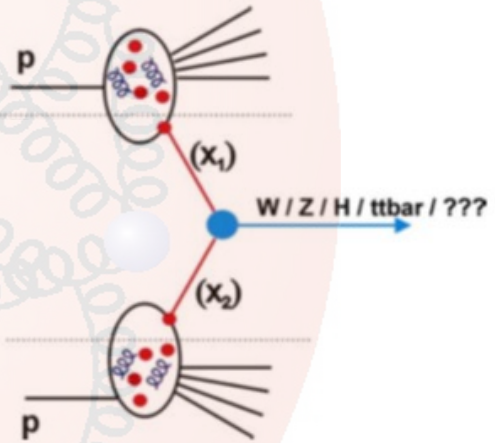
Determination of Collinear Proton Parton Distribution Functions using LHC Data

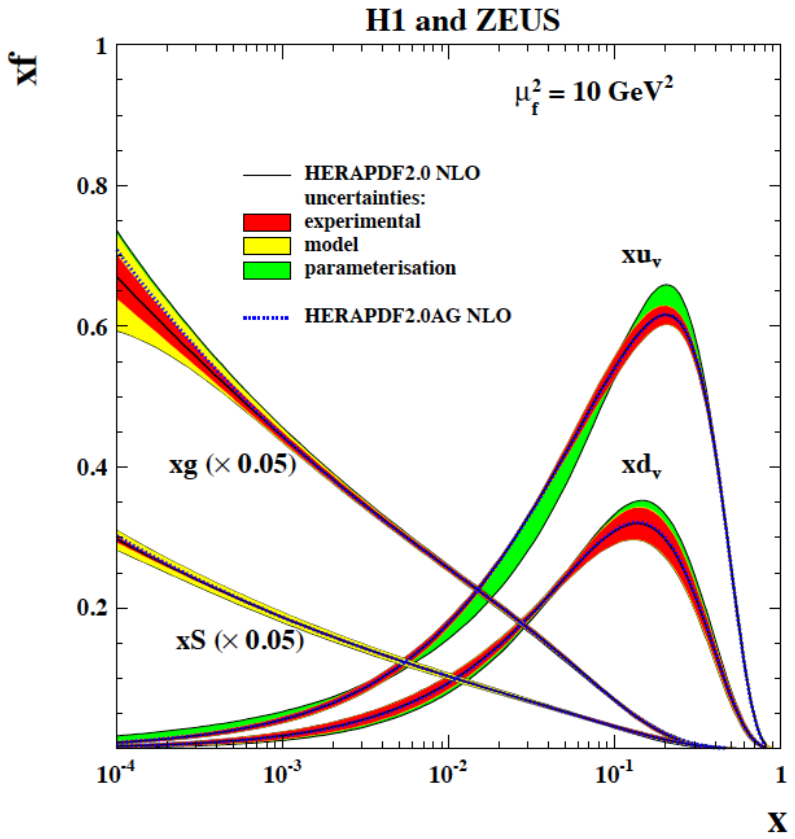
Paul Newman
(University of Birmingham)

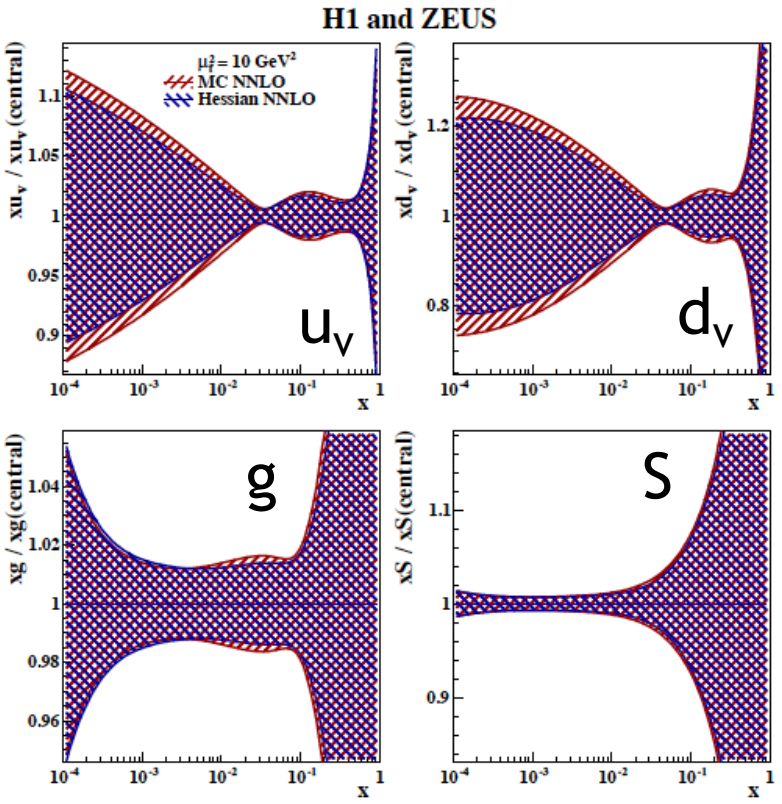
on behalf of
the ATLAS, CMS &
LHCb collaborations



QCD@LHC2022
28 November 2022 to 2 December 2022
IJCLab Orsay, France

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

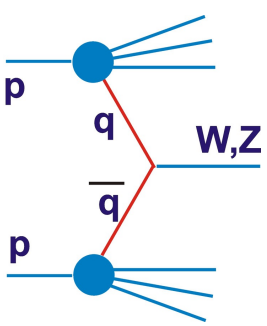


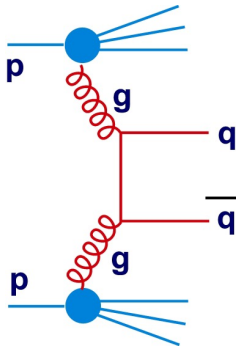


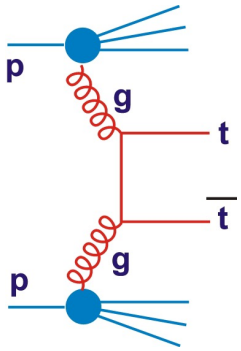
- ~2% gluon precision, 1% on sea quarks for x ~ 10^{-2} … BUT …
- Low x gluon rising in non-sustainable way at large Q^2
- Uncertainties explode at largest x, where HERA lacked precision

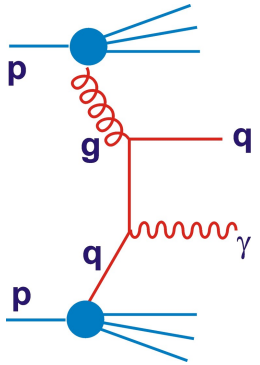
Constraining PDFs with LHC Data

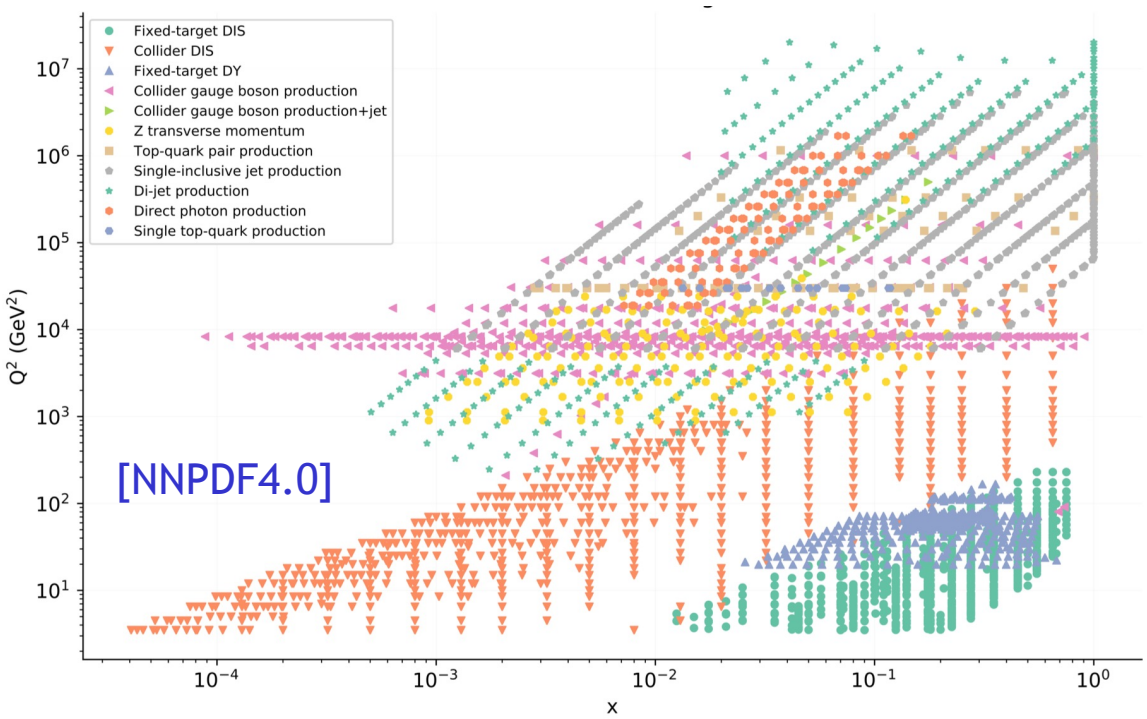
- Many pp processes are sensitive to PDFs …
  - Electroweak gauge boson production
  - Drell Yan (away from Z pole)
  - High pT jet production
  - Top Quarks
  - Direct Photons
  - Associated W+c, Z+c production





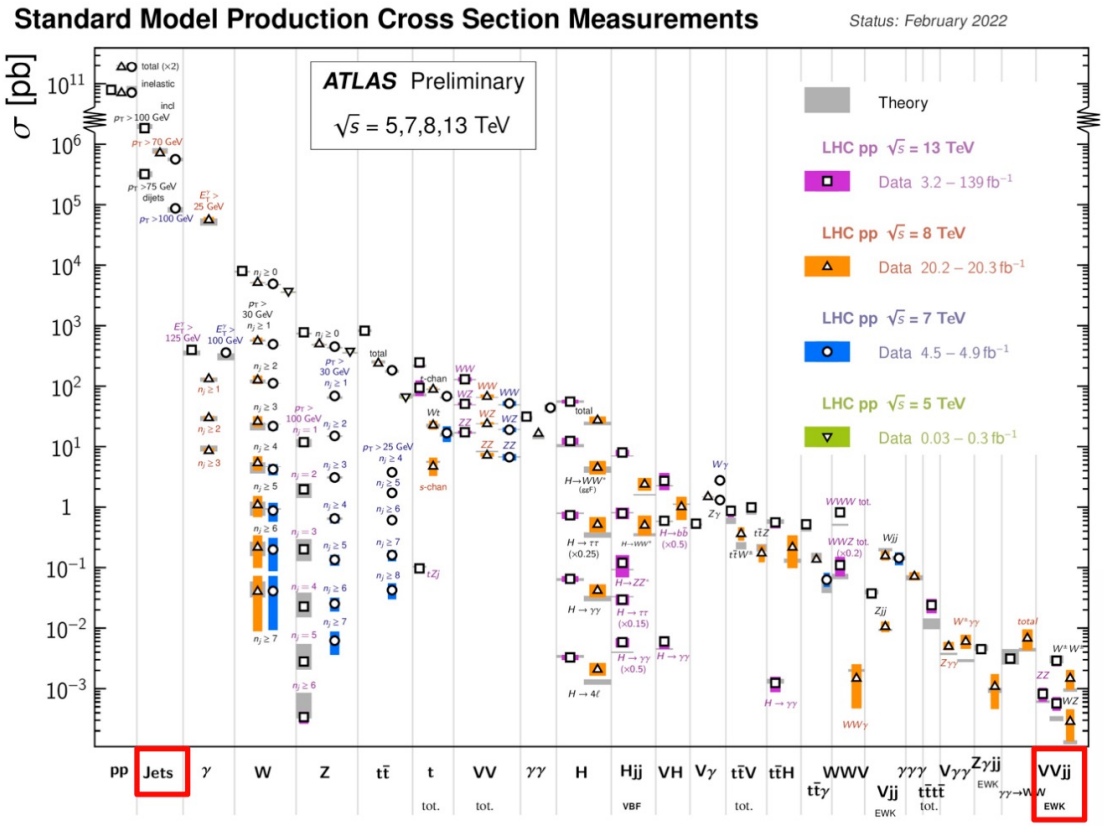




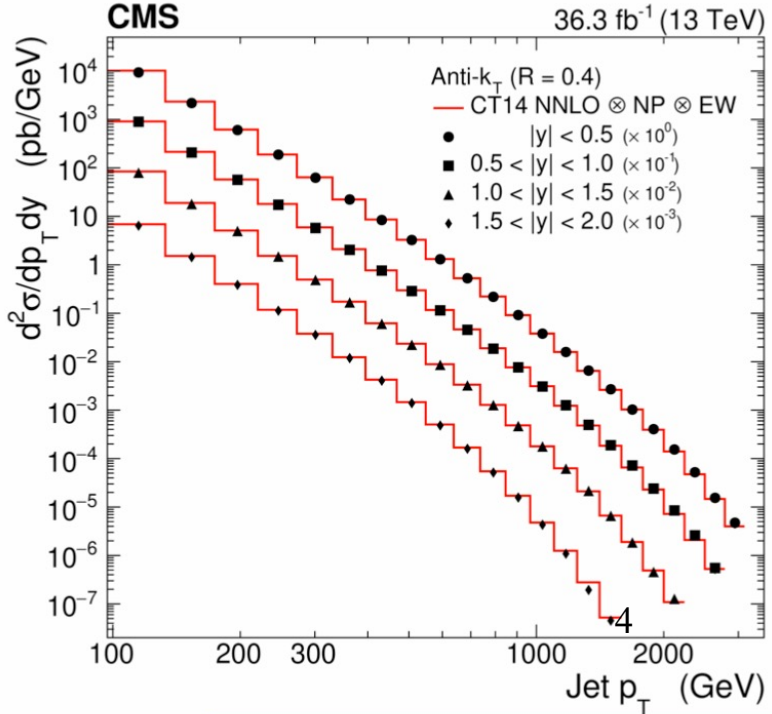


… programme to better constrain PDFs with LHC data both by experimental collaborations and by global fitting groups

Theory v Data at LHC



PDFs are a vital ingredient in almost all predictions



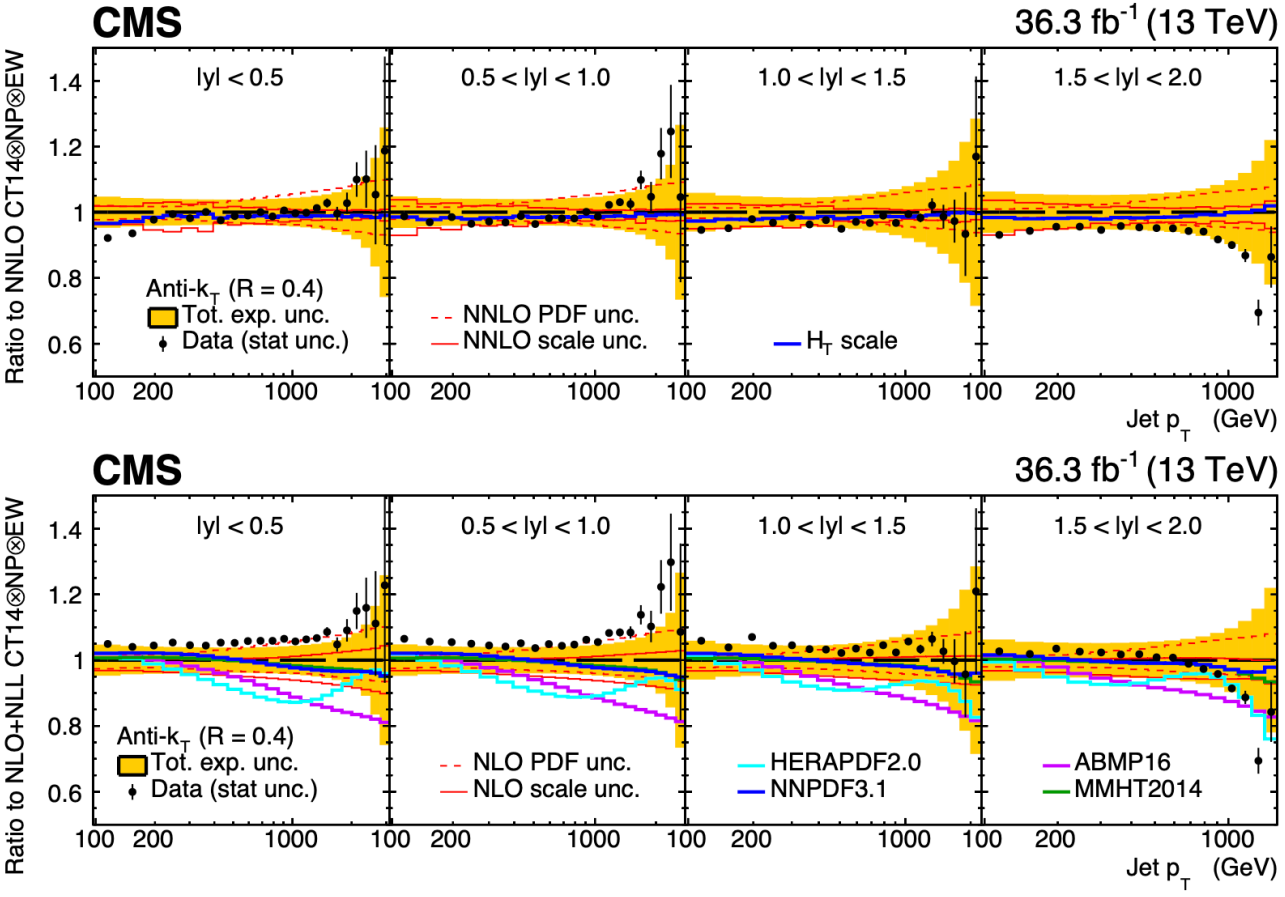
High x starting point: **Inclusive jets:**

- 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 …

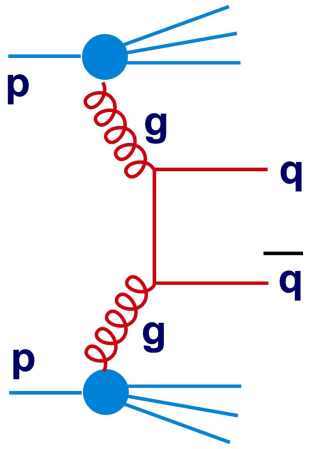
[JHEP 02 (2022) 142]

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



NNLO

NLO



- 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

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

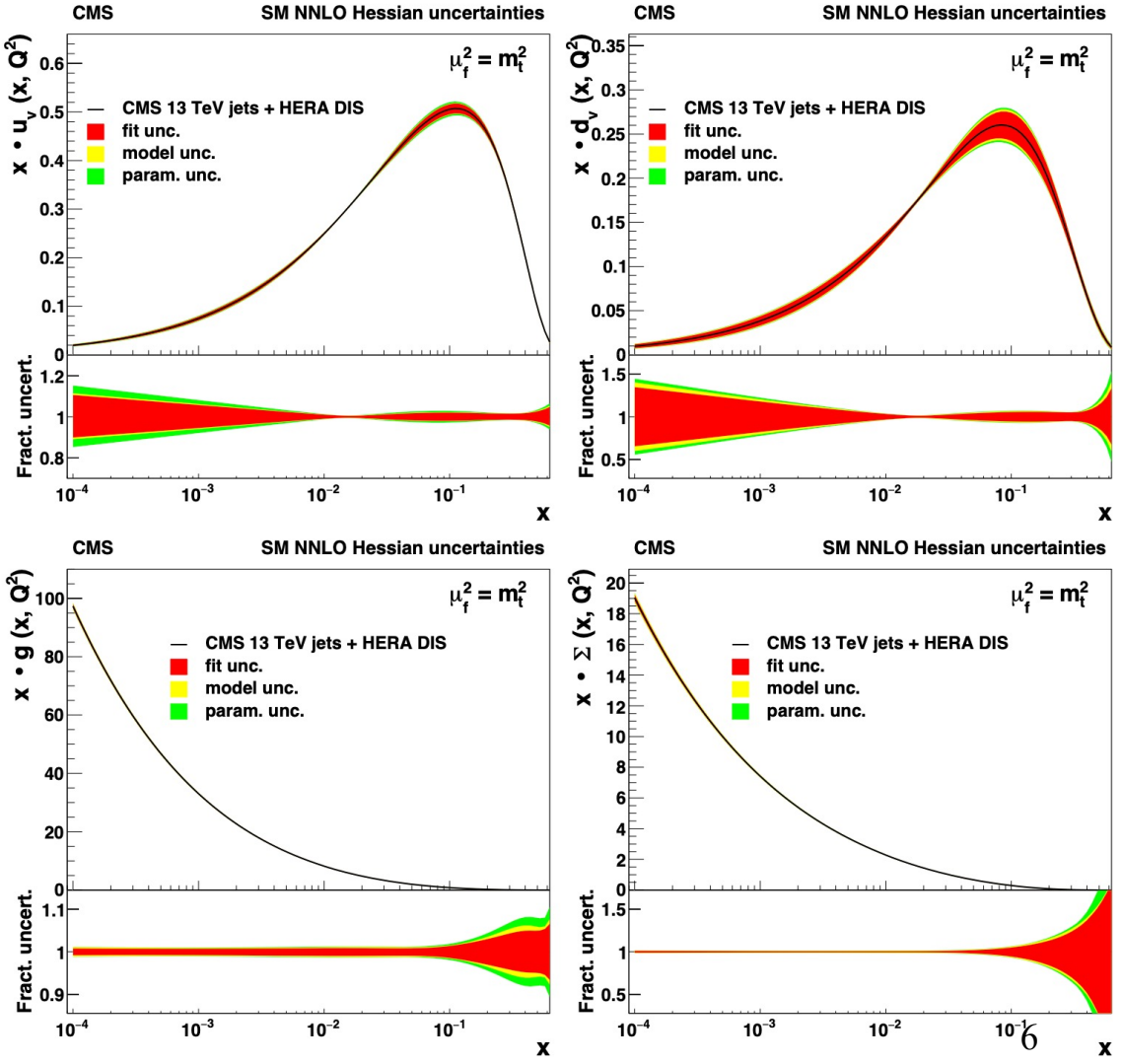
- Singlet quark precision also improves

- Simultaneously, NNLO extraction of strong coupling …

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

… uncertainty still dominated by scale uncertainty (0.0025)

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



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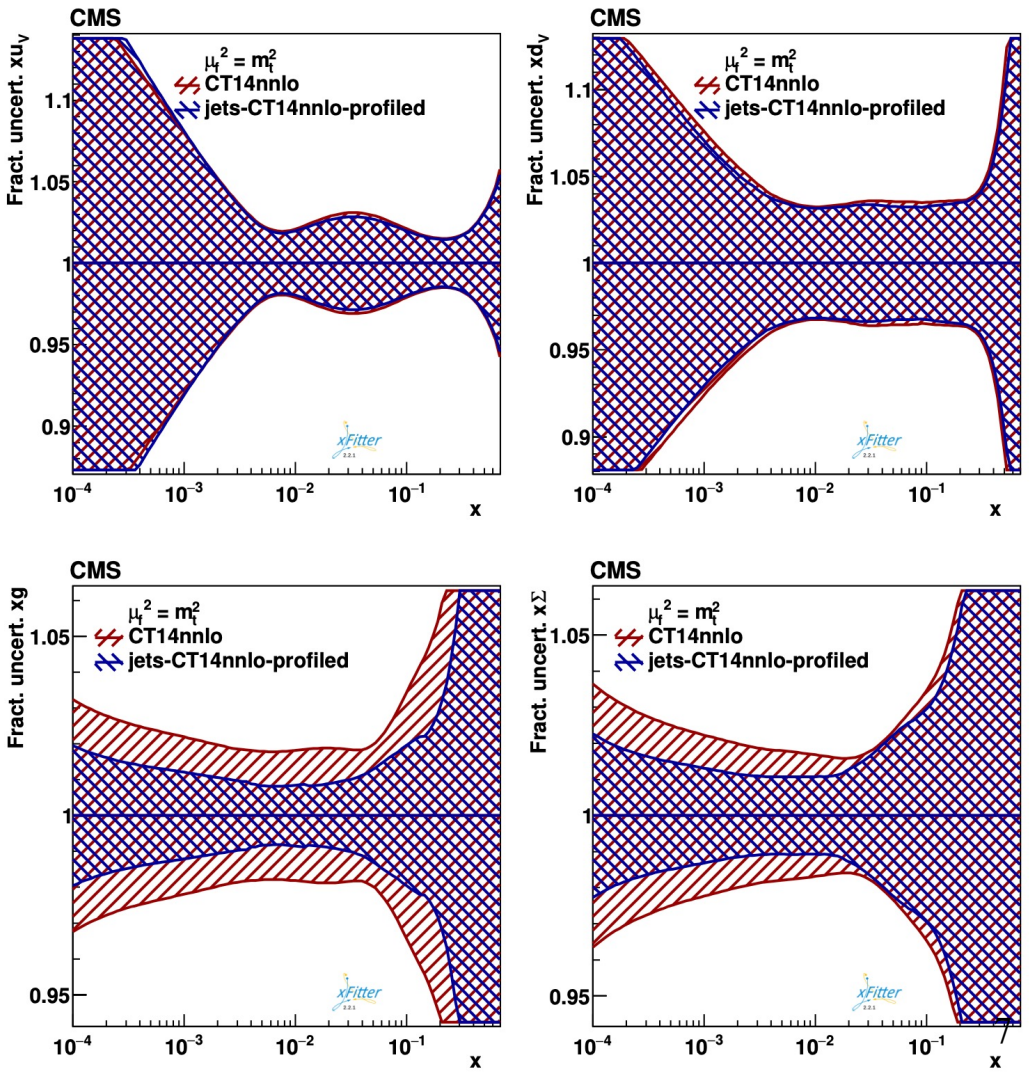
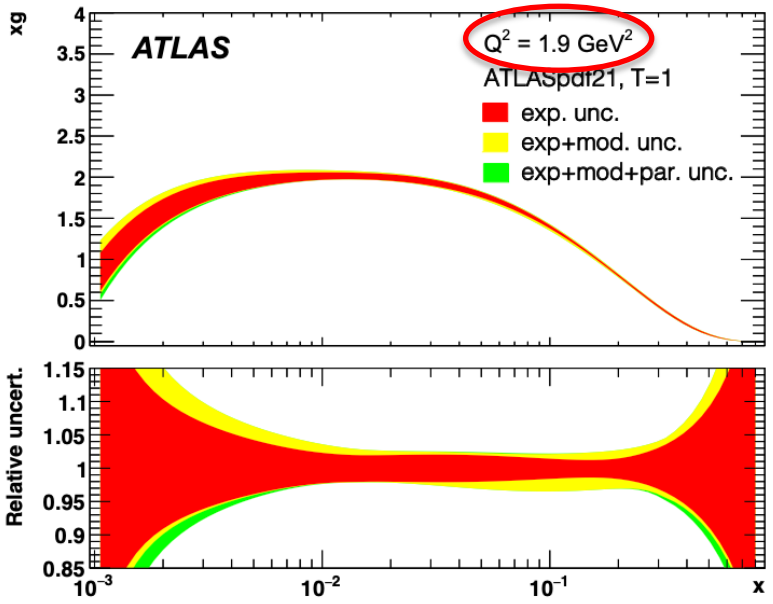


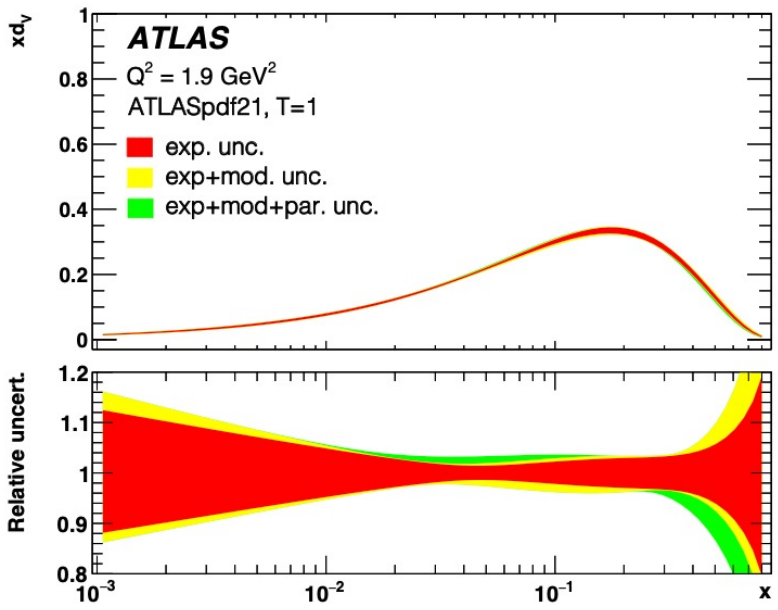
ATLAS ‘Global’ Fit (ATLASpdf21)

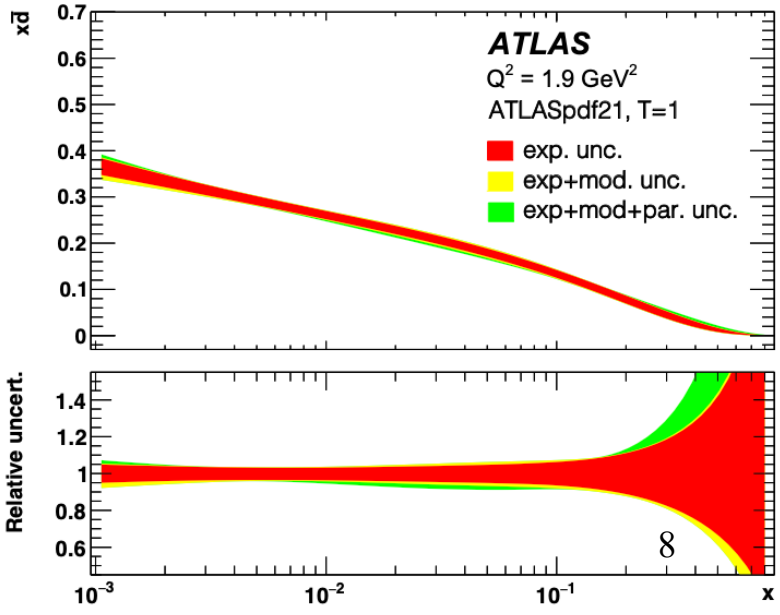
[EPJ C82 (2022) 438]

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

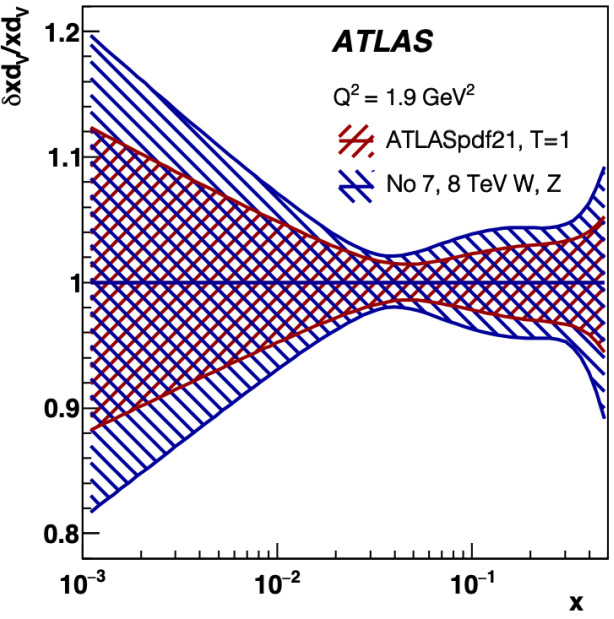
Detailed study of correlations between uncertainties in different data sets and of different χ^2 tolerances







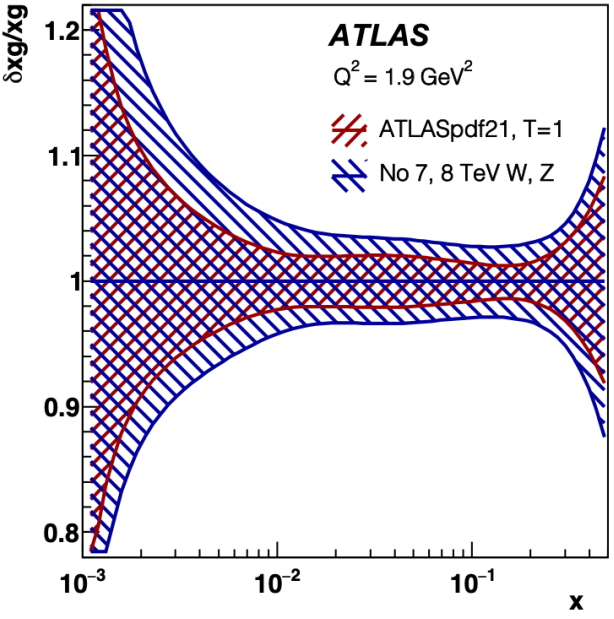
Impact of Different Data Sets

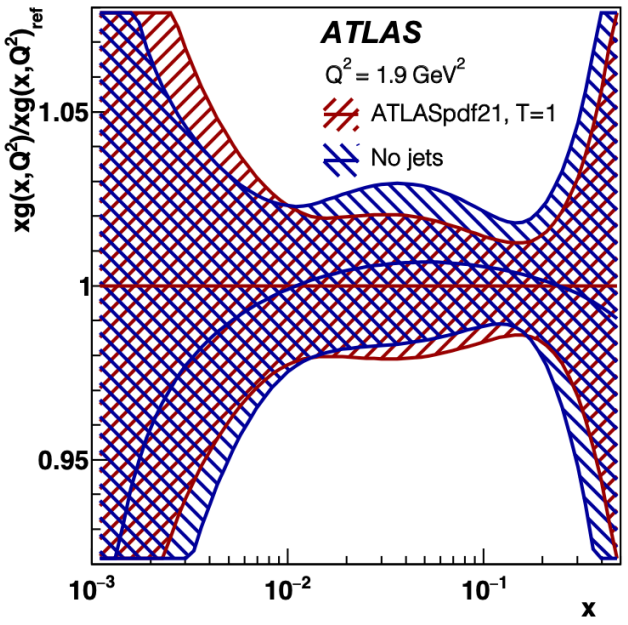


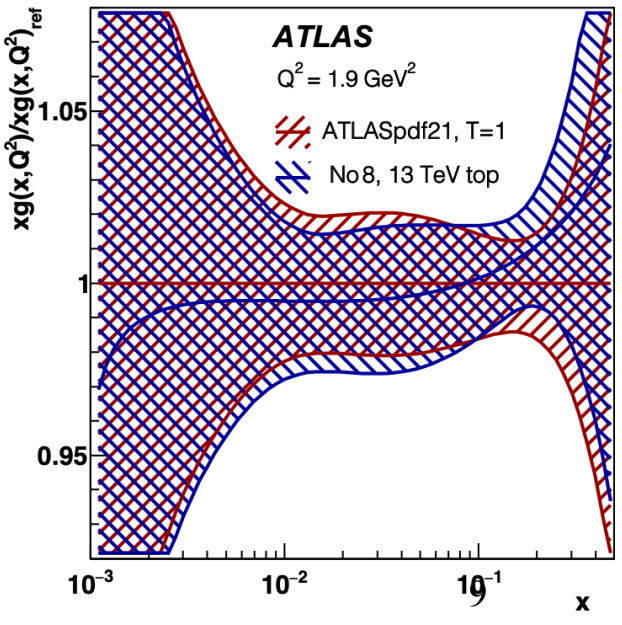
- W and Z data strongly constrain quark densities (and also gluon)

- Jet data primarily reduce gluon uncertainty at large x

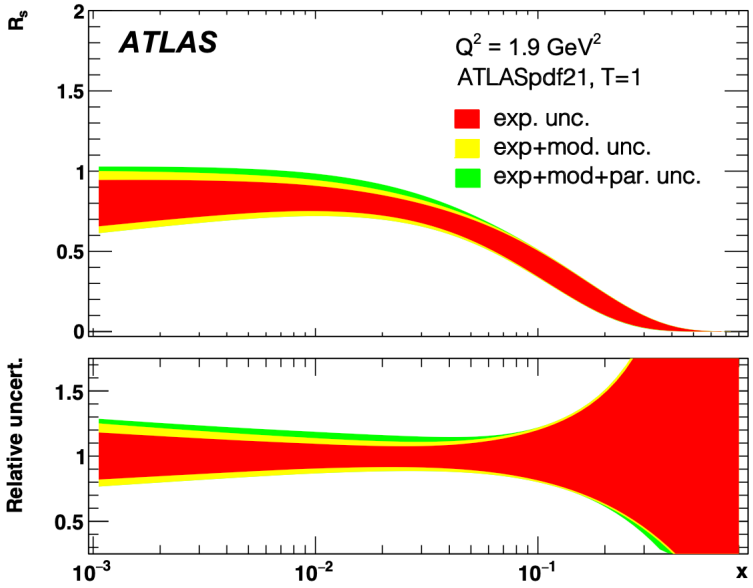
- Top data also have an influence and soften high x gluon (mild tension with jets)







Further Constraints: Strangeness Fraction

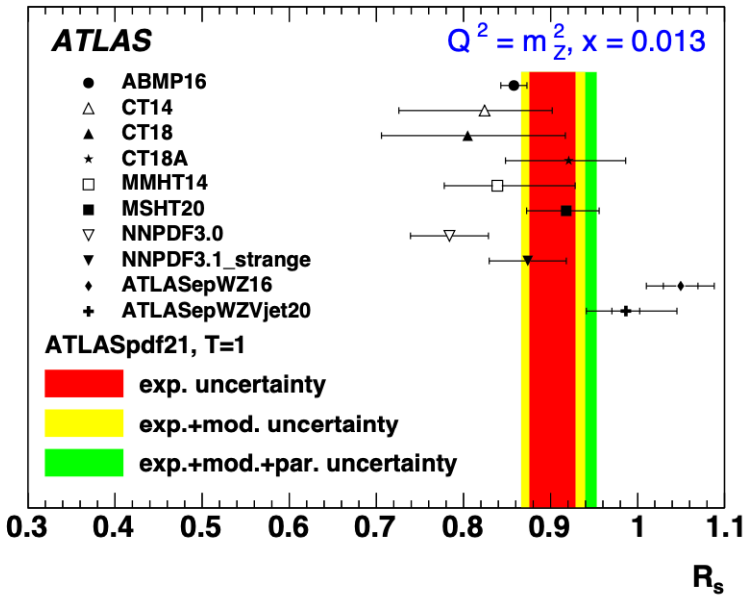


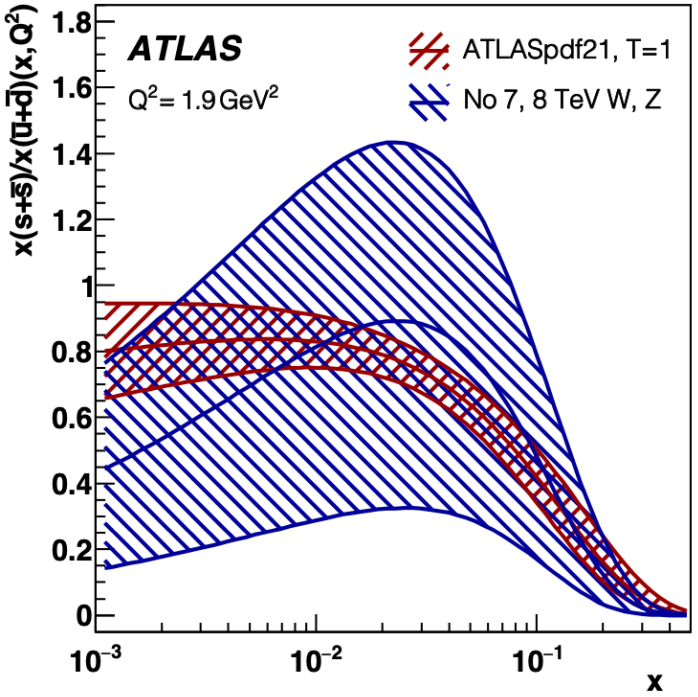
$$R_s = x(s+\bar{s})/x(\bar{u}+\bar{d})$$

- 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



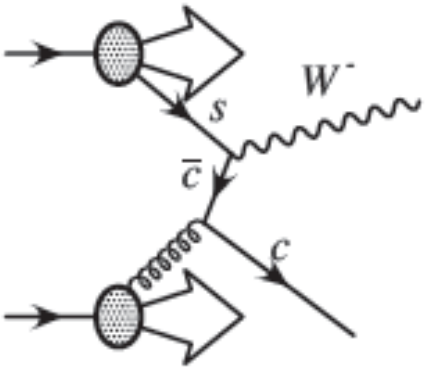


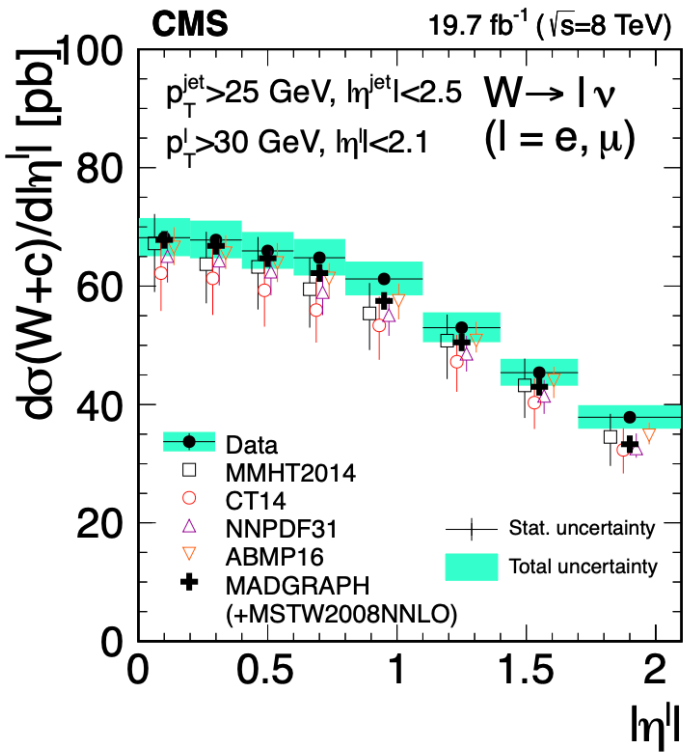
Strange Density @ CMS: W + c

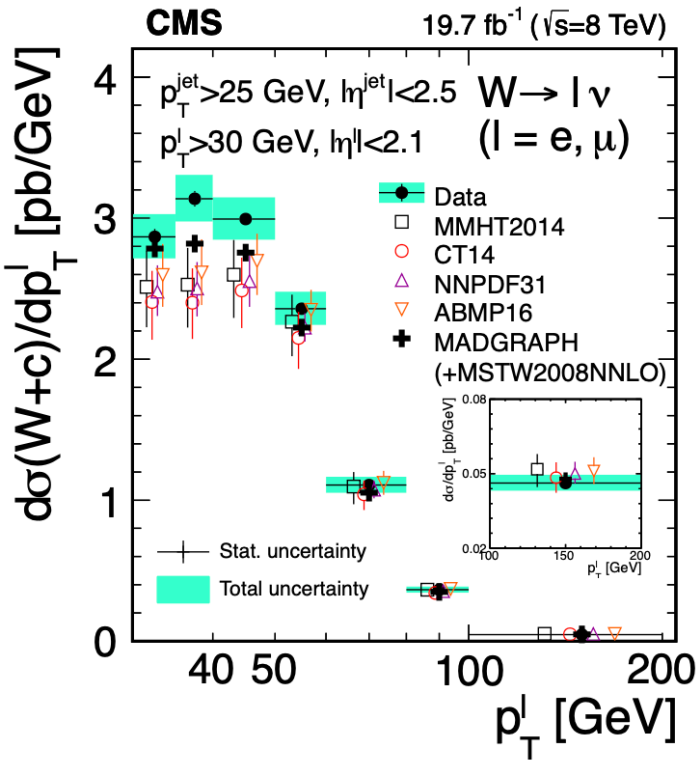
[arXiv:2112.00895]

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:





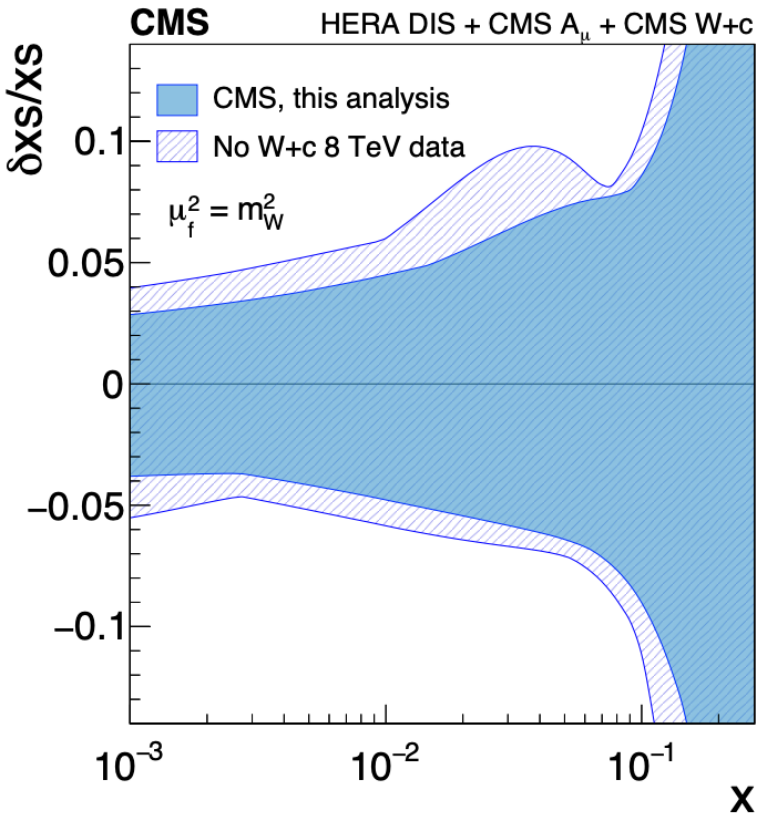


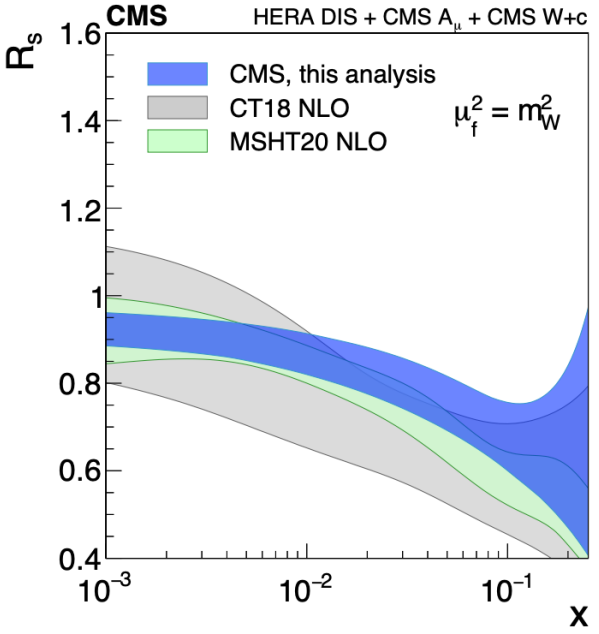
- Reasonable agreement with NLO fits

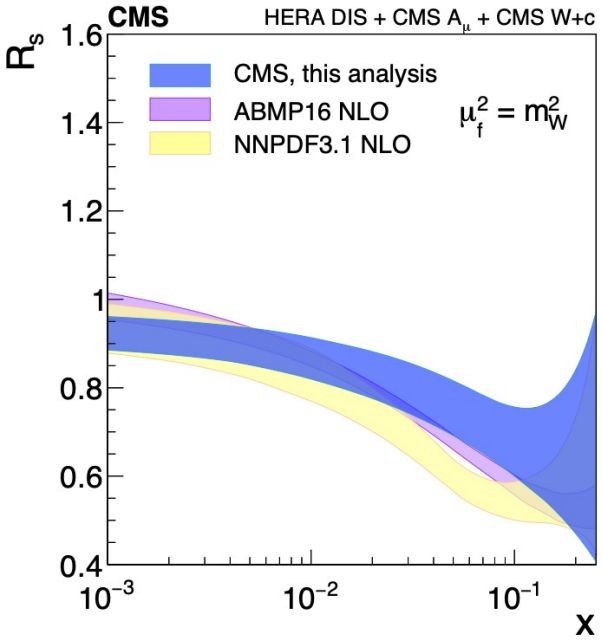
- Up to 10% disagreements @ low lepton p_T

- Comparisons using NNLO PDFs better?

Strange Density at CMS / Overall Picture



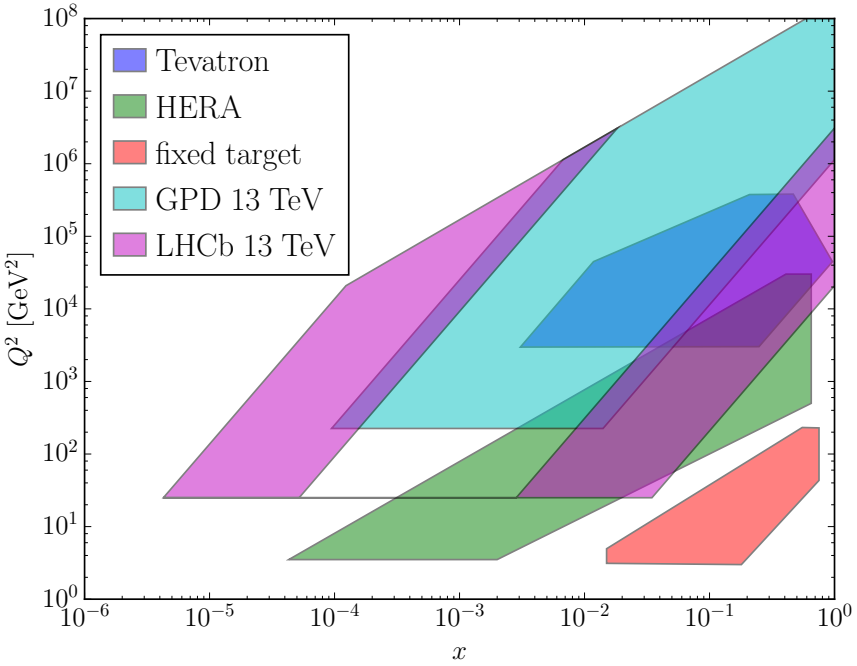




- Including CMS W+c data in fit with HERA data and previous CMS W, W+c data shows significant improvement on strange precision

- Also suggestive of small strangeness suppression at low x

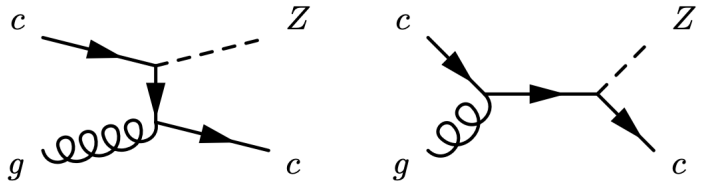
Favourable LHCb Kinematics



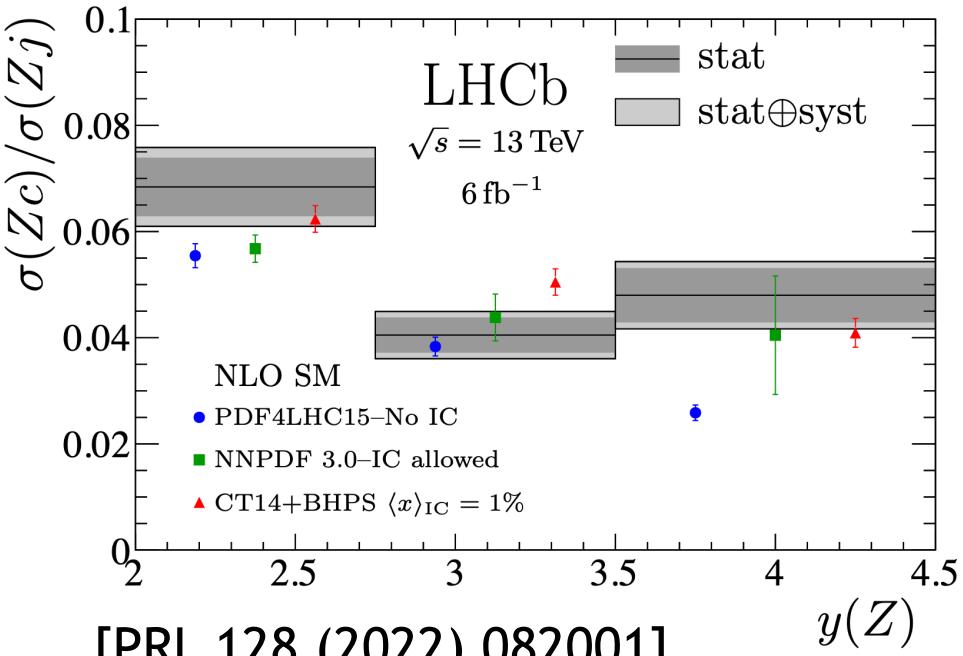
"Fixed target-like" forward instrumentation ($2 < \eta < 4.5$) gives sensitivity to asymmetric x values,

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

Forward Z+c data provide evidence for intrinsic charm in the proton



[also NNPDF, Nature 608 (2022) 483]



[PRL 128 (2022) 082001]

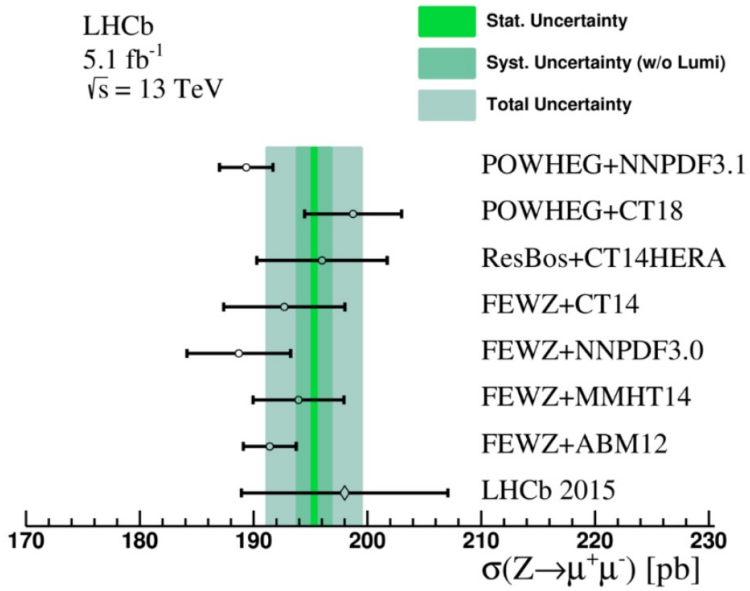
LHCb inclusive Z

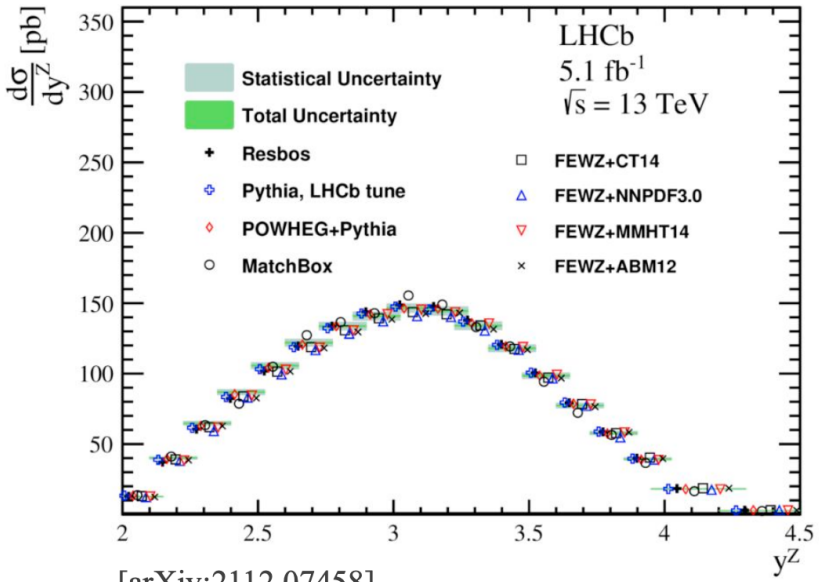
[JHEP 07 (2022) 026]

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

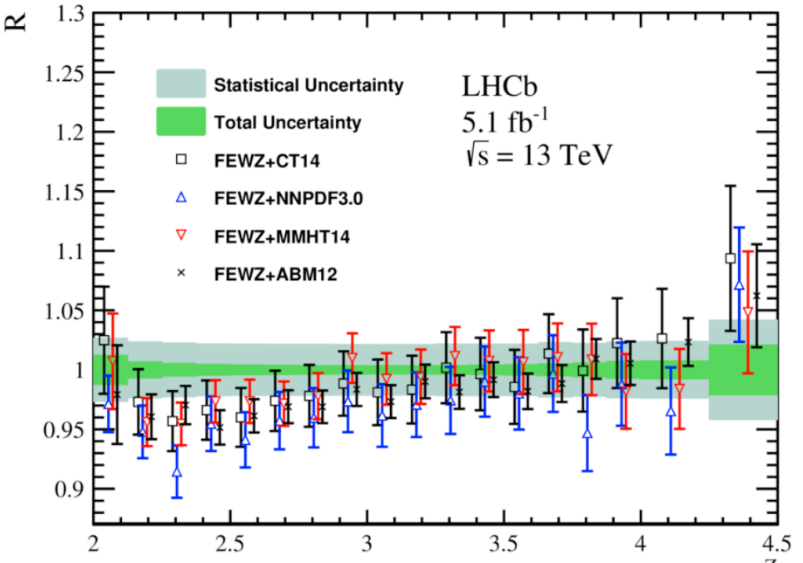
- FEWZ predictions systematically low at low rapidities for all PDF sets (corresponding to more modest x).

- Further studies on W, top, Drell-Yan, (not shown here).



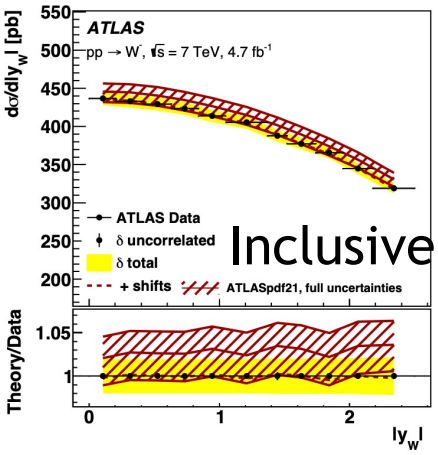


[arXiv:2112.07458]

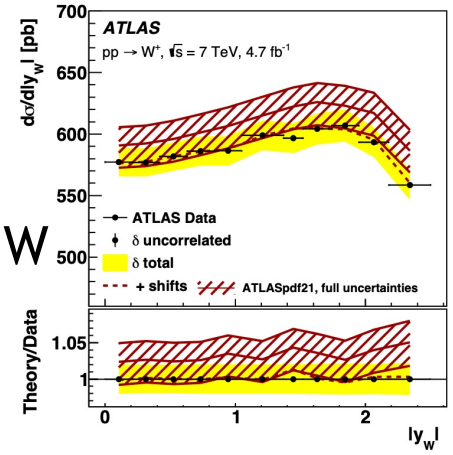


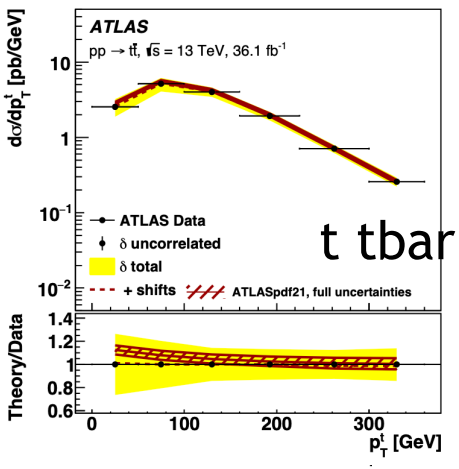
[arXiv:2112.07458]

Back to ATLAS: Quality of Description of Data



Inclusive W





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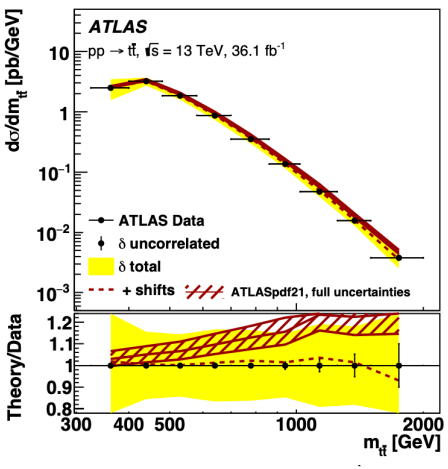
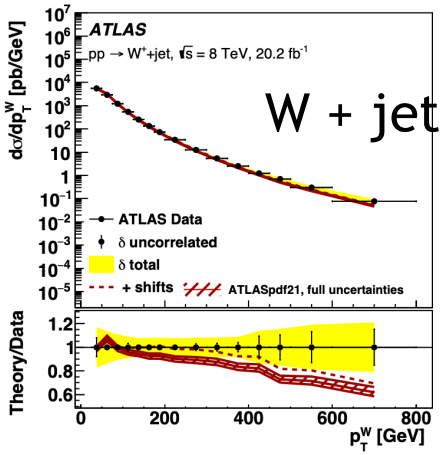
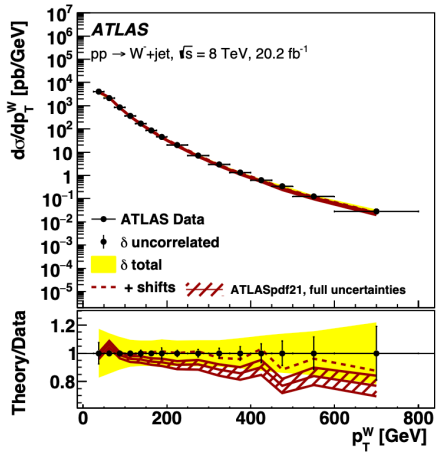
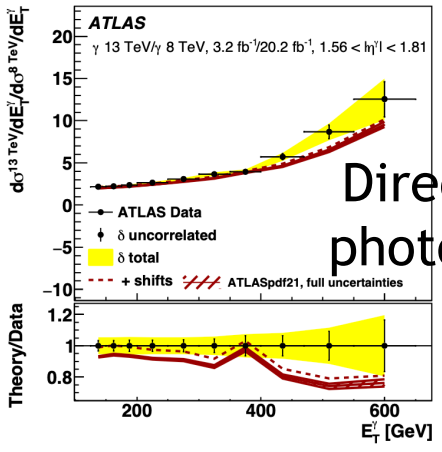


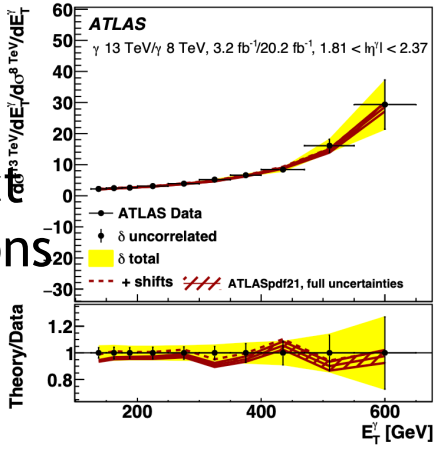


W + jet





Direct photons



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

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

Thanks to the Organisers!