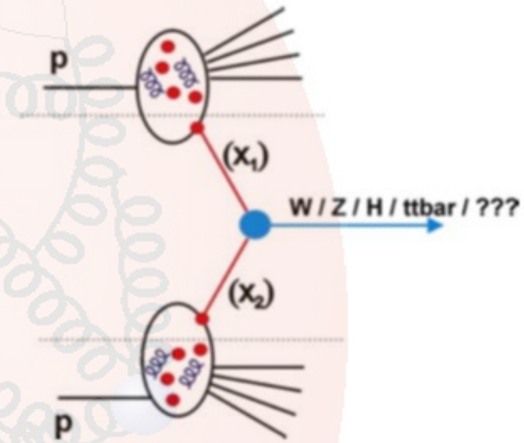
Latest Constraints on Proton Parton Densities from the LHC

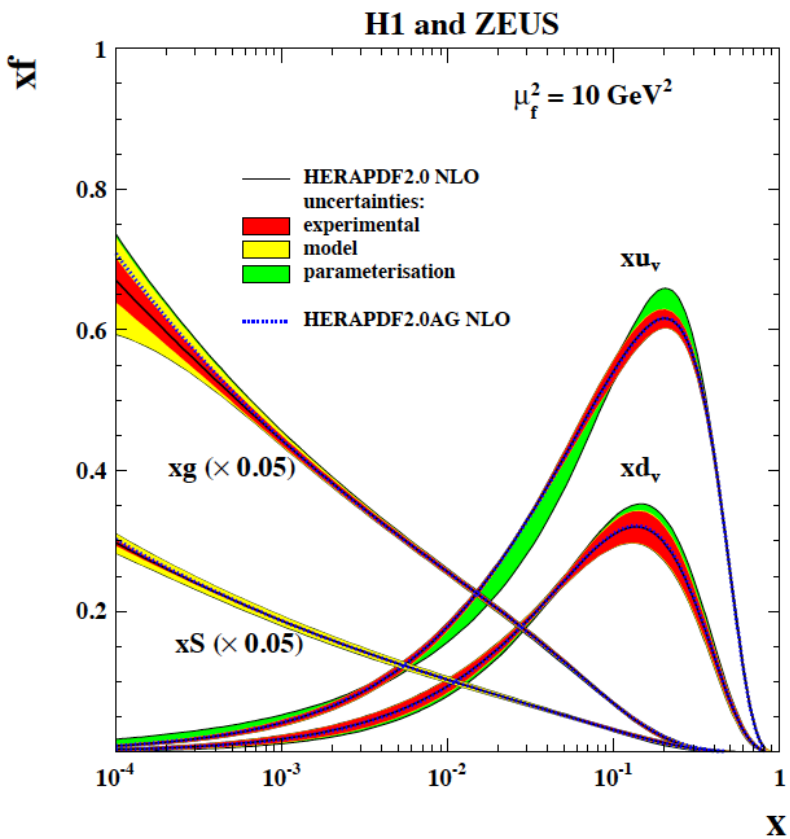
Paul Newman
(University of Birmingham)

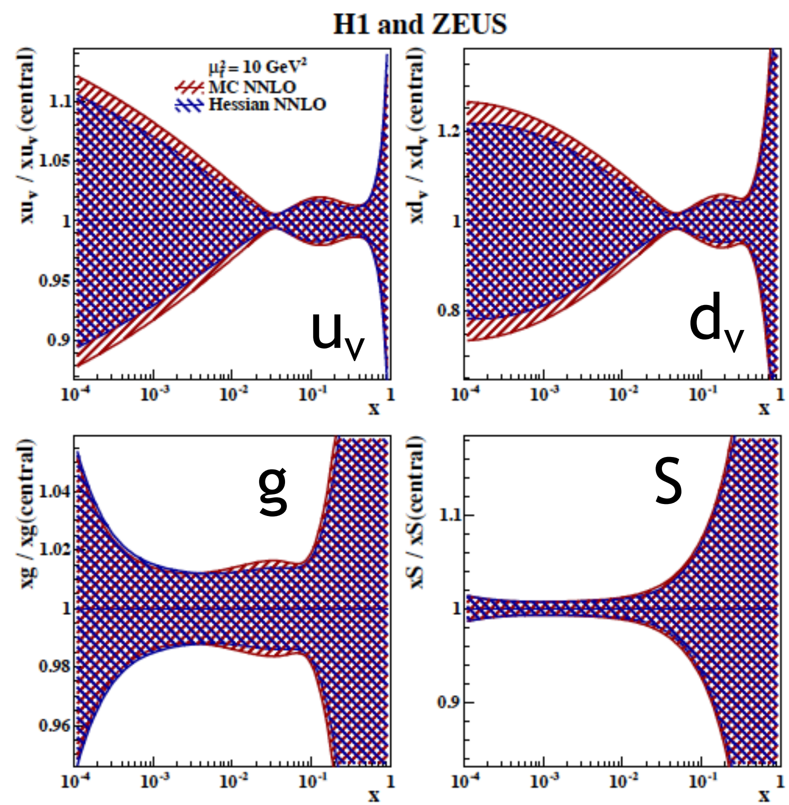
on behalf of
the ATLAS, CMS &
LHCb collaborations



Kick-off meeting on Synergies between the Electron-Ion Collider and the Large Hadron Collider
20 June 2022

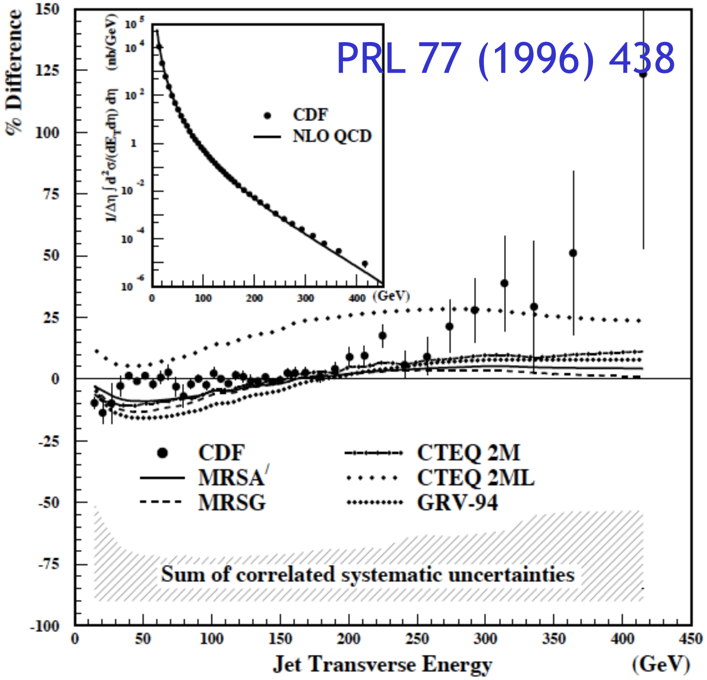
Proton PDFs from ep Physics only: Final HERA Results (HERAPDF2.0)





- ~2% gluon precision, 1% on sea quarks for x ~ 10^{-2} ... BUT …
- Low x gluon rising in a non-sustainable way at large Q^2
- Uncertainties explode above x=10^{-1}

Focusing on High x

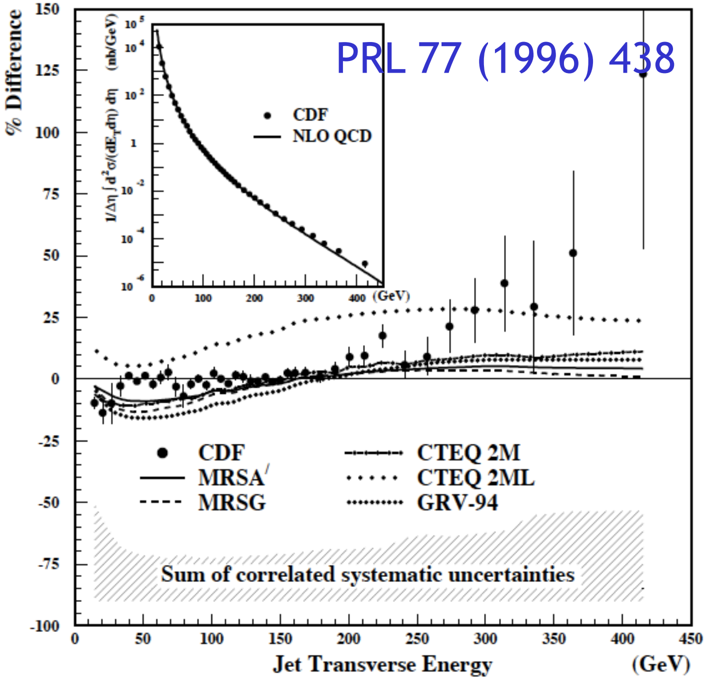


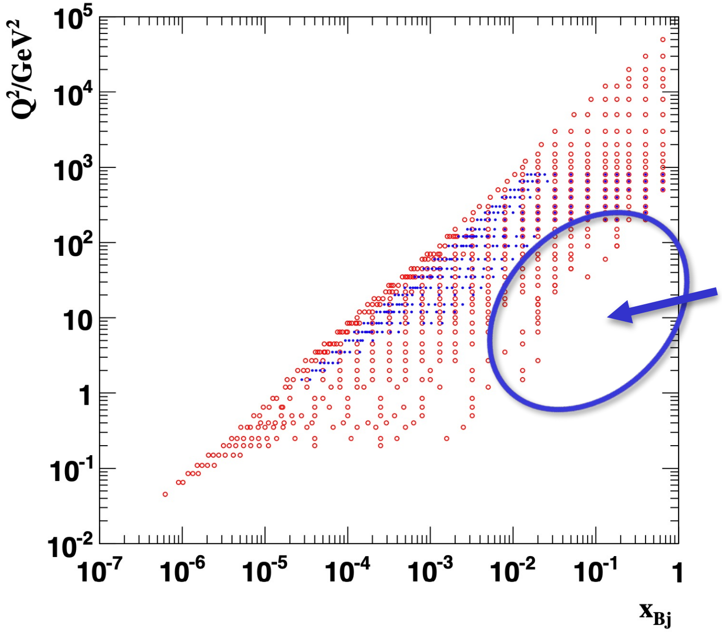
Ancient history (HERA v Tevatron)

- Signatures for new physics near kinematic limit can be hidden (or faked!) by imprecise PDFs as $x \rightarrow 1$

- e.g. Apparent excess in large E_T Tevatron jets turned out to be well within uncertainties on high x gluon …

Focusing on High x





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HERA's High x Limitations

- HERA's lack of high x precision is due to limited luminosity and $1/Q^4$ factor in cross section + kinematic correlation between x, Q^2

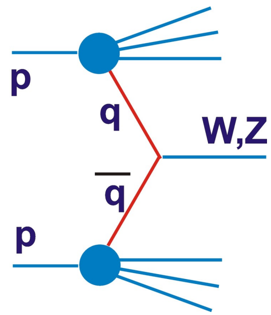
- High x, intermediate Q^2 region will one day be filled by EIC.

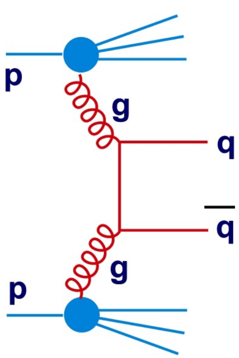
- For now, the best constraints come from fixed target experiments and (especially) the LHC

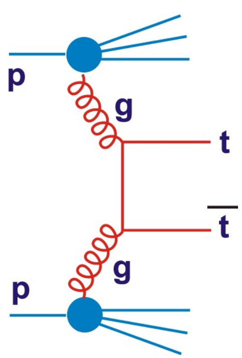
Constraining PDFs with LHC Data

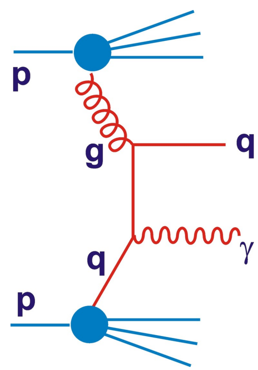
- Many pp processes are sensitive to PDFs …

- Electroweak gauge boson production
- Drell Yan (away from Z pole)
- High pT jet production
- Top Quarks
- Direct Photons
- W+c, Z+c …

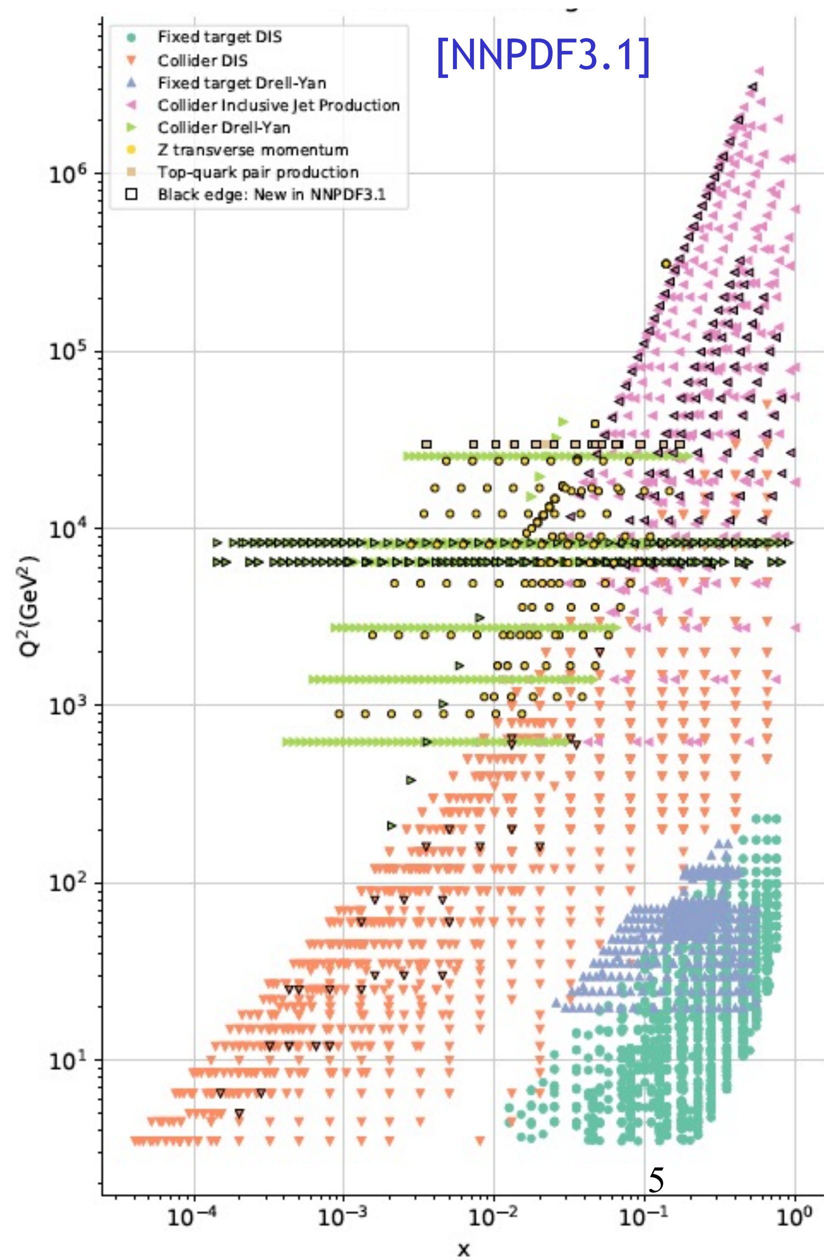




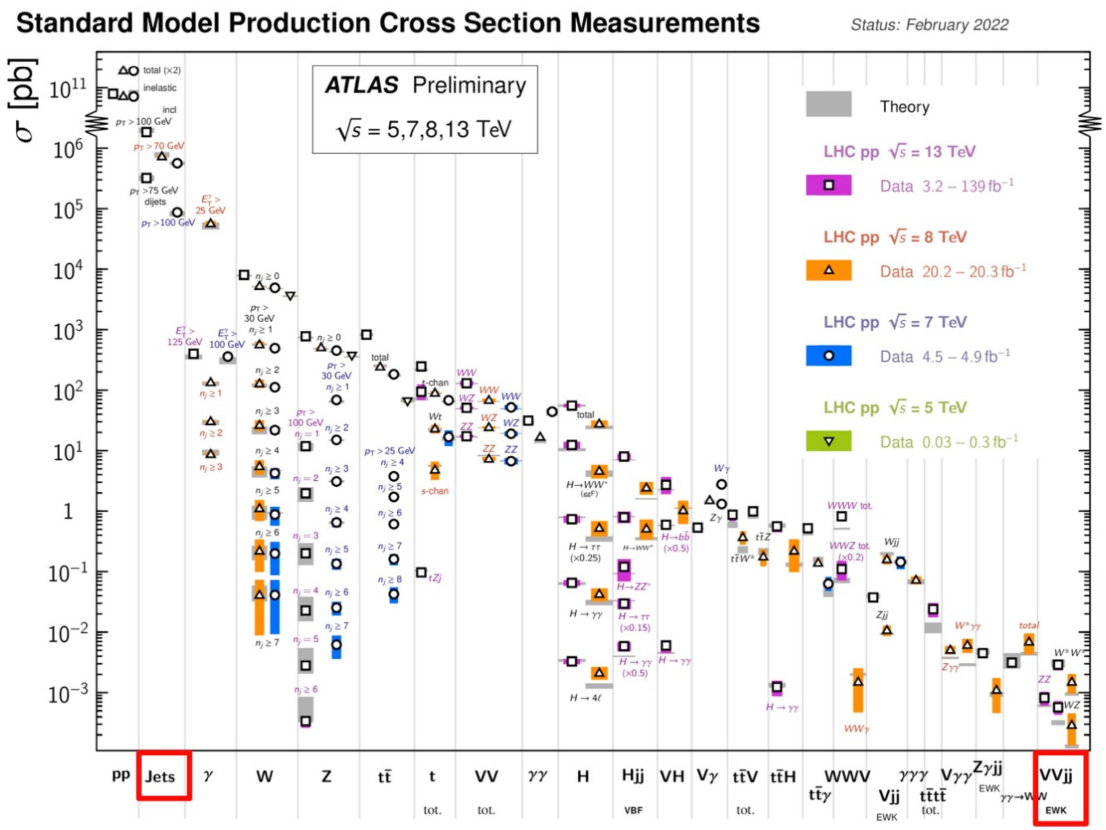




… programme to better constrain PDFs with LHC data both by experimental collaborations and by fitting groups

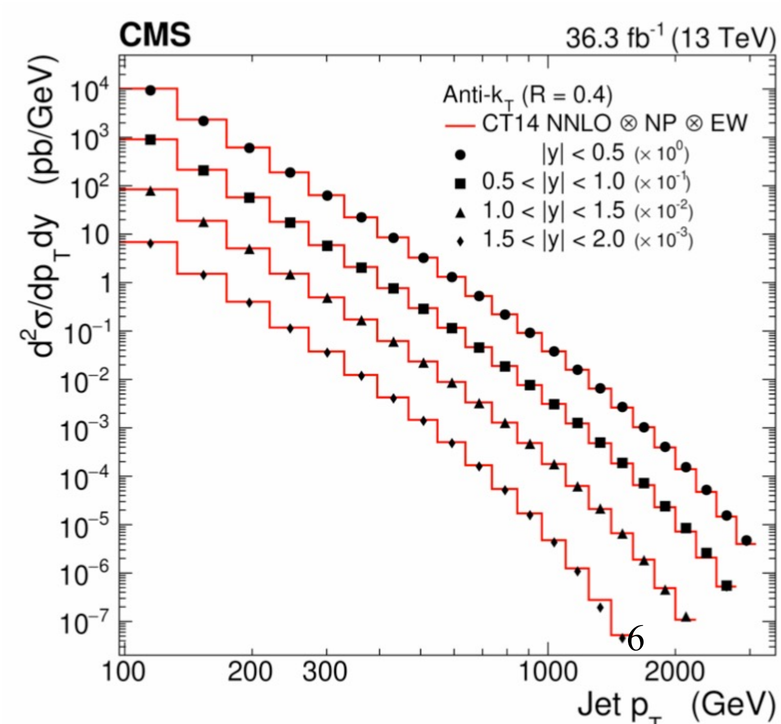


Theory v Data at LHC



PDFs are a vital ingredient in almost all predictions

Factorisation between ep and pp works.



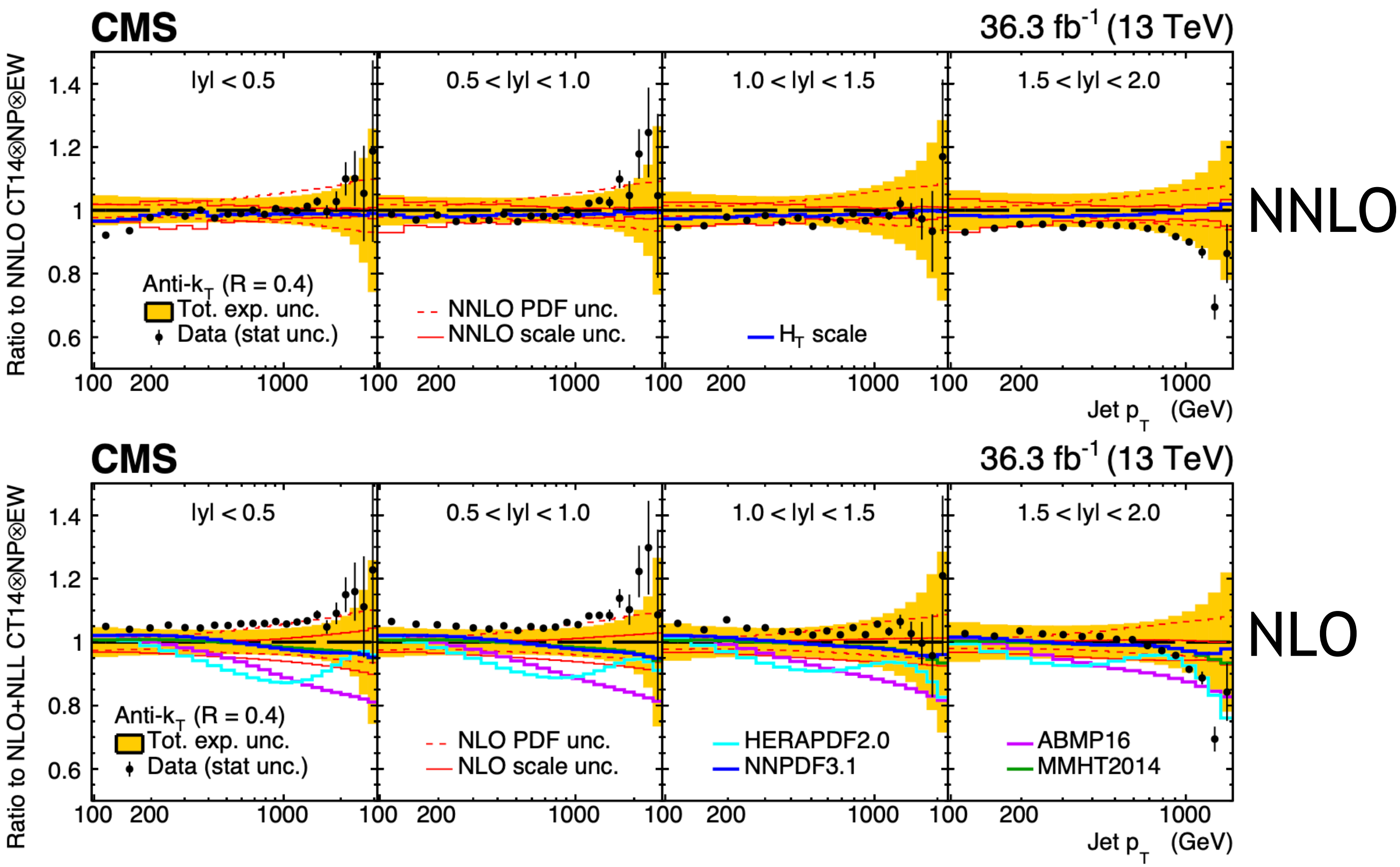
High x starting point: **Inclusive jets:**

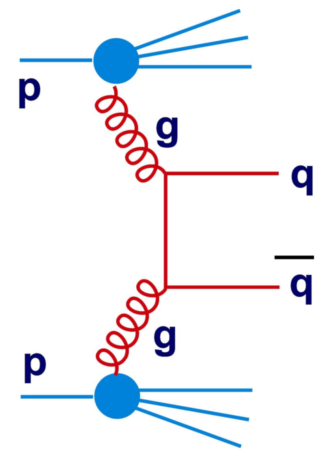
- High rates, wide kinematic range
- 'Astonishing' agreement between data and (N)NLO QCD over many orders of magnitude in x-section, up to scales with p_T~2 TeV

Looking in more Detail ..

[JHEP 02 (2022) 142]

e.g. CMS inclusive jets (R=0.4) versus CT14 and others + non-pert, EW coors





- Deviations at typically 5% level, worse at largest p_T
  → consistent with experiment + theory (including PDF!) systematics.
- What happens if you include the data in PDF fits?...

Recent CMS PDF-Fitting ANALYSIS

- CMS 13 TeV Double-differential inclusive jets with R=0.7
- NC and CC cross sections from HERA
- (Optionally) CMS Triple-differential ttbar cross sections

Fits using xFitter framework, NNLO DGLAP (with Non-Pert + EW corrections)

Parameterisation:

$$xg(x) = A_g x^{B_g}(1-x)^{C_g}(1+D_g x + E_g x^2)$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v} x^2),$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},$$
$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}}(1+D_{\overline{U}} x),$$
$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}}(1+E_{\overline{D}} x^2).$$

Data sets		HERA-only Partial χ^2/N_{dp}	HERA+CMS Partial χ^2/N_{dp}
HERA I+II neutral current	e^+p, $E_p = 920$ GeV	378/332	375/332
HERA I+II neutral current	e^+p, $E_p = 820$ GeV	60/63	60/63
HERA I+II neutral current	e^+p, $E_p = 575$ GeV	201/234	201/234
HERA I+II neutral current	e^+p, $E_p = 460$ GeV	208/187	209/187
HERA I+II neutral current	e^-p, $E_p = 920$ GeV	223/159	227/159
HERA I+II charged current	e^+p, $E_p = 920$ GeV	46/39	46/39
HERA I+II charged current	e^-p, $E_p = 920$ GeV	55/42	56/42
CMS inclusive jets 13 TeV	$0.0 < \|y\| < 0.5$	—	13/22
	$0.5 < \|y\| < 1.0$	—	31/21
	$1.0 < \|y\| < 1.5$	—	18/19
	$1.5 < \|y\| < 2.0$	—	14/16
Correlated χ^2		66	83
Global χ^2/N_{dof}		1231/1043	1321/1118

- Addition of jet data constrains high x whilst maintaining χ^2 /dof.

- Tension between high |y| jet data and top data?

PDF Constraints from CMS QCD ANALYSIS

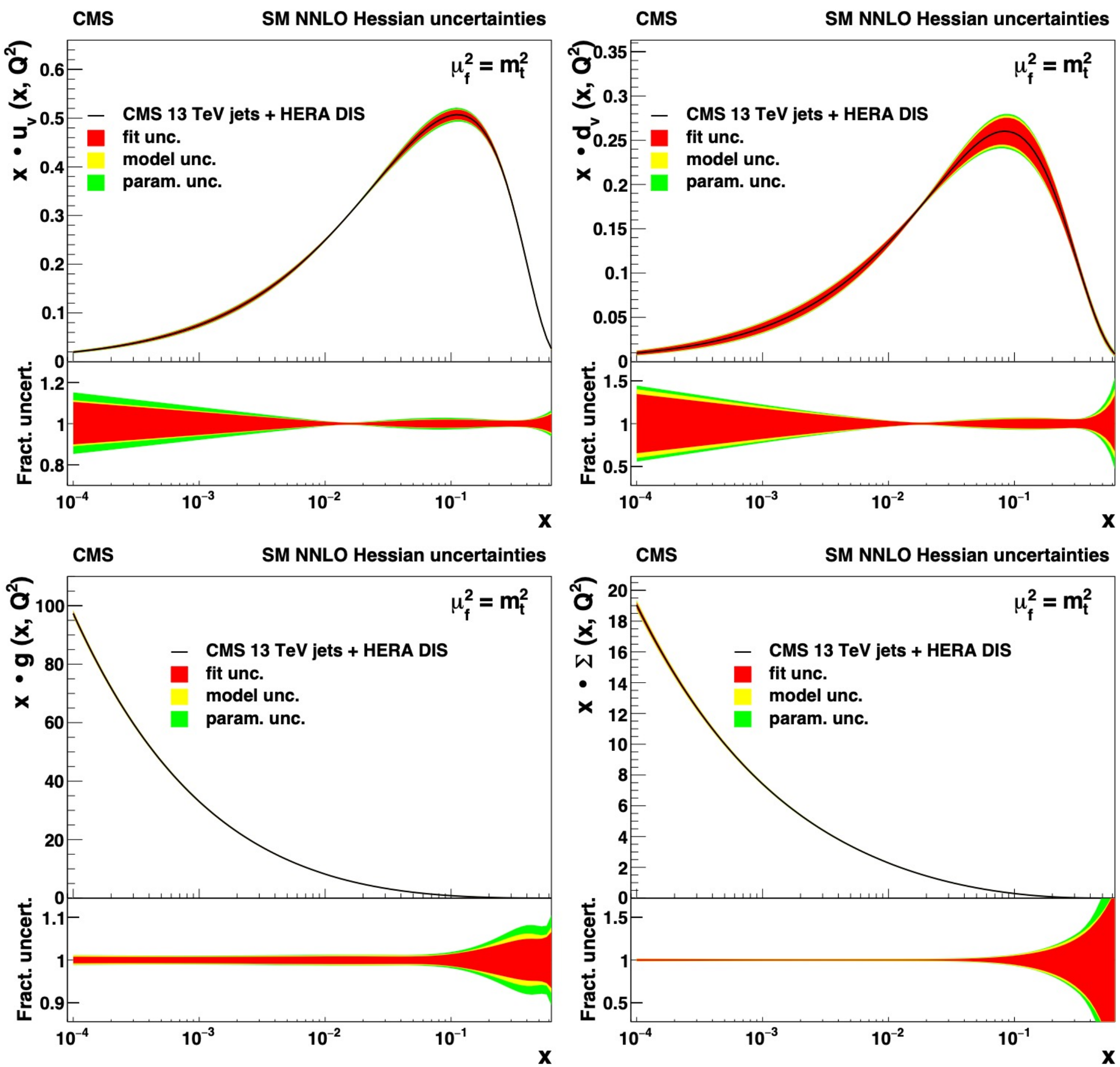
- Inclusive jets have substantial impact on gluon precision at all x relative to CT14 PDFs that already used previous LHC data.

- Singlet quark precision also improves

- Simultaneously, NNLO extraction of strong coupling …

$\alpha_s(m_Z) = 0.1188 \pm 0.0031$

… uncertainty still dominated by scale uncertainty (0.0025)



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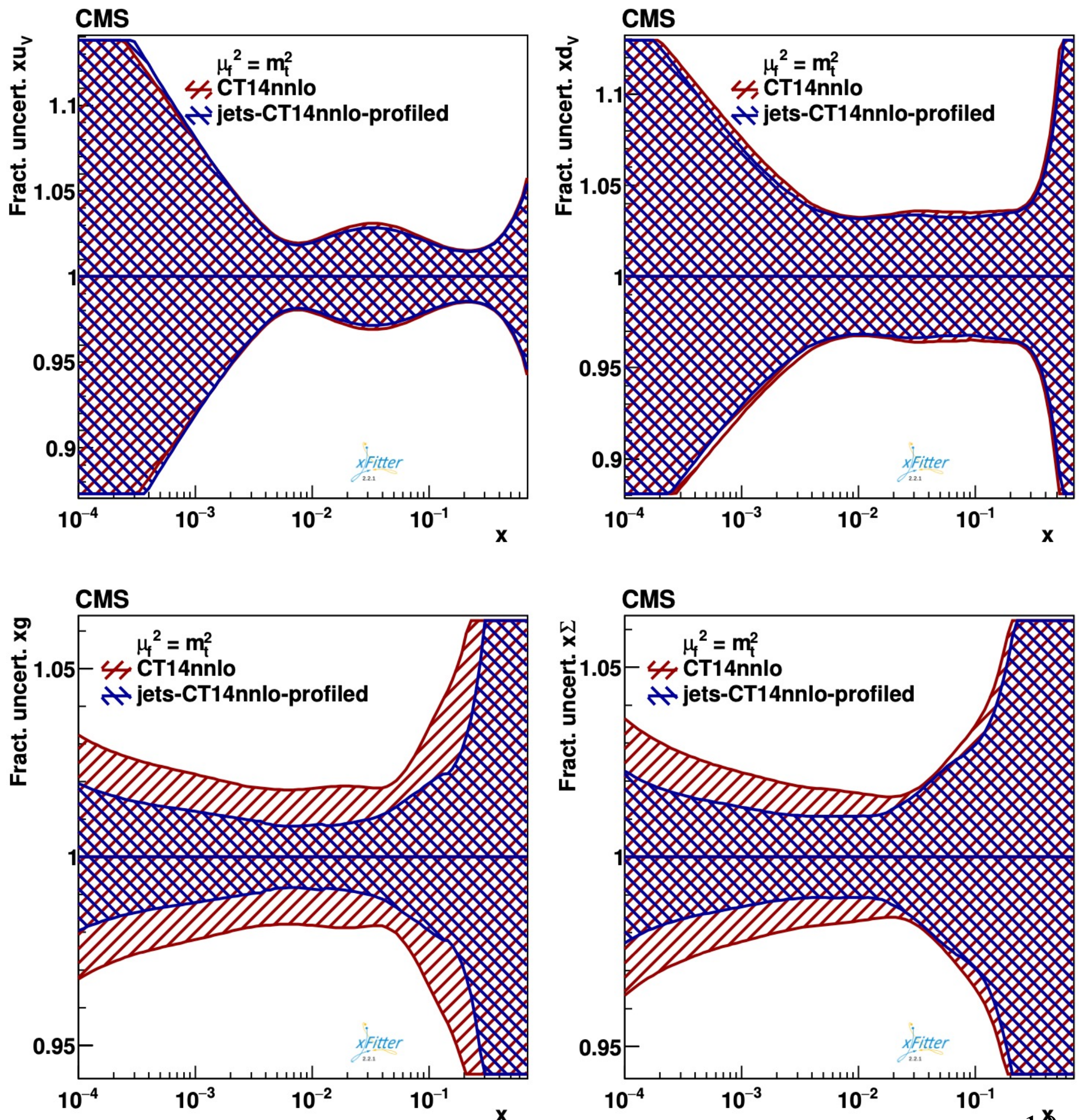


ATLAS 'Global' PDF Fit (ATLASpdf21)

[Eur Phys J C82 (2022) 438]

- Using xFitter framework, NNLO (QCD) + NLO (EW), fixed $\alpha_s(M_Z)=0.118$
- Data included in addition to HERA:

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 [23]	8	20.2	e	p_T^W
Z + jets [24]	8	20.2	e	p_T^{jets} in bins of $\lvert y_{\text{jets}}\rvert$
$t\bar{t}$ [25, 26]	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, $y_{t\bar{t}}$
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_T in bins of $\lvert y_{\text{jets}}\rvert$

- Detailed assessment of correlations between uncertainties in different observables and at different energies and of different χ^2 tolerances

$$xq_i(x) = A_i x^{B_i}(1-x)^{C_i} P_i(x) \quad \text{with} \quad P_i(x) = (1 + D_i x + E_i x^2 + F_i x^3)$$

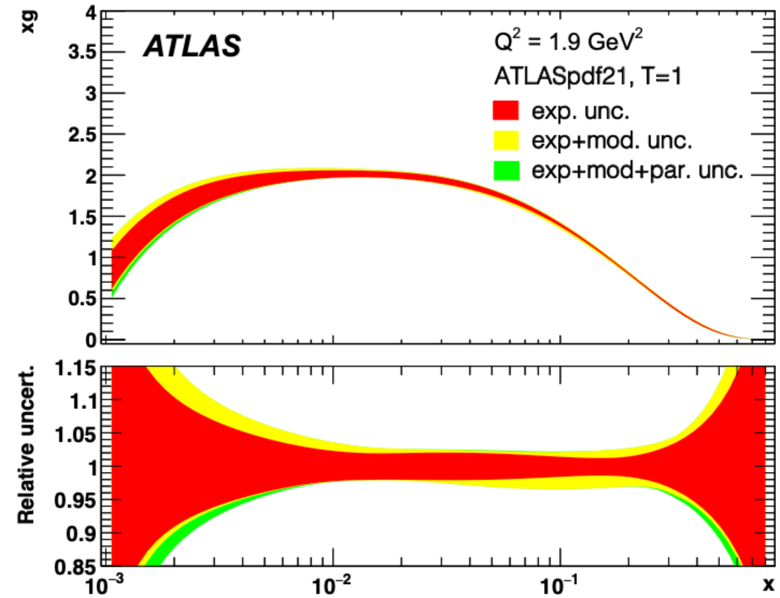
(applying χ^2 saturation technique)

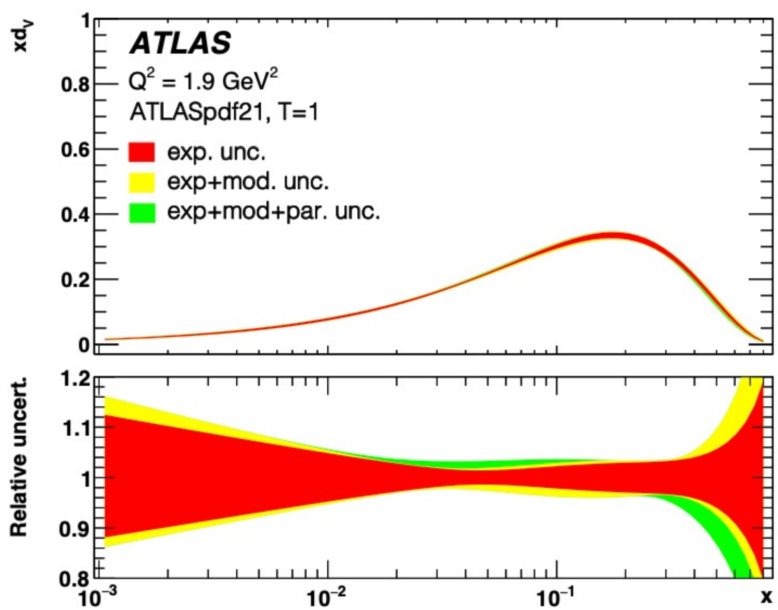
Additional 'negative gluon' term: $xg(x) = A_g x^{B_g}(1-x)^{C_g} P_g(x) - A'_g x^{B'_g}(1-x)^{C'_g}$

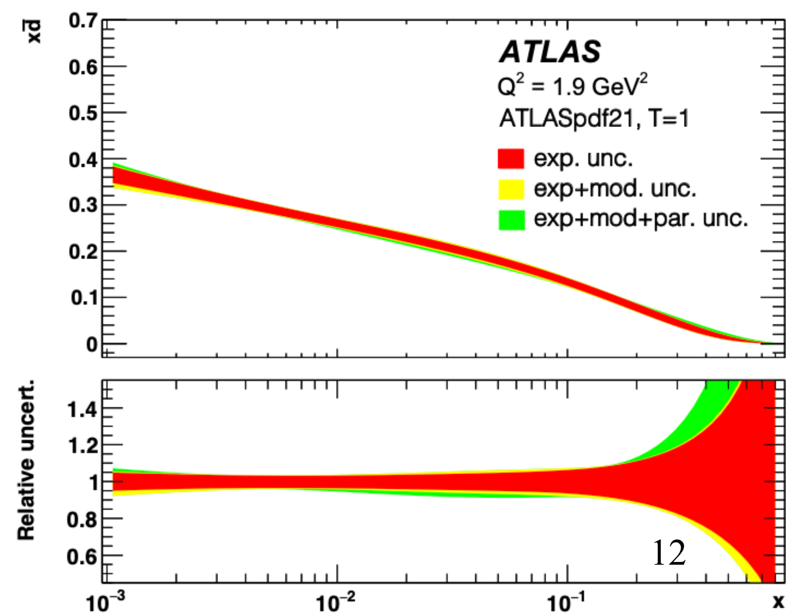
[21 parameters overall]

ATLAS PDFs (at very different scale from CMS)

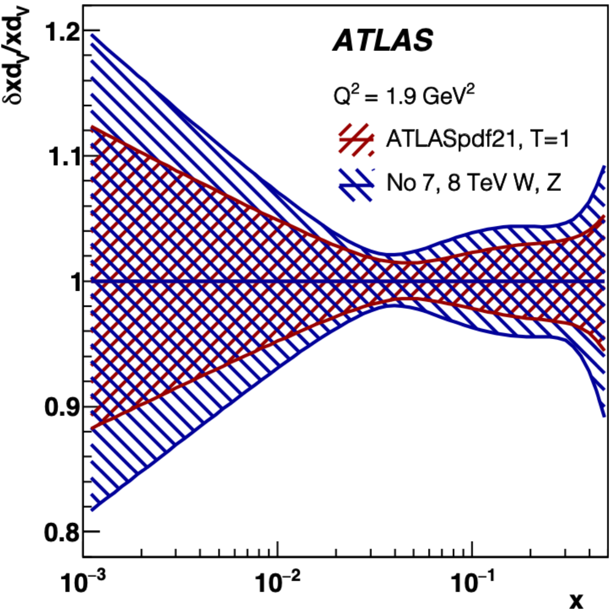
Total χ^2/NDF	2010/1620
HERA χ^2/NDP	1112/1016
HERA correlated term	50
ATLAS W, Z 7 TeVχ^2/NDP	68/55
ATLAS Z/γ^* 8 TeVχ^2/NDP	208/184
ATLAS W 8 TeVχ^2/NDP	31/22
ATLAS W and Z/γ^* 7 and 8 TeV correlated term	$71 = (38 + 33)$
ATLAS direct γ 13/8 TeVχ^2/NDP	27/47
ATLAS direct γ 13/8 TeV correlated term	6
ATLAS V+jets 8 TeVχ^2/NDP	105/93
ATLAS $t\bar{t}$ 8 TeVχ^2/NDP	13/20
ATLAS $t\bar{t}$ 13 TeVχ^2/NDP	25/29
ATLAS inclusive jets 8 TeVχ^2/NDF	207/171
ATLAS V+jets 8 TeV and $t\bar{t}$ + jets 8,13 TeV and $R = 0.6$ inclusive jets 8 TeV correlated term	$87 = (16 + 9 + 21 + 41)$







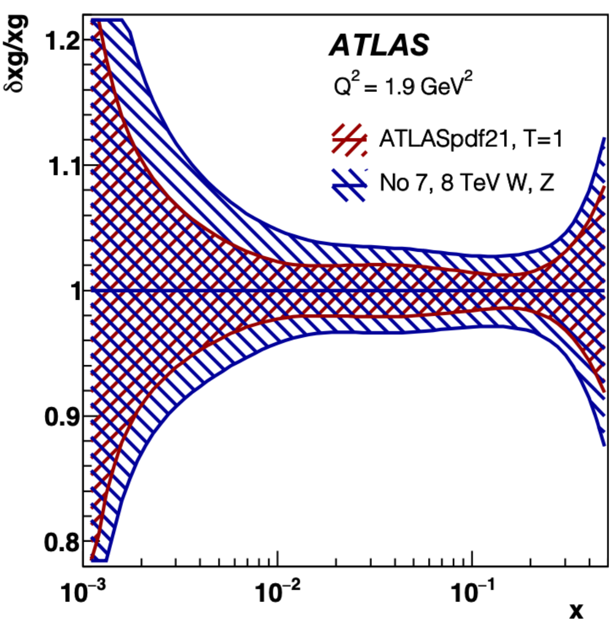
Impact of Different Data Sets

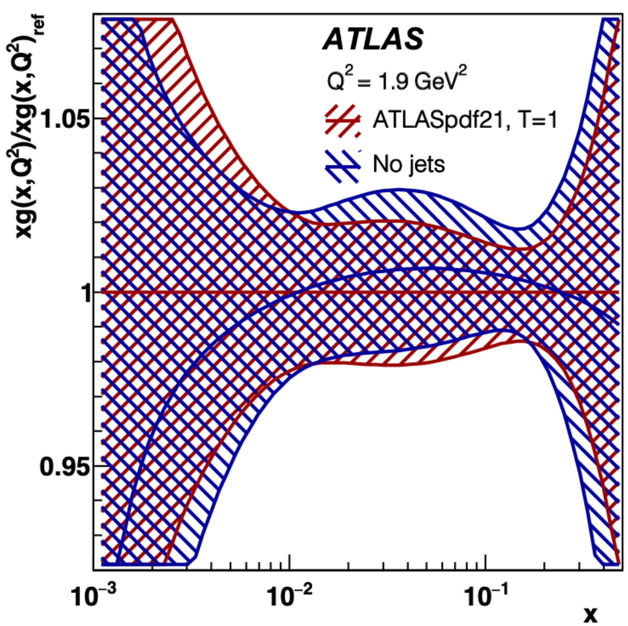


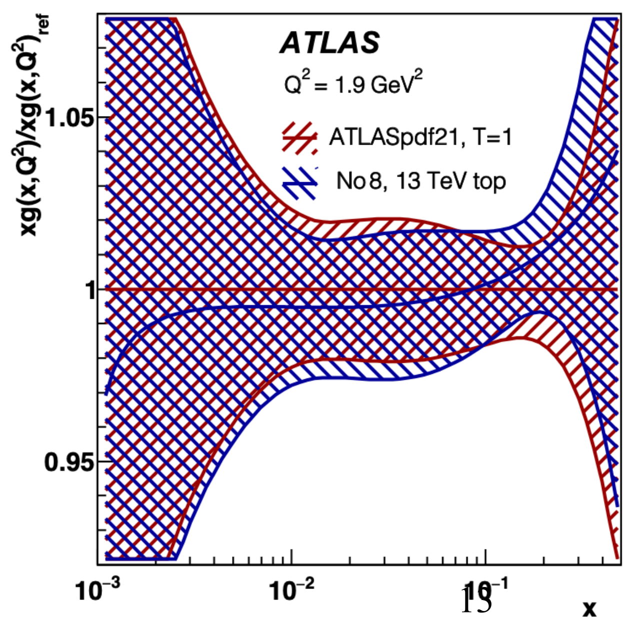
- W and Z data strongly constrain quark densities (and also gluon)

- Jet data primarily reduce gluon uncertainty at large x

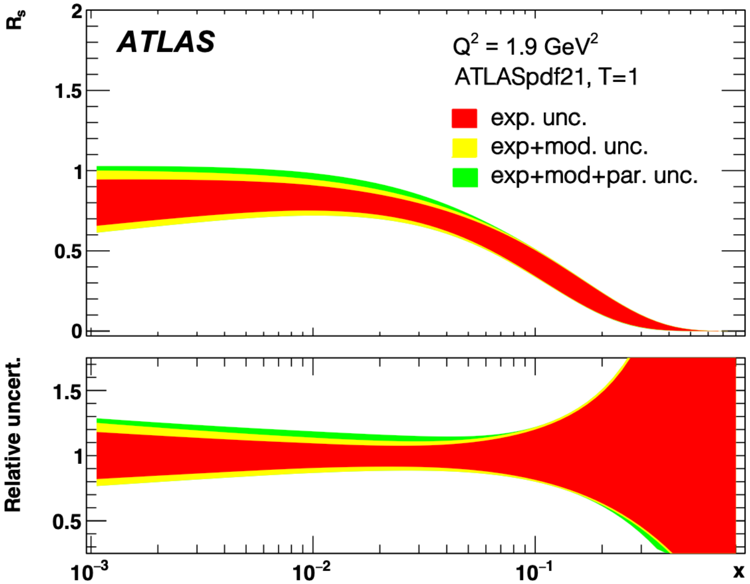
- Top data also have an influence and soften high x gluon (mild tension with jets)







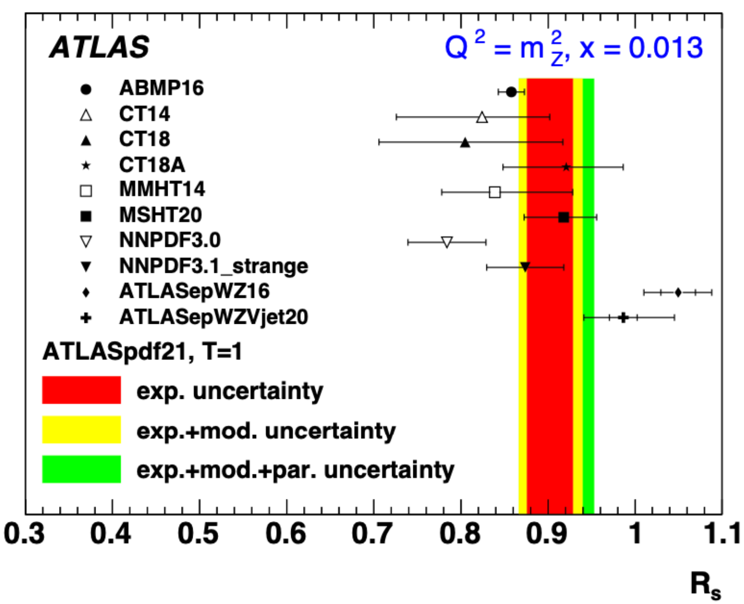
Further Constraints: Strangeness Fraction

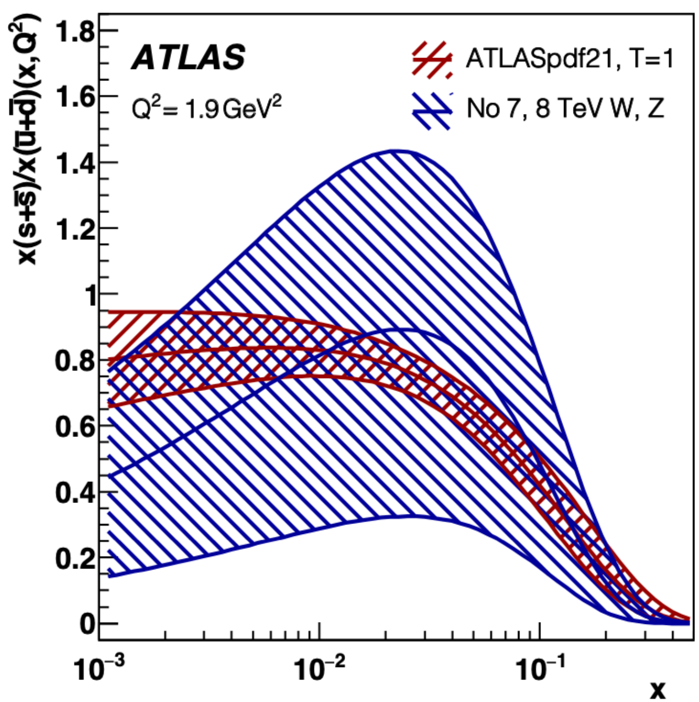


$$R_s = x(s+\bar{s})/x(\bar{u}+\bar{d})$$

- ATLAS fits constrain strange quark density mainly through inclusive W, Z

- Suggests a small strangeness suppression relative to u,d sea at low x.
… compatible with other (global) analyses



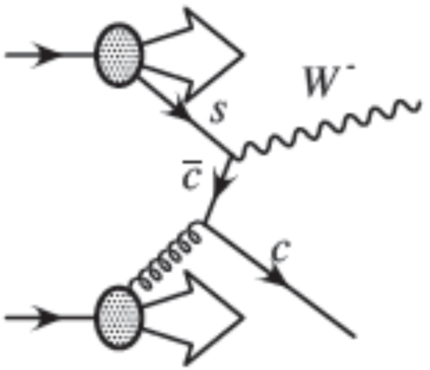


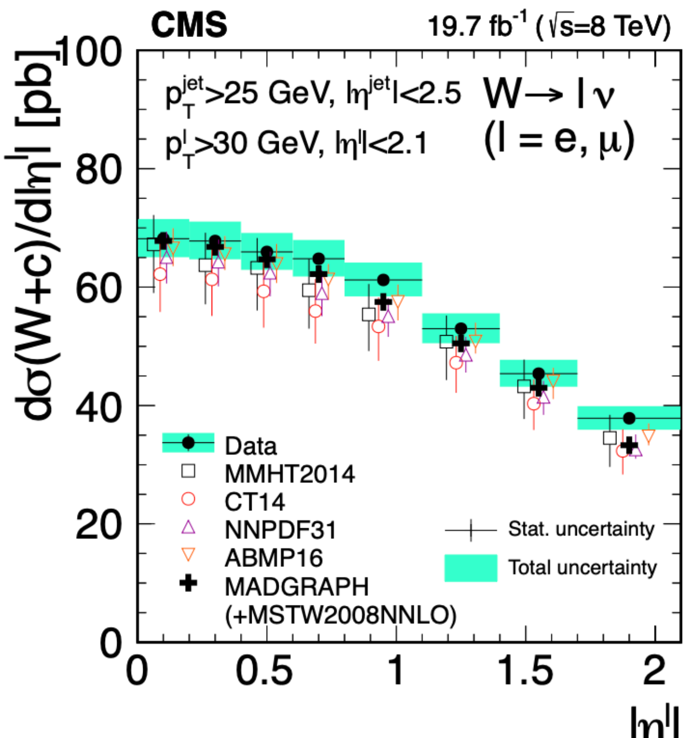
Strange Density @ CMS: W + c

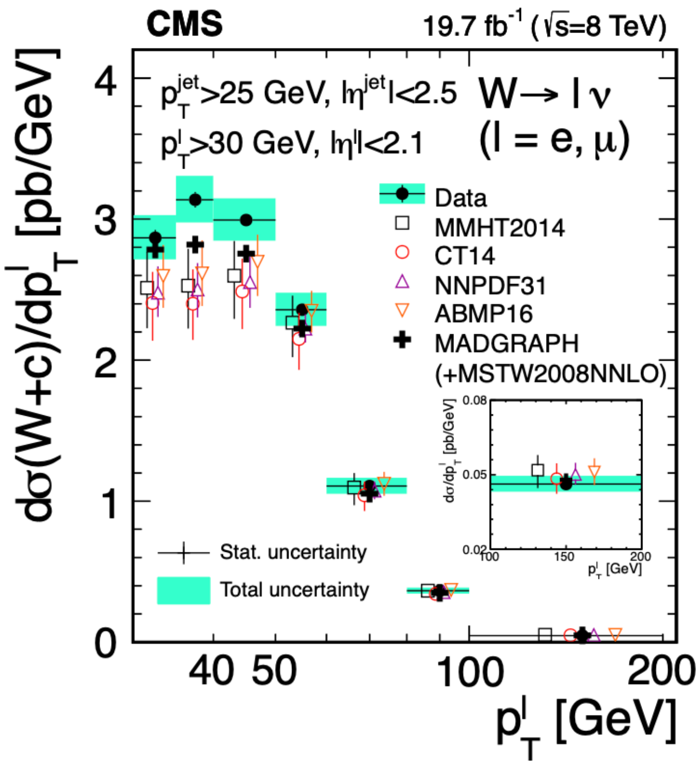
[arXiv:2112.00895]

Final states with W + charm are directly sensitive to the strange density at lowest order

CMS measurements using jets with charm tags from secondary vertices of low p_T^{rel} muons:



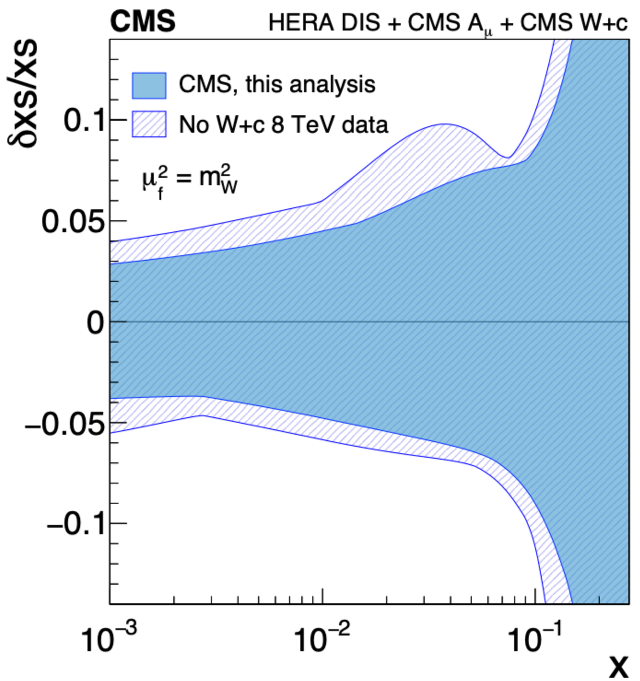




- Reasonable agreement with NLO fits

- Up to 10% disagreements @ low lepton p_T

- Comparisons using NNLO PDFs better?

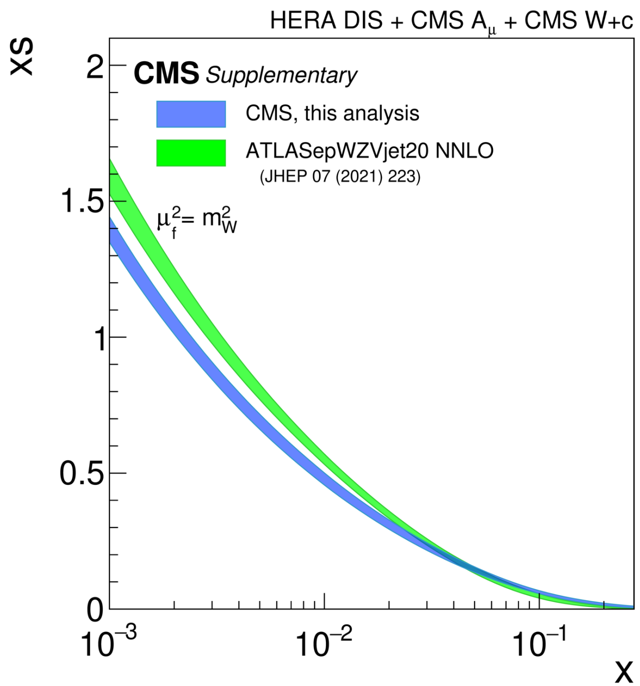


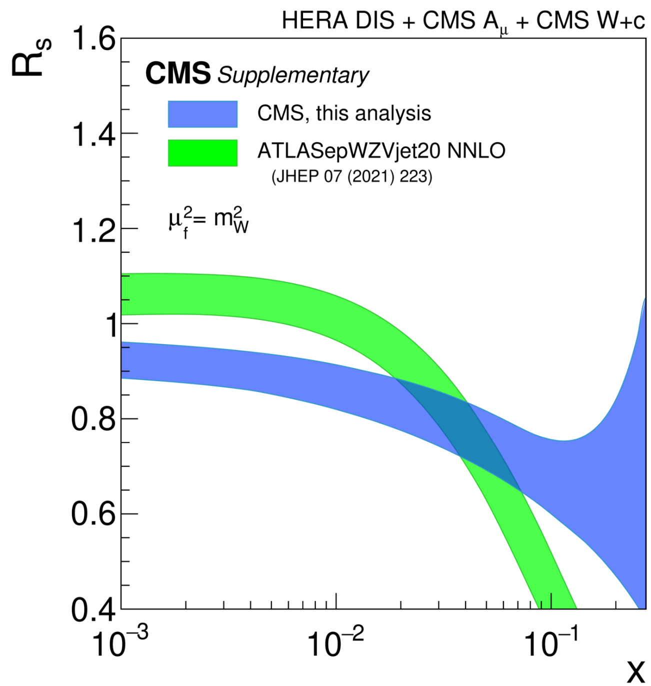
Strange Density CMS v ATLAS

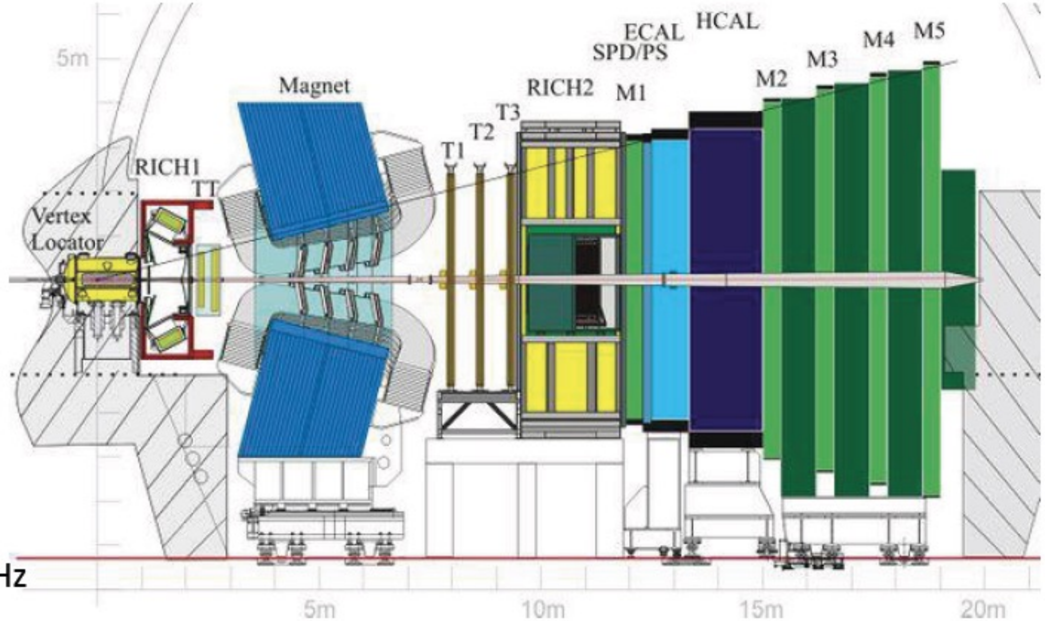
- Including CMS W+c data in fit with HERA data and previous CMS W, W+c data shows significant improvement on strange precision

- Small differences between CMS and ATLAS (constrained by different observables)

- Low x flavour democracy holds at least approximately



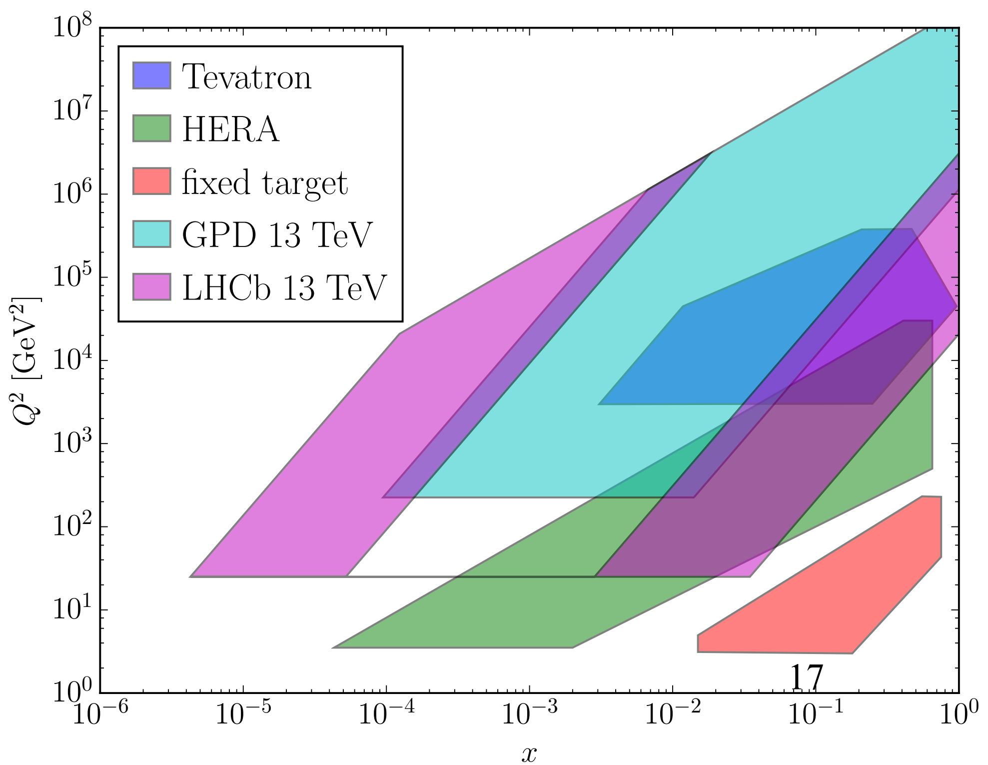




Favourable Low and High x Kinematics at LHCb

"Fixed target-like" forward instrumentation ($2 < \eta < 4.5$) gives sensitivity to asymmetric incoming x values,

… to $x \sim 10^{-5}$ and at $x \rightarrow 1$

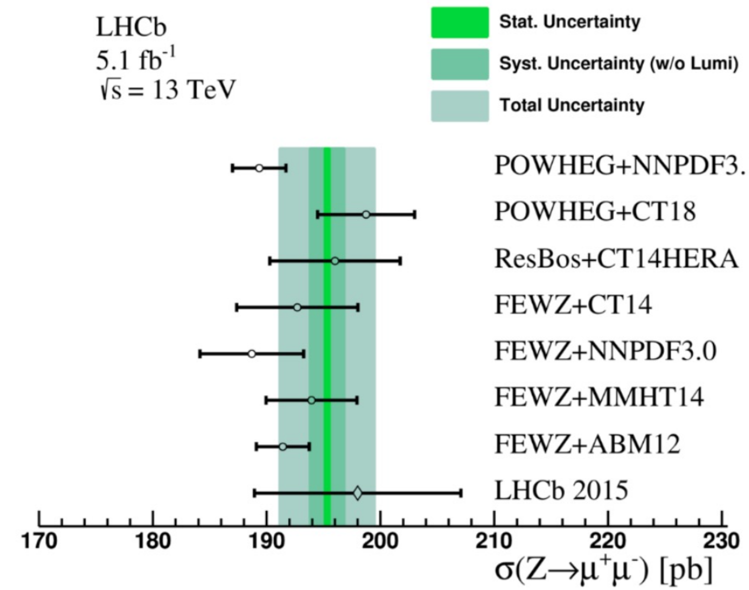


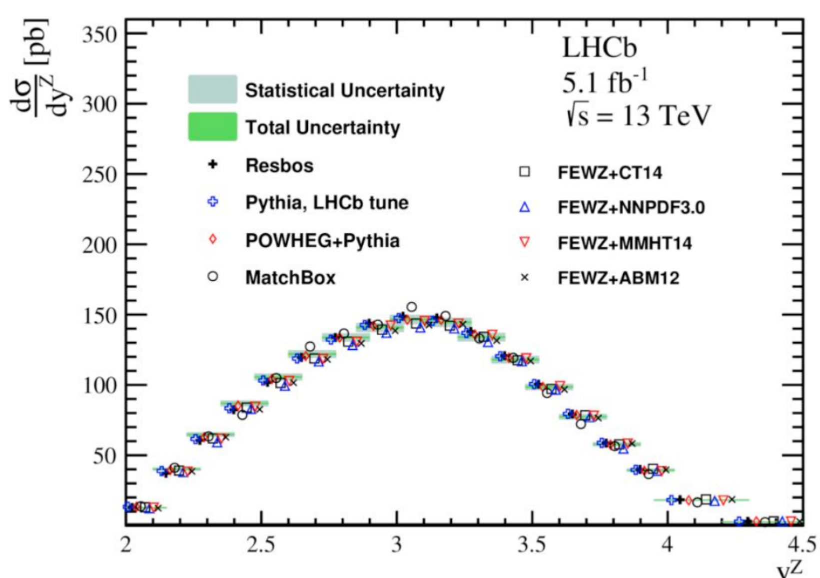
LHCb Z [arXiv:2112.07458]

- Broad agreement with fixed (NLO) order predictions based on global fits

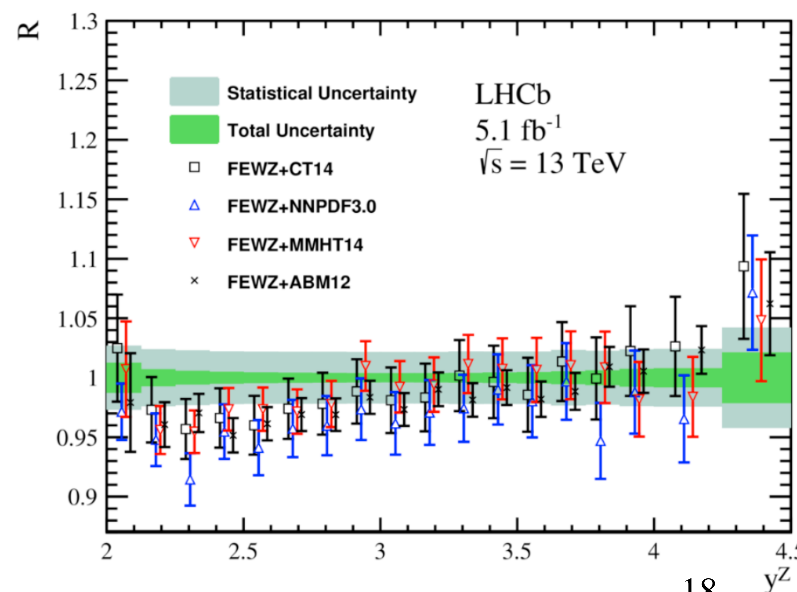
- FEWZ predictions systematically low at low rapidities for all PDF sets (corresponding to more modest x).

- Further studies on W, top, Drell-Yan, intrinsic charm with Z+c (not shown here).



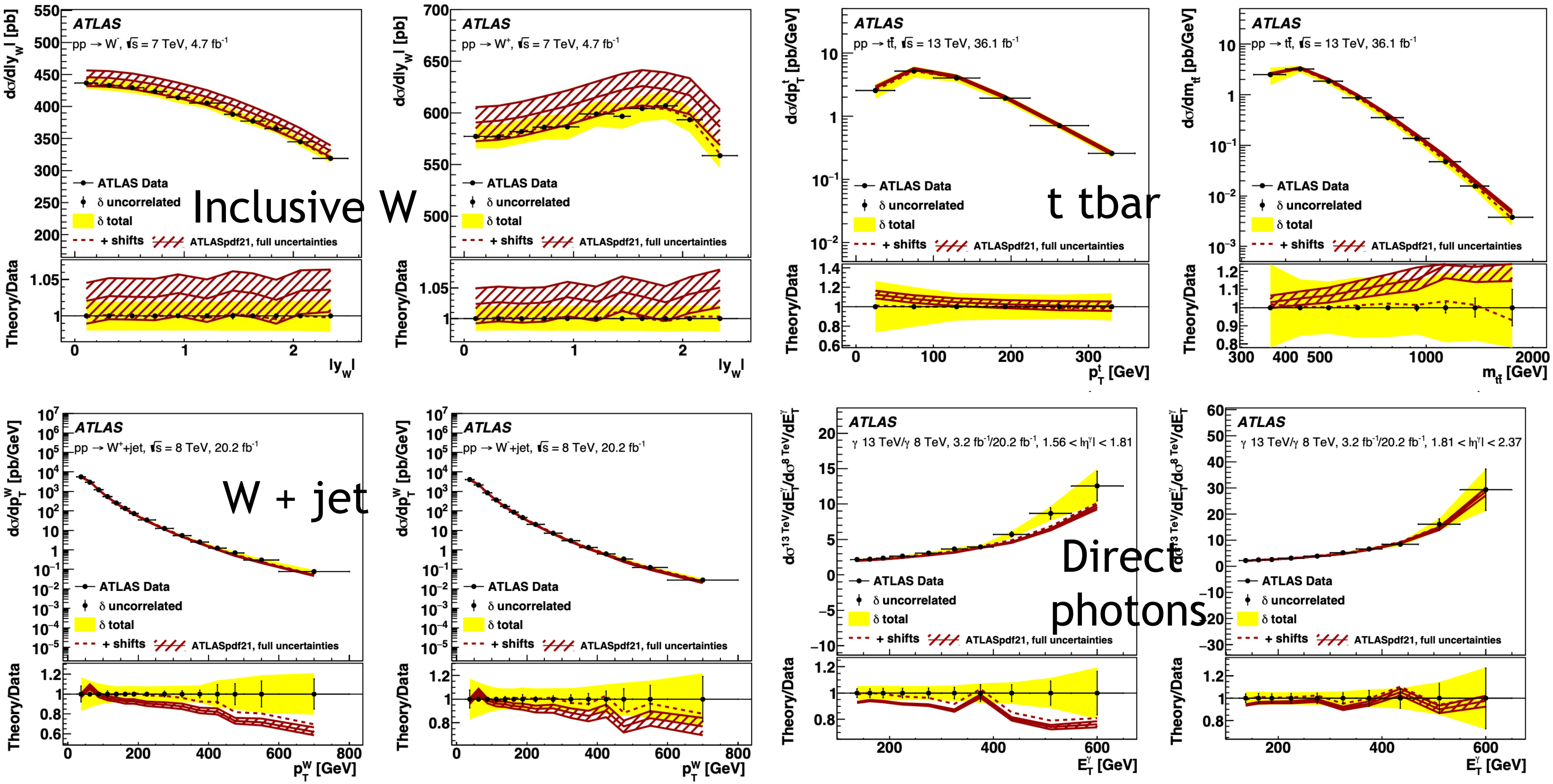


[arXiv:2112.07458]



[arXiv:2112.07458]

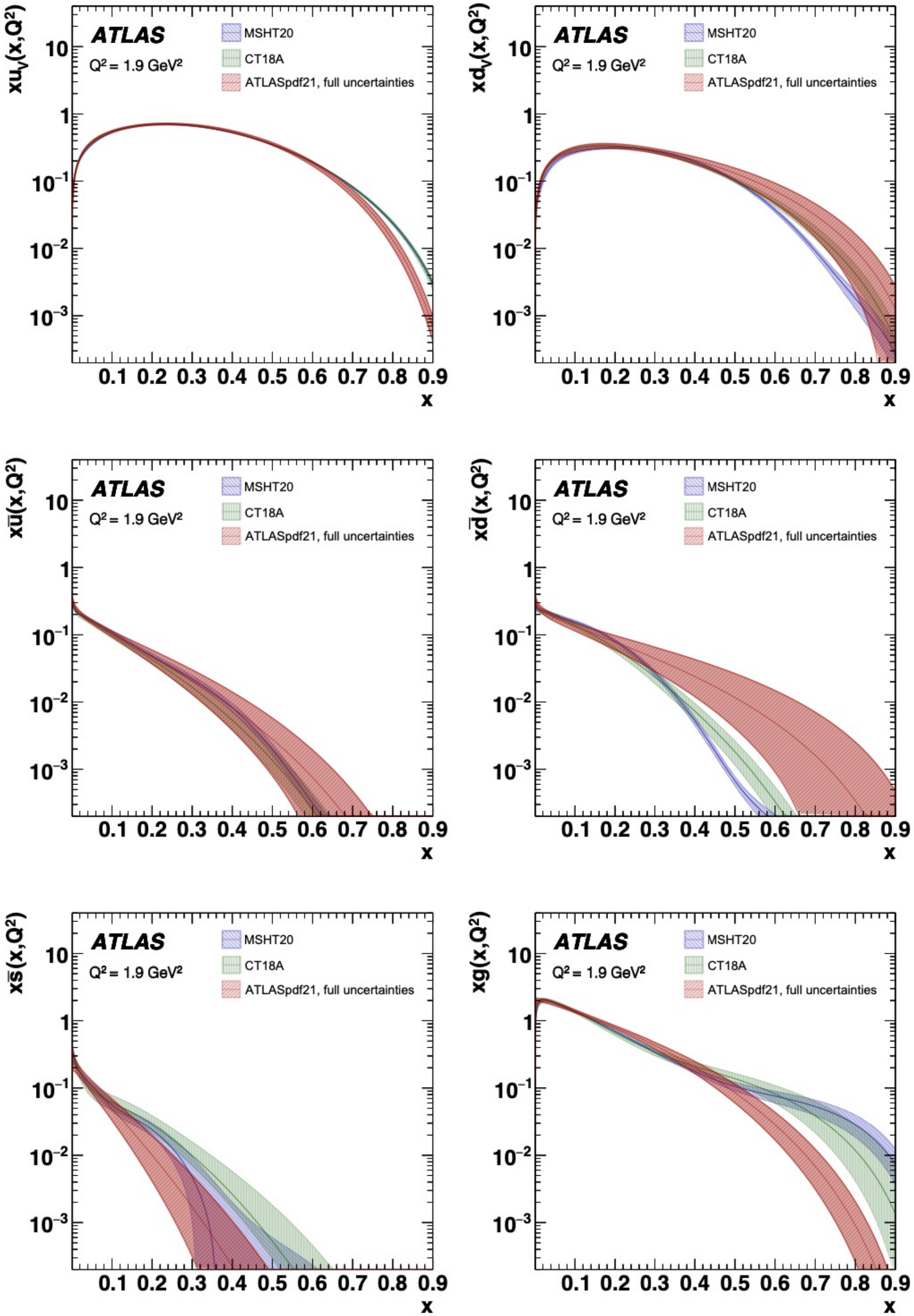
Back to ATLAS: Quality of Description of Data



Level of agreement within expectations … but deviations 5-20%

Theoretical Limitations:
- Hadronisation and Underlying Event
- Missing higher orders (QCD & EW)
- Large logs needing resummations

Experimental Limitations:
- Systematics (energy scale …)
- Correlations between measurements



ATLAS v Global Fits at high x

- Progress compared with HERA only fits

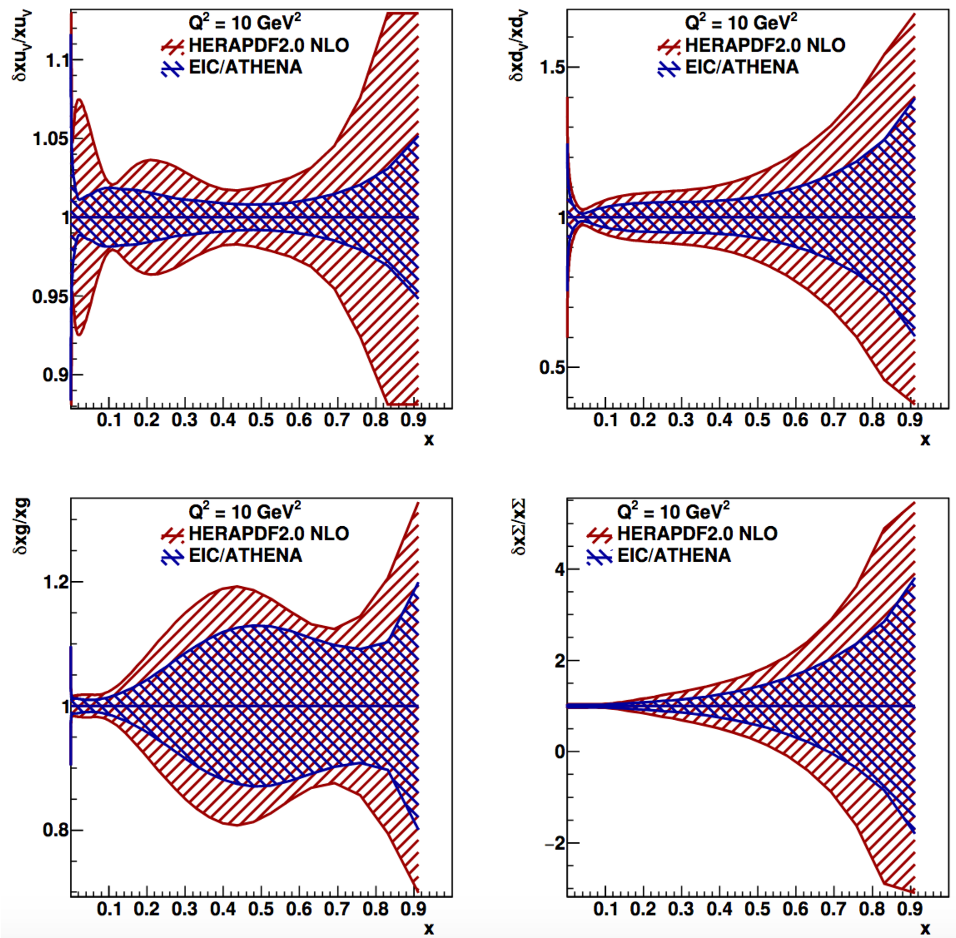
- Notably, gluon density hardens compared with HERA, but remains softer than MSHT / CT

- Detailed ATLAS analysis showed importance of proper treatment of correlated uncertainty sources and the power of NNLO

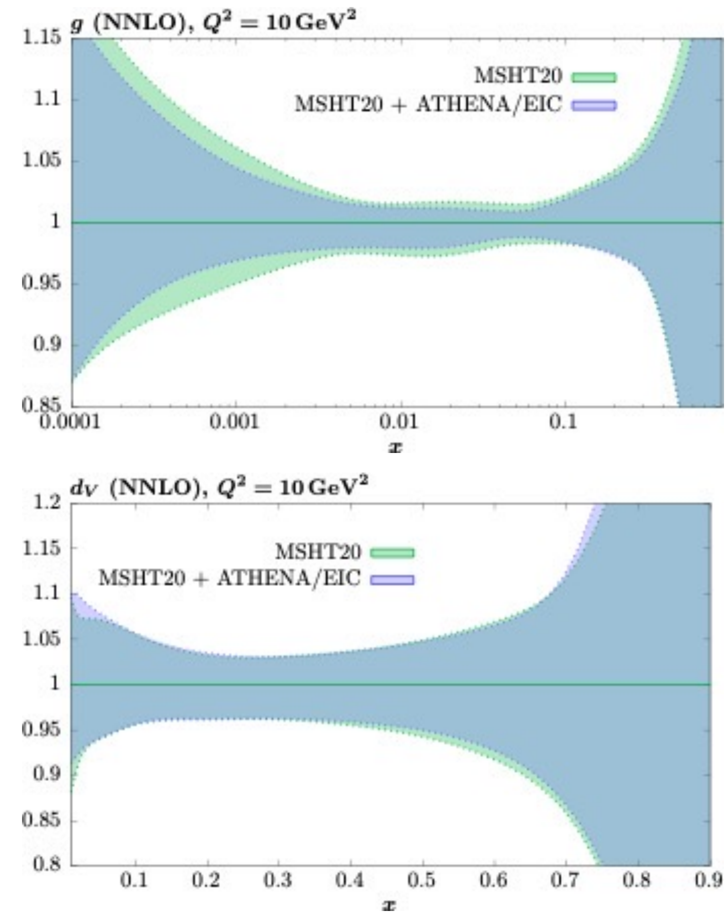
… but there are still tensions and difficulties, particularly at highest x → plenty will remain for EIC to clarify

Simulated impact of EIC

Relative to HERAPDF (lin x scale)



Relative to MSHT20



Work done in the context of EIC ATHENA proposal

… EIC will bring significant reduction in uncertainties at large x, beyond LHC - and with reduced theory uncertainty

Final Words

- Current state of the art in collinear proton parton densities is driven primarily by HERA + LHC (with main LHC impact at high x)

- Substantial progress in experimental precision and theoretical description across a wide range of sensitive observables

- Diminishing returns?...
  → limits in experimental and theoretical precision
  → ever-increasing pile-up
  → need for independence between PDF constraints and searches near the kinematic limit

- Plenty of space for EIC-LHC synergy in short-to medium term and transformational EIC results in medium-to-long term

Thanks to the Organisers!