- Fitting PDFs with LHC data – opportunities, status, & outlook

Synergy workshop between ep/eA and pp/pA/AA physics experiments, CERN

Feb. 29th, 2024

Simone Amoroso (DESY)

Parton Distribution Functions

- Predictions at a hadron collider require knowledge of the PDFs

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s)$$

- Cross-sections calculated as convolution of short-distance cross-sections with Parton Distribution Functions (PDFs)

- A universal quantity, PDFs are inferred from a given set of measurements and can be used to predict any cross-section

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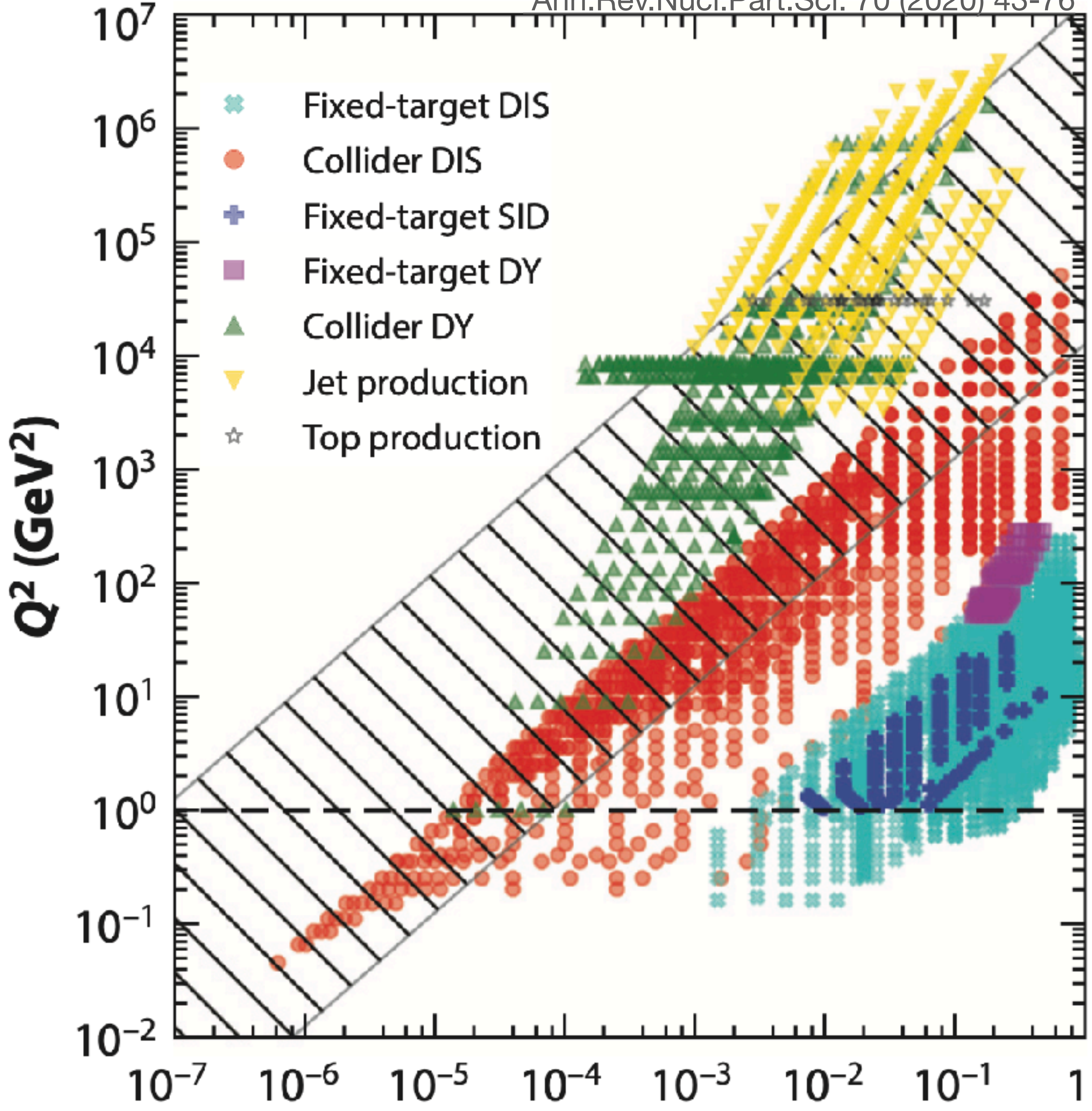
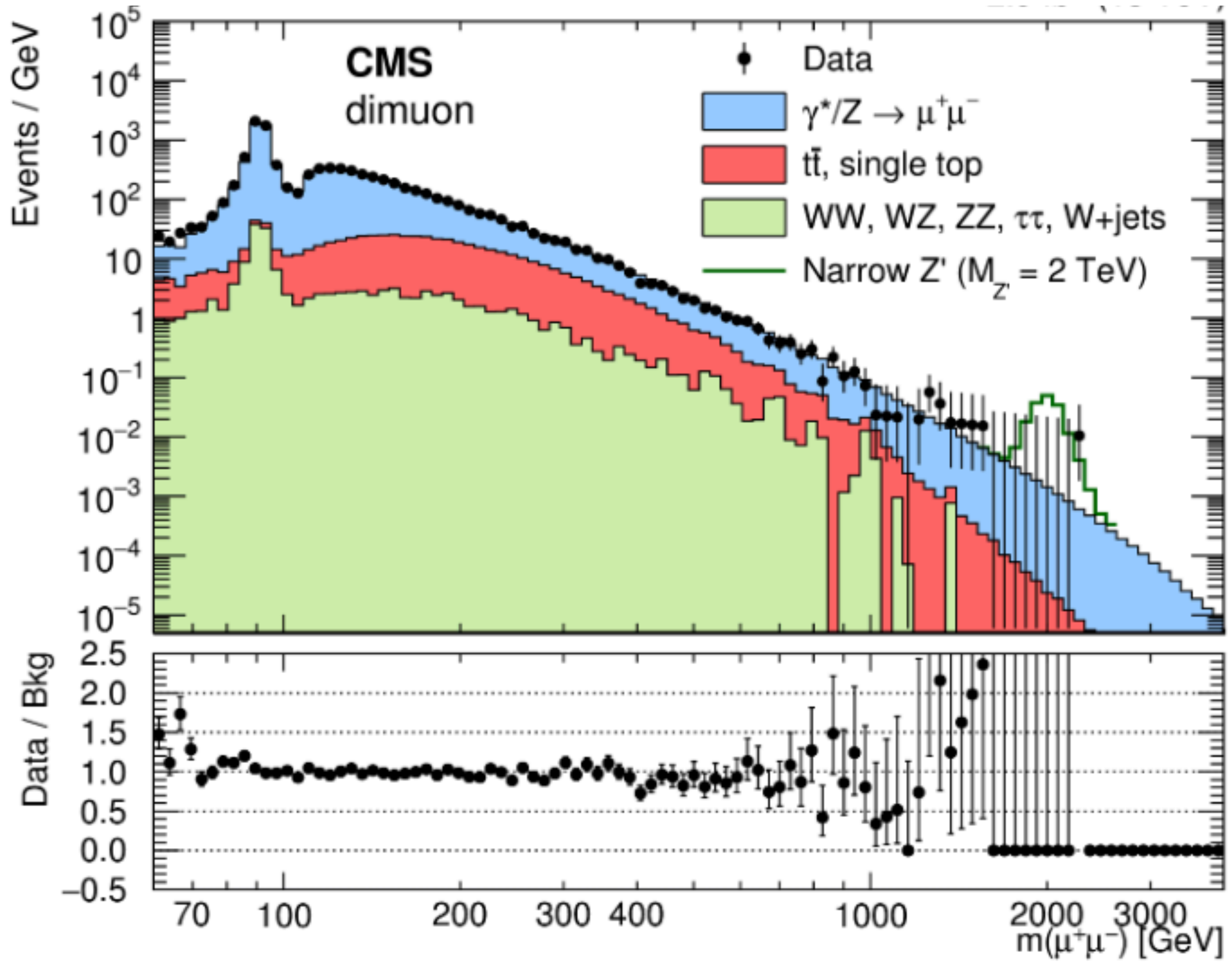


PDFs as a "necessary evil"

- Accurate knowledge of the PDFs crucial for direct searches for new physics and for indirect searches through precision measurements



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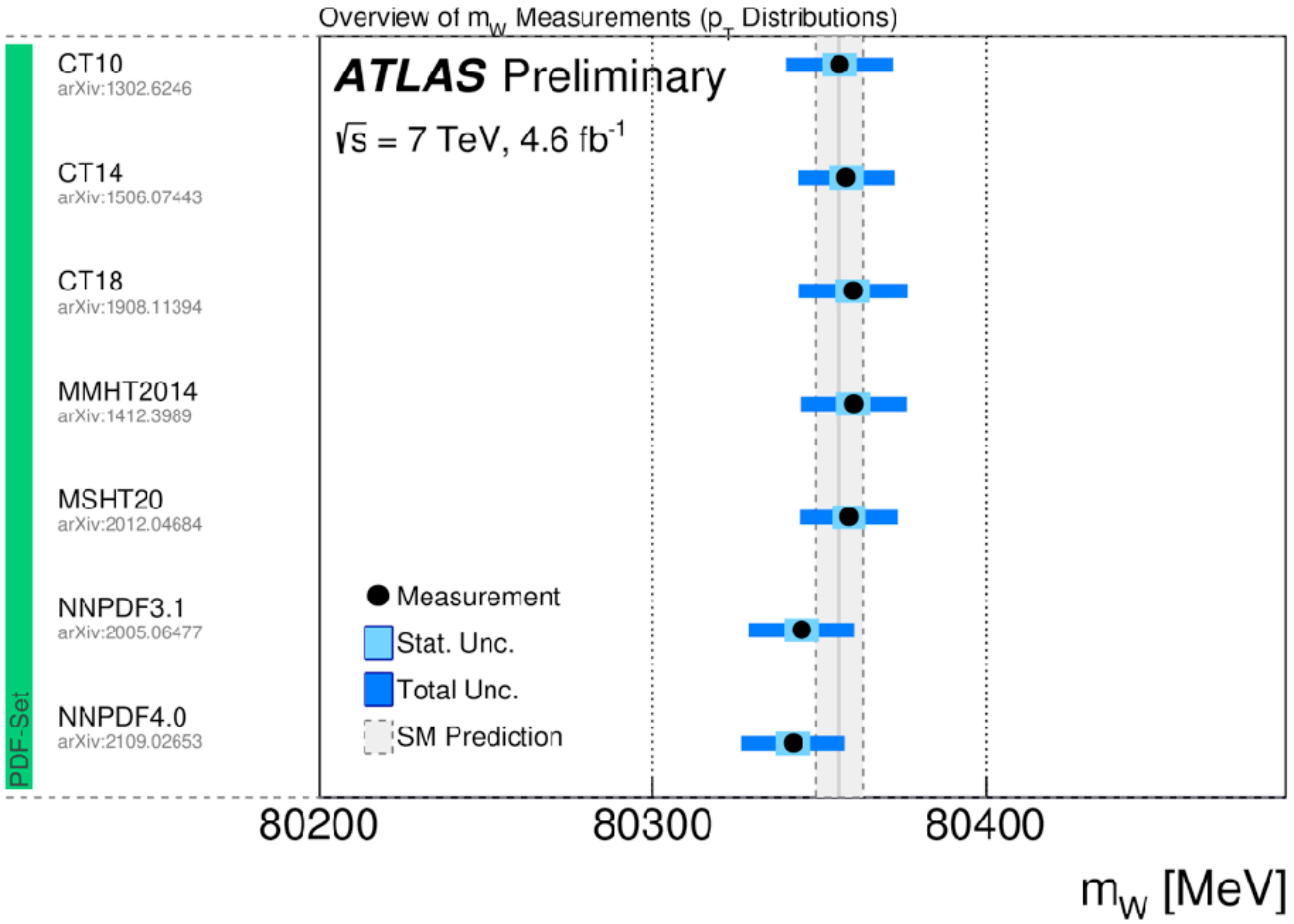
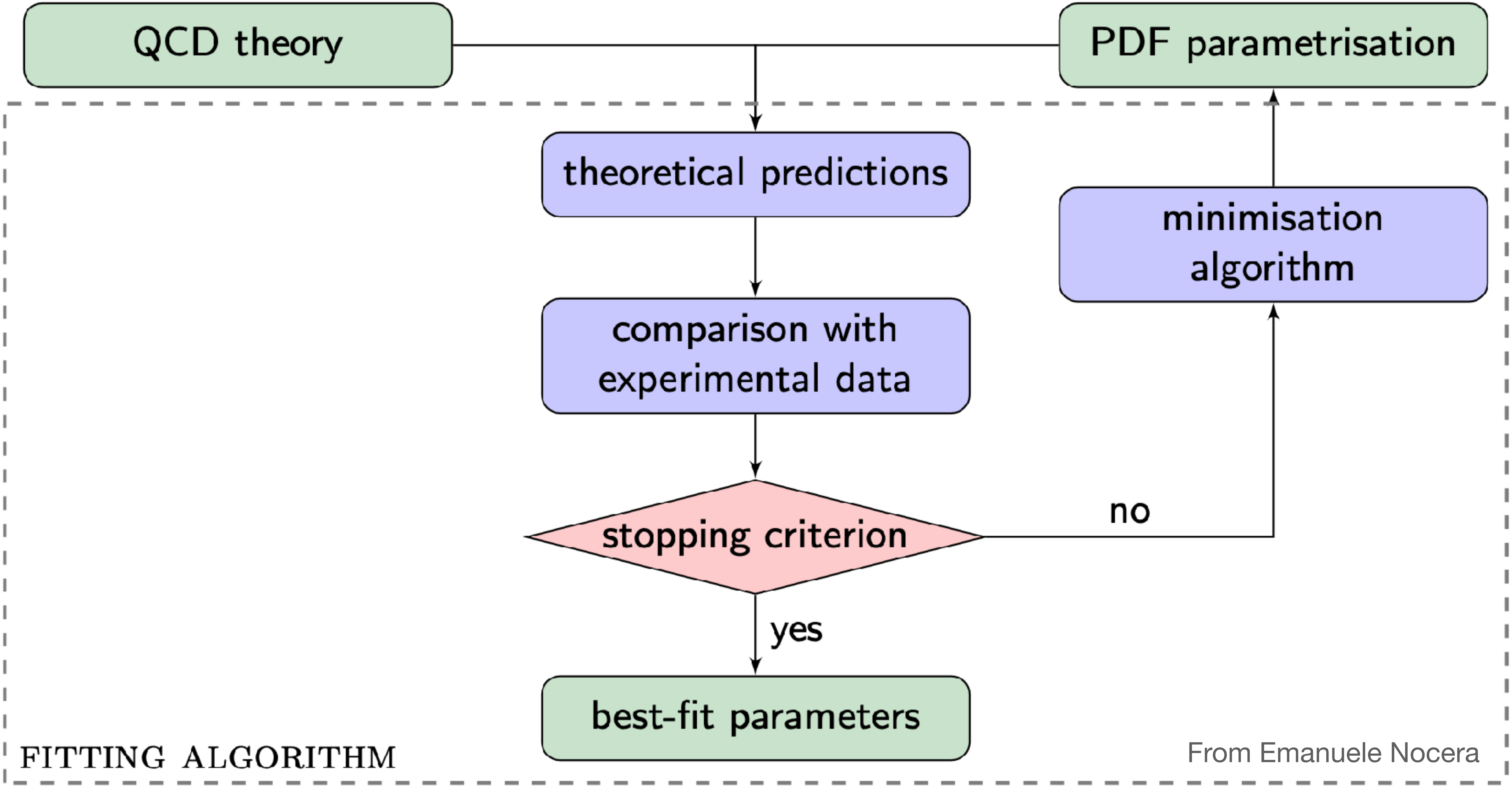


PDFs fitting 101



From Emanuele Nocera

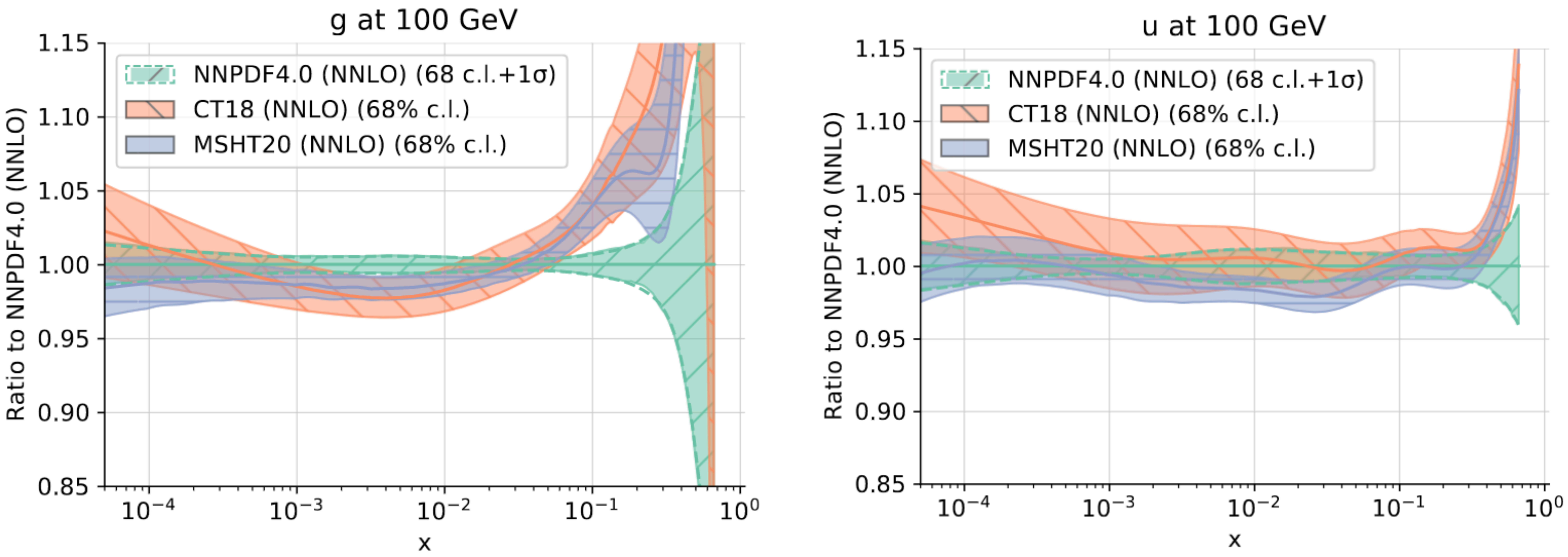
History of PDF determinations

- Global PDFs extracted by several groups making different choices in their input data, non-perturbative parametrization, heavy-flavor scheme and fit methodology: ABMP, CTEQ-TEA, MSHT, NNPDF

From Jun Gao

The Status of global PDF fits

- A complex problem leads to a variety of solutions …



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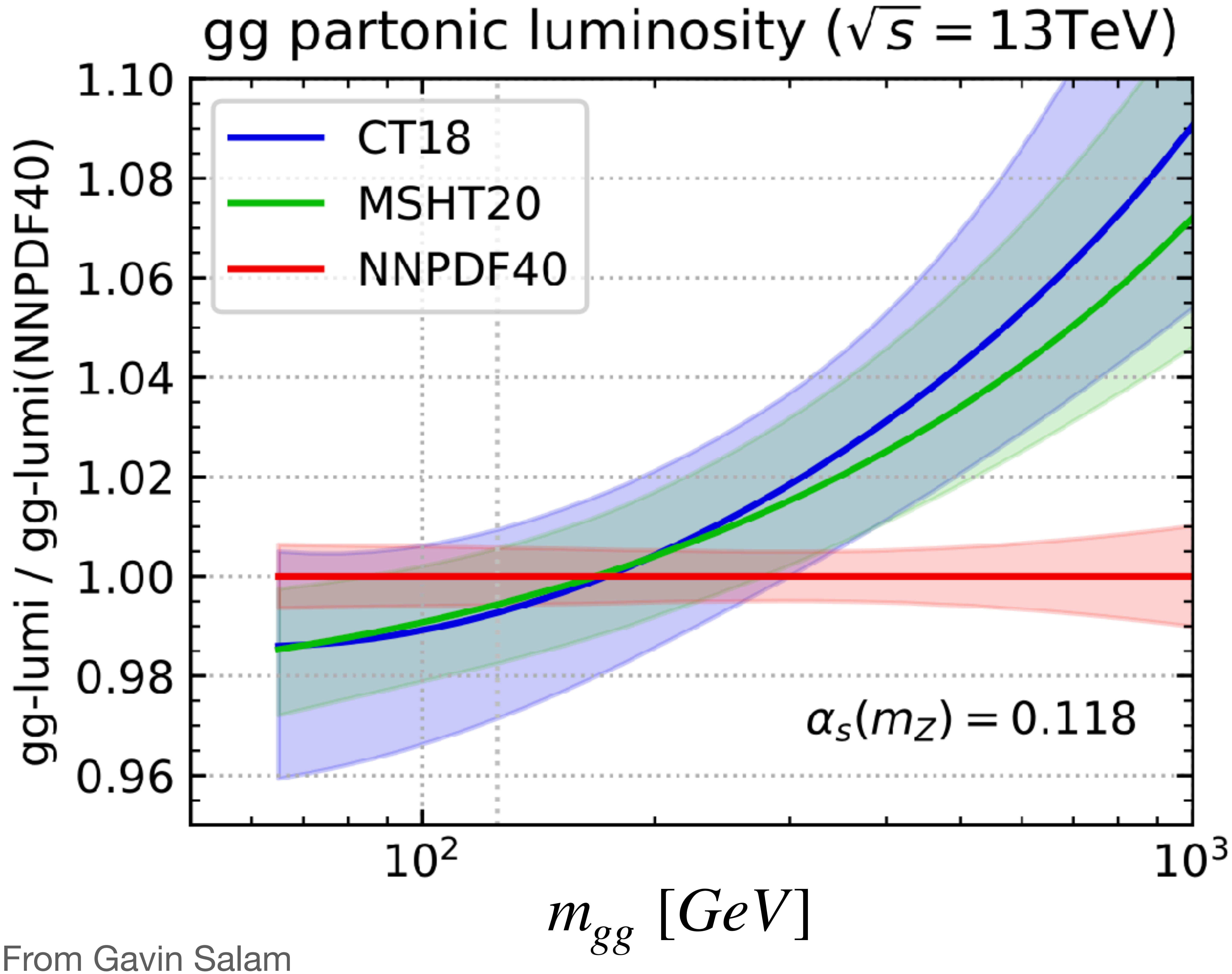
The status of global PDF fits



gg-lumi, ratio to PDF4LHC15 @ m_H

PDF4LHC15	1.0000	±	0.0184
PDF4LHC21	0.9930	±	0.0155
CT18	0.9914	±	0.0180
MSHT20	0.9930	±	0.0108
NNPDF40	0.9986	±	0.0058

× 3

- NNPDF and MSHT now at %-level precision
- Yet in significant tension with each other

From Gavin Salam

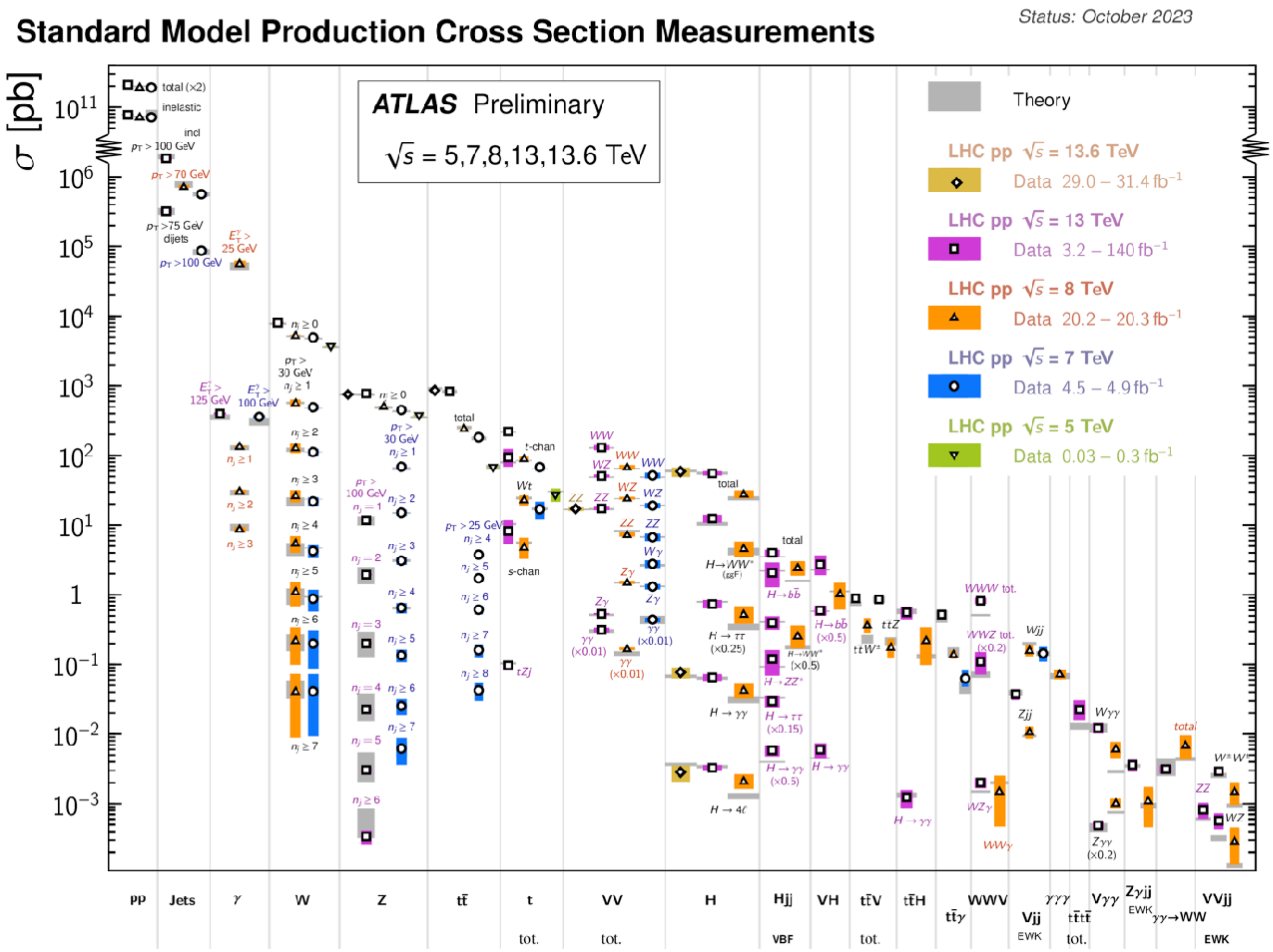
Where can the LHC help ?

- PDFs most precisely determined from DIS data, but not all combinations probed
  - d_v is less precisely determined than u_v, no flavour decomposition of the light sea

- LHC data cannot replace DIS, but can provide complementary information and help resolve tensions and disagreements which happen in global fits (or among them)

Drell-Yan	Flavour decomposition of the sea, u_v, d_v, γ PDF
W+charm	Strange PDF
Jets	High-x gluon PDF
Photon	Medium-x gluon PDF
Top pair	Medium- and high-x gluon PDF

Input measurements from LHC



LHC data in PDF fits

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
ATLAS W, Z 7 TeV ($\mathcal{L} = 35$ pb^{-1})	[51]	✓	✓	✓	✓	✓
ATLAS W, Z 7 TeV ($\mathcal{L} = 4.6$ fb^{-1})	[52]	✓	✓	✗	(✓)	✓
ATLAS low-mass DY 7 TeV	[53]	✓	✓	✗	(✓)	✗
ATLAS high-mass DY 7 TeV	[54]	✓	✓	✗	(✓)	✓
ATLAS W 8 TeV	[79]	✗	(✓)	✗	✗	✓
ATLAS DY 2D 8 TeV	[78]	✗	✓	✗	✗	✓
ATLAS high-mass DY 2D 8 TeV	[77]	✗	✓	✗	(✓)	✓
ATLAS $\sigma_{W,Z}$ 13 TeV	[81]	✗	✓	✓	✗	✗
ATLAS W+jet 8 TeV	[93]	✗	✓	✗	✗	✓
ATLAS Z p_T 7 TeV	[259]	(✓)	✗	✗	(✓)	✗
ATLAS Z p_T 8 TeV	[63]	✓	✓	✗	✓	✓
ATLAS $W + c$ 7 TeV	[83]	✗	✓	✗	(✓)	✗
ATLAS σ_{tt}^{tot} 7, 8 TeV	[65]	✓	✓	✓	✗	✗
ATLAS σ_{tt}^{tot} 7, 8 TeV	[260–265]	✗	✗	✓	✗	✗
ATLAS σ_{tt}^{tot} 13 TeV ($\mathcal{L} = 3.2$ fb^{-1})	[66]	✓	✗	✓	✗	✗
ATLAS σ_{tt}^{tot} 13 TeV ($\mathcal{L} = 139$ fb^{-1})	[134]	✗	✓	✗	✗	✗
ATLAS σ_{tt}^{tot} and Z ratios	[266]	✗	✗	✗	✗	(✓)
ATLAS $t\bar{t}$ lepton+jets 8 TeV	[67]	✓	✓	✗	✓	✓
ATLAS $t\bar{t}$ dilepton 8 TeV	[89]	✗	✓	✗	✗	✓
ATLAS single-inclusive jets 7 TeV, R=0.6	[73]	✓	(✓)	✗	✓	✓
ATLAS single-inclusive jets 8 TeV, R=0.6	[86]	✗	✓	✗	✗	✗
ATLAS dijets 7 TeV, R=0.6	[148]	✗	✓	✗	✗	✗
ATLAS direct photon production 8 TeV	[100]	✗	(✓)	✗	✗	✗
ATLAS direct photon production 13 TeV	[101]	✗	✓	✗	✗	✗
ATLAS single top R_t 7, 8, 13 TeV	[94, 96, 98]	✗	✓	✓	✗	✗
ATLAS single top diff. 7 TeV	[94]	✗	✓	✗	✗	✗
ATLAS single top diff. 8 TeV	[96]	✗	✓	✗	✗	✗

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
CMS W asym. 7 TeV ($\mathcal{L} = 36$ pb^{-1})	[267]	✗	✗	✗	✗	✓
CMS Z 7 TeV ($\mathcal{L} = 36$ pb^{-1})	[268]	✗	✗	✗	✗	✓
CMS W electron asymmetry 7 TeV	[55]	✓	✓	✗	✓	✓
CMS W muon asymmetry 7 TeV	[56]	✓	✓	✓	✓	✗
CMS Drell-Yan 2D 7 TeV	[57]	✓	✓	✗	(✓)	✓
CMS Drell-Yan 2D 8 TeV	[269]	(✓)	✗	✗	✗	✗
CMS W rapidity 8 TeV	[58]	✓	✓	✓	✓	✓
CMS W, Z p_T 8 TeV ($\mathcal{L} = 18.4$ fb^{-1})	[270]	✗	✗	✗	(✓)	✗
CMS Z p_T 8 TeV	[64]	✓	✓	✗	(✓)	✗
CMS $W + c$ 7 TeV	[76]	✓	✓	✗	(✓)	✓
CMS $W + c$ 13 TeV	[84]	✗	✓	✗	✗	(✓)
CMS single-inclusive jets 2.76 TeV	[75]	✓	✗	✗	✗	✓
CMS single-inclusive jets 7 TeV	[147]	✓	(✓)	✗	✓	✓
CMS dijets 7 TeV	[74]	✗	✓	✗	✗	✗
CMS single-inclusive jets 8 TeV	[87]	✗	✓	✗	✓	✓
CMS 3D dijets 8 TeV	[149]	✗	(✓)	✗	✗	✗
CMS σ_{tt}^{tot} 5 TeV	[88]	✗	✓	✗	✗	✗
CMS σ_{tt}^{tot} 7, 8 TeV	[146]	✓	✓	✗	✗	✗
CMS σ_{tt}^{tot} 8 TeV	[271]	✗	✗	✗	✗	✓
CMS σ_{tt}^{tot} 5, 7, 8, 13 TeV	[68, 272–280]	✗	✗	✓	✗	✗
CMS σ_{tt}^{tot} 13 TeV	[69]	✓	✓	✓	✗	✗
CMS $t\bar{t}$ lepton+jets 8 TeV	[70]	✓	✓	✗	✗	✓
CMS $t\bar{t}$ 2D dilepton 8 TeV	[90]	✗	✓	✗	✓	✓
CMS $t\bar{t}$ lepton+jet 13 TeV	[91]	✗	✓	✗	✗	✗
CMS $t\bar{t}$ dilepton 13 TeV	[92]	✗	✓	✗	✗	✗
CMS single top $\sigma_t + \sigma_{\bar{t}}$ 7 TeV	[95]	✗	✓	✓	✗	✗
CMS single top R_t 8, 13 TeV	[97, 99]	✗	✓	✓	✗	✗
CMS single top 13 TeV	[281, 282]	✗	✗	✗	✗	(✓)

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
LHCb Z 7 TeV ($\mathcal{L} = 940$ pb^{-1})	[59]	✓	✓	✗	✗	✓
LHCb $Z \to ee$ 8 TeV ($\mathcal{L} = 2$ fb^{-1})	[61]	✓	✓	✓	✓	✓
LHCb W 7 TeV ($\mathcal{L} = 37$ pb^{-1})	[283]	✗	✗	✗	✗	✓
LHCb $W, Z \to \mu$ 7 TeV	[60]	✓	✓	✓	✓	✓
LHCb $W, Z \to \mu$ 8 TeV	[62]	✓	✓	✓	✓	✓
LHCb $W \to e$ 8 TeV	[80]	✗	(✓)	✗	✗	✗
LHCb $Z \to \mu\mu, ee$ 13 TeV	[82]	✗	✓	✗	✗	✗

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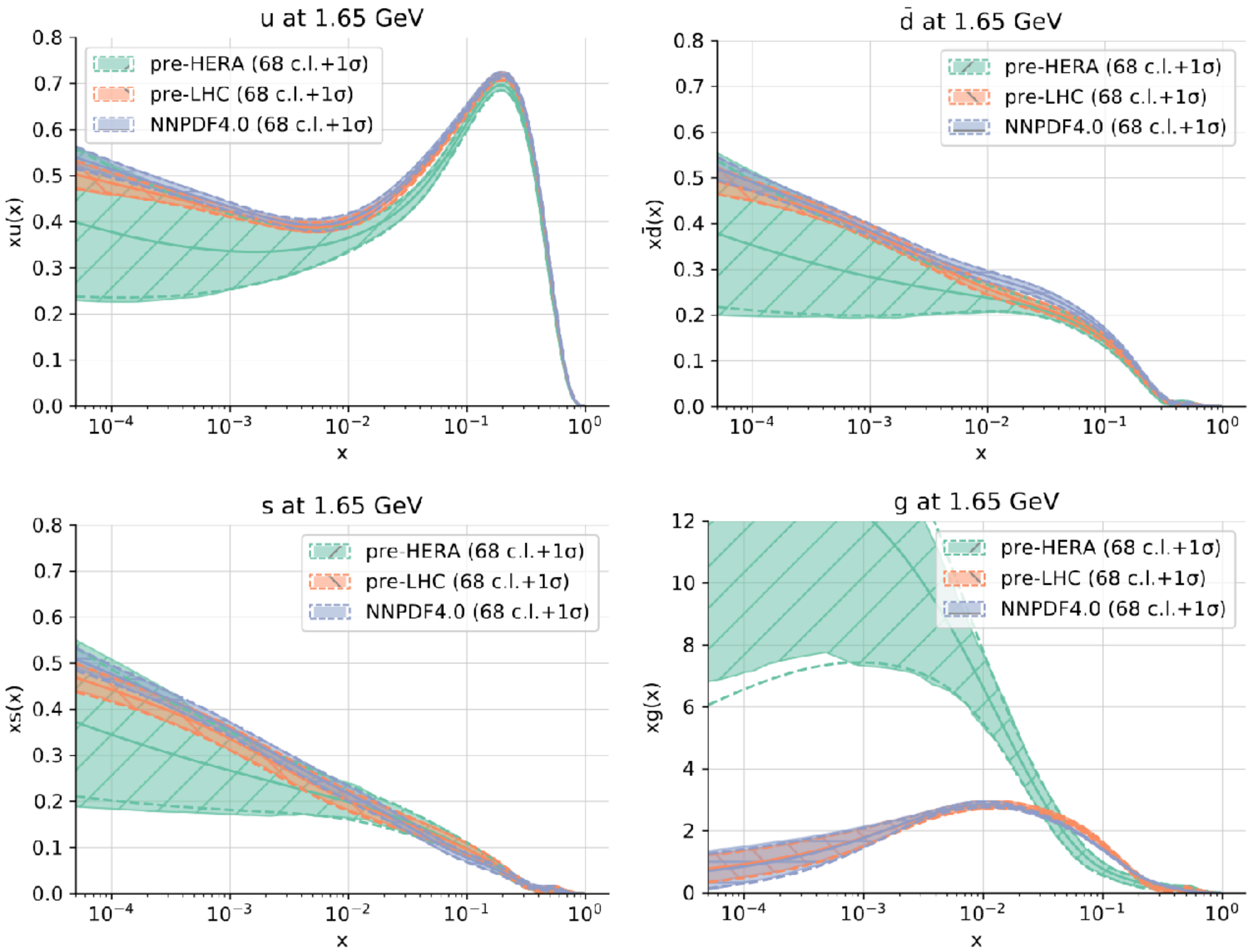
✓	in baseline dataset
✗	not considered
(✓)	impact assessed but excluded from baseline

LHC data in PDF fits and their impact



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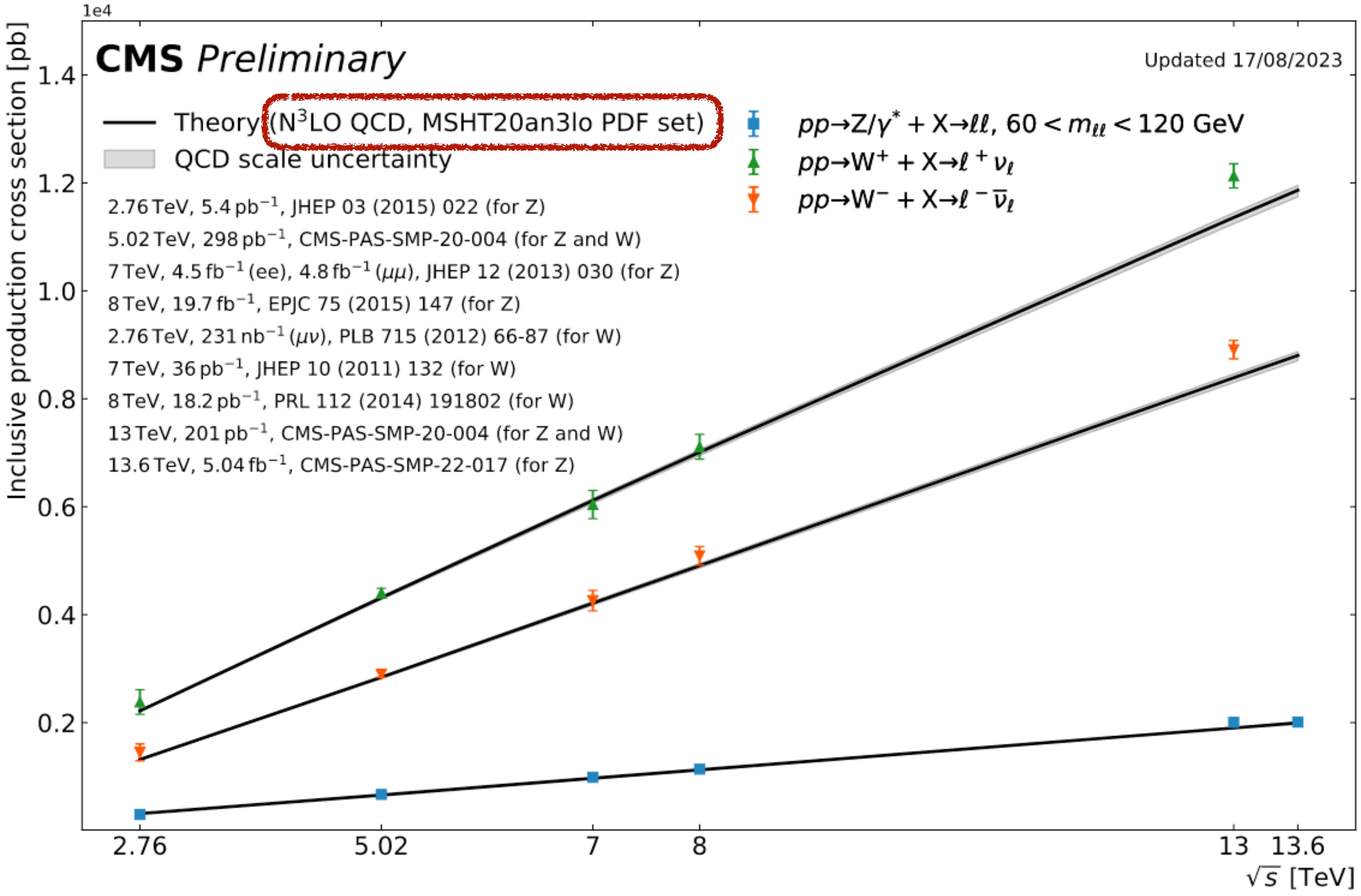
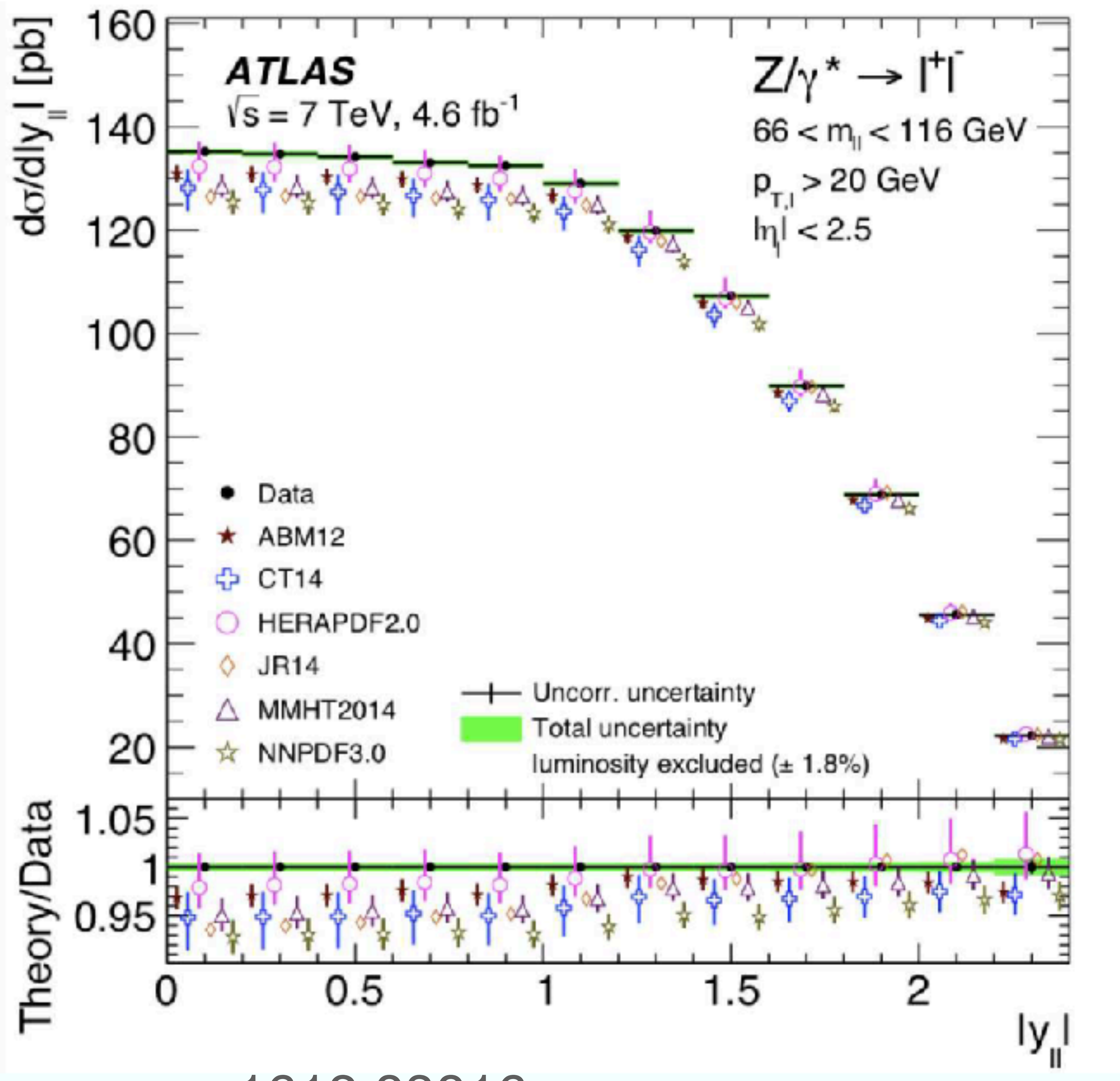
Drell-yan cross-sections



- Drell-Yan is special
  - Large data samples
  - Clean final state
  - Predictions at N3LO QCD + NLO EW
- Measurements performed at different LHC energies
- Precise probe of PDFs at different x-ranges

- Cross-section uncertainties dominated by luminosity uncertainty, ~2%
  - PDF uncertainties smaller, typically at the 2-3% level

- Shapes of distributions or cross-section ratios measured to a few per-mille precision



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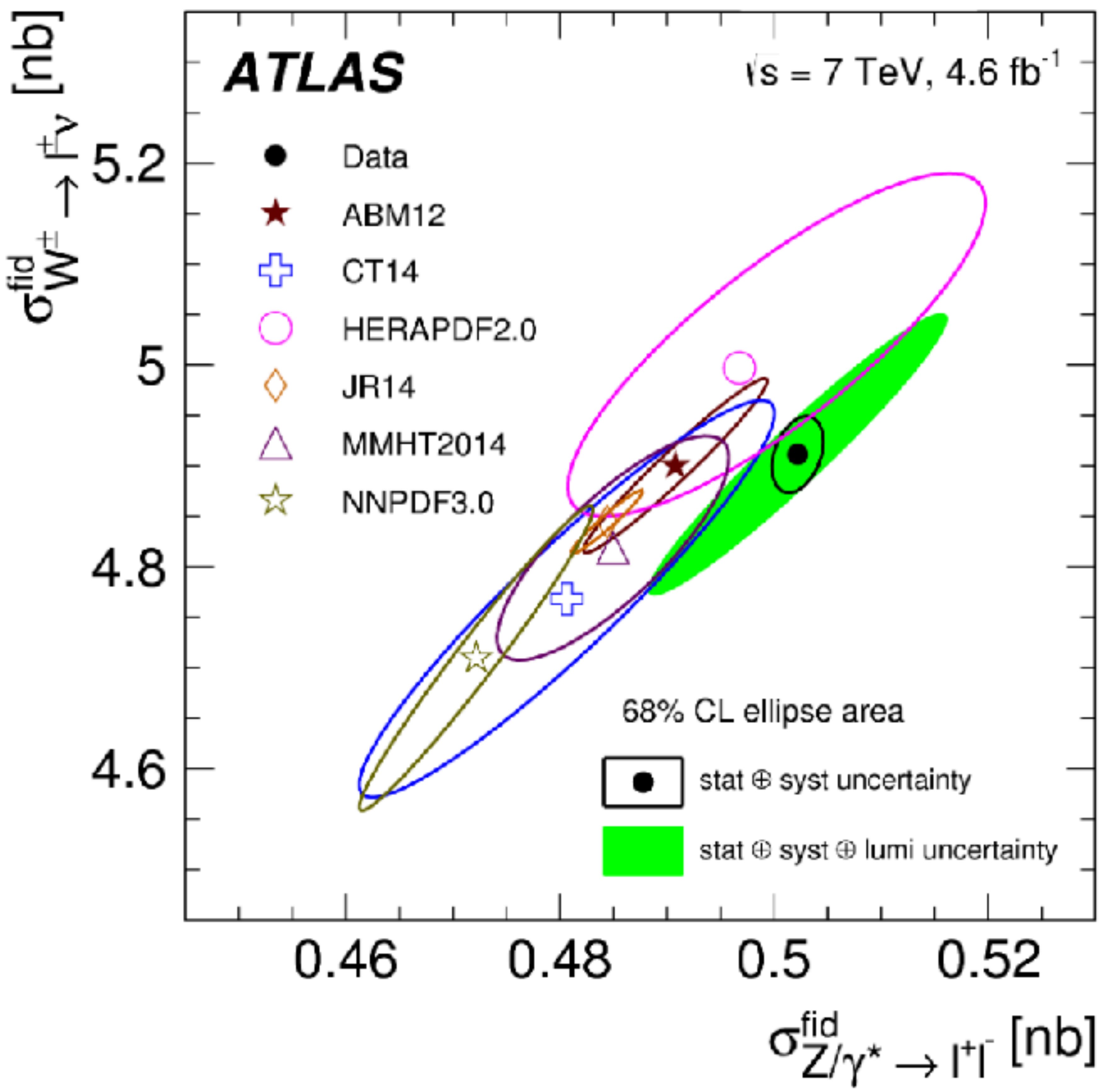
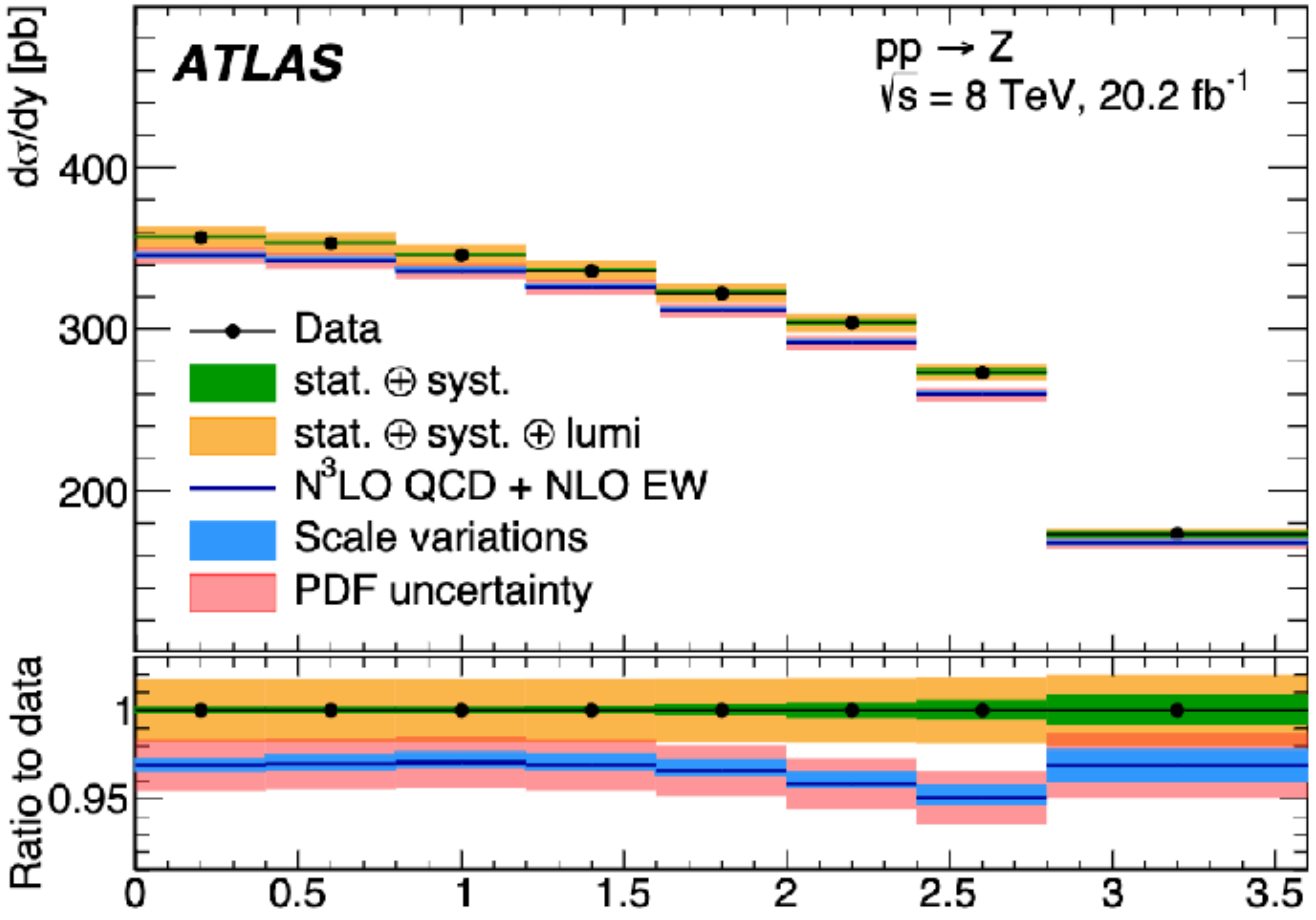
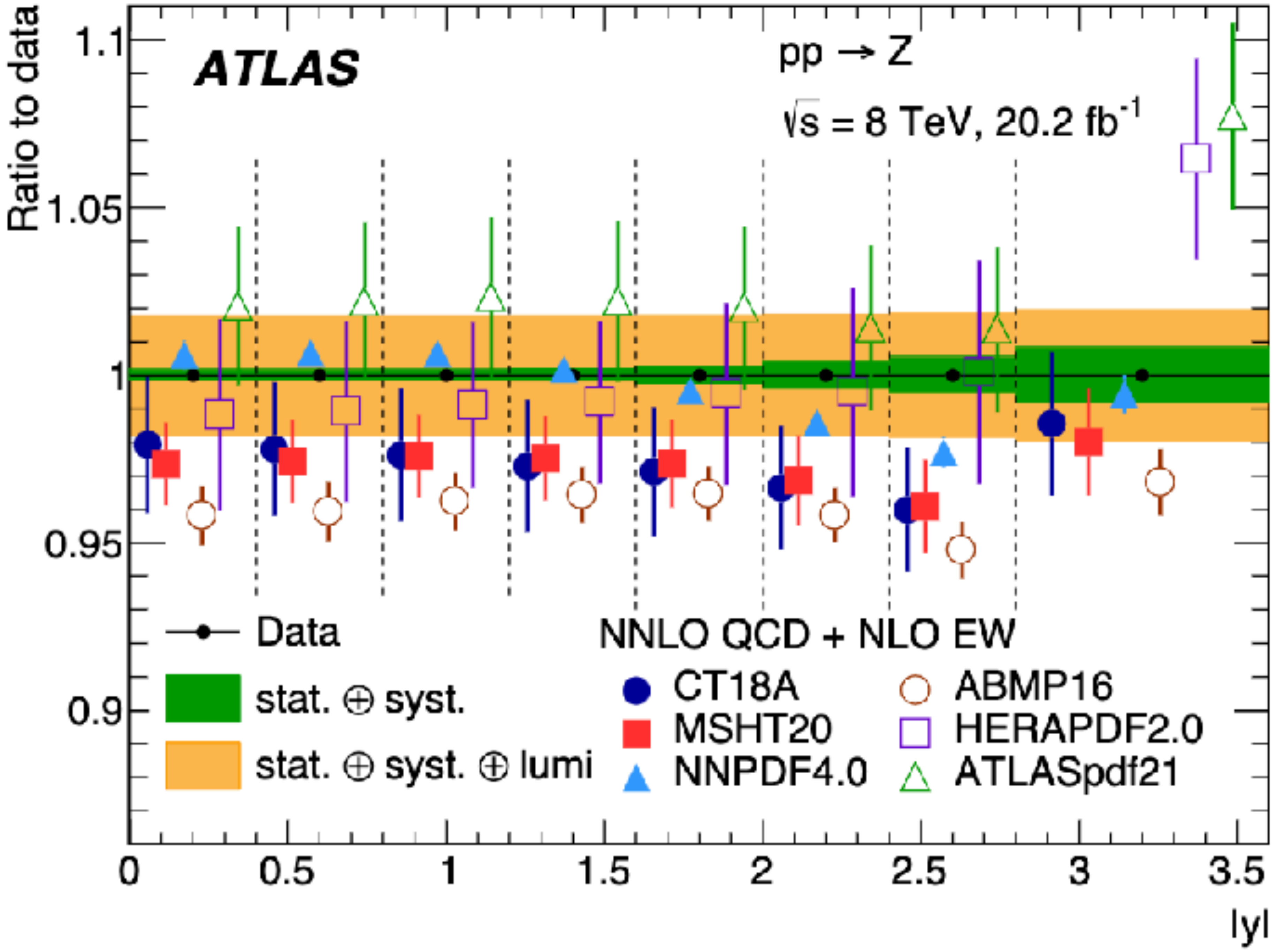






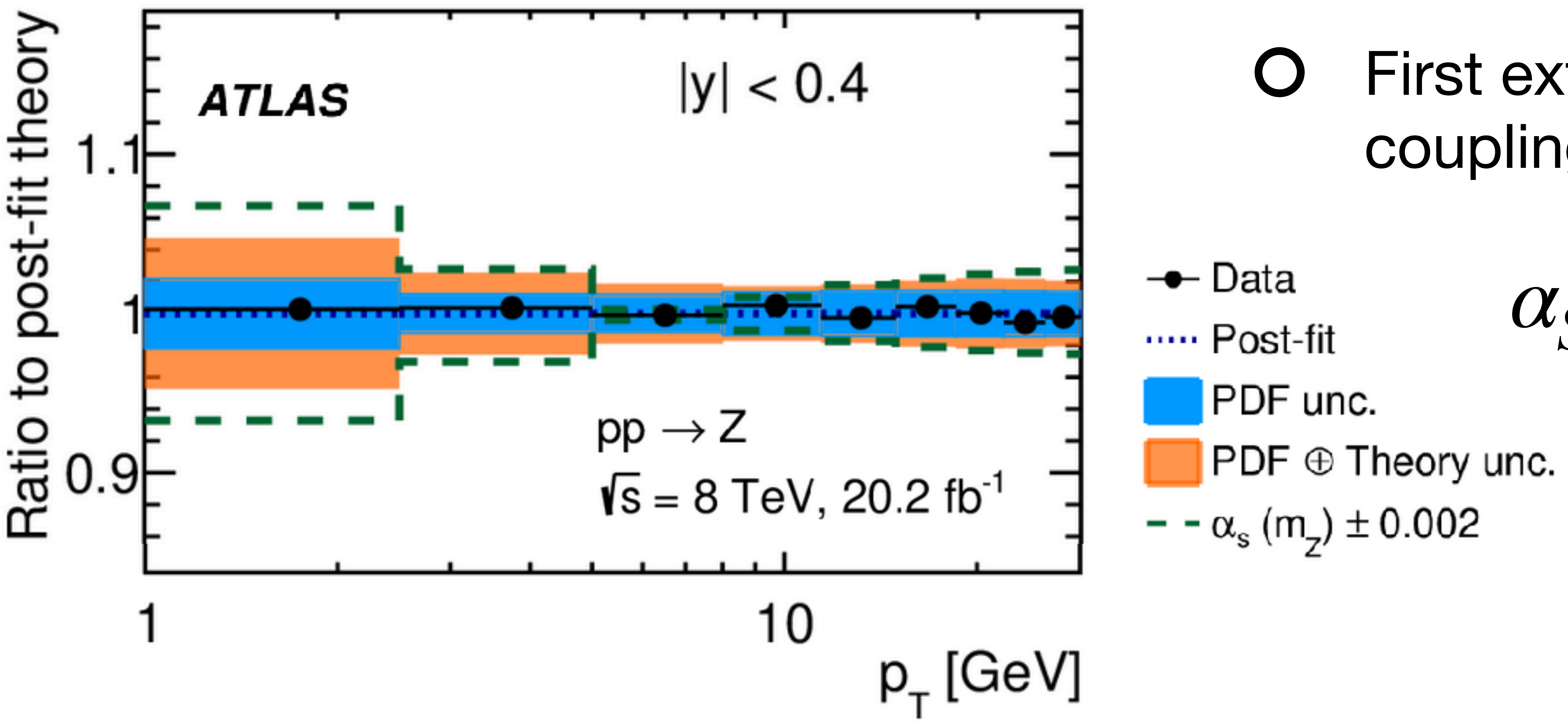
New observables - unpolarized full phase-space rapidity

- ATLAS measurement of the Z-boson rapidity distribution at 8 TeV in full phase-space
- Exploit decomposition into angular coefficients to have small extrapolation uncertainties
- Compared to predictions at N3LO in QCD

2309.09318

PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN^{3}LO [58]	13/8	0.11	1.2 ± 0.6
CT18A [59]	12/8	0.17	0.9 ± 0.7
MSHT20 [60]	10/8	0.26	0.9 ± 0.6
NNPDF4.0 [61]	30/8	0.0002	0.0 ± 0.2
ABMP16 [62, 63]	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0 [64]	22/8	0.005	-1.3 ± 0.8
ATLASpdf21 [65]	20/8	0.01	-1.1 ± 0.8

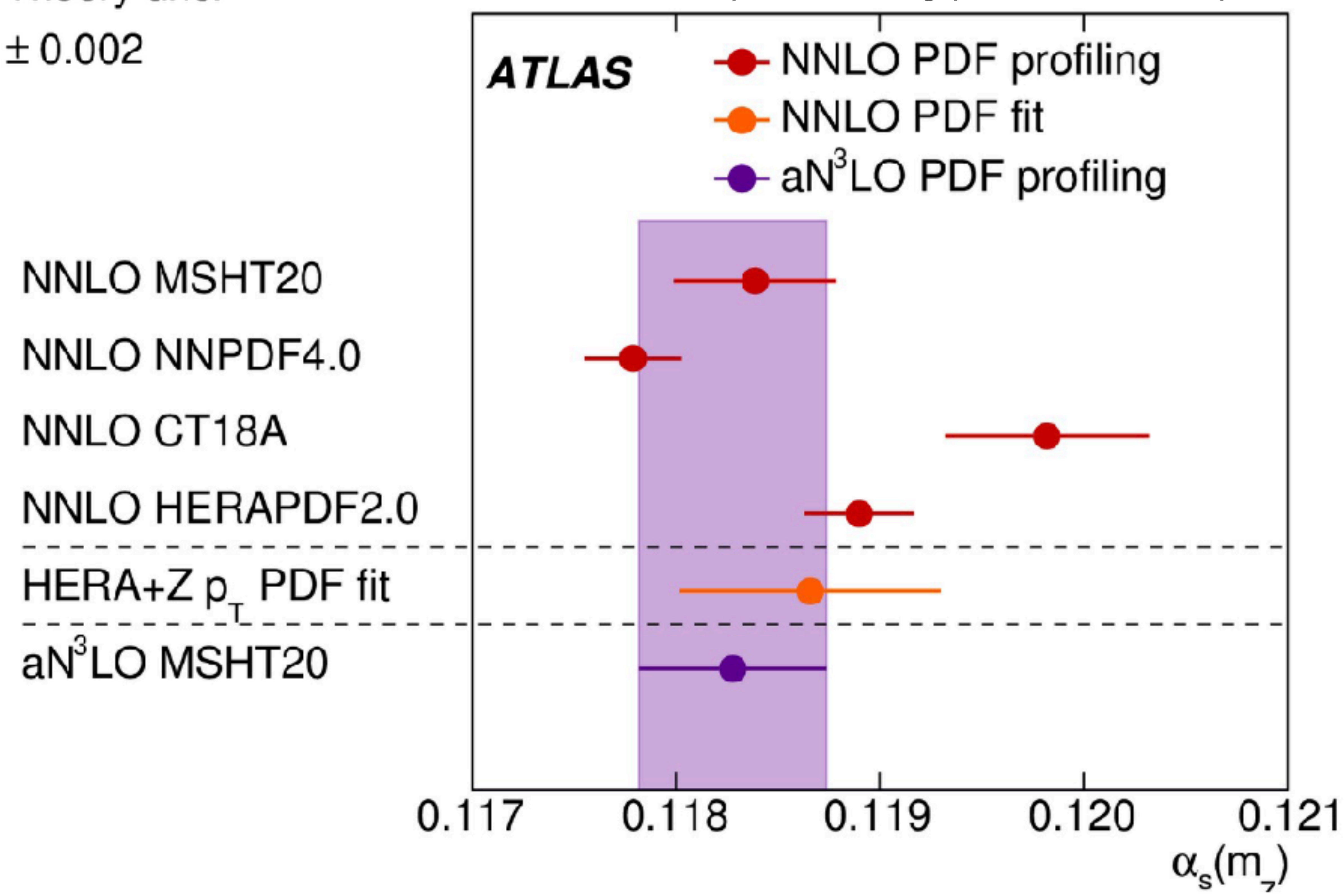
New observables - Z p_T and α_S



- First extraction of the value of the strong coupling from the Sudakov peak of the Z p_T

$$\alpha_S(m_Z) = 0.1183 \pm 0.0009$$

https://arxiv.org/pdf/2309.12986.pdf



- Unfolding to full phase space facilitates use of computationally challenging N3LO+N4LLa predictions
- High levels of control needed over perturbative and non-perturbative theory uncertainties

New observables - Z p_T and PDFs

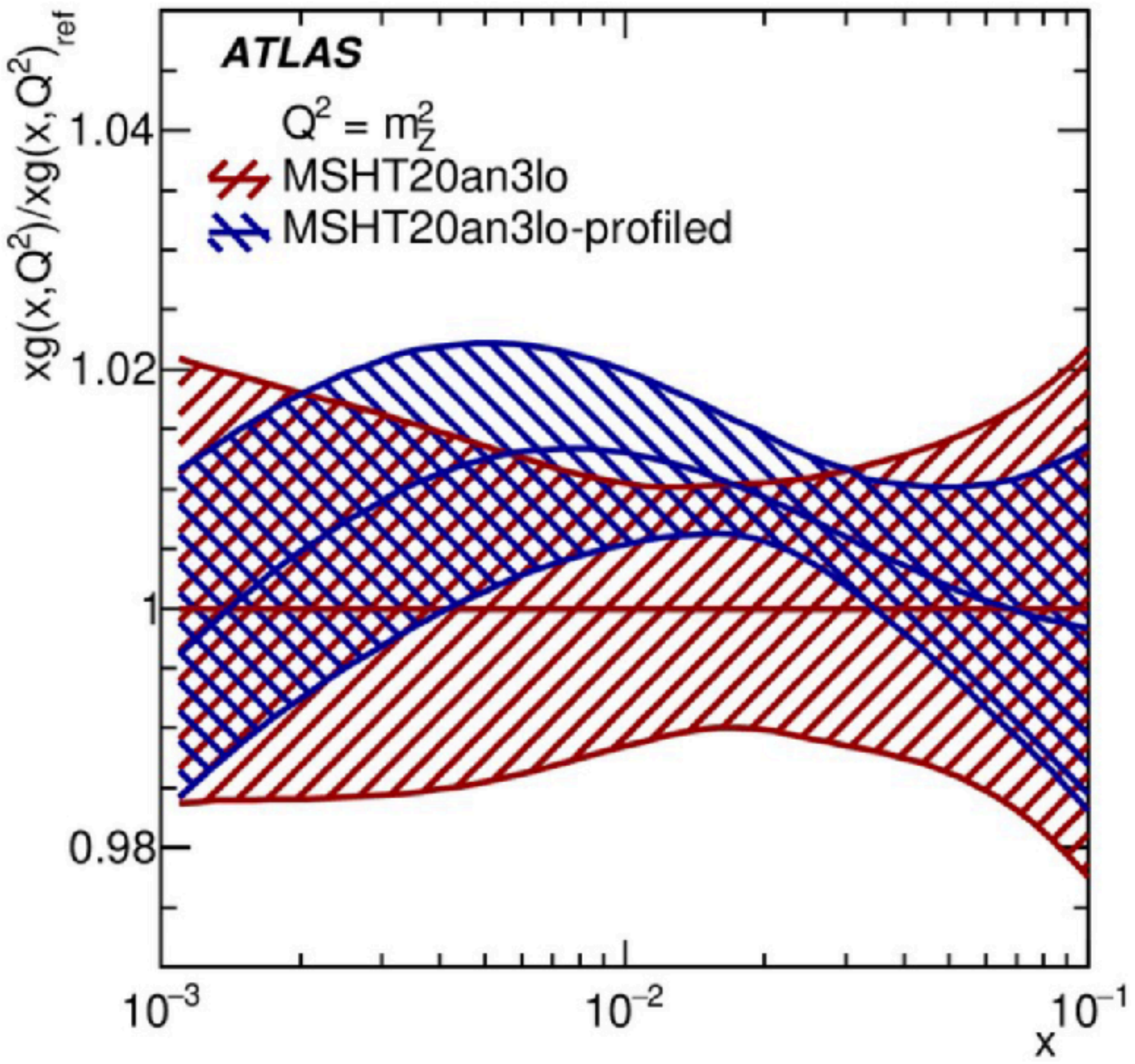
- Large sensitivity of the data (and α_S) to the gluon PDF

2309.12986

- Nominal result quoted with MSHTan3lo PDFs for consistency with theoretical predictions
  - MSHT gluon in agreement pre/post-fit

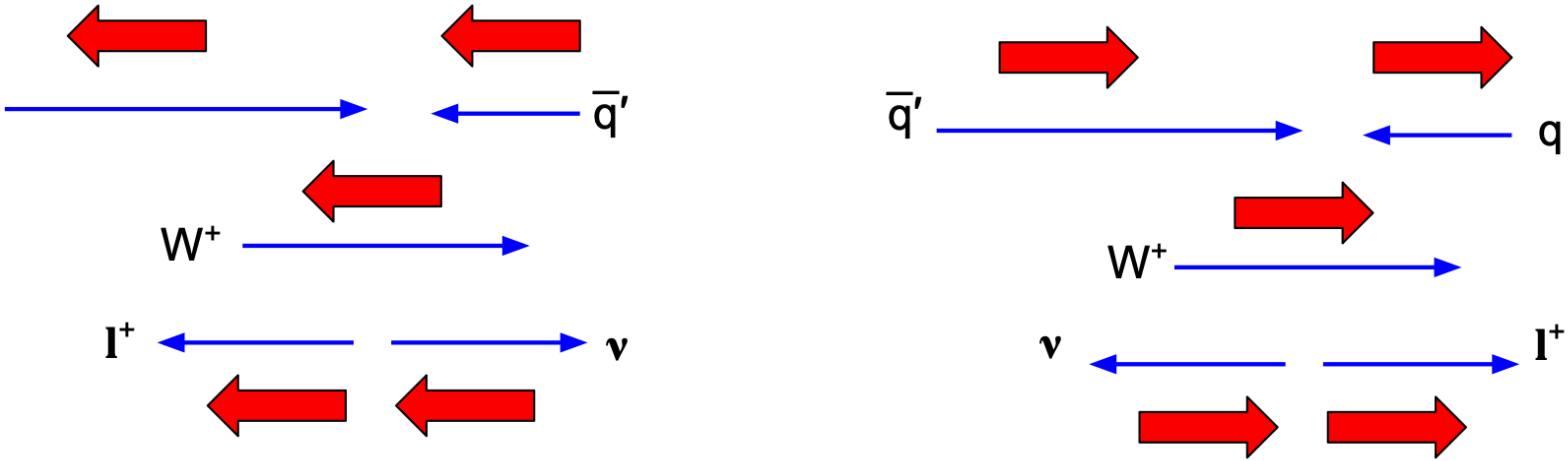
- NNLO PDFs show a large post-fit pull of the gluon, going towards the N3LO one

PDF set	$\alpha_s(m_Z)$	PDF uncertainty
MSHT20 [37]	0.11839	0.00040
NNPDF4.0 [84]	0.11779	0.00024
CT18A [29]	0.11982	0.00050
HERAPDF2.0 [65]	0.11890	0.00027



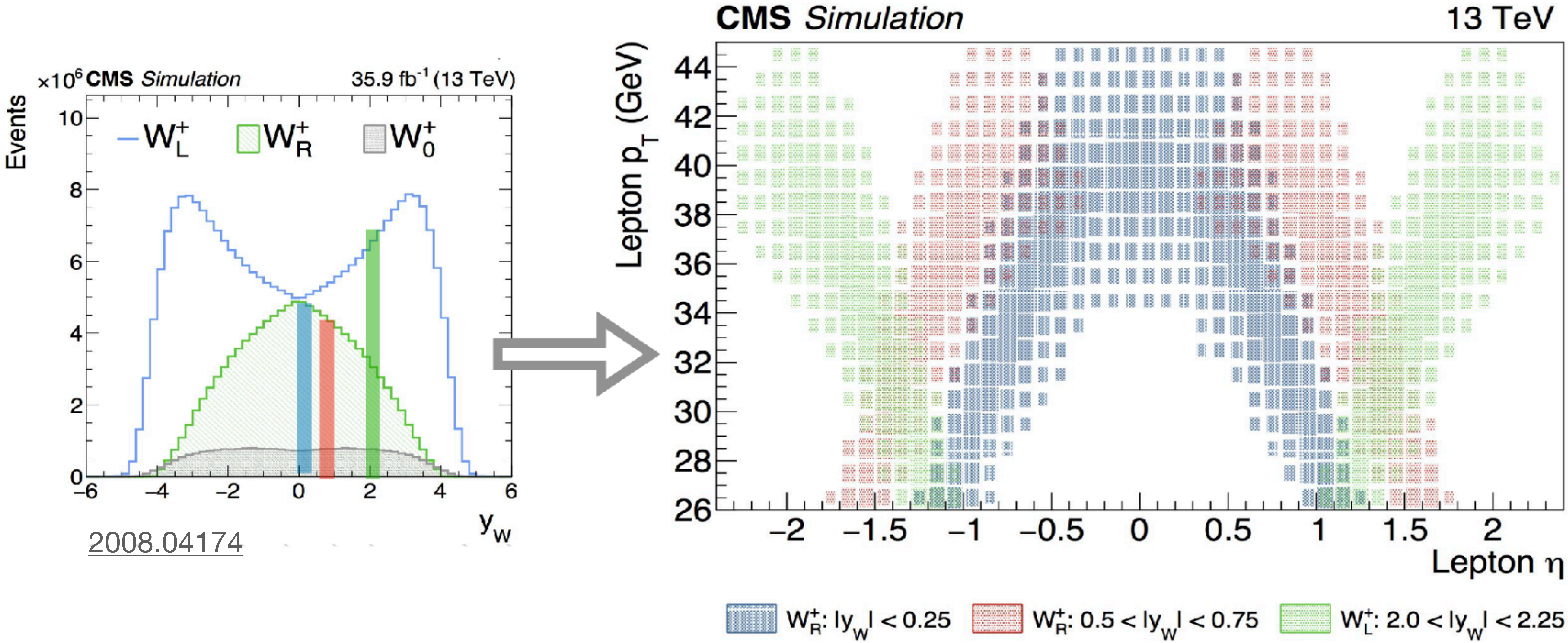
CMS W-helicity measurement

- Lepton direction in W-boson decays retains information on the boson polarization
- Left-handed couplings of the W means correlate the polarization and rapidity of the boson with the direction of the quark/ani-quark, and hence the direction of the outgoing lepton



13 TeV W-helicity measurement

- W-boson rapidity and helicity can be inferred statistically from p_T^{lep}- η^{lep}



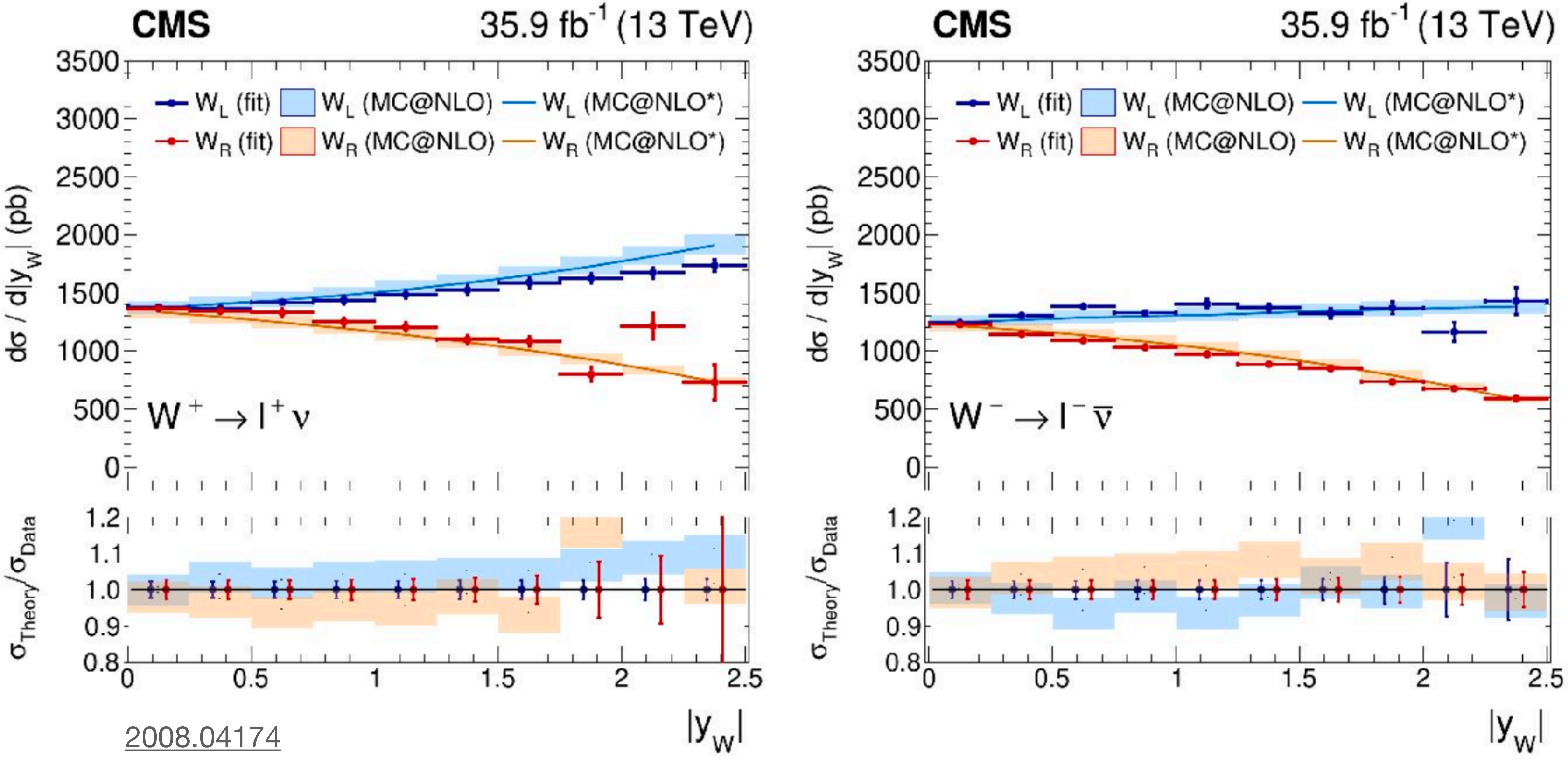
2008.04174

Lepton pT/eta cross-sections

- W-boson rapidity and helicity can be inferred statistically from p_T^{lep}- η^{lep}
- Need predictions with q_T-resummation to describe p_T^{lep}

2008.04174

Polarized W cross-sections



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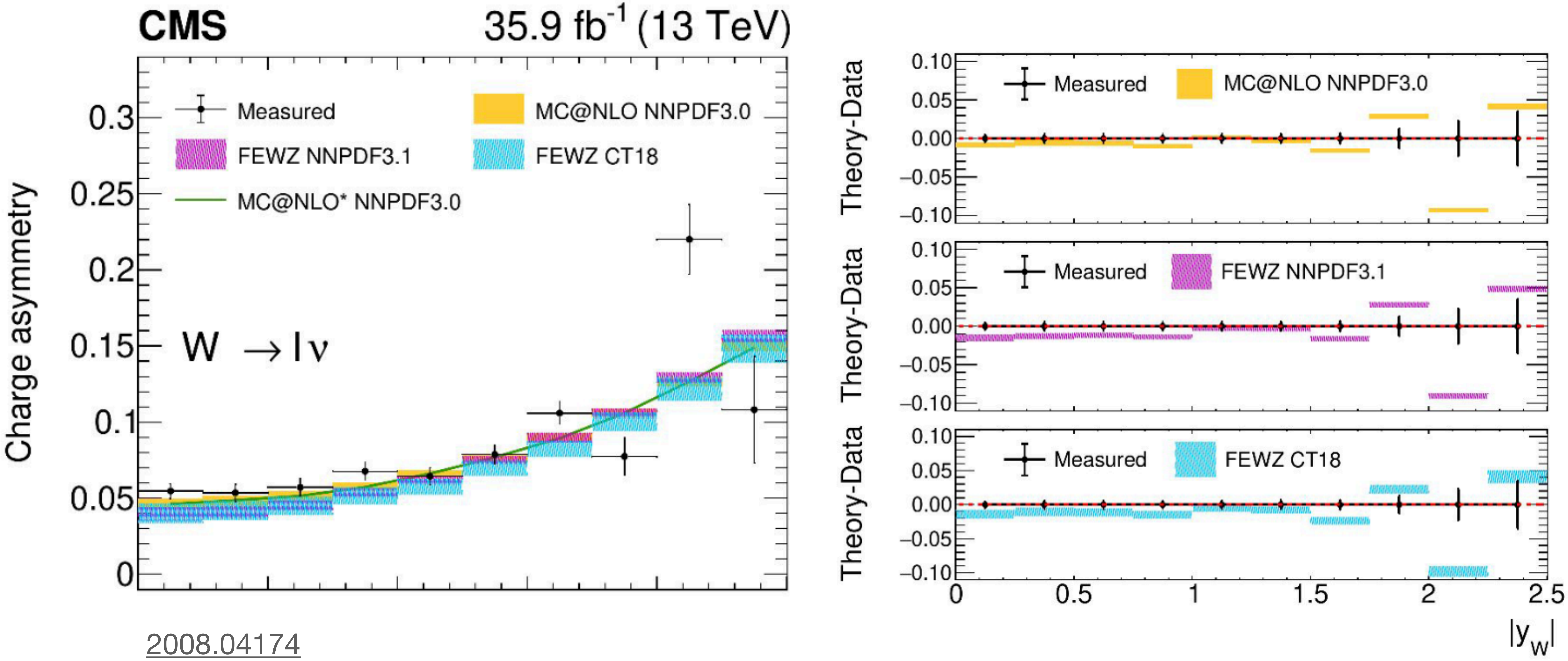
W charge asymmetry measurement

- Helicities in W integrated results measured without assumptions on underlying polarization
- Avoids circularity in PDF uncertainties in e.g. Tevatron W-asymmetry measurements



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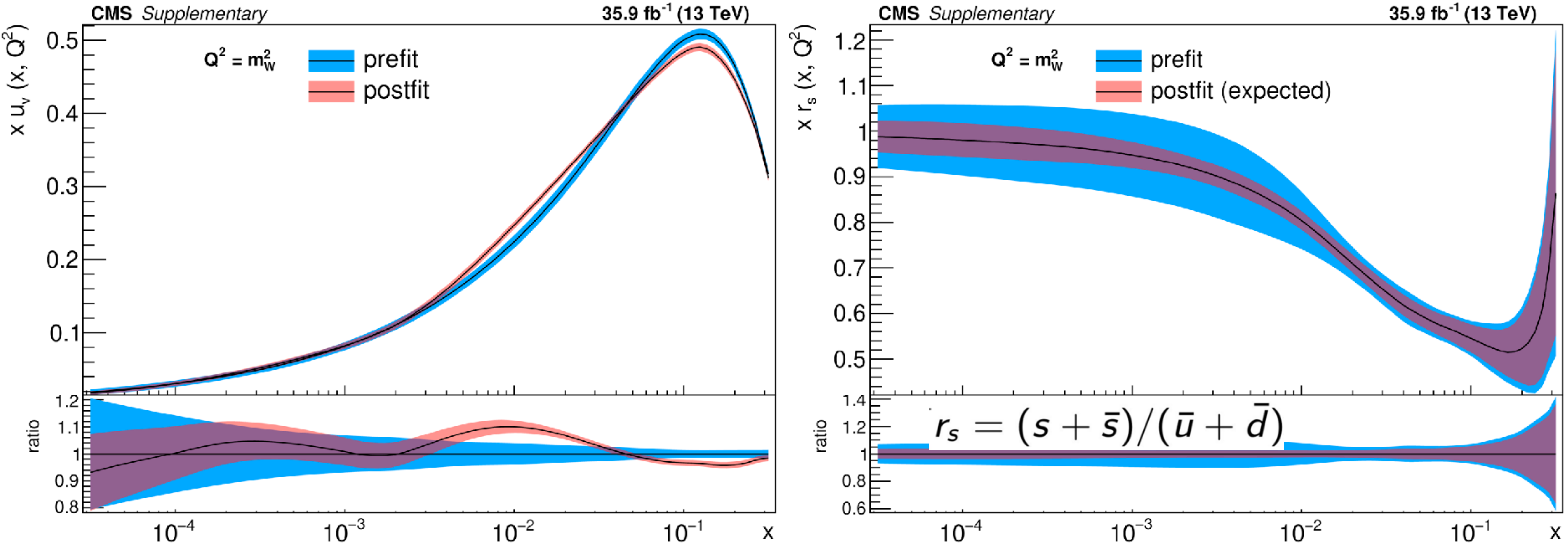
PDF constraints

- Sensitivity to PDFs evaluated using aMC@NLO+Pythia predictions and NNPDF30
- Large reduction in uncertainties for valence and strange PDFs



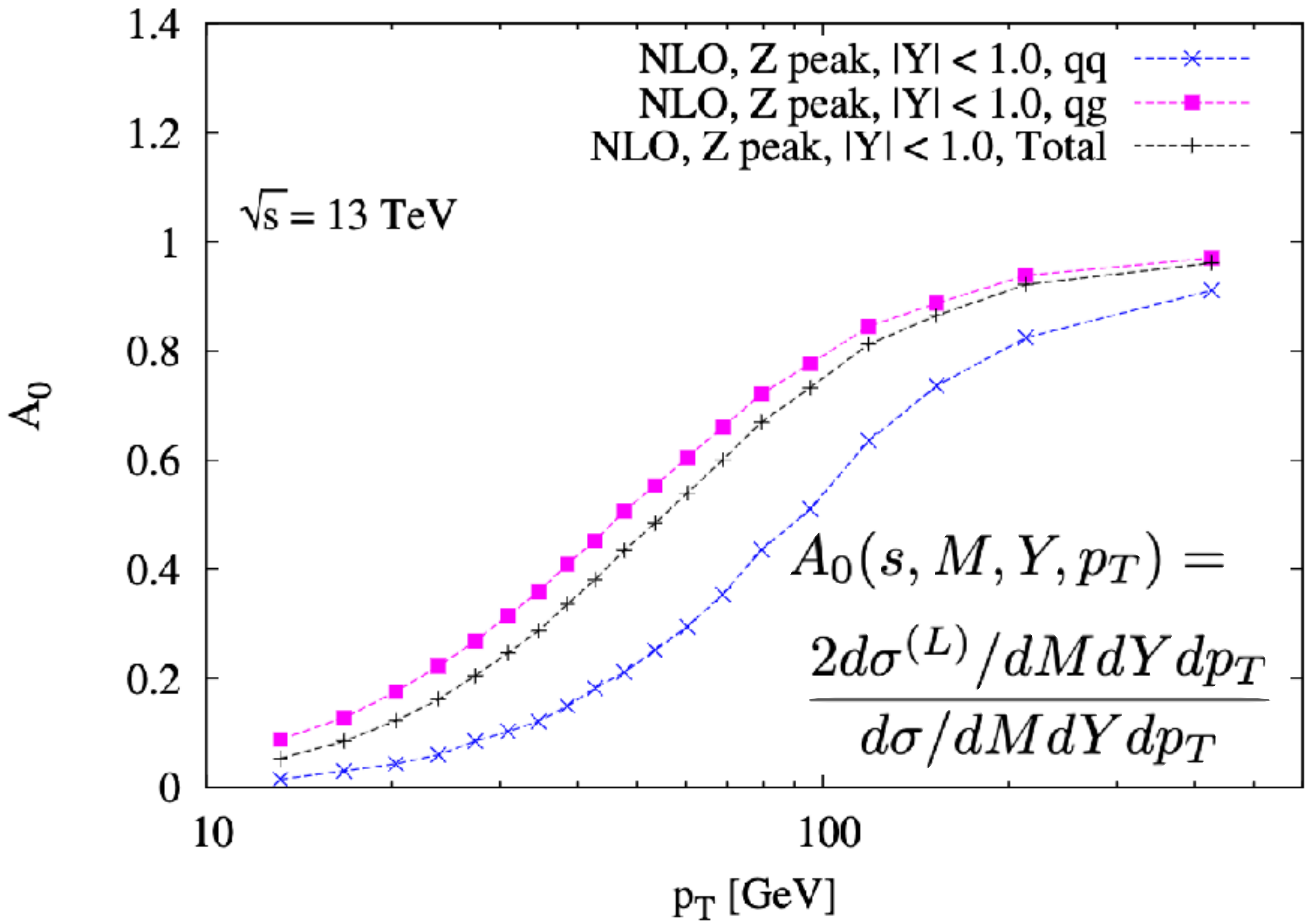
$r_s = (s + \bar{s})/(\bar{u} + \bar{d})$

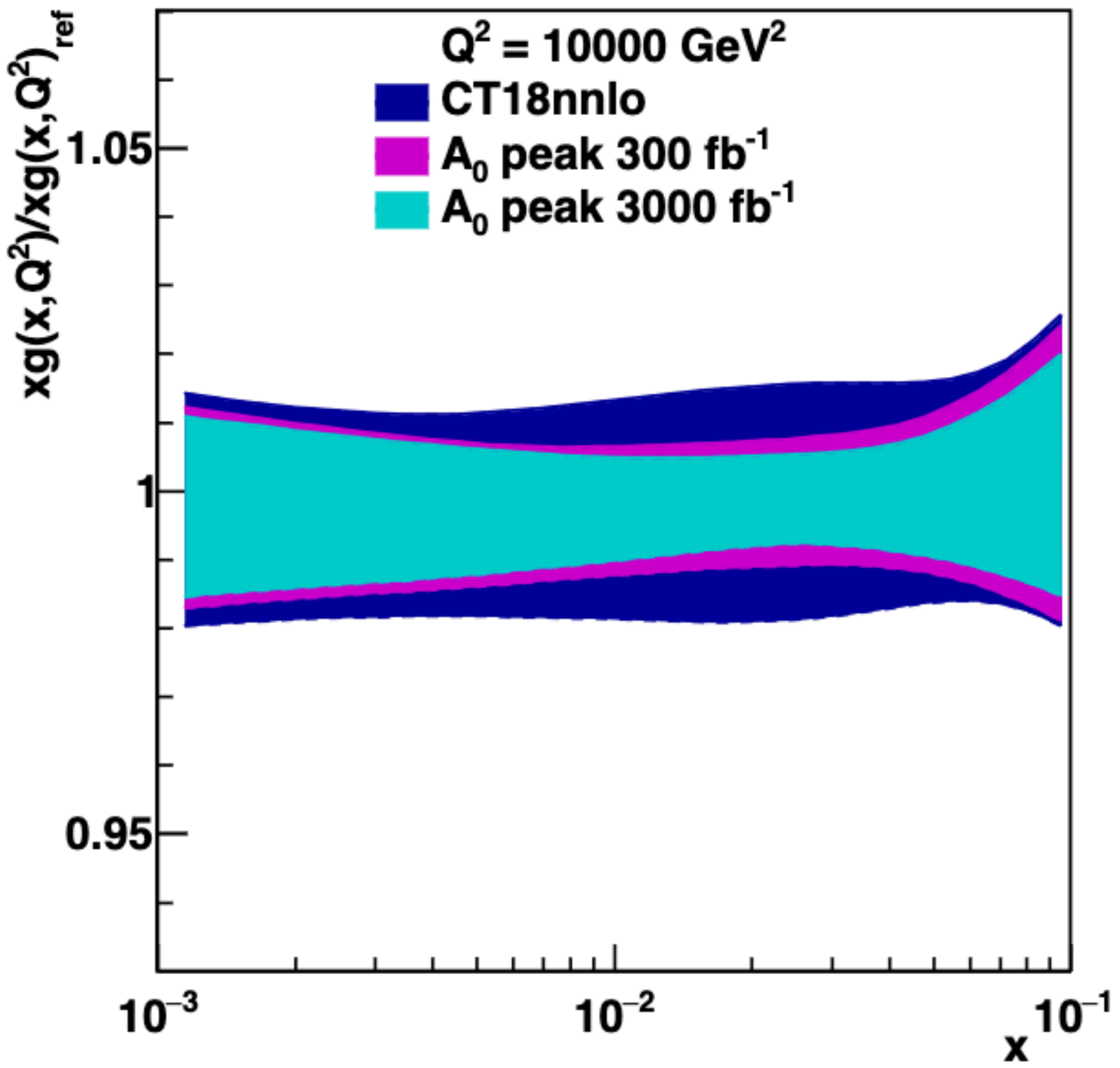
2008.04174

Longitudinal polarization in Drell-Yan

- Z-boson longitudinal polarization sensitive to the fraction of qg/qq in initial state
- Constraints the gluon PDF in the region relevant to Higgs physics from the measurement of a color singlet observable
- Measured at 8TeV, not yet precisely enough for useful constraints, but Run-2/3 measurements are ongoing

2012.10298

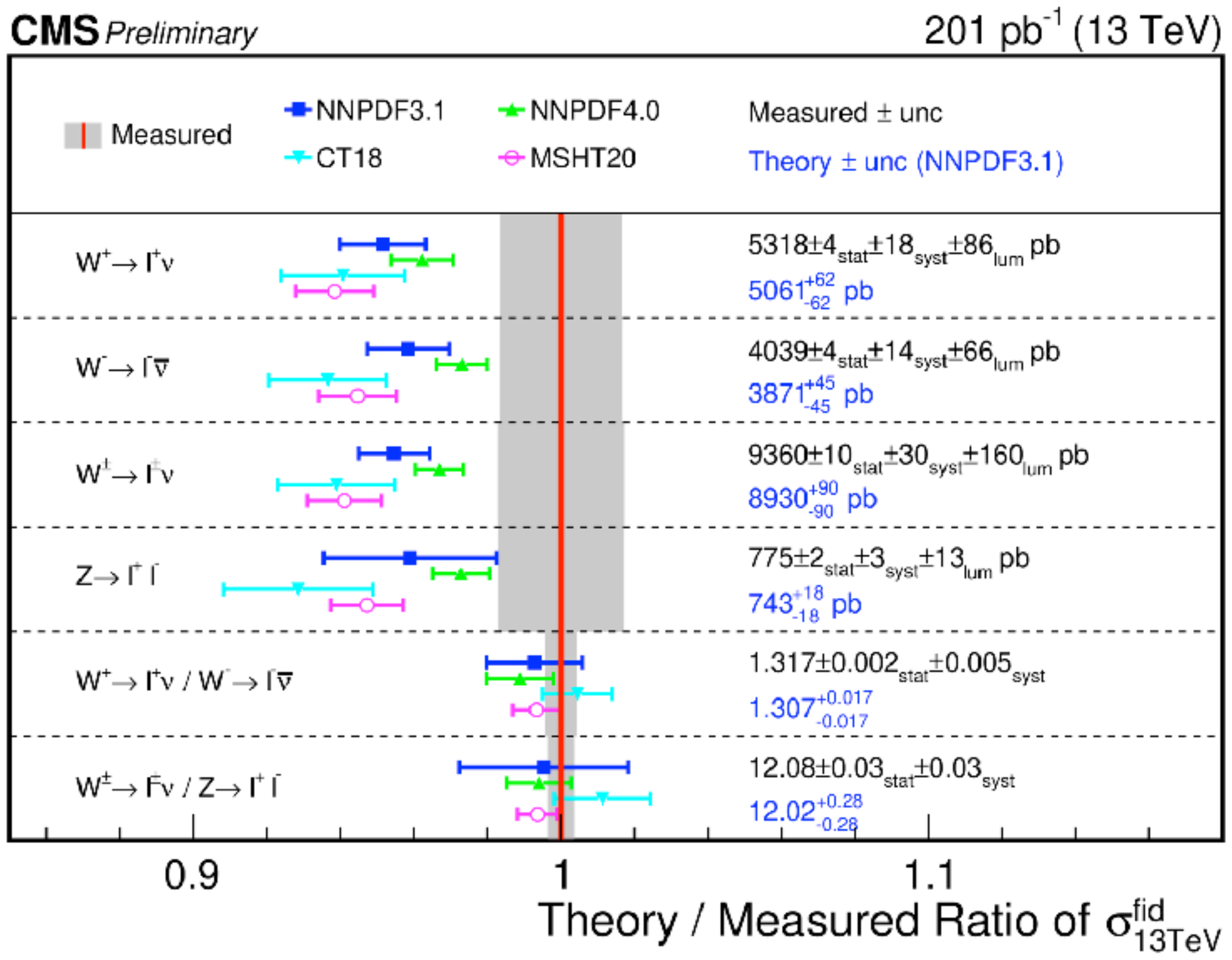


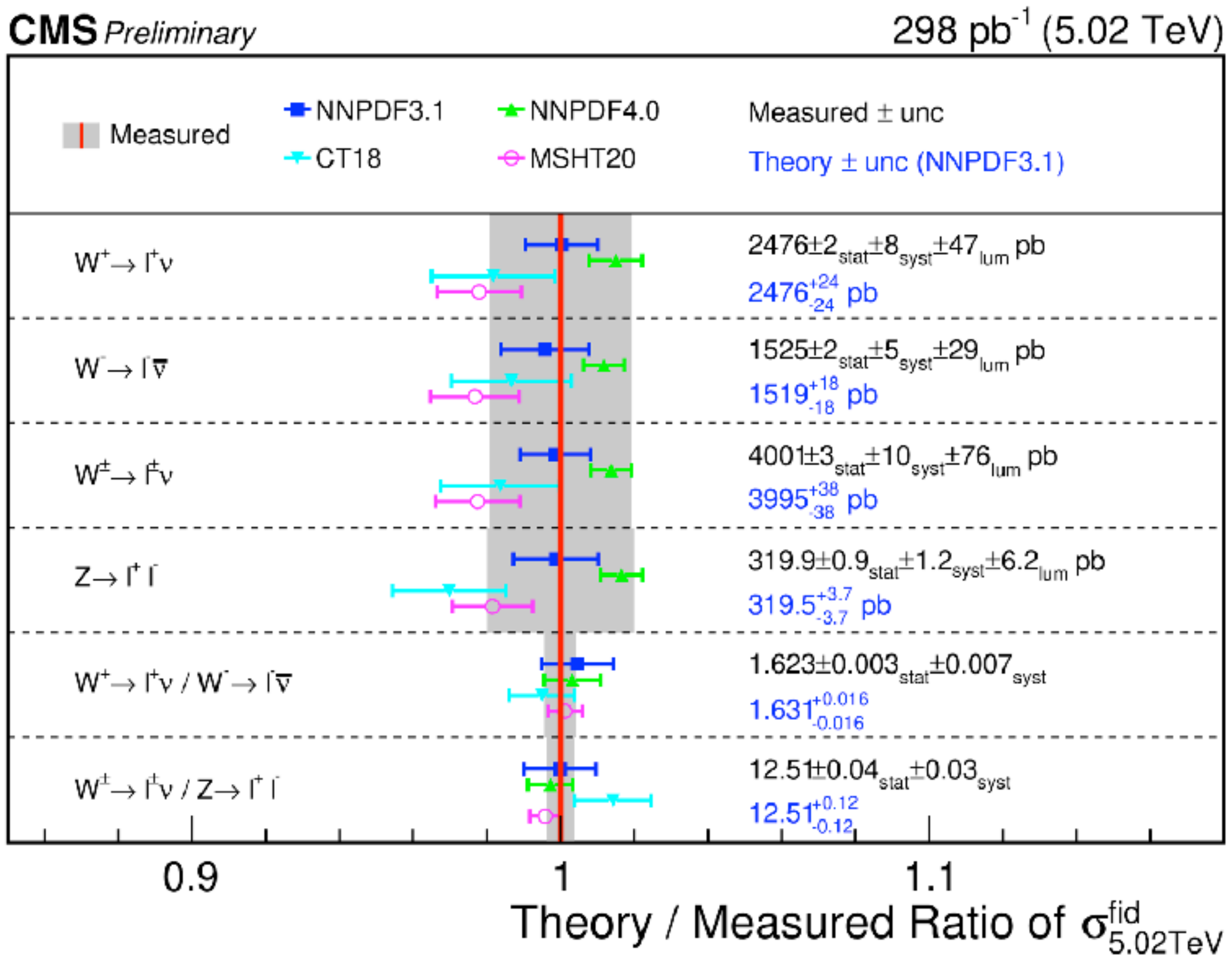


Drell-yan low-mu XS - ATLAS

- Special low pile-up runs collected by ATLAS/CMS at 5 TeV and 13 TeV

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-20-004/index.html





- Sensitive to PDFs also through ratios at different energies

Drell-yan low-mu XS - ATLAS

- Special low pile-up runs collected by ATLAS/CMS at 5 TeV and 13 TeV
- Small ATLAS luminosity uncertainty of 1% should pose very stringent constraints on the PDFs

ATLAS-CONF-2023-028

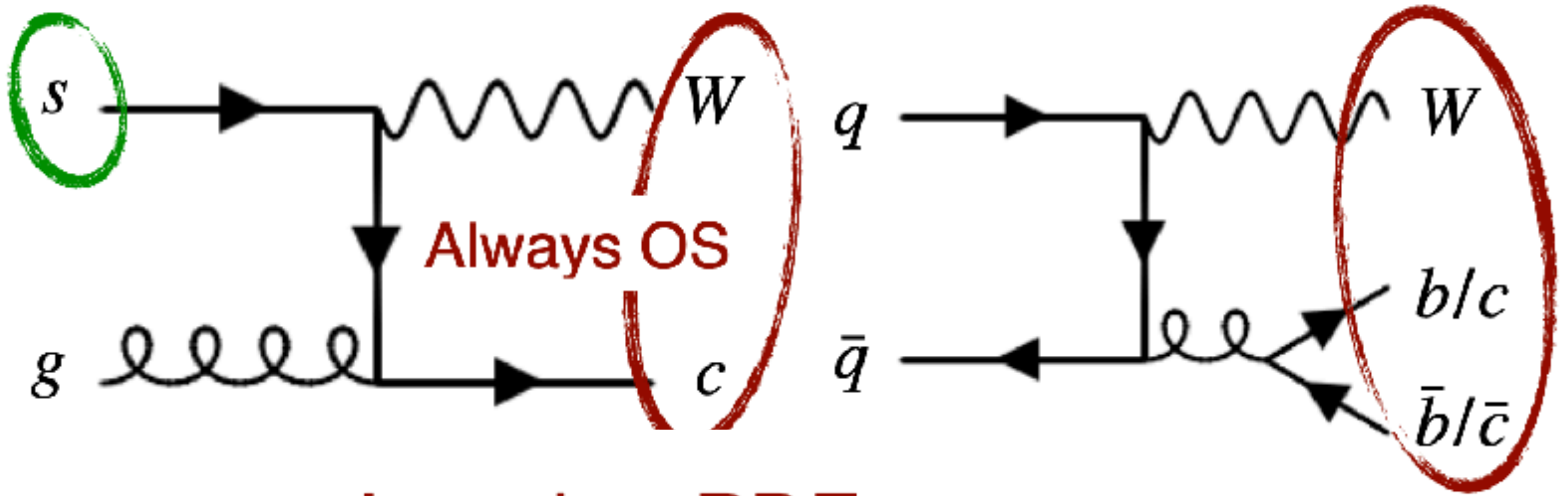
PDF set	$W^- \to \ell\nu$	$W^+ \to \ell\nu$	$Z \to \ell\ell$
Cross-section at 5.02 TeV [pb]			
CT18	1364 -1.25σ	2199 -1.16σ	320.9 -2.95σ
MSHT20	1351 -2.06σ	2185 -2.69σ	324.3 -2.12σ
NNPDF3.1	1381 -0.19σ	2232 +0.16σ	329.8 -0.78σ
Data	1384 ± 16	2228 ± 25	333.0 ± 4.1
Cross-section at 13 TeV [pb]			
CT18	3410 -2.00σ	4462 -2.22σ	749.8 -2.93σ
MSHT20	3397 -2.34σ	4457 -2.33σ	766.1 -1.37σ
NNPDF3.1	3452 -0.89σ	4513 -1.18σ	771.4 -0.86σ
Data	3486 ± 38	4571 ± 49	780.3 ± 10.4

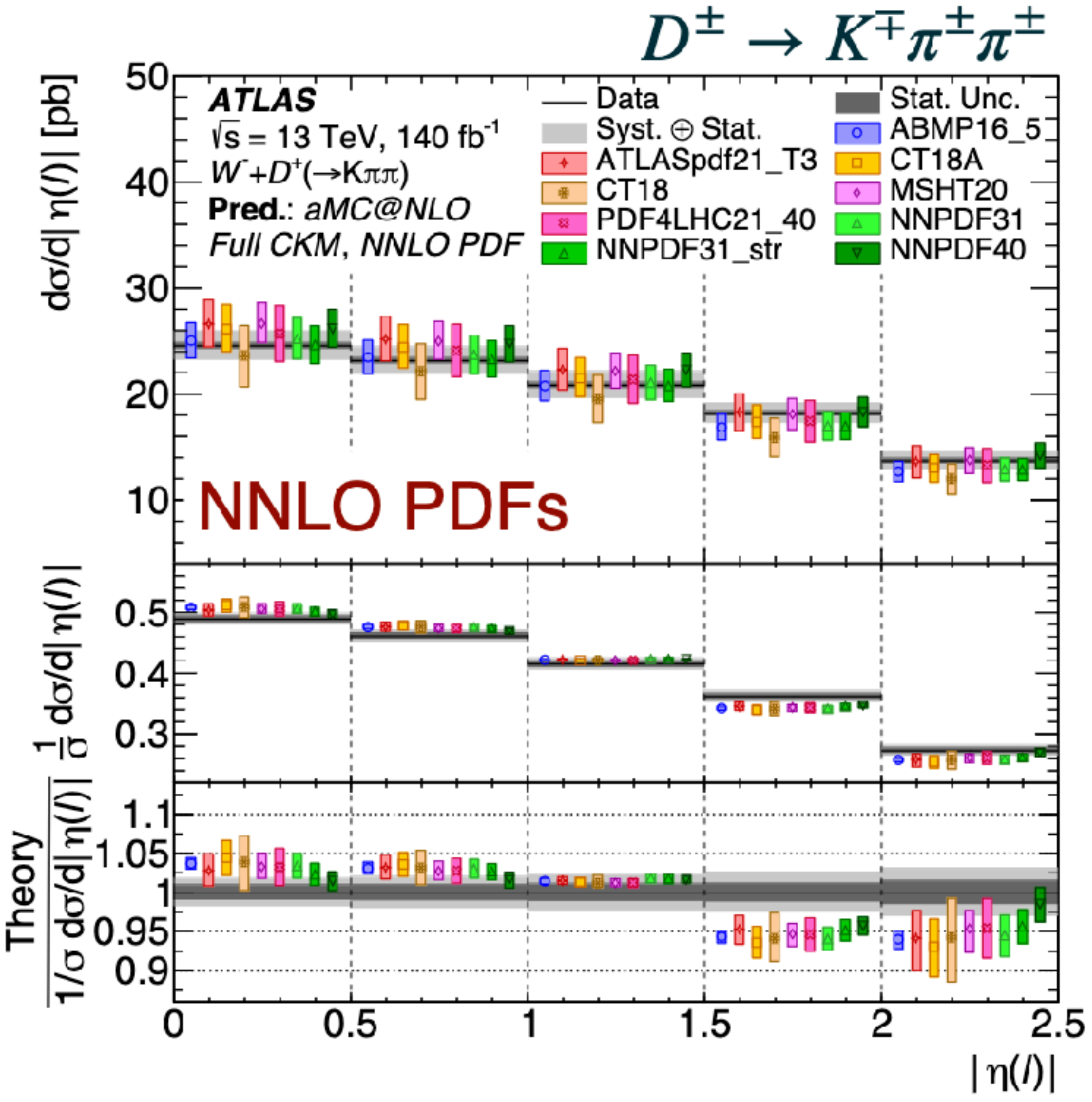
PDF set	$W^- \to \ell\nu$	$W^+ \to \ell\nu$	$Z \to \ell\ell$
Ratio $\sigma_{\mathrm{fid}}(13\,\mathrm{TeV})/\sigma_{\mathrm{fid}}(5.02\,\mathrm{TeV})$			
CT18	2.499	2.029	2.337
MSHT20	2.515	2.040	2.362
NNPDF3.1	2.500	2.022	2.339
Data	2.517 ± 0.038	2.047 ± 0.031	2.340 ± 0.036

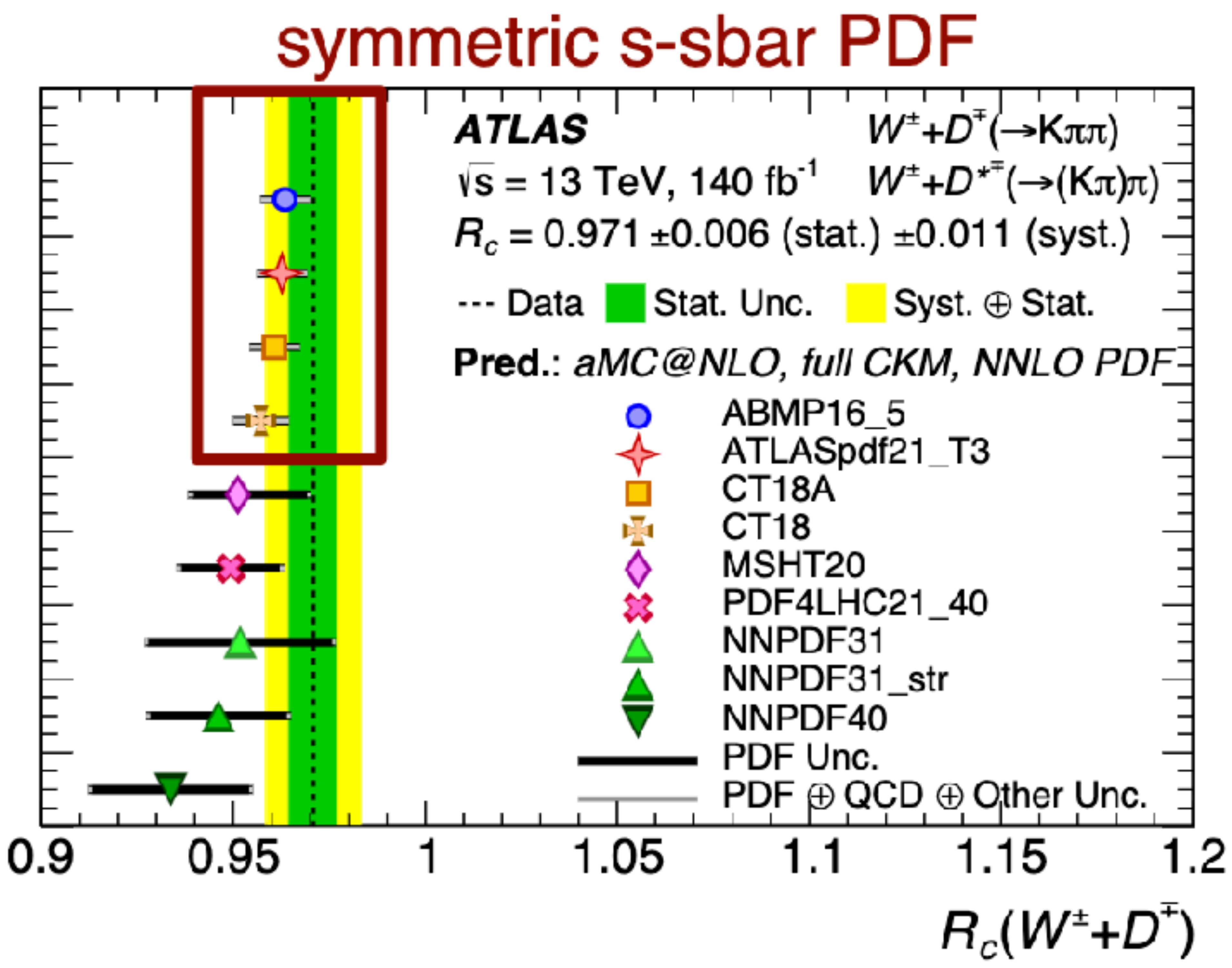
PDF set	W^+/W^-	W^-/Z	W^+/Z	$W^\pm/Z$
Cross-section ratios at 5.02 TeV				
CT18	1.612	4.25	6.85	11.10
MSHT20	1.618	4.16	6.74	10.90
NNPDF3.1	1.616	4.19	6.77	10.95
Data	1.611 ± 0.005	4.16 ± 0.05	6.69 ± 0.08	10.85 ± 0.12
Cross-section ratios at 13 TeV				
CT18	1.309	4.55	5.95	10.50
MSHT20	1.312	4.43	5.82	10.25
NNPDF3.1	1.307	4.48	5.85	10.33
Data	1.312 ± 0.003	4.46 ± 0.07	5.84 ± 0.09	10.31 ± 0.15

W+CHARM

- New measurements of W + charm meson
- Remove gluon splitting with charge subtraction

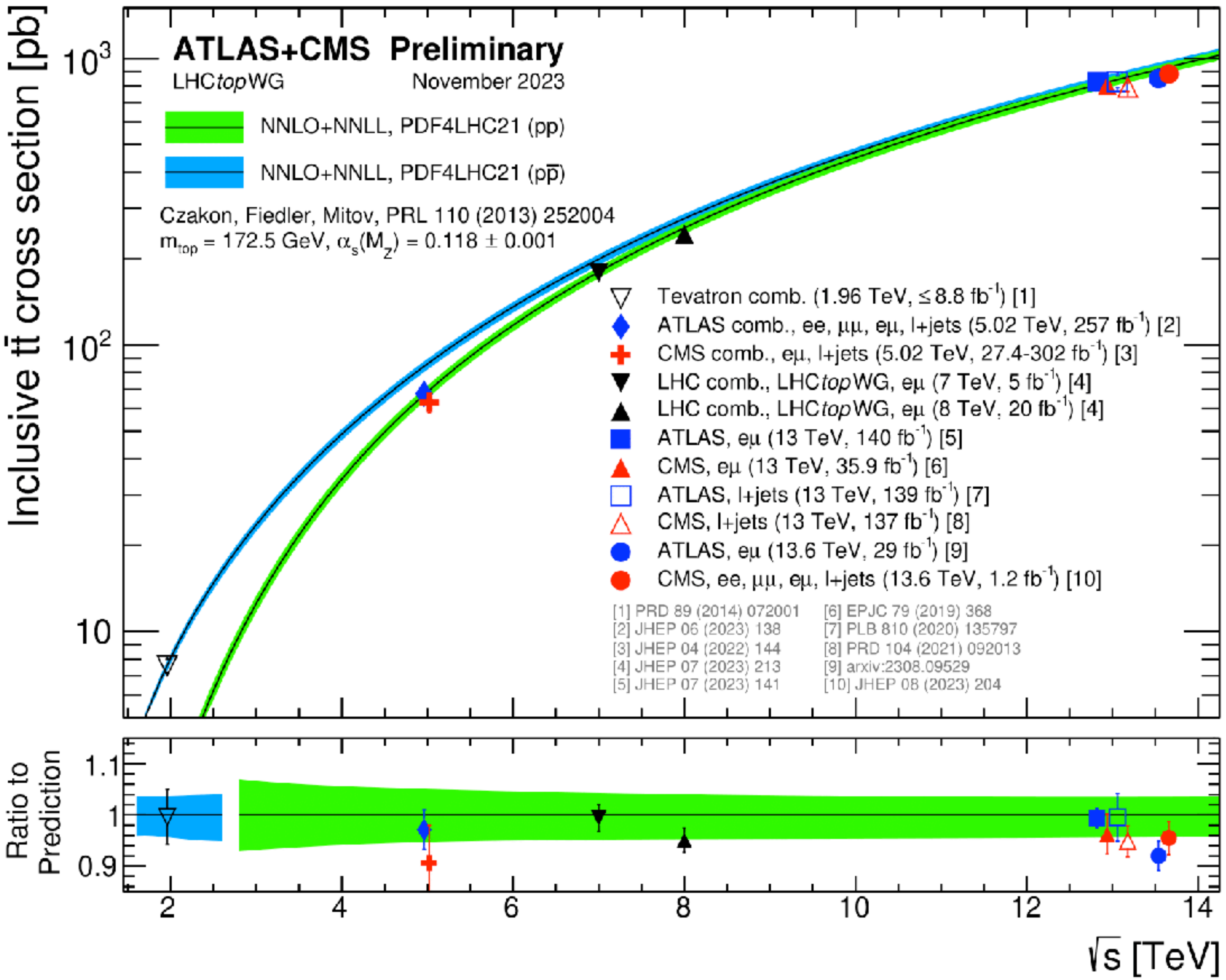




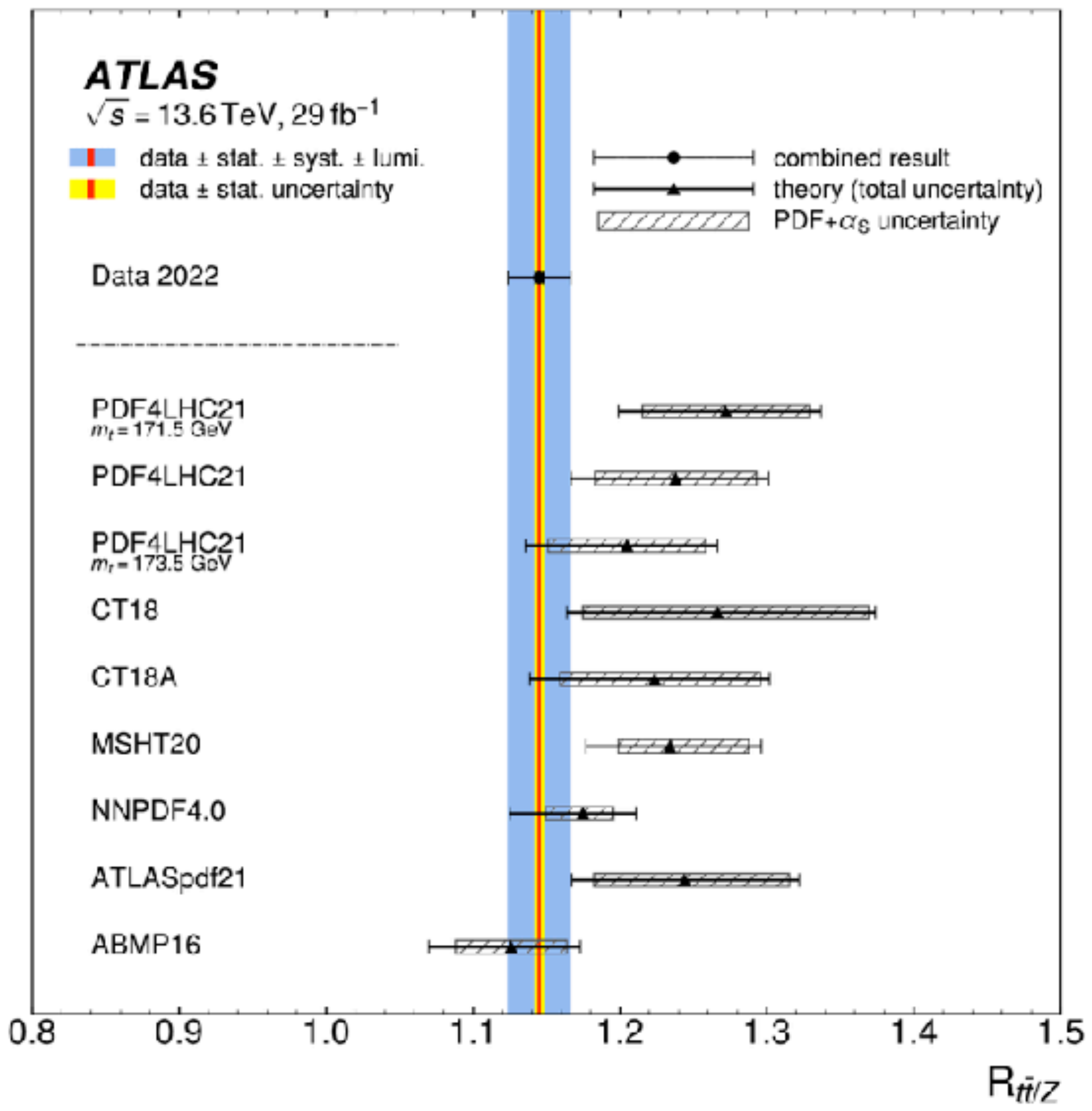


- Experimentally very precise and sensitive to the strange PDF
- NNLO charm fragmentation functions missing for NNLO PDF fits

Top-pair production cross-sections

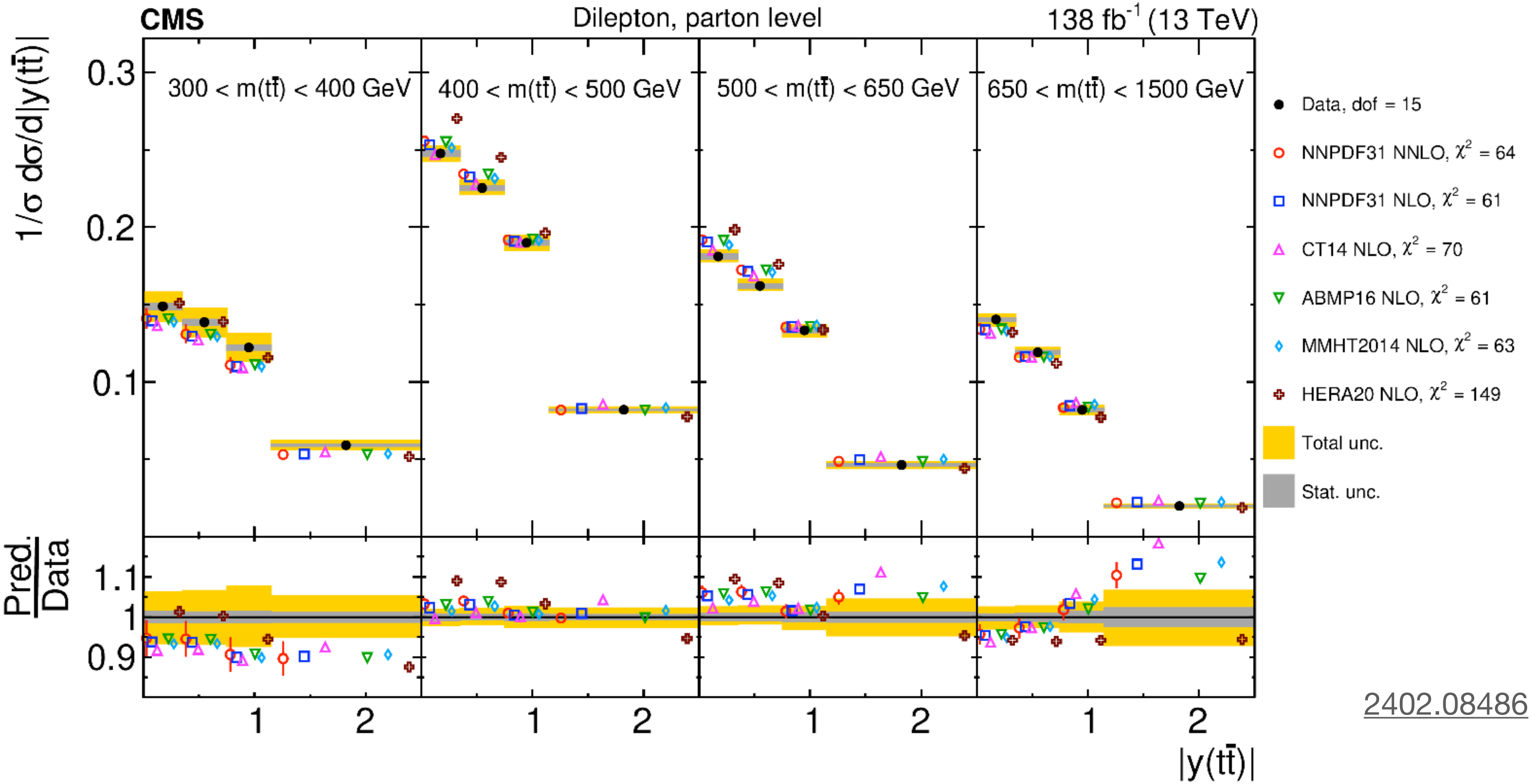


- Better than 2% precision on $t\bar{t}$ cross-sections
- $t\bar{t}/Z$ cross-section ratios powerful probe of PDFs



Parton-level ttbar cross-sections and PDFs

- Differential cross-sections for stable tops below 5% accuracy
- Probe of the gluon PDF, m_t^{pole} and the strong coupling



2402.08486

LEPTONIC OBSERVABLES IN TTBAR

- Since a few years, we can also predict top decay observables at NNLO QCD (NWA)
- Unlike stable-top cross-sections, they can be measured much more precisely and have no theoretical ambiguity
- Would be nice to see them included into PDF fits

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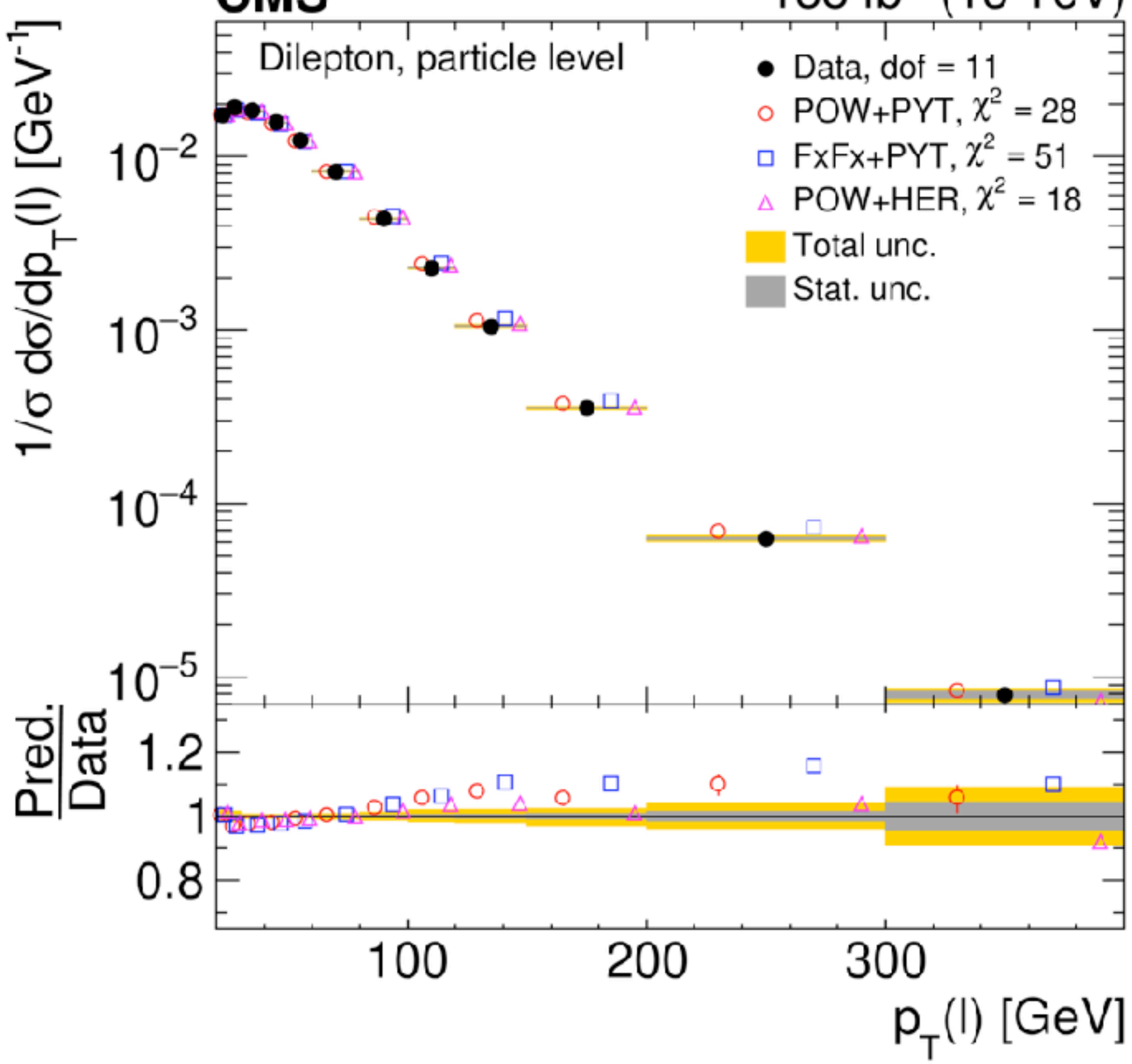

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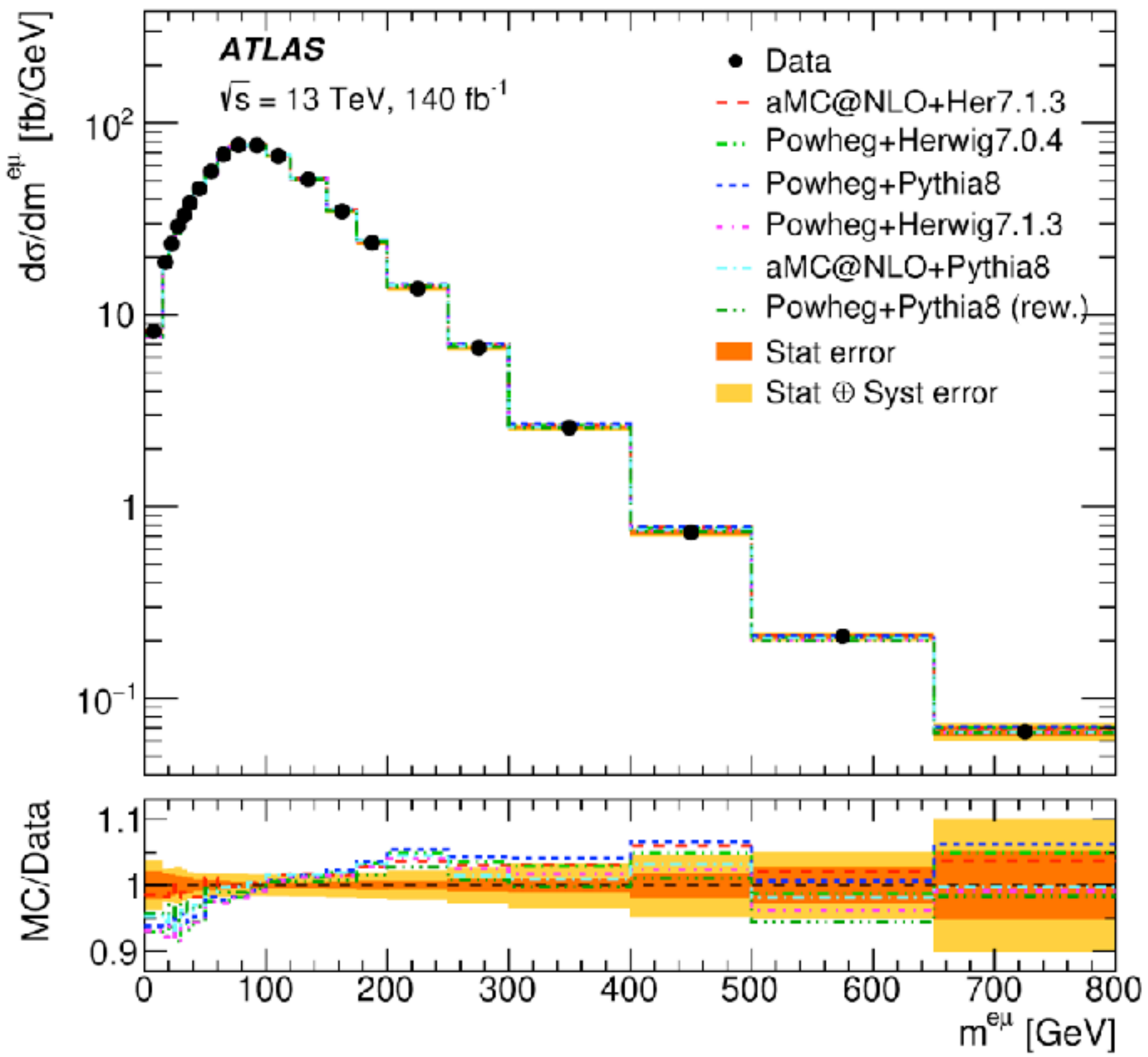
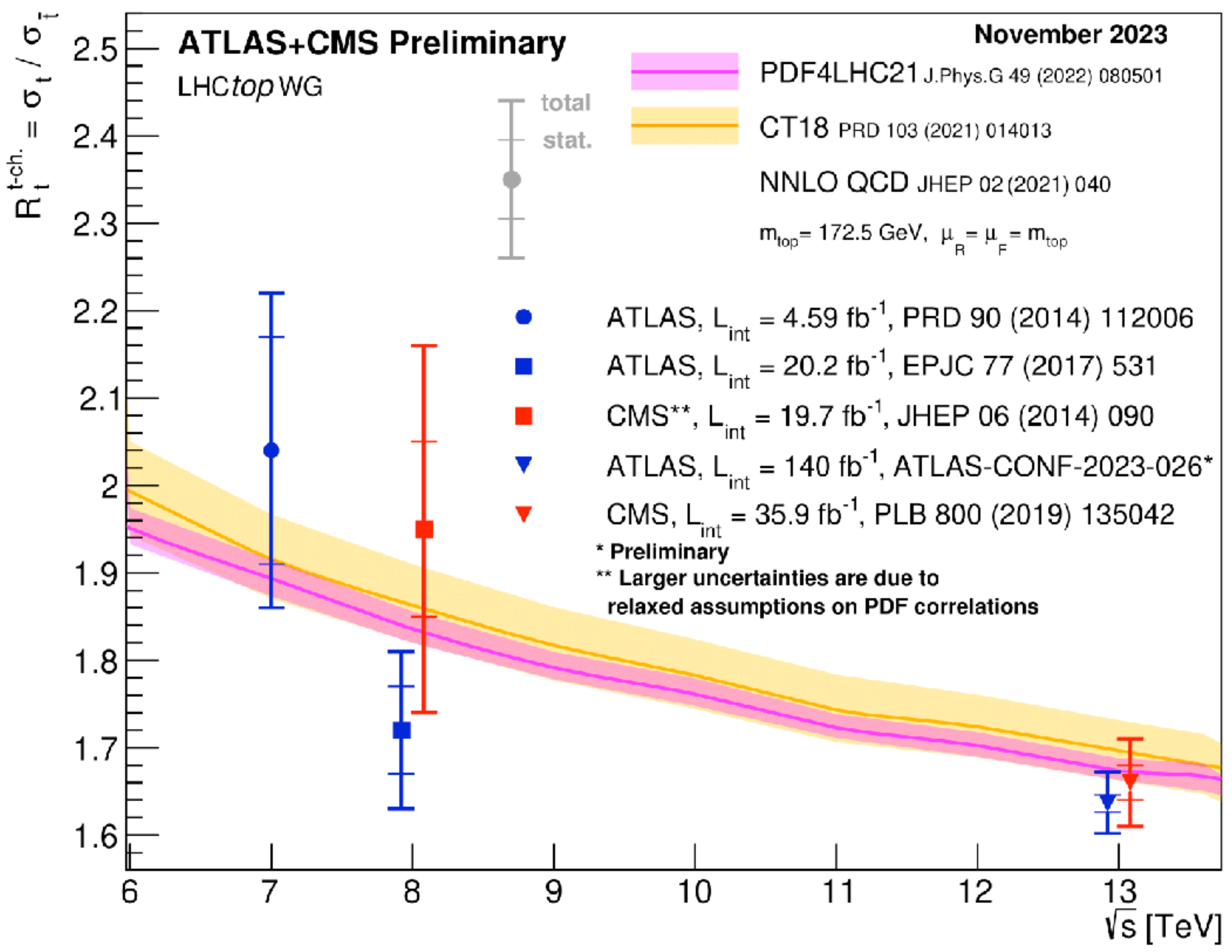
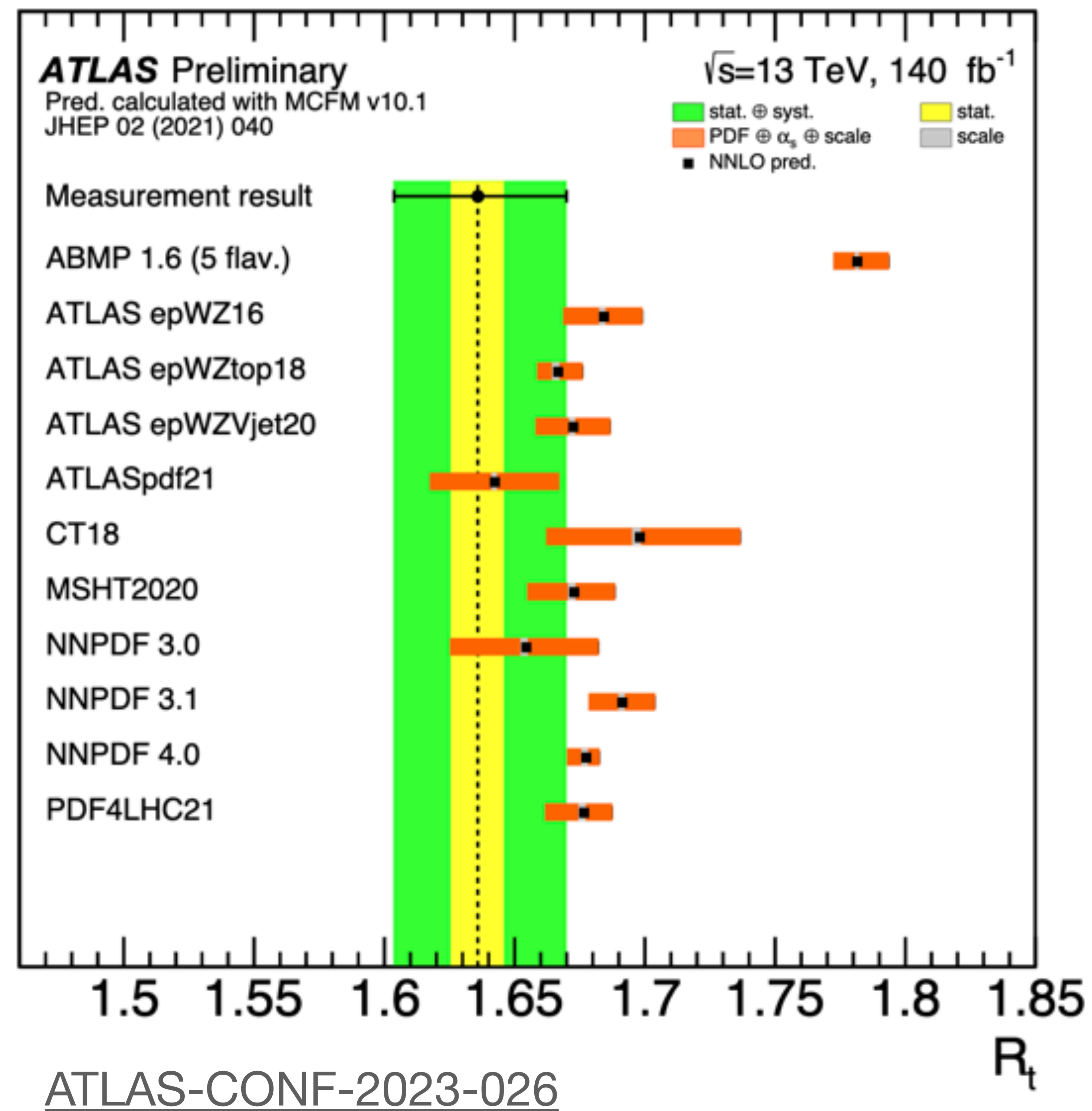


Single top t-channel cross-sections



- t-channel single top sensitive to the u/d ratio at large-x
- Cross-section ratio to cancel out systematic effects

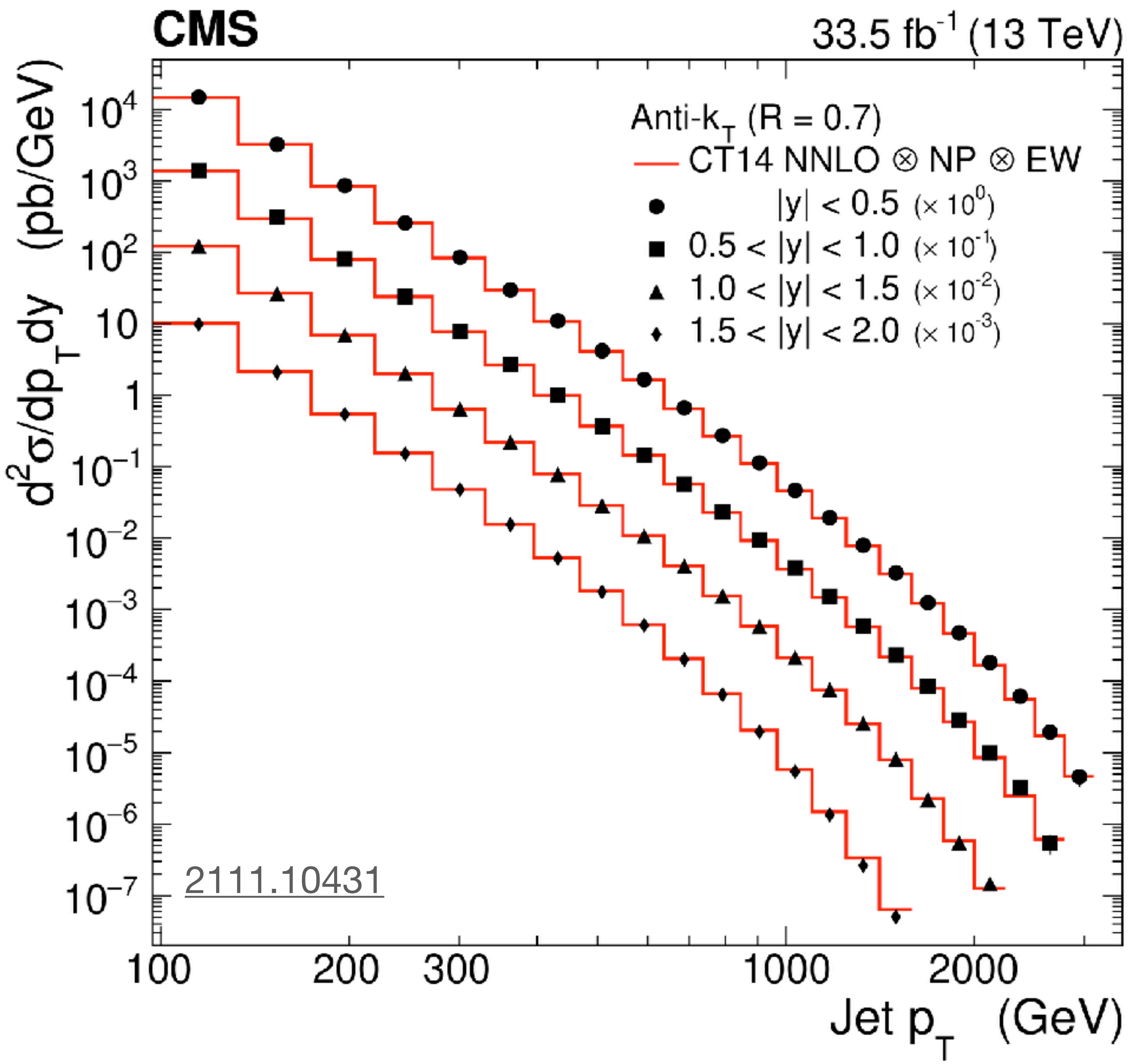
$$R_t = \sigma(tq)/\sigma(\bar{t}q)$$



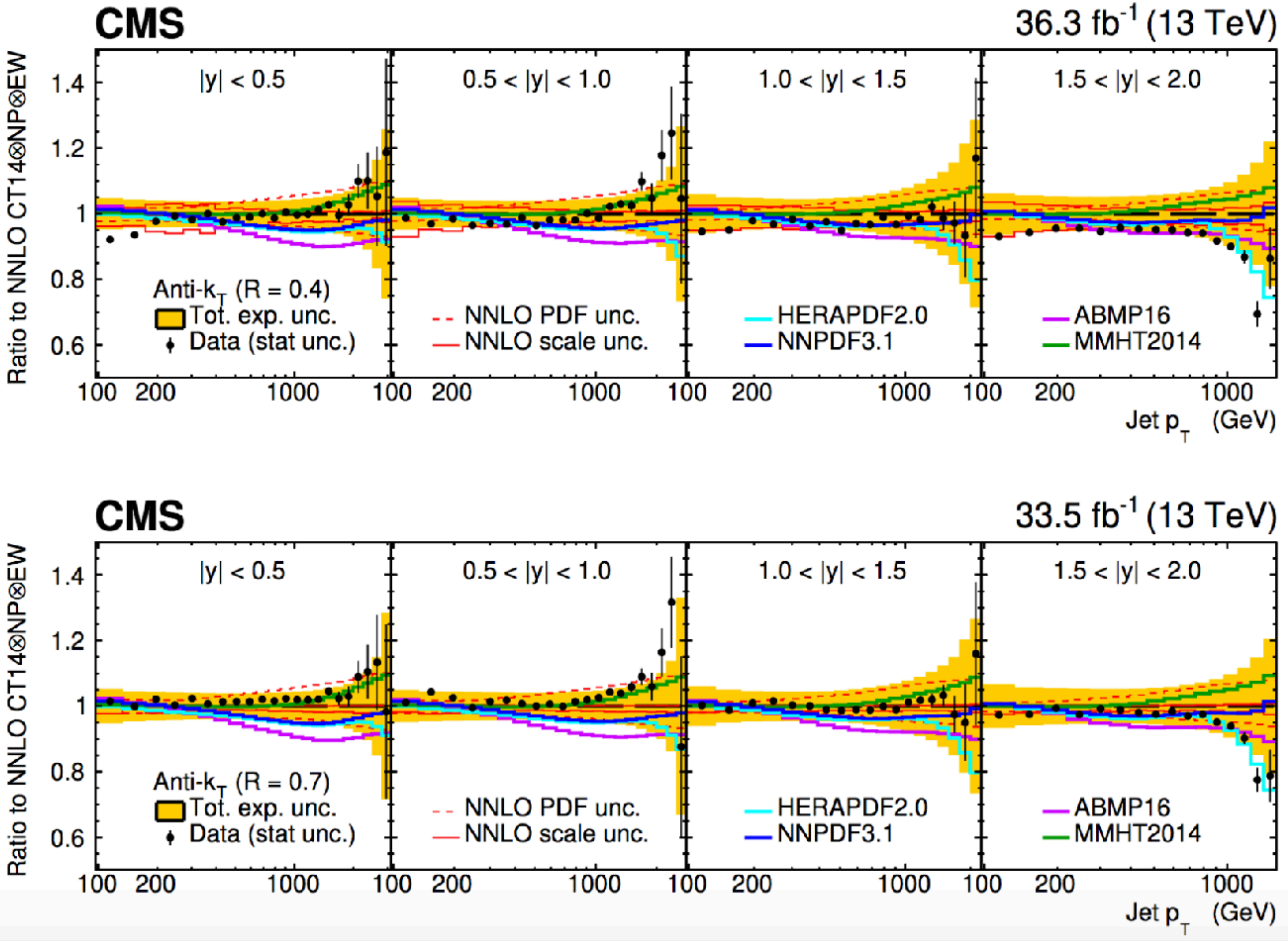
ATLAS-CONF-2023-026

CMS Inclusive jets at 13 TeV

- CMS 13 TeV inclusive jet cross-sections using 36 fb^{-1} of data
- Very sensitive to the strong coupling, but also to the gluon PDF
- Avoid possible biases on the result by performing a simultaneous PDF fit using the HERA DIS data
- Jets now with NNLO QCD theory



CMS 13 TeV inclusive jets



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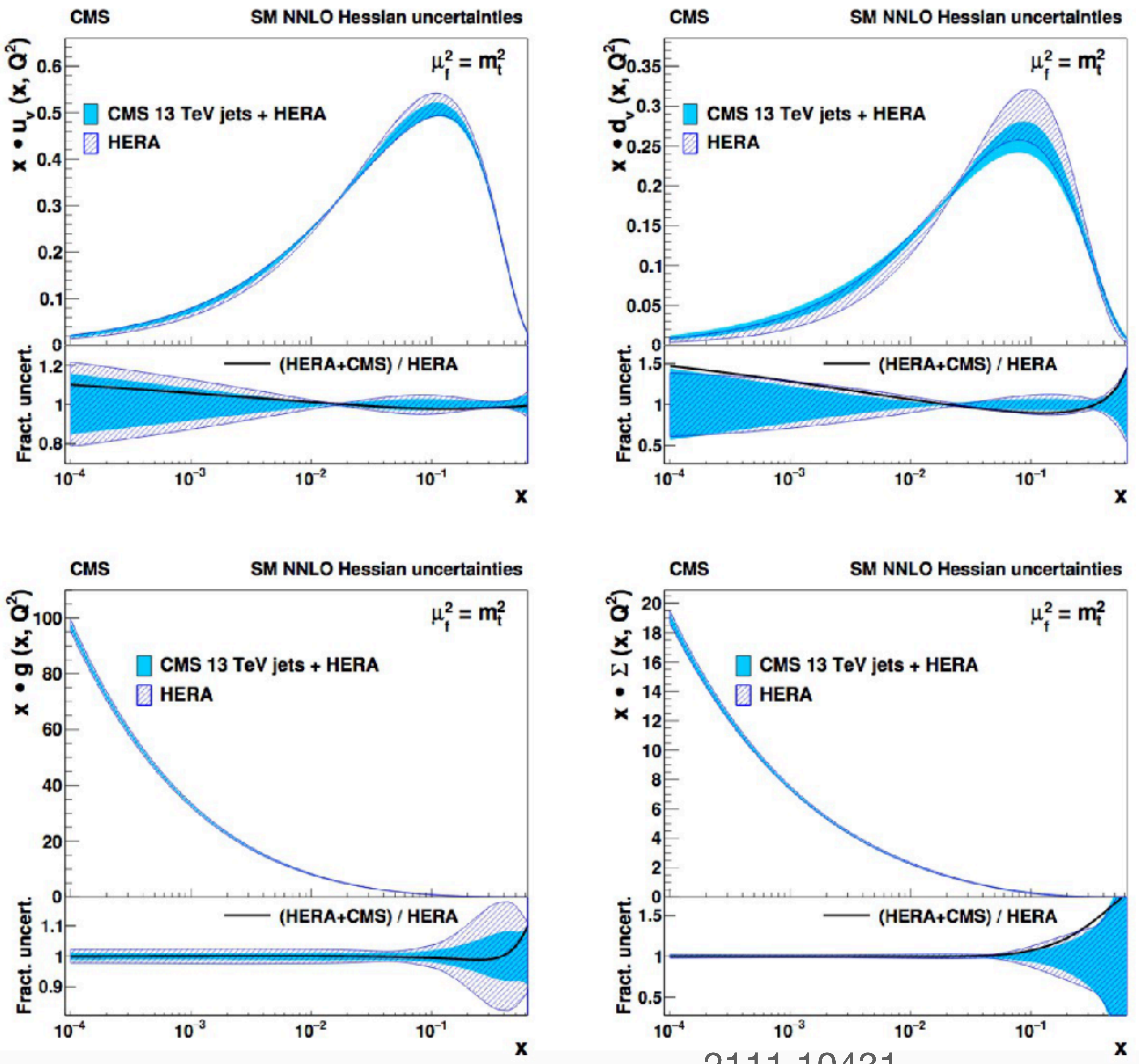
Determination of PDFs and strong coupling



2111.10431

- Improved gluon constraints in the "usual" HERA+X fit
- Reduction in the MHOU on the strong coupling constant using the NNLO grids
- Additionally constraints EFT operators in the PDF fit

With NNLO k-factors

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

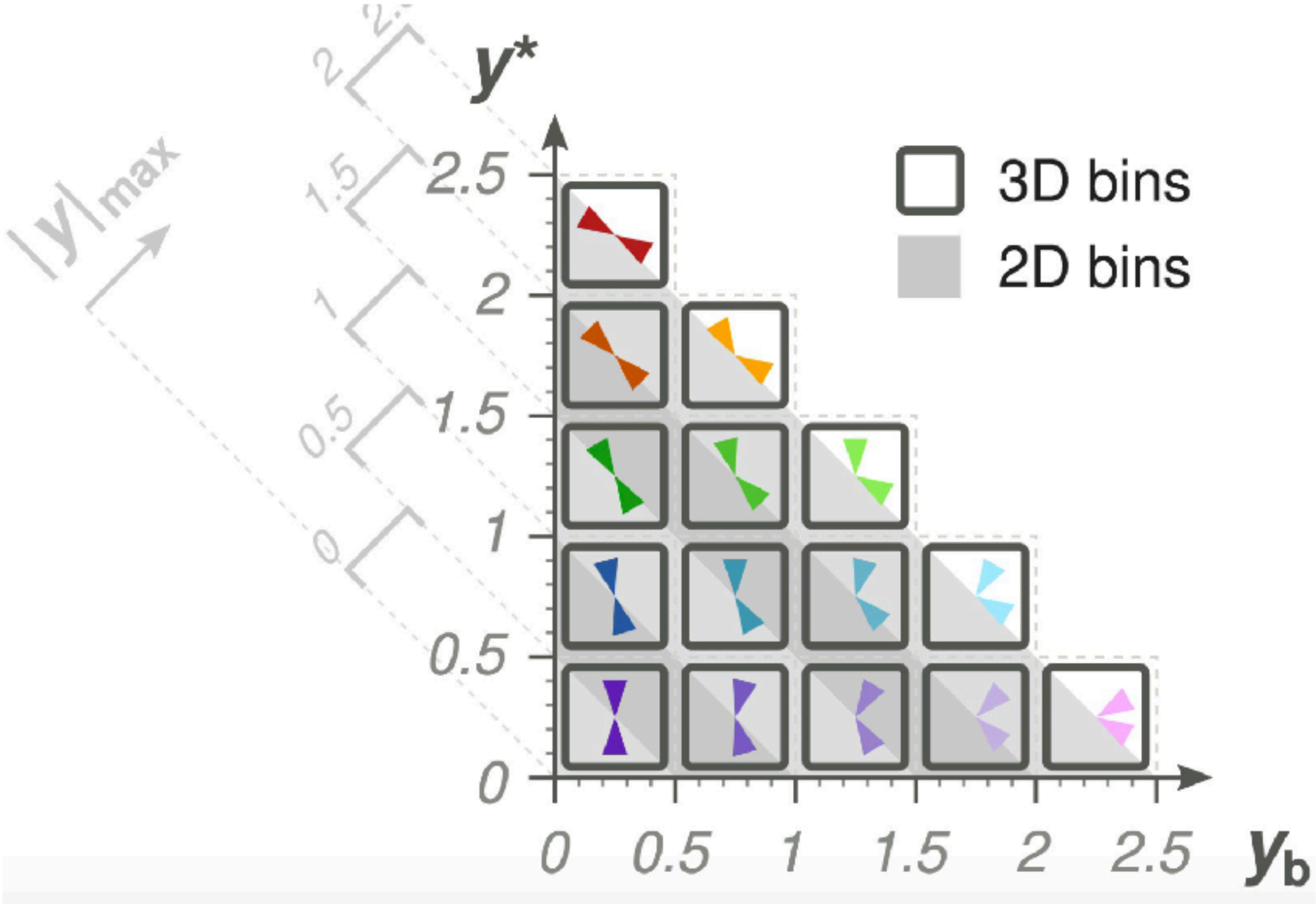
With NNLO grids

$$\alpha_S(m_Z) = 0.1166 \pm 0.0014\,(\text{fit}) \pm 0.0007\,(\text{model}) \pm 0.0004\,(\text{scale}) \pm 0.0001\,(\text{param.})$$

Triple-differential dijet cross-sections at 13 TeV

- Measured double- and triple-differentially as a function of leading dijet variables
- **2D** : dijet mass in five rapidity regions $y_{\max} = \mathrm{sign}(|\max(y_1, y_2)| - |\min(y_1, y_2)|) \max(|y_1|, |y_2|)$
- **3D**: mass and average pT in bins of rapidity separation and boost of the diet system

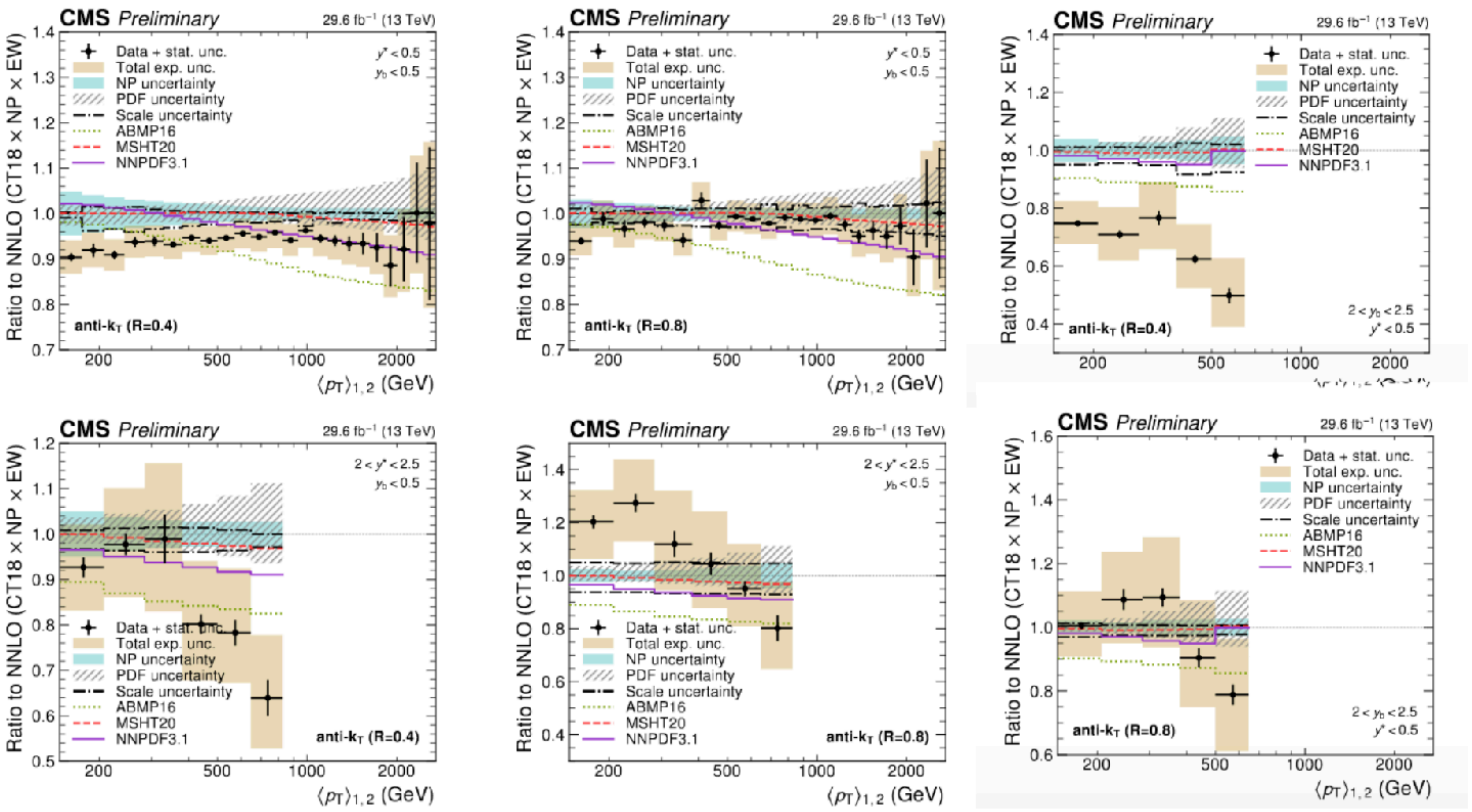
$$y^* = \frac{1}{2}|y_1 - y_2|, \quad y_b = \frac{1}{2}|y_1 + y_2| \quad m_{1,2} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}, \quad \langle p_T \rangle_{1,2} = \frac{1}{2}(p_{T,1} + p_{T,2})$$



The dijet rapidity phase-space, highlighting the relationship between variables used for 2D and 3D measurements

Colored triangles suggest the orientation of two jets in different phase-space regions in the lab frame

Data/predictions - 3D dijets



2312.16669

- Some differences in the shapes which do not seem to be due to PDFs

PDFs and strong coupling

- Performed a simultaneous PDF + strong coupling extractions
- Stronger PDF constraints and smaller strong coupling uncertainties with 3D data

2D: $\alpha_s(m_Z) = 0.1201 \pm 0.0012\,(\text{fit}) \pm 0.0008\,(\text{scale}) \pm 0.0008\,(\text{model}) \pm 0.0005\,(\text{param.})$
$= 0.1201 \pm 0.0021\,(\text{total}),$

3D: $\alpha_s(m_Z) = 0.1201 \pm 0.0010\,(\text{fit}) \pm 0.0005\,(\text{scale}) \pm 0.0008\,(\text{model}) \pm 0.0006\,(\text{param.})$
$= 0.1201 \pm 0.0020\,(\text{total}),$

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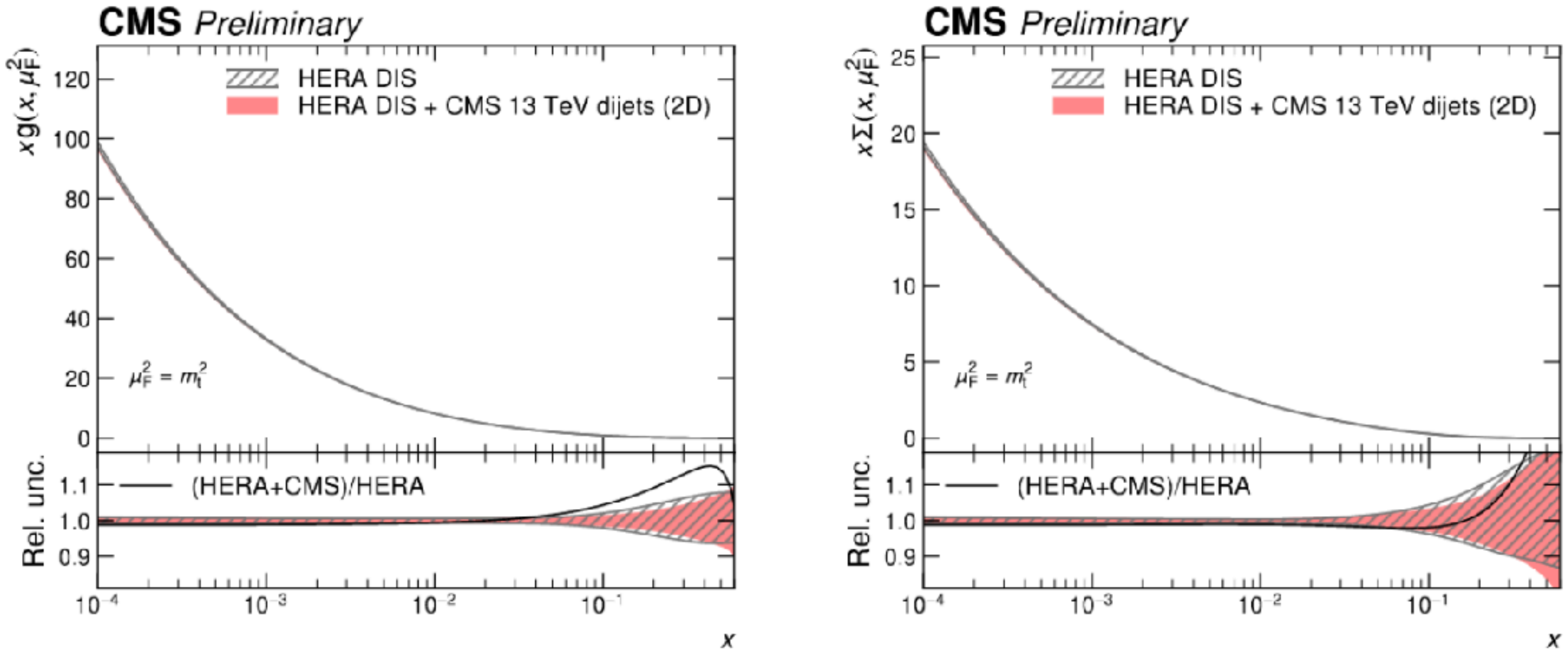
- Some tensions with 3D data at high rapidities
- Is NNLO QCD enough?



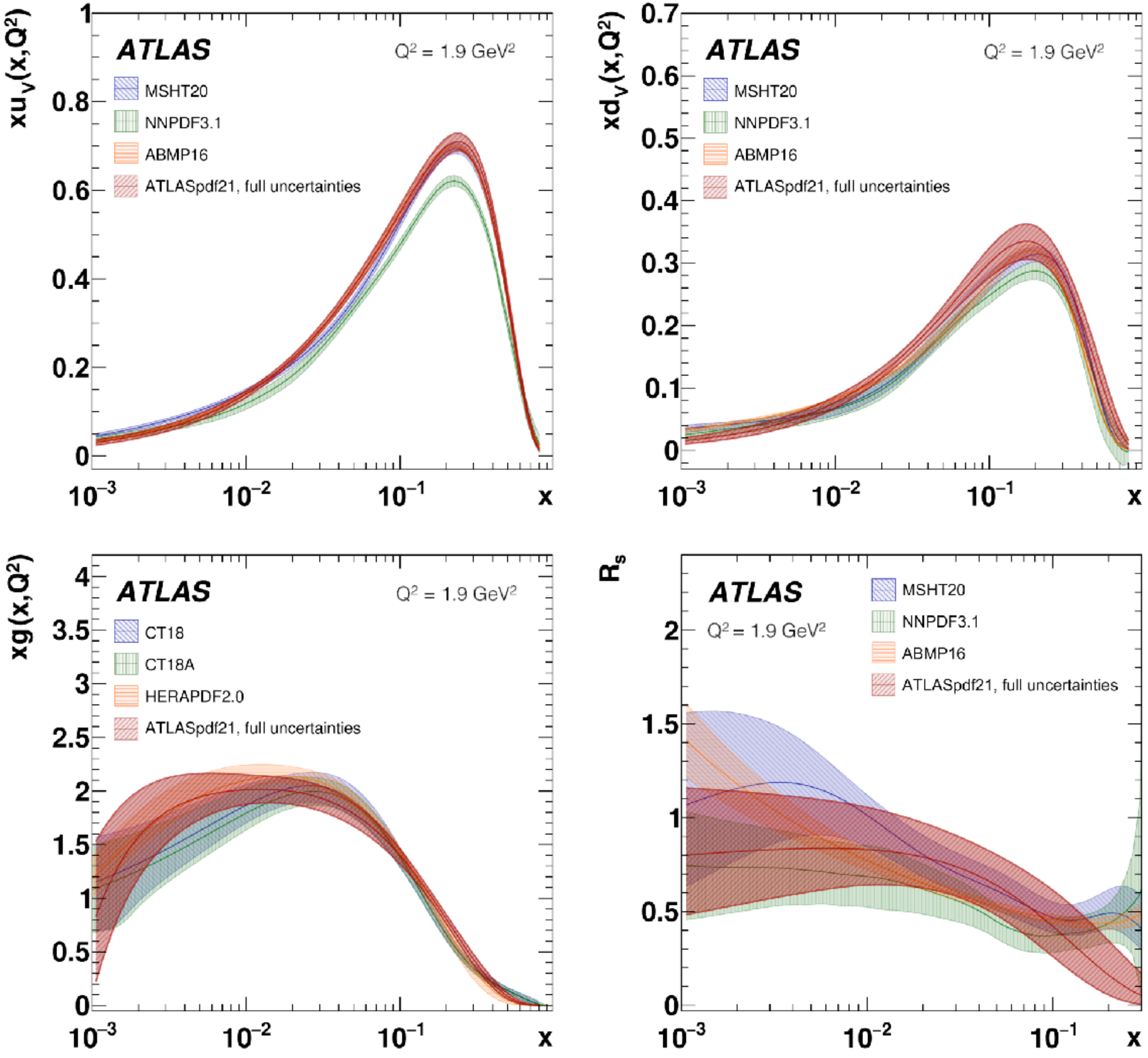
An LHC PDF fit - ATLASpdf21

- First attempt at a global fit by an LHC Collaboration
- Test (internal) consistency of the ATLAS data and systematic correlation models

Data set	$\sqrt{s}$ [TeV]
Inclusive $W, Z/\gamma^*$	7
$t\bar{t}$	8
$W^{\pm}$ + jets	8
Z + jets	8
Inclusive Z/γ^*	8
Inclusive W	8
Inclusive isolated γ	8, 13
$t\bar{t}$	13
Inclusive jets	8

2112.11266

- Consider a variety of ATLAS measurement at different energies and HERA2 inc. DIS
- Analysis performed at NNLO QCD (+NLO EW when available) using xFitter code
- Enlarged dataset and experimental accuracy required:
  - Careful studies of systematic correlations beyond published material
  - Inflated uncertainties with a dynamic tolerance to cover for tensions in the fit
  - Evaluate the impact of the high-Q^2 data which could bias BSM searches

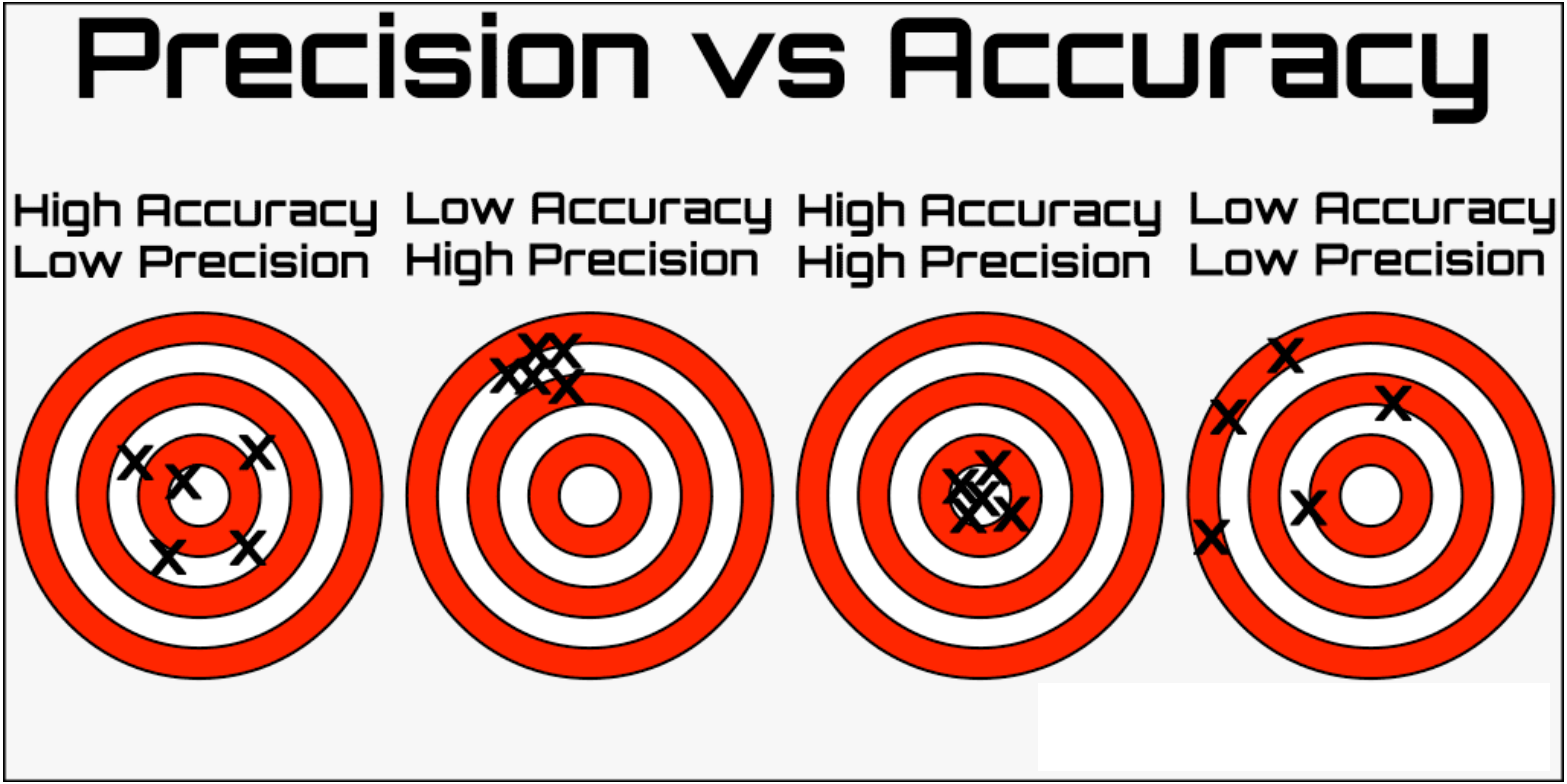


ATLASpdf21 results

- Good description of the fitted data

ATLASpdf21	CT18	CT18A
2010/1620 (1.24)	2135/1641 (1.30)	2133/1641 (1.30)
MSHT20	**HERAPDF2.0**	**NNPDF3.1**
2218/1641 (1.35)	2262/1641 (1.37)	2109/1641 (1.29)

- Significant impact of the ATLAS data on the valence distributions
- PDFs in agreement with global fits


Precision vs Accuracy
High Accuracy
Low Precision
Low Accuracy
High Precision
High Accuracy
High Precision
Low Accuracy
Low Precision

Not all measurements are born equal

- Certain measurements provide enough of information for reinterpretation, others do not
- Certain measurements have been cross-checked across multiple channels, others not
- Certain measurements can be shown to agree with theory, others not
- Certain observables are direct measurements, others extrapolations using theory (stable tops, parton-level jets, Born-leptons, …)

- Suggest to identify a subset of precise and self-consistent measurements which we believe to be well described by theory to be used for **"reduced data PDF fits"**
- Involving both PDF fitting groups and experimental collaborations
- Similar to PDF4LHC benchmarking, but aimed at a deeper understanding of differences in PDFs and alleviate the need for tolerances
- Could consider a "PDF challenge" in which we provide you with pseudo data generated under a known probability distribution (including tensions) and we compare the PDF+uncertainties returned by the various PDF fitting approaches

Summary

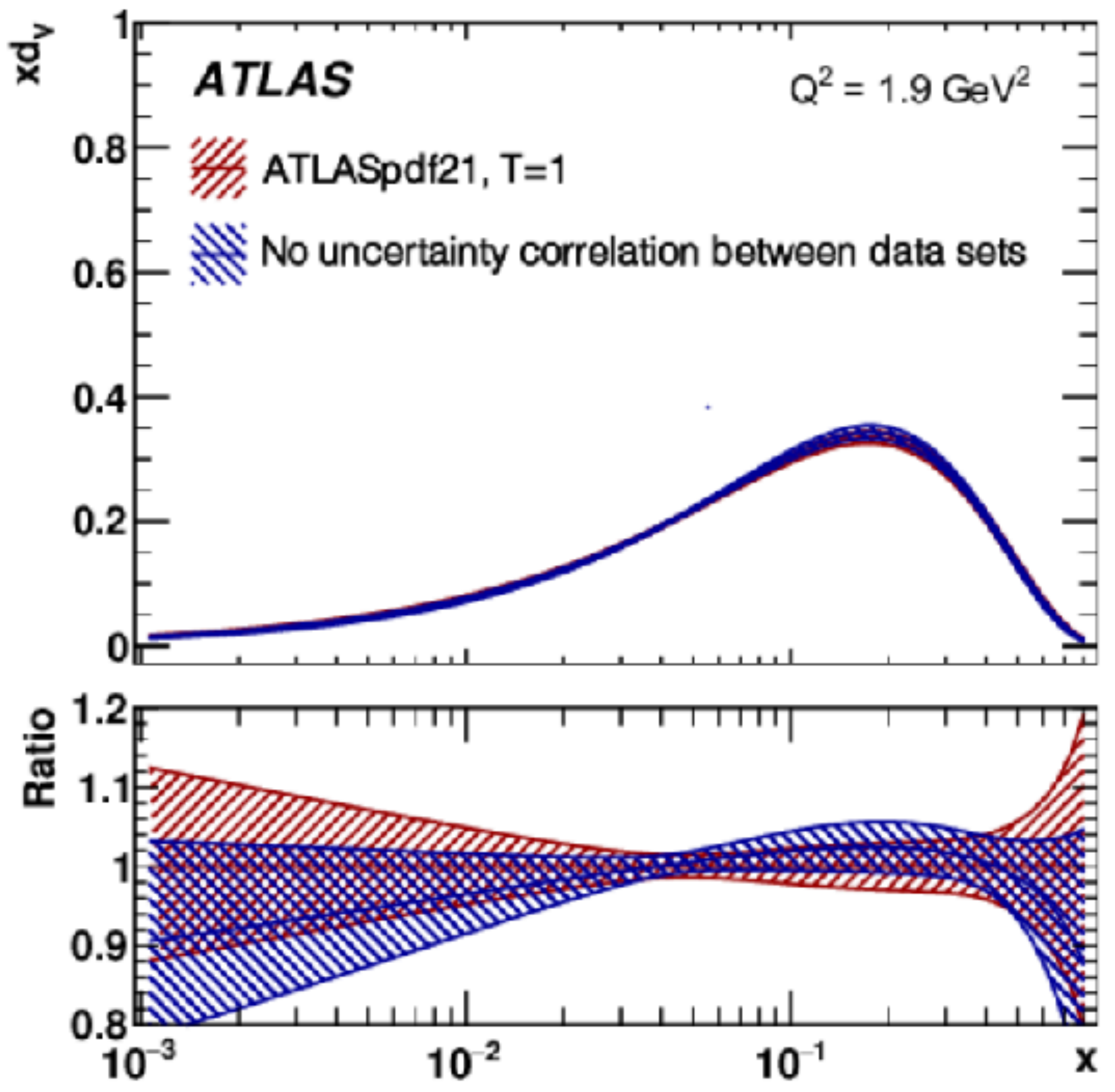
- Experimental accuracy of LHC measurements is very high
- They provide important constraints for the PDFs
  - Different energies allow to cover extended x range
  - Large (or special) data samples to reduce uncertainties
  - Small luminosity uncertainty highly constraining PDFs

- Data however is not/cannot be used to its full potential
- Without self-consistency between measurements/processes/experiments and theory predictions PDF uncertainties won't go down in global fits
- A problem for precision measurements limited by PDFs (α_S, m_W, …)
- Some discussions ongoing on how to improve over the current situation

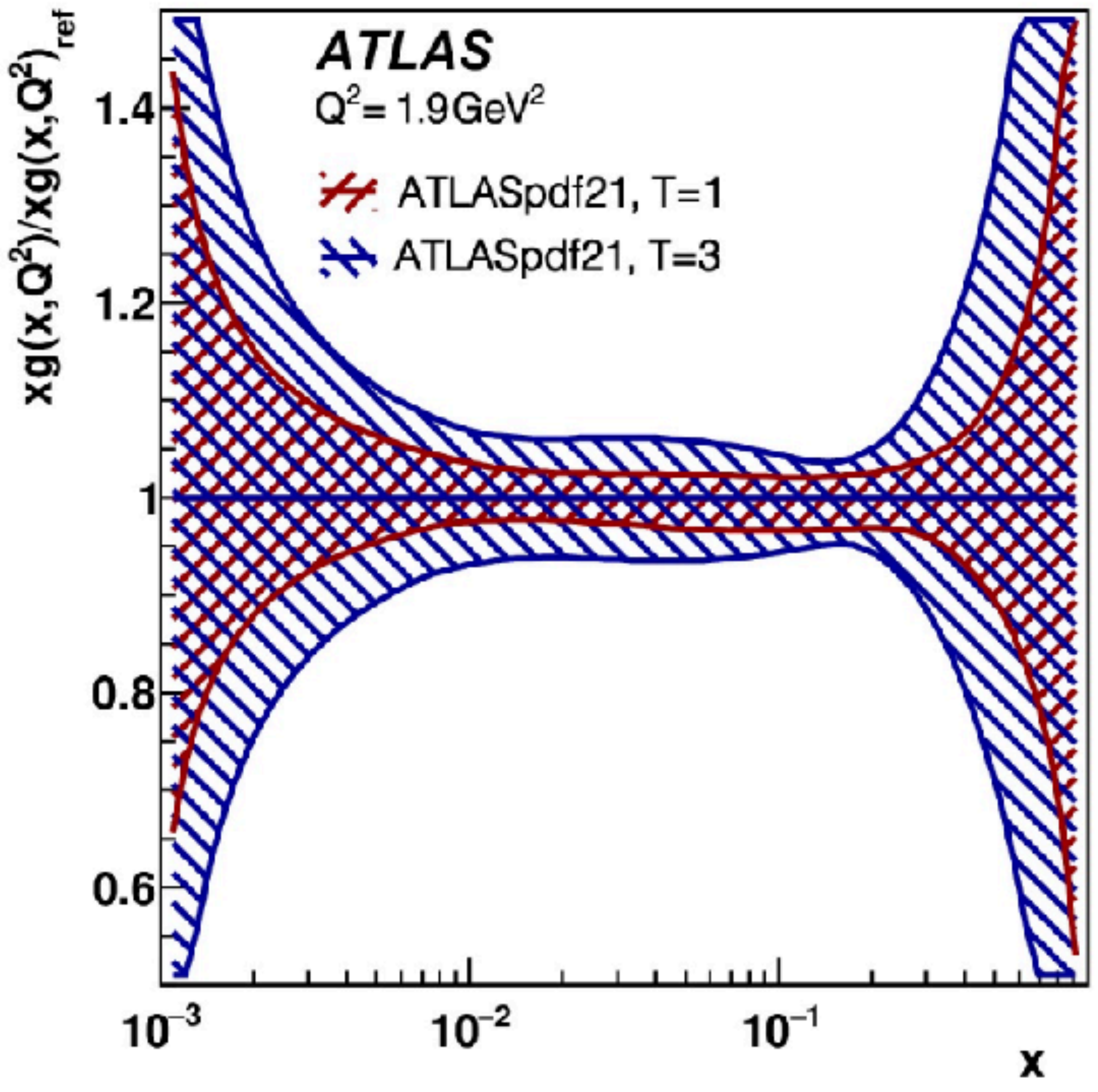
Backup

ATLASpdf21

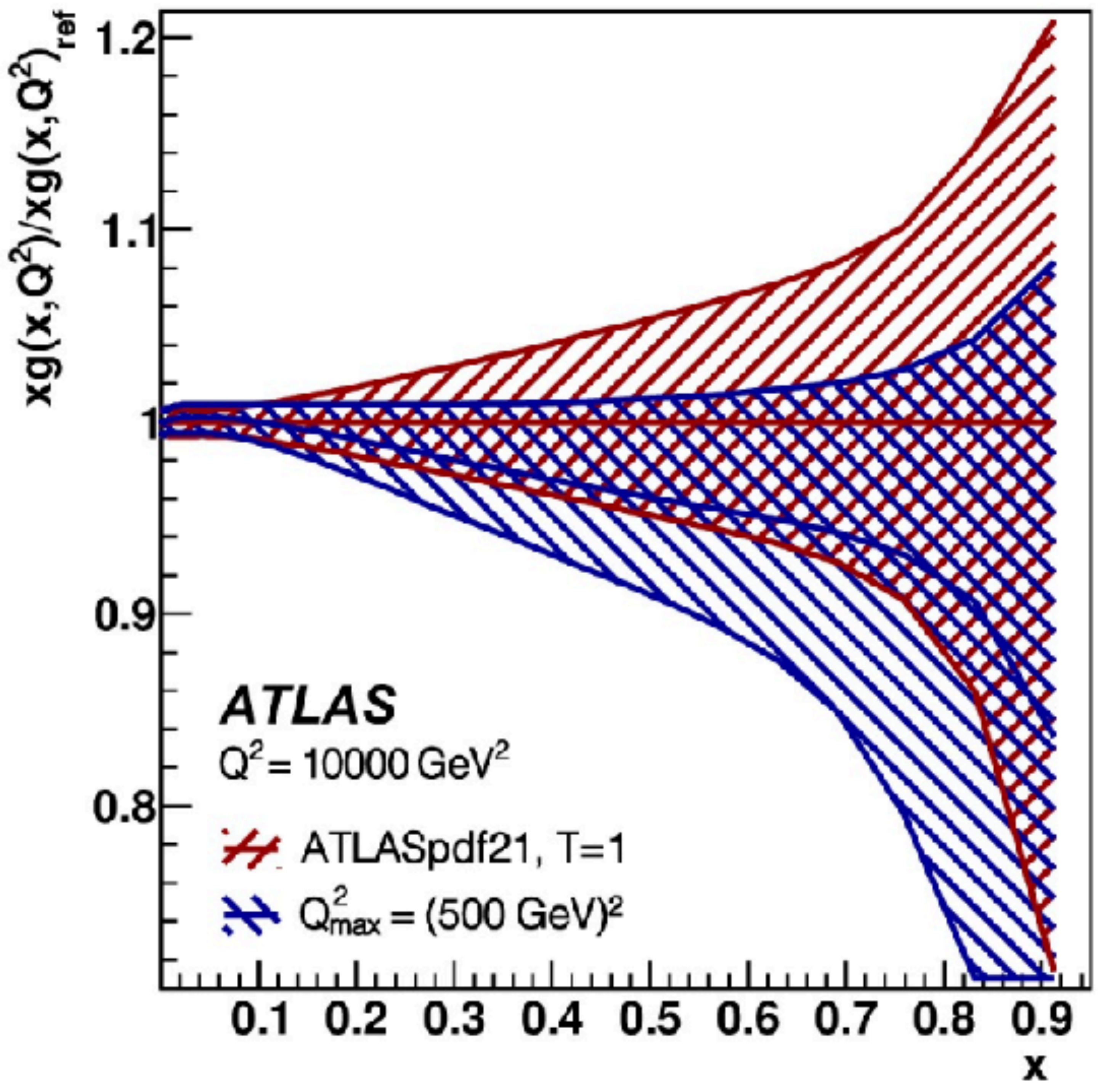
Study impact of systematic correlations within and across measurements



Dynamic tolerance (a la MSHT) to account for tensions in the data

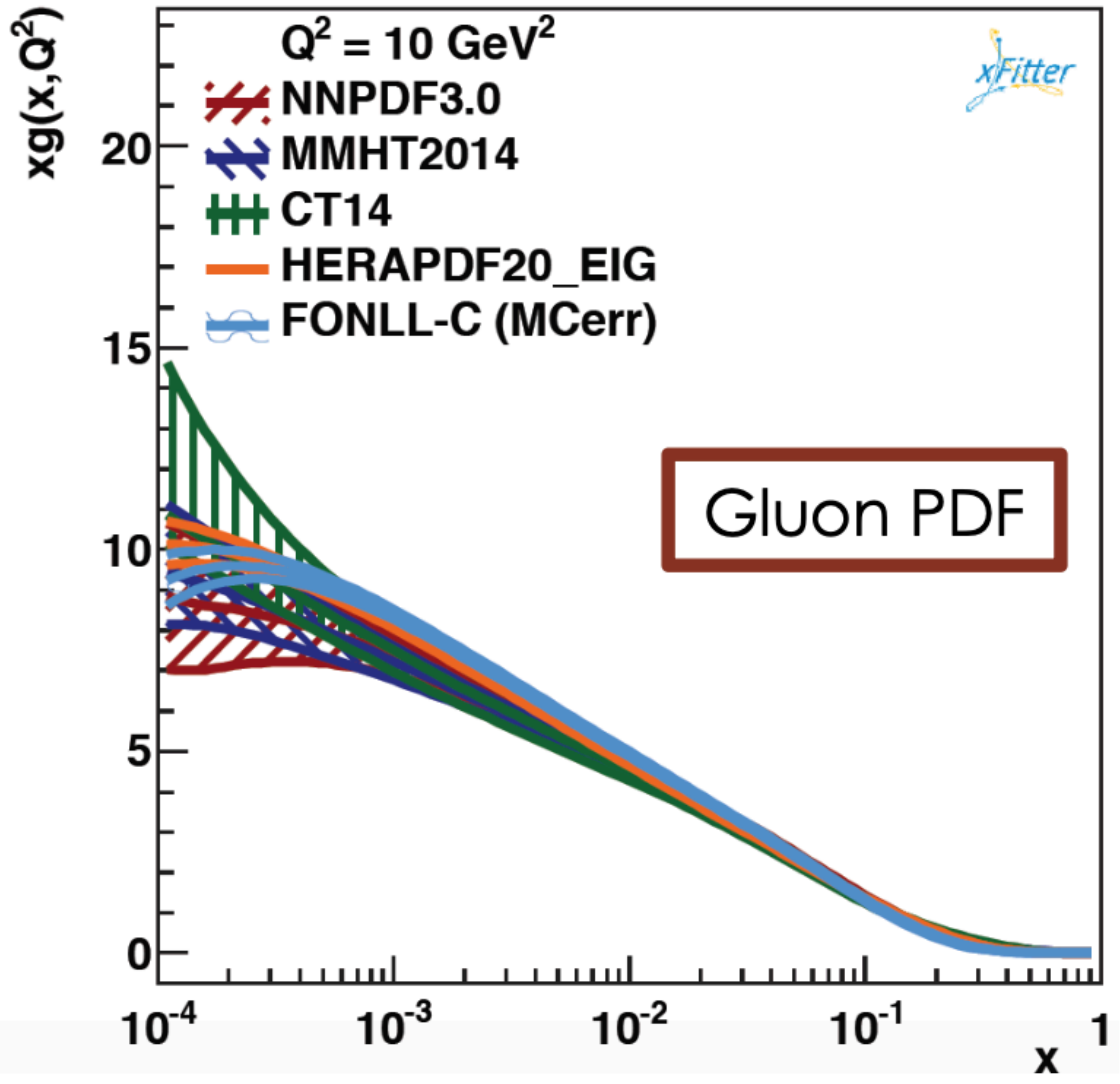


Check impact of high-Q^2 data not to bias new physics searches



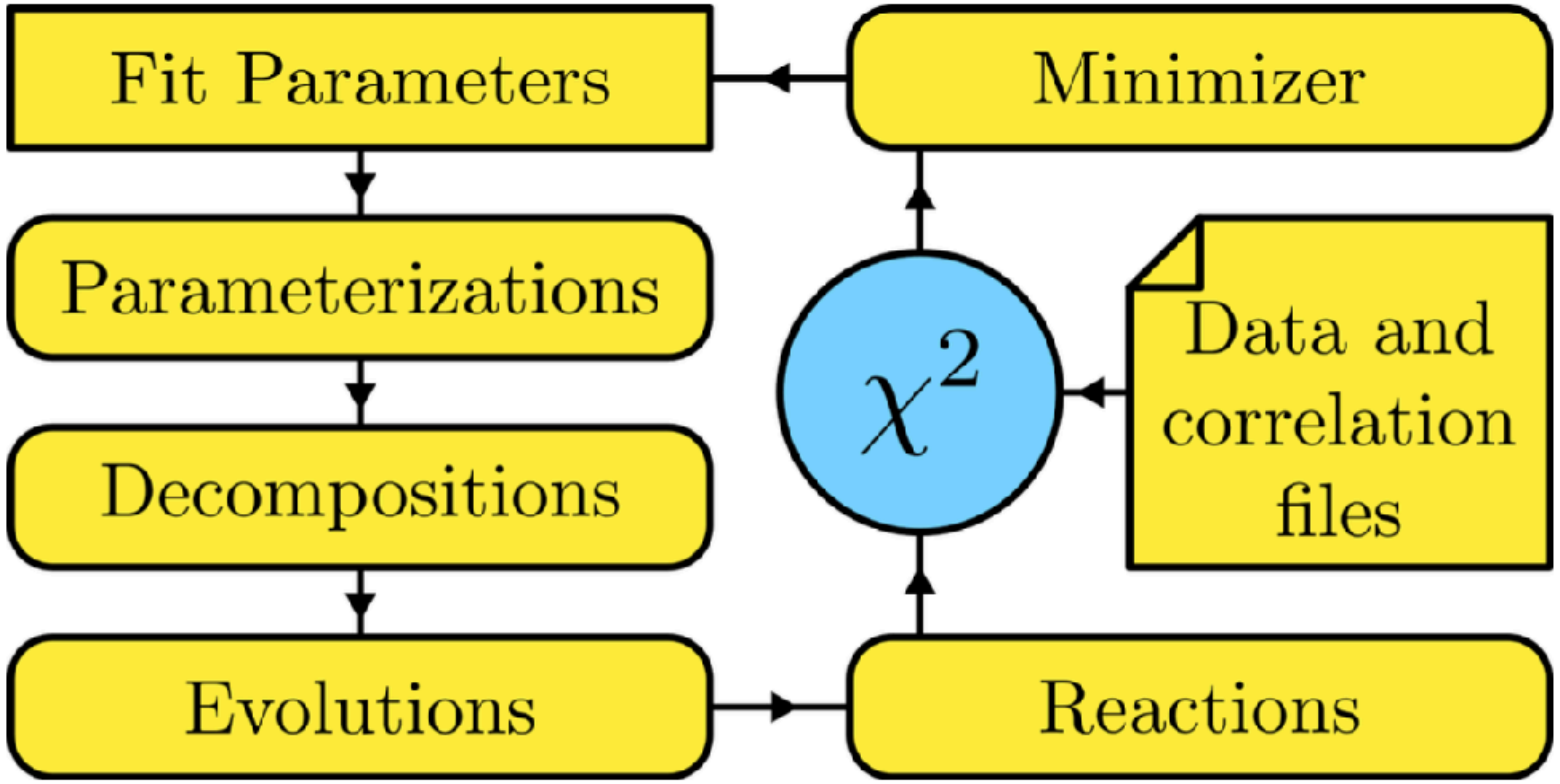
What is xFitter - I

- **Parametrise PDFs** at a given scale
  - Several parametrisations and decompositions
- **Evolve them** at the scale of the measured data
  - DGLAP evolution up to N3LO QCD and NLO QED with APFEL/APFEL++/QCDNUM
- **Compute theory** predictions:
  - DIS at NNLO with different mass schemes: ZM-VFNS,ACOT, FONLL, TR
  - Fast interfaces: APPLgrid, FastNLO, pineAPPL



- **Compare with data** using a χ^2:
  - Systematics are linearized: “profiling” as a trivial matrix inversion
  - For unconstrained minimisation: MINUIT, ceres-solver

What is xFitter - II

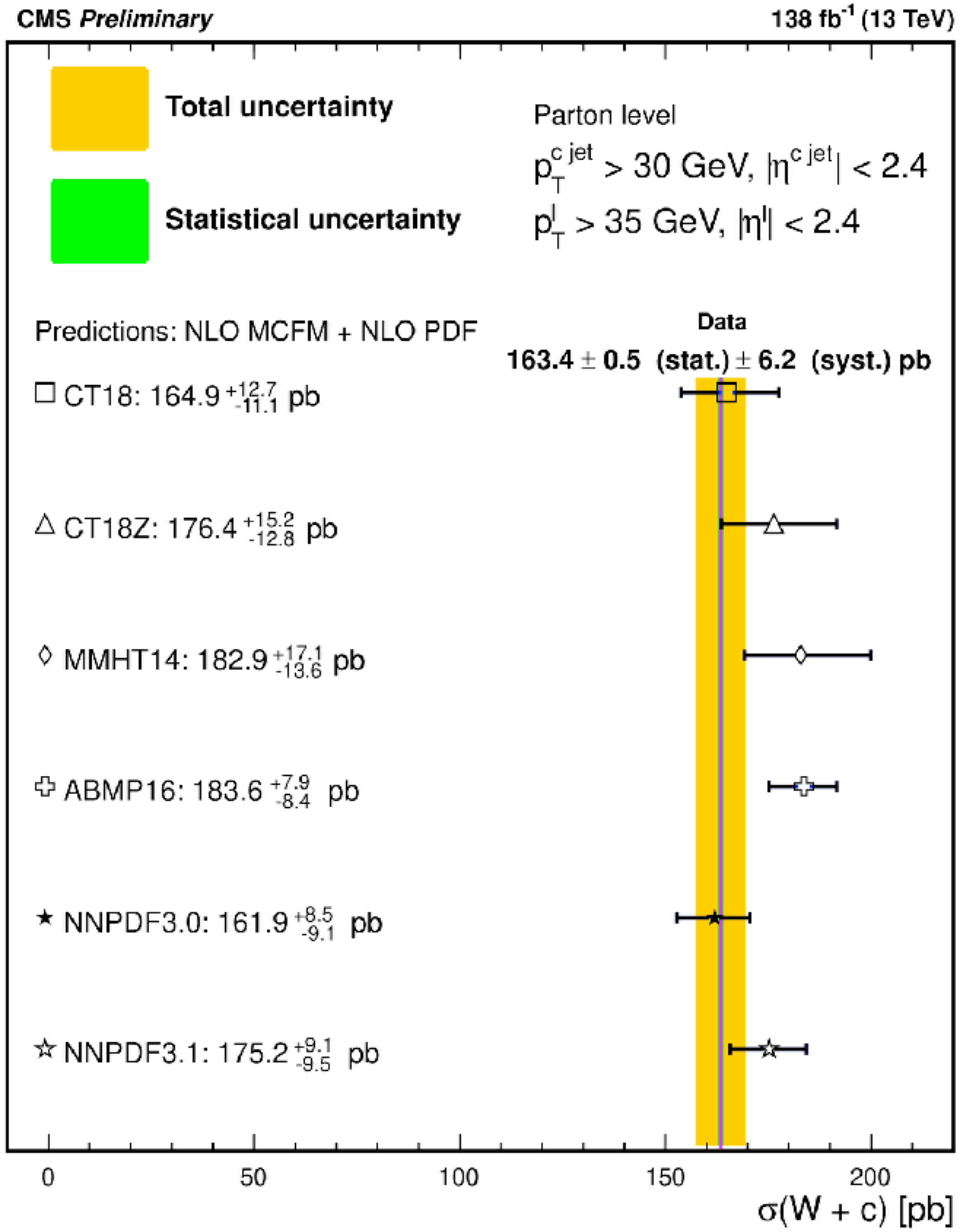


- Significant **overhauling of the code** starting from version 2.0
- **Flexible interfaces** to minimizers, PDF parameterisation and decomposition, evolution and many new theory reactions
- Many example of analyses available as a starting point
- For a nice overview talk xFitterIntroduction

W+charm and strangeness

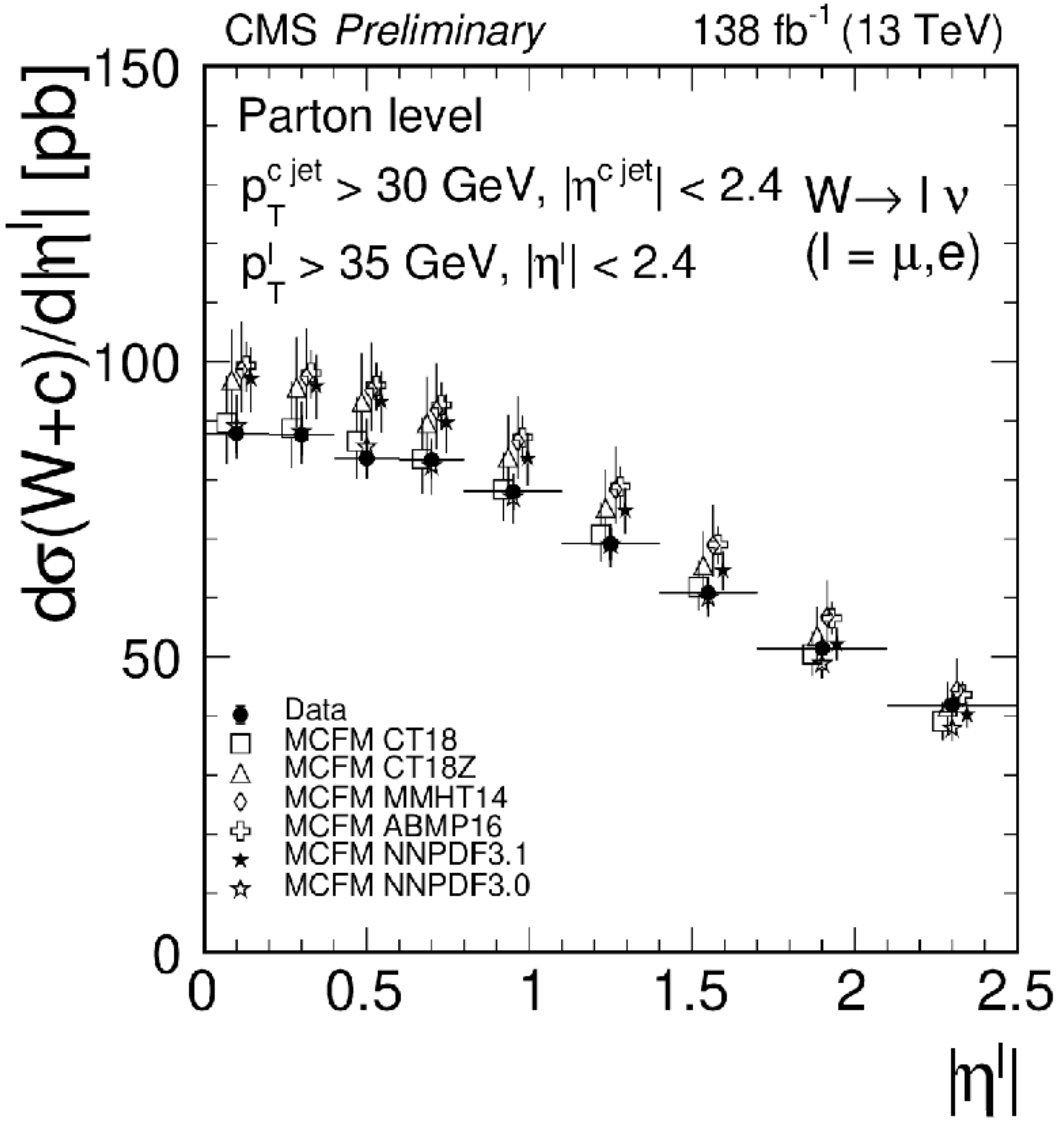
- CMS measurements of W+charm production at 8 TeV and 13 TeV
  - Charm identified through a combination of soft-muon and secondary vertex
  - Usual opposite-sign - same-sign subtraction
  - Unfolded to particle- and particle-level anti-kT charm jets with R=0.4

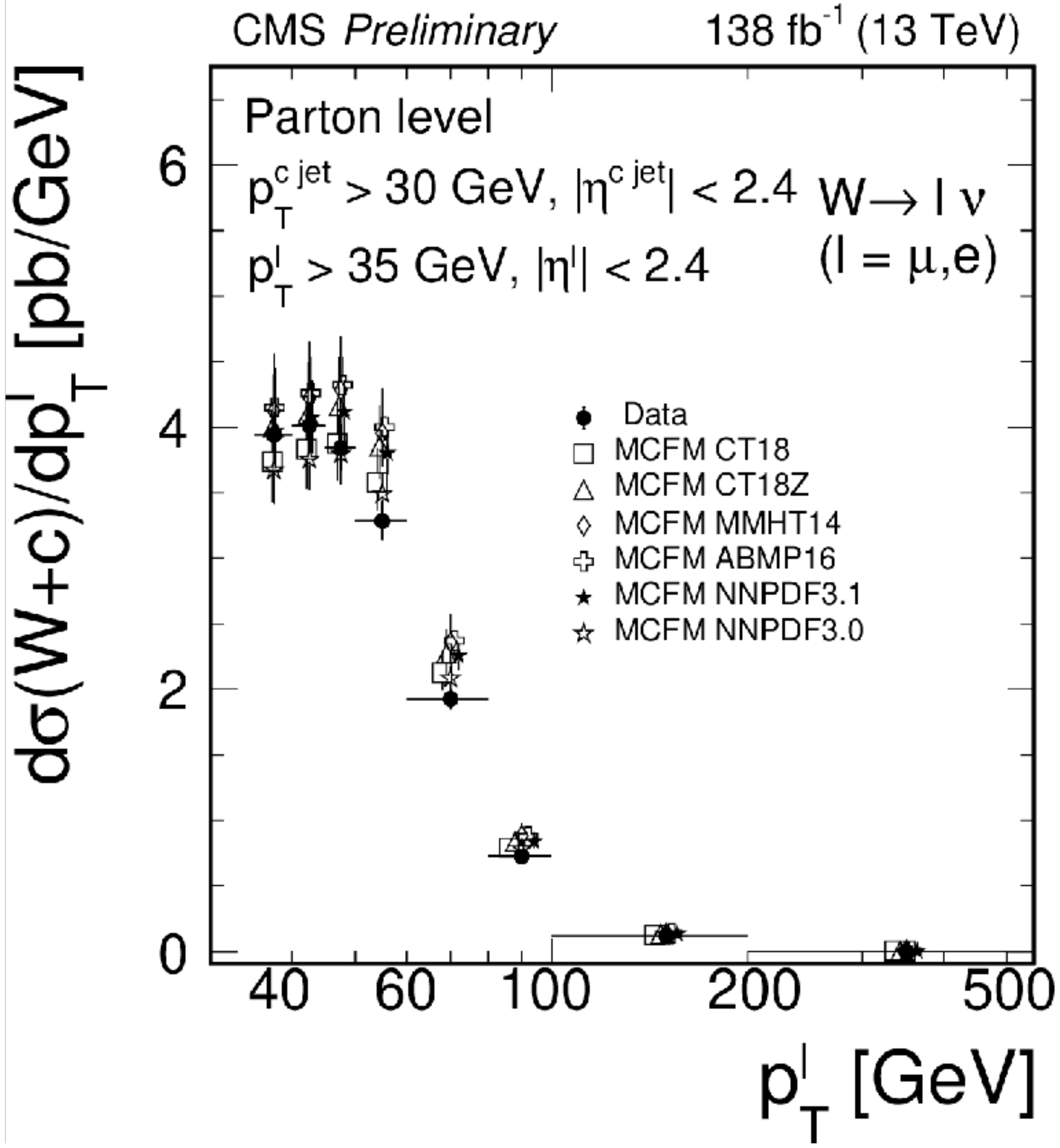
- Compared to NLO QCD theory from MCFM
  - Jet definition soft unsafe starting at NNLO QCD, needs to correct the data to a calculable algorithm
  - Involves large extrapolation down to charm p_T~0



http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-21-005/

W+charm and strangeness





http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-21-005/index.html