Latest EWK precision measurements from the ATLAS experiment

Xingguo Li[1] on behalf of ATLAS Collaboration

[1]**McGill University**

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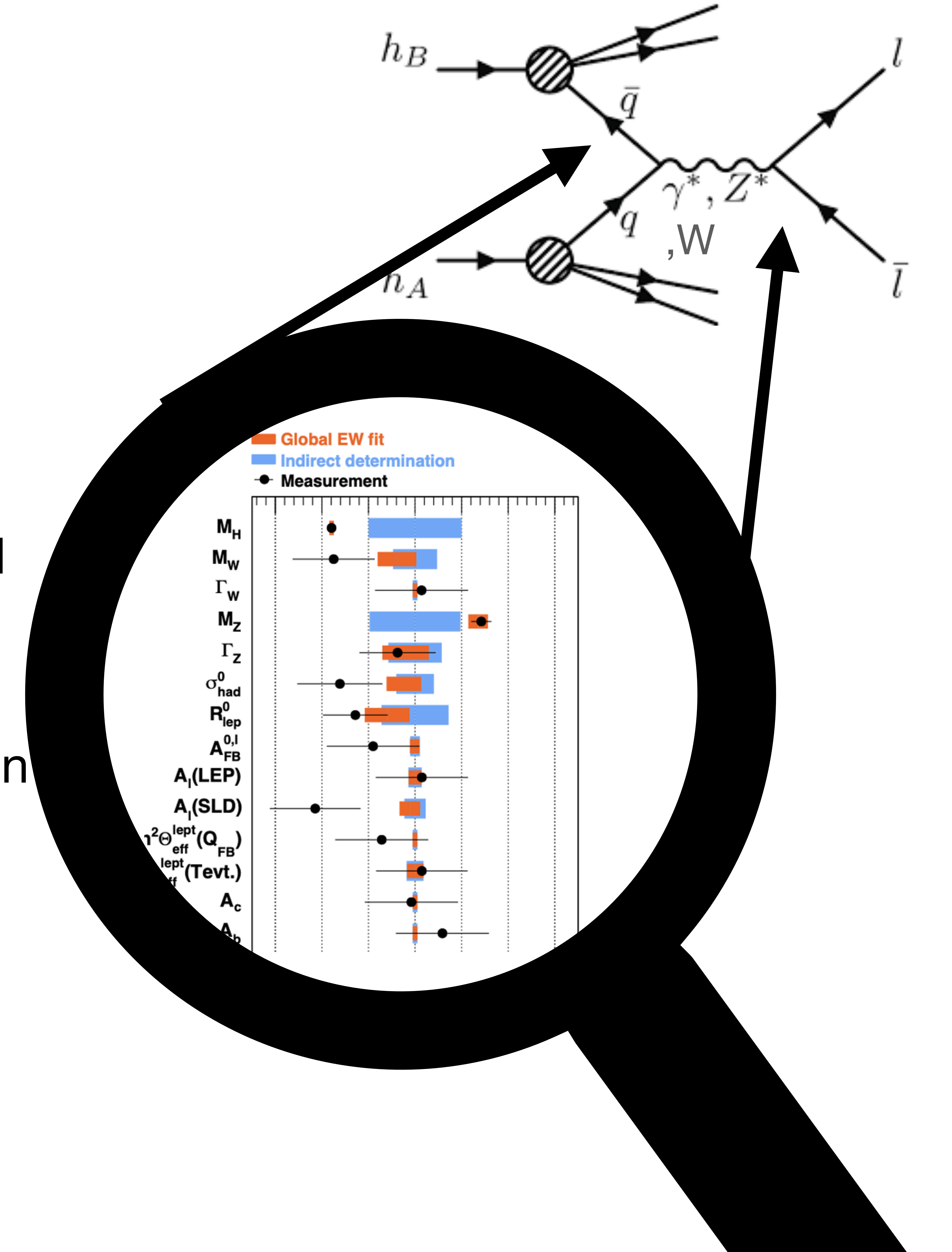
Introduction

- Drell-Yan mechanism led to the discovery of W and Z bosons in 1983, confirming electroweak unification
  - Standard candle for precision measurements and theory at LHC
  - Probe fundamental physics parameters that can only be determined experimentally with a focus on
    - $Z\ p_T$ and rapidity at 8 TeV
    - α_S extraction at Z pole from $Z\ p_T$ precision measurement at 8 TeV
    - W boson mass re-analysis at 7 TeV



$Z\ p_T$ and rapidity at 8 TeV

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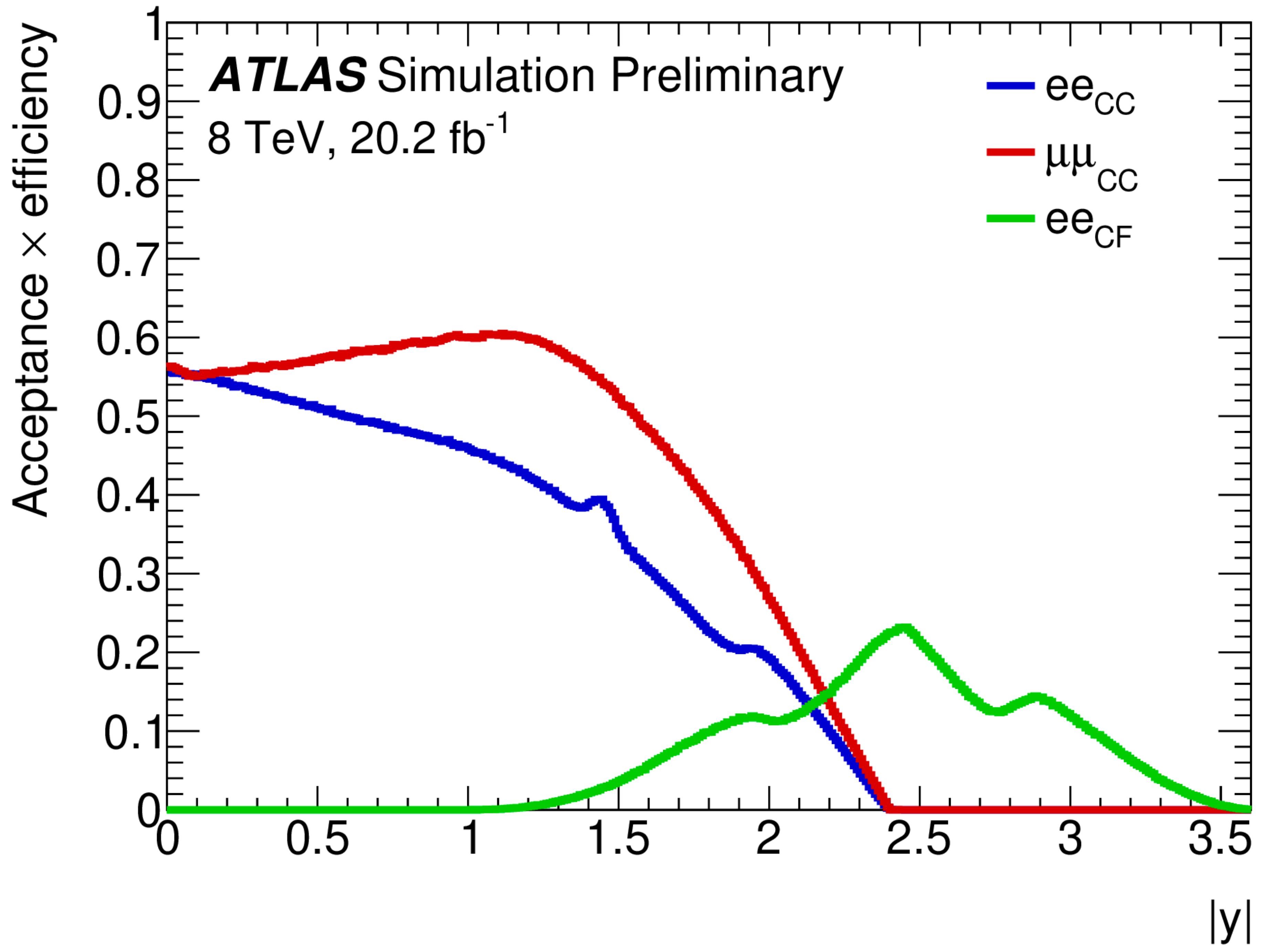
- Stringent test of the state-of-art perturbative QCD theories
- Probe large rapidity/small parton momentum fraction x using forward electrons
- Unique full lepton phase space rapidity cross section with per mille total uncertainties to provide a gateway to a rich field of precise interpretations



- ee_{CC}: two electrons with $p_T > 20$ GeV and $|\eta| < 2.4$
- $\mu\mu_{CC}$: two muons with $p_T > 20$ GeV and $|\eta| < 2.4$
- ee_{CF}: central electron with $p_T > 20$ GeV and $|\eta| < 2.4$ forward electron with $p_T > 20$ GeV and $2.5 < |\eta| < 4.9$

$Z\ p_T$ and rapidity at 8 TeV

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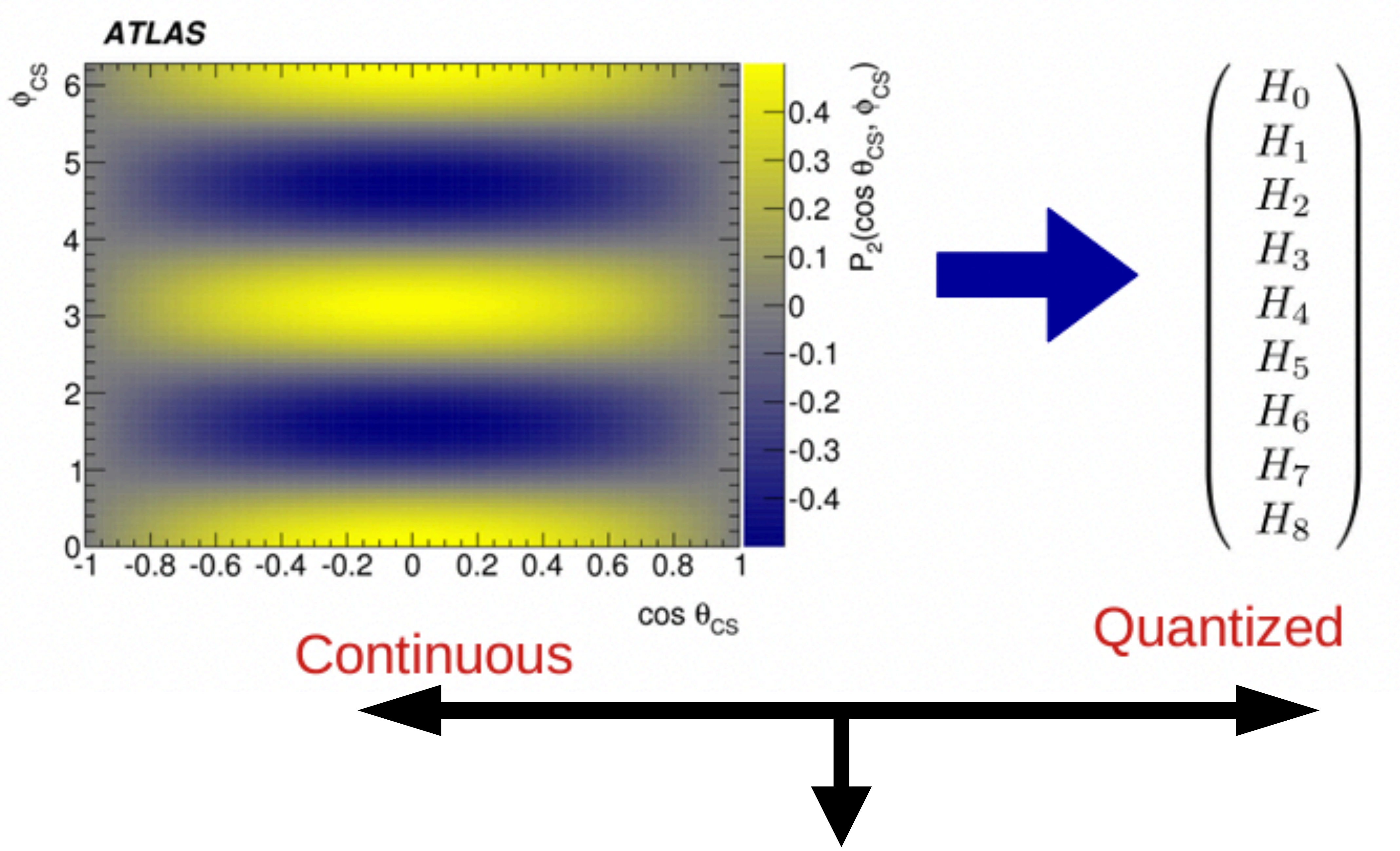
$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T dy dm}\left(1+\cos^2\theta + \sum_{i=0}^{7} A_i(y, p_T, m)P_i(\cos\theta,\phi)\right)$$

- $d\sigma/dp_T$: Transverse dynamics
- $d\sigma/dy$: longitudinal dynamics (PDFs)
- Decomposition of $(\cos\theta, \phi)$ into 9 helicity cross sections ⟶ basis of spherical harmonics



- **Measuring the angular coefficients corresponds to building a synthetic quantised representation of the $(\cos\theta, \phi)$kinematic space**
- **Trade systematics for statistics**
- **Fiducial cuts removed by analytic integration of $(\cos\theta, \phi)$ in the full phase space of decay leptons via measured Ai coefficients**

Expected Yield

$$N^n_{\exp}(A,\sigma,\theta) = \left\{\sum_{j=1}^{N^{ana}_{bins}} \mathcal{L}\sigma_j\left[t^n_{8j}(\beta) + \sum_{i=0}^{7} A_{ij}t^n_{ij}(\beta)\right]\right\}\gamma^n + \sum_{B}^{bkgs} T^n_B(\beta)$$

Reco ($p_T^Z, y^Z, m^Z, \cos\theta, \phi$) bin; Cross section; Background template; Truth (p_T^Z, y^Z, m^Z) bin; Angular coefficient; Templated polynomial

- Likelihood defined in 22528 $(\cos\theta, \phi, p_T)$ bins
- Parameters of interests are 8 Ai + 1 cross section in (p_T, y) bins in total 176 bins

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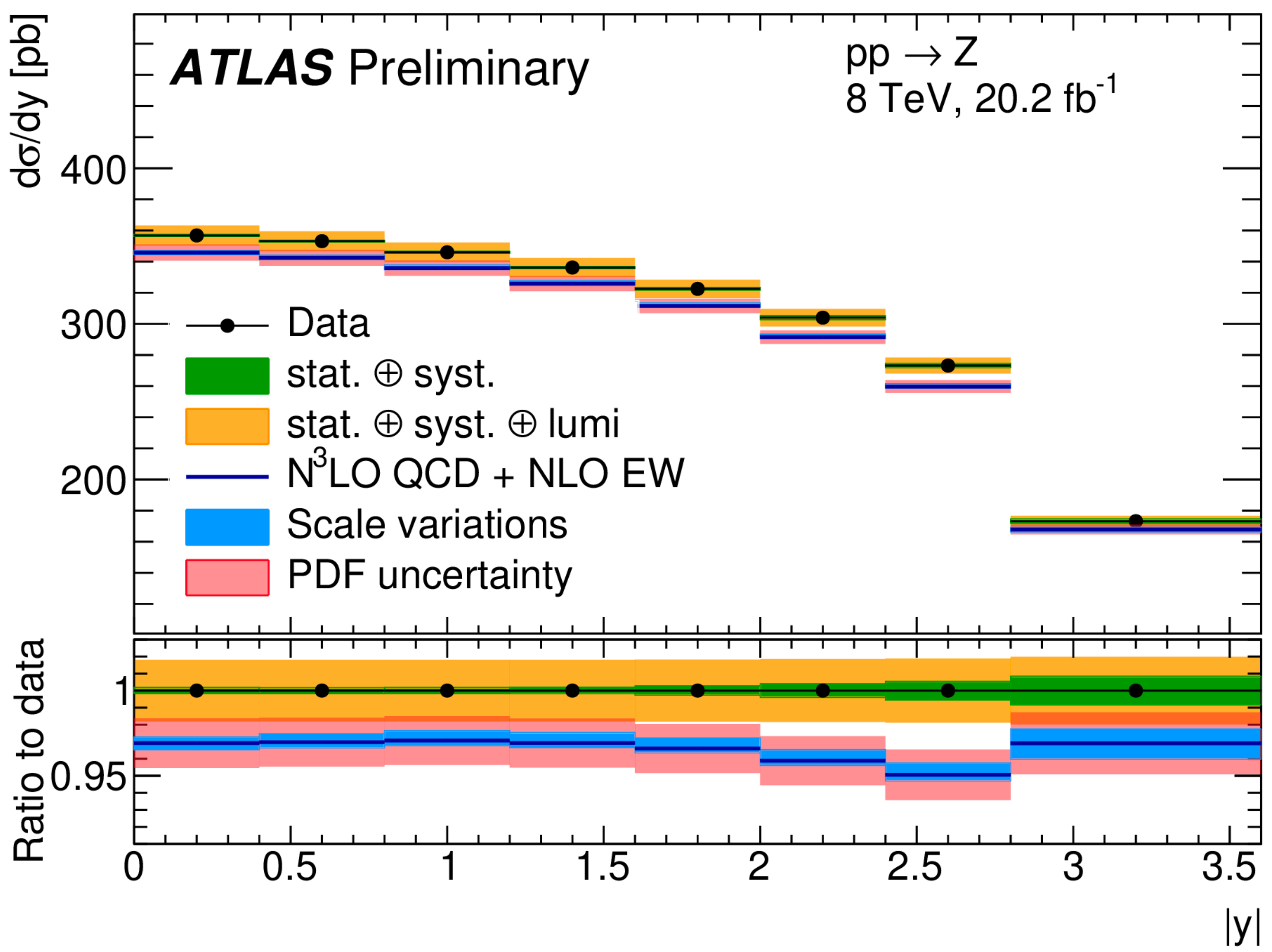
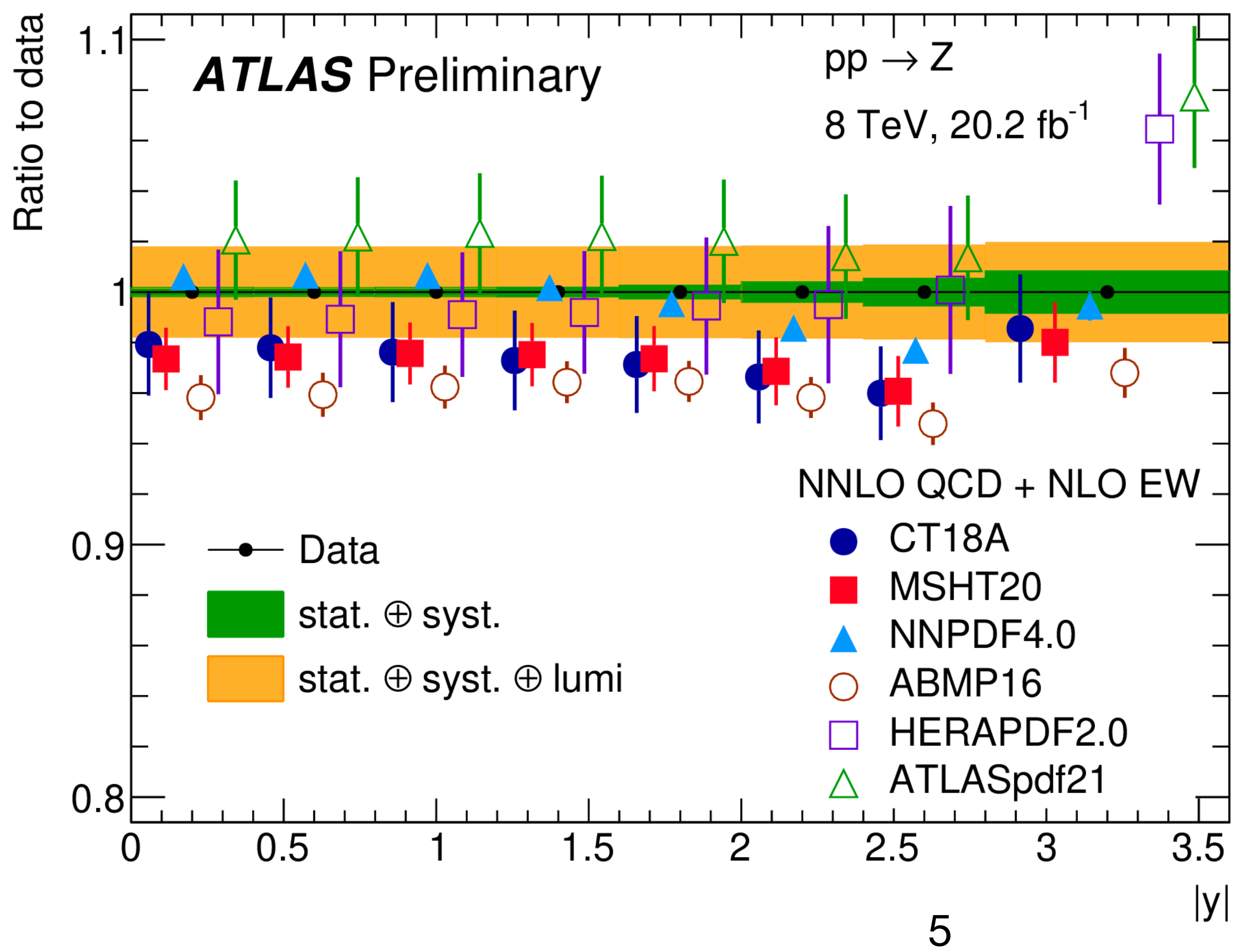
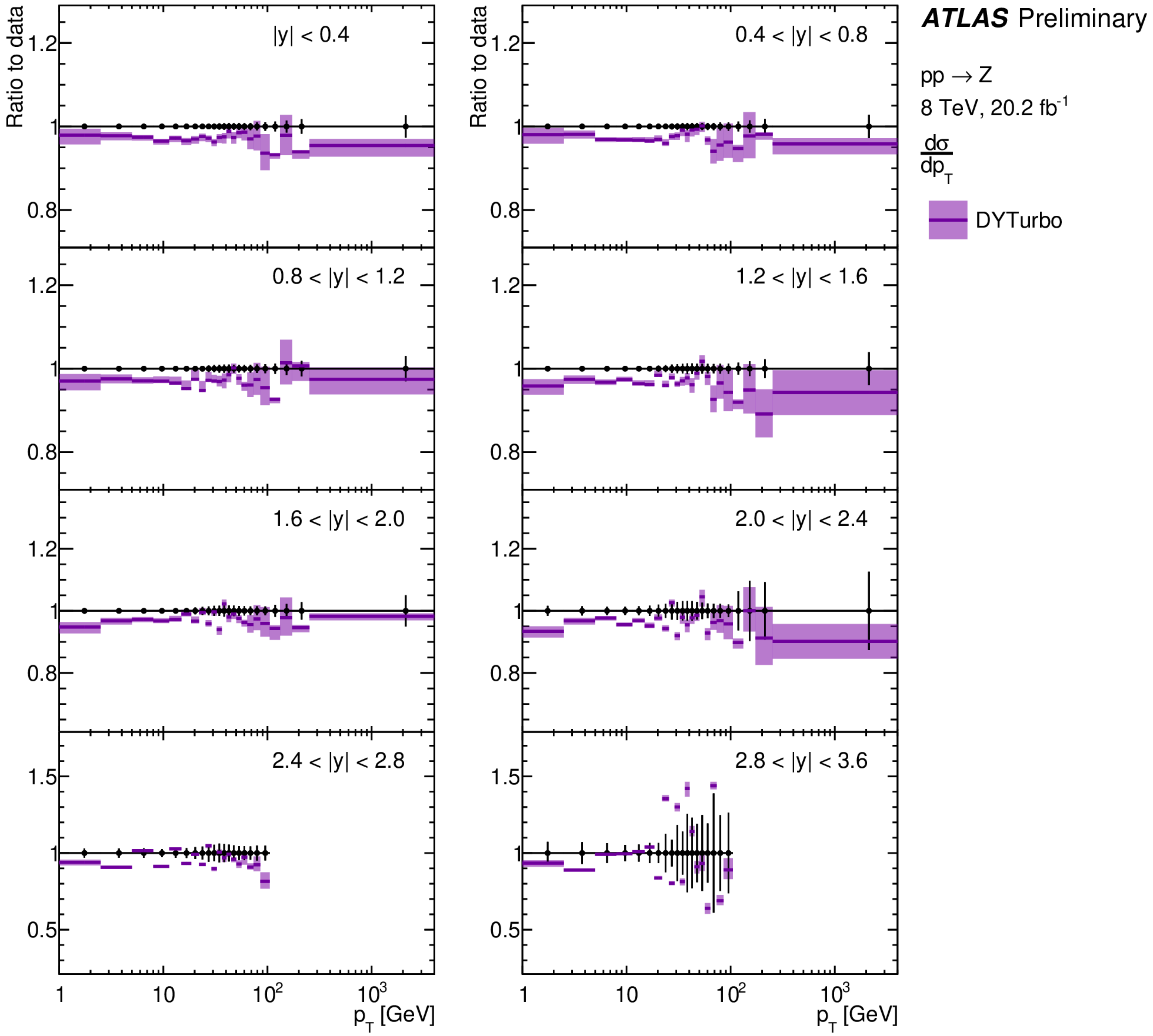
- Per mille level precision in the central region
- Sub-percent precision up to $|y| < 3.6$
- First comparison to N^{3}LO QCD (+ NLO EW) predictions
- Allow precise PDF interpretations with QCD scale uncertainties smaller than PDF uncertainties







α_S extraction from $Z\ p_T$ precision measurement

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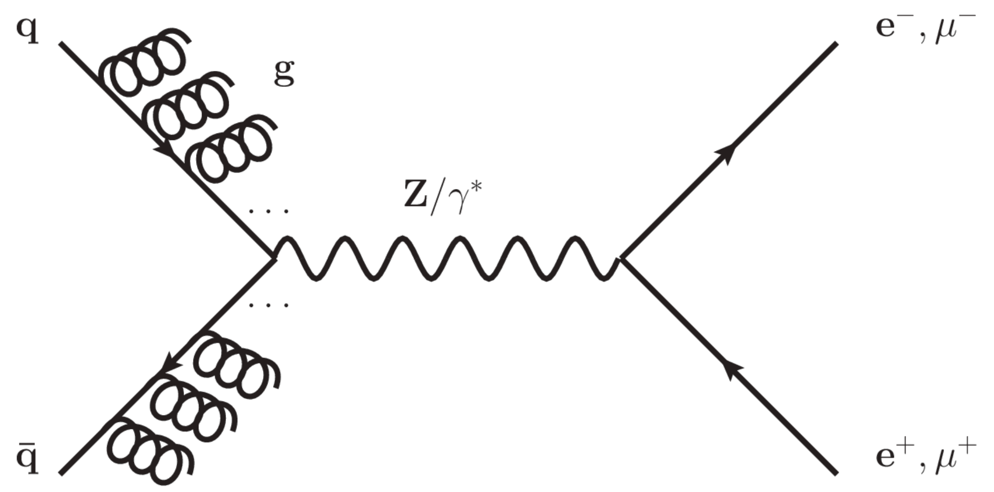
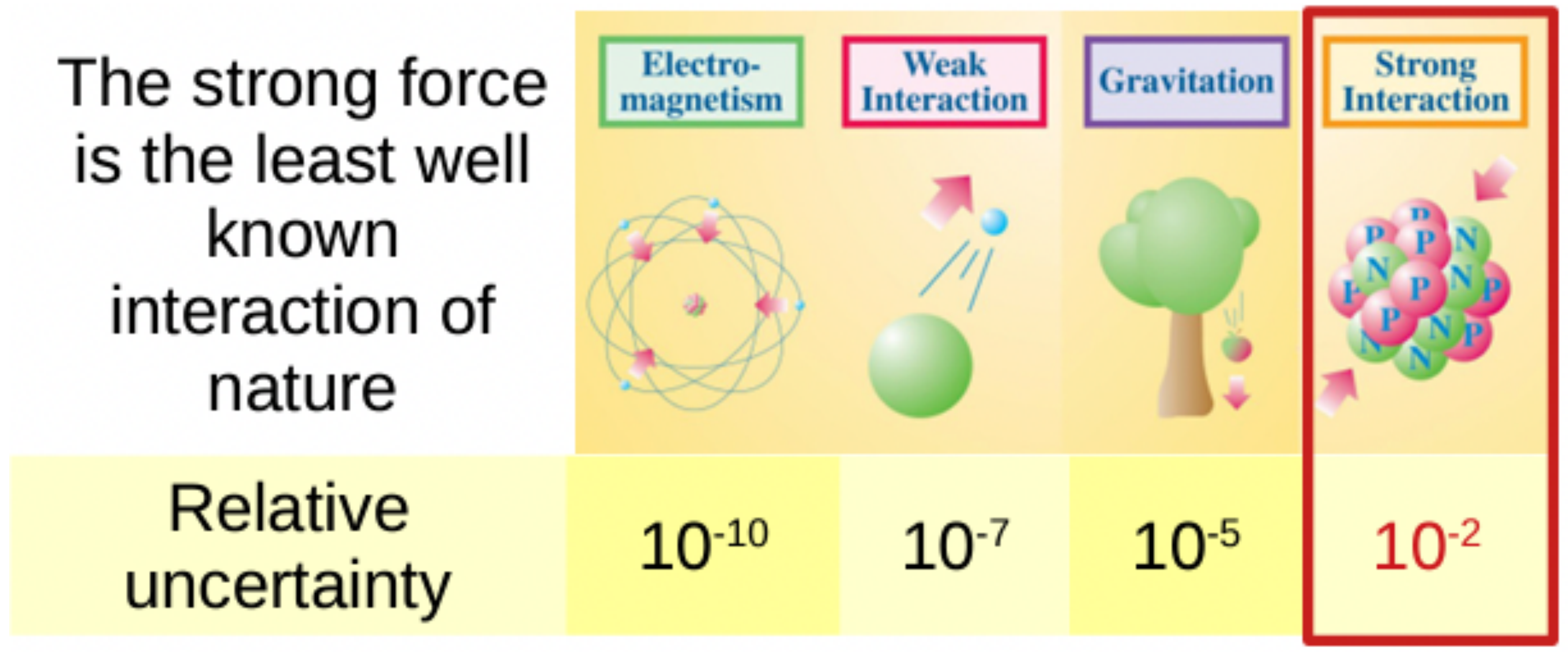


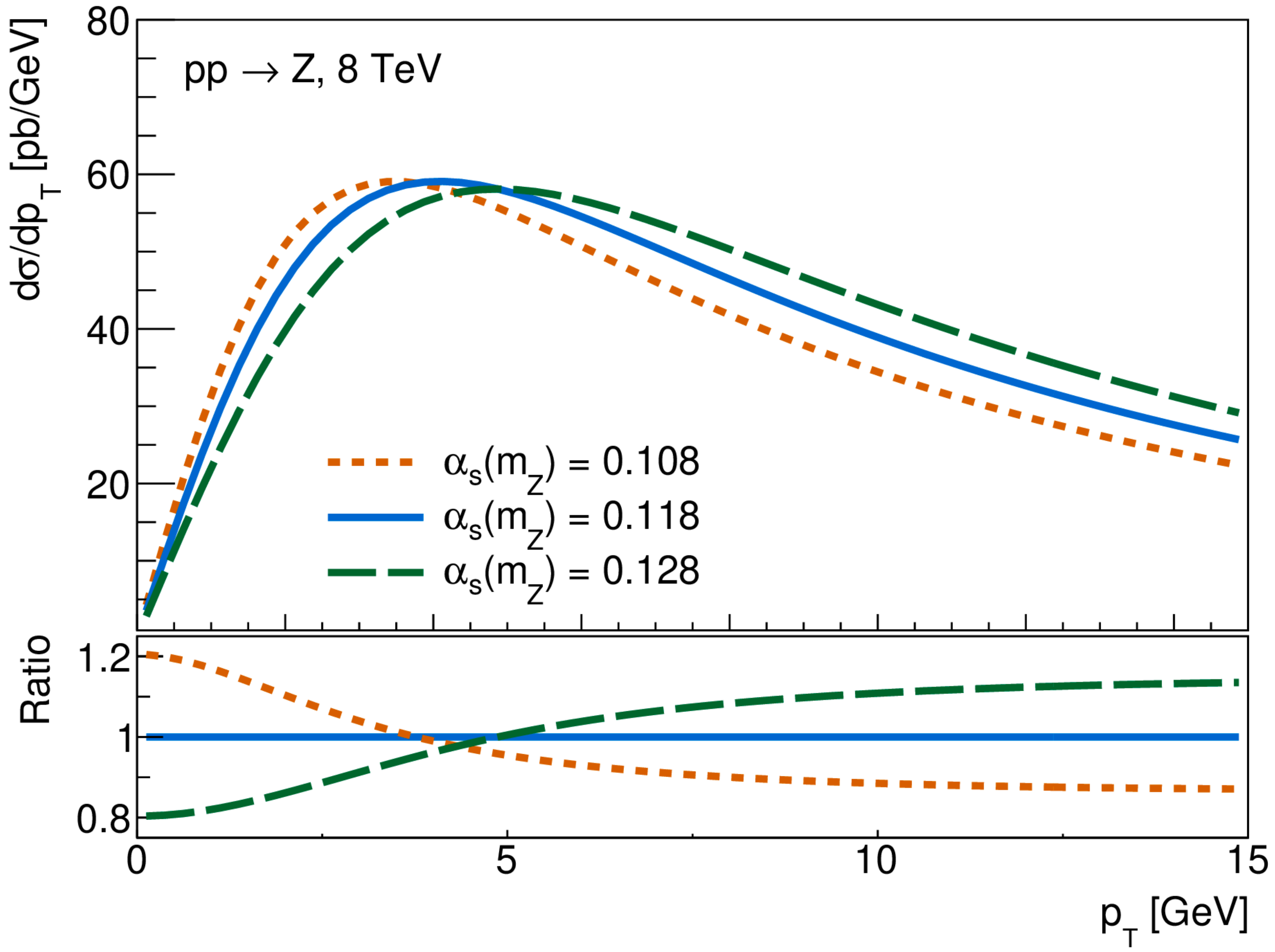


- Strong coupling strength α_S is the least well known in nature

- Dominant uncertainties to precision measurements of Higgs coupling at LHC or EW precision observables at e^+e^- colliders

- Non-zero value of $Z\ p_T$ arises from initial state radiations from incoming partons due to momentum conservation

- The peak position of $Z\ p_T$ and above is sensitive to $\alpha_S(m_Z)$



α_S extraction methodology

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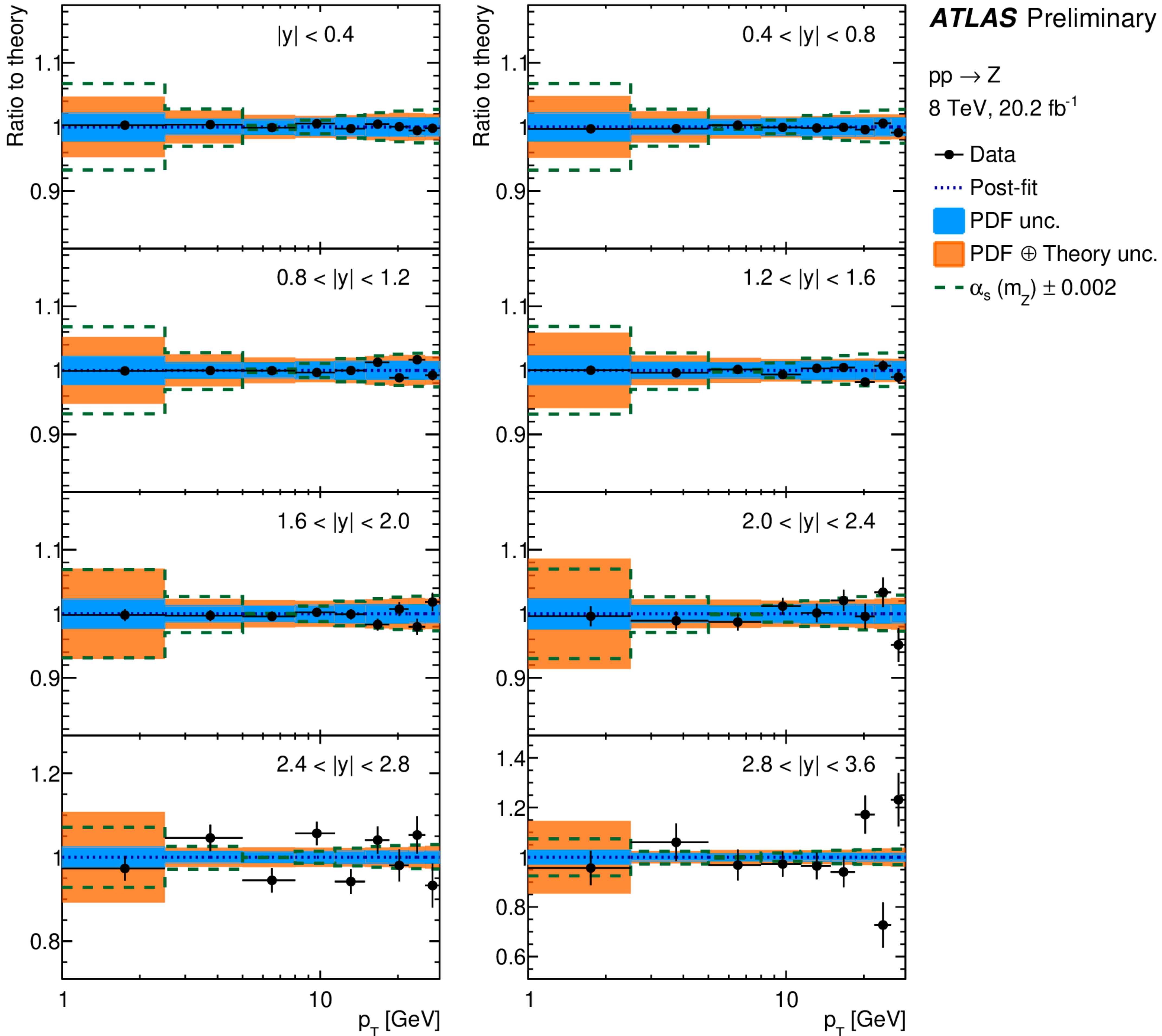
$$\chi^2(\beta_{\exp}, \beta_{\mathrm{th}}) = \sum_{i=1}^{N_{\mathrm{data}}} \frac{\left(\sigma_i^{\exp} + \sum_j \Gamma_{ij}^{\exp}\beta_{j,\exp} - \sigma_i^{\mathrm{th}} - \sum_k \Gamma_{ik}^{\mathrm{th}}\beta_{k,\mathrm{th}}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\exp}^2 + \sum_k \beta_{k,\mathrm{th}}^2 .$$

- Evaluate $\chi^2(\alpha_S)$ with α_S variations provided in LHAPDF
  - Include experimental ($\beta_{j,exp}$) and PDF ($\beta_{k,th}$) uncertainties in the $\chi^2(\alpha_S)$
  - For each value of $\alpha_S(m_Z)$, $\beta_{k,th}$ terms explore the PDF space to find the best fit to Z p_T data
  - MSHT20 PDF set is used for the α_S extraction
- Fit Z $p_T < 29$ GeV region
  - Non-perturbative form factor (affecting Z $p_T < 5$ GeV) is added with unconstrained nuisance parameter
- $\alpha_S(m_Z)$ is extracted by fitting the double differential $p_T - y$ Z cross section in full lepton phase space
  - $\chi^2/ndf = 82/72$



α_S extraction results

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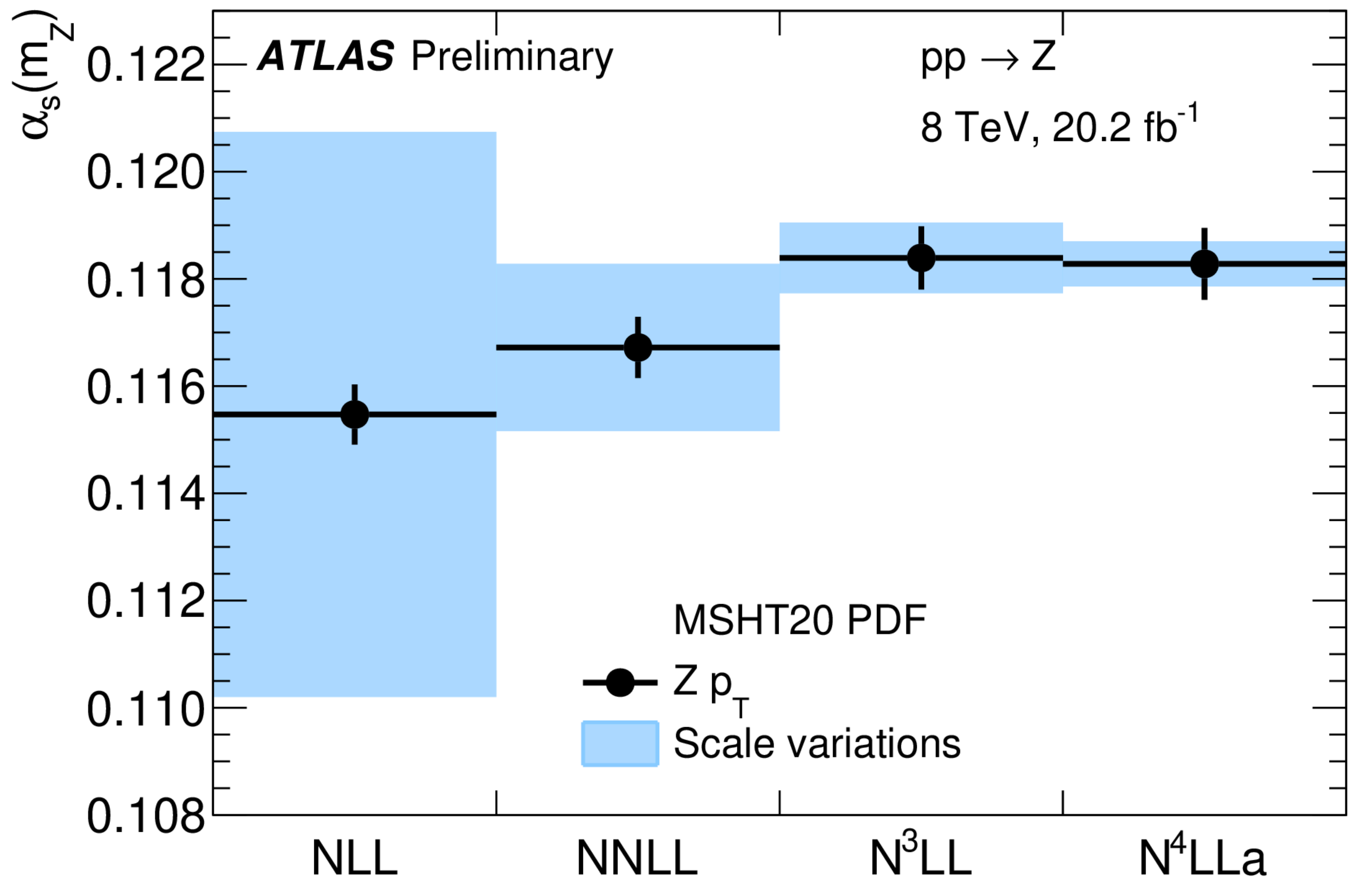
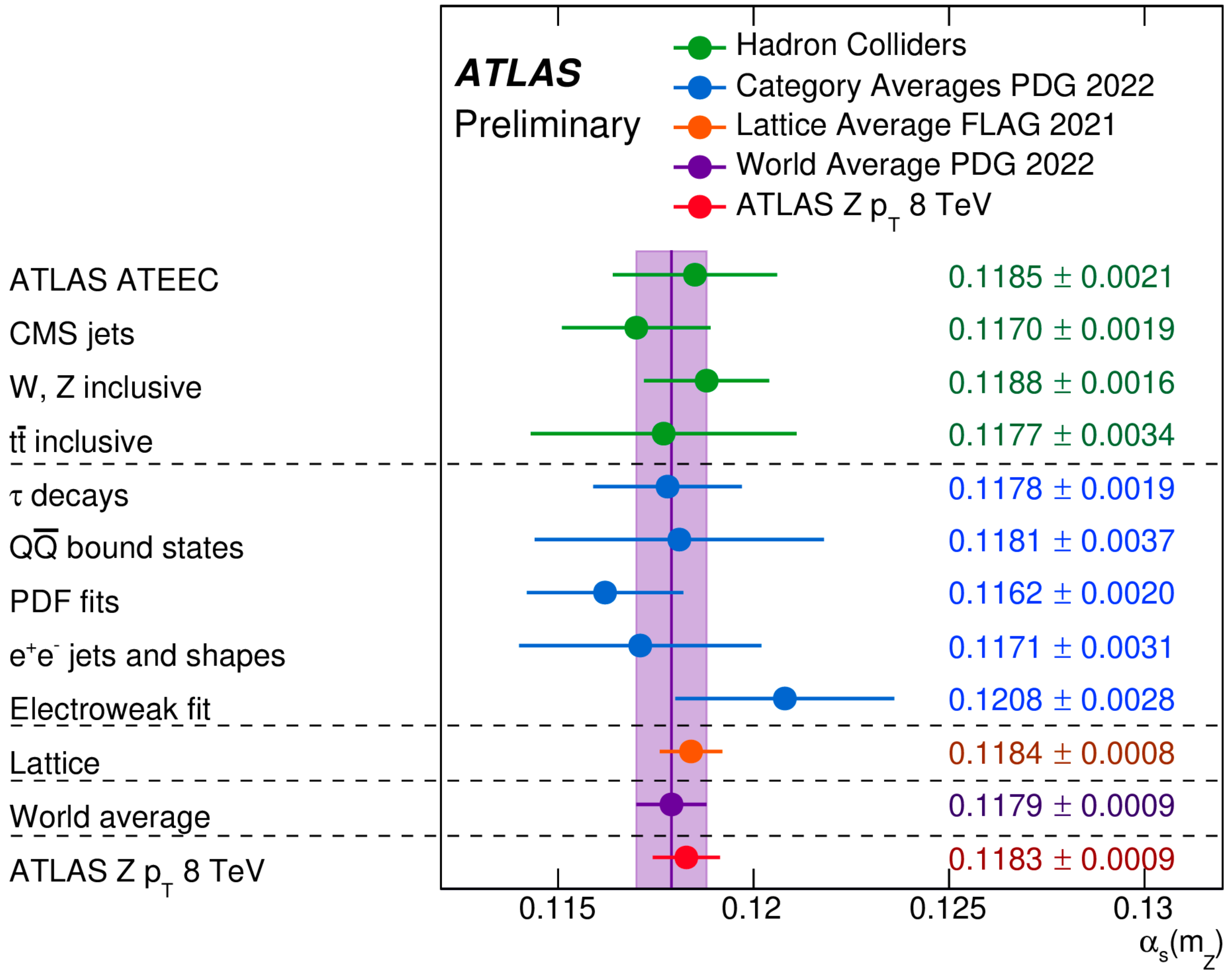
- $\alpha_S(m_Z)$ determined at lower orders, demonstrating good convergence of perturbative series
- First $\alpha_S(m_Z)$ determination at N^{3}LO+N^{4}LL
- Precision similar to world average

Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

α_s = 0.11828 +0.00084 –0.00088





W mass re-analysis at 7 TeV

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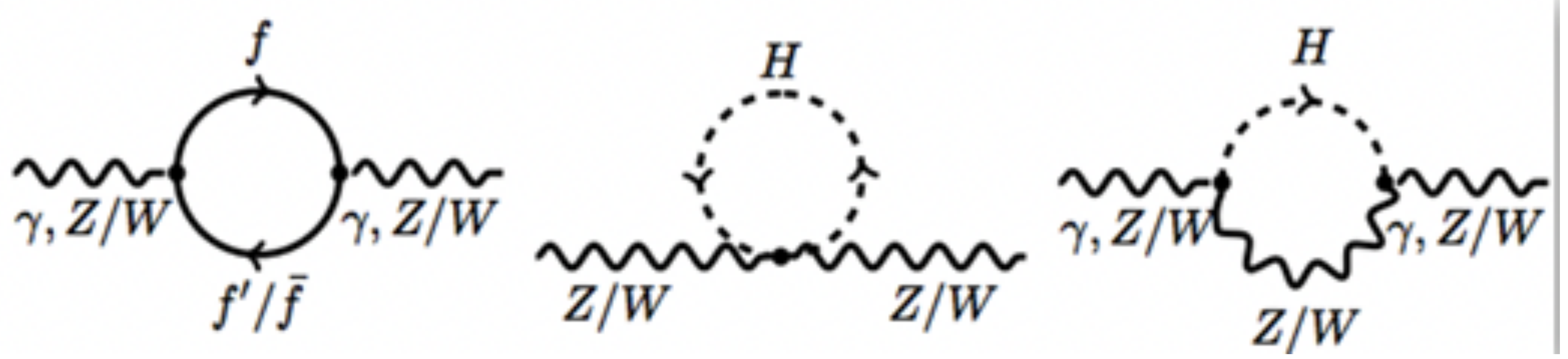
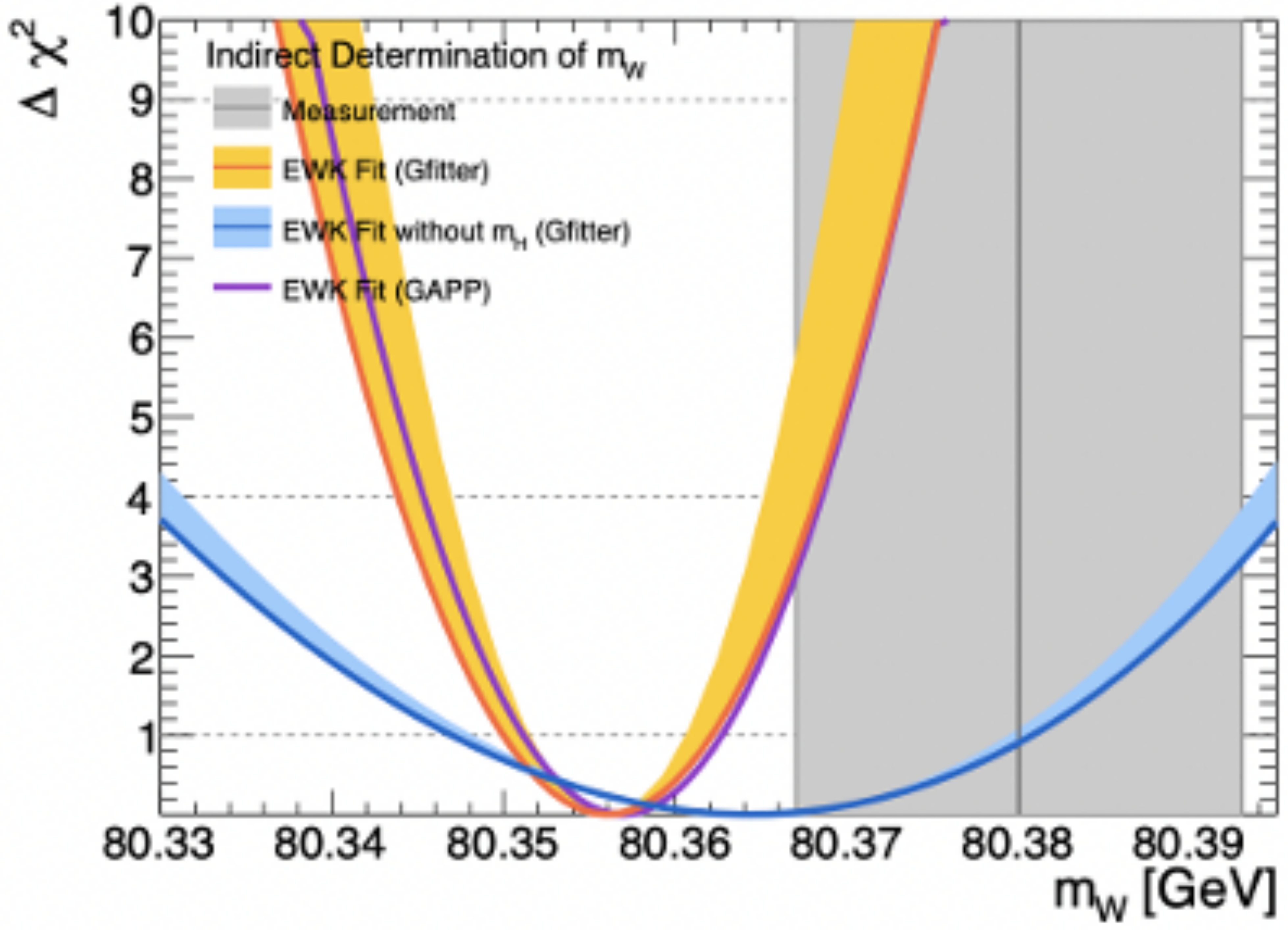
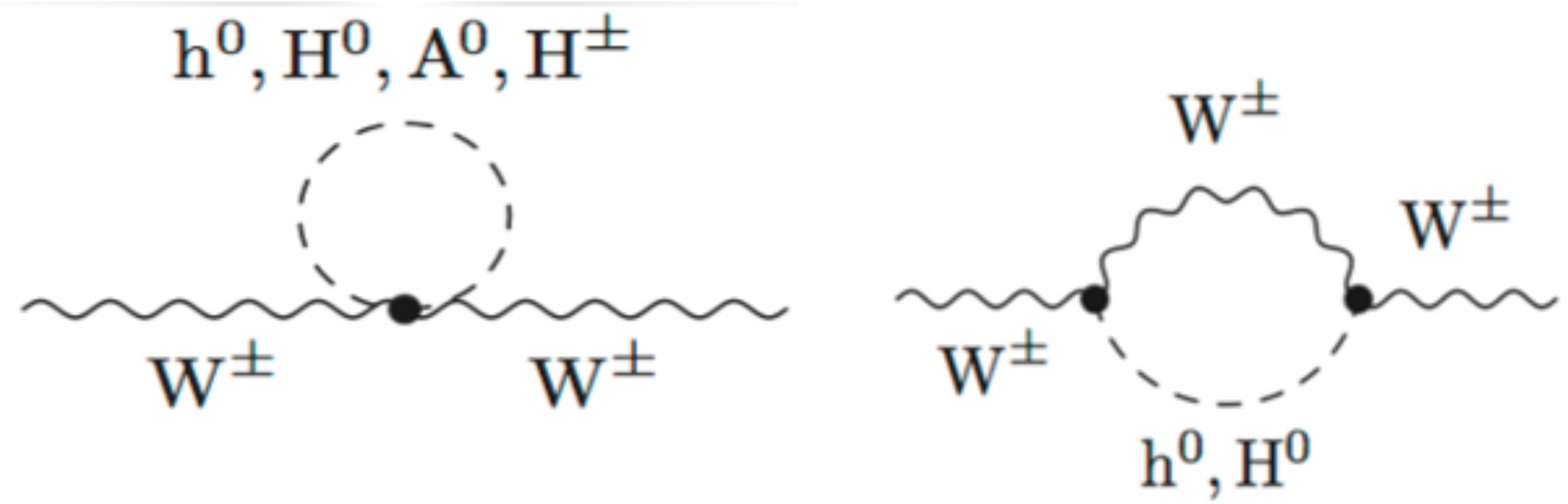


- m_W can be determined indirectly in EW global fit using four EW parameters (α_{em}, G_F, m_Z and $\sin\theta_W$) and m_H, m_{top}
  - $\Delta m_W = 7$ MeV
- New particles in the virtual loops can potentially modify the SM prediction of m_W





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

W mass re-analysis at 7 TeV

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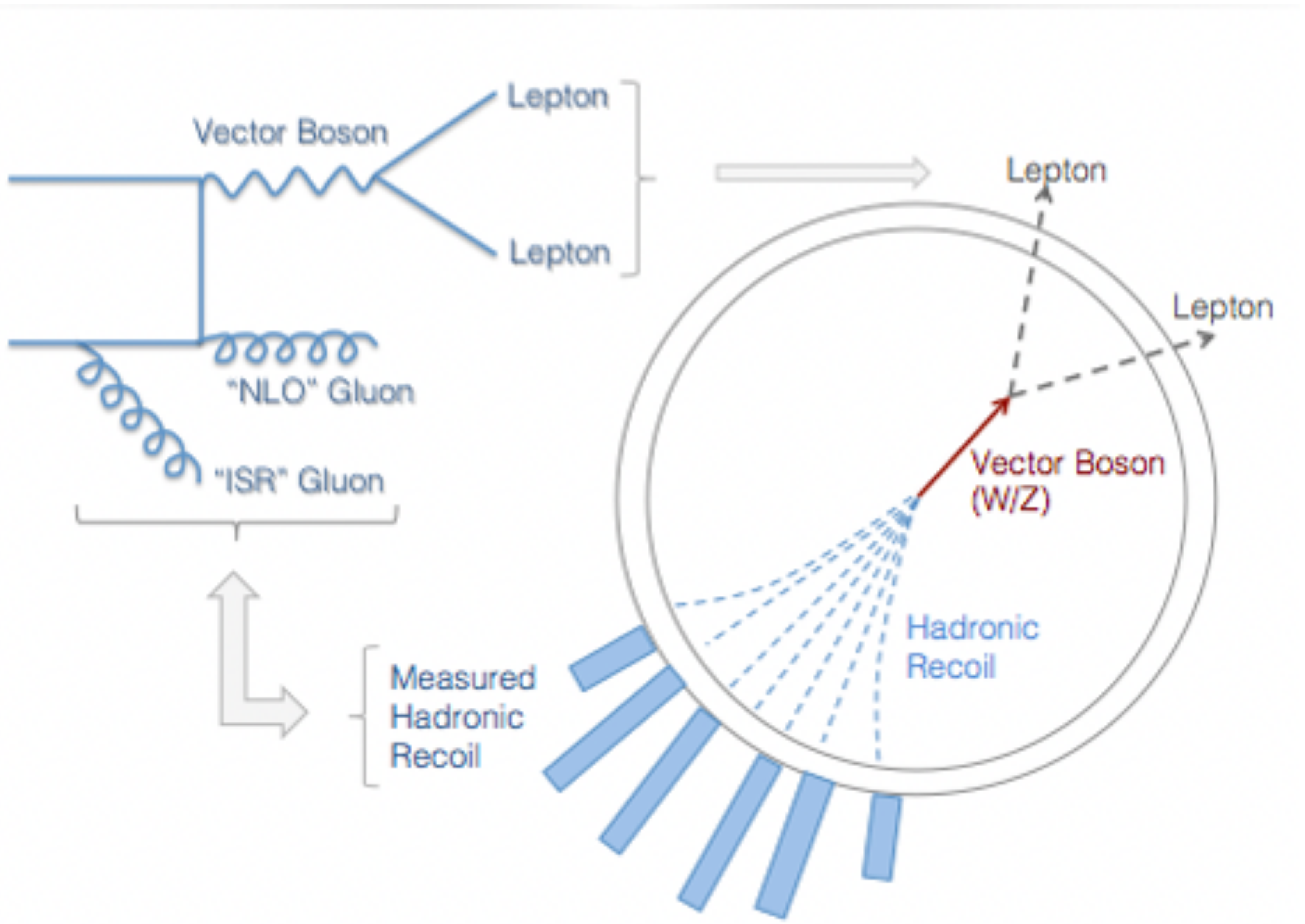
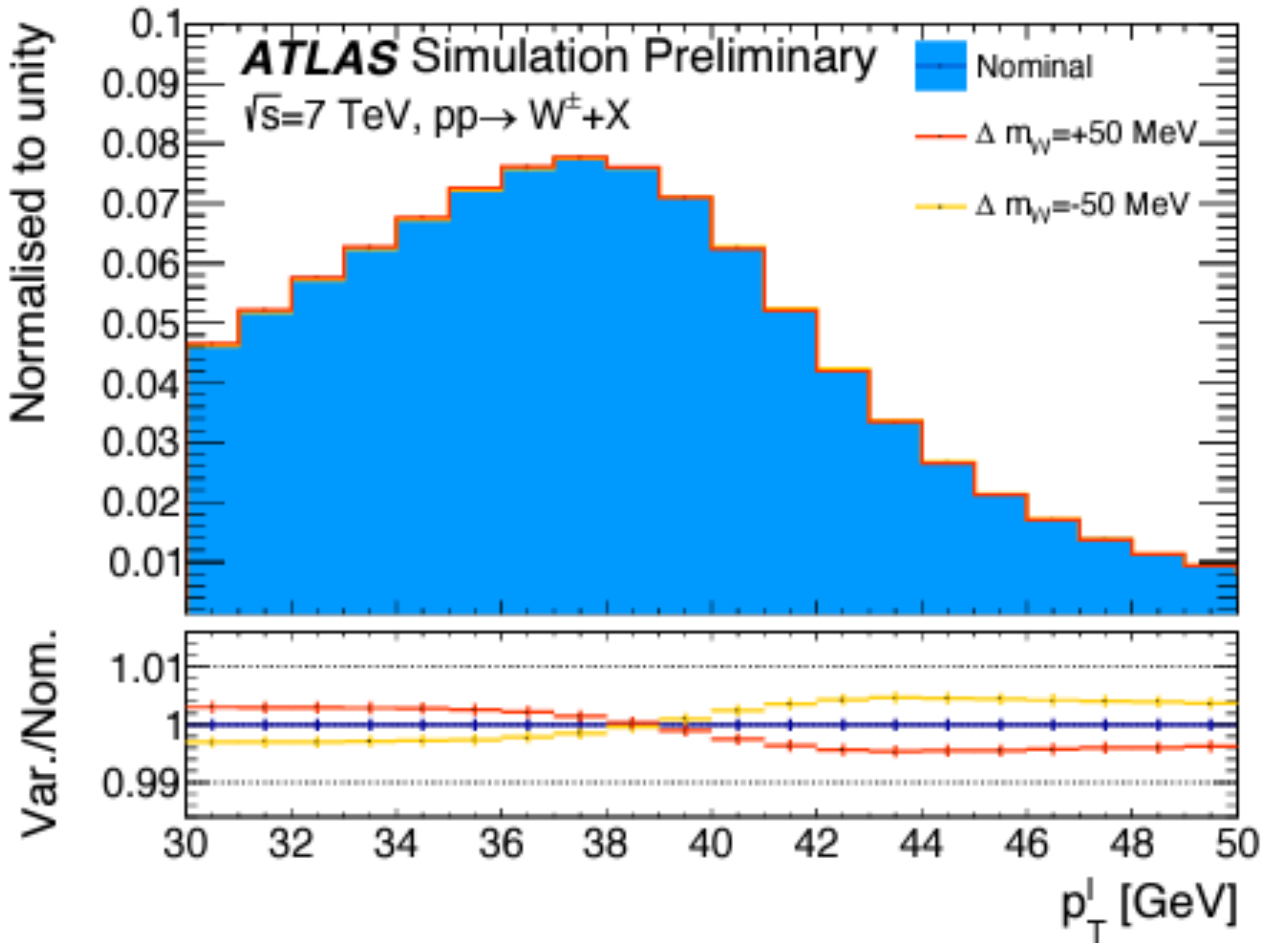
- m_W is determined using its dependence on the leptonic momentum p_T and the transverse mass m_T
- 2016 measurement revisited with advanced physics model and profile likelihood fitting
  - Advantages: Constrain systematic uncertainties in the fit
  - Disadvantages: Computational expensive, challenging to inspect systematics





W mass re-analysis at 7 TeV

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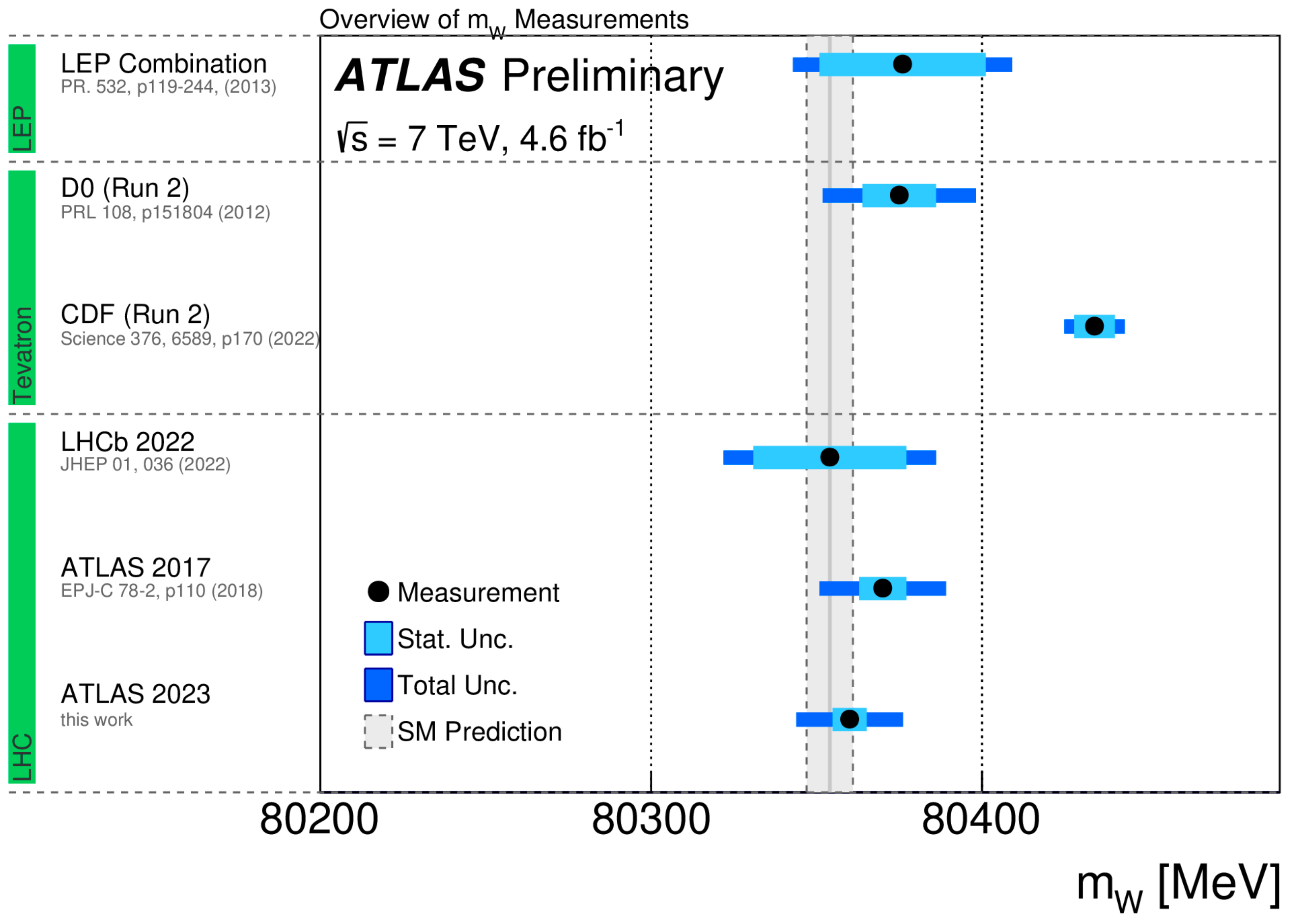
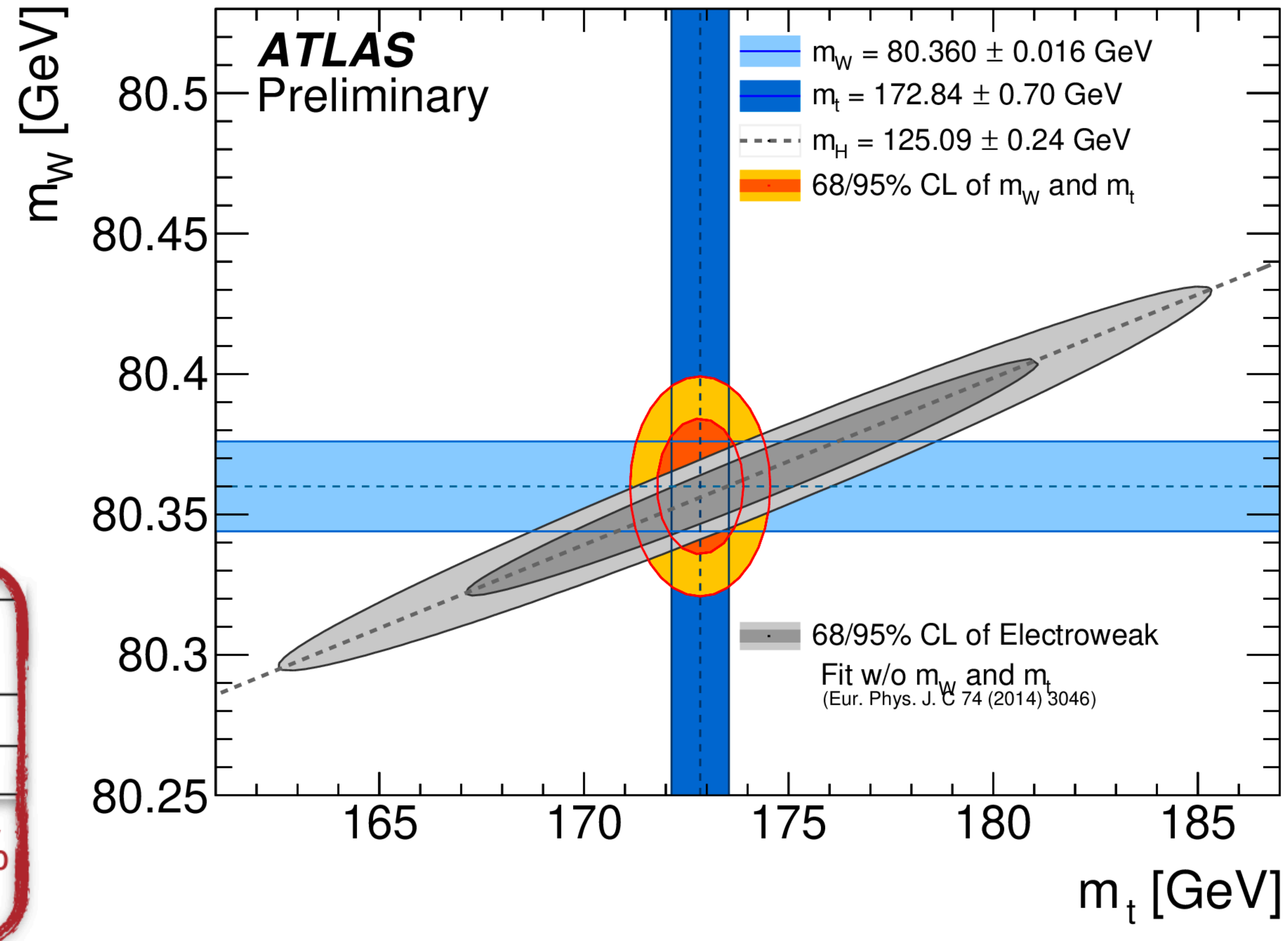
- The new measurement gives

$$m_W = 80360 \pm 5_{(stat.)} \pm 15_{(syst.)} = 80360 \pm 16 \text{ MeV}$$

- Systematics dominated by the electron performance, PDF, EW and Parton Shower (PS)
- All in all, SM wins





Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3
Improvements			≅15% ≅30%			≅40% ≅10%								≅15%

Summary

- SM model continues to be a successful theory under immense inspection with unprecedented precision from LHC
  - No significant tension from the state of art predictions with accuracy up to N^3LO+N^4LL
  - Most precise determination of α_S and m_W from LHC
- LHC will continue to test SM with more to come!

Back-up

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PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN^{3}LO [60]	13/8	0.11	1.2 ± 0.6
CT18A [61]	12/8	0.17	0.9 ± 0.7
MSHT20 [62]	10/8	0.26	0.9 ± 0.6
NNPDF4.0 [63]	30/8	0.0002	0.0 ± 0.2
ABMP16 [64]	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0 [65]	22/8	0.005	-1.3 ± 0.8
ATLASpdf21 [66]	20/8	0.01	-1.1 ± 0.8

Back-up

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