Recent measurements sensitive to PDFs

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on behalf of the ATLAS, CMS and LHCb Collaborations

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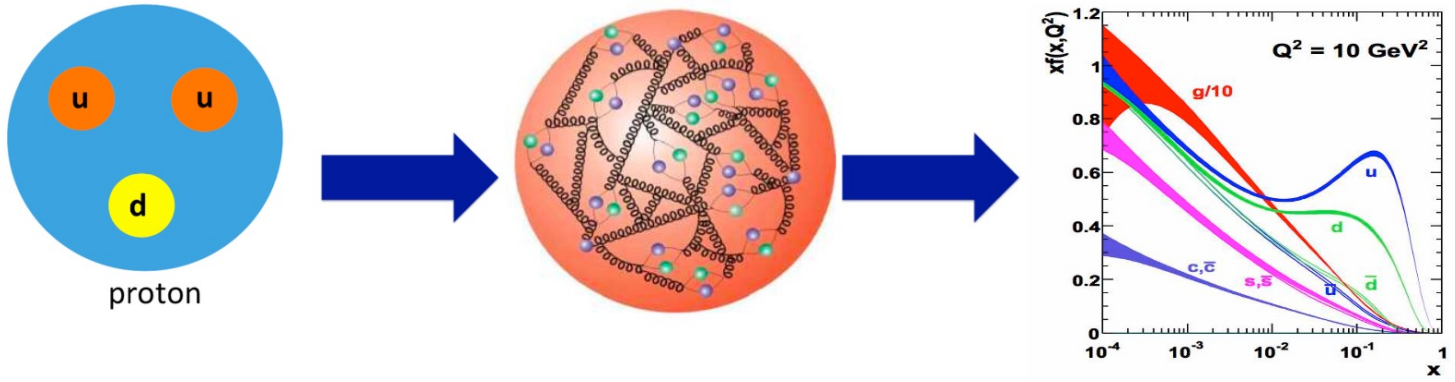
Introduction

Parton Distribution Functions (PDFs) is an essential input for most of measurements at the Large Hadron Collider(LHC)



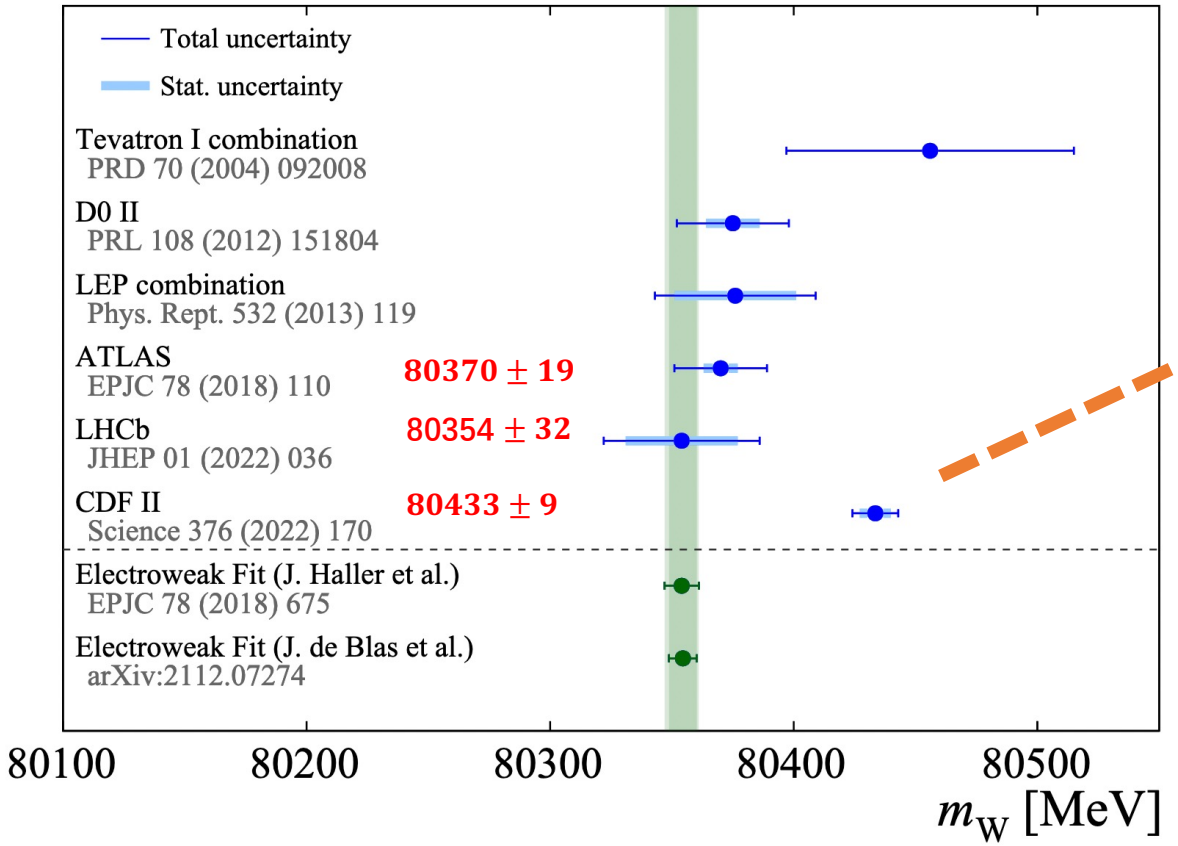
PDFs can not be directly calculated, must be determined using experimental inputs

PDFs are generally extracted from a global analysis of high-energy scattering data, including both data from Deep Inelastic Scattering (DIS) and hadron-hadron colliders

Impact of PDFs

Many precision measurements are dominated by the PDF uncertainty

- e.g. The PDF uncertainty in CDF/ATLAS/LHCb W boson mass measurements is determined to be 3.9, 8, 9 MeV



Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W / p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

LHCb-FIGURE-2022-003

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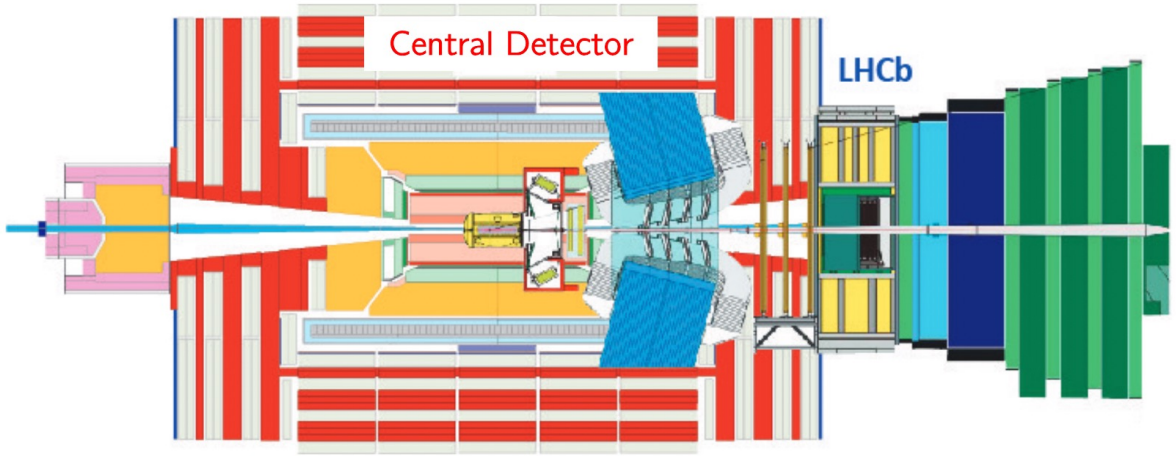
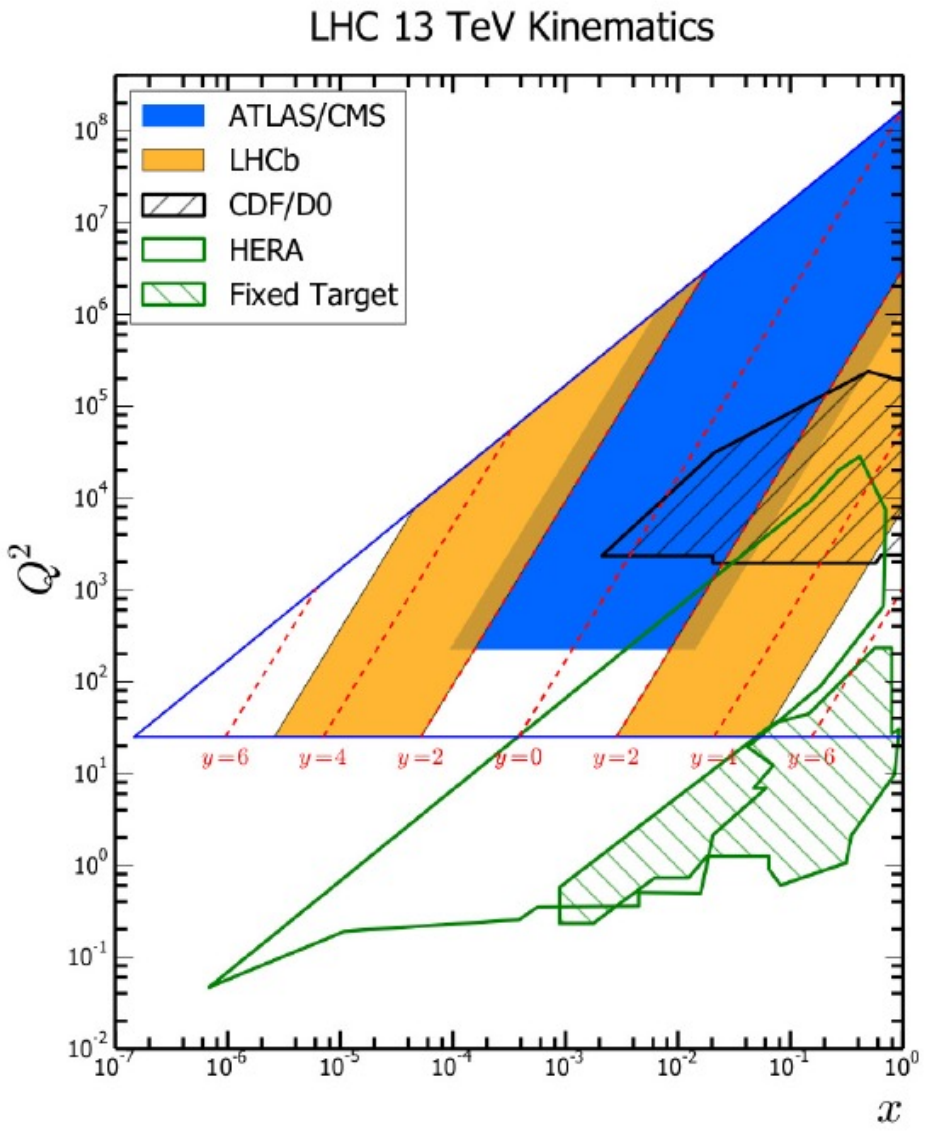
Kinematic regions at LHC

ATLAS, CMS and LHCb are complementary phase space to study electroweak processes



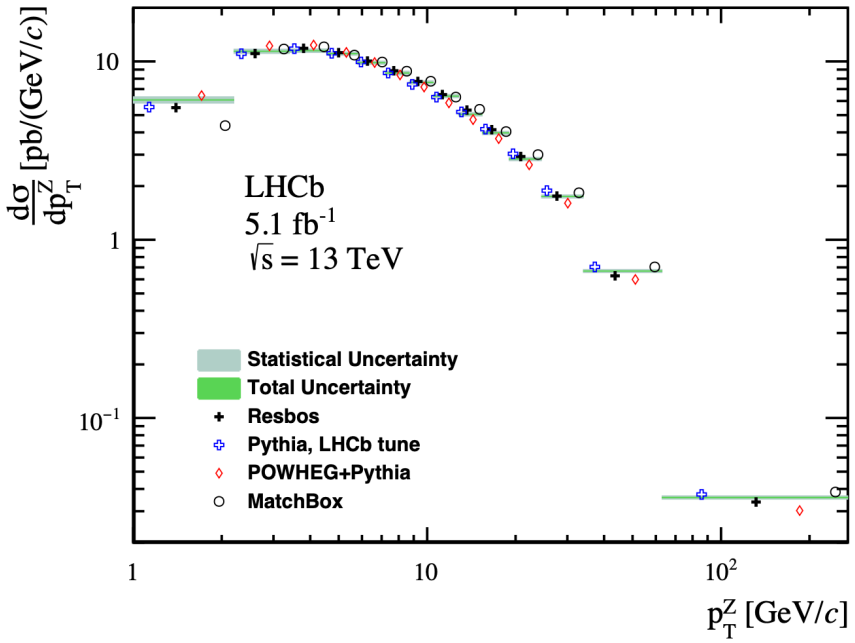


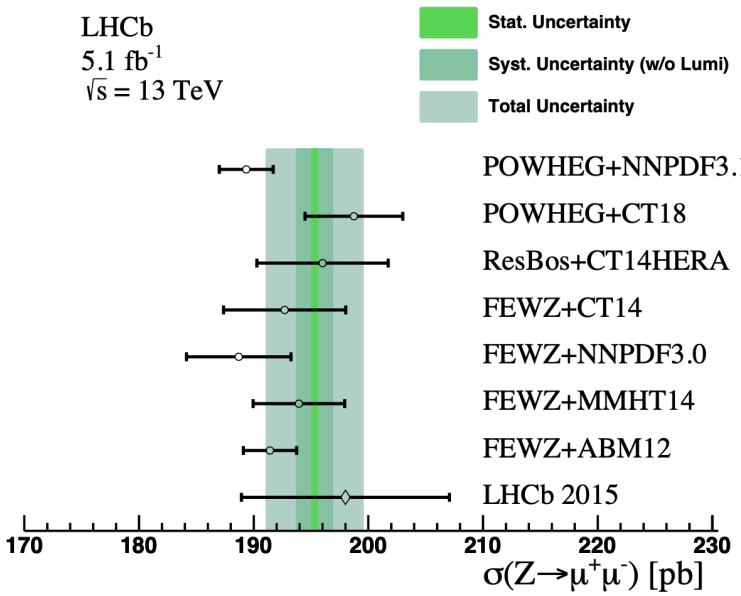
Recent measurements overview

- **ATLAS**
  - Determination of PDFs using diverse ATLAS data from pp collisions at $\sqrt{s} = 7, 8$ and 13 TeV
  - Cross-section measurements for the production of Z+jets in pp collisions at $\sqrt{s} = 13$ TeV
  - Measurement of cross-sections for production of a Z boson in association with a flavor-inclusive or doubly b-tagged large-radius jet in pp collisions at $\sqrt{s} = 13$ TeV
- **CMS**
  - Measurement of the production cross section for Z + b jets in pp collisions at $\sqrt{s} = 13$ TeV
  - Measurement of differential cross sections for Z bosons produced in association with c jets in pp collisions at $\sqrt{s} = 13$ TeV
  - Measurements of the associated production of a W boson and a charm quark in pp collisions at $\sqrt{s} = 8$ TeV
  - Measurements of differential cross section for Z + jets in pp collisions at $\sqrt{s} = 13$ TeV
  - Measurement and QCD analysis of double-differential inclusive jet cross section in pp collisions at $\sqrt{s} = 13$ TeV
- **LHCb**
  - Measurement of forward Z production in pp collisions at $\sqrt{s} = 13$ TeV
  - Z angular coefficients measurement in the forward region in pp collisions at $\sqrt{s} = 13$ TeV
  - Z production in association with charm in the forward region in pp collisions at $\sqrt{s} = 13$ TeV

Measurement of Z production in the forward region

arXiv:2112.07458



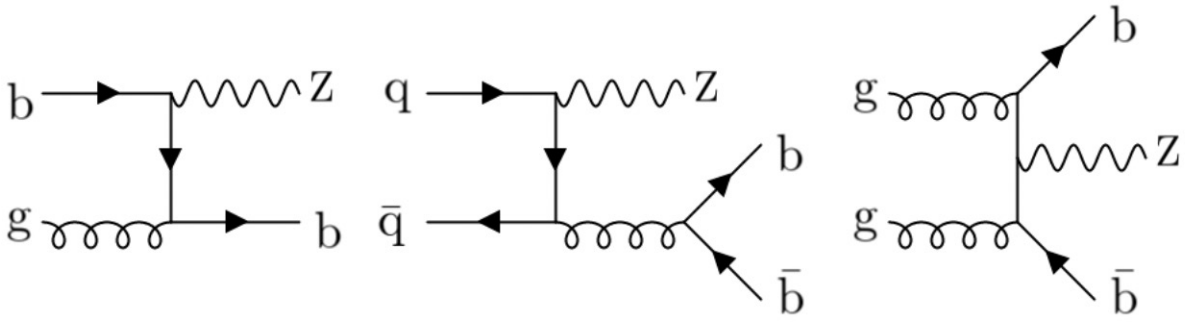


- $5.1\ \mathrm{fb}^{-1}$ of 13 TeV data used
- Forward region $2 < \eta < 4.5$
- Differential and double differential cross section are measured

$$\sigma(Z \to \mu^+\mu^-) = 195.3 \pm 0.2(\mathrm{stat}) \pm 1.5(\mathrm{sys}) \pm 3.9(\mathrm{lumi})\ \mathrm{pb}$$

Z+b-jets production at 13 TeV

arXiv:2112.09659

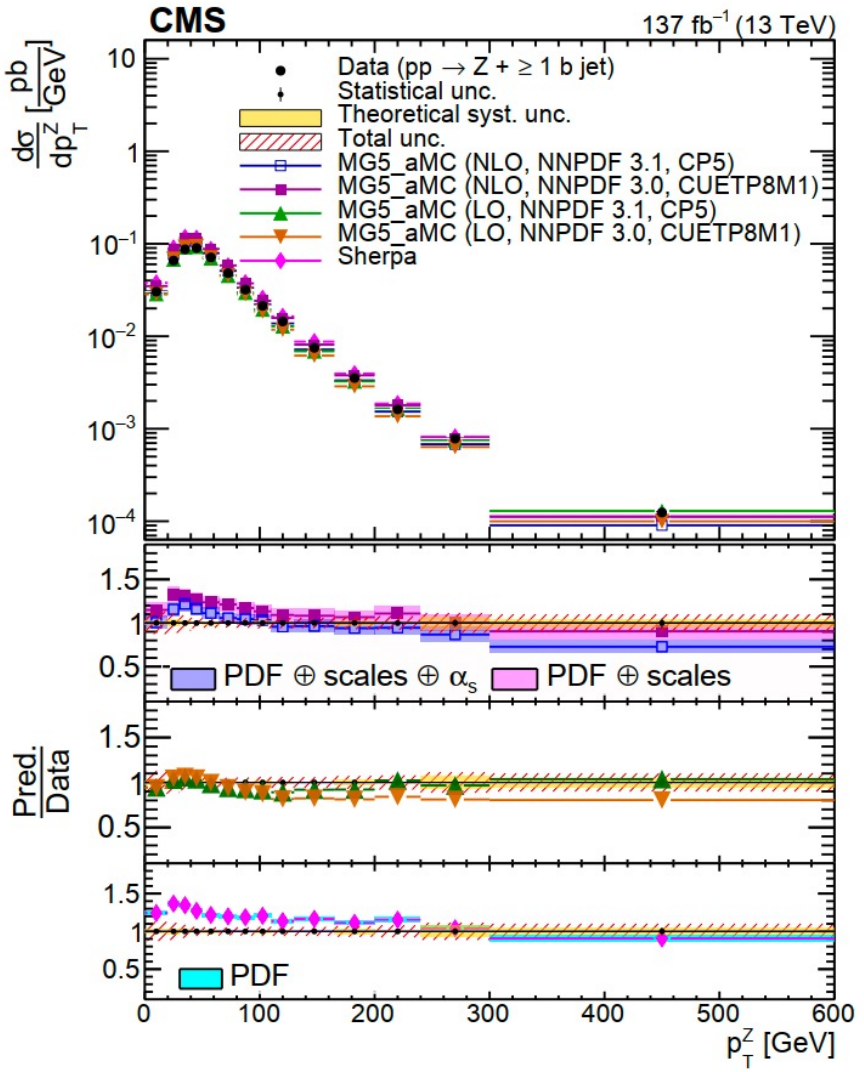


- Cross sections for $Z + \geq 1, \geq 2$ b jets are measured , using 137 fb^{-1} data, combining the electron and muon Z decay channels
- The ratios of integrated and differential cross sections are measured

$$\sigma_{Z+\geq 1\,b} = 6.52 \pm 0.04(stat) \pm 0.40(syst) \pm 0.14(theo)\ pb$$

$$\sigma_{Z+\geq 2\,b} = 0.65 \pm 0.03(stat) \pm 0.07(syst) \pm 0.02(theo)\ pb$$

$$\frac{\sigma_{Z+\geq 2\,b}}{\sigma_{Z+\geq 1\,b}} = 0.100 \pm 0.005(stat) \pm 0.007(syst) \pm 0.003(theo)$$



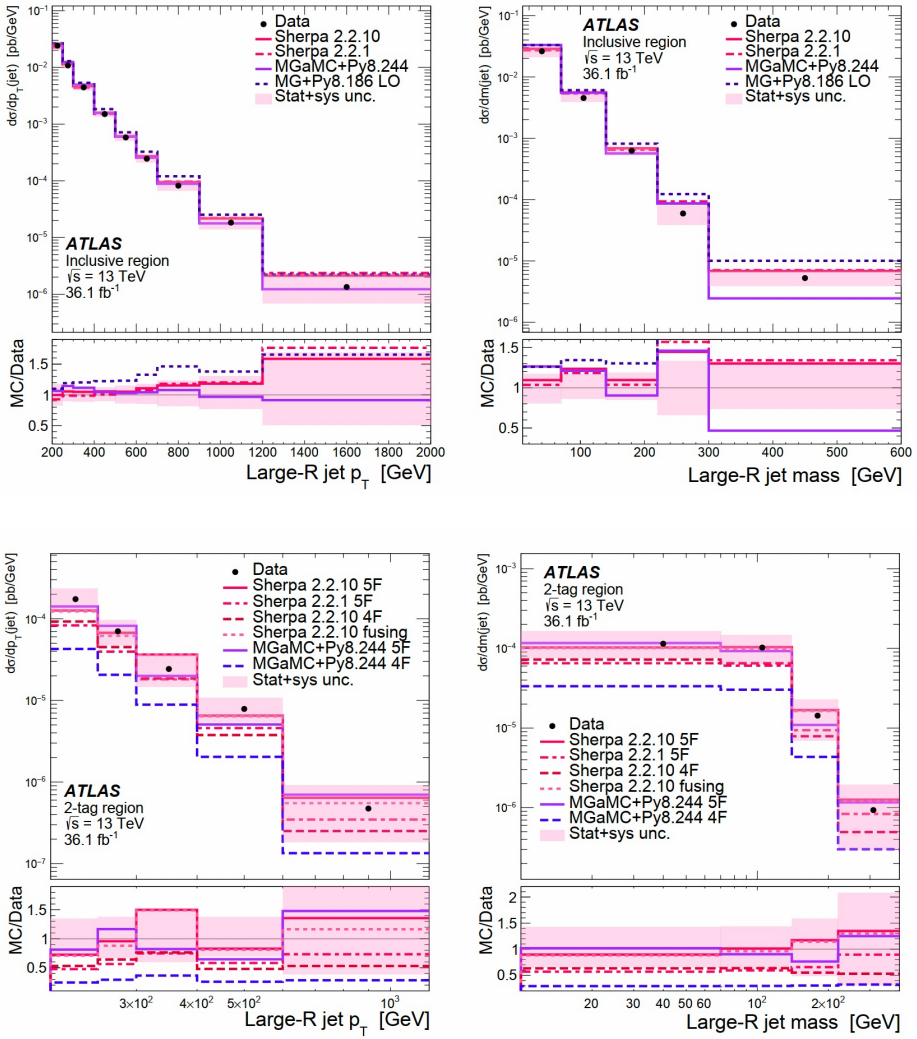
Z+flavor-inclusive or doubly b-tagged large-radius jet

arXiv:2204.12355

- Cross section for production Z boson in association with a large-radius jet
- 36 fb^{-1} of 13 TeV data used
- Integrated and differential cross-sections are measured at particle-level

$$\sigma^{incl} = 2.37 \pm 0.28\ \mathrm{pb}$$
$$\sigma^{2-\mathrm{tag}} = 14.6 \pm 4.6\ \mathrm{fb}$$

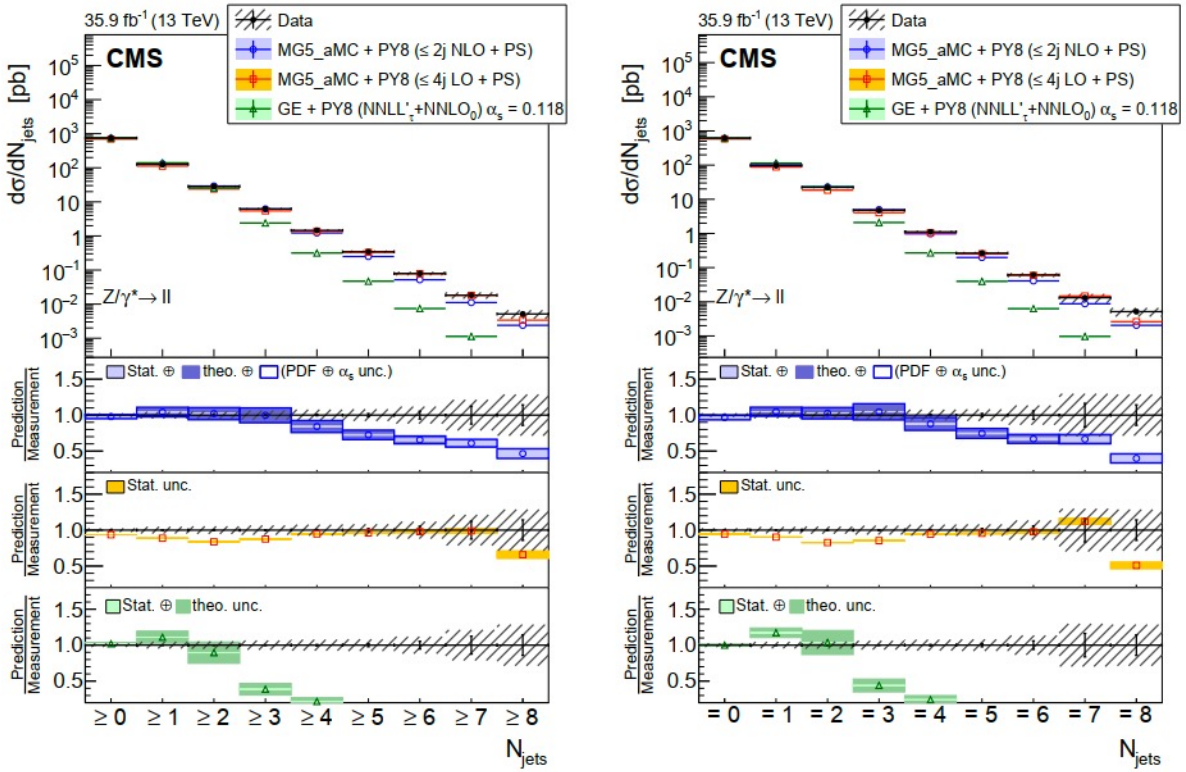
- The measurements are compared with current MC predictions



Z+jets production at 13 TeV

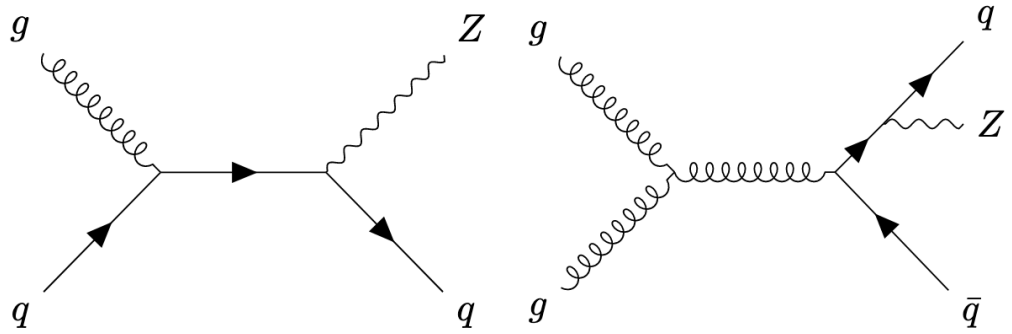
arXiv:2205.02872

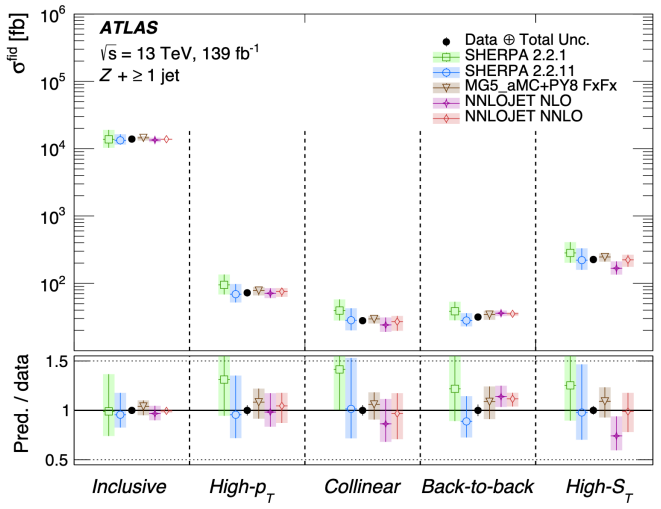
- Measurement of production of Z+jets that decay into two electrons or muons
- Using 35.9 fb^{-1} of 13 TeV data
- The jet multiplicity distribution is measured for up to eight jets
- The results are compared with three theoretical predictions



Z+jets production at 13 TeV

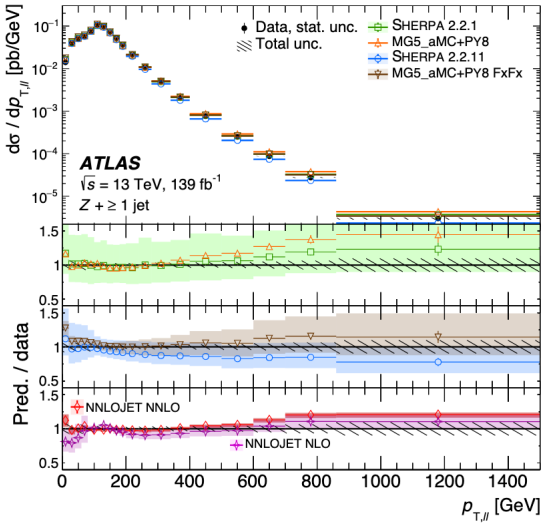
arXiv:2205.02597

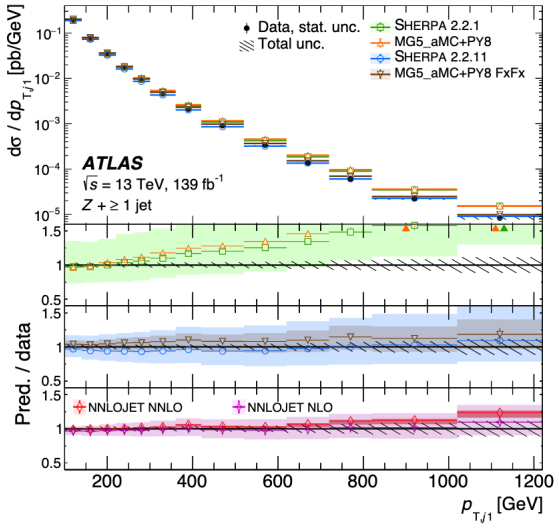




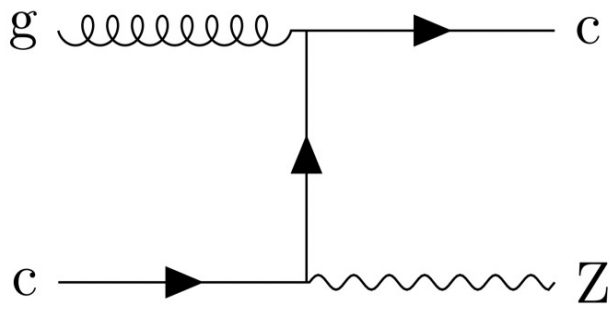
- Cross section measurements for Z + jets ($p_T > 100\mathrm{GeV}$) and decaying into a charged-lepton pair($e^+e^-, \mu^+\mu^-$)
- The integrated fiducial and differential cross section are measured

	Integrated cross section
Inclusive	$13.90 \pm 0.01(stat) \pm 0.47(syst)$
High-p_T	$72.3 \pm 1.5(stat) \pm 3.5(syst)$
Collinear	$27.9 \pm 0.8(stat) \pm 1.2(syst)$
Back-to-back	$31.6 \pm 0.8(stat) \pm 1.7(syst)$

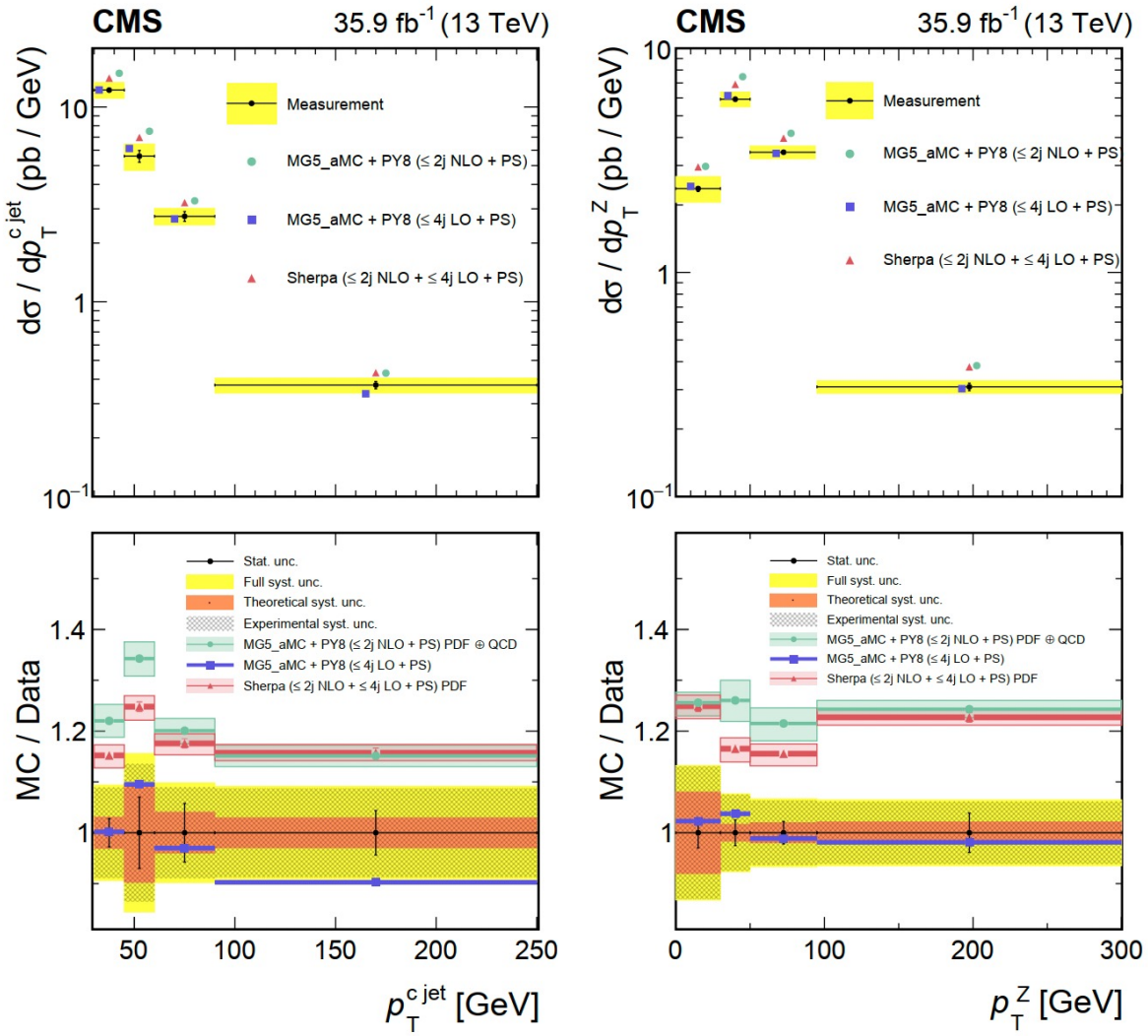




Z+c-jets production at 13 TeV



JHEP04(2021)109



- First measurements of cross section for Z+c in

fiducial region with 2016 data, in both electron and muon Z decay channels

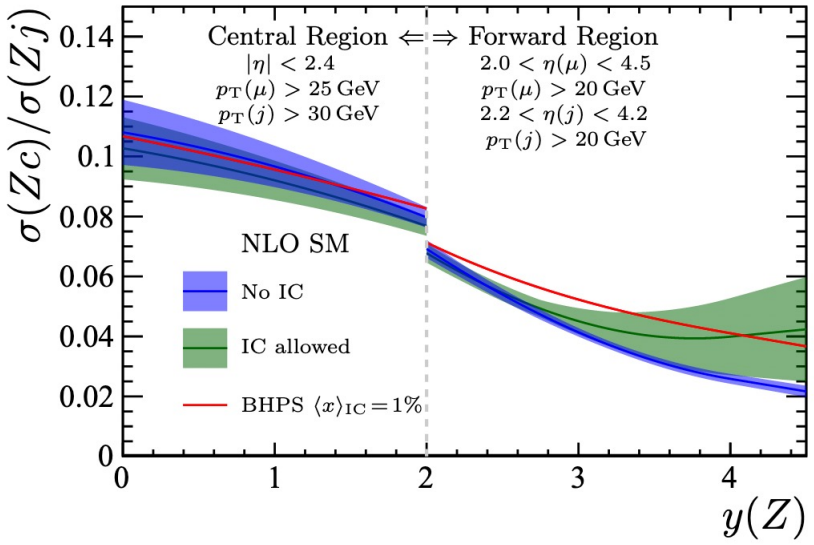
- Fiducial region $|\eta| < 2.4$

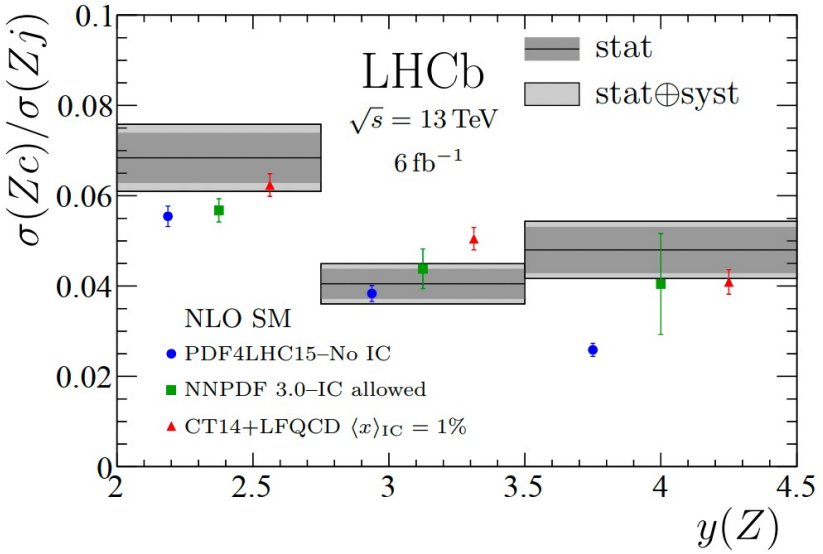
$$\sigma_{z+c} = 405.4 \pm 5.6(\text{stat}) \pm 24.3(\text{syst}) \pm 3.7(\text{theo})\ \text{pb}$$

- Good agreement with MG5_aMC L0
- SHERPA and MG5_aMC NLO above the data

Z boson produced in association with charm

PhysRevLett.128.082001

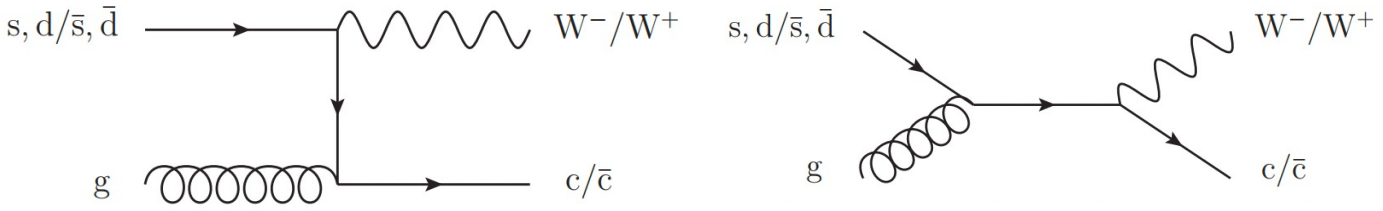




- Using 6 fb^{-1} of 13 TeV data
- Inconsistent with NO-IC theory at $> 3\sigma$
- Incorporating forward results into a global analysis should strongly constrain the large-x charm PDF
- Current results are statistically limited

W+c-jet production at 8 TeV

arXiv:2112.00895

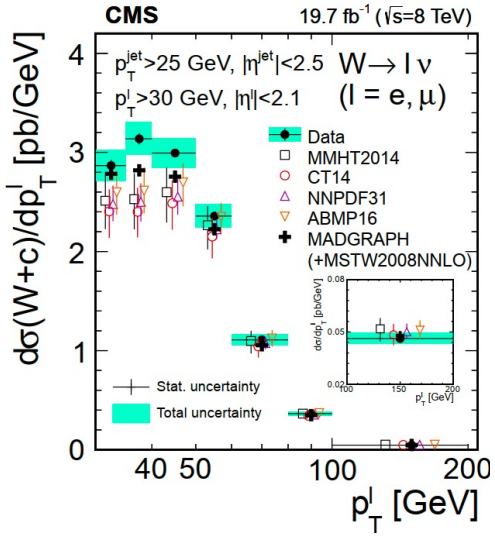


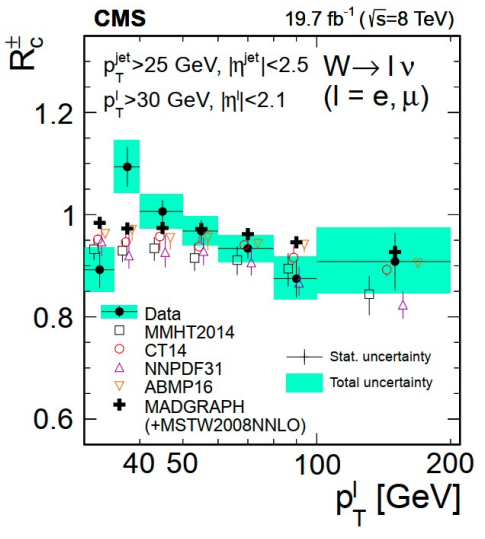
- Measurements of inclusive W+c production cross section, in W leptonic decays to an electron or a muon, and a neutrino

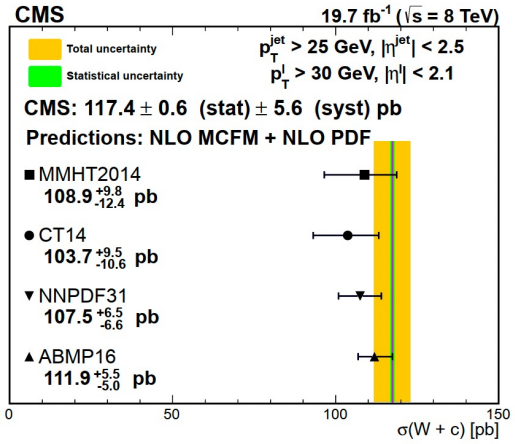
$$\sigma(pp \to W + c + X)B(W \to l\nu) = 117.4 \pm 0.6(stat) \pm 5.4(syst)\ pb$$

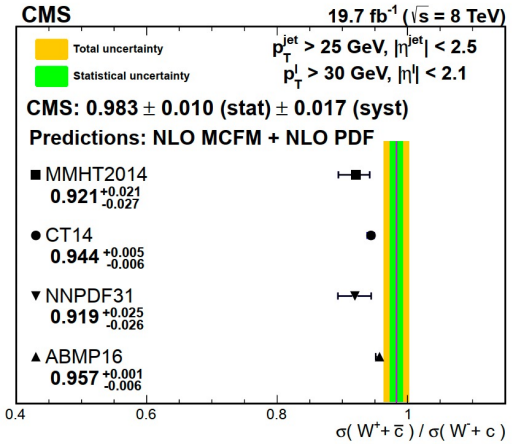
$$\frac{\sigma(pp \to W^+ + \bar{c} + X)}{\sigma(pp \to W^- + c + X)} = 0.983 \pm 0.010(stat) \pm 0.017(syst)$$

- Differential distribution in used to extract strange parton density in the proton
- Measurements slightly higher than MCFM NLO calculation with different PDF sets

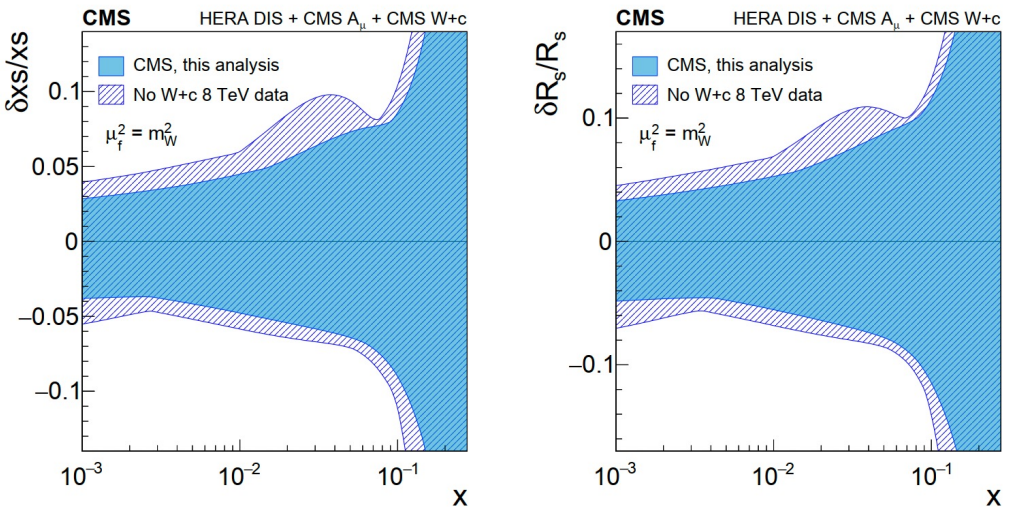


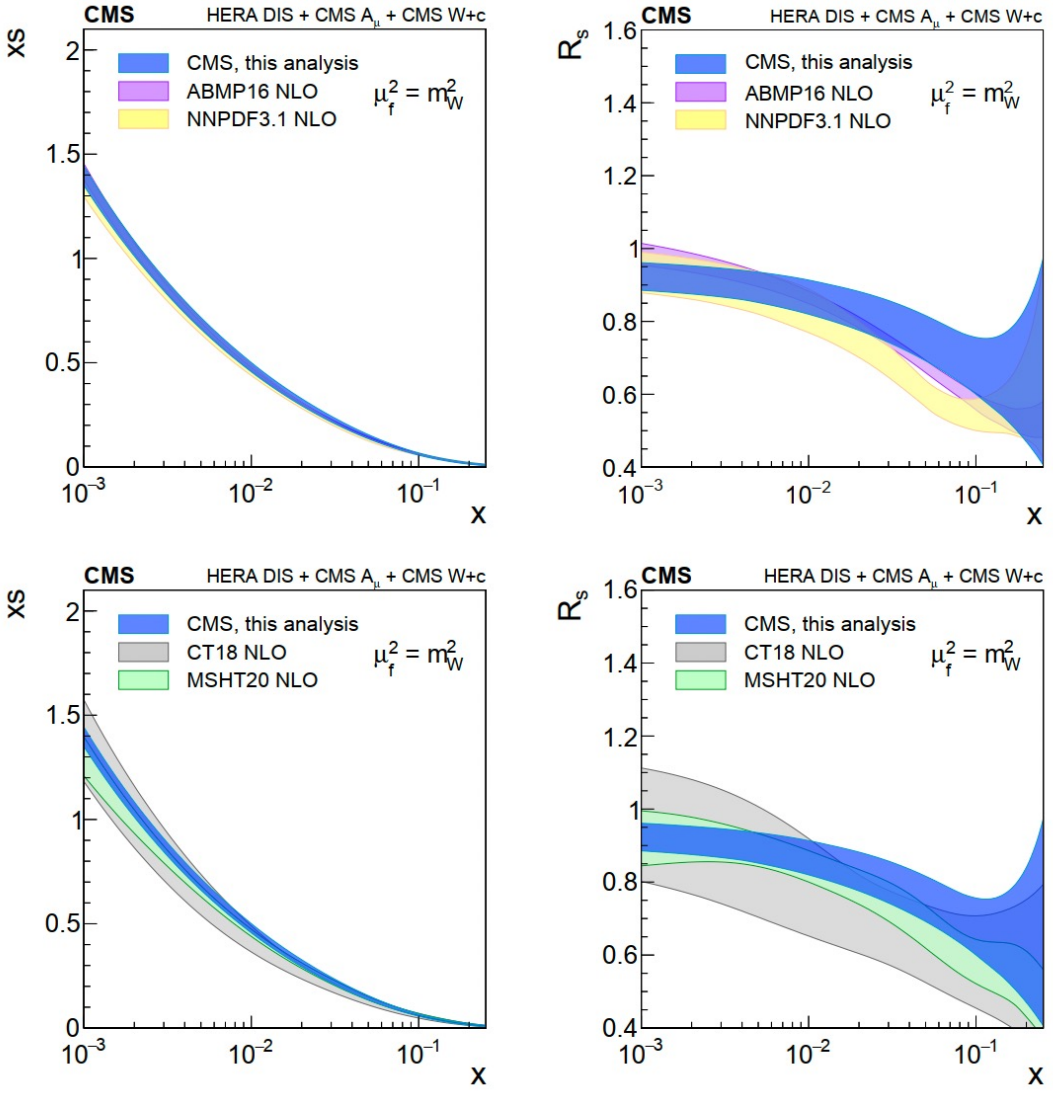






W+c-jet production at 8 TeV





- Fit with and without these data show impact on strange distribution and on strangeness suppression factor：

$$R_s(x, \mu_f^2) = (s + \bar{s})/(\bar{u} + \bar{d})$$

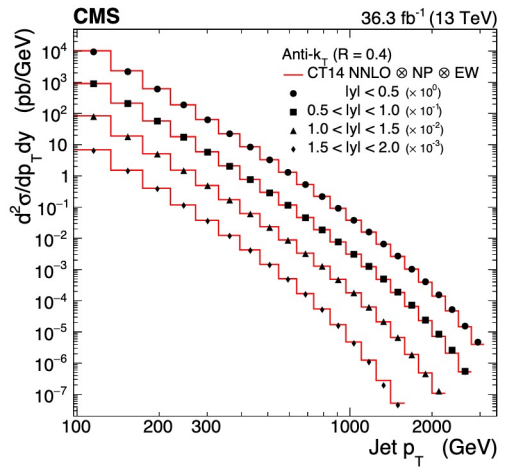
- Extracted strange distribution and strangeness suppress in factor in agreement with other PDF sets

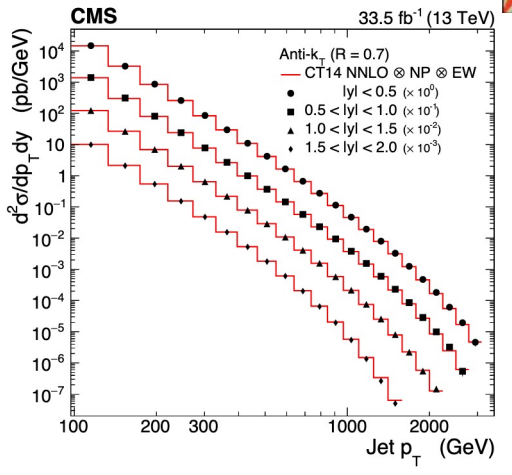
Double differential inclusive jet cross sections at 13 TeV

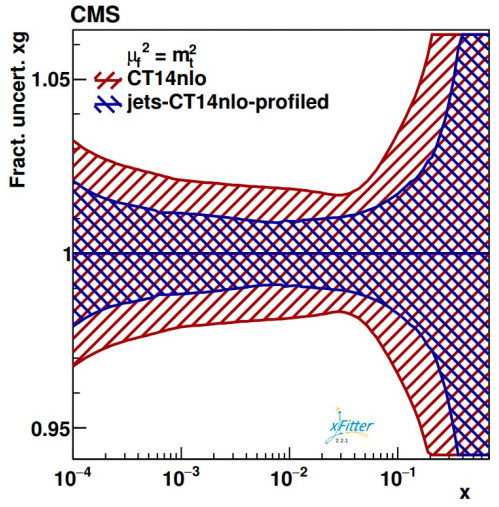
- The double differential cross section of inclusive jet are measured
- 36.3(33.5) fb^{-1} of 13 TeV data used
- The data cover a wide range of the jet p_T from 97 GeV up to 3.1 TeV
- All predictions describe the data well within the experimental and theory uncertainties

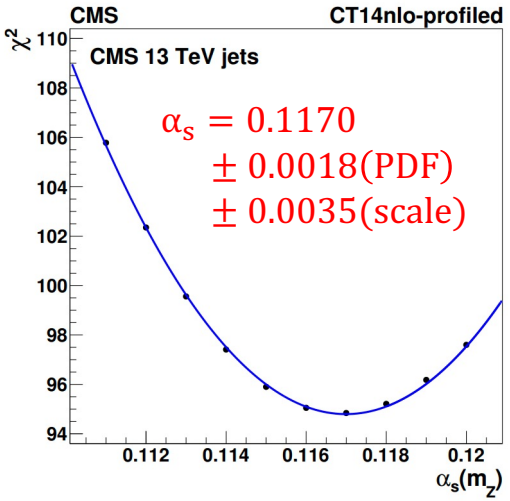
- The impact of CMS jet data for CT14NLO
  - Significant improvement in gluon PDF precision
  - Profiled $\mathrm{m_t} = 170.3 \pm 0.5(\mathrm{PDF}) \pm 0.2(\mathrm{scale})$

  consistent with previous CMS results [arXiv:1904.05237]







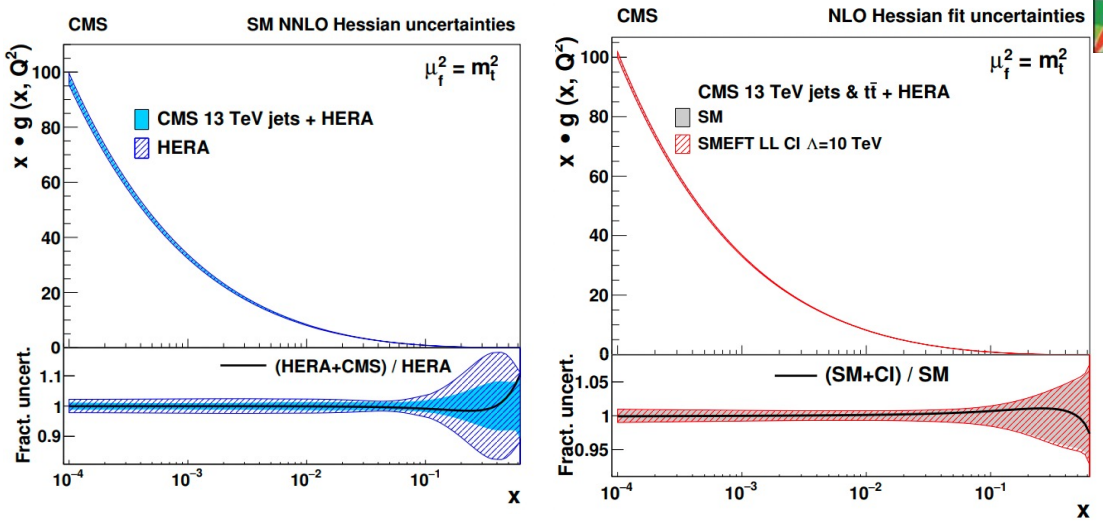


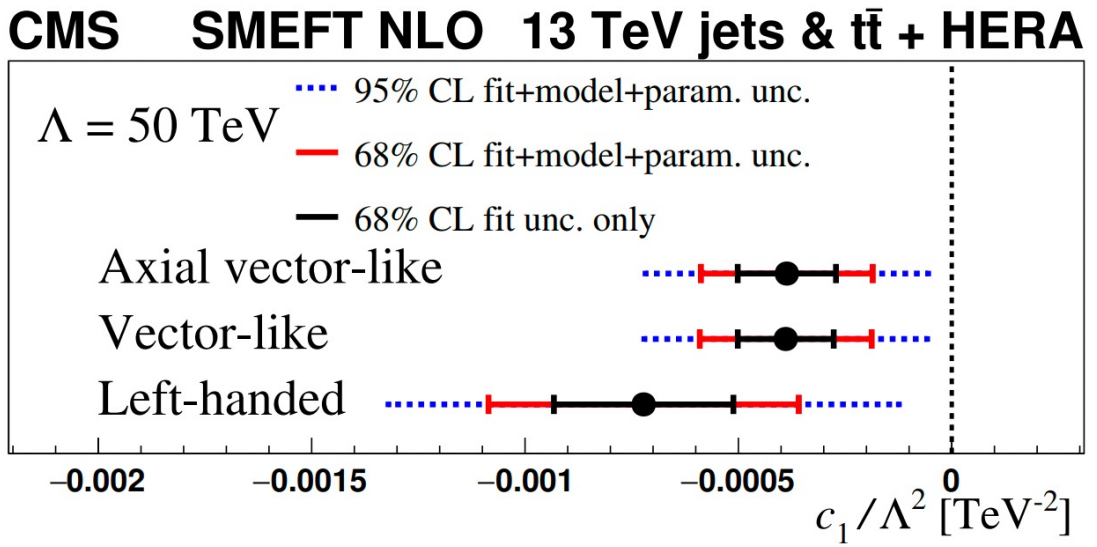
Double differential inclusive jet cross sections at 13 TeV

- SM QCD analysis at NNLO
  - Adding jet data on the NNLO fit using HERA DIS leads to significant improvement in PDF precision
  - α_s extracted simultaneously with the PDFs

$$\alpha_s = 0.1170 \pm 0.0014(\text{fit}) \pm 0.0007(\text{model}) \pm 0.0008(\text{scale}) \pm 0.0001(\text{param.})$$

- SMEFT analysis at NLO
  - Using the HERA DIS data, CMS inclusive jet and $t\bar{t}$ cross section measurements at 13TeV
  - The PDFs from SMEFT and SM fits agree, differences within fit uncertainties
  - All models results in very similar PDFs, strong coupling and top mass values as the SM fit
- Unbiased exclusion limits for 4-quark CI
  - First time at LHC: the Wilson coefficient for 4-quark CI ls fitted together with the PDFs
  - All CI fits result in negative c1. There are the translated into unbiased 95% CL exclusion limits for CI





Z angular coefficients measurement in the forward region

arXiv:2203.01602

- The kinematic distribution of the final-state leptons provides a direct probe of the polarization of the intermediate gauge boson

- Ai: the ratio of helicity dependent cross-section over the unpolarized cross-section

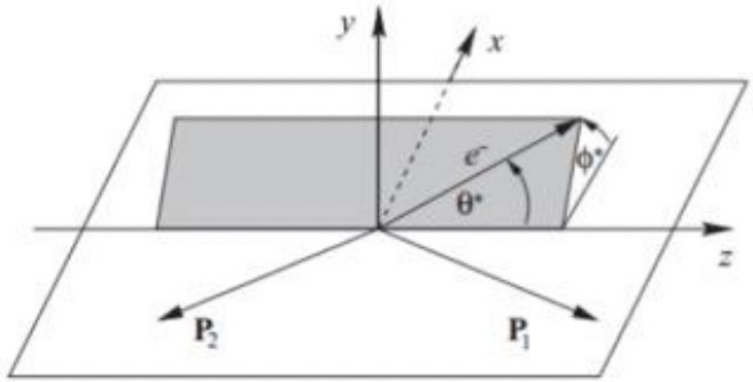
$$\frac{d\sigma}{dP_T^2 dy d\cos\theta d\phi} \propto (1+\cos^2\theta) \rightarrow \text{LO term}$$

$$+ \frac{1}{2}A_0(1-3\cos^2\theta) \rightarrow \cos^2\theta : \text{higher order term}$$

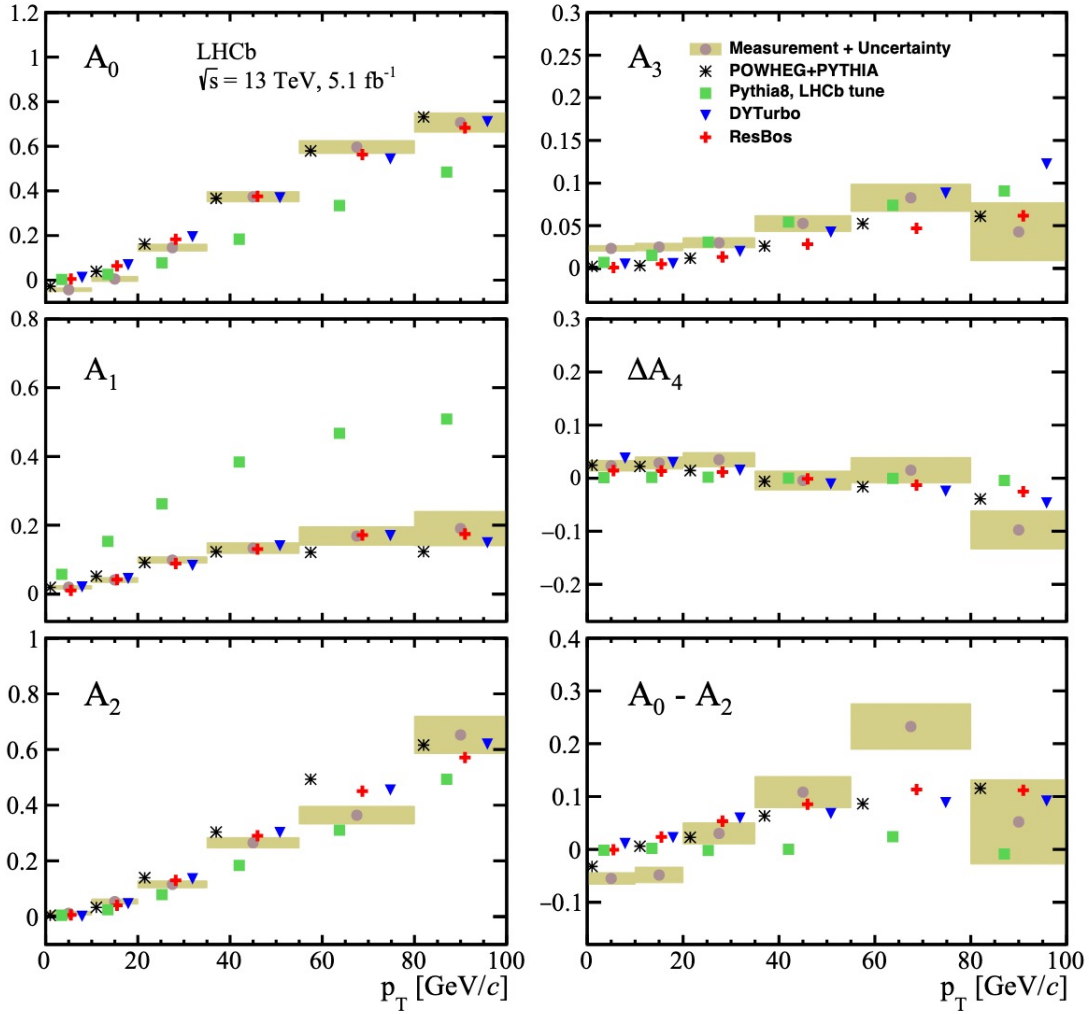
$$+ A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi \rightarrow (\theta, \phi) \text{ terms}$$

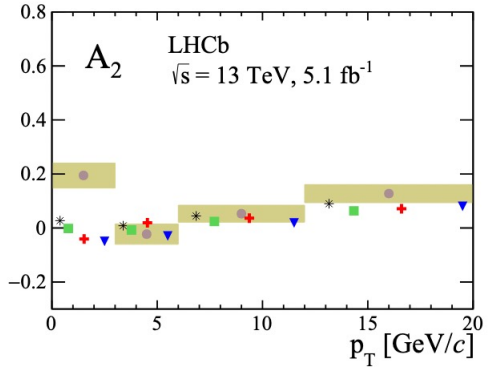
$$+ A_4 \cos\theta \rightarrow \text{LO term : determine } A_{fb}$$

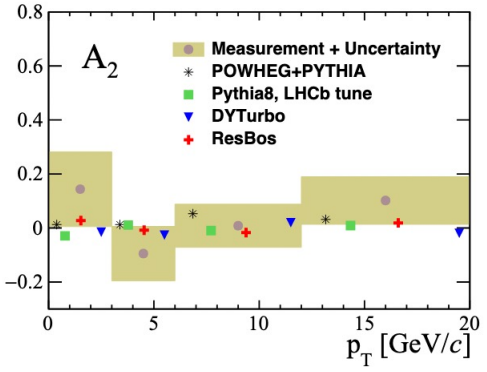
$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \rightarrow \text{very small terms}$$



Z angular coefficients measurement in the forward region







- The first measurements of the angular coefficients of Drell-Yan $\mu^+\mu^-$ pairs in forward region
- 5.1 fb^{-1} of 13 TeV data used
- Measurements are corrected to the Born level
- The uncertainty is dominated by statistical uncertainty

Determination of PDFs using ATLAS data

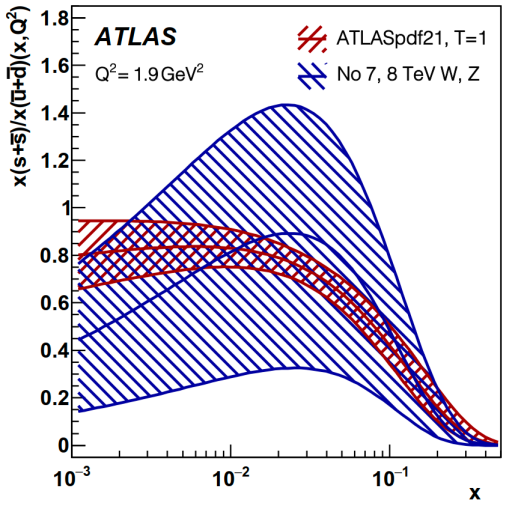
arXiv:2112.11266

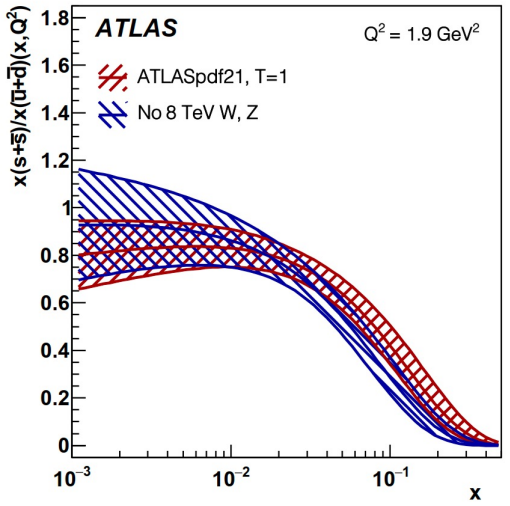
- ATLASpdf21 is a PDF fit to multiple ATLAS data sets
- Based on DIS HERA data and ATLAS data sets
- All the fits performed using xFitter
- All the ATLAS input data sets considered in QCD fit

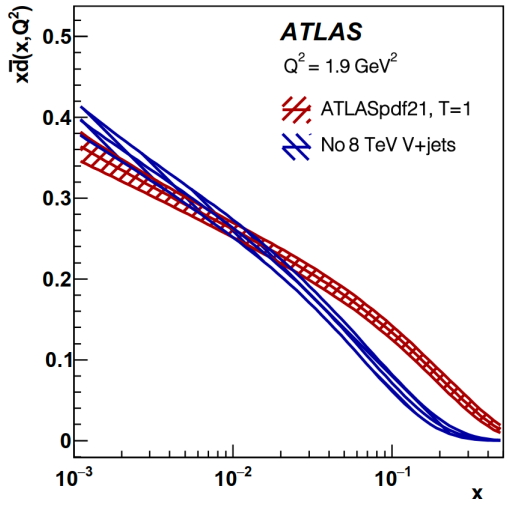
Data set	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	Decay channel	Observables entering the fit
Inclusive $W, Z/\gamma^*$ [9]	7	4.6	e, μ combined	η_ℓ (W), y_Z (Z)
Inclusive Z/γ^* [13]	8	20.2	e, μ combined	$\cos\theta^*$ in bins of $y_{\ell\ell}, m_{\ell\ell}$
Inclusive W [12]	8	20.2	μ	η_μ
$W^\pm$ + jets [24]	8	20.2	e	p_{T}^W
Z + jets [25]	8	20.2	e	$p_{\mathrm{T}}^{\mathrm{jet}}$ in bins of $\lvert y^{\mathrm{jet}}\rvert$
$t\bar{t}$ [26, 27]	8	20.2	lepton + jets, dilepton	$m_{t\bar{t}}$, p_{T}^t, $y_{t\bar{t}}$
$t\bar{t}$ [15]	13	36	lepton + jets	$m_{t\bar{t}}$, p_{T}^t, y_t, $y_{t\bar{t}}^{\mathrm{b}}$
Inclusive isolated γ [14]	8, 13	20.2, 3.2	-	E_{T}^γ in bins of η^γ
Inclusive jets [16–18]	7, 8, 13	4.5, 20.2, 3.2	-	$p_{\mathrm{T}}^{\mathrm{jet}}$ in bins of $\lvert y^{\mathrm{jet}}\rvert$

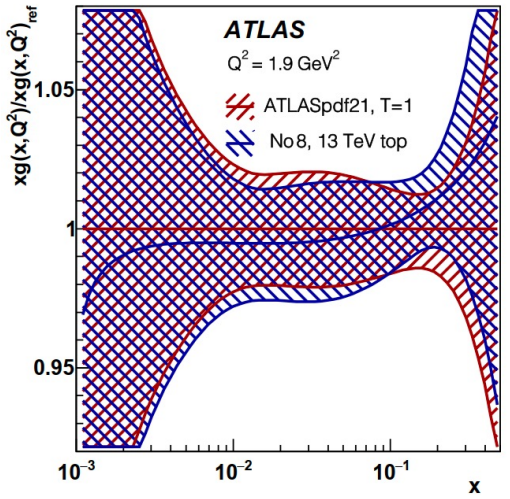
Determination of PDFs using ATLAS data

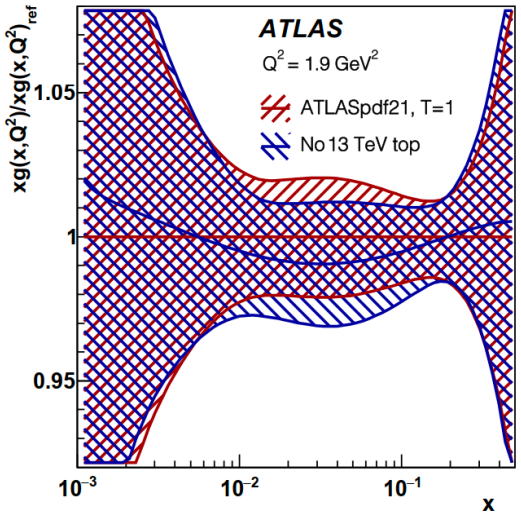
Impact of the various data sets on PDFs

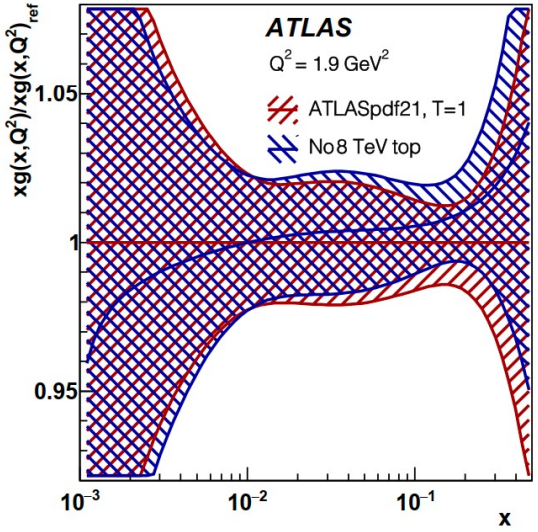


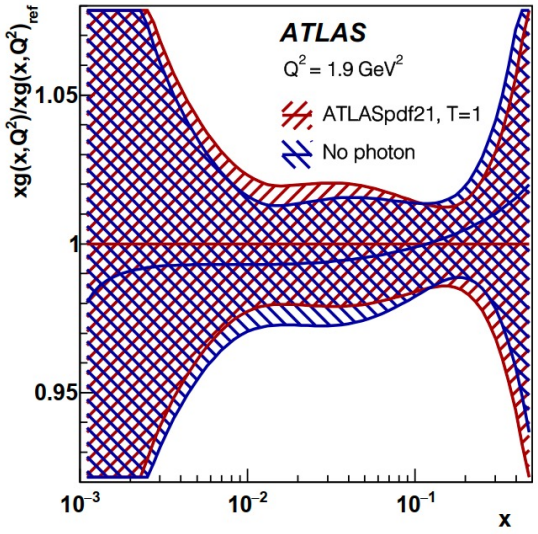


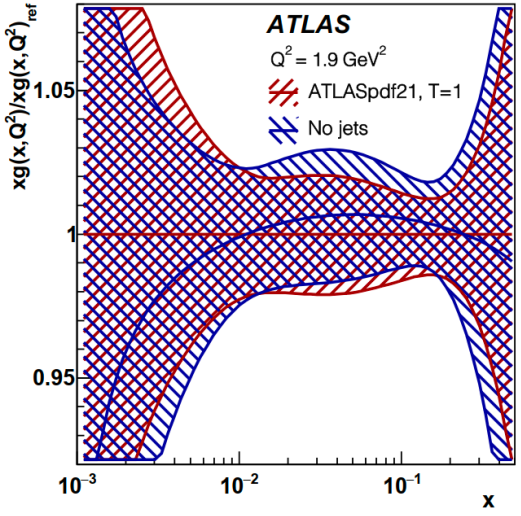






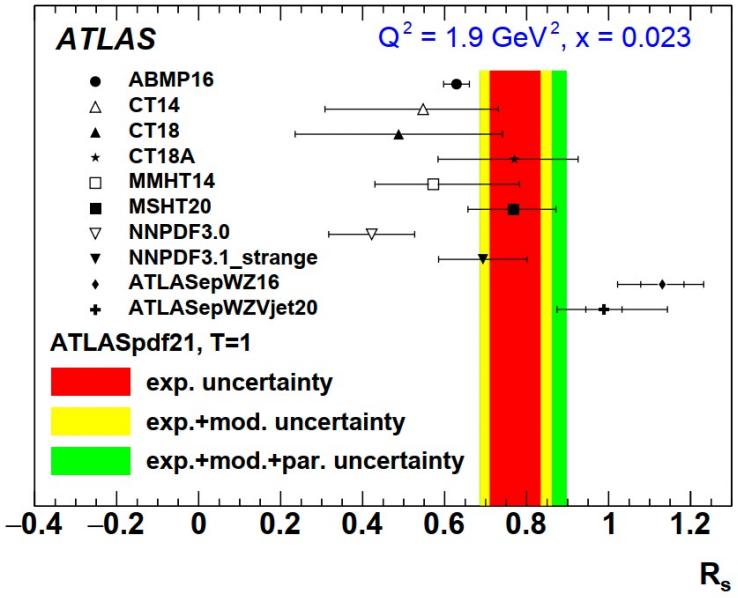


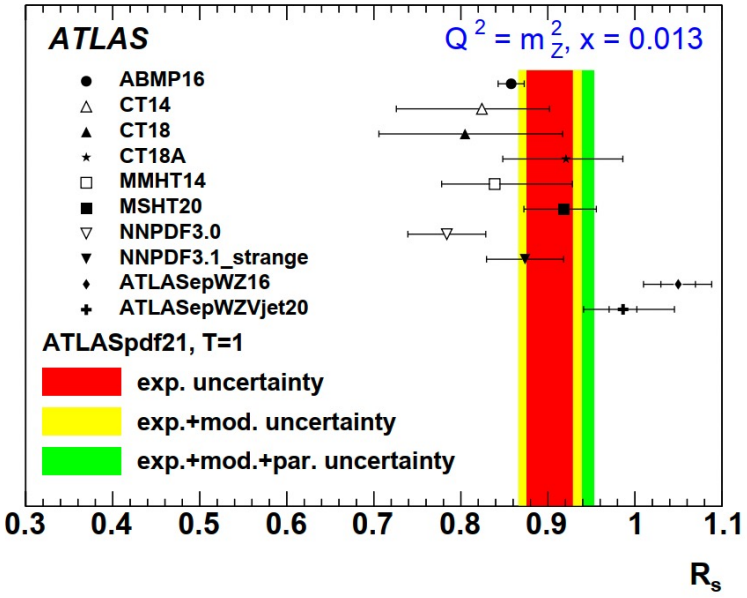




Determination of PDFs using ATLAS data

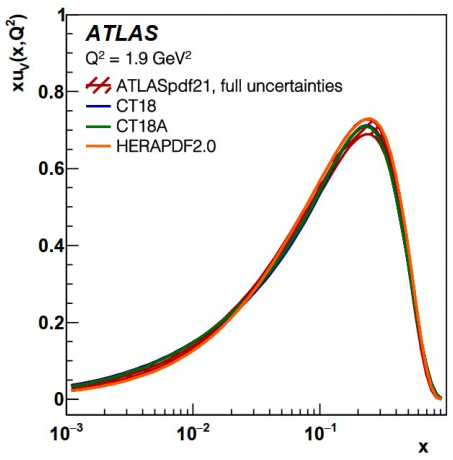
- HERA + ATLAS W,Z 7TeV Data
  → unsuppressed strange at low-x
- ATLAS R_s has come down from ~1.0 to 0.8
- MSHT, CT and NNPDF R_s have come up from ~0.5 to 0.8 when including W,Z 7TeV ATLAS data
- Shift from ATLASepWZVjet20 to ATLASpdf21 due to a combination of adding W,Z 8 TeV data and freer low-x parameterization

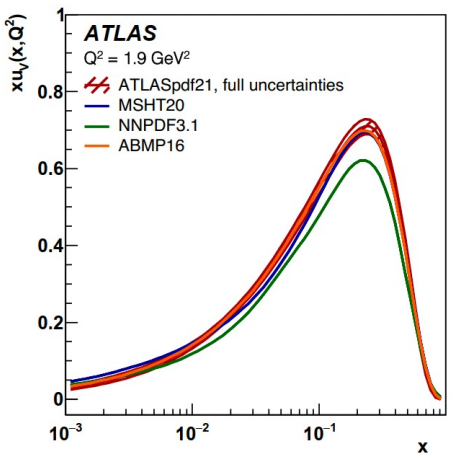


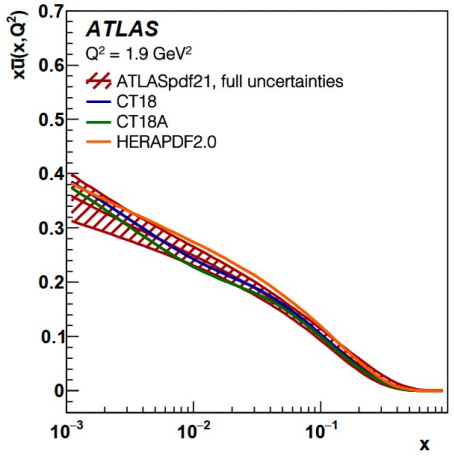


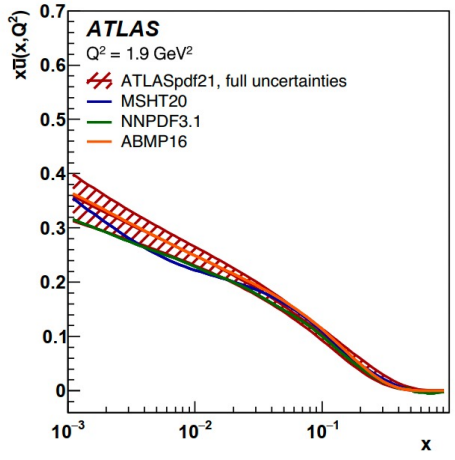
Determination of PDFs using ATLAS data

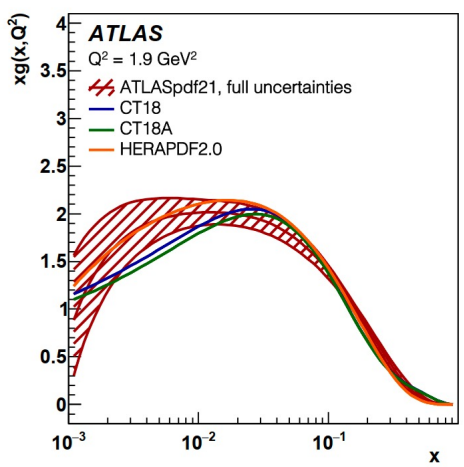
Comparison of ATLASpdf21 with global PDF sets

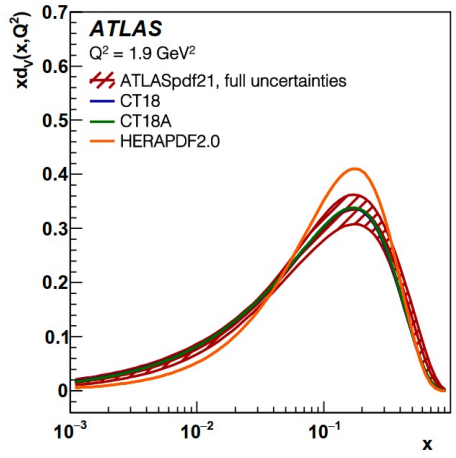


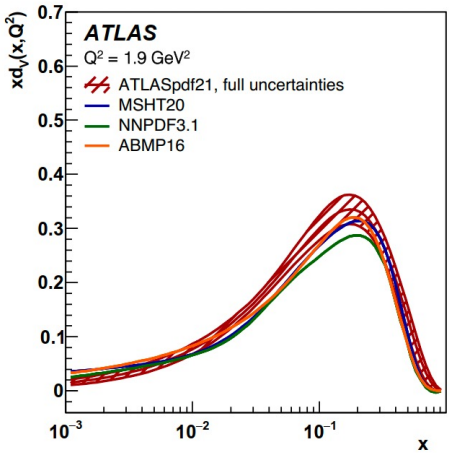


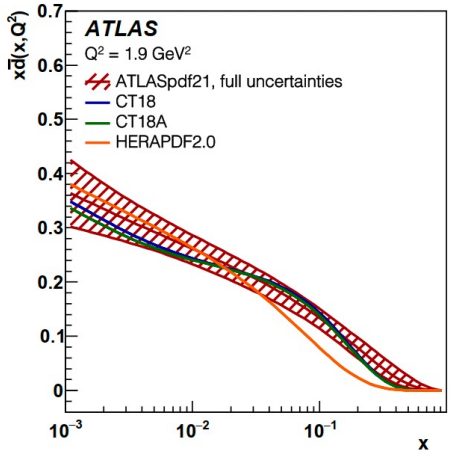


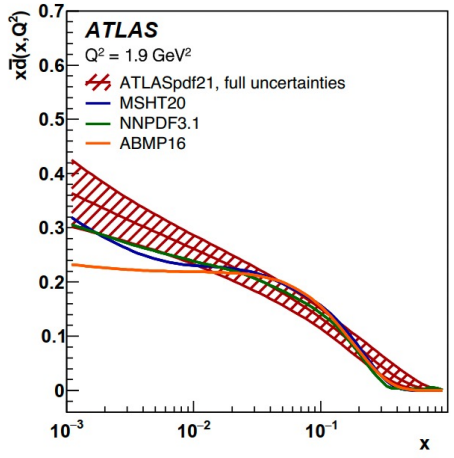


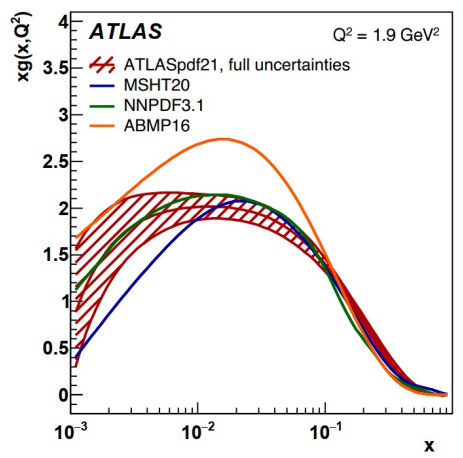












Conclusions

- ATLAS releases the most recent 2021 PDFs with several new features explored

The uniqueness of the ATLAS PDF is that the correlation of the experimental uncertainties across different ATLAS data sets was investigated

- LHC delivers plenty of PDF sensitive data with high statistics
- LHC data have a significant impact on PDF extractions
- LHC measurements start to dominate the global PDF fit results

Thanks for your attention.

Backup

PDF uncertainty of CDF

Previous CDF Result (2.2 fb^{-1})
Combined Fit Systematic Uncertainties

Source	Uncertainty (MeV)
Lepton Energy Scale	7
Lepton Energy Resolution	2
Recoil Energy Scale	4
Recoil Energy Resolution	4
$u_{\|\|}$ efficiency	0
Lepton Removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton Distributions	10
QED radiation	4
W boson statistics	12
Total	19

New CDF Result (8.8 fb^{-1})
Combined Fit Systematic Uncertainties

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W / p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

Taken from Ashutosh Kotwa' s Talk

PDF uncertainty of CDF

Parton Distribution Functions

- Affect W boson kinematic line-shapes through acceptance cuts
- We use NNPDF3.1 as the default NNLO PDFs
- Use ensemble of 25 'uncertainty' PDFs => 3.9 MeV
  - Represent variations of eigenvectors in the PDF parameter space
  - compute δM_W contribution from each error PDF
- Central values from NNLO PDF sets CT18, MMHT2014 and NNPDF3.1 agree within 2.1 MeV of their midpoint
- As an additional check, central values from NLO PDF sets ABMP16, CJ15, MMHT2014 and NNPDF3.1 agree within 3 MeV of their midpoint
- Missing higher-order QCD effects estimated to be 0.4 MeV
  - varying the factorization and renormalization scales
  - comparing two event generators with different resummation and non-perturbative schemes.

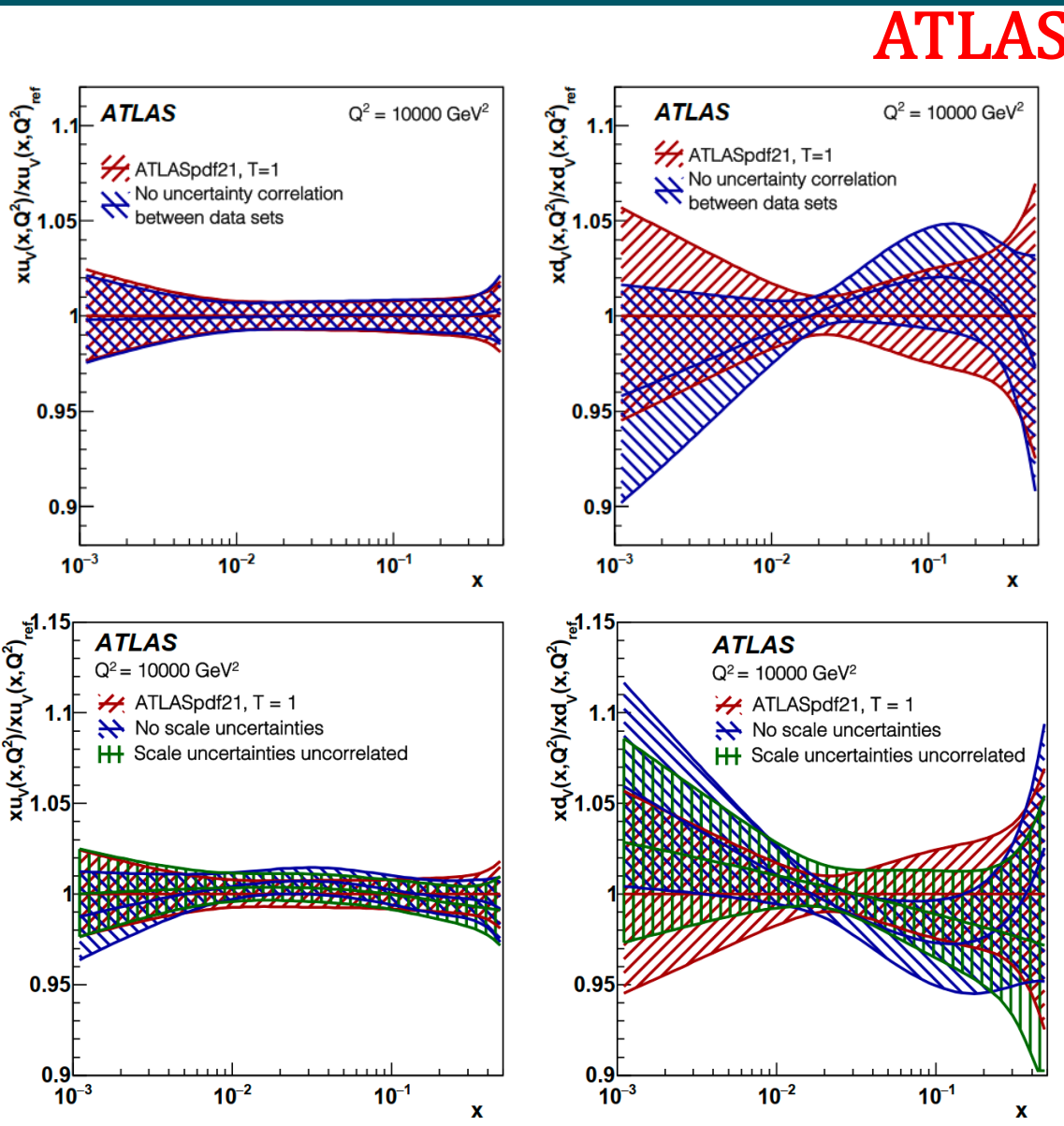
Taken from Ashutosh Kotwa' s Talk

Determination of PDFs using ATLAS data

- The correction between various data sets do not give big effects on PDFs, but visible differences in χ^2 e.g. the fit without correlation exhibits a smaller χ^2 by ~30 units

- The different in magnitude of the PDF uncertainties are very small

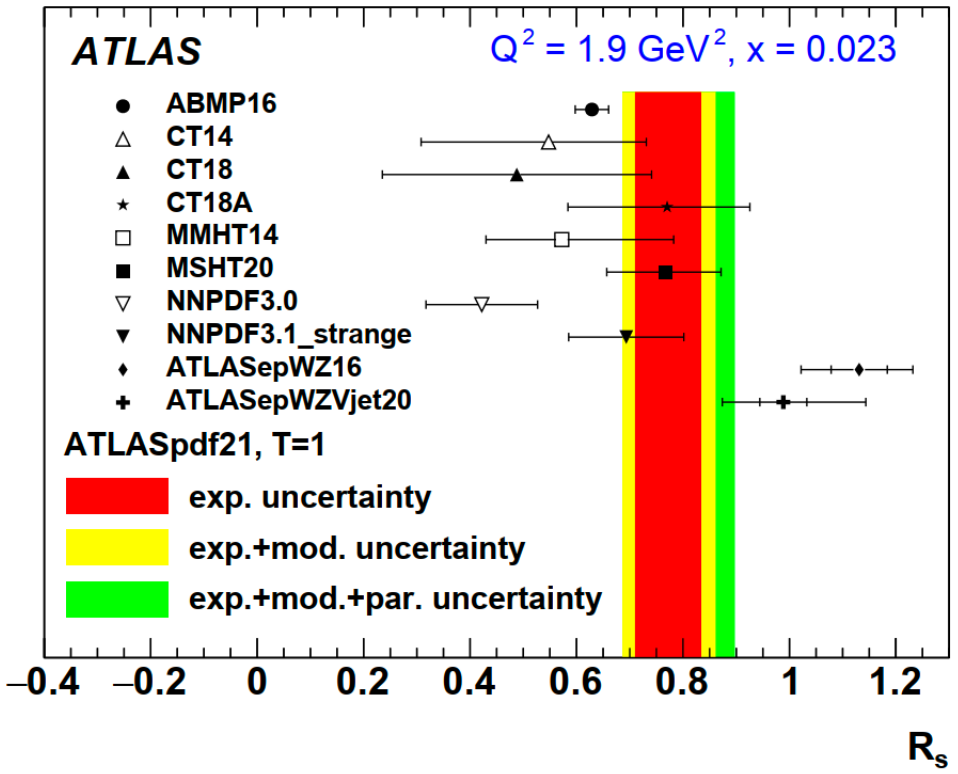
- The differences between the PDF shapes are not large, but they can be important if $0(1\%)$ is sought on PDFs

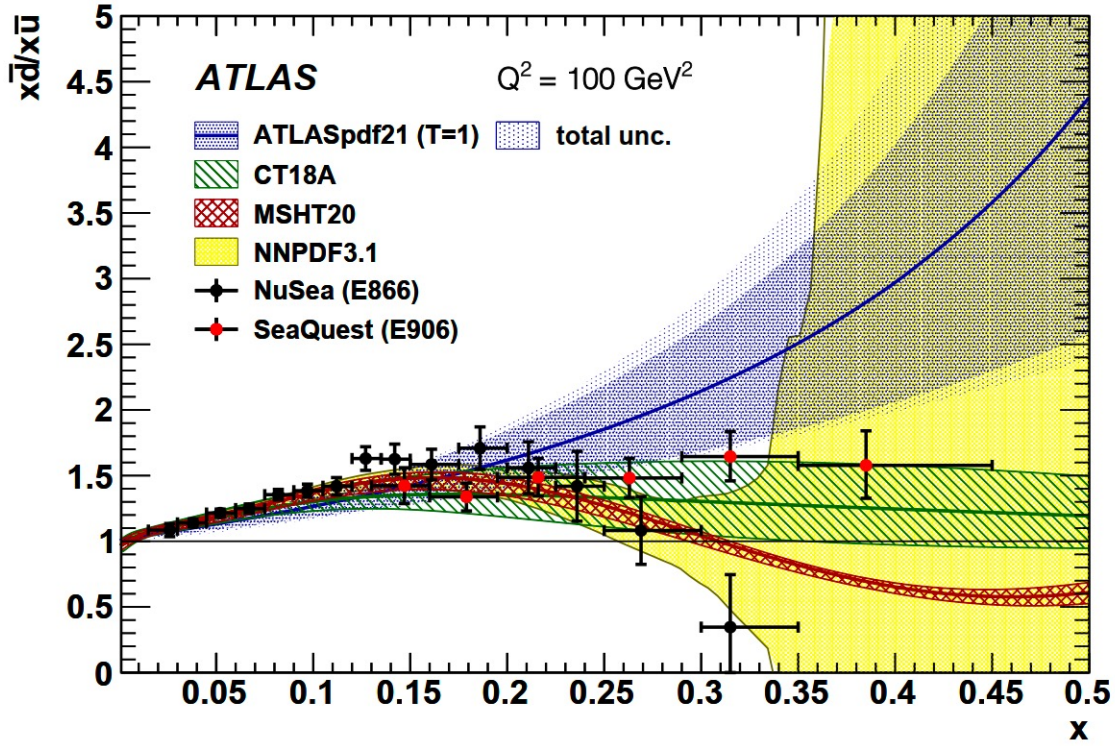


Determination of PDFs using ATLAS data

ATLAS

Constraints from ATLAS data





The ATLASpdf21 fit is in better agreement with the new data from E906 in the high-mass region