PDFs studies with LHeC pseudo-data

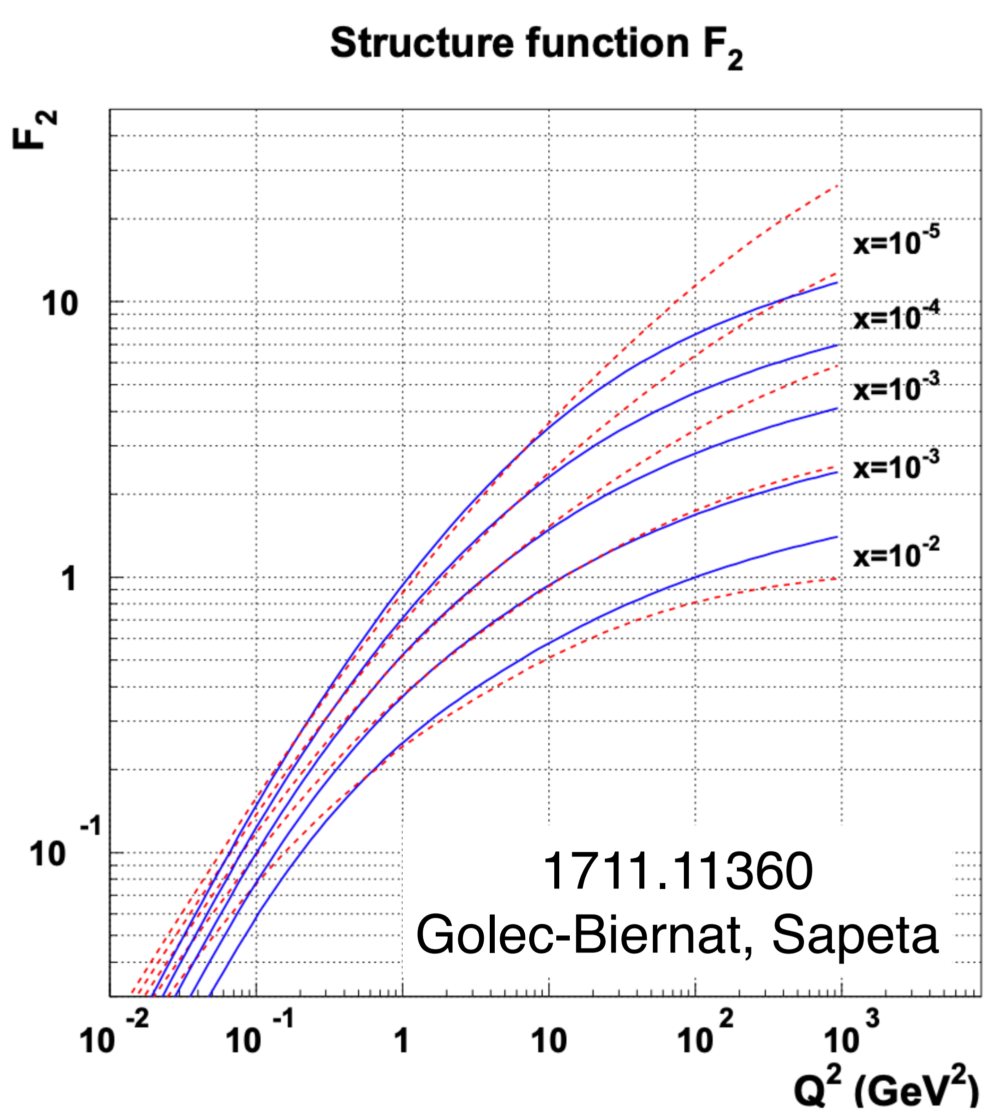
Juan Rojo
VU Amsterdam & Nikhef Theory group

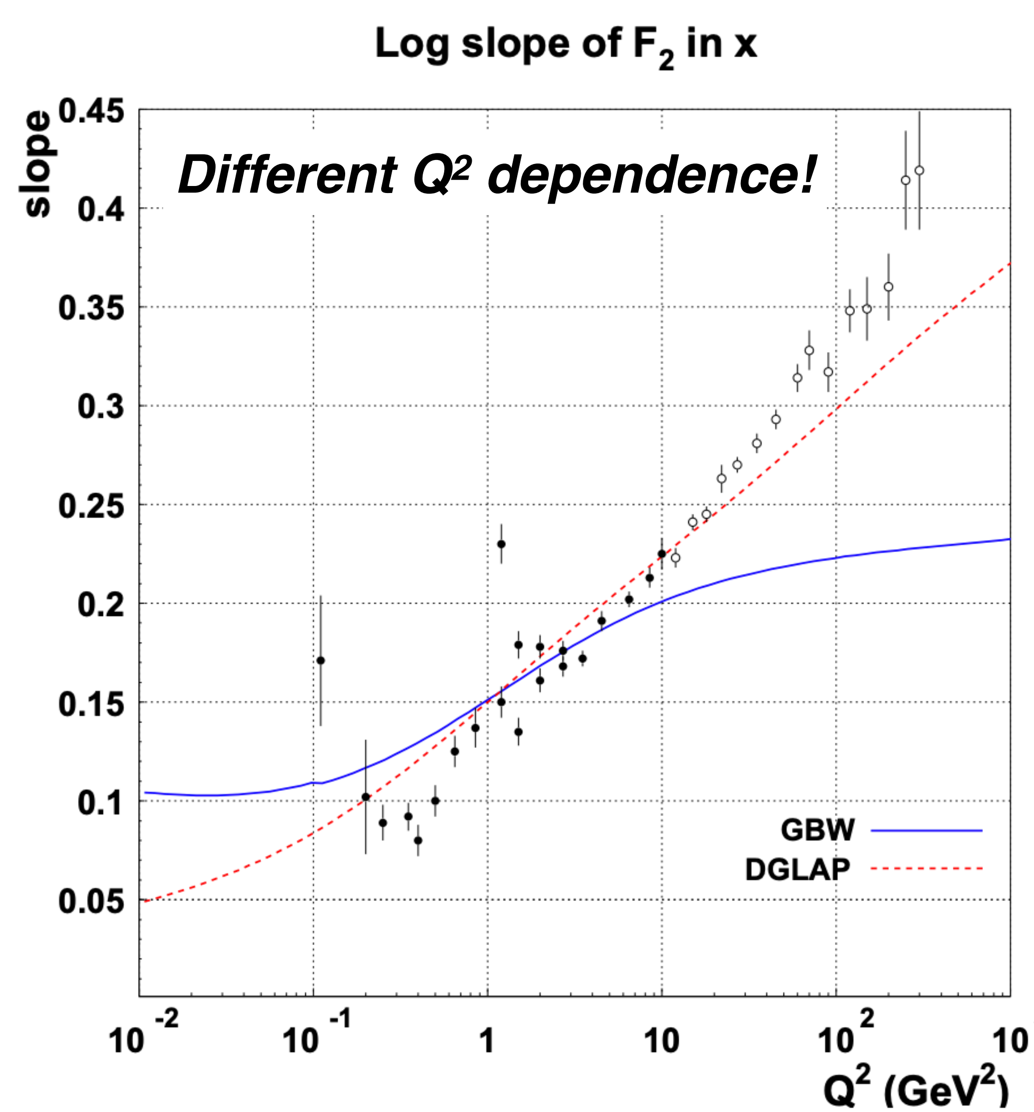
LHeC PDF and small-x meeting, 30/09/2019

Abdul-Khalek, Bailey, Harland-Lang, Gao, JR
arXiv:1810.03639 (EPJC) + arXiv:1906.10127 + contribution to CDR

Motivation

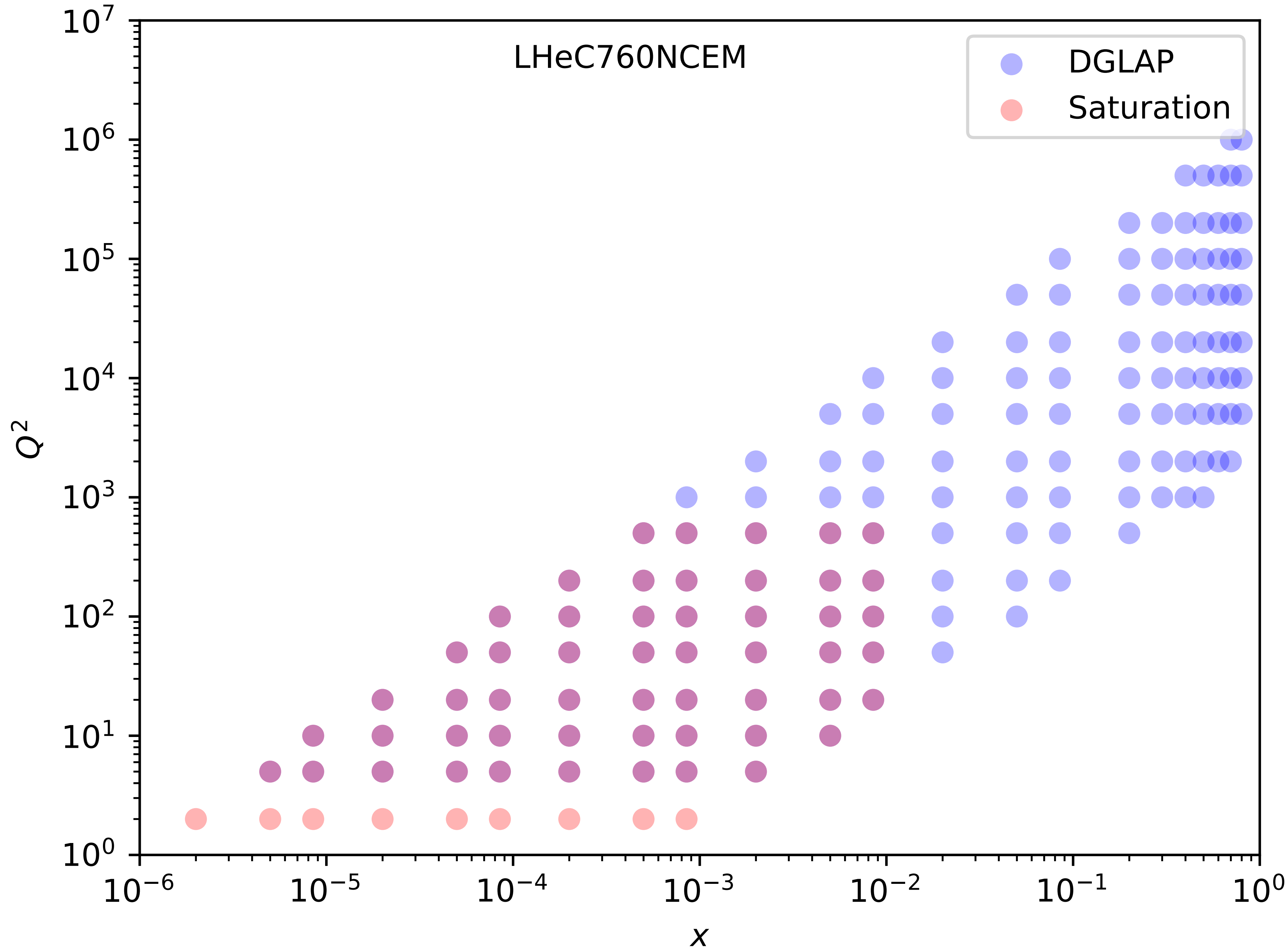
- Evidence for the need of BFKL small-x resummation in HERA data reported
- At the LHeC the used of resumed calculations will be unavoidable
- If furthermore **non-linear (saturation) effects** are present in the LHeC kinematic range, can we disentangle them in an efficient way?
- Fitting **LHeC pseudo-data based on saturation models** with the **standard DGLAP framework** will tell us whether or not saturation effects can be ``fitted away''!





Disentangling saturation at LHeC

Replace DGLAP pseudo-data by saturation-based predictions (from Nestor) and redo profiling



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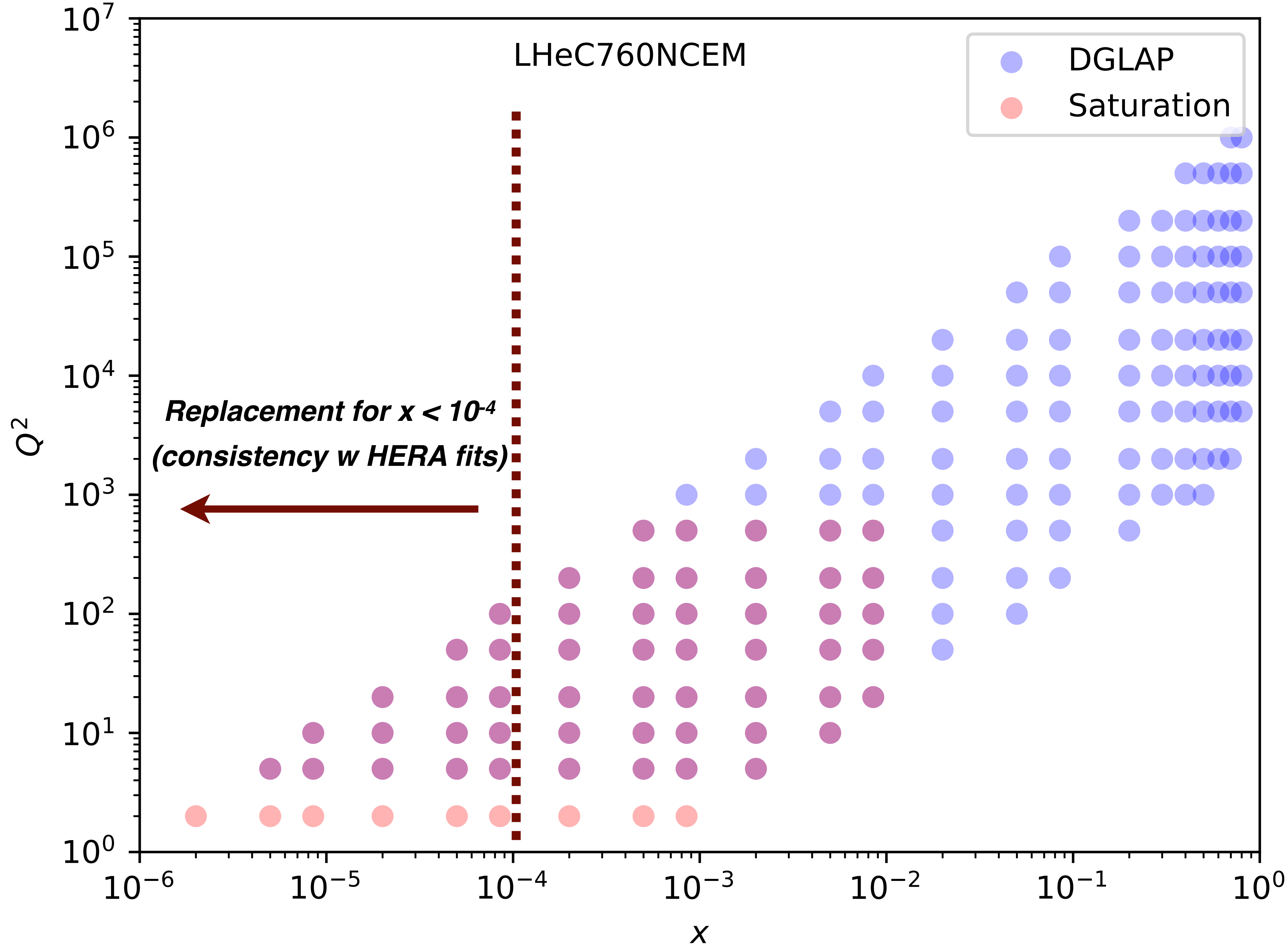
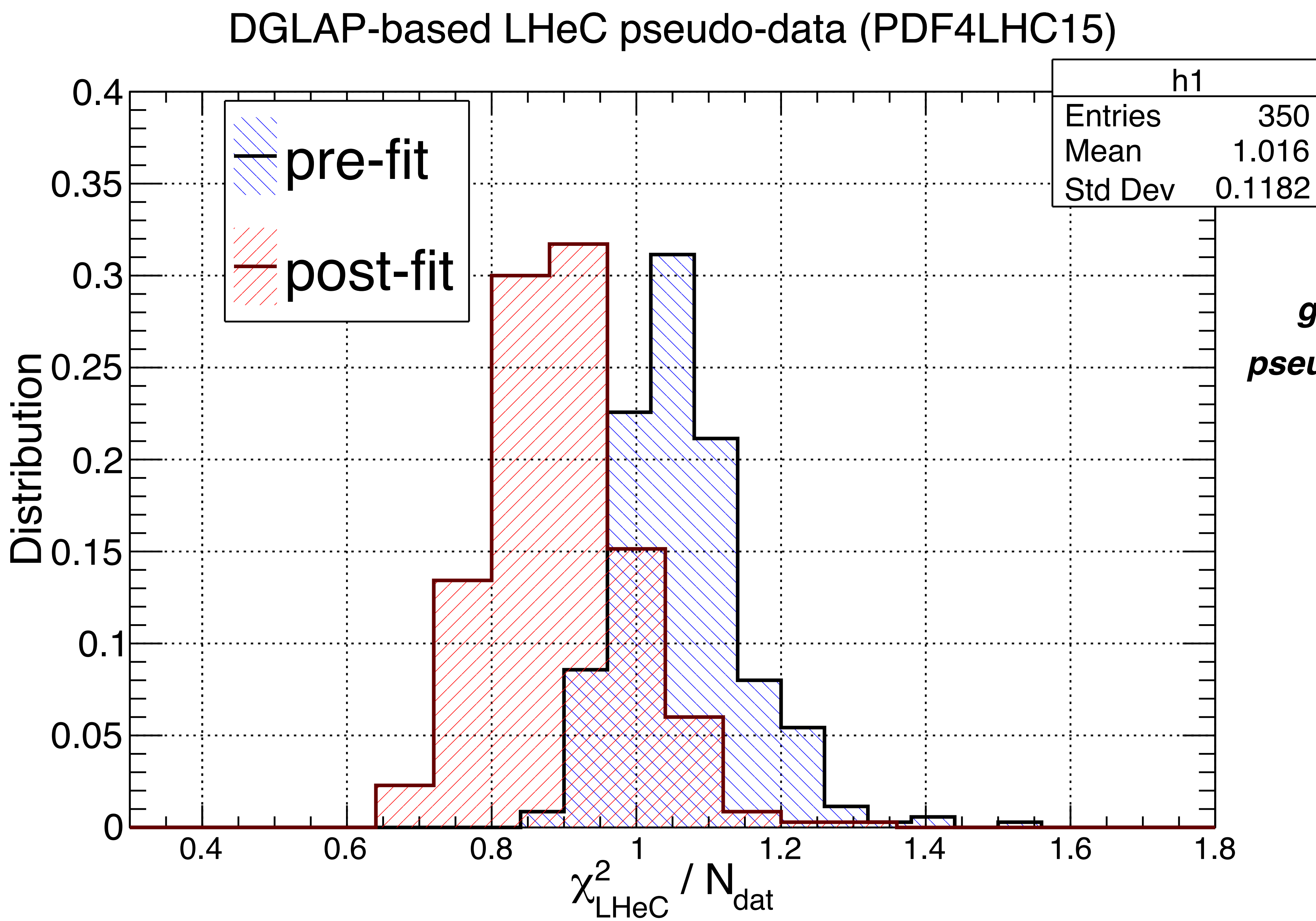


Disentangling saturation at LHeC

Compare fit quality before and after profiling



generated 500 pseudo-experiments

By construction, agreement after profiling essentially unchanged

Disentangling saturation at LHeC

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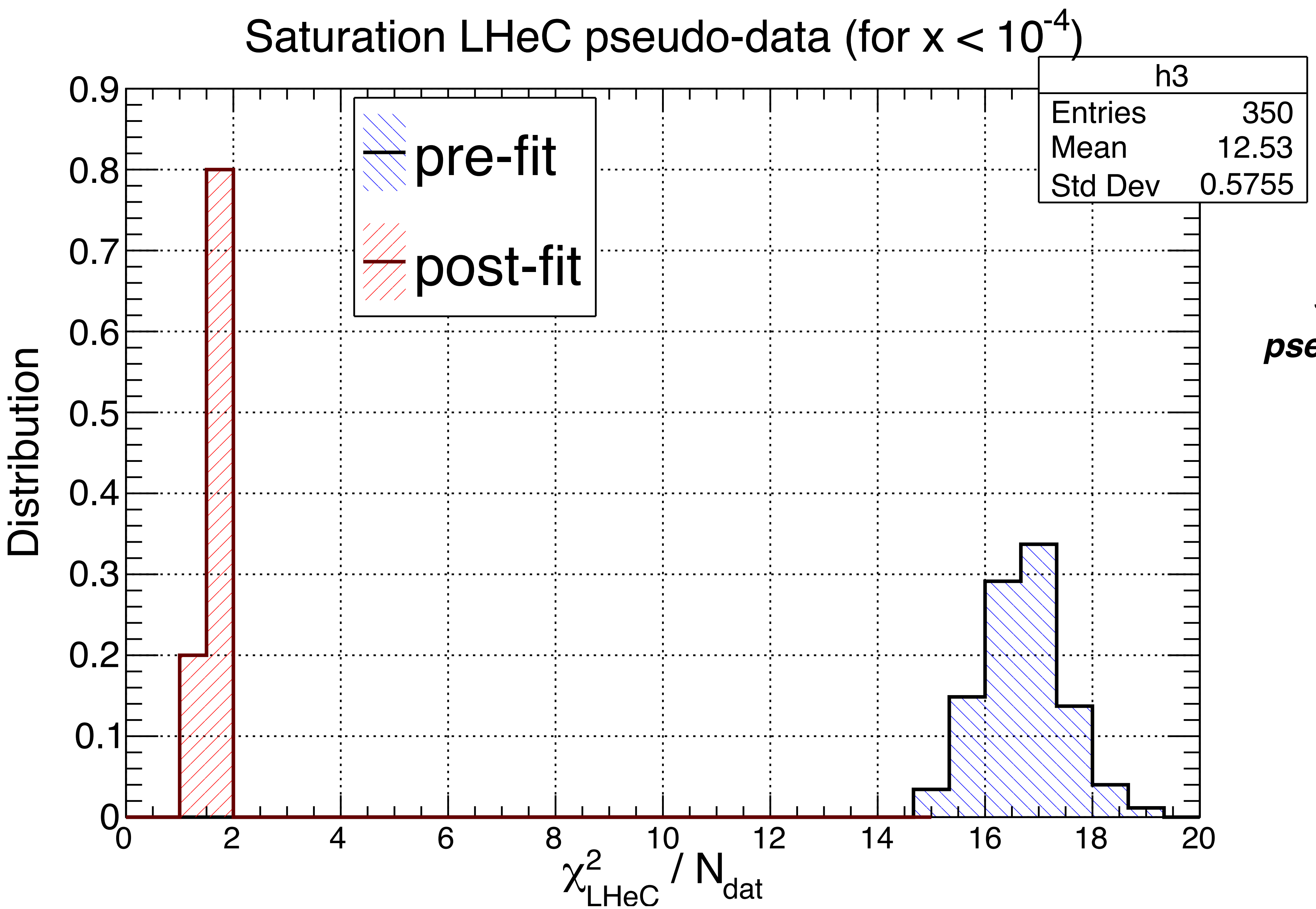

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Initially saturation pseudo-data strongly disagrees with PDF4LHC15 (DGLAP) prior, most of the disagreement can be fitted away ….

Disentangling saturation at LHeC

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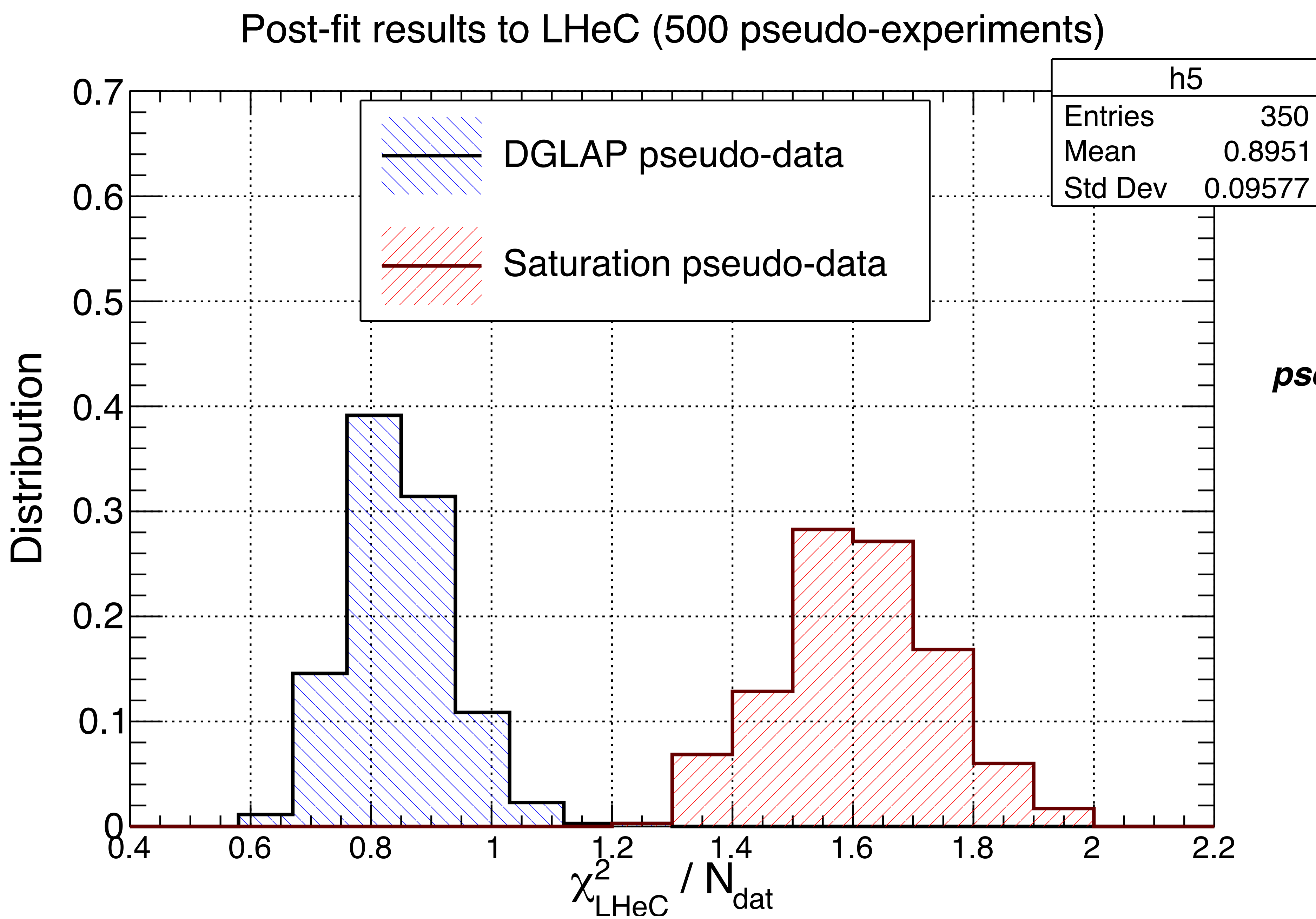
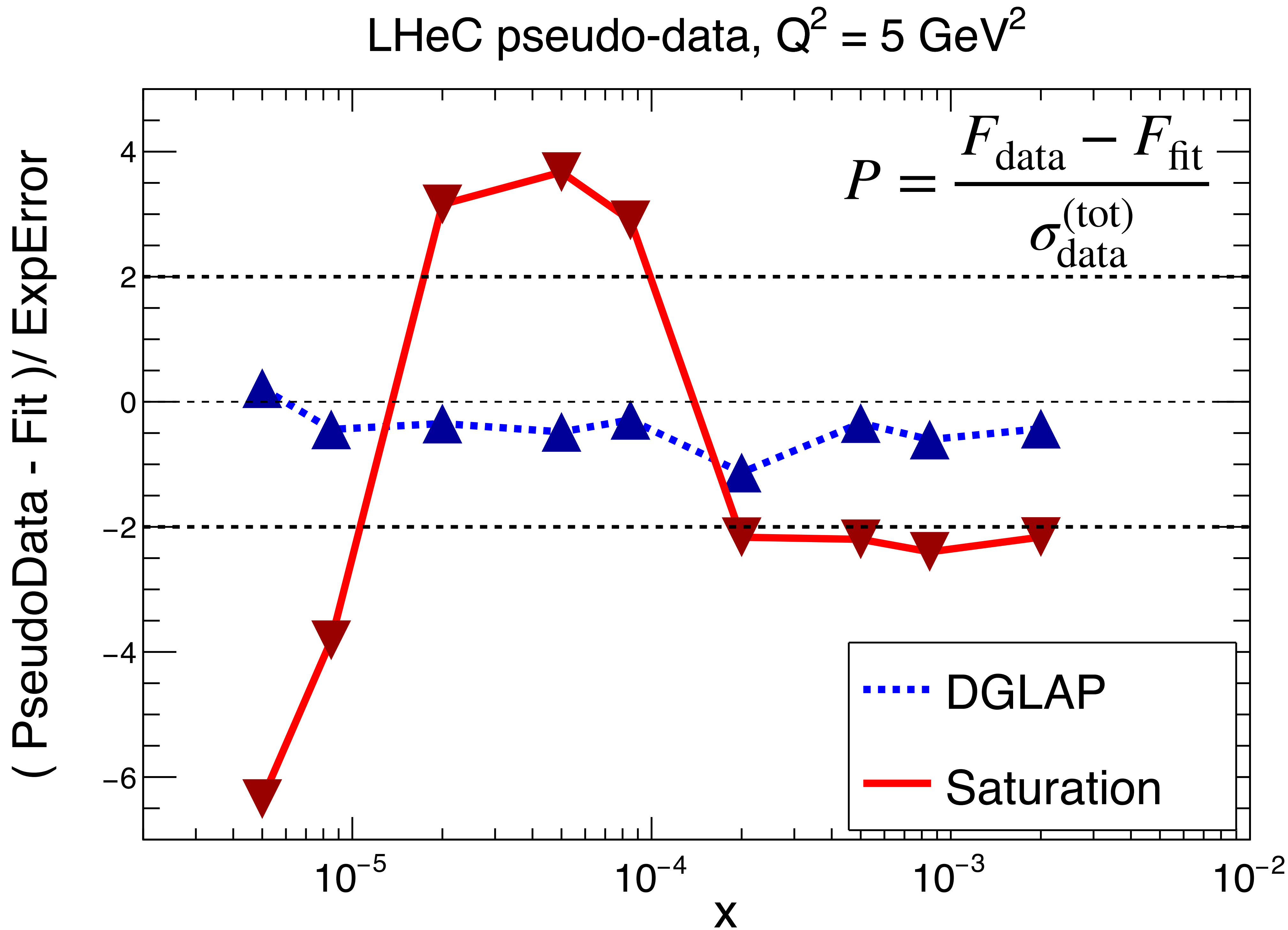


generated 500 pseudo-experiments

… but not all: it should be possible to disentangle saturation from DGLAP at LHeC with promising significance!

Disentangling saturation at LHeC

Compute the post-fit pulls between pseudo-data and theory



Disentangling saturation at LHeC

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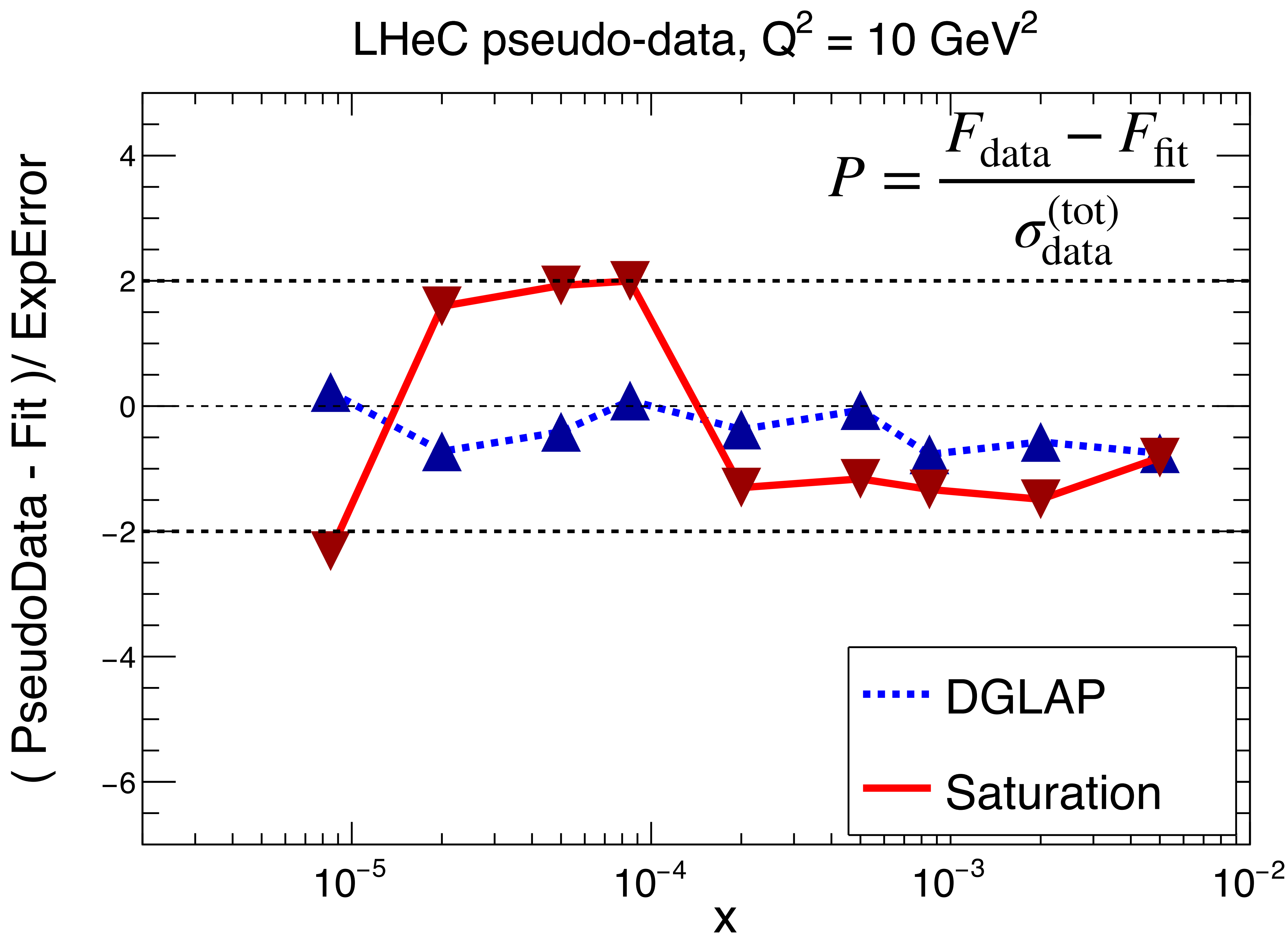

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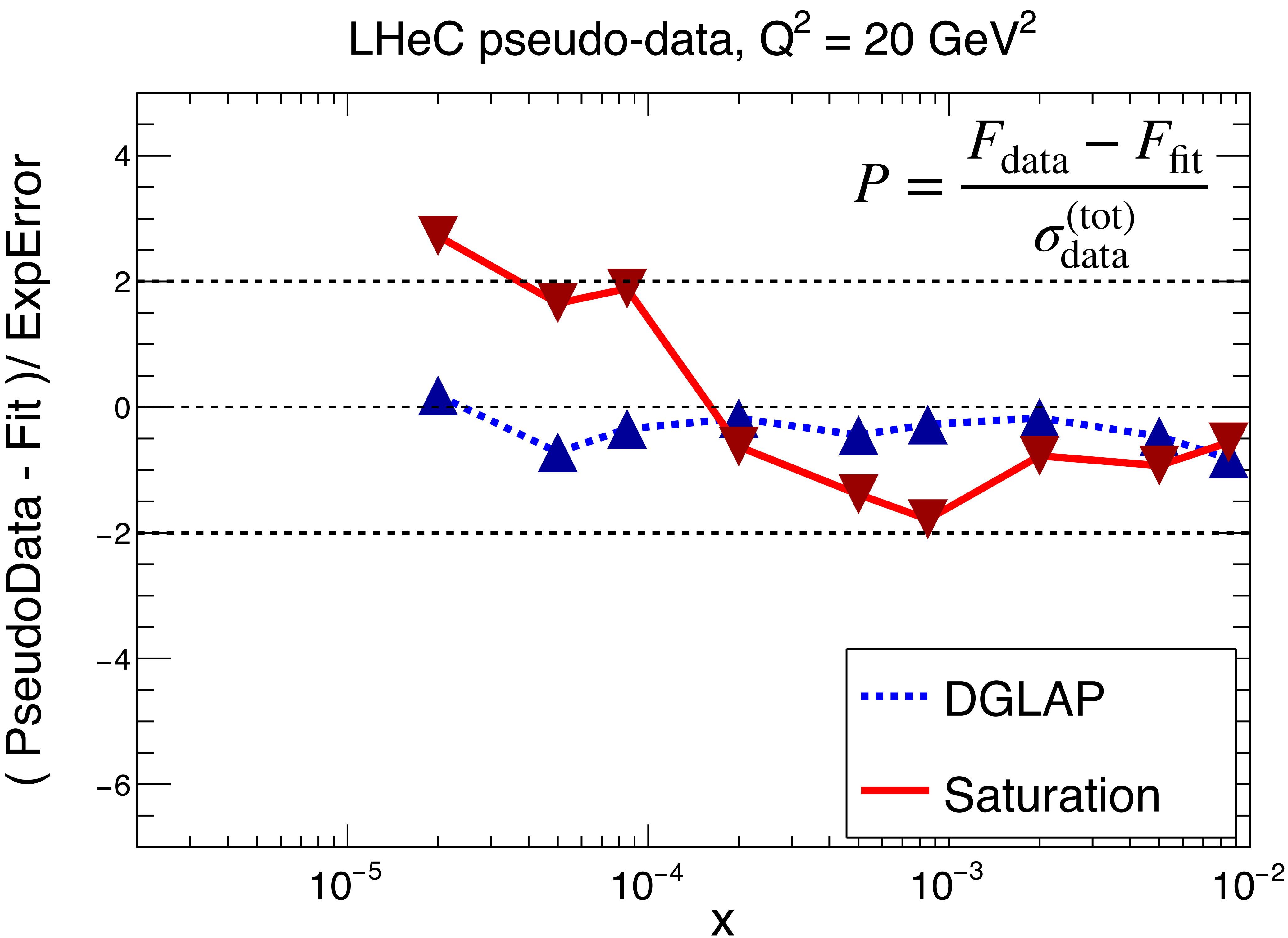

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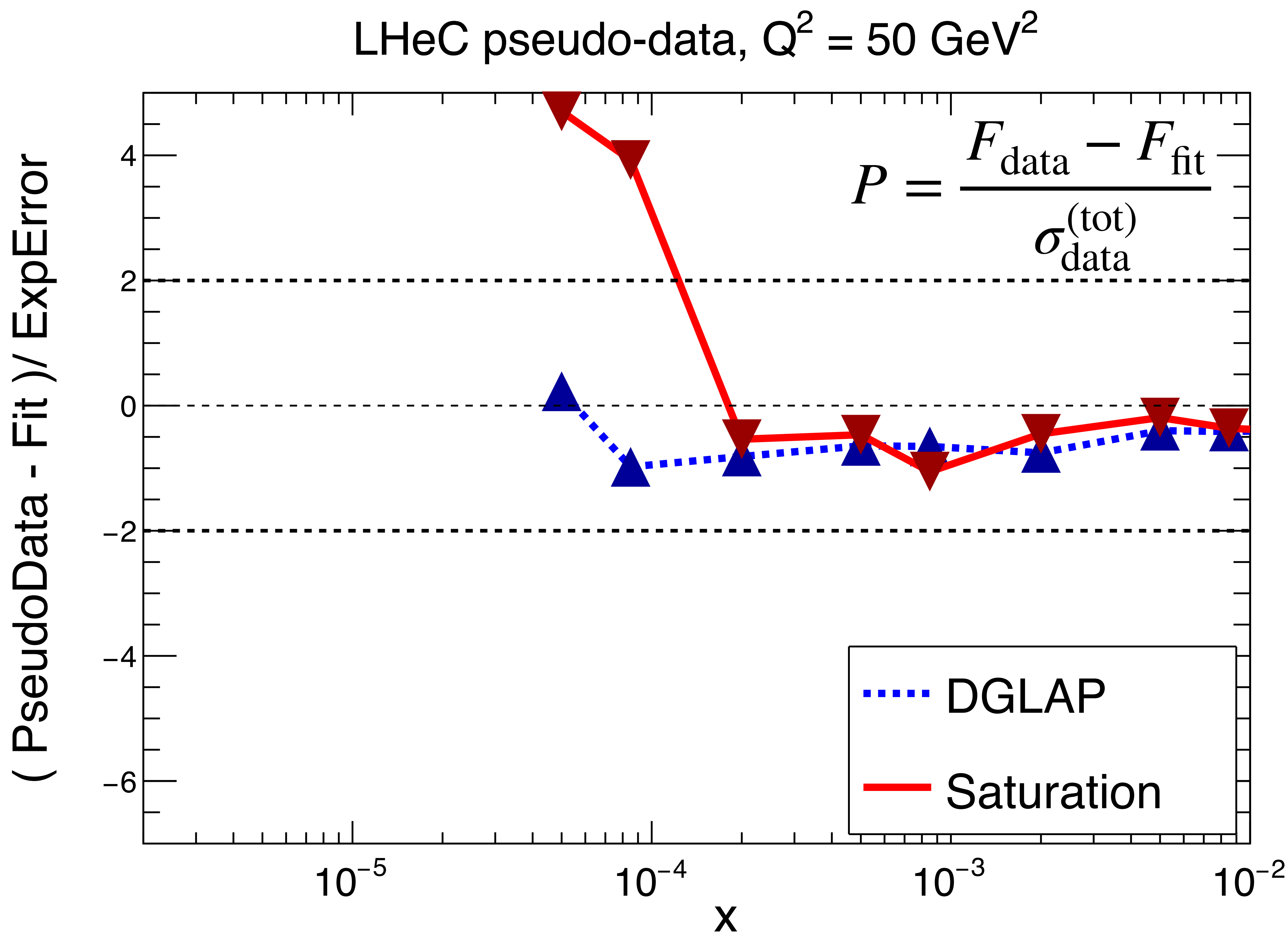

Disentangling saturation at LHeC

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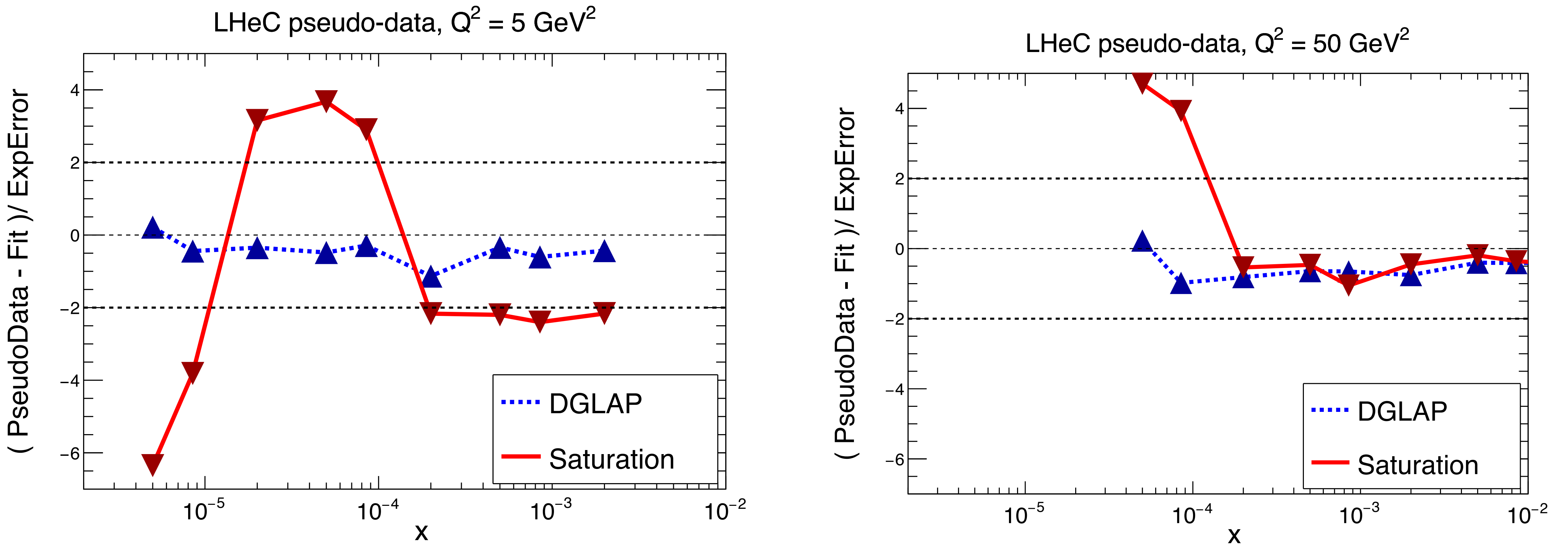
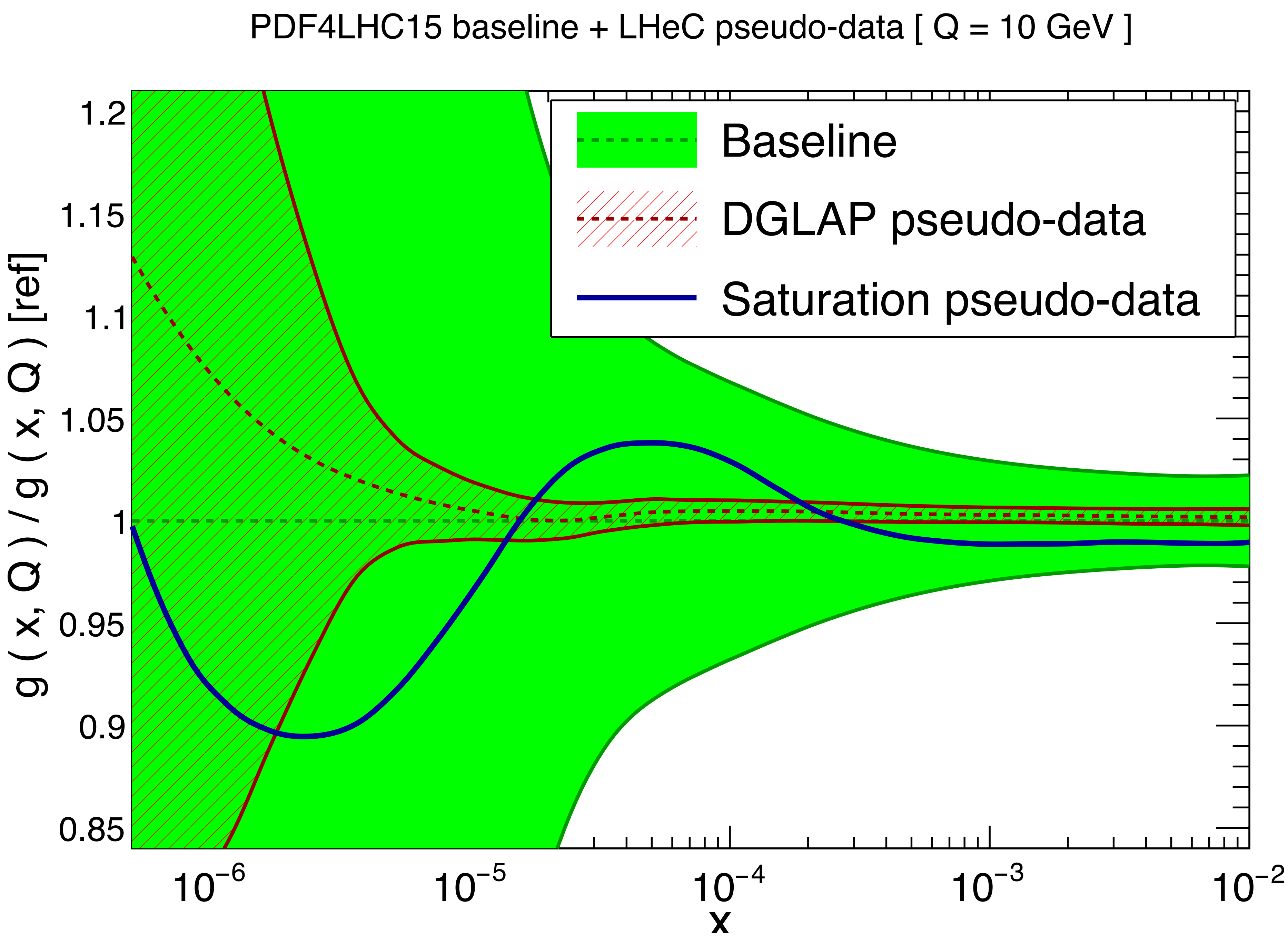


- DGLAP fit (profiling) **unable to reproduce the LHeC saturation pseudo-data** in all *Q* bins
- Different scaling in Q^2 between DGLAP and saturation most likely reason
- As much lever arm in Q^2 at small-*x* as possible crucial for these studies
- Our results indicate that, if non-linear saturation effects are present in the LHeC kinematics, it should be possible **to disentangle them**

Disentangling saturation at LHeC

Compute the fits based on DGLAP and Saturation pseudo-data



Tension between Saturation pseudo-data and DGLAP assumption used in fit

distorts PDFs >> PDF error: observable effect at the LHeC

Disentangling saturation at LHeC

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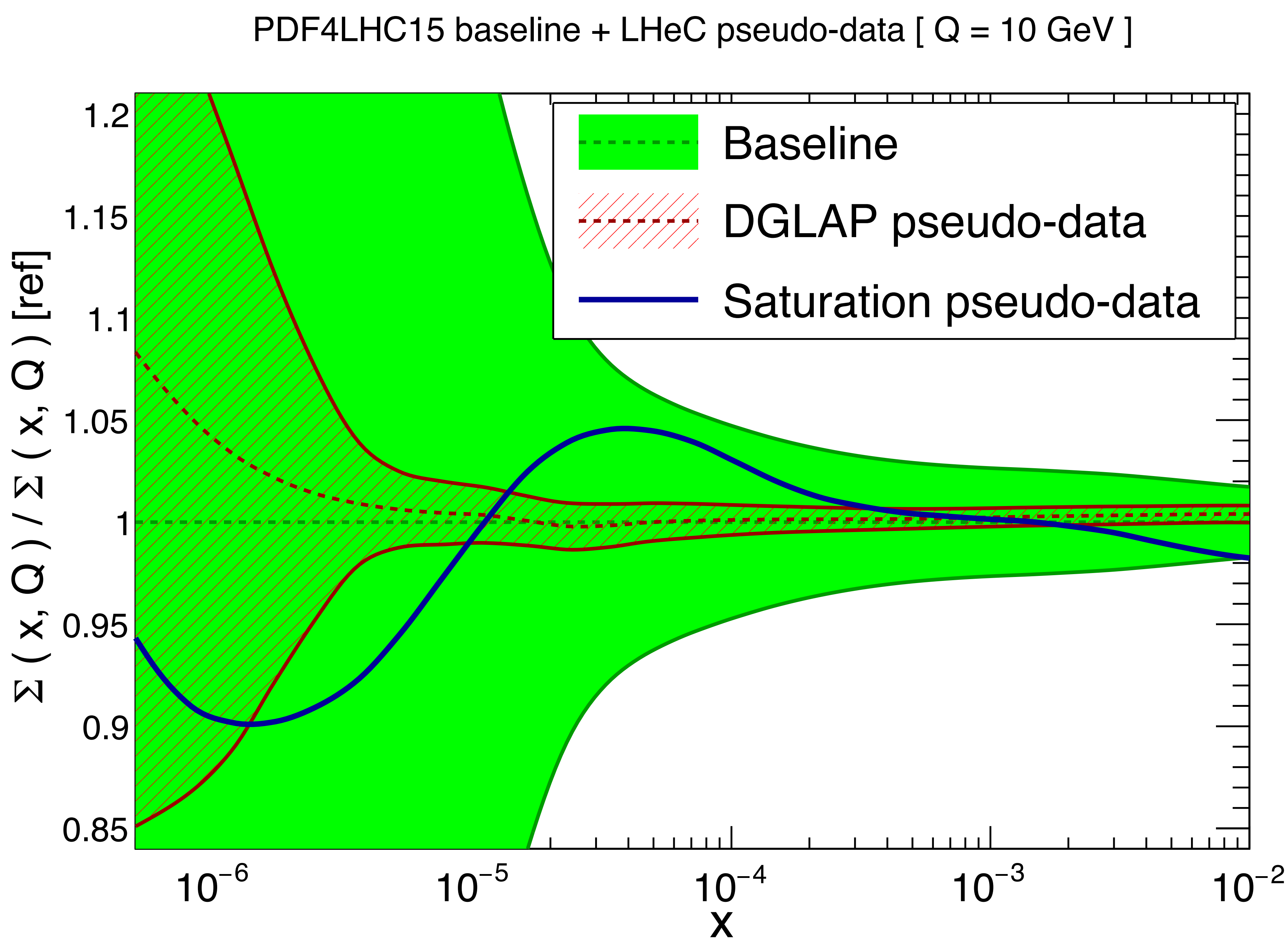
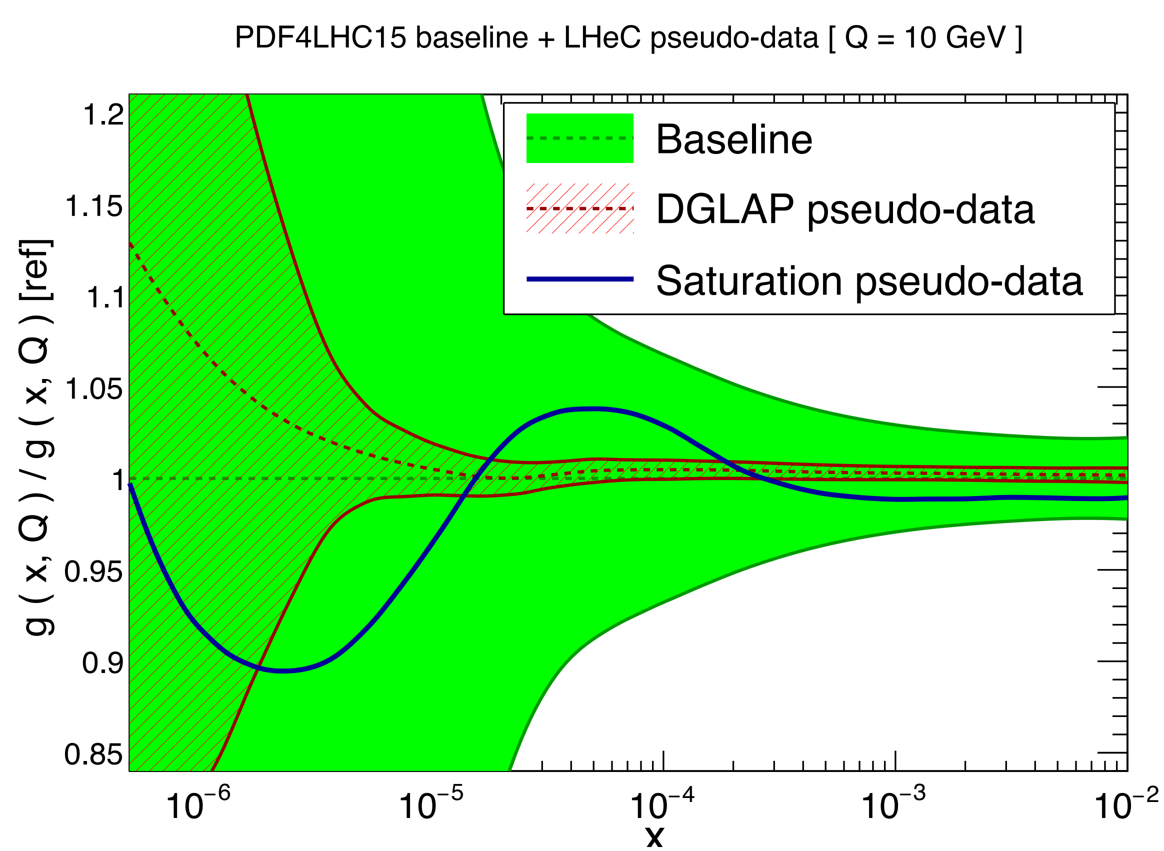
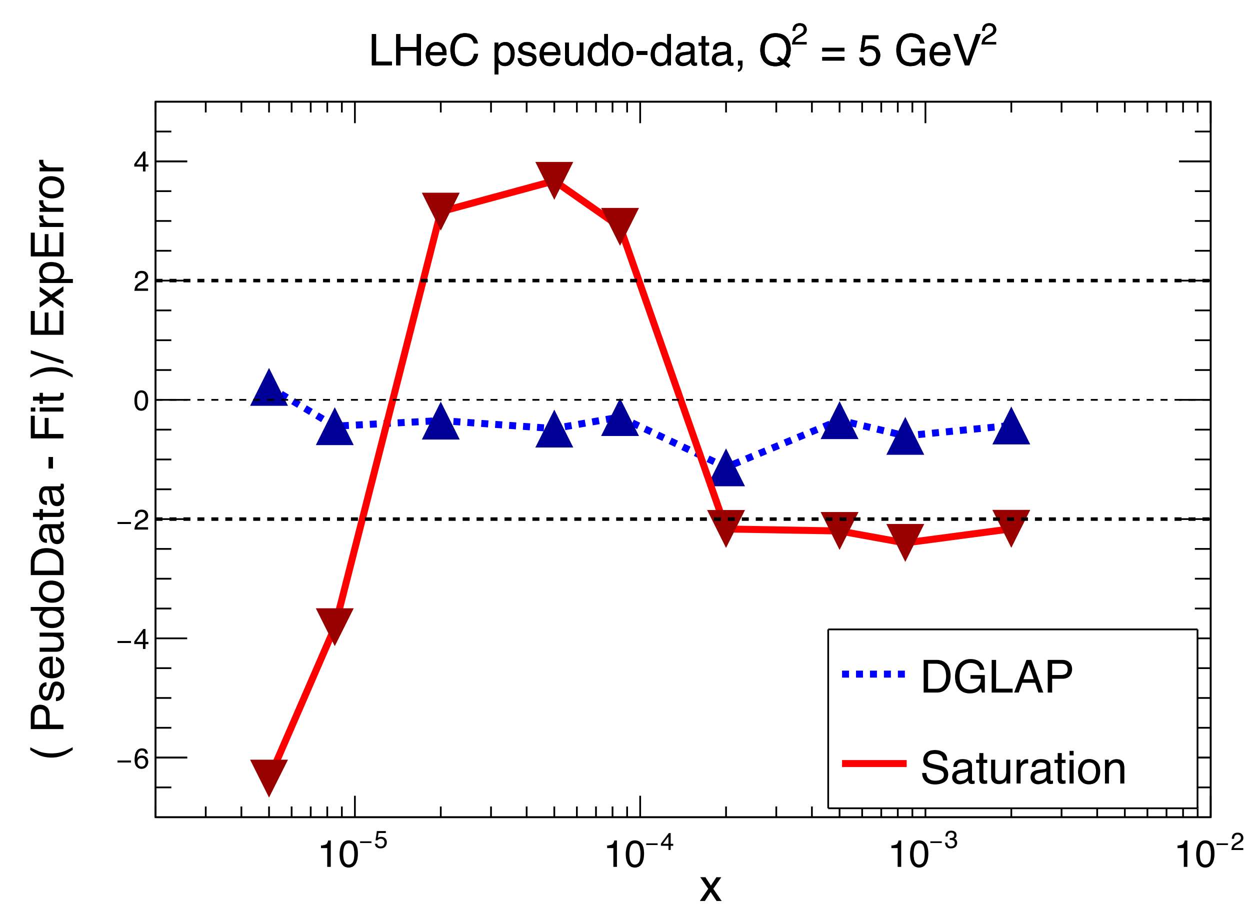


Tension between Saturation pseudo-data and DGLAP assumption used in fit **distorts PDFs >> PDF error**: observable effect at the LHeC

Summary

- If saturation (non-linear) dynamics are within the LHeC reach (and are well modelled by current models that describe HERA data) **they will be detected at the LHeC**
- Need to combine complementary estimators: **PDF distortion, fit quality**, and their dependence with the kinematics
- The use of a **state-of-the-art global PDF fit baseline** (incl small-x BFKL effects) will be crucial to unambiguously ascertain the presence or not of non-linear dynamics





PDF LHeC studies presented on 07/12/18

Strategy

Assess PDF impact of LHeC pseudo-data via three ***completely independent approaches***

LHeC pseudo-data

NNPDF fits

- *Same methodology as in the NNPDF3.1 fits*
- *8 independently parametrised PDFs*
- *Input data: either LHeC-only or LHeC+DIS*
- *Fitting methodology validated on closure tests*

NNPDF, arXiv:1710.05935

Hessian profiling

- *Same methodology as in our HL-LHC projections*
- *The PDF4LHC15 set is profiled with LHeC data, with and without HL-LHC constraints*
- *Assume that PDF4LHC15 flexible enough to describe LHeC data*

Abdul-Khalek, Bailey, Harland-Lang, Gao, JR, arXiv:1810.03639 + Work in progress

xFitter fits

- *LHeC-only fits produced with xFitter code*
- *LHAPDF grid provided by Claire/Gavin/FrancescoG*
- *Only experimental PDF errors (no VAR/MOD yet)*
- *Hessian method with* ***T=1****, as usual in HERAPDF*

Claire/Gavin/FraG + LHeC team

LHeC pseudo-data

- High-luminosity, high energy (E_p=7 TeV, E_e=60 GeV) **electron NC and CC reduced cross-sections** (ignore electron polarisation, not relevant for PDF studies
- High-luminosity, high energy (E_p=7 TeV, E_e=60 GeV) **positron NC and CC reduced cross-sections**
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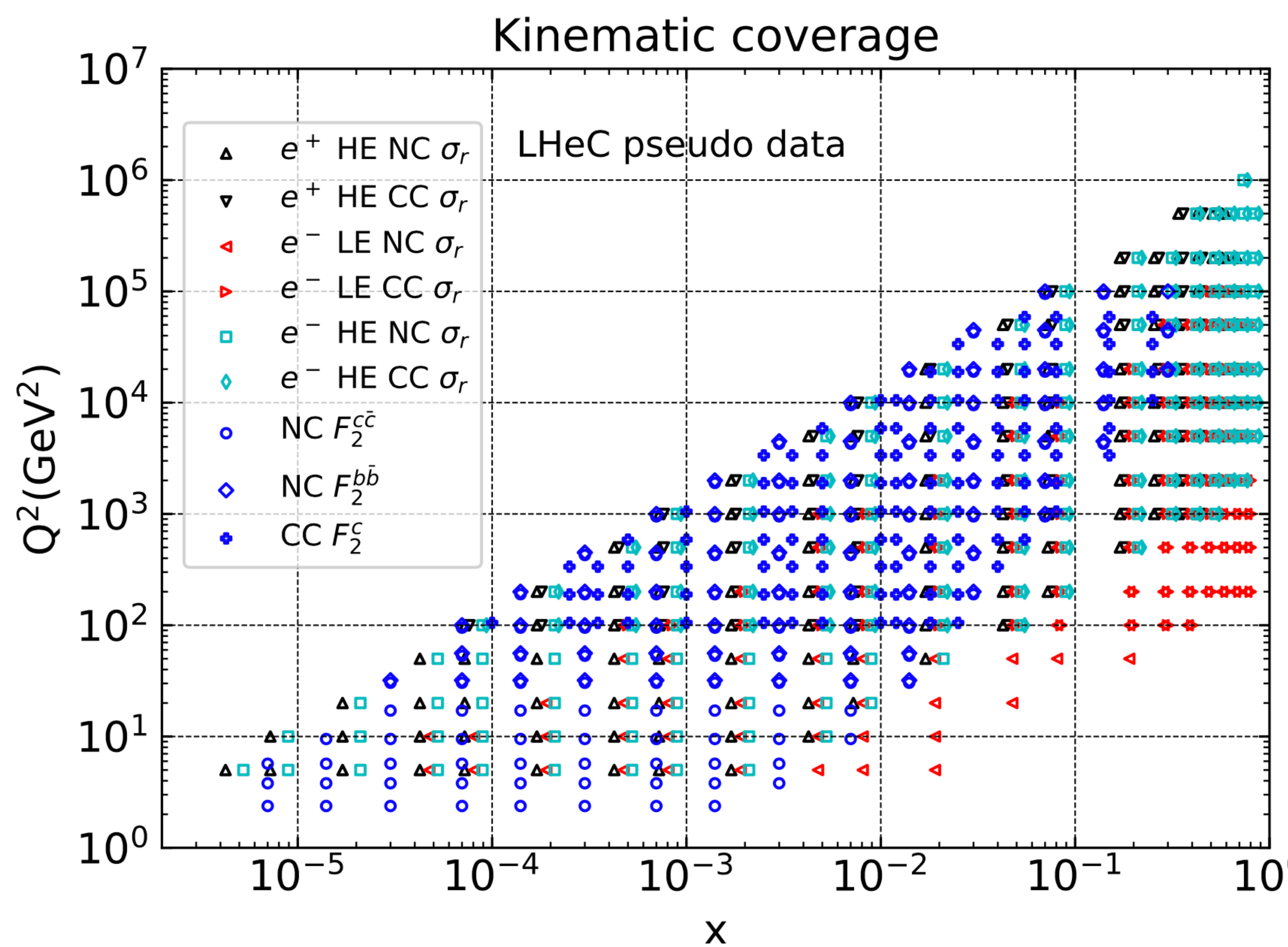
- **NC DIS charm and bottom** structure functions
- **CC strange production** structure functions (the dimuon process)



New

- Investigate impact of **correlating LHeC systematic uncertainties**

Hessian profiling

- **Hessian Profiling** is based on the minimisation of the figure of merit:

$$\chi^2(\beta_{\rm exp},\beta_{\rm th}) = \frac{1}{\left(\delta^{\rm exp}_{{\rm tot},i}\right)^2}\sum_{i=1}^{N_{\rm dat}}\left(\sigma_i^{\rm exp} + \sum_j \Gamma_{ij}^{\rm exp}\beta_{j,{\rm exp}} - \sigma_i^{\rm th} + \sum_k \Gamma_{ik}^{\rm th}\,\beta_{k,{\rm th}}\right)^2 + \sum_j \beta_{j,{\rm exp}}^2 + T^2\sum_k \beta_{k,{\rm th}}^2$$

Exp data nuisance parameters — ***Hessian PDF nuisance parameters*** — ***Effective Tolerance***

- To avoid the need of introducing a correlation model for the pseudo-data, we **rescale the total experimental systematic error** by a suitable factor f_{corr}

$$\delta^{\rm exp}_{{\rm tot},i} \equiv \left(\left(\delta^{\rm exp}_{{\rm stat},i}\right)^2 + \left(f_{\rm corr}\times f_{\rm red}\times \delta^{\rm exp}_{{\rm sys},i}\right)^2\right)^{1/2}$$

$$\delta^{\rm exp}_{{\rm stat},i} = \left(f_{\rm acc}\times N_{{\rm ev},i}\right)^{-1/2}$$

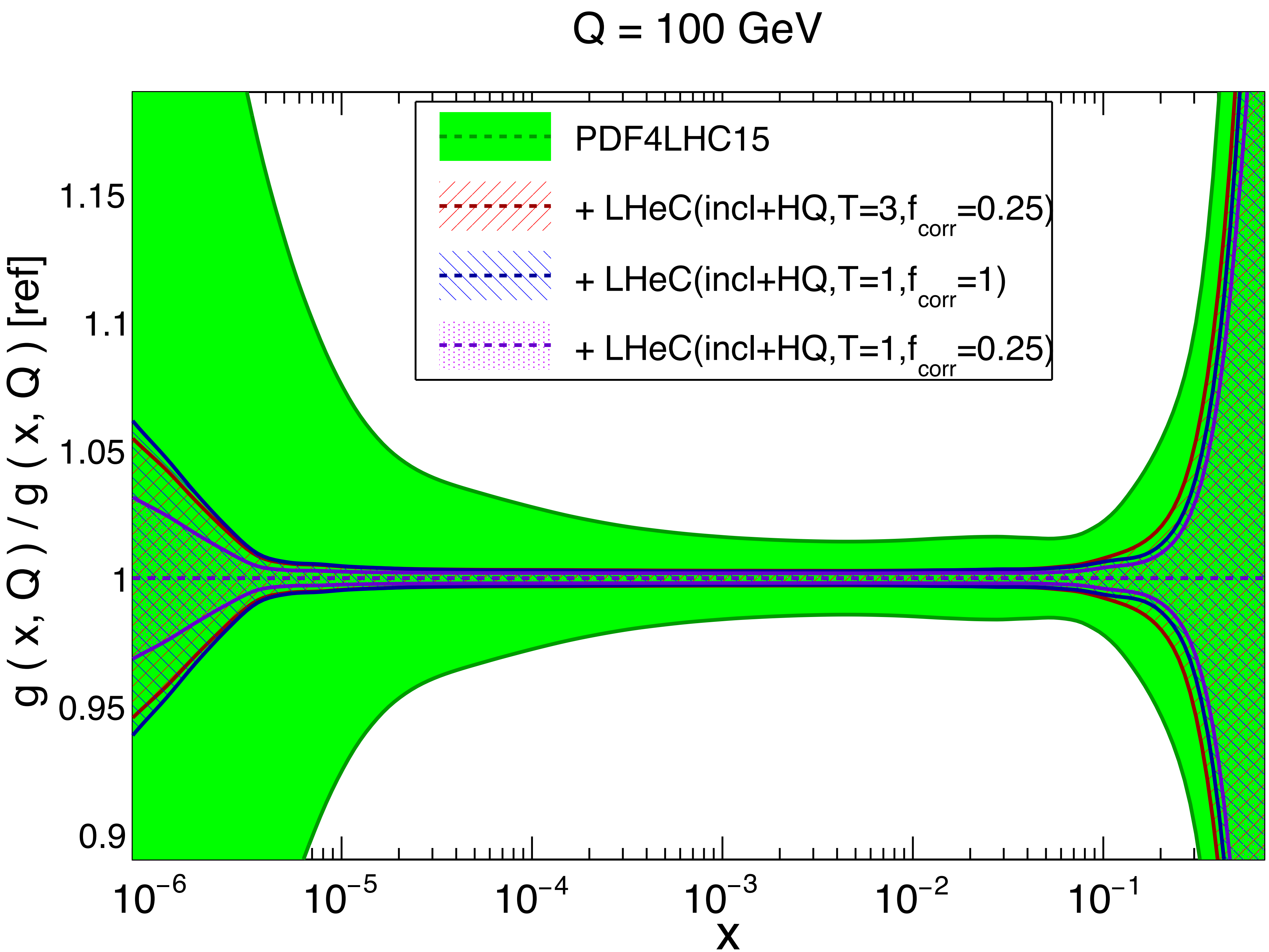
- Results for the LHeC data from our side so far obtained for $f_{corr}=1$, now we investigate other options

- We have also tried to implement the full correlation model

- The final HERA combination had more that **150 independent sources** of correlated systematics!

Impact of f_{corr}

Assess impact of f_{corr} for ***T=3*** and for ***T=1***



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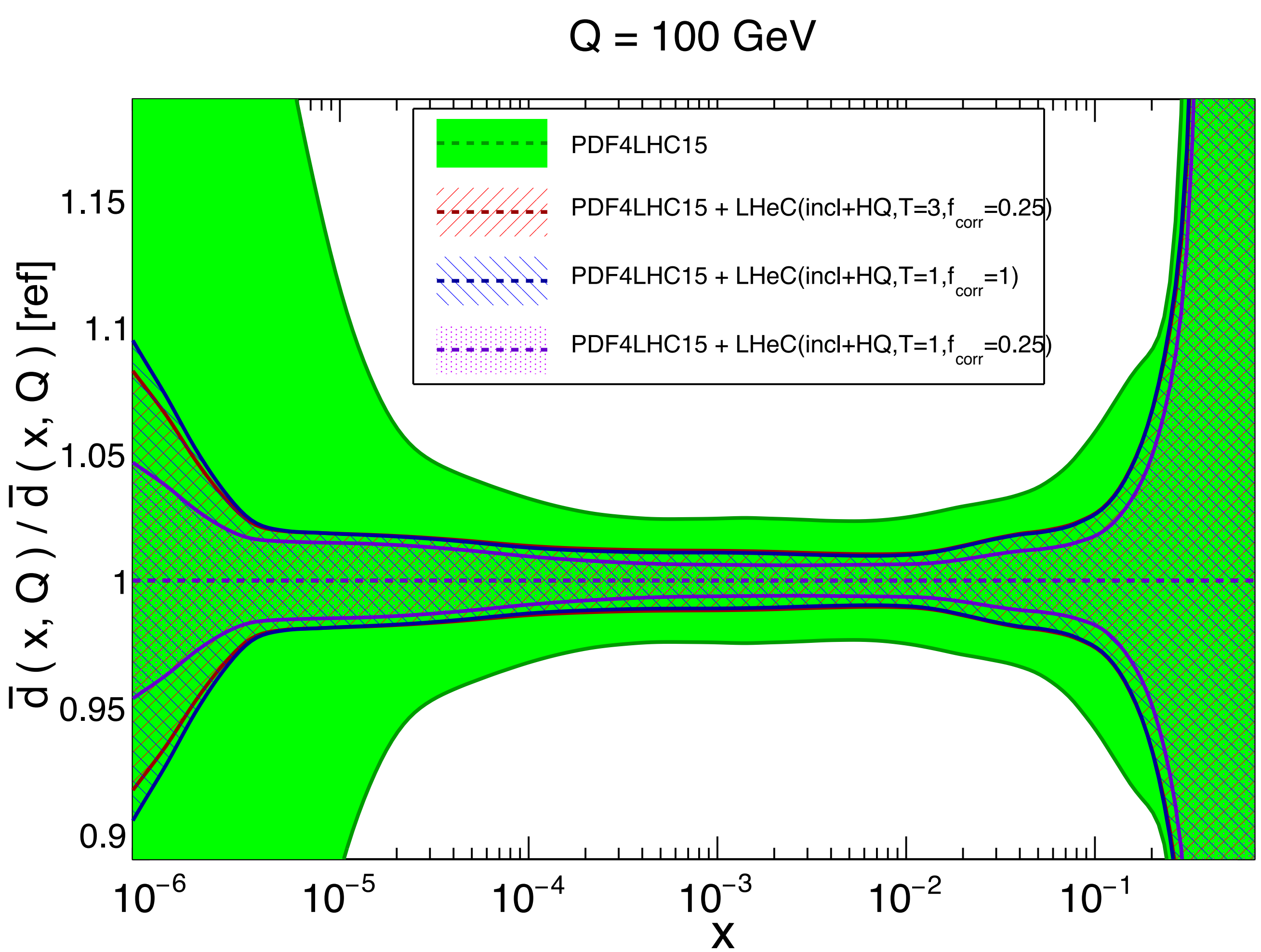
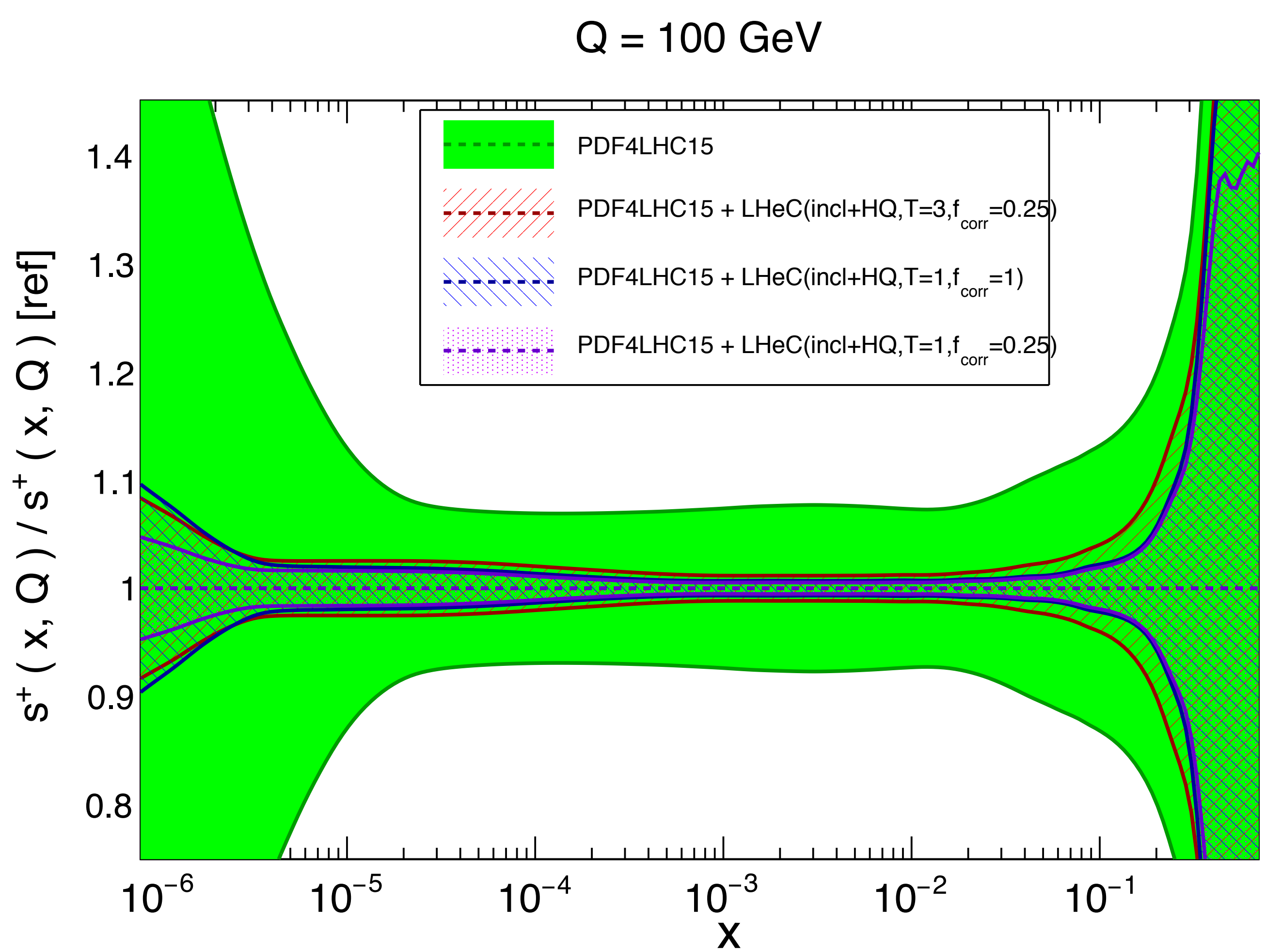
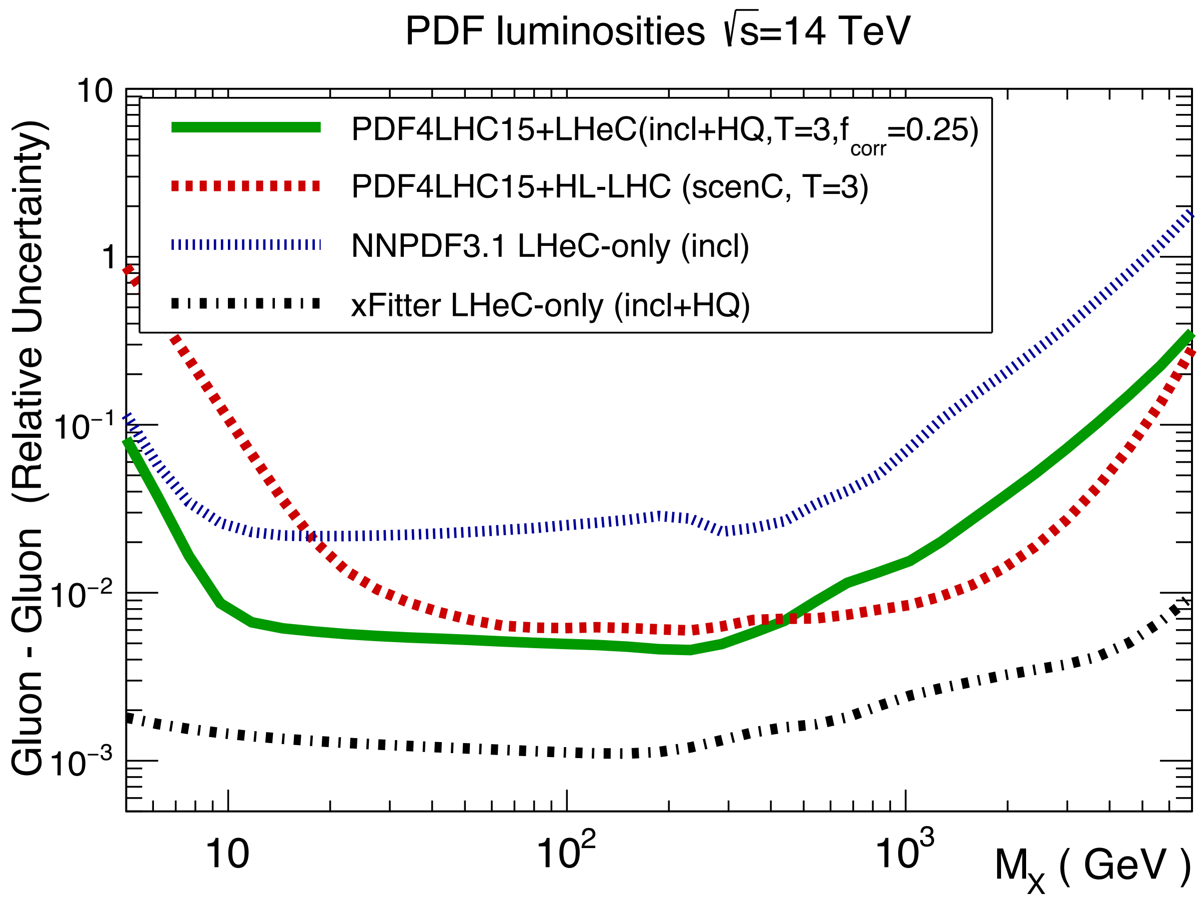
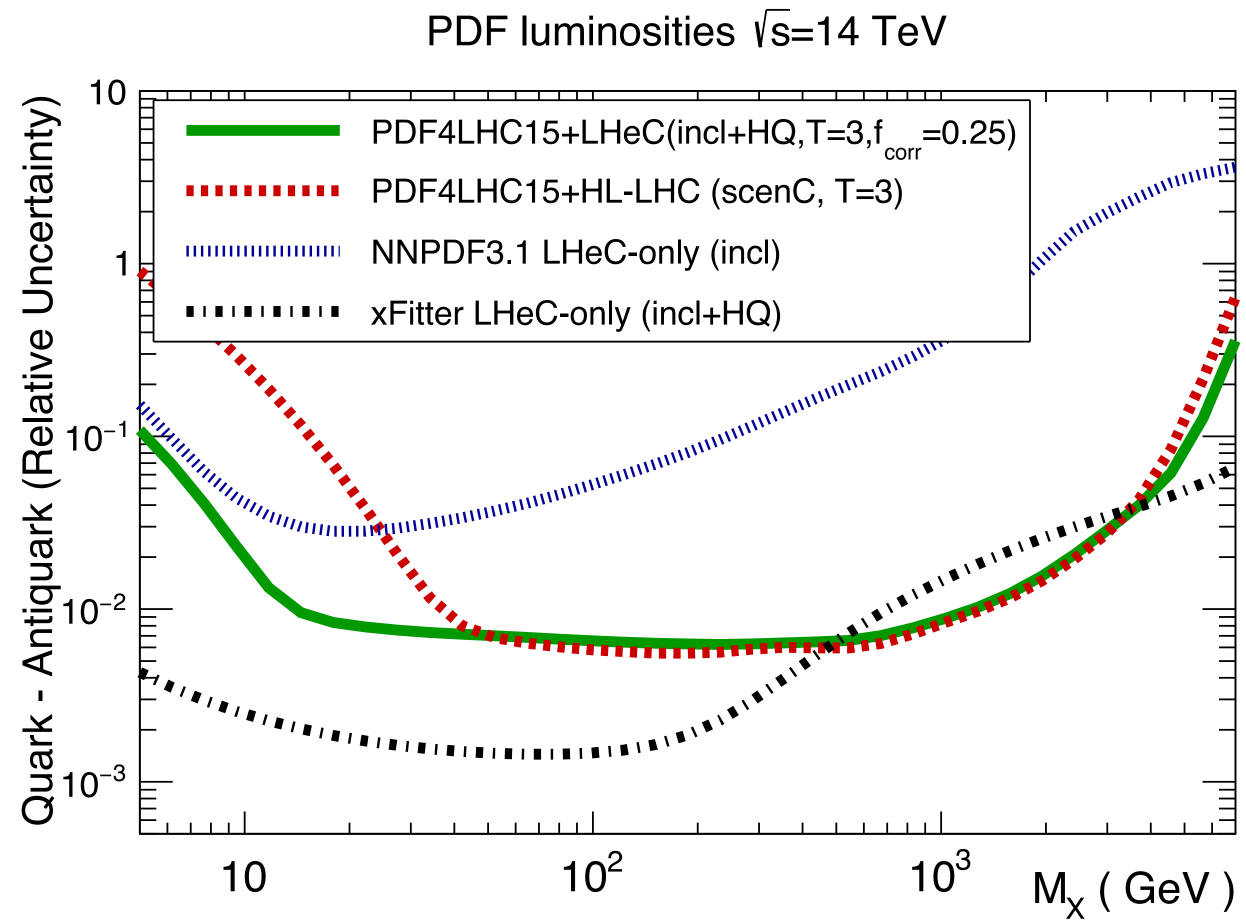


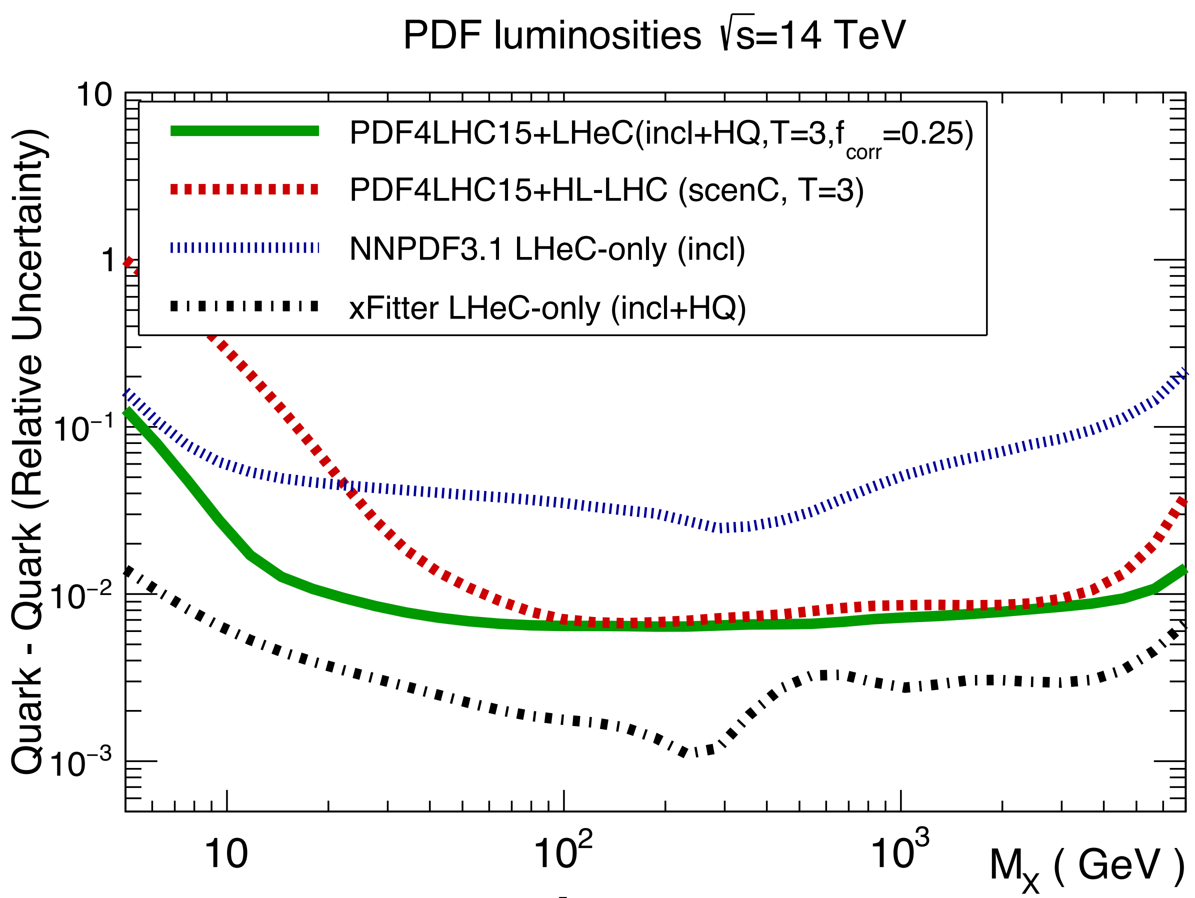


Even with optimistic value of $\boldsymbol{f_{corr} = 0.25}$, for ***T=3*** the PDF error reduction is at most comparable to adding statistical and systematic errors in quadrature and use ***T=1***

LHeC and HL-LHC

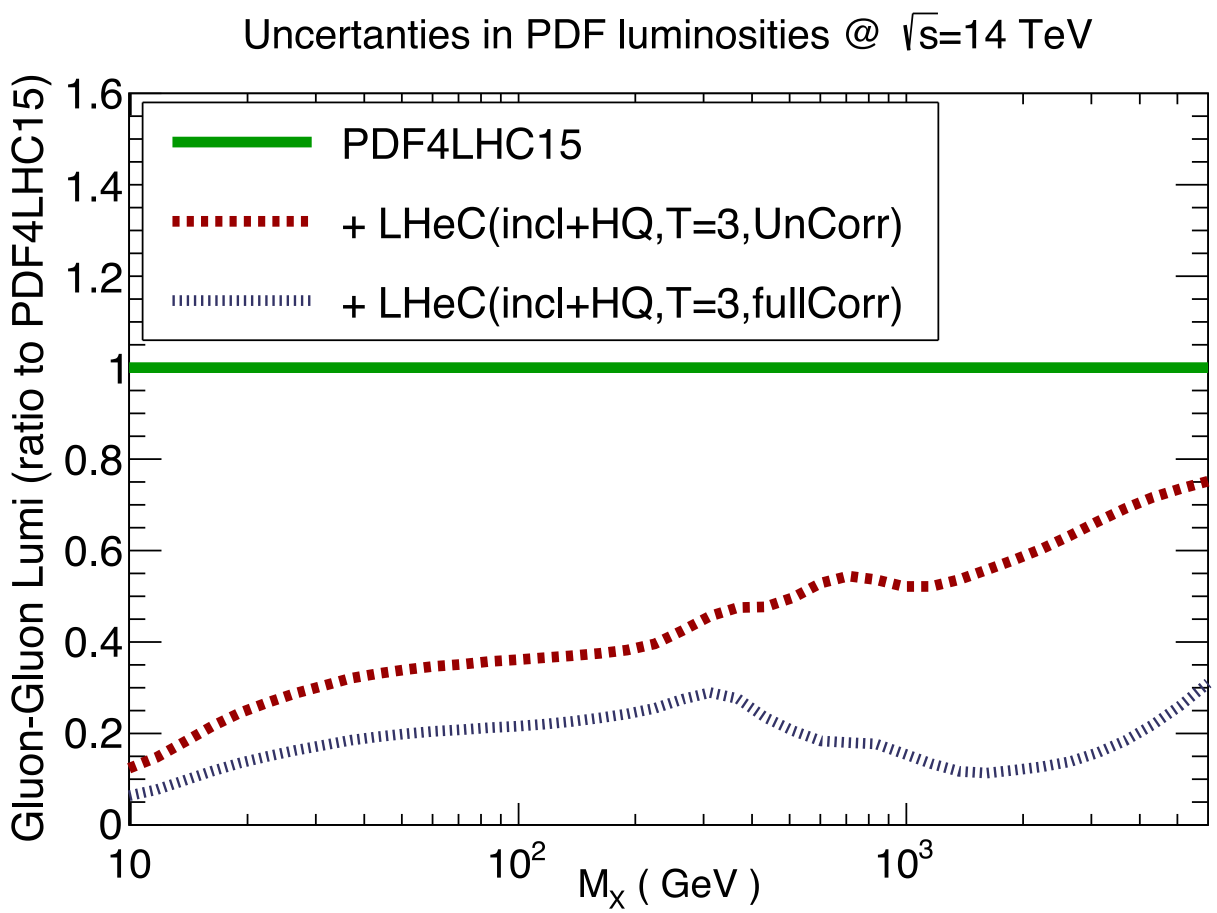


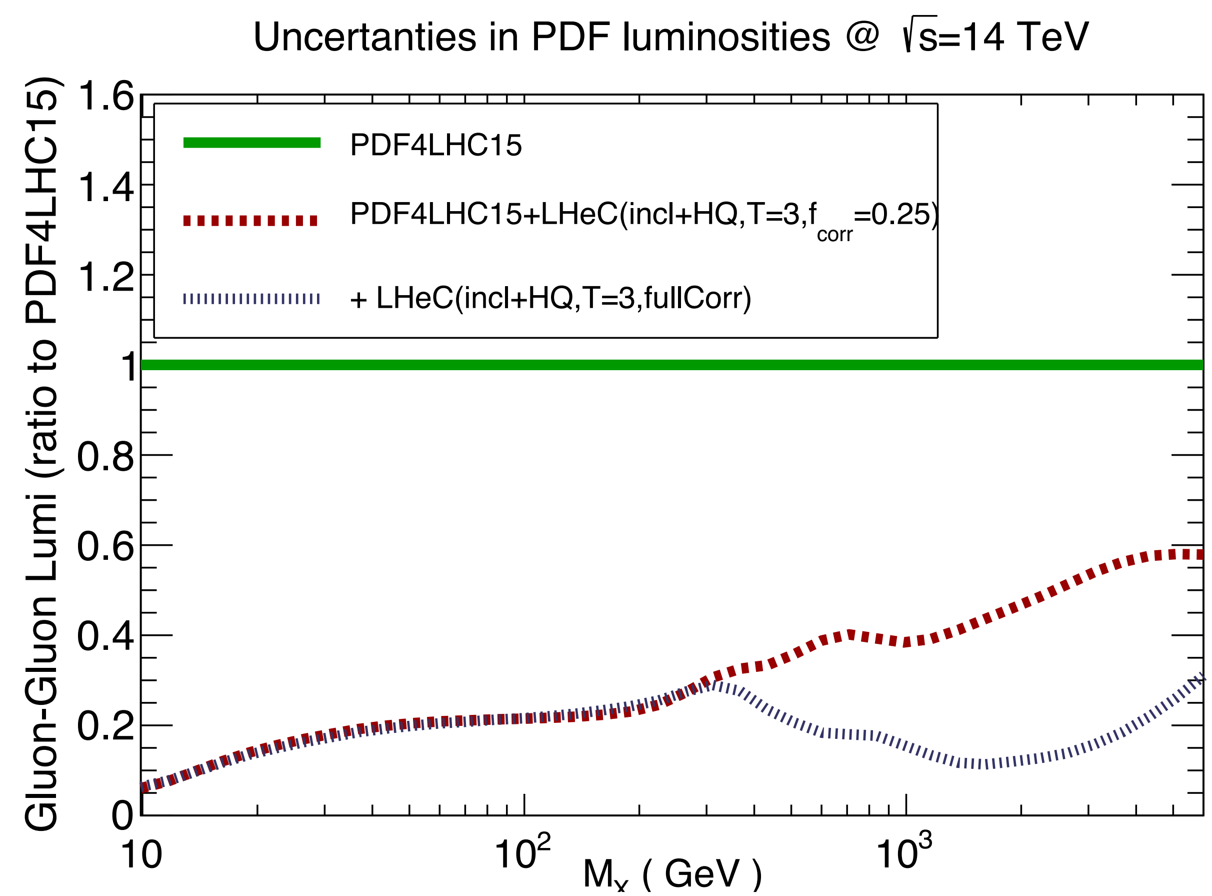


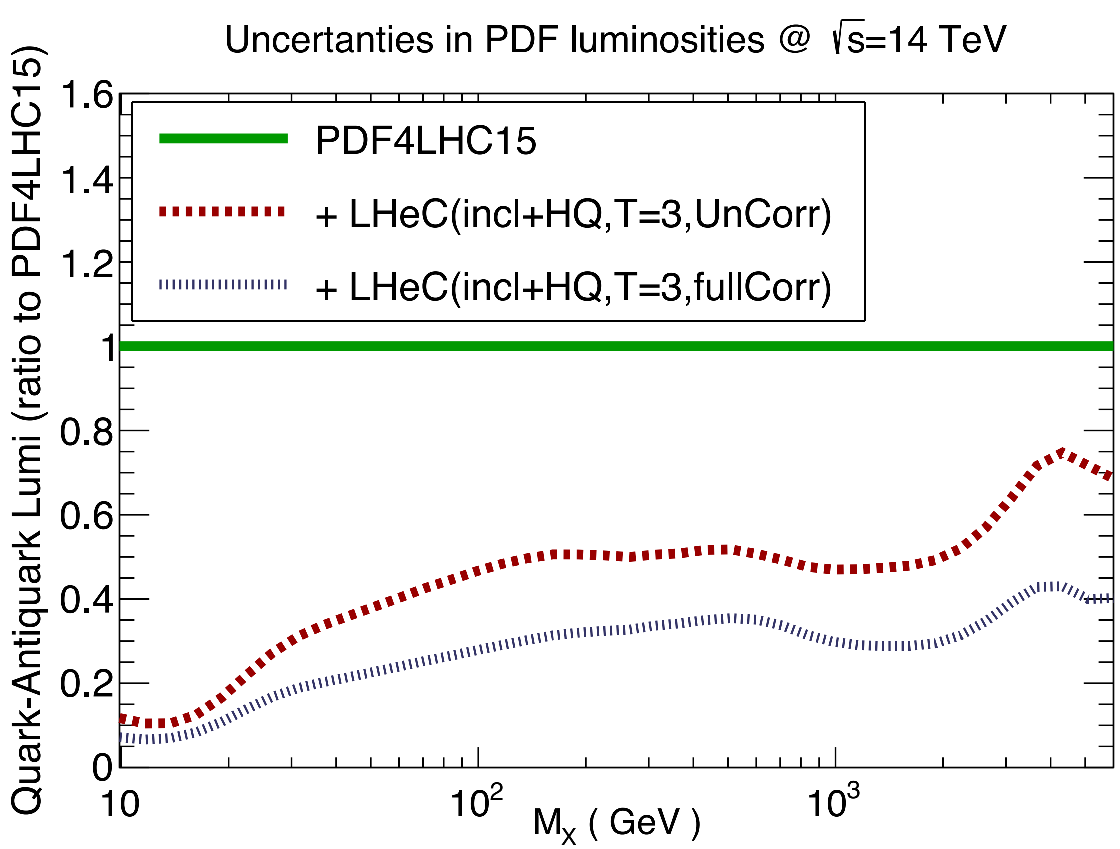


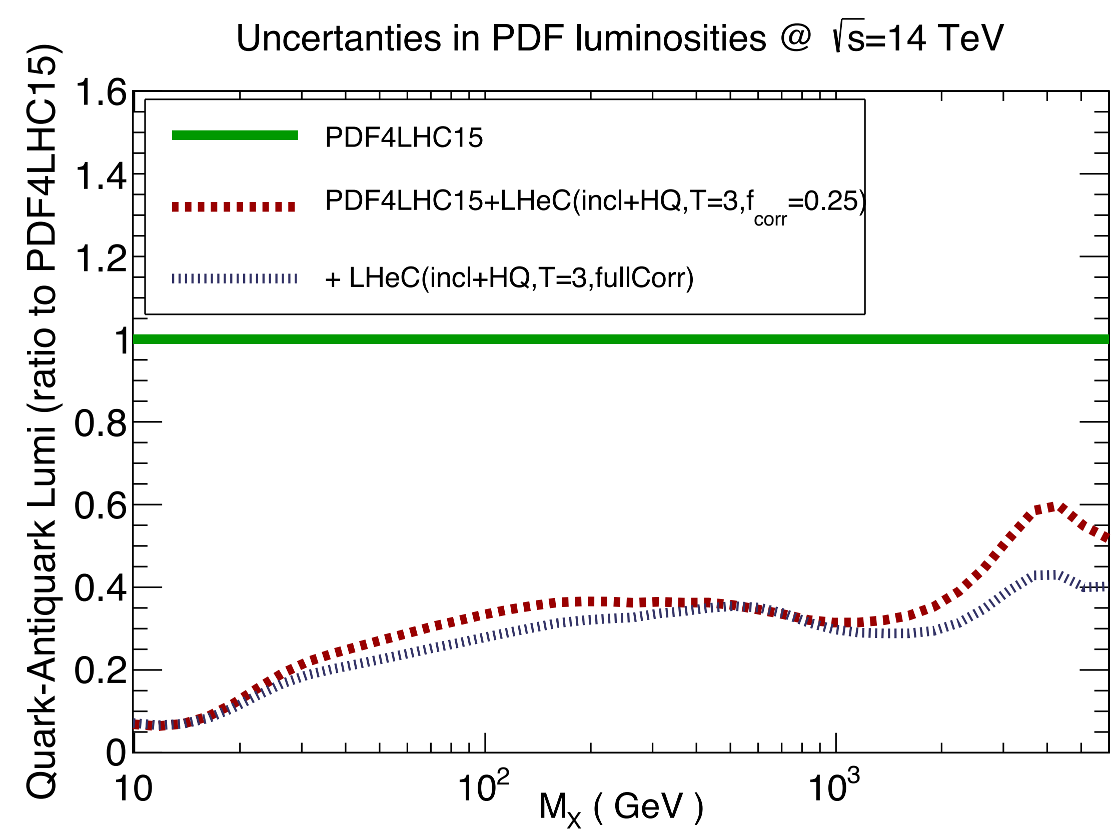
- Take-away message: **comparable PDF sensitivity** of LHeC and HL-LHC
- The picture that emerges is of **full complementarity** rather than opposition
- **LHeC-only fits** not competitive with global fits

Assume all LHeC syst fully correlated









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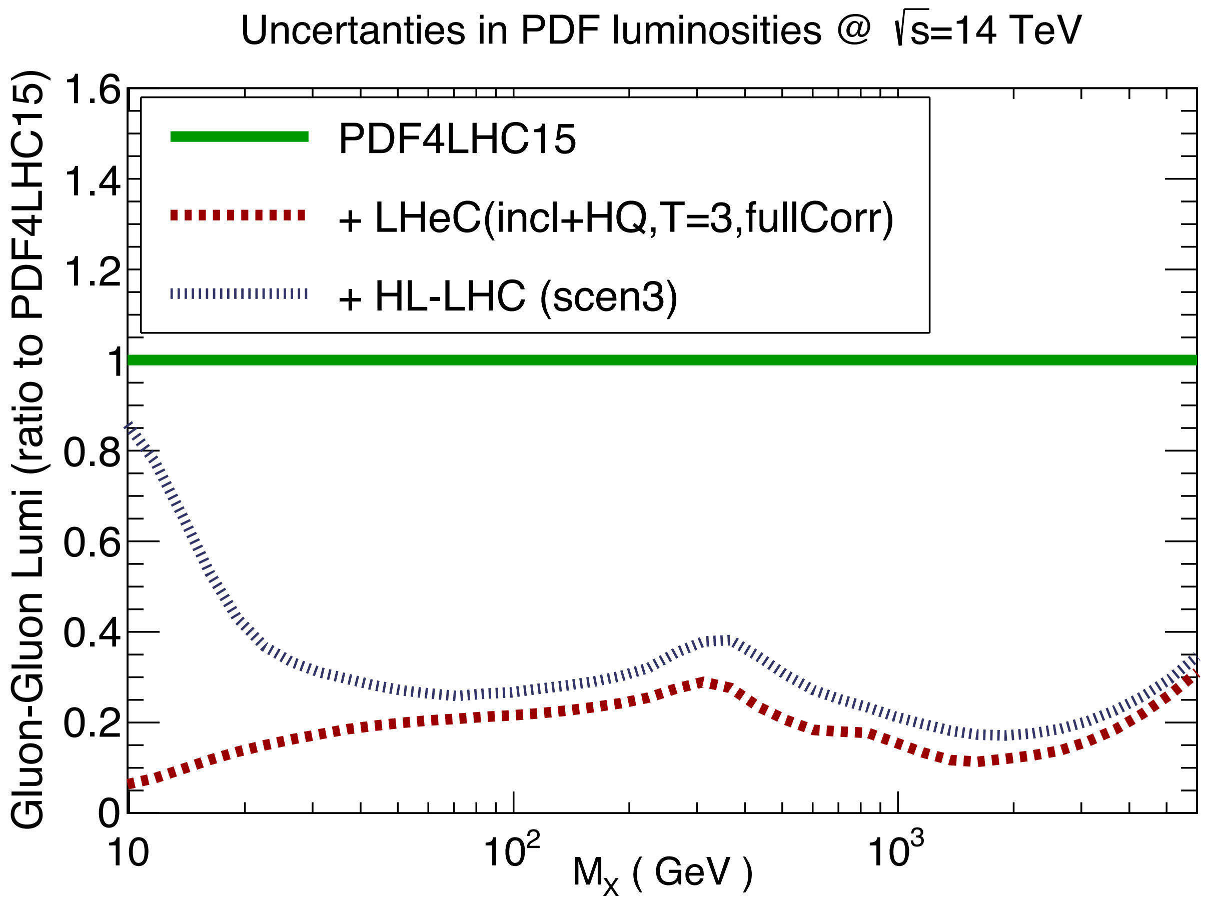

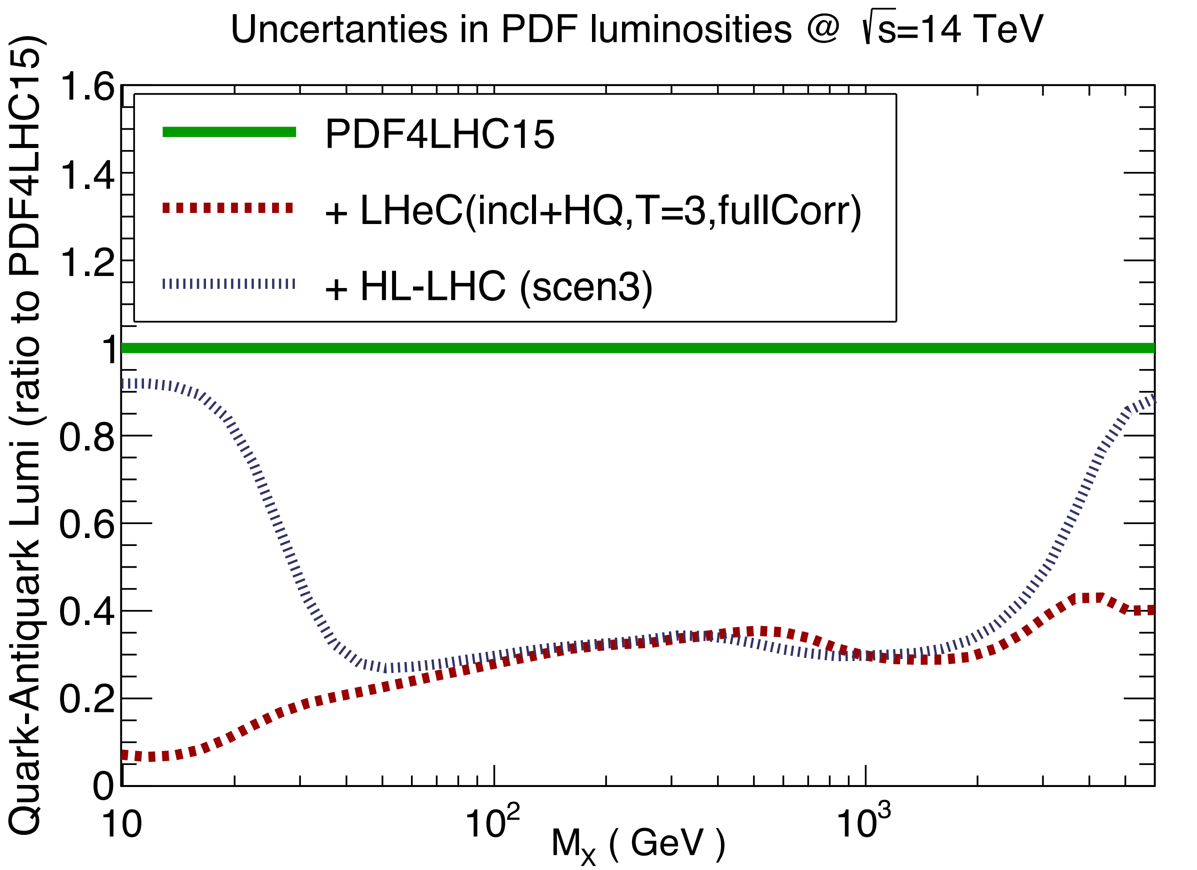

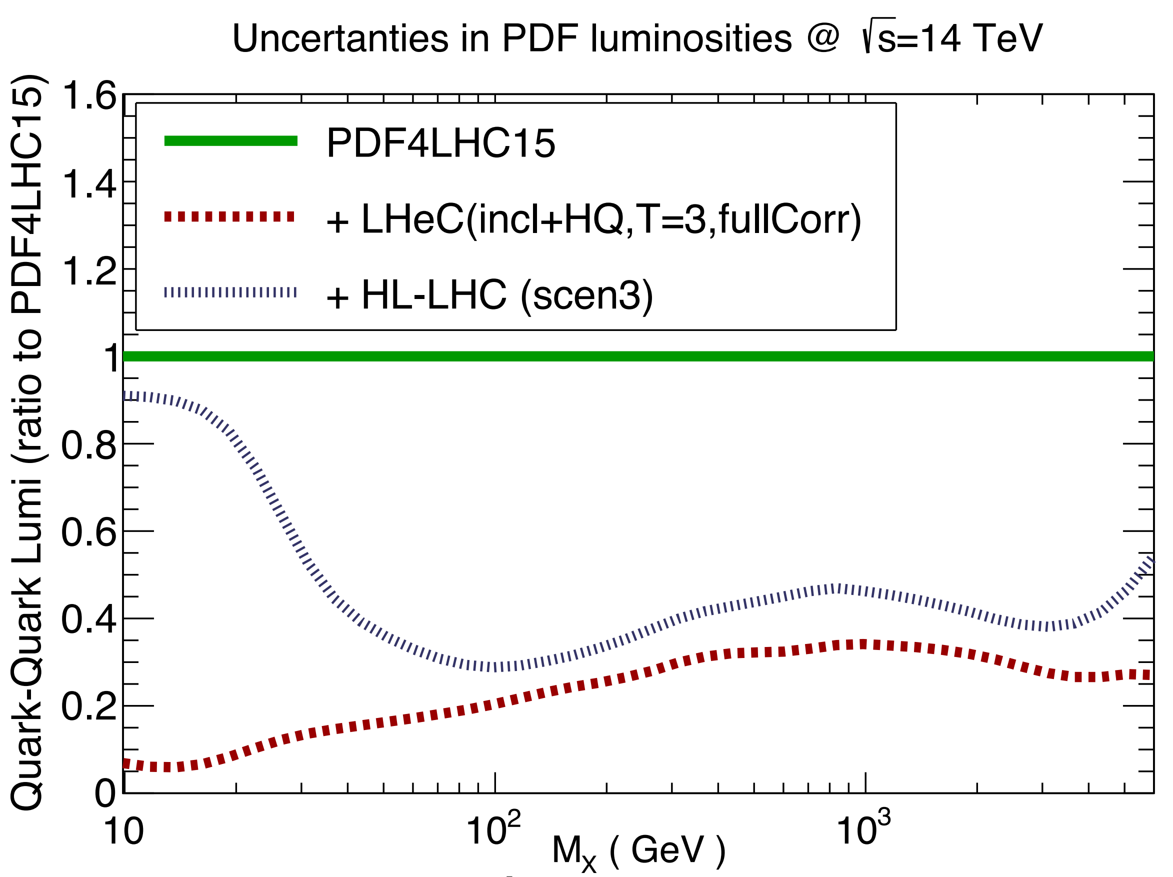

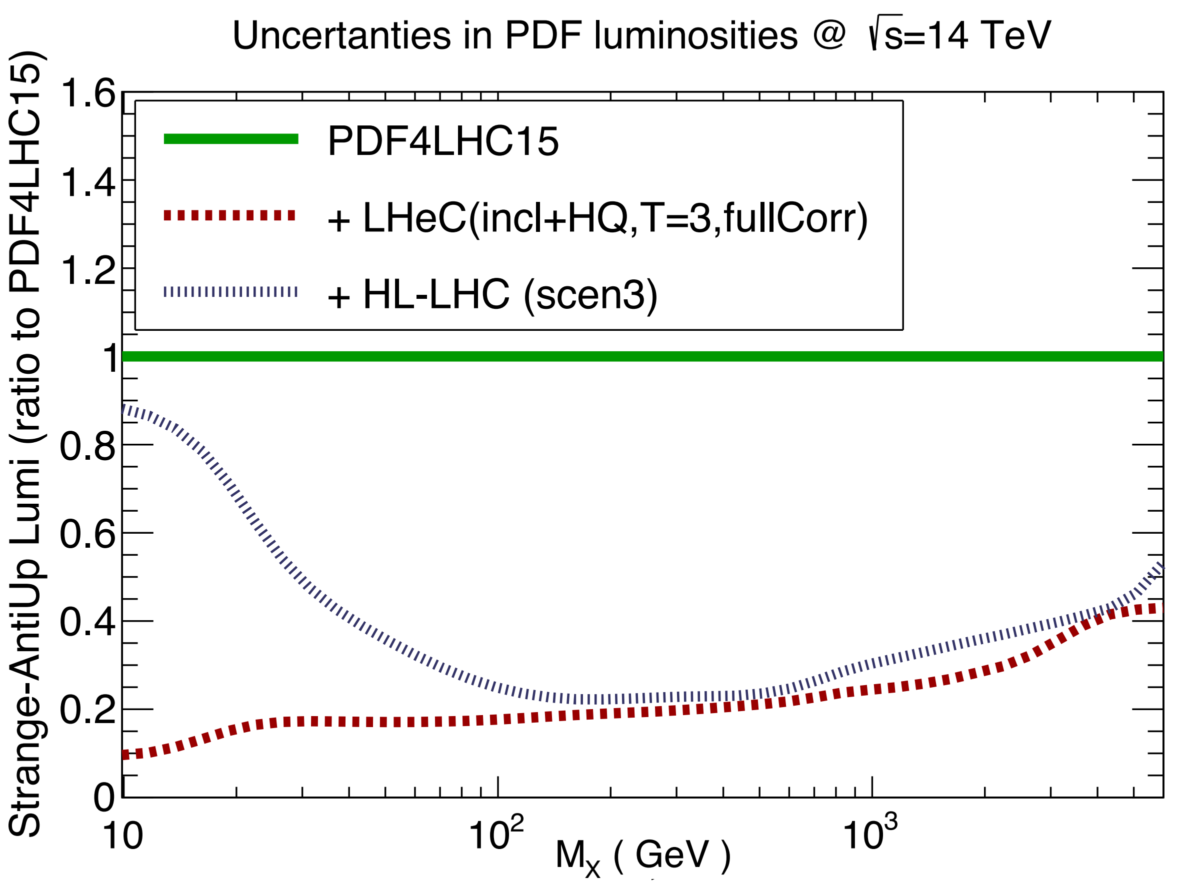

Summary v3

- The combination of the **constraints from the LHeC and HL-LHC** is the best option for precision LHC phenomenology and searches.

- The above statement holds only in the context of **global PDF analyses**, LHeC-only fits are not competitive

- This is **not** by any means a negative message, on the contrary, I see it as providing a **very strong case for the LHeC**

- How to proceed from here?

PDF LHeC studies presented on 20/11/18

Strategy

Assess PDF impact of LHeC pseudo-data via three ***completely independent approaches***

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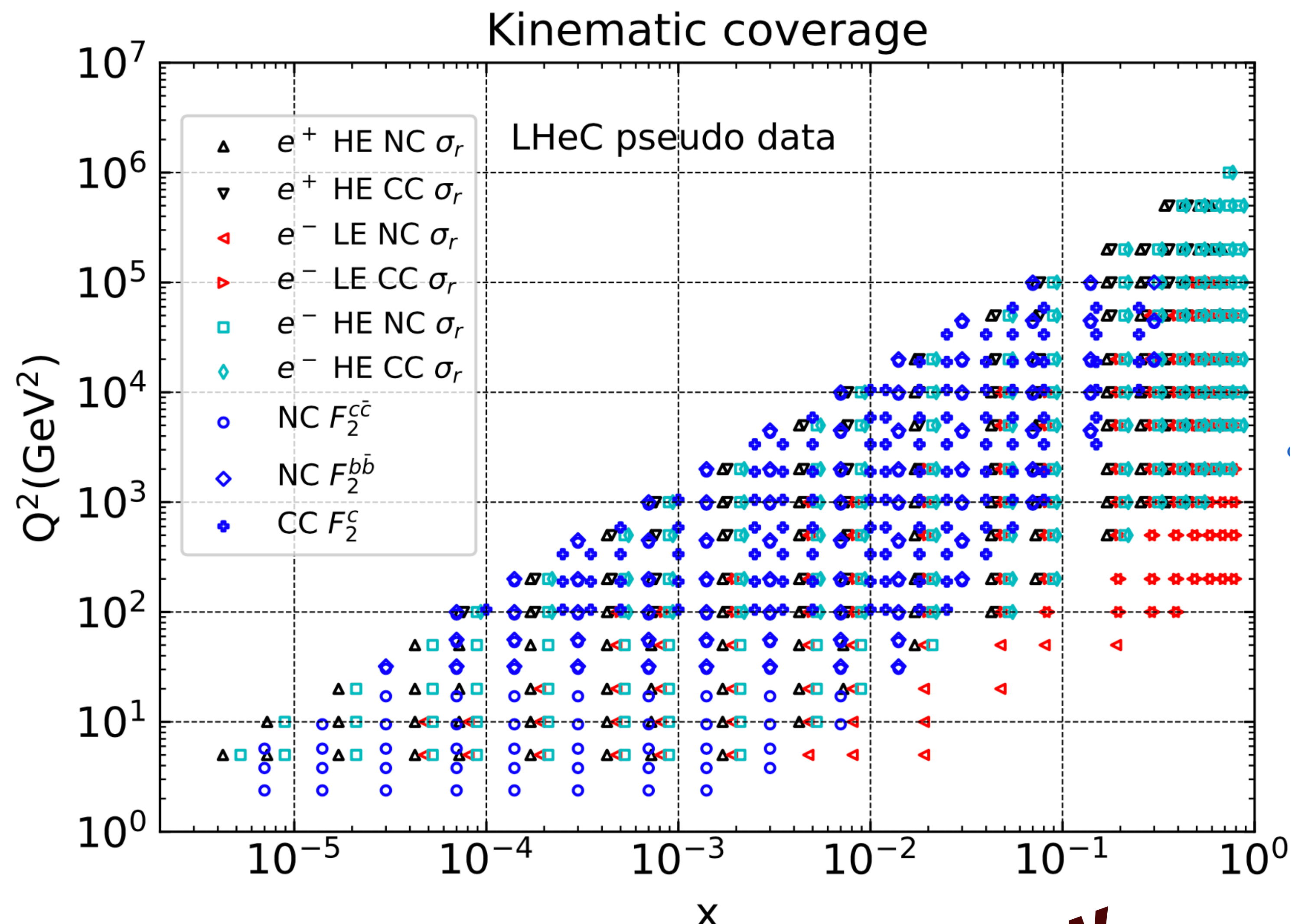
New

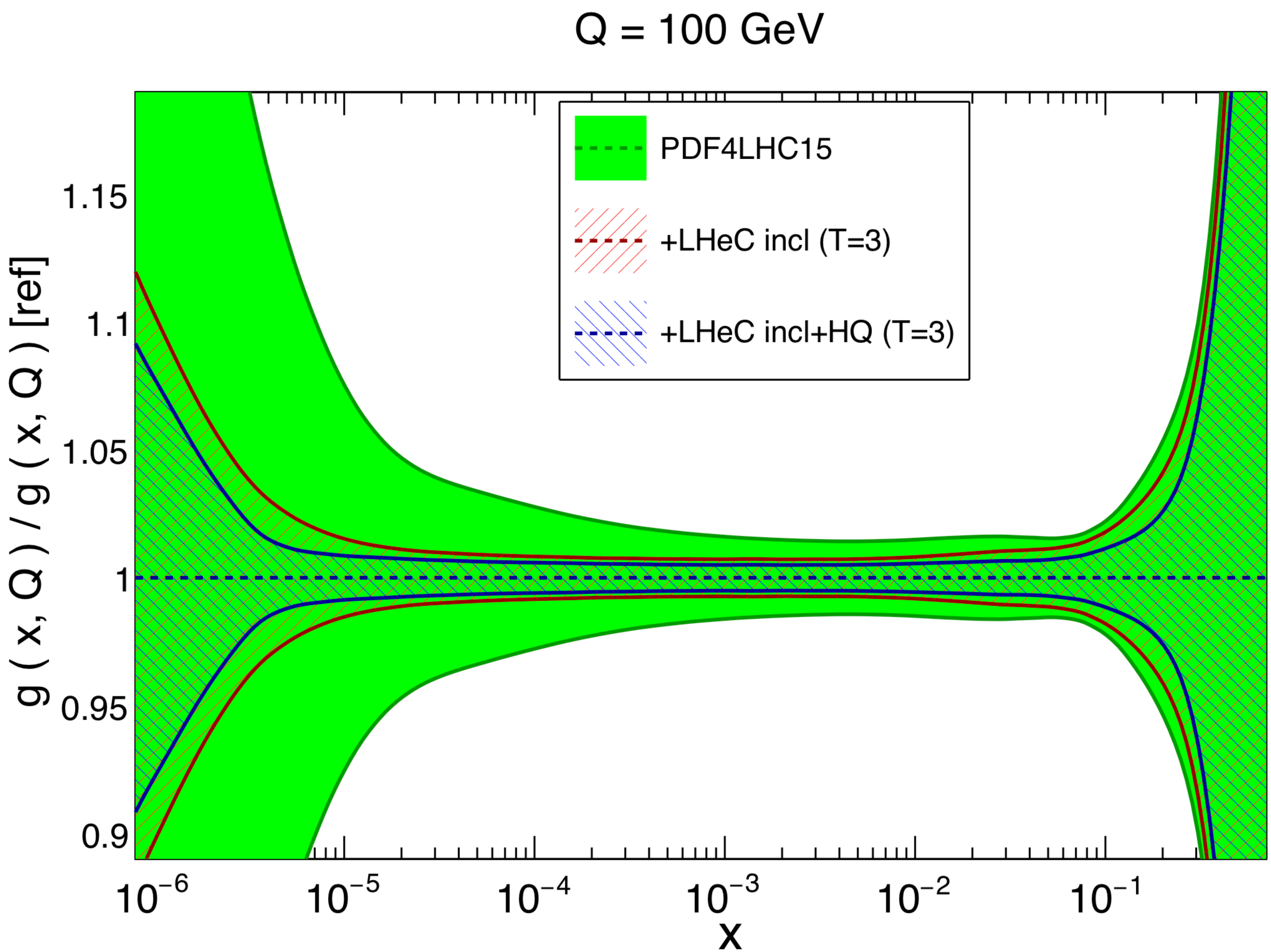


New

- Investigate how results vary if ***T=1*** is used instead of ***T=3*** used for the HL-LHC case
- Assess dependence on **Q_{min} cut**
- Profiling of **HERAPDF2.0** with the LHeC pseudo-data (in progress)

Impact of the heavy quark data

Compare impact of LHeC pseudo-data **with and without the heavy quark SFs**



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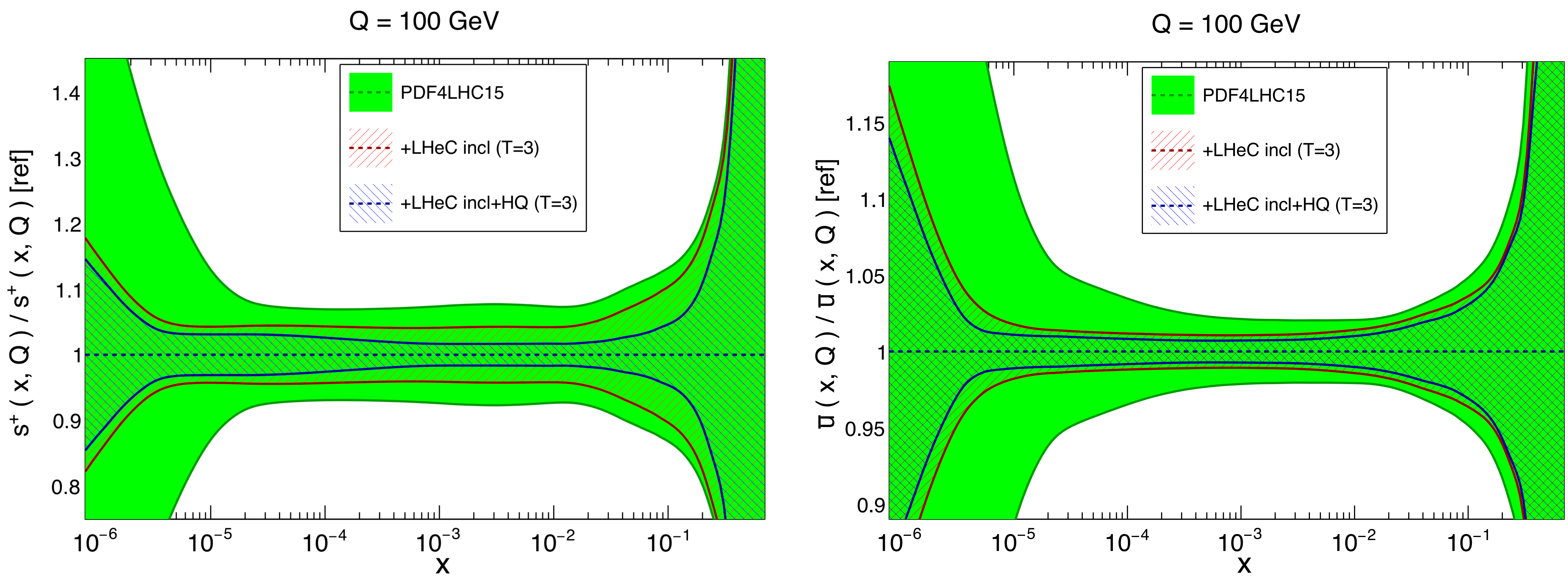


- Heavy quark SFs provide **additional moderate information** on gluon and antiquarks
- Most impact is for the **strange PDF for $10^{-4} < x < 0.2$** from the CC strange SFs
- **Large-x PDF uncertainties** not modified from the semi-inclusive data

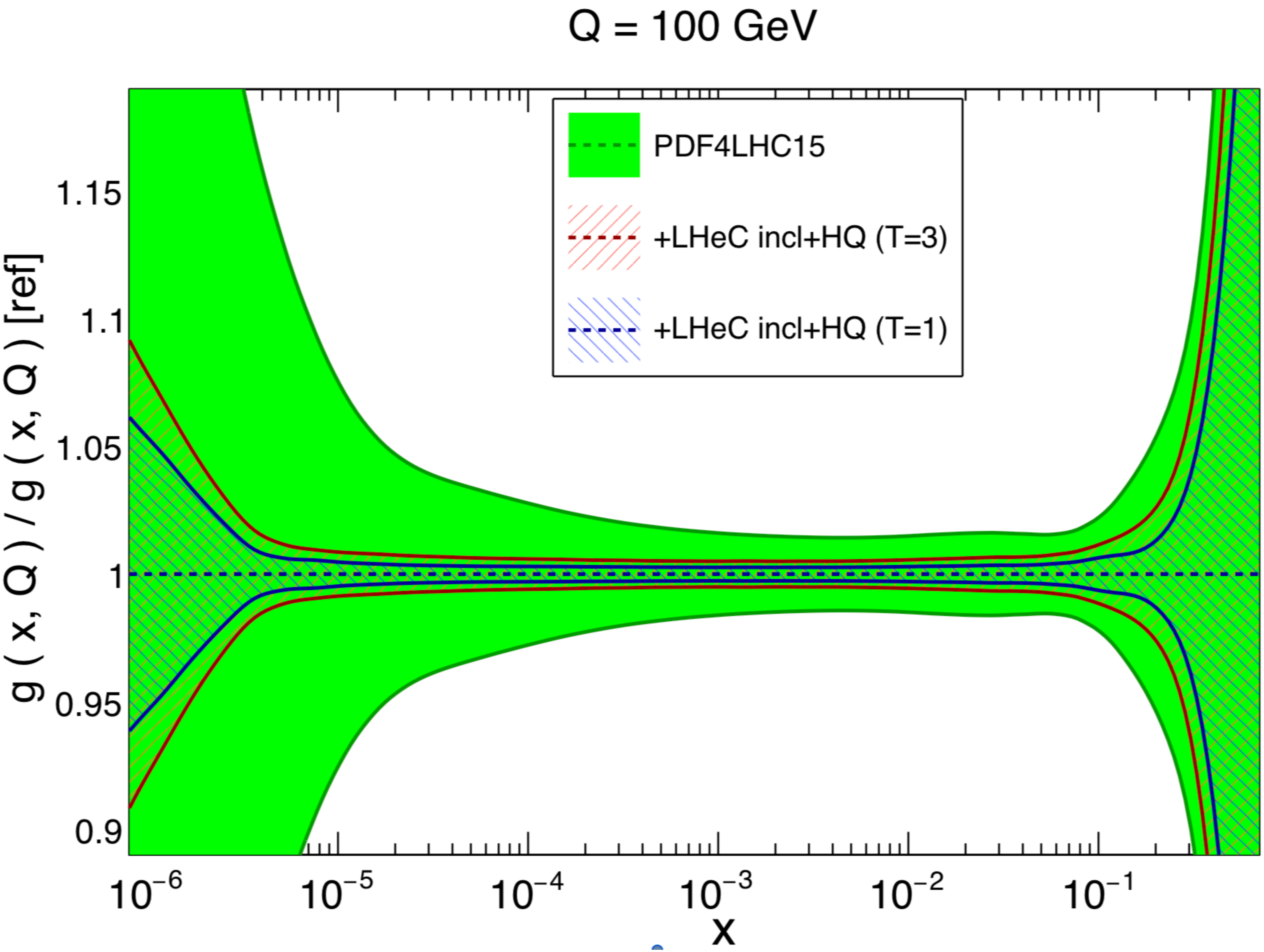
Effect of tolerance

The figure of merit used for the PDF Hessian profiling includes a **tolerance factor T**

$$\chi^2\left(\beta_{\rm exp},\beta_{\rm th}\right) = \sum_{i=1}^{N_{\rm dat}} \frac{1}{\left(\delta_{{\rm tot},i}^{\rm exp}\sigma_i^{\rm th}\right)^2}\left(\sigma_i^{\rm exp}+\sum_j \Gamma_{ij}^{\rm exp}\beta_{j,{\rm exp}}-\sigma_i^{\rm th}+\sum_k \Gamma_{ik}^{\rm th}\,\beta_{k,{\rm th}}\right)^2 + \sum_j \beta_{j,{\rm exp}}^2 + T^2\sum_k \beta_{k,{\rm th}}^2\,,$$

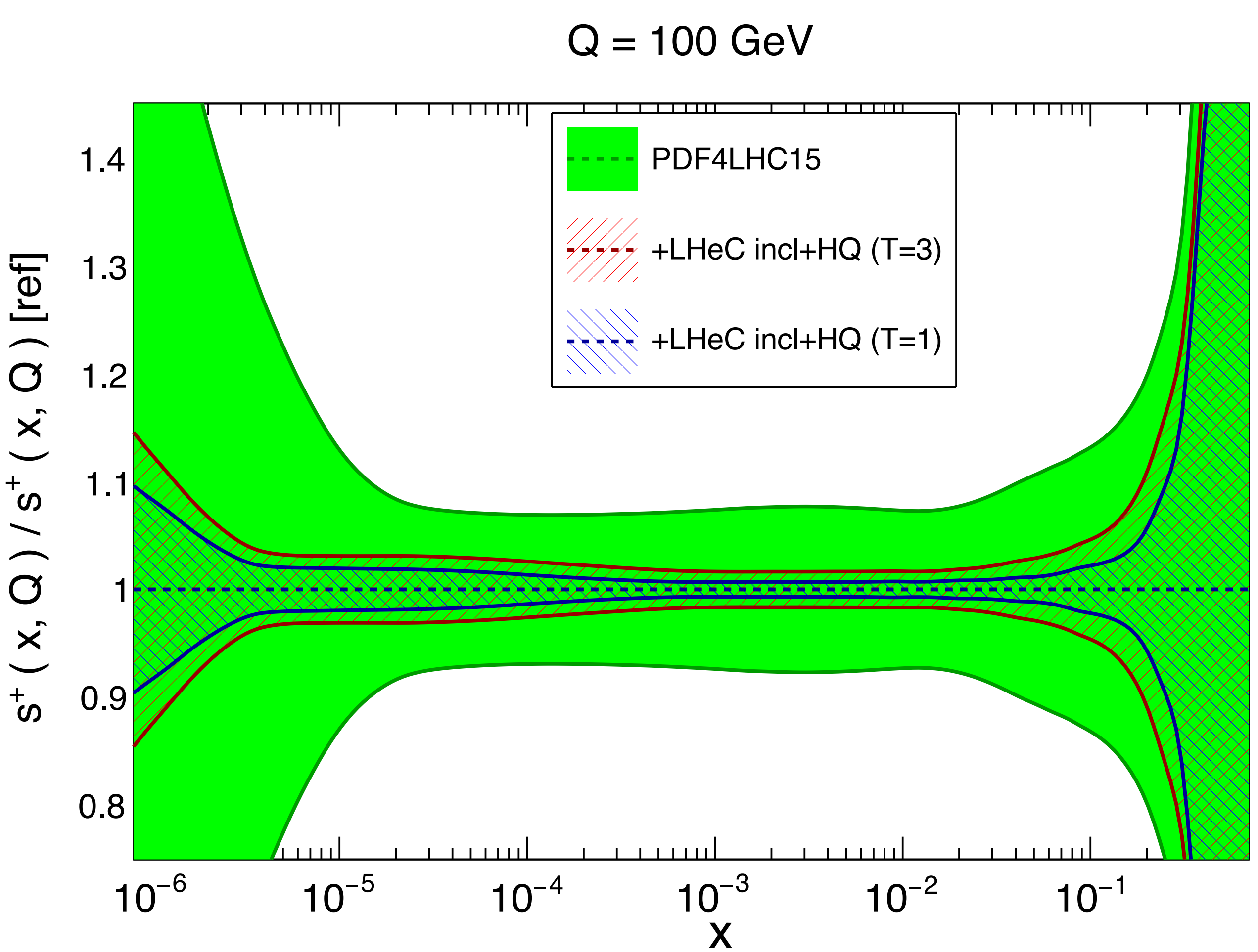
- In Hessian global fits, ***T>1*** is required (and **dynamically determined**) to account for factors such as inconsistencies between datasets and/or functional form uncertainties
- In this exercise we have used ***T=3*** in the ballpark of what is used in CT14/MMHT14
- Note that the need for ***T>1*** is also validated by comparisons with NNPDF, based on the Monte Carlo method (which does not require introducing any tolerance)
- We have studied how the results of the **LHeC profiling** change if ***T=1*** is used instead (only for the LHeC pseudo-data, for everything else the standard ***T=3*** is used)
- Using ***T=1*** does not reproduce the global fit situation, but is merely useful in this context to attempt to compare with the xFitter LHeC fits

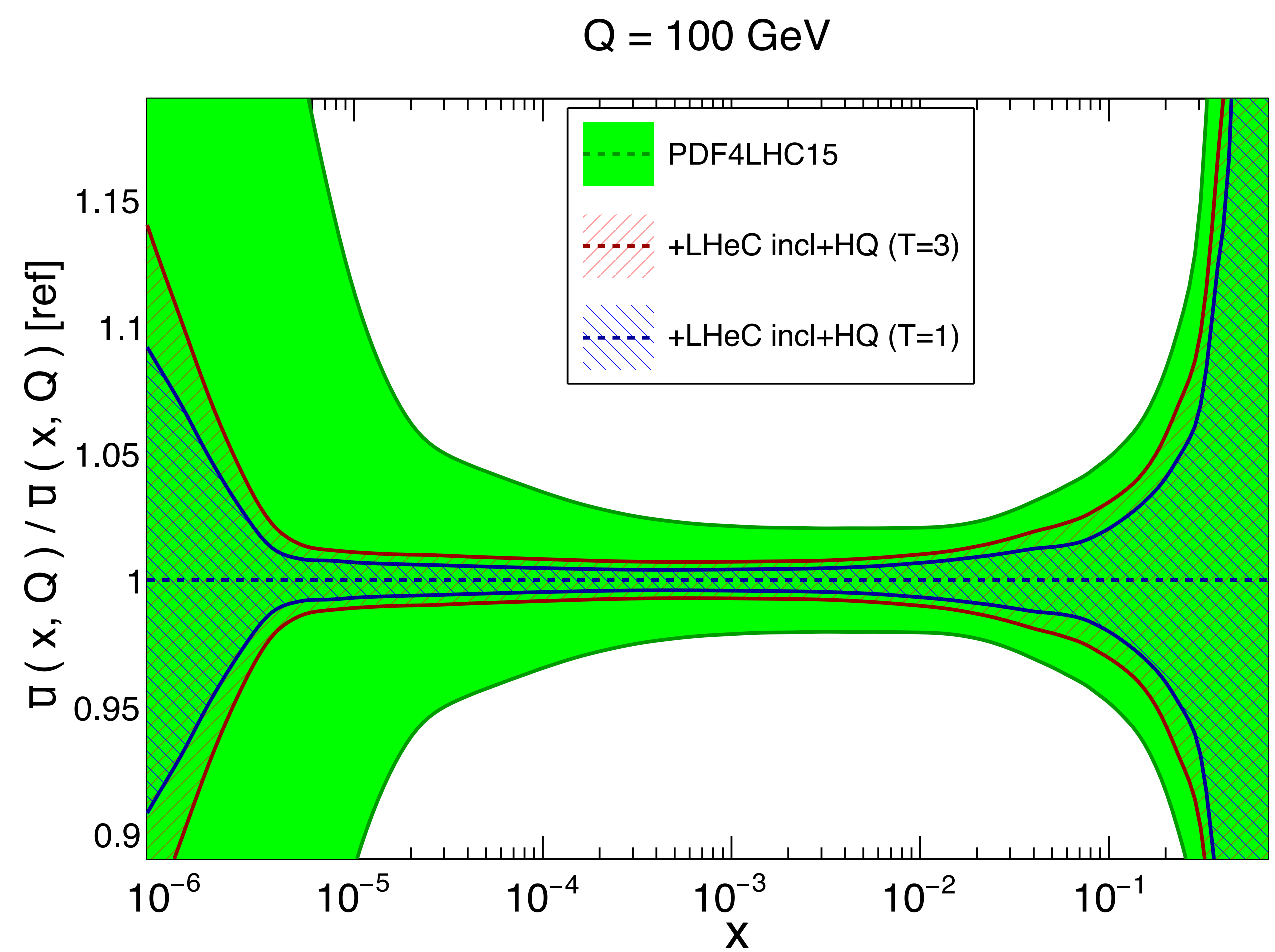
Effect of tolerance



Effect of tolerance

Compare the impact of LHeC pseudo-data using ***T=3*** vs ***T=1*** in the profiling

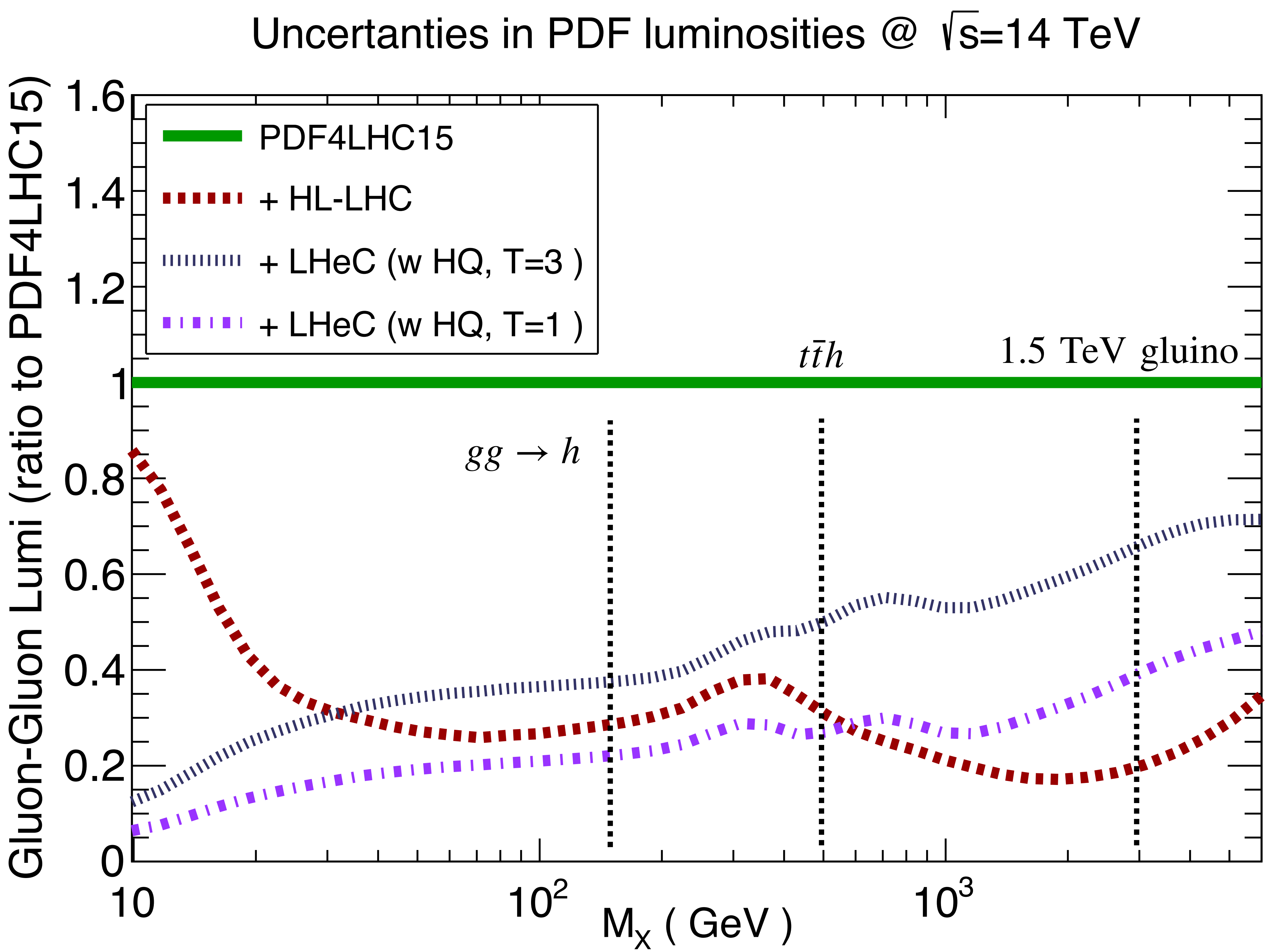




- As expected some **moderate reduction** of the PDF uncertainties
- **Qualitative impact** of LHeC data unchanged if ***T=1*** is used instead of ***T=3***
- The **large-*x* region** is still affected by large uncertainties

LHeC vs HL-LHC

Compare impact of LHeC pseudo-data (***T=1,*** optimistic scenario) with that of HL-LHC (***T=3,*** as in the published PDF sets) for luminosities



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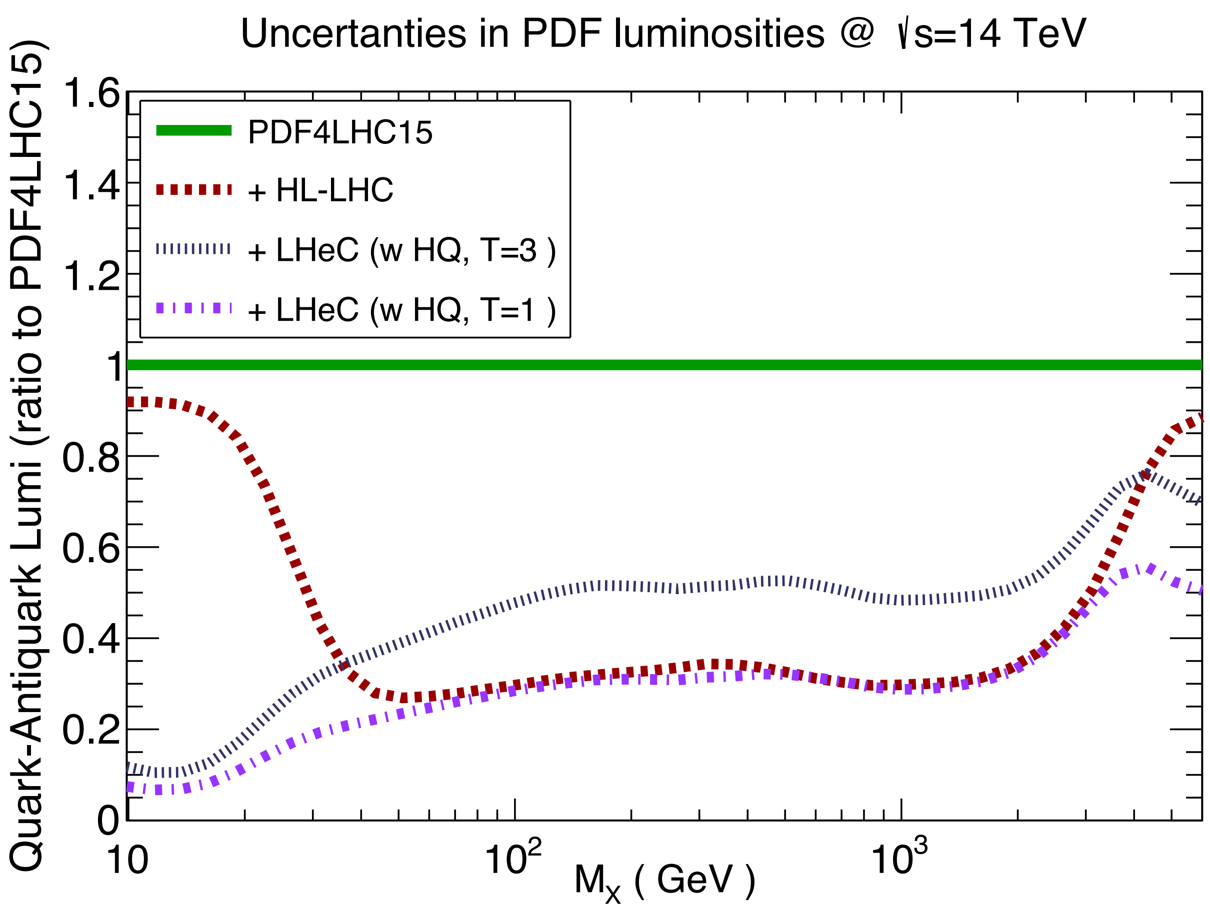
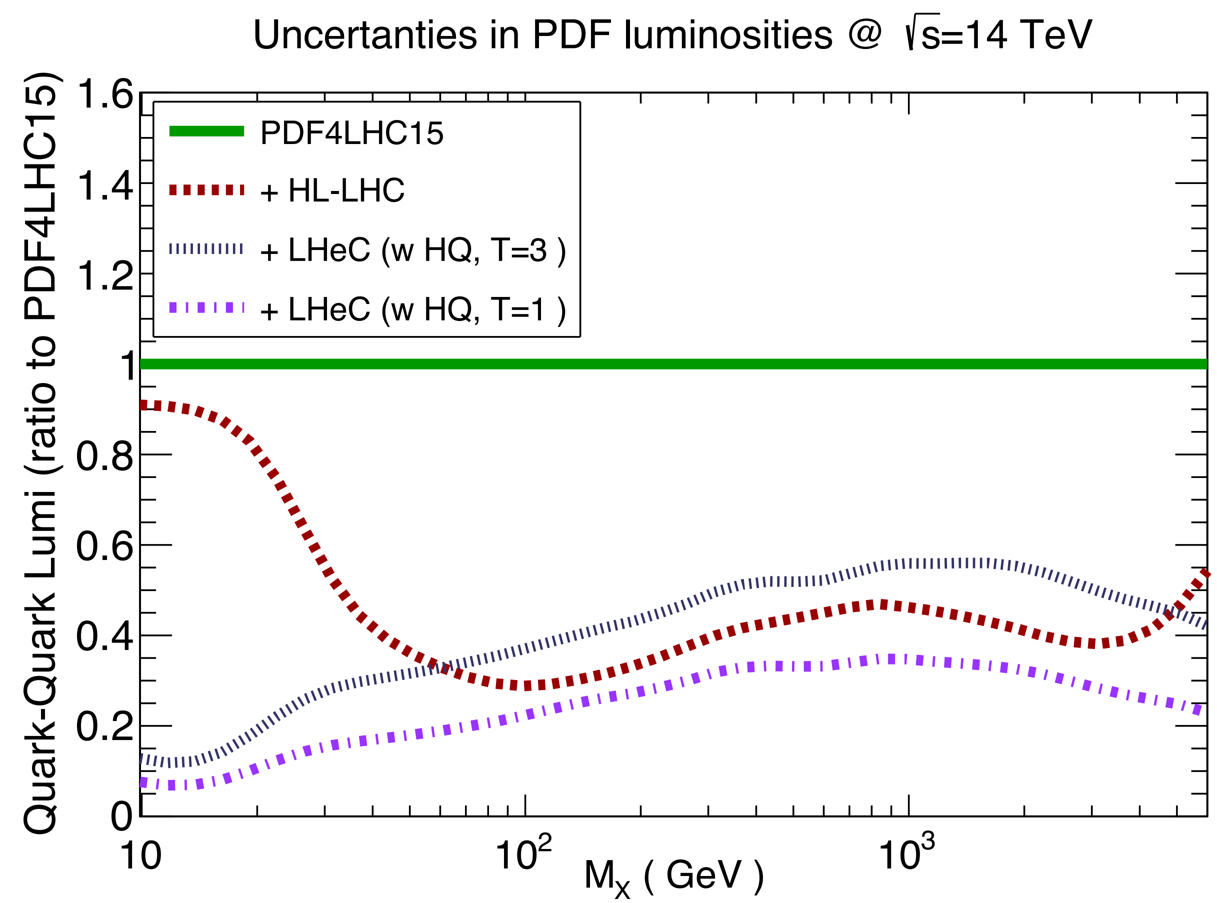
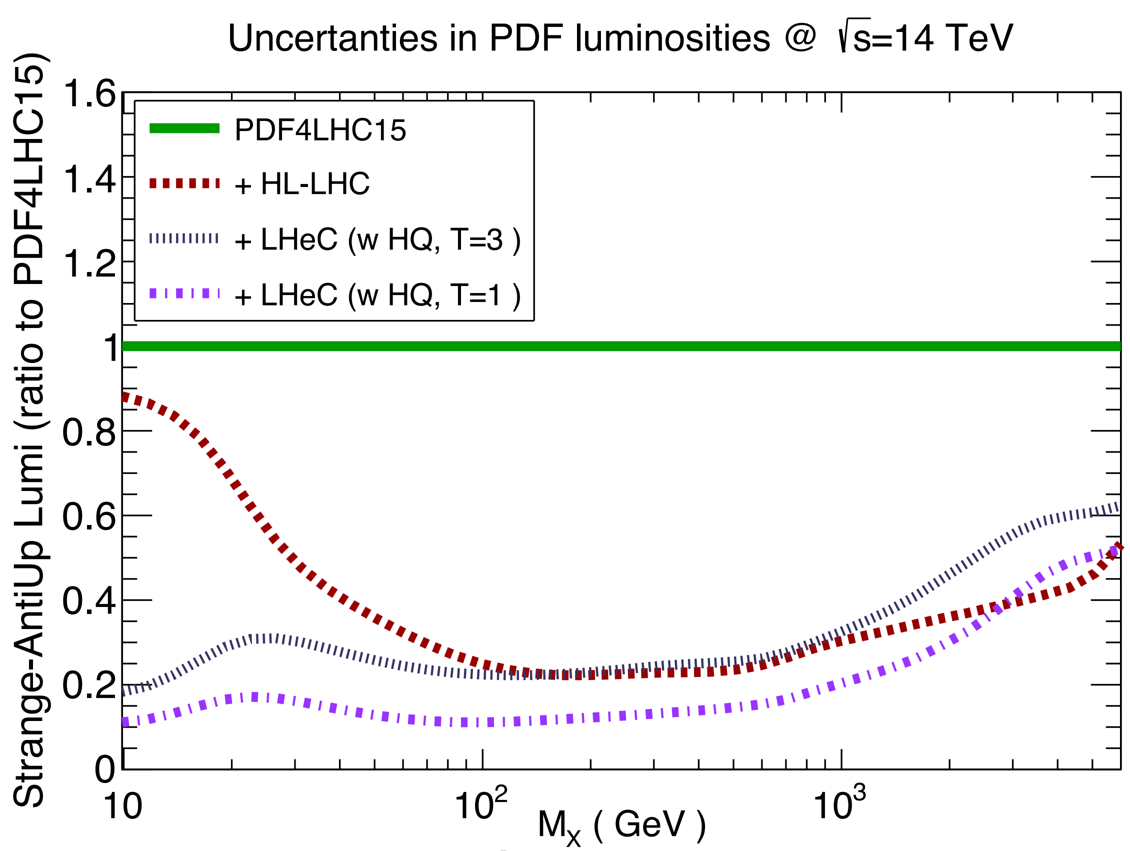


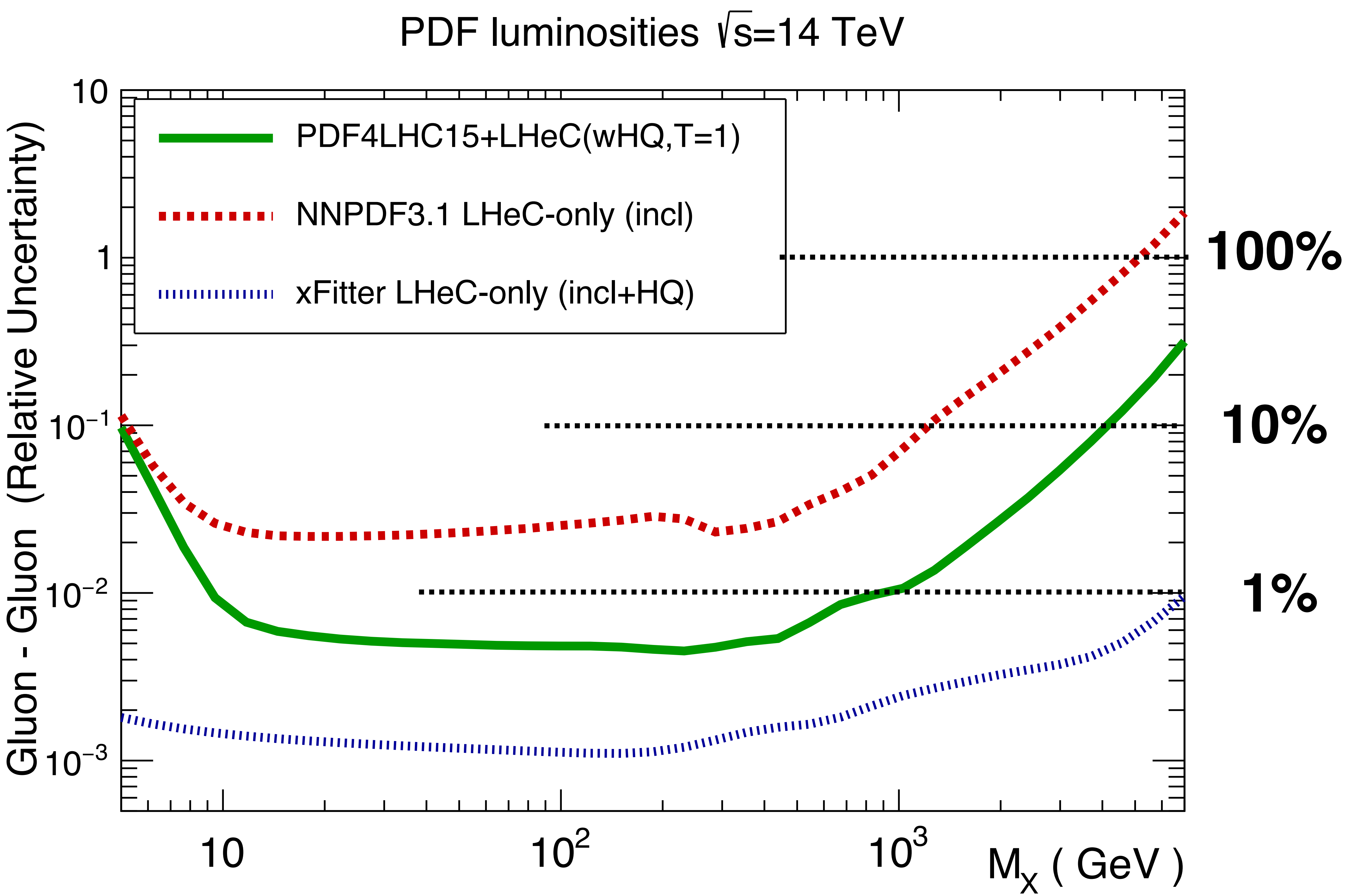




- Depending on the value of ***T,*** the overall impact of LHeC data is either **comparable** or **a bit better** than the HL-LHC when **added on top of a global PDF fit**
- This comparison further illustrates the **excellent compatibility** between HL-LHC and LHeC in terms of PDF constraints

LHeC: profiling vs fitting

Compare the effects of the LHeC on the uncertainties in the PDF luminosities for ***i)*** PDF4LHC15 profiling (incl.+HQ, T=1), ***ii)*** xFitter fits (only exp. errors) and ***iii)*** NNPDF fits (only incl. SFs)



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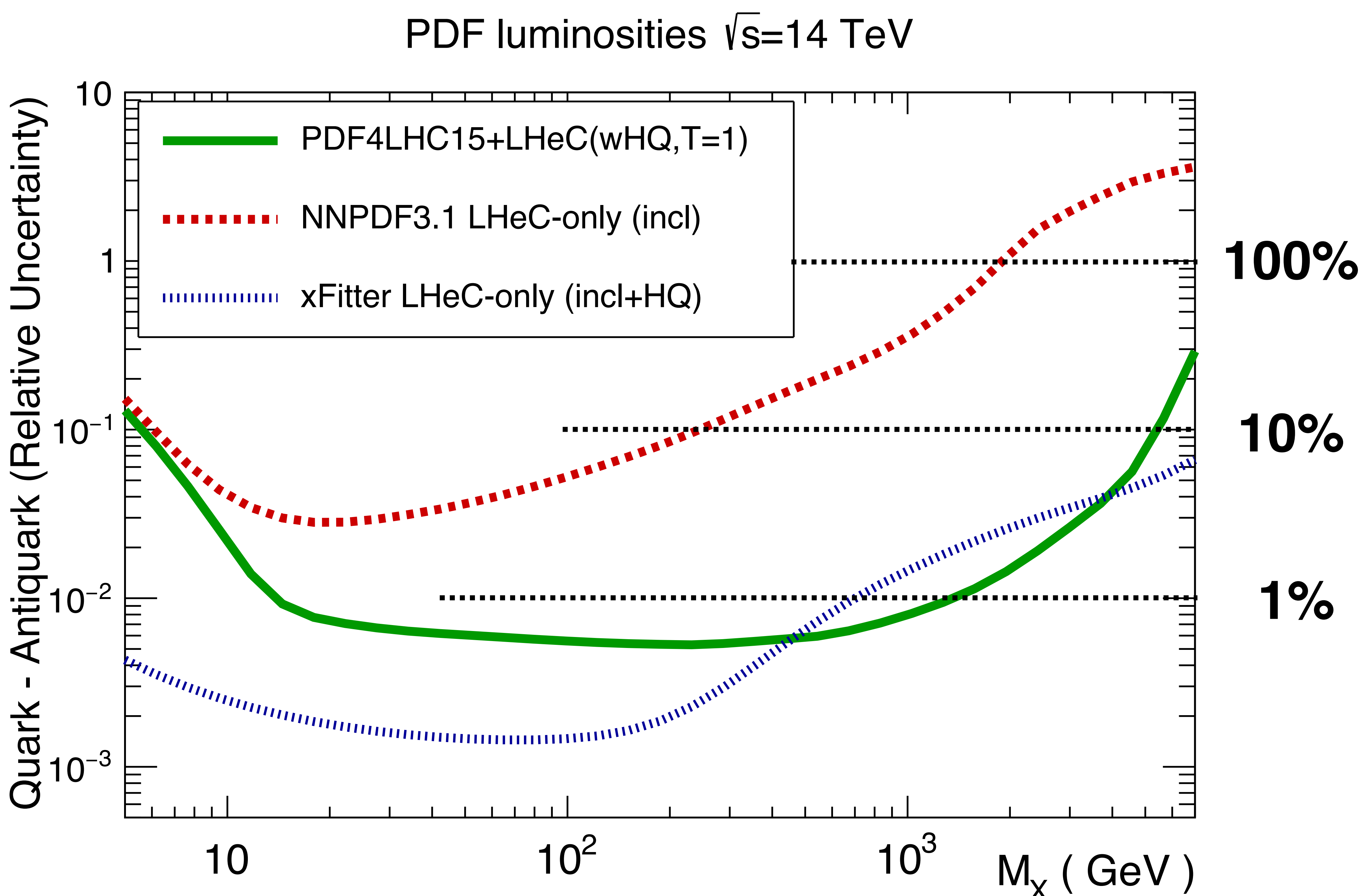
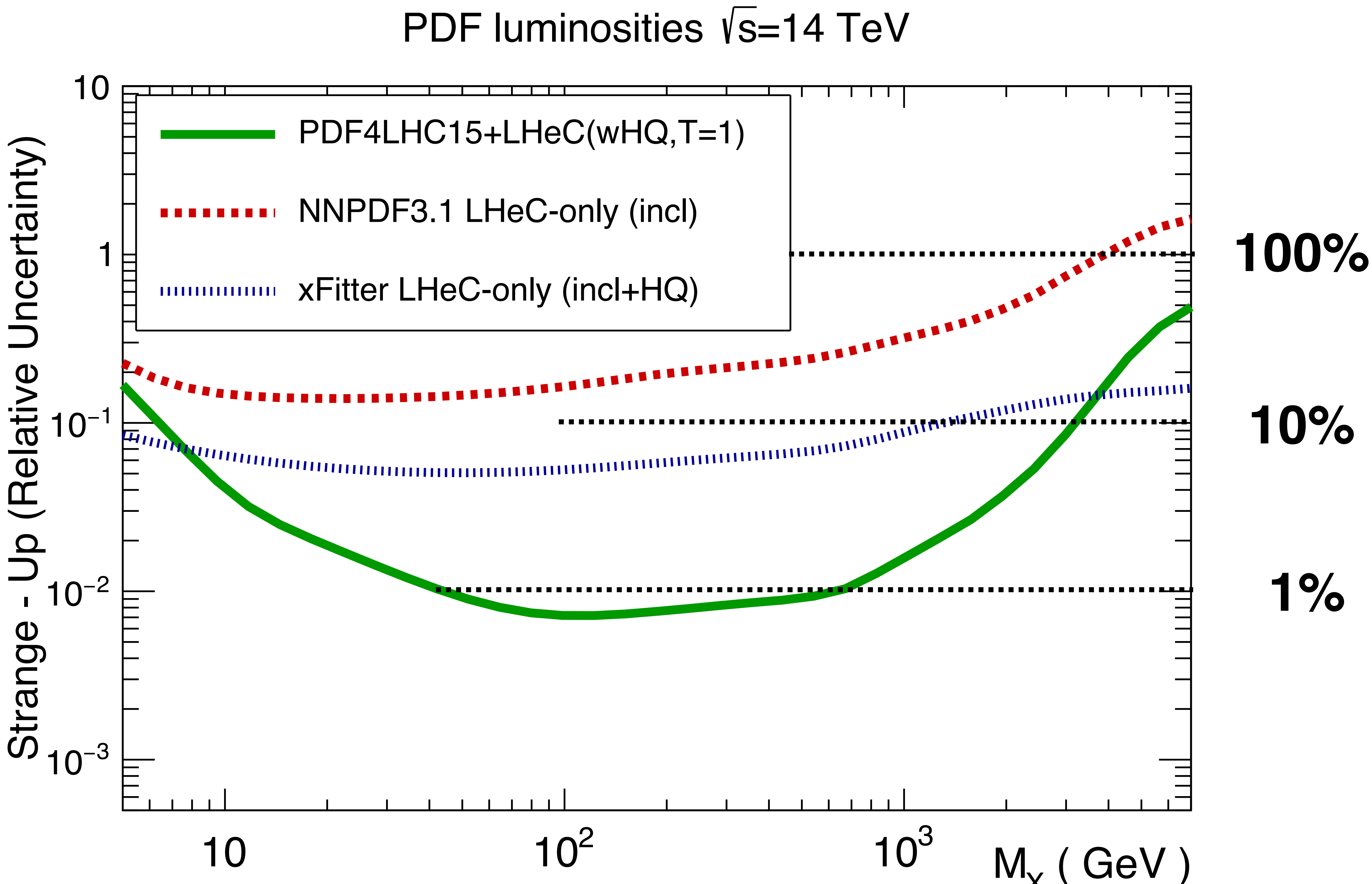


LHeC: profiling vs fitting

Compare the effects of the LHeC on the uncertainties in the PDF luminosities for ***i)*** PDF4LHC15 profiling (incl.+HQ, T=1), ***ii)*** xFitter fits (only exp. errors) and ***iii)*** NNPDF fits (only incl. SFs)



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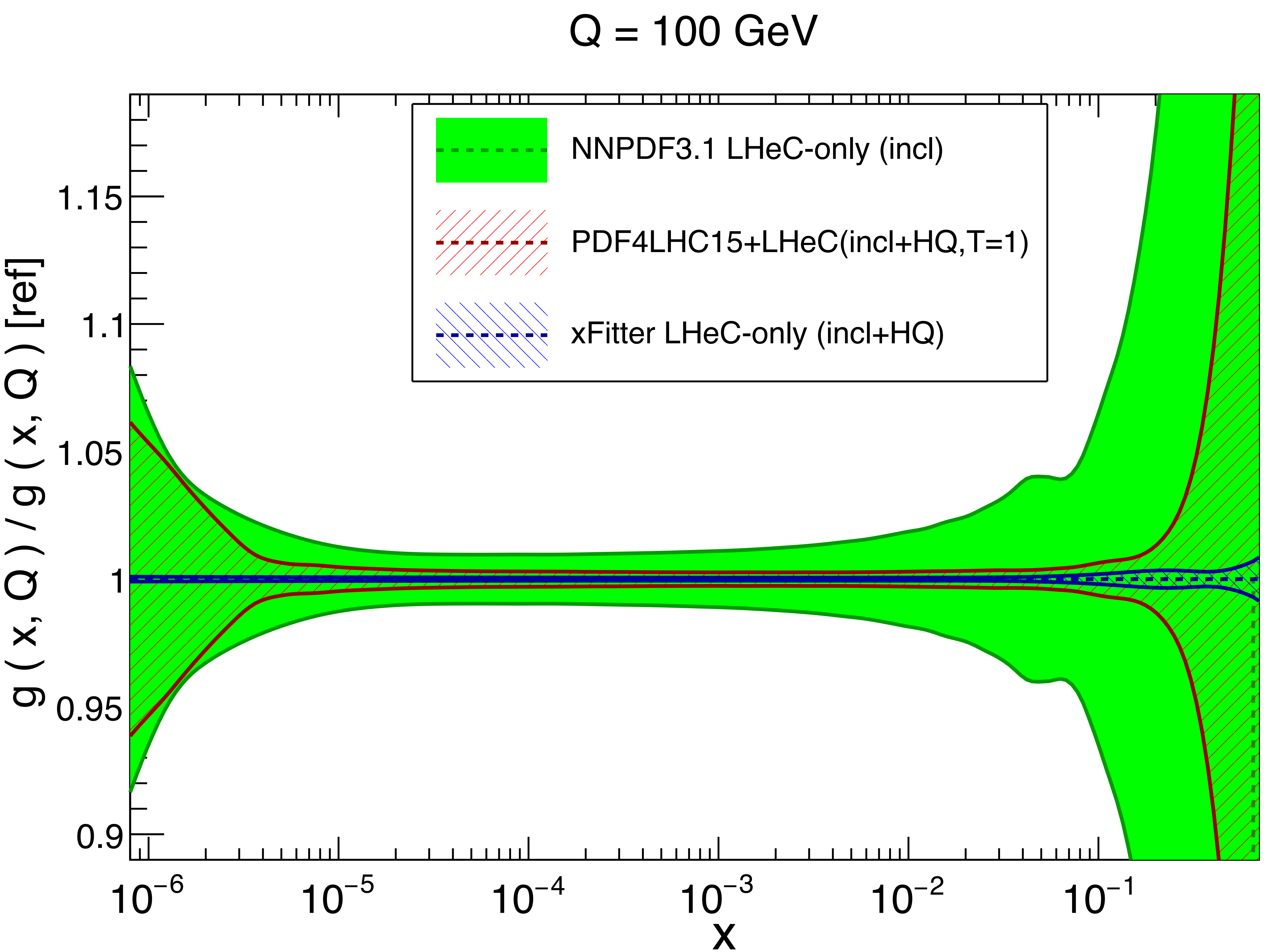
- Q: can observed differences be explained by **different flavour assumptions?**
- Compare exactly the same PDF combinations that are **parametrised in xFitter**

$$u_V(x,Q_0) \equiv (u-\bar{u})(x,Q_0)$$
$$d_V(x,Q_0) \equiv \left(d-\bar{d}\right)(x,Q_0)$$
$$\bar{U}(x,Q_0) \equiv \bar{u}(x,Q_0)$$
$$\bar{D}(x,Q_0) \equiv \left(\bar{d}+\bar{s}\right)(x,Q_0)$$
$$g(x,Q_0)$$

LHeC: profiling vs fitting

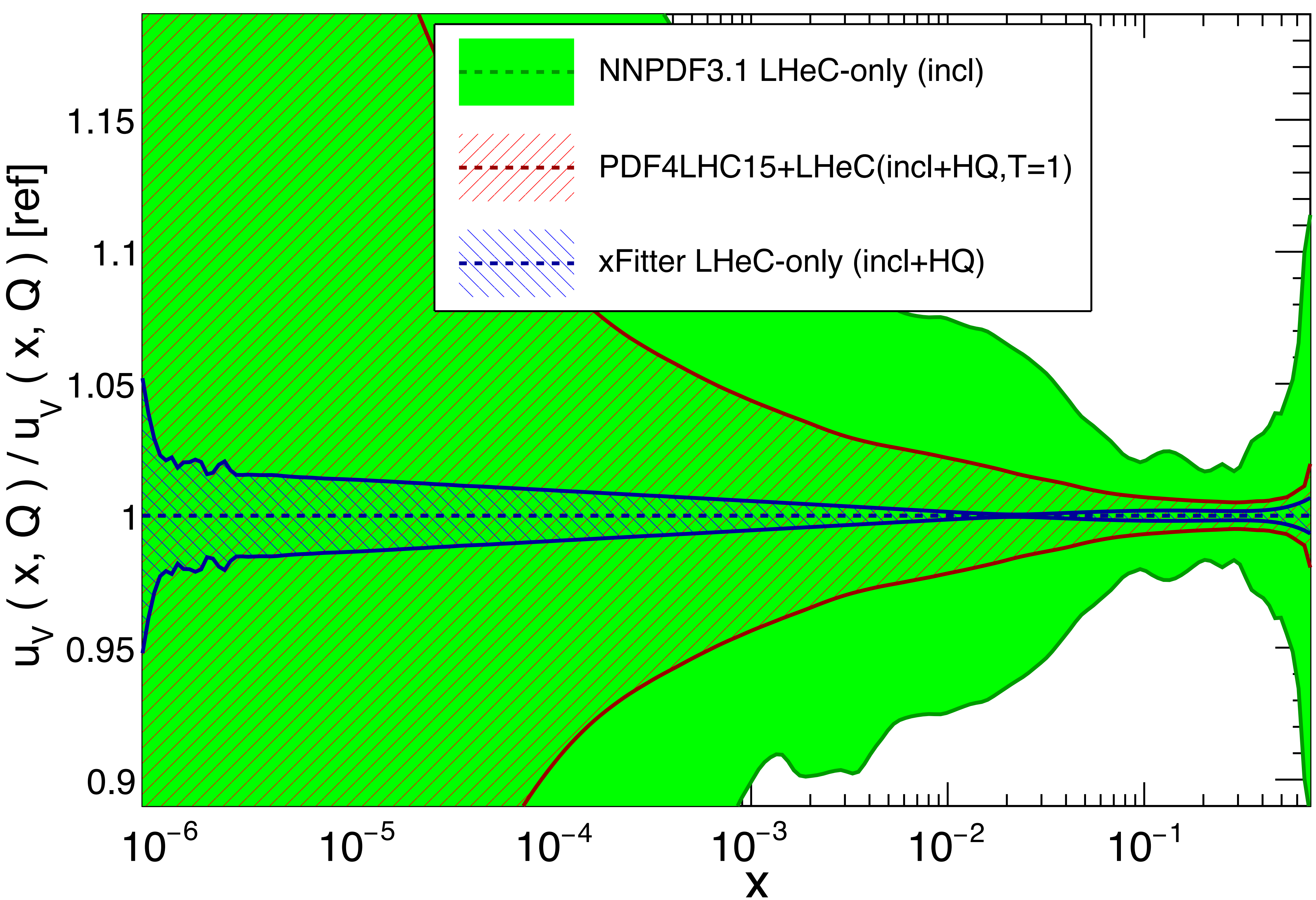
$g(x, Q_0)$



LHeC: profiling vs fitting

$$u_V(x, Q_0) \equiv (u - \bar{u})(x, Q_0)$$

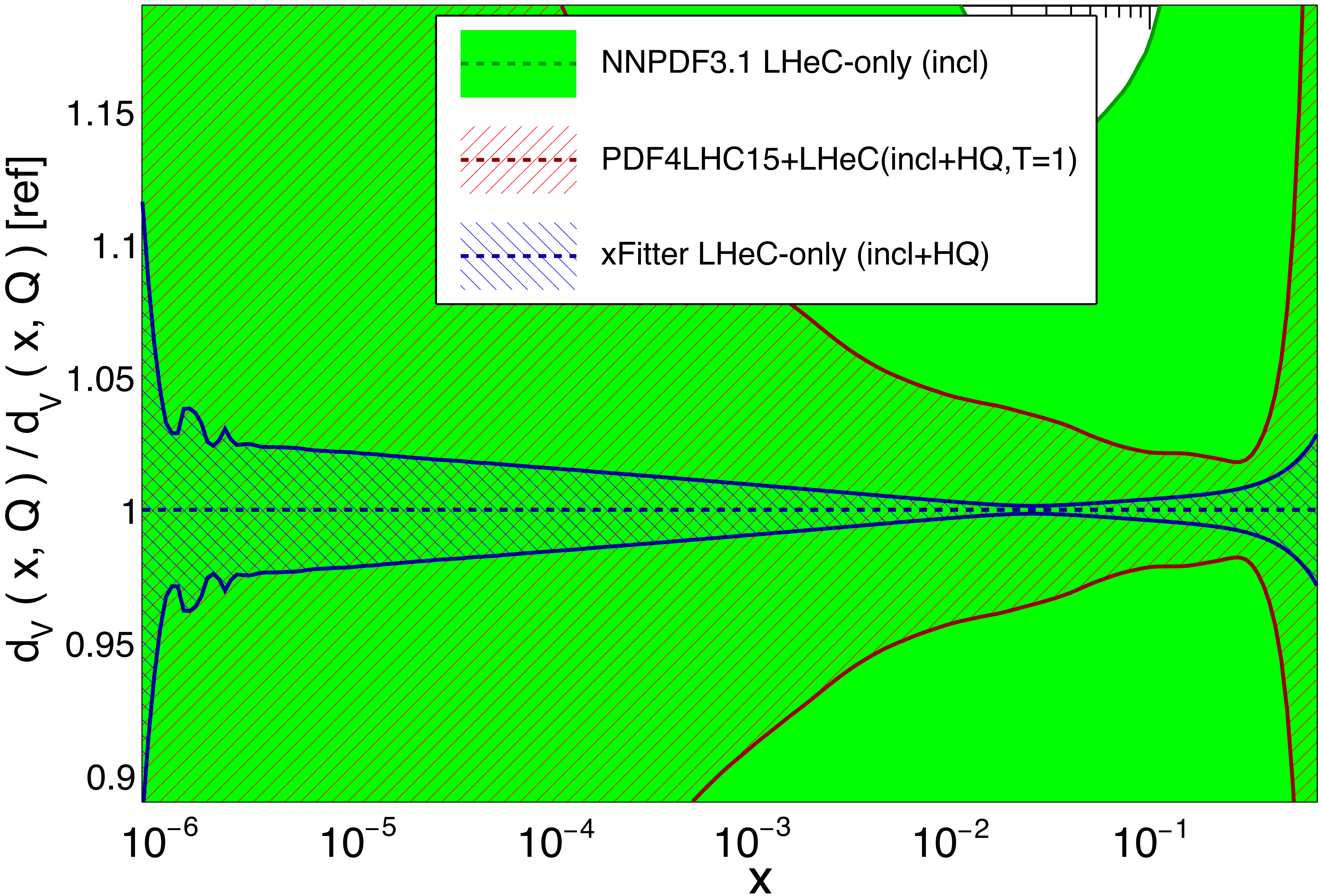
Q = 100 GeV



LHeC: profiling vs fitting

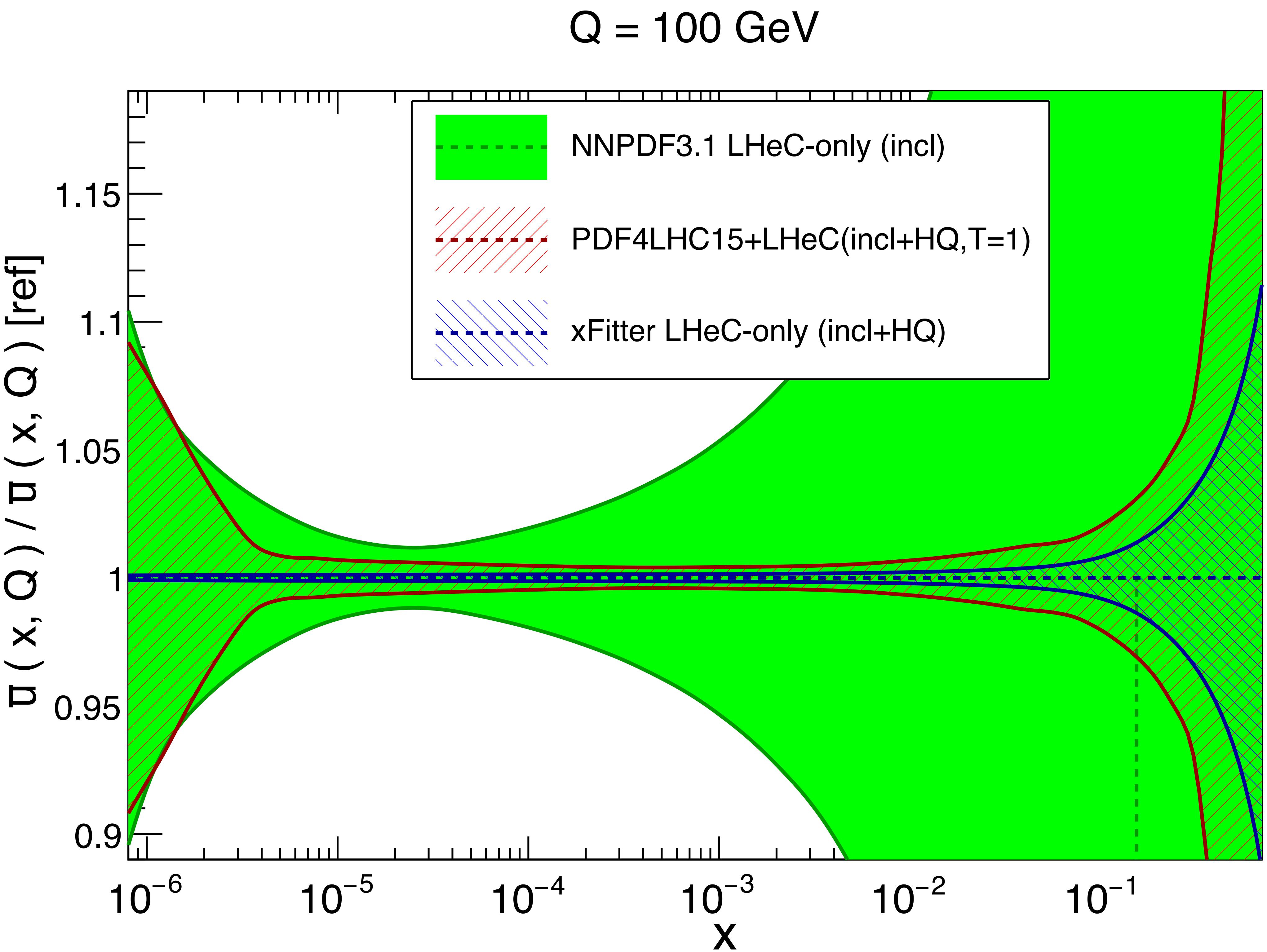
$$d_V(x, Q_0) \equiv \left(d - \bar{d}\right)(x, Q_0)$$

Q = 100 GeV



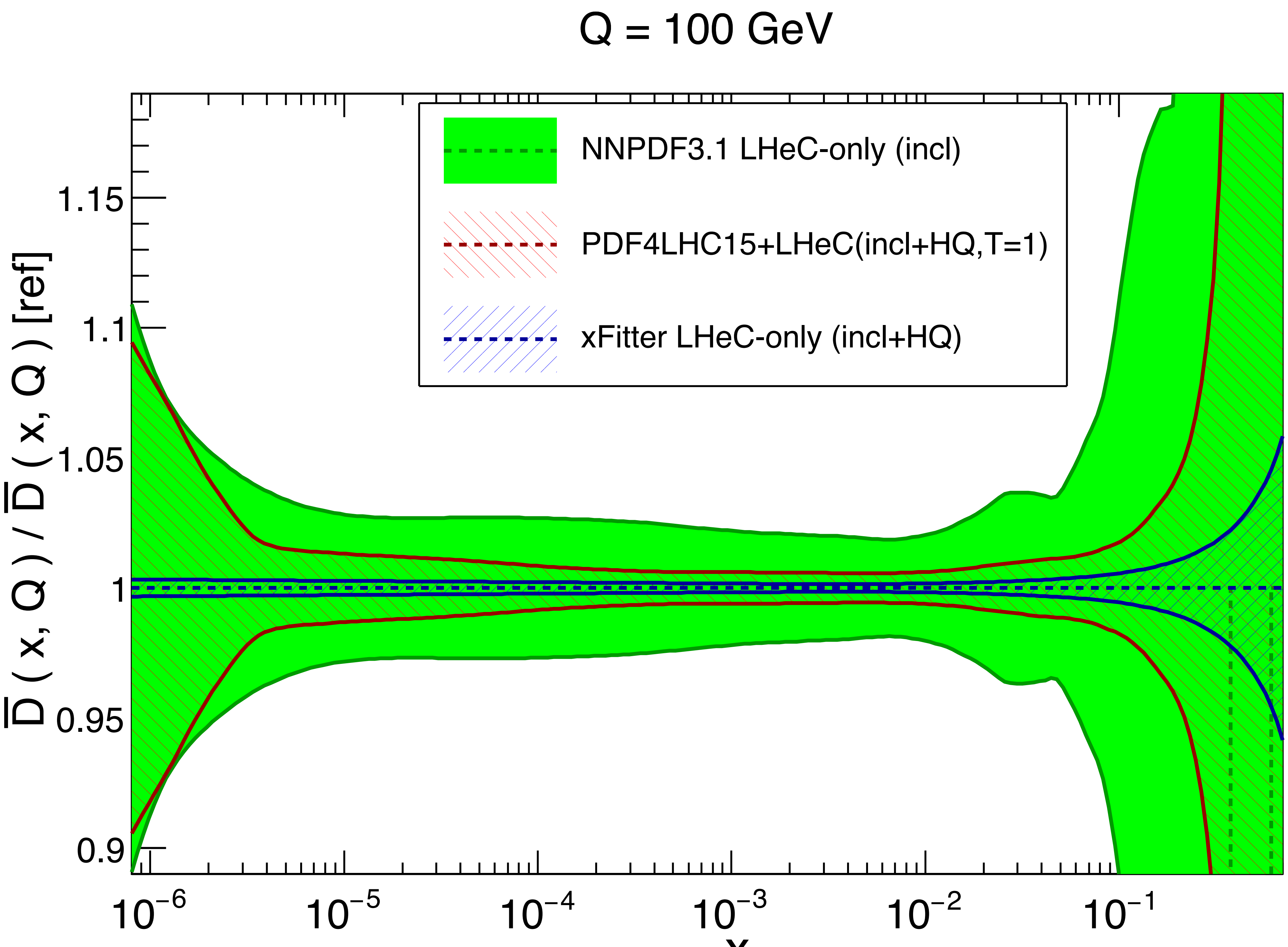
LHeC: profiling vs fitting

$$\bar{U}(x, Q_0) \equiv \bar{u}(x, Q_0)$$



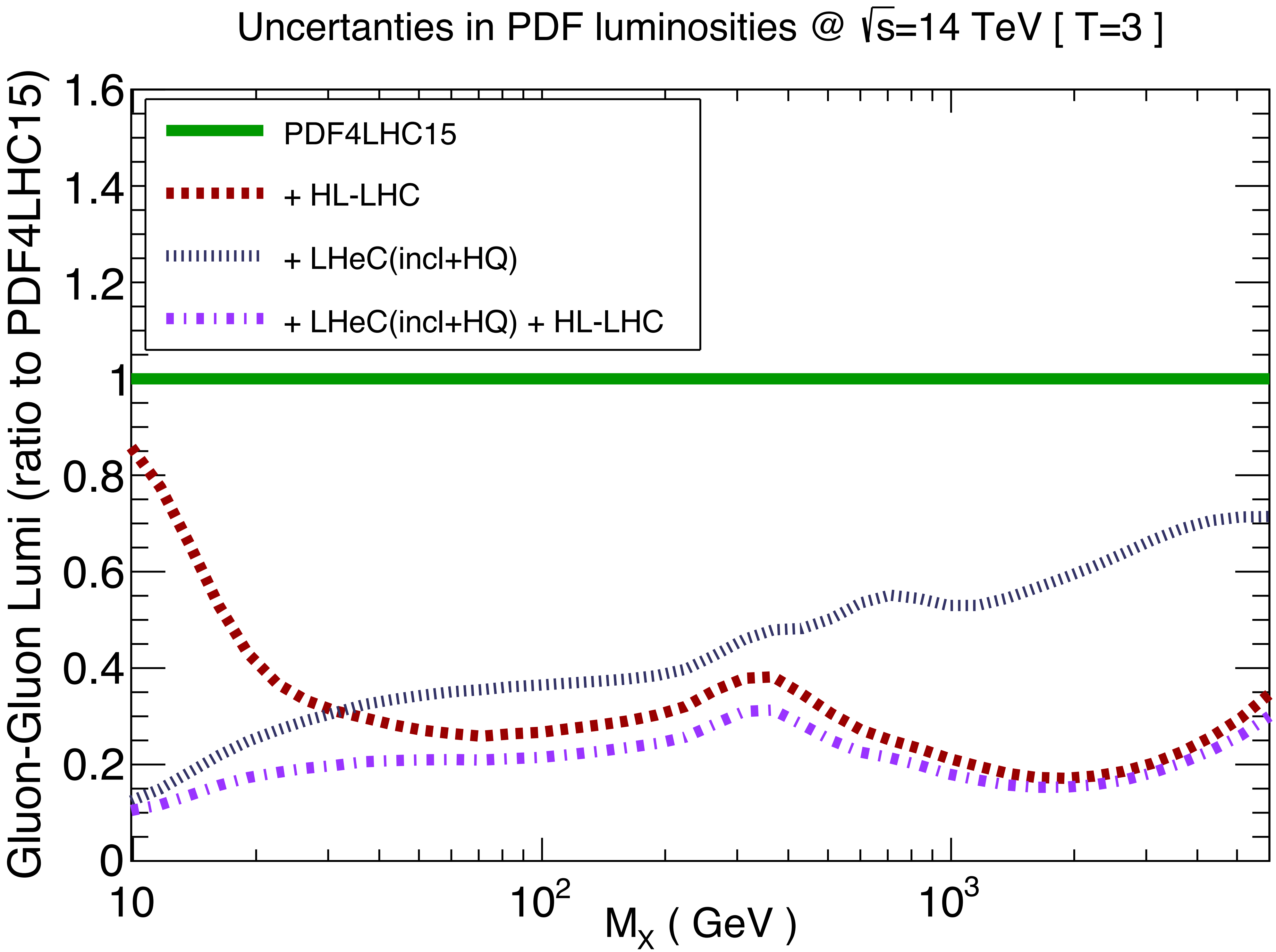
LHeC: profiling vs fitting

$$\bar{D}(x, Q_0) \equiv \left(\bar{d} + \bar{s}\right)(x, Q_0)$$

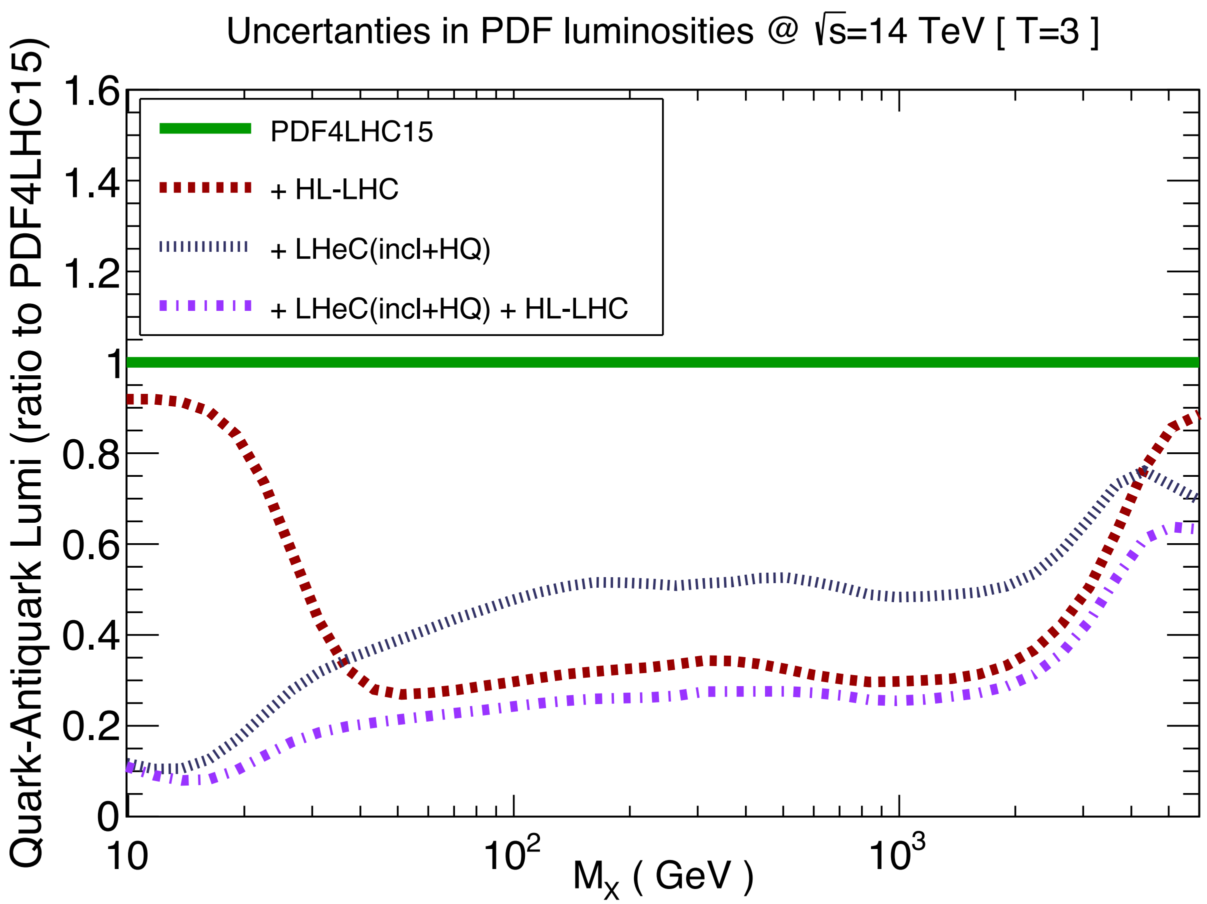


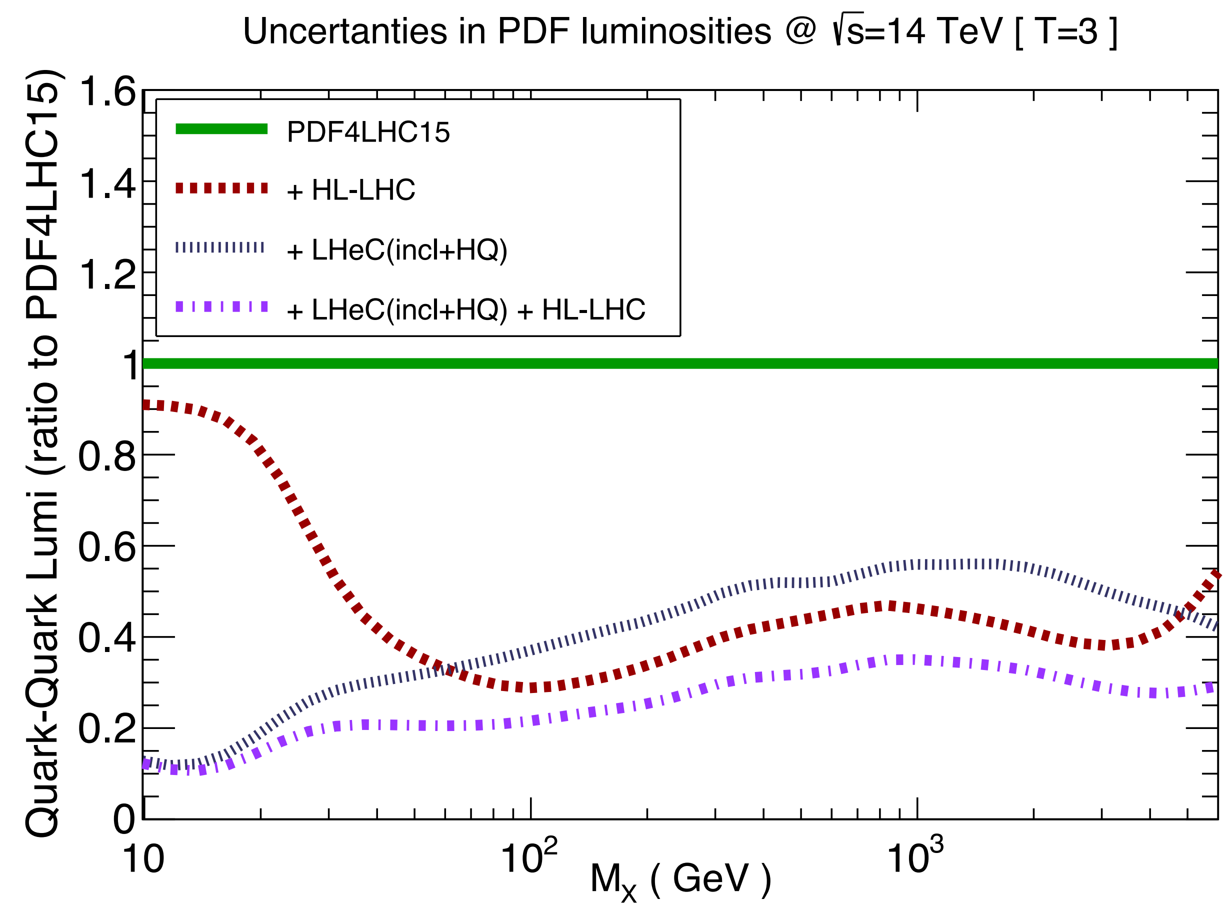
HL-LHC + LHeC combination

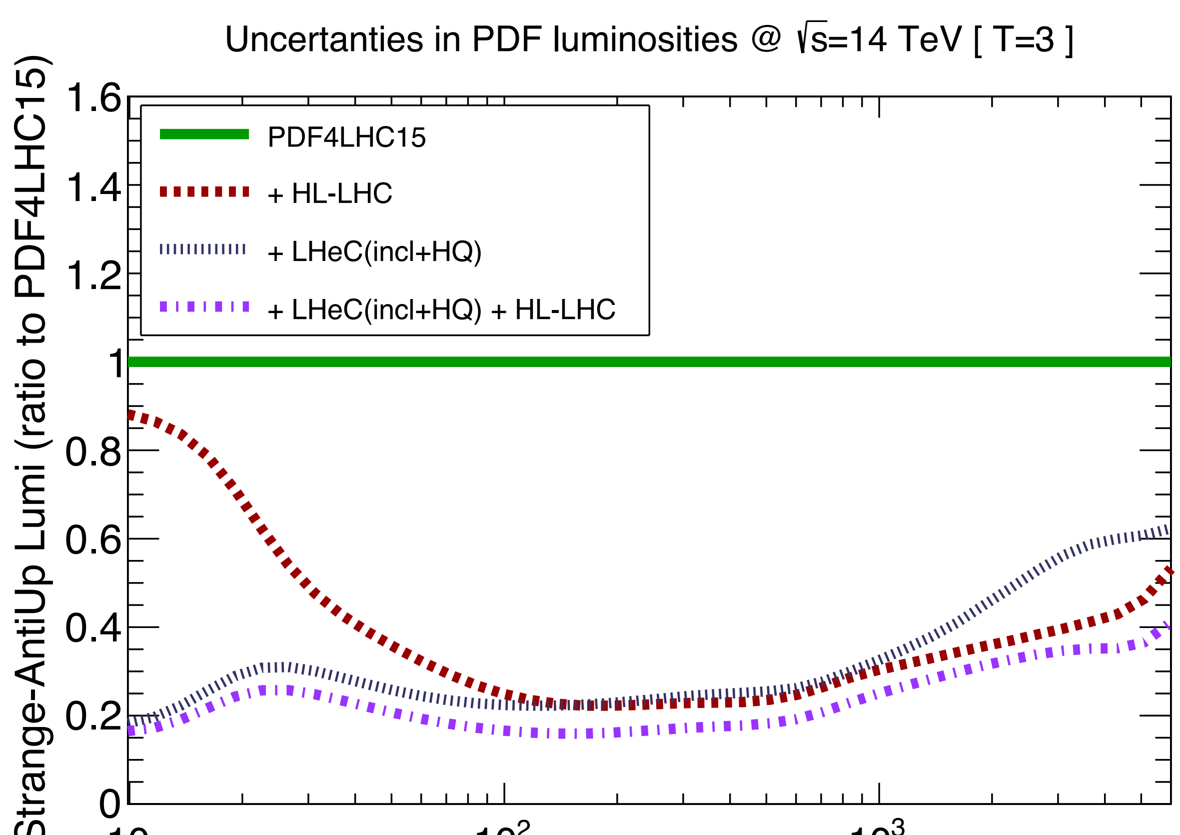
Compare the effects of the adding **simultaneously LHeC and HL-LHC** to PDF4LHC15 (with ***T=3***) as compared to add them separately



HL-LHC + LHeC combination





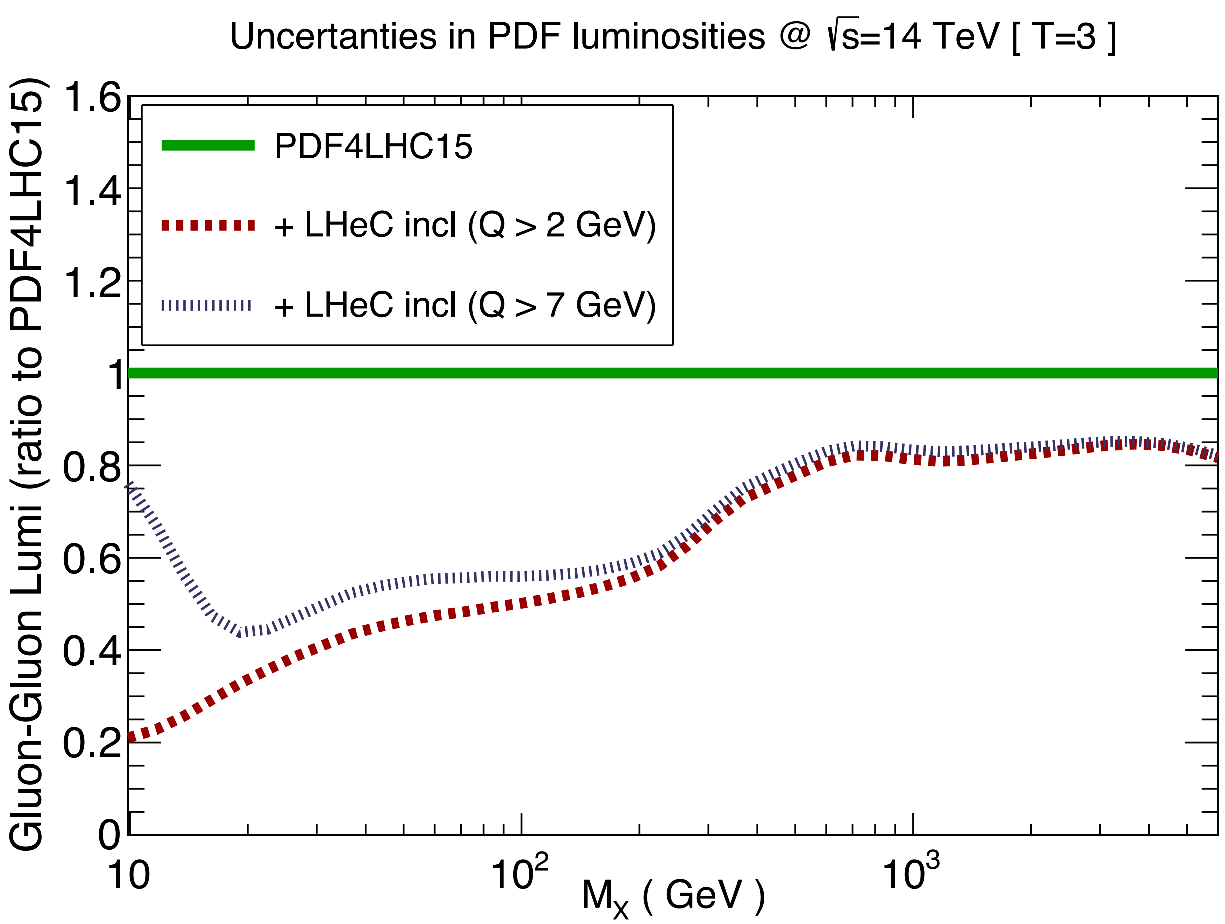


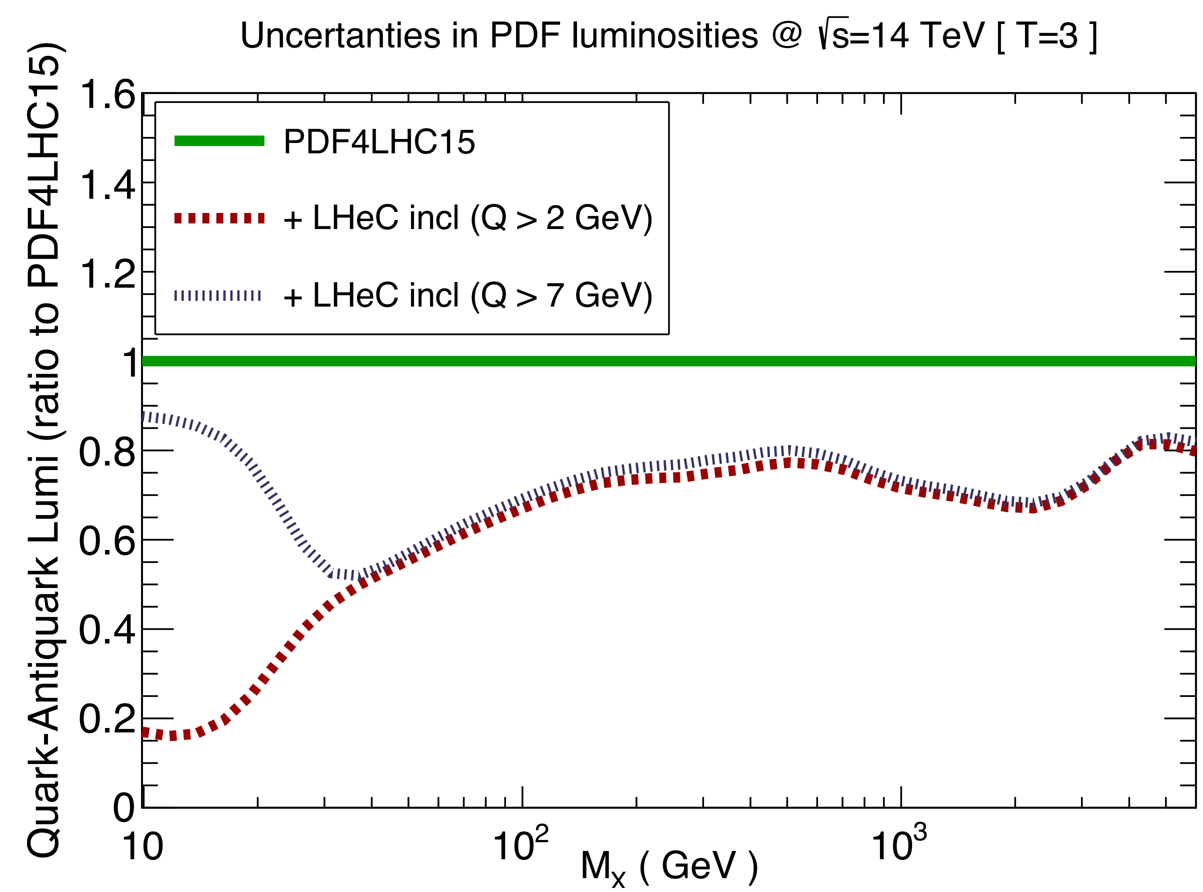
- The combination of LHeC+HL-LHC leads to a significant reduction of PDF errors in the **entire invariant mass range**
- For **M_X > 50 GeV** the additional information provided by LHeC on top of HL-LHC is moderate
- Crucial complementarity specially since LHC data might contain **bSM contributions**

The impact of the low-*x* data

PDF4LHC15 is the combination of three different global fits with **different heavy flavour schemes** and **heavy quark masses**

How is LHeC impact modified if we **include only Q > 7 GeV** in profiling?





Results essentially unchanged for **M_X > 40 GeV**

The use of PDF4LHC15 as a prior is robust to gauge the impact of LHeC constraints for **electroweak** and **TeV-scale processes**

Summary v2 and proposal

- The **heavy quark data** is an important deliverable of the LHeC project, leads to further PDF error reduction for **$10^{-4} < x < 0.2$** as compared to inclusive data only

- The **current xFitter-based LHeC estimates** are demonstrably **overoptimistic**, specially for the gluon in the entire range of ***x,*** for the large-x quarks, and for flavour separation

- Our results are robust wrt to ***i)*** removing low-*x* data, ***ii)*** using a tolerance **T=1**

- The combination of the **constraints from the LHeC and HL-LHC** within a global PDF analysis is the best option for precision LHC phenomenology and searches

- Personally, I would show the PDF luminosities comparing ***i)*** impact of HL-LHC(incl+HQ), ***ii)*** impact of HL-LHC, and ***iii)*** their combination into the global fit

PDF LHeC studies presented on 6/11/18

LHeC pseudo-data

- High-luminosity, high energy (E_p=7 TeV, E_e=60 GeV) **electron NC and CC reduced cross-sections** (ignore electron polarisation, not relevant for PDF studies)

- High-luminosity, high energy (E_p=7 TeV, E_e=60 GeV) **positron NC and CC reduced cross-sections**

- Low energy (E_p=1 TeV, E_e=60 GeV) **electron NC and CC reduced cross-sections**

Further PDF information would be provided by semi-inclusive (charm, bottom) and jet cross-sections

NC/CC	Name	Ee[GeV]	Ep[TeV]	P(e)	Charge	Lum[ab-1]
nominal, high luminosity data, negative polarisation						
NC	datlhec760ncem	60	7	-0.8	-1	1
CC	datlhec760ccem	60	7	-0.8	-1	1
nominal, high luminosity data, opposite polarisation						
NC	datlhec760ncep	60	7	0.8	-1	0.3
CC	datlhec760ccep	60	7	0.8	-1	0.3
positron data, unpolarised						
NC	datlhec760ncepp	60	7	0	+1	0.1
CC	datlhec760ccepp	60	7	0	+1	0.1
low energy data, unpolarised						
NC	datlhec160ncem	60	1	0	-1	0.1
CC	datlhec160ccem	60	1	0	-1	0.1

For the present simulation the following cuts were applied:

eta_max=5, .95 < y < 0.001

Error assumptions

energy scales: e: 0.1%, h=0.5%
this is the D/MC scale difference

Radcor 0.3% Photoproduction at high y: 1%
uncorrelated extra efficiency 0.5%

The luminosity error is kept aside, one may assume 0.5-1%.

Strategy

Assess PDF impact of LHeC pseudo-data via three ***completely independent approaches***

LHeC pseudo-data

NNPDF fits

- *Same methodology as in the NNPDF3.1 fits*
- *8 independently parametrised PDFs*
- *Input data: either LHeC-only or LHeC+DIS*
- *Fitting methodology validated on closure tests*

NNPDF, arXiv:1710.05935

Hessian profiling

- *Same methodology as in our HL-LHC projections*
- *The PDF4LHC15 set is profiled with LHeC data, with and without HL-LHC constraints*
- *Assume that PDF4LHC15 flexible enough to describe LHeC data*

Abdul-Khalek, Bailey, Harland-Lang, Gao, JR, arXiv:1810.03639

xFitter fits

- *LHeC-only fits produced with xFitter code*
- *LHAPDF grid provided by Claire*
- *Only experimental PDF errors (no VAR/MOD yet)*
- *Hessian method with* ***T=1****, as usual in HERAPDF*

Claire, Voica + LHeC team

Strategy

Assess PDF impact of LHeC pseudo-data via three ***completely independent approaches***

LHeC pseudo-data

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NNPDF, arXiv:1710.05935

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- *The PDF4LHC15 set is profiled with LHeC data, with and without HL-LHC constraints*
- *Assume that PDF4LHC15 flexible enough to describe LHeC data*
- *PDF4LHC15: combination of CT14, MMHT14, NNPDF3.0 global fits*
- *Fixed tolerance T=3*
- *Here use the Hessian set with 100 eigenvectors*
- *Baseline Higgs Cross Section WG recommedations*

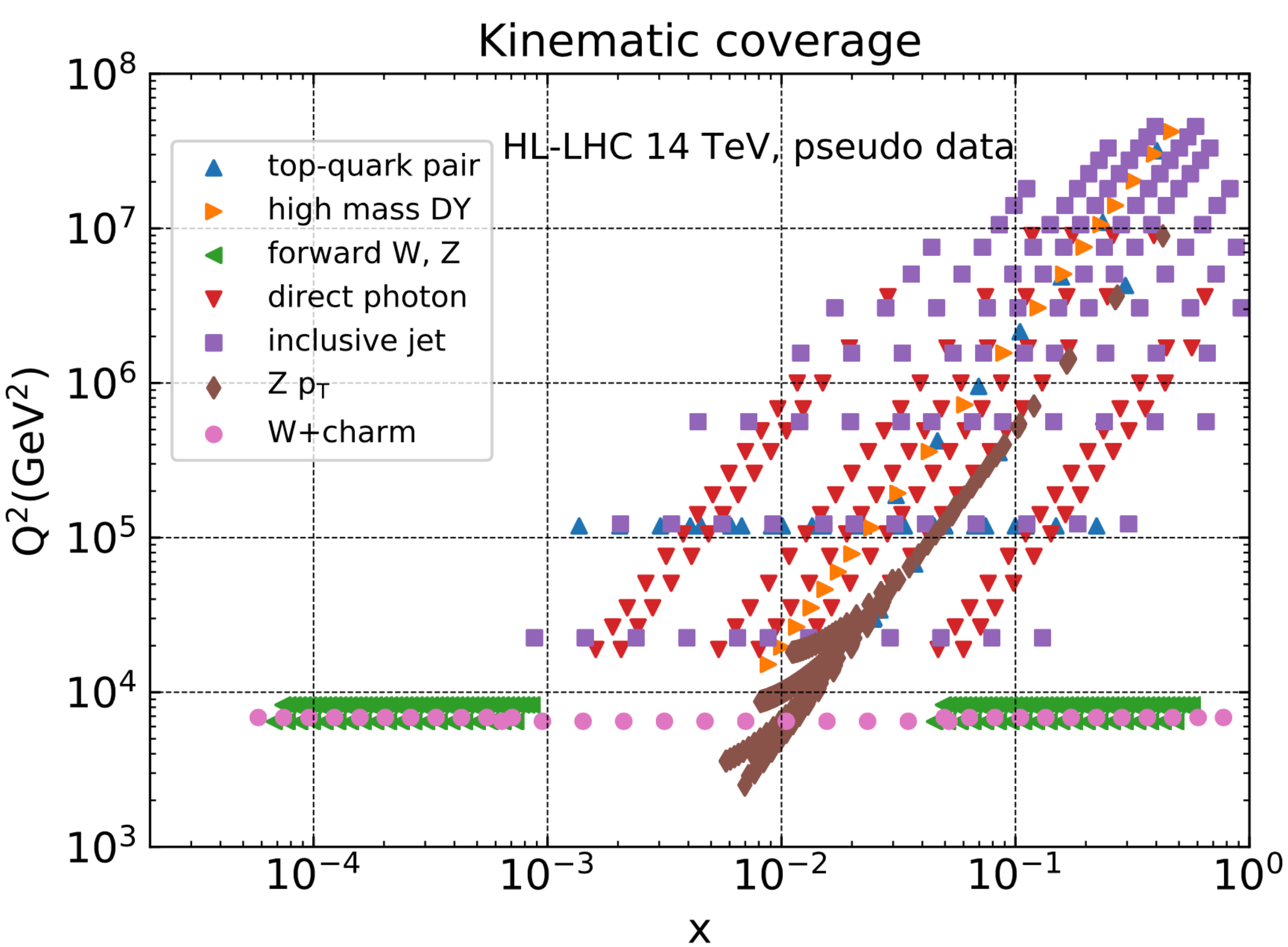
Abdul-Khalek, Bailey, Harland-Lang, Gao, JR, arXiv:1810.03639

- *LHeC-only fits produced with xFitter code*
- *LHAPDF grid provided by Claire*
- *Only experimental PDF errors (no VAR/MOD yet)*

Claire, Voica + LHeC team

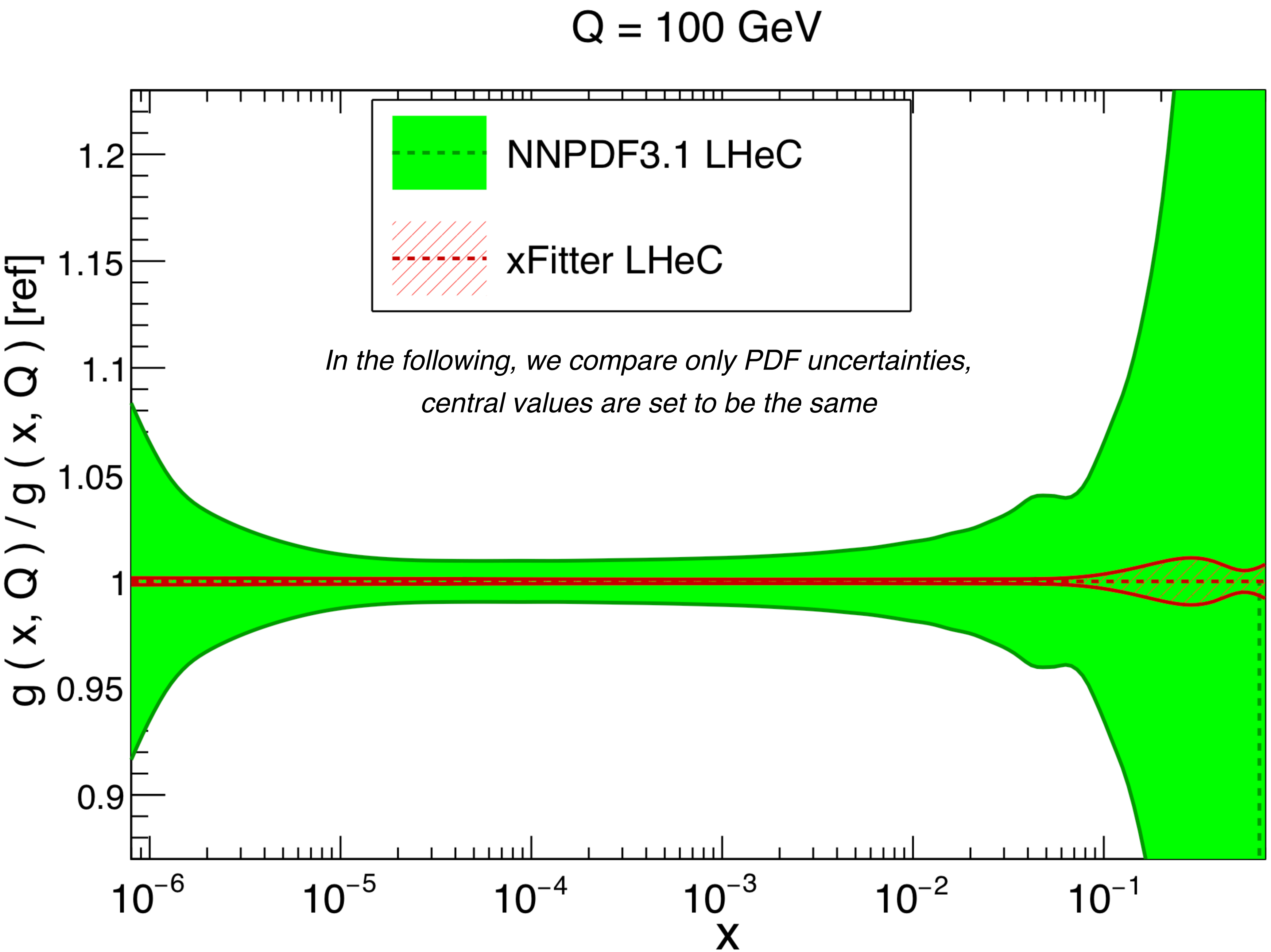
HL-LHC projections

- Wide kinematic coverage in ***x*** and ***Q***
- Total of 424 pseudo-data points generated
- Constraints on medium and large-*x* antiquarks, gluon, strangeness….



Process	Kinematics	$N_{\rm dat}$
$Z\ p_T$	$20\,\text{GeV} \le p_T^{ll} \le 3.5$ TeV $12\,\text{GeV} \le m_{ll} \le 150$ GeV $\lvert y_{ll}\rvert \le 2.4$	162
high-mass Drell-Yan	$p_T^{l1(2)} \ge 40(30)\,\text{GeV}$ $\lvert\eta^l\rvert \le 2.5,\ m_{ll} \ge 116\,\text{GeV}$	21
top quark pair	$m_{t\bar t} \simeq 5$ TeV, $\lvert y_t\rvert \le 2.5$	26
W+charm (central)	$p_T^{\mu} \ge 26\,\text{GeV},\ p_T^{c} \ge 5\,\text{GeV}$ $\lvert\eta^{\mu}\rvert \le 2.4$	6
W+charm (forward)	$p_T^{\mu} \ge 20\,\text{GeV},\ p_T^{c} \ge 20\,\text{GeV}$ $p_T^{\mu+c} \ge 20\,\text{GeV}$ $2 \le \eta^{\mu} \le 5,\ 2.2 \le \eta^{c} \le 4.2$	12
Direct photon	$E_T^{\gamma} \lesssim 3$ TeV, $\lvert\eta_\gamma\rvert \le 2.5$	53
Forward W, Z	$p_T^{l} \ge 20\,\text{GeV},\ 2.0 \le \eta^l \le 4.5$ $2.0 \le y_{ll} \le 4.5$ $60 \le m_{ll} \le 120\,\text{GeV}$	90
Inclusive jets	$\lvert y\rvert \le 3,\ R = 0.4$	54
Total		424

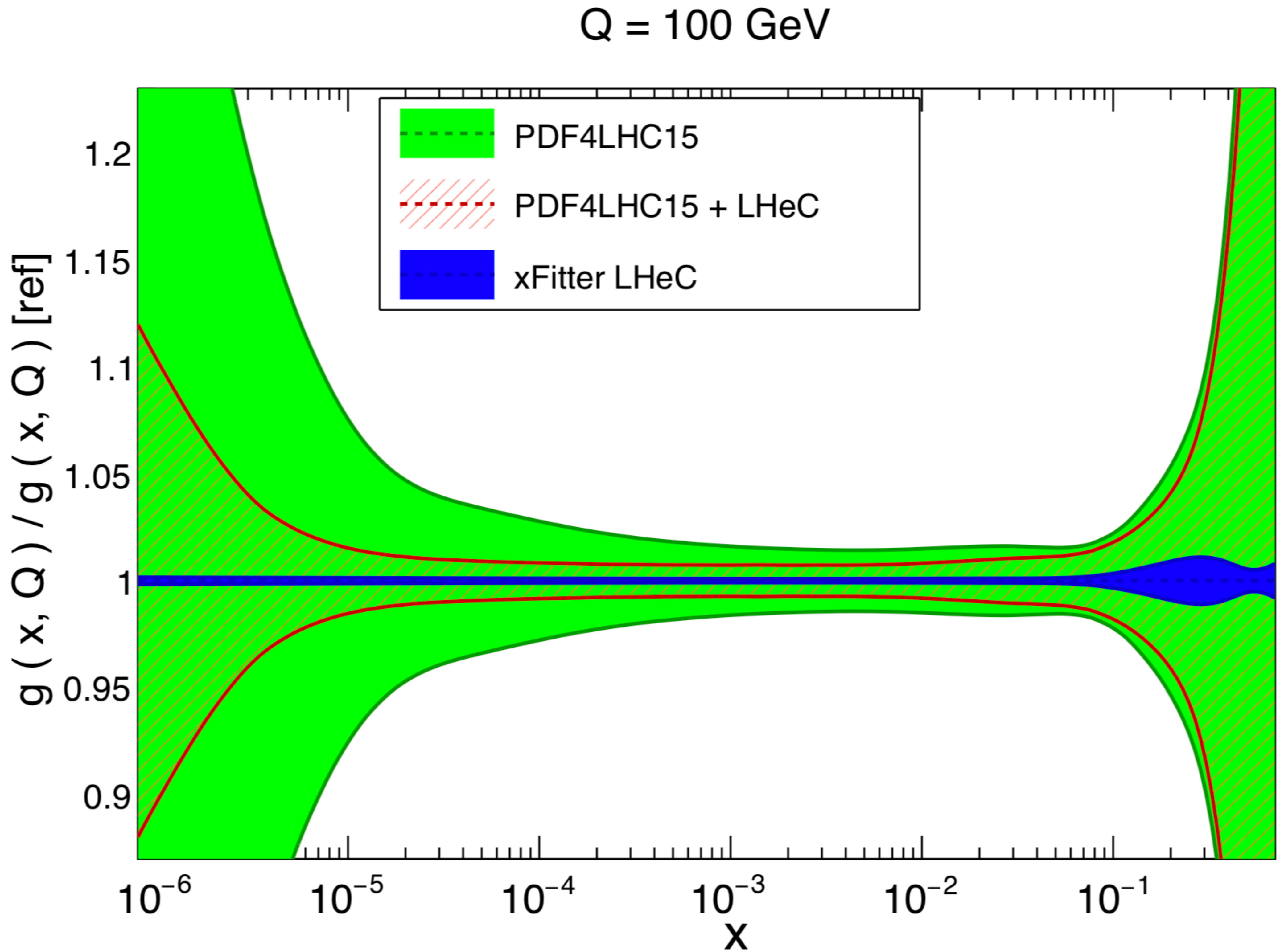
The gluon PDF



For fits based on identical datasets, large differences between the NNPDF and xFitter approaches

Specially marked in the small-x and large-x regions (DIS only mild constrains on large-x gluon)

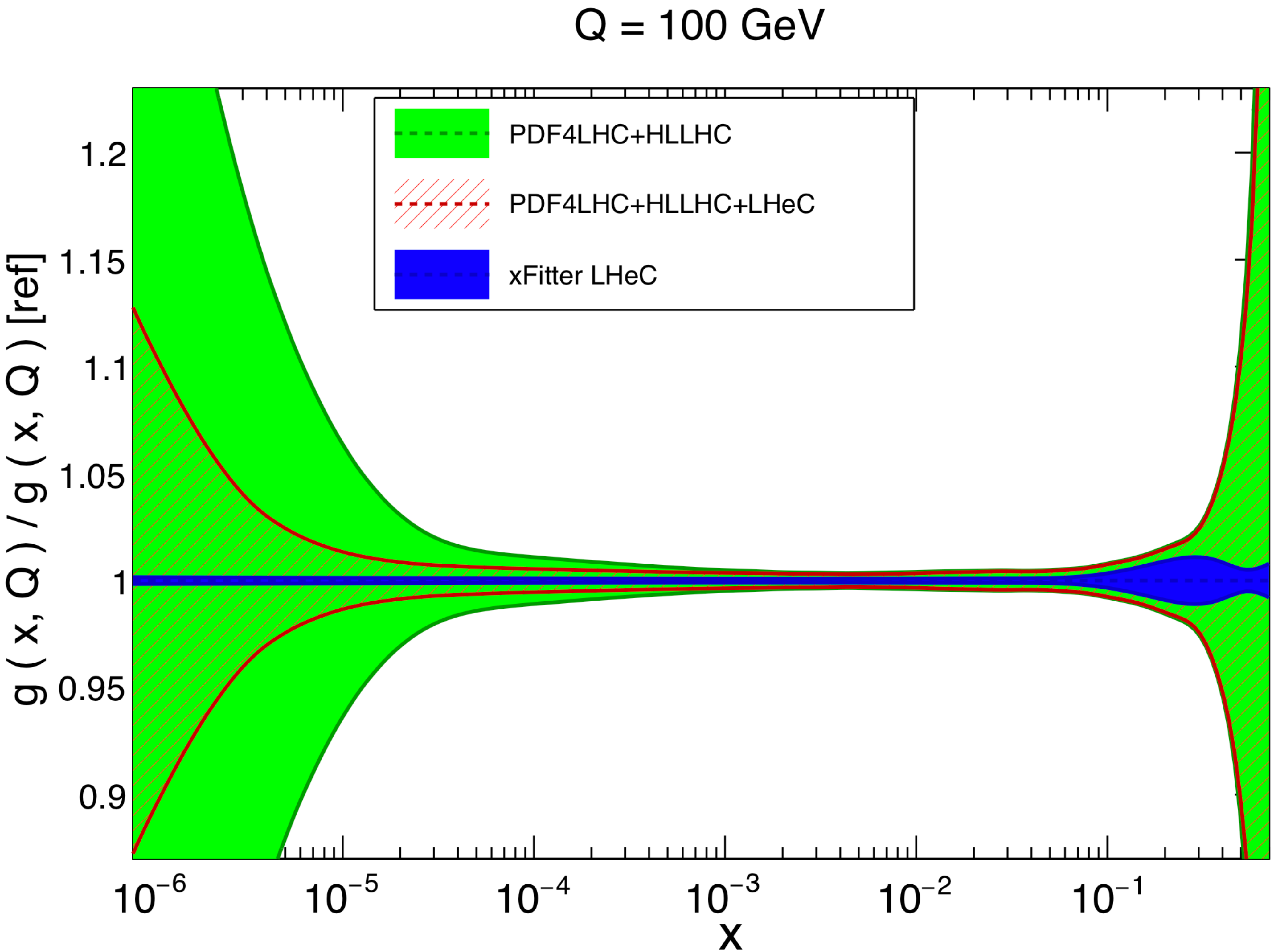
The gluon PDF



Significant impact of LHeC data on PDF4LHC15 when added via profiling

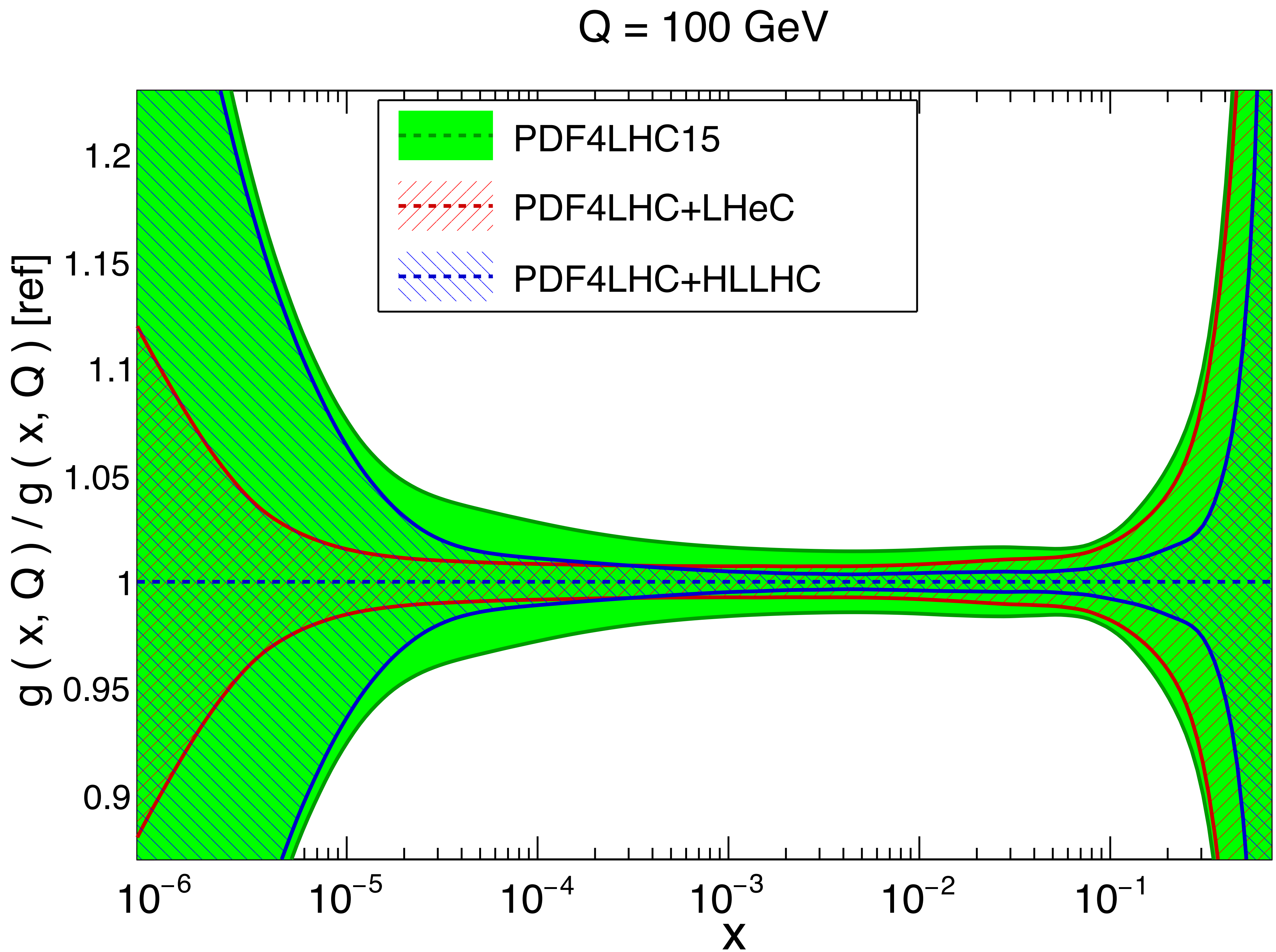
Impact localised at small and medium-x, very moderate impact at large-x

The gluon PDF



When HL-LHC pseudo-data also included, LHeC impact restricted to $x < 10^{-3}$

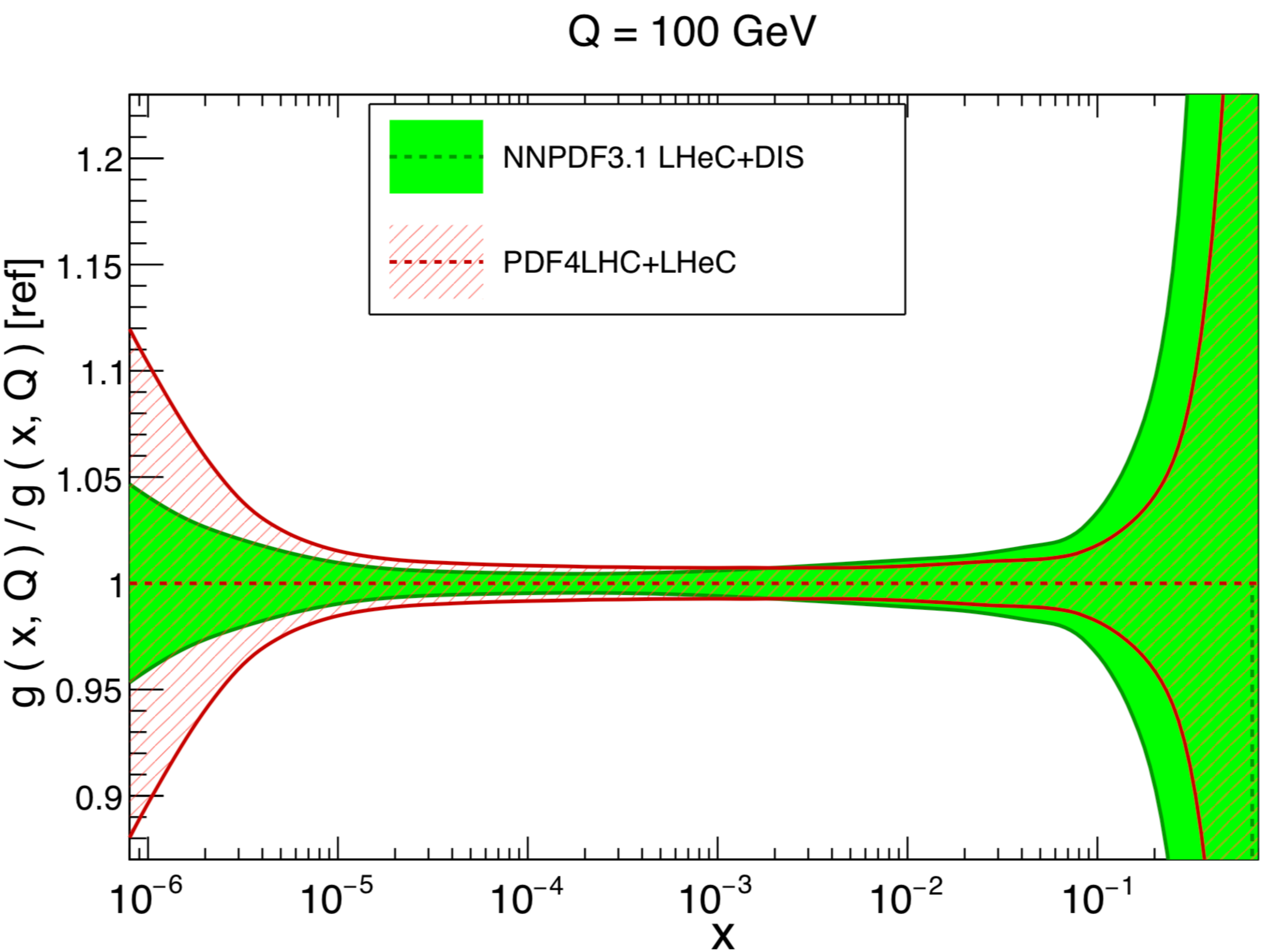
The gluon PDF



The impact of LHeC and HL-LHC data on PDFs is complementary (and comparable at medium x)

HL-LHC constrains dominate for $x > 10^{-3}$, while LHeC dominates for $x < 10^{-3}$

The gluon PDF

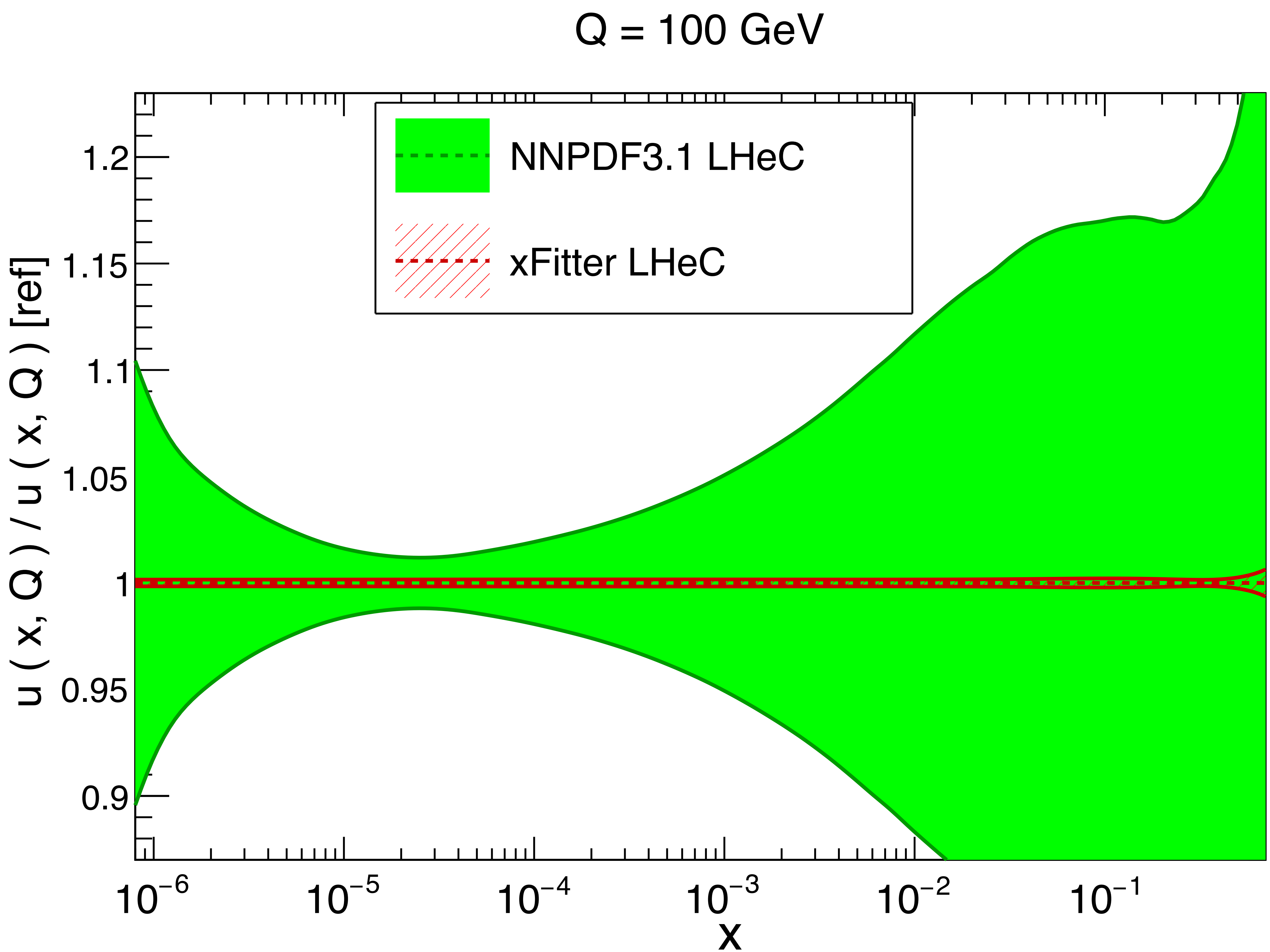


Note the rather ***different PDF priors*** *in this comparison*

The NNPDF3.1 LHeC+DIS fits are similar to the profiled PDF4LHC15+LHeC results

No major differences between fitting and profiling, same qualitative behaviour

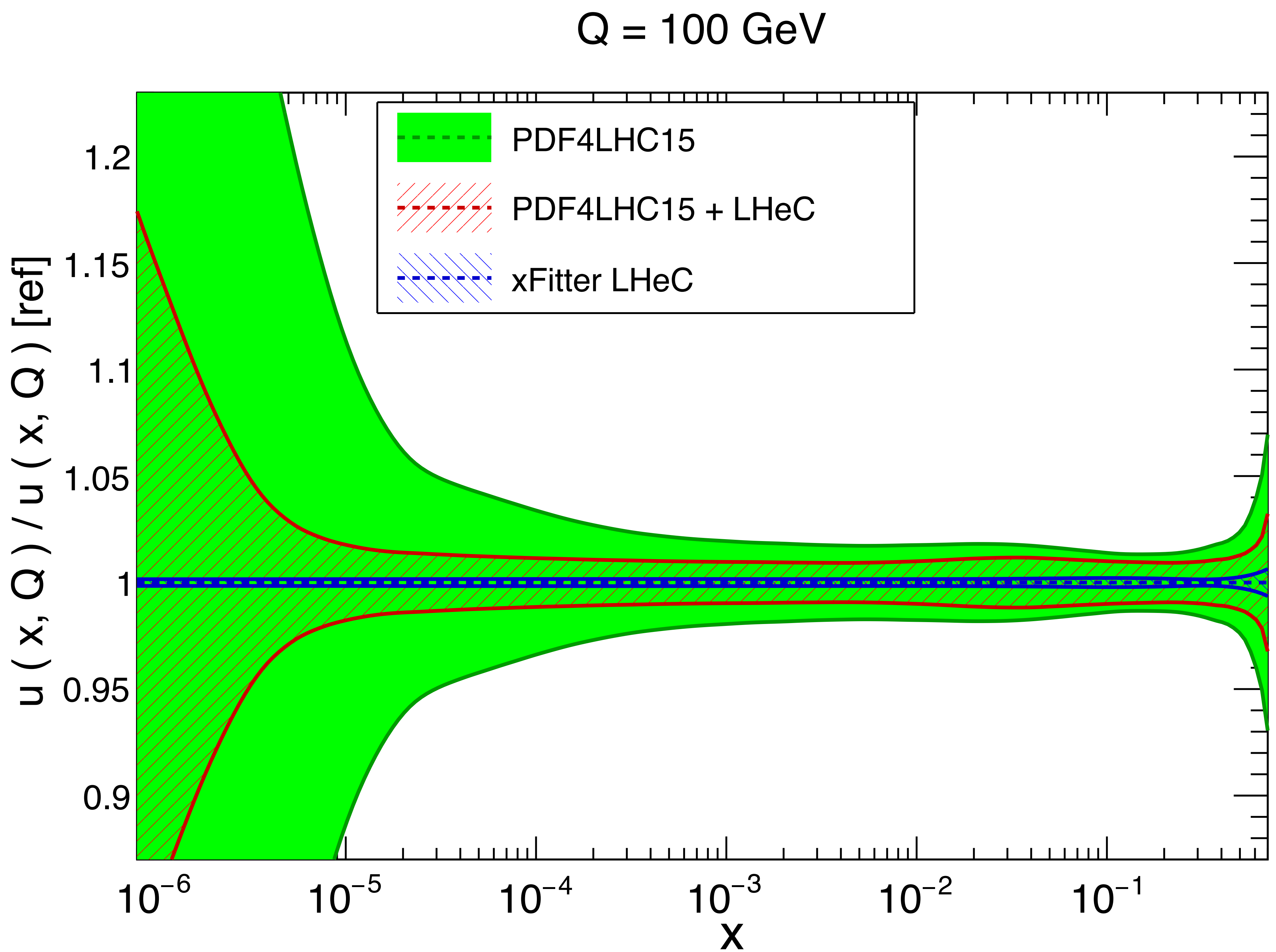
The up quark PDF



For fits based on identical datasets, large differences between the NNPDF and xFitter approaches

Unless specific assumptions adopted, quark flavour separation from inclusive LHeC data is challenging

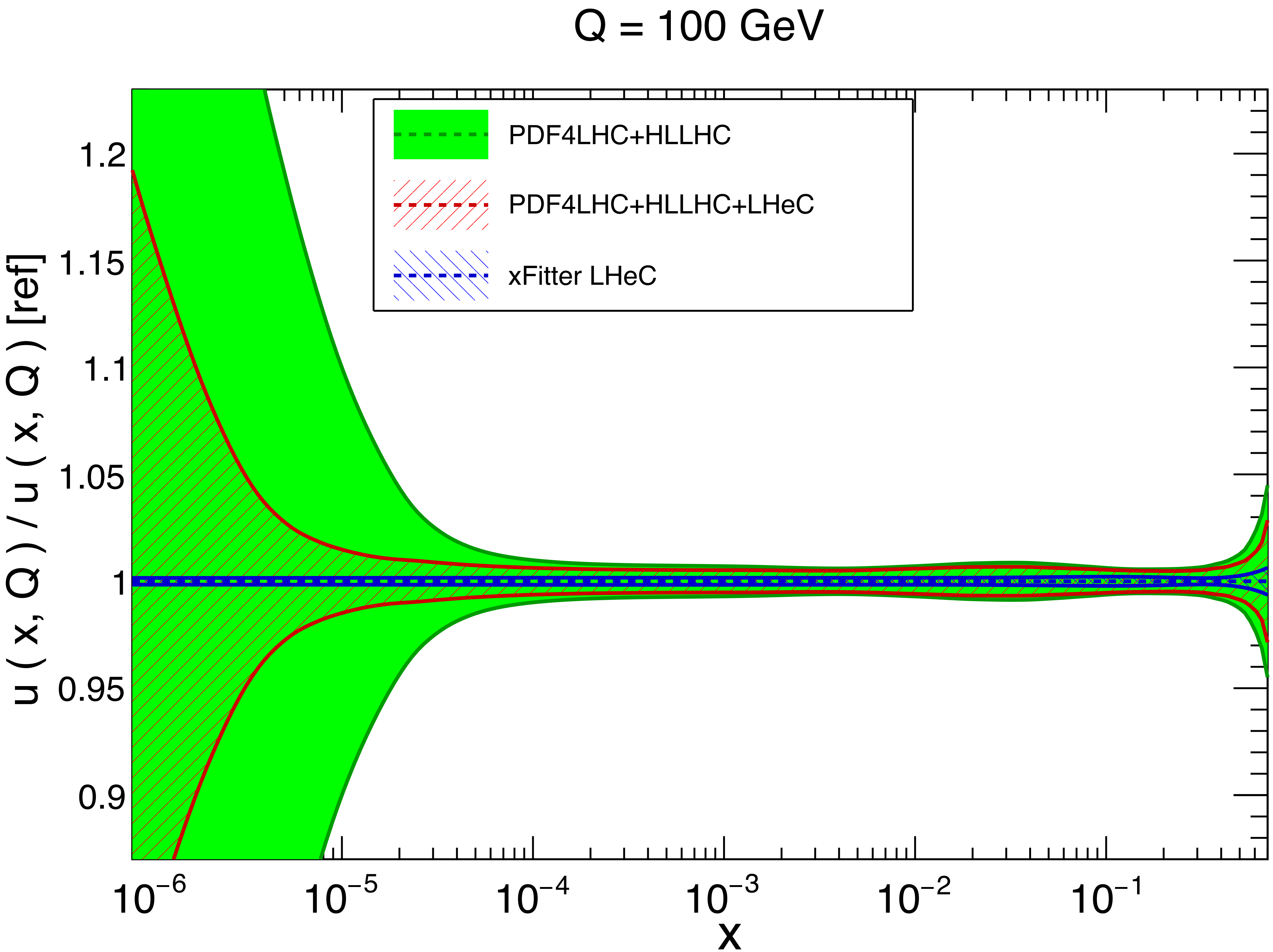
The up quark PDF



Significant impact of LHeC data on PDF4LHC15 when added via profiling

Impact specially marked at small-x, but also PDF error reduction at medium and large-x

The up quark PDF

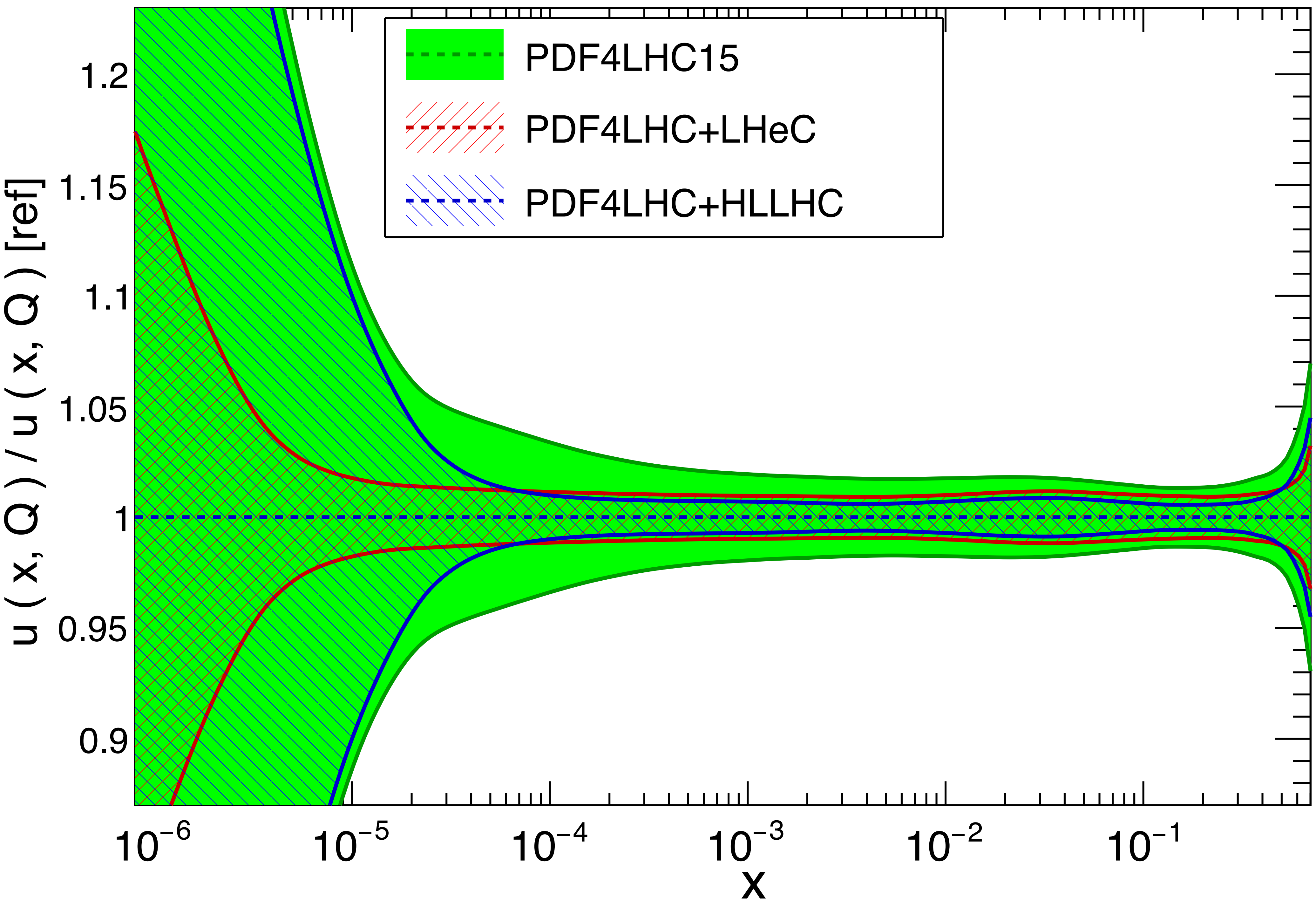


When HL-LHC pseudo-data also included, LHeC impact restricted to $x < 10^{-4}$

The xFitter small-x results seem to be driven by assumptions on PDF functional form

The up quark PDF

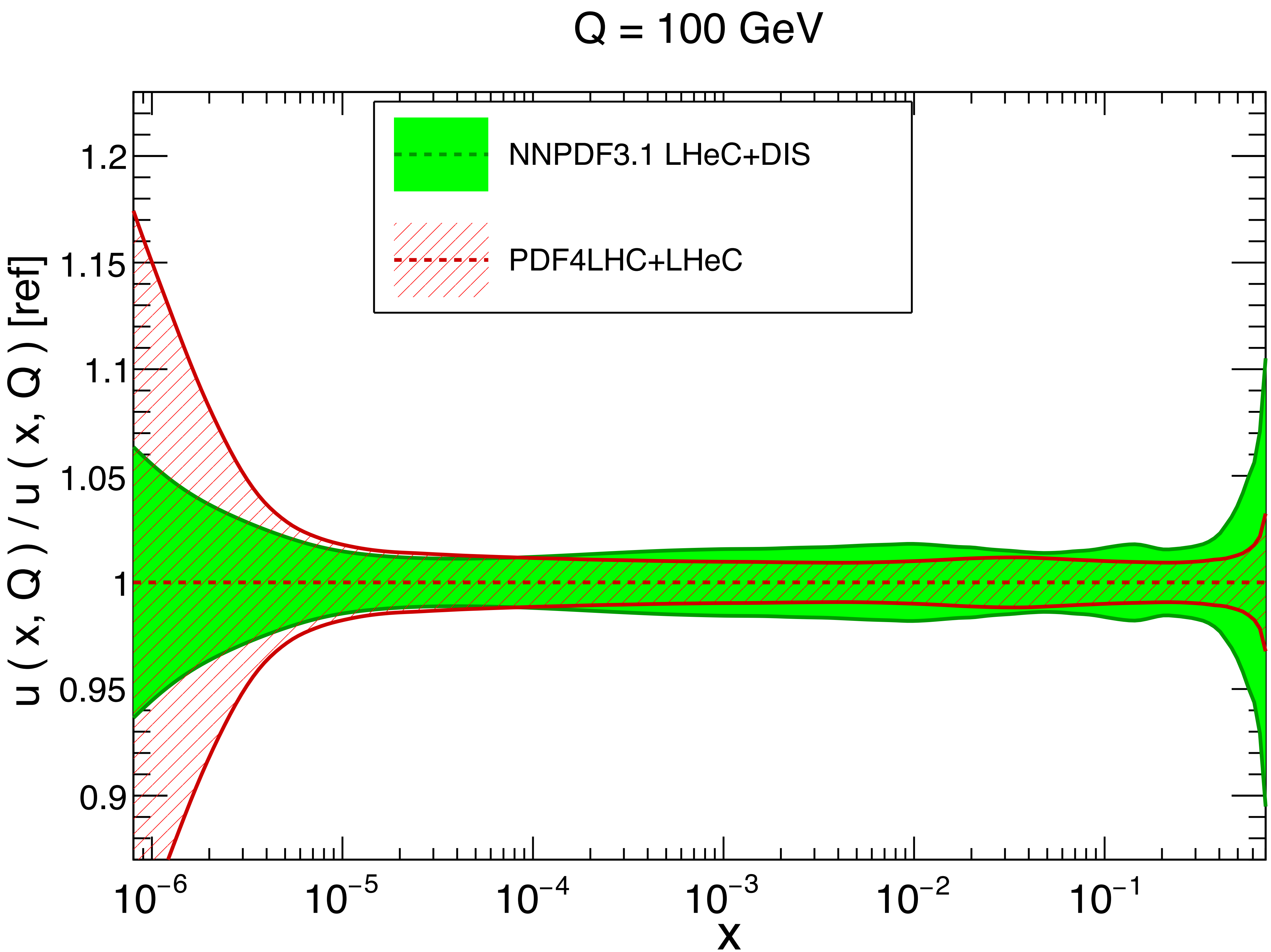
Q = 100 GeV



As for the gluon, the impact of LHeC and HL-LHC data on PDFs is complementary

HL-LHC and LHeC constrains similar for $x > 10^{-4}$, LHeC dominates for $x < 10^{-4}$

The up quark PDF



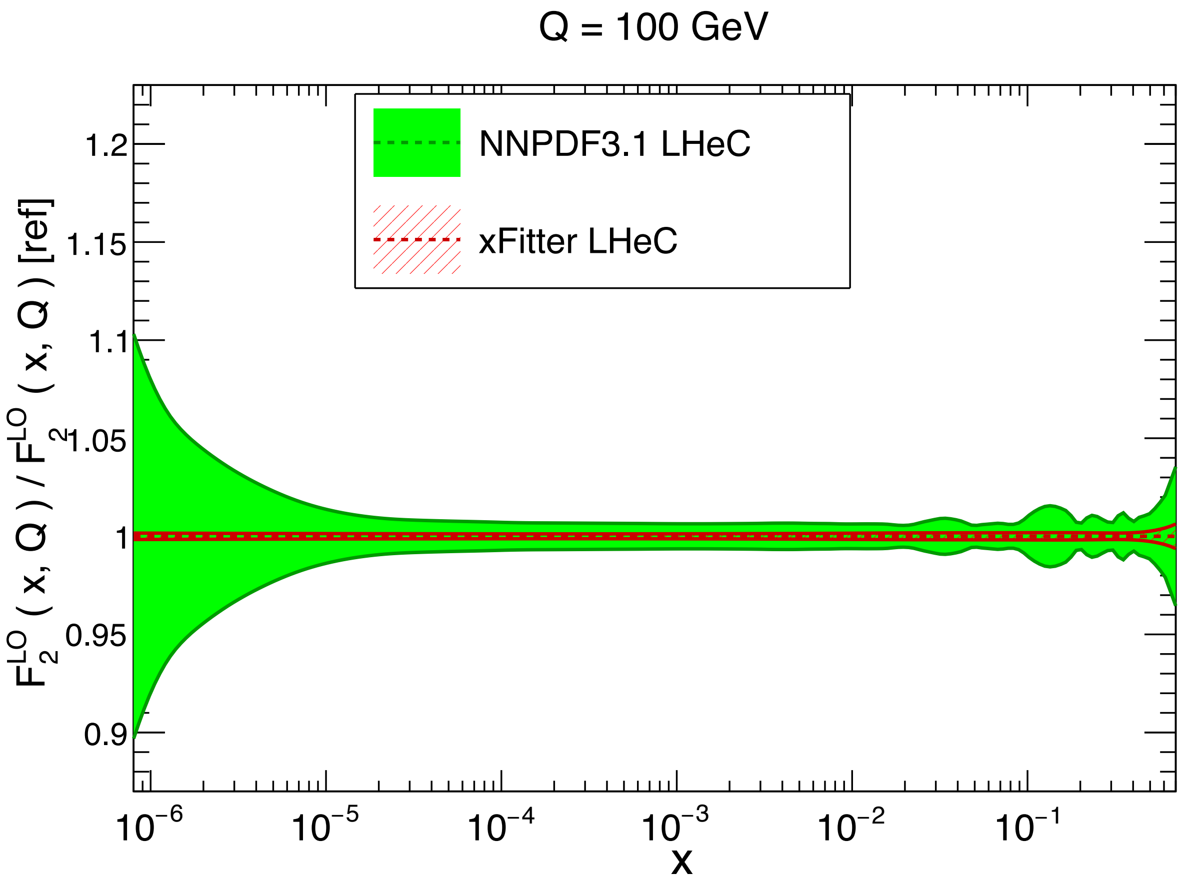
Note the rather ***different PDF priors*** *in this comparison*

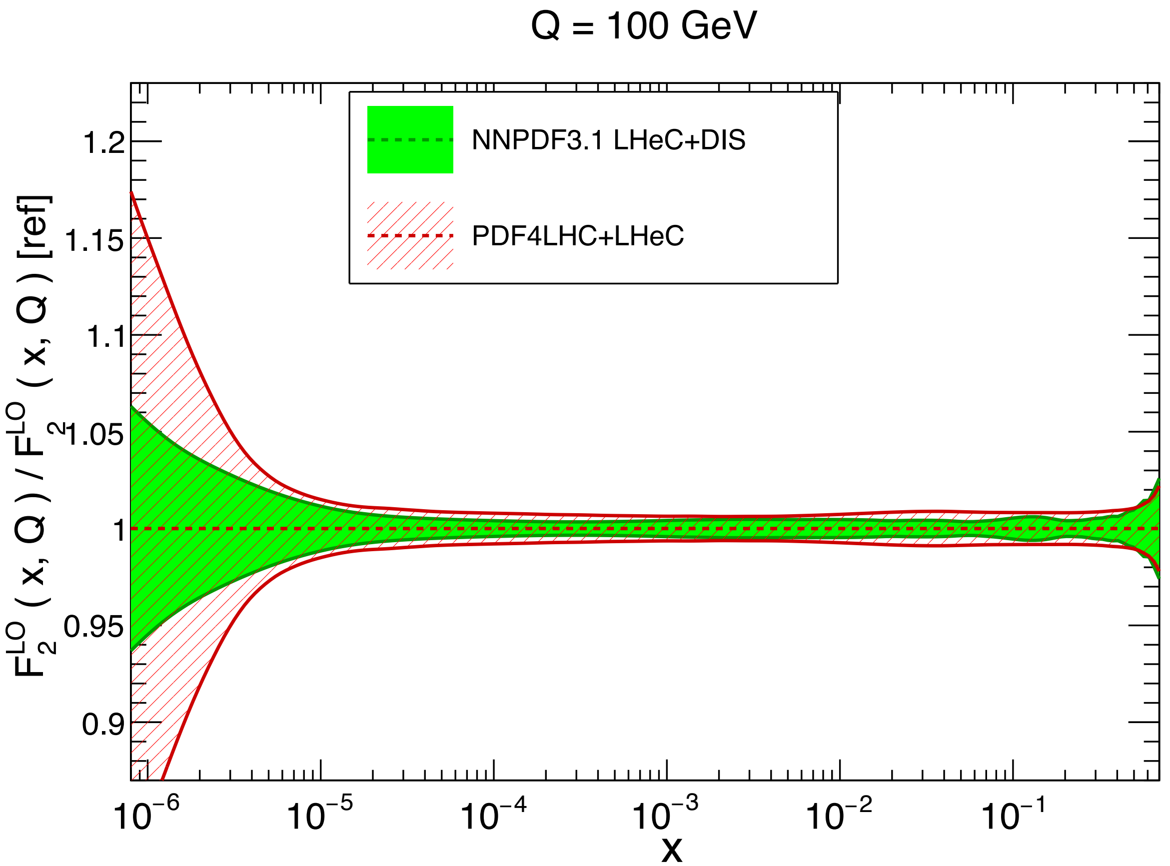
The NNPDF3.1 LHeC+DIS fits are similar to the profiled PDF4LHC15+LHeC results

No major differences between fitting and profiling, similar qualitative behaviour

What is LHeC constraining?

$$F_2^{\mathrm{LO}}(x,Q) \equiv \frac{4}{9}\left(u^+(x,Q) + c^+(x,Q)\right) + \frac{1}{9}\left(d^+(x,Q) + s^+(x,Q) + b^+(x,Q)\right)$$



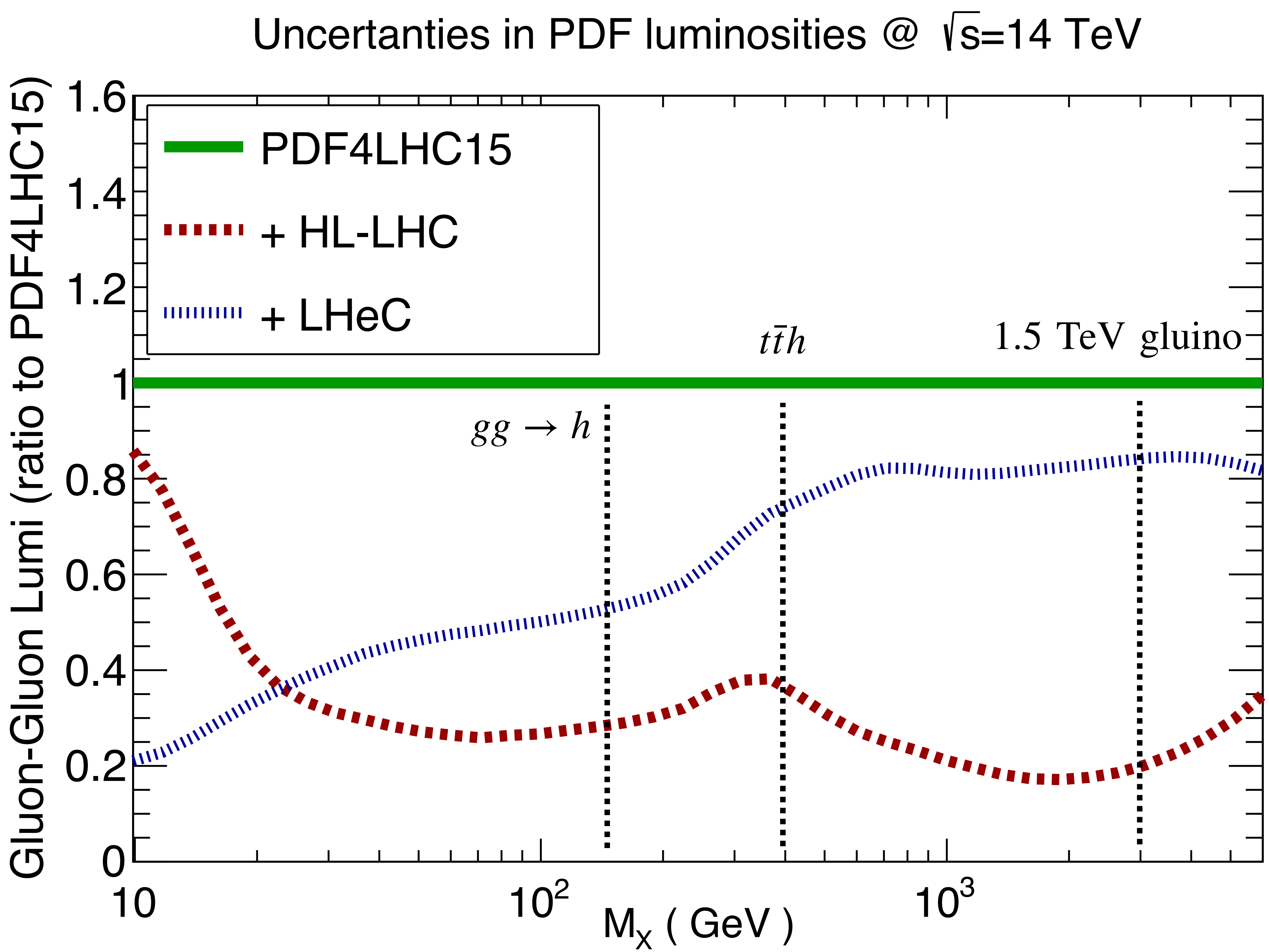


*Differences reduced if one plots the **quark flavour combination** directly constrained by LHeC*

Additional processes beyond DIS required to pin down i) quark-flavour separation and ii) large-x gluon

Implications for LHC pheno

Compare impact of profiling PDF4LHC15 with either HL-LHC or LHeC pseudo-data



Implications for LHC pheno

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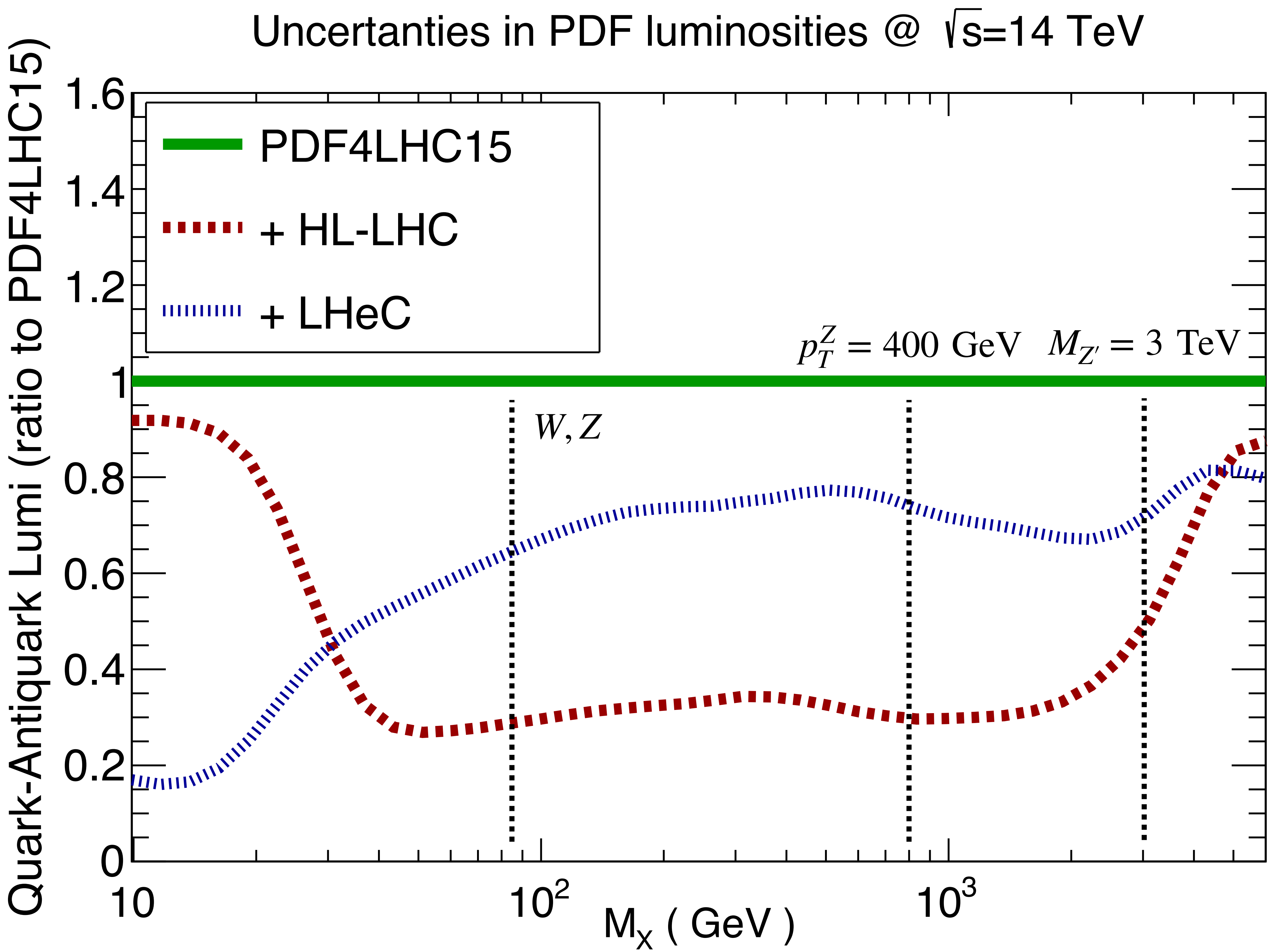
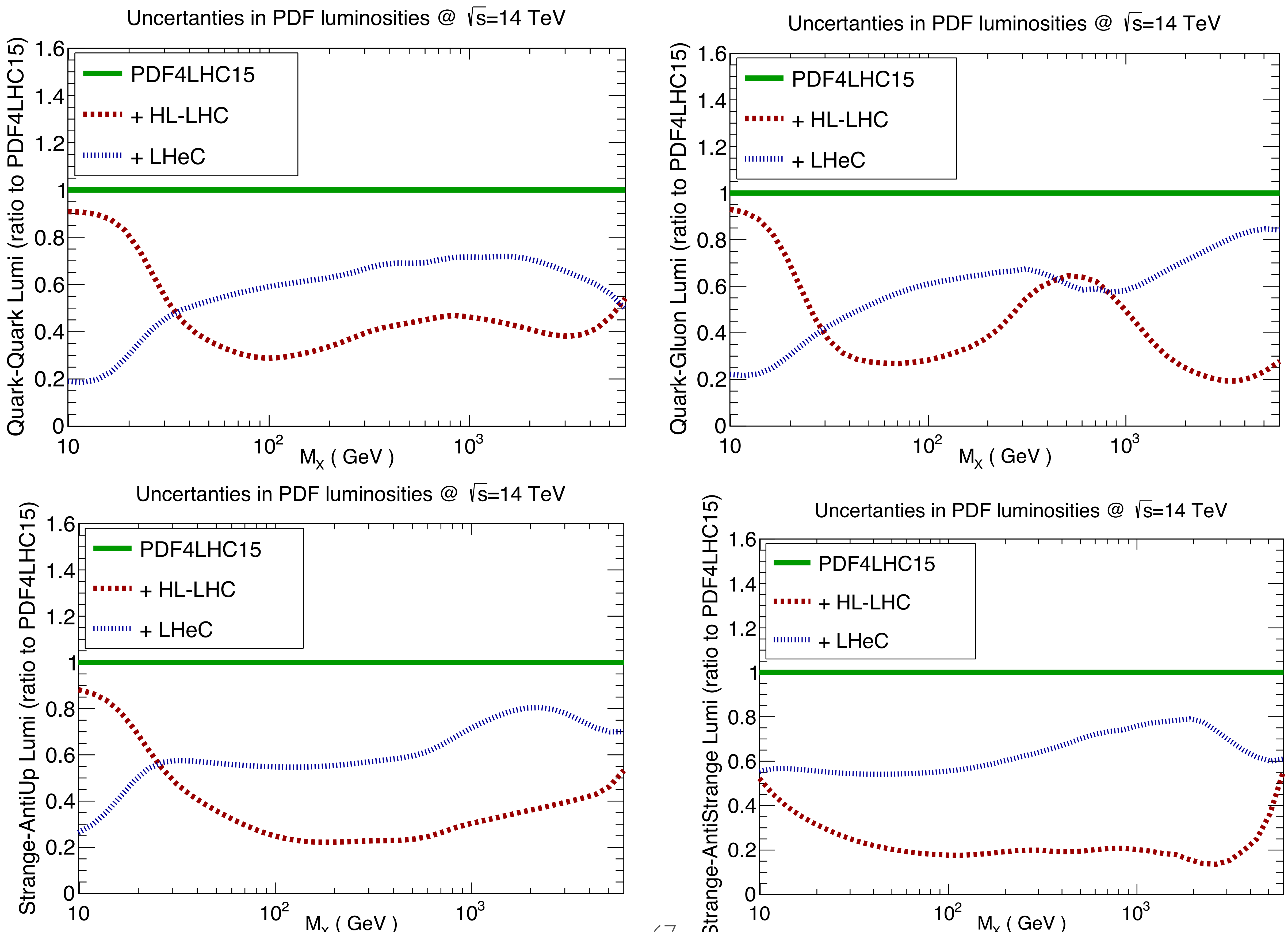
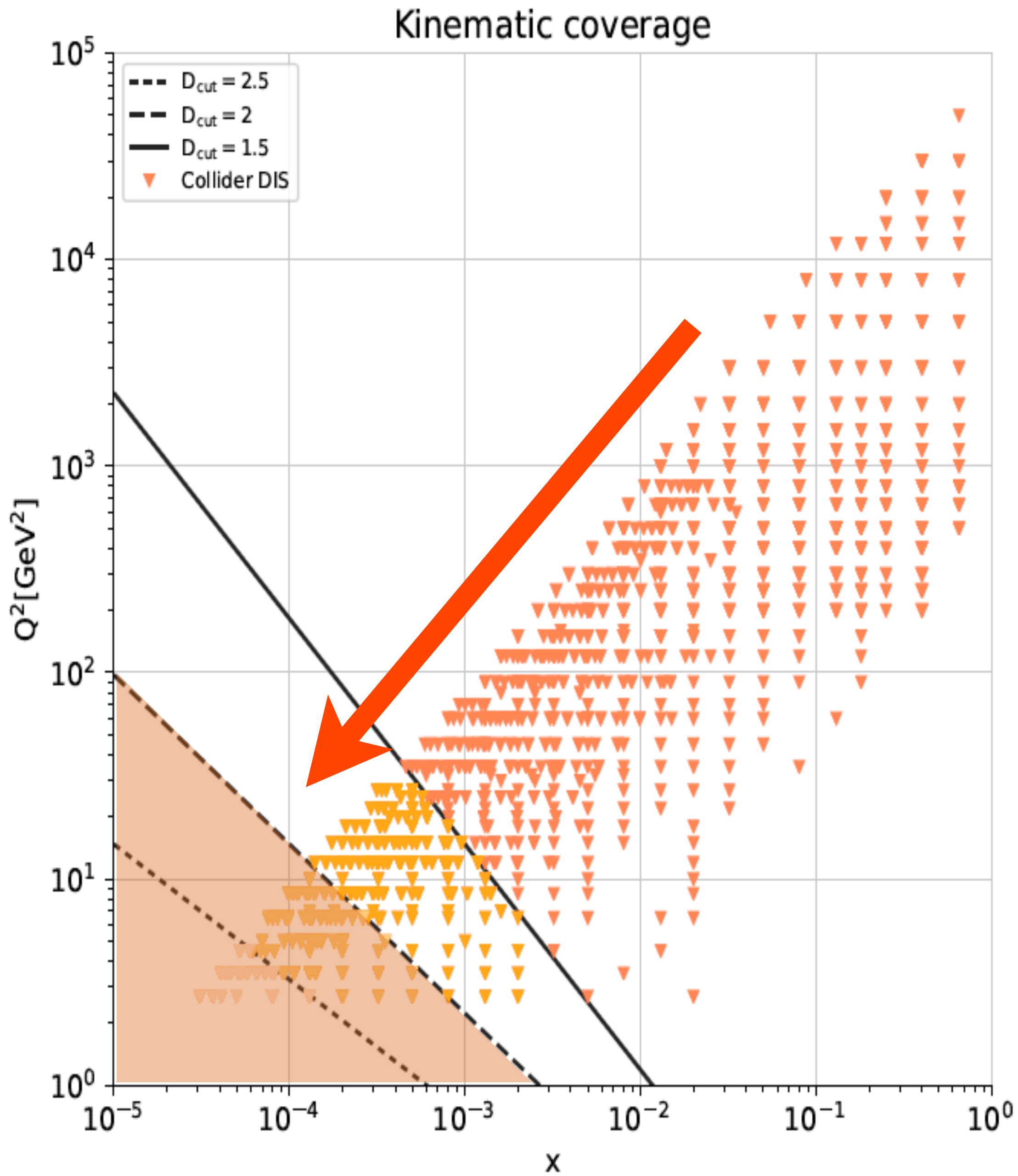


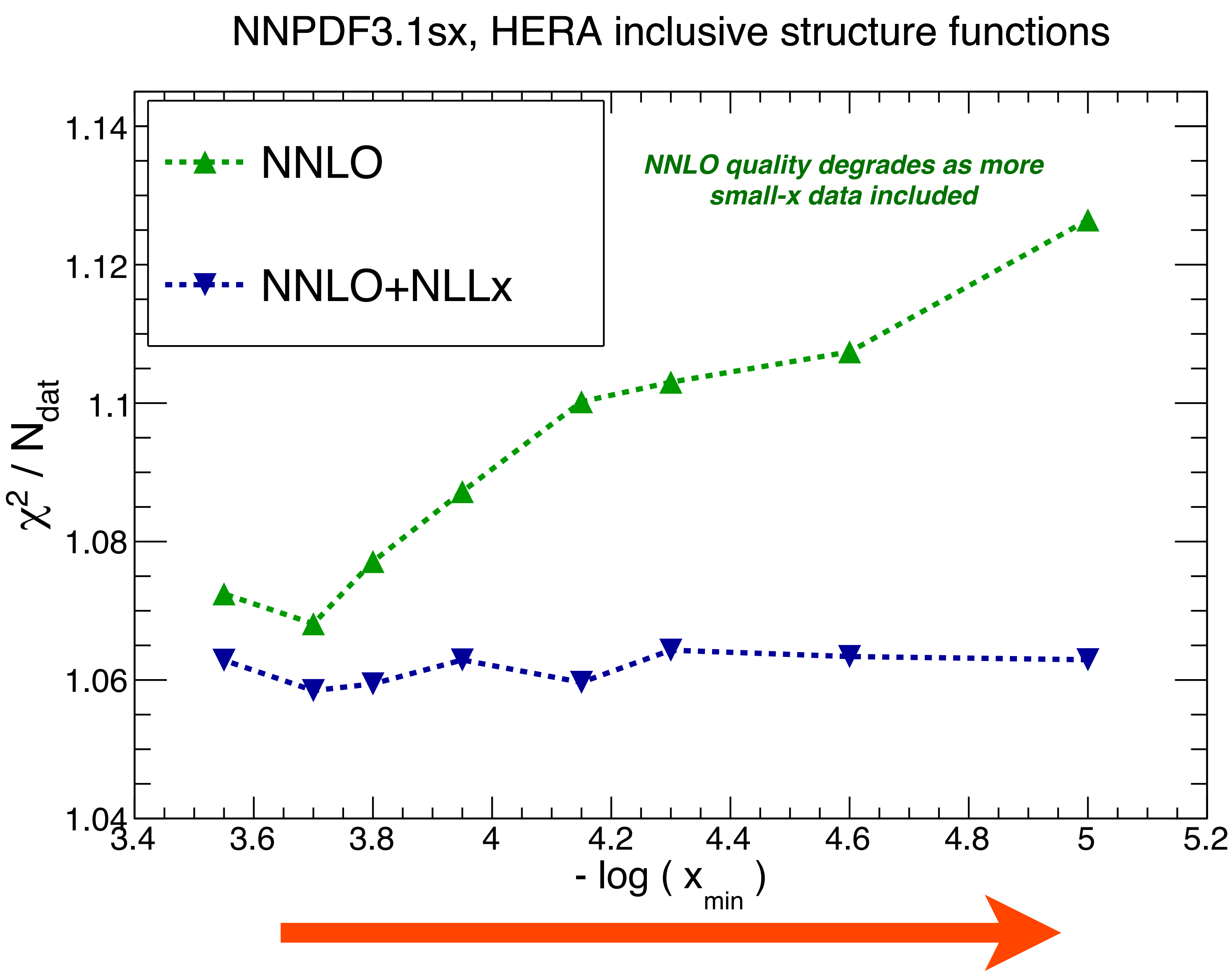
Implications for LHC pheno



Novel QCD dynamics at small-x

Ball, Bertone, Bonvini, Marzani, JR, Rottoli 17, see also xFitter 18

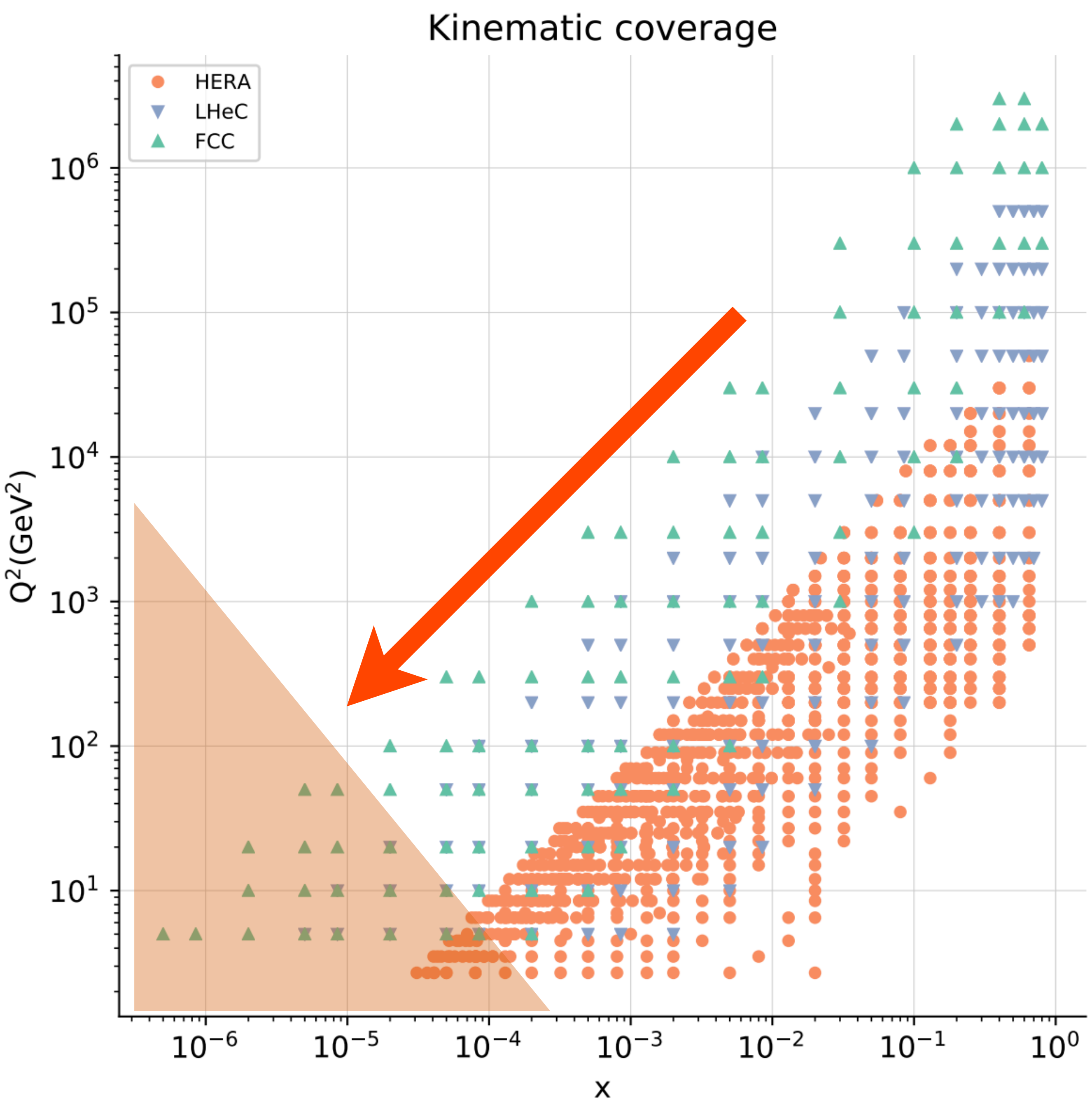


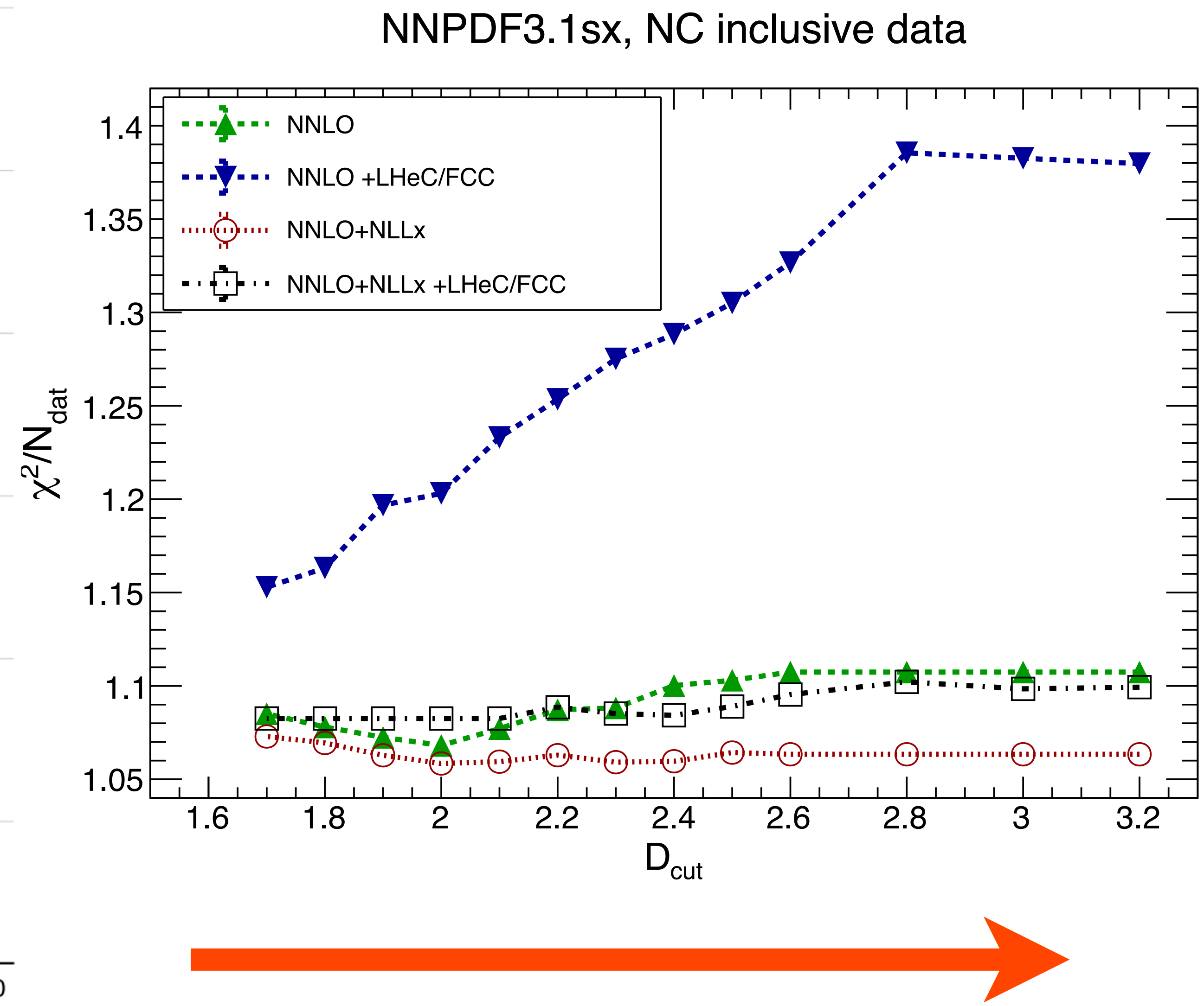


Monitor the **fit quality** as one includes more data from the **small-*x* region**

Best description of **small-*x* HERA data** only possible with **BFKL effects!**

Novel QCD dynamics at small-x





Monitor the **fit quality** as one includes more data from the **small-*x* region**

BFKL effects essential to describe LHeC data at small-*x*

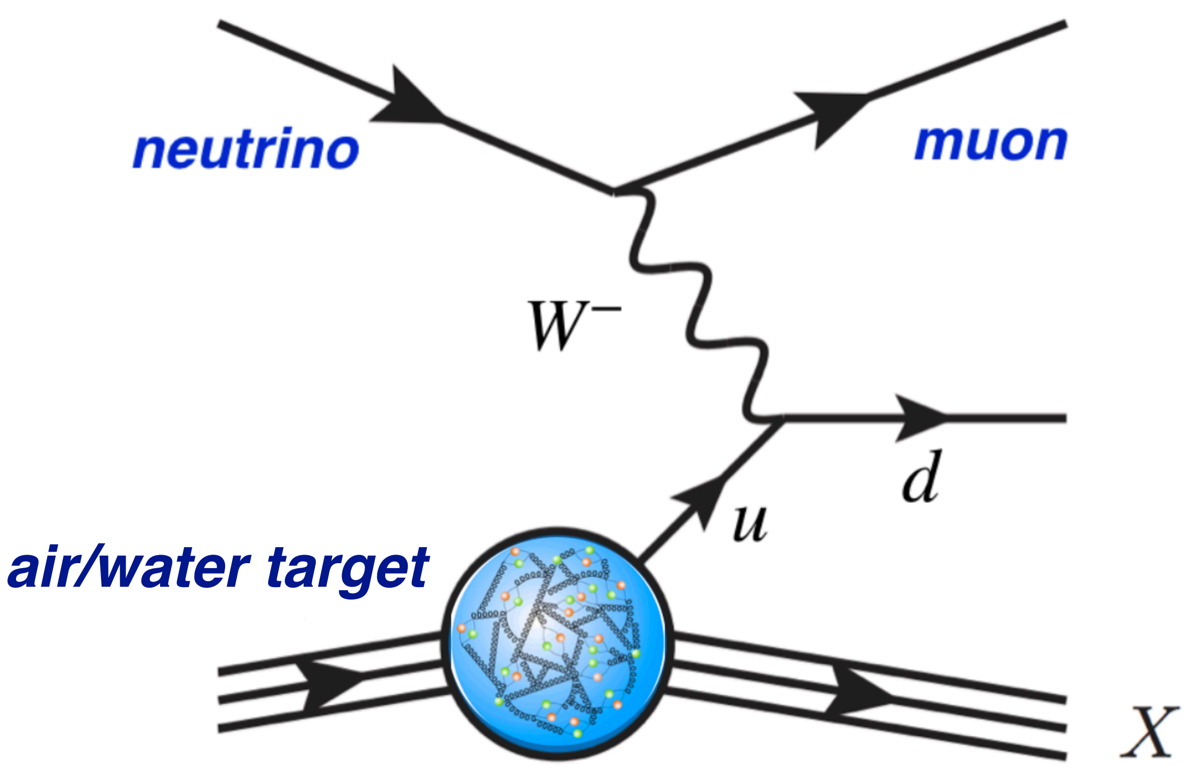
Impact for neutrino astronomy

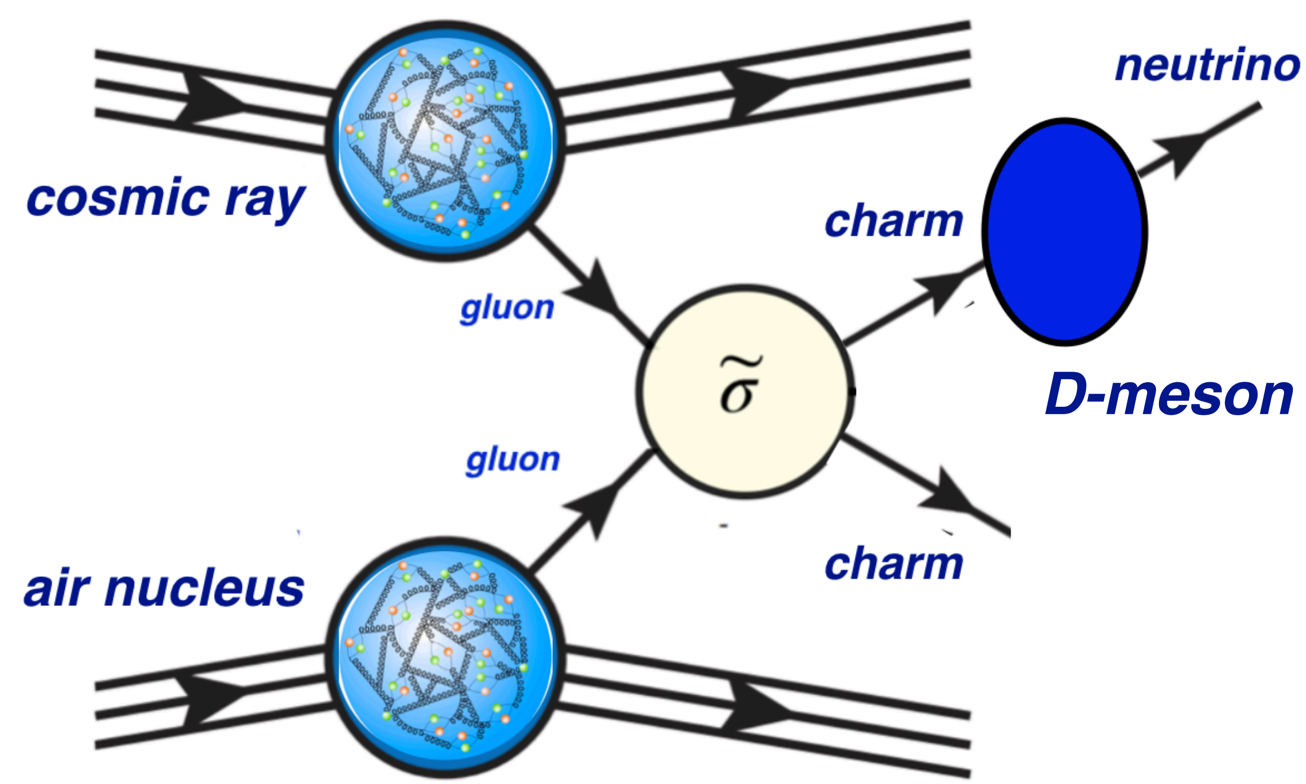

Science
Life and Physics

Jon Butterworth
@jonmbutterworth
Thu 28 Dec 2017 17.30 GMT

After 40 years of studying the strong nuclear force, a revelation

This was the year that analysis of data finally backed up a prediction, made in the mid 1970s, of a surprising emergent behaviour in the strong nuclear force





Sensitive to **small-x quarks** (and thus gluons) down to **$x \simeq 10^{-8}$**

Sensitive to **small-x gluons** down to **$x \simeq 10^{-6}$** and **$Q \simeq M_{charm}$**

Summary

- **Very different estimates** for the PDF uncertainties in the LHeC-only fits found when using NNPDF methodology as compared to the xFitter approach

- The picture s that of **complementarity** between HL-LHC and LHeC, with the former dominating for $\mathbf{x > 10^{-2}}$, the latter for $\mathbf{x < 10^{-4}}$, and similar impact for $\mathbf{10^{-4} < x < 10^{-2}}$

- Similar qualitative impact of LHeC data in NNPDF fits and in PDF4LHC15 profiling studies

- We are not able to **reproduce the current xFitter-based LHeC estimates** not even at the qualitative level (due overly restrictive parametrisation?). The projections appear to be too optimistic, specially in the large-x region (*e.g.* DIS-only provides little constraints on gluon)

- **LHeC-only fits** cannot achieve a complete determination of the proton structure: for some regions and PDF combinations (large-*x*, flavour separation) the information provided hadronic processes cannot be ignored

- LHeC contains unique opportunities for the study of **novel QCD phenomena at small-x:** BFKL dynamics, saturation and non-linear dynamics, UHE neutrinos, cosmic rays, ….