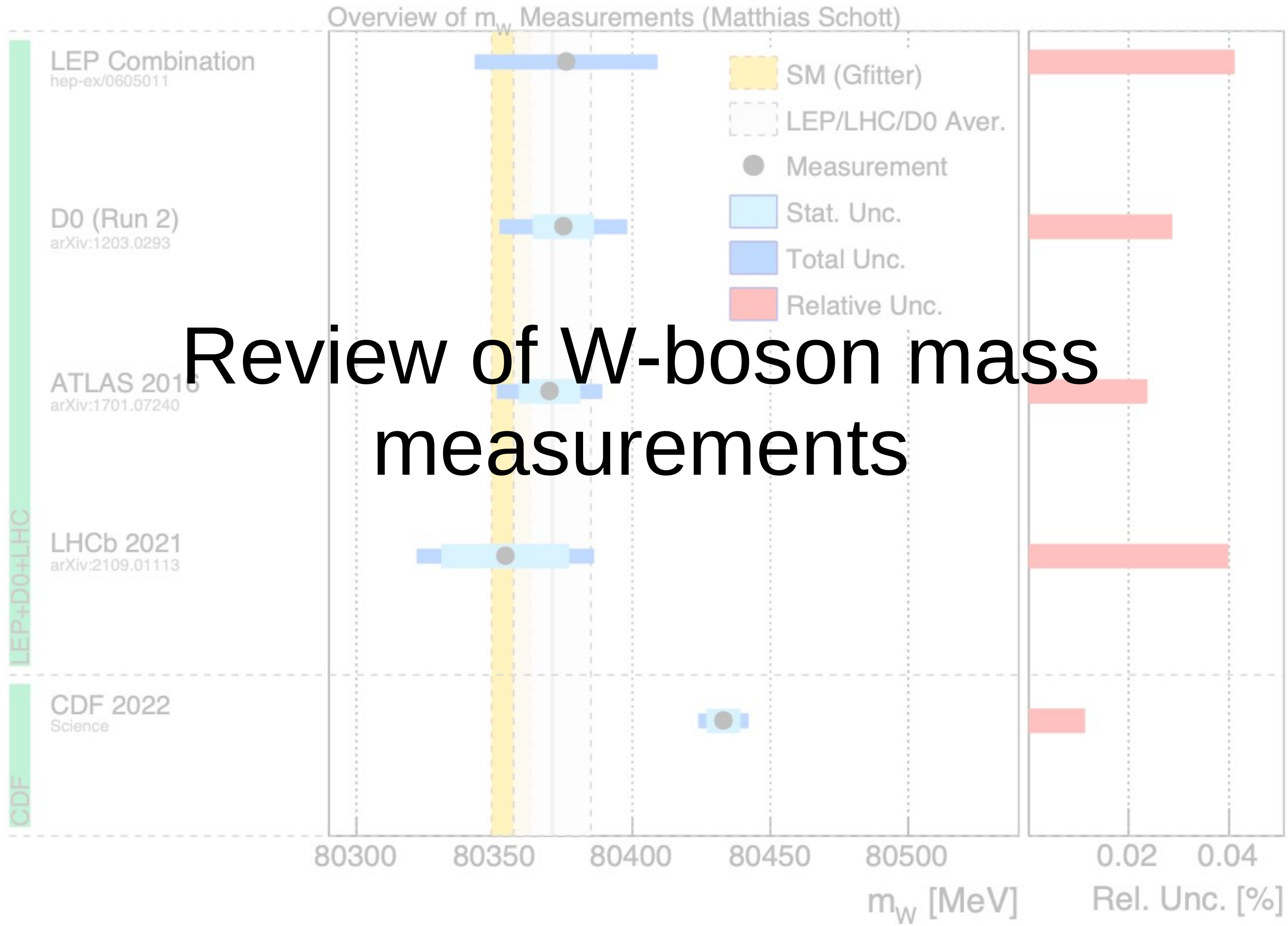
Review of W-boson mass measurements



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CAT physics
11 May 2022

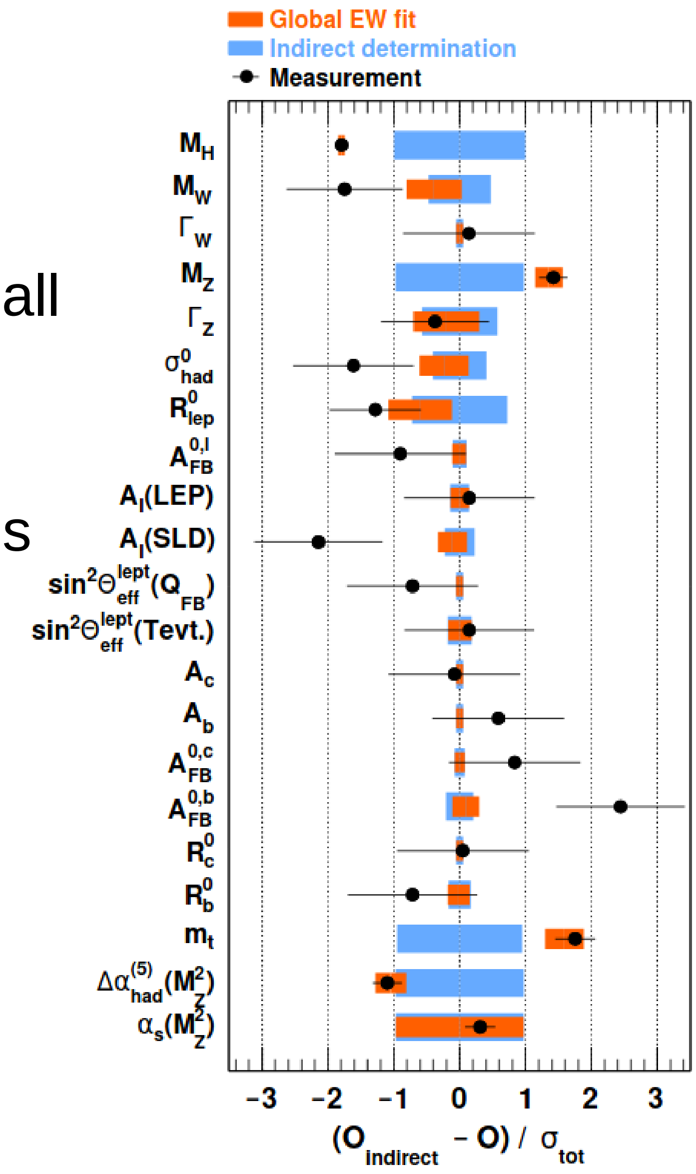
Precision measurements of EW parameters

In the recent past, the global electroweak fit was able to predict the masses of the top quark and Higgs boson before their discovery

- After the measurement of the Higgs mass, all the free parameters of the Standard Model are known
- Relations between electroweak observables can be predicted at 2-loop level

Precise measurements of the electroweak parameters allow

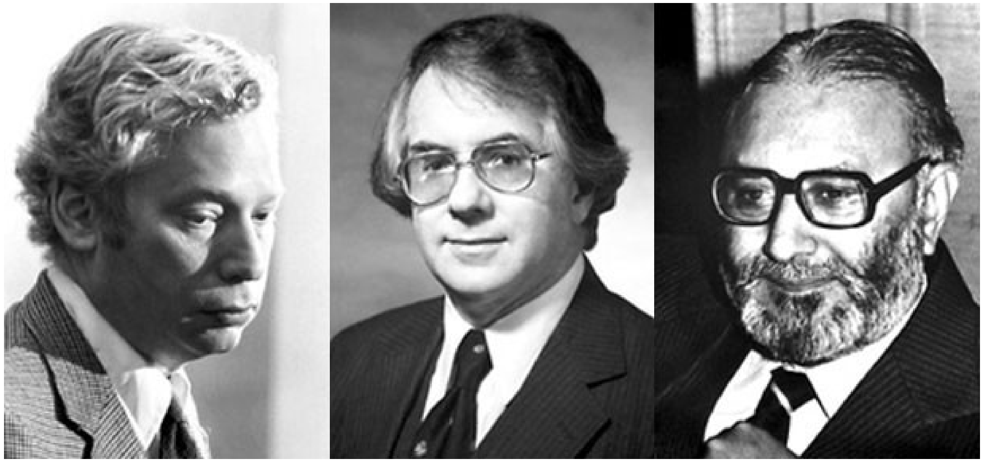
- Stringent test of the self consistency of the SM
- Looking for hints of physics beyond the SM



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

Electroweak sector

The electroweak gauge sector of the Standard Model is constrained by three precisely measured parameters



$$\begin{aligned} \alpha &= 1/137.035999139(31) \\ G_F &= 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2} \\ m_Z &= 91.1876(21)\ \mathrm{GeV} \end{aligned}$$

At tree level, other EW parameters can be expressed as

$$\begin{cases} m_W^2 = \dfrac{\pi\alpha}{\sqrt{2}G_F\left(1-\frac{m_W^2}{m_Z^2}\right)} \\ \sin^2\theta_W = 1-\dfrac{m_W^2}{m_Z^2} \\ \Gamma_W = \dfrac{3G_F m_W^3}{2\sqrt{2}\pi} \end{cases}$$

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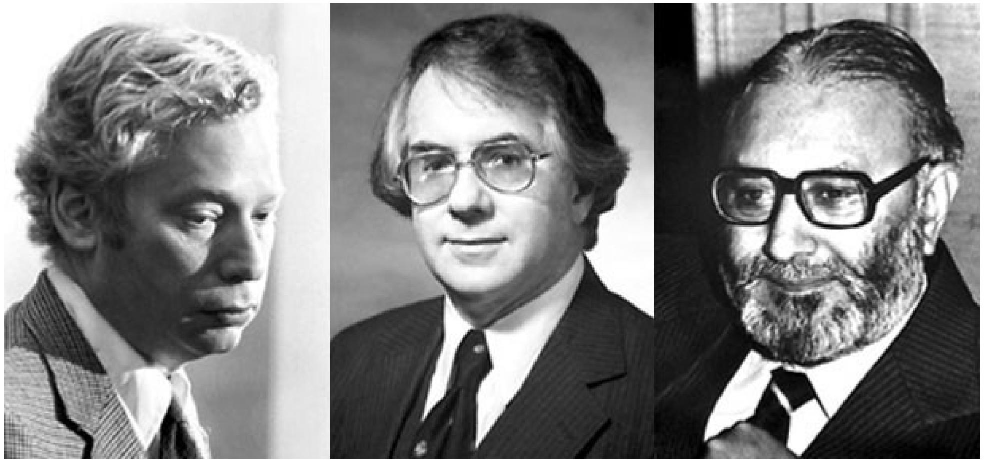

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$$m_Z = 91.1876(21)\ \mathrm{GeV}$$

At tree level, other EW parameters can be expressed as

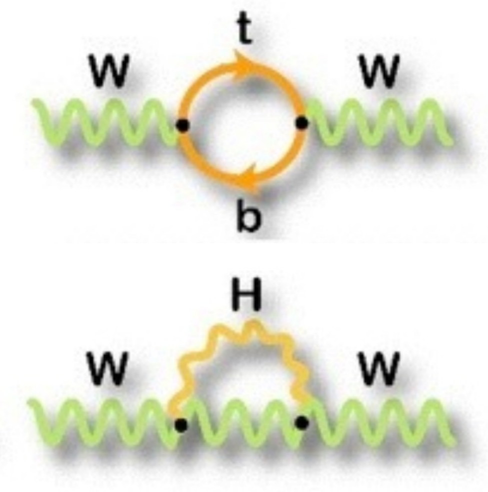
$$\begin{cases} m_W^2 = \dfrac{\pi\alpha}{\sqrt{2}G_F\,(1 - m_W^2/m_Z^2)\,(1 - \Delta r)} \\ \sin^2_{\mathrm{eff}}\theta_W = \left(1 - \dfrac{m_W^2}{m_Z^2}\right)\kappa \\ \Gamma_W = \dfrac{3G_F m_W^3}{2\sqrt{2}\pi}\rho \end{cases}$$

Higher order corrections modify these relations, and determine sensitivity to other particle masses and couplings

Relation between top, Higgs and W masses

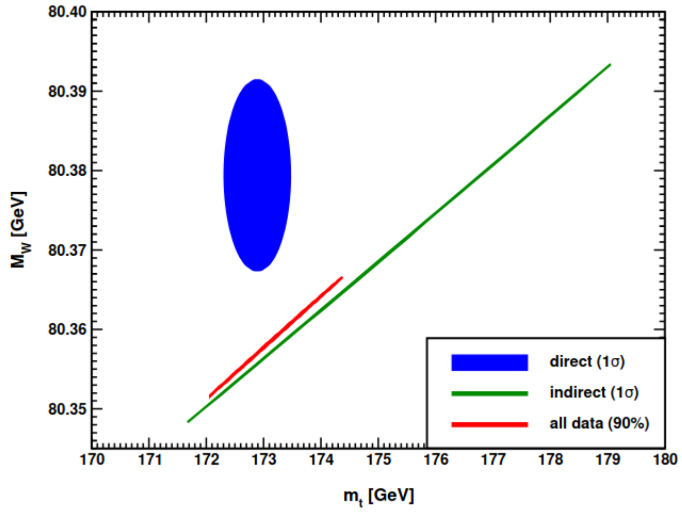
Radiative corrections Δr to mW are dominated by top-quark and Higgs loops

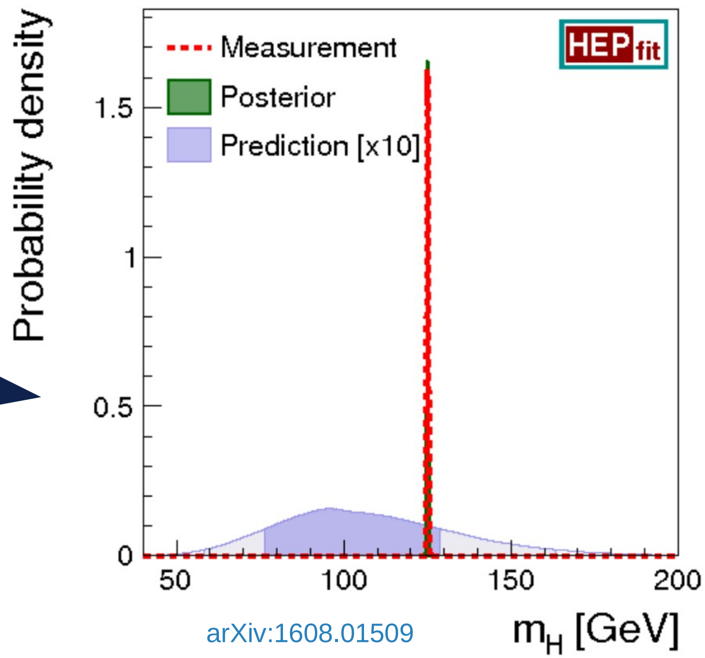
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F\,(1 - m_W^2/m_Z^2)\,(1-\Delta r)}$$



- The relation between m_t, m_H and m_W provides a stringent test of the SM

Prog. Theor. Exp. Phys. 2020, 083C01 (2020)



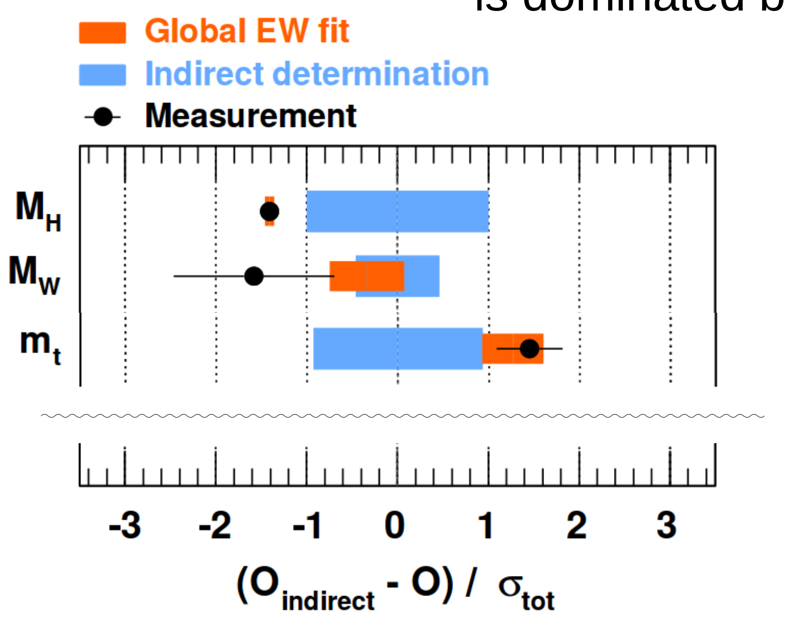


arXiv:1608.01509

- The comparison between the measured m_H and the predicted m_H is sensitive to new physics

Motivation for m_W

The global fit of the electroweak observables is dominated by the measurement of m_W



	Measurement	SM Prediction (*)
m_H	**125.09 ± 0.24**	**100.6 ± 23.6**
m_t	**173.1 ± 0.6**	**176.1 ± 2.2**
m_W	**80.379 ± 0.012**	**80.360 ± 0.007**

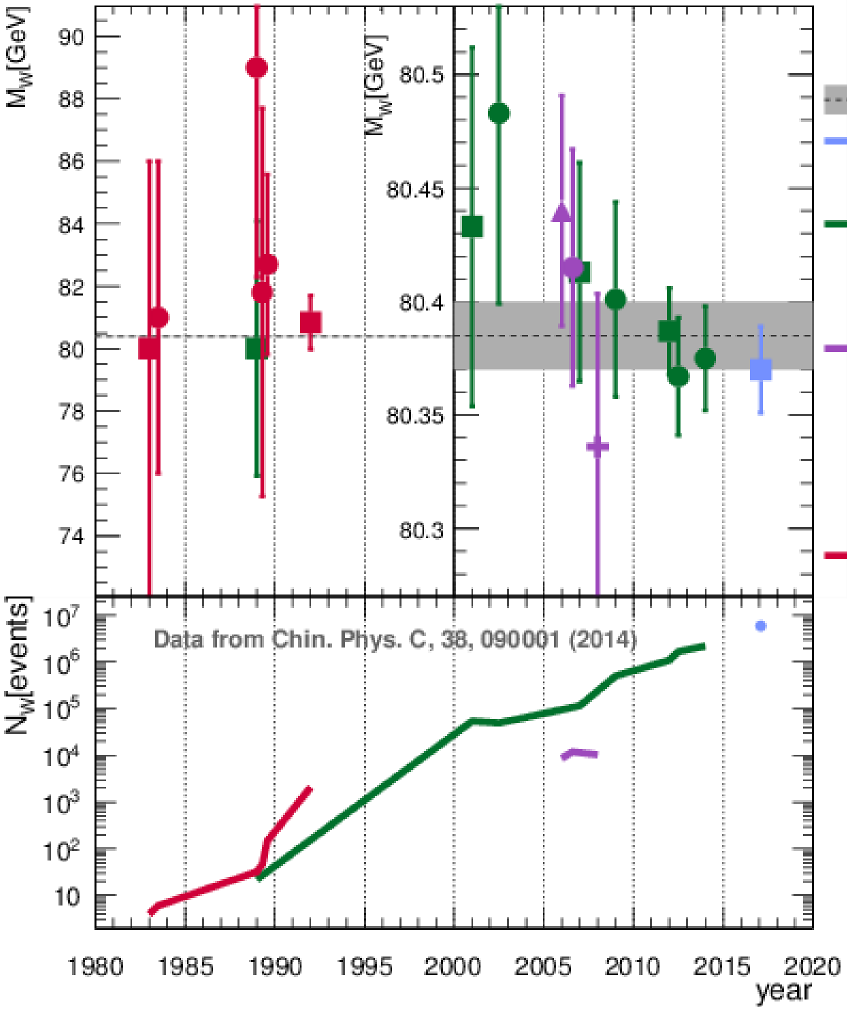
(*) arXiv:1710.05402

The measurements of the Higgs and top-quark masses are currently more precise than their indirect determination from the global fit of the electroweak observables → Improving precision will not increase sensitivity to new physics

Indirect determination of m_W (±7 MeV) is more precise than the experimental measurement → Call for δm_W^{exp} ~ 5 MeV

The W mass is nowadays the crucial measurement to improve the sensitivity of the global EW fits to new physics

W-boson mass history



- 1983 CERN SPS – W discovery
- 1983 – UA1

  m_W = 81 ± 5 GeV
- 1992 – UA2 (with m_Z from LEP)

  m_W = 80.35 ± 0.37 GeV
- 2013 – LEP combined

  m_W = 80.376 ± 0.033 GeV
- 2013 – Tevatron combined

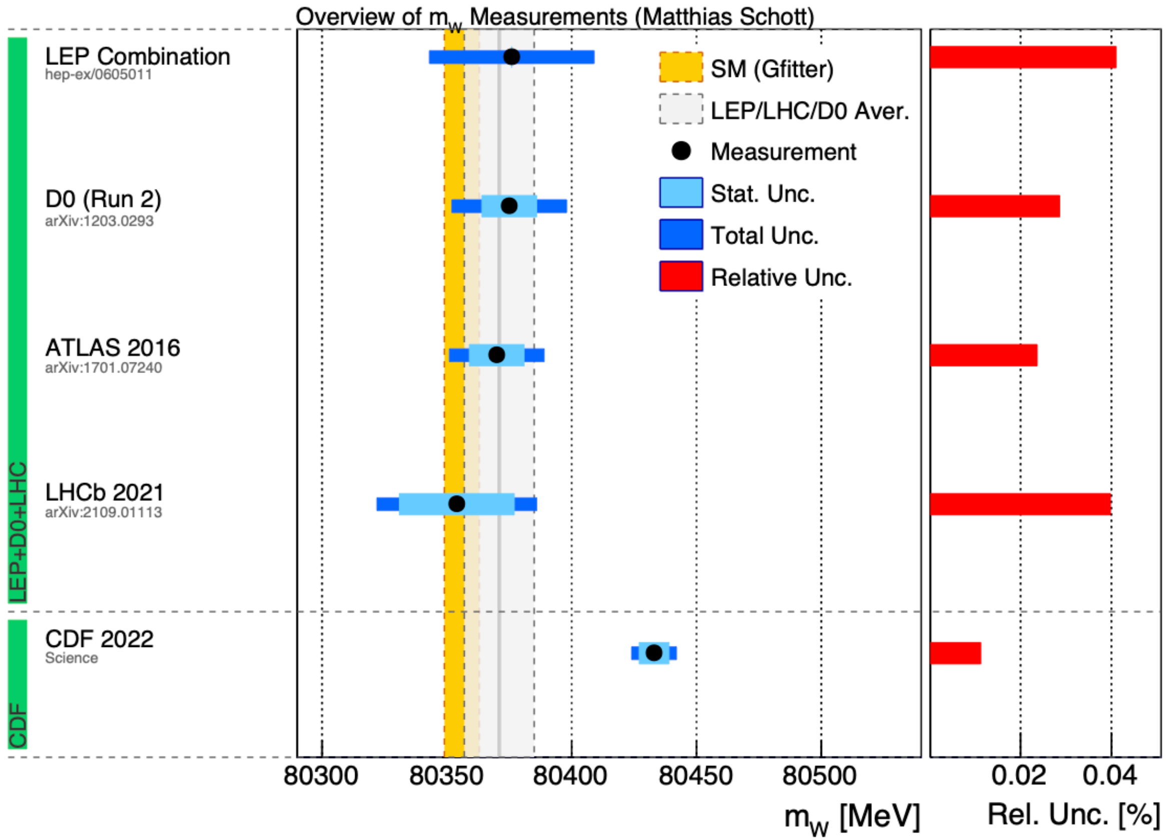
  m_W = 80.387 ± 0.016 GeV
- 2017 – LHC (ATLAS)

  m_W = 80.370 ± 0.019 GeV

- Only four W-boson mass measurements in the last 10 years

→ Complex measurements which require O(5-7) years

W-boson mass today



Before we can make any conclusive statement on measurement/prediction, we should address tensions between measurements

Experimental measurements at colliders

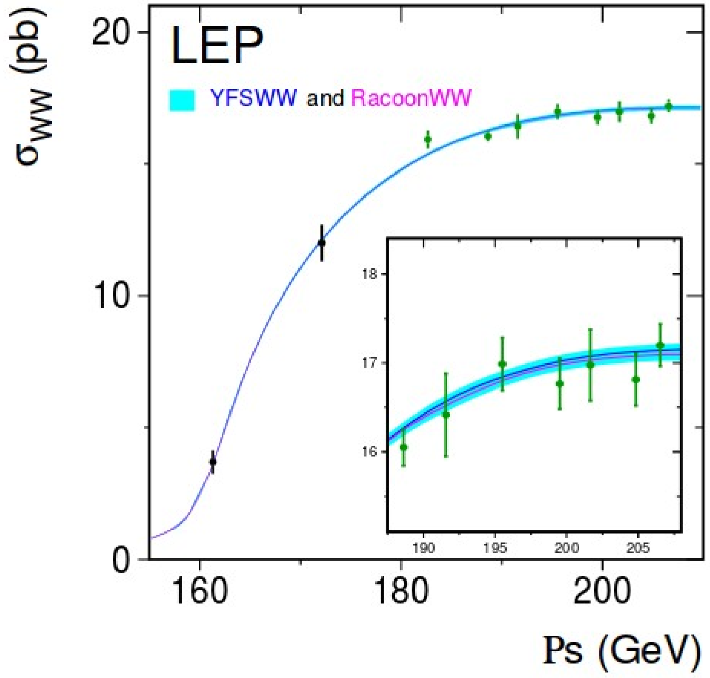
The W-boson mass can be measured from:

- Kinematic properties of decay leptons in the final state in $pp \rightarrow W \rightarrow l\nu$ processes (hadron colliders)
- Direct reconstruction from the final state in $ee \rightarrow WW \rightarrow qqqq/qql\nu$ (e+e- colliders)
- W-pair production at thresholds (e+e- colliders)

SPS, Tevatron, LHC

LEP best measurements

Limited by statistics at LEP, but most precise prospect at future colliders

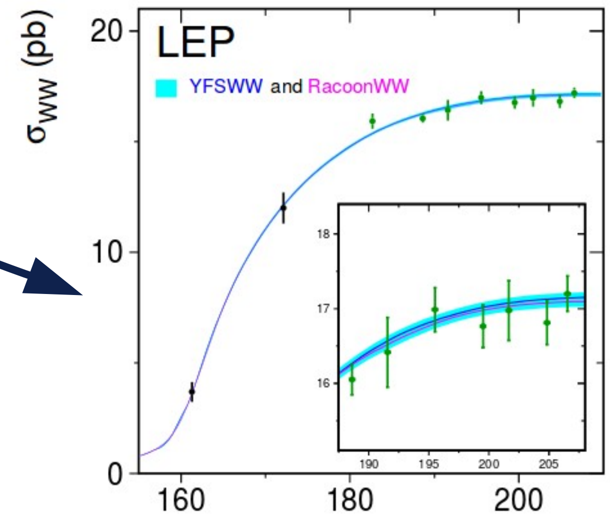


W mass at future colliders

- The ultimate precision on m_W can be achieved at e^+e^- colliders through an energy scan of the WW production threshold

- Near threshold, the WW cross section is proportional to the non-relativistic W velocity

$$\sigma(WW) \propto \beta_W$$

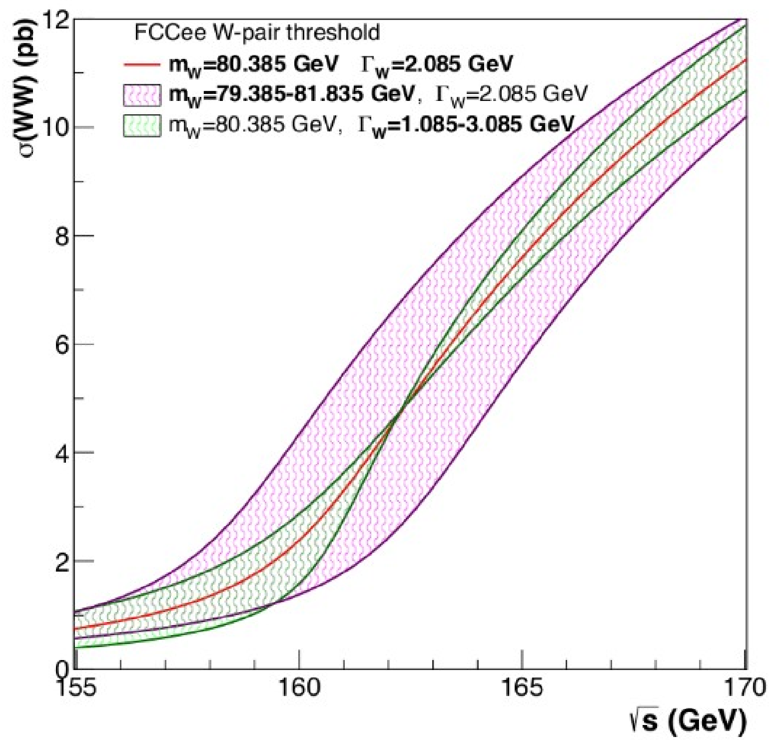


Phys.Rept. 532 (2013) 119-244

arXiv:1306.6352

ILC Giga-Z program
- Energy scan 160 to 170 GeV
- δM_W = 6-7 MeV

FCCee WW program
- δM_W = 0.5 MeV
  → dominated by statistical uncertainty



Dominant theory uncertainties
- Initial state QED corrections
- Parametrization of cross section near threshold

PDF uncertainties for the W mass

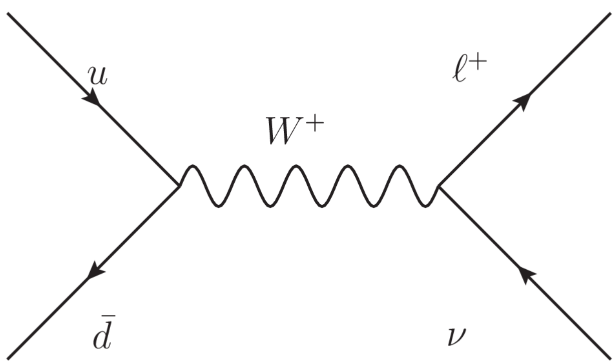
- Sea quarks composition of protons is charge symmetric

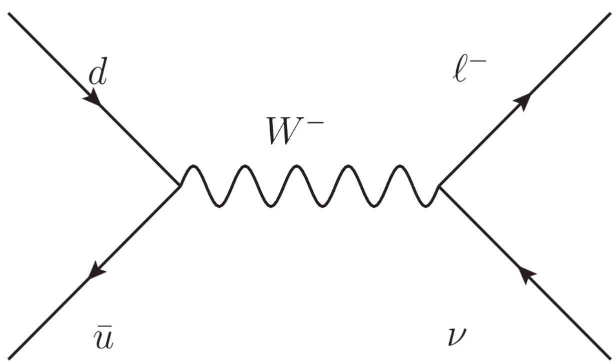
  → same amount of q_s and $\bar{q}_s$ from sea
- Valence quarks determines a charge asymmetry in the proton:

$u = u_v + u_s \qquad \bar{u} = \bar{u}_s$

$d = d_v + d_s \qquad \bar{d} = \bar{d}_s$

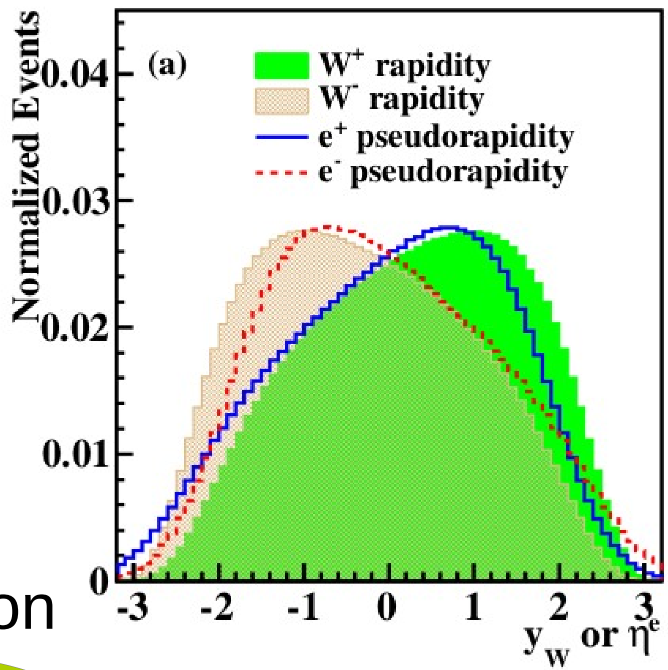
What is the effect of this valence asymmetry for Charged Current Drell-Yan (W-boson) production?



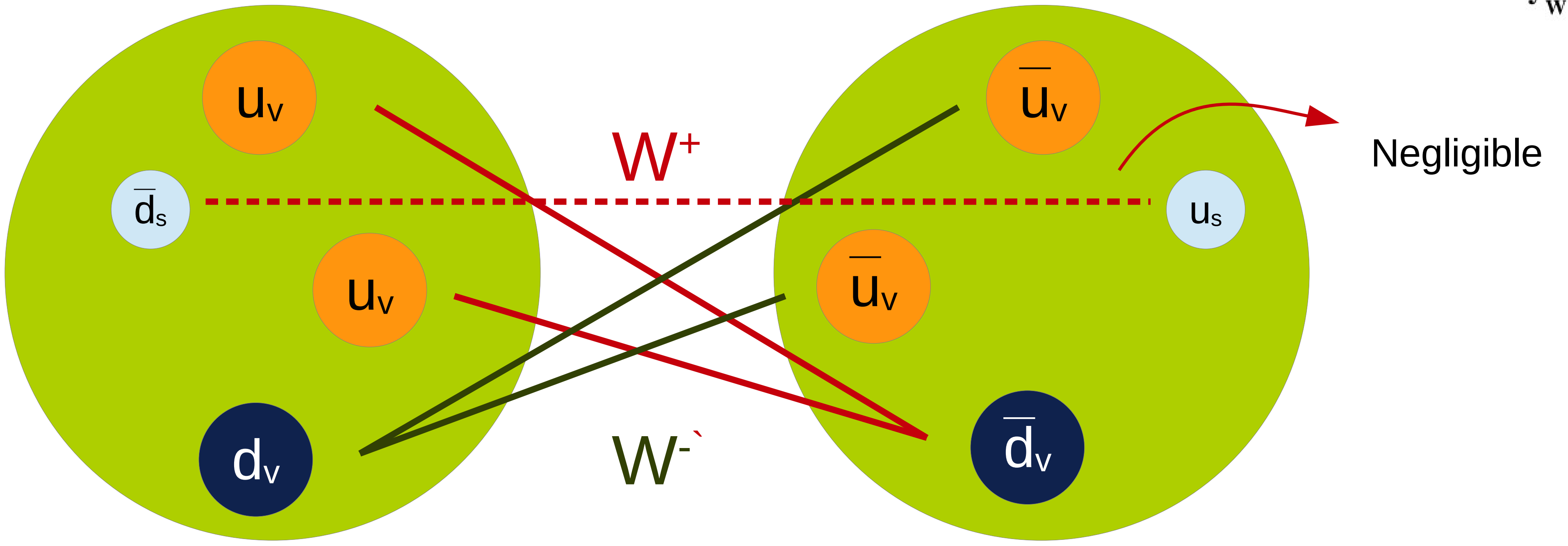


PDF uncertainties for the W mass

- In proton-antiproton collision
- Asymmetry of the W rapidity
- Same cross section for W+ and W-
- Valence-dominated production
- Very small ambiguity for the incoming parton: quark from proton, antiquark from antiproton

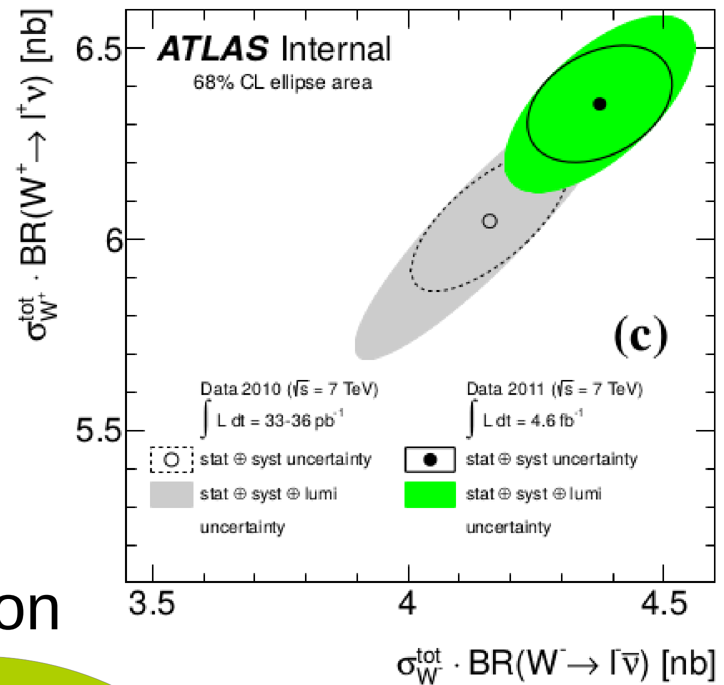


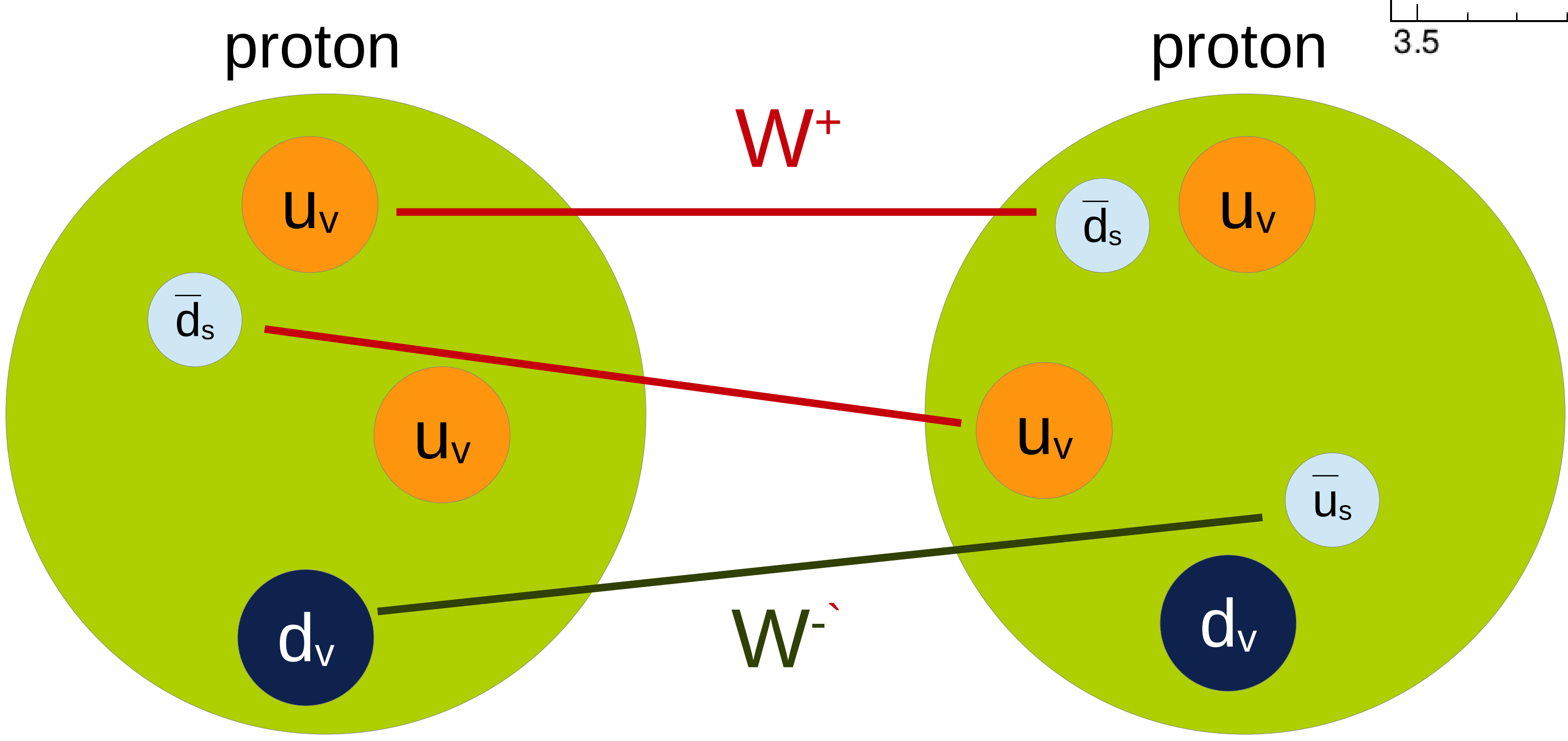
proton antiproton



PDF uncertainties for the W mass

- In proton-proton collision
- Different cross section for W+ and W-
- Large ambiguity in the direction of the incoming quark



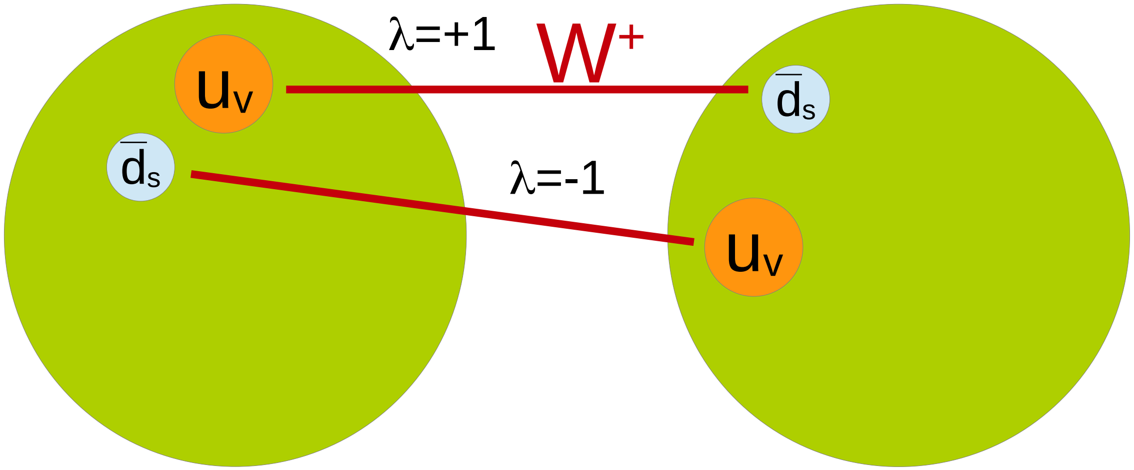


PDF uncertainties for the W mass

- What is the consequence of the ambiguity in the direction of the incoming quark?

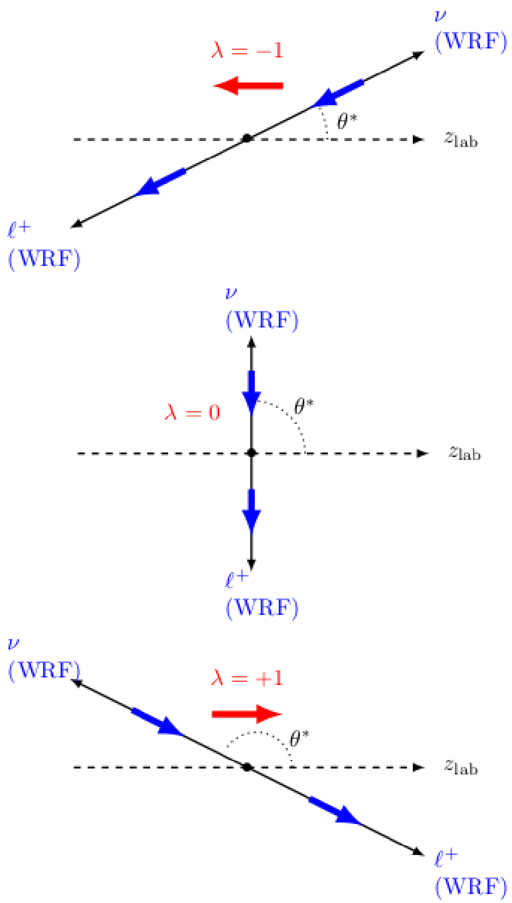
$$\sigma_{W^+}(y) \propto u(x_1) \cdot \bar{d}(x_2) + \bar{d}(x_1) \cdot u(x_2)$$
$$\sigma_{W^-}(y) \propto d(x_1) \cdot \bar{u}(x_2) + \bar{u}(x_1) \cdot d(x_2)$$

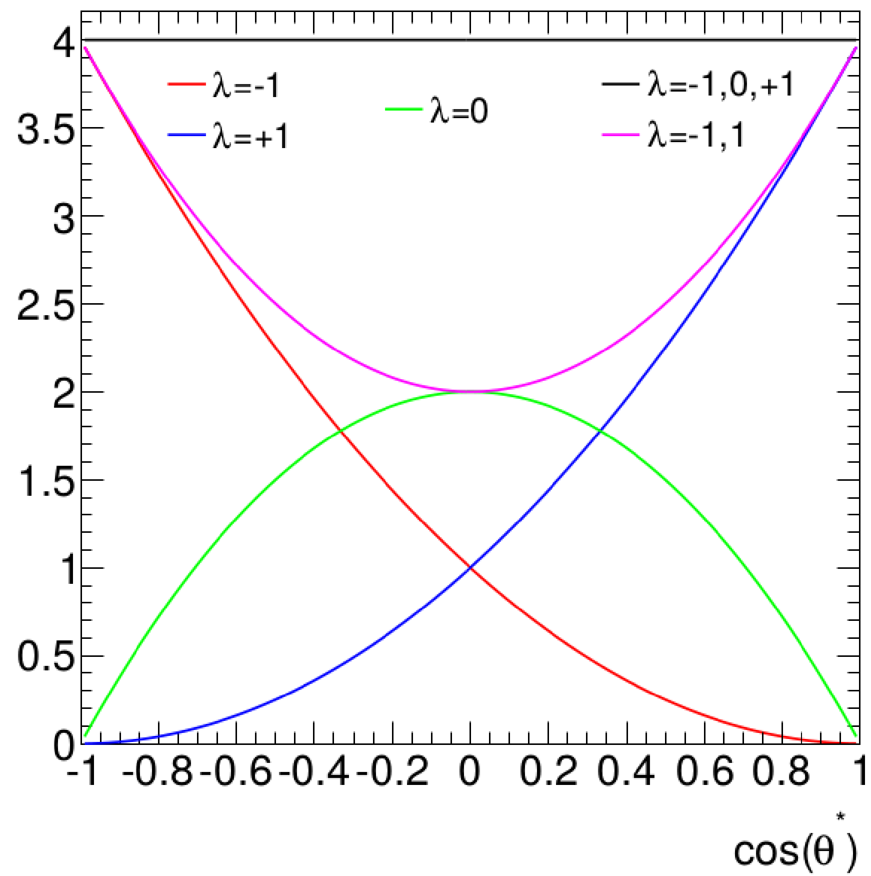
- The helicity is the projection of the spin on the momentum axis
- The W is a spin 1 particle, with 3 possible helicity states: λ = +1,0,-1
- Ambiguity in the average helicity of the W (polarisation)



PDF uncertainty → polarisation uncertainty

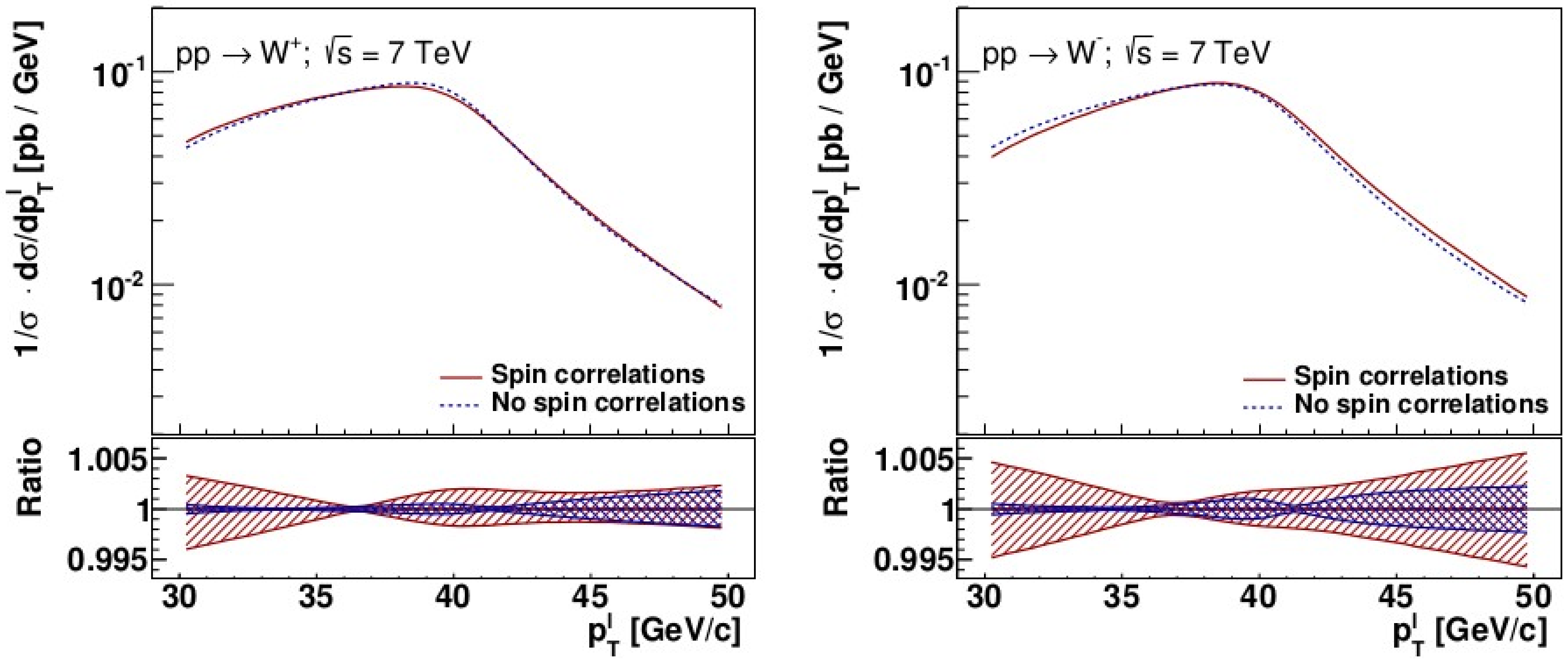
W polarisation





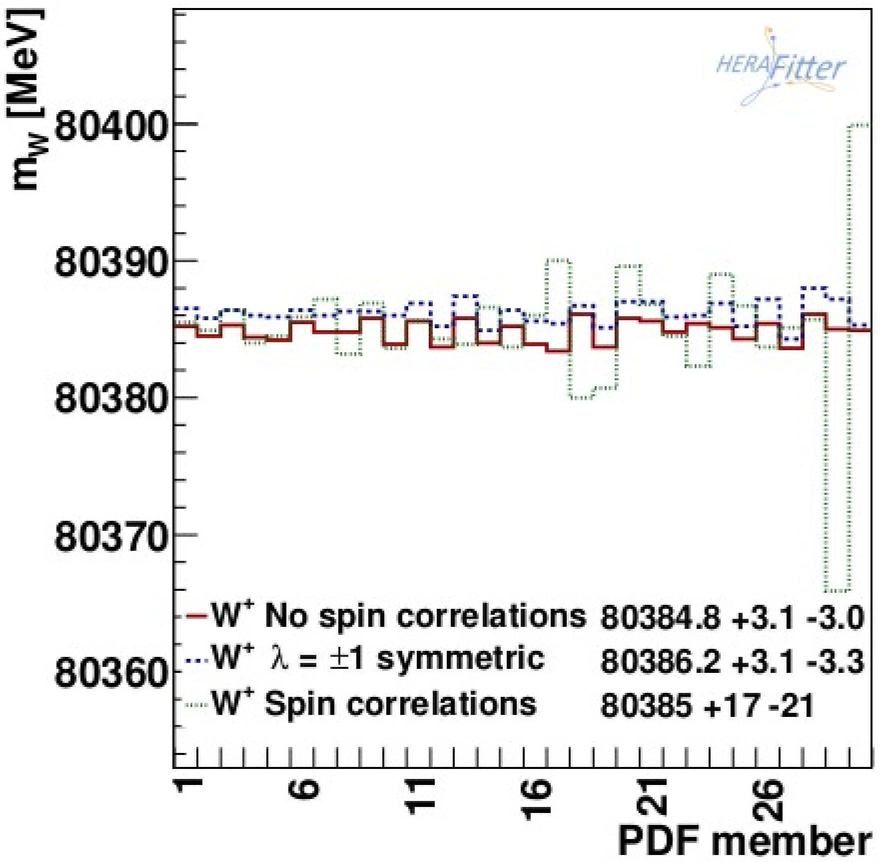
- The 3 helicity states have very different decay polar angles
- The average polarisation heavily affects the lepton kinematic

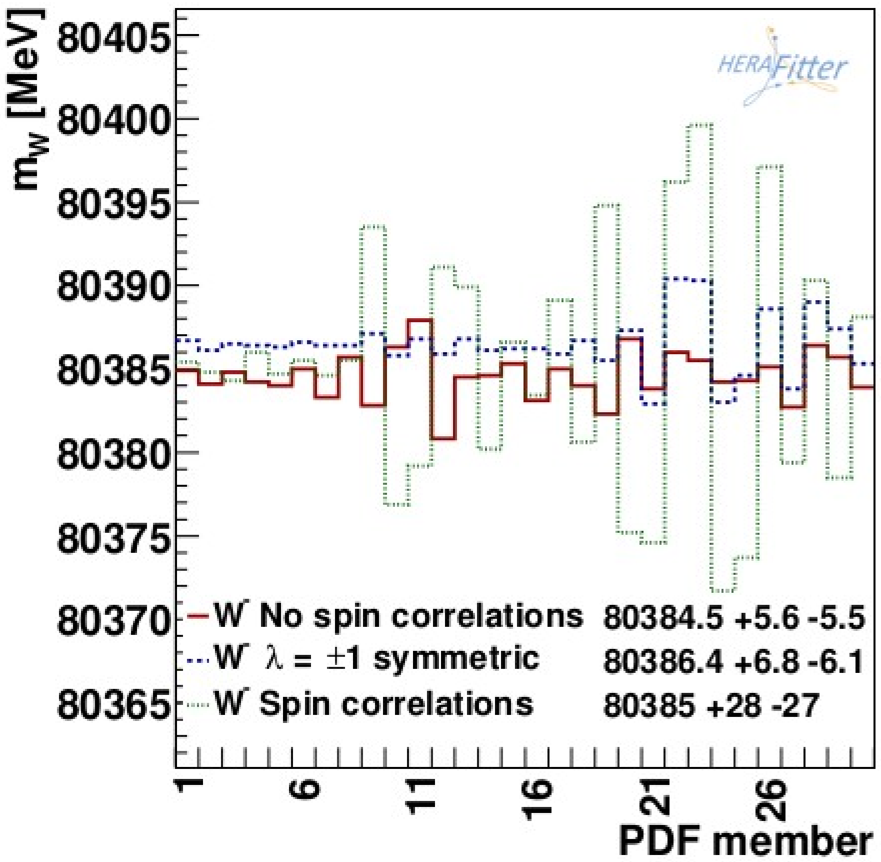
W polarisation



- We can artificially remove the ambiguity in the W helicity by removing spin correlations → Unpolarised W
- Dramatic effect on PDF uncertainties of lepton p_T distribution

W polarisation





- This effect accounts for 20 (30) MeV uncertainty to the W mass extracted from W+ (W-) lepton p_T

W mass at the LHC

- Experimental m_W is limiting the precision of the EW fit
- Measuring is m_W very challenging: slow progress in uncertainty, few measurements, very long analysis
- Hierarchy in expected precision and trustworthiness of m_W measurements: pair production at threshold, proton-antiproton, proton-proton

ERC projects

ERC funded projects on the W mass measurement at the LHC

- ATLAS UMWA → completed

  Ultimate measurement of the W boson mass with ATLAS, at the LHC

- LHCb SPEAR → ongoing

  Standard model Precision Electroweak tests at Acute Rapidities

- CMS ASYMOW → starting

  Power to the LHC data: an ASYmptotically MOdel-independent measurement of the W boson mass