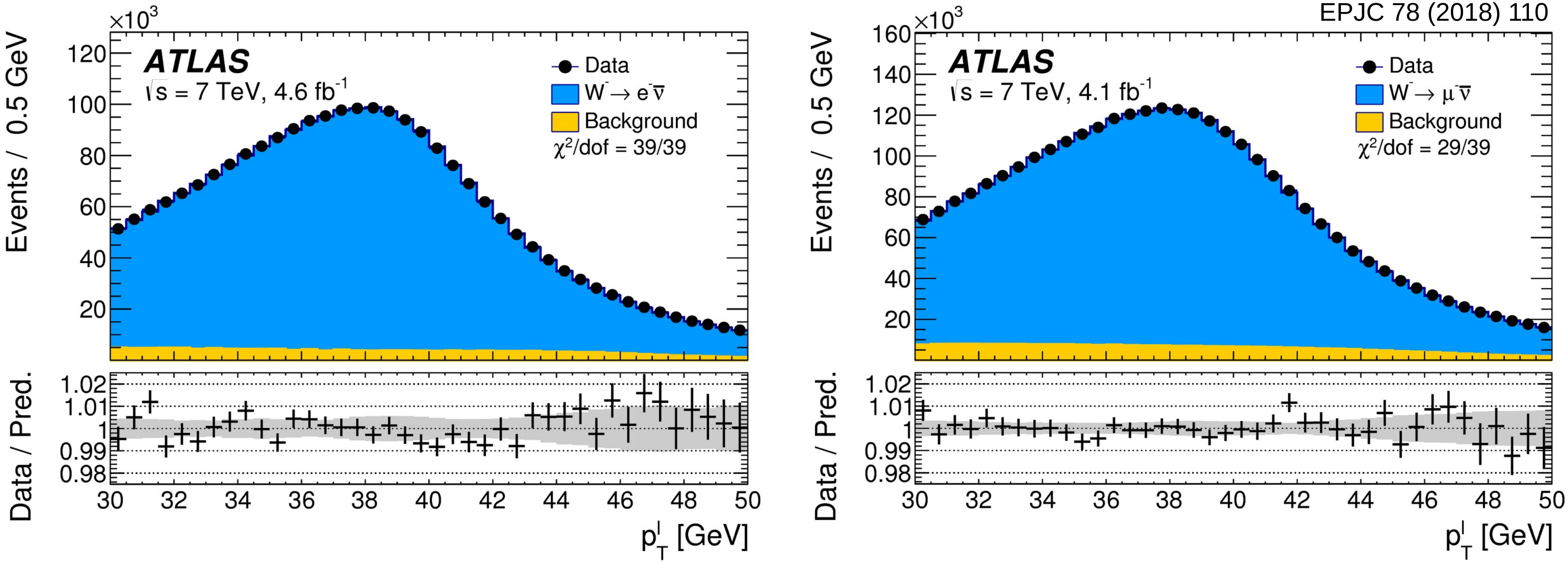

m_W = 80370 ± 7 (stat.) ± 18 (sys.) MeV

ATLAS measurement : $\sqrt{s}$=7 TeV; ~4.6 fb^{-1}

- Transverse mass :

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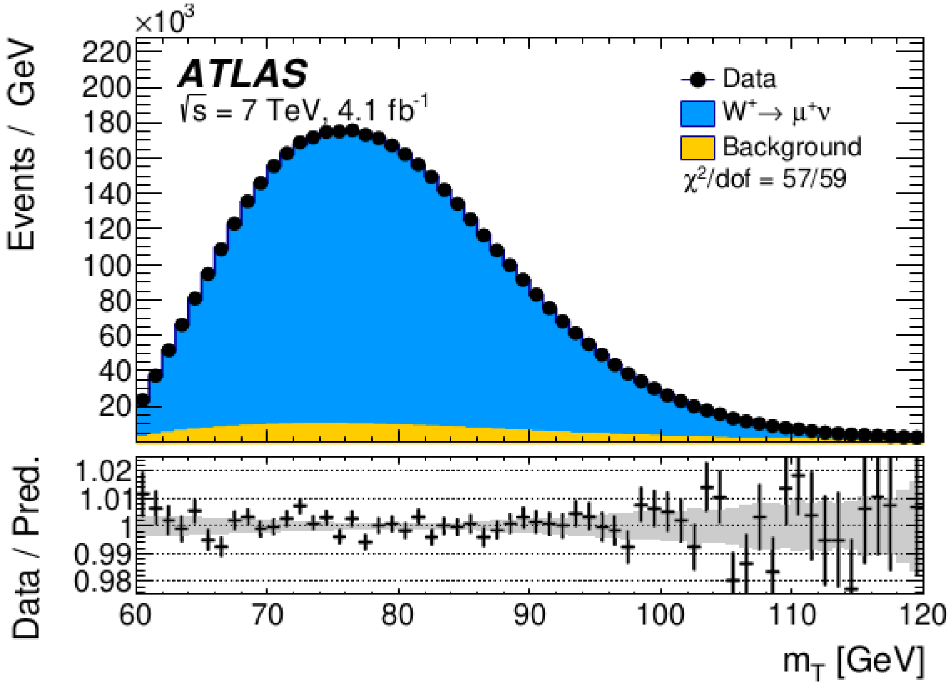

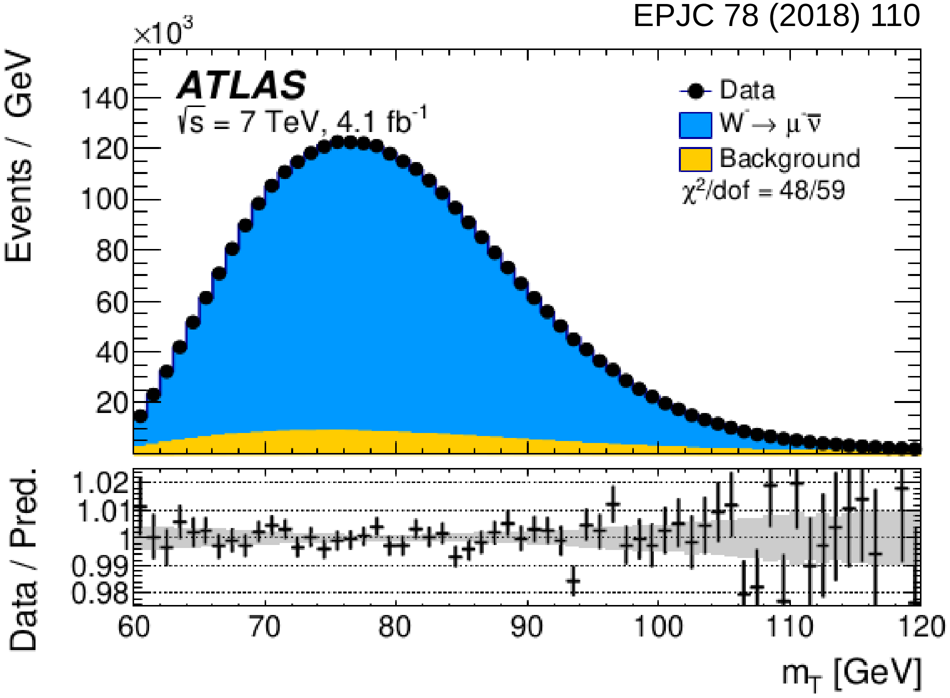

m_W = 80370 ± 7 (stat.) ± 18 (sys.) MeV

A look back..

- Final measurement by UA2 :

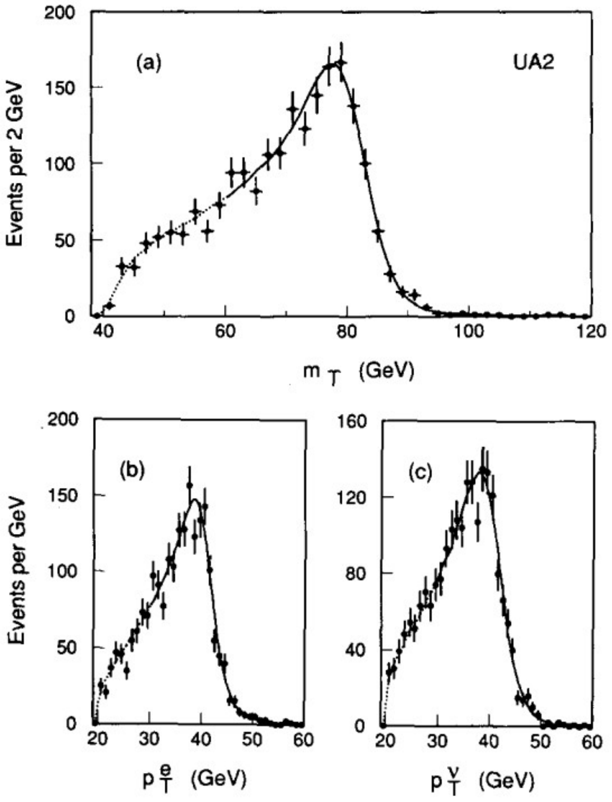

Table 3
The size (in MeV) of the systematic uncertainties in measuring m_W and m_Z.

	$\delta m_W(m_T)$	$\delta m_W(p_T^e)$	$\delta m_W(p_T^\nu)$	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

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

Transverse momentum distribution

- **LHCb** :
  - No recoil measurement!
  - Z data : p_T^Z, ϕ^*
  - simultaneous fits to m_W and p_T^W in W events
  - repeated for different models:
    - Pythia, Herwig
    - Powheg+Pythia, Herwig
    - Dyturbo

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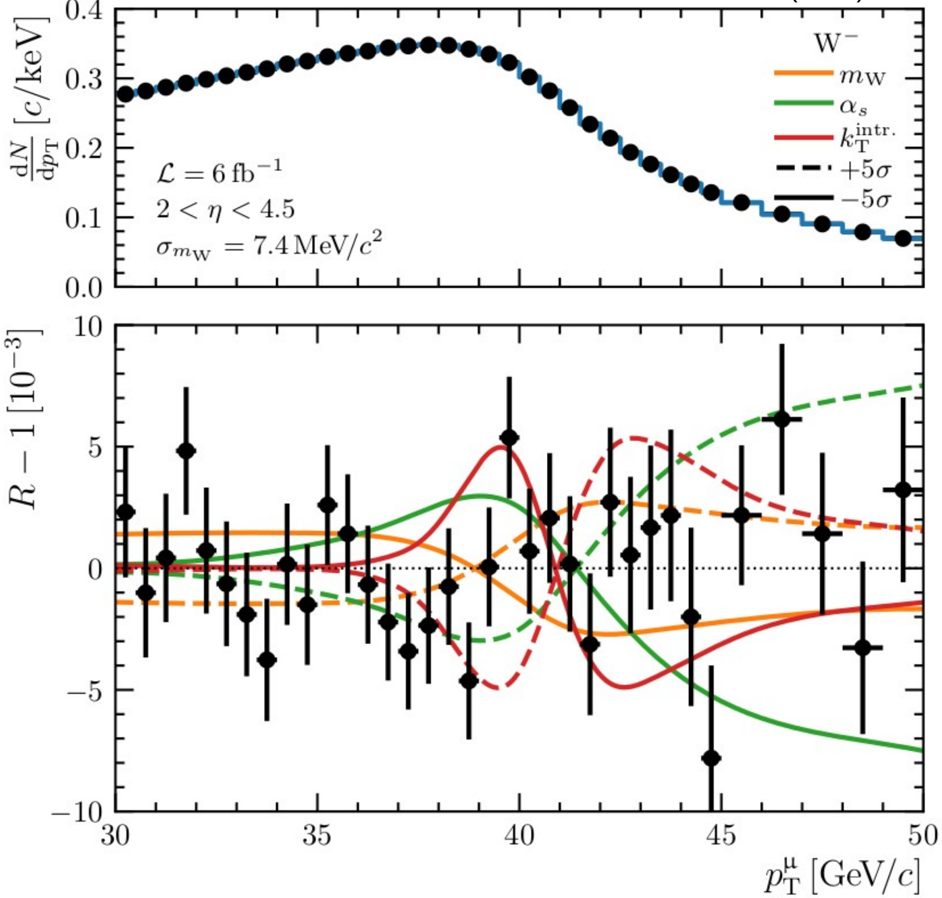

LHCb measurement : $\sqrt{s}$=13 TeV; ~1.7 fb^{-1}

- LHCb

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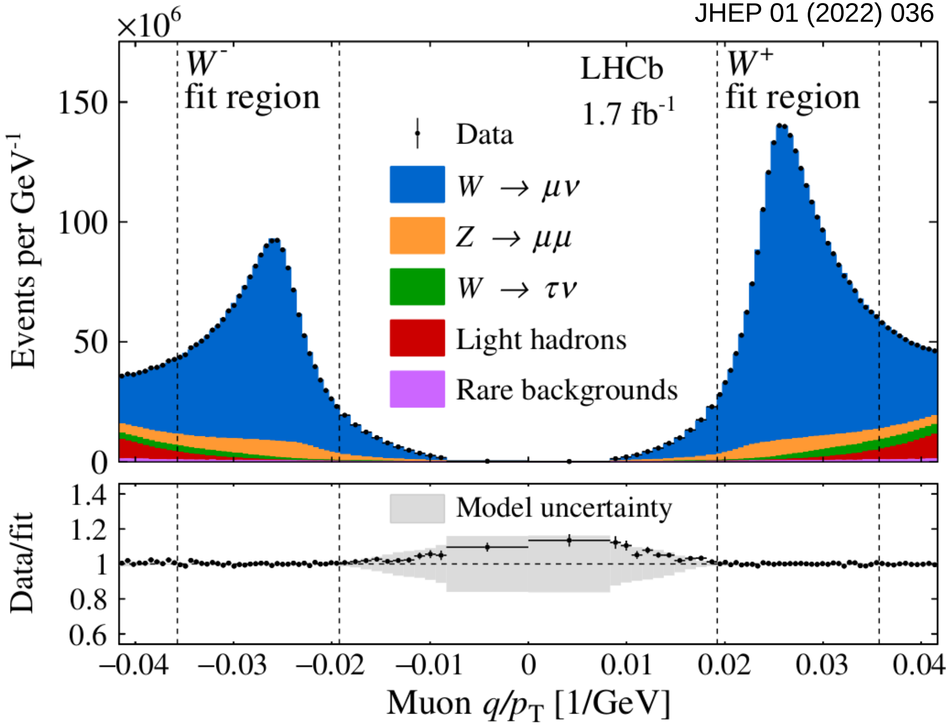
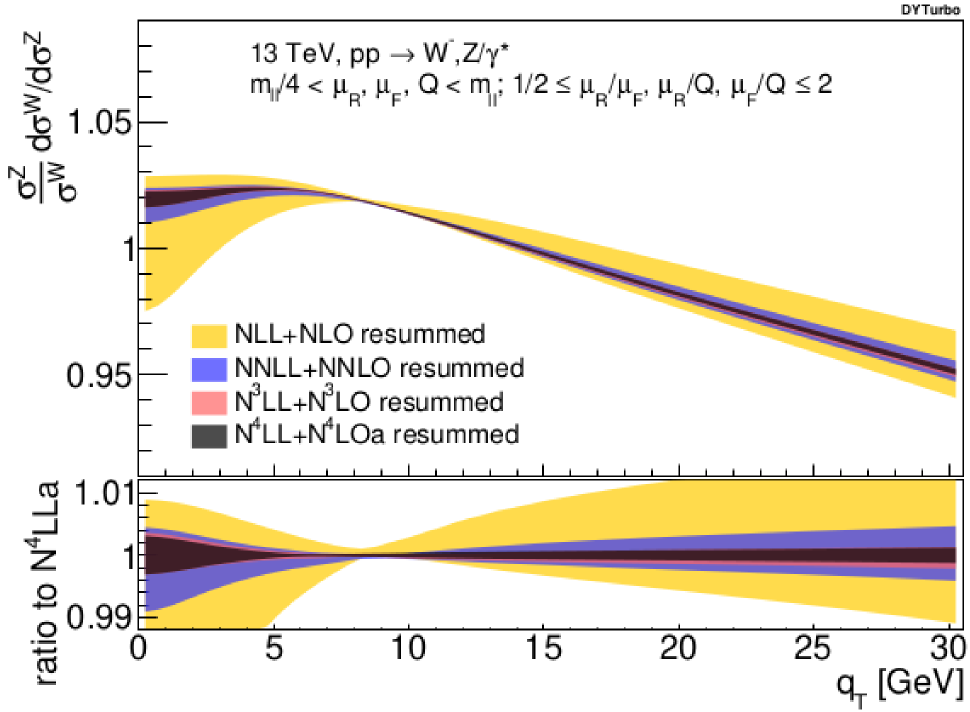


$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}.$$

Theory developments

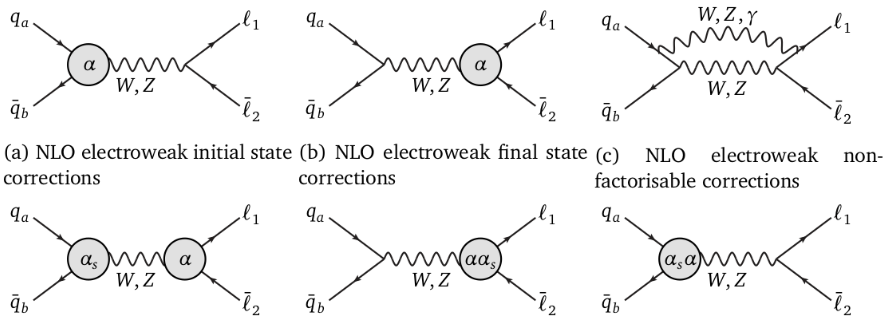
- QCD & p_T resummation

Phys.Lett.B 845 (2023) 138125 + Refs.



- QCD x EW corrections

SciPost Phys. Proc. 7, 003 (2022) + Refs.



(a) NLO electroweak initial state corrections (b) NLO electroweak final state corrections (c) NLO electroweak non-factorisable corrections

δm_W [MeV]		$\mu = m_V/4$	$\mu = m_V/2$	$\mu = m_V$
Inclusive	NLO EW	−0.1	0.3	0.2
	QCD-EW	−5.1	−7.5	−9.3
Fiducial	NLO EW	0.2	2.3	4.2
	QCD-EW	−16	−17	−19
Tuned fiducial	NLO EW	−4.4	−2.5	−0.8
	QCD-EW	3.9	−1.0	−5.7

M_W : present experimental situation

- At hadron colliders :

D0 (4.3+1.1 fb^{-1}) [*Phys. Rev.* ***D89*** *(2014) 012005*]

m_W = 80375 ± 11 (stat.) ± 20 (sys.) MeV

CDF (8.8 fb^{-1}) [*Science* ***376*** *(2022) 170*]

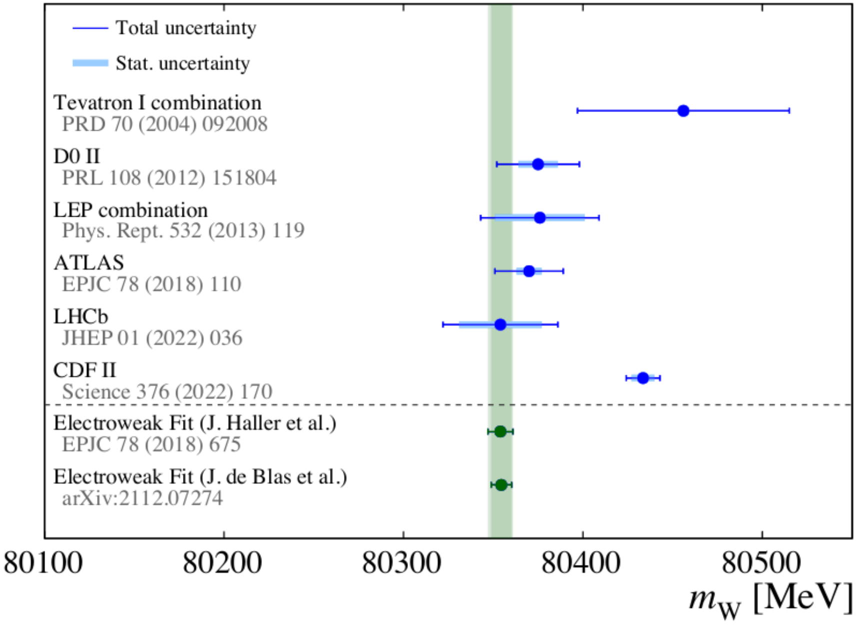
m_W = 80433.5 ± 6.4 (stat.) ± 6.9 (sys.) MeV

ATLAS (4.6 fb^{-1}) [*Eur. Phys. J.* ***C78*** *(2018) 110*]

m_W = 80370 ± 7 (stat.) ± 18 (sys.) MeV

LHCb (1.7 fb^{-1}) [*JHEP* ***01*** *(2022) 036*]

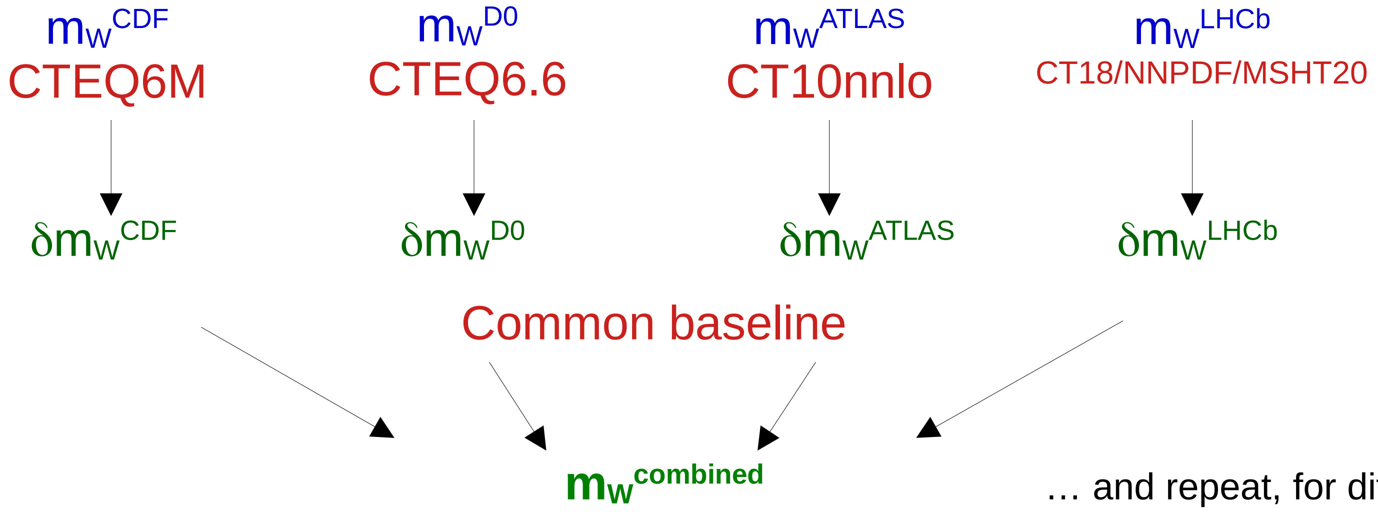
m_W = 80354 ± 23 (stat.) ± 22 (sys.) MeV



- LEP legacy : m_W = 80376 ± 33 MeV

Measurement comparisons and combinations

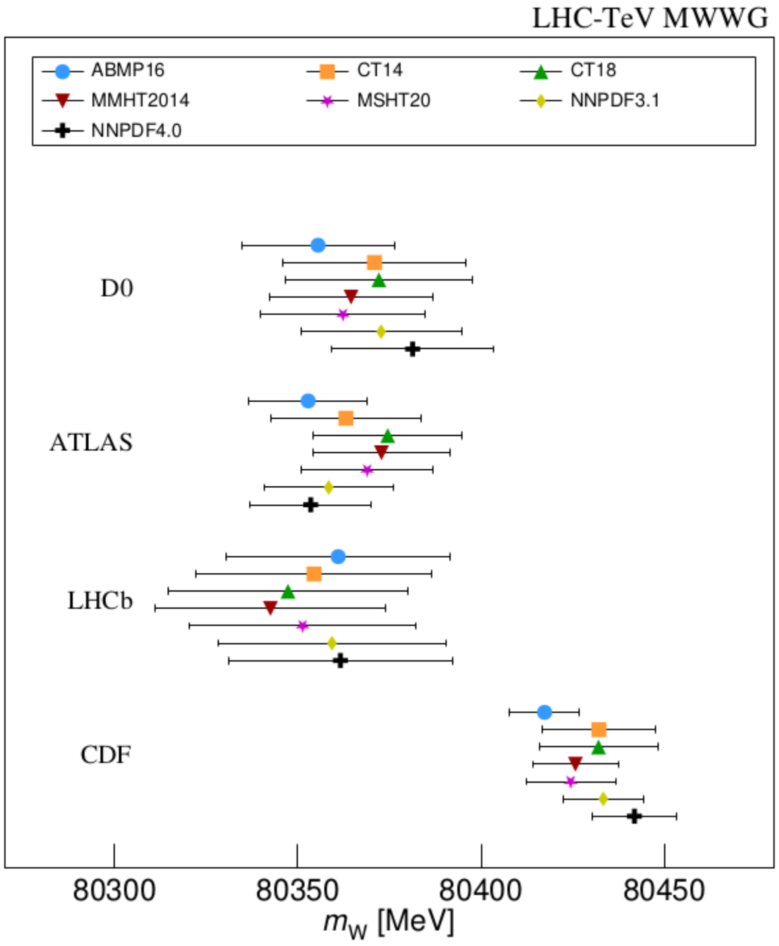
- Measurements performed at different times, using different baseline PDFs and QCD tools : “translate” existing result to common baseline
- Two-step procedure :
  - correct to common PDF & QCD accuracy
  - combination including correlations



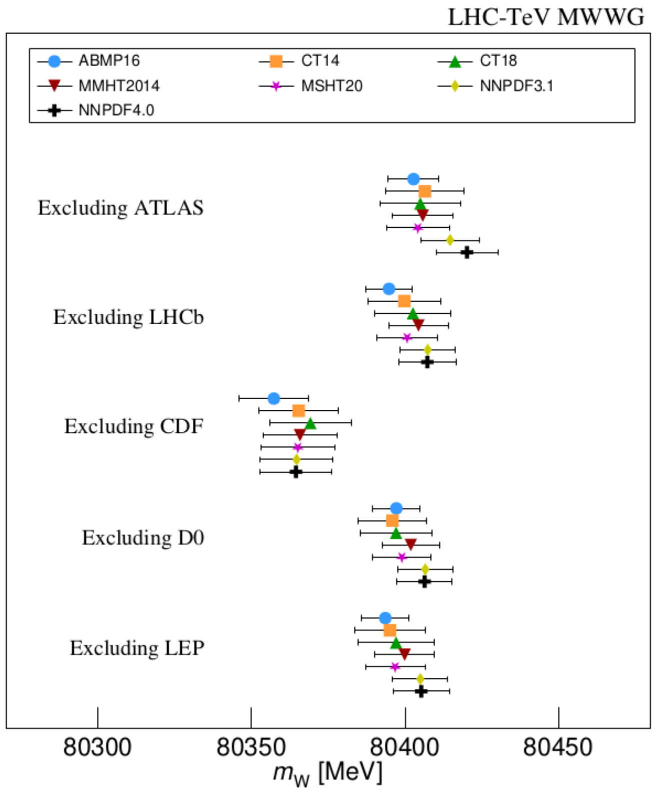
… and repeat, for different PDFs

PDF dependence of LHC & Tevatron results

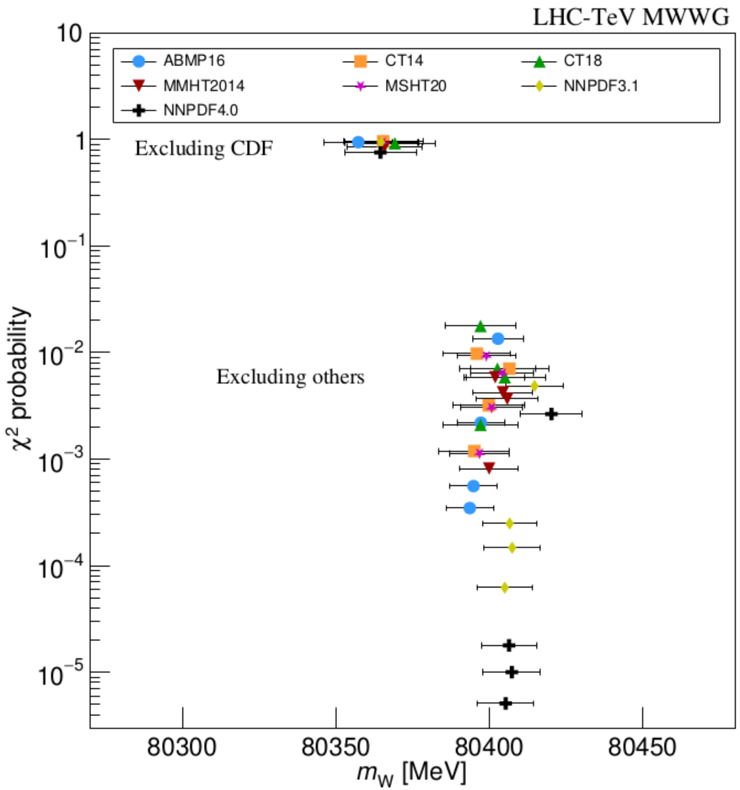
- Effects generally significant compared to quoted PDF uncertainties
- To be accounted for, when comparing measurements
- Partial or even negative correlations across colliders : combinations may help stabilise such effects



Results



LHC-TeV MWWG
ABMP16
CT14
CT18
MMHT2014
MSHT20
NNPDF3.1
NNPDF4.0
Excluding ATLAS
Excluding LHCb
Excluding CDF
Excluding D0
Excluding LEP
80300
80350
80400
80450
m_W [MeV]



LHC-TeV MWWG
ABMP16
CT14
CT18
MMHT2014
MSHT20
NNPDF3.1
NNPDF4.0
Excluding CDF
Excluding others
χ^2 probability
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
80300
80350
80400
80450
m_W [MeV]

Combinations - summary

- Full world average has a p-value of 0.5% and can not be recommended
- CDF result : m_W = 80433.5 ± 6.4 (stat) ± 6.9 (syst) MeV.
- Average of all measurements except CDF :

  m_W = 80369.2 ± 13.3 MeV P(χ^2) = 91%

  - PDF envelope 5 MeV, reduced to partial or negative correlations – good!
  - An important positive result : D0, LHCb, ATLAS are all hadron-collider measurement, but experimental conditions are a different as can be

- New, independent measurements required to clarify the picture.

Back to page 1…

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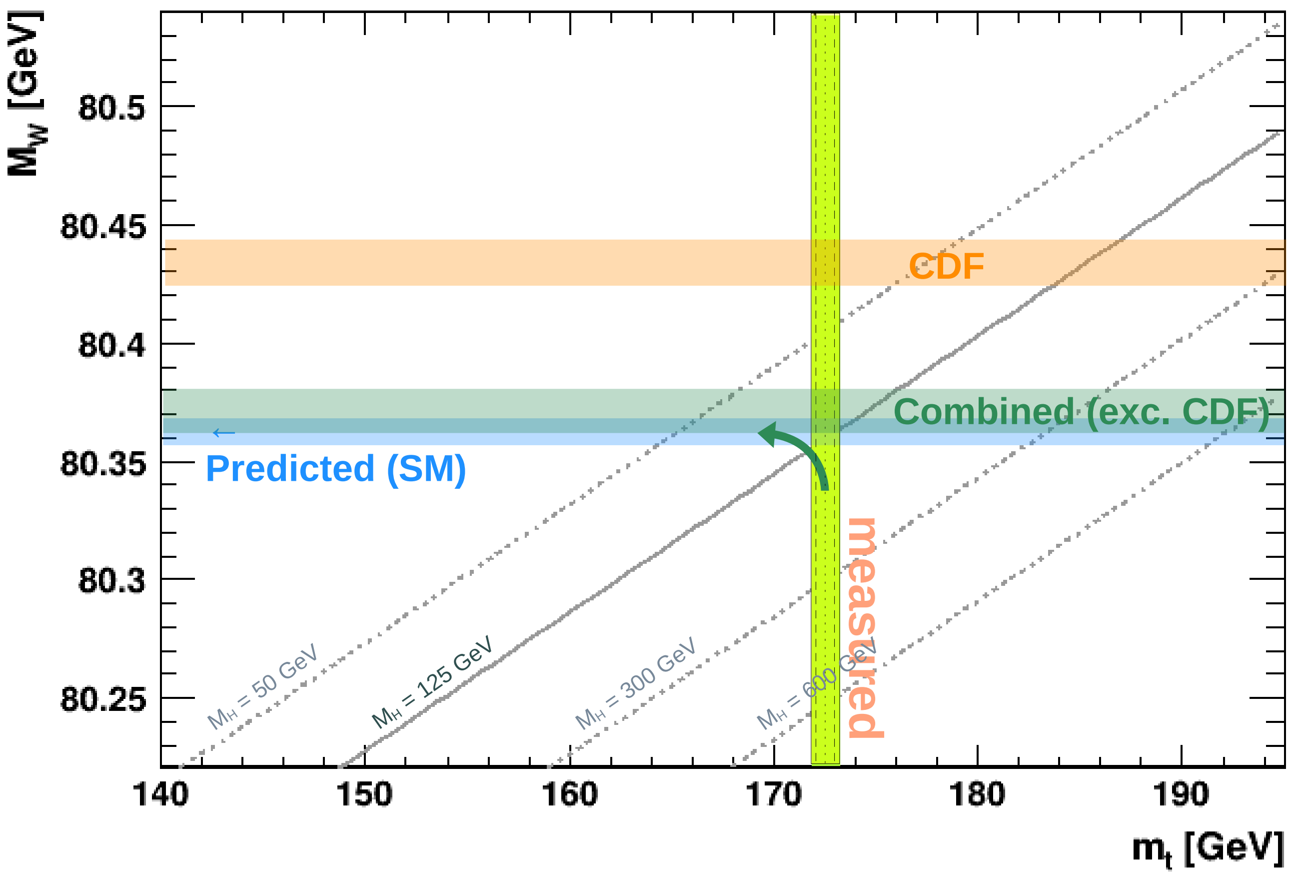
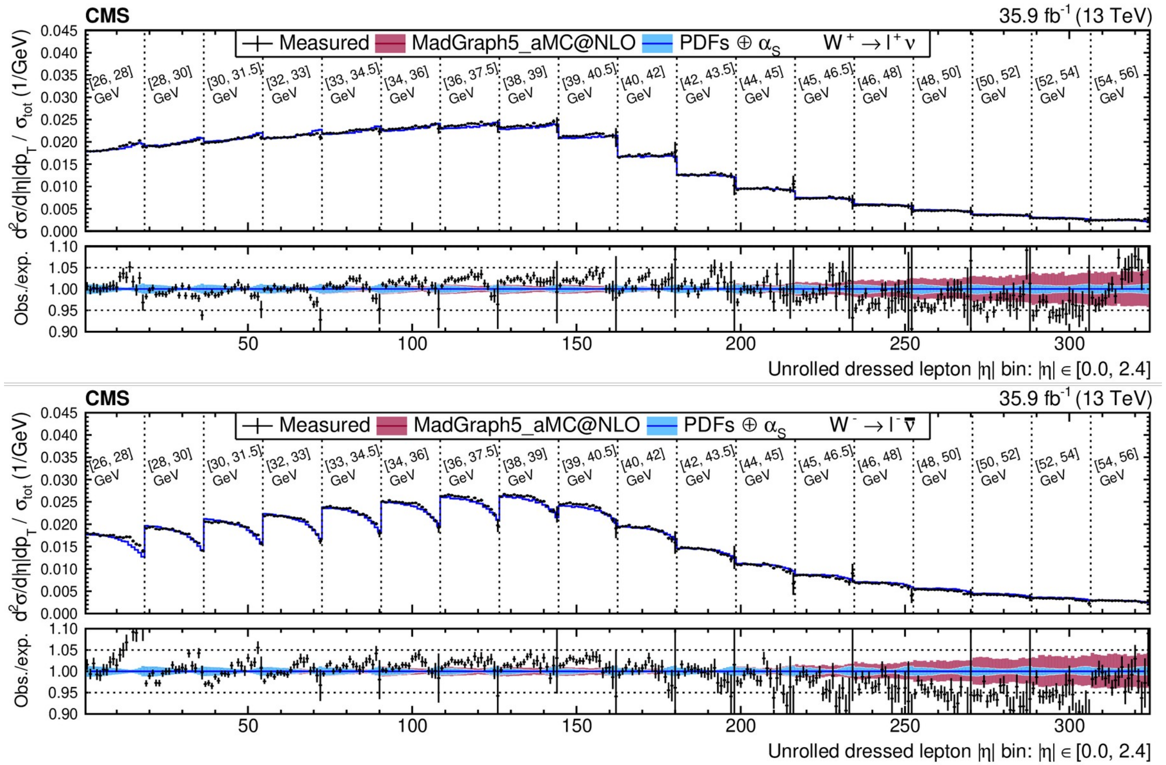


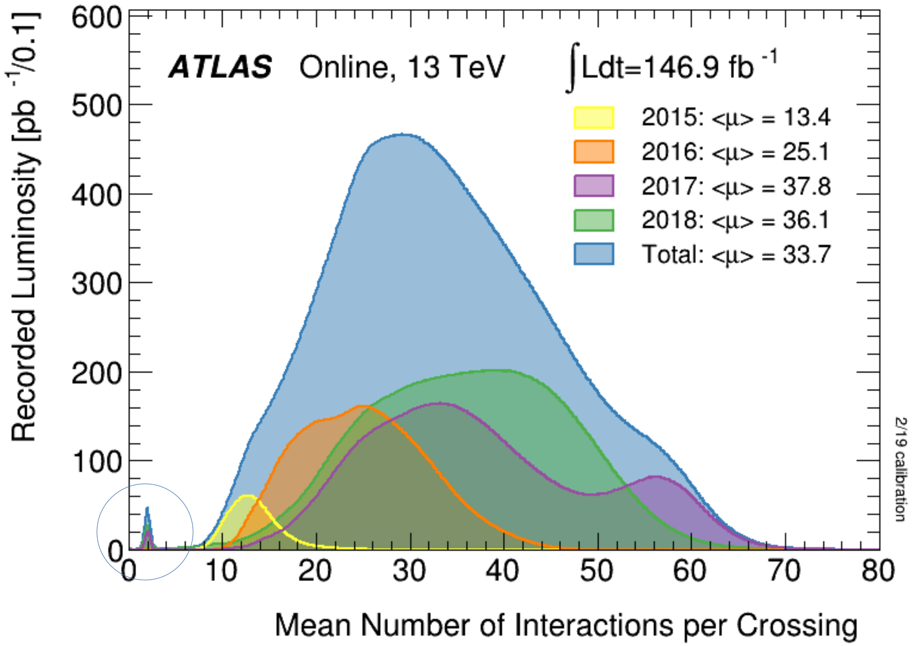
Future

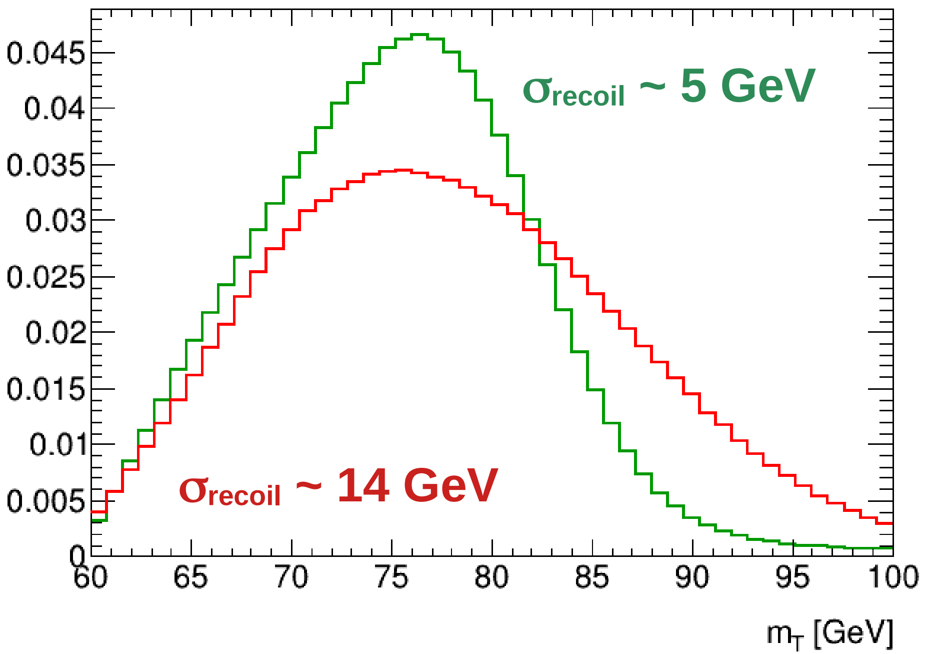
- CMS : extensive (p_T^l,η_l) cross section measurement, 36 fb^{-1} @ 13 TeV
  - first step towards m_W; analysis with O(10^8) signal events (!)



Future

- ATLAS





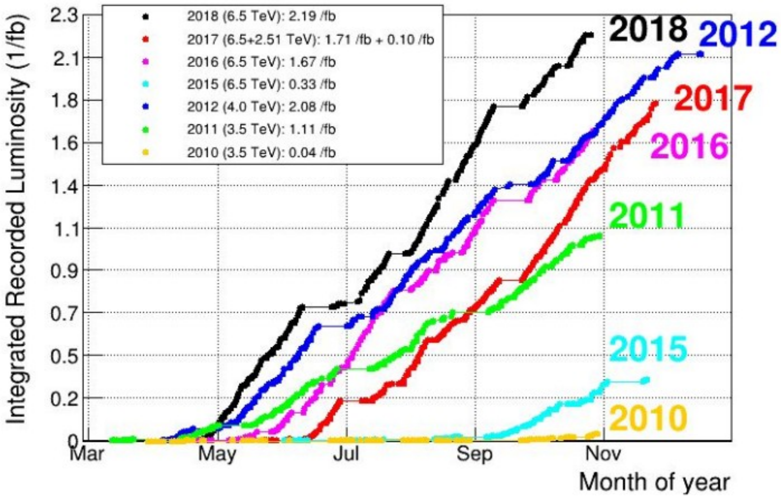
Future

- LHCb

(mWdays'23)

Expected sensitivity for the full Run 2 analysis

- We expect to reduce the overall experimental uncertainty to ~14 MeV
- The systematic uncertainties increase their relevance:
  - A more careful treatment of the detector effects must be adopted
  - Improvements in the physics modelling become crucial



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

(2016 result) [JHEP 01 (2022) 036]

Conclusions

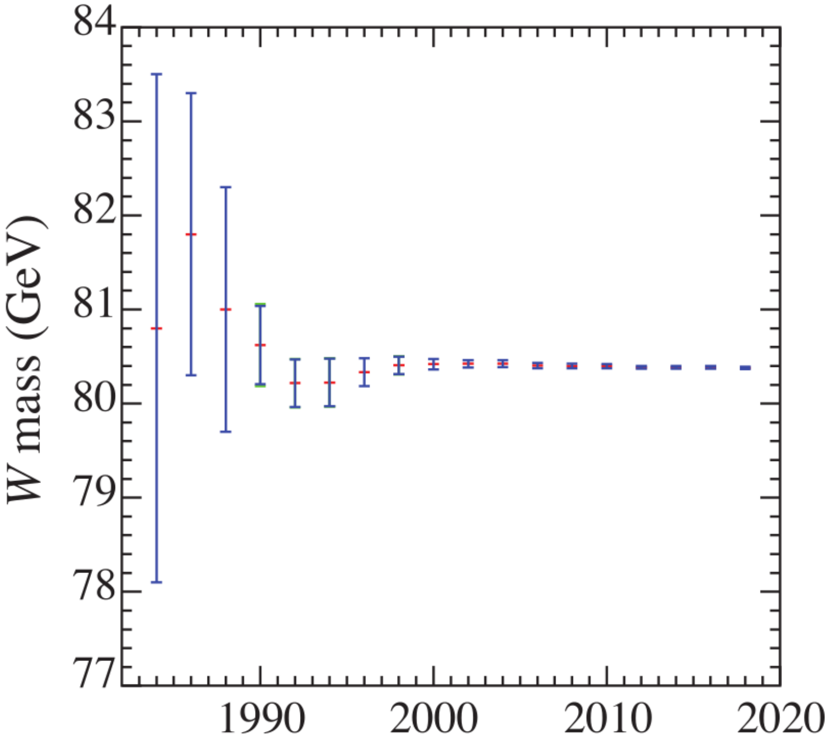
- Measurements of m_W already have a long history.

  At hadron colliders, concepts developed in the early 90's still fly!

- Model dependence needs to be kept under control
  - Theory developments and improvements in the proton structure are crucial
  - Improved analysis techniques allow reducing the impact of such effects

- The experimental situation currently unclear; new measurement are eagerly expected.

  δm_W < 10 MeV at the LHC : still the goal.



Thank you!