Toward the next generation of Parton Distribution Functions

Pavel Nadolsky

CTEQ-TEA (Tung et al.) working group

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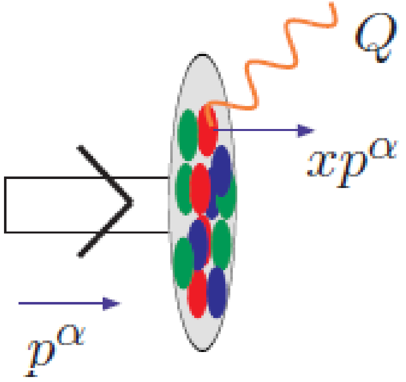
Southern Methodist University: P. Nadolsky, B. T. Wang, K. P. Xie

Xinjiang University: S. Dulat, T.-J. Hou



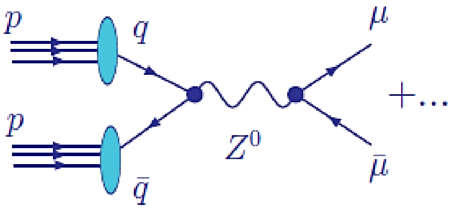
Outline

Lots of activity in the PDF analysis! Focus on three recent topics:

1. **New LHC experiments in PDF fits**
   - -Released PDF sets: ABMP'16, NNPDF3.1
   - In progress: CT1X (preliminary), MMHT'XX
2. **Fitted charm, intrinsic charm…**
   - NNLO PDF fits may depend on a new nonperturbative function in charm scattering
3. **Photon PDF** (CT14qed, LUXqed17)

Apologies for skipping many important topics and essential references

QCD factorization and PDFs



According to QCD factorization theorems, typical cross sections (e.g., for $p(k_1)p(k_2) \to [Z(q) \to \ell(k_3)\bar{\ell}(k_4)]\, X$) take the form

$$\sigma_{pp\to\ell\bar{\ell}X} = \sum_{a,b=q,\bar{q},g} \int_0^1 d\xi_1 \int_0^1 d\xi_2\, \widehat{\sigma}_{ab\to Z\to\ell\bar{\ell}} \left(\frac{x_1}{\xi_1}, \frac{x_2}{\xi_2}; \frac{Q}{\mu}\right) f_{a/p}(\xi_1,\mu) f_{b/p}(\xi_2,\mu) + \mathcal{O}\left(\Lambda^2_{QCD}/Q^2\right)$$

- $\widehat{\sigma}_{ab\to Z\to\ell\bar{\ell}}$ is the **hard-scattering cross section** (perturbative)
- $f_{a/p}(\xi,\mu)$ are the **PDFs** (nonperturbative)
- $Q^2 = (k_3+k_4)^2$, $x_{1,2} = (Q/\sqrt{s})\, e^{\pm y_V}$ — measurable quantities
- ξ_1, ξ_2 are partonic momentum fractions (integrated over)
- μ is a factorization scale (=renormalization scale from now on)

Perturbative QCD loop revolution

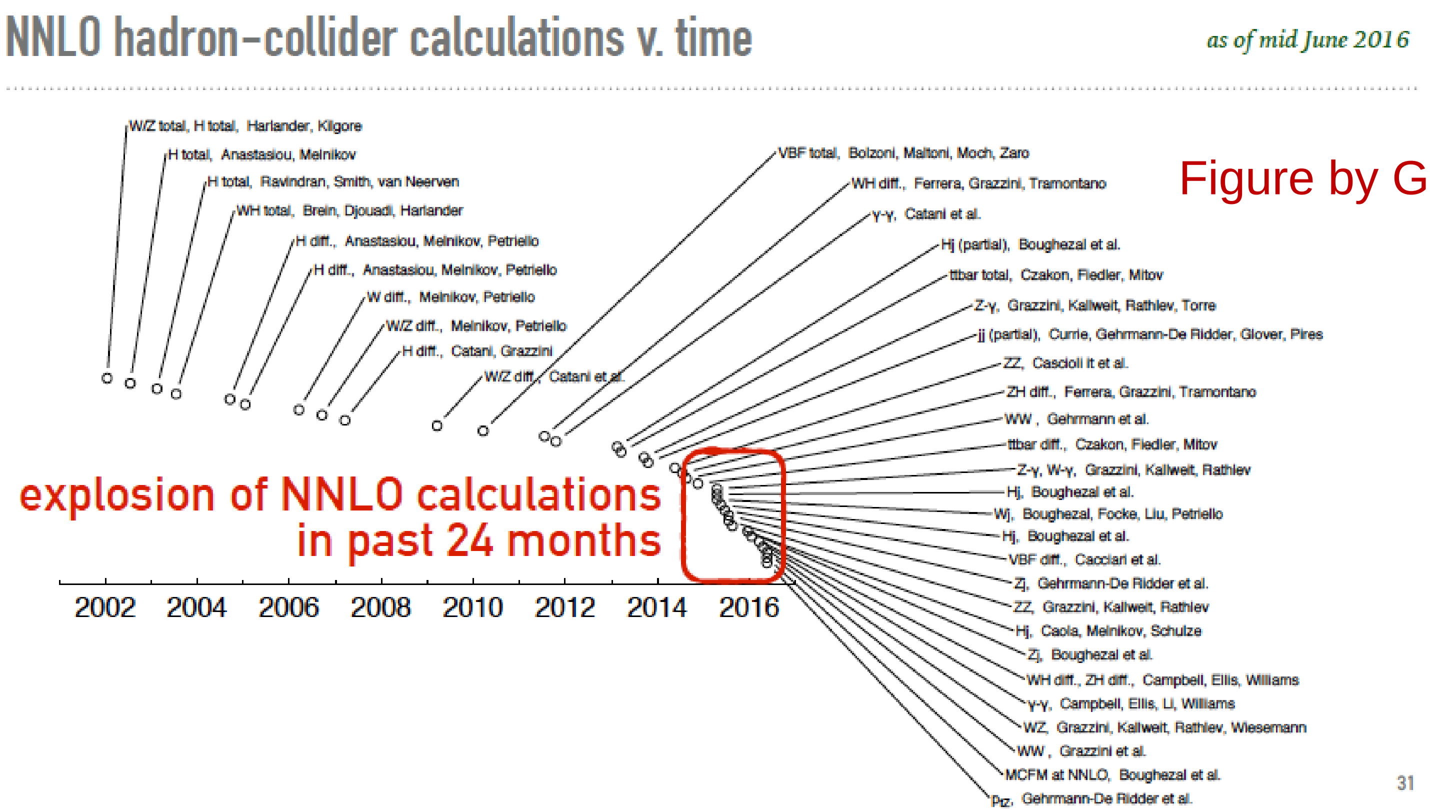


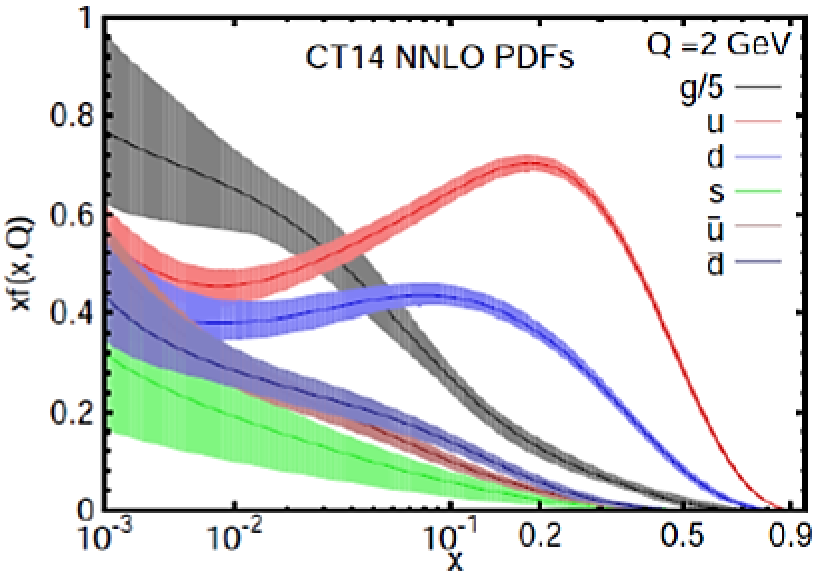
Figure by G. Salam

Since 2005, generalized unitarity and related methods dramatically advanced the computations of **perturbative** NLO/NNLO/N3LO hard cross sections $\hat{\sigma}$.

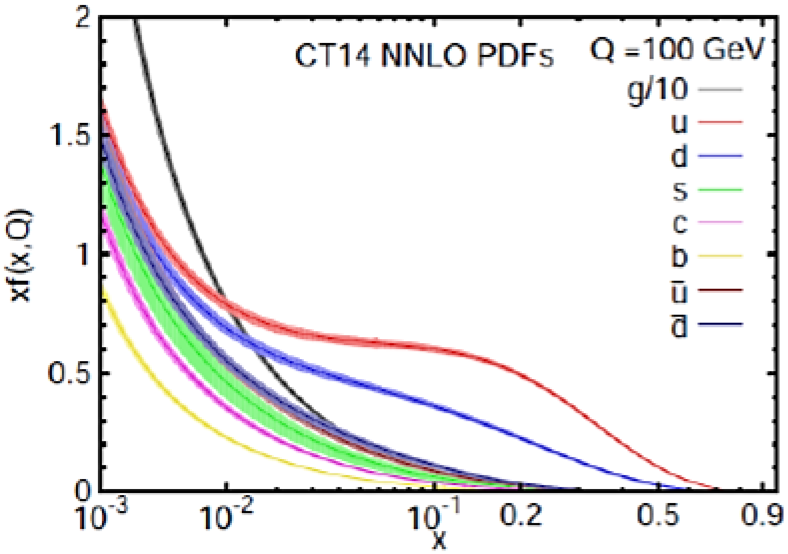
To make use of it, accuracy of PDFs $f_{a/p}(x,\mu)$ must keep up

General-purpose CT14 PDFs

(S. Dulat et al., arXiv:1506.07443)



Q= 2 GeV



Q= 100 GeV

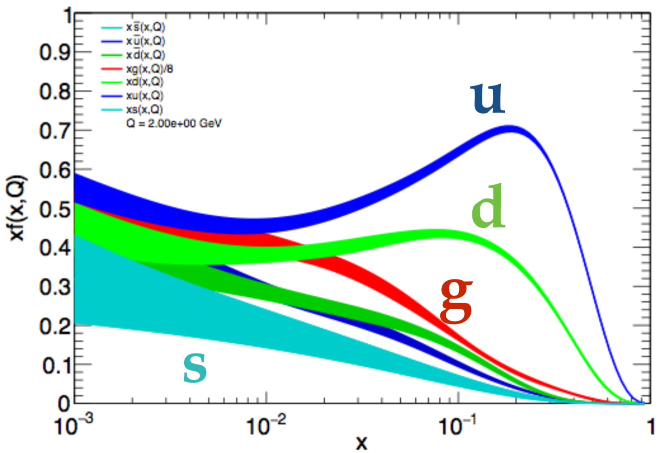
Phenomenological parametrizations of PDFs are provided with estimated uncertainties of multiple origins (**uncertainties of measurement, theoretical model, parametrization form, statistical analysis**, …)

The shape of PDFs is optimized w.r.t. hundreds of **nuisance parameters**

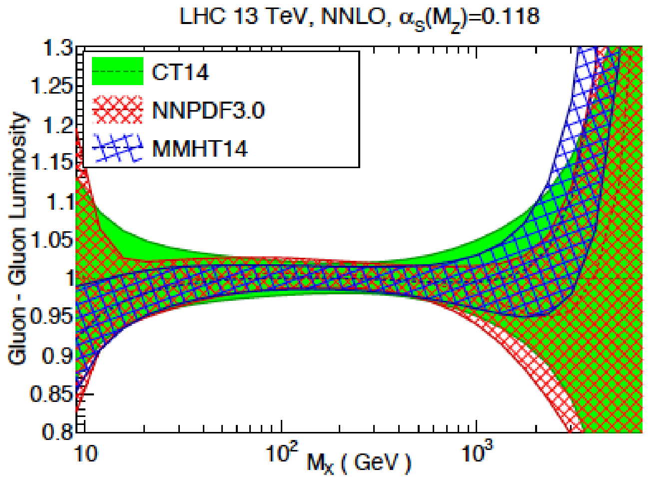
CT14 Parton distributions

- 2015 major release, CT14 NNLO/NLO sets including alternative α_s series and $N_f = 3,4,6$ **[1506.07443]**

CT14 NNLO PDFs



gluon-gluon luminosity



- combined HERA charm production, H1 FL data in NC DIS
- early LHC Run I data on W/Z charged lepton rapidity and asymmetry data;
- old D0 W-electron asymmetry data superseded by the new one with full luminosity;
- inclusive jet production from ATLAS and CMS

- more flexible parametrization for gluon, d/u at large-x, both d/u and dbar/ubar at small-x, 28 eigenvectors comparing to 25 for CT10

http://hep.pa.msu.edu/cteq/public/index.html

Classes of PDFs

General-purpose

For (N)NLO calculations with $N_f \leq 5$ active quark flavors

From several groups:
ABMP'16
HERA2.0
CT14 (→ 17p)
MMHT'14 (→ 16)
NNPDF3.1
…

Specialized

For instance, for CT14:
CT14 LO
CT14 $N_f = 3$, 4, 6
CT14 HERA2 **[arXiv:1609.07968]**
CT14 Intrinsic charm **[1707.00065]**
CT14 QCD+QED **[1509.02905]**
CT14 Monte-Carlo **[1607.06066]**

ATLAS & CMS exploratory
New techniques ⇒ Markov chains, talk by Yemalin Gbedo

Combined **[1509.03865]**

PDF4LHC'15=CT14+MMHT'14+NNPDF3.0

DON'T PANIC

OUTP-15-17P
SMU-HEP-15-12
TIF-UNIMI-2015-14
LCTS/2015-27
CERN-PH-TH-2015-249

PDF4LHC recommendations for LHC Run II

Jon Butterworth[1], Stefano Carrazza[2,4], Amanda Cooper-Sarkar[3], Albert De Roeck[4,5], Joël Feltesse[6], Stefano Forte[2], Jun Gao[7], Sasha Glazov[8], Joey Huston[9], Zahari Kassabov[2,10], Ronan McNulty[11], Andreas Morsch[4], Pavel Nadolsky[12], Voica Radescu[13], Juan Rojo[14] and Robert Thorne[1].

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A Hitchhiker's Guide to choosing the right PDF set

"A common mistake that people make when trying to design something completely foolproof is to underestimate the ingenuity of complete fools."
–D. Adams

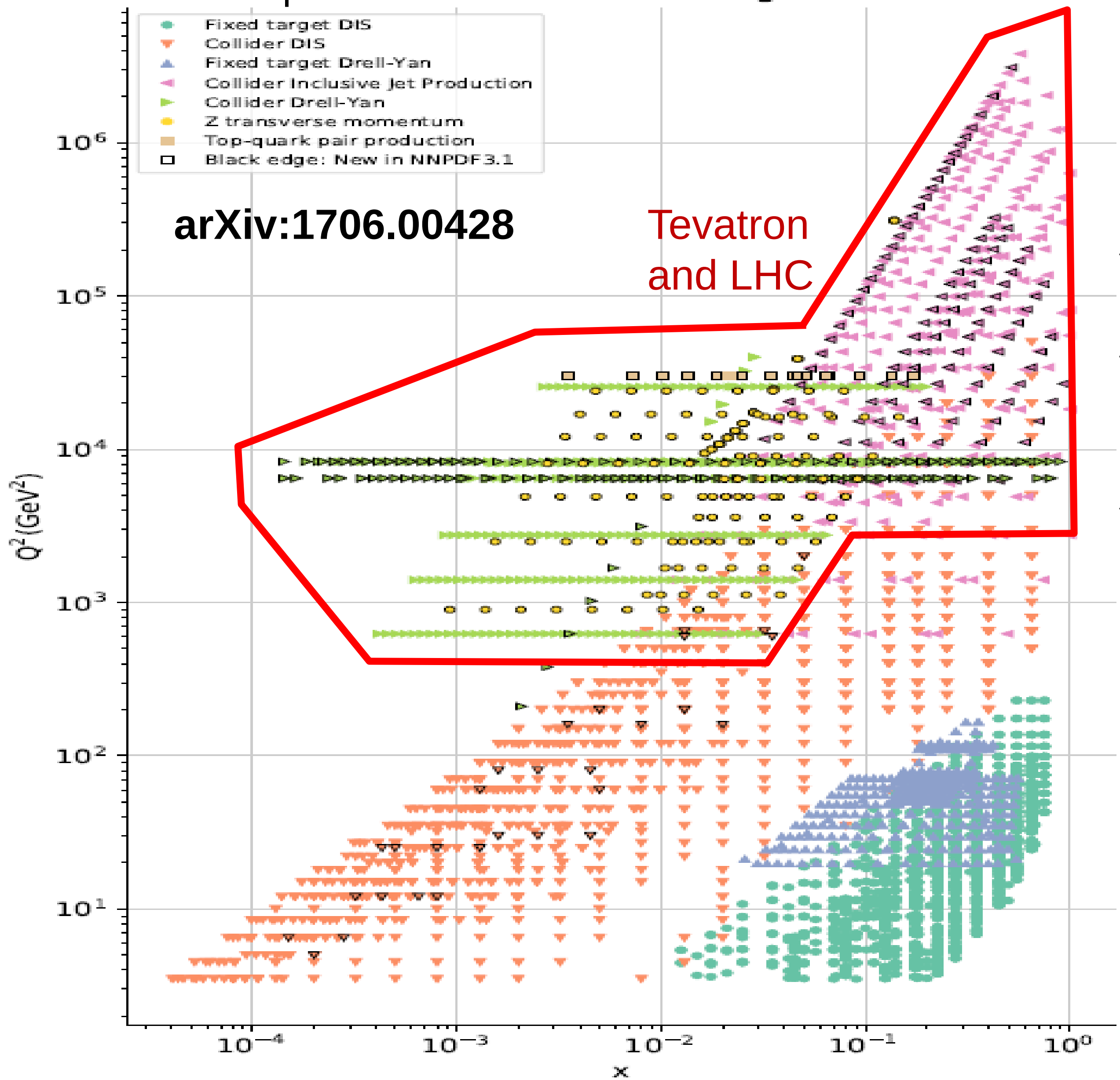
2017: explicit and implicit advancements

All major groups rush toward implementing LHC data on **jet**, **W/Z,** $Z\ p_T\ t\bar{t}$ production in the PDF analysis

- **ABMP'16** (arXiv:1701.05838) includes a large LHC W/Z data set, got closer to the other PDF sets
- The **NNPDF3.1** set has been released (arXiv:1706.00428), including a compatible subset of the new LHC data
- **CT1X** and **MMHT'XX** to be released within a few months, once compatibility of the new experiments is understood

However, reduction of the current PDF uncertainties is conditioned on understanding of (dis)agreement between the available data sets and improved control of theoretical and methodological uncertainties

Impressive Kinematic coverage



NNPDF3.1: the most **extensive** data set to date

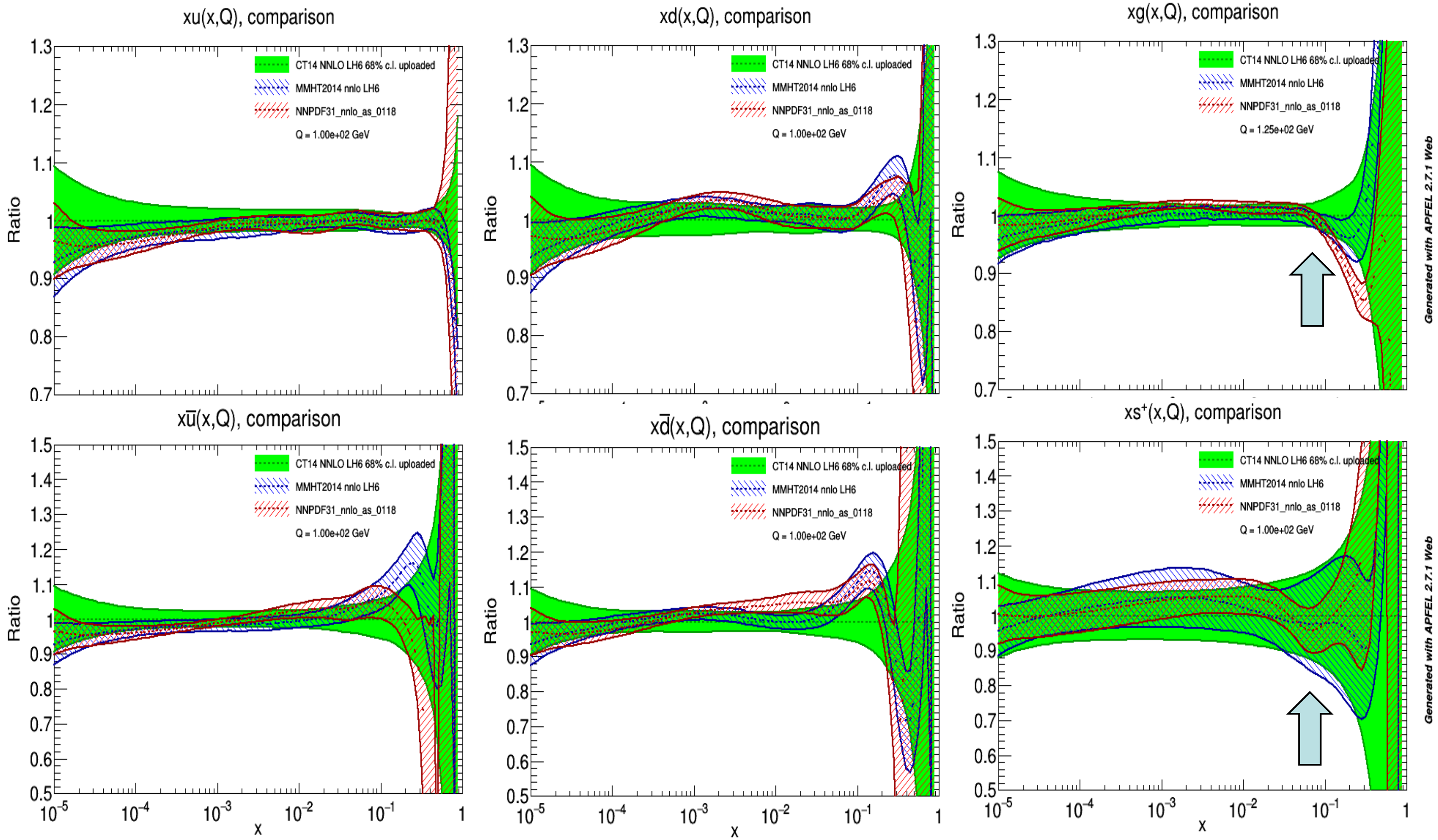
3431 non-LHC (75%)+ **854 LHC data points (25%)**

A **subset** of available LHC data on $\ell\bar{\ell}$, jet, $\boldsymbol{Z\, p_T}$, $\boldsymbol{t\bar{t}}$ production, analyzed at NNLO

$Z\, p_T$, $t\bar{t}$ moderately improve on NNPDF3.0 constraints on $g(x,Q)$ at x relevant for SM Higgs production

CT, MMHT also include D0 Run-2 jet production, get only slightly weaker constraints on $g(x,Q)$

CT14, MMHT14, NNPDF3.1 PDFs



Central PDFs of 3 sets are compatible. The NNPDF3.1 uncertainty is moderately reduced on $g(x, Q)$ at $x > 0.05$, $s + \bar{s}$ at all x. The effect of the LHC data on the error bands does not exceed dependence on the definition of the PDF uncertainty (CT vs. MMHT vs. NNPDF).

LHC: new processes for PDF fits

High-luminosity LHC data with a potential for constraining the PDFs:

1. Inclusive jet production in a wide rapidity range ($|y_{jet}| \lesssim 4.5$)
2. High-p_T Z production ($40 \lesssim p_T(Z) \lesssim 150$ GeV)
3. $t\bar{t}$ production (mostly y_t and $y_{t\bar{t}}$)
4. Low-mass and high-mass DY process
5. LHCb low-p_T heavy-quark production (test $g(x, Q)$ at $x \sim 10^{-5}$)
6. …

Issues:

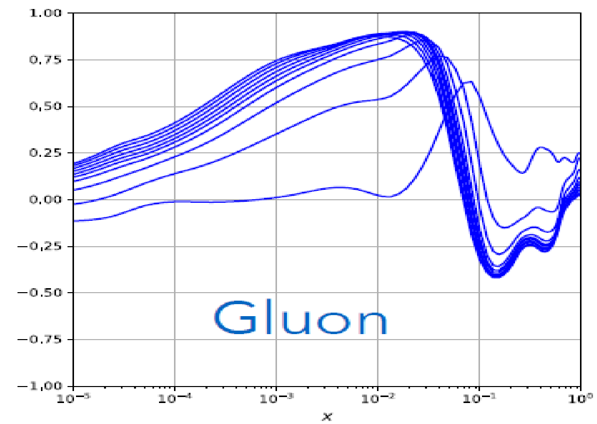
- Experimental, theoretical, and procedural **systematic** uncertainties dominate the PDF uncertainty in many cases, we work on estimating them
  - Tensions between some experimental data sets
  - Large QCD uncertainties in some kinematic regions (e.g., large y)

Let’s go through some experiments

NNPDF3.0red+$Z\ p_T$

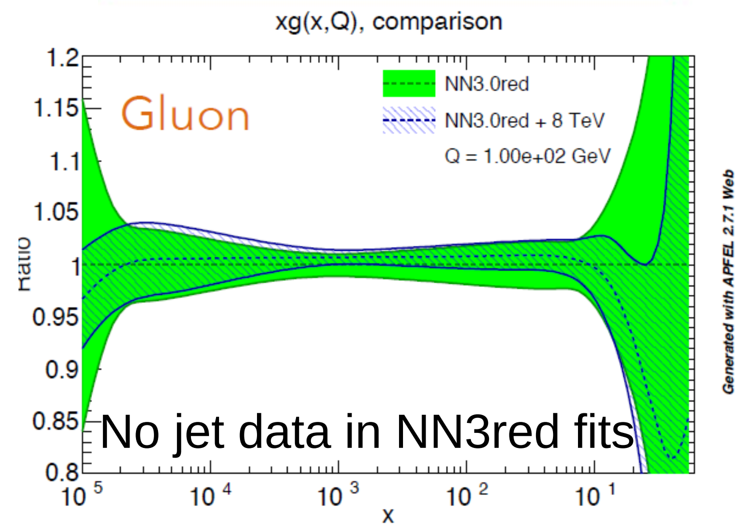
Boughezal, Guffanti, Petriello, Ubiali -1705.00343

- The **first** published NNLO fit including LHC $Z\ p_T$ data
- Potential sensitivity to $g(x,Q)$ at $x > 0.05$ (in the Higgs production region)
- Fitting absolute, not normalized, cross sections seems to be more reliable
- Includes only ATLAS 8 TeV, CMS 8 TeV data sets
- The ATLAS 7 TeV data is badly fit under all circumstances



NNLO fit cuts

30 GeV < p_T^Z < 500 GeV (ATLAS 7 TeV)
30 GeV < p_T^Z < 150 GeV (ATLAS 8 TeV, on peak)
30 GeV < p_T^Z < 170 GeV (CMS 8 TeV)



2017-08-31, Pavel Nadolsky

NNPDF3.0red+$Z\ p_T$

Boughezal, Guffanti, Petriello, Ubiali -1705.00343

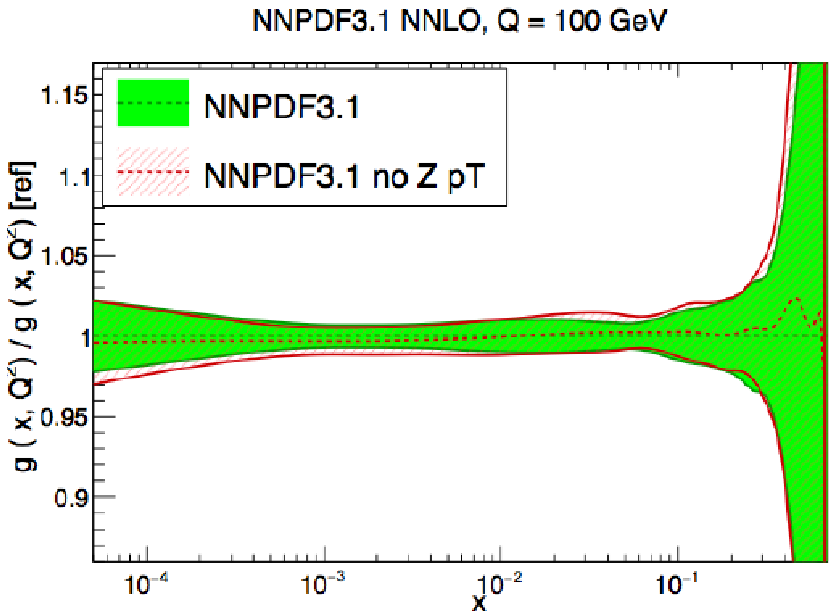
- Tabulated NNLO/NLO K-factors from the N-jettiness calculation
- NLO is calculated with APPLGRID
- Jitter in NNLO theoretical predictions: good χ^2 if a 1% uncorrelated error is added to account for this
- Scale $\mu_{F,R} = M_T(Z)$
- Scale uncertainty is not negligible, is not included

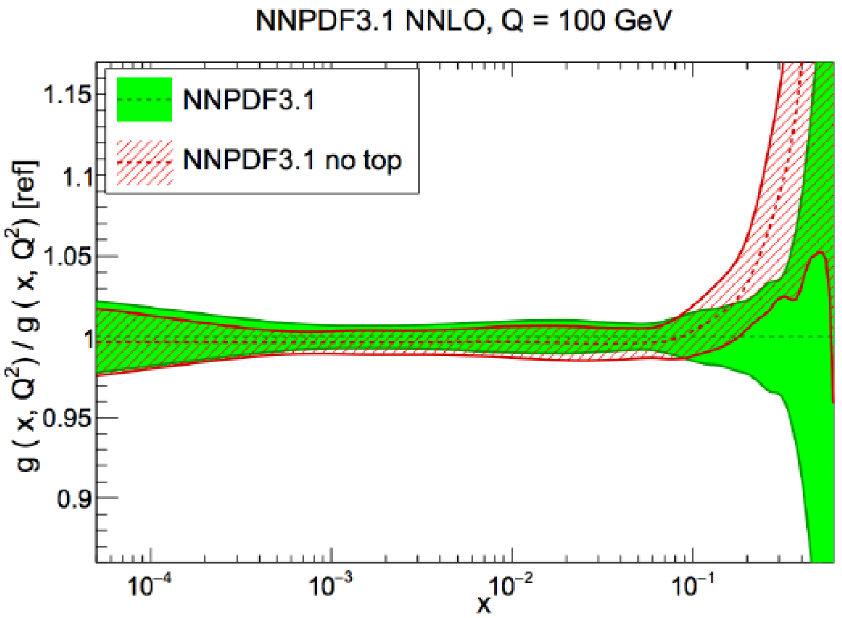
Fit (extra Δ=1%)	χ^2 ATLAS 7 TeV	χ^2 ATLAS 8 TeV (M)	χ^2 ATLAS 8 TeV (Y)	χ^2 CMS 8 TeV (Y)
NNPDF3.0red	(7.0)	(1.0)	(1.1)	(1.4)
NNPDF3.0red + ZpT 8 TeV	(7.9)	1.0	0.9	1.3

Implication for Higgs physics

	Before ZpT data	After ZpT data
H(ggF)	48.22 ± 0.89 (1.8%)	48.61 ± 0.61 (1.3%)
H(VBF)	3.92 ± 0.06 (1.5%)	3.96 ± 0.04 (1.0%)

Impact of $Z\ p_T$ and $t\bar{t}$ data on NNPDF3.1





Ball et al - 1706.00428

NNPDF3.1: constraints on $g(x,Q)$ from a combination of $Z\ p_T$ and $t\bar{t}$ production are comparable to the constraints from jets (truly exciting!)

These conclusions will benefit from an independent cross-validation with alternative selections of experiments and theoretical inputs

CT17p: preliminary PDFs with new LHC data

Included experiments:

- **Combined HERA1+2 DIS**
- **LHCb 7 TeV Z, W muon rapidity dist.**
- **LHCb 8 TeV Z rapidity dist.**
- **ATLAS 7 TeV inclusive jet (?)**
- **CMS 7 TeV inclusive jet (extended y range)**
- **ATLAS 7 TeV Z pT dist. (?)**
- **LHCb 13 TeV Z rapidity dist.**
- **CMS 8 TeV Z pT and rapidity dist. (double diff.)**
- **CMS 8 TeV W, muon asymmetry dist.**
- **ATLAS 7 TeV W/Z, lepton(s) rapidity dist.**
- **CMS 7,8 TeV tT differential dist.**
- **ATLAS 7,8 TeV tT differential dist.**

Alternative choices on:

… settings of NNLO calculations

(SACOT-χ heavy-quark scheme, QCD scales, m_c, numerical codes,…)

… selection of experiments and kinematic cuts

For instance, $g(x,Q)$ at $x > 0.05$ is already constrained in CT14/MMHT14 by D0 Run-2 incl. jet data which is not in NNPDF3.1. Disagreements exist within available ATLAS/CMS experiments and between some LHC and non-LHC experiments

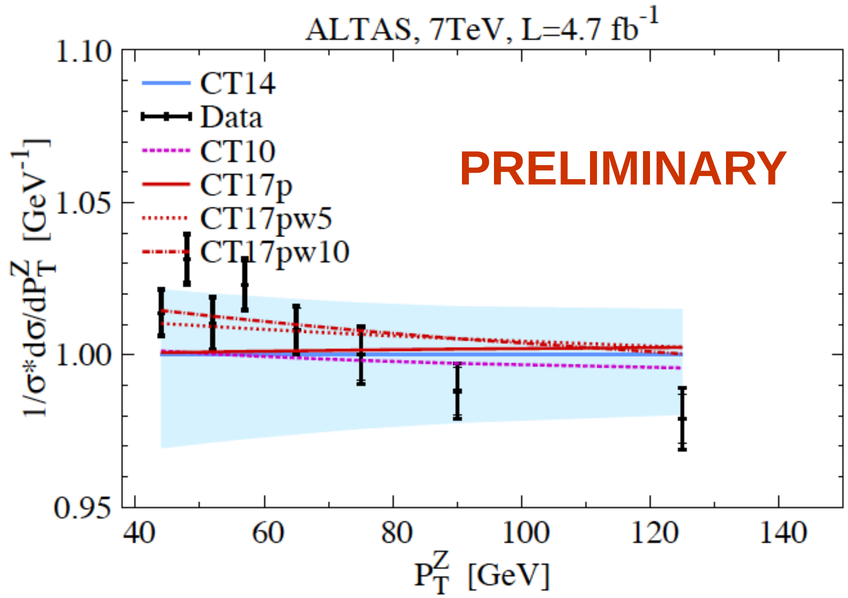
…the fitting procedure

Definition of PDF uncertainties
Parametrization forms
PDF error analysis (Hessian vs. Monte-Carlo)

…

CT17p: ATLAS Z p_T

- Preliminary fits with $Z\ p_T$ data are broadly consistent with NNPDF3.1
- Independently generated APPLGRIDS
- Prefer to work with absolute Z p_T data in range from 40 to 150 GeV/c at NNLO, with $\mu_R=\mu_F=M_T$
- Study scale dependence

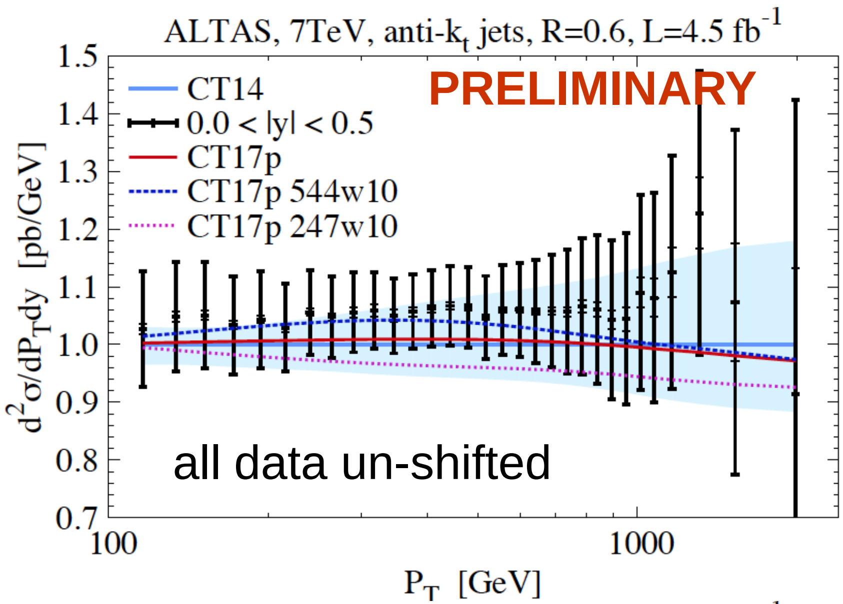


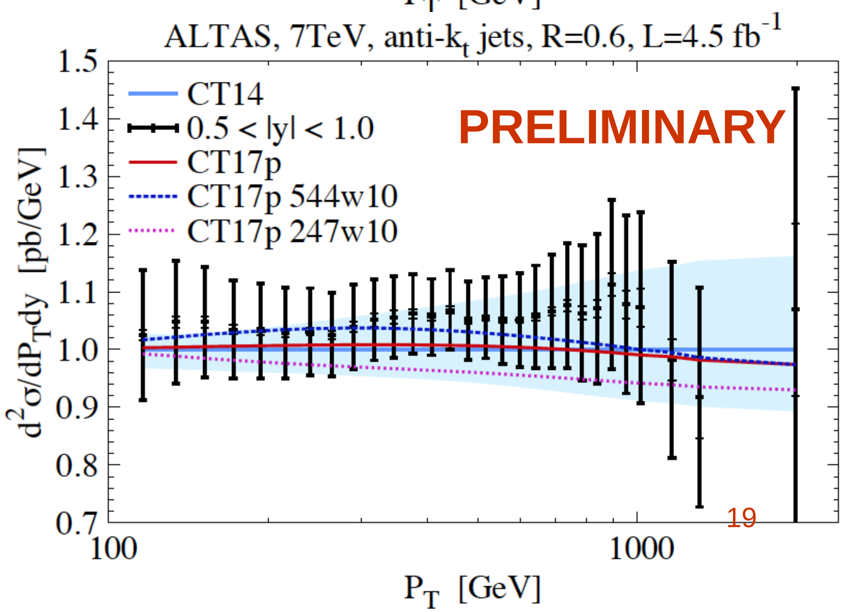
- Add an uncorrelated error of $\Delta = 0.5\%$ (1%) to account for Monte-Carlo uncertainties in the NNLO K factor

- ATLAS 7 TeV $Z\ \ p_T$ data are poorly fitted even with large χ^2 weight (w=5 or 10)
  - prefer softer gluon at high x
- ATLAS 8 TeV and CMS 8 TeV $Z\ p_T$ are fitted with $\frac{\chi^2}{N_{pt}} \approx 1$ even with CT14 NNLO with $\Delta = 0.5\%$; marginal change in the central $g(x, Q)$

CT17p: ATLAS 7 TeV jet data

- Cannot get a good fit simultaneously to all rapidity bins: χ^2/DOF~2, even with weight 10 for combined jet data
  - outer error bars are with stat and syst errors added in quadrature; inner error bars are uncorrelated errors alone
- Individual rapidity bins can be fit well
- In general, ATLAS jet data favors a larger gluon PDF around x=0.2
- Some tension with ATLAS7 Z p_T data regarding high x gluon
  - jet data with weight=10 **(544w10)** likes a harder gluon (x~0.2)
  - Z p_T data with weight=10 (normalized, **247w10**) likes a softer gluon
  - CMS 8 TeV data is better described





Attempted fit to high luminosity ATLAS 7 TeV inclusive jet data (JHEP 02 (2015) 153)

(MMHT'2016, R. Thorne)

Take as default $R = 0.4$ and $\mu = p_{T,1}$ and work at NLO.

Prediction at NLO gives $\chi^2/N_{pts} = 413.1/140$.

Refit gives improvement only to $\chi^2/N_{pts} = 400.4/140$.

Significant improvement in chi^2 if three experimental systematic parameters (jes21, 45,62) are decorrelated, although no clear indication why these three parameters are important

Compared to the original $\chi^2/N_{pts} = 400/140$ we get instead

	21	45	62
χ^2	221	316	330

	21,45	21,62	45,62
χ^2	213	178	230

	21,45,62
χ^2	172

Very significant improvement, particularly from decorrelating jes21.

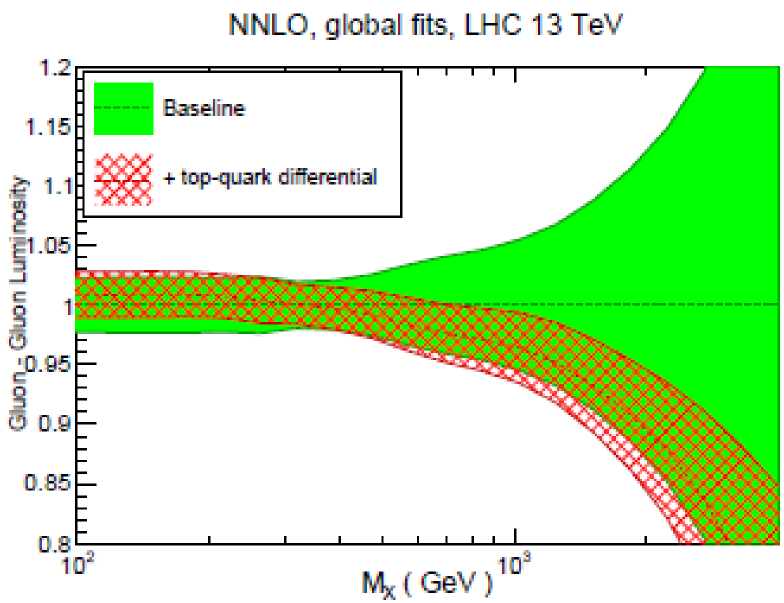
Little improvement if jes45 decorrelated on top of jes21 and jes62.

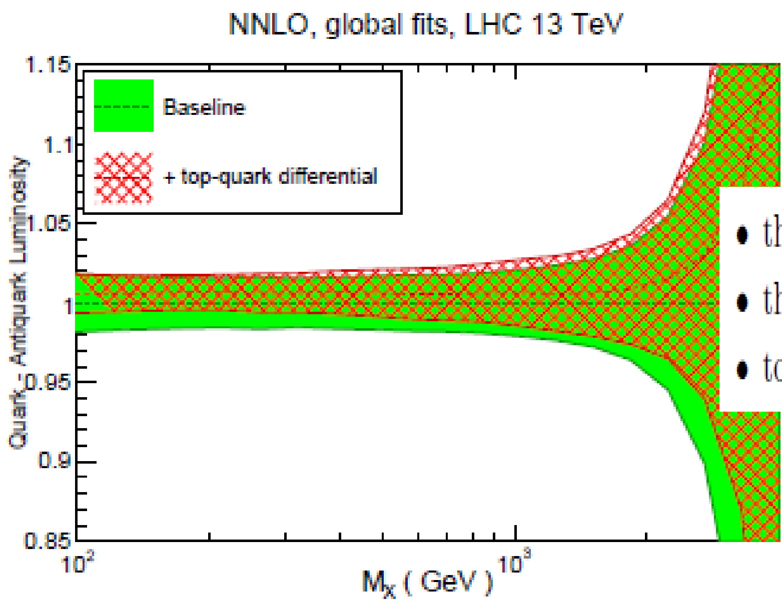
With correlations between rapidity bins relaxed for just two sources of systematics $\chi^2/N_{pts} = 178/140 = 1.27$.

Top distributions

- Several distributions measured by ATLAS and CMS may provide information on the high x gluon
  - $y_{t\bar{t}},\ M_{t\bar{t}}, p_{T,t\bar{t}}$ (pair-inclusive)
  - $y_{avt}, p_{T,avt}$ (single-particle inclusive, averaged over t and $\bar{t}$)
- Only one distribution should be used, unless a correlation model can be developed
  - similar to what we were talking about with ATLAS jet data in different y bins
  - $y_{t\bar{t}}$ (y_{avt}) is best described by theory
- Many ATLAS and CMS diff. distributions have different trends; e.g., ATLAS favors harder gluon (than NNPDF3.1) at high x, CMS weaker gluon
- This is similar to some tension that exists between the ATLAS and CMS jet data, although there the tension is in the opposite direction
- If tension, then gluon PDF uncertainty may not decrease and may even increase
- Study in progress

Talk by A. Mitov ⇒ Theory aspects





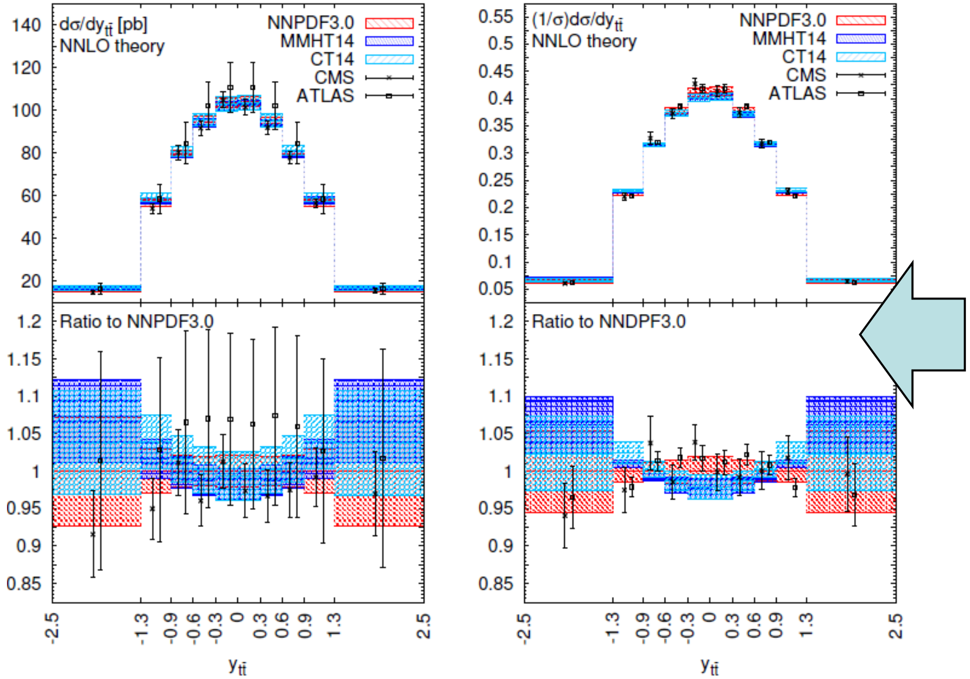
Pinning down the large-x gluon with NNLO $t\bar{t}$ differential distributions

Czakon, Hartland, Mitov, Nocera, Rojo, 1611.08609

Baseline global fit: no $t\bar{t}$ data, no inclusive jet data

"+top-quark differential" fit: add

- the normalized y_t distribution from ATLAS at $\sqrt{s} = 8$ TeV (lepton+jets channel),
- the normalized $y_{t\bar{t}}$ distribution from CMS at $\sqrt{s} = 8$ TeV (lepton+jets channel),
- total inclusive cross-sections at $\sqrt{s} = 7$, 8 and 13 TeV (all available data).



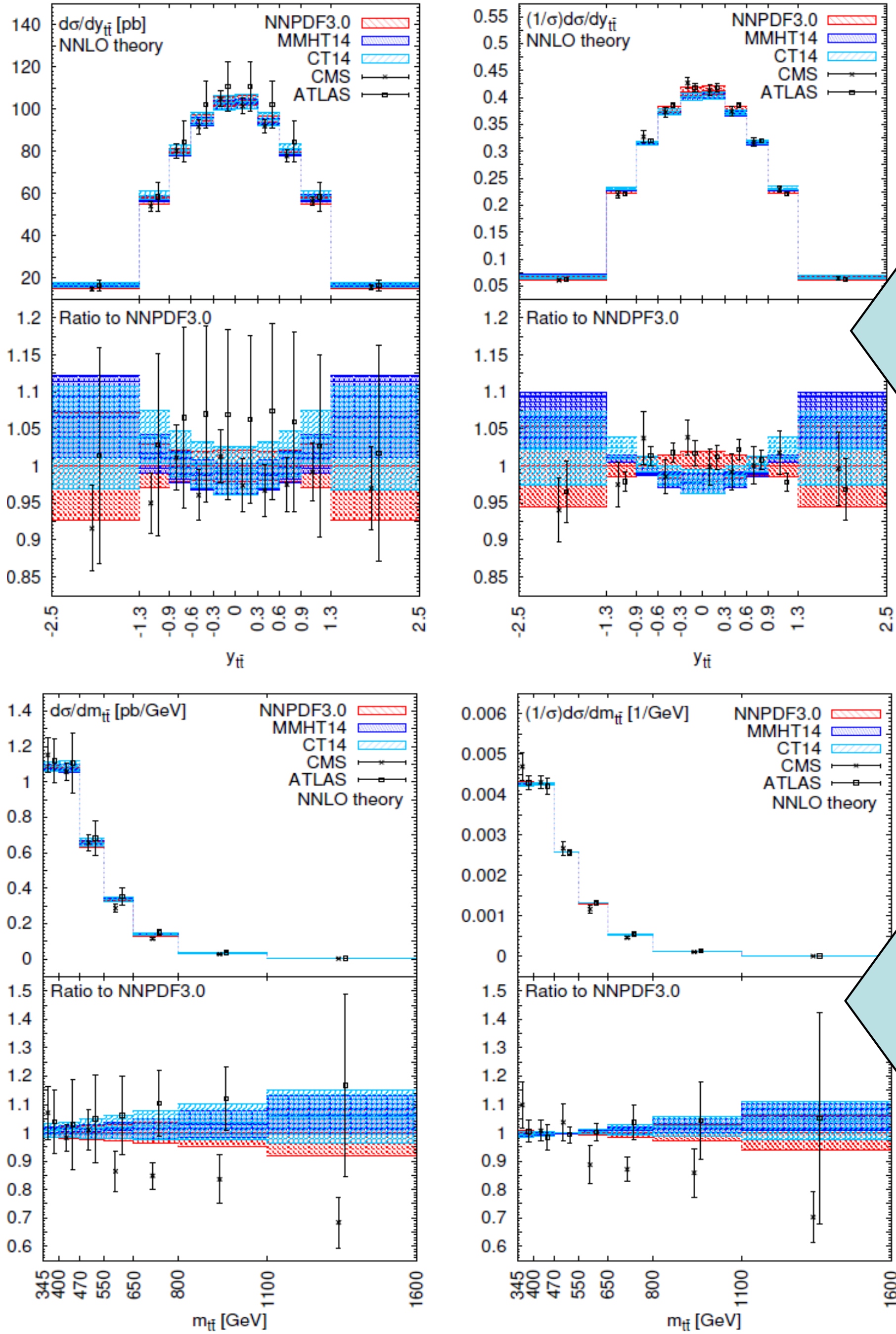
Pinning down the large-x gluon with NNLO $t\bar{t}$ differential distributions

Czakon, Hartland, Mitov, Nocera, Rojo, 1611.08609

Normalized $y_{t\bar{t}}$ data included in the "+top-quark differential" fit, compared to prior PDFs

CT14 in reasonable agreement with shape, normalization, and uncertainties

MMHT14 shows less agreement in shape



Pinning down the large-x gluon with NNLO $t\bar{t}$ differential distributions

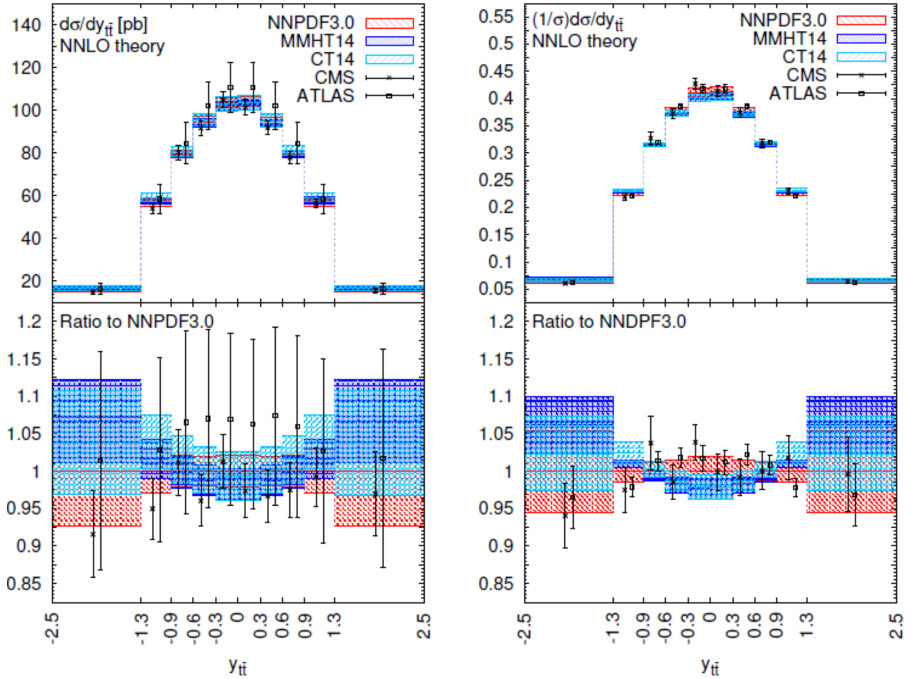
Czakon, Hartland, Mitov, Nocera, Rojo, 1611.08609

Normalized $y_{t\bar{t}}$ data included in the "+top-quark differential" fit, compared to prior PDFs

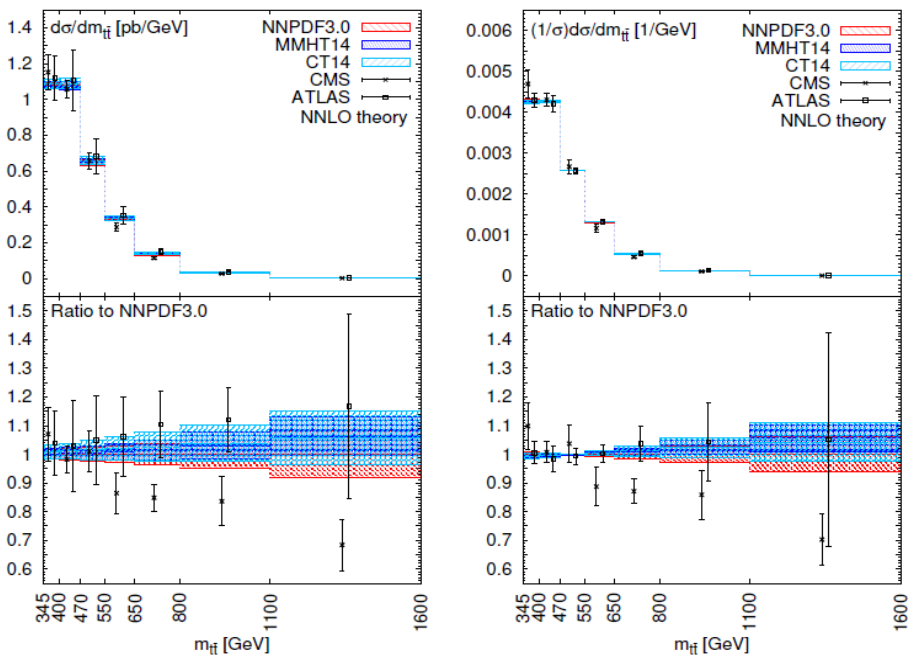
ATLAS/CMS $M_{t\bar{t}}$ data is described ok at $M_{t\bar{t}}$<500 GeV, poorly above 500 GeV, compared to prior PDFs

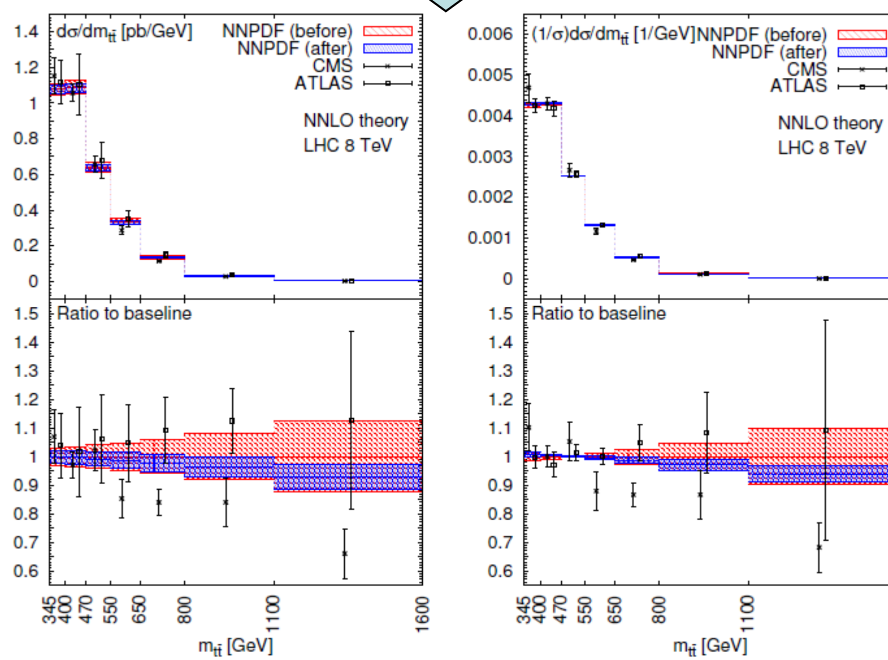
Pinning down the large-x gluon with NNLO $t\bar{t}$ differential distributions

Czakon, Hartland, Mitov, Nocera, Rojo, 1611.08609



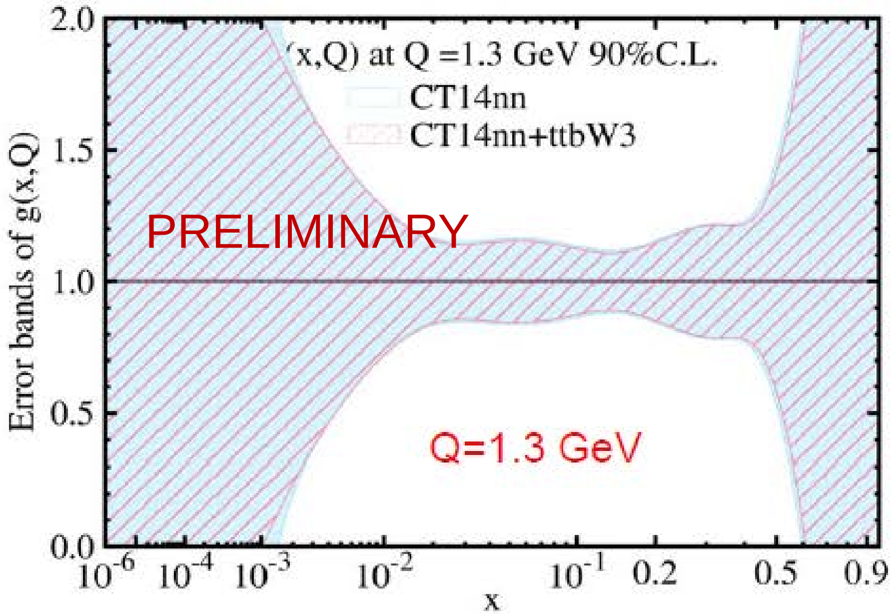
NNPDF: ATLAS/CMS $M_{t\bar{t}}$ data still have poor χ^2 **after** the fit, in spite of the reduced PDF uncertainty after the fit

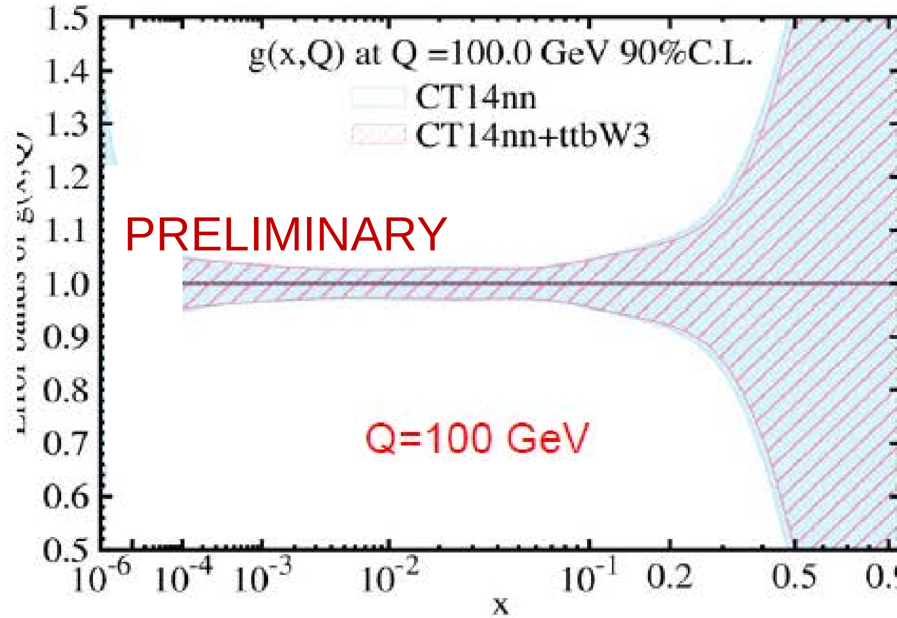




An Alternative estimation of the impact of $t\bar{t}$ data

When the ATLAS 8 TeV $M_{t\bar{t}}, p_{T,avt}, y_{avt}$ data were added to the CT14 NNLO data set (CT14nn) according to the Hessian reweighting method (CT14nn+ttbW3), no significant change in the PDF uncertainty was observed
[C.-P. Yuan, 2017 EPS conference]





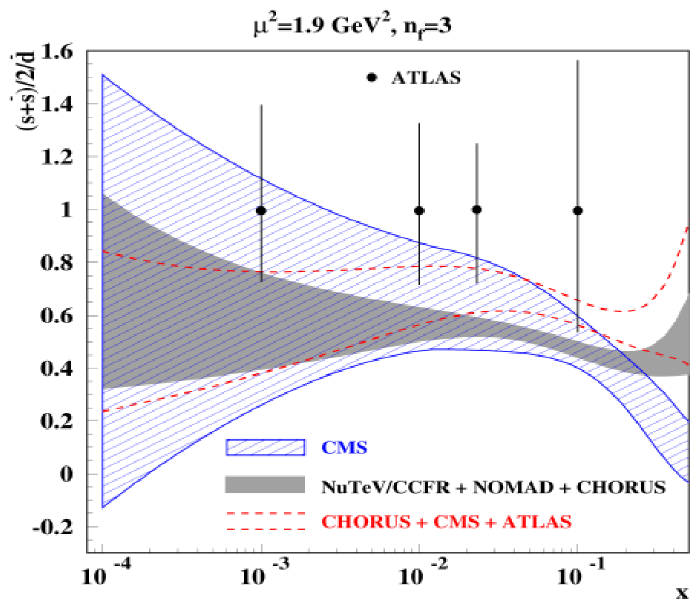
Slight reduction in gluon PDF uncertainty at $x \sim 0.2$.

The outcome of reweighting is strongly dependent on the tolerance, set to be equal to $\Delta\chi^2 = 100$ at 90% c.l. in this study

ABMP16 Highlights: Strange Sea

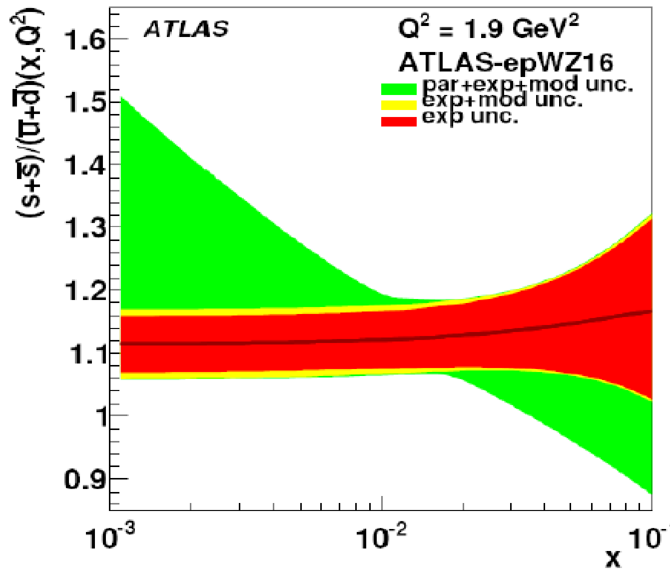
Strange quark is the least known from the light quarks

Update of **ABMP** PDFs with latest fixed target data (NOMAD+CHORUS) with smaller uncertainties on s-quark PDF



PRD 91, no 9 (2015) 094002, arXiv:1404.6469

arXiv:1612.03016



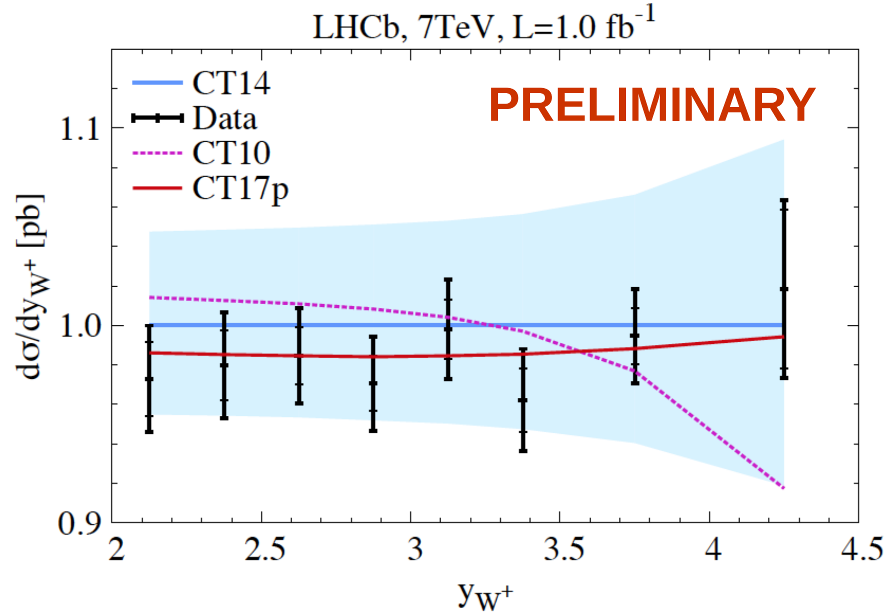
→ new results from ATLAS with improved accuracy
→ disagreement with the neutrino-beam results?

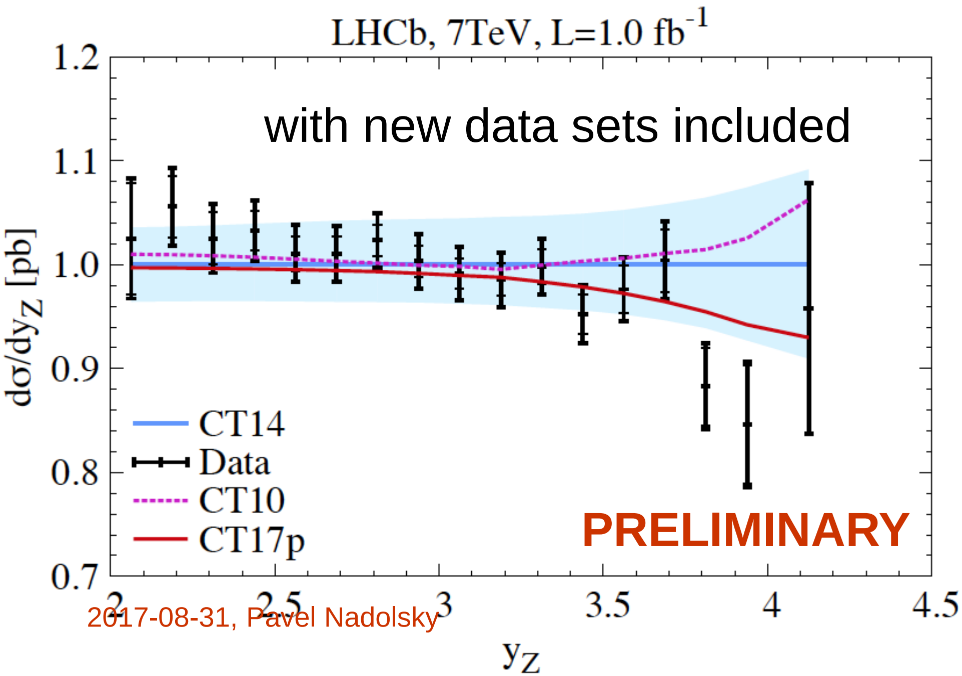
R. Plačakytė xFitter external meeting Oxford, 19-22 March 2017 12

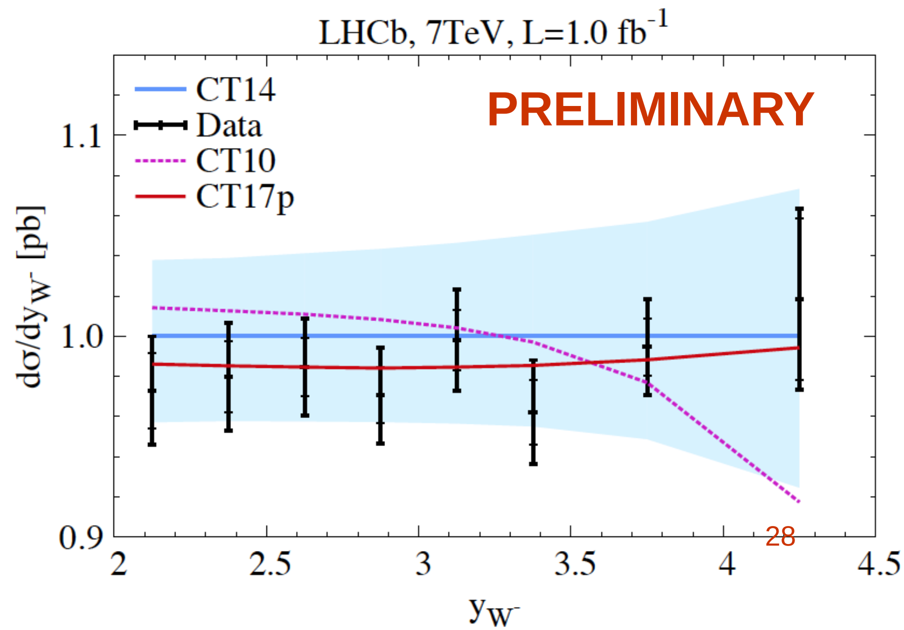
Tensions on R_s persists between ATLAS W/Z and other measurements
⇒ K. Gasnikova

CT17p: ATLAS, LHCb W,Z rapidity data

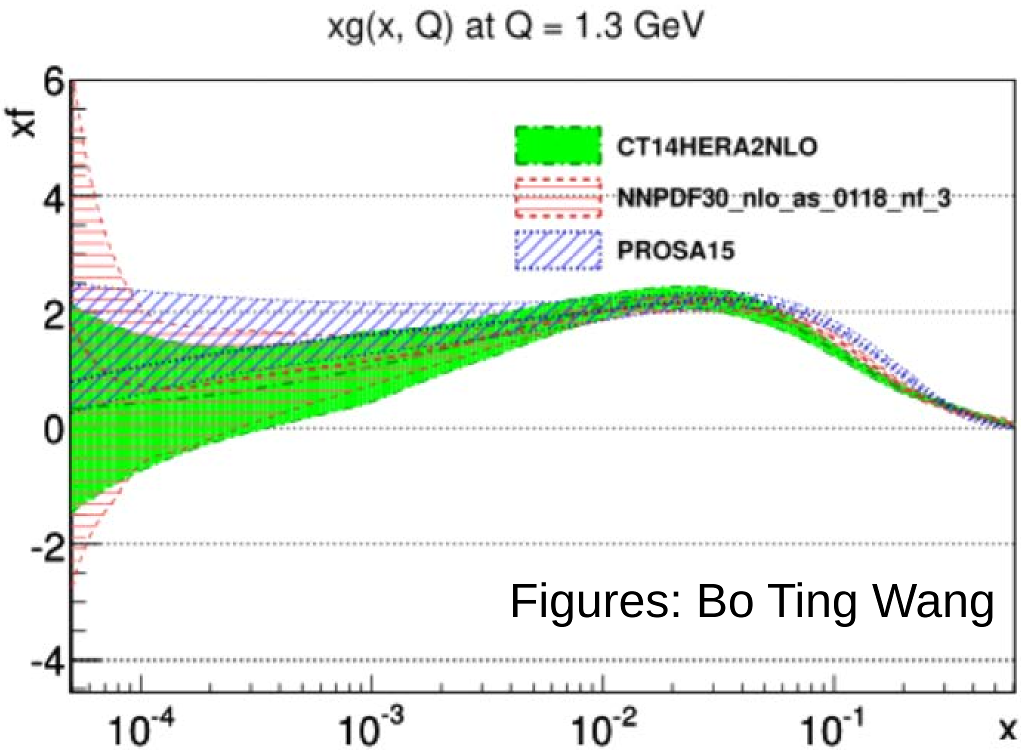
- Shown are LHCb 7 TeV: W,Z muon rapidity, LHCb 8 TeV Z(->ee) rapidity
- Unshifted data; outer error bars are with stat and syst errors added in quadrature; inner error bars are uncorrelated errors alone
- Major change is an increase in the strange quark distribution to that similar to CT10

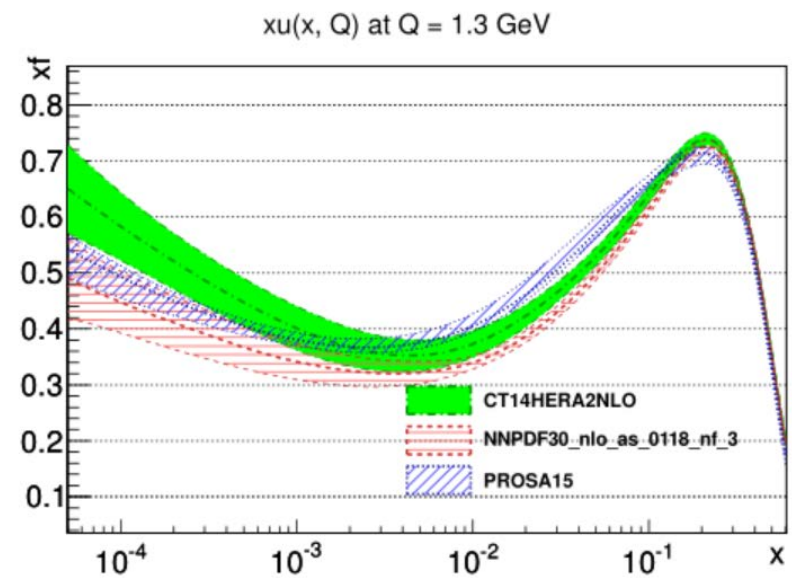


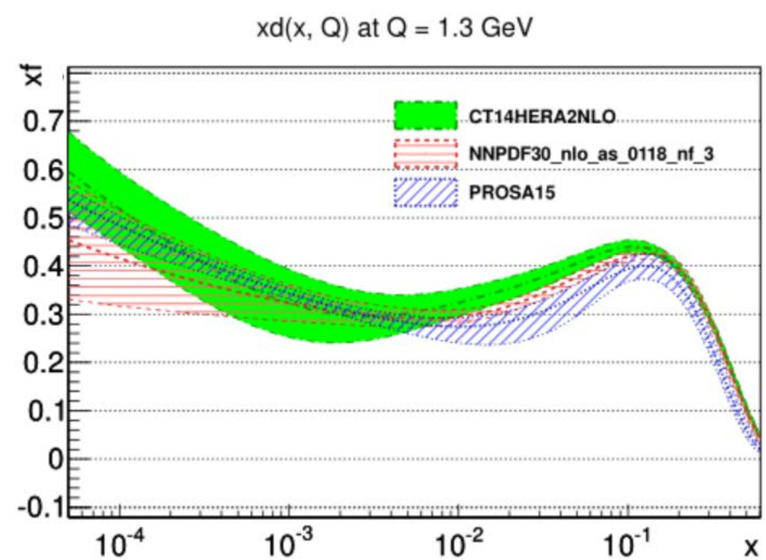




CT14HERA2 PDFs at small x







At $x < 10^{-2}$, the CT14HERA2 NLO $N_f = 3$ gluon is compatible with PROSA'15 PDFs fitted to 7 TeV LHCb heavy-flavor production data. Next rounds of LHCb measurements may help constrain the small-x gluon.

CT14 IC PDFs: intrinsic/fitted charm component,

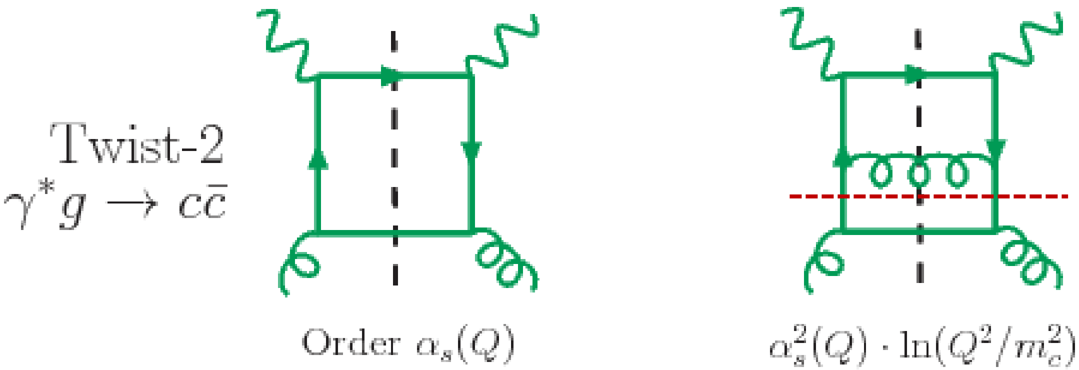
[arXiv:1707.00065]

A year-long investigation by CT group (T.-J. Hou, M. Guzzi, J. Winter, K. Xie, J. Gao,…), with valuable insights from CTEQ colleagues (J. Collins, D. Soper, F. Olness,…) and discussions with S. Alekhin, T. Hobbs, W. Melnitchouk, L. Del Debbio, J. Rojo, M. Ubiali, K.-F. Liu, …

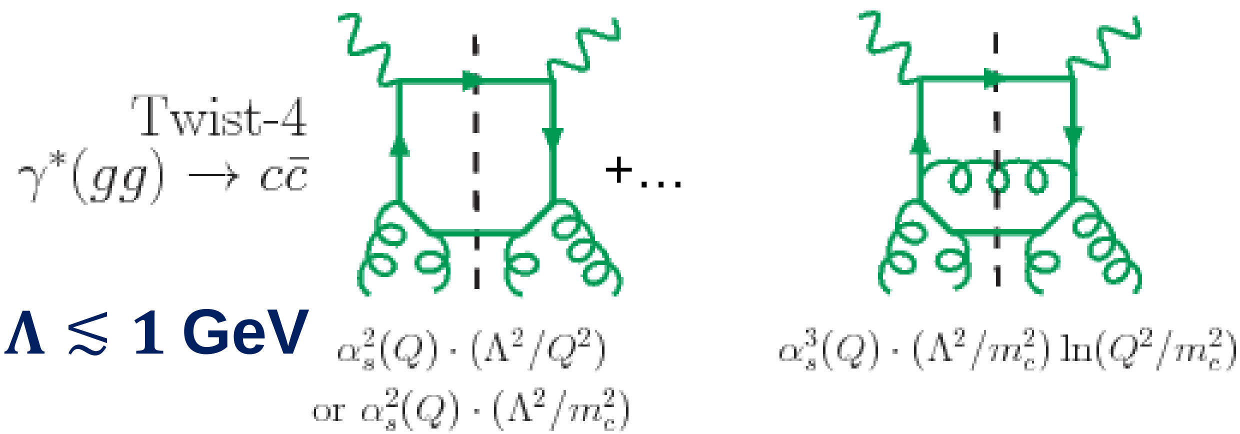
Are twist-2 contributions sufficient for describing current data at NNLO? Can the data hide important process-dependent twist-4 components?

NNPDF3.1 implements a freely fitted charm parameterization at $Q_0 = m_c^{pole} = 1.51$ GeV as a default choice. What is the theory motivation for the fitted charm? Is it necessary?

A twist-4 contribution in HERA DIS charm production ($\subset$ “intrinsic charm”)



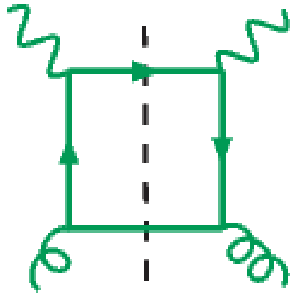
A ladder; must be resummed in $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2$; e.g., in the ACOT scheme



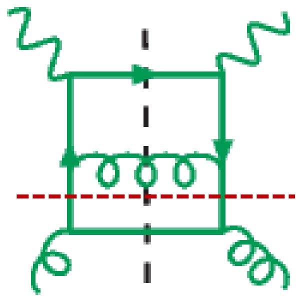
$\Lambda \lesssim 1$ GeV

A twist-4 contribution in HERA DIS charm production ($\subset$ "intrinsic charm")

Twist-2
$\gamma^* g \to c\bar{c}$



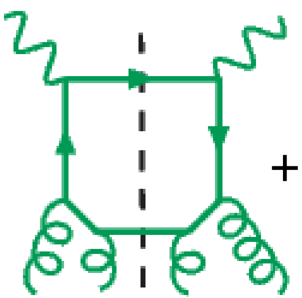
Order $\alpha_s(Q)$



$\alpha_s^2(Q) \cdot \ln(Q^2/m_c^2)$

A ladder; must be resummed in $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2$; e.g., in the ACOT scheme

Twist-4
$\gamma^*(gg) \to c\bar{c}$



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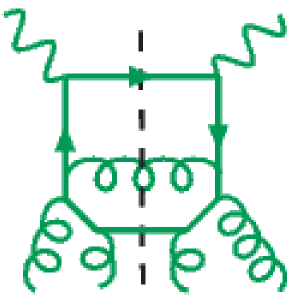


$\Lambda \lesssim 1$ GeV

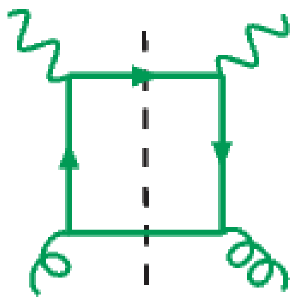
$\alpha_s^2(Q) \cdot (\Lambda^2/Q^2)$
or $\alpha_s^2(Q) \cdot (\Lambda^2/m_c^2)$

$\alpha_s^3(Q) \cdot (\Lambda^2/m_c^2) \ln(Q^2/m_c^2)$

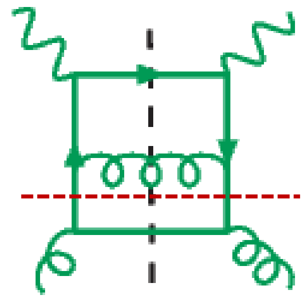
Can be of order ~10% of the twist-2 α_s^2 term

A twist-4 contribution in HERA DIS charm production ($\subset$ "intrinsic charm")

Twist-2
$\gamma^* g \to c\bar{c}$



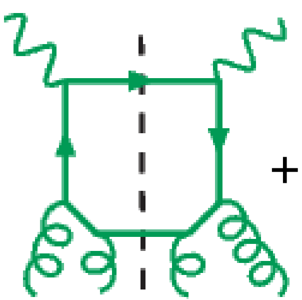
Order $\alpha_s(Q)$



$\alpha_s^2(Q) \cdot \ln(Q^2/m_c^2)$

A ladder; must be resummed in $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2$; e.g., in the ACOT scheme

Twist-4
$\gamma^*(gg) \to c\bar{c}$



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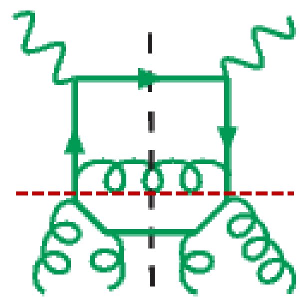


$\alpha_s^3(Q) \cdot (\Lambda^2/m_c^2)\ln(Q^2/m_c^2)$

The ladder subgraphs can be resummed as a part of $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2 > \Lambda^2$;

$\Lambda \lesssim 1$ GeV

$\alpha_s^2(Q) \cdot (\Lambda^2/Q^2)$
or $\alpha_s^2(Q) \cdot (\Lambda^2/m_c^2)$

Can be of order ~10% of the twist-2 α_s^2 term

contribute to the boundary condition for $c(x,Q_0)$ at $Q_0 \approx m_c$;

obey twist-2 DGLAP equations.

CT14 IC study clarifies important questions

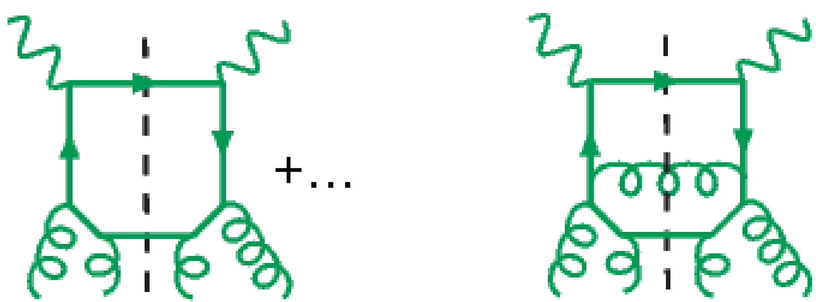
What are phenomenological constraints on the "intrinsic charm" from the global QCD data?

⇒ The CT14 charm PDFs allow a "nonperturbative" component carrying a total momentum fraction $\langle x_{IC} \rangle = 1 - 2\%$ in DIS at $Q \approx m_c$.

Can we estimate its impact on the LHC predictions?

Yes, based on the simplest approximation of the "nonperturbative" charm contribution. In most cases, the estimated impact is less than the net CT14 PDF uncertainty.

Twist-4
$\gamma^*(gg) \to c\bar{c}$



$\alpha_s^2(Q) \cdot (\Lambda^2/Q^2)$
or $\alpha_s^2(Q) \cdot (\Lambda^2/m_c^2)$

$\alpha_s^3(Q) \cdot (\Lambda^2/m_c^2) \ln(Q^2/m_c^2)$

Note:
"intrinsic charm" ≠ "fitted charm"

PDF fits may include a ``fitted charm'' PDF

``Fitted charm'' = ``higher-twist charm''
+ other (possibly not universal)
higher O(α_s) / higher power terms

QCD factorization theorem for DIS structure function $F(x,Q)$ [Collins, 1998]:

All α_s orders:

$$F(x,Q) = \sum_{a=0}^{N_f} \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_a\left(\frac{x}{\xi}, \frac{Q}{\mu}, \frac{m_c}{\mu}; \alpha(\mu)\right) f_{a/p}(\xi,\mu) + \mathcal{O}(\Lambda^2/m_c^2, \Lambda^2/Q^2).$$

The PDF fits implement this formula up to (N)NLO (N_{ord} = 1 or 2):

PDF fits:

$$F(x,Q) = \sum_{a=0}^{N_f} \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_a^{(N_{ord})}\left(\frac{x}{\xi}, \frac{Q}{\mu}, \frac{m_c}{\mu}; \alpha(\mu)\right) f_{a/p}^{(N_{ord})}(\xi,\mu).$$

The perturbative charm PDF component cancels at $Q \approx m_c$ up to a higher order

The 'fitted charm component' may approximate for missing terms of orders α_s^p with $p > N_{ord}$, or Λ^2/m_c^2, or Λ^2/Q^2 -- generally process-dependent

Dependence on the switching scale (no IC)

If the "fitted charm" is purely twist-2, we expect its effect to vanish for a sufficiently high α_s order of the calculation.

This is analogous to the reduction in the dependence on the switching scale μ_c from 3FS to 4FS, when the α_s order increases for a fixed Q_0 and m_c, as demonstrated recently by the xFitter group

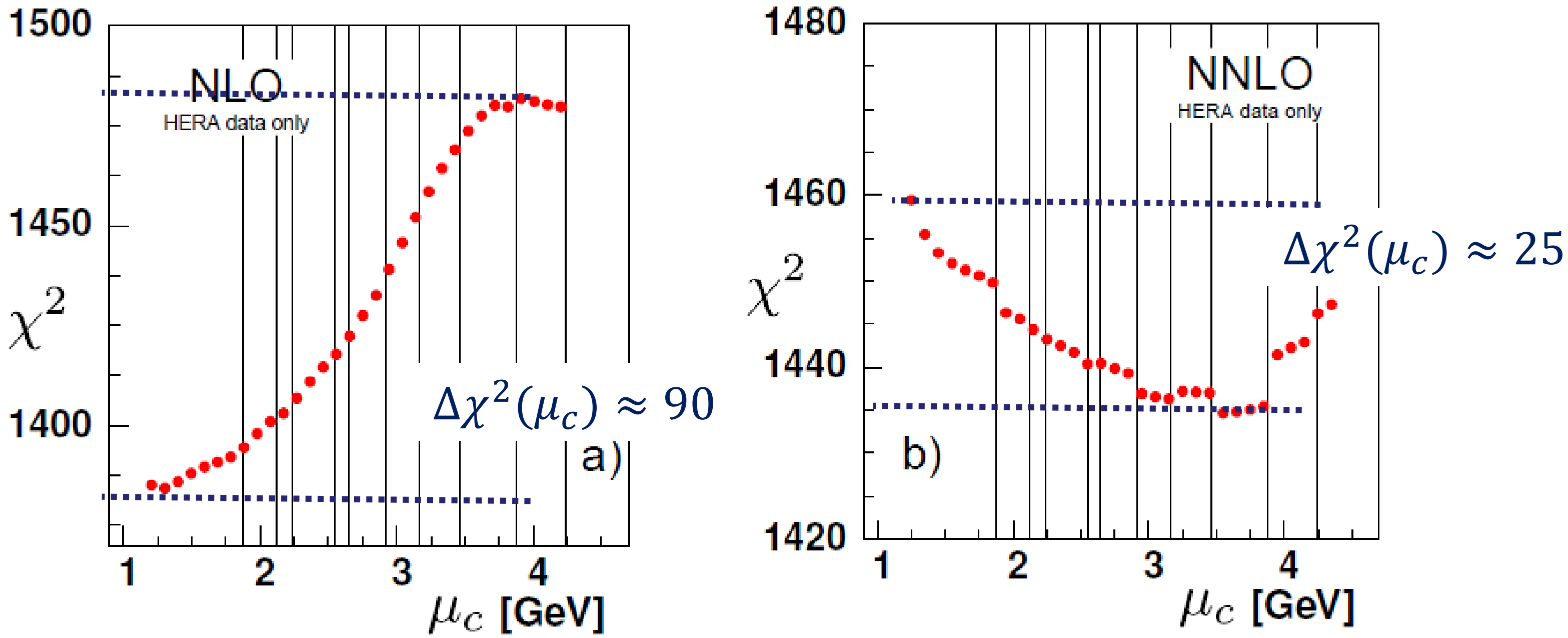


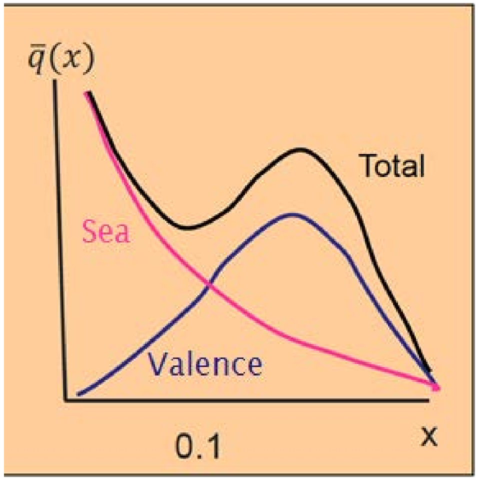
Fig. 5 χ^2 vs. the charm matching scale μ_c at a) NLO and b) NNLO for all data sets. The bin boundaries for the HERA data set "HERA1+2 NCep 920" are indicated by the vertical lines.

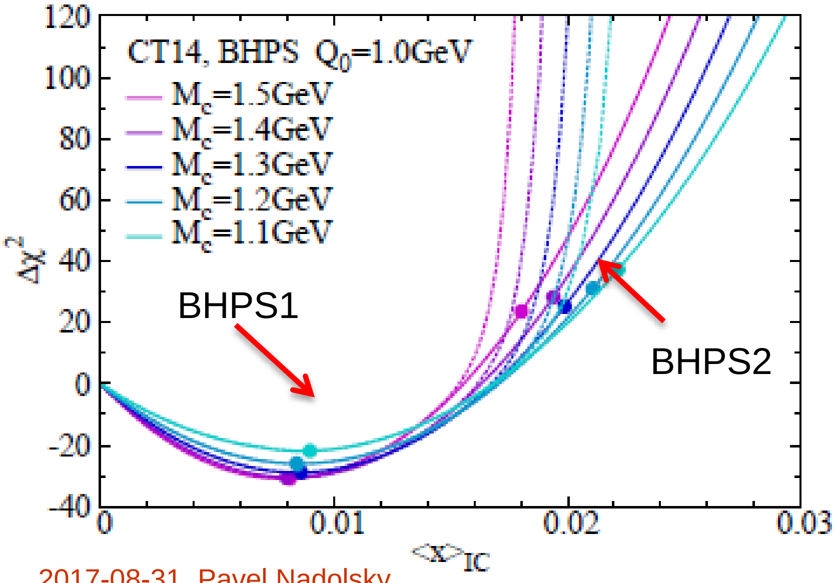
Bertone et al. (xFitter), arXiv:1707.05343

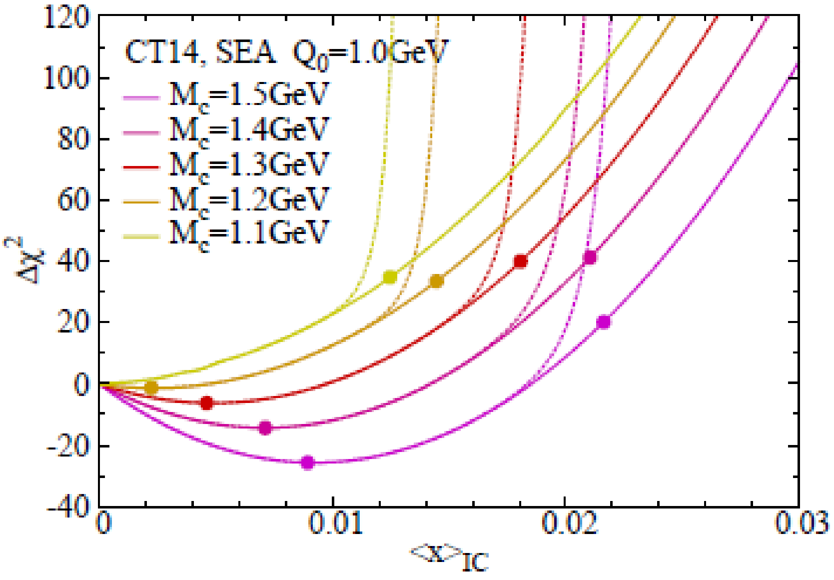
Dependence of $\Delta\chi^2$ on the IC momentum fraction $\langle x\rangle_{IC}$

In contrast, a twist-4 "IC" contribution will not decrease when going from N^kLO to $N^{k+1}LO$.

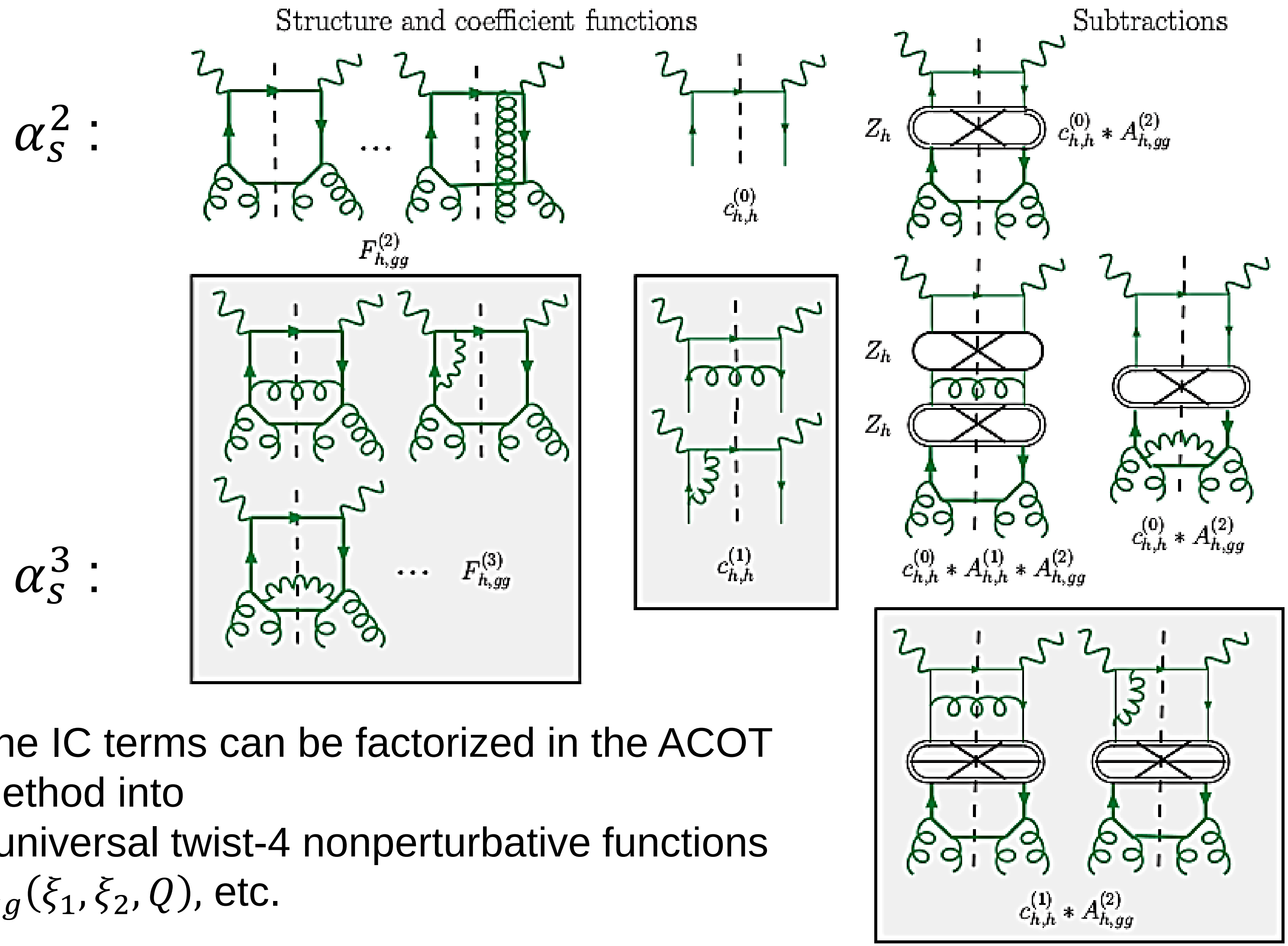
Depending on its dynamical origin, the IC charm takes a variety of shapes, e.g., a "sea-like" (SEA) or "valence-like" form. The Brodsky-Hoyer-Peterson-Sakai form (BHPS) predicts a "valence-like" $c(x, Q_0)$ peaked at $x \sim 0.2$. A sea-like form is monotonic in x.







ACOT-like factorization for twist-4 charm contributions (an example)



The IC terms can be factorized in the ACOT method into

- universal twist-4 nonperturbative functions $f_{gg}(\xi_1, \xi_2, Q)$, etc.

- process-dependent coefficient functions $c^{(k)}_{h,h}, C^{(k)}_{h,gg}$, etc.

Charm momentum fraction

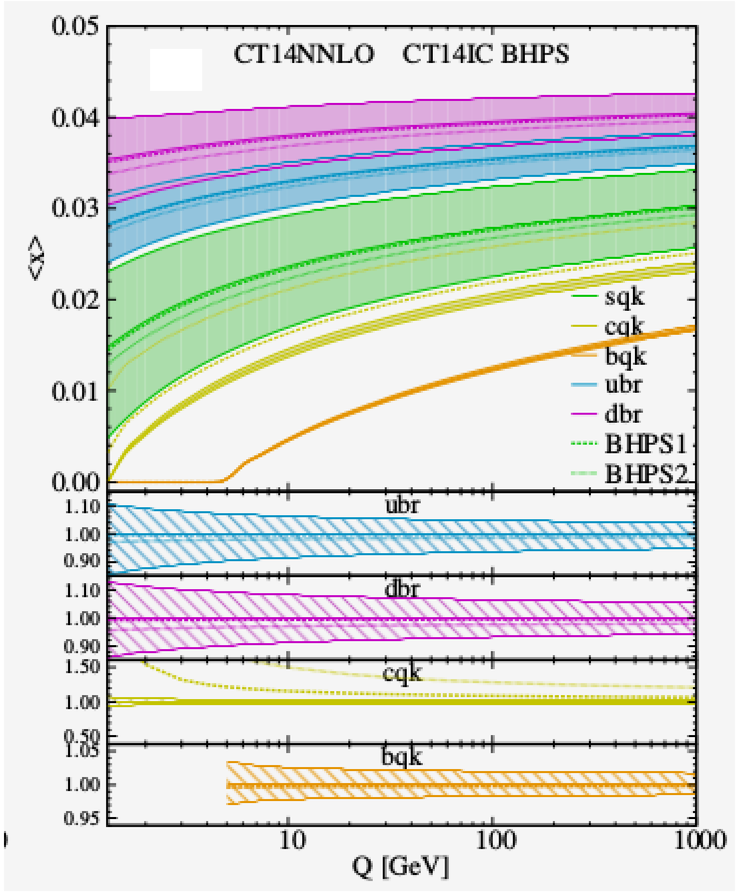
$$\langle x \rangle_{c+\bar{c}}(Q) \equiv \int_0^1 x\,[c(x,Q) + \bar{c}(x,Q)]$$

Initial scale $Q_0 = \mu_c \leq m_c$: intrinsic component only

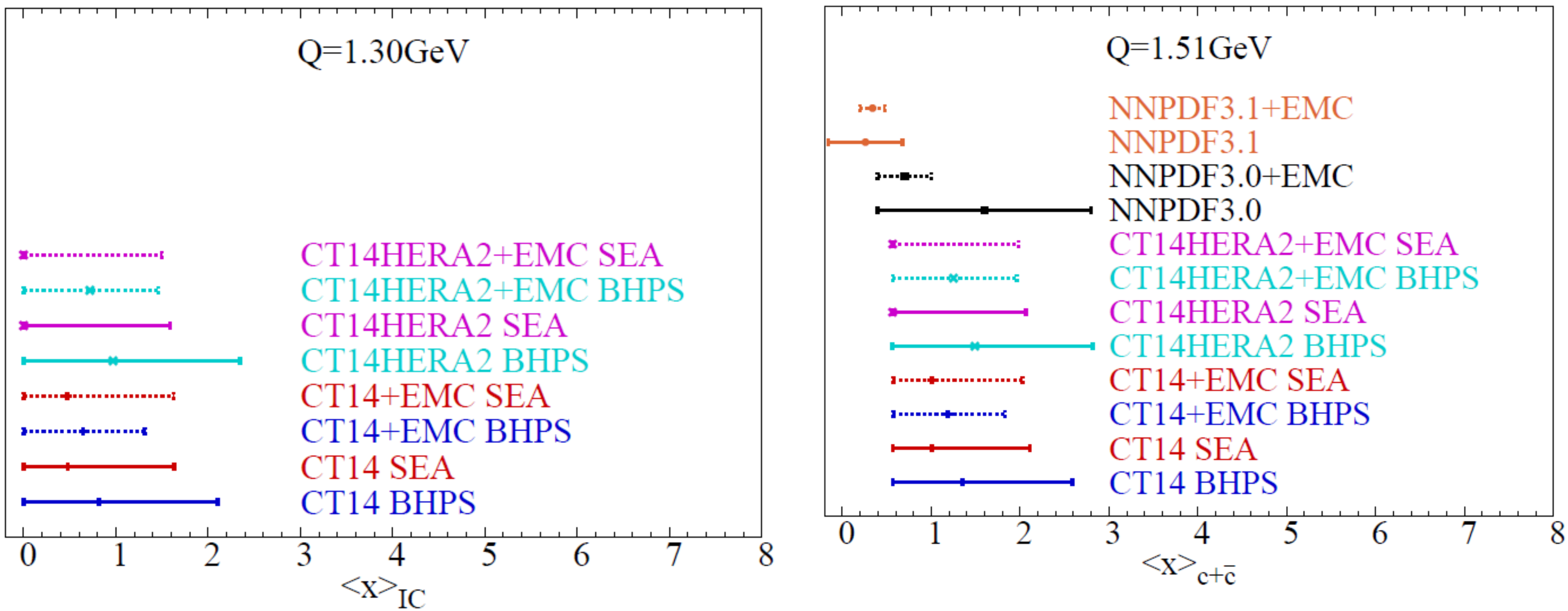
$$\langle x \rangle_{IC} \equiv \langle x \rangle_{c+\bar{c}}(Q_0)$$

At $Q > Q_0$, growth due to perturbative $c(x,Q)$

Enhancement in $c(x,Q)$ from IC survives to $Q \gg m_c$!

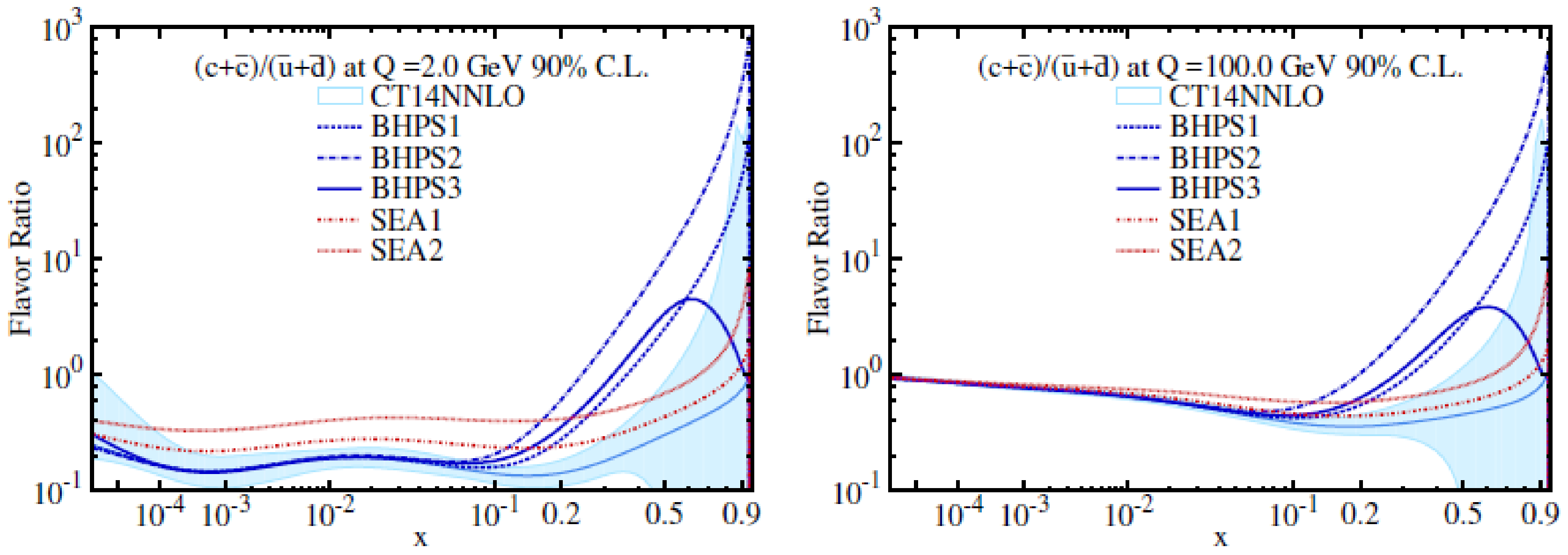


Allowed $c + \bar{c}$ momentum fractions



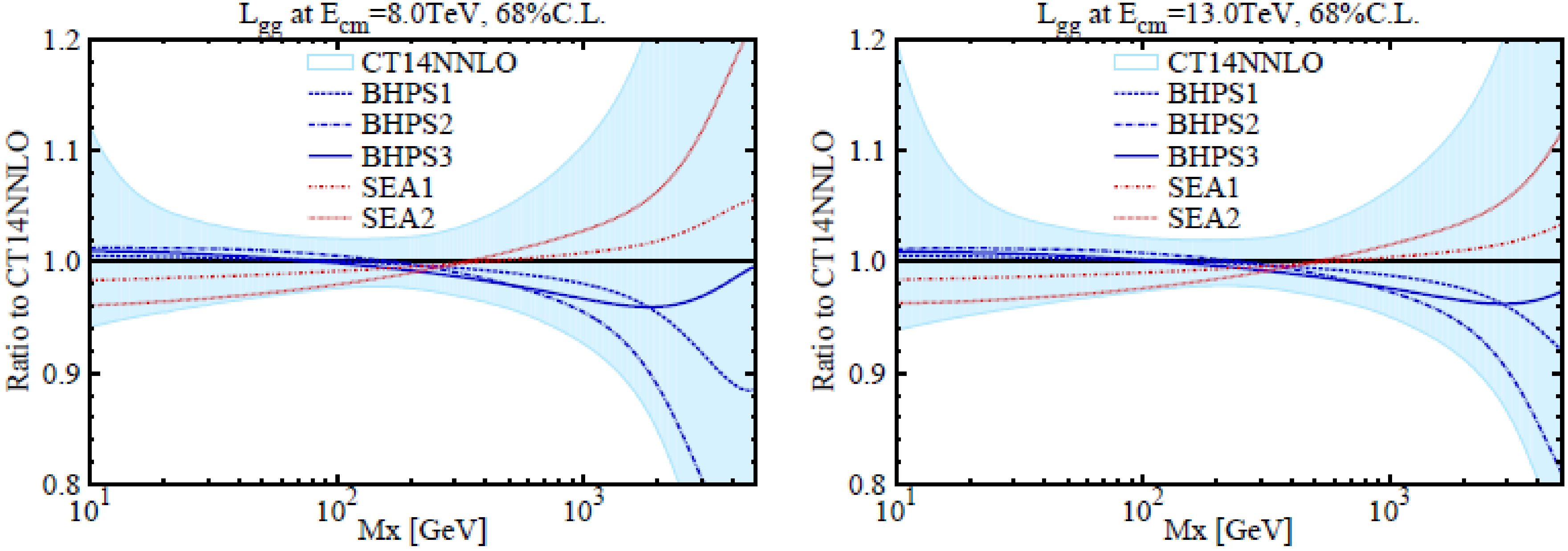
Sources of differences	CT14 IC	NNPDF3.x
α_s order	NNLO only	NLO, NNLO
Settings	90% c.l. from Lagrange multiplier scan $Q_0 = m_c^{pole} = 1.3$ GeV	Symmetric. 68% c.l. from Monte-Carlo sampling, $Q_0 = m_c^{pole} =$ 1.51 GeV
LHC 8 TeV W, Z	Under validation; mild tension with HERA DIS data	Included; strong effect despite a smallish data sample
1983 EMC F_{2c} data included?	Only as a cross check (unknown syst. effects in EMC data)	Optional, strong effect on the PDF error

Impact of IC on the PDF ratios



Common parametrizations of the IC may produce an unphysically large ratio $\left(c(x,Q)+\bar{c}(x,Q)\right)/\left(\bar{u}(x,Q)+\bar{d}(x,Q)\right)$ at $x\to 1$ and low $Q\sim m_c$. This is resolved in the BHPS3 parametrization, which solves the BHPS model numerically and introduces small valence-like components in $\bar{u}(x,Q_0)$ and $\bar{d}(x,Q_0)$ to moderate their drop at $x\to 1$.

Impact of IC on gg luminosities



At √s = 8 TeV the most prominent distortions are from the SEA2 model which is suppressed at lower MX and is notably larger than CT14 for MX in the TeV range. The BHPS models are almost coincident with CT14 for MX < 200 GeV: BHPS1 and BHPS2 are suppressed above MX > 300 GeV, while BHPS3 is suppressed for 0.3 <MX < 3 TeV and enhanced above this energy by approximately 3%.

The impact on the Higgs cross section is small, with sizable impacts on the high mass gg PDF luminosities, but still within uncertainties.

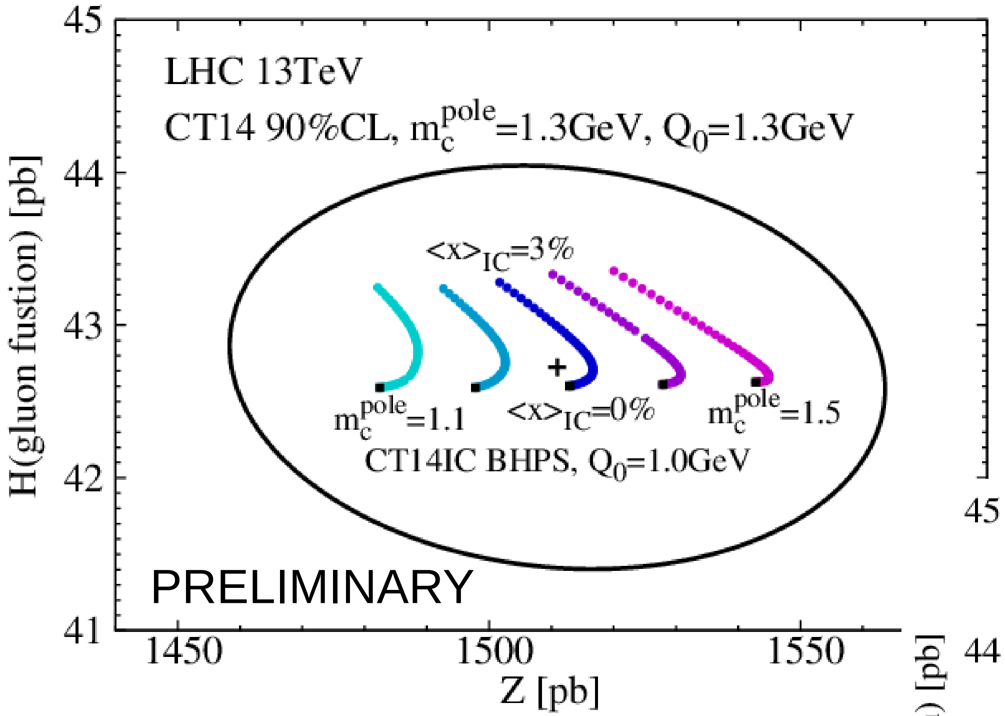
Impact of IC on key LHC observables is mild

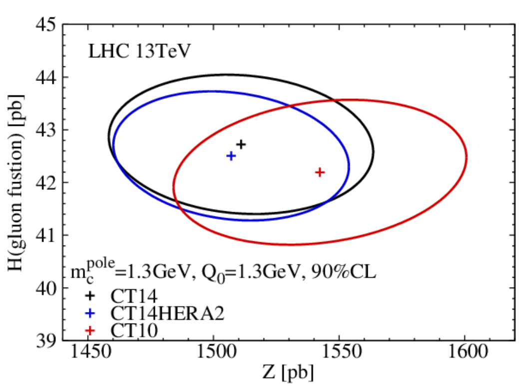
Our estimates assume that the IC PDF component does not depend on the hard process.

Correlated dependence on IC and charm mass m_c.

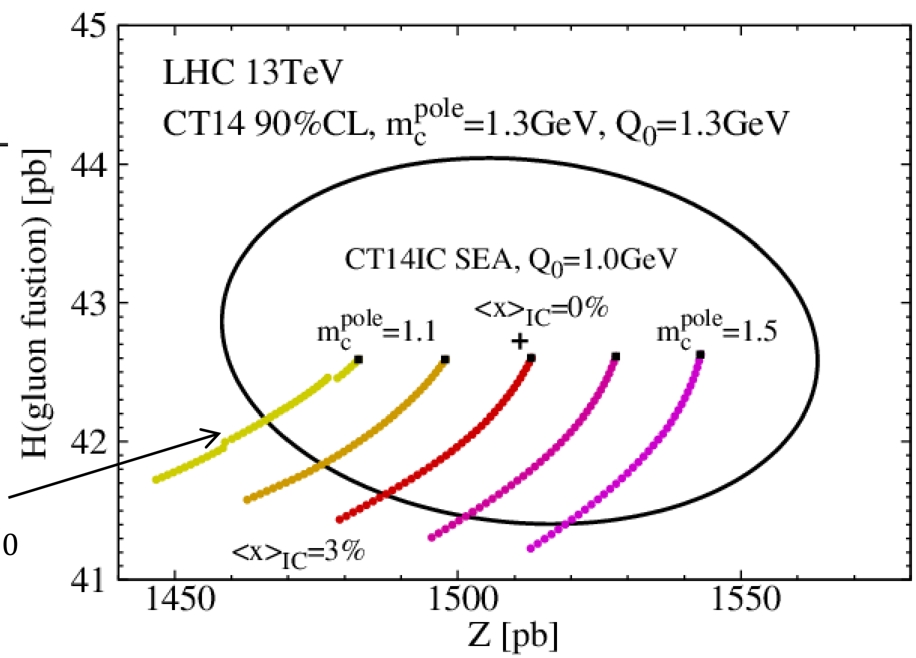
Final-state parton showering dampens sensitivity to the initial-state IC.

NNLO Total inclusive electroweak boson production cross sections $\sigma_{tot}(pp \to VX)$



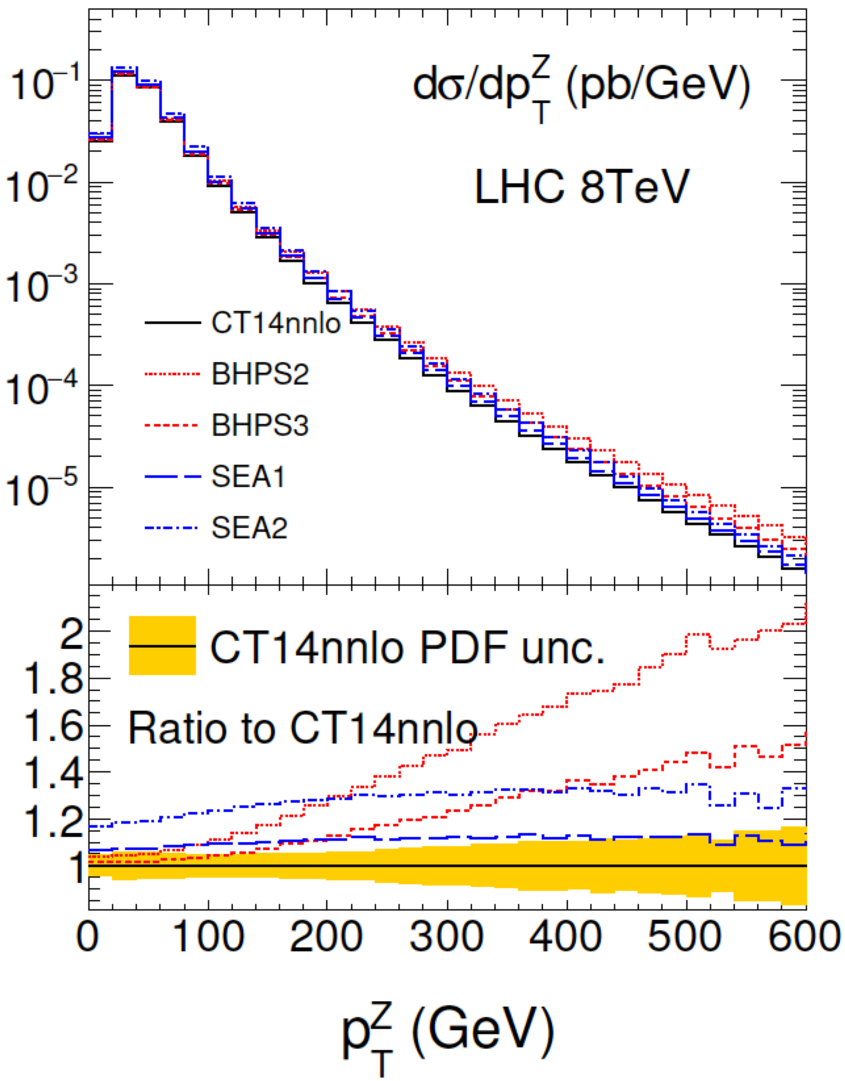


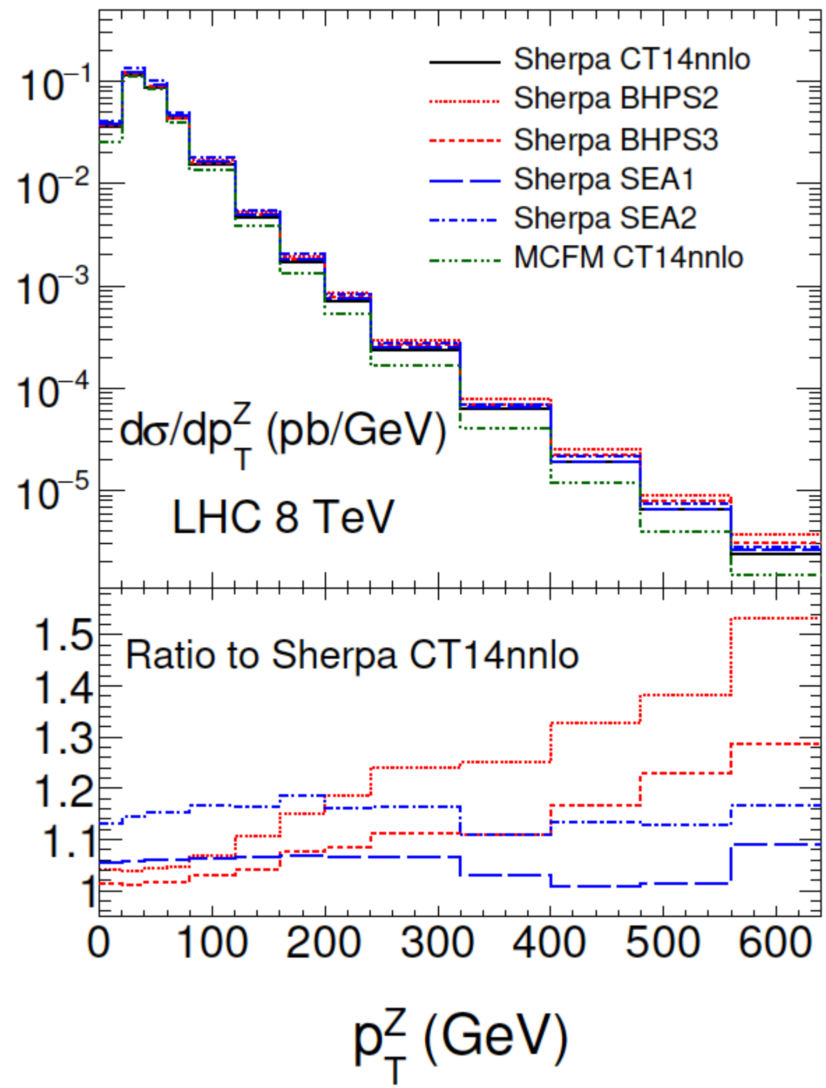
Disfavored,
$\Delta\chi^2_{global} > 100$



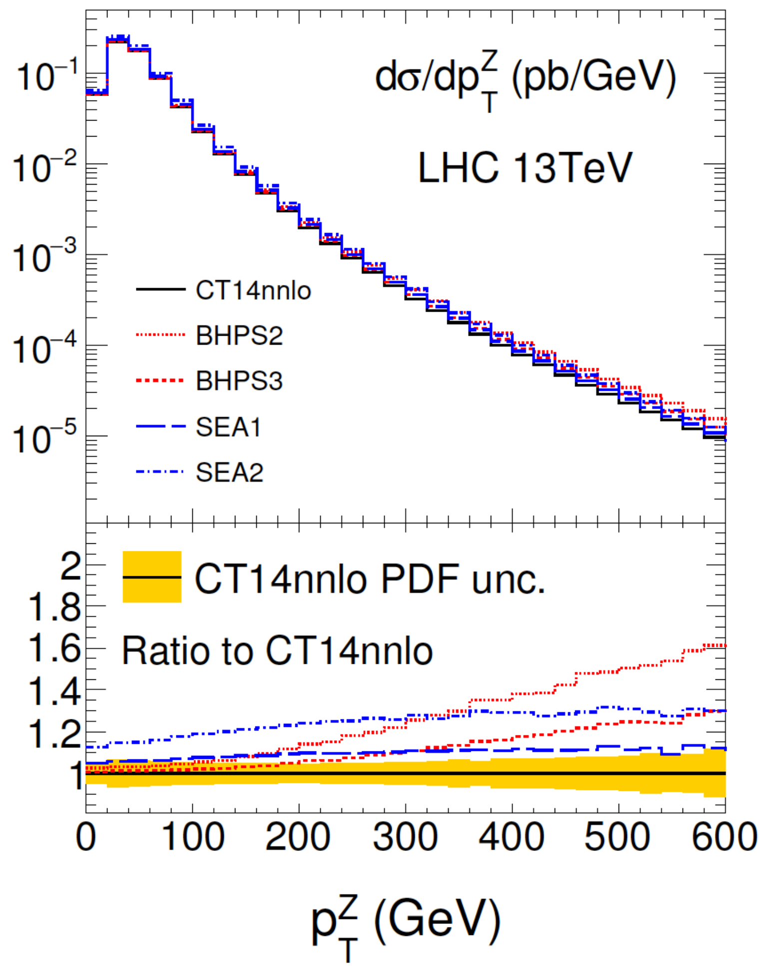
LHC searches for intrinsic charm

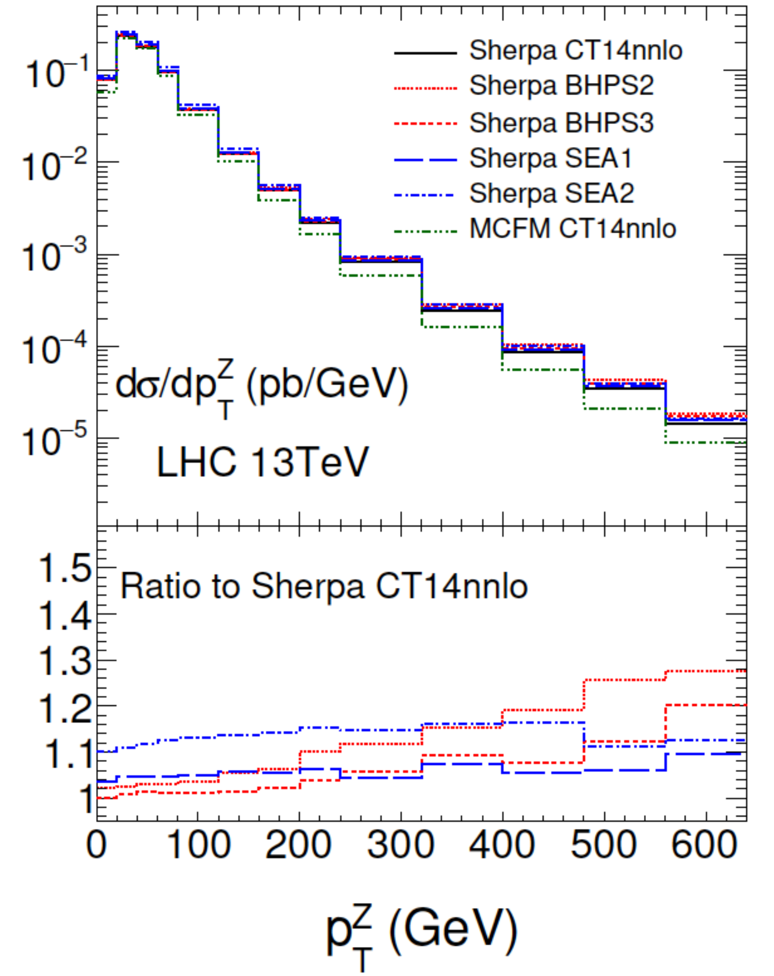
Z+c NLO computation with various models, without (left) and with parton shower (right)





Z+c NLO LHC 13 TeV





The parton shower has the most significant effect in dampening the hard pT(Z) tail, especially for BHPS fits. Sherpa predictions include HO tree-level MEs compared to MCFM and therefore show enhancements in the harder pT(Z) region compared to MCFM. Similarly increasing or decreasing the number of multileg MEs in the merging changes the absolute level of pT.

Recap: fitted charm and twist-4 charm

- The twist-4 charm SIDIS cross section consists of ladder diagrams and everything else
  - The **universal** part of ladder contributions can be resummed into $c(x, Q)$ at $Q^2 \gg m_c^2$ in **any version of the ACOT scheme**
  - **the non-universal component is** of order $\boldsymbol{\alpha_s^2\, \Lambda^2/\mathrm{m_c^2}}$; hard to separate from the missing twist-2/N3LO and $O(\Lambda^2/Q^2)$ contributions – unless explicitly computed

- Fitted $c(x, Q_0)$ approximates for the twist-4 universal $c(x, Q_0)$ and other missing terms
- Constraints on the fitted component of a proton from the CT14 NNLO global QCD analysis: $\langle x\rangle_{IC} < 2\%$ for BHPS IC and $\langle x\rangle_{IC} < 1.6\%$ for SEA IC at 90% C.L.
- The impact of the IC on the LHC predictions is still within the standard CT14 NNLO uncertainty
- Enhancement in $Z + c$ production at high $p_T(Z)$ in the BHPS model under the assumption of full universality. Final-state parton showering dampens the enhancement

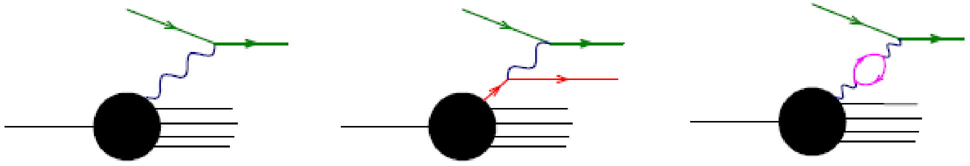
$f_{\gamma/p}(x,\mu^2)$: photon PDF in a proton

The essential part of NLO electroweak corrections in W, Z, $t\bar{t}$, … production at TeV scales

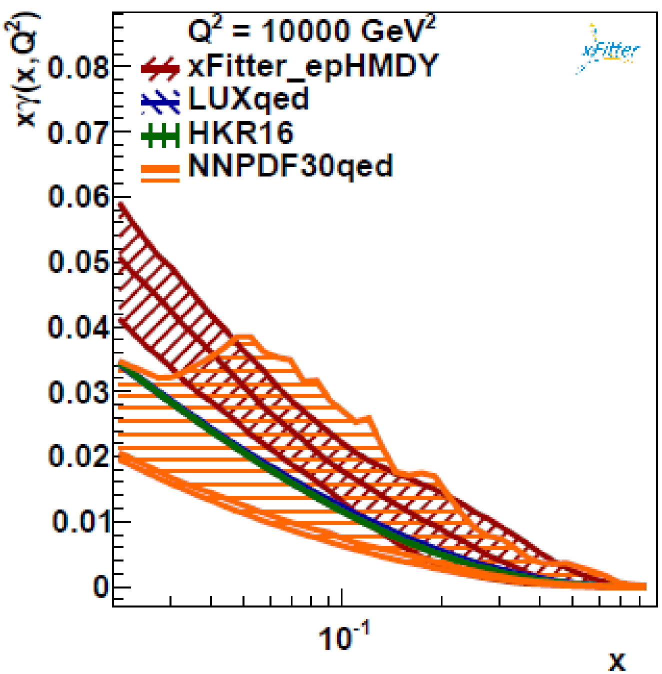
⇒ A. Vicini, A. Mitov

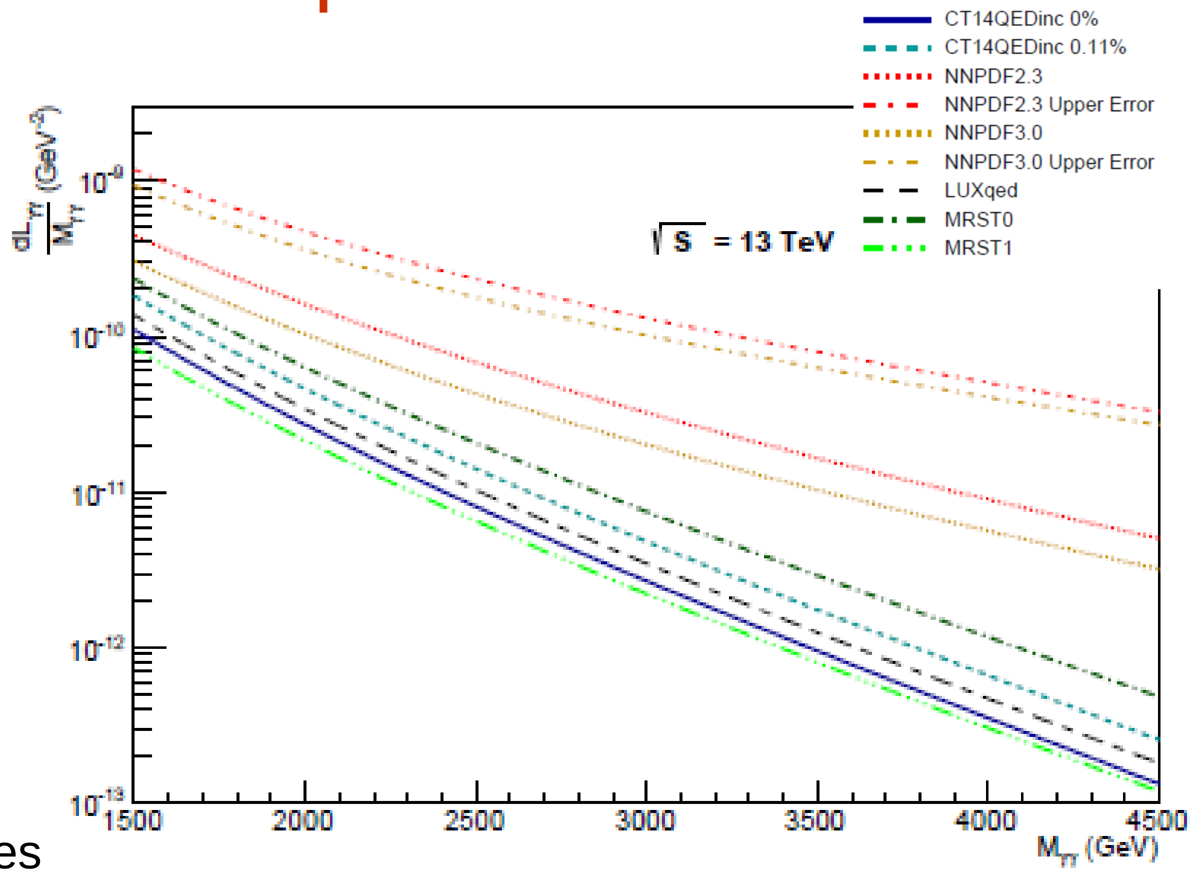
Two strategies to constrain $f_{\gamma/p}(x,\mu^2)$:

1. from a global fit including photon-scattering processes
   CT14qed_inc, HKR16, NNPDF30_qed, xFitter_epHMDY sets
2. by relating $f_{\gamma/p}(x,\mu^2)$ to the inclusive hadronic tensor
   LUXqed17 – an updated PDF set from the LUX group



Comparisons of photon PDFs





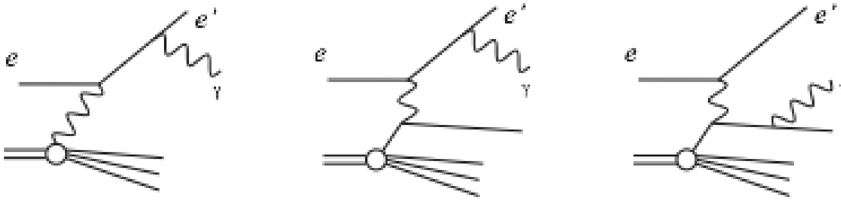
The magnitude of uncertainties spans a large range, from LUXqed (smallest) to NNPD3.0 (largest)

FIG. 5: Photon-photon luminosity predicted by various photon PDFs for an invariant mass of 1.5 TeV to 4.5 TeV, at the LHC with 13 TeV collider energy. The lower error curves of NNPDF2.3QED and NNPDF3.0QED predictions are below the x-axis of this plot.

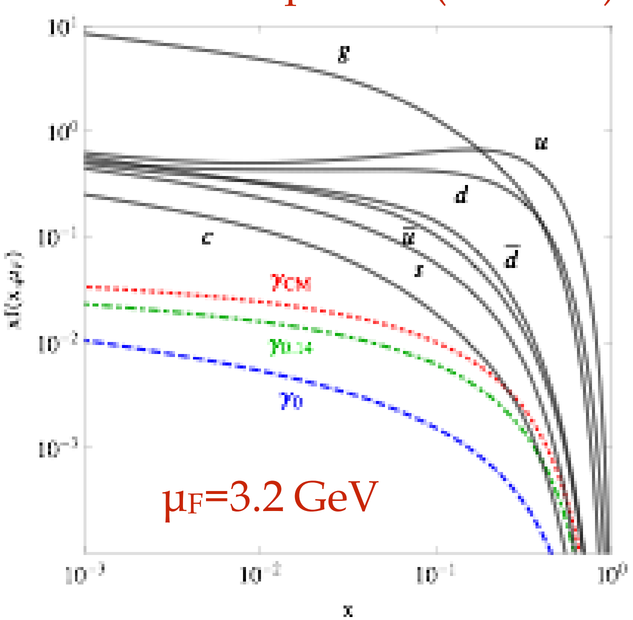
CT14 QED PDFs

- CT14 set including photon PDF (NLO QCD+LO QED) based on radiative ansatz and with constraints from photon production in DIS
  - elastic part: equivalent photon approach, momentum frac. ~0.15%
  - inelastic part: radiative ansatz with one free parameter (momentum frac.), similar to MRST QED

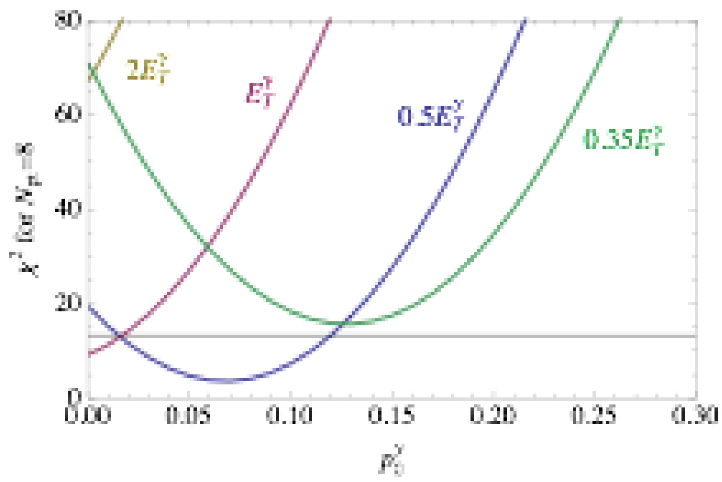
momentum frac. of inelastic part constrained from ZEUS isolated photon data



PDFs with photon (inelastic)



90% C.L. limit on momentum frac. ~0.14%

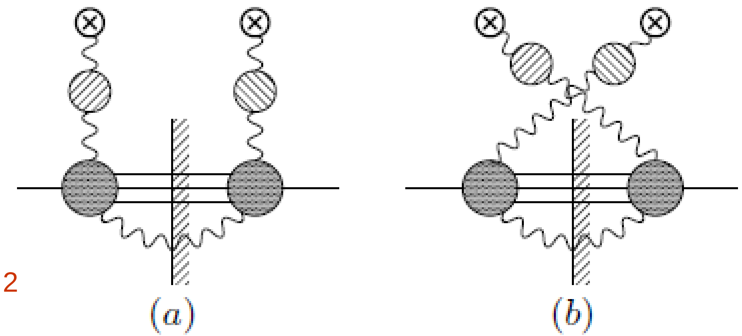


The Photon Content of the Proton

A. Manohar, P. Nason, G. Salam, G. Zanderighi, 1607.04266, 1708.01256

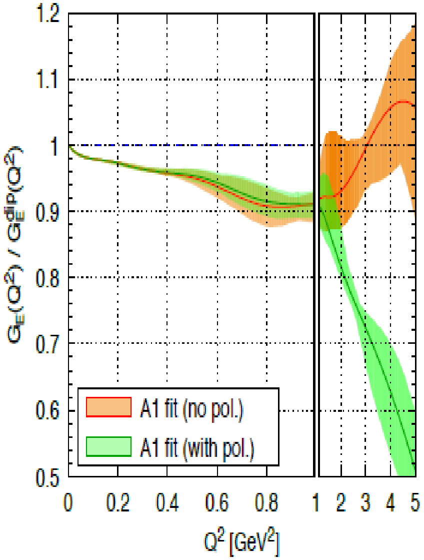
$$x f_\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu)} \int_x^1 \frac{dz}{z} \Bigg\{ \int_{Q^2_{\rm min}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2_{\rm ph}(-Q^2) \Bigg[-z^2 F_L(x/z,Q^2) + \left(z p_{\gamma q}(z) + \frac{2x^2 m_{\rm p}^2}{Q^2} \right) F_2(x/z,Q^2) \Bigg] - \alpha^2(\mu)\, z^2 F_2(x/z,\mu^2) \Bigg\} + \mathcal{O}(\alpha\alpha_s, \alpha^2)\,.$$

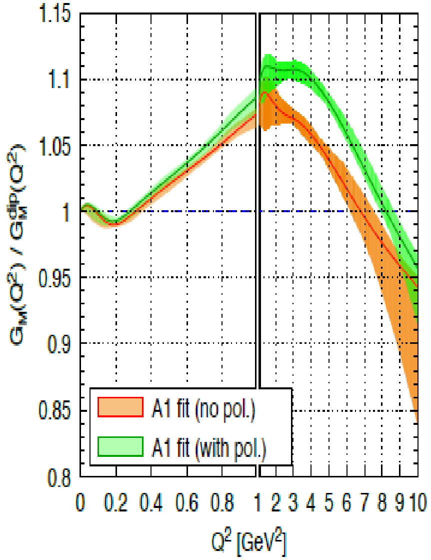
The **LUXqed17** analysis ~~estimates~~ calculates $f_{\gamma/p}(x,\mu^2)$ from a Q^2 integral of inclusive DIS structure functions $F_{2,L}(x,Q^2)$. This works because $f_{\gamma/p}(\xi,\mu^2)$ and inclusive hadronic tensor $W^{\mu\nu}$ are derived from the same matrix element in various kinematic regimes.

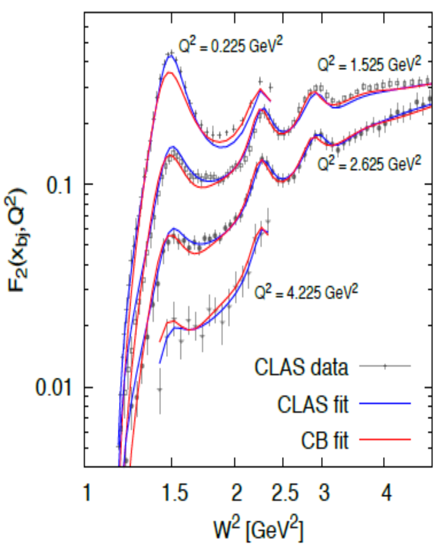


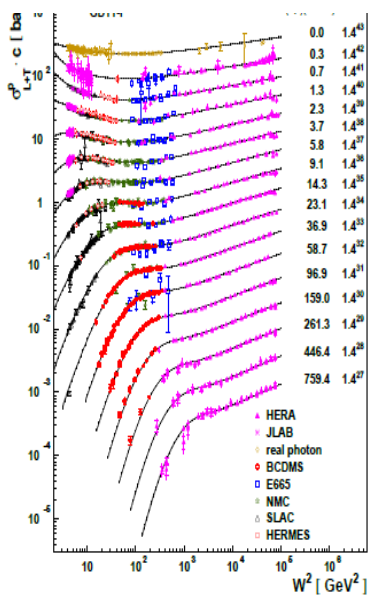
Matrix elements of the PDF operator in a proton state.

Contributions to the $f_{\gamma/p}(x,\mu^2)$ integral









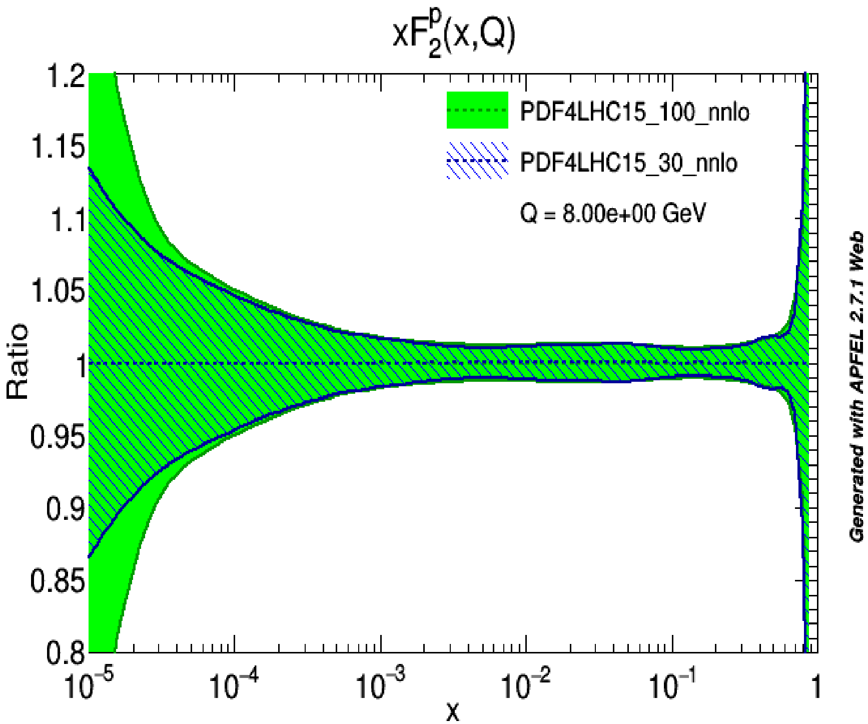
- The inputs are known with good accuracy at all Q

$Q < 3$ GeV:

– elastic E & M form-factors

– inelastic structure functions from a variety of DIS experiments

Contributions to the $f_{\gamma/p}(x,\mu^2)$ integral

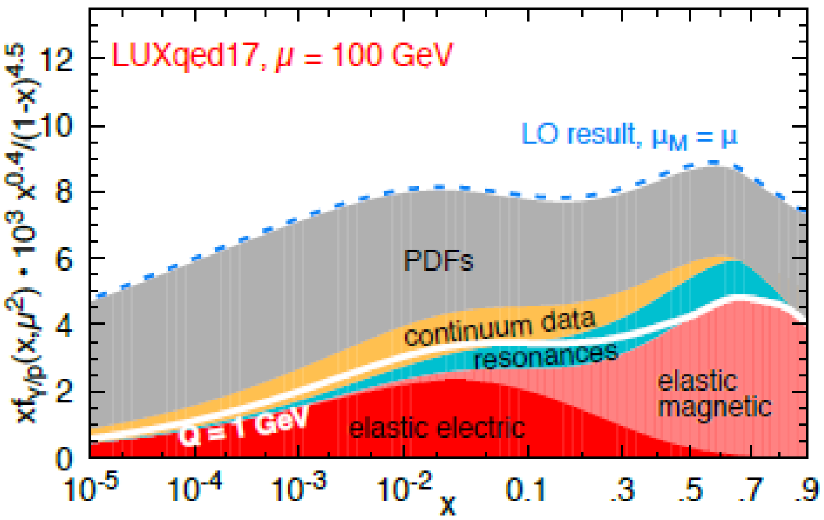


- The inputs are known with good accuracy at all Q

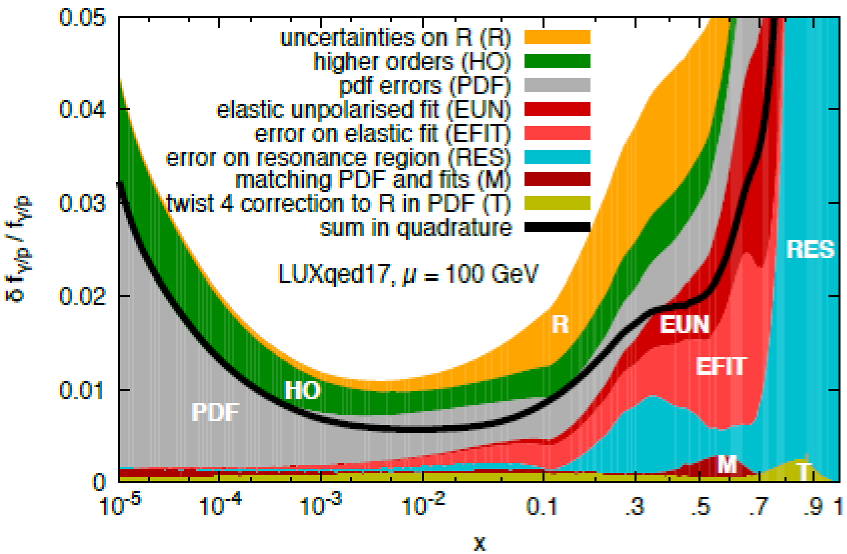
  $Q > 3$ GeV:

  - $F_{2,L}(x,Q^2)$ (summed over all flavors) computed from standard PDFs using the PDF4LHC15_100 set
  - The missing $f_{\gamma/p}(x,\mu^2)$ in $F_{2,L}(x,Q^2)$ is a subleading correction

Breakdown of contributions to $f_{\gamma/p}(x,\mu^2)$



- Photon PDF



- Relative photon PDF uncertainty

Summary: news from the PDF groups

- Development of a new generation of NNLO ensembles
- Progress in understanding consistency among the input LHC measurements on inclusive jet, gamma*/W/Z, tT production
- Reduction of PDF uncertainties is contingent on a coordinated effort by the LHC collaborations to cross-examine the benchmark SM measurements, understand or reduce systematic effects
- Advances in understanding of “intrinsic charm/fitted charm” PDFs and photon PDFs
- Support computations, programs (e.g., **xFitter**), and young people contributing to this task!

Backup slides

Parametrizations of $c(x,Q_0)$

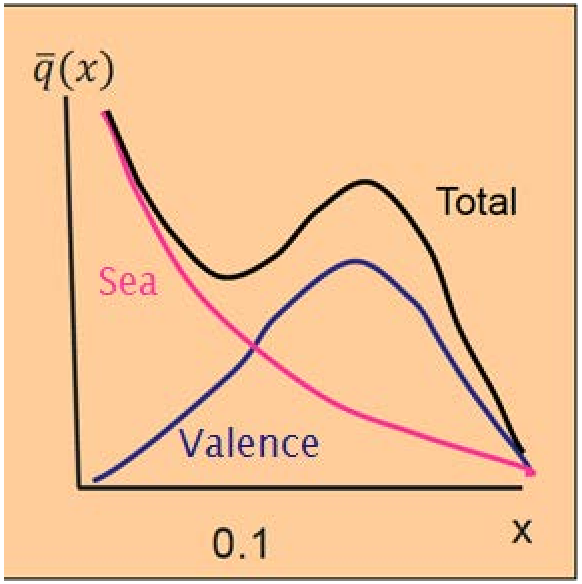
1. "**Valence-like**" $c(x,Q_0)$ according to the BHPS model: BHPS1 and BHPS2

Brodsky et al PLB 1980

$$c(x)=\bar{c}(x)=\frac{1}{2}Ax^2\left[\frac{1}{3}(1-x)\ (1+10x+x^2)-2x(1+x)\ln(1/x)\right]$$

2. BHPS3 model: include intrinsic $u\bar{u}$, $d\bar{d}$, and $c\bar{c}$ with **numerical** solutions for the BHPS model.

   ⇒ Physical behavior of $c/\bar{u}$, $c/\bar{d}$ ratios



3. ``**Sea-like**'' $c(x,Q_0)$: SEA1, SEA2

$$c(x)=\bar{c}(x)=A\left[\bar{d}(x,Q_0)+\bar{u}(x,Q_0)\right]$$

SET UP FOR THE GLOBAL ANALYSIS for CT14 and CT14HERA2:
We mainly focus on the CT14 analysis, CT14HERA2 gives similar results

For all three models:

- ❖ $\alpha_s(M_Z) = 0.118$, compatible with the world average value $\alpha_s(M_Z) = 0.1184 \pm 0.0007$; the default value for recent CT PDF fits.

- ❖ HOPPET - evolution code used to include nonperturbative charm models with NNLO matching, and to evolve the PDFs at NNLO.

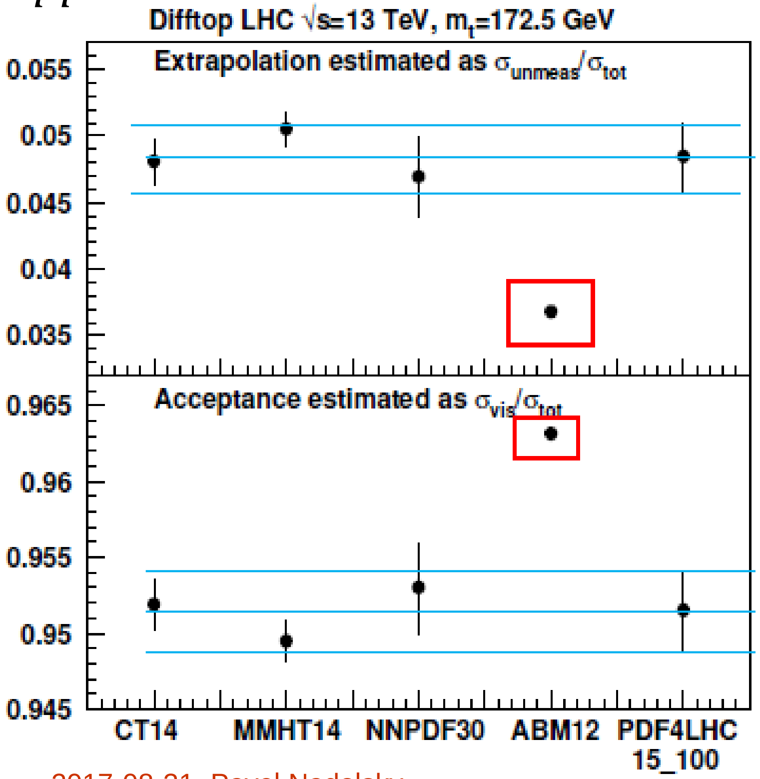
- ❖ S-ACOT-χ at NNLO --- CT GM-VFN default scheme for heavy-flavour treatment in the inclusive DIS structure functions.
  Differences between ACOT vs S-ACOT-χ for IC contr. are $\mathcal{O}\left(\Lambda^2/Q^2\right)$

- ❖ Production threshold kinematics are accounted for by using the χ convention. The other partons are parametrized at an initial scale $Q_0 = 1.295$ GeV, as in the CT14 analysis.

- ❖ The default charm-quark mass, $m_c^{pole} = 1.3$ GeV, is varied as a part of the analysis

Choosing the estimator for the PDF+α_s uncertainty

$pp \to t\bar{t}X$



⇒**PDF4LHC recommendations for LHC Run-II** (arXIV:1510.03865)

See also
A Critical Appraisal and Evaluation of Modern PDFs (arXIV:1603.08906)

Given numerous PDF sets, what is the PDF uncertainty in my analysis?

$pp \to t\bar{t}X$

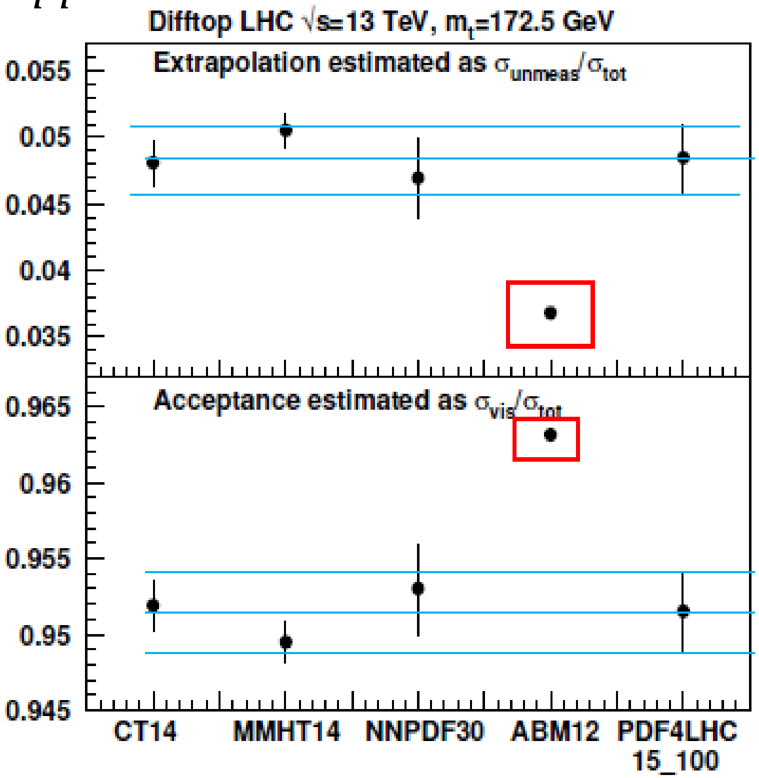


Figure: K. Lipka
1603.08906

The procedure for computing the PDF uncertainty must vary depending on the goals. The options may include

a) Using one individual set out of several similar ones (e.g., CT, MMHT, or NNPDF)

b) Using an envelope of all sets, including the outlier sets

c) 2015 recommendation by the PDF4LHC working group (arXiv:1510.03865)**:**

1. Several procedures spelled out for computation of PDF uncertainties, depending on the context
2. Estimation of PDF uncertainties is streamlined in many cases by using combined PDF4LHC15 sets based on CT14, MMHT14, and NNPDF3.0

Why PDF4LHC recommendation is necessary

Estimates of PDF uncertainties may vary drastically depending on the method.

An overly conservative estimate greatly reduces sensitivity to BSM physics.

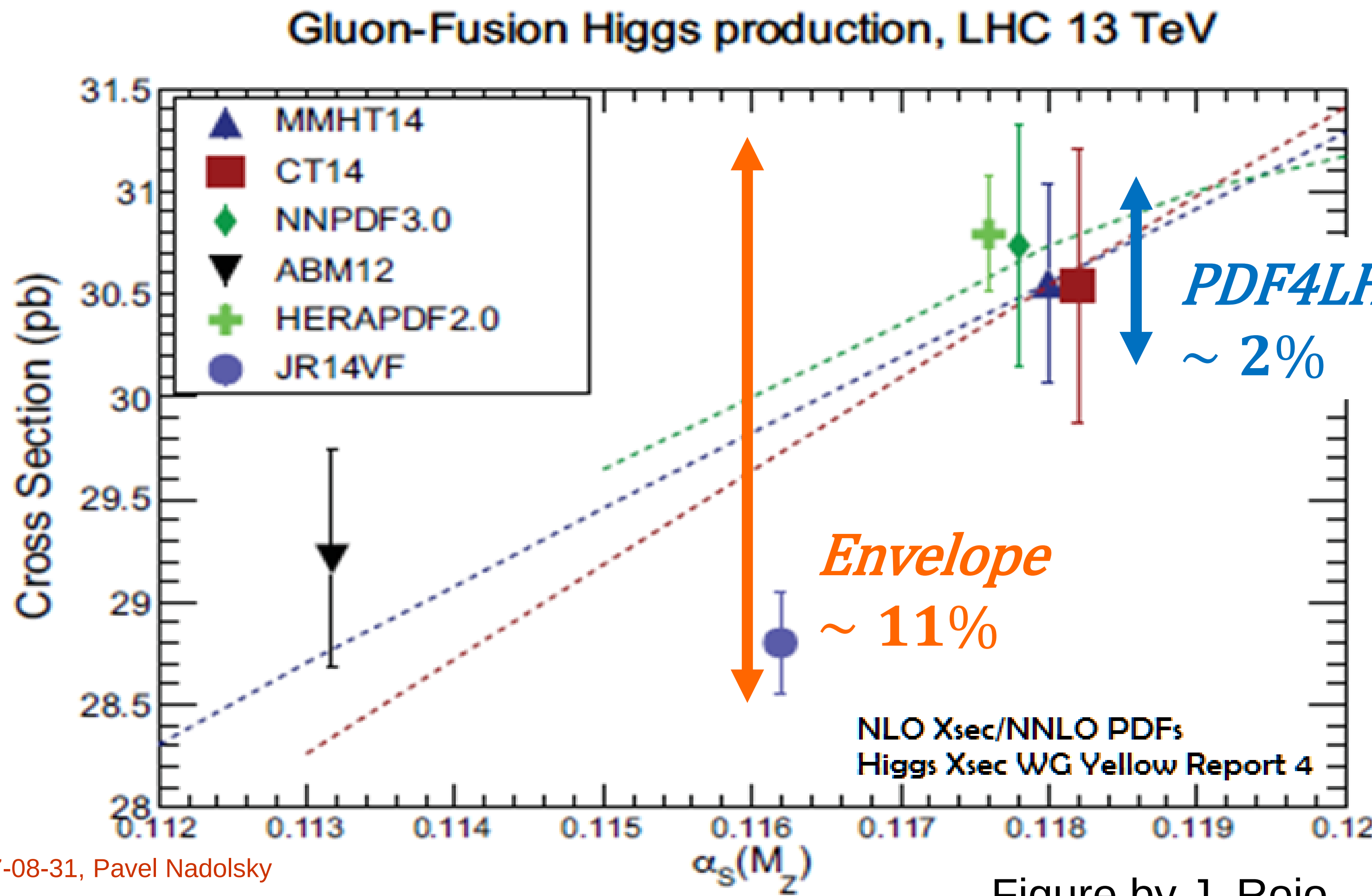


Figure by J. Rojo

Why PDF4LHC recommendation is needed

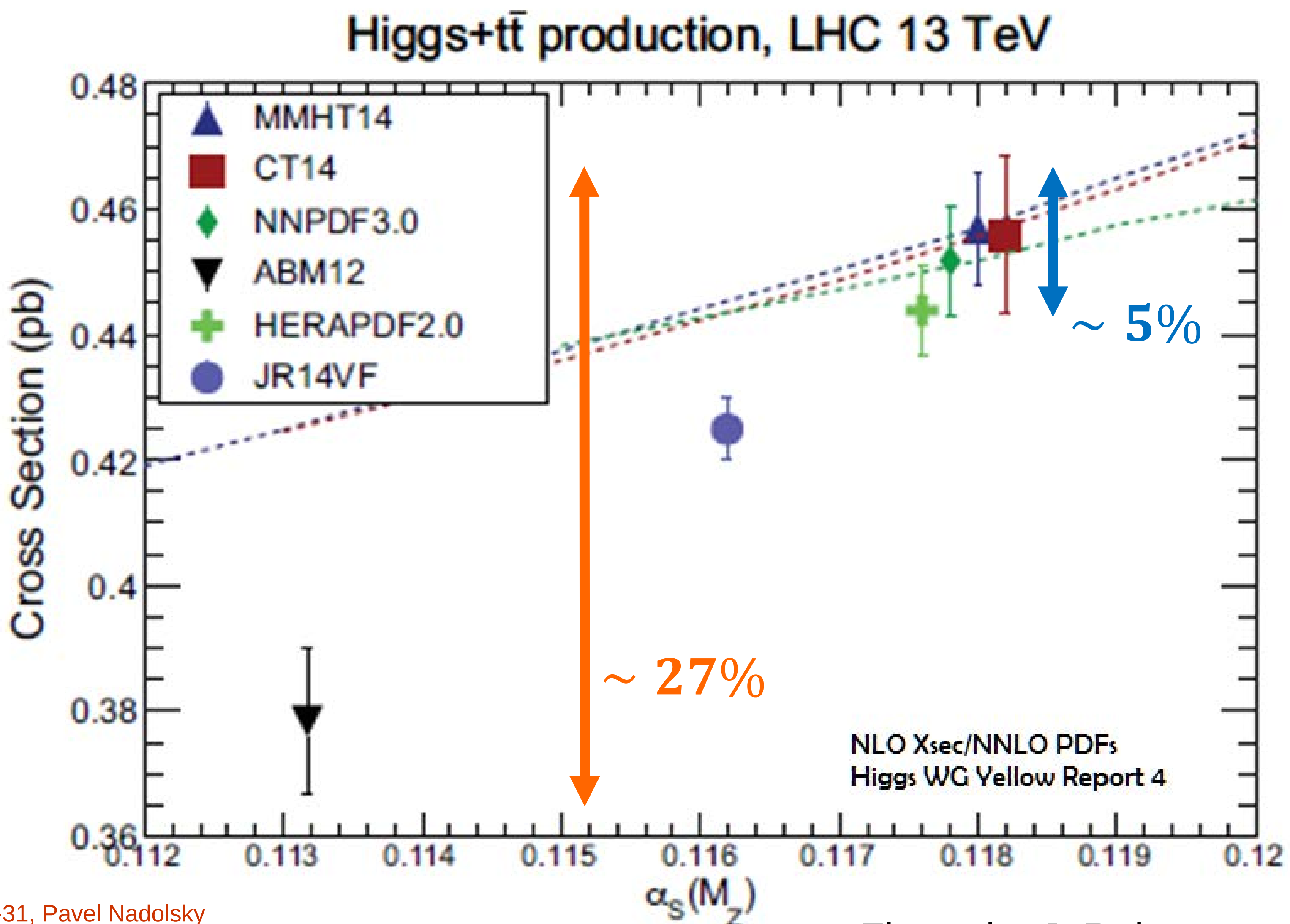


Figure by J. Rojo

OUTP-15-17P
SMU-HEP-15-12
TIF-UNIMI-2015-14
LCTS/2015-27

DON'T PANIC

PDF4LHC recommendations for LHC Run II

Jon Butterworth[1], Stefano Carrazza[2], Amanda Cooper-Sarkar[3], Albert De Roeck[4,5], Joël Feltesse[6], Stefano Forte[2], Jun Gao[7], Sasha Glazov[8], Joey Huston[9], Zahari Kassabov[2,10], Ronan McNulty[11], Andreas Morsch[4], Pavel Nadolsky[12], Voica Radescu[13], Juan Rojo[14] and Robert Thorne[1].

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"A common mistake that people make when trying to design something completely foolproof is to underestimate the ingenuity of complete fools." –D. Adams

PDF4LHC publication, topics

1. **Review of updates on PDFs from various groups**

NNLO Global PDF sets: CT14, MMHT'14, NNPDF3

PDFs using other methodologies: ABM'12, CJ15, HERAPDF2.0

2. Average PDF sets by PDF4LHC group: PDF4LHC15_30, _100, _MC

Criteria for combination

$\alpha_s(M_Z) = 0.1180 \pm 0.0015$ at 68% c.l.

3. Recommendation on selecting PDF sets for various LHC applications

A. New physics searches

B. Precision tests of SM and PDFs

C. Monte-Carlo simulations

D. Acceptance estimates

Average PDF sets **can** be used **for bulk of applications** in A, C, D