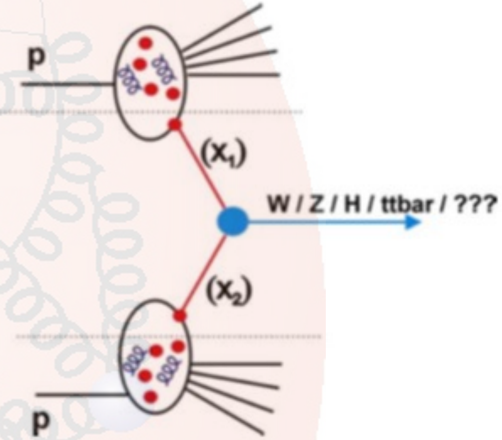
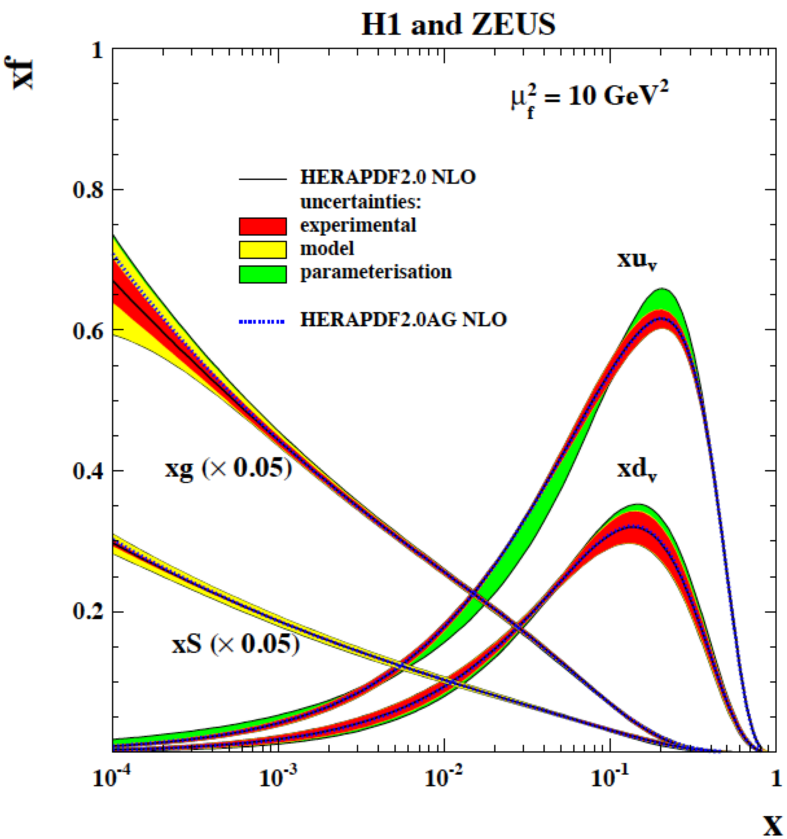
Constraining Proton Parton Distributions at the LHC

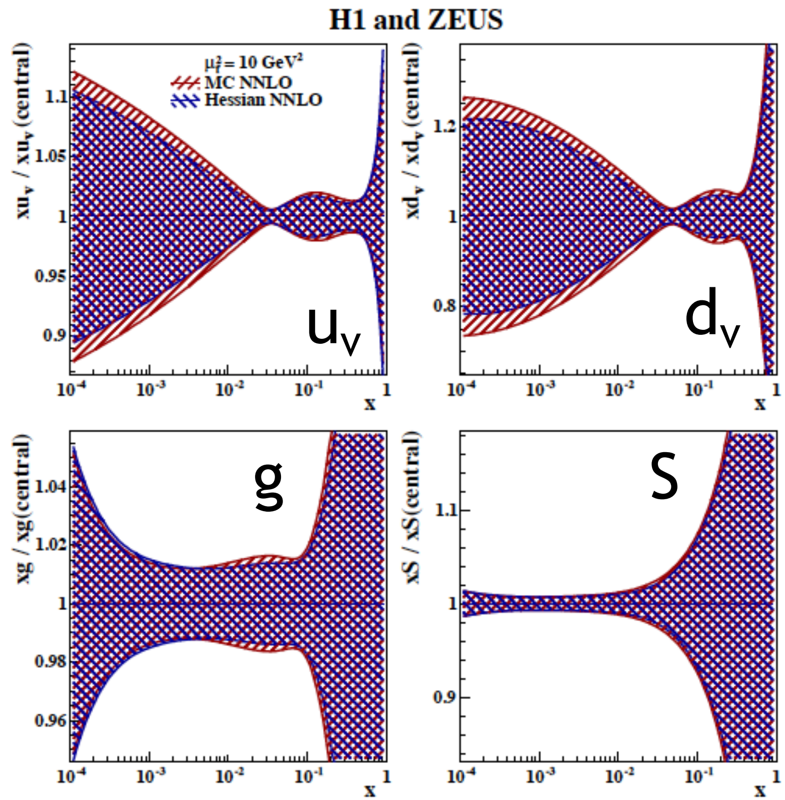
Paul Newman
(University of Birmingham)

on behalf of
the ATLAS, CMS &
LHCb collaborations



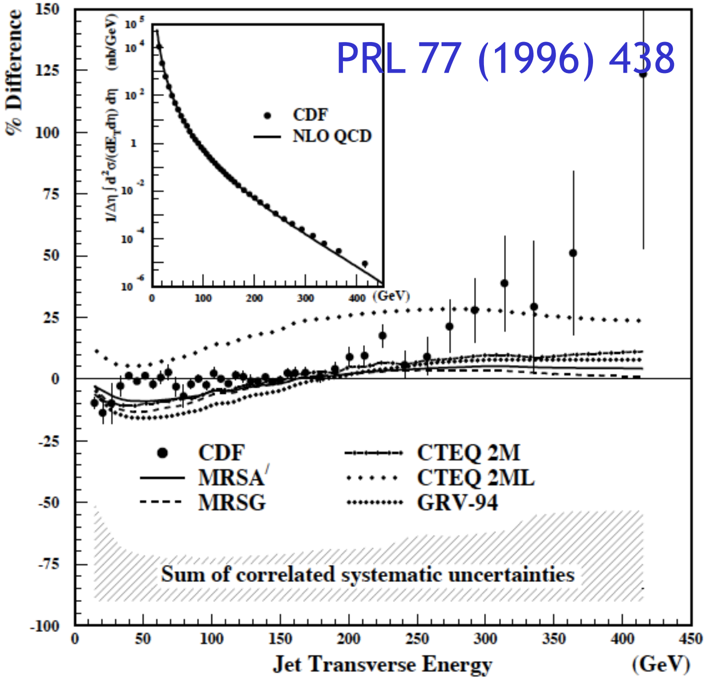
Proton PDF Pre-LHC Baseline: Final HERA Results (ep only: HERAPDF2.0)

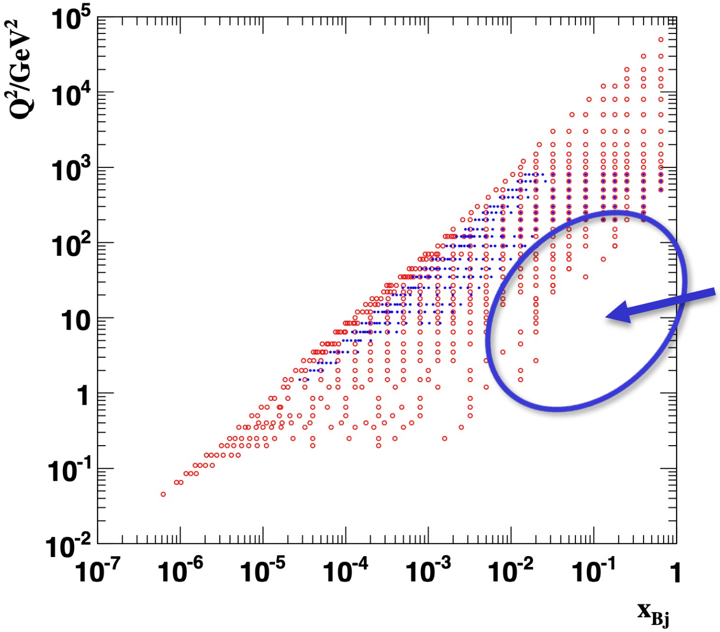




- ~2% gluon precision, 1% on sea quarks for x ~ 10^{-2} ... BUT …
- Low x gluon rising in a non-sustainable way at large Q^2
- Uncertainties explode above x=10^{-1}

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→ 1

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

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

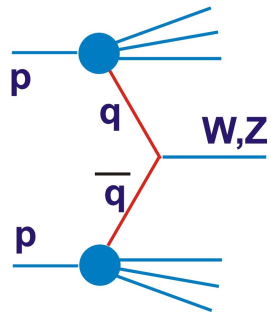
- High x, intermediate Q^2 region will one day be filled by EIC.

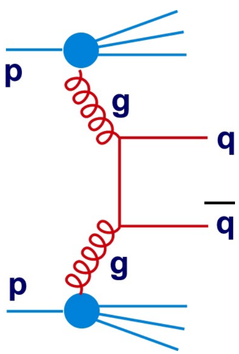
- For now, the best constraints come from fixed target experiments and (especially) the LHC

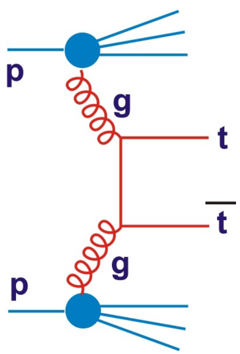
Constraining PDFs with LHC Data

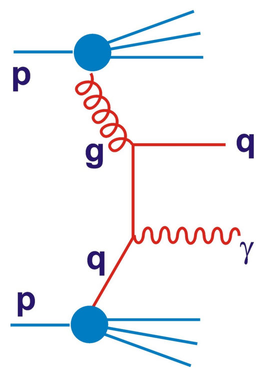
- Many pp processes are sensitive to PDFs …

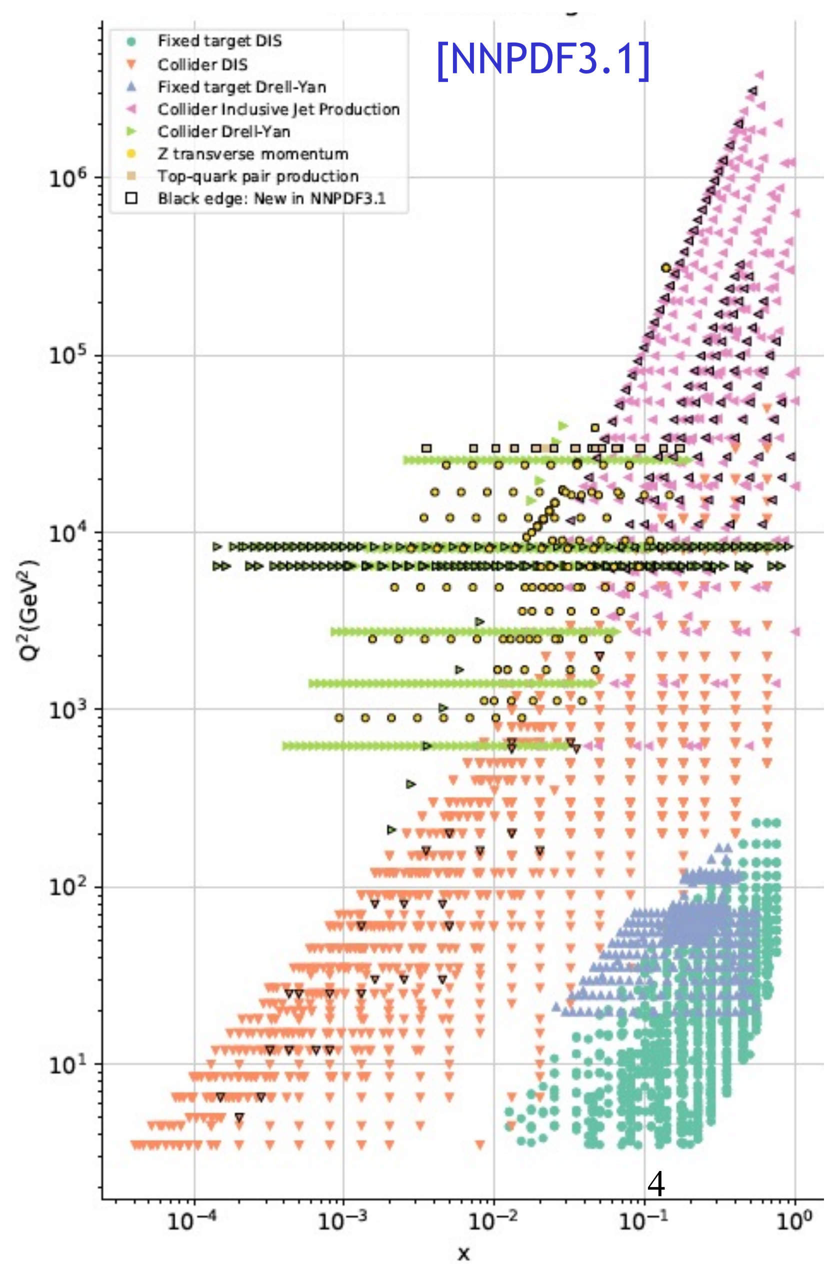
- Electroweak gauge boson production
- Drell Yan (away from Z pole)
- High pT jet production
- Top Quarks
- Direct Photons
- W+c, Z+c …





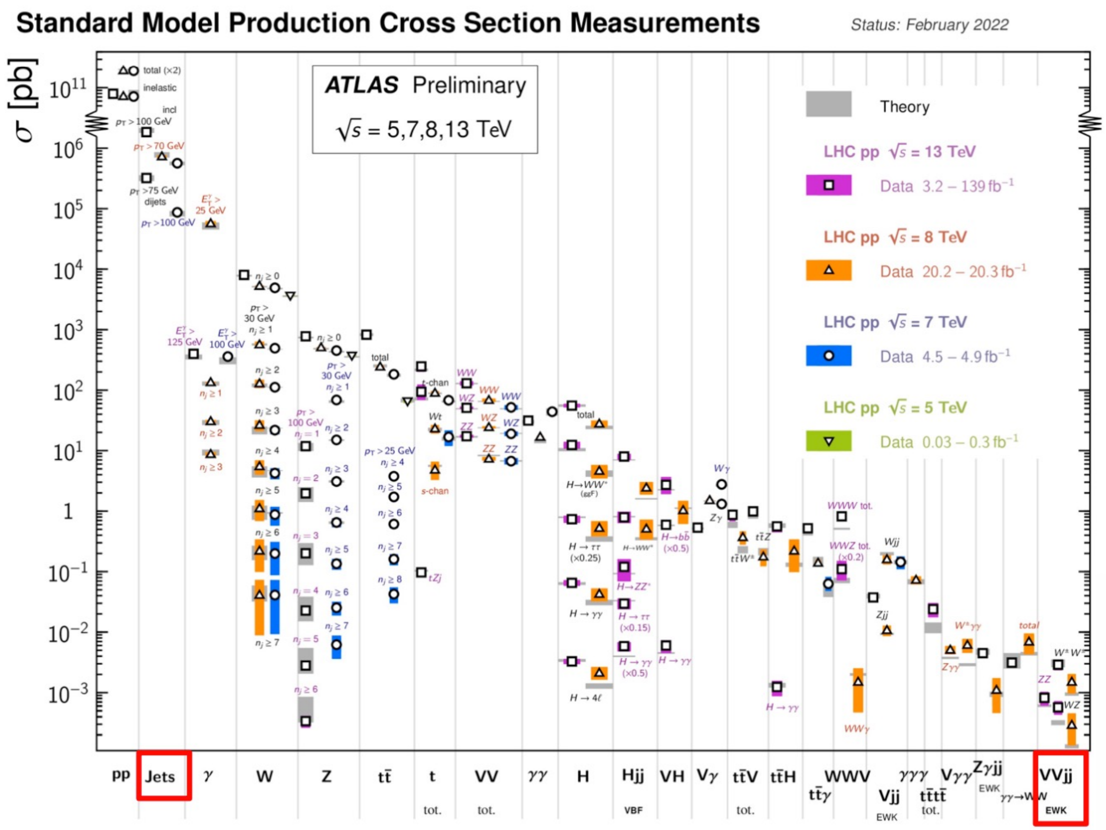






… programme to better constrain PDFs with LHC data both by experimental collaborations and by fitting groups

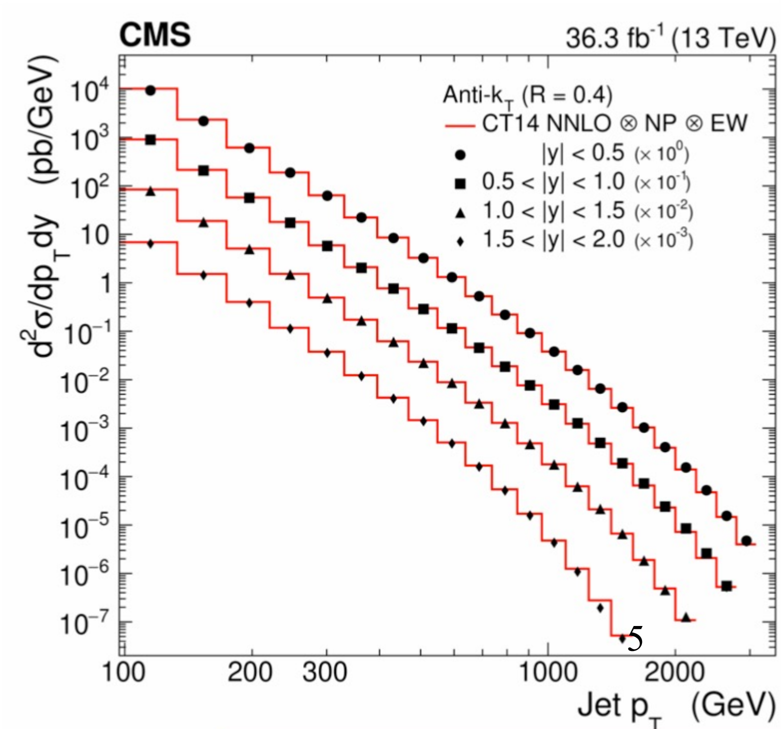
Theory v Data at LHC



PDFs are a vital ingredient in almost all predictions

High x starting point: <u>**Inclusive jets:**</u>

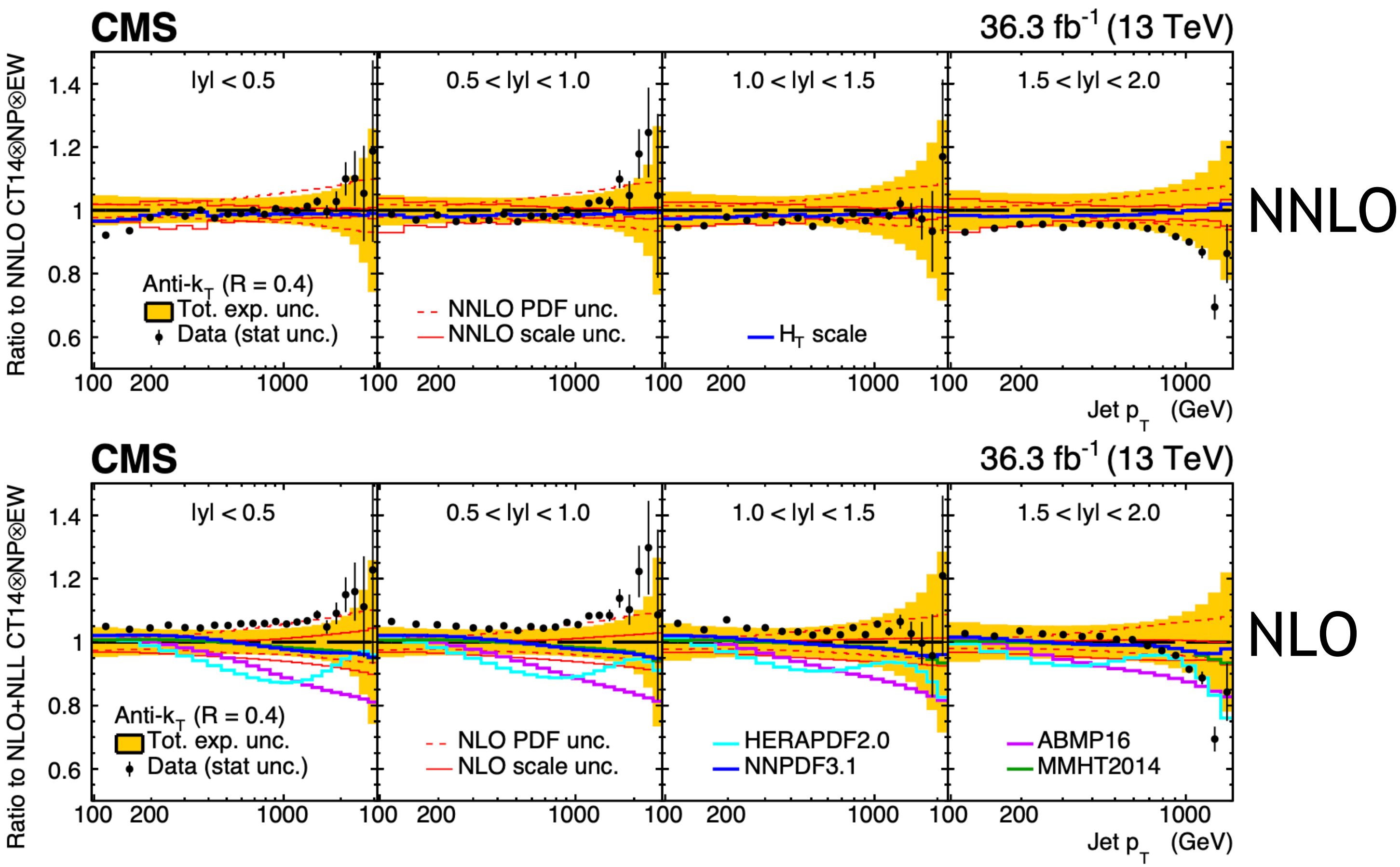
- High rates, wide kinematic range
- 'Astonishing' agreement between data and (N)NLO QCD over many orders of magnitude in x-section, up to scales with p_T~2 TeV

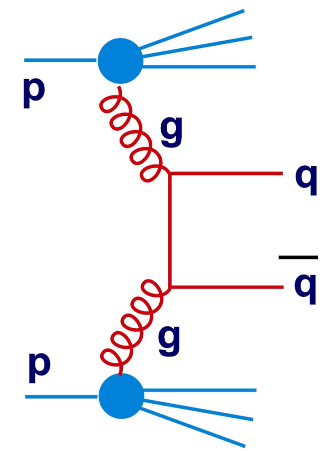


Looking in more Detail ..

[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?...

PDF Constraints from CMS QCD ANALYSIS

- CMS 13 TeV Double-differential inclusive jets
- NC and CC cross sections from HERA

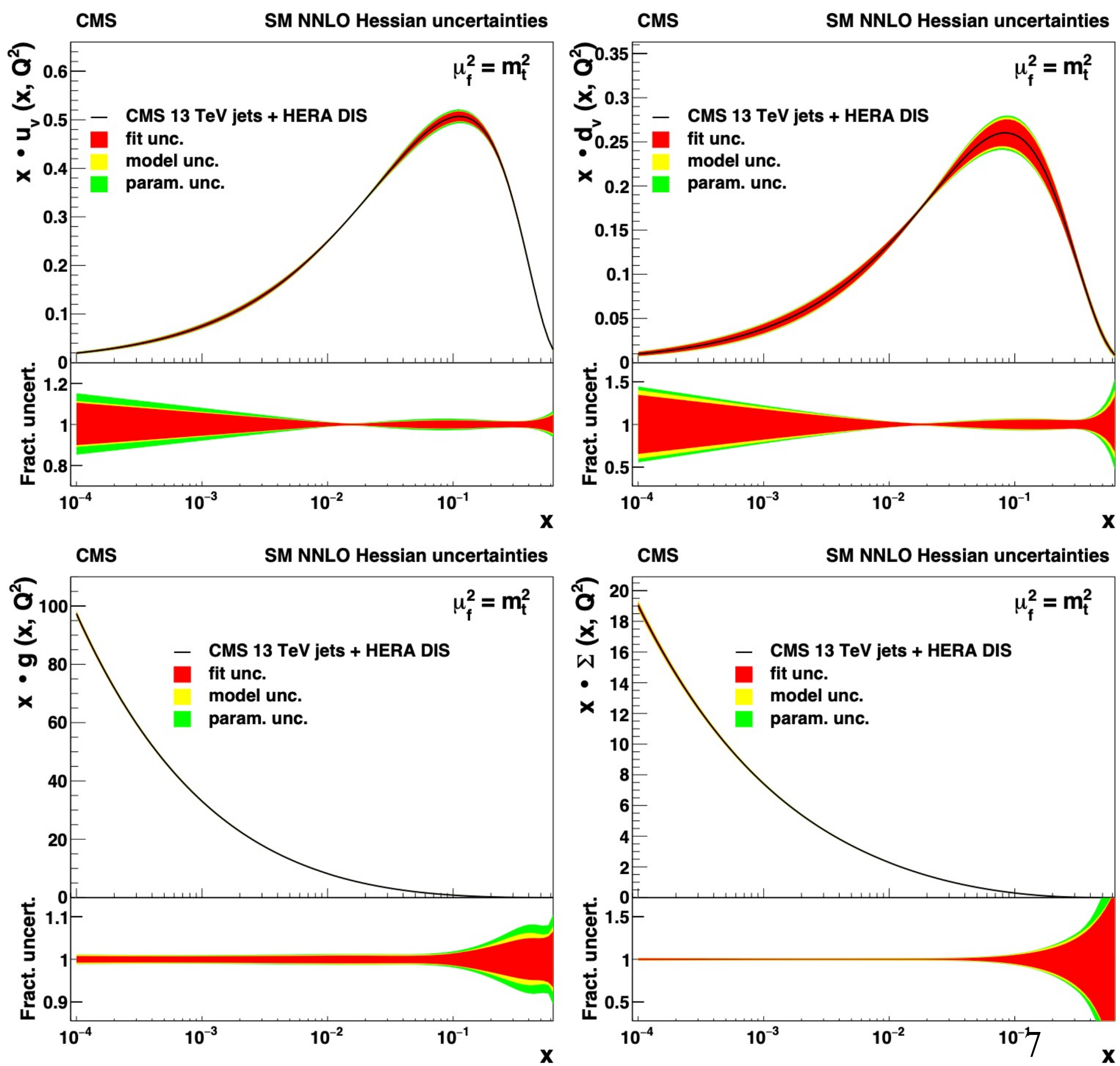
- Inclusive jets have substantial impact on gluon precision at all x relative to CT14 PDFs that already used previous LHC data.

- 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)



PDF Constraints from CMS QCD ANALYSIS

- CMS 13 TeV Double-differential inclusive jets
- NC and CC cross sections from HERA

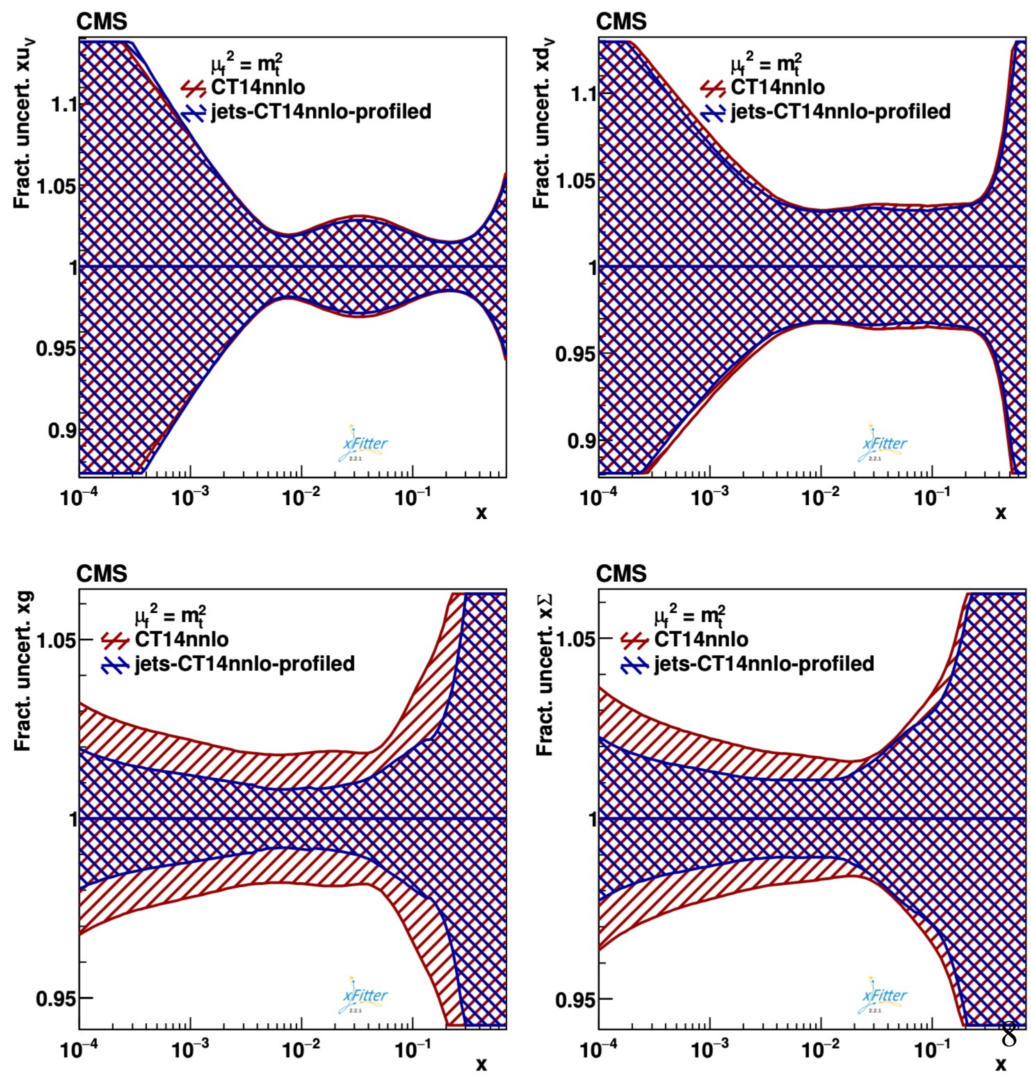
- Inclusive jets have substantial impact on gluon precision at all x relative to CT14 PDFs that already used previous LHC data.

- Singlet quark precision also improves

- Simultaneously, NNLO extraction of strong coupling …

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

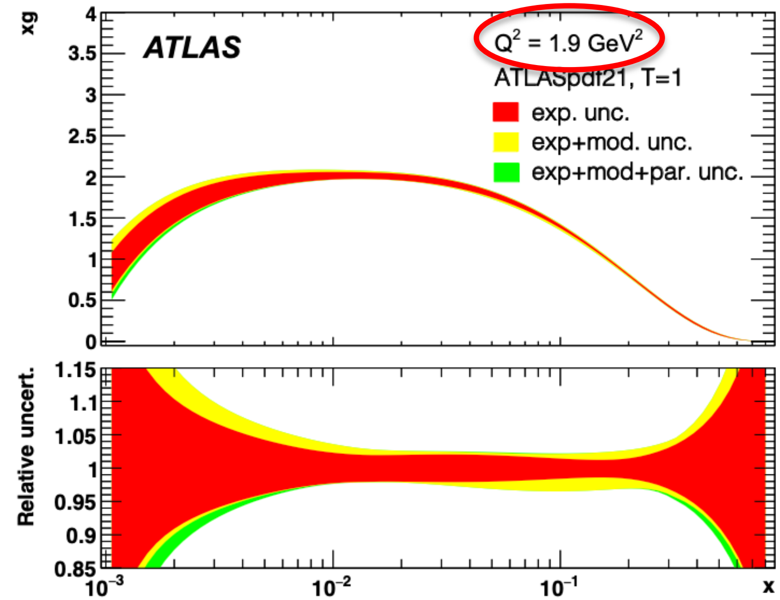
… uncertainty still dominated by scale uncertainty (0.0025)



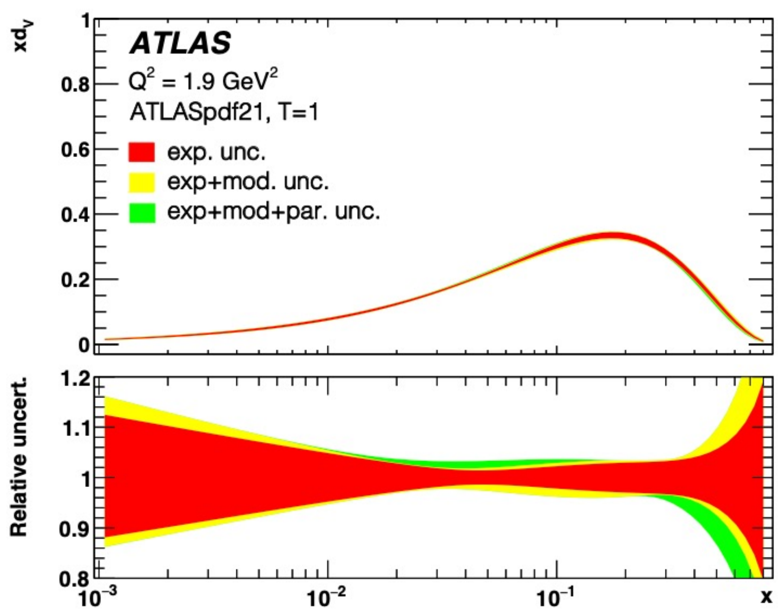
ATLAS ‘Global’ Fit (ATLASpdf21)

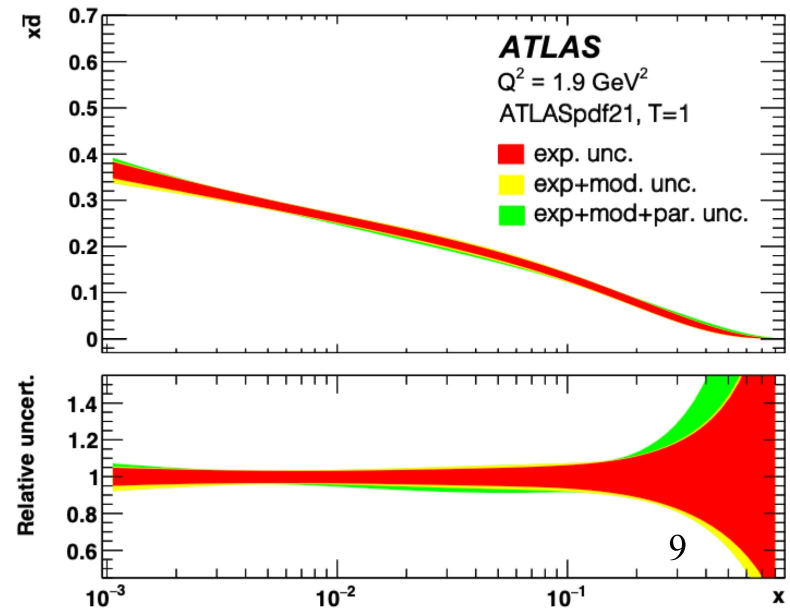
[EPJ C82 (2022) 438]

Data set	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]
Inclusive $W, Z/\gamma^*$ [9]	7	4.6
Inclusive Z/γ^* [13]	8	20.2
Inclusive W [12]	8	20.2
$W^{\pm}$ + jets [23]	8	20.2
Z + jets [24]	8	20.2
$t\bar{t}$ [25, 26]	8	20.2
$t\bar{t}$ [15]	13	36
Inclusive isolated γ [14]	8, 13	20.2, 3.2
Inclusive jets [16–18]	7, 8, 13	4.5, 20.2, 3.2

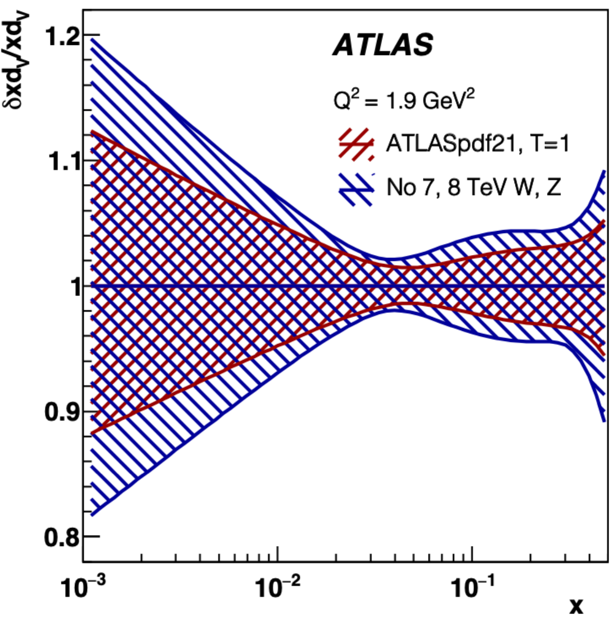


Detailed study of correlations between uncertainties in different data sets and of different χ^2 tolerances





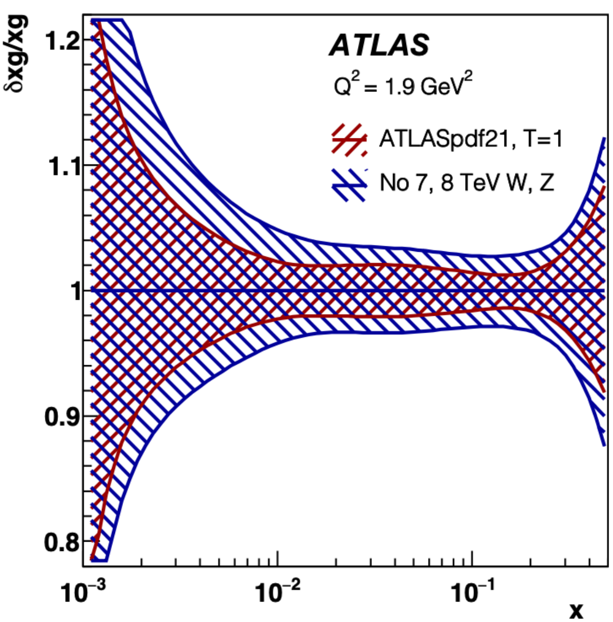
Impact of Different Data Sets

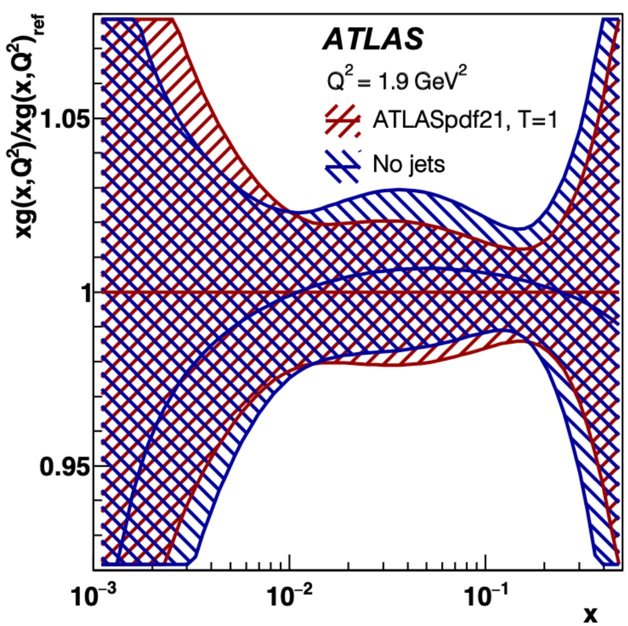


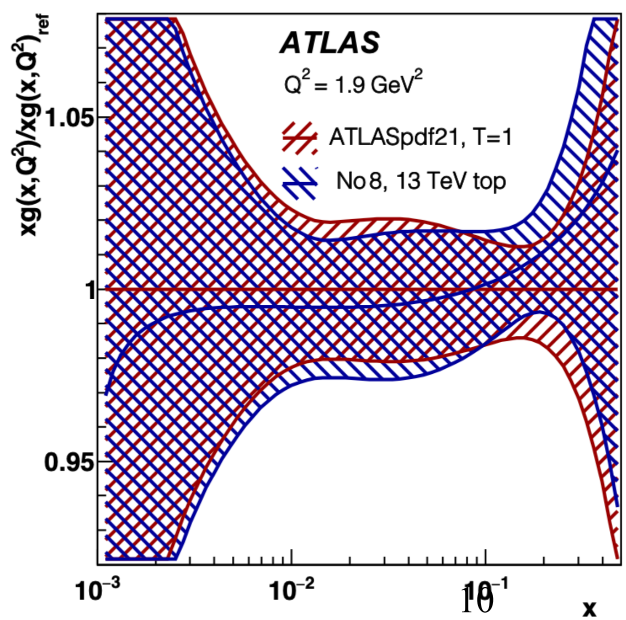
- W and Z data strongly constrain quark densities (and also gluon)

- Jet data primarily reduce gluon uncertainty at large x

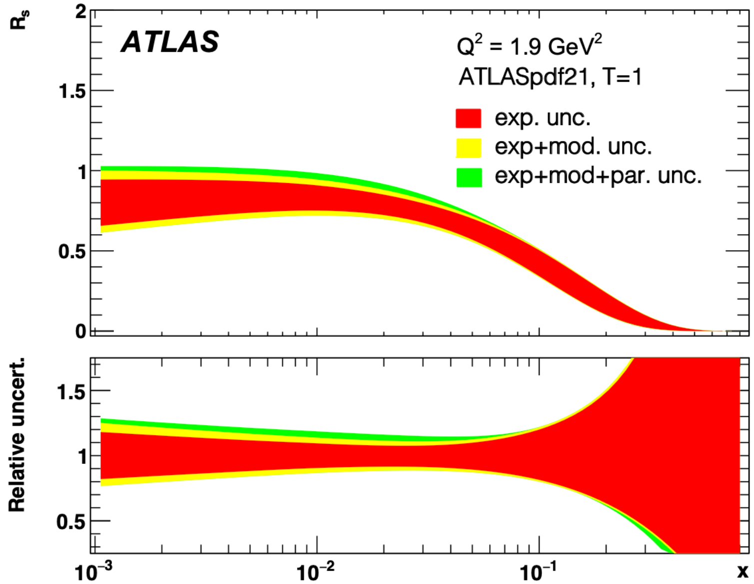
- Top data also have an influence and soften high x gluon (mild tension with jets)







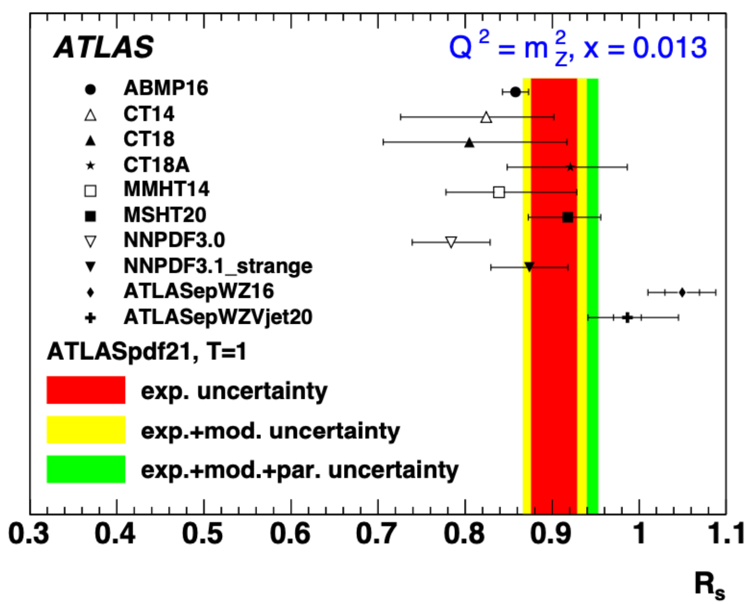
Further Constraints: Strangeness Fraction

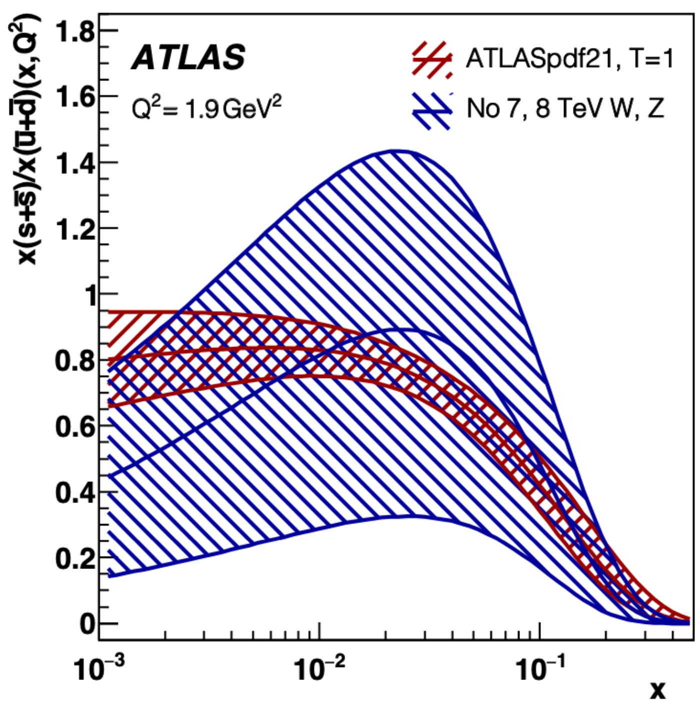


$$R_s = x(s+\bar{s})/x(\bar{u}+\bar{d})$$

- 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

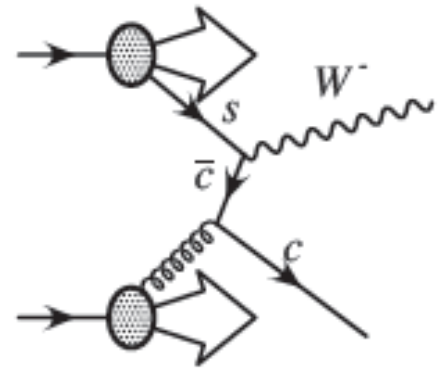




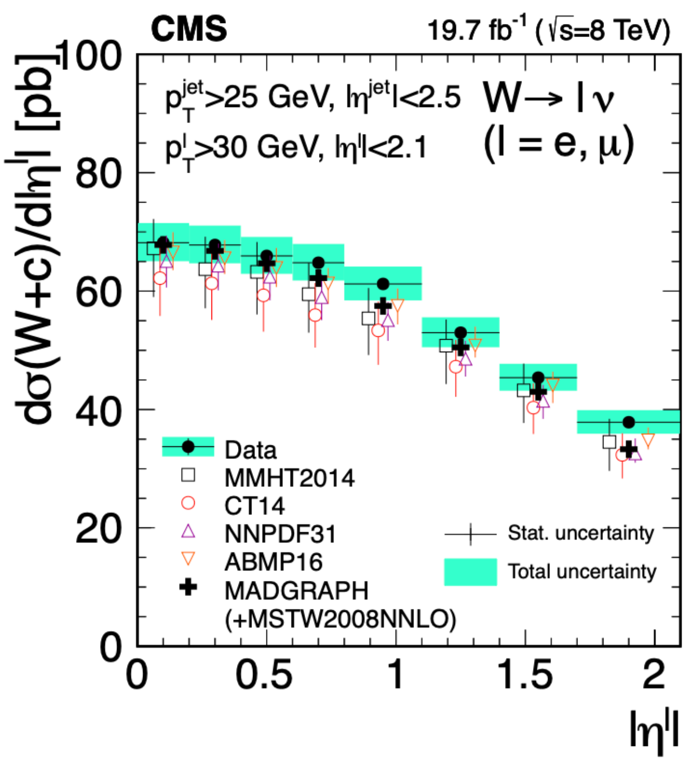
Strange Density @ CMS: W + c

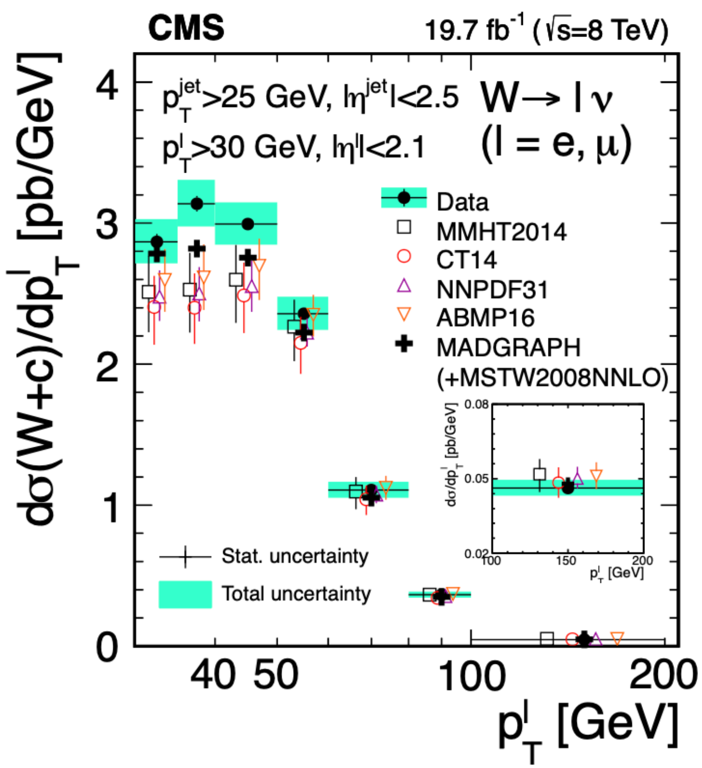
[arXiv:2112.00895]

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:



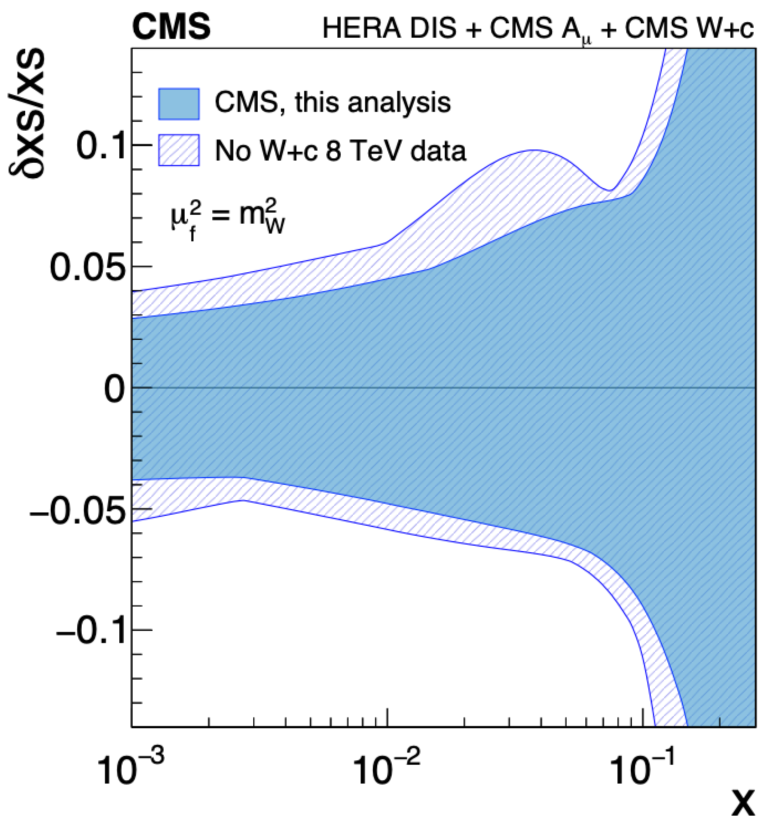


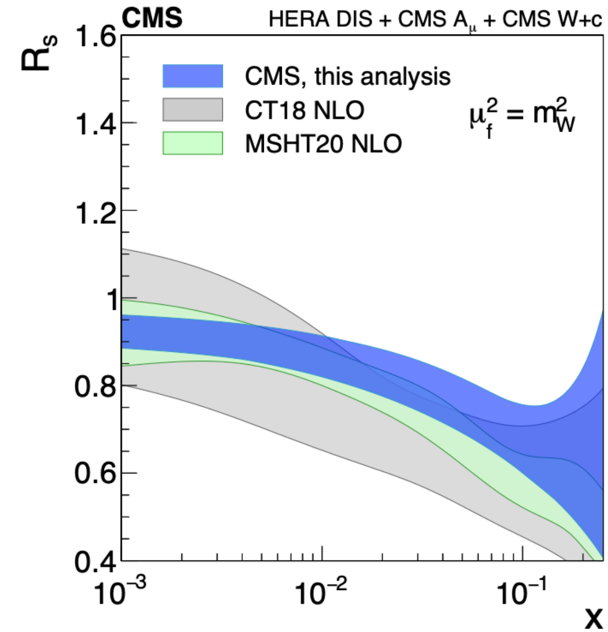
- Reasonable agreement with NLO fits

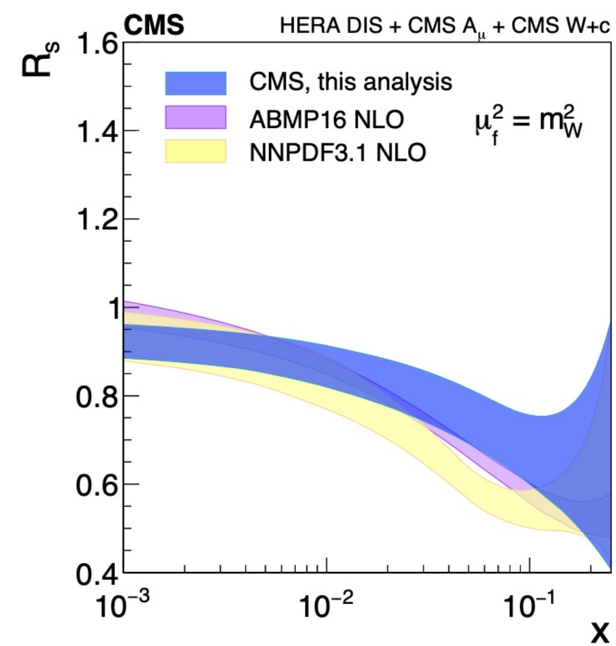
- Up to 10% disagreements @ low lepton p_T

- Comparisons using NNLO PDFs better?

Strange Density at CMS / Overall Picture

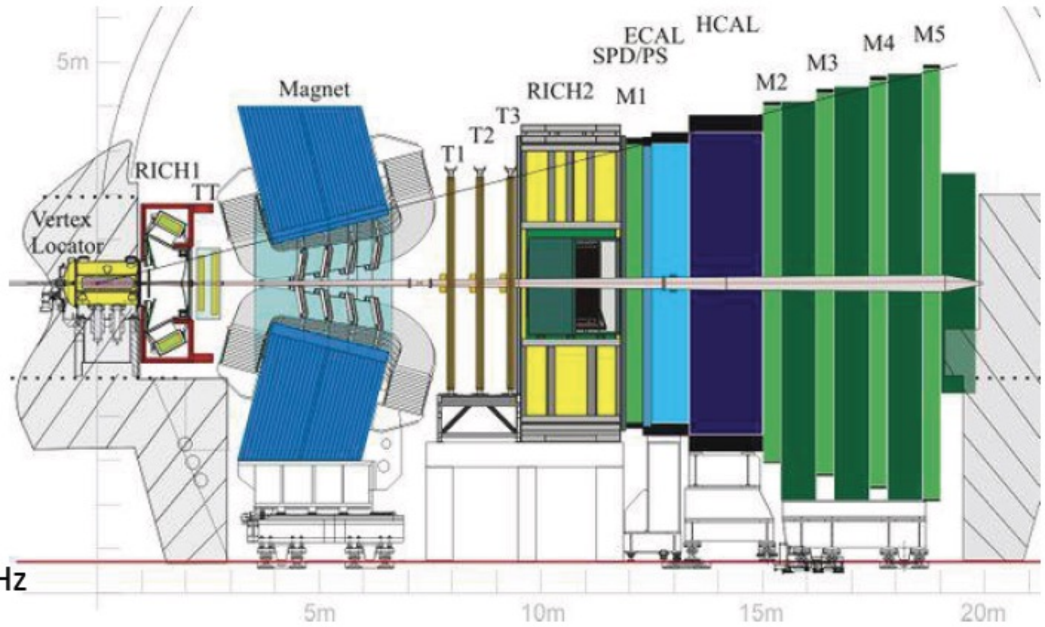






- Including CMS W+c data in fit with HERA data and previous CMS W, W+c data shows significant improvement on strange precision

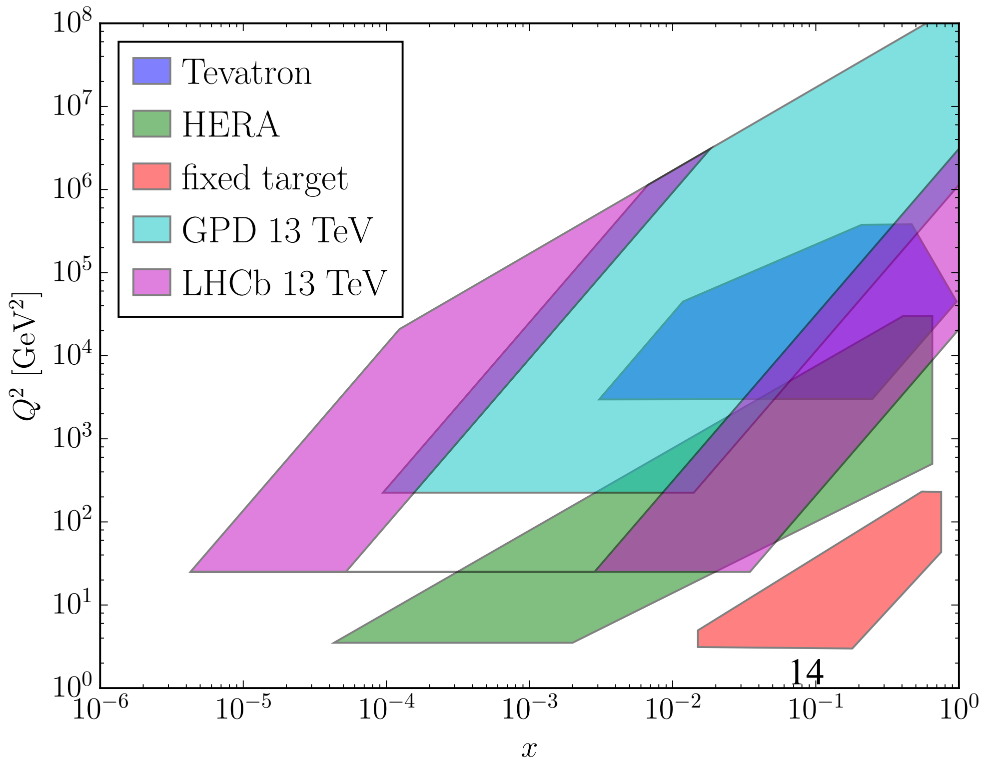
- Also suggestive of small strangeness suppression at low x



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 $x \rightarrow 1$

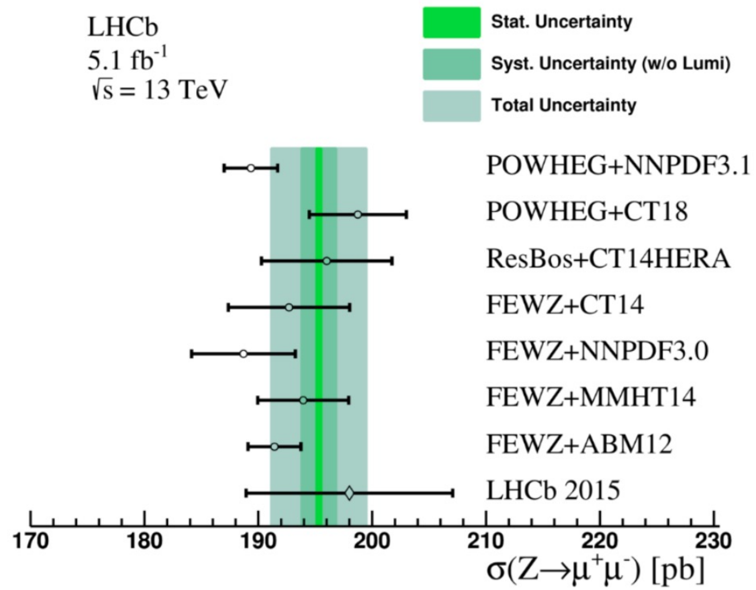


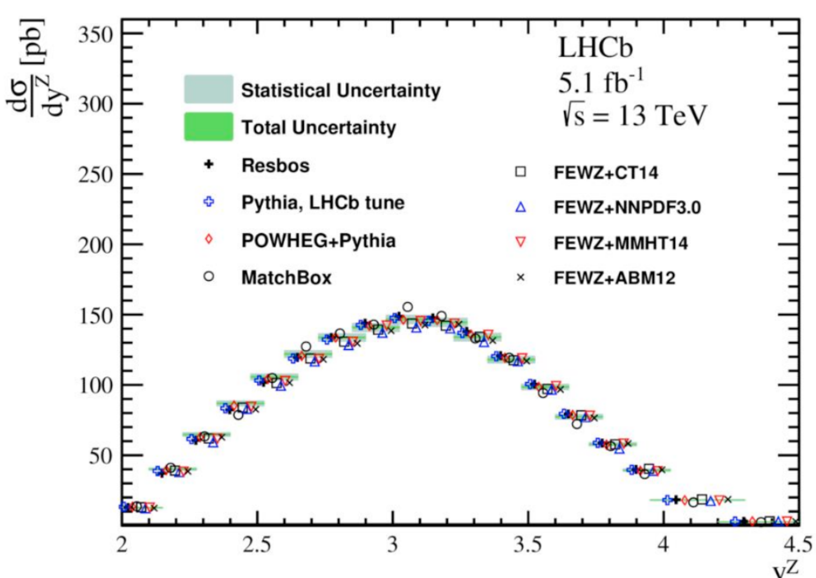
LHCb Z [arXiv:2112.07458]

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

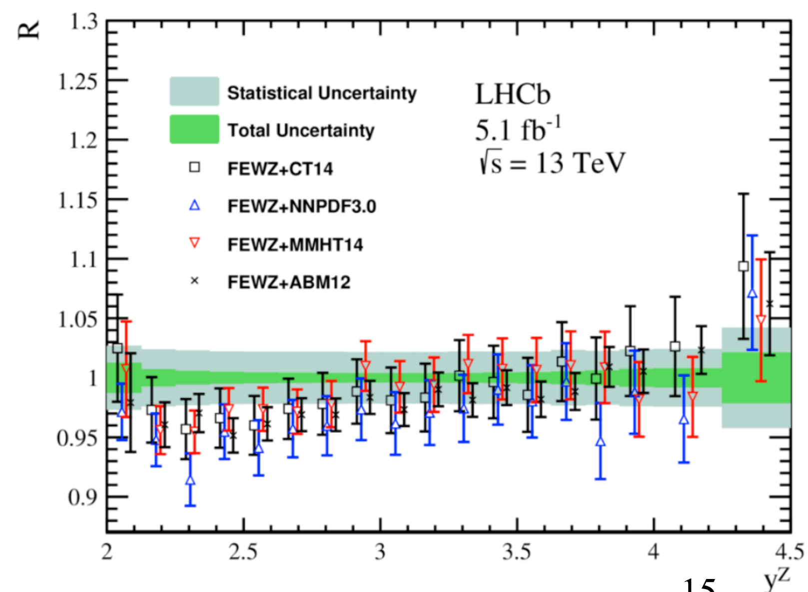
- FEWZ predictions systematically low at low rapidities for all PDF sets (corresponding to more modest x).

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



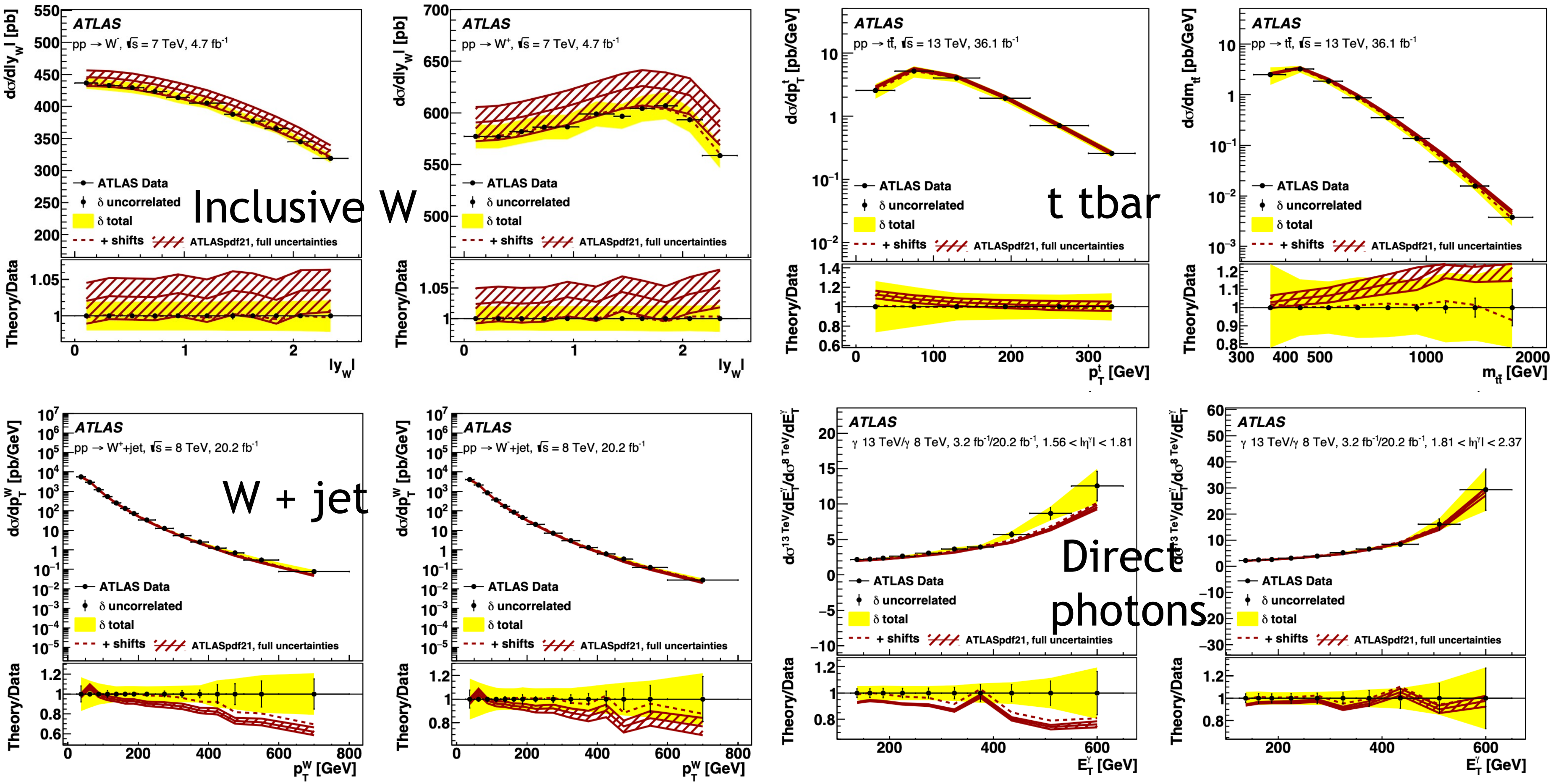


[arXiv:2112.07458]



[arXiv:2112.07458]

Back to ATLAS: Quality of Description of Data



Level of agreement within expectations … but 5-20% effects remain

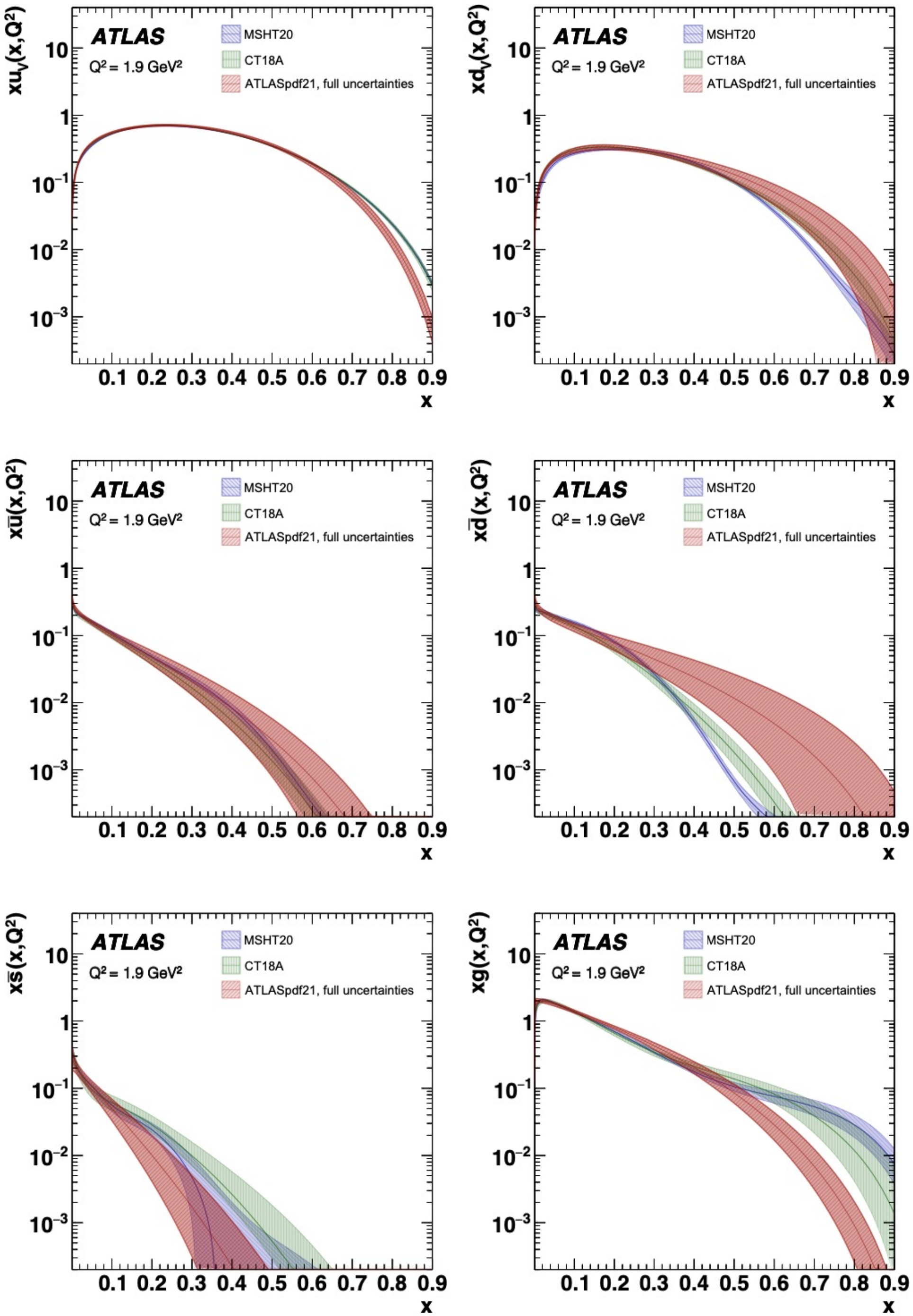
Theoretical Limitations: - Hadronisation and Underlying Event

- 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

- Still tensions at the very highest x values, particularly for gluon

Final Words

- Current state of the art in collinear proton parton densities is driven primarily by HERA + LHC

- LHC brought progress in experimental precision and associated theory understanding for wide range of sensitive observables

- LHC impact primarily at high x and in flavour decomposition

- Future challenges:
  → Very large x→1 region
  → Limits in experimental and theoretical precision
  → Increasing pile-up
  → Need to maintain independence between PDF-based predictions and searches near the kinematic limit

Thanks to the Organisers!