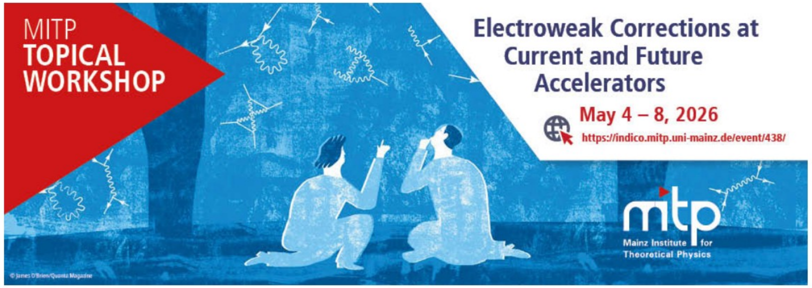
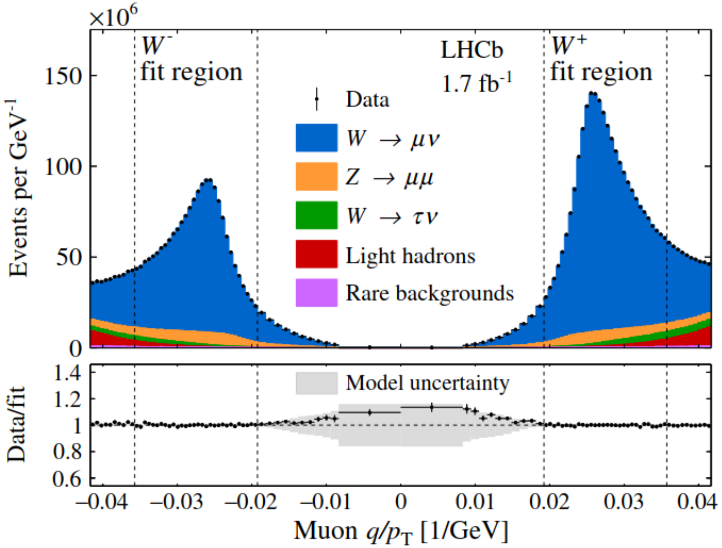


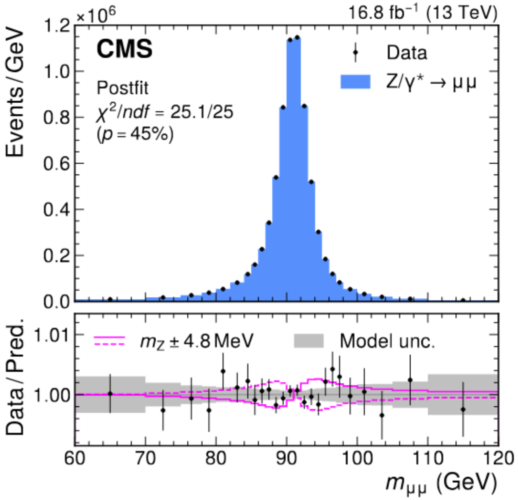
Impact of the proton structure on electroweak precision measurements at the LHC

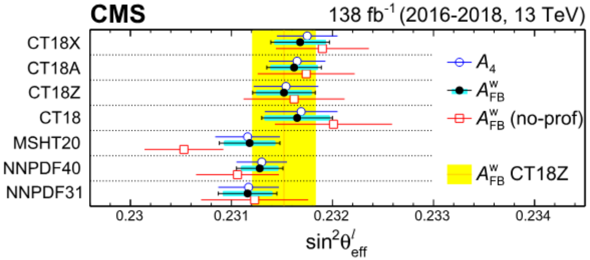
M.Boonekamp, CEA/IRFU

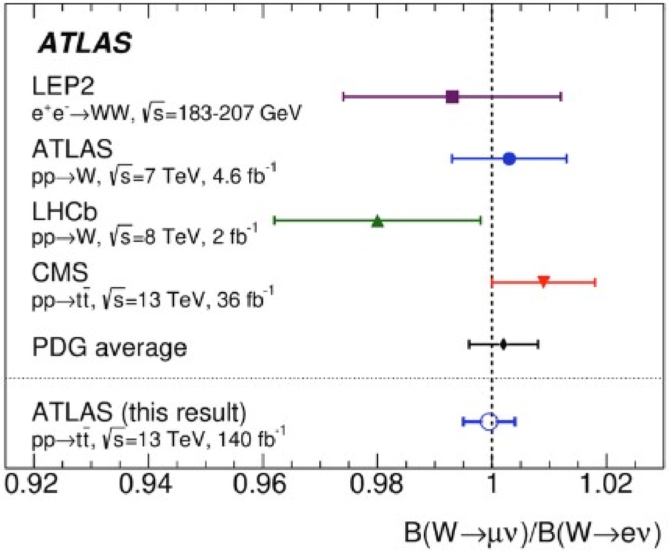
Electroweak precision at the LHC

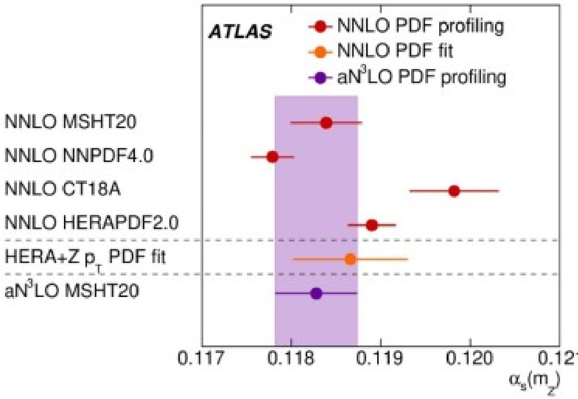
- A compelling landscape, in spite of a complex environment and “large” theoretical uncertainties











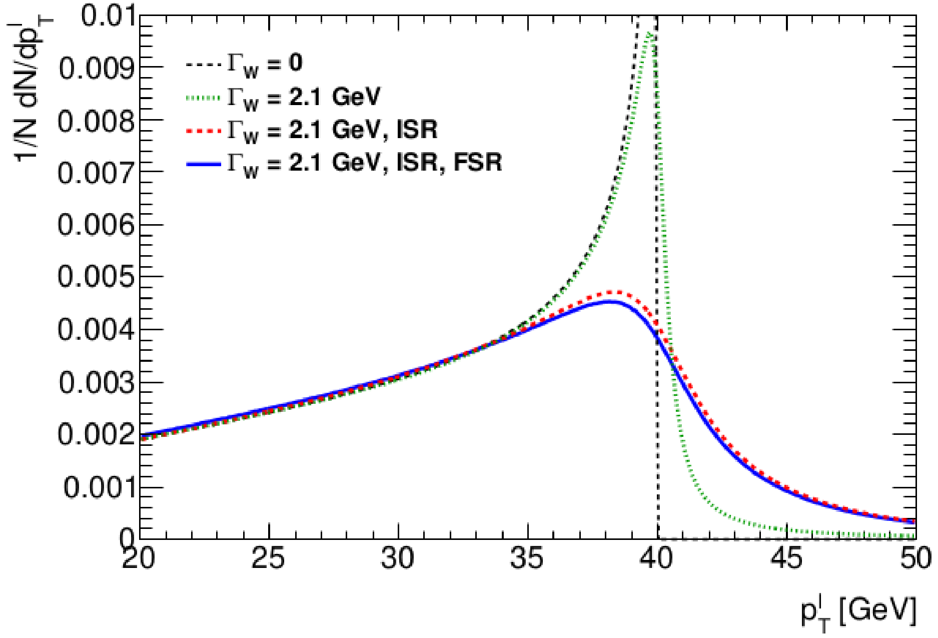
This presentation

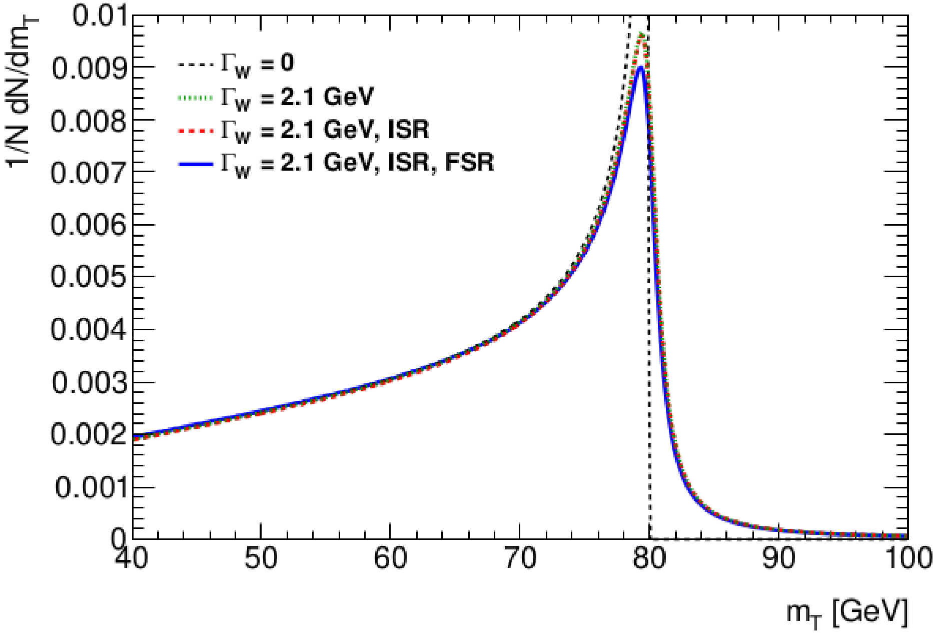
- Brief introduction review of some leading measurements
- Impact of PDF uncertainties on measurement uncertainties and model dependence
- Means to address PDF uncertainties – measurement design, “profiling”, ...
- Ongoing discussion in LHC/PDF community

- summary

The W-boson mass

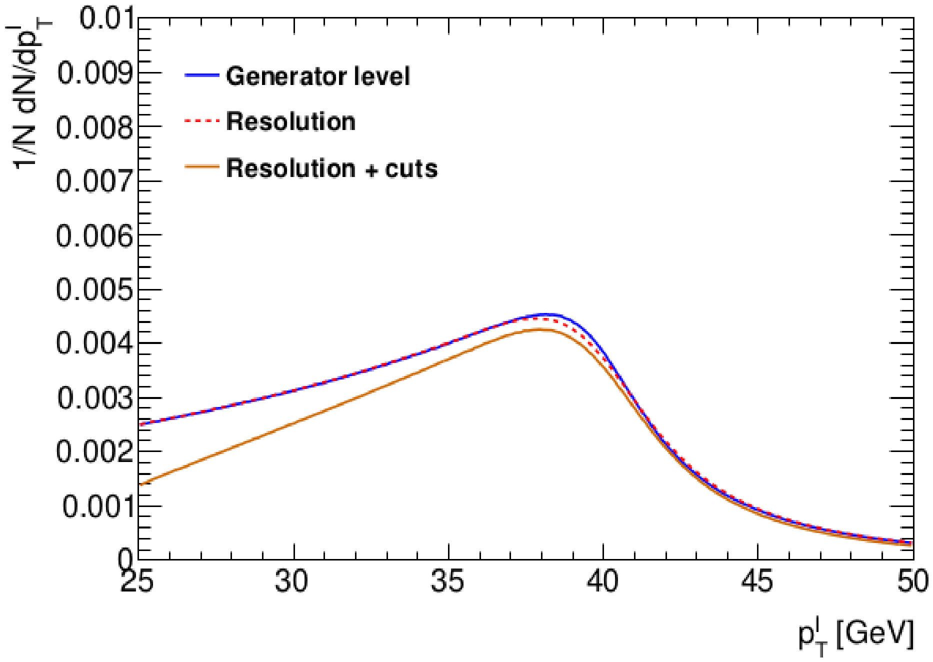
- Distributions in the transverse plane : the jacobian peak, gradually including
  - Physics corrections

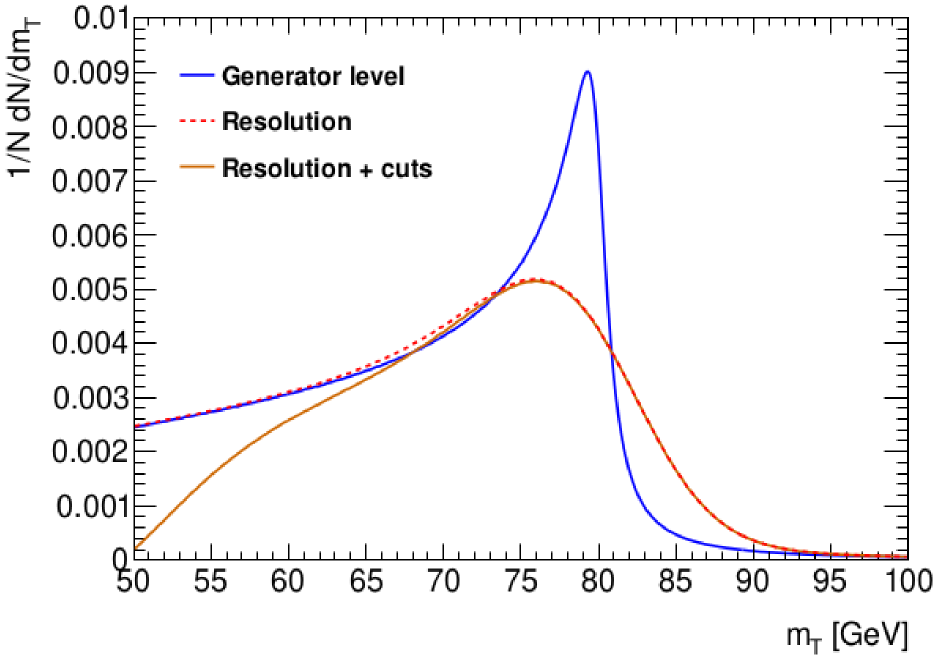




The W-boson mass

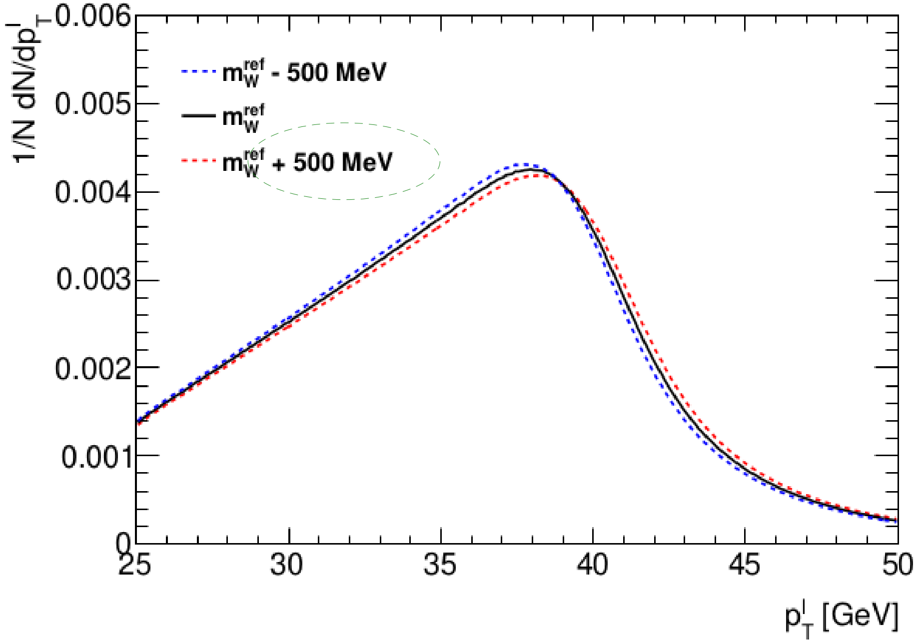
- Distributions in the transverse plane : the jacobian peak, gradually including
  - Physics corrections
  - And detector effects

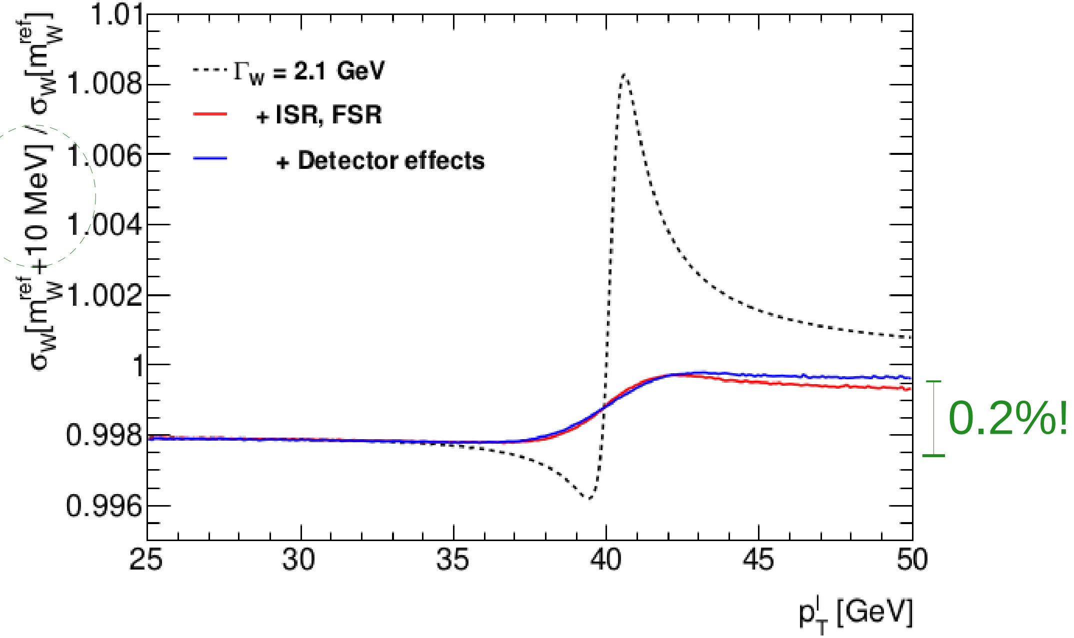




The W-boson mass

- Distributions in the transverse plane : the jacobian peak, gradually including
  - Sensitivity:





Parameter estimation

- LHC measurements almost universally use a so-called "profile likelihood" and extract the parameter of interest through a fit of the model to the relevant final-state distrubutions:

$$\nu_{ji}(\mu,\vec{\theta}) = \Phi \times \left[S_{ji}^{\mathrm{nom}} + \mu \times \left(S_{ji}^{\mu} - S_{ji}^{\mathrm{nom}}\right)\right] + \sum_s \theta_s \times \left(S_{ji}^{s} - S_{ji}^{\mathrm{nom}}\right) + B_{ji}^{\mathrm{nom}} + \sum_b \theta_b \times \left(B_{ji}^{b} - B_{ji}^{\mathrm{nom}}\right),$$

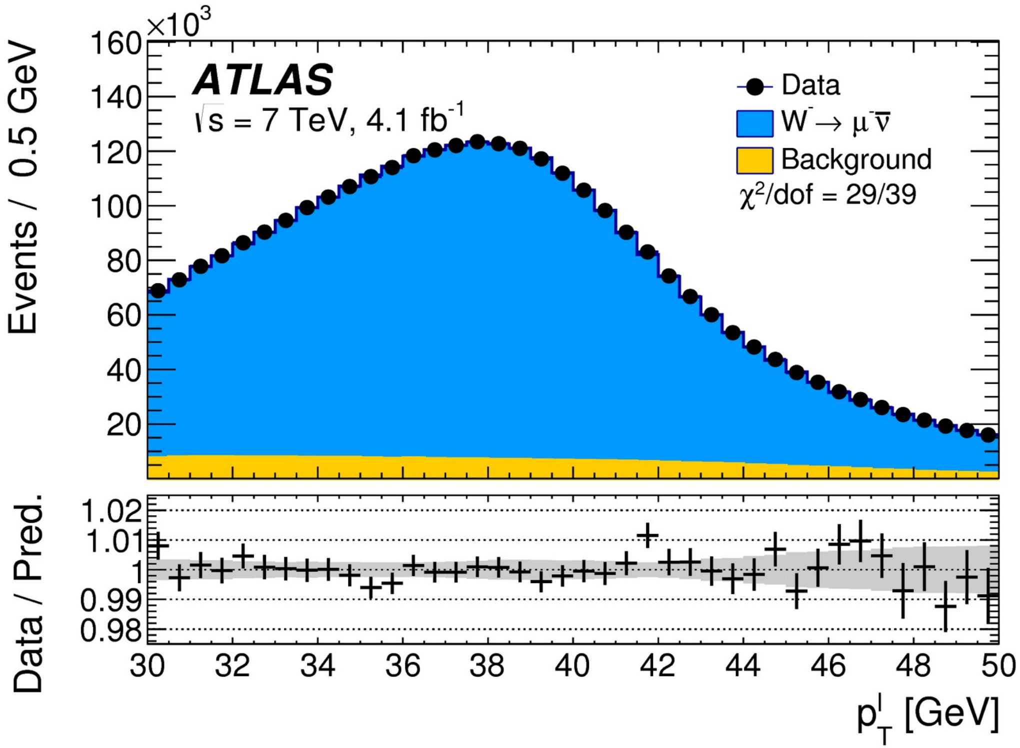
μ : m_W, in this case

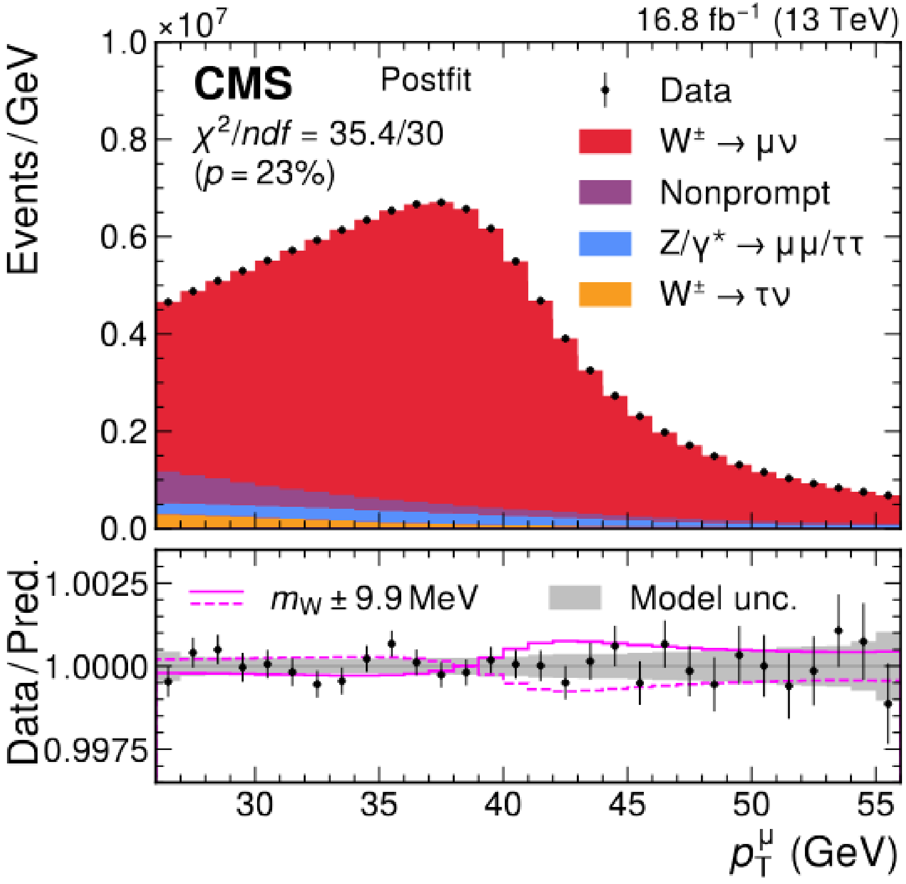
θ : nuisance parameters (including PDFs)

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

The W-boson mass

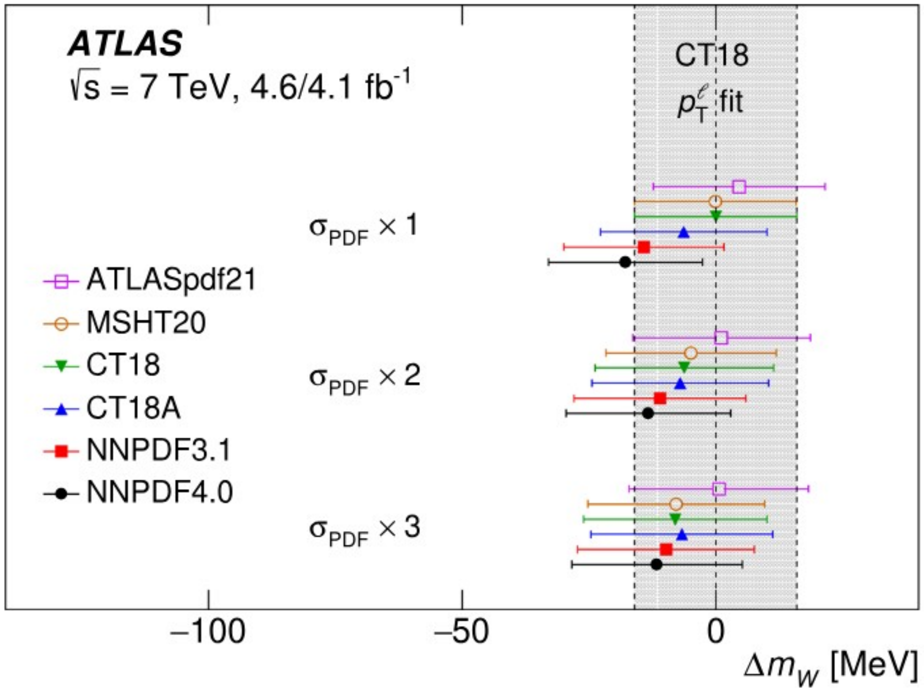
- Results

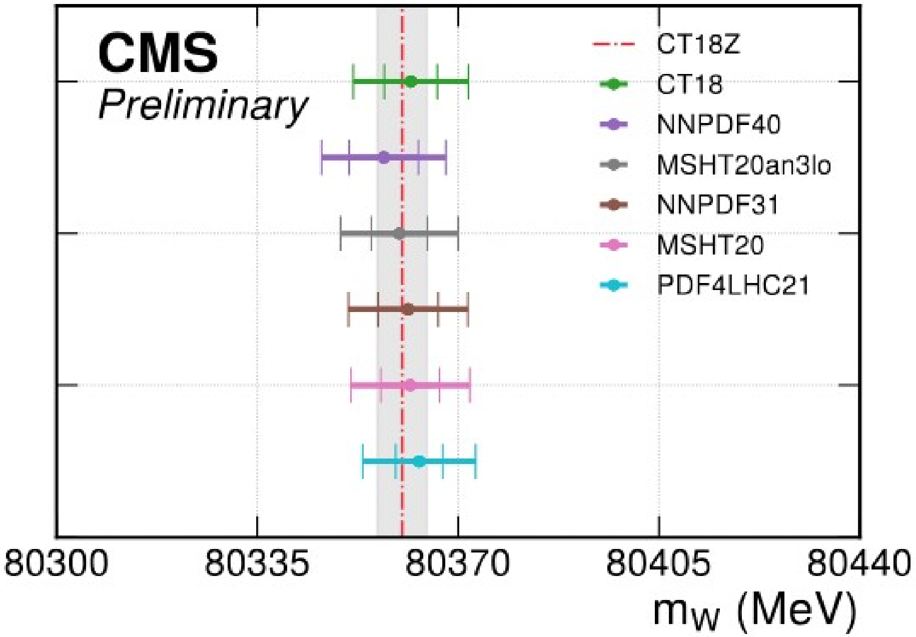




The W-boson mass

- PDF dependence



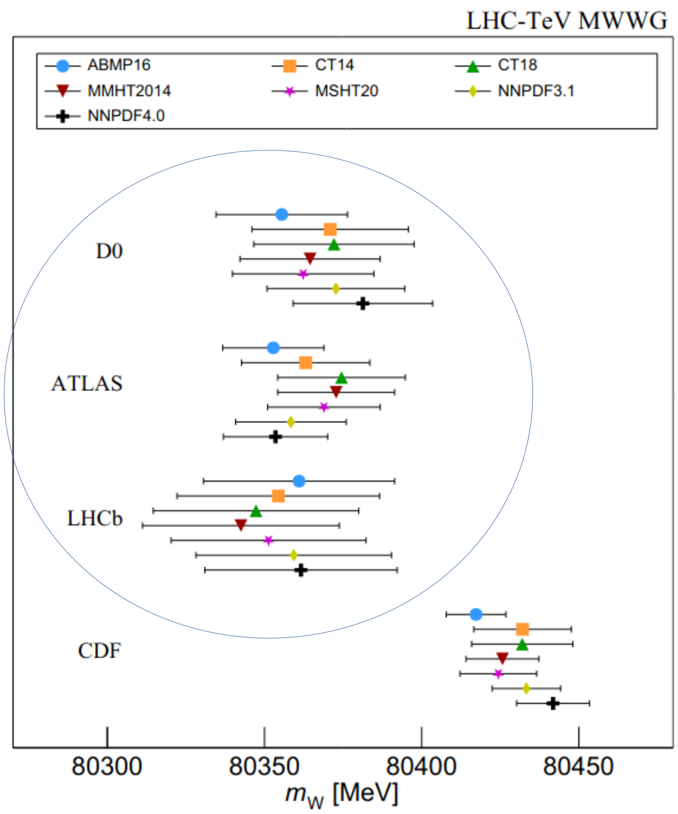


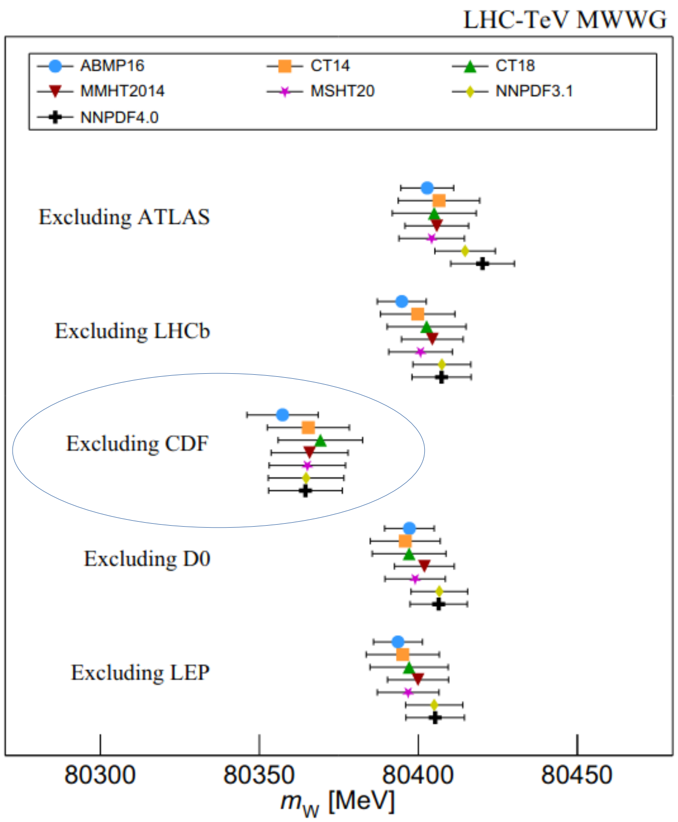
Significant PDF dependence in ATLAS, mitigated through a scaling of the pre-fit PDF uncertainties.

The larger CMS dataset constraints the different PDFs to a more common model.

The W-boson mass and width

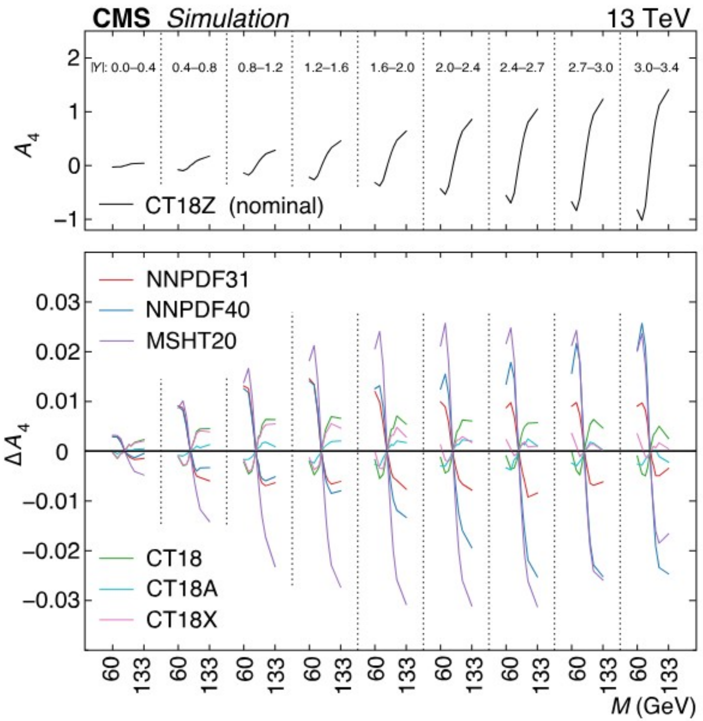
- PDF dependence : combinations help reduce model dependence

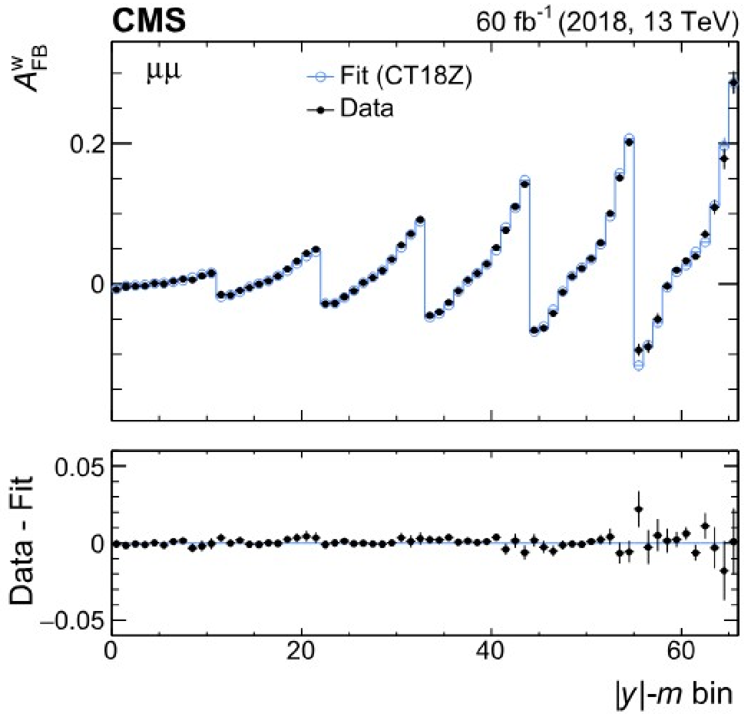




Effective leptonic weak mixing angle

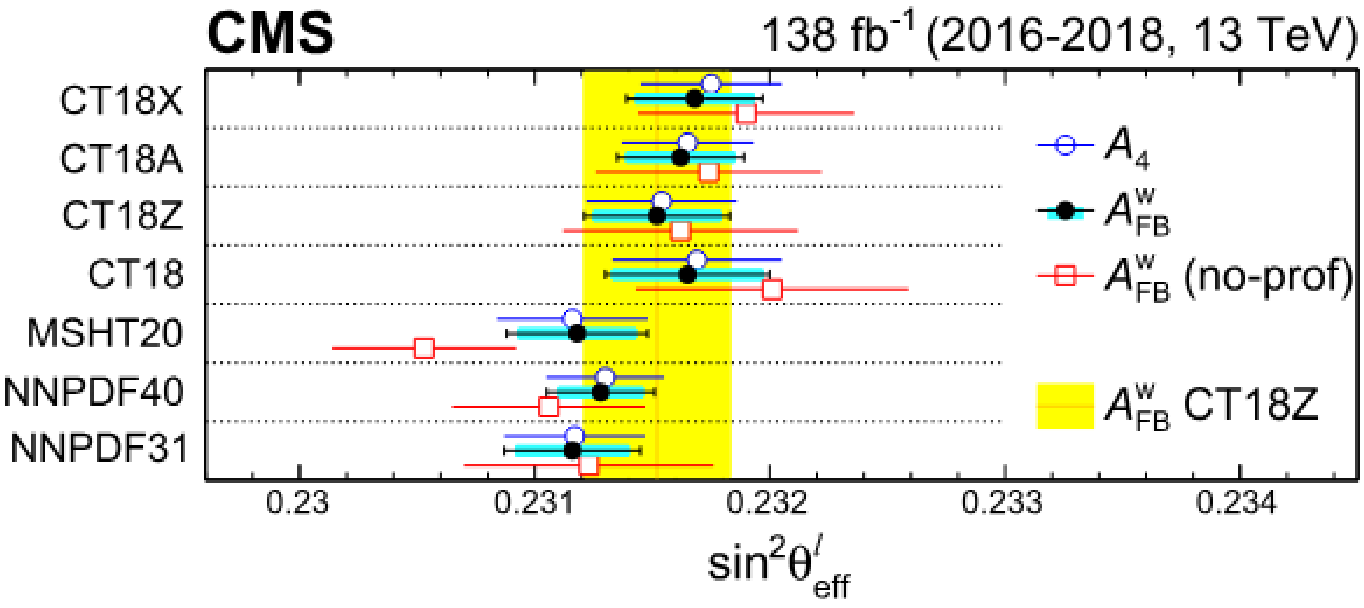
- Measured from forward-backward asymmetries in Z → ee, μμ decays
  - As at LEP, but beam charge and flavour is only determined statistically!
  - Mass and rapidity dependence of A_{FB} separate PDF from weak mixing effects





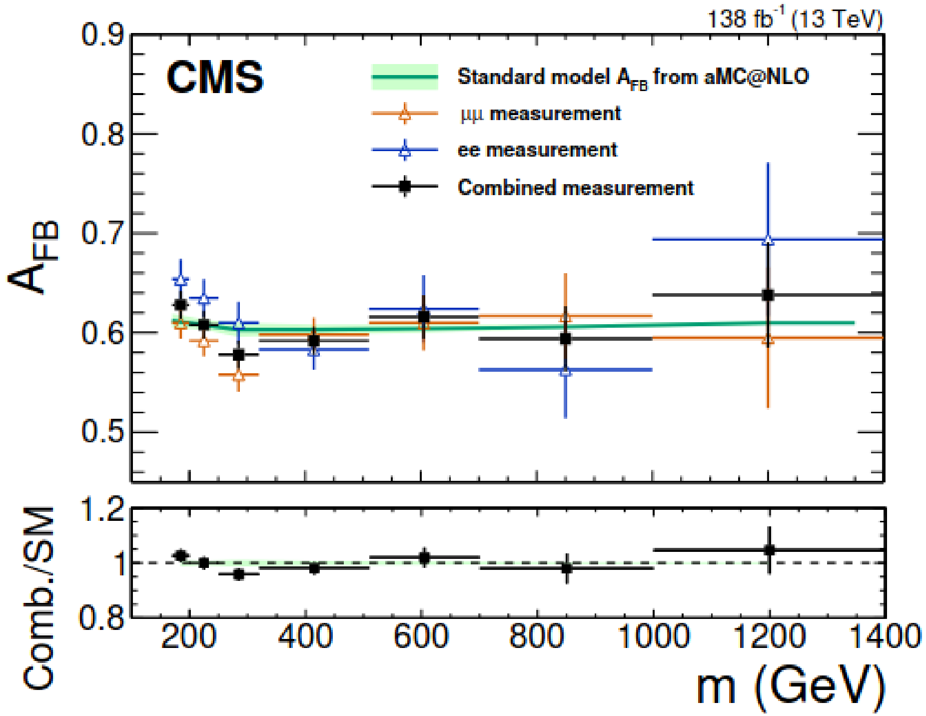
Effective leptonic weak mixing angle

- Measured from forward-backward asymmetries in Z $\rightarrow$ ee, $\mu\mu$ decays
  - Also in this case, a significant PDF dependence, in part mitigated through the use of profiling and further constraining distributions
  - PDF model-dependence still O(measurement uncertainty)



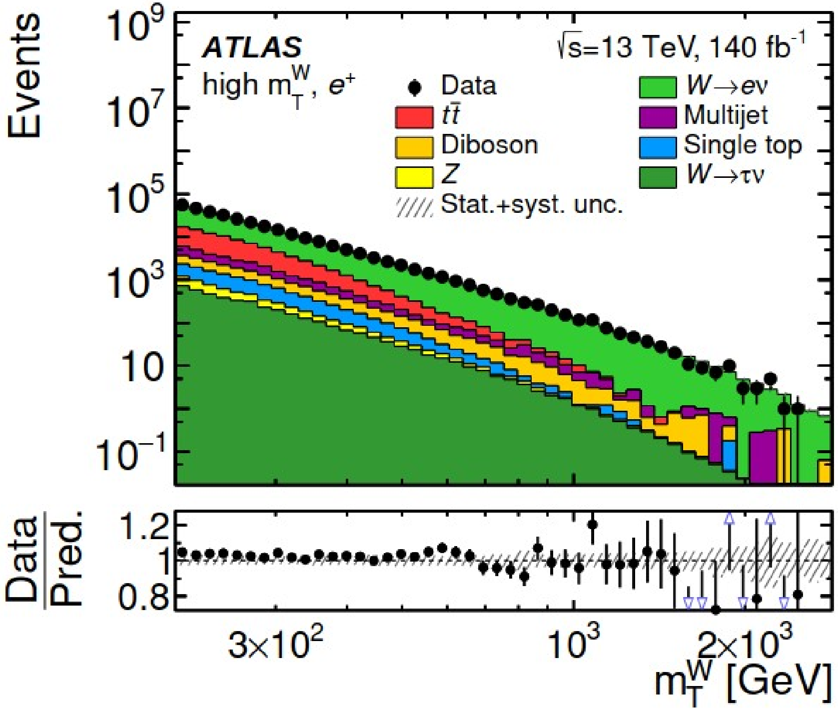
High-mass Drell-Yan (interpretation)

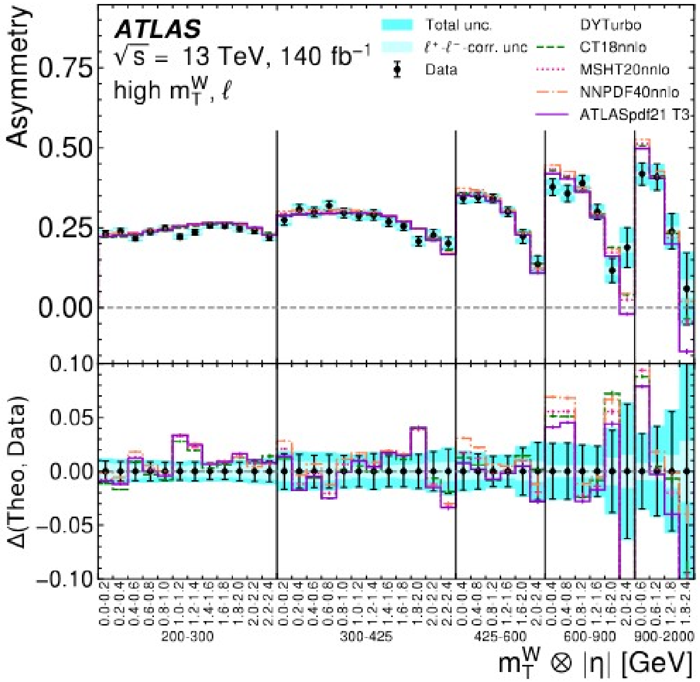
- Forward-backward asymmetry is also measurement above the Z resonance
  - Correcting for the PDF “dilution” brings in significant uncertainty in the measurement



High-mass Drell-Yan (interpretation)

- Data measurements are performed with percent-level precision well into the TeV scale
  - Charged-current Drell-Yan in this example

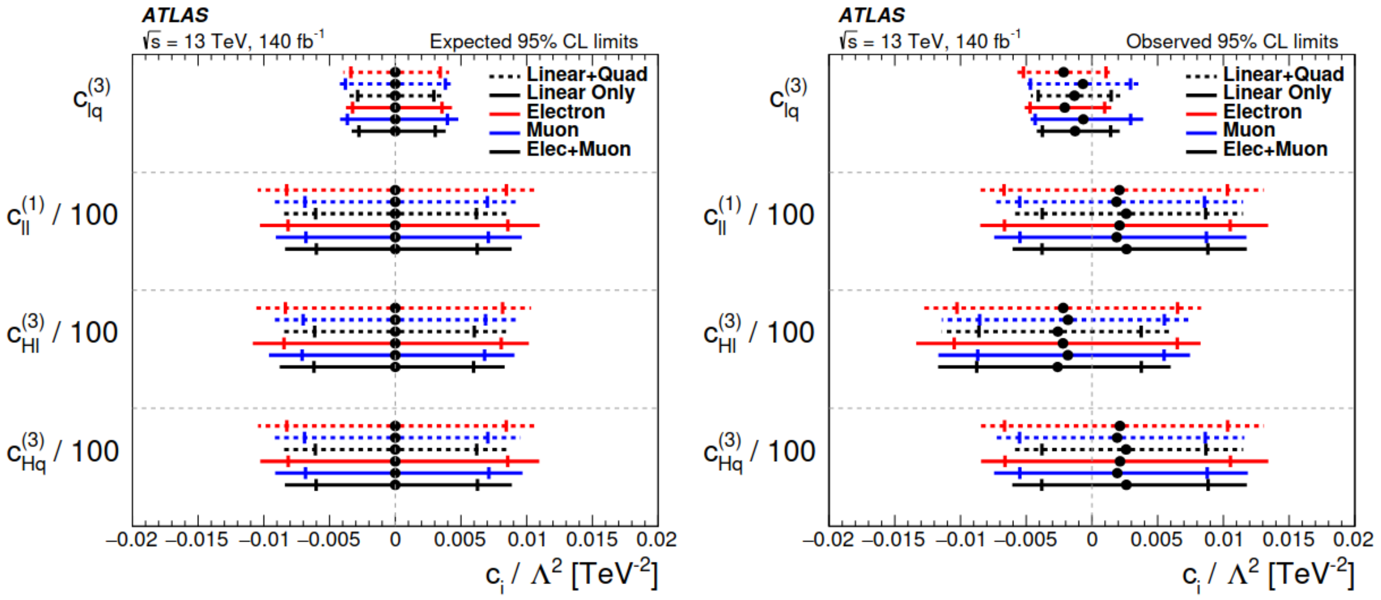




High-mass Drell-Yan (interpretation)

- PDF uncertainties however come in when interpreting these data, for example in the context of SMEFT fits :

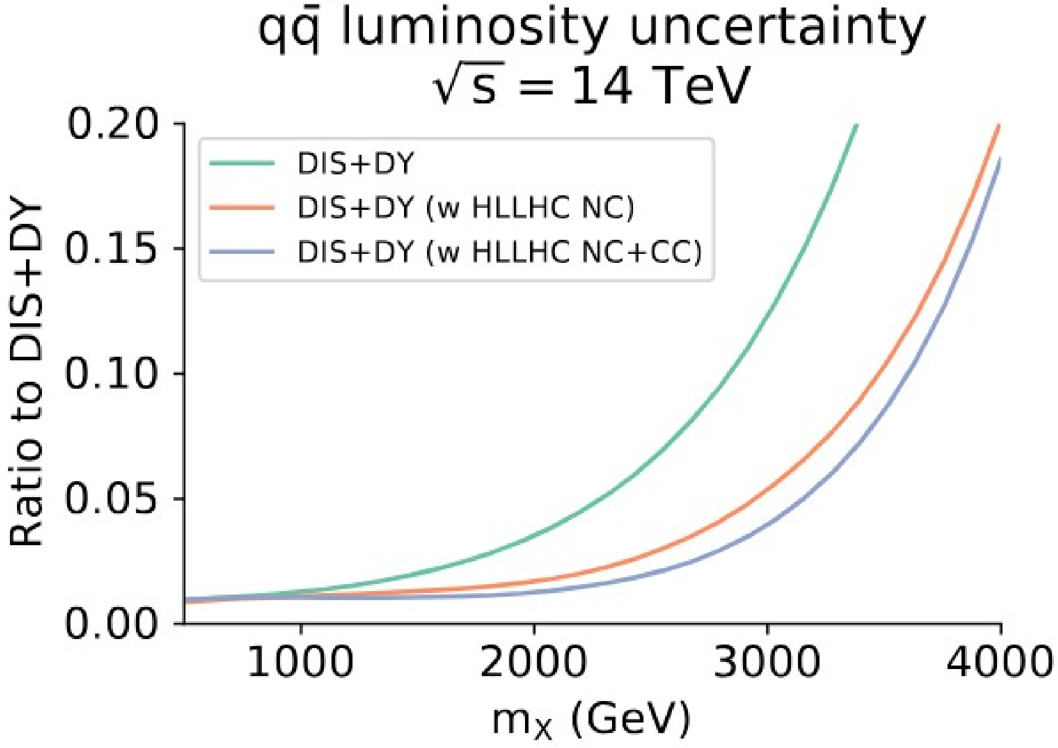
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)},$$



inner/outer error bars : 68% / 90% CL PDF uncertainties

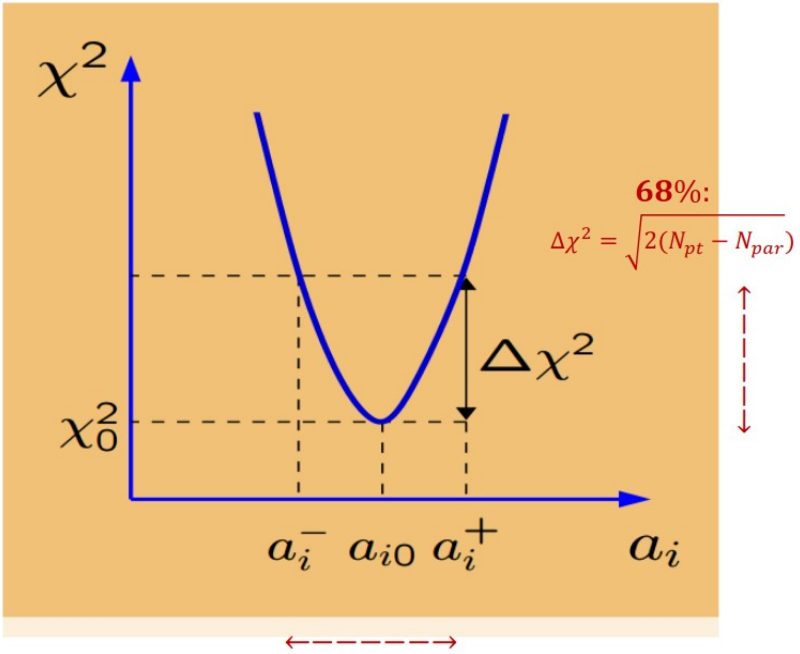
High-mass Drell-Yan (interpretation)

- PDF uncertainties expected to improve at the HL-LHC, from a combination on-resonance CC and NC measurements :



PDF profiling

- Global PDF fits deal with a large number of sometimes inconsistent data sets, theoretical uncertainties that are difficult to estimate, and typically bad fit quality. Concept of “Tolerance” introduced to mitigate such issues



68%: $\Delta\chi^2 = 1$ → **T², typically T²~10**

- Establish a confidence region for $\{a_i\}$ for a given tolerated increase in χ^2
- In the ideal case of perfectly compatible Gaussian errors, 68% c.l. on a physical observable X corresponds to $\Delta\chi^2 = 1$ independently of the number N of PDF parameters

See, e.g., P. Bevington, K. Robinson, Data analysis and error reduction for the physical sciences

PDF profiling – the ongoing debate

Consistent profiling of PDFs with tolerance

1. Start by defining the correspondence between $\Delta\chi^2$ and cumulative probability level: 68% c.l. ⇔ $\Delta\chi^2 = T^2$.
2. Write the **augmented** likelihood density for this definition:

$$P(D_i|T_i) \propto e^{-\chi^2/(2T^2)}$$

3. When profiling 1 new experiment with the prior imposed on PDF nuisance parameters $\lambda_{\alpha,th}$:

$$\chi^2(\vec{\lambda}_{\rm exp}, \vec{\lambda}_{\rm th}) = \sum_{i=1}^{N_{pt}} \frac{\left[D_i + \sum_\alpha \beta^{\rm exp}_{i,\alpha}\lambda_{\alpha,\rm exp} - T_i - \sum_\alpha \beta^{\rm th}_{i,\alpha}\lambda_{\alpha,\rm th}\right]^2}{s_i^2} + \sum_\alpha \lambda^2_{\alpha,\rm exp} + \sum_\alpha T^2 \lambda^2_{\alpha,\rm th}. \qquad \beta^{\rm th}_{i,\alpha} = \frac{T_i(f^+_\alpha) - T_i(f^-_\alpha)}{2},$$

new experiment

priors on expt. systematics and PDF params

arXiv:1912.10053, App. F

4. Alternatively, we can reparametrize $\chi^{2\prime} \equiv \chi^2/T^2$, so that 68% c.l. ⇔ $\Delta\chi^{2\prime} = 1$. We have

$$P(D_i|T_i) \propto e^{-\chi^{2\prime}/2}$$

$$\chi^{2\prime}(\vec{\lambda}_{\rm exp}, \vec{\lambda}_{\rm th}) = \sum_{i=1}^{N_{pt}} \frac{\left[D_i + \sum_\alpha \beta^{\rm exp}_{i,\alpha}\lambda_{\alpha,\rm exp} - T_i - \sum_\alpha \beta^{\rm th}_{i,\alpha}\lambda_{\alpha,\rm th}\right]^2}{s_i^2\ T^2} + \sum_\alpha \frac{\lambda^2_{\alpha,\rm exp}}{T^2} + \sum_\alpha \lambda^2_{\alpha,\rm th}.$$

consistent redefinition

(Pavel Nadolsky)

Profiling of PDFs

- In principle a question to be addressed upstream, by the measurements
  - Claim : tolerance criteria used in PDF fits should be treated consistently in downstream fits
  - Improved Proposal 2 (MSHT)

> - Include tolerance by two-step profiling:
>   1. First profile PDFs including factor of T^2 to correctly account for existing PDF uncertainties ⇒ obtain consistently profiled PDFs.
>   2. Then perform fit with $\Delta\chi^2 = 1$ and obtain PDF uncertainty by scanning profiled PDFs as new input set.
>
> *Tom Cridge*

has the nice property that it reproduces offset error propagation exactly, for large T

  - NB : regardless, such treatments will enhance differences between “aggressive” PDF sets defined without tolerances, and “conservative” sets defined with tolerances

Conclusions

- The LHC covers a very significant portion of the electroweak measurement program. I couldn’t do justice to all in this short talk
- Theoretical calculations steadily improve, thanks to a huge effort form the theoretical community.
- PDFs can be expected to represent the main limitation in the long run. A proper estimation of the corresponding uncertainties, and consistent mitigation strategies will play a crucial role
- In preparation of the HL-LHC, a primordial objective is the definition of a (set of) PDF sets that are optimized for electroweak precision:
  - Maybe less global than eg CTEQ, MSHT : reduced datasets, avoid inconsistencies
  - Focusing on the theoretically best understood processes, minimizing related uncertainties
  - Aim for reduced tolerances and consistent separation of EXP and TH uncertainties