Parton distribution functions: measurements and interpretations

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On behalf of the ATLAS, CMS and LHCb Collaborations

Preface

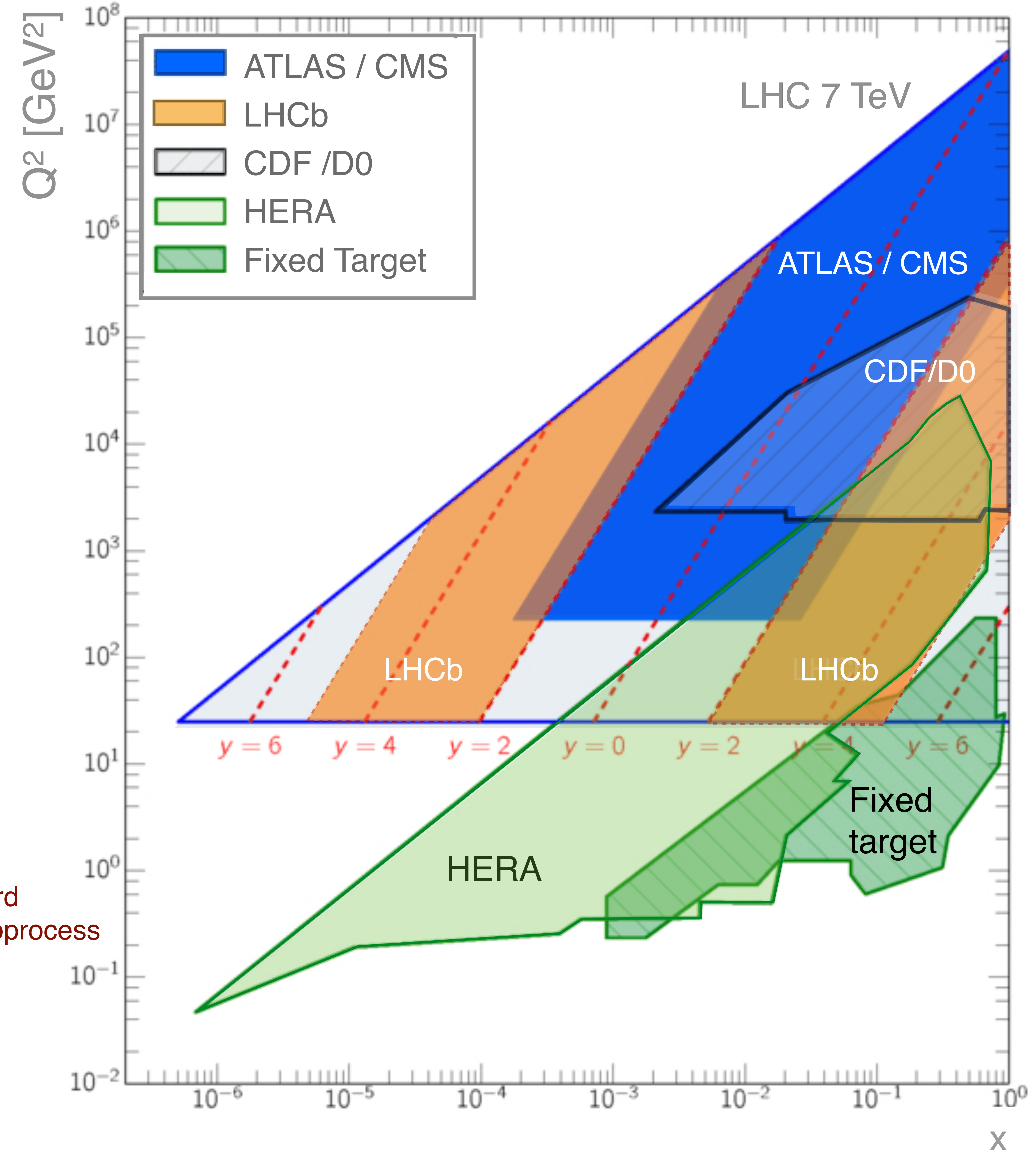
- The LHC has performed extremely well during Run 1 and Run 2
- Information on the internal structure of the proton from the parton distribution functions (PDFs)
- The LHC has unprecedented coverage of the kinematic plane, extending by several orders of magnitude
- The LHC experimental collaborations each have a large, and developing portfolio of precision measurements with the potential to constrain the PDFs in the proton
  - Concentrate only on constraints from some of the newer results from ATLAS, CMS and LHCb
- For LHC collisions with two momentum fractions, x_1 and x_2

$$d\sigma_X = \sum_{i,j} \int dx_1 dx_2 \; f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2) \times \hat{\sigma}_{ij\to X}(x_1,x_2,\mu_R^2)$$

PDFs

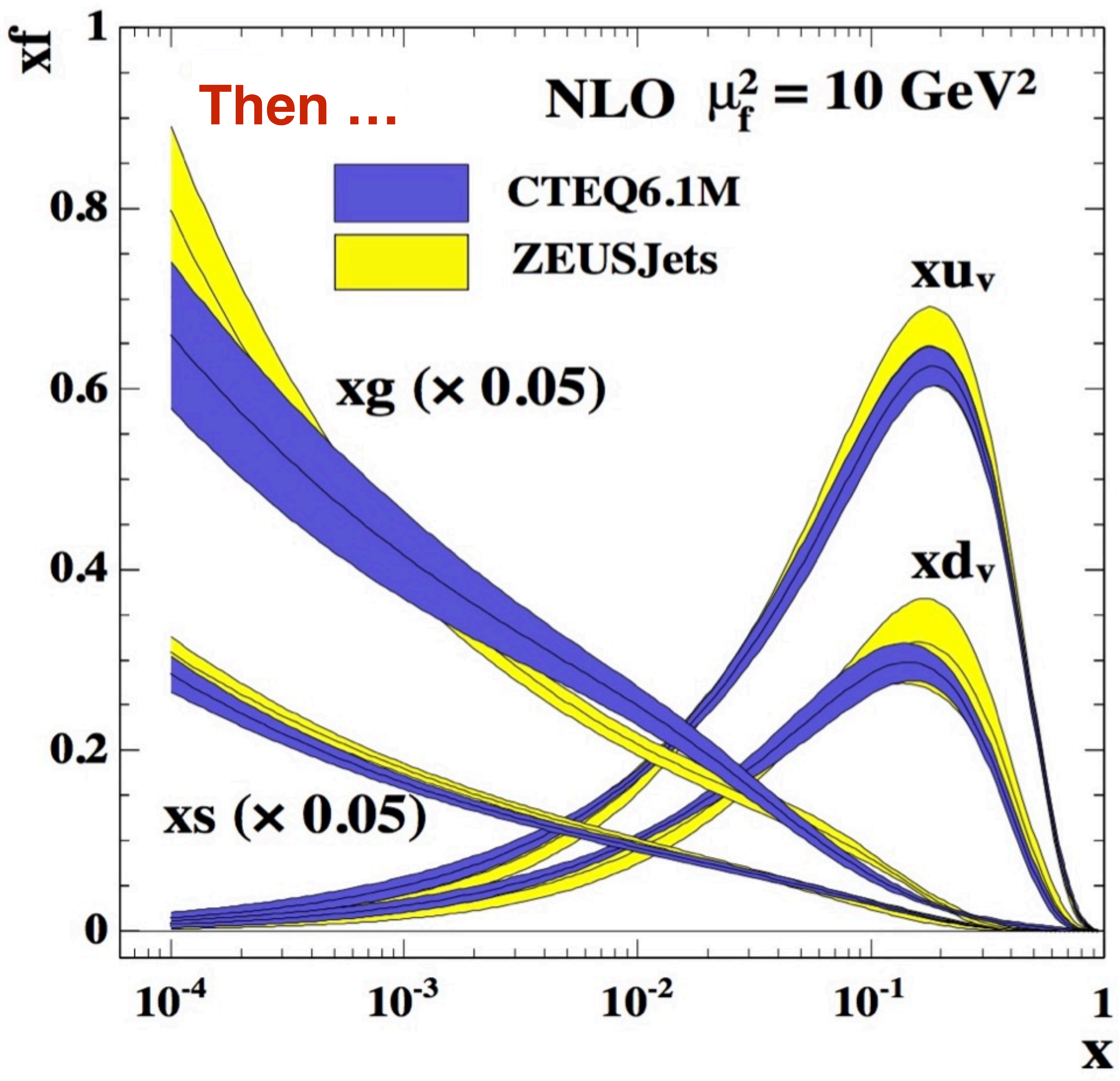
Hard subprocess

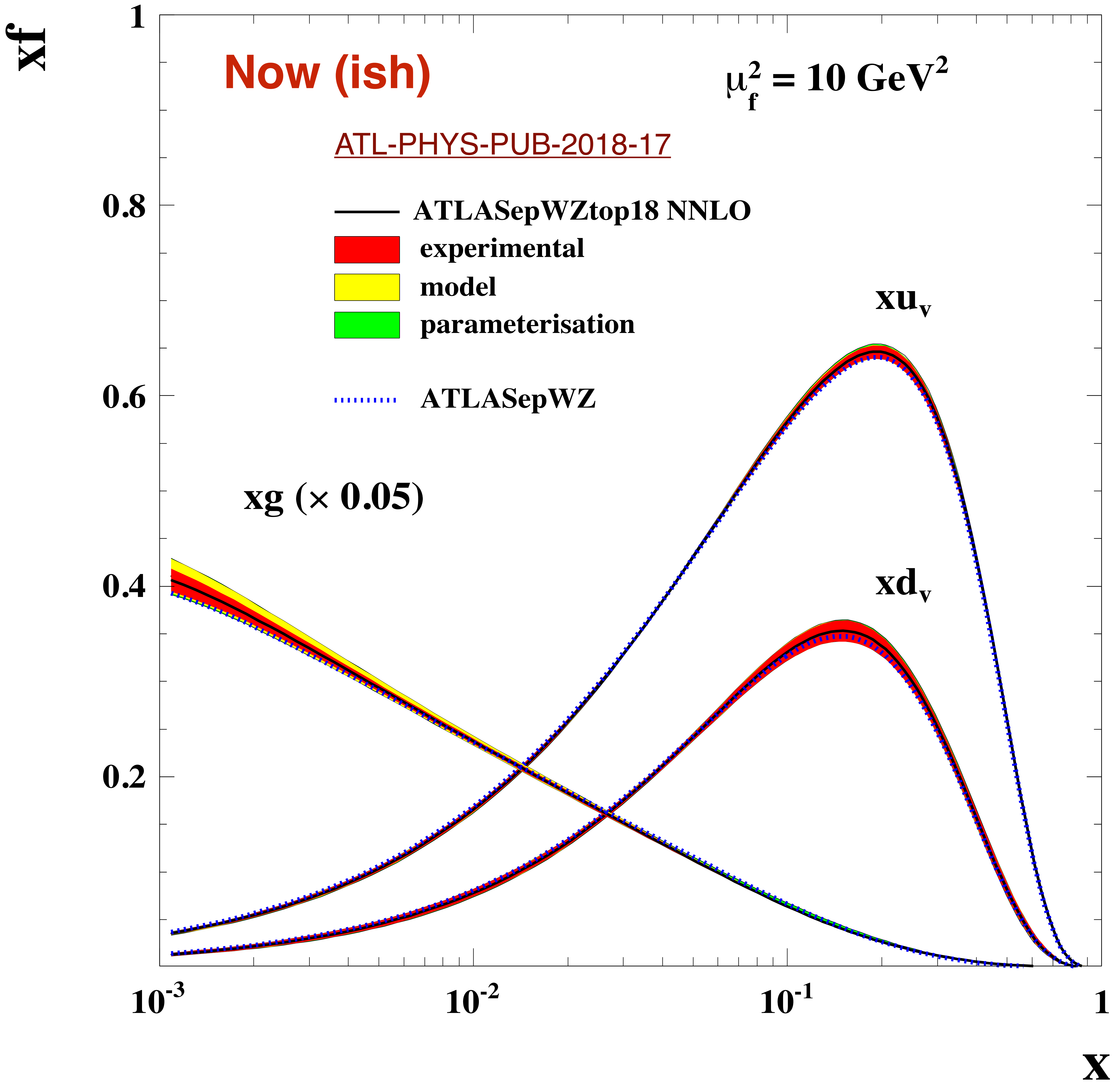
- The LHC provides unprecedented access to a previously unexplored region of phase space essential for the discovery and understanding of any new physics



Cast your minds back …

- … to the dark days at the turn of the century …
- … the best fits, naturally without LHC or HERA II data, but with HERA I and Tevatron data …





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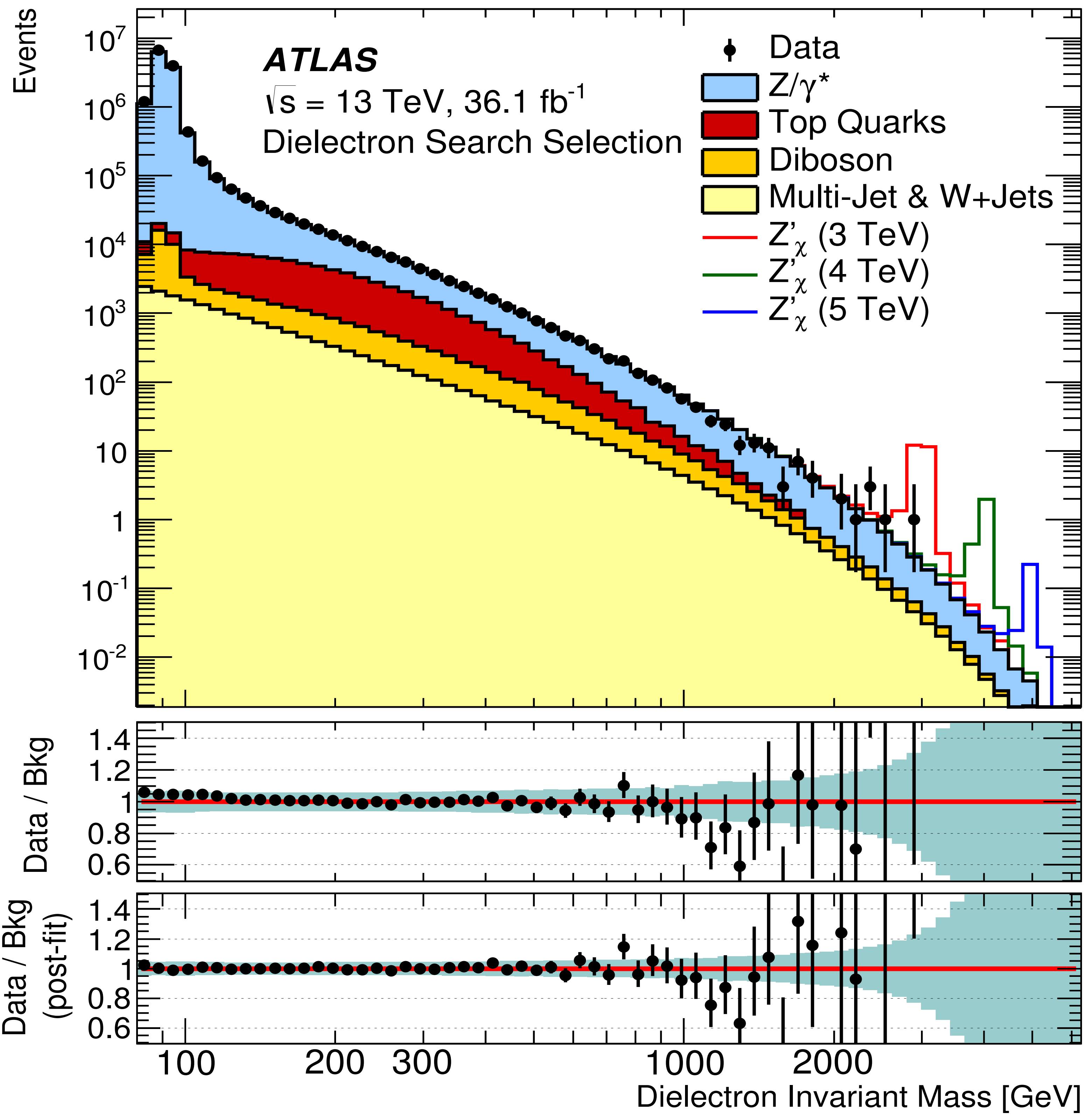

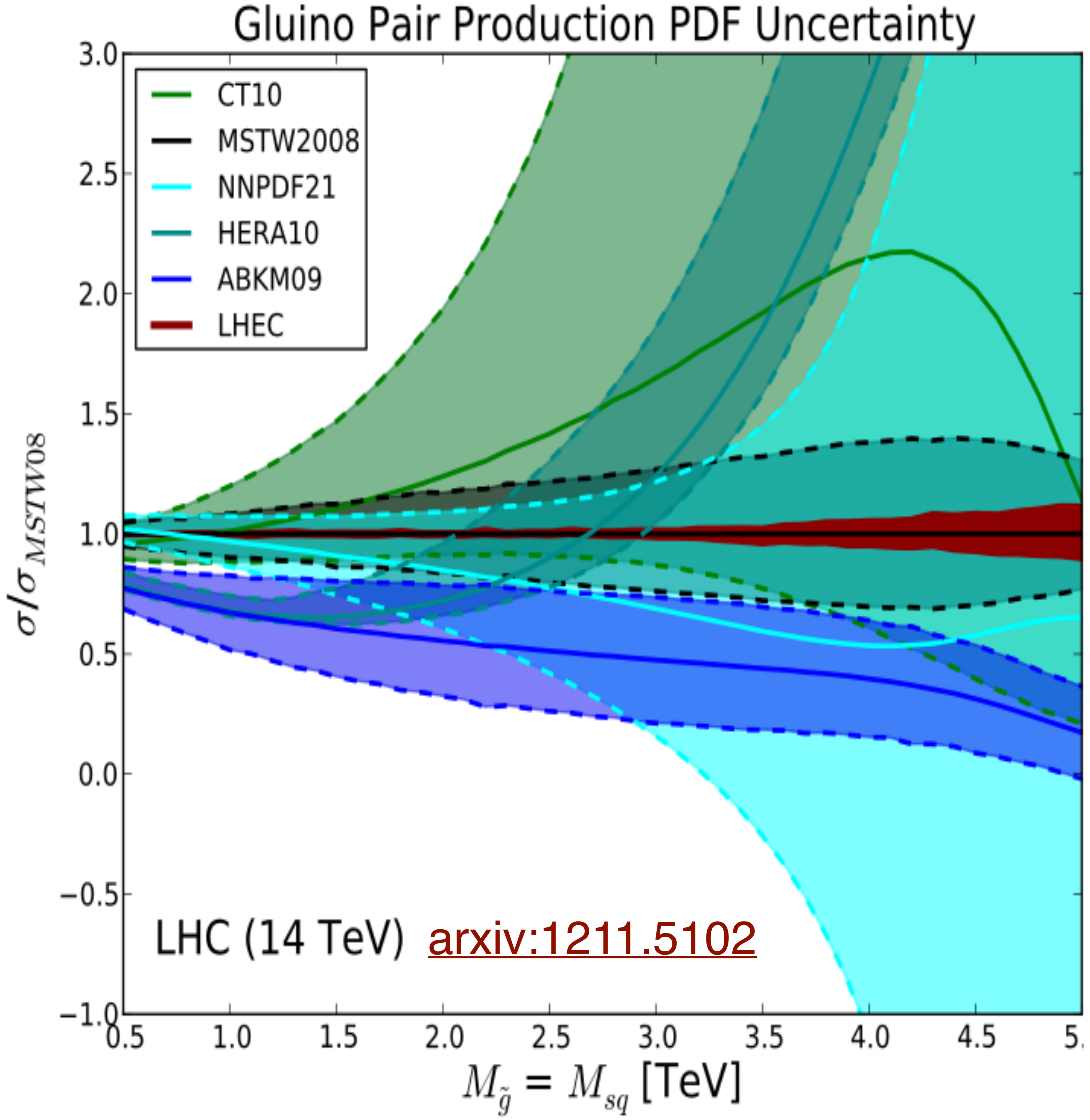

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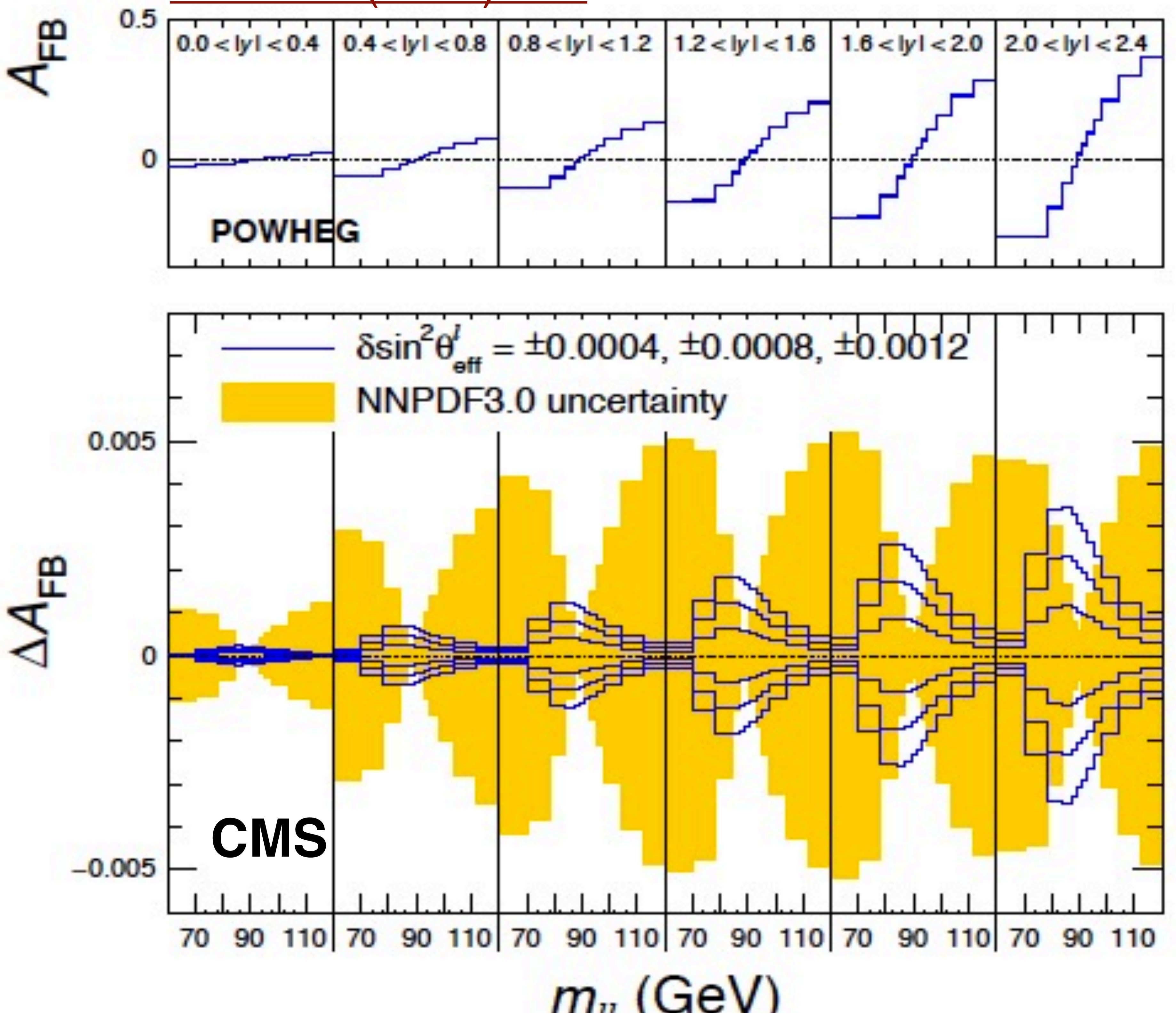
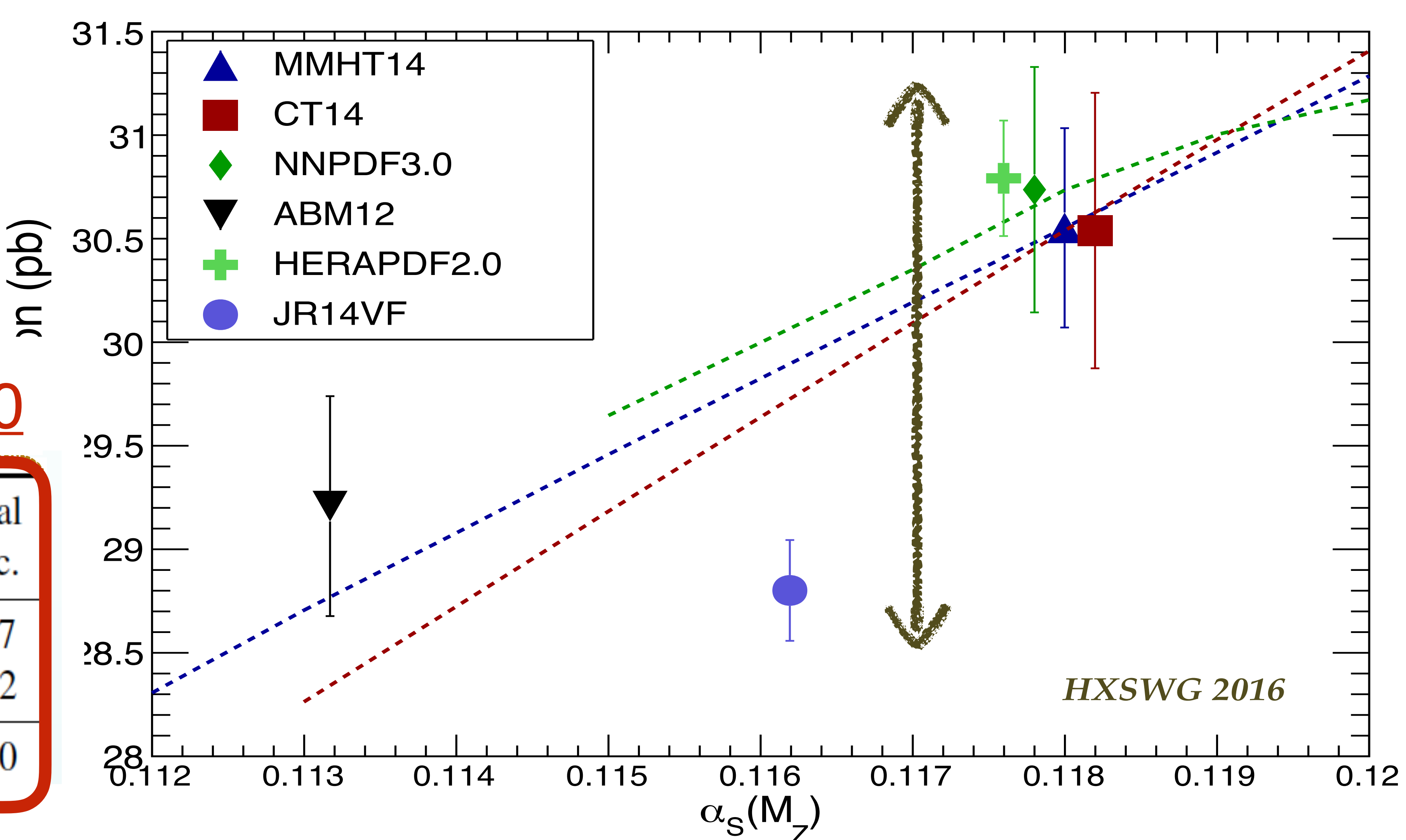


Gluon-Fusion Higgs production, LHC 13 TeV



The proton PDF ? Should I give a monkey's ?

- Essential for the Standard Model and physics Beyond the Standard Model at the LHC
  - Dominant theory uncertainty for Higgs and top production, limits precision on fundamental parameters (MW, α_s, …)
  - Limits searches for new massive particles
- Other questions of factorisation, heavy quark dynamics etc …

ATLAS Mw, arxiv: 1701.07240

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

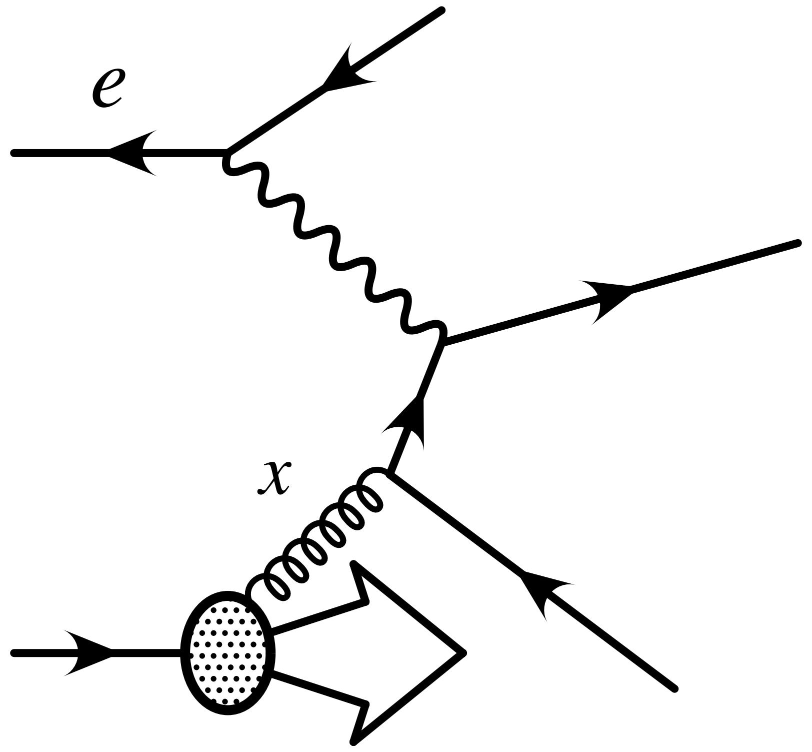
Different final states inform different subprocesses

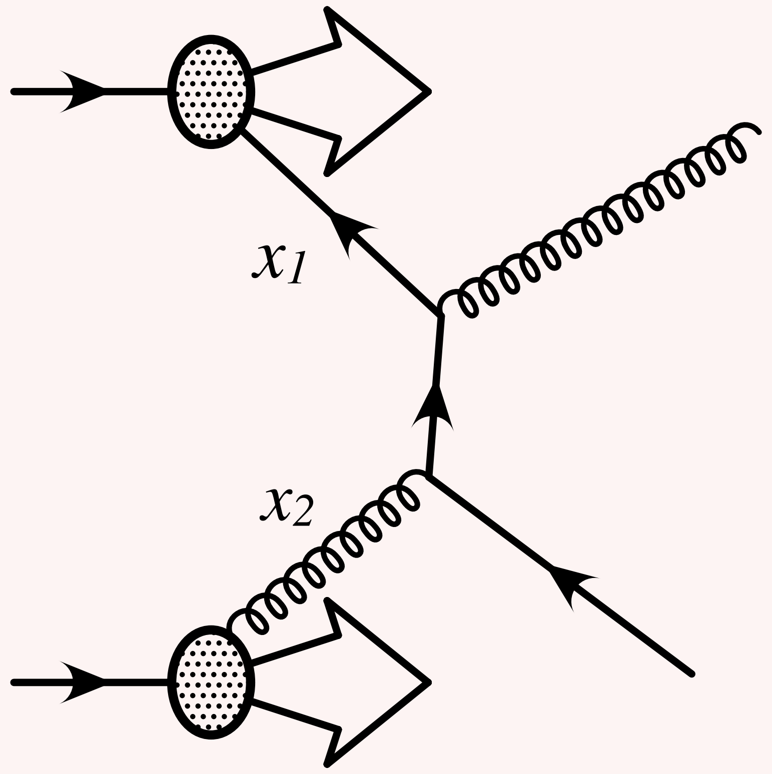
- DIS data constrains quarks at low-x
  - Born level scattering off of quarks, one momentum parton fraction x

$$d\sigma_{\mathrm{DIS}} \sim (1+(1-y_{\mathrm{Bj}})^2)F_2(x,Q^2) - y_{\mathrm{Bj}}^2 F_L(x,Q^2)$$

$$F_2 = x\sum_q e_q^2(q(x)+\bar{q}(x))$$

  - Sensitive to the gluon distribution through $\mathcal{O}(\alpha_s)$ corrections



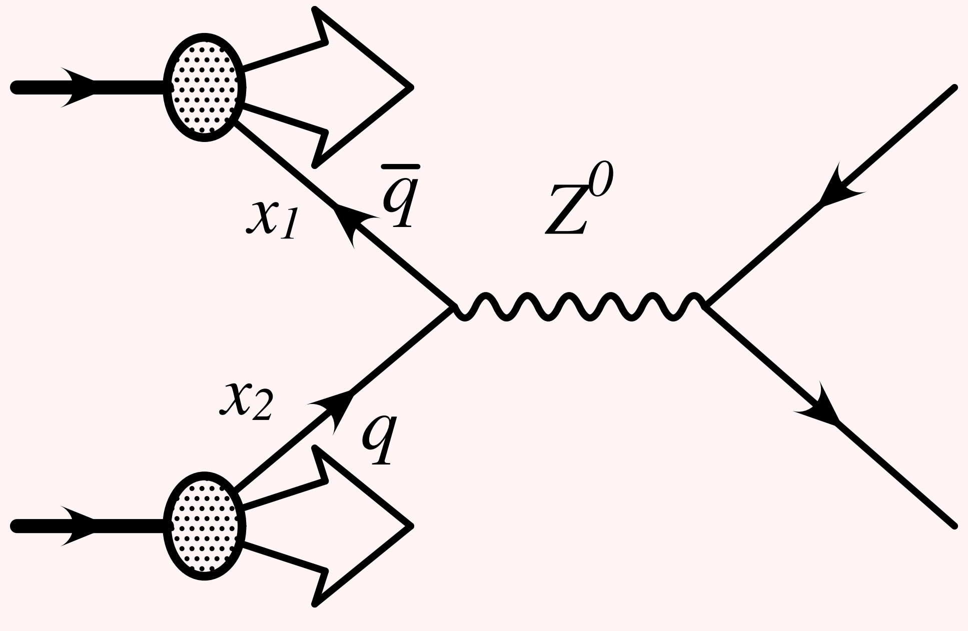


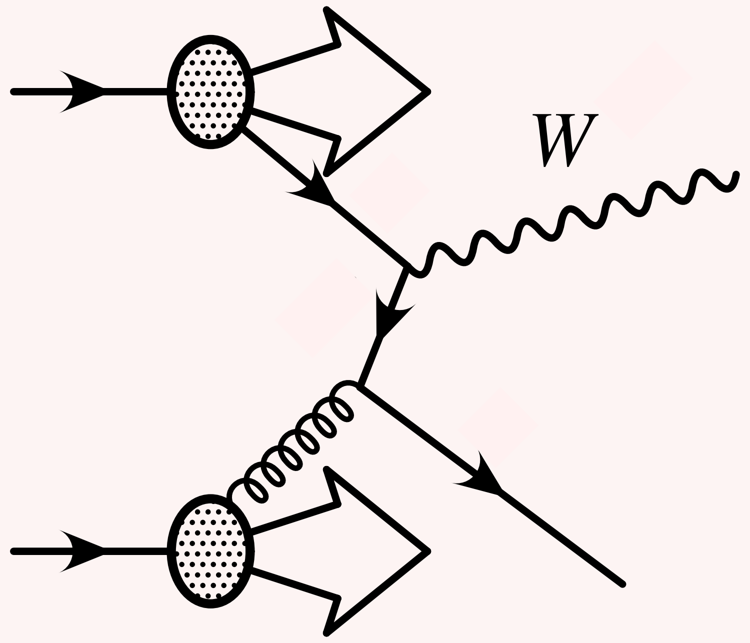
- For LHC collisions with two momentum fractions, x_1 and x_2

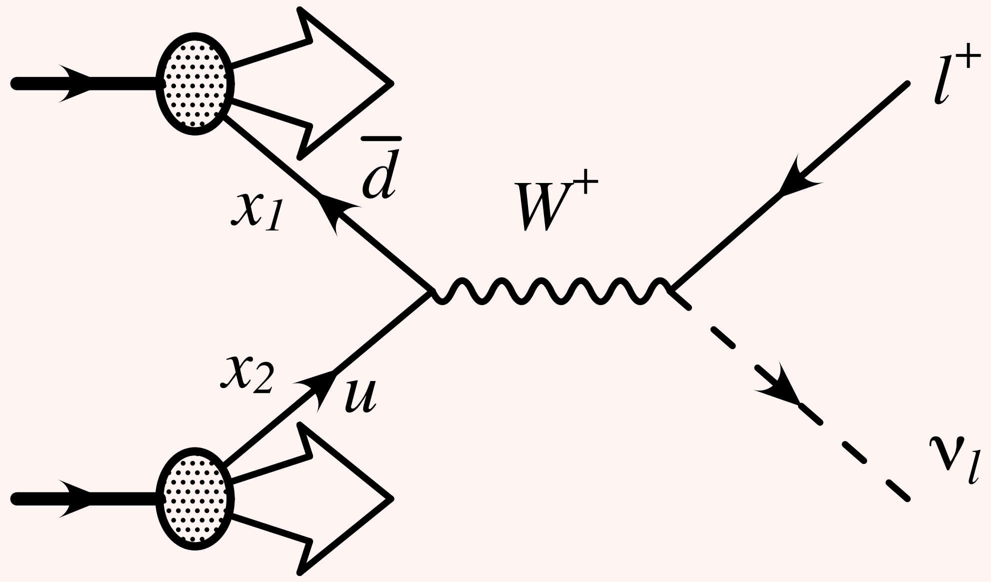
$$d\sigma = \sum_{i,j}\int dx_1\int dx_2\; f_i(x_1,\mu_F^2)f_j(x_2,\mu_F^2)\;\hat{\sigma}_{ij}(x_1,x_2,\mu_R^2)$$

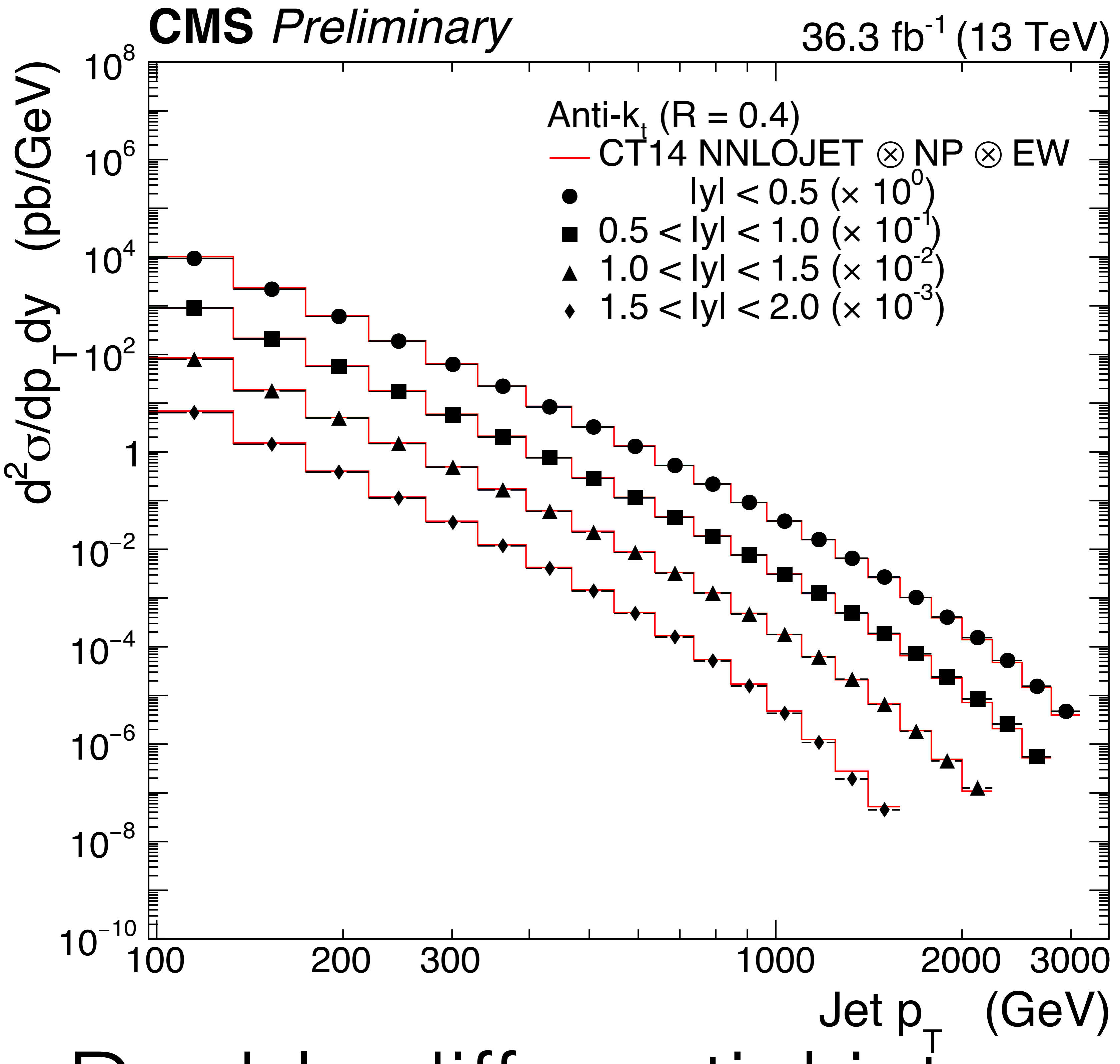
- Inclusive jets, dijet, and trijet production, ttbar, inclusive photon …
  all directly sensitive to the **gluon distribution**, the **strong coupling,** and the valence quarks at high E_T

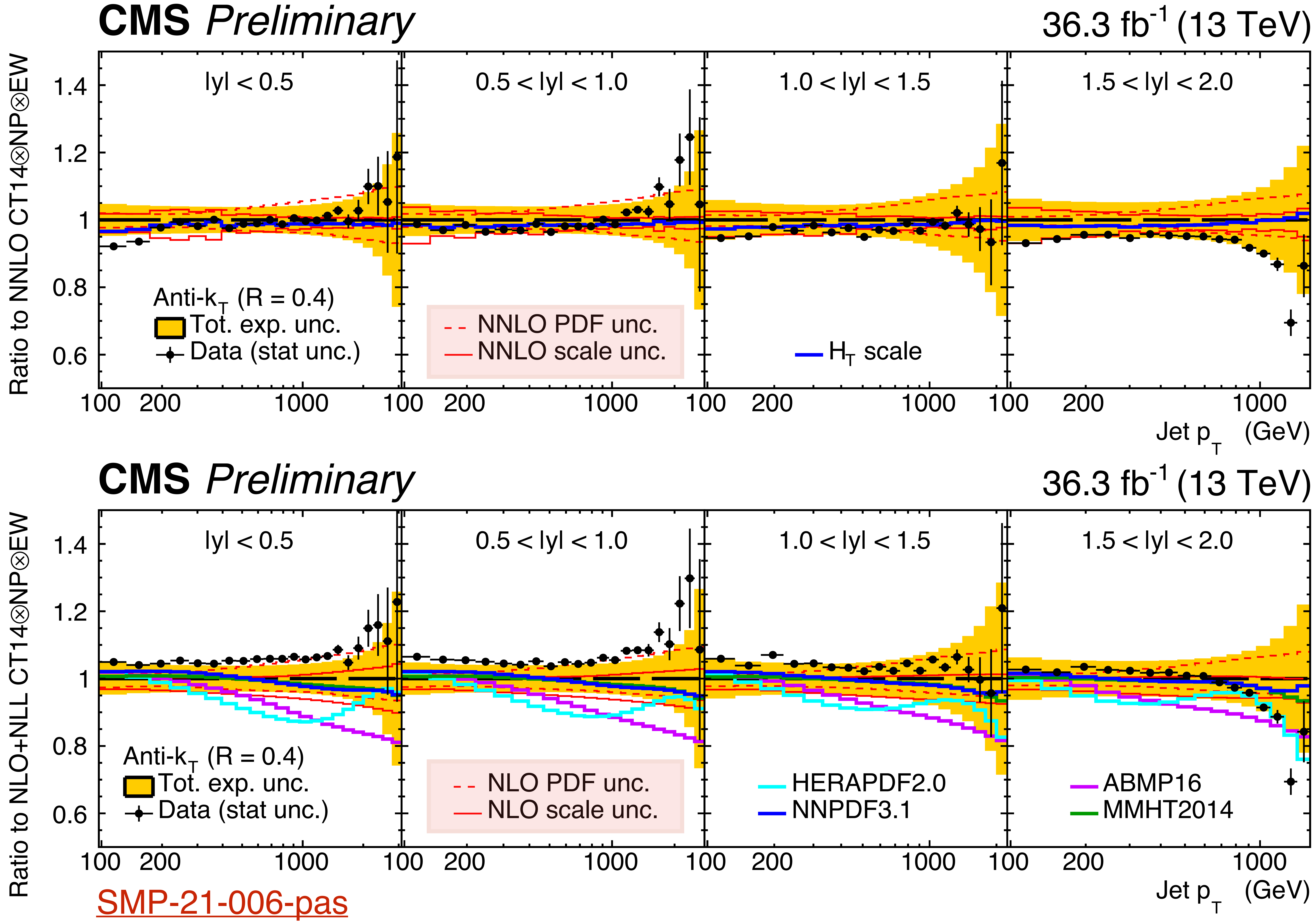
- Electroweak boson production
  - Inclusive W, Z and asymmetries: **quark flavour separation**
  - Off peak Drell-Yan: u, d at high or low-x
  - W+charm: sensitivity to the **s-quark**
  - **W, Z + jets** (jet need not be unobserved)











Double differential jet production from CMS

- Inclusive jet production, doubly differential in p_T and rapidity
- Very precise, NNLO theory NNLOJET agrees well within the uncertainties over 9 orders of magnitude in the cross section, but …

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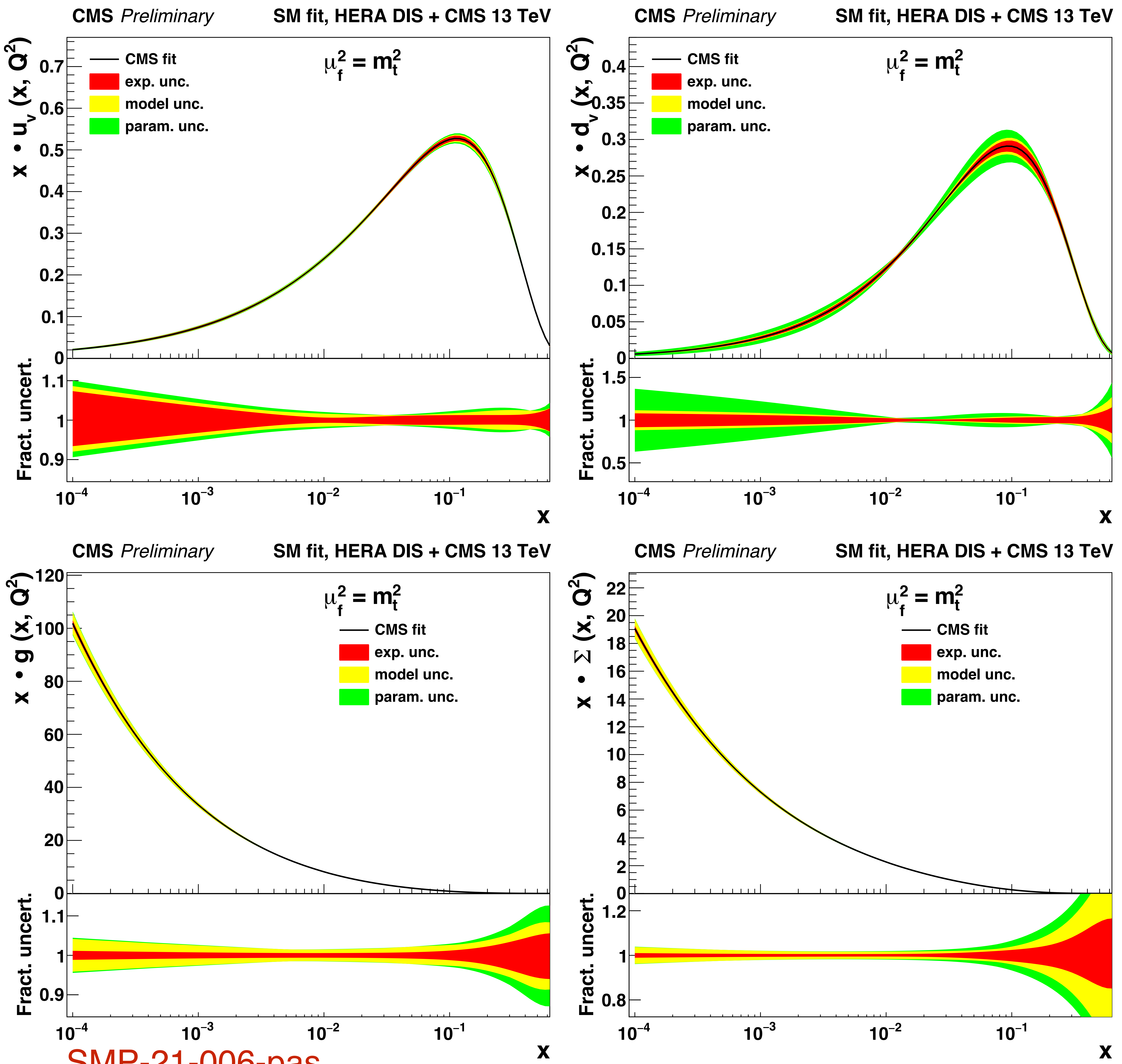
- Large variability of the of the different predictions from different PDFs, the PDF uncertainty itself within the sets is extensive
  - Large potential for constraining the gluon PDF, particularly at large-x

CMS PDF Profile

- Fit the data by profiling the PDF - fitting the data by allowing variations of the eigenvalues for the eigenvector PDFS from an existing PDF fit
  - For instance, CT14nlo and CT14nnlo
  - Use CMS inclusive jet data at 13 TeV and differential top data EPJC 80 (2020) 656 arXiv:1904.05237
- Small uncertainties
  - Uncertainties larger for the d valance
  - Gluon uncertainty large at larger x



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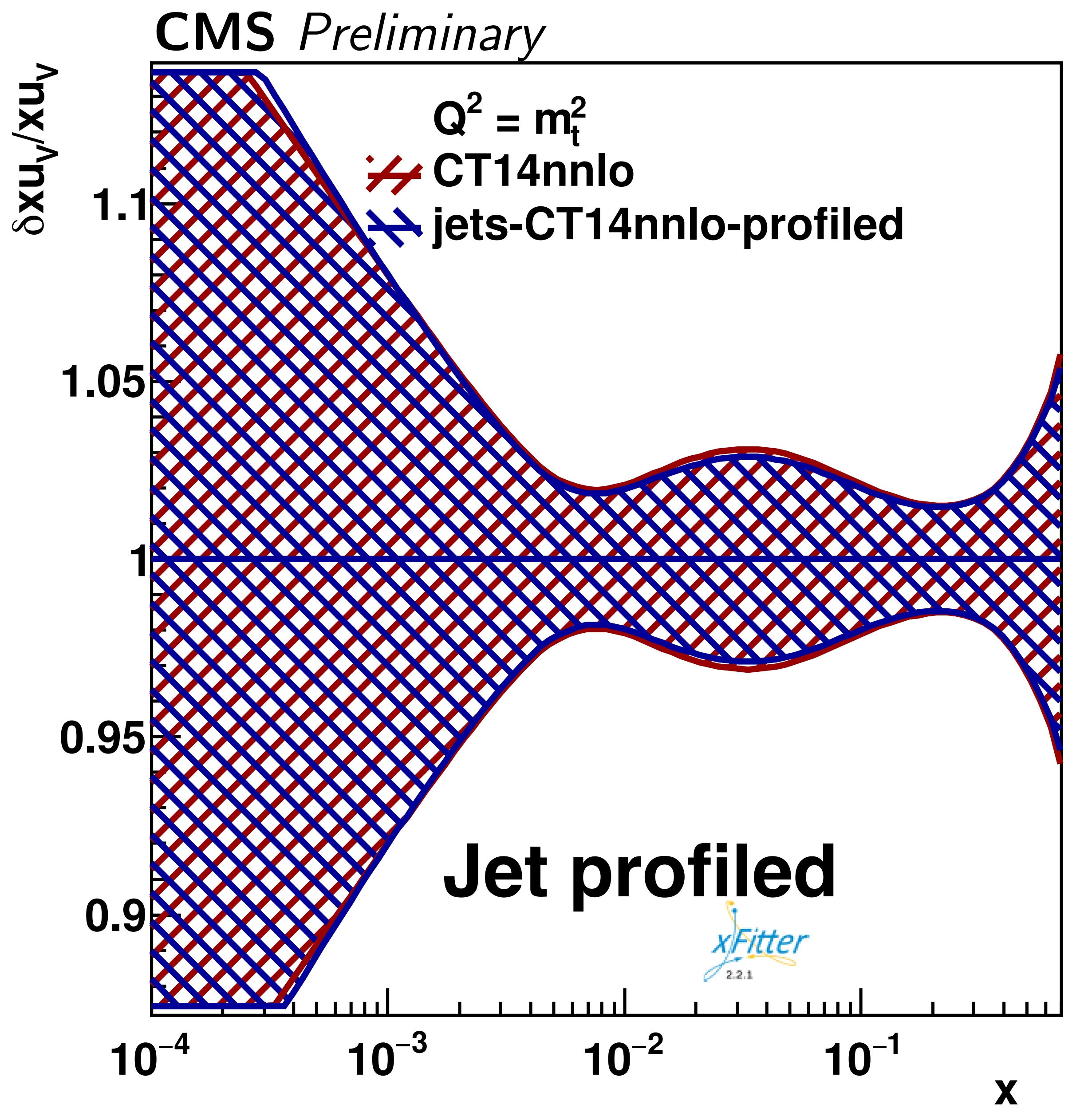

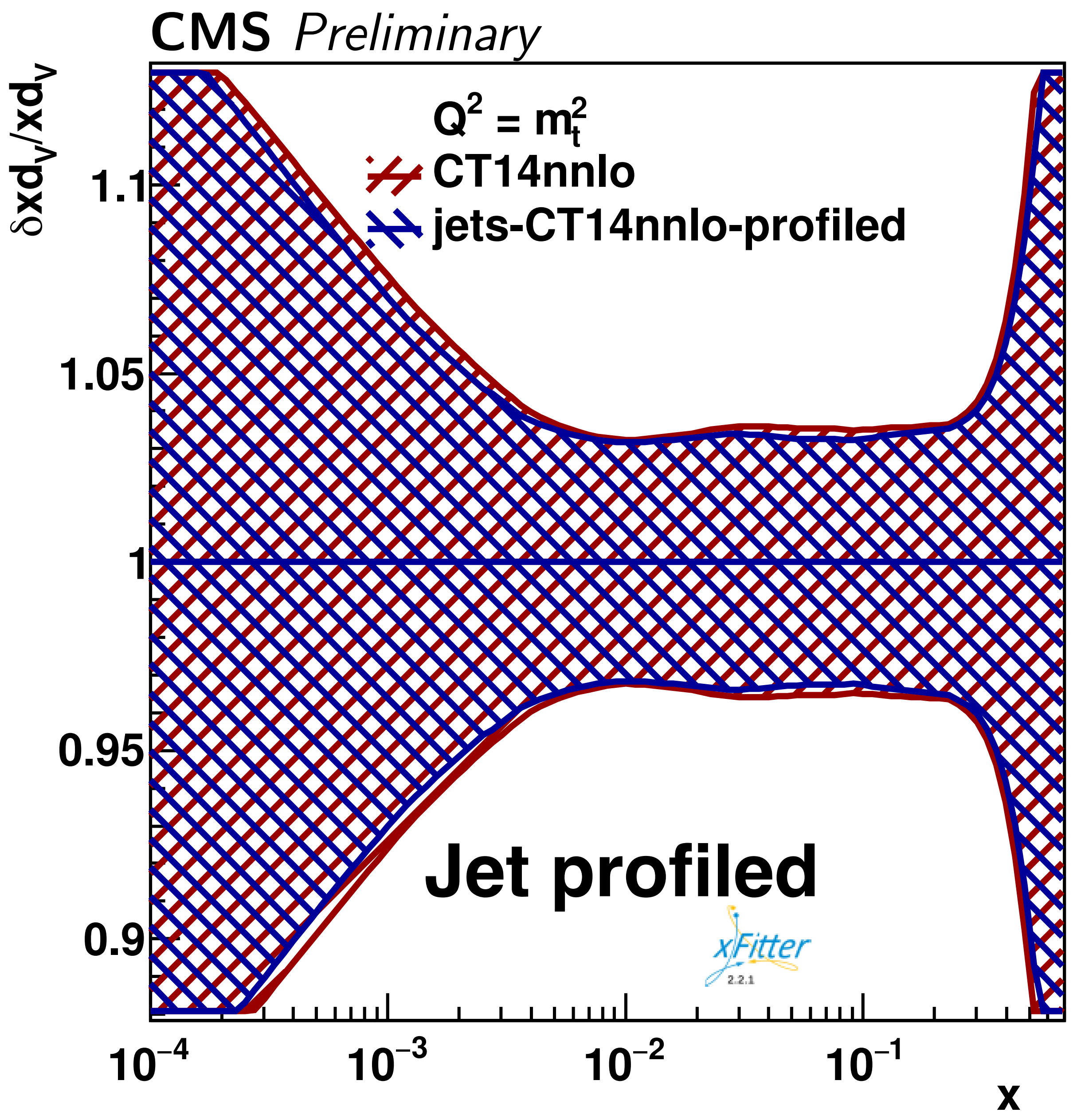

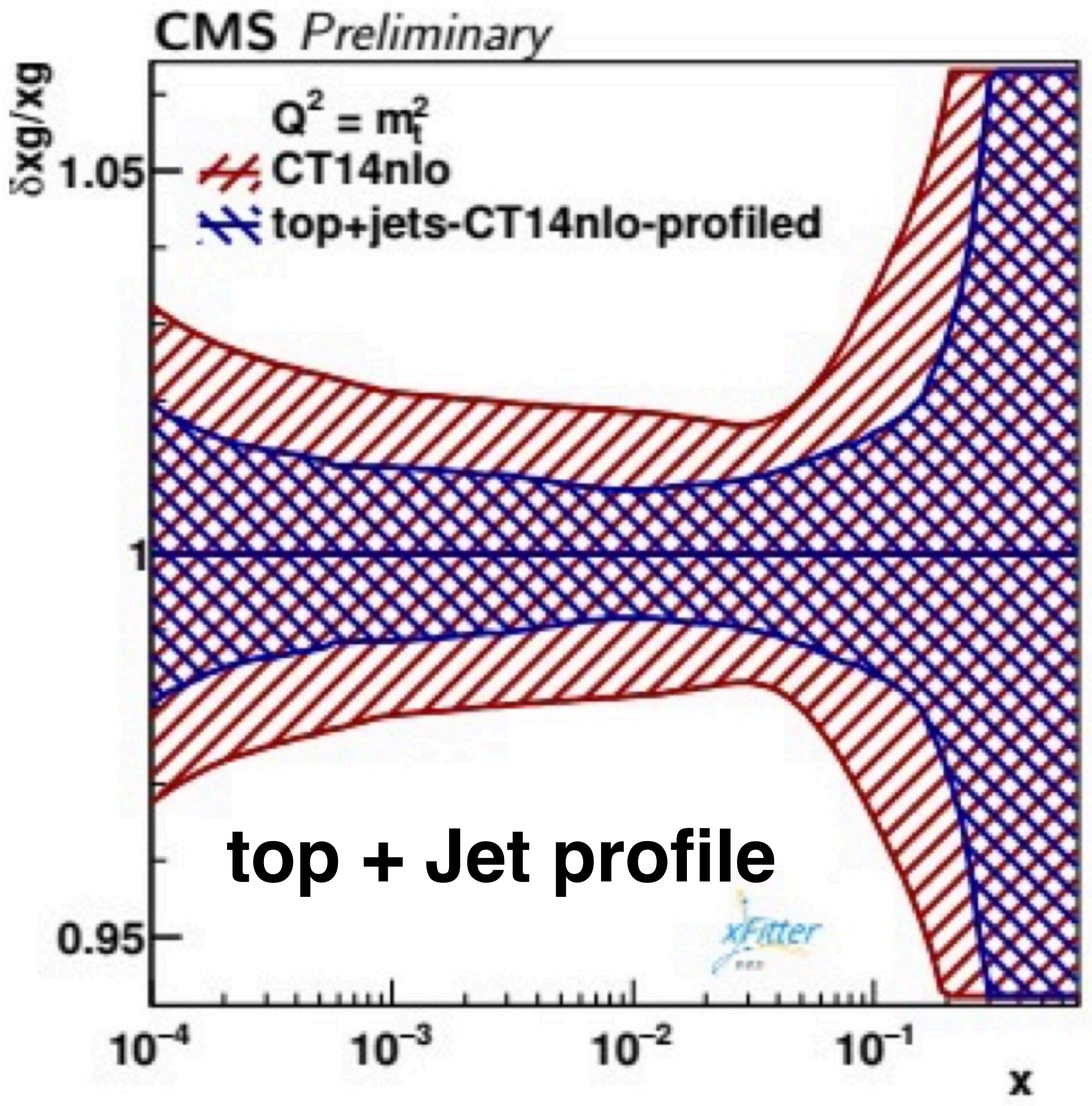

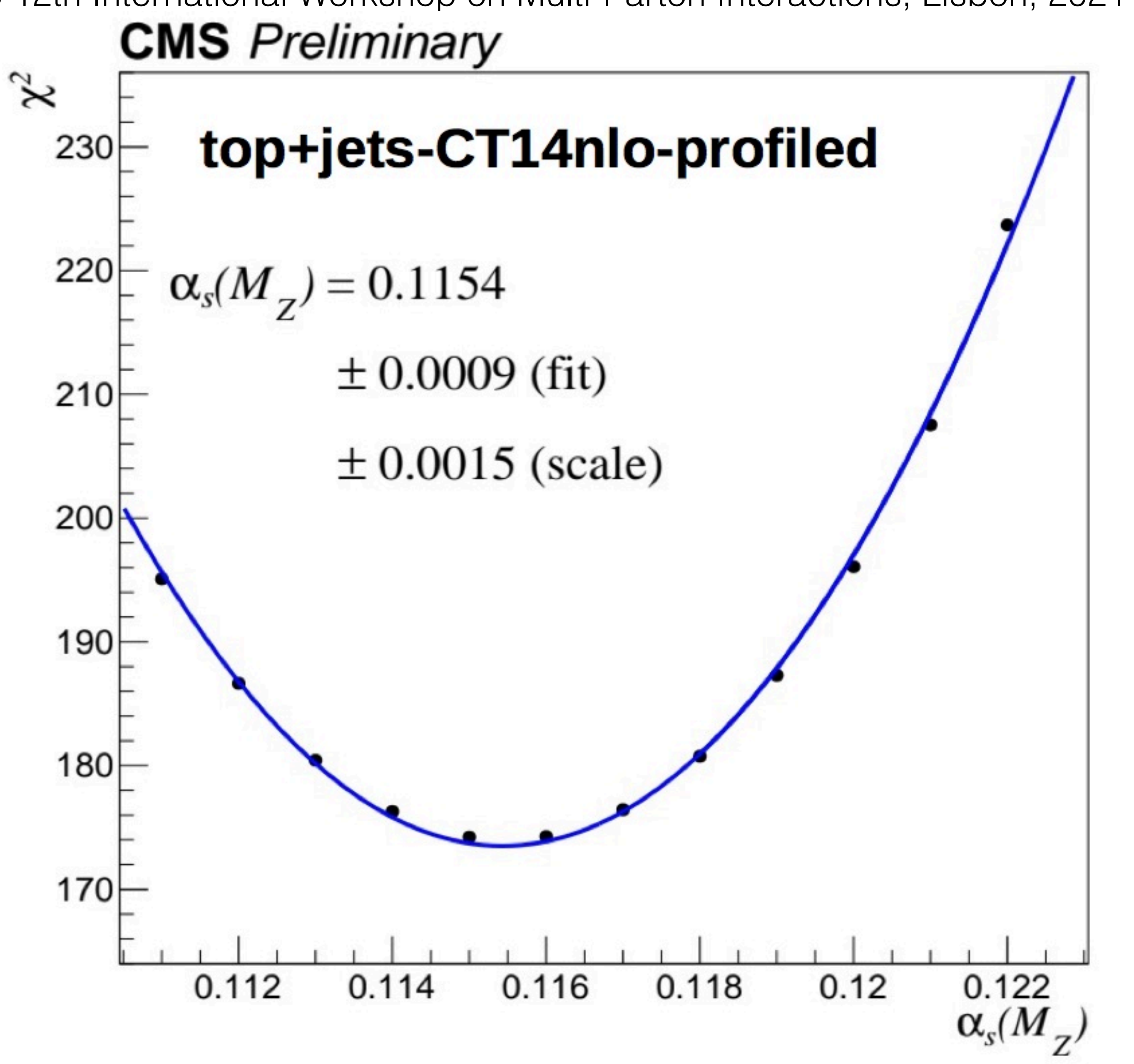

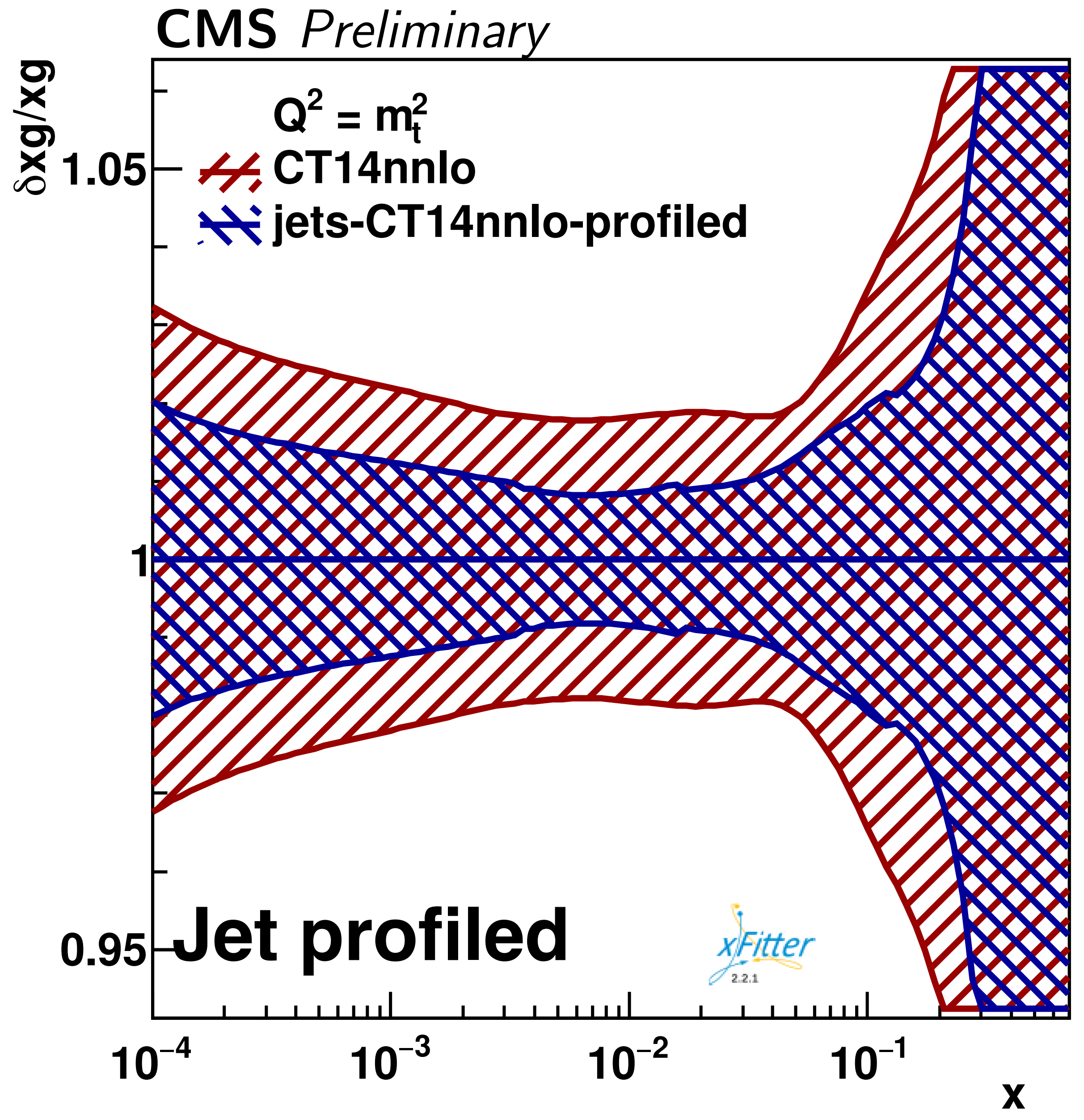

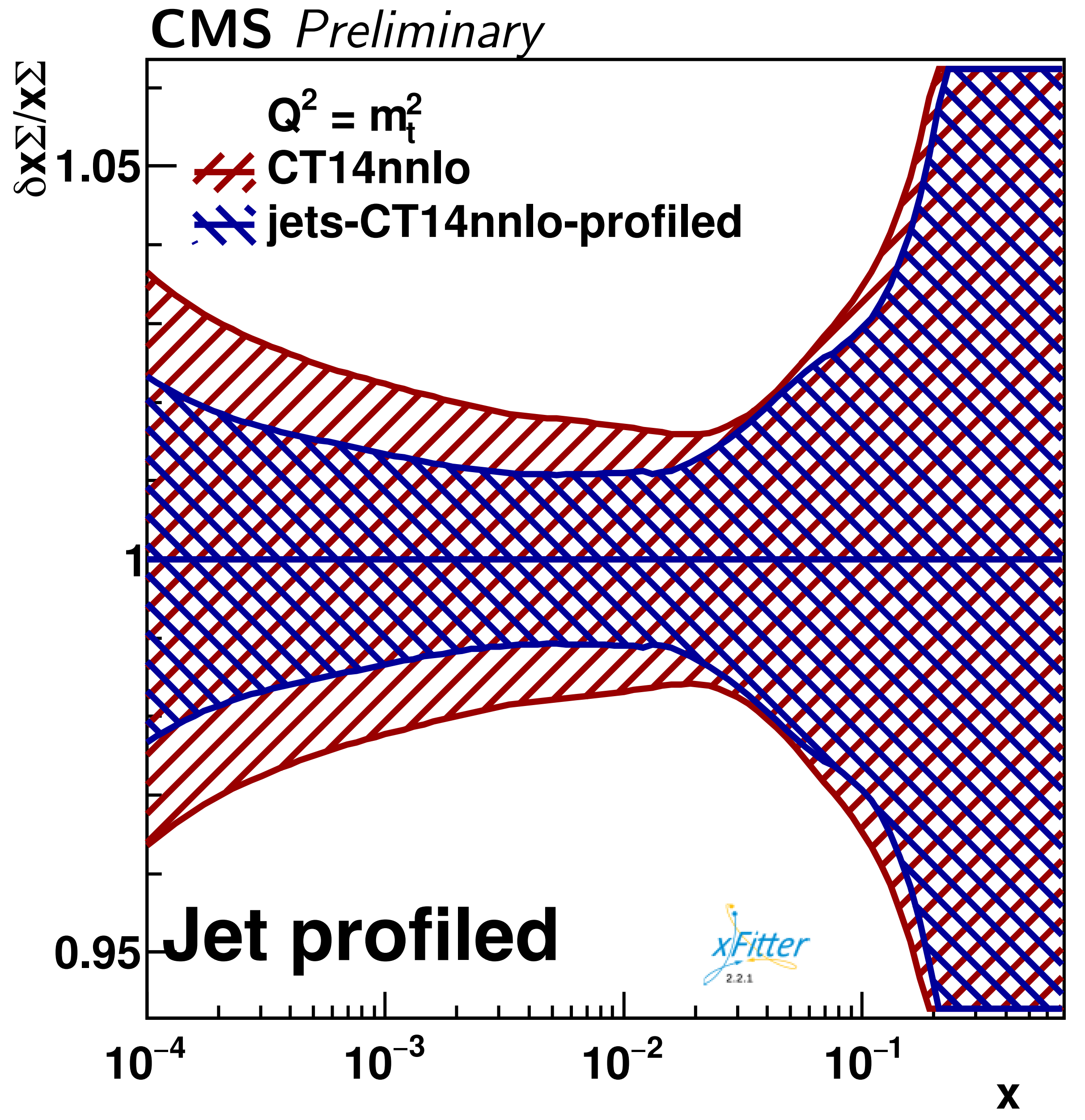

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CMS PDF Profile uncertainties

$\alpha_S(m_Z) = 0.1170 \pm 0.0018(\text{fit}) \pm 0.0035(\text{scale})$ at NLO and

$\alpha_S(m_Z) = 0.1128 \pm 0.0016(\text{fit}) \pm 0.0007(\text{scale})$ at NNLO.

- Uncertainties for the u and d valance, largely unchanged
  - Gluon uncertainty is around a factor of two smaller
  - Marginally smaller for x ~0.1 when including the top data
- The singlet uncertainty smaller for x less than ~ 0.03

CMS Standard Model QCD analysis at NLO

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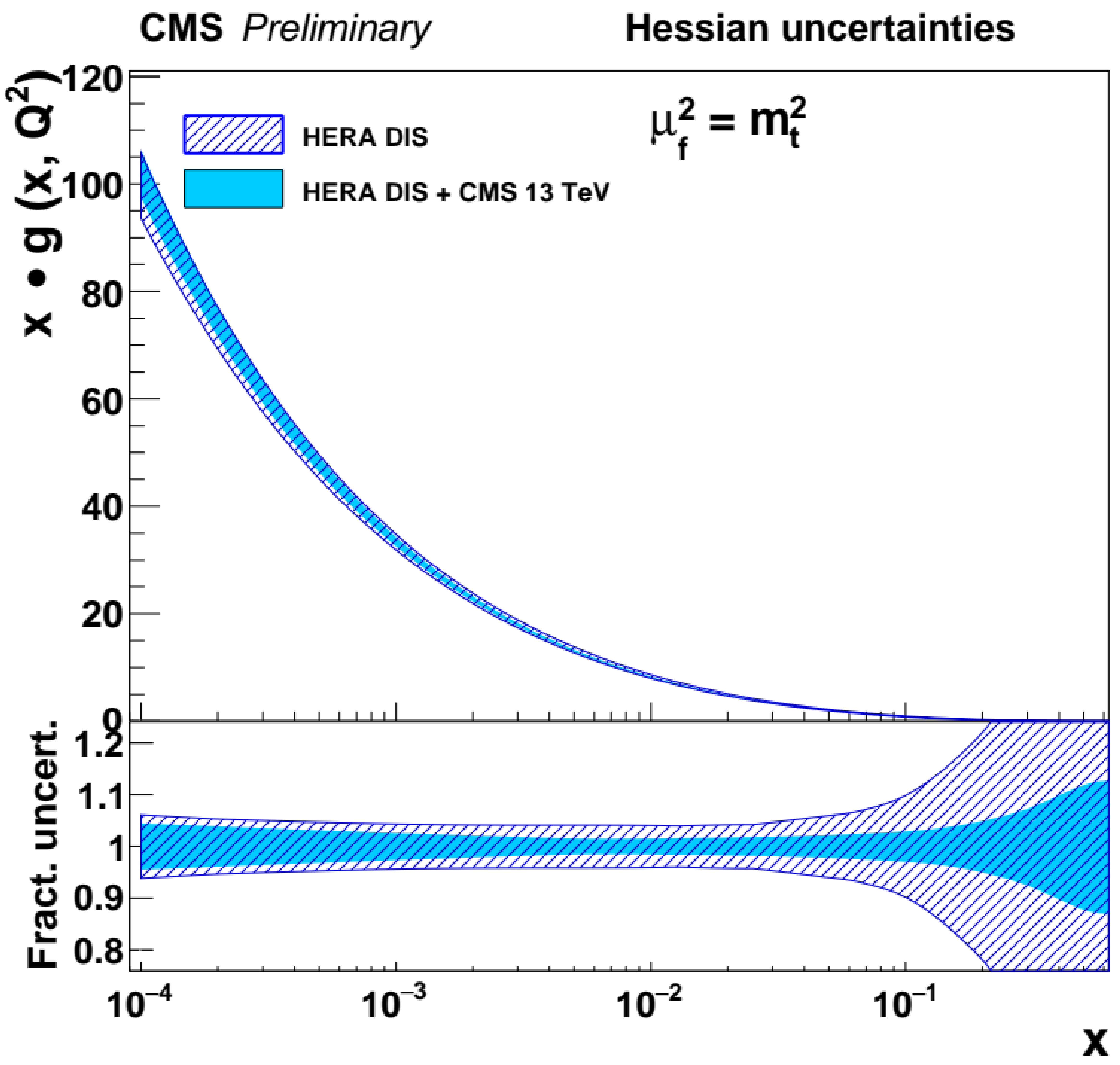
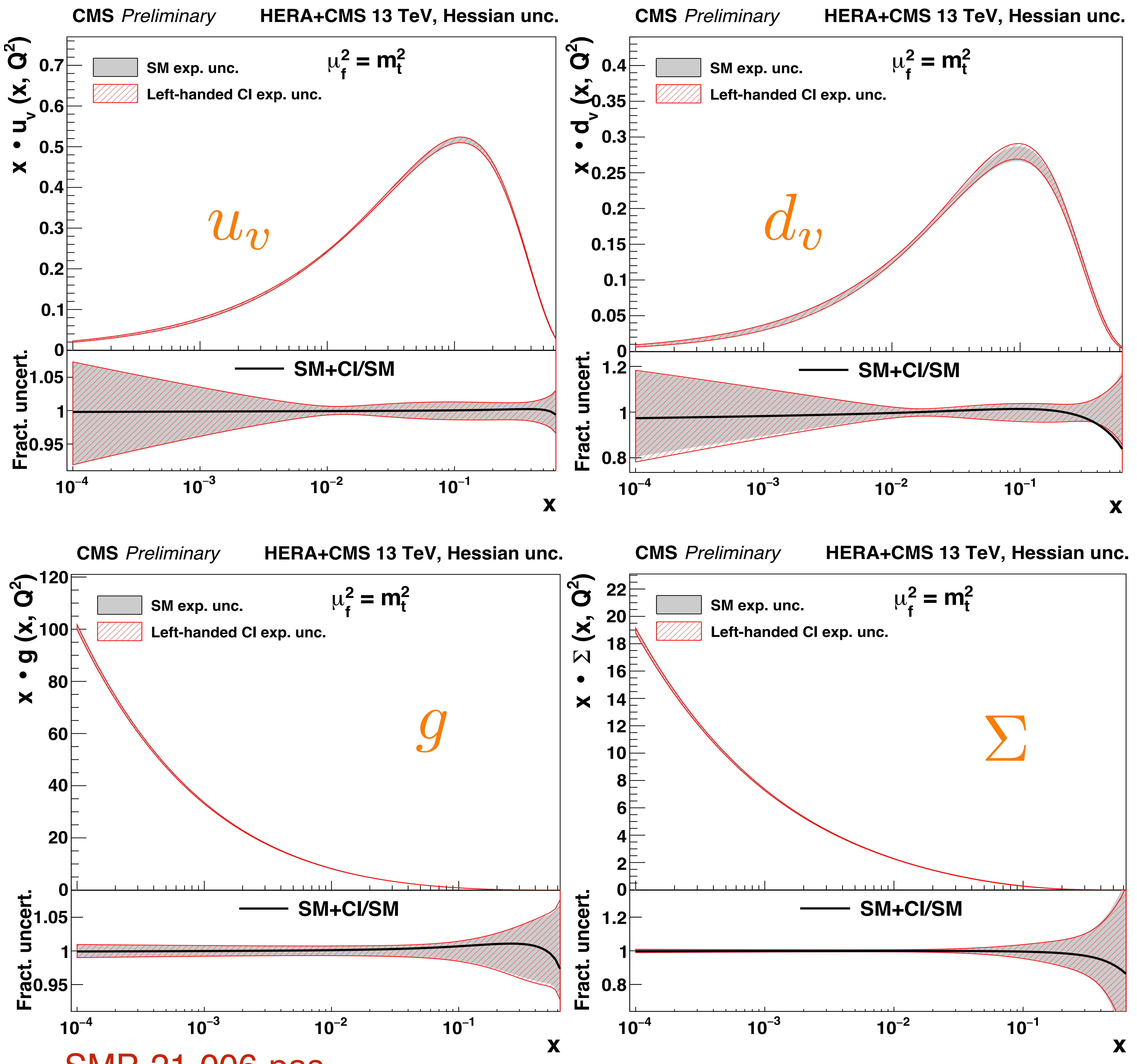


- Perform a simultaneous fit of the PDF, the strong coupling and the the top mass at NLO Comparison
  - Resulting PDF in fits including the CMS data demonstrate clear reduction in the gluon uncertainty
  - Expected similar - or better - improvement with a full fit at NNLO, as demonstrated by the profiling

$$\alpha_S(m_Z) = 0.1177 \pm 0.0014(\text{fit}) \pm 0.0022(\text{model and param.}),$$
$$m_t^{\text{pole}} = 170.2 \pm 0.6(\text{fit}) \pm 0.1(\text{model and param.})\,\text{GeV}.$$

- Fitted strong coupling and top mass consistent with world averages

CMS Standard Model + Effective Field Theory Fit



- QCD analyses performed using Standard Model (SM) predictions at NLO, and additionally with Standard Model + Contact Interaction (SMEFT) theory predictions
- The PDFs from SM and SMEFT fits agree within the respective uncertainties
- All CI models result in very similar PDFs, strong coupling and top mass values
- No statistically significant deviation from the SM observed

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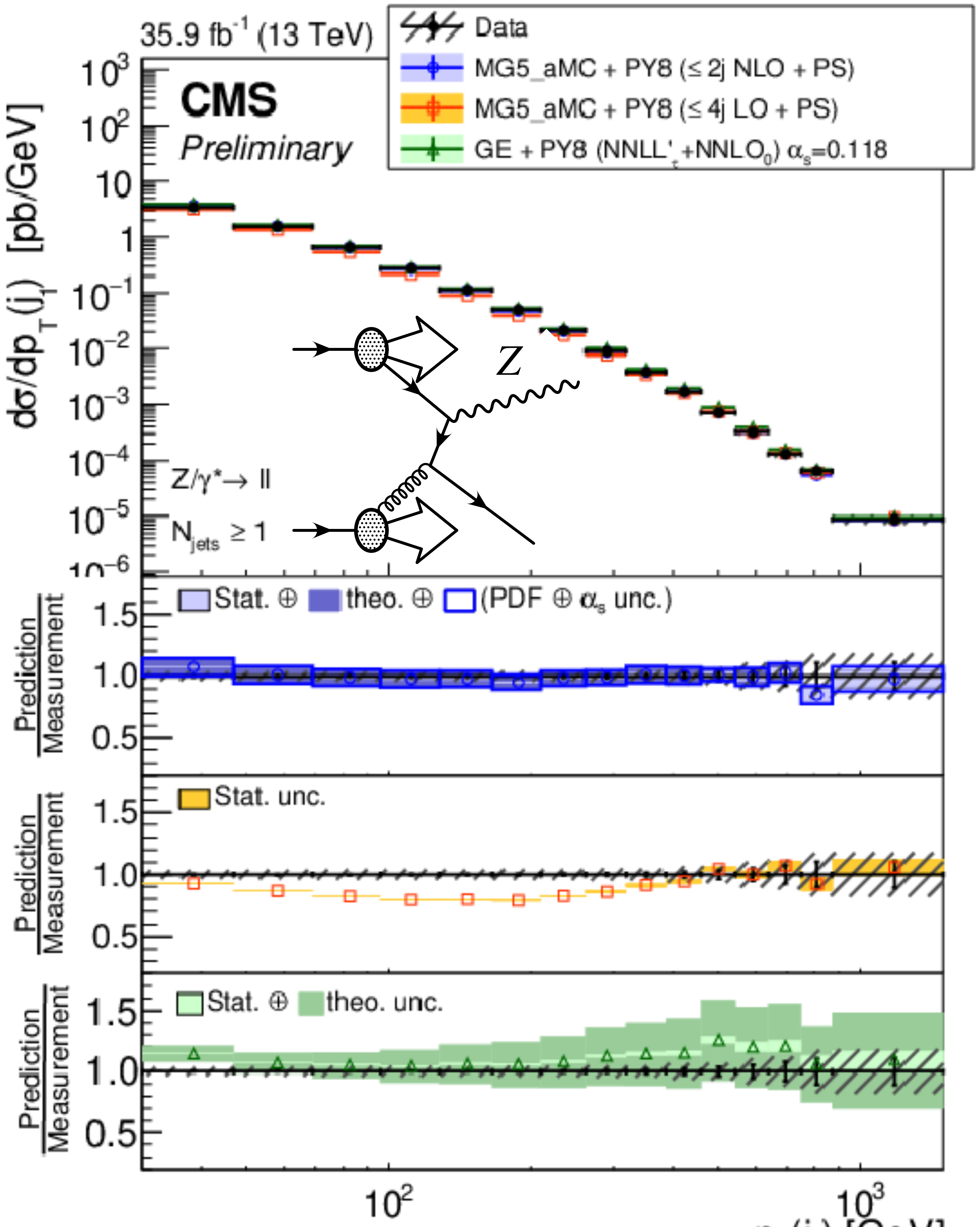

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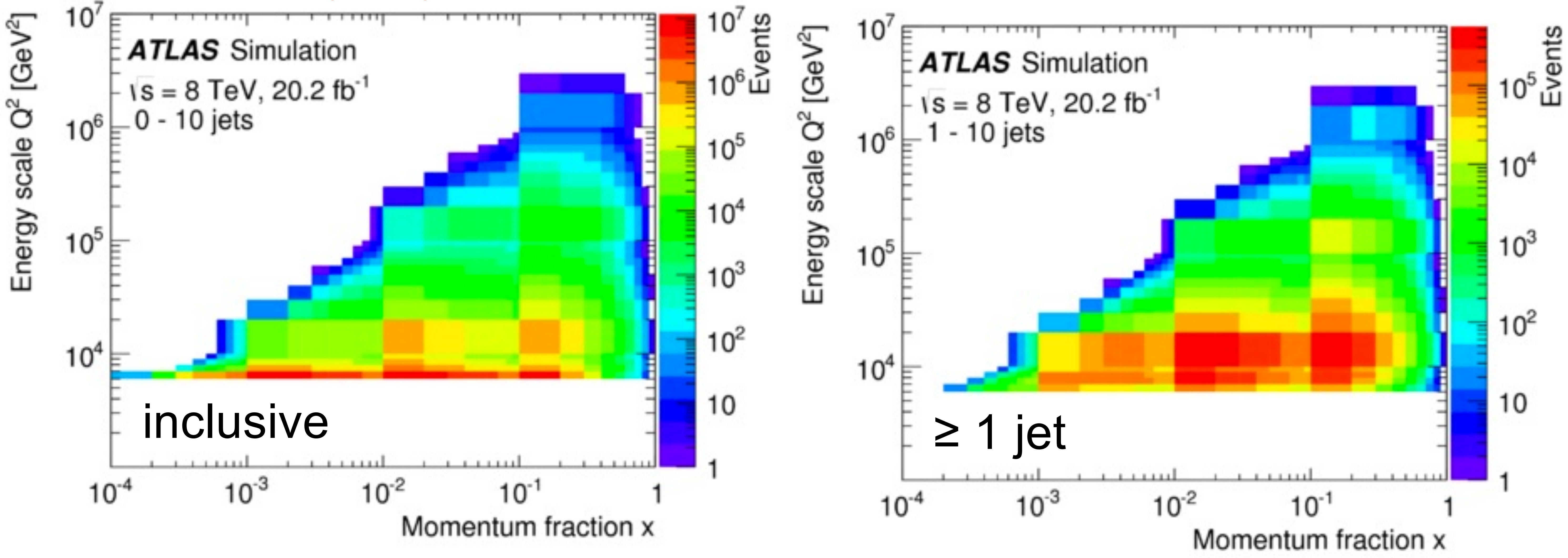
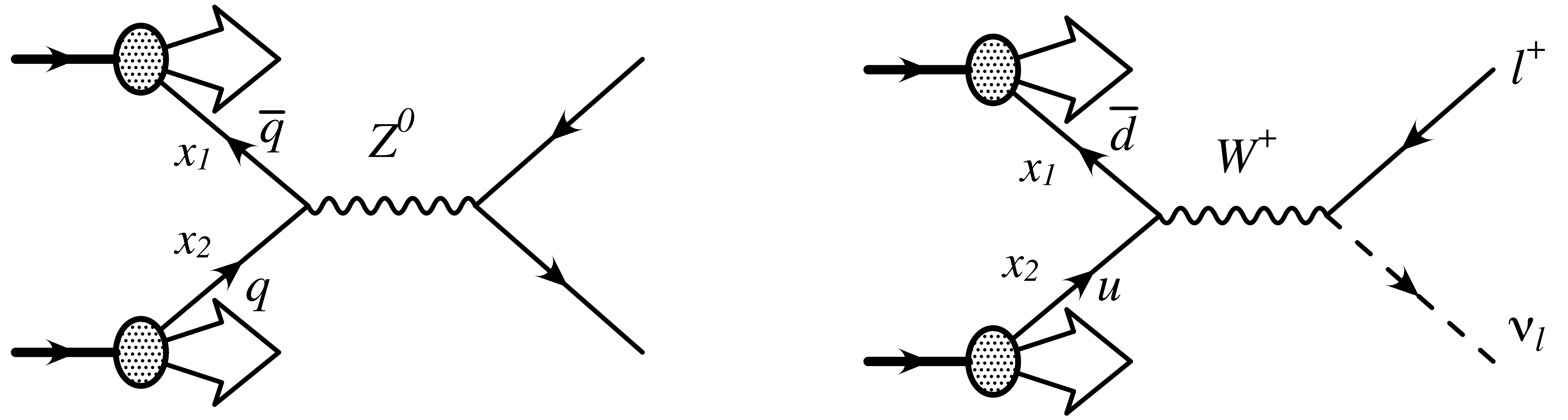
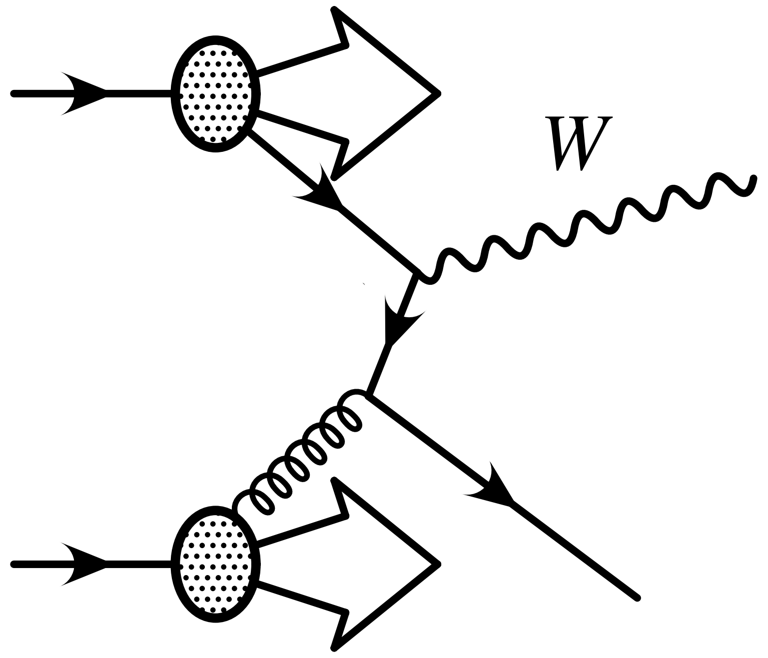
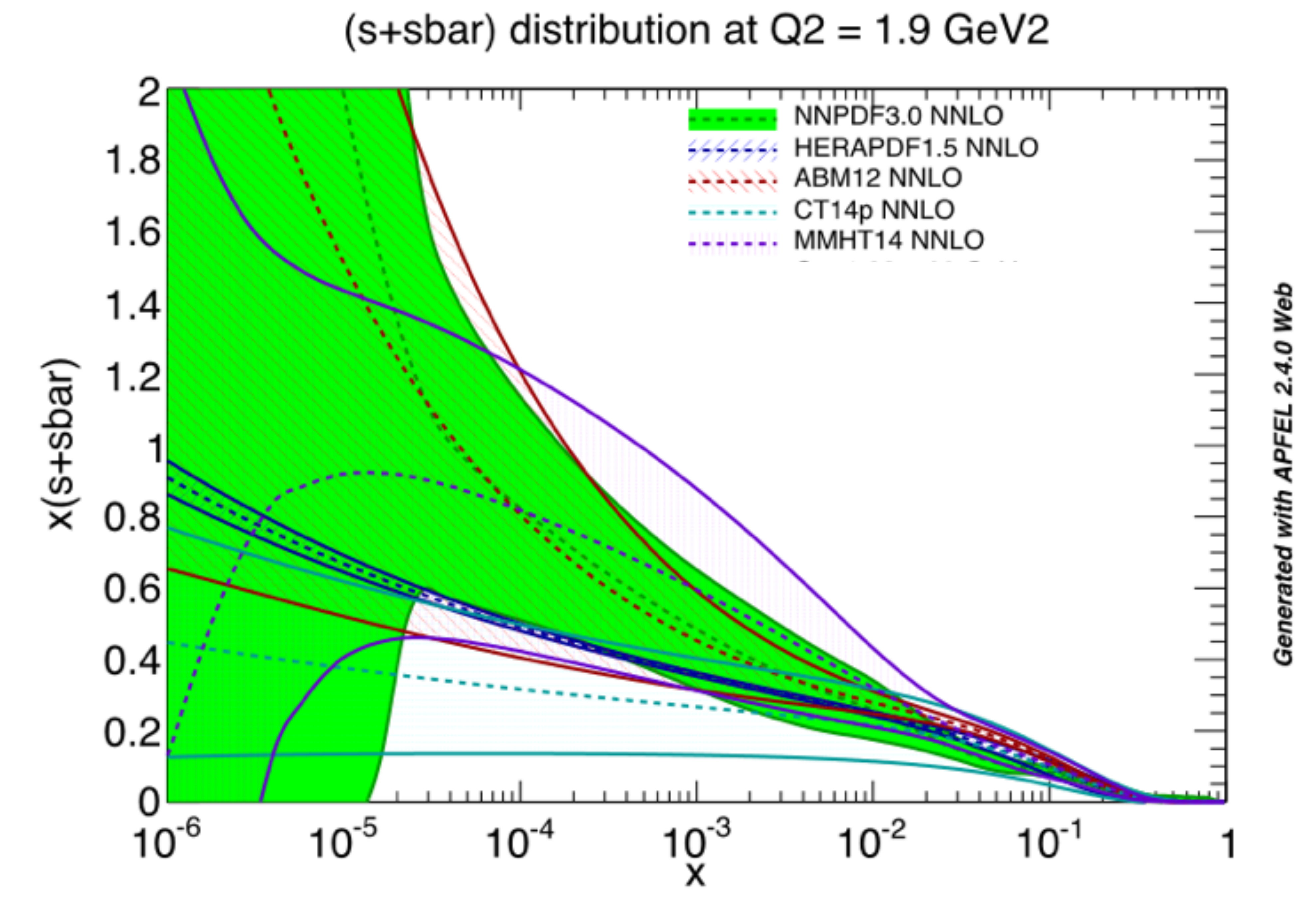


Electroweak boson data



- Sensitive to the flavour separation
  - Inclusive data access the valance quarks
- W+charm: directly sensitivity to the s-quark
- W or Z + jets (V+jets) where the jet need not be unobserved, sensitive to both the quarks and gluon at lowest order
  - Increased centre of mass energy from the balancing jet samples the PDF at larger x





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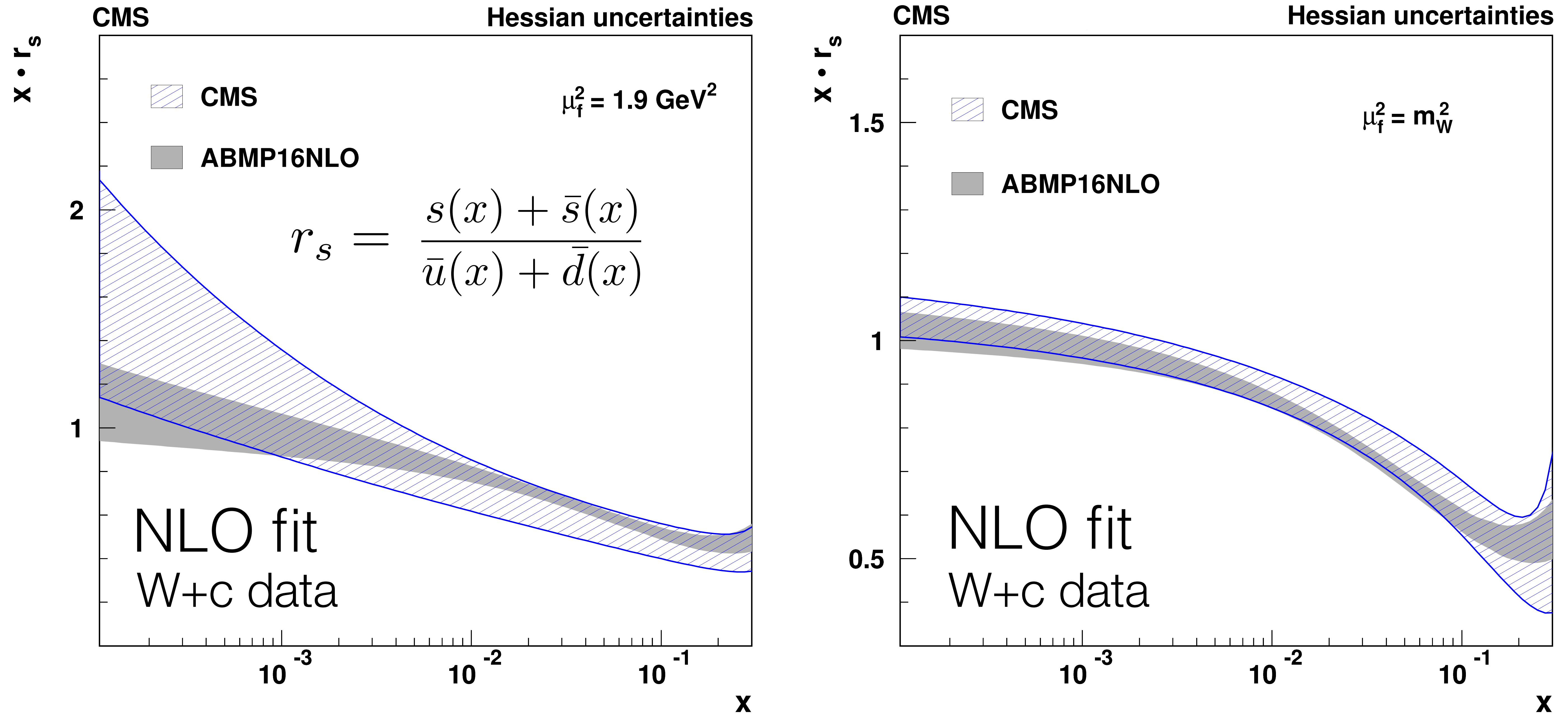


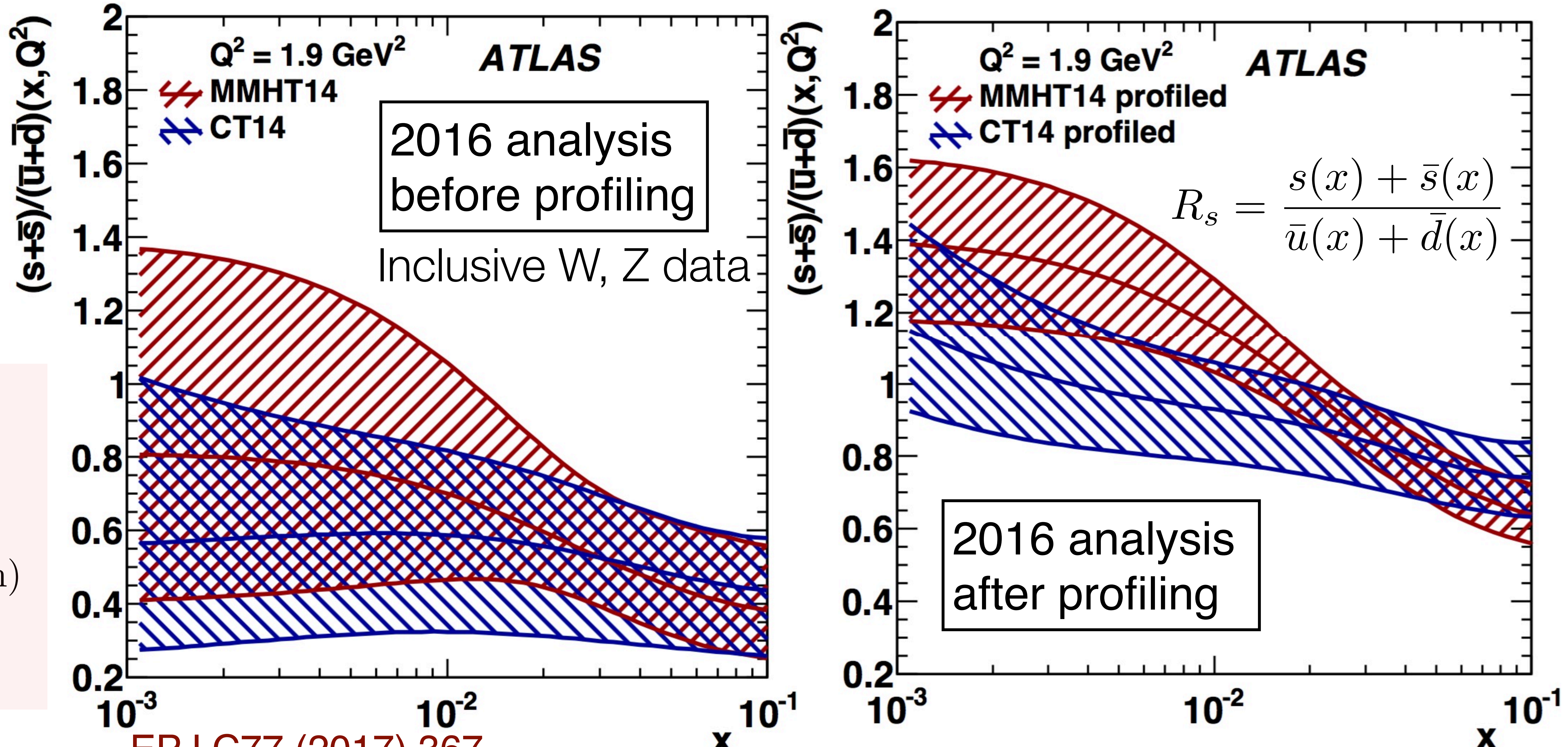
The proton is more strange than we imagined …

- Strange quark density poorly known
  - Often assumed sbar ~ 0.5 dbar from s⟶Wc in NuTeV, CCFR data
  - Large c fragmentation and nuclear corrections uncertainties
- Early ATLAS epWZ12 fit to 2010 inclusive Z and W± data found an unsuppressed strangeness contribution

$$r_s = \frac{1}{2}(s+\bar{s})/\bar{d}$$

$$= 1.00 \pm 0.07(\mathrm{exp}) \pm 0.03(\mathrm{mod})^{+0.04}_{-0.06}(\mathrm{par}) \pm 0.03(\mathrm{th})$$

- Subsequent data and fits to ATLAS and CMS data still suggest unsuppressed strange at low-x



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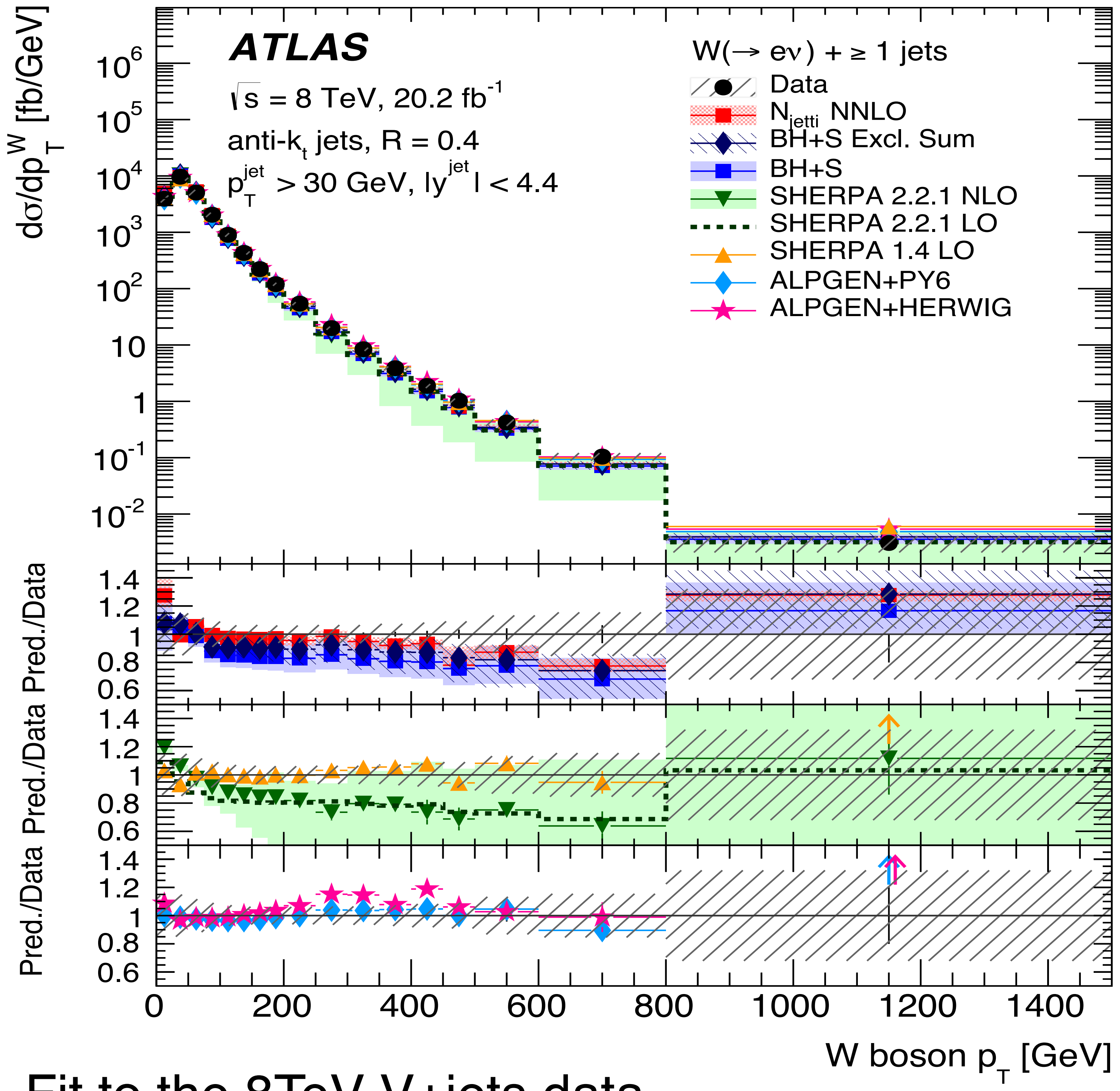
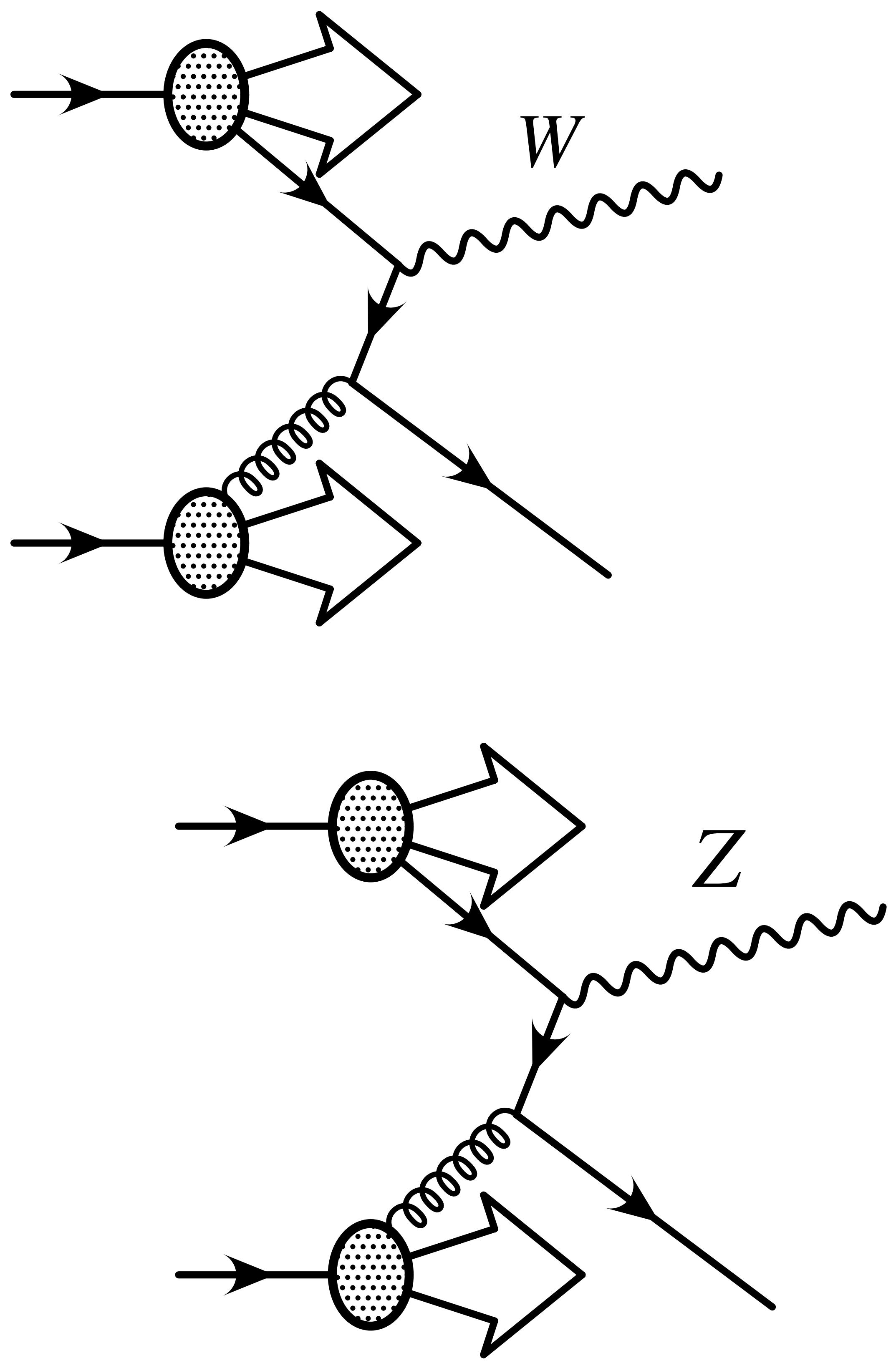
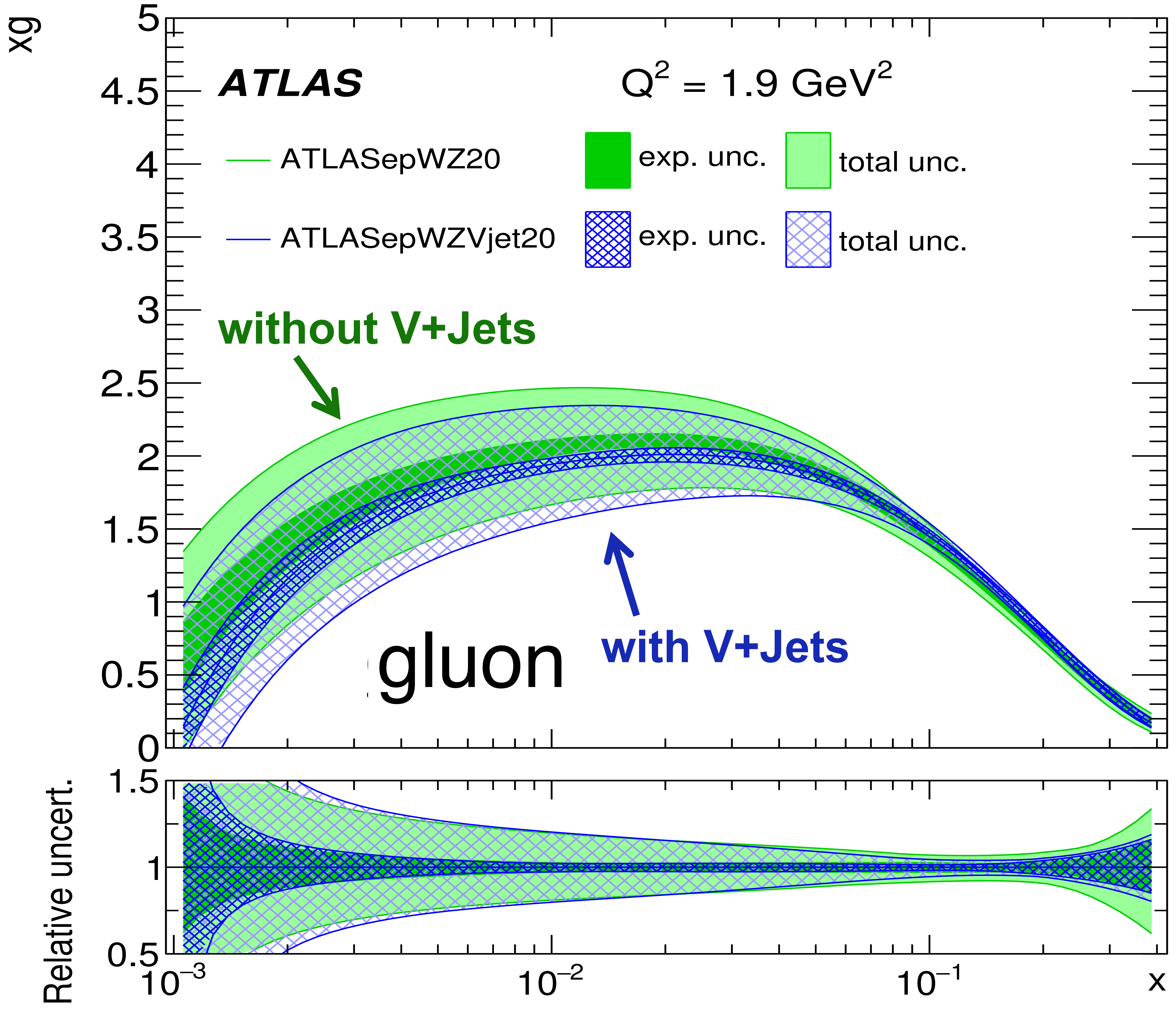
ATLAS fit to the W+jet and Z+jet data at NNLO JHEP 2107 (2021) 223

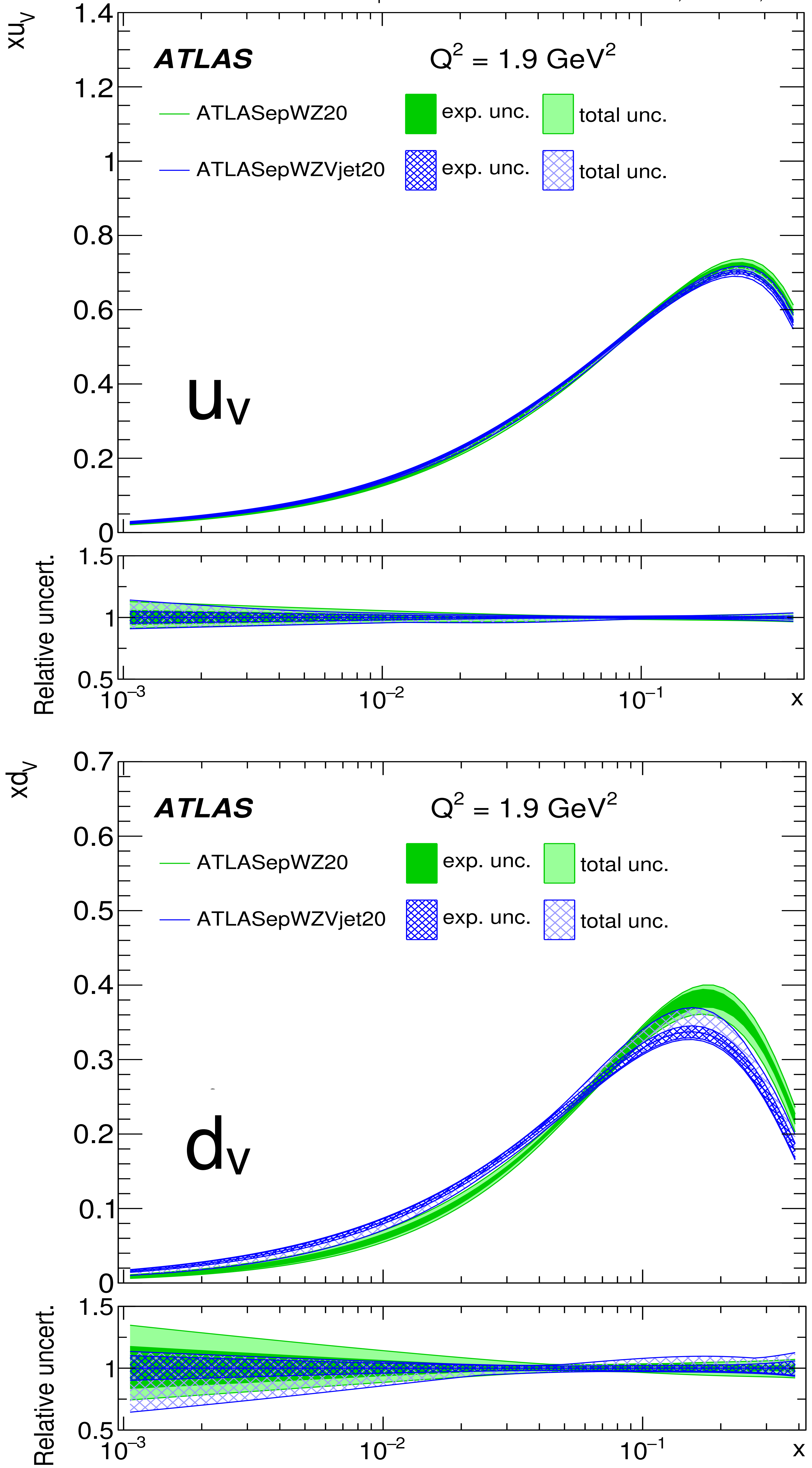


- Fit to the 8TeV V+jets data
- Detailed study of the correlated uncertainties between the jet and lepton reconstruction in each analysis
- Fit performed with NLO grids + NNLO k-factors
  - Grids available from ploughshare.web.cern.ch
- Refit inclusive boson data from 2016, with consistent methodology for comparison with new fit including inclusive boson and V+jets data

Systematic Uncertainty	7 TeV inclusive W, Z	8 TeV W + jets	8 TeV Z + jets
Jet energy scale [54]	*	JetScaleEff1	ATL_JESP1
		JetScaleEff2	ATL_JESP2
		JetScaleEff3	ATL_JESP3
		JetScaleEff4	ATL_JESP4
		JetScaleEff5	ATL_JESP5
		JetScaleEff6	ATL_JESP6
		JetScaleEta1	ATL_JESP7
		JetScaleEta2	ATL_JESP8
		JetScaleHighPt	ATL_JESP9
		JetScaleMC	ATL_JESP10
	JetScaleNPV	JetScalePileup1	ATL_PU_OffsetNPV
	JetScaleMu	JetScalePileup2	ATL_PU_OffsetMu
Jet punchthrough [54]	-	JetScalepunchT	ATL_PunchThrough
Jet resolution [54]	JetRes	JetResolution10	ATL_JER
Jet flavour composition [54]	-	JetScaleFlav1Known	ATL_Flavor_Comp
Jet flavour response [54]	-	JetScaleFlav2	ATL_Flavor_Response
Pile-up jet rejection (JVF) [55]	-	JetJVFcut	ATL_JVF
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale [56]	MetScaleWen	METScale	-
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution [56]	MetRes	METResLong	-
		METResTrans	-
Electron energy scale [57]	*	ElScaleZee	ATL_ElecEnZee
Electron trigger efficiency [58]	*	ElSFTrigger	ATL_Trig
Electron reconstruction efficiency [59, 60]	*	ElSFReco	ATL_RecEff
Electron identification efficiency [59, 60]	*	ElSFId	ATL_IDEff
Luminosity [61, 62]	*	LumiUncert	ATL_lumi_2012_8TeV
WW background cross section [63]	*	XsecDibos	ATL_WW_xs
Top background cross section [64]	*	XsecTop	ATL_ttbar_xs







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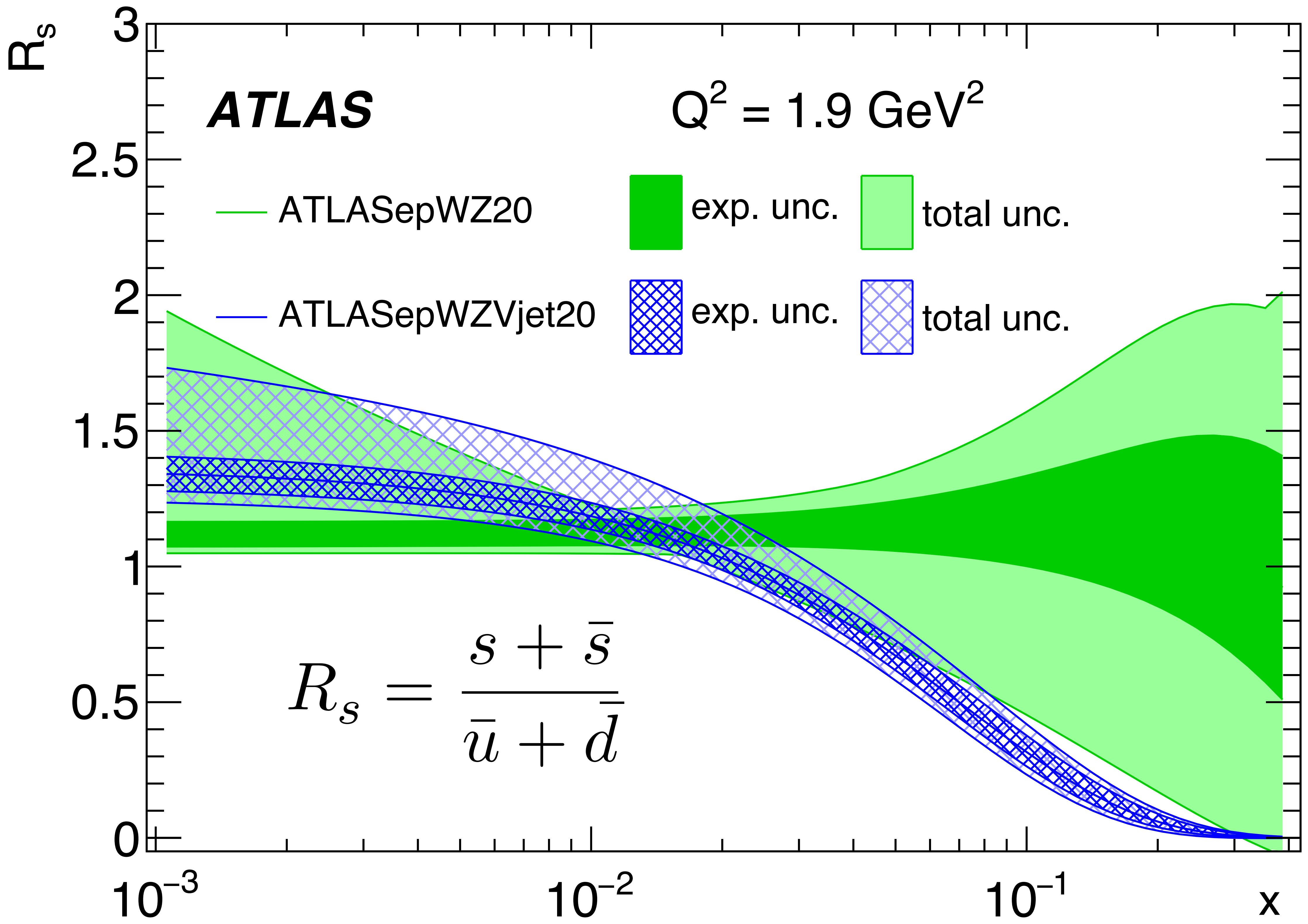
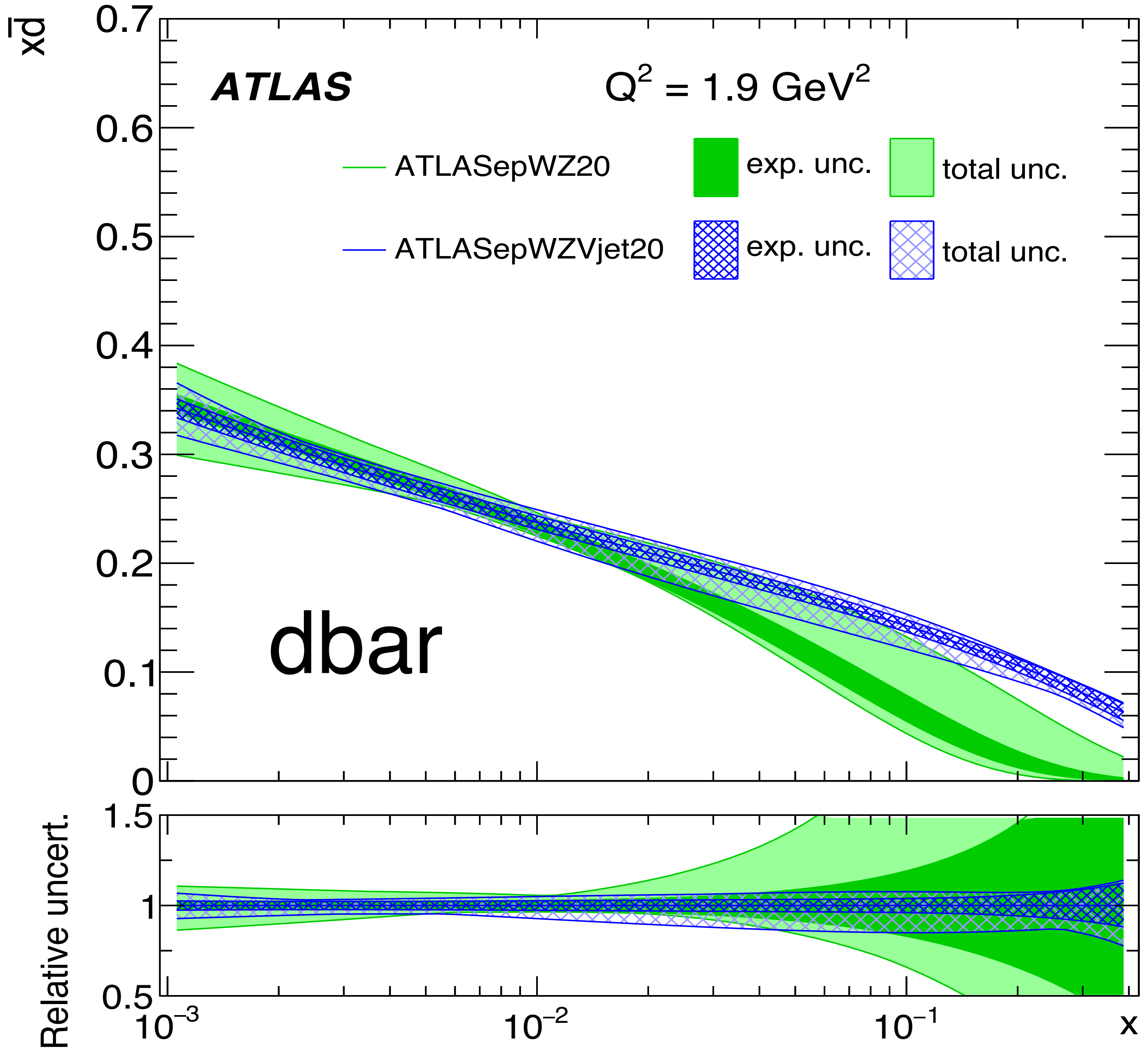
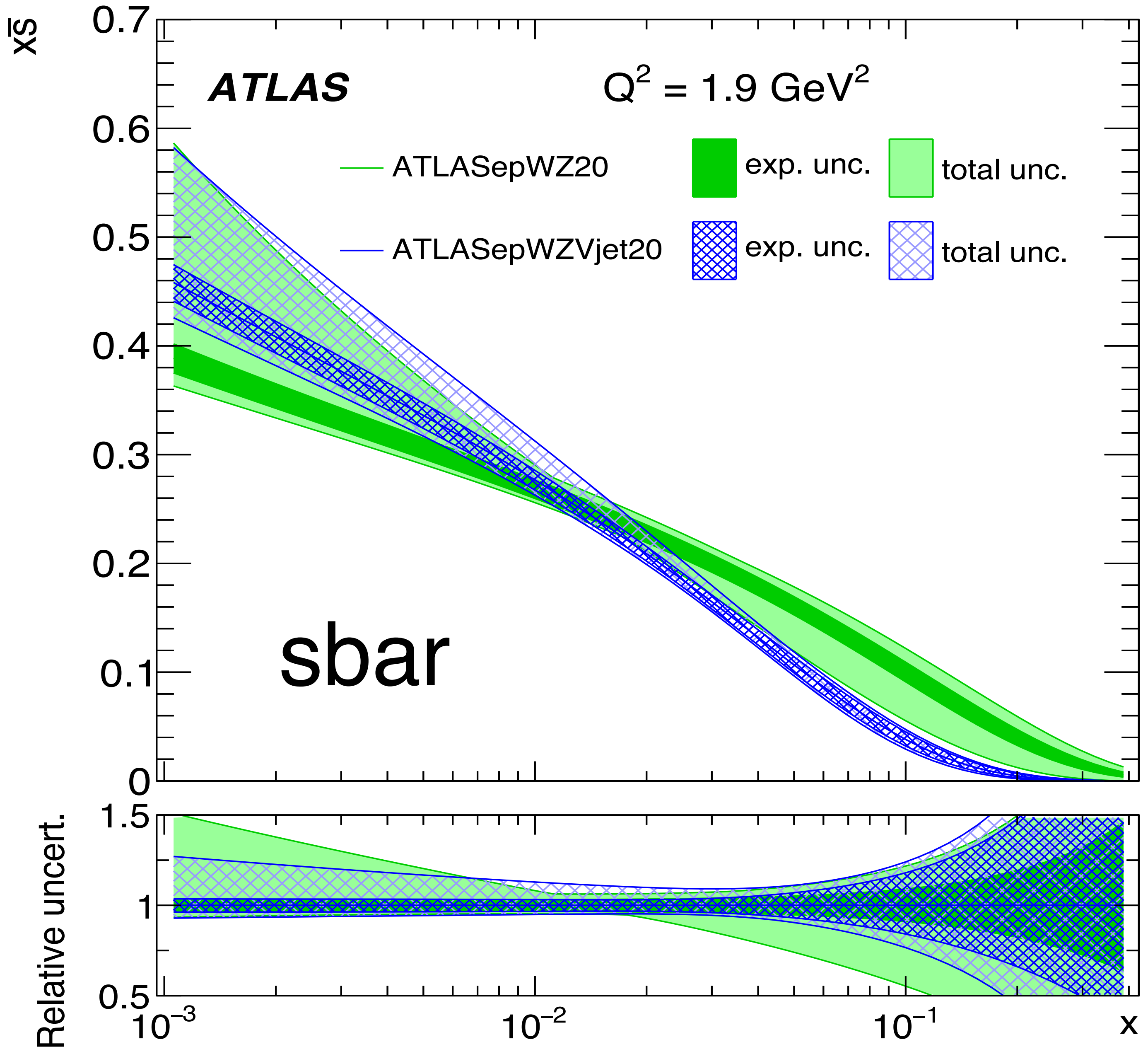
Including the Z+jets and W+jets data

- Sensitivity to the gluon at lowest order - slightly reduced gluon uncertainty at higher x
- V+jets impact on d valence
  - Moves result closer to that from the global PDFs







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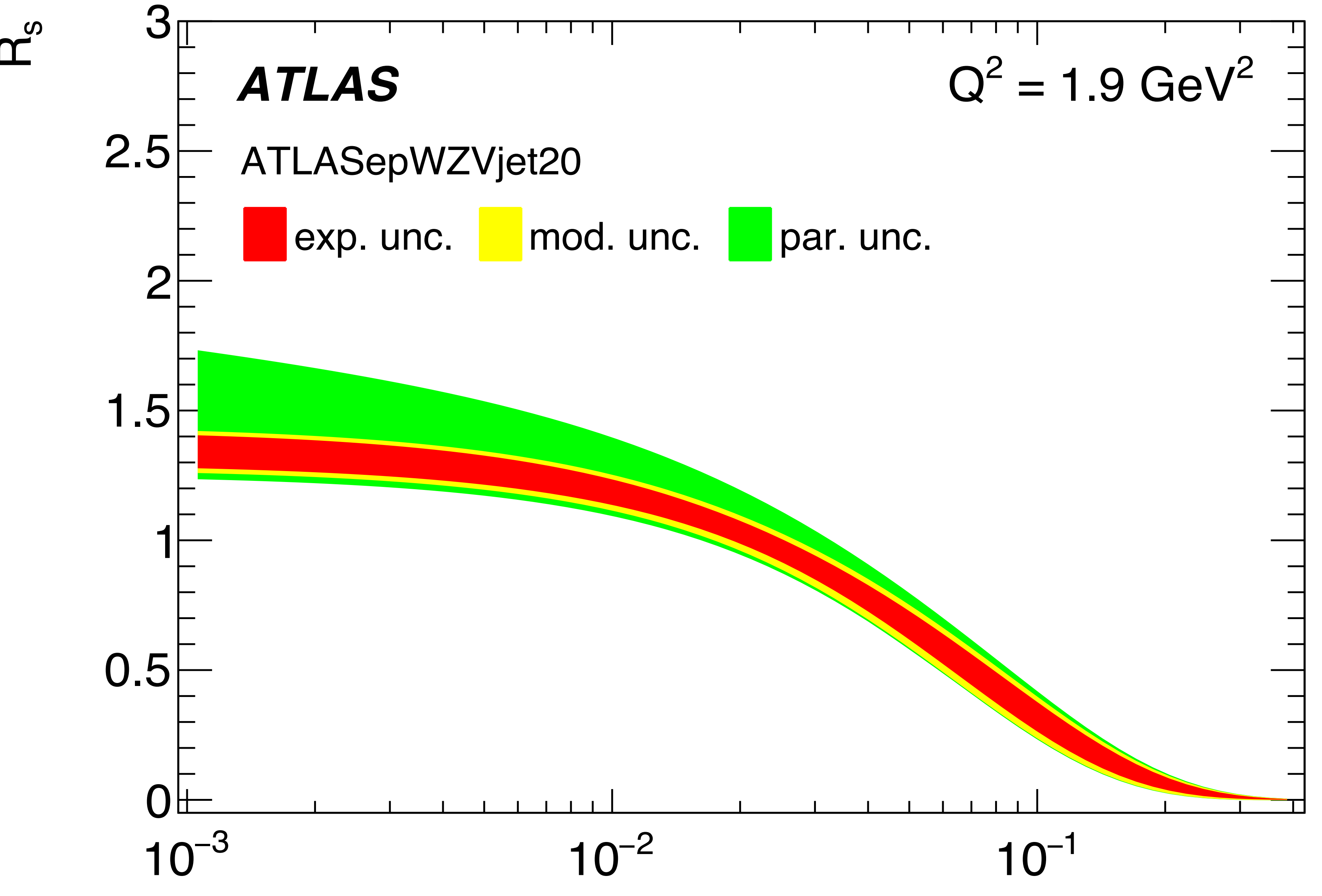
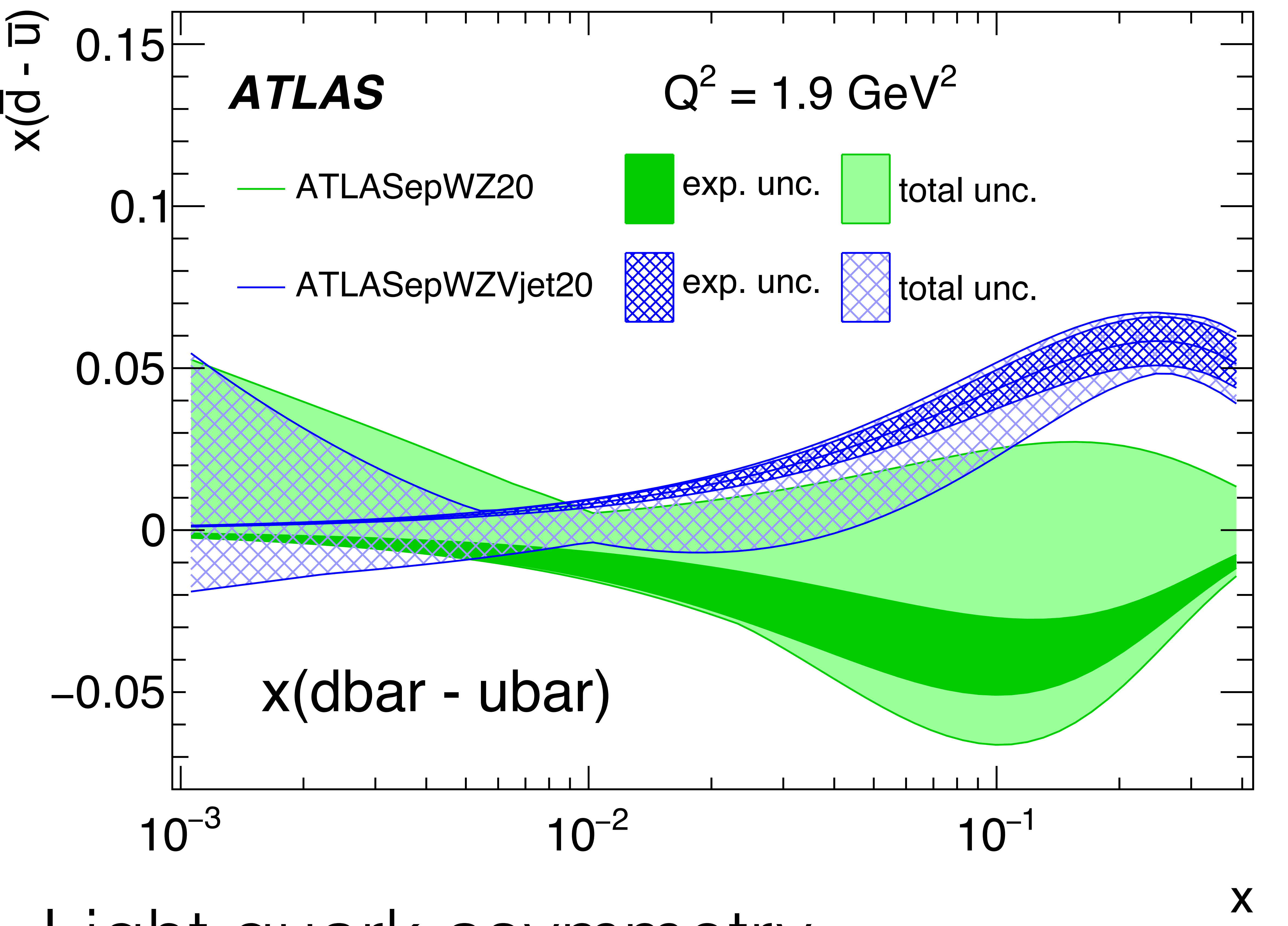
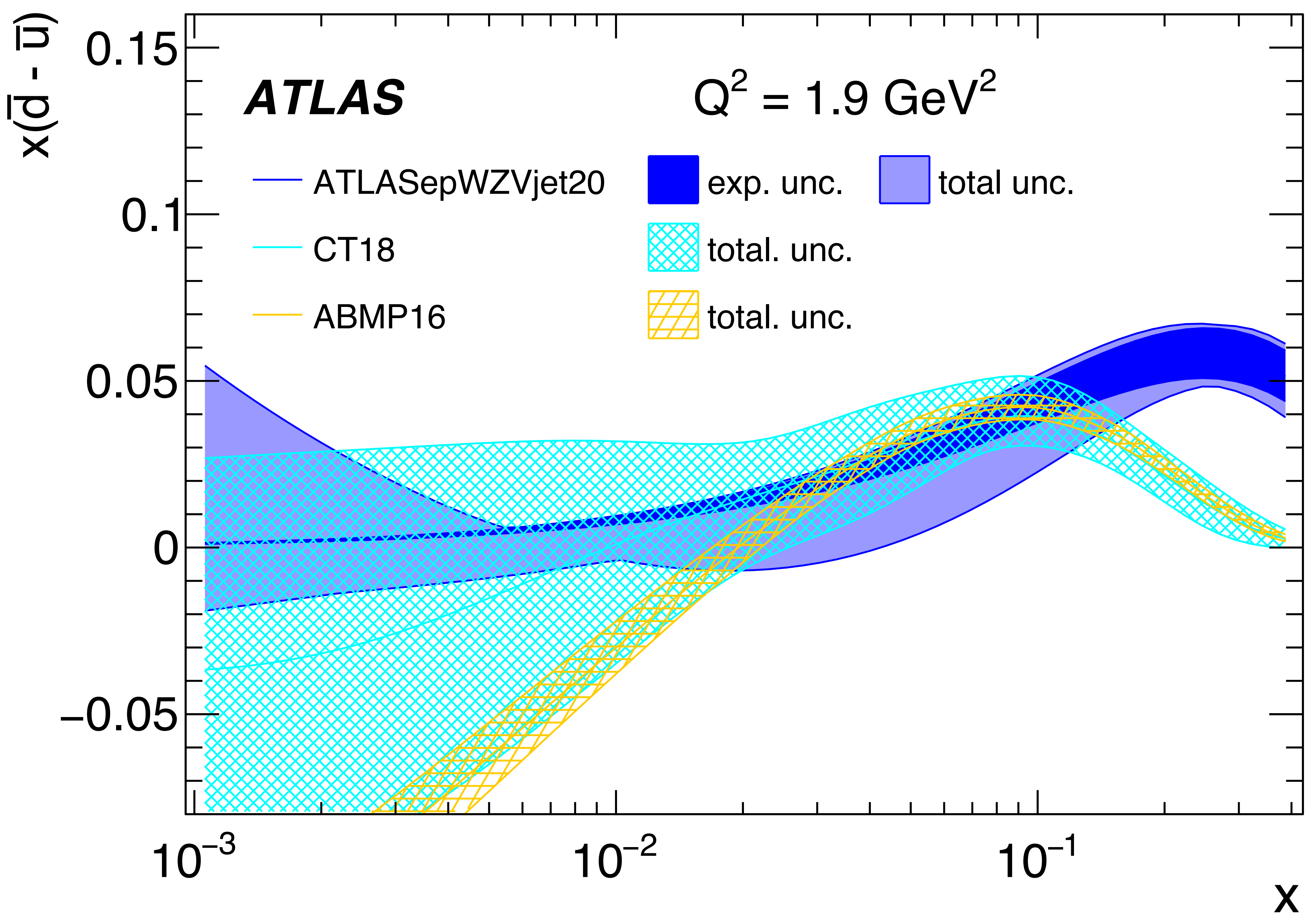
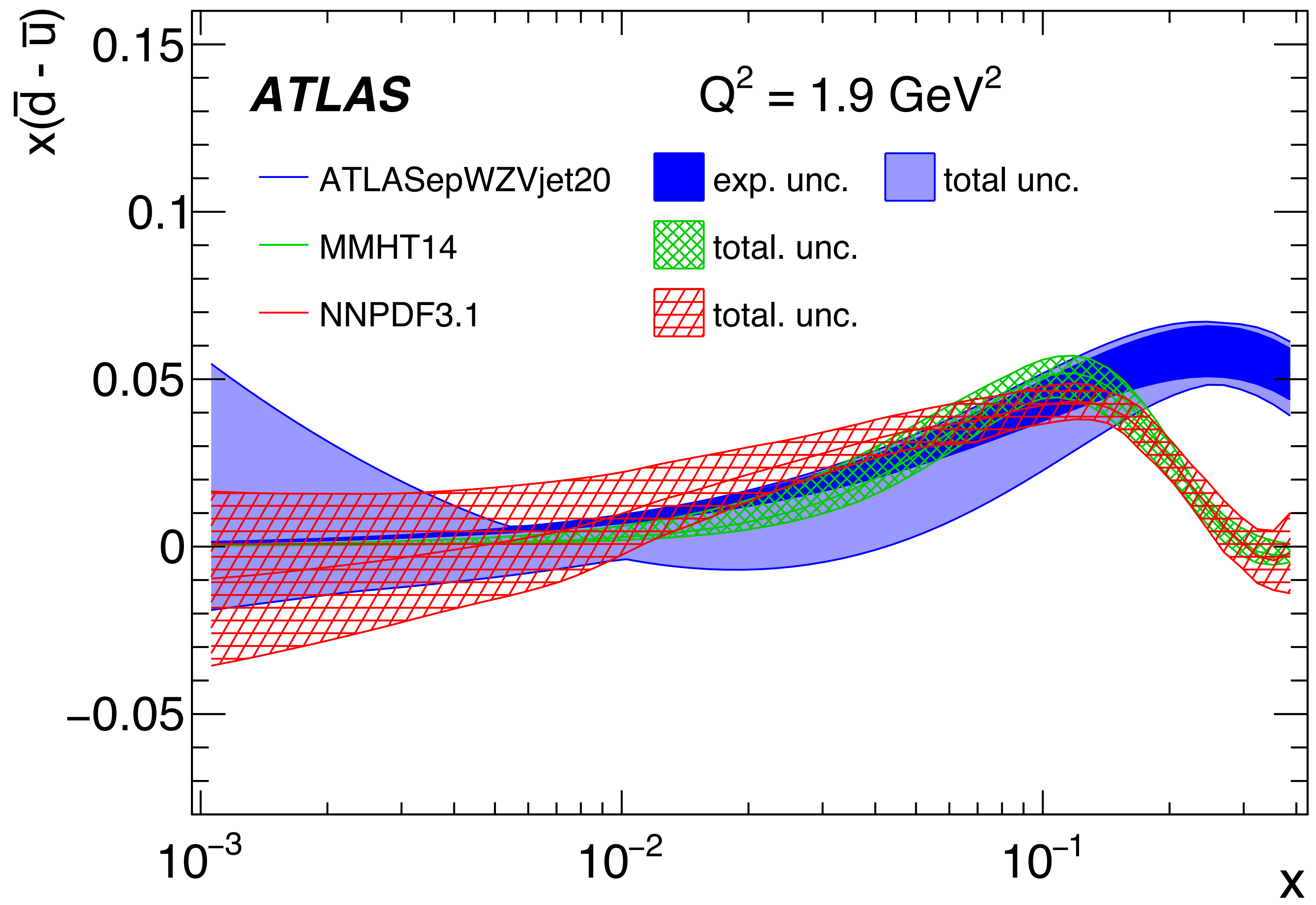


Including the Z+jets and W+jets data

- With the new fit, confirms the unsuppressed strangeness ratio at low x
- Now, the sensitivity to higher x due to the increased centre of mass energy of the boson plus jet system tames the increase at large x
  - Follows from an increase in the dbar density and a reduction in the sbar density at large x







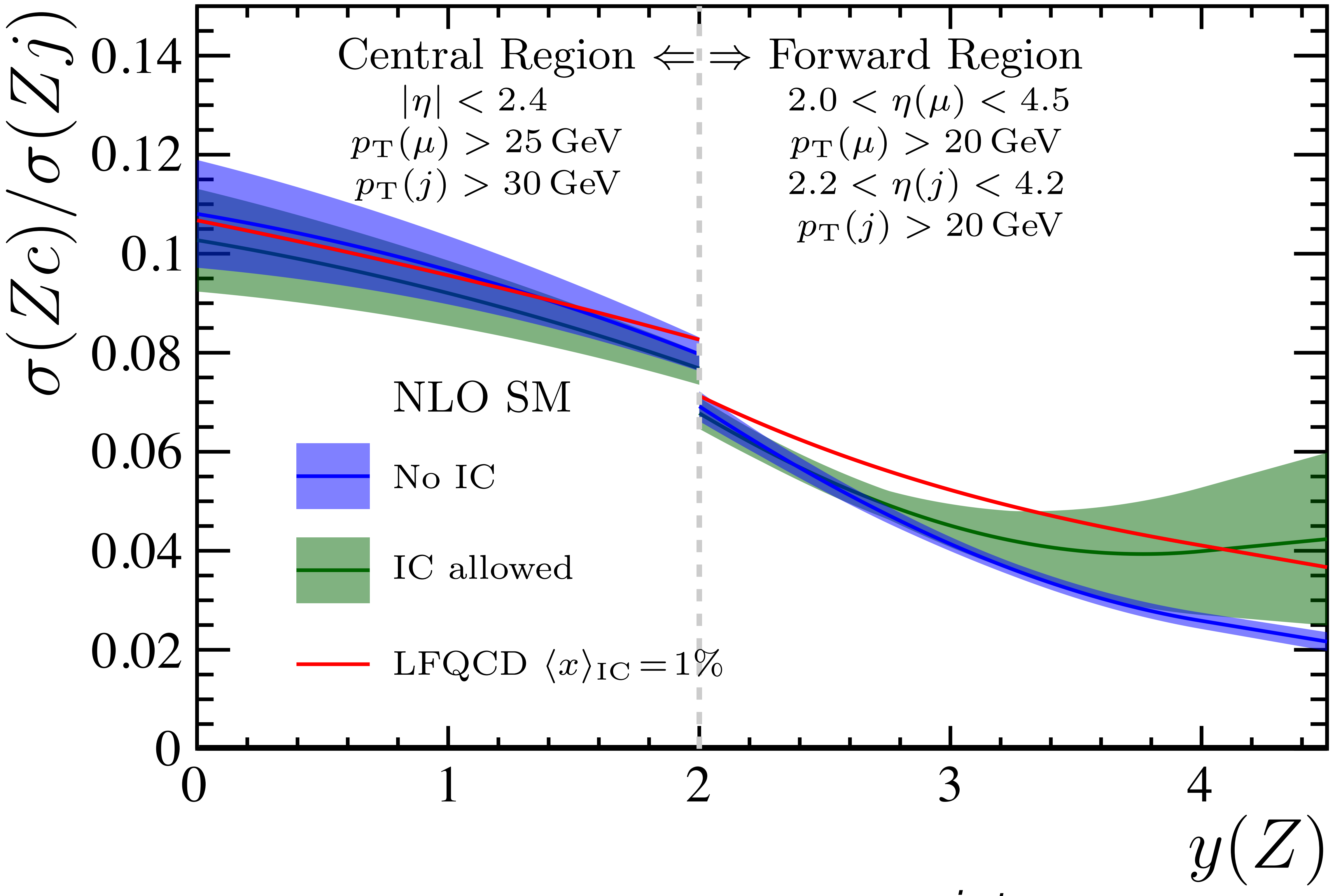
Light quark asymmetry JHEP 2107 (2021) 223

- The original ATLASepWZ16 fit has a negative dbar - ubar, with large uncertainties
- New fit with the V + jet data results has a positive (dbar - ubar) distribution
  - More consistent with the fits from the global fitters, up to 0.1, but differs for x > 0.1 where the fit has increased sensitivity to the V+jets data
  - Global fits include E866 data which seems in tension wit the new Seaquest / E906 data Nature 590 (2021) 561

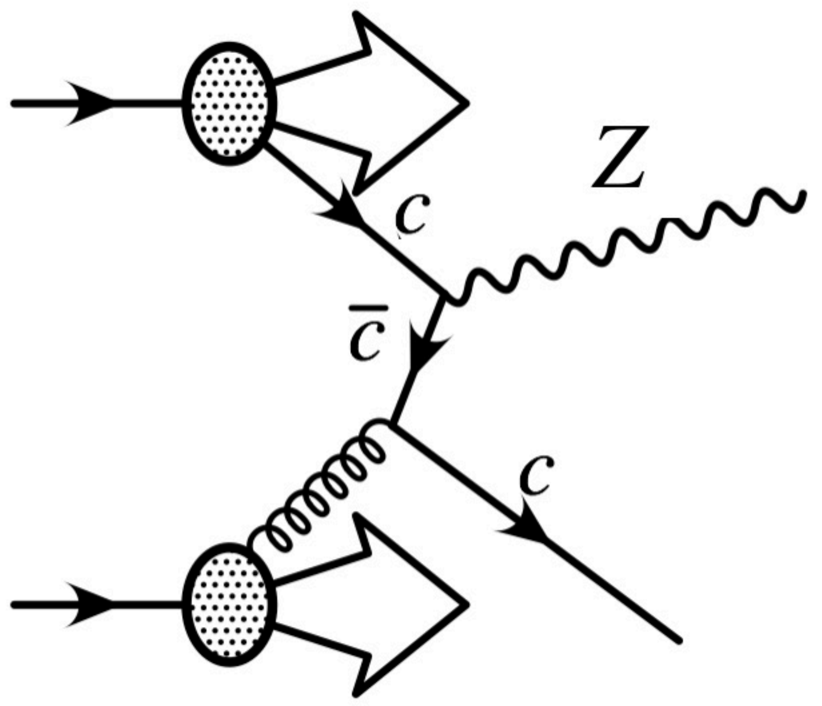
Forward Z+charm from LHCb arxiv:2109.08084

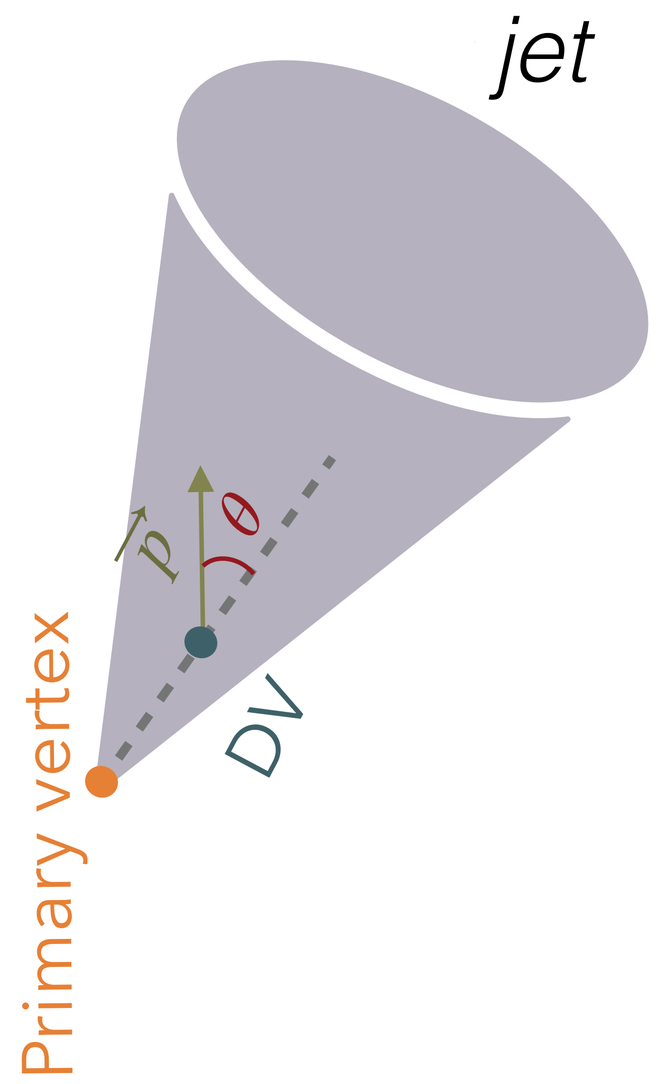
- Proton charm content:
  - Extrinsic charm, from perturbative gluon radiation (g → ccbar).
- Intrinsic charm (IC), valence-like c-content, proton:
  - |uudcc⟩.
  - Predicted by Light Front QCD (LFQCD).
- Previous measurements hampered by nuclear effects
- Intrinsic charm only excluded for contributions above ~ 1%
- Full Run 2 pp dataset
- Z→ μμ events + one jet with $p_T > 20$ GeV
- Charm jets identified using a displaced vertex tagger

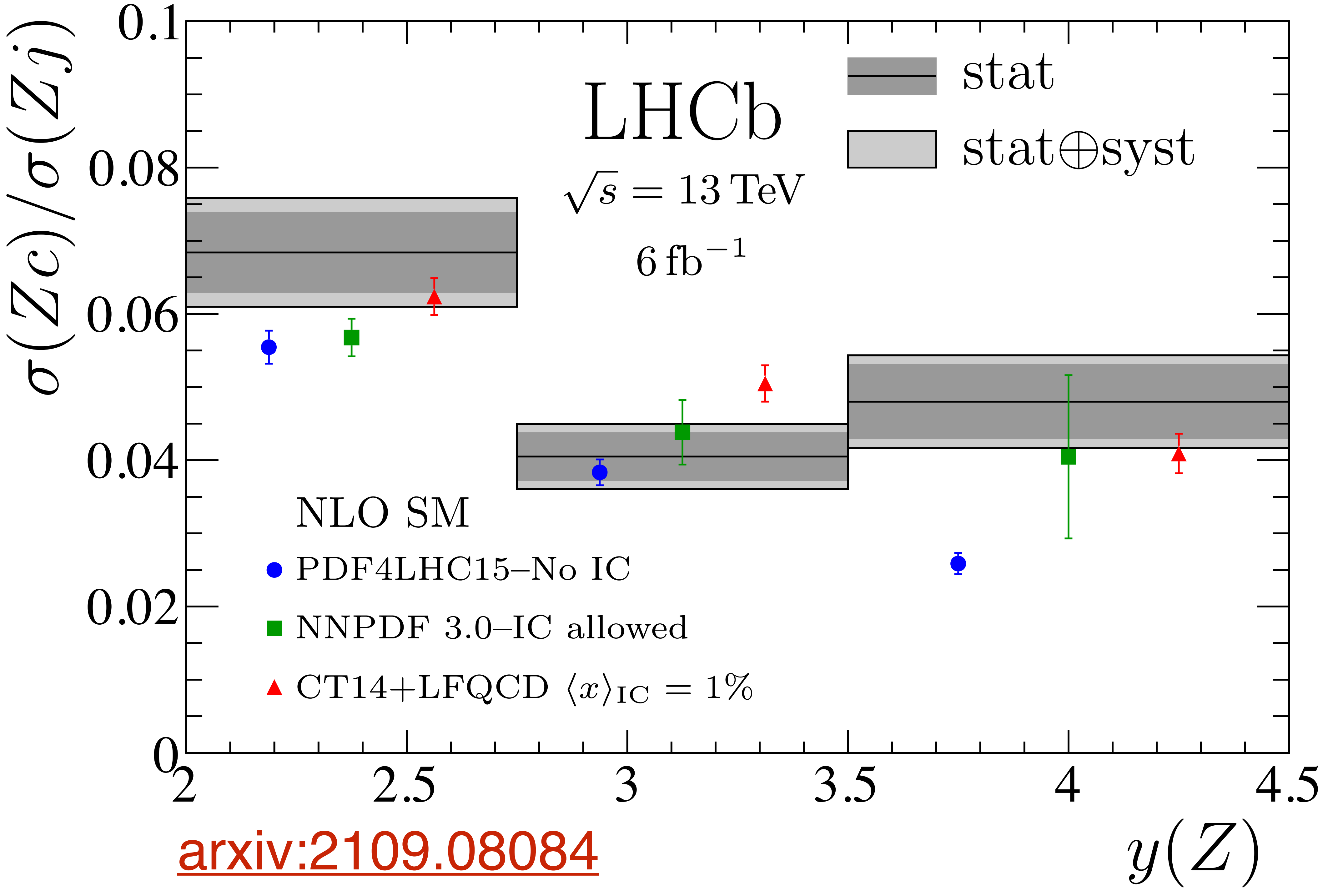
$$\mathcal{R}_j^c \equiv \sigma(Zc)/\sigma(Zj)$$



- Investigate possibility of Intrinsic Charm in the proton
  - Intrinsic charm suggests increased charm production in the very forward region
  - Very forward region not accessible at either ATLAS or CMS
  - Ideally suited for the LHCb forward detector configuration



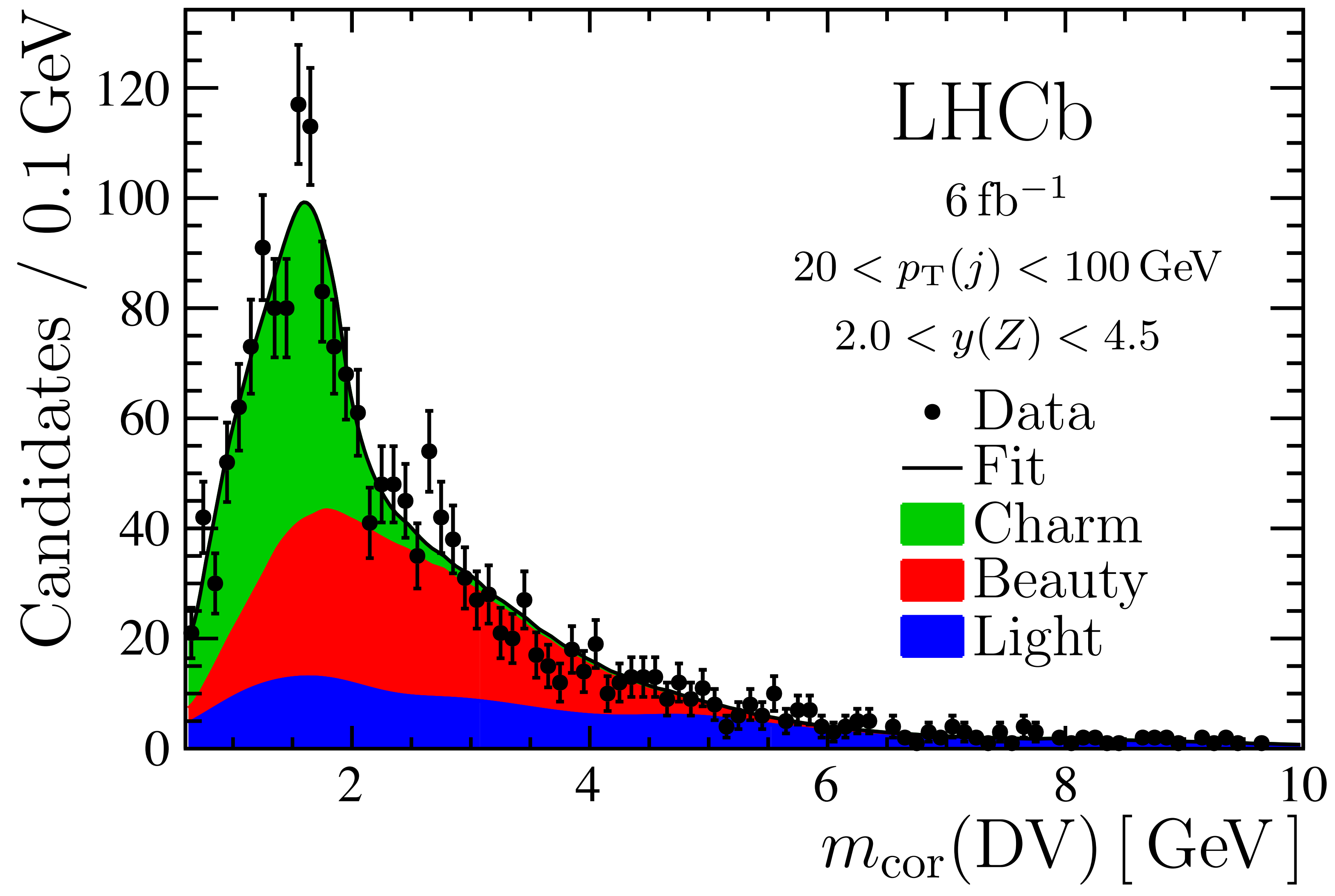




arxiv:2109.08084

$y(Z)$	$\mathcal{R}_j^c$ (%)
2.00–2.75	$6.84 \pm 0.54 \pm 0.51$
2.75–3.50	$4.05 \pm 0.32 \pm 0.31$
3.50–4.50	$4.80 \pm 0.50 \pm 0.39$
2.00–4.50	$4.98 \pm 0.25 \pm 0.35$

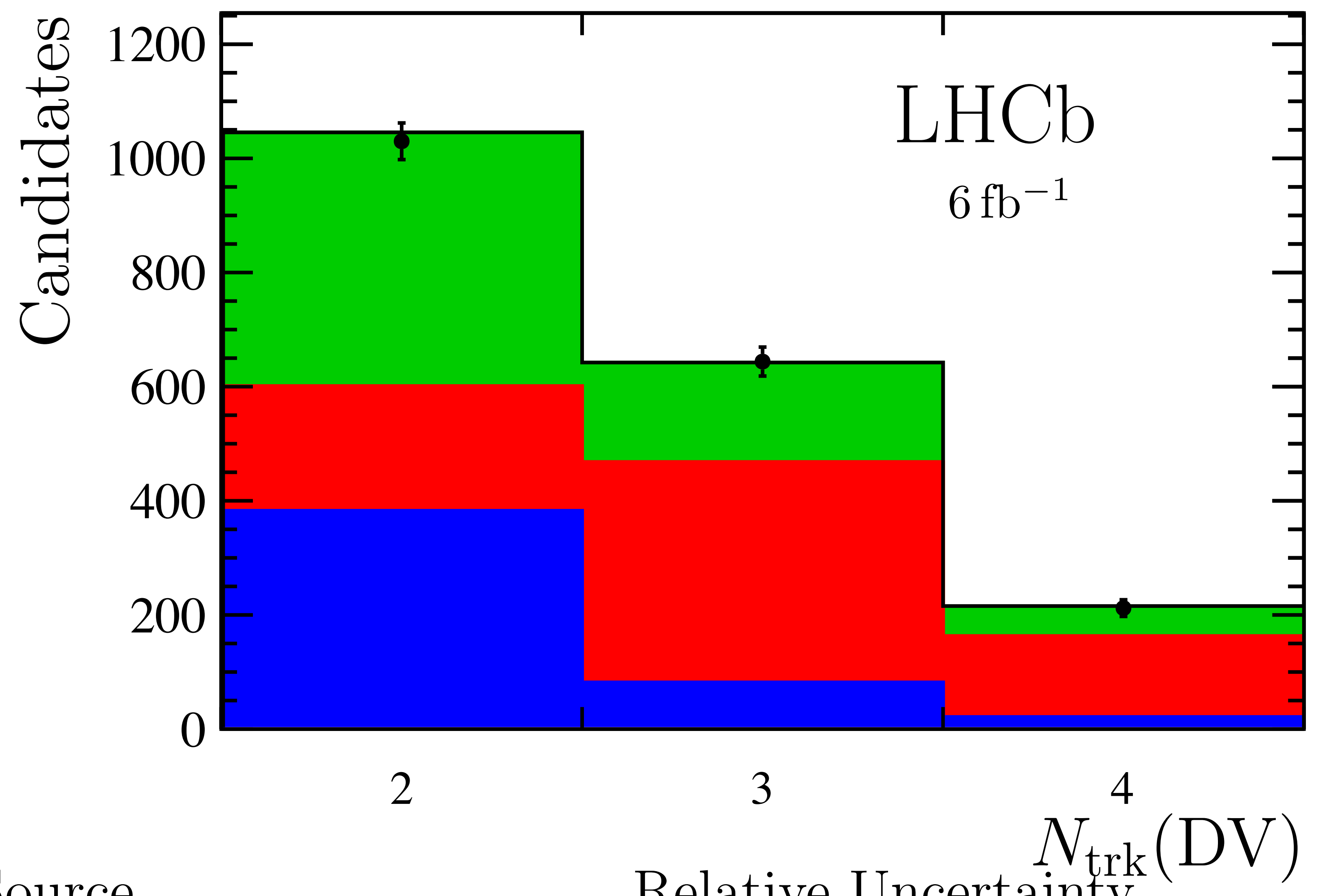
$$\mathcal{R}_j^c \equiv \sigma(Zc)/\sigma(Zj)$$



Forward Z+charm from LHCb

Table 1: Definition of the fiducial region.

Z bosons	$p_T(\mu) > 20$ GeV, $2.0 < \eta(\mu) < 4.5$, $60 < m(\mu^+\mu^-) < 120$ GeV
Jets	$20 < p_T(j) < 100$ GeV, $2.2 < \eta(j) < 4.2$
Charm jets	$p_T(c$ hadron$) > 5$ GeV, $\Delta R(j, c$ hadron$) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$



- With the NLO analysis, suggestion of consistency with NO intrinsic charm at less forward rapidities …
- But greater than 3σ excess observed over non-intrinsic charm contribution in the most forward rapidity bin, consistent with Intrinsic charm
- Interesting to see the effect of these data with the global fits

Source	Relative Uncertainty
c tagging	6–7%
DV-fit templates	3–4%
Jet reconstruction	1%
Jet p_T scale & resolution	1%
Total	8%

Looking forward …

- An increasingly large portfolio of **precise data** from the LHC experiments is available
- This precision challenges the uncertainty of the theoretical predictions, themselves now becoming rather precise at NNLO and N3LO for inclusive W and Z production
- Progress in understanding the **correlated experimental uncertainties** is essential to exploit the **real potential** of the data
    - Many previous results, fits including - top etc
- Can learn a lot by looking back, and updating fits with the newer data, or additional data sets
    - Complementary data from the LHC experiments needs to be considered
- LHC Run 3 is almost upon us
    - We need to be ready to meet the challenge of the newer, higher precision data that will be coming over the next few years
- We should perhaps be thankful that we live in such interesting times