CT18 studies (related to flavoured jets at the LHC)

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Family of CT18 PDFs

- CT18: nominal set (NNLO and NLO; work ongoing on N3LO); enhanced precision (denser) grids available
- CT18A: same as above except ATLAS 7 TeV W and Z data included
- CT18As, CT18As_lat: s and sbar not equal, lattice information included
- CT18X: same as CT18, but special scale mimicking low-x resummation used for DIS
- CT18Z: special scale and ATLAS W/Z data both included
- CT18qed: NNLO QCD and NLO QED evolution
- CT18lux
- CT18 neutron photon PDFs
- CT18LO: same data set, LO formalism (not recommended)
- CT18FC: fitted charm series; 4 model series (BHPS (CT18 and CT18X), MBMC, MCME, each with 3 sets with $\Delta\chi^2$=0, 10, 30
- CT18_NF4: four flavor scheme
- CT18MC: NLO PDFs intended for MC use (within next few weeks)
- See talks at DIS24 by Aurore Courtoy, Marco Guzzi, Pavel Nadolsky
- See also https://cteq-tea.gitlab.io

Prelude: uncertainties

- PDF uncertainties depend first on the experimental uncertainties of the data
- Data from two measurements, or even from within the same measurement, can both be very precise, but the result of adding both to the PDF fit can be an increase in the PDF uncertainty (or more likely) a smaller decrease in uncertainty than expected) if the data are in tension with each other
- The resultant PDF uncertainty relies on the definition of a tolerance, i.e. what is a significant increase from the global minimum χ^2, i.e. PDF uncertainty can be adjusted by changing the tolerance
- $\Delta\chi^2=1$ is not applicable for ~4000 data points from different experiments
- NB: CT (Tier 2) and MSHT (dynamic tolerance) have introduced criteria to restrict the pull of data sets that disagree with global fit
- More details in extra slides

PDF uncertainties

CT and MSHT both use a Hessian technique to determine the central PDF. By definition, this is at the best χ^2. This is not necessarily true for NNPDF.

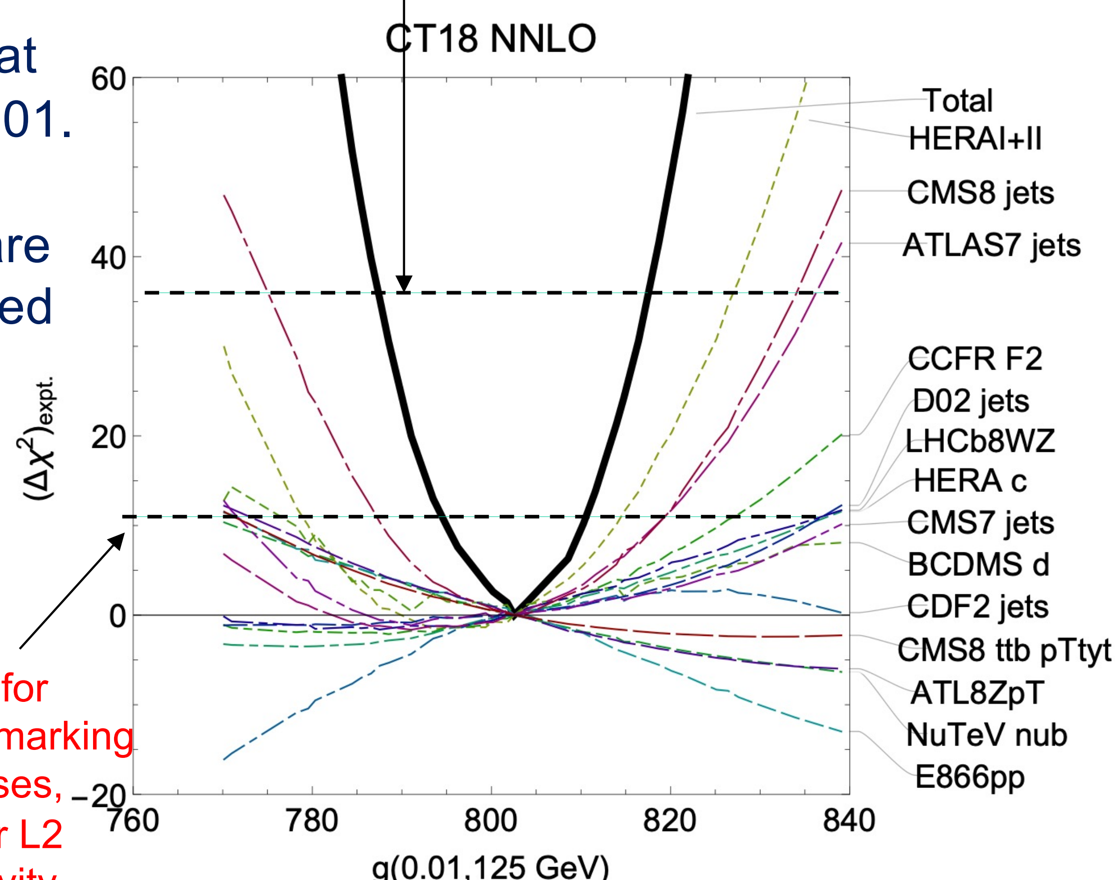
The uncertainty is determined by allowing an excursion from that central value. CT18 uses $\Delta\chi^2$=37 for a 68% CL error.

The plot on the right shows a Lagrange Multiplier scan for the gluon distribution at a Q value of 125 GeV at an x value of 0.01.

The pulls of the individual experiments are in general not Gaussian, but the combined pulls of all of the data sets are.

This is a very time-consuming (and specific) way of studying the PDF uncertainty. The L2 sensitivity provides similar, but more general, information.

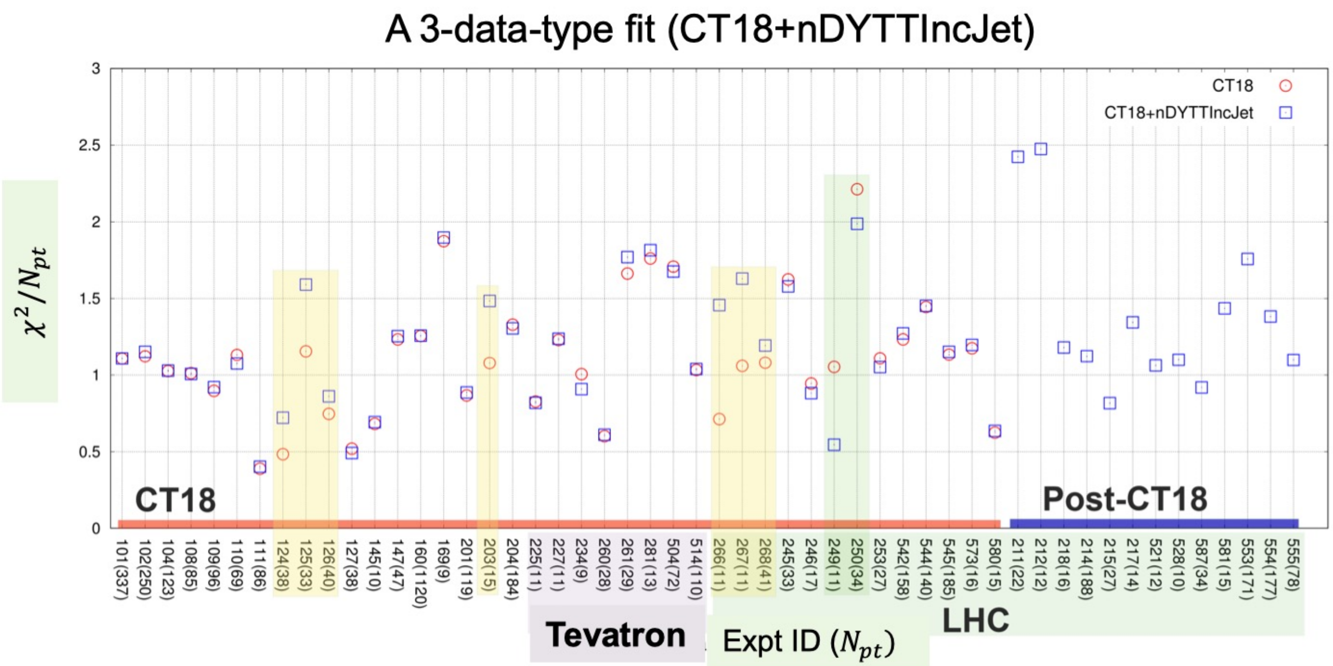
T^2=10 useful for benchmarking exercises, and for L2 sensitivity



Towards a new generation of CT202X PDFs

- New LHC Run 2 data added: (di)jet, vector boson, ttbar
  - based on experiment selections recommended in 2305.10733, 2307.11153
- Work on implementation of N3LO contributions
- A number of other areas of development
  - next-generation PDF uncertainty quantification
  - Bezier curves
  - META combination
  - ML stress-testing
  - multi-Gaussian approaches
  - subtracted heavy-quark PDFs in S-ACOT-MPS scheme…

Post CT18 data



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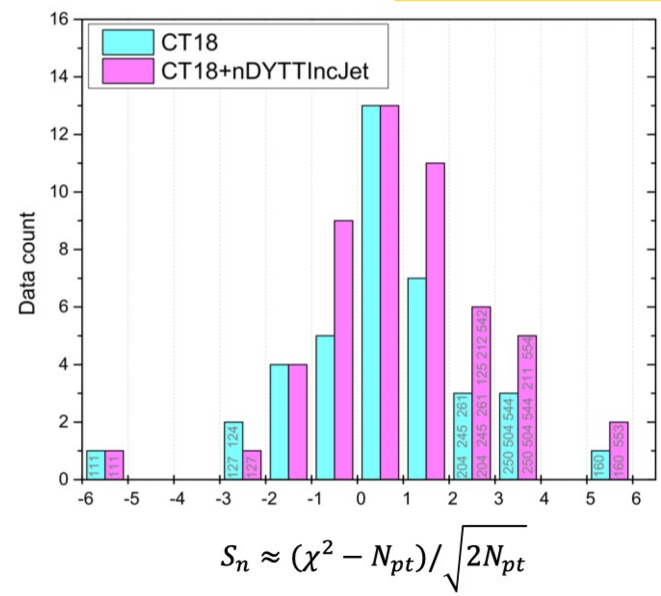


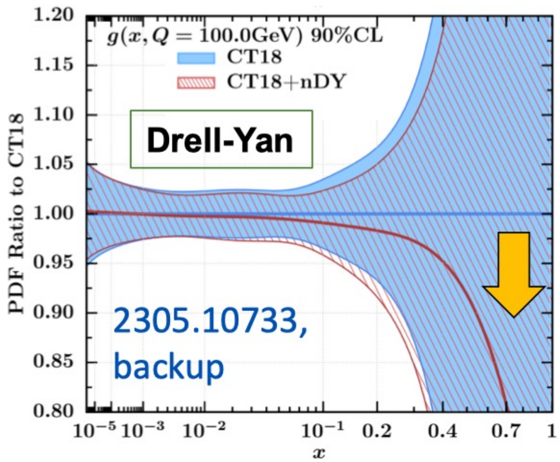
The most precise new experiments tend to have an elevated χ^2/N_{pt}, in the same pattern as observed for CT18

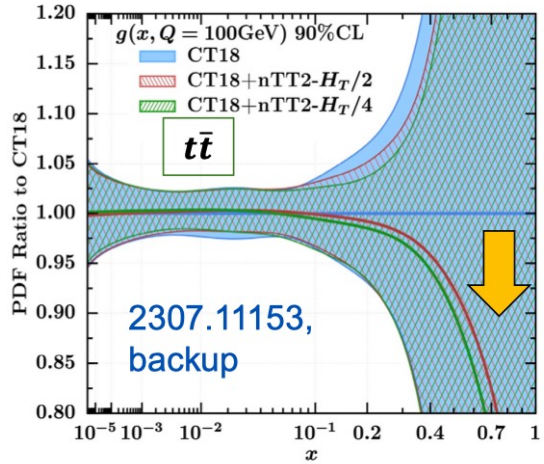
χ^2/N_{pt} increases for experiments 124 and 125 (NuTeV), 126 and 127 (CCFR) and 203 (E866 DY), 266 and 267 (CMS 7TeV Ach), 268 (ATLAS 7TeV W, Ach).

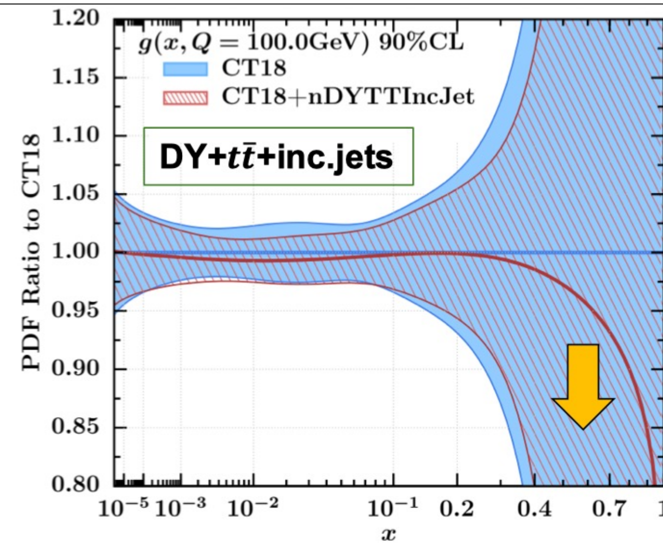
χ^2/N_{pt} decreases for experiments 249 (CMS 8 TeV Ach), 250 (LHCb 8 TeV W/Z)

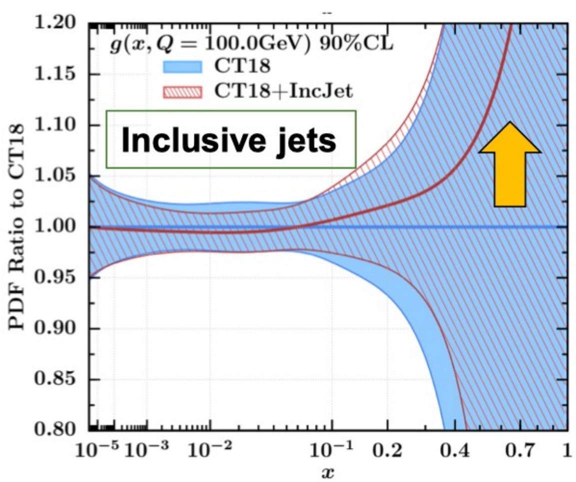
Impact of new data

Pulls on the gluon PDF by the new data type









After including DY, $t\bar{t}$, and inc. jet data simultaneously, we get a softer gluon. Note that new DY and $t\bar{t}$ data favor a softer gluon, new inc. jet data prefer a harder gluon.

Mild changes in the gluon uncertainty

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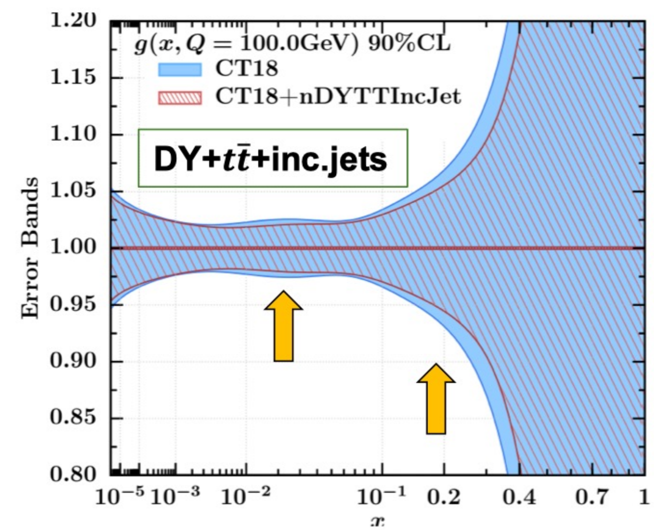
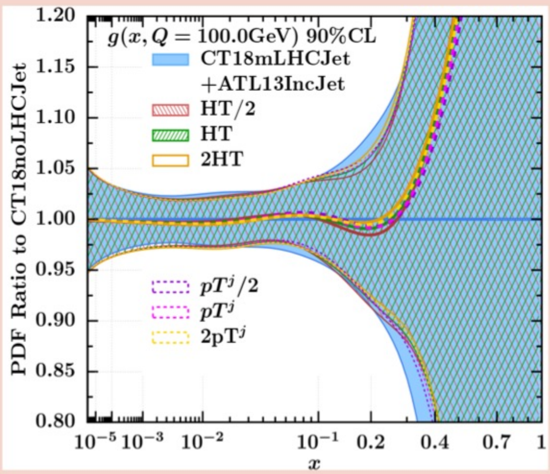
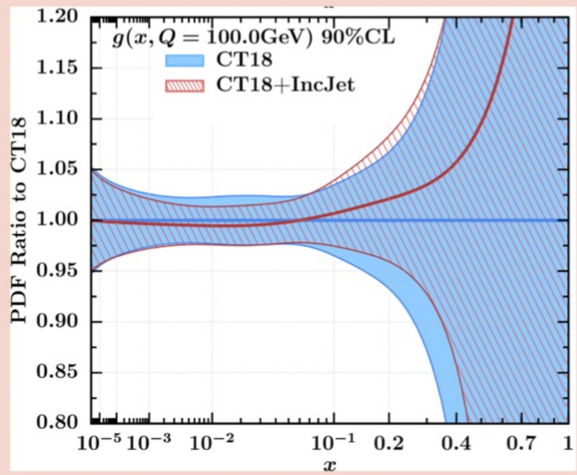
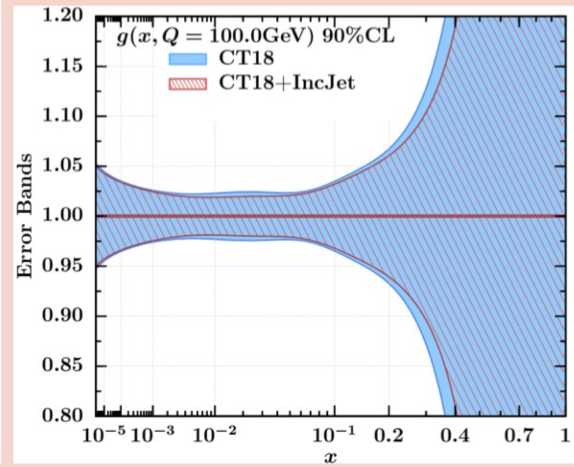


Inclusive jet vs. dijet data sets: impact on the gluon for various QCD scales

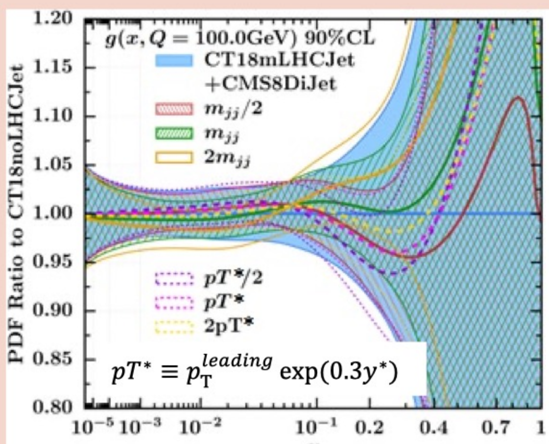
+ inclusive jets: small scale dependence, a harder $g(x,Q)$







+ dijets: significant scale, dependence, varied pulls on $g(x,Q)$



The impact of the Inc. jet data on $g(x,Q)$ is relatively independent of the scale choice. The final fit uses $\mu_{R,F} = p_T^j$, giving better χ^2.

The impact of dijet data substantially depends on scale choices, especially in the case of CMS8 TeV dijet.

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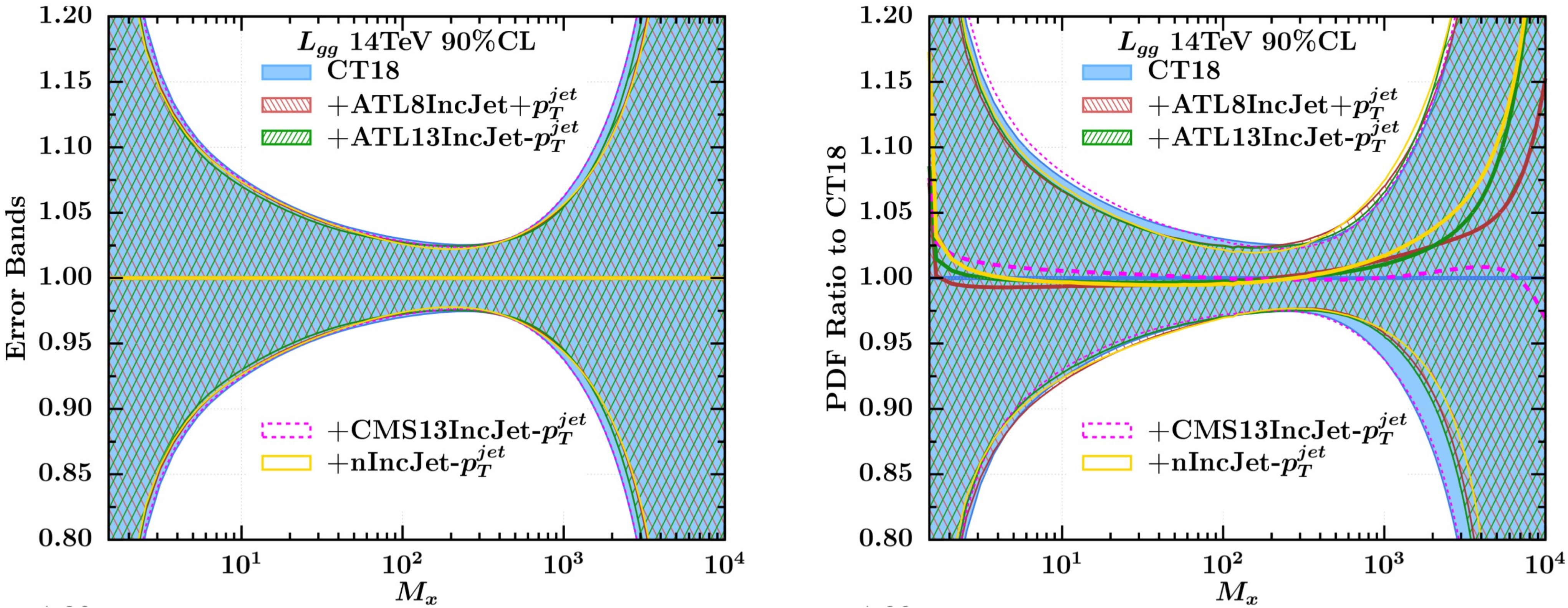
dijet data tend to have larger uncertainties, leading to smaller χ^2 than inclusive jets, but similar constraints on PDFs

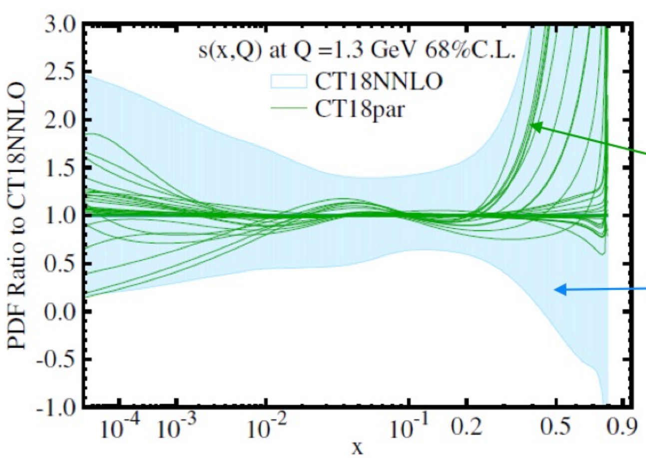
Impact of new jet data on gluon



Taming PDF uncertainties in CT202X PDFs

Several efforts to refine PDF uncertainty quantification:

- understand conceptual underpinnings of the multivariate inverse problem. Much can be learned from non-HEP statistics applications
- suppress aleatory and perturbative uncertainties (e.g., from higher-order contributions)
- comprehensively estimate epistemic uncertainties (e.g., due to the PDF parametrization forms)



CT approach: "Bayesian exploration with Gaussian emulation"

preliminary PDFs for alternative parametrizations

final uncertainty with one parametrization

Preliminary fits explore experimental, theoretical, parametrization, methodological uncertainties

The final Hessian error set (50-60) approximates the total uncertainty due to the above factors.

GMVN schemes in a nutshell

Heavy-flavor production dynamics is nontrivial due to the interplay of massless and massive schemes which are different ways of organizing the perturbation series

Massive Schemes: final-state HQ with $p_T \leq m_Q \Longrightarrow p_T$-spectrum can be obtained in the **fixed-flavor number (FFN) scheme**.
- No heavy-quark PDF in the proton. Heavy flavors generated as massive final states. m_Q is an infrared cut-off.
- Power terms $\left(p_T^2/m_Q^2\right)^p$ are correctly accounted for in the perturbative series.

Massless schemes: $p_T \gg m_Q \gg m_P \Longrightarrow$ appearance of log terms $\alpha_s^m \log^n\left(p_T^2/m_Q^2\right)$ that spoil the convergence of the fixed-order expansion. Essentially, a **zero mass (ZM) scheme**.
- Heavy quark is considered essentially massless and enters also the running of α_s.
- Need to resum these logs with DGLAP: initial-state logs resummed into a heavy-quark PDF, final-state logs resumed into a fragmentation function (FF)

Interpolating (GMVFN) schemes: composite schemes that retain key mass dependence and efficiently resum collinear logs, so that they combine the FFN and ZM schemes together. They are crucial for:

- a correct treatment of heavy flavors in DIS and PP,
- accurate predictions of key scattering rates at the LHC,
- global analyses to determine proton PDFs.

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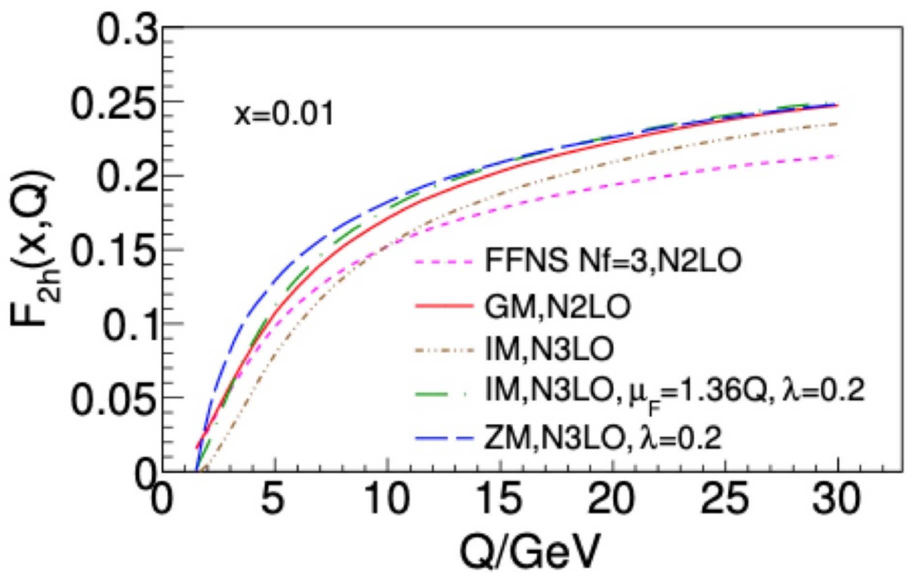
Work in progress

QCD cross sections @N3LO



- **DIS:** The CTEQ-TEA code implements complete flavor decompositions of DIS SFs at N3LO using approximate zero-mass Wilson coefficients with a rescaling variable (the **Intermediate-Mass VFN scheme**, cf. the figure)

Boting Wang's and Keping Xie's Theses, SMU

- **Imminent implementation of** massive N3LO heavy-quark coefficients to obtain N3LO DIS cross sections in **the SACOT-MPS General-Mass VFN scheme**

see talk of Marco Guzzi at DIS

Factorization schemes	Mass dependence in the FC terms	Mass dependence of the FE and subtraction terms	Introduce heavy-quark PDFs at large Q
FFN	Exact	N/A	no
ZM	None	None	yes
IM	Approximate	Approximate	yes
GM	Exact	Approximate	yes

- **DGLAP evolution** is performed at N3LO with APFEL/APFEL++.
- **Drell-Yan:** Ongoing work to include N3LO DY effects using NNLO ApplFast + N3LO/N2LO K-factor tables

Main idea behind S-ACOT-MPS (massive phase space)

$$\sigma = \mathrm{FC} + \underbrace{\mathrm{FE} - \mathrm{SB}}_{\text{``Residual FE''}}$$

FC = Flavor creation contributions with full mass dependence
FE = Flavor excitation contribution with approximate mass dependence

(available from public codes)

Mass fully retained in the PS in all terms.
Kinematical power corrections under control.

Subtraction well defined at the quark mass threshold

FE and Subtraction ➡ facilitated by introducing residual PDF:

allows us to get (FE-Subtraction) in one step

$$\delta f_Q(x,\mu^2) = f_Q(x,\mu^2) - \frac{\alpha_s}{2\pi}\log\left(\frac{\mu^2}{m_Q^2}\right) f_Q(x,\mu^2) \otimes P_{Q\leftarrow g}(x)$$

at LO

Subtracted and Residual PDFs are provided in the form of LHAPDF grids for phenomenology applications: https://sacotmps.hepforge.org/downloads?f=PDFs

More details in K. Xie PhD Thesis: “Massive elementary particles in the standard model and its supersymmetric triplet higgs extension.” https://scholar.smu.edu/hum_sci_physics_etds/7, 2019.

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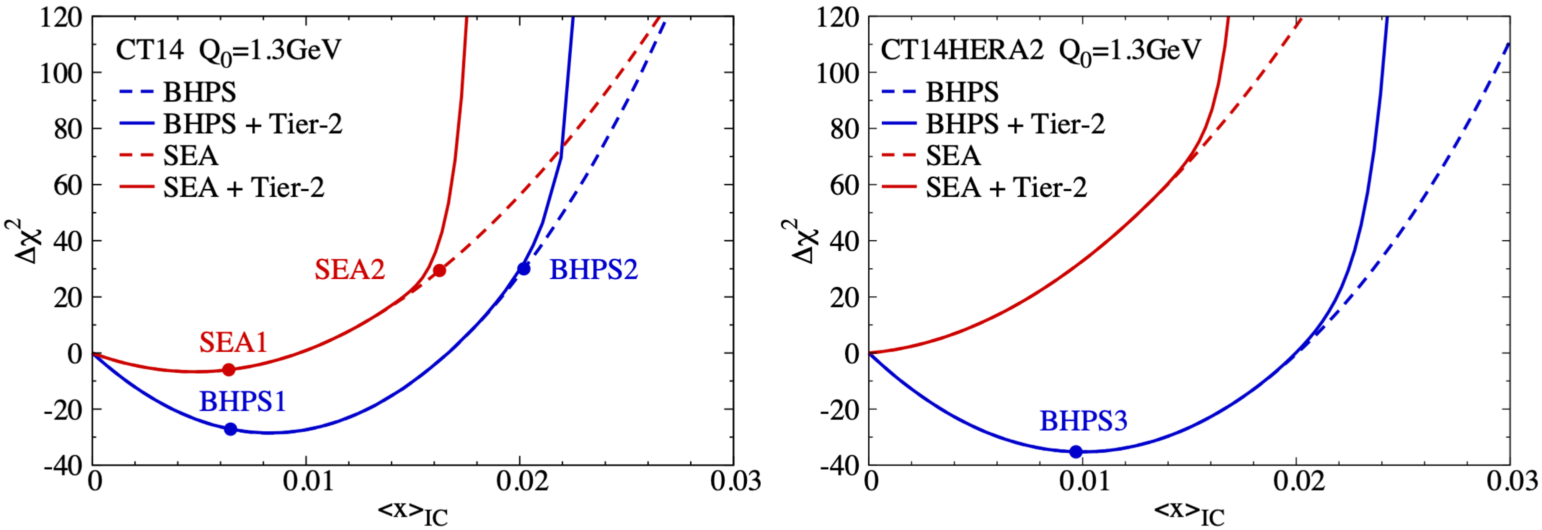
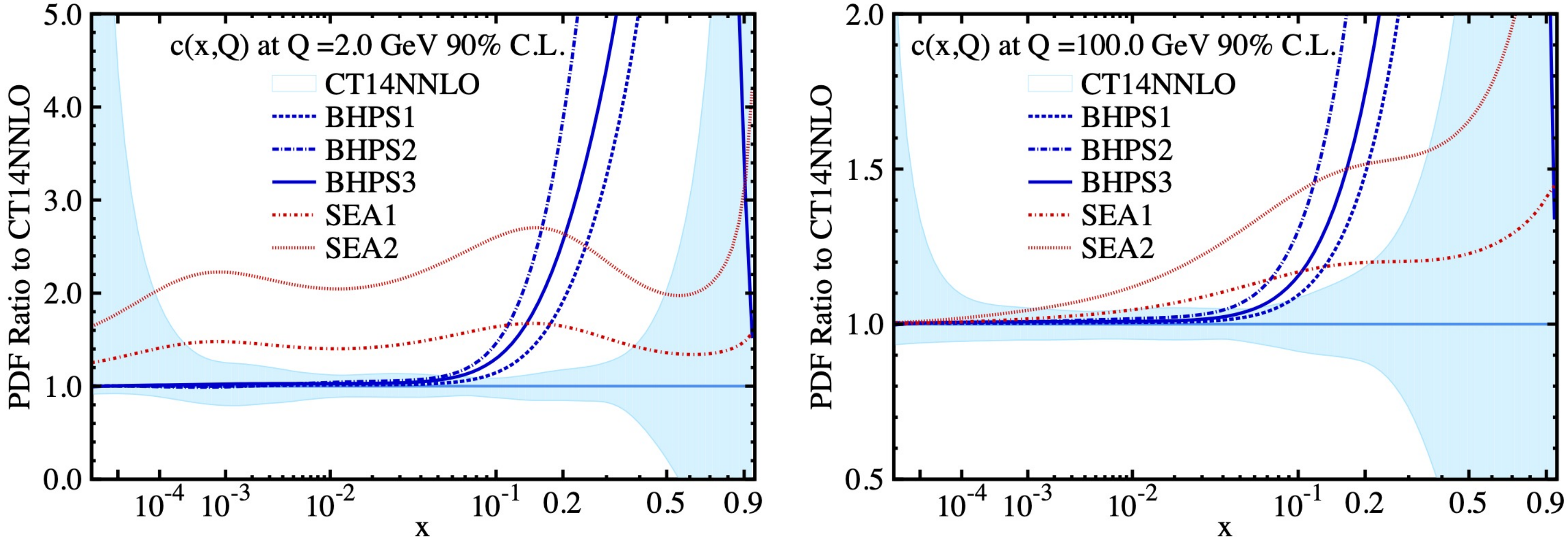
Charm and b quark distributions

- Perturbative view is that c and b quarks are not present in the proton at scales lower then their masses
- They can be produced in the initial state at scales higher then their masses through gluon splitting into quark-antiquark pairs (thus primarily at lower x)
  - only things that drive production (besides the gluon distribution) are the heavy quark mass and the value of $\alpha_s(m_Z)$
- But the proton can also have an intrinsic charm (and bottom for that matter) component arising from scattering contributions beyond leading twist
  - there are models (BHPS, incorporated by the CTEQ group), and increasingly, predictions from lattice gauge theory, some of which have been incorporated into CT fits
- CT has published PDF sets in which an intrinsic component of charm is modeled. The addition of this intrinsic component leads to a small, but noticeable, reduction in global χ^2



Note: not free fits ->models

FIG. 5: The change $\Delta\chi^2$ in the goodness of fit to the CT14 (left) and CT14HERA2 (right) data sets as a function of the charm momentum fraction $\langle x\rangle_{\mathrm{IC}}$ for the BHPS (blue) and SEA (red) models.



Greatest sensitivity for BHPS models comes from BCDMS and ATLAS 7 TeV W and Z

FIG. 8: Ratio of $c(x,Q)_{\mathrm{IC}}/c(x,Q)_{\mathrm{CT14}}$ within the CT14 uncertainties at 90% C.L. at the scale $Q = 2$ GeV (left) and $Q = 100$ GeV (right).

The L_2 sensitivity

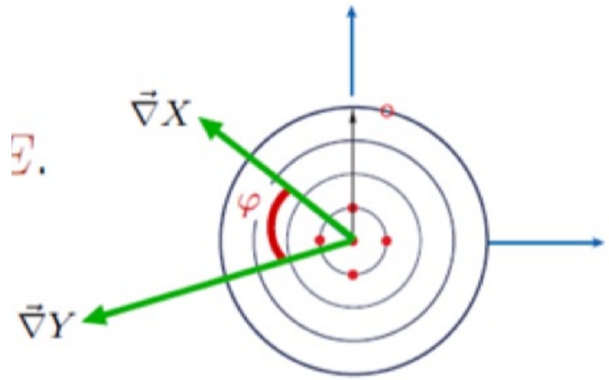
- For data to influence the PDF fit in a particular region of x and Q^2, two conditions must be met
  - the parton-level dynamics must depend on a particular PDF (say that of the gluon), as manifested in a statistical correlation
  - the data must have sufficient resolving power to contribute to the PDF likelihood analysis
- The L_2 sensitivity incorporates both of these features
- The L_2 sensitivity is a way of viewing the pulls of all of the experiments used in a global PDF fit, for a particular parton flavor, as a function of a kinematic variable, such as parton x
  - or, when plotted for a PDF luminosity, as a function of the mass
- The fit value for a particular PDF(x,Q) is determined by the sum of these pulls

L_2 sensitivity

$$S^{\mathrm{H}}_{f,L2}(E) \equiv \frac{\vec{\nabla}\chi^2_E \cdot \vec{\nabla} f}{\Delta^{\mathrm{H}} f} = \left(\Delta^{\mathrm{H}}\chi^2_E\right)\ C^{\mathrm{H}}(f,\chi^2_E)$$

2nd Lagrangian technique

- C^H represents the cosine of the correlation angle between PDF flavor f (or any defined quantity) and experimental χ^2



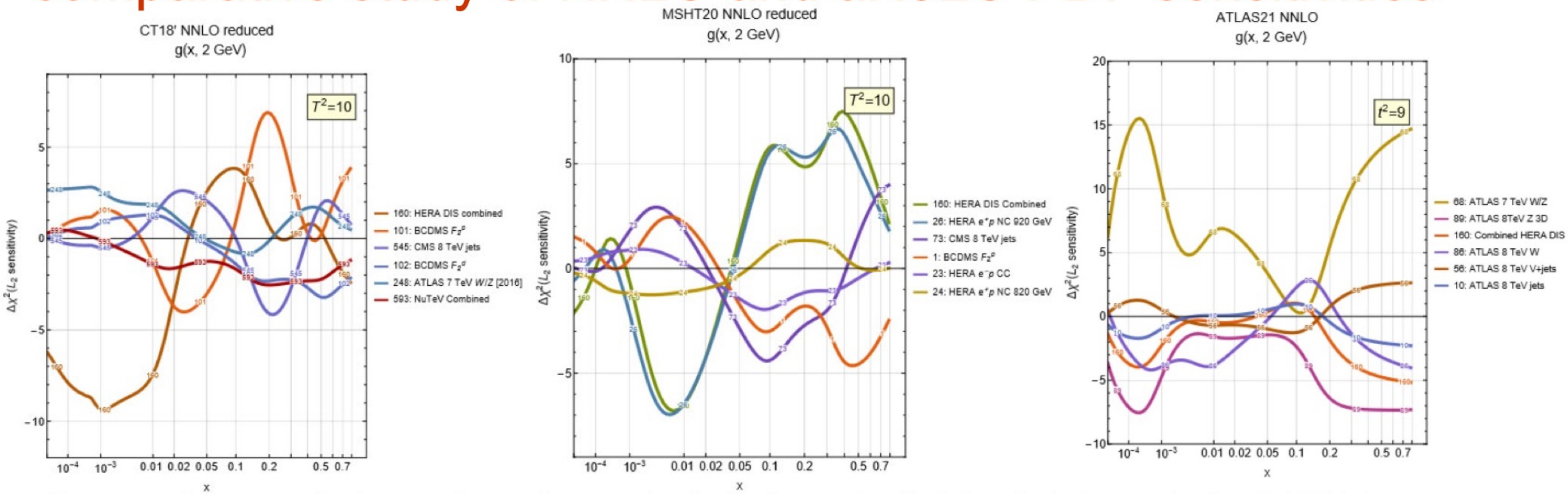
The importance of an experiment for a particular PDF depends not only on the correlation of the cross section with that PDF, but the degree to which the cross section can determine that PDF.

- Can also be defined for the MC PDF approach

A positive value of the L2 sensitivity indicates the data wants to pull the PDF down, while a negative value indicates an upwards pull.

An ATLAS, CTEQ-TEA, and MSHT comparative study of NNLO and aN3LO PDF sensitivities

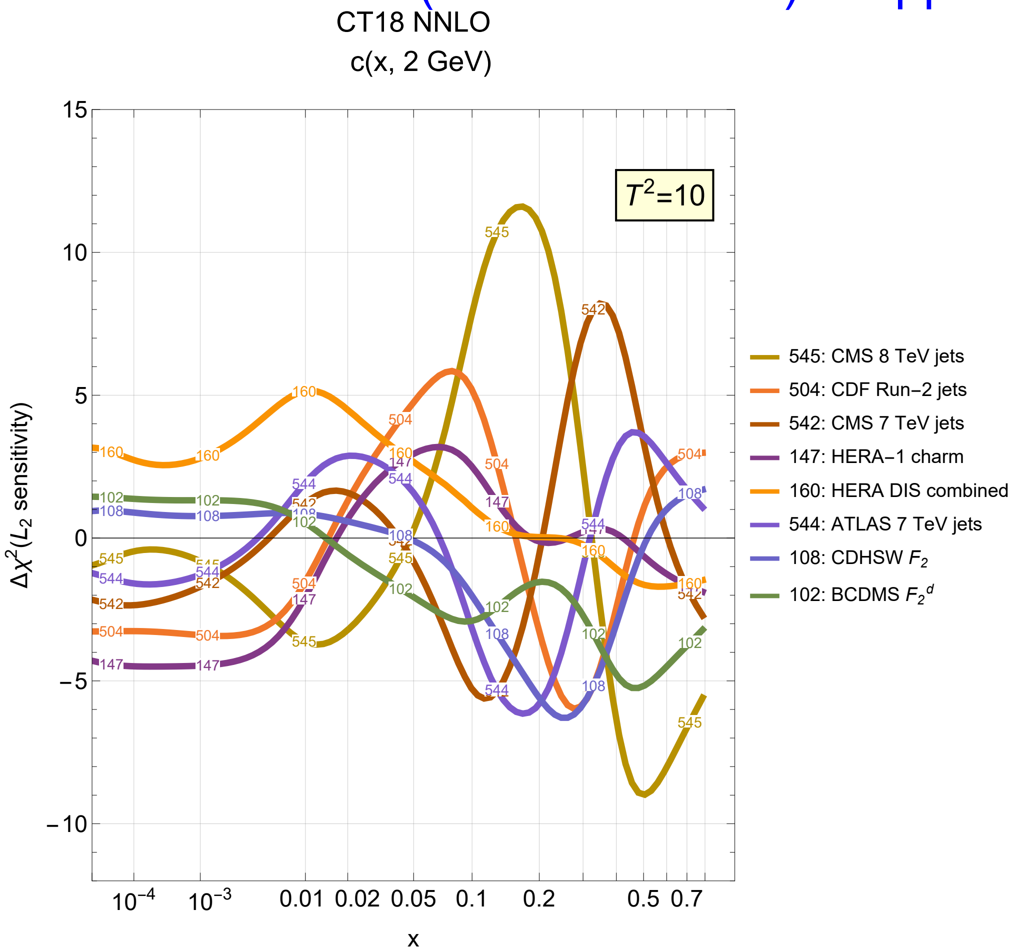
X.Jing et al.,arXiv:2306.03918

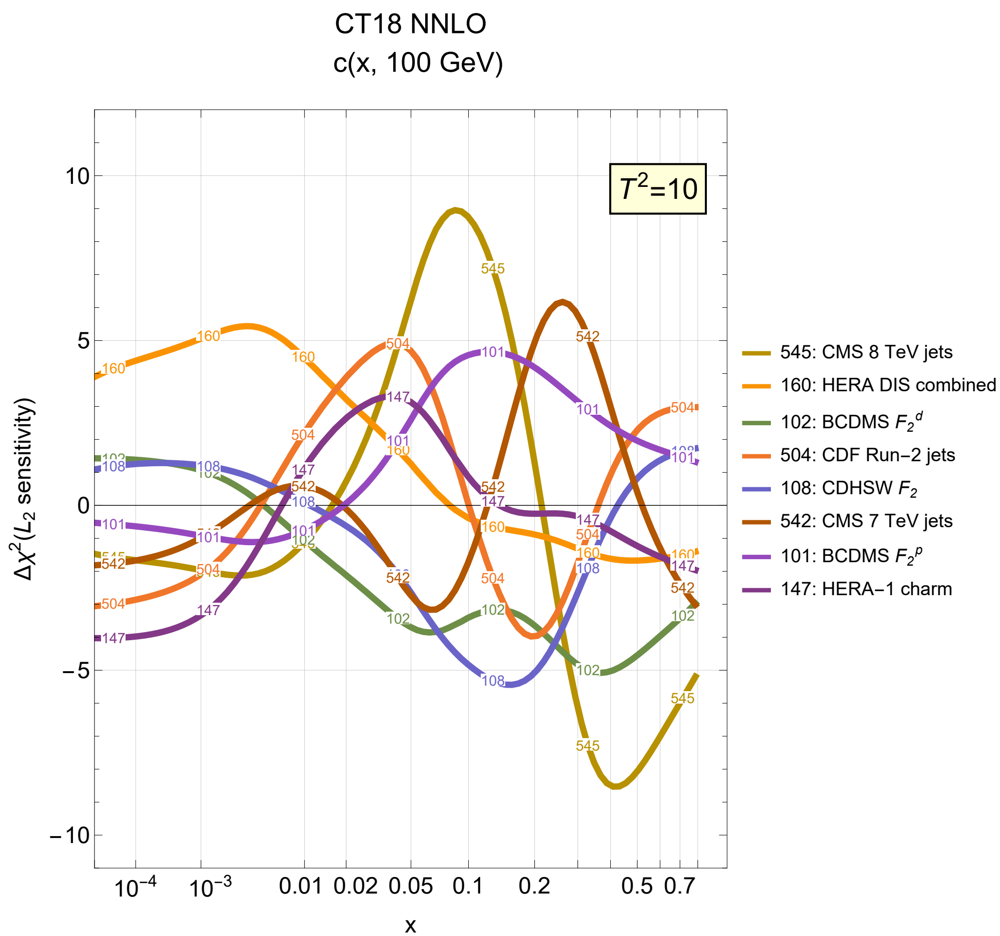


- Comparisons of strengths of constraints from individual data sets in 8 PDF analyses using the common L_2 sensitivity metric. [Definitions in the backup.]
- An interactive website (https://metapdf.hepforge.org/L2/) to plot such comparisons [2070 figures in total; a code L2LHAexplorer to plot L2 sensitivities for LHAPDF grids]

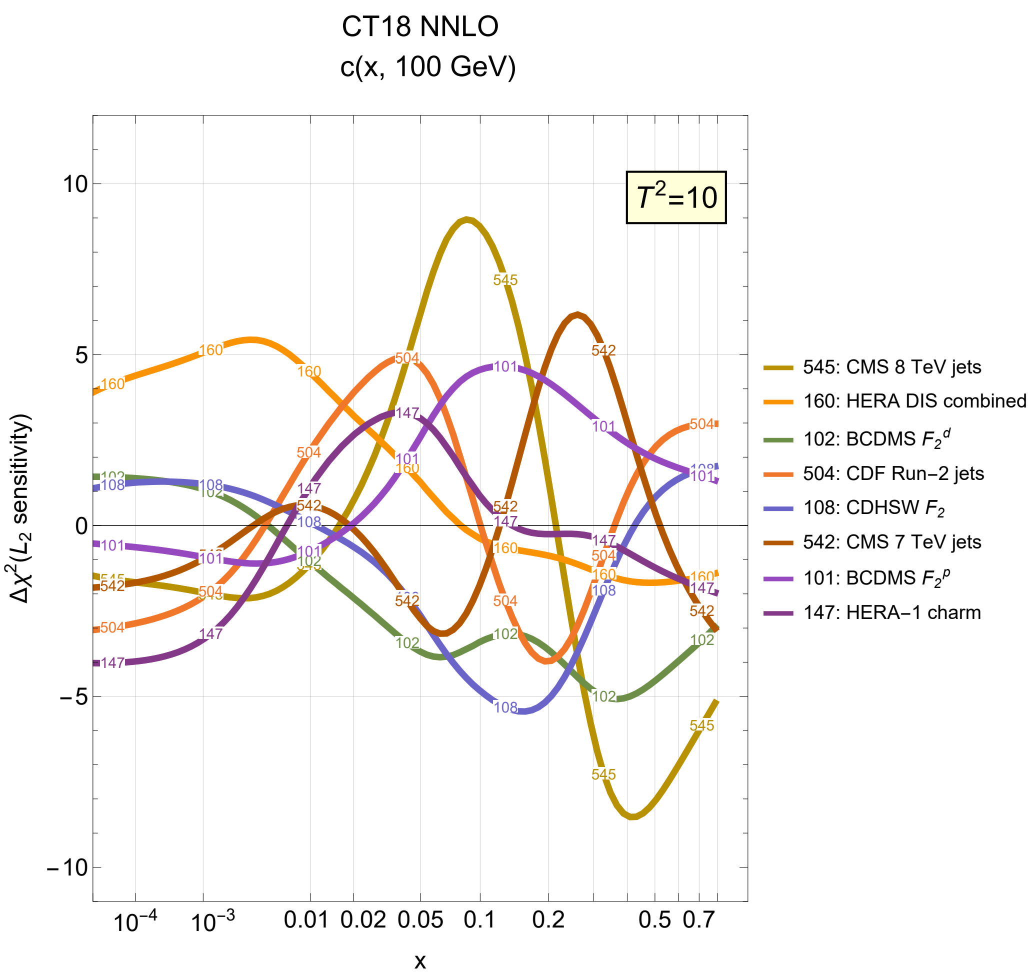
What defines the c and b quark distributions in CT18?

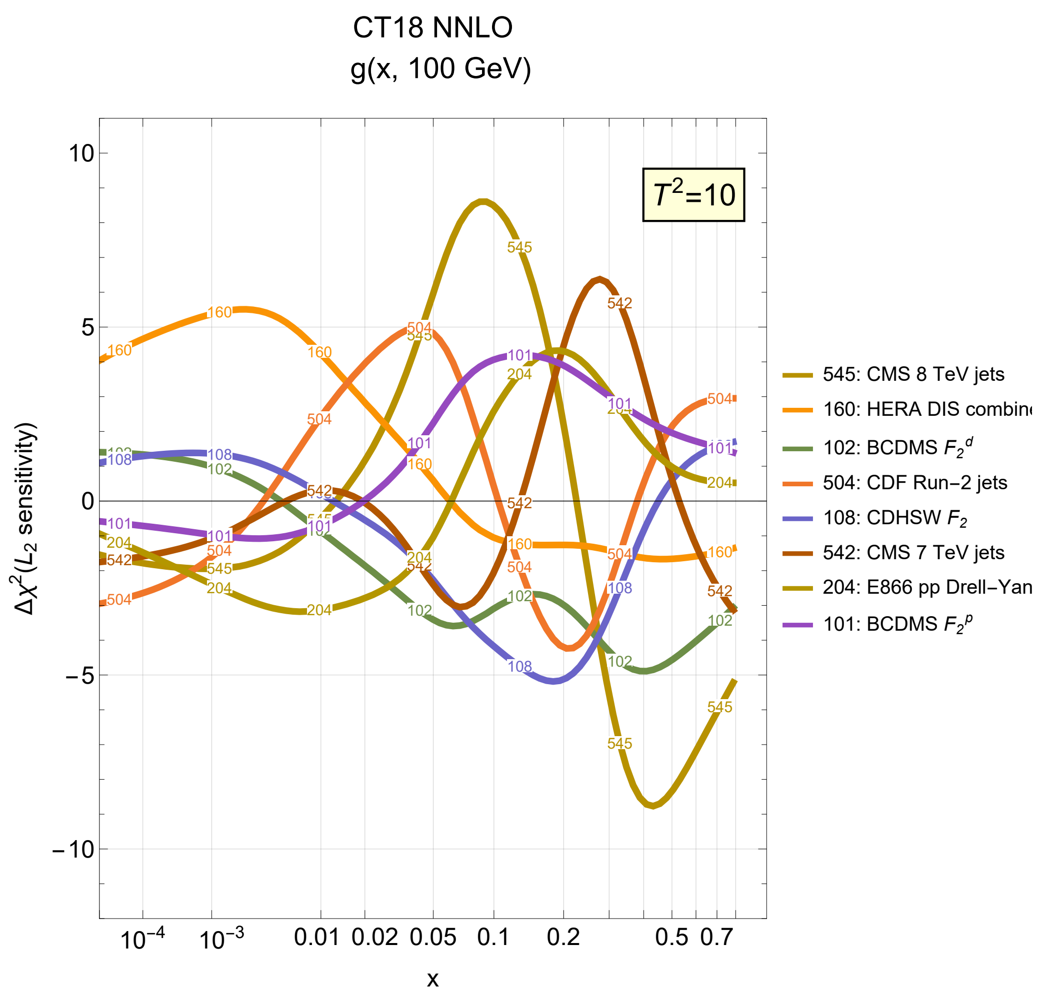
- Use the L2 sensitivity to show the most sensitive experiments (in this case the 8 most sensitive)
- Some experiments have positive L2 sensitivity (want to pull charm down), while others have negative (want to pull charm up)
- The sum (at each x value) is approximately zero





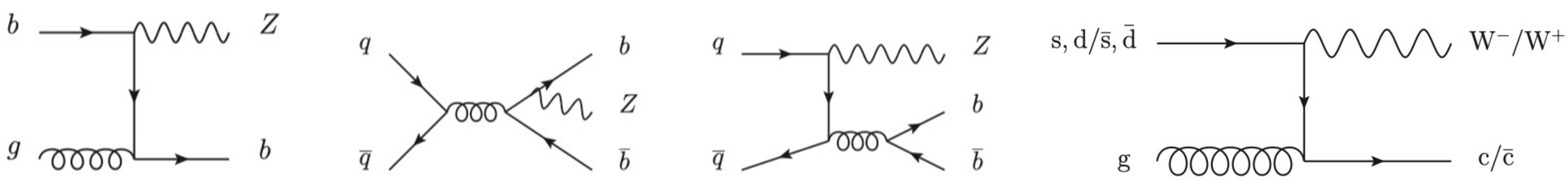
- Compare sensitivities of charm quark and gluon (at Q=100 GeV)
- Very similar (as might be expected), since this is perturbative charm (so would also be similar for b-quark distributions)





V+HF: inputs for (s),b,c PDFs

- A heavy flavor quark can be present in the initial state or produced through gluon splitting



- The calculation can be performed in a scheme where there are only 4 parton flavours (4FNS) or in which the b-quark is included (5-FNS)
- The kinematics can drive the subprocess for the production, as for example, whether the final state heavy quark (jet) has to pass only some minimum p_T requirement, or whether it has to roughly balance the boson transverse momentum
- If it's the former, then the final state c or b quark is likely to arise through gluon splitting, especially given the additional gluon splittings that may occur in a parton shower (*JHEP* 02 (2018) 059)
    - this effect is more pronounced if there is a hierarchy of scales, i.e. $p_T^{jet} >> p_T^{charm}$ (would be useful to measure differentially in p_T^{jet})

arXiv:1707.00657;JHEP02 (2018) 059

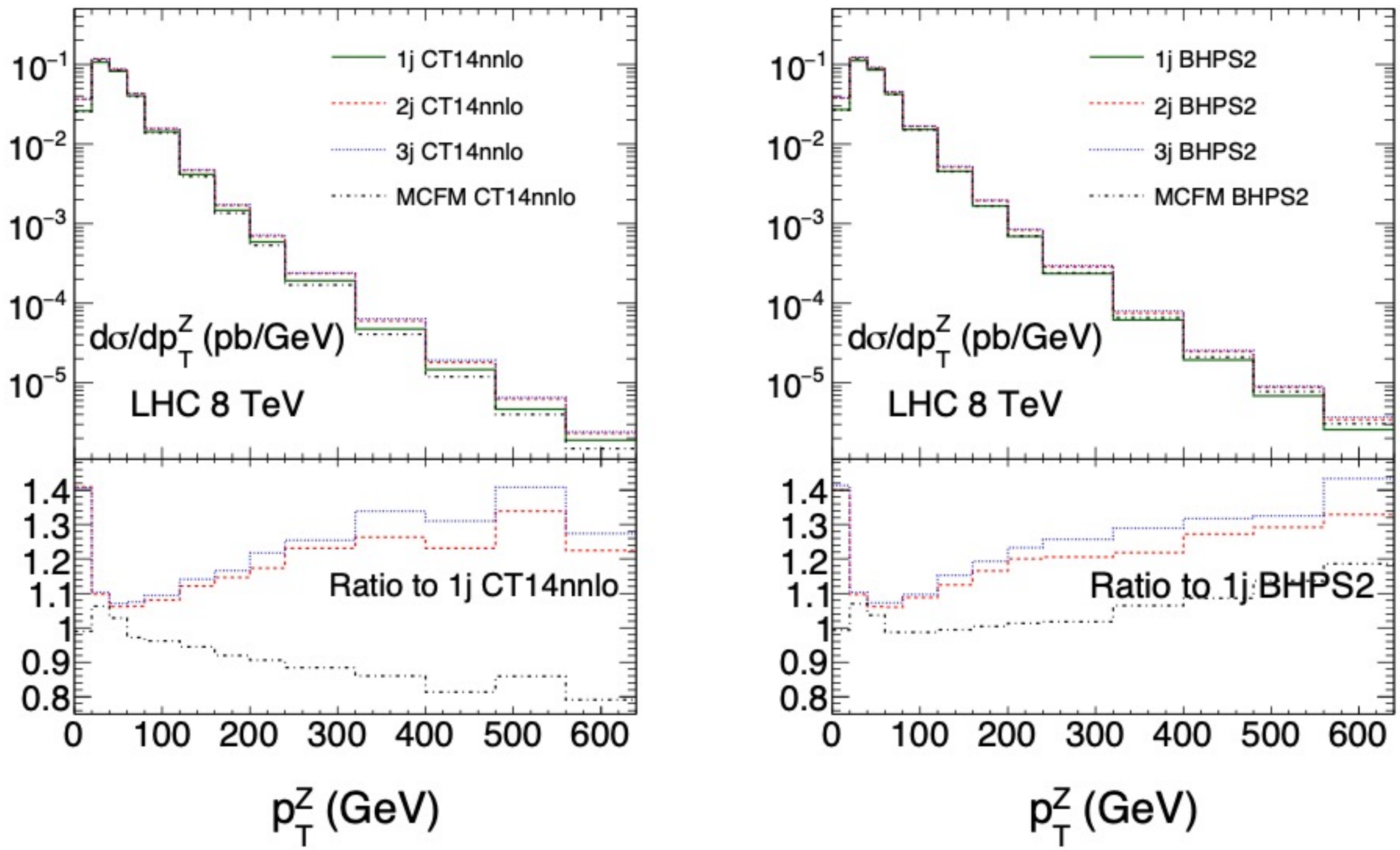
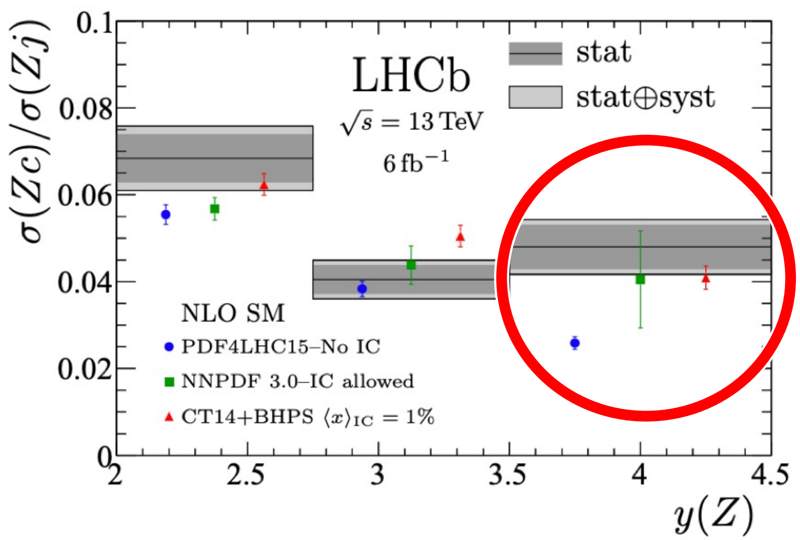


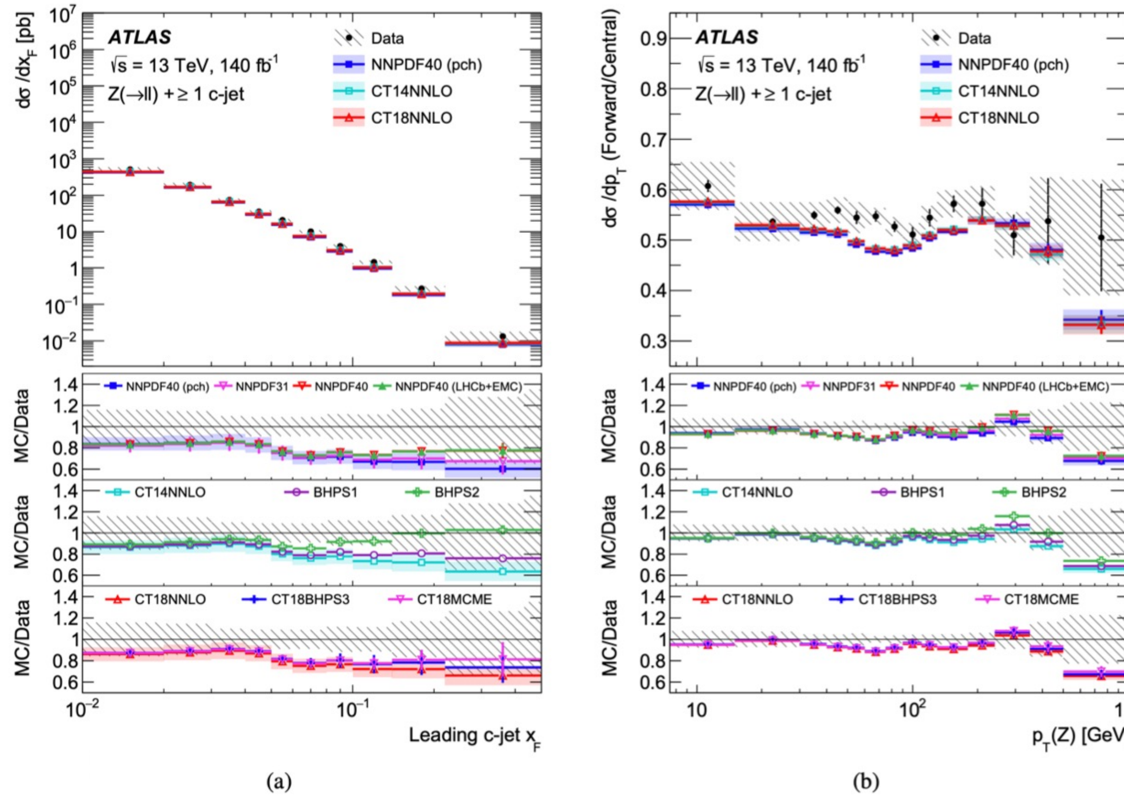
FIG. 19: Transverse momentum distribution of Z bosons produced in association with at least one charm jet at the LHC for $\sqrt{S} = 8$ TeV. Both panels show SHERPA MEPS@LO predictions (obtained by using proper charm tagging) for Z+jets production with a successively increasing number of multileg matrix elements taken into account (i.e. $n_{\rm ME} = 1, 2, 3$ where the $n_{\rm ME} = 1$ curves serve as the reference).

Intrinsic charm

Probing HF content of the proton



LHCb 13 TeV, arXiv:2109.08084, PRL128 (2022)



ATLAS13 TeV, Z+c-jet, 140 fb^{-1} arXiv:2403.15093

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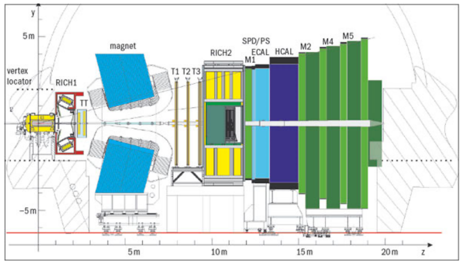
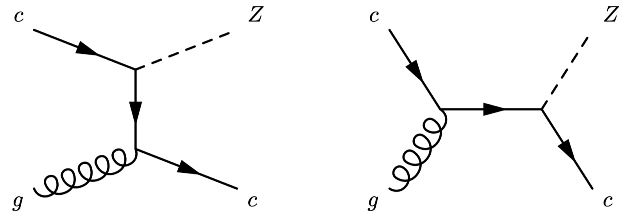
Z+c jets (arXiv:2109.08084)

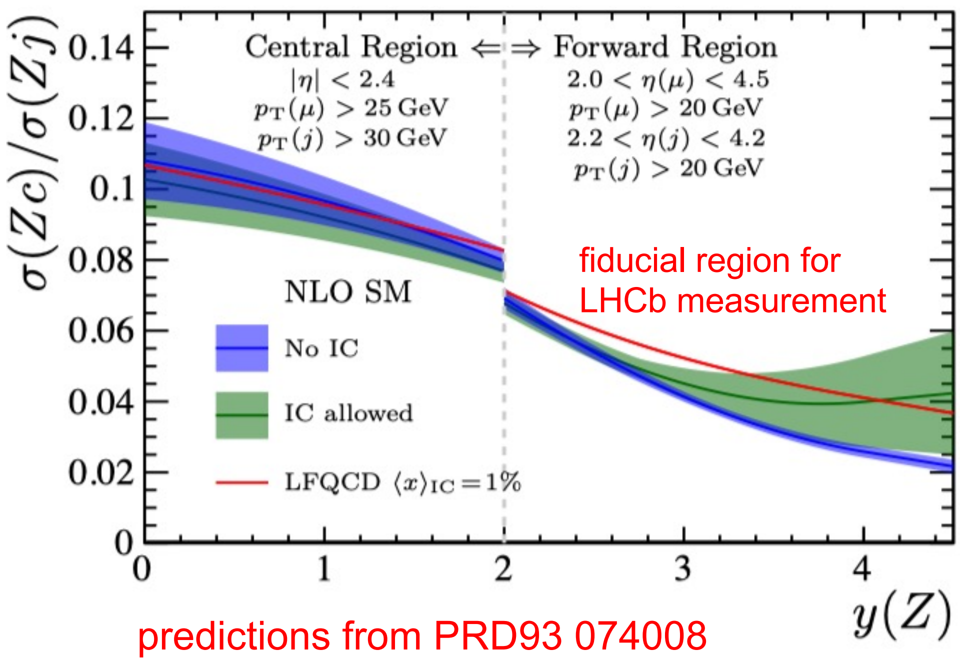
- The forward layout of LHCb makes it particularly sensitive to the presence of any charm component at high x



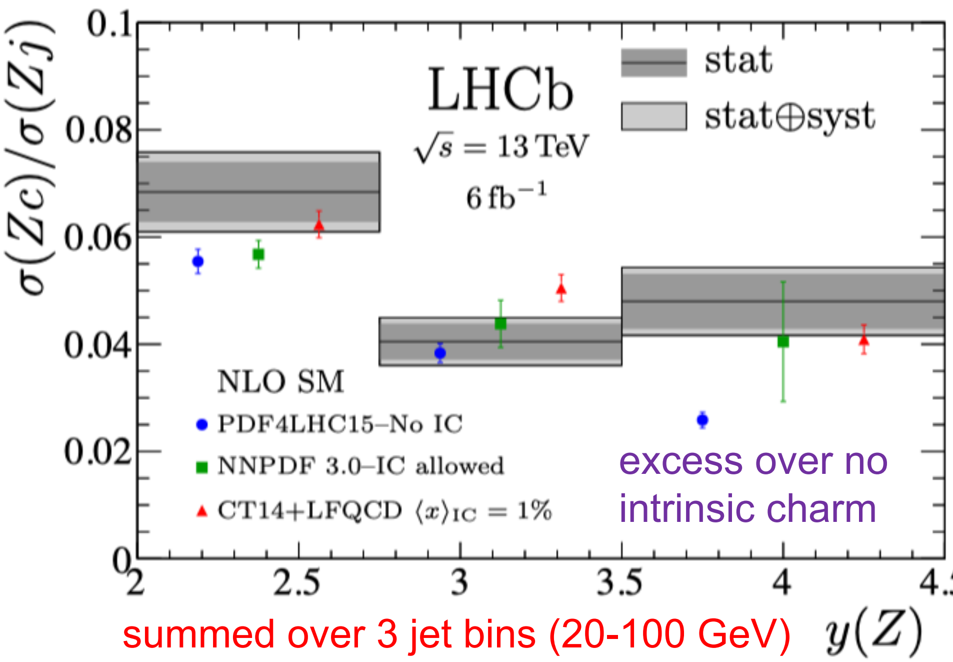
Z bosons	$p_T(\mu) > 20\,\text{GeV}$, $2.0 < \eta(\mu) < 4.5$, $60 < m(\mu^+\mu^-) < 120\,\text{GeV}$
Jets	$20 < p_T(j) < 100\,\text{GeV}$, $2.2 < \eta(j) < 4.2$
Charm jets	$p_T(c\text{ hadron}) > 5\,\text{GeV}$, $\Delta R(j, c\text{ hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$

- For greater sensitivity, measure the ratio of Zc to Zj





predictions from PRD93 074008



summed over 3 jet bins (20-100 GeV)

Future inputs

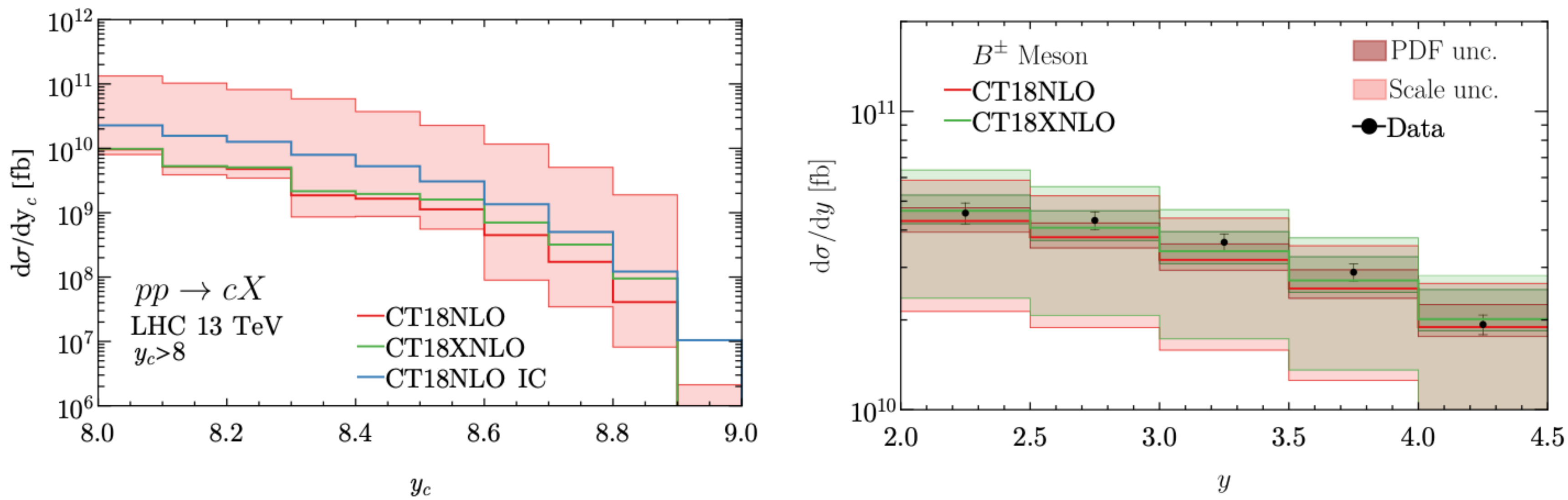


Figure 1. Left: Rapidity distributions of prompt charm at the LHC 13 TeV in the very forward region ($yc > 8$) [11]. The error band represents the CT18NLO induced PDF uncertainty at 68% CL.
Right: NLO theory predictions for the rapidity distributions obtained with CT18NLO and CT18XNLO PDFs compared to $B^{\pm}$ production data [28] from LHCb 13 TeV.

Summary

- A key aspect of understanding the physics of heavy flavor jets at the LHC is the understanding of heavy flavor quark distributions in the proton
- c and b quarks are produced perturbatively through gluon splitting, but there is the possibility of an intrinsic component, which however has not been firmly established
- From BHPS-type of models for intrinsic charm, expect the effects to be primarily at higher x
  - we are starting to probe this region with LHCb, and will probe even higher x values with forward detectors at the LHC
- A full utilization of this data in PDF fits requires:
  - a proper match/mapping of algorithms used in NNLO theory and in the data, i.e. the reason for this workshop
  - GM-VFN schemes that work at N3LO in the PDF fitting

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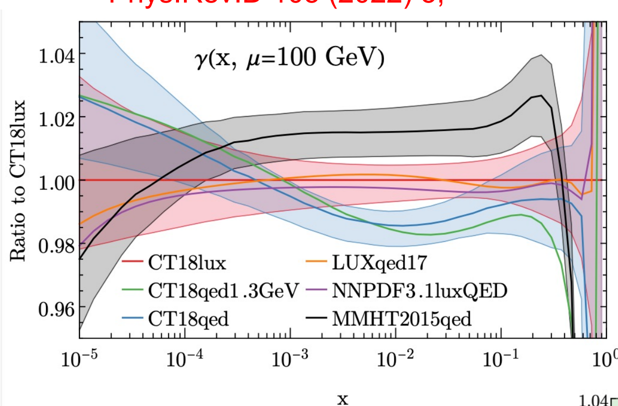
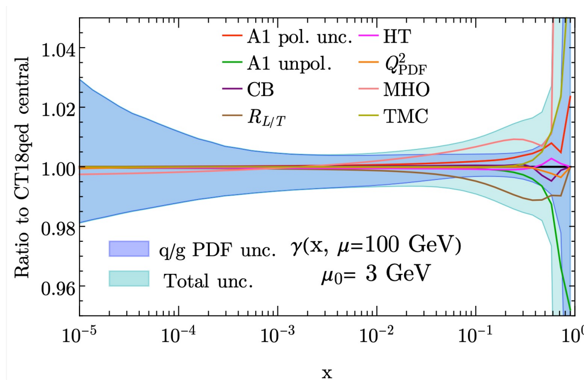
Extra

CT18QED: Photon PDF in the CTEQ-TEA global analysis

K. Xie, T. Hobbs, et al.

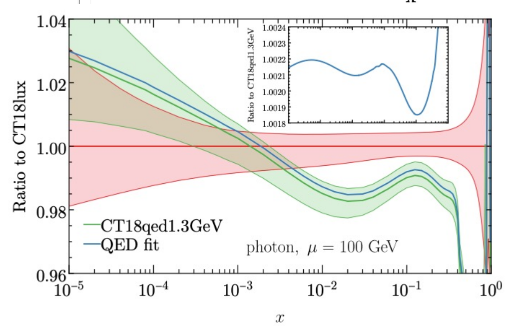
Phys.Rev.D 105 (2022) 5,

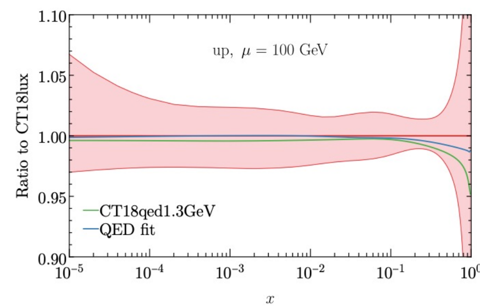




1. In the small-x region, the uncertainty mainly originates from the quark and gluon PDFs.
2. At large x, all nonperturbative sources contribute.

1. CT18lux provides the photon PDF at all scales, μ.
2. CT18qed initializes photon PDF at μ_0, and evolves to high scales.
3. CT18lux gives the photon in between LUXqed(17) and MMHT2015qed, while CT18qed gives smaller photon.



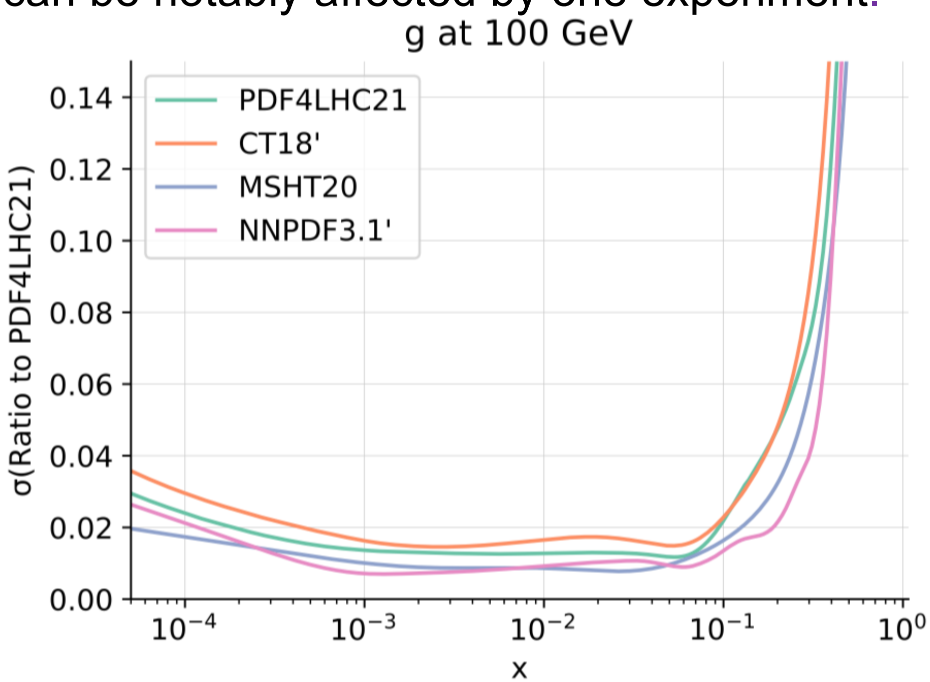


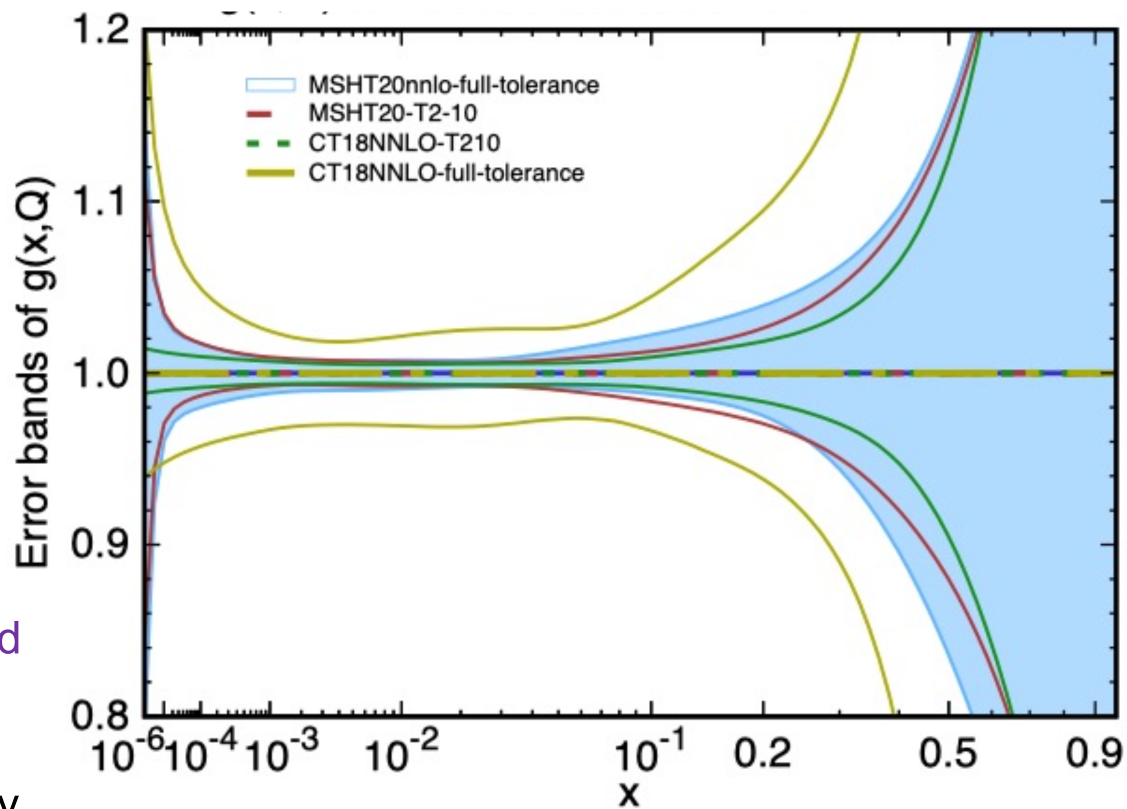
Global fit with QED evolution pull the quark PDFs back to the global minimum and therefore enahces photon slightly.

The PDF uncertainties for the combination in the PDF4LHC21 exercise is shown below. Same data sets used for all PDF fits.

NNPDF3.1'is the smallest and CT18 is the largest, with MSHT20 in-between.

NB: MSHT20 nominally does not use a fixed tolerance, but instead cuts off an eigenvector direction when a particular experiment is badly fit. Thus, the uncertainty can be notably affected by one experiment.

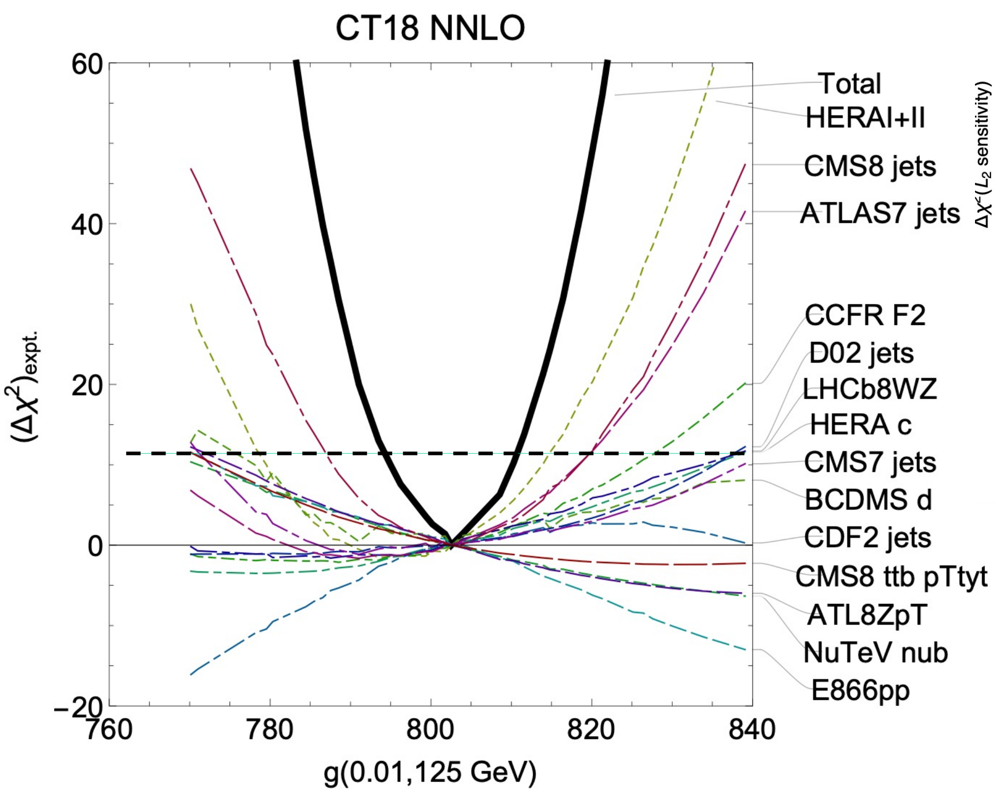


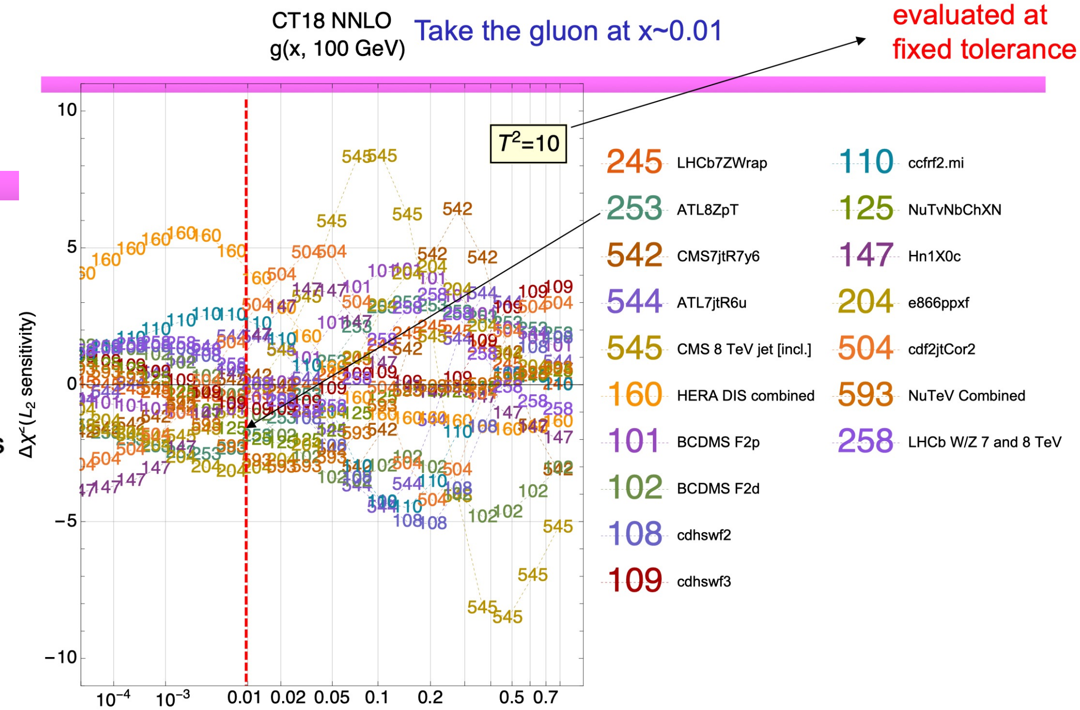


For some special cases, MSHT20 and CT18 were both defined using a $\Delta\chi^2$ of 10 (see above). **The uncertainties are equivalent, as may be expected from them both using similar data sets, and in this case having the same criteria for determining the uncertainty.**

MSHT20-full-tolerance (i.e. the canonical MSHT20) in some cases has a larger uncertainty than MSHT20-T210, and in some cases smaller, indicating that the effective tolerance for the full fit is sometimes less than 10 and sometimes greater.

PDF uncertainties



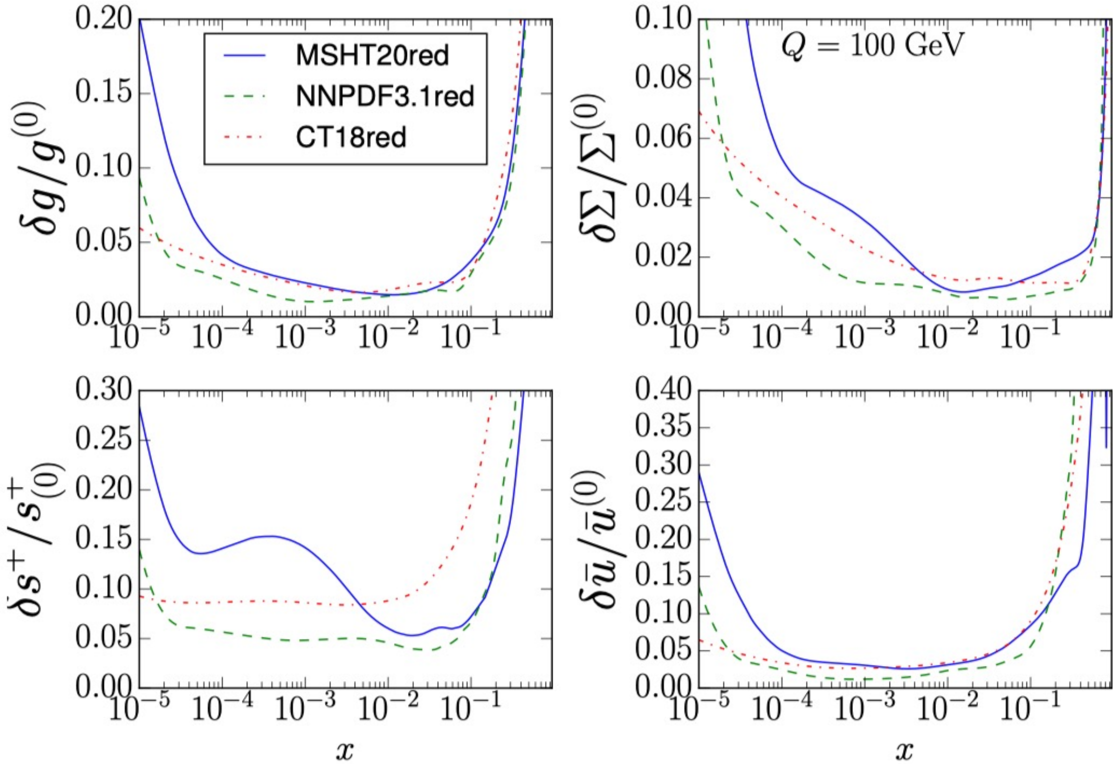


In a global PDF fit, there are tensions between the input data sets, by definition. These tensions are most easily demonstrated by the use of the L2 sensitivity above. For, example, some data sets pull the gluon up at x~0.01, some down.

The end result of the pulling is the central PDF. The PDF uncertainty reflects the size of those pulls/tensions.

Typical χ^2/dof are of the order of 1.1 for >4000 points, or very unlikely from the pure statistical POV. $\Delta\chi^2$=1 does not capture the full uncertainty.

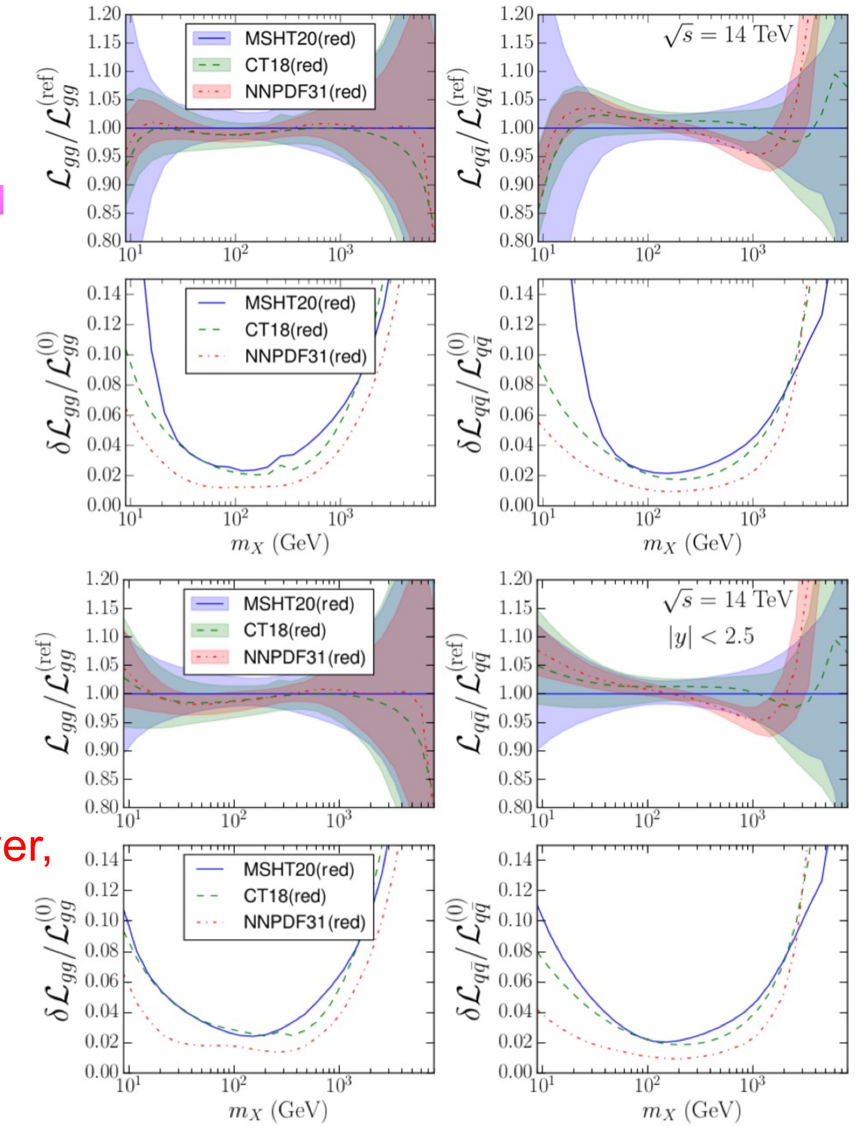
CT and MSHT use different criteria to define those tensions/define the uncertainty.



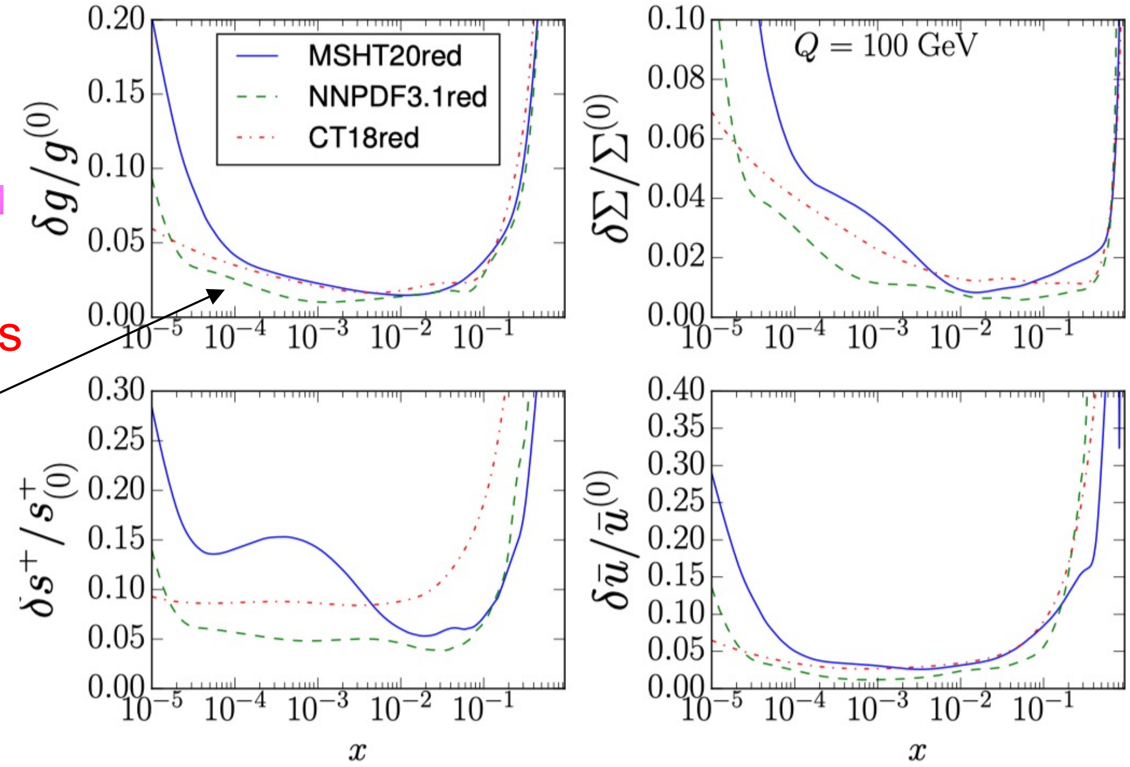
It is difficult to perform a directly similar comparison to NNPDF, as they don't use the Hessian formalism. However, as part of the PDF4LHC exercise, fits were carried out to a reduced data set, using similar theory parameters, in which equivalent results should be obtained, if the uncertainty criteria were the same. The uncertainties are larger than for the full fit.

CT18red and MSHT20red agree for the most part. There are fewer experiments included, so less likely for a particular experiment to truncate the uncertainty from a particular eigenvector.

NNPDF consistently has a consistently smaller uncertainty, especially at low x, partially explained in 2404.10056.

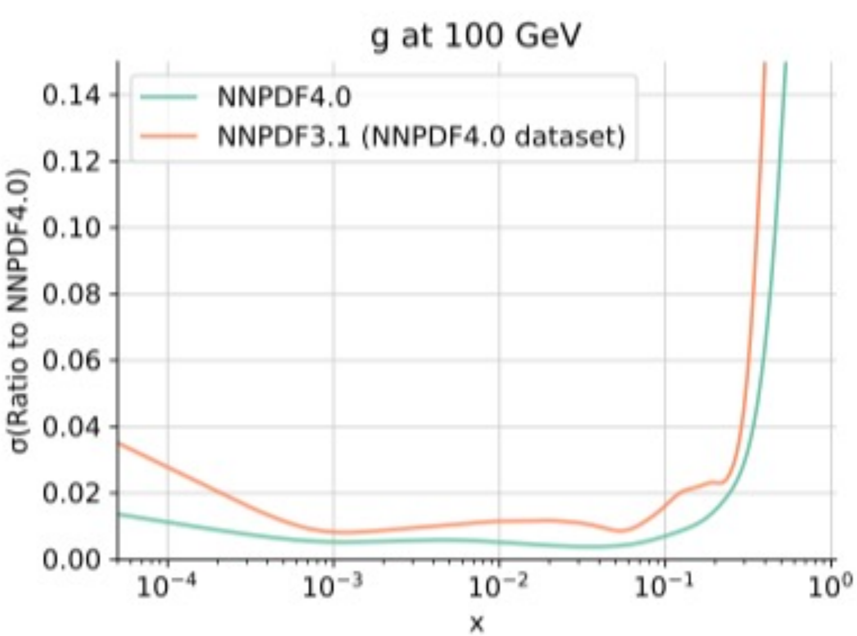


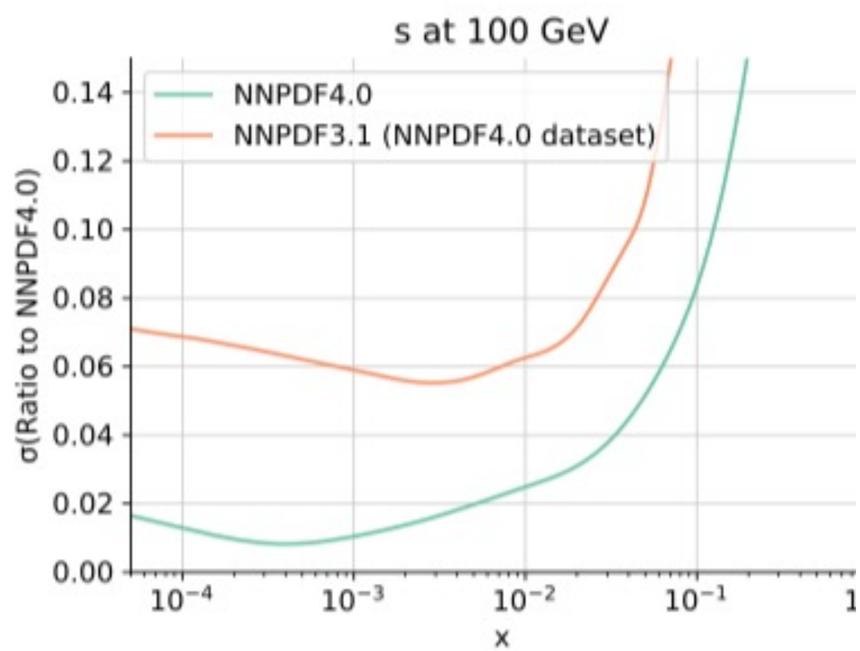
This difference is even more prominent when the PDF luminosities are compared (above). **For gg fusion at the Higgs mass, it is a factor of 2.**



note the smaller uncertainties
in regions not
constrained by data

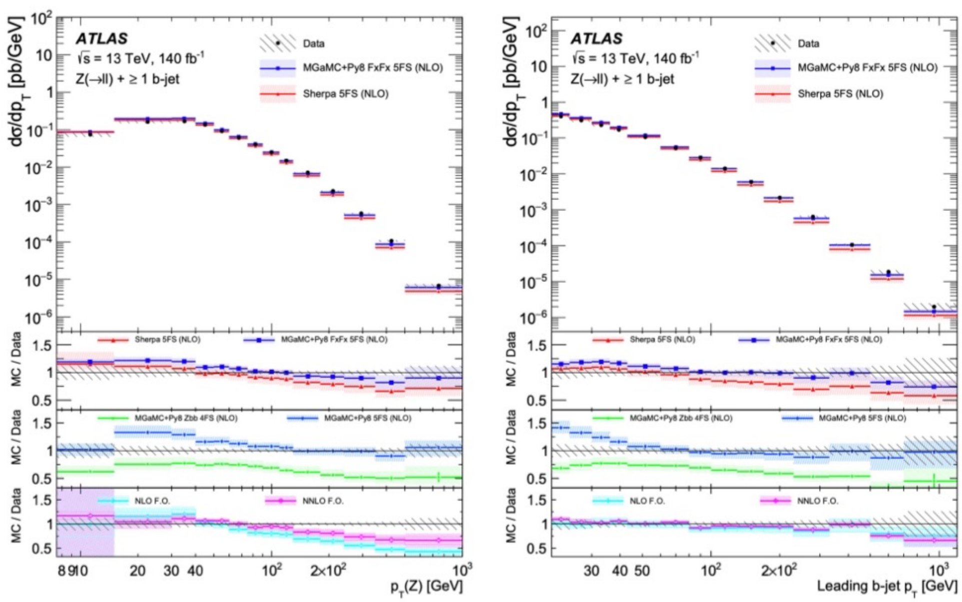
uncertainties are reduced even further for 4.0





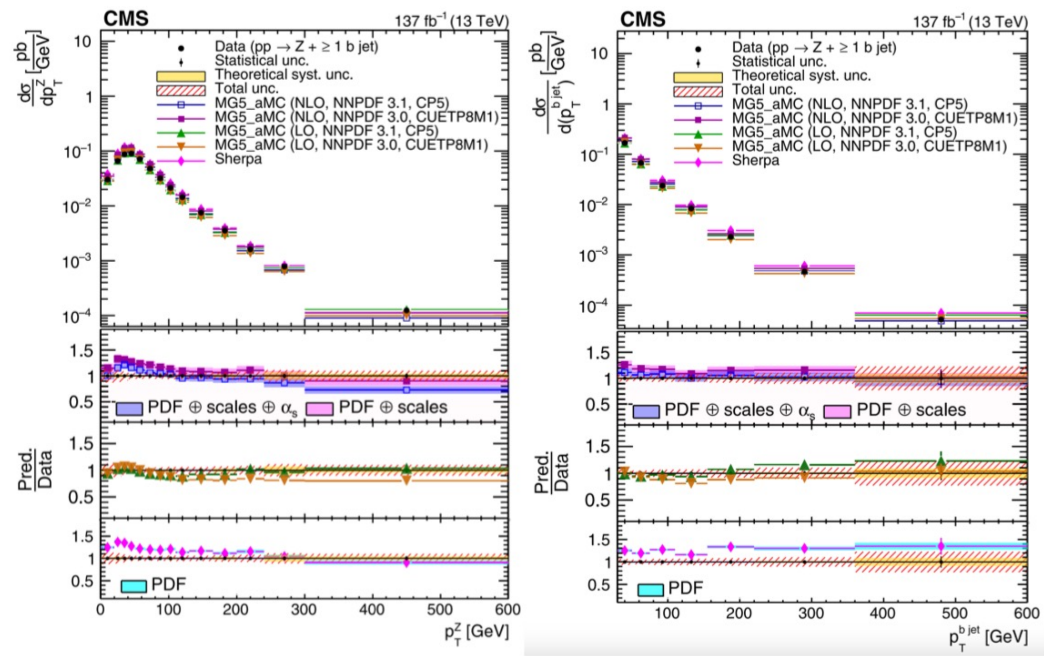
Large inflow of new measurements @LHC

Precise measurements Z + c/b-jets available from the ATLAS, CMS and LHCb collaborations at the LHC



(a) (b)

ATLAS13 TeV, Z+b-jet, 140 fb^{-1} 2403.15093

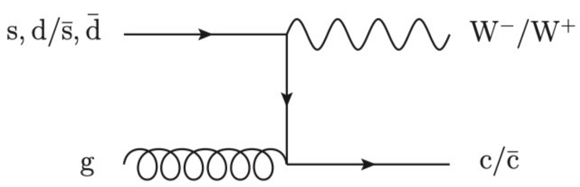


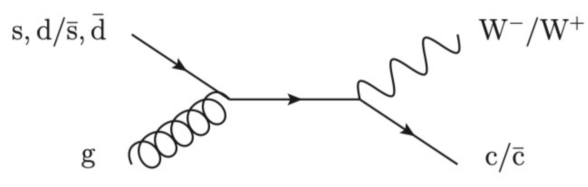
CMS13 TeV, Z+b-jet, 137 fb^{-1} 2112.09659 PRD 105 (2022)

M. Guzzi DIS24

W+c jets

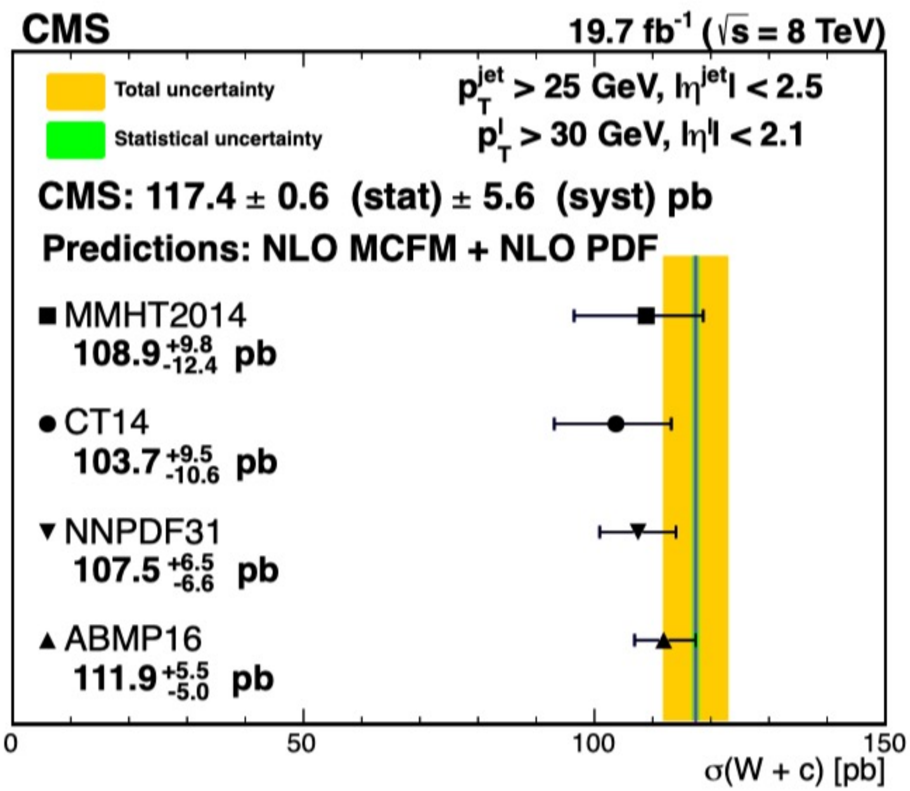
- Measurement carried out inclusively, and differentially as function of p_T and η of lepton

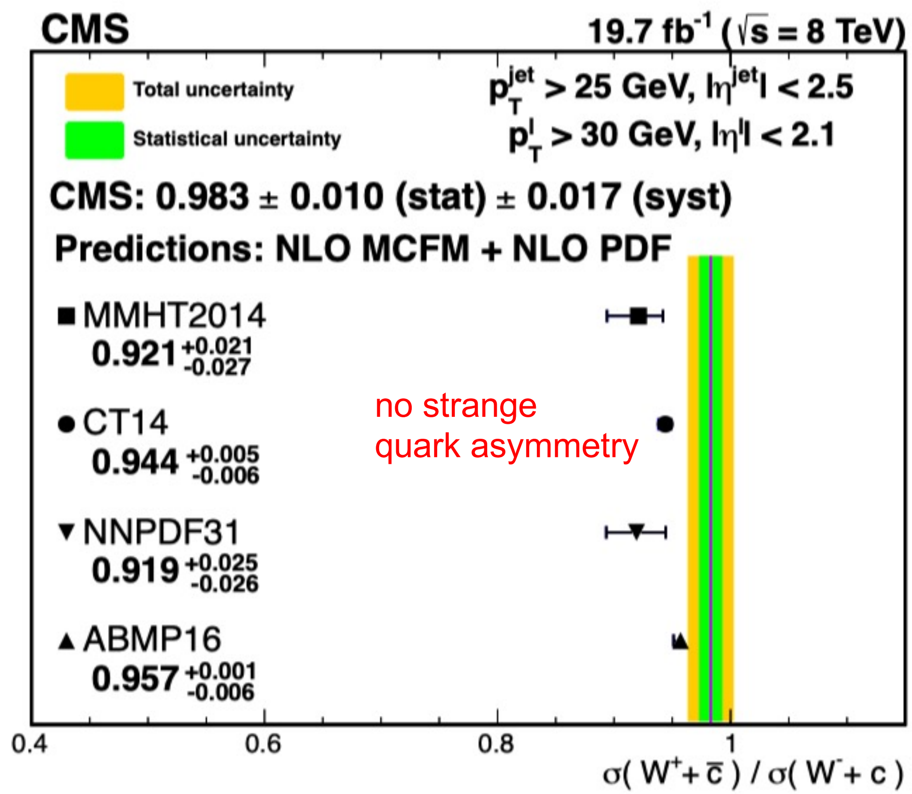




Note: W and c quark should be of opposite sign; SS-OS suppresses contributions from gluon splitting

arXiv:2112.00895 (submitted to EPJC)



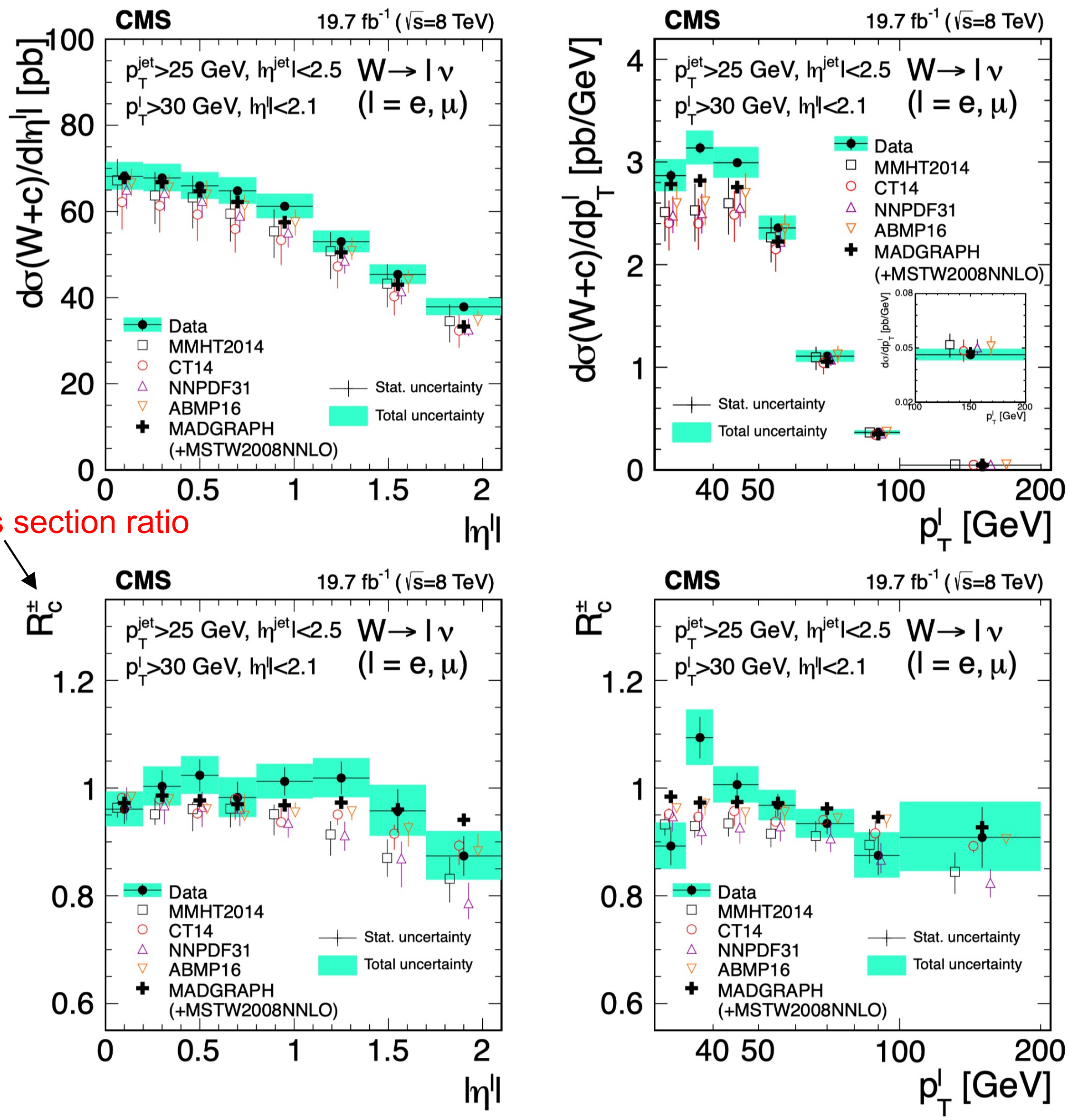


Differential cross sections

- Require an isolated lepton (e or μ) with p_T>30 GeV and $|\eta|$<2.1
- Require a jet with p_T>25 GeV with $|\eta_{jet}|$<2.5. Jets not selected if $\Delta R(\text{jet},l)$<0.5
- Data are larger then (NLO+PS) predictions for lepton p_T less then 65 GeV, but compatible within uncertainties
- NNLO corrections for W+c predicted to be on the order of 5% for lepton p_T less then 60 GeV and about 1% for larger p_T values
  - *JHEP* 06 (2021) 100
- This would improve the level of agreement with the data

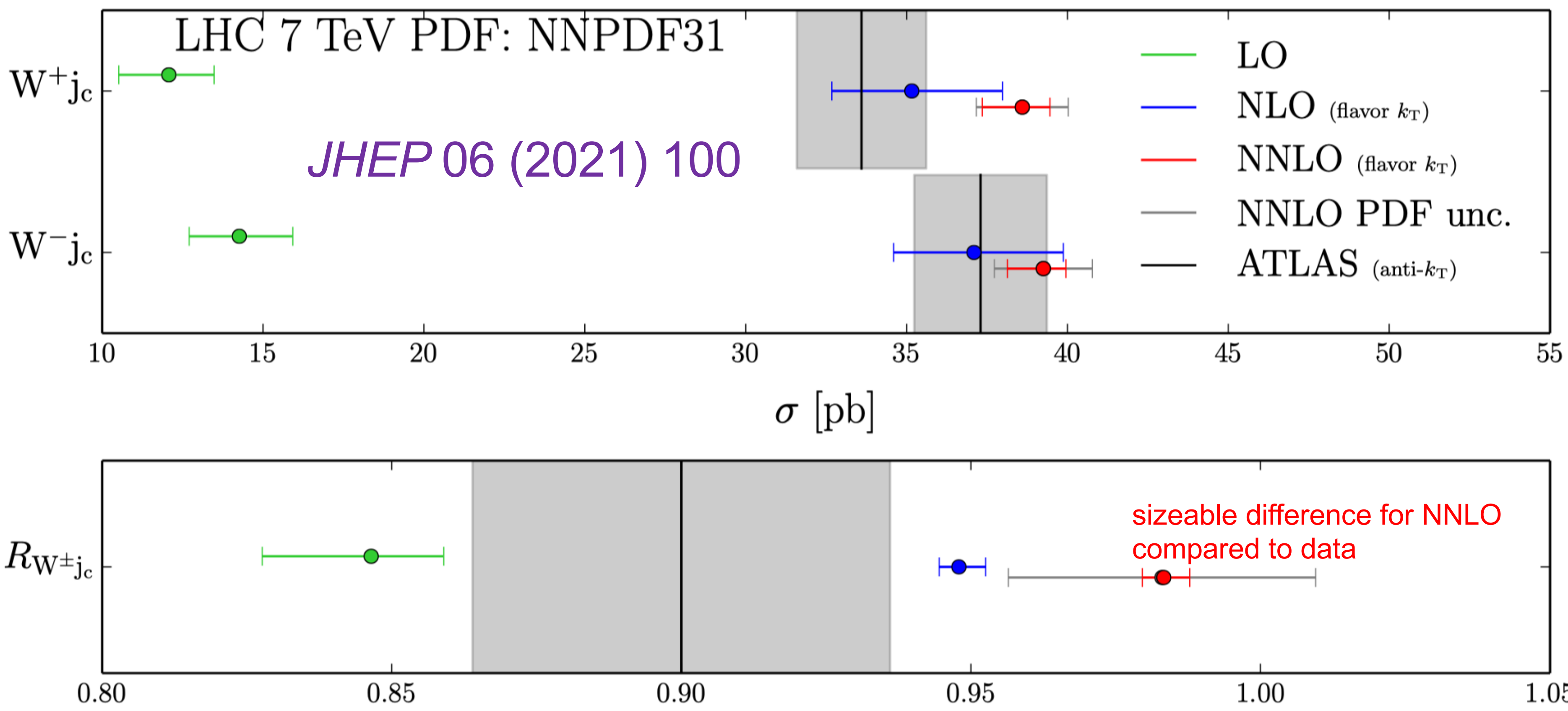
arXiv:2112.00895 (submitted to EPJC)

cross section ratio



NNLO W+c-jet cross section calculation

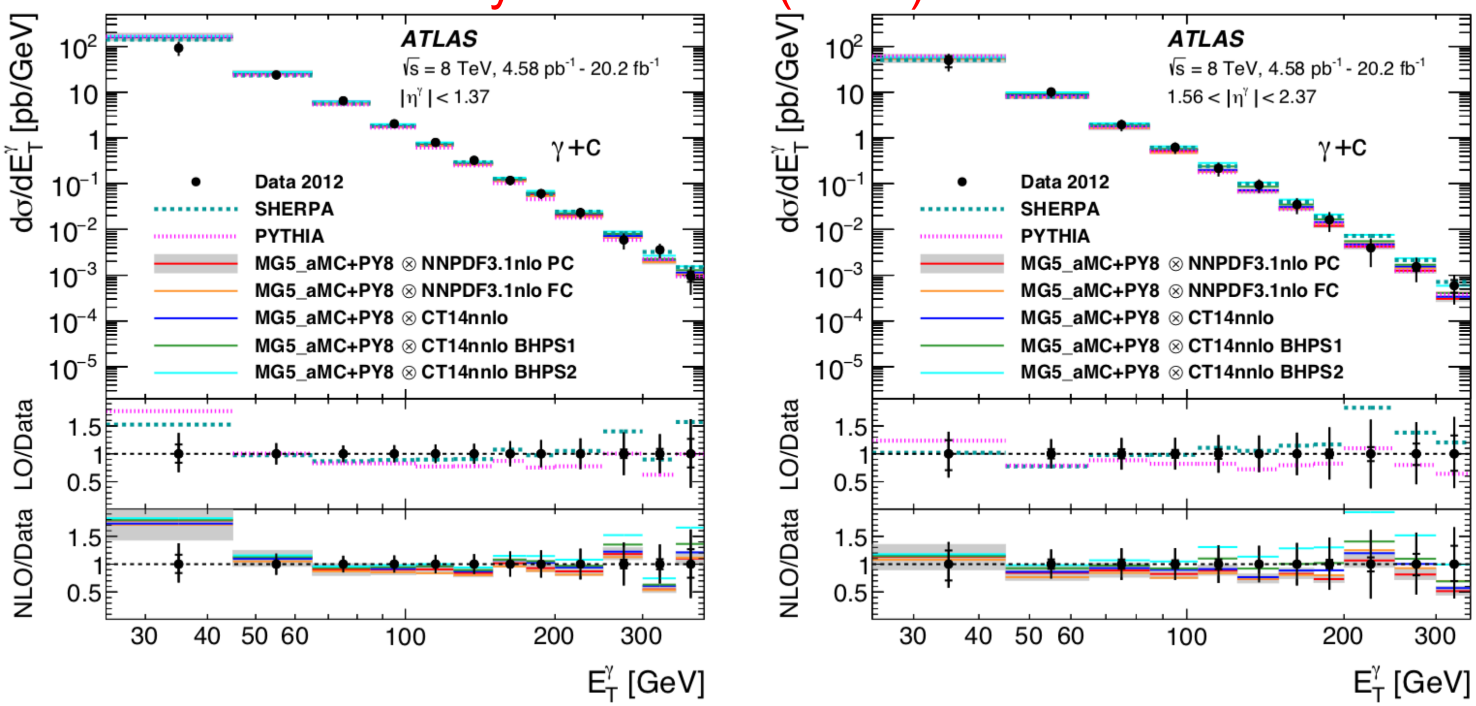
- Large reduction in uncertainties from NLO->NNLO
- NNLO scale uncertainties smaller then PDF uncertainties
- NB: the NNLO calculation used flavor tagging for the charm jet; the experimental measurement used the antikT algorithm with later flavor identification; NNLO corrections to subleading CKM-mediated processes not included in this calculation (but are now available)



Photon+charm jets

- Photons measured in central and forward rapidity
- Jets are defined with antikT algorithm, R=0.4; p_T^{jet}>20 GeV
  - if jet contains a b-hadron with p_T>5 GeV within ΔR=0.3 of jet, then it is assigned as a b-jet; if there is no b-hadron, but there is a charm hadron, it is assigned as a c-jet
- All predictions agree reasonably well with data (relatively large uncertainties)
- There are differences at high E_T when intrinsic charm included in predictions of similar size to uncertainties
- NNLO predictions would be very useful (have to deal with photon isolation)

Phys.Lett.B776(2018) 295

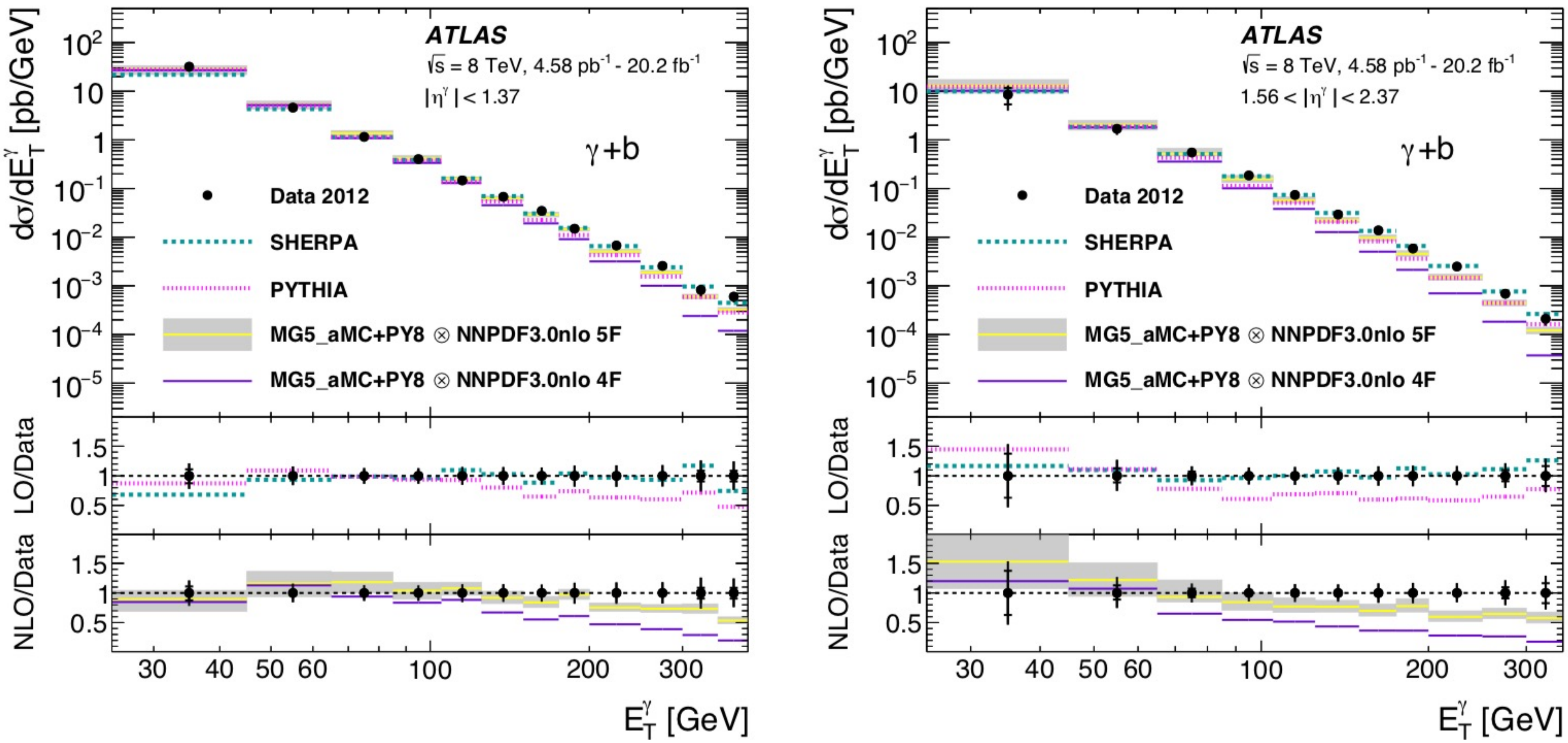


2 intrinsic charm PDFs

Photon+b jets

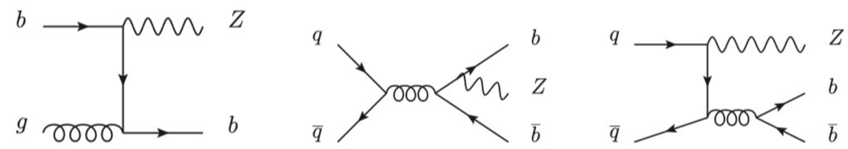
- 5FNS scheme works better then 4FNS scheme
- Best description of the data provided by Sherpa with up to 3 additional partons included in 5FNS scheme
- Again, NNLO would be useful

Phys.Lett.B776(2018) 295



Z+b jets

- The b quark is treated as perturbatively produced by all PDF fitting groups; i.e. inside the proton, at higher Q^2 scales, only things that drive it are the b-quark mass and the value of $\alpha_s(m_Z)$
- Also sensitive to final state gluon splitting



- Calculation can be performed either in 4FNS or 5FNS

ATLAS *JHEP* 07 (2020) 44

- Partial run 2 dataset: 35.6 fb^{-1}
- $Z + \geq 1$ or ≥ 2 b jets, b-jet $p_T > 20$ GeV, $|y| < 2.5$
- b-jet tagger: ≈ 70% efficiency
- Testing several MC predictions with 4 and 5 FNS: 5FNS includes b quark in PDF

Kinematic variable	Acceptance cut
Lepton p_T	$p_T > 27$ GeV
Lepton η	$\lvert\eta\rvert < 2.5$
$m_{\ell\ell}$	$m_{\ell\ell} = 91 \pm 15$ GeV
b-jet p_T	$p_T > 20$ GeV
b-jet rapidity	$\lvert y\rvert < 2.5$
b-jet–lepton angular distance	$\Delta R(b\text{-jet}, \ell) > 0.4$

CMS-SMP-20-015 arxiv:2112.09659

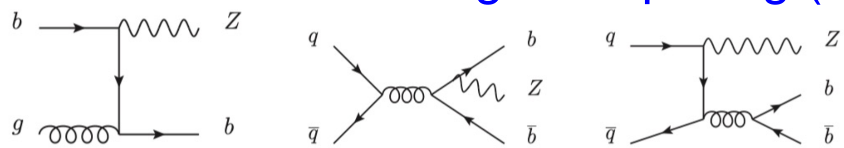
- Full run 2 dataset: 137 fb^{-1}
- $Z + \geq 1$ or ≥ 2 b jets, b-jet $p_T > 30$ GeV $|\eta| < 2.4$
- b-jet tagger: ≈ 50% efficiency (tight WP)

1

Object	Selection
Dressed leptons	p_T (leading) > 35 GeV, p_T (subleading) > 25 GeV, $\lvert\eta\rvert < 2.4$
Z boson	$71 < M_{\ell\ell} < 111$
Particle-level bjet	bhadron jet, $p_T > 30$ GeV, $\lvert\eta\rvert < 2.4$

Z+b jet

- The b quark is treated as perturbatively produced by all PDF fitting groups; i.e. inside the proton, at higher Q^2 scales only things that drive the PDF are the b-quark mass and the value of $\alpha_s(m_Z)$
- Also sensitive to gluon splitting (and multiplicative factor of parton shower)

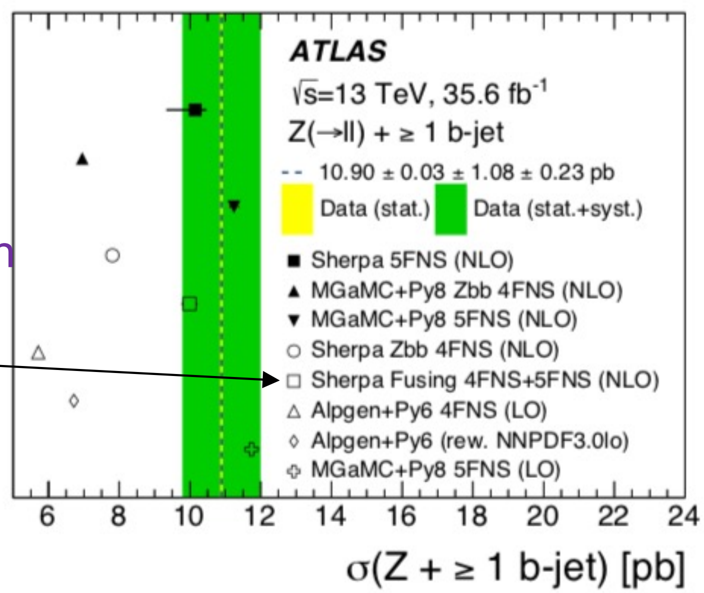


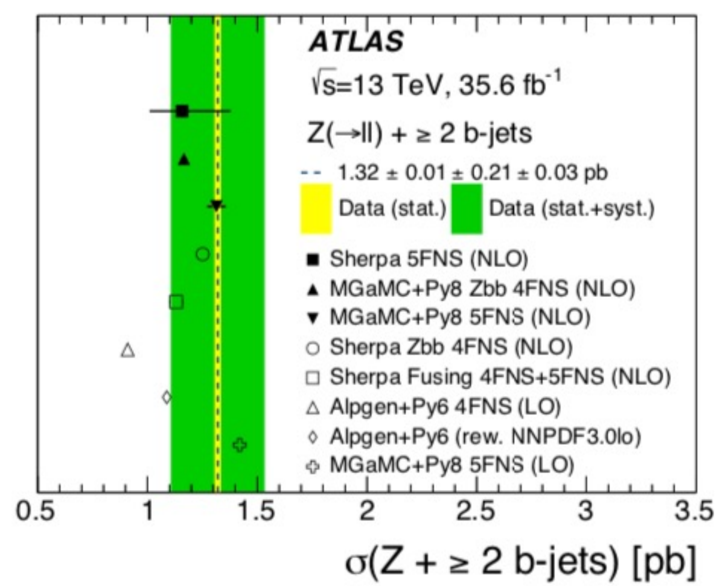
- Calculation can be performed either in 4FNS or 5FNS
  - 4FNS underestimates cross section; better agreement with5FNS

ATLAS *JHEP* 07 (2020) 44

note Fusing prediction of 4FNS+5FNS schemes

Monte Carlo equivalent of FONLL/ ACOT





Most important information comes from differential distributions, though

- NNPDF3.1 PDF is the most up-to-date of the PDFs shown; would be nice to have comparisons of more modern PDFs as well (CT18, MSHT20, NNPDF4.0 (NNPDF3.1’)

arxiv:2112.09659 CMS-SMP-20-015

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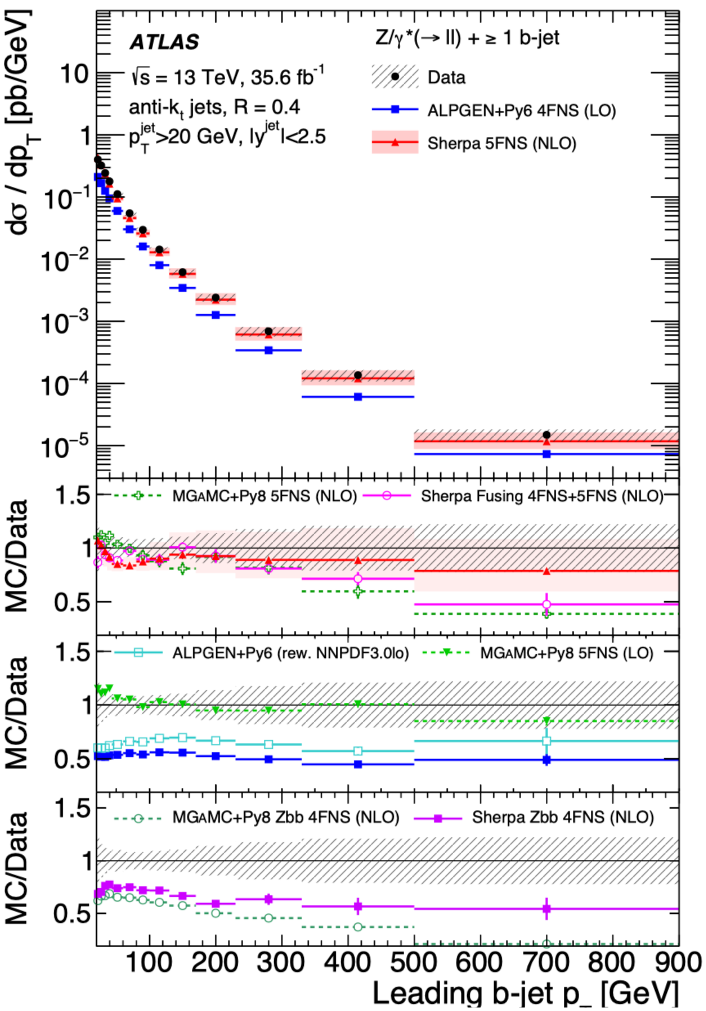
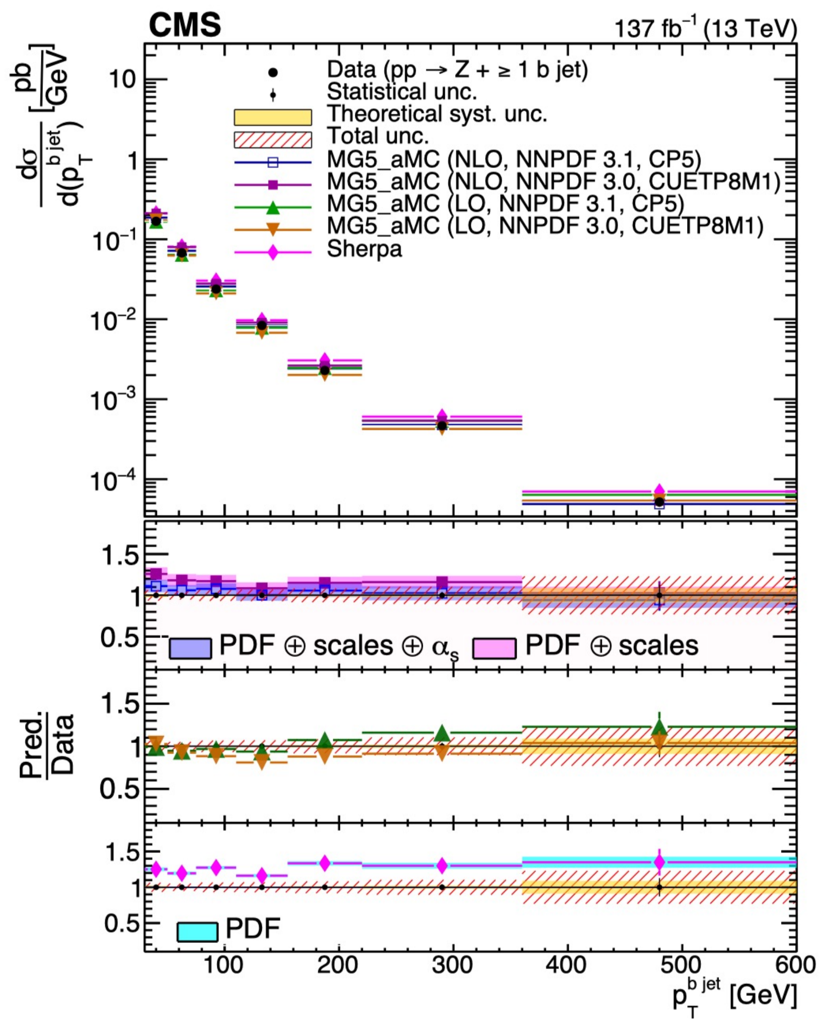


sizeable difference depending on whether massless or massive NLO+PS prediction used



Z+b at NNLO prediction

- Carried out by combining a massless NNLO and a massive NLO computation at order (α_s^3) (arXiv:2005.03016)
  - initial state b-quarks from gluon splitting resummed by PDF evolution; finite b-quark mass effects also incorporated (presumably same could be done for Z+c)
  - note: massless calculation means IR-safe definition of jet flavour must be used; not consistent with experimental choice
  - desired to have data unfolded to level of partonic flavour-kT jets or some equivalent

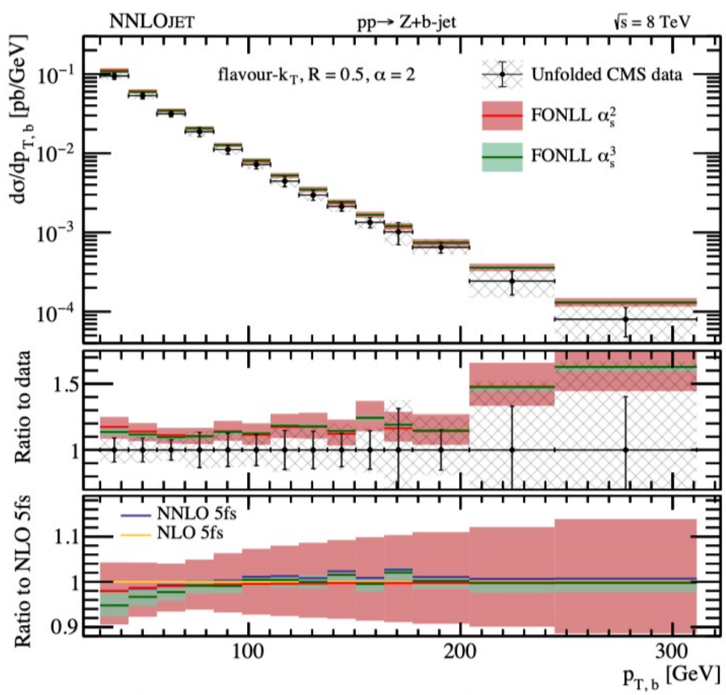


Figure 2: The transverse momentum distribution of the leading flavour-k_T b-jet. The absolute cross-section is shown in the upper panel, the ratio to the unfolded data in the central panel, and the ratio to the NLO 5fs prediction in the lower panel. The shown uncertainty of the FONLL distributions are due to scale variations alone.

large reduction in uncertainty in going from NLO to NNLO

reasonable agreement with data

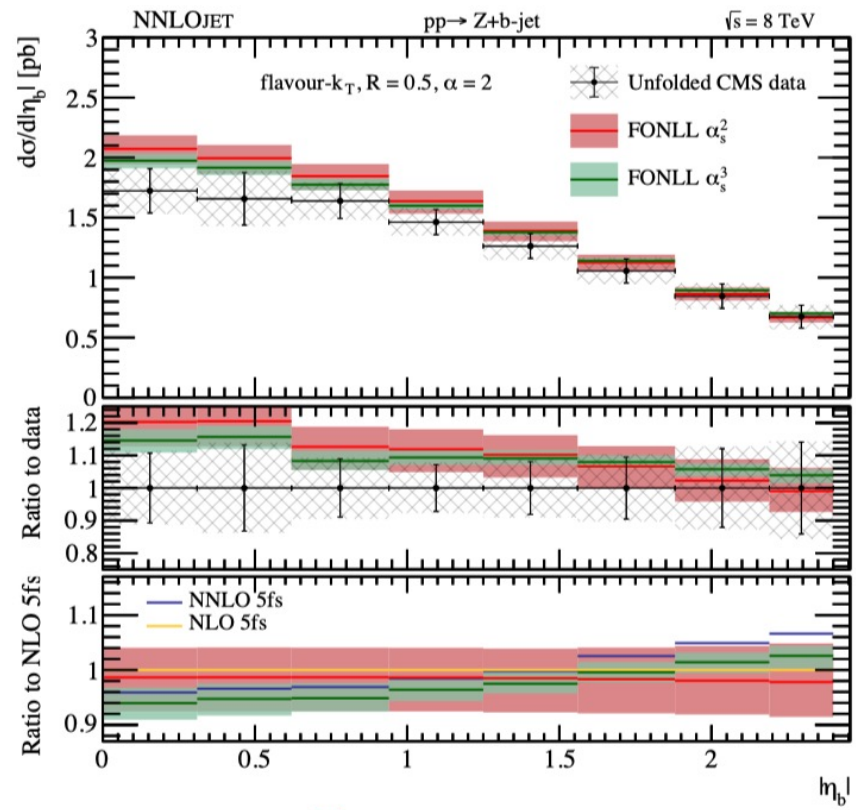


Figure 3: As in Fig. 2, now for the absolute psudorapidity distribution of the leading flavour-k_T b-jet.

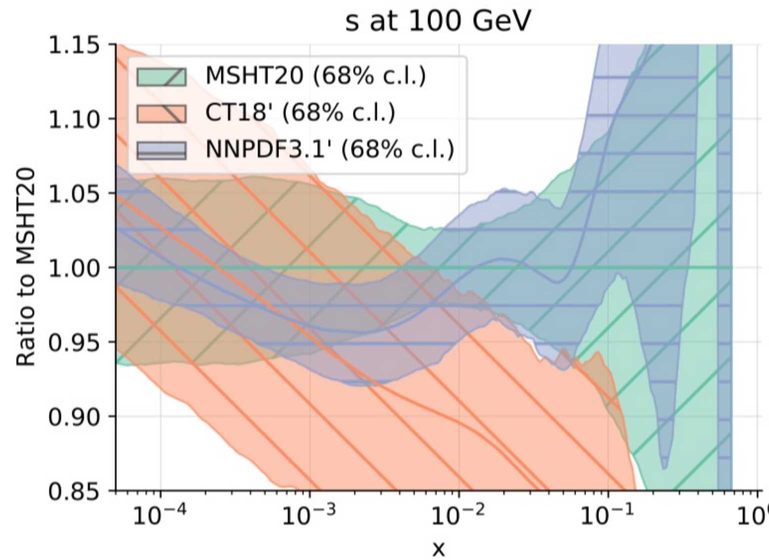
What is the L_2 sensitivity…continued?

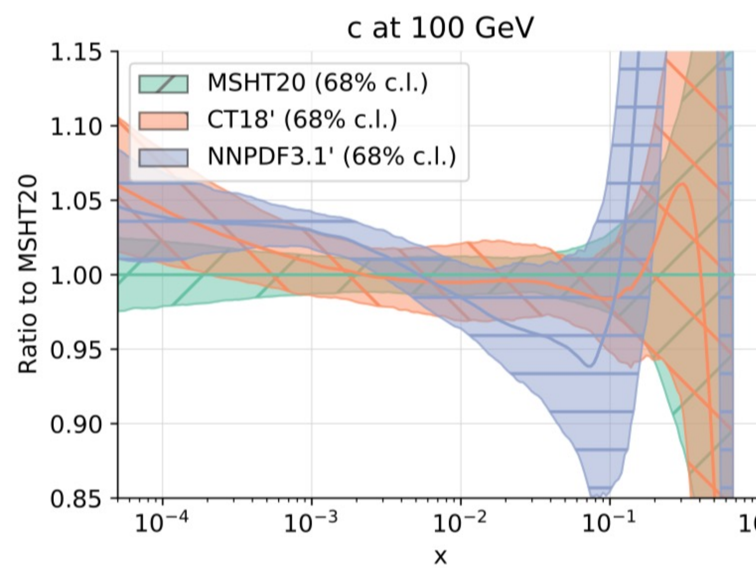
- The L_2 sensitivity provides a visualization of what is happening inside the PDF fit
- It can be considered as a faster version of Lagrange Multiplier scans (but dependent on the Gaussian approximation)
- The L_2 sensitivity streamlines comparisons among independent analyses, using the log-likelihood (χ^2) values for the fitted experiments and the error PDFs
- Both the L_2 and LM methods explore the parametric dependence of the χ^2 function in the vicinity of the global minimum
- The L_2 sensitivity has been used internally by CT (in CT18), by the PDF4LHC21 benchmarking group (to determine which data sets should be in the reduced PDF fit used for benchmarking), and now by CT, MSHT and ATLASpdf in this upcoming paper

Strange/charm PDFs

- Consider the strange quark PDF
- There is a large difference between CT18 and CT18A/MSHT20/NNPDF3.1 due almost entirely to the ATLAS 7 TeV W/Z data (see my talk on Monday)
- The difference between the W and Z cross sections requires a larger strange quark (s-sbar->Z)
- **All 3 groups fit the ATLAS W/Z data equally poorly**
- Because of its fitting criteria, CT18 does not use the 7 TeV W/Z data for its main fit (but it is in CT18A)
- W+c data offer another window on the strange quark distribution
- NNPDF3.1 has a different charm distribution then CT18/MSHT20, due to its fitting the charm distribution as a free parameter, rather then generating perturbatively through gluon splitting; an intrinsic charm component may be present at high x
- CT has published PDF sets in which an intrinsic component of charm is modeled. The addition of this intrinsic component leads to a small, but noticeable, reduction in global χ^2
- Z+c/γ+c offers another window on the charm quark

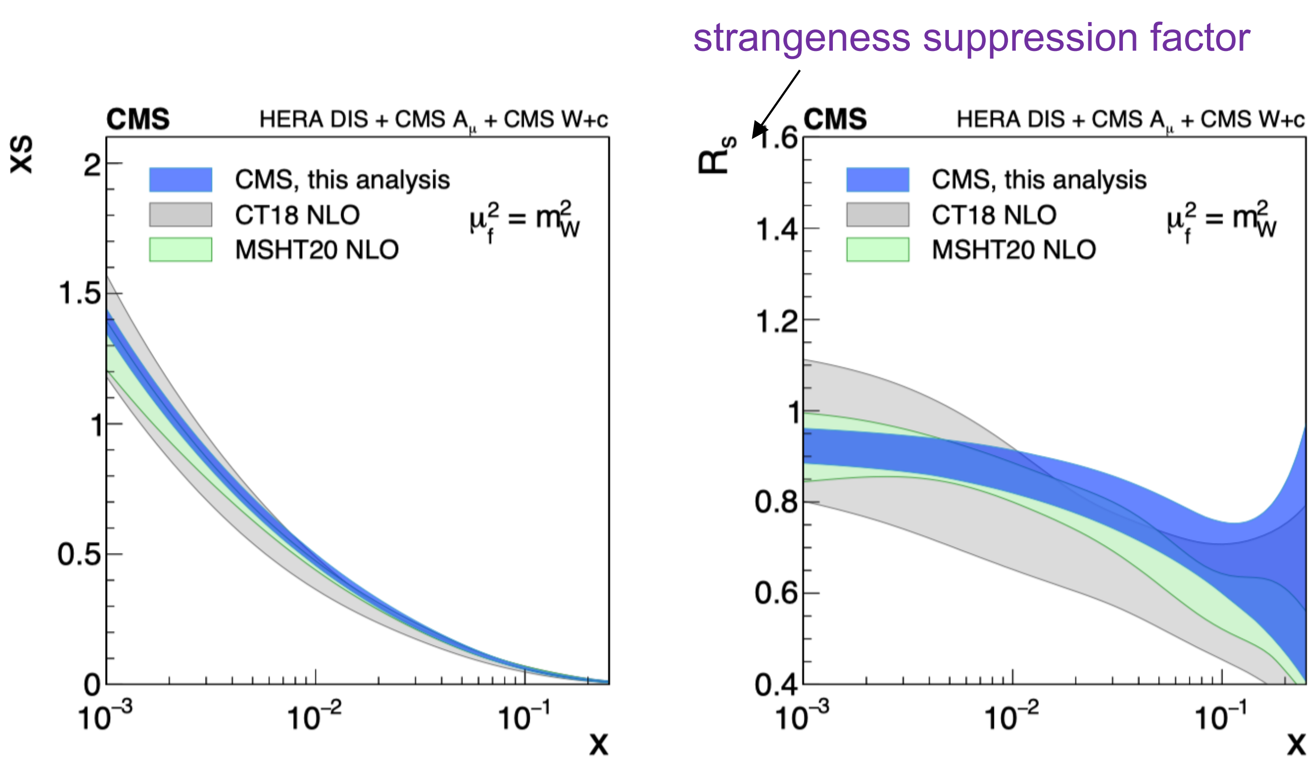
PDF4LHC21: arXiv:2203.05506





(W+c) strange quark PDF

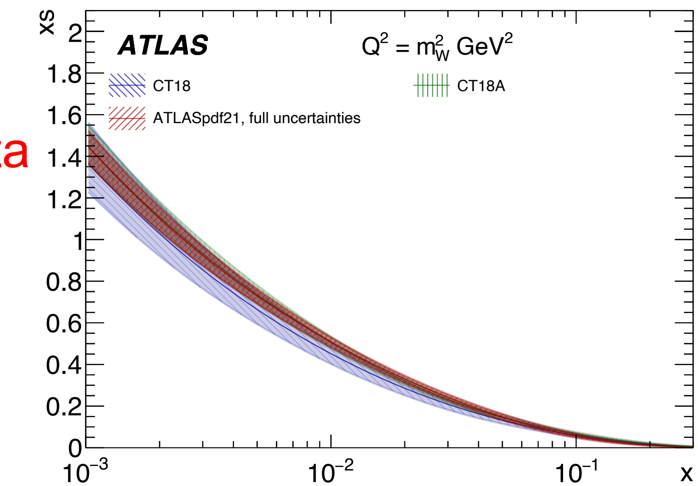
- Derived CMS strange quark consistent with that obtained by CT18 and MSHT20 for x<0.01; somewhat larger at higher x
  - NB: MSHT20 includes ATLAS 7 TeV W/Z data



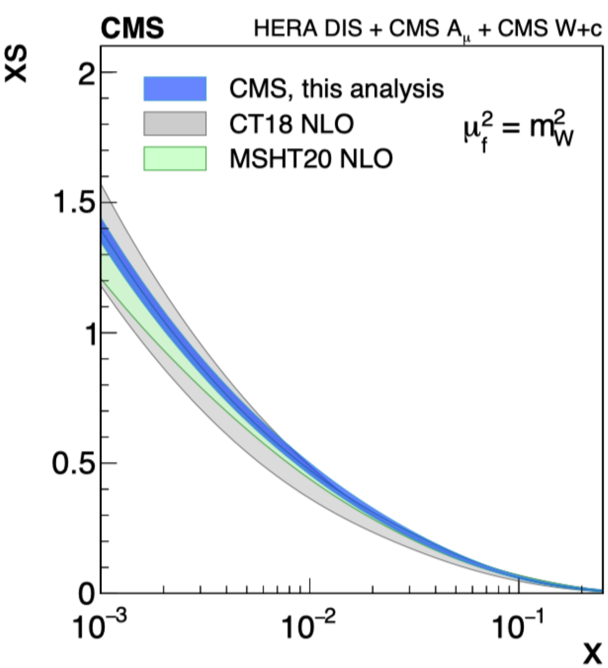
arXiv:2112.00895 (submitted to EPJC)

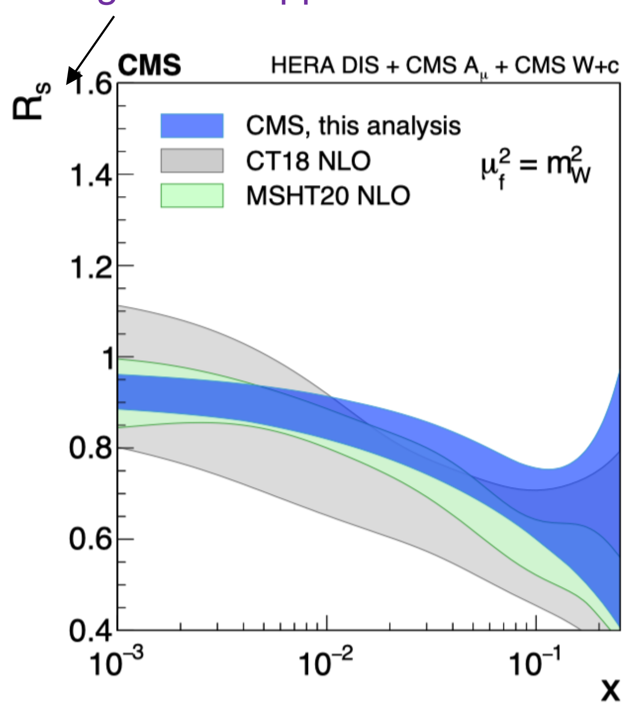
(W+c) strange quark PDF

- Derived CMS strange quark consistent with that obtained by CT18 and MSHT20 for x<0.01; somewhat larger at higher x
  - NB: MSHT20 includes ATLAS 7 TeV W/Z data
- Compare to results from ATLAS PDF21 fit
  - CT18 does not include ATLAS 7 TeV W/Z data, CT18A does

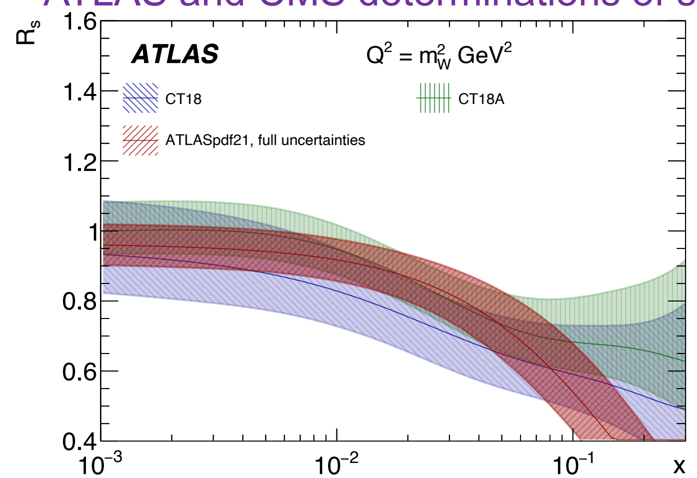


strangeness suppression factor





perhaps more consistency between ATLAS and CMS determinations of s



thanks to Francesco Giuli for making the ATLAS plots

arXiv:2112.00895 (submitted to EPJC)

W+c at NNLO-differential

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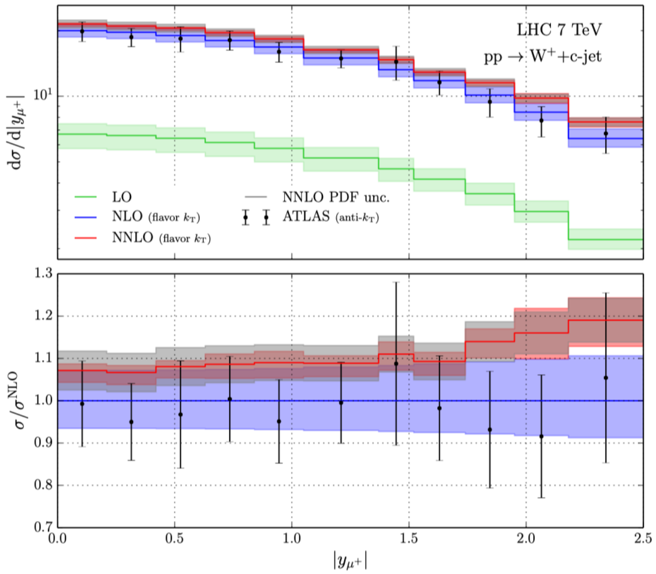

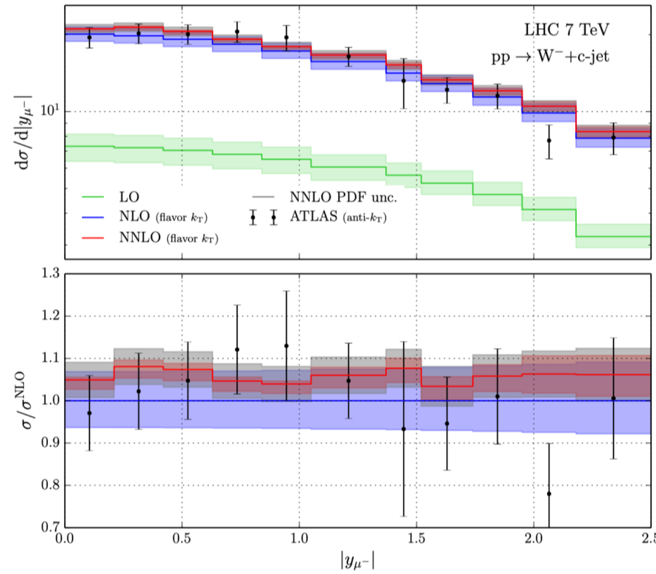

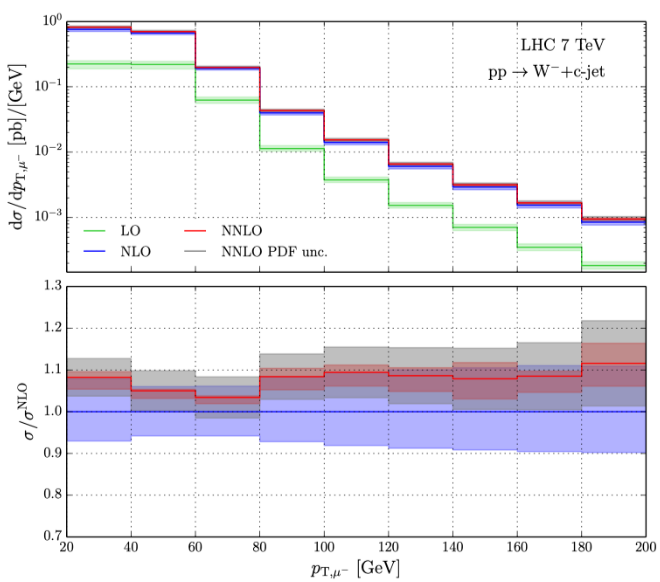

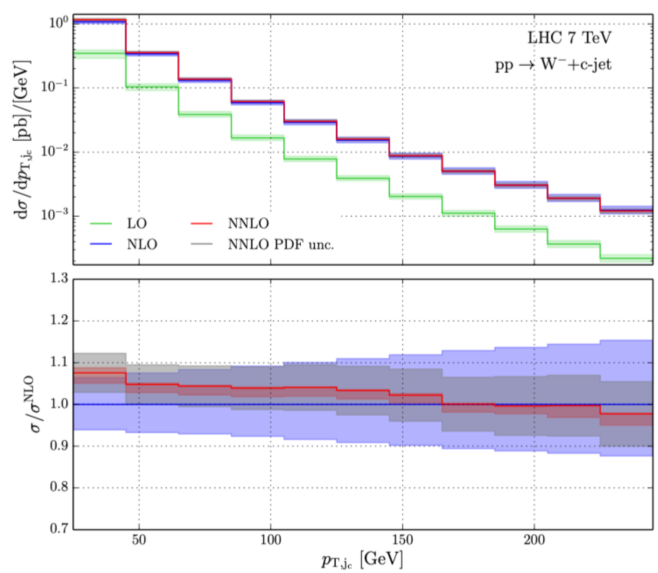

W+c at NNLO

- Ratio plots sensitive to s-$\bar{s}$ asymmetry

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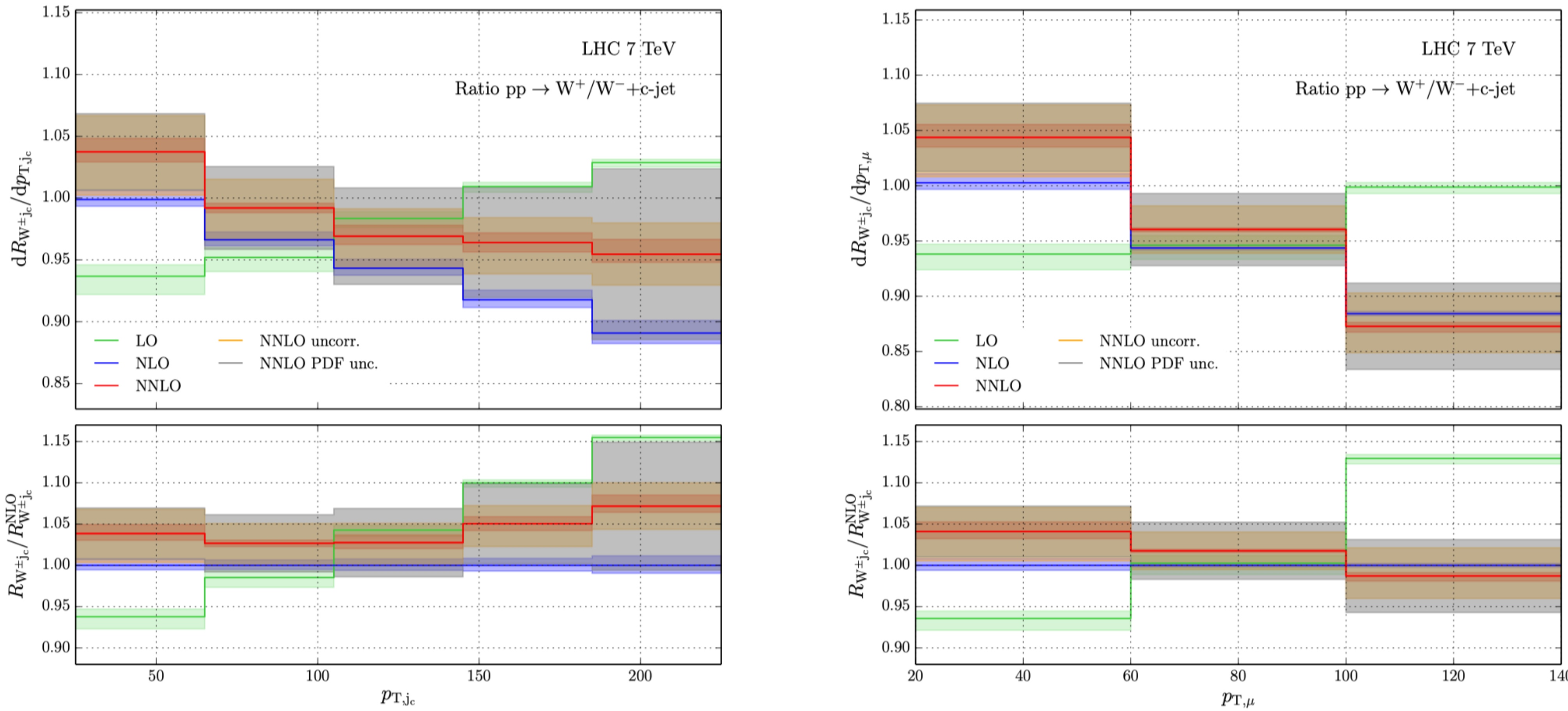

NNLO uncertainties very small; potential for constraining asymmetry