Longitudinally polarised Z-bosons and the Higgs cross-section at the LHC (based on 2012.10298)

DIS 2021 - virtual conference
Apr. 13th, 2021

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for the xFitter developers

The xFitter project

- *xFitter*, an open-source QCD fit framework
  - Allows for extraction of PDFs
  - Asses the impact of new measurements on PDF (Hessian profiling or Bayesian reweighting)
  - Evaluate consistency of experimental data
  - Test various theoretical assumptions

- Over *80 publications* using *xFitter* since the project beginning https://www.xfitter.org/xFitter/xFitter/results

- And the tool of choice for PDF studies by ATLAS/CMS

Latest release

- *xFitter* 2.0.1 - updated dependencies + bug fixes

  https://www.xfitter.org/xFitter/xFitter/DownloadPage

  - Script to install *xFitter* and all its dependencies: install-xFitter-2.0.1
  - xfitter-users@googlegroups.com for feedback and help

Releases of the xFitter QCD analysis package

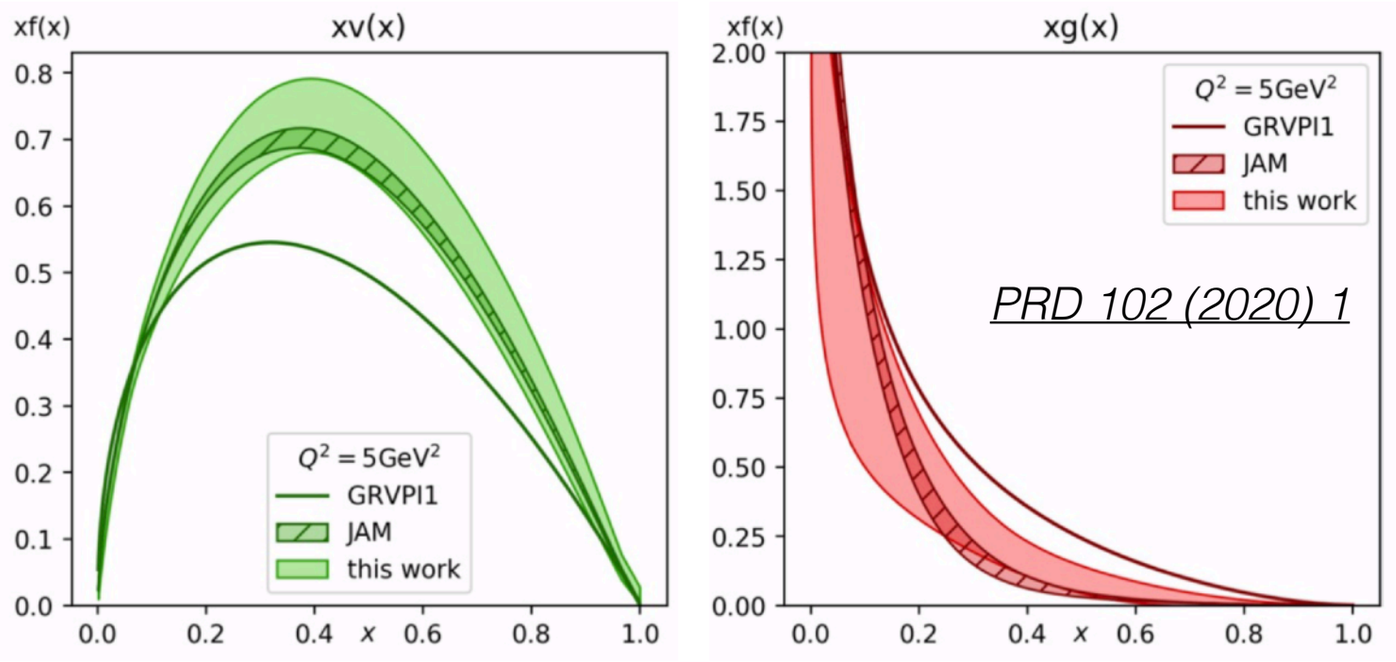
- The release notes can be found in this attachment: xFitter_release_notes.pdf .
- Installation script for xFitter together with QCDNUM, APFEL, APPLGRID, LHAPDF install-xFitter-2.0.1
  - New installation script from master branch install-xfitter-master
- Data and theory files can be downloaded from gitlab gitlab data repository

Date	Version	Files	Remarks
 05/2019	**2.0.1 OldFashioned**	xfitter-2.0.1.tgz	update/bug fix to 2.0.0 FrozenFrog
 03/2017	**2.0.0 FrozenFrog**	xfitter-2.0.0.tgz	stable release with decoupled data and theory files

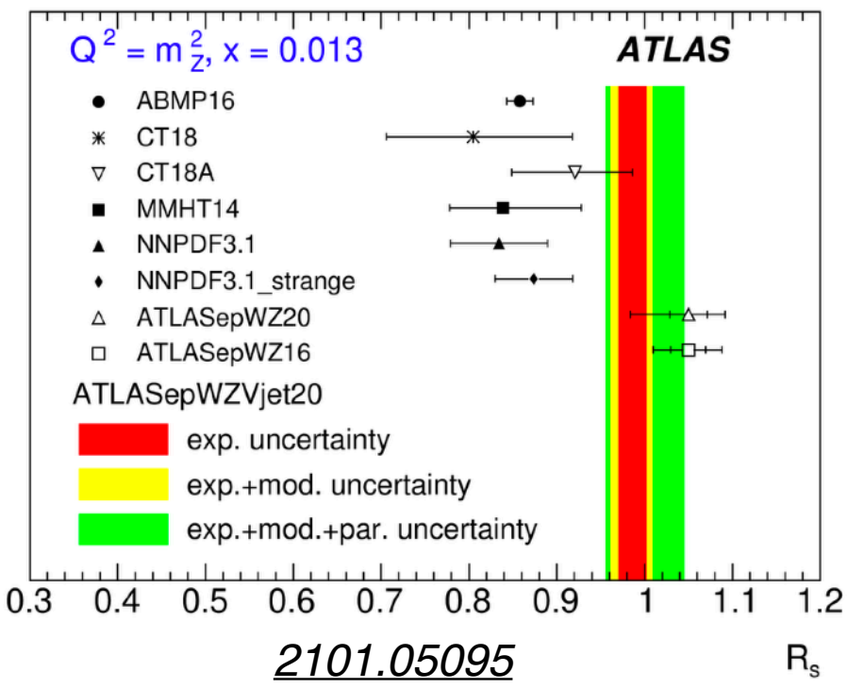
- Large overhaul of the code ongoing in the master version

And recent results

- *xFitter* determination of the Pion PDF
  - PDFs agree with JAM determination
  - Need for more data to determine g, Σ unambiguously



- ATLAS PDFs from W/Z+1jet data



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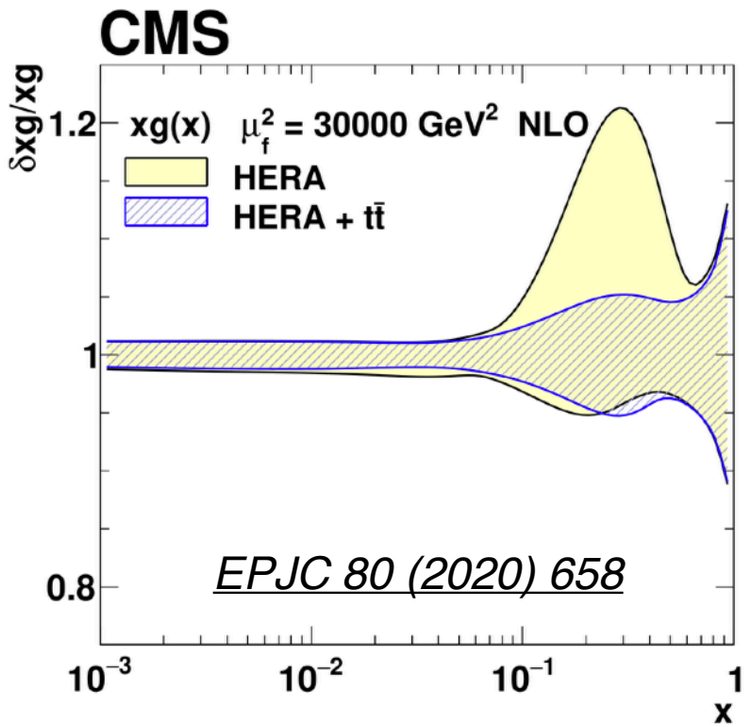
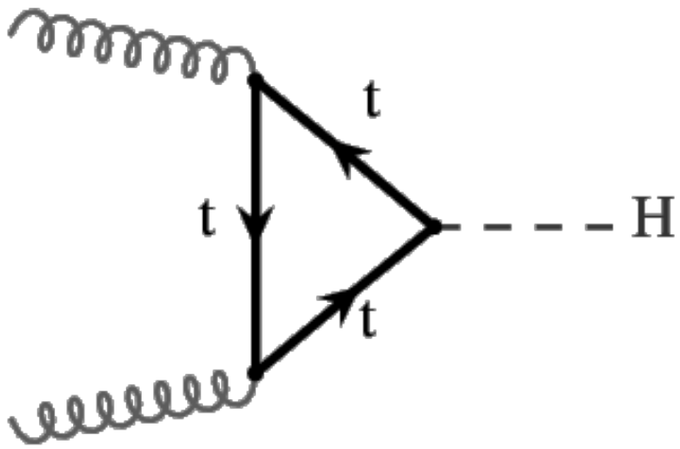
- CMS determination of $\alpha_S(m_Z)$, m_t and the gluon PDF from top quark pair production data

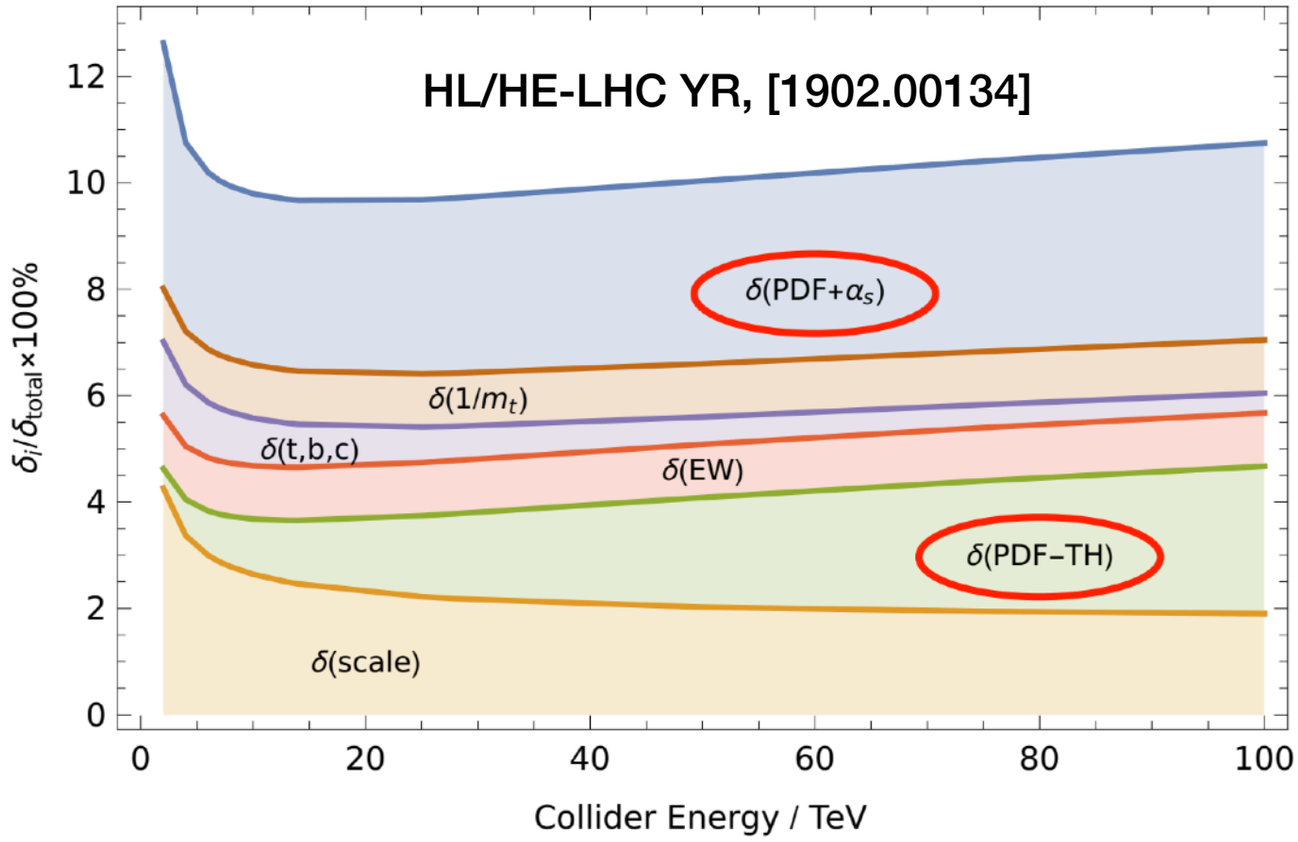


Higgs cross-section and PDFs

- A precise characterisation of the Higgs sector is one of the main goals of the (HL-)LHC physics program



Gluon gluon fusion Higgs cross-section



- Uncertainties due to the knowledge of PDFs are an important limiting factor

- Gluon PDF relevant for ggF, mostly constrained by DIS data
- LHC extractions from jets and top-quark production, challenging to measure and predict to very high accuracy, (see e.g. *EPJC 80 (2020) 60*, *EPJC 80 (2020) 8*)

Higgs cross-section and PDFs

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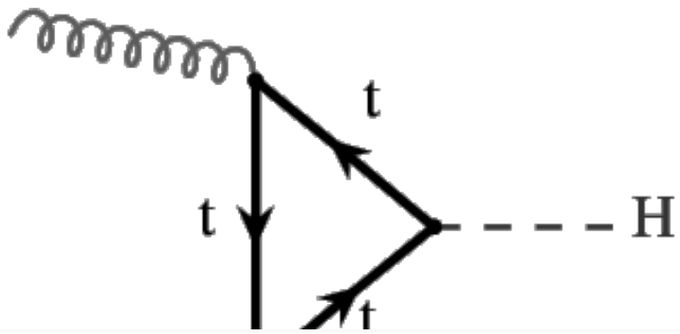
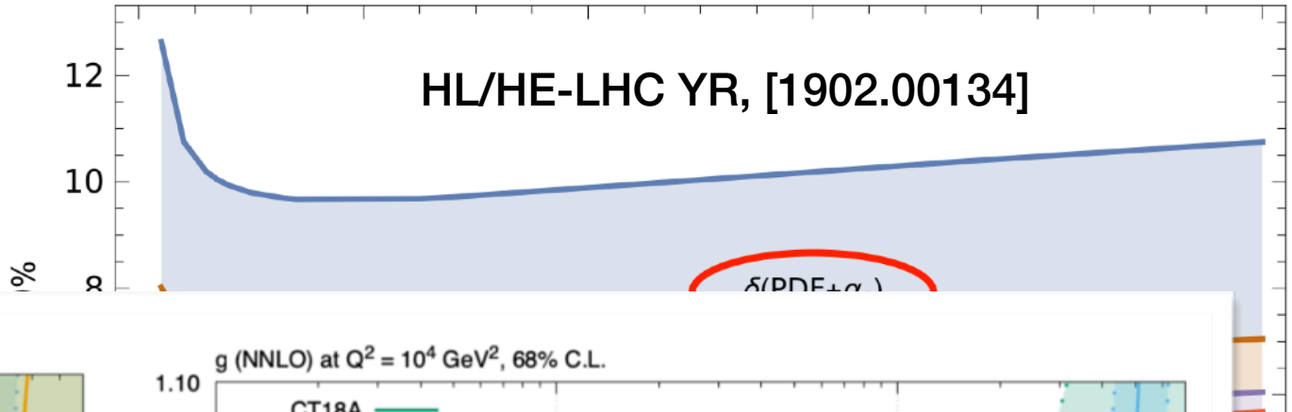
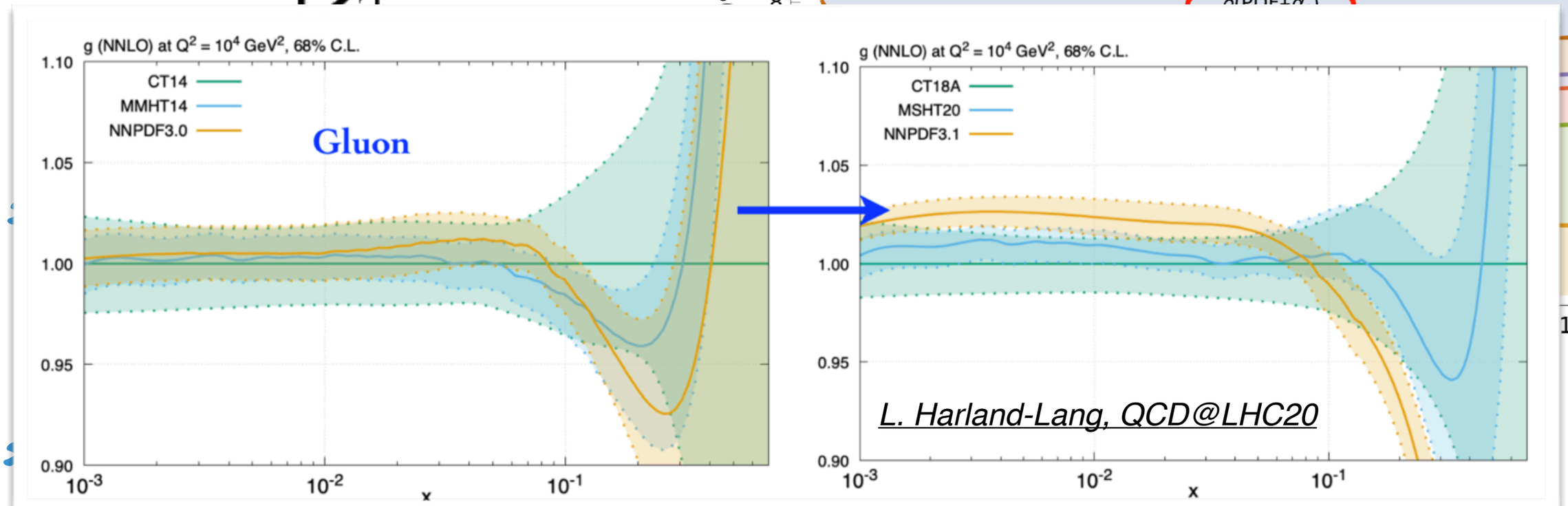


Gluon gluon fusion Higgs cross-section





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Angular coefficients in Drell-Yan

- Interesting to consider wether electroweak bosons could provide a handle to constrain Higgs cross-sections
- Angular distributions of the decay leptons in Drell-Yan production are a portal to its production dynamics
- All-order decomposition of the Drell-Yan cross-section into nine **angular coefficients**, the *Ai*
  - $\cos\theta, \phi$ angles measured in the Collins-Super frame

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{U+L}}{\mathrm{d}p_{\mathrm{T}}^{Z}\,\mathrm{d}y^{Z}\,\mathrm{d}m^{Z}}$$

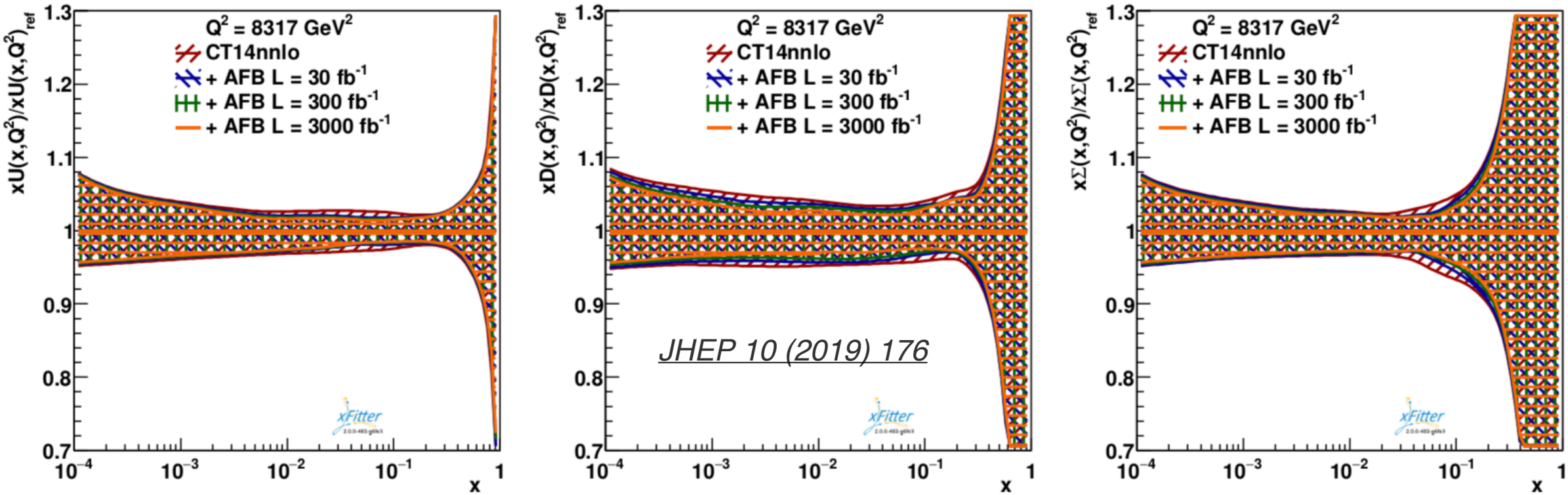
Unpolarised cross-section

Helicity cross-sections

$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\ \sin 2\theta\ \cos\phi + \frac{1}{2}A_2\ \sin^2\theta\ \cos 2\phi + A_3\ \sin\theta\ \cos\phi + A_4\ \cos\theta + A_5\ \sin^2\theta\ \sin 2\phi + A_6\ \sin 2\theta\ \sin\phi + A_7\ \sin\theta\ \sin\phi\Big\}.$$

A_4 and PDFs

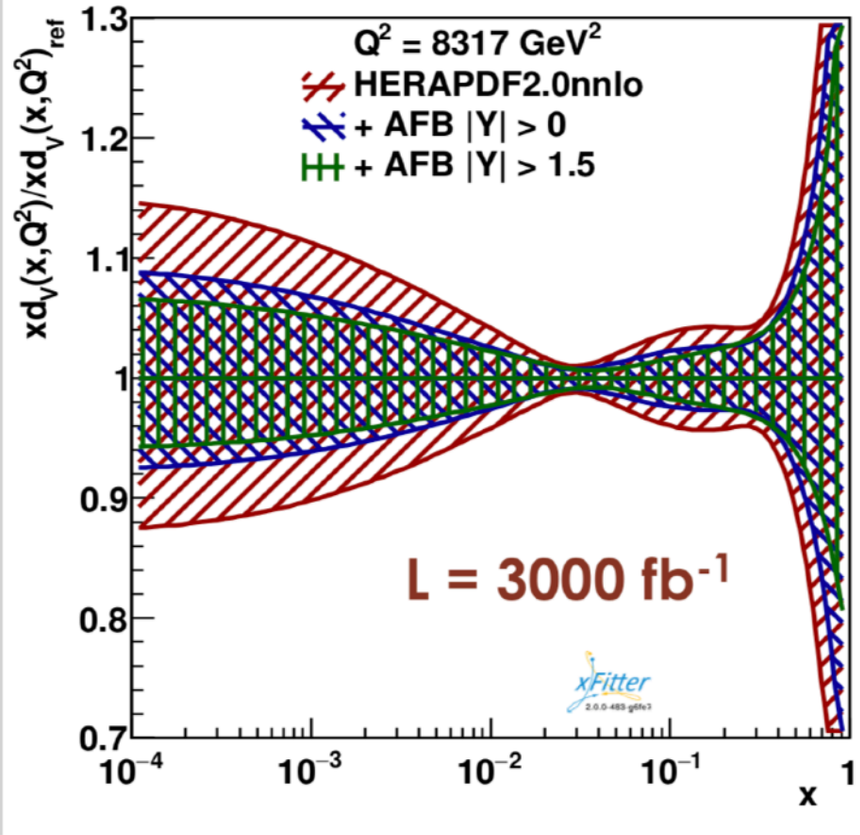
- The A_4 coefficient is parity-violating, sensitive to $\sin^2\theta^l_{\text{eff}}$ and to the flavor non-singlet PDFs
  - Related to the forward-backward asymmetry, in full lepton phase-space $A_{FB} = 3/8\ A_4$
- Sensitivity to PDFs explored in previous xFitter study

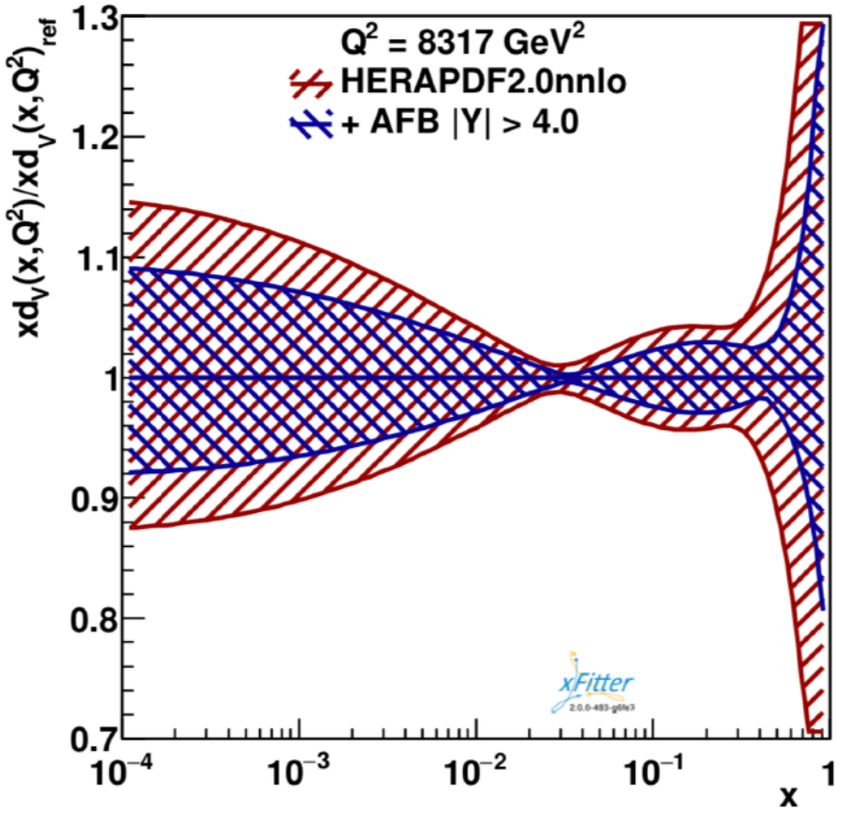


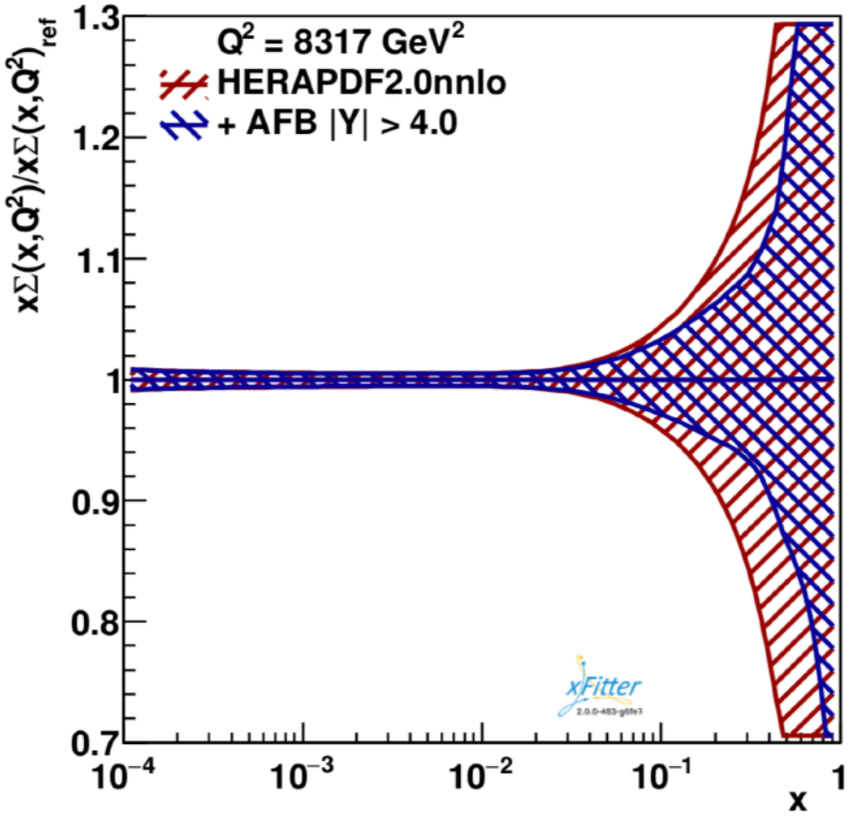
- Largest reduction in uncertainties for u_V PDF, but sizeable reduction also for d_V ($A_{FB} \sim 2/3\ u_V + 1/3\ d_V$)
- Improvements mostly in the low- and intermediate x regions

A_4 and Z rapidity

- The rapidity dependence of A_4 allows to further enhance the PDF sensitivity, particularly for d_V
- The sensitivity at even higher rapidities ($|Y| > 4.0$) is hindered by the reduced data statistics available at small/intermediate x
- But in the high-x region is able to provide significant constraints





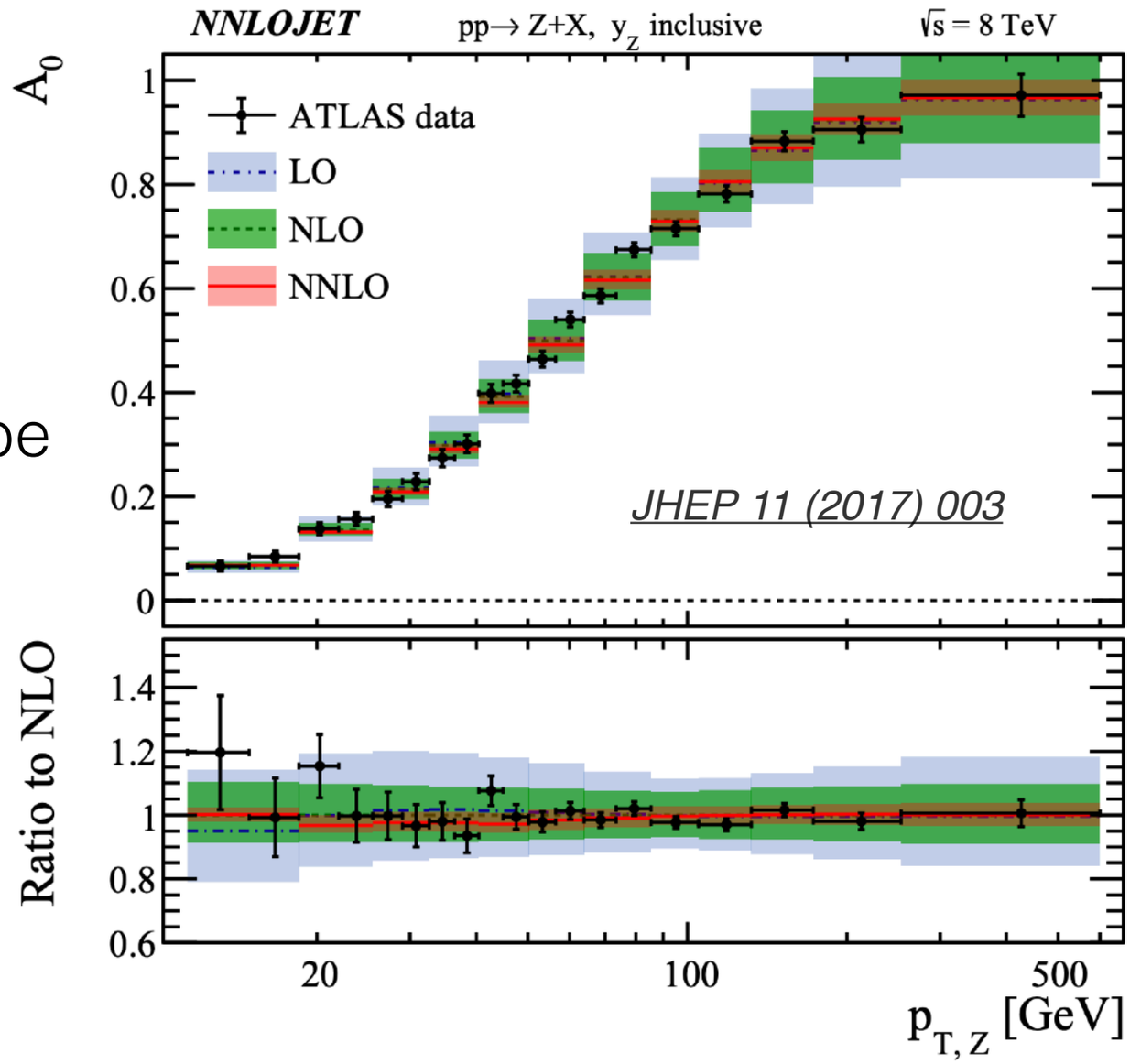


The A_0 coefficient

- In *2012.10298* we explored the PDF sensitivity of A_0
- The A_0 coefficient is parity-conserving and sensitive to the flavour-singlet PDFs
  - Ratio of the longitudinal to unpolarised cross-sections

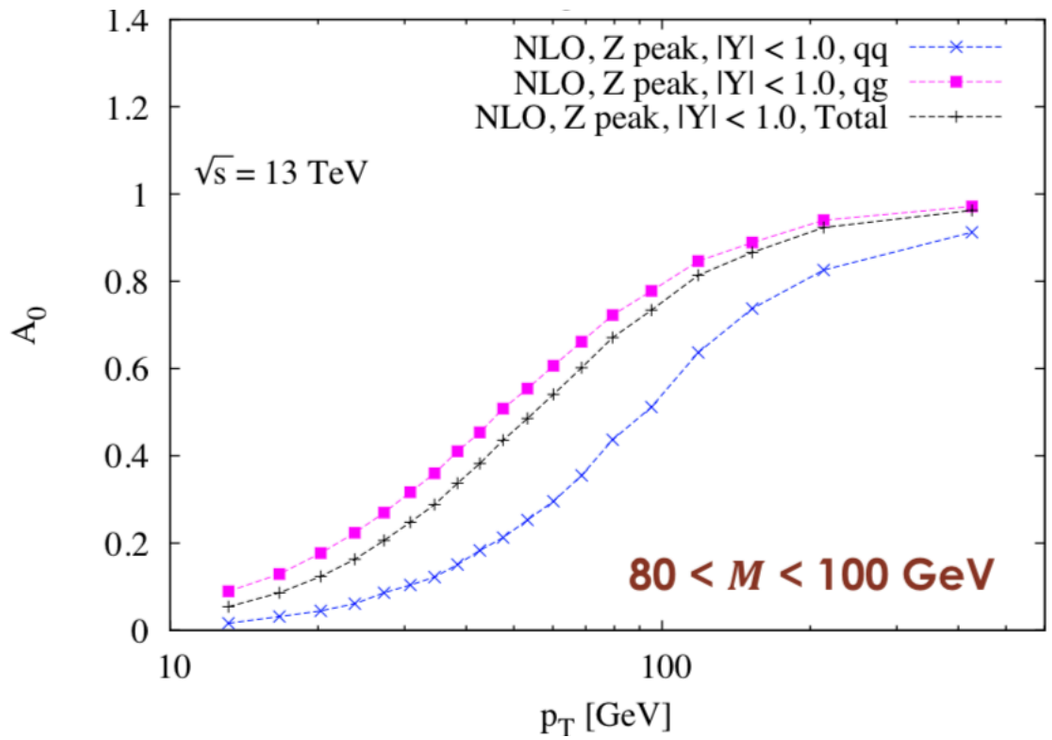
$$A_0(s, M, Y, p_T) = \frac{2d\sigma^{(L)}/dM\,dY\,dp_T}{d\sigma/dM\,dY\,dp_T}$$

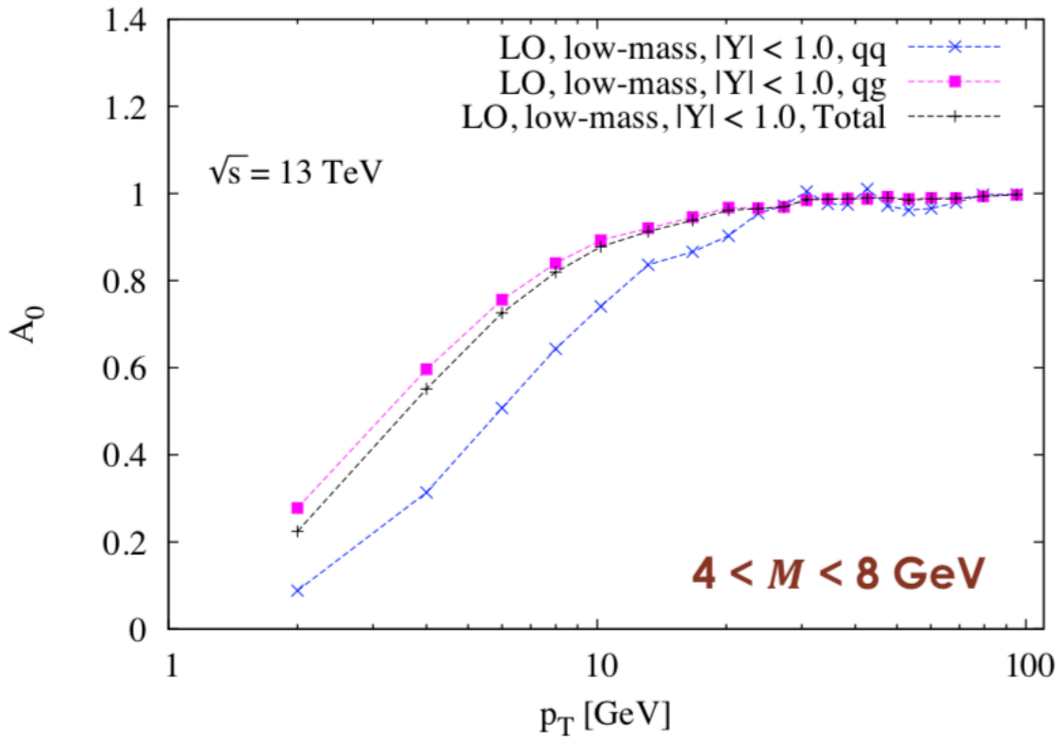
  - Reconstructed from dilepton angular distributions, A_0 can be measured with high accuracy
  - Known to NNLO in QCD and showing remarkable perturbative convergence
  - NLO EW small at high p_T^Z *EPJC 80(2020)10*

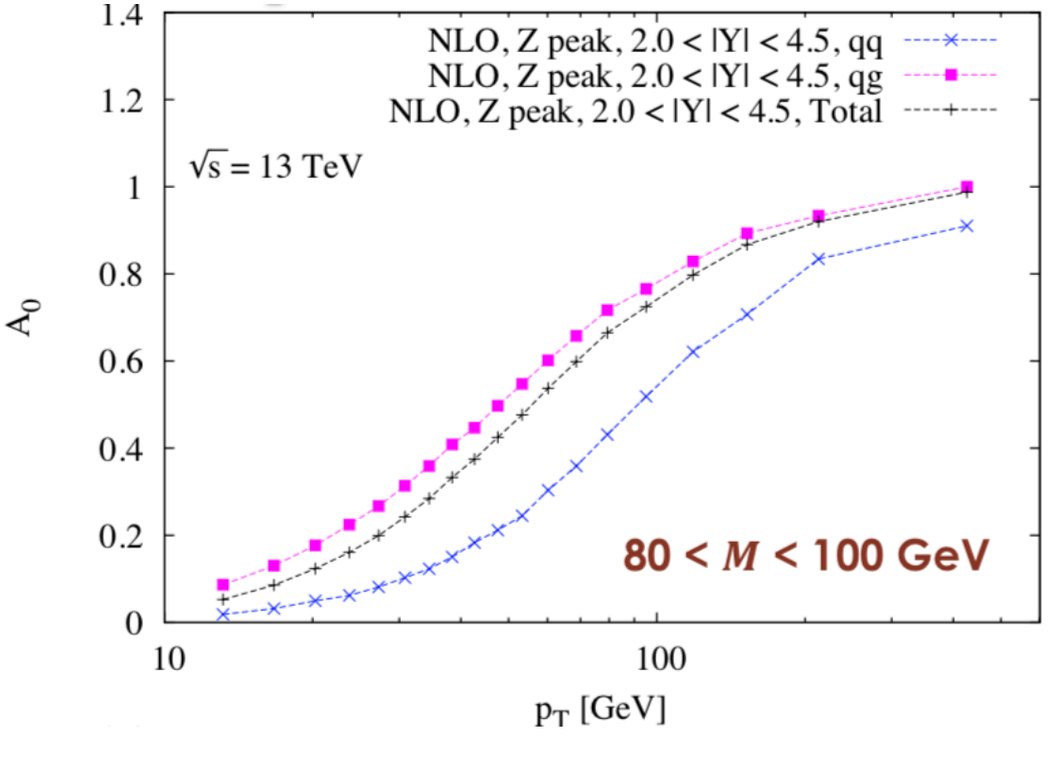


A_0 and the gluon PDF

- A_0 receives different contributions from $q\bar{q}/qg$ subchannels
- The measured value of A_0 constraints the $\bar{q}/g$ ratio
- Largest sensitivity from the region where $\partial^2 A_0/\partial p_T^2 = 0$



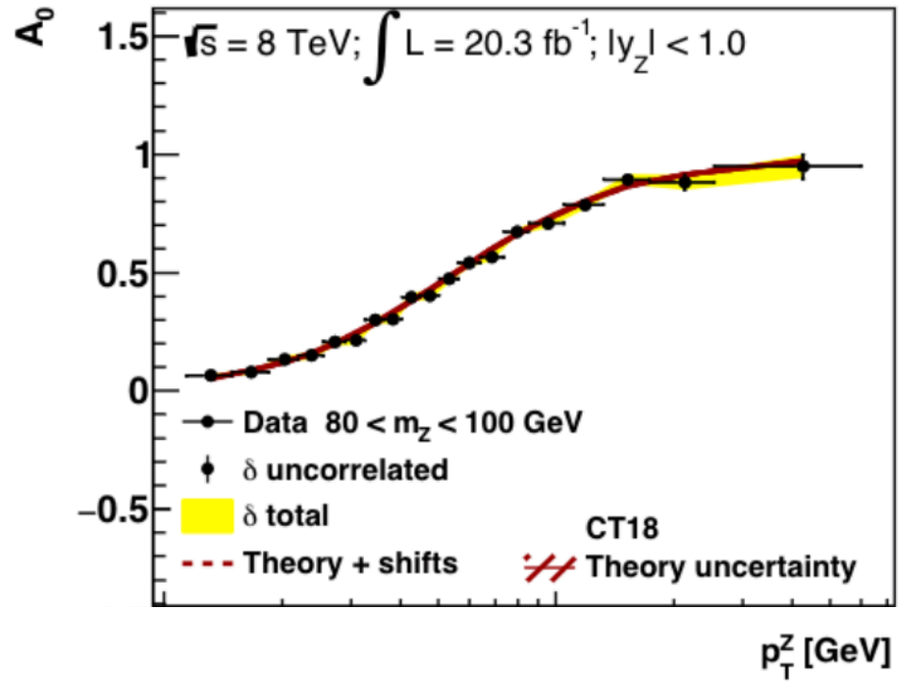




PDFs profiling

- Considered the **ATLAS 8 TeV measurement** of angular coefficients in three Z rapidity bins, $y_Z \in [0, 1, 2, 3.5]$
  - Considering only the bins with $p_T^Z > 11.4$ GeV
  - Predictions at $o(\alpha_S^2)$ from mg5_aMC@NLO
  - Including covariance matrix of experimental uncertainties

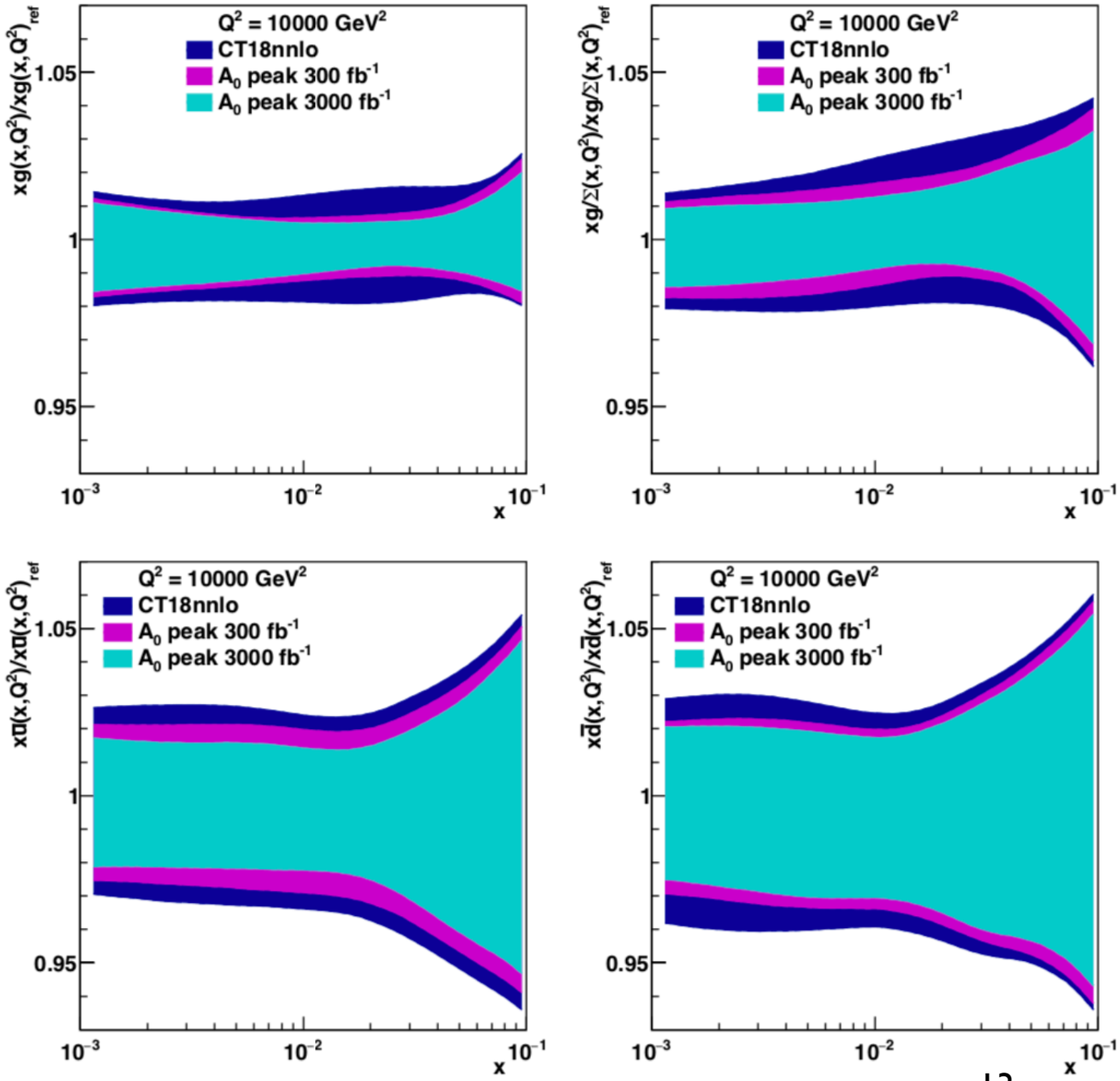
PDF set	Total χ^2/d.o.f.
CT18NNLO	59/53
CT18Annlo	44/53
NNPDF31_nnlo_as_0118_hessian	60/53
ABMP16_5_nnlo	62/53
MSHT20nnlo_as118	59/53
HERAPDF20_NNLO_EIG	60/53



- Good description of the data by all modern PDF sets
- But only marginal constraints on PDFs
- Can the huge HL-LHC statistics change this picture?

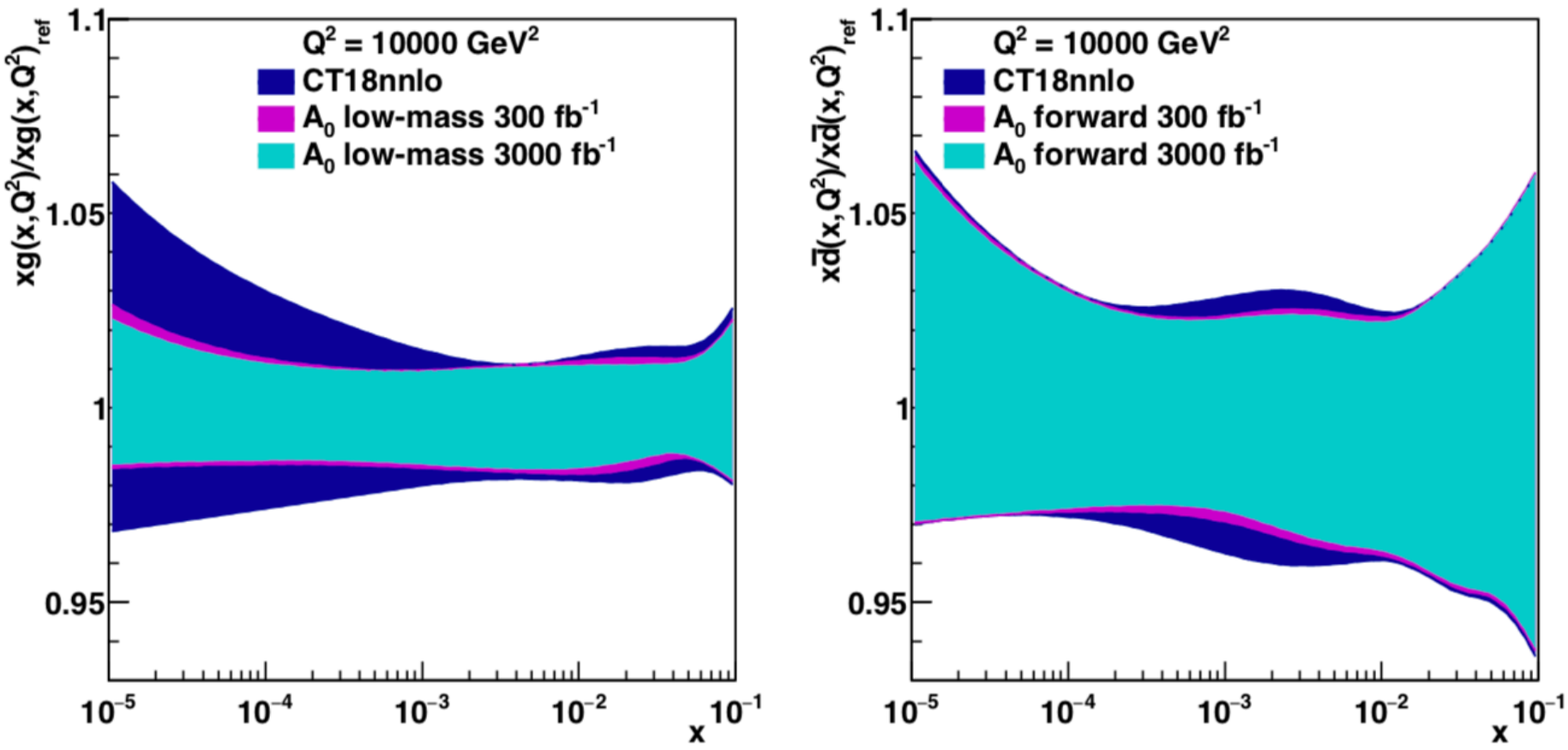
Z PEAK RESULTS

- Considered A_0 pseudodata at 13 TeV for 300 fb^{-1} and 3 ab^{-1}
- With the increase in statistics we found a significant reduction in the PDF uncertainties
- Largest constraints for $xg, xg/\Sigma, x\bar{u}, x\bar{d}$ in the region $10^{-3} < x < 10^{-1}$
- Most of the gain from the 300 fb^{-1} dataset, but 3 ab^{-1} can further constrain $x\bar{u}, x\bar{d}$
- Profiling results stable under variations of μ_R, μ_F scales in the predictions, confirming perturbative stability of A_0



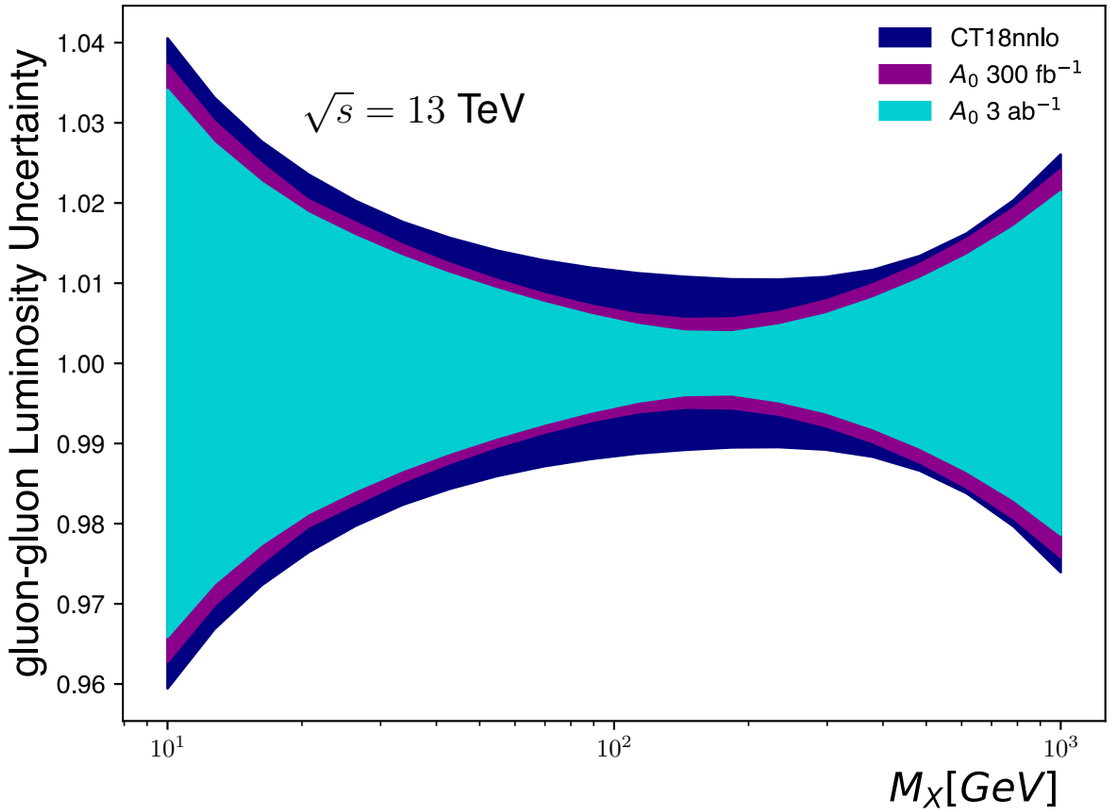
High rapidity and low masses

- Interesting to consider different kinematical regions



- Low invariant-masses: **$4 < m^{ll} < 8$ GeV**
  - Sensitive to the gluon PDF at small-x, $x < 10^{-3}$
  - Possibly relevant for TMD PDFs
- Forward dilepton rapidities (LHCb): **$2.0 < y^Z < 4.5$**
  - Additional sensitivity to the sea quark PDFs at $x \sim 10^{-3}$

Impact on Higgs uncertainties

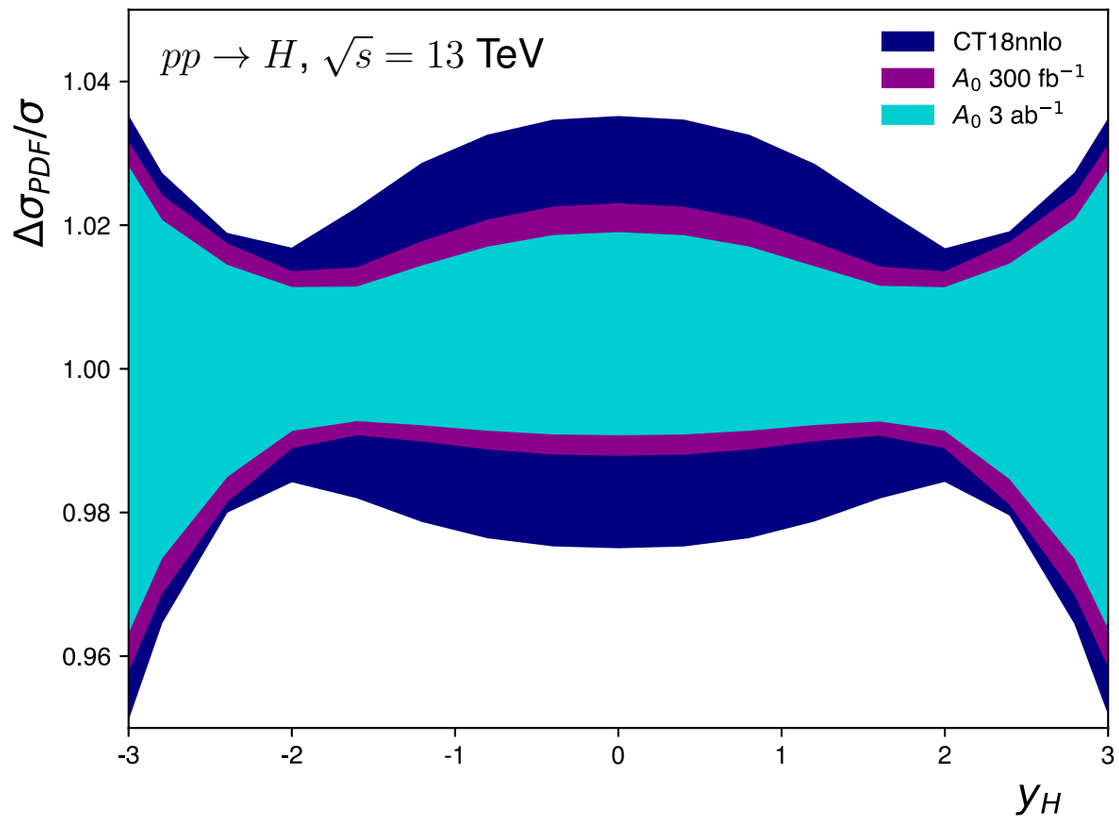


- 13 TeV gluon-gluon luminosity as a function of M_X

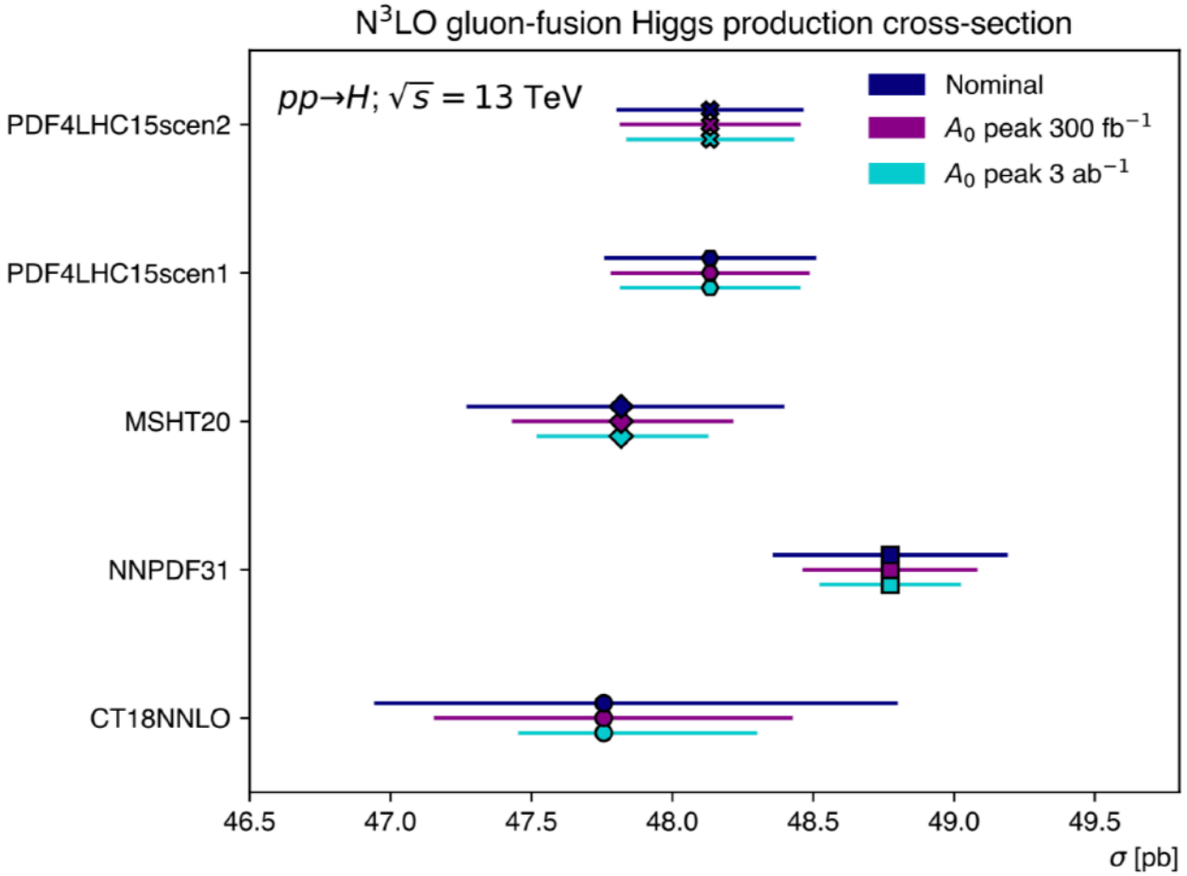
- PDF uncertainties are halved at M_X~125 GeV with 3 ab-1

- PDF uncertainties on the NLO ggH production cross-section from MCFM

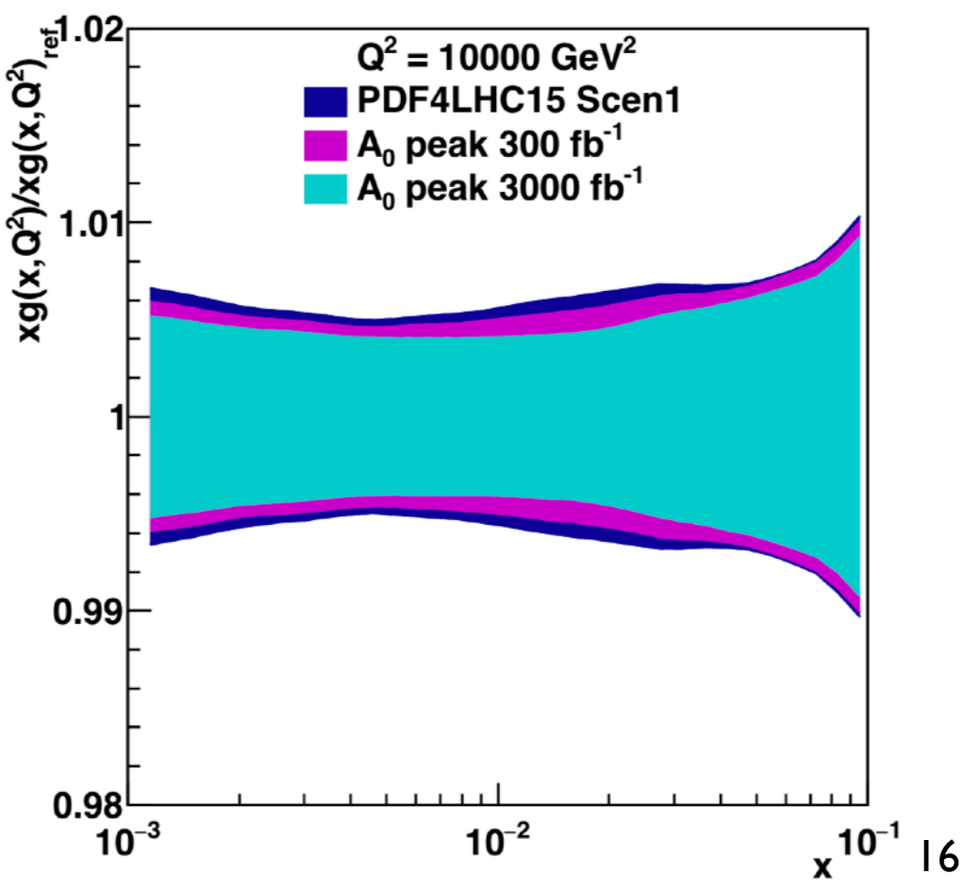
- Large reduction in PDF uncertainties at central rapidities y_H



And Higgs cross-section



- N³LO ggF Higgs cross-section computed with ggHiggs for the different (profiled) PDFs
- Strong uncertainty reductions for all modern PDF sets
- At the HL-LHC we expect a further reduction in PDF uncertainties from new jets and top measurements
- But we find the A_0 data can reduce PDF uncertainties even when using these projected PDFs



Conclusions

- Proposal for a determination of the gluon PDF from precise measurements of the Drell-Yan angular coefficient A_0

- Significant reduction in the gluon PDF uncertainties, visible even with the projected PDF sets based on the full (HL-) LHC data sample

- Important reduction on Higgs cross-section uncertainties

- Possible extension to a fit of the full set of Ai coefficients, further sensitivity expected from the A_1 and A_3 coefficients, and from a combination with A_4

Backup

Angular Coefficients

- The Ais can be determined as averages of projection operators, with the *moment method*

$$\left\langle P\left(\cos\theta,\phi\right)\right\rangle = \frac{\int P(\cos\theta,\phi)\, d\sigma(\cos\theta,\phi)\, d\cos\theta\, d\phi}{\int d\sigma(\cos\theta,\phi)\, d\cos\theta\, d\phi}$$

$$< 1+\cos^2\theta >$$ Normalization of the unpolarised cross-section

$$<\frac{1}{2}(1-3\cos^2\theta)>=\frac{3}{20}(A_0-\frac{2}{3})$$ Longitudinal polarisation

$$<\sin 2\theta\ \cos\phi>=\frac{1}{5}A_1$$ Interference term: longitudinal/transverse

$$<\sin^2\theta\ \cos 2\phi>=\frac{1}{10}A_2$$ Transverse polarisation

$$<\sin\theta\ \cos\phi>=\frac{1}{4}A_3$$ Product of V-A couplings, sensitive to the Weinberg angle

$$<\cos\theta>=\frac{1}{4}A_4$$ $8/3*A_{FB}$, non-zero at LO

$$<\sin^2\theta\ \sin 2\phi>=\frac{1}{5}A_5$$

$$<\sin 2\theta\ \sin\phi>=\frac{1}{5}A_6$$

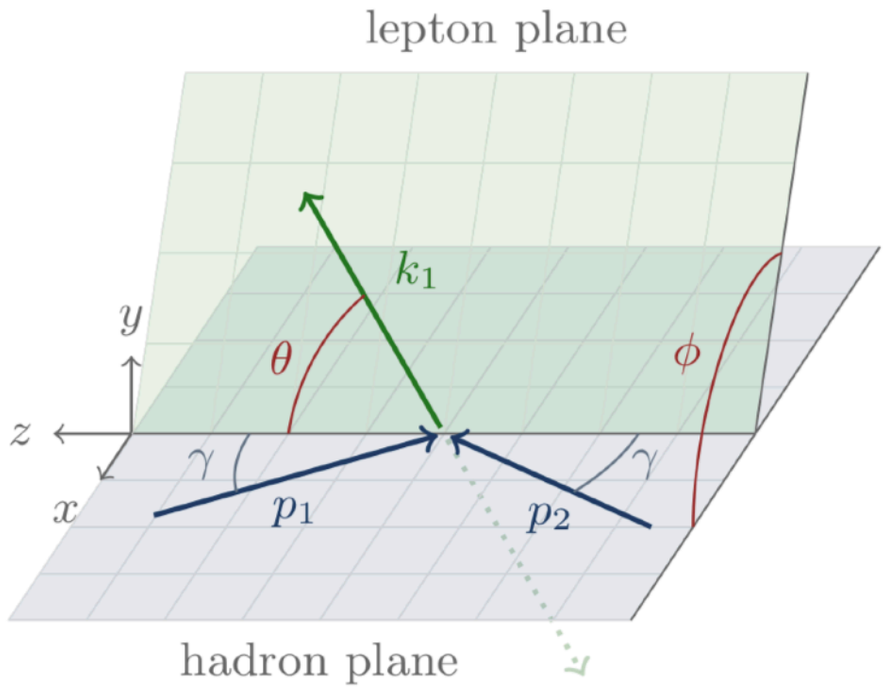
$$<\sin\theta\ \sin\phi>=\frac{1}{4}A_7$$

} Zero at NLO, first contributions at NNLO

ATLAS A_{FB}/A_4

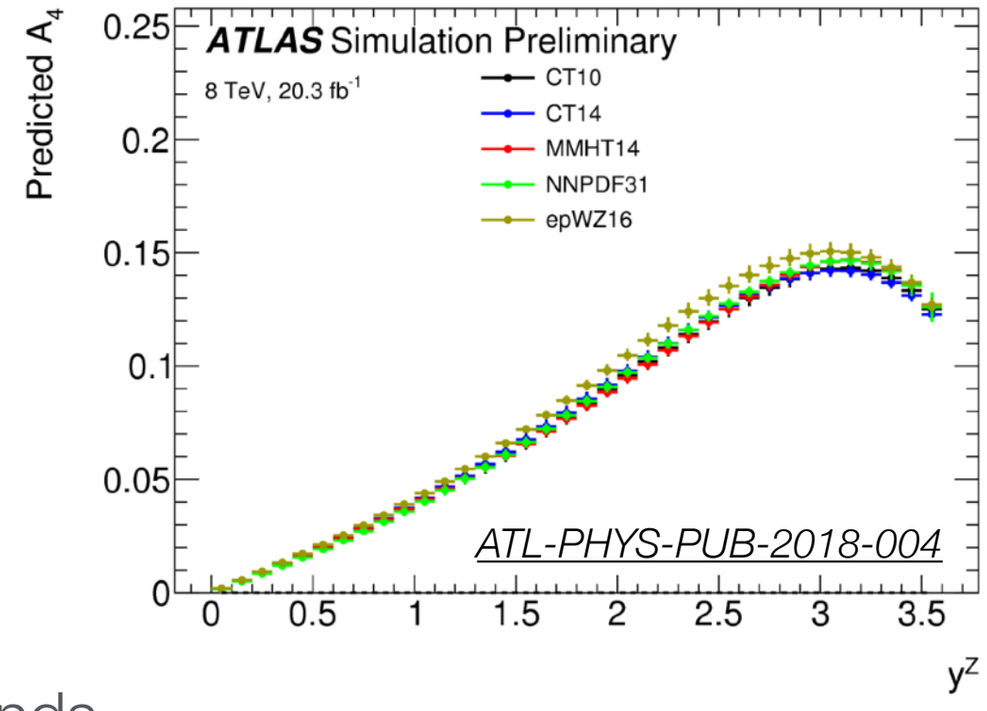
- A_{FB} is a parton-level effect that we measure at proton level
  - Introduces a strong dependence on PDFs

$$A_{\mathrm{FB}} = \frac{\mathrm{d}^3\sigma(\cos\theta^* > 0) - \mathrm{d}^3\sigma(\cos\theta^* < 0)}{\mathrm{d}^3\sigma(\cos\theta^* > 0) + \mathrm{d}^3\sigma(\cos\theta^* < 0)}$$



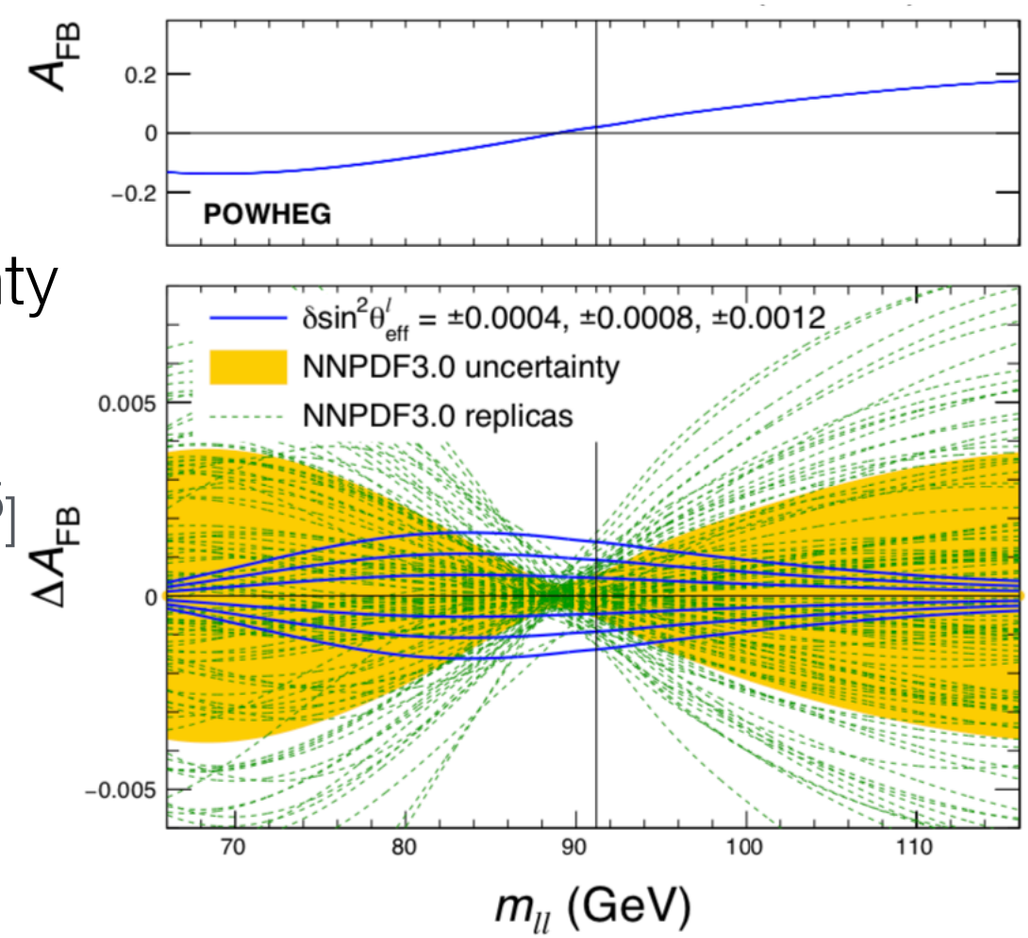
- Quark direction estimated from Z rapidity
  - Z mainly originate from valence quarks and have large x than antiquarks
  - Creates a "dilution of the asymmetry, larger at central rapidities

- Central leptons ($|\eta|<2.4/2.5$)
  - High statistics, helpful to constrain PDFs
- Central-forward leptons ($2.5<|\eta_e|<4.9$)
  - Unique to ATLAS, high sensitivity
  - Challenging calibrations and large backgrounds

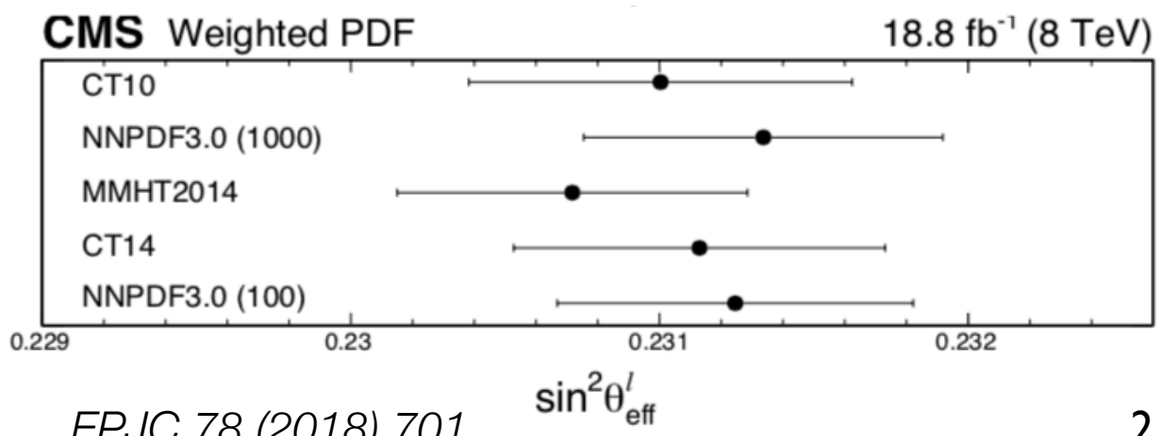


PDFs and $\sin^2\theta_W$

- PDF uncertainties are constrained in the interpretation of A_4, A_{FB}
  → $\sin^2\theta^f_{eff}$ exploiting their different dependence on mll, yll
  - ATLAS using profiling of the Hessian eigenvectors
  - CMS using Bayesian reweighing
- PDFs remain the largest source of uncertainty
  - CMS: PDF syst ±31, spread among sets ~65 [10^{-5}]
  - ATLAS: PDF syst ±24, spread among sets ~28 [10^{-5}]
- Work ongoing within the LHCEWWG to benchmark different global fits and provide correlations between different PDFs



	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^\ell_{eff}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31



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