Towards the ultimate PDF constraints from hadron collider data

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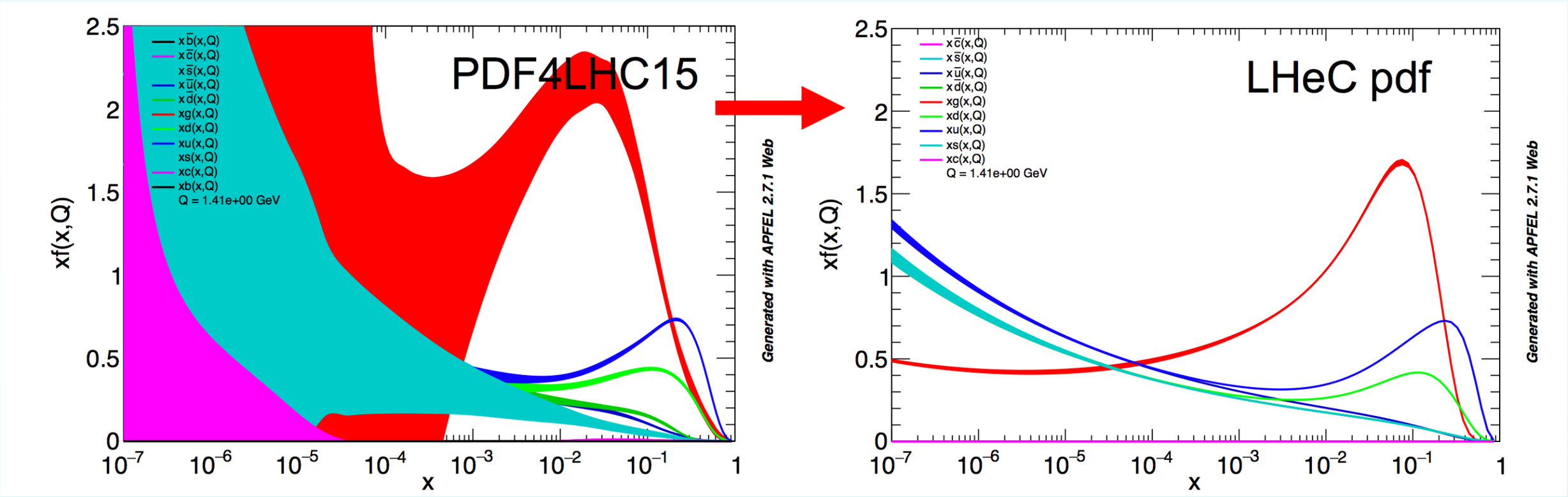
Towards ultimate parton distributions at the HL-LHC

- **LHC measurements** have been shown to provide **stringent constraints on the PDFs**, and they are nowadays an essential ingredient of the global PDF analyses toolbox

- How far we can go in this direction? What is the ``*ultimate*'' constraining power on the PDFs of hadron colliders? How much we can **reduce PDF errors based on HL-LHC data alone**?

*Our goal is to carry out a **PDF sensitivity analysis** similar to that of **LHeC/FCC-eh studies***



*For the first time, PDF prospects will be quantified systematically for **future proton-proton colliders***

The strategy

Generate **NLO APPLgrids** and the corresponding pseudo-data for HL-LHC

Explore different options for **binning** and **systematic uncertainties**

↓

Quantify the impact of the individual processes on the

PDF4LHC15 set using Hessian Profiling

↓

Combine all pseudo-data and perform a joint profiling to construct the

``PDF4LHC_HLLHC'' sets in different scenarios for the pseudo-data

↓

Make the resulting sets **available via LHAPDF** so that they can be

used in related studies for the upcoming **Yellow Report**

PDF-sensitive processes at the HL-LHC

Our analysis is based on a **non-exhaustive** list of **PDF-sensitive processes** at the HL-LHC, with emphasis on **high-p_T region,** and on measurements that are not already **limited by systematic uncertainties**

Process	Kinematics	$N_{\rm dat}$	
Z p_T	$20\,\text{GeV} \leq p_T^{ll} \lesssim 3.5$ TeV $12\,\text{GeV} \leq m_{ll} \leq 150$ GeV $\lvert y_{ll}\rvert \leq 2.4$	130	→ *medium-x gluon*
high-mass Drell-Yan	$m_{ll} \geq 116\,\text{GeV},\ \lvert\eta_l\rvert < 2.5$ $p_T^{l1(2)} \geq 40\ (30)$	21	→ *antiquarks*
top quark pair	$m_{t\bar{t}} \lesssim 5$ TeV, $\lvert y_t\rvert \leq 2.5$	26	→ *large-x gluon*
W+charm (central)	$p_T^{\mu} \geq 26\,\text{GeV},\ p_T^{c} \geq 5\,\text{GeV},$ $\lvert\eta^{\mu}\rvert \leq 2.4$	6	→ *strangeness*
W+charm (forward)	$p_T^{\mu} \geq 20\,\text{GeV},\ p_T^{c} \geq 20\,\text{GeV},\ p_T^{\mu+c} \geq 20\,\text{GeV},$ $2 \leq \eta^{\mu} \leq 2.4,\ 2.2 \leq \eta^{c} \leq 3.2$	12	→ *strangeness*
Direct photon	$E_T^{\gamma} \lesssim 3$ TeV, $\lvert\eta_{\gamma}\rvert \leq 2.5$	60	→ *medium-x gluon*
Forward W, Z	$p_T^{l} \geq 20\,\text{GeV},\ 2.0 < \eta_l < 4.5$ $60 < m_{ll} < 120\,\text{GeV},\ 2.0 < y_{ll} < 4.5$	90	→ *antiquarks*
Inclusive jets ($R = 0.4$)	$\lvert y_{\rm jet}\rvert \leq 3,\ p_T^{\rm jet} \lesssim 4$ TeV	54	→ *large-x gluon*

HL-LHC pseudo-data

- Theoretical predictions computed at **NLO QCD** theory (sufficient for a pseudo-data analysis)
- Based on the theory predictions provided by PDF4LHC15, generate **HL-LHC pseudo-data** with a sensible binning taking recent 8 TeV and 13 TeV LHC measurements as reference
- Explore different assumptions (conservative to optimistic) for the expected reduction of experimental **systematic uncertainties** (without attempting to construct an explicit correlation model)

$$\sigma_i^{\rm exp} = \sigma_i^{\rm th} \times \left(1 + r_i \cdot \delta_{{\rm tot},i}^{\rm exp}\right)$$

MCFM+PDF4LHC15

Gaussian fluctuations

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

Systematic error from reference LHC measurement

Total exp error *Total stat error* *effective correlation* *Assumed reduction of exp systs*

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

PDF profiling

- The impact of the HL-LHC pseudo-data on the PDF4LHC15 set is quantified with **Hessian Profiling**, based on the minimisation of the figure of merit

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

Total exp error

Exp data nuisance parameters

Hessian PDF nuisance parameters

Effective Tolerance

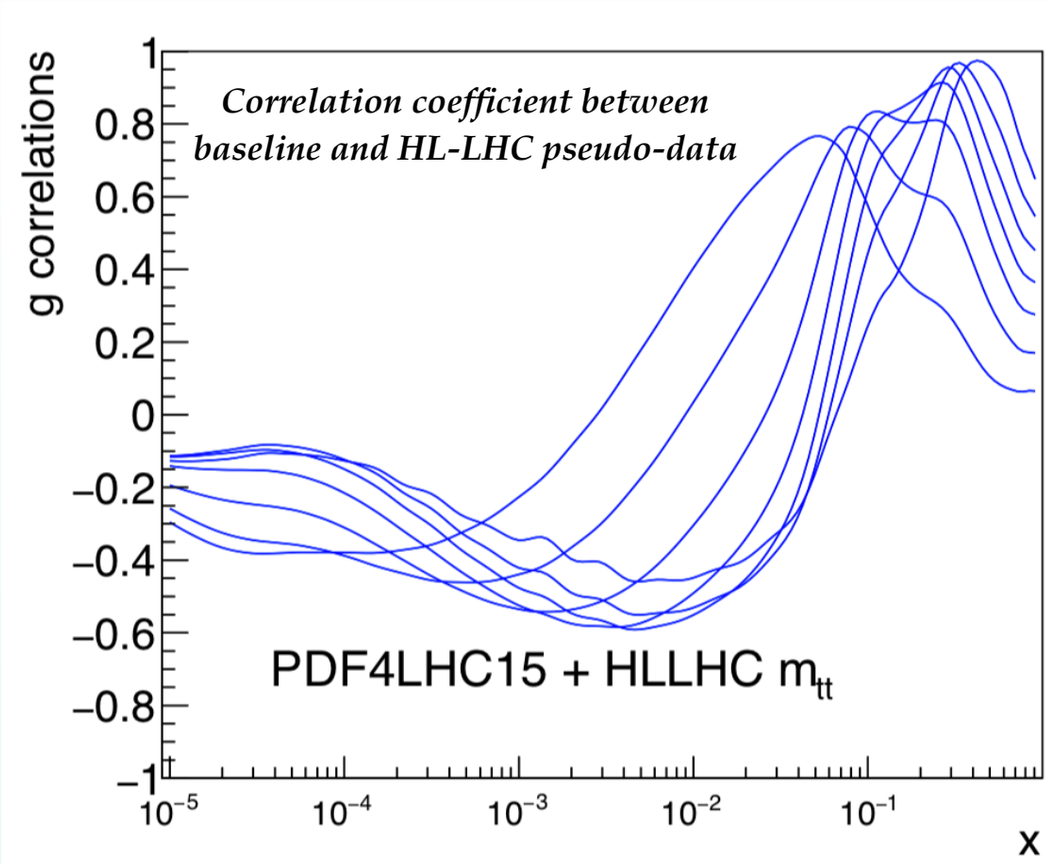
- Only luminosity uncertainties treated as fully correlated, other systematic errors added in quadrature to statistical errors (plus one extra syst for forward W+c).

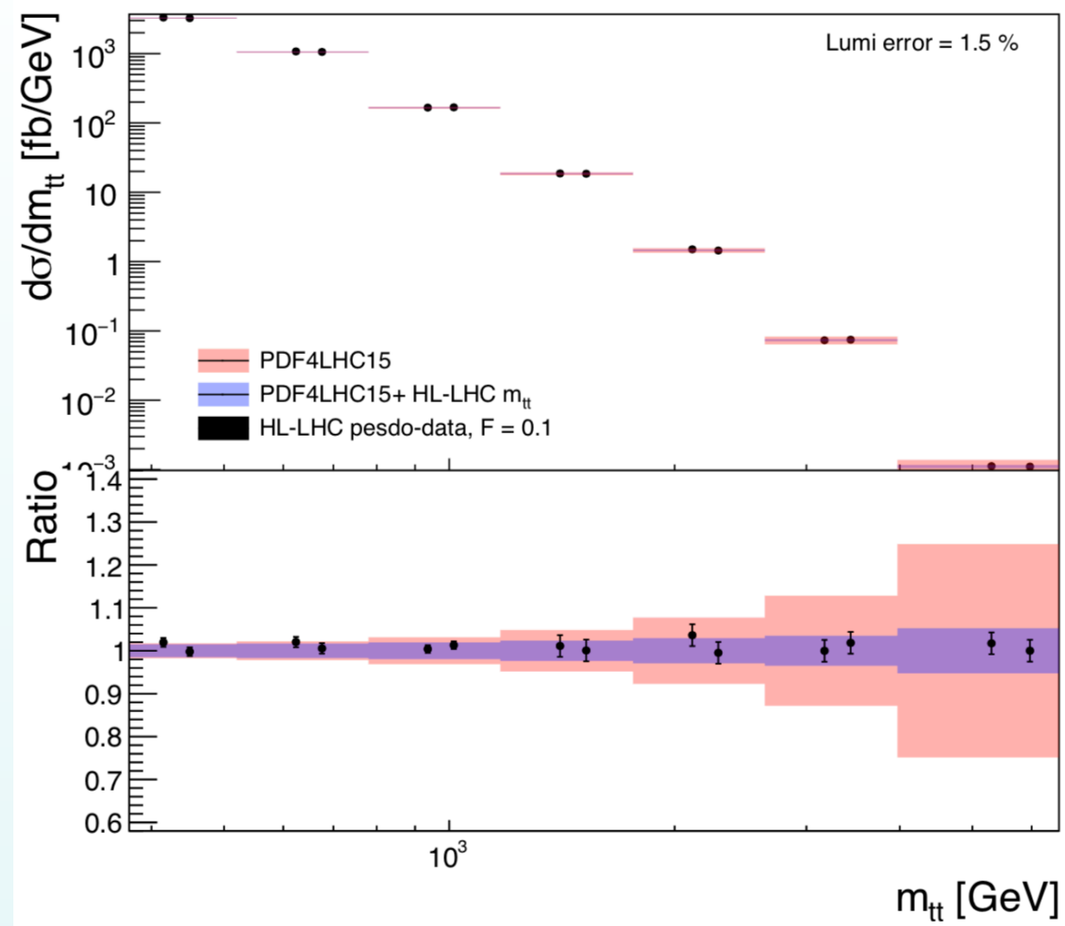
- The **effects of correlations** is added by means of $f_{\rm corr} \simeq 0.4 - 0.5$, determined from the 8 TeV LHC top quark pair production data

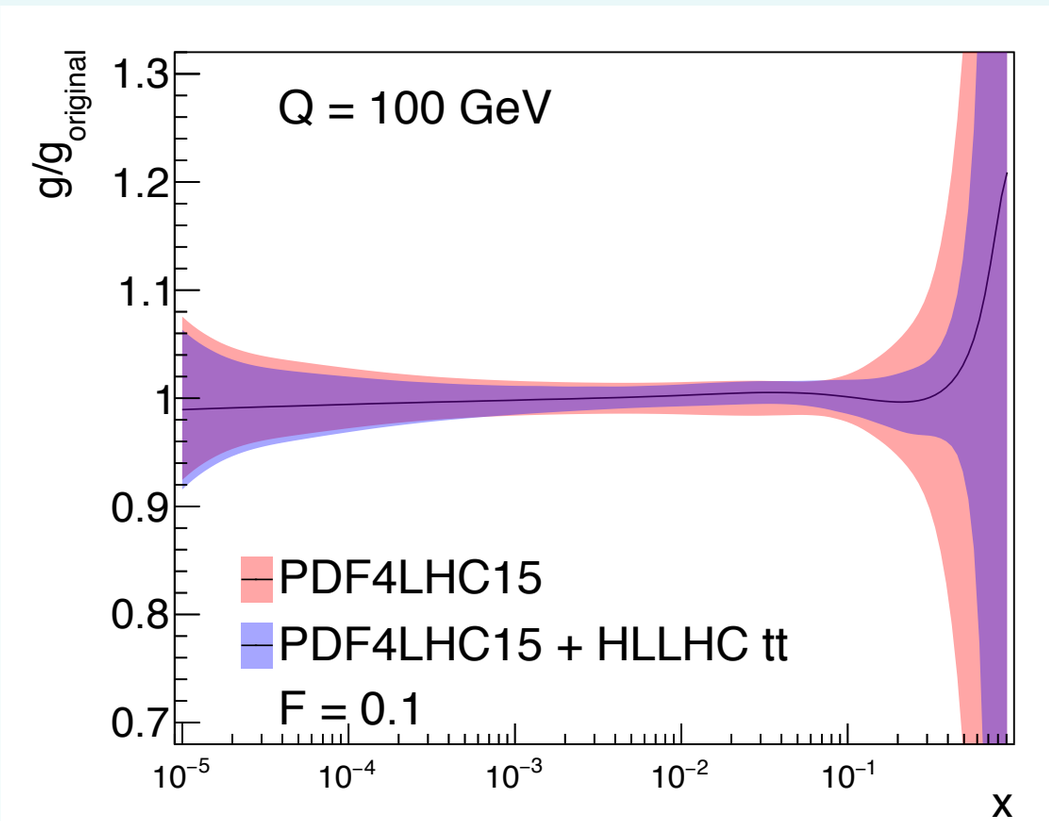
- We adopt an **effective tolerance of *T*=3,** which corresponds to the average of the dynamic tolerances determined in the CT14 and MMHT14 analyses

- For measurements in the **central region**, assume total lumi of **L=6 ab^{-1}** (ATLAS + CMS). For LHCb pseudo-data assume **L=300 fb^{-1}**

Top quark pair production

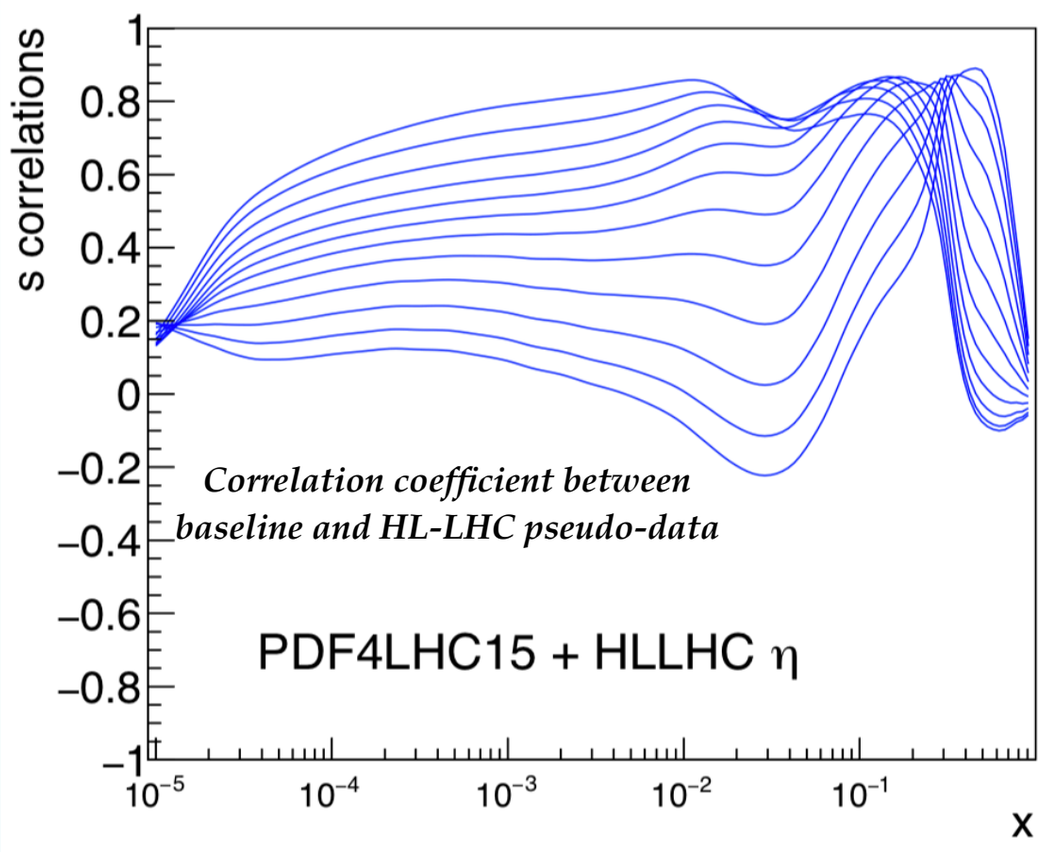


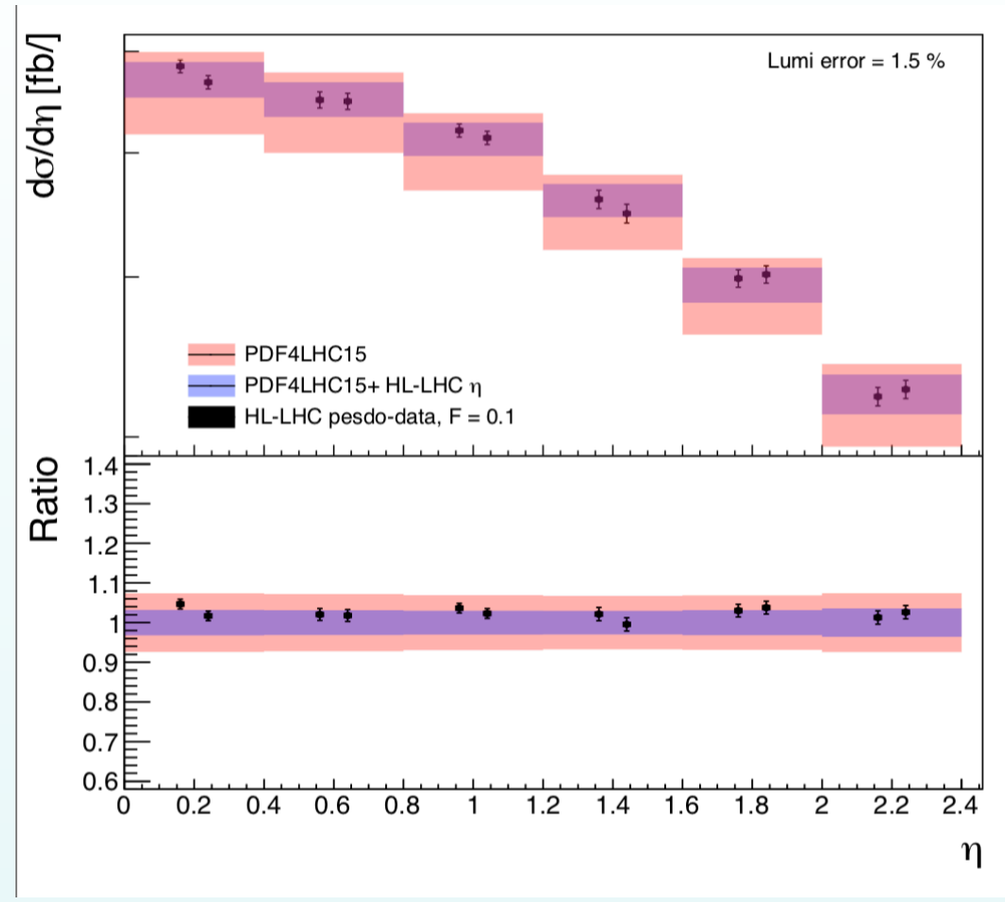


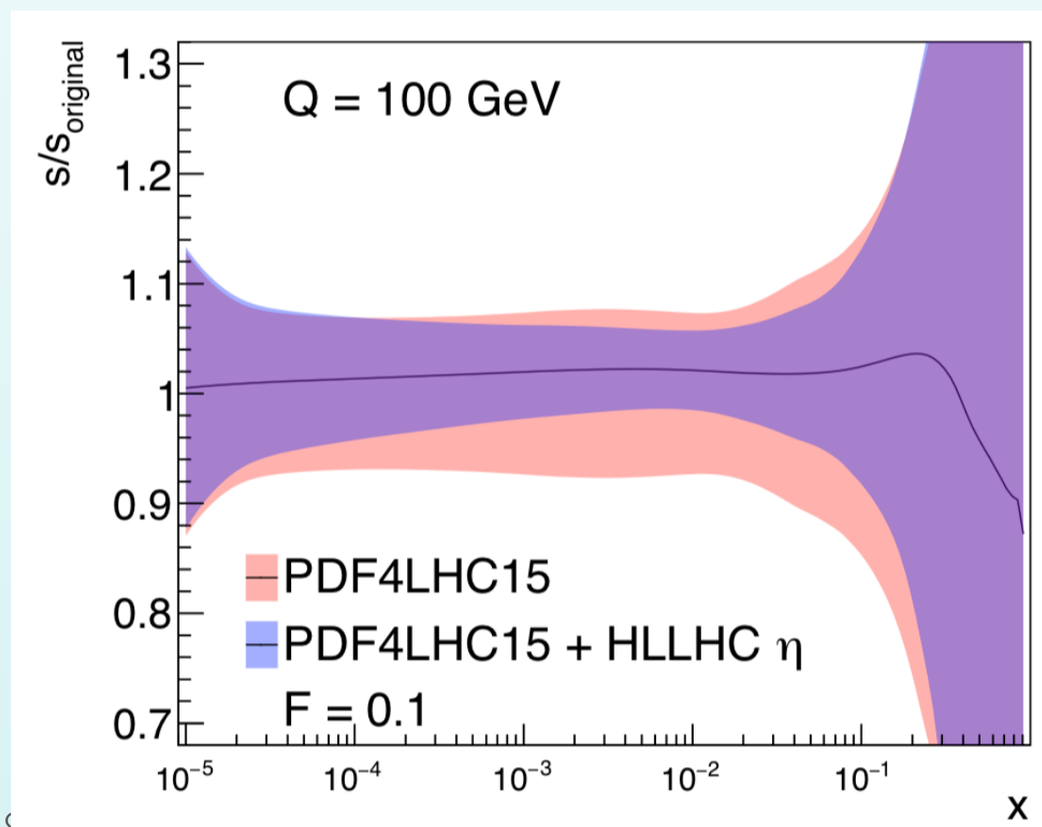


- Instrumental to pin down the **gluon at very large *x*** (m_{tt} reach up to **6 TeV**)
- The kinematical coverage can extend up to **several TeV** at the HL-LHC
- Promising results even without assuming any reduction in systematic errors

W+charm production



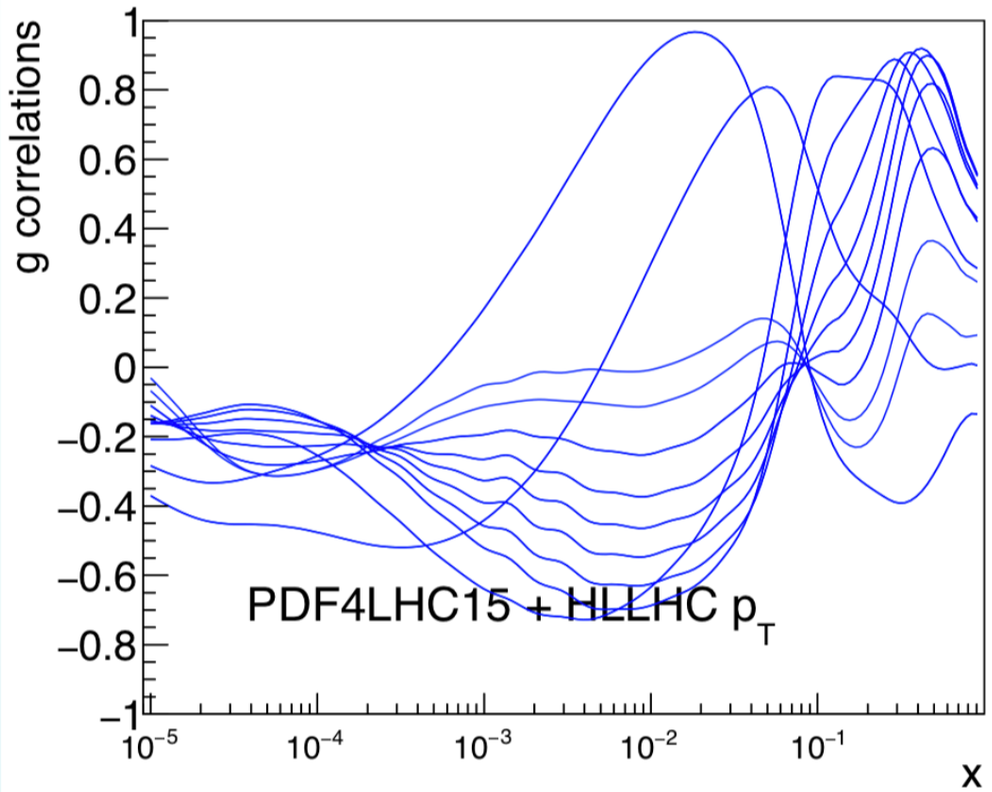


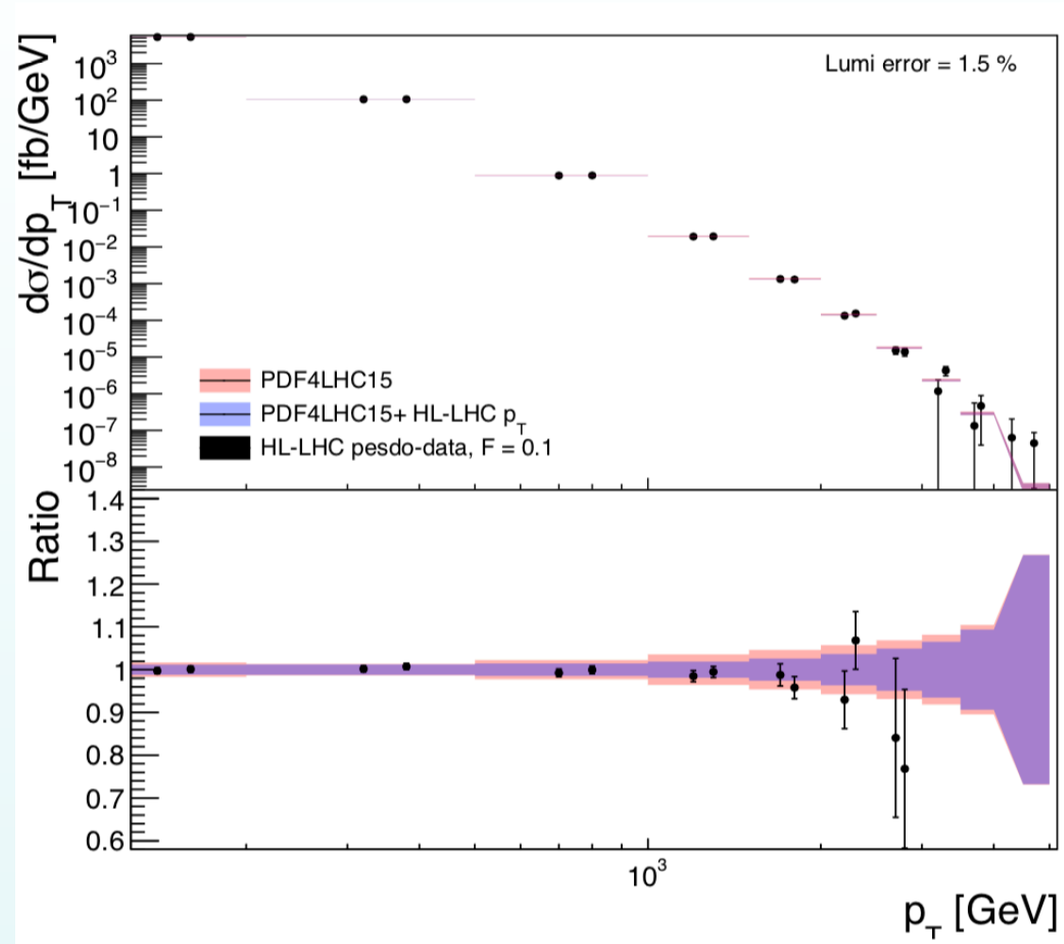


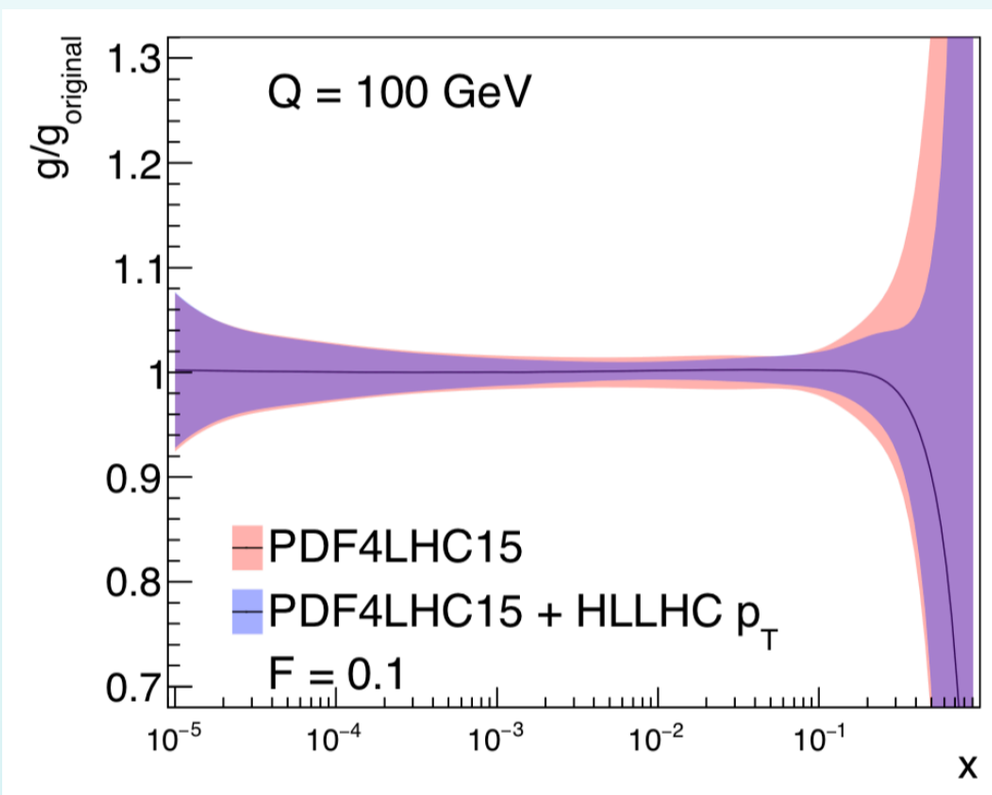
- Direct access to the **strange content** of the proton
- Included pseudo-data both in the **central** and in the **forward** region (LHCb)
- Promising error reduction in strangeness, feeds into other analyses (*e.g.* M_W)

Inclusive jets

Correlation coefficient between baseline and HL-LHC pseudo-data

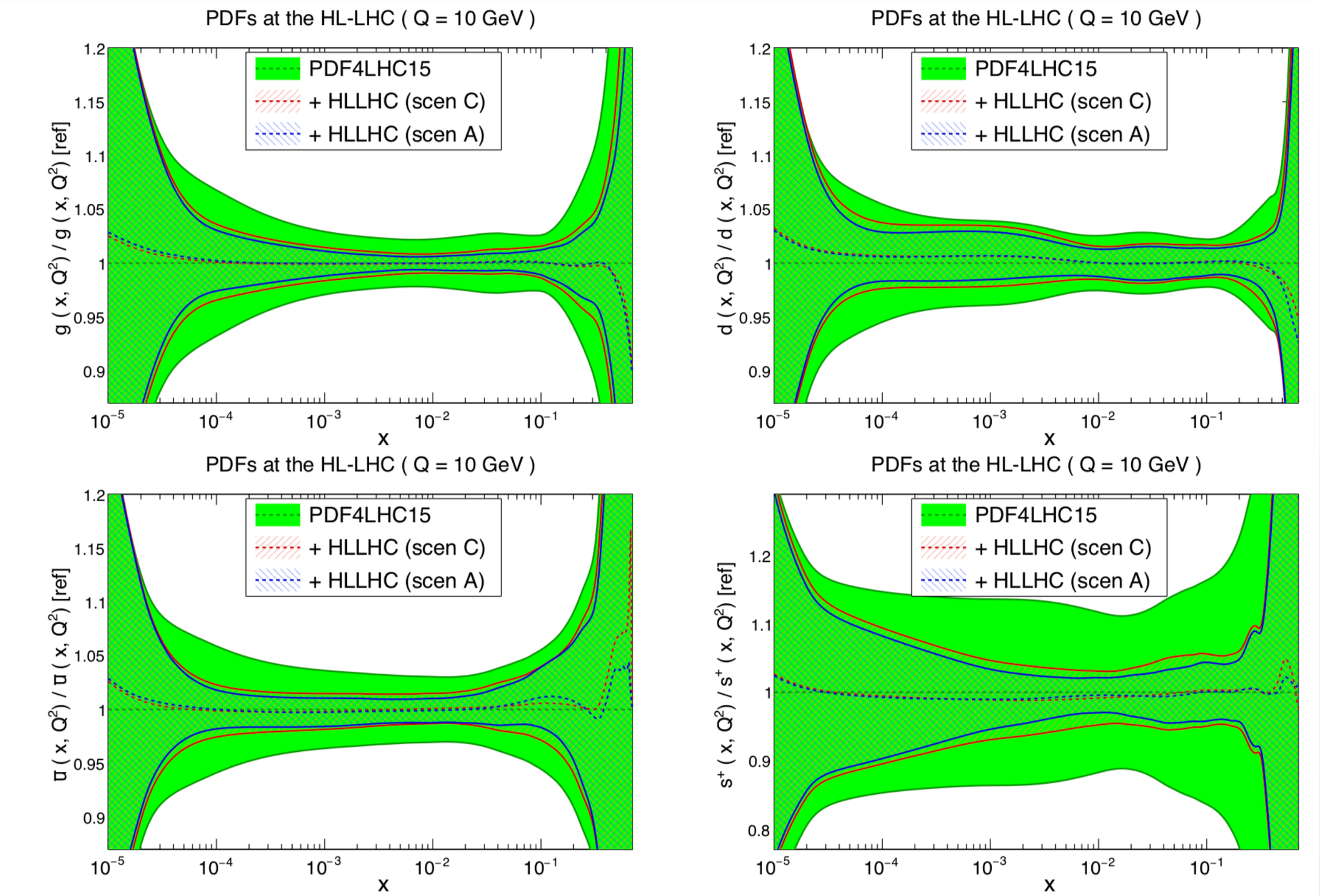






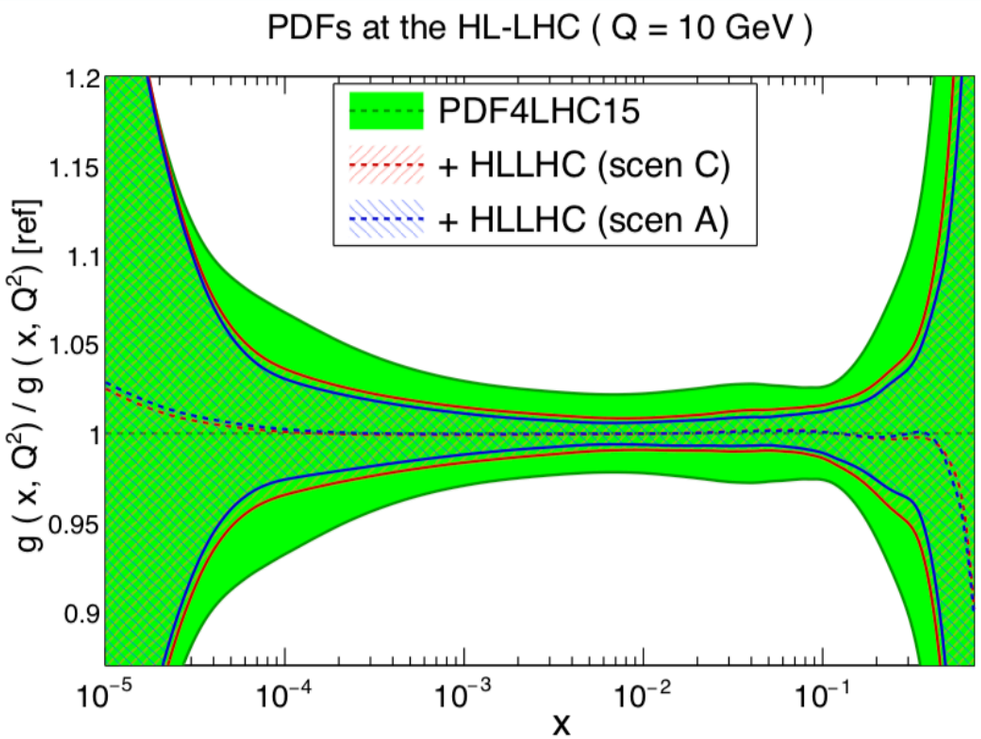
- HL-LHC projections (and APPLgrids) provided by P. Starovoitov
- Data on jets with transverse momenta **up to 3 TeV** will become available
- Improvement on the large-x gluon and quarks, but **less marked that in the top case**

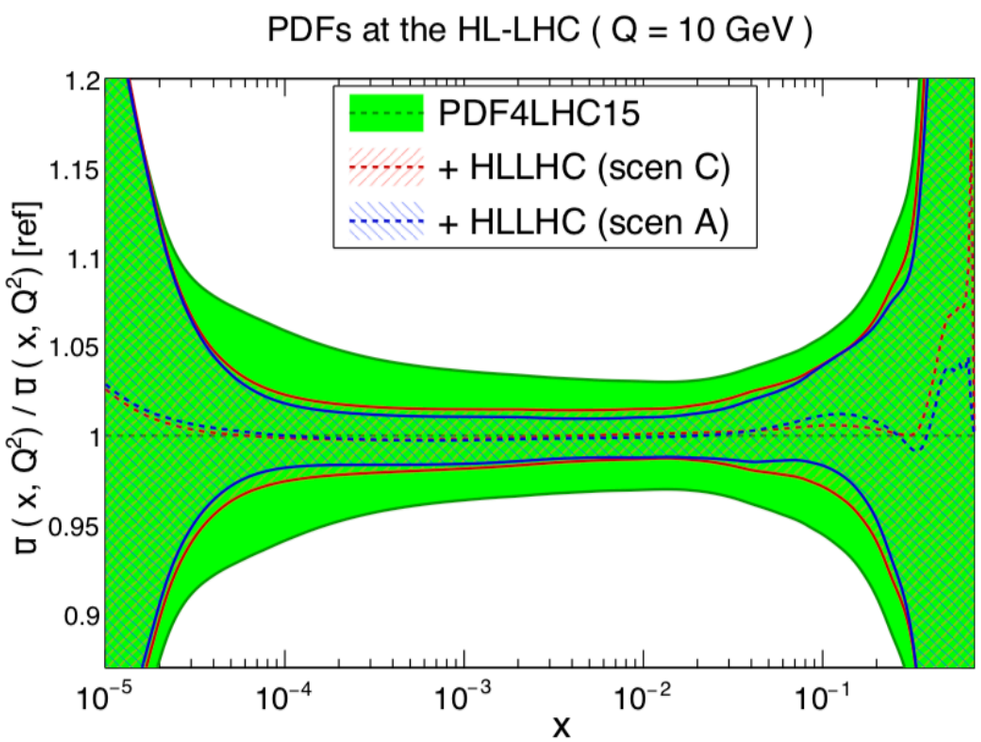
Parton distributions at the HL-LHC



- **Scenario A: optimistic** (assume systematic uncertainty reduction by factor 2.5)
- **Scenario B: Conservative** (assume no reduction in systematic errors)

Parton distributions at the HL-LHC



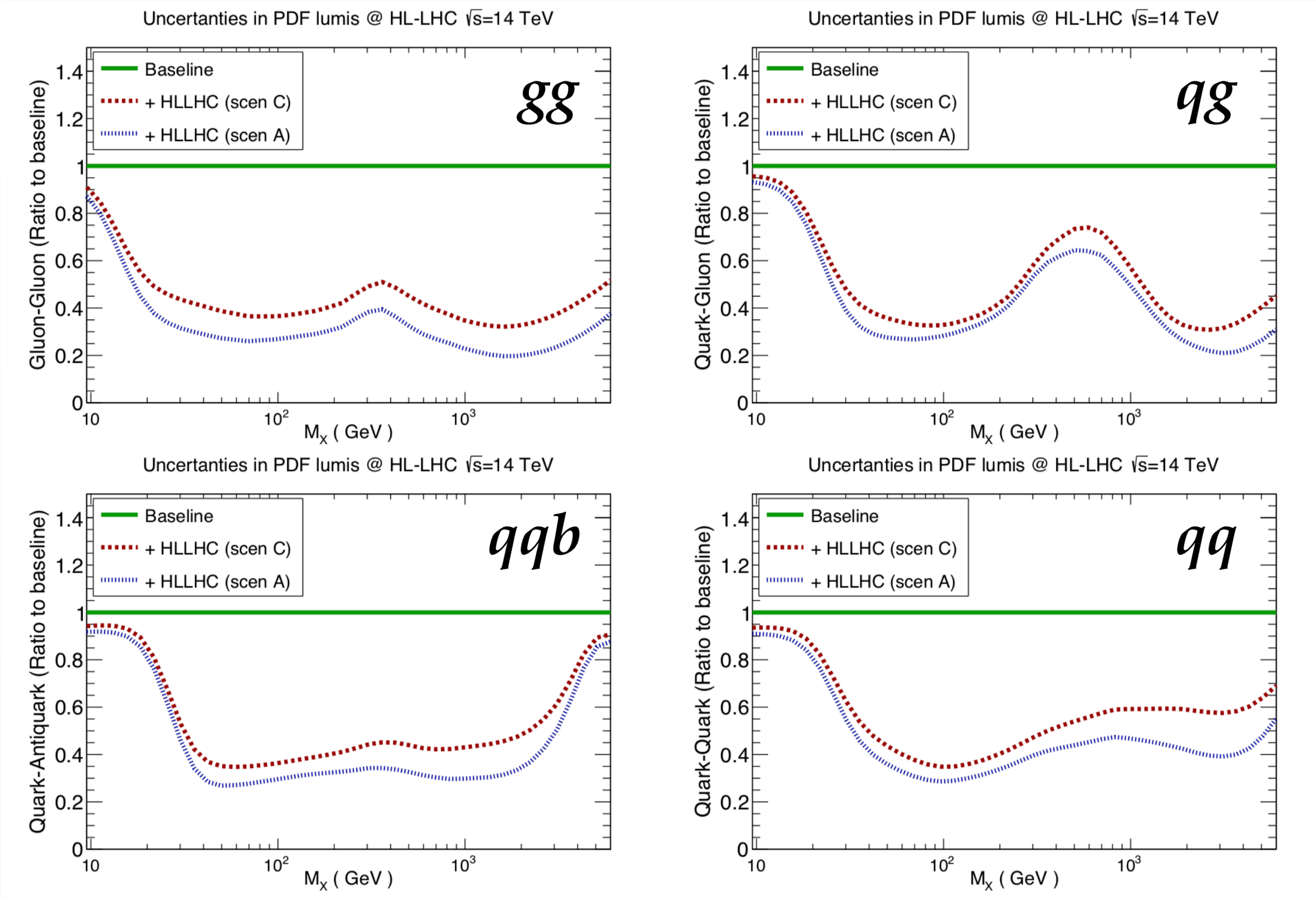


- Results exhibit **little dependence on the specific scenario** for the experimental systematic errors
- Significant PDF error reduction predicted for the **gluon and the sea quarks**
- Relevant both for precision Higgs physics and for BSM high-mass searches

- **Scenario A: optimistic** (assume systematic uncertainty reduction by factor 2.5)
- **Scenario B: Conservative** (assume no reduction in systematic errors)

Partonic luminosities at the HL-LHC

Uncertainty reduction in PDF luminosities as compared to the baseline (current situation)



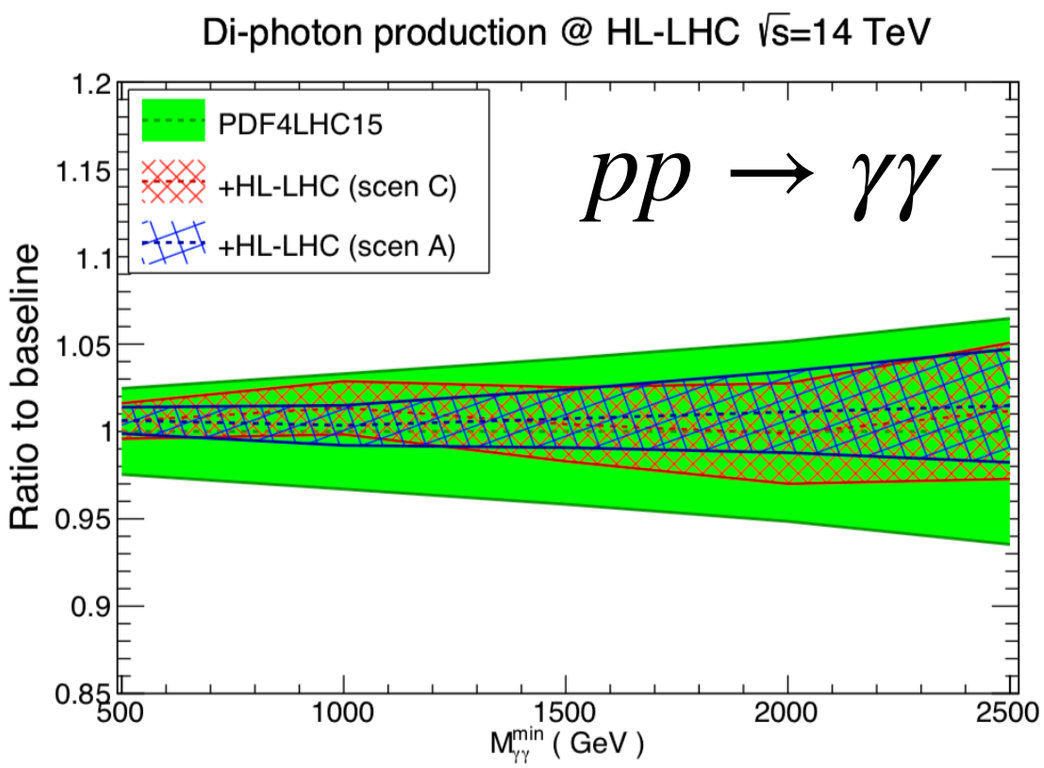
Partonic luminosities at the HL-LHC

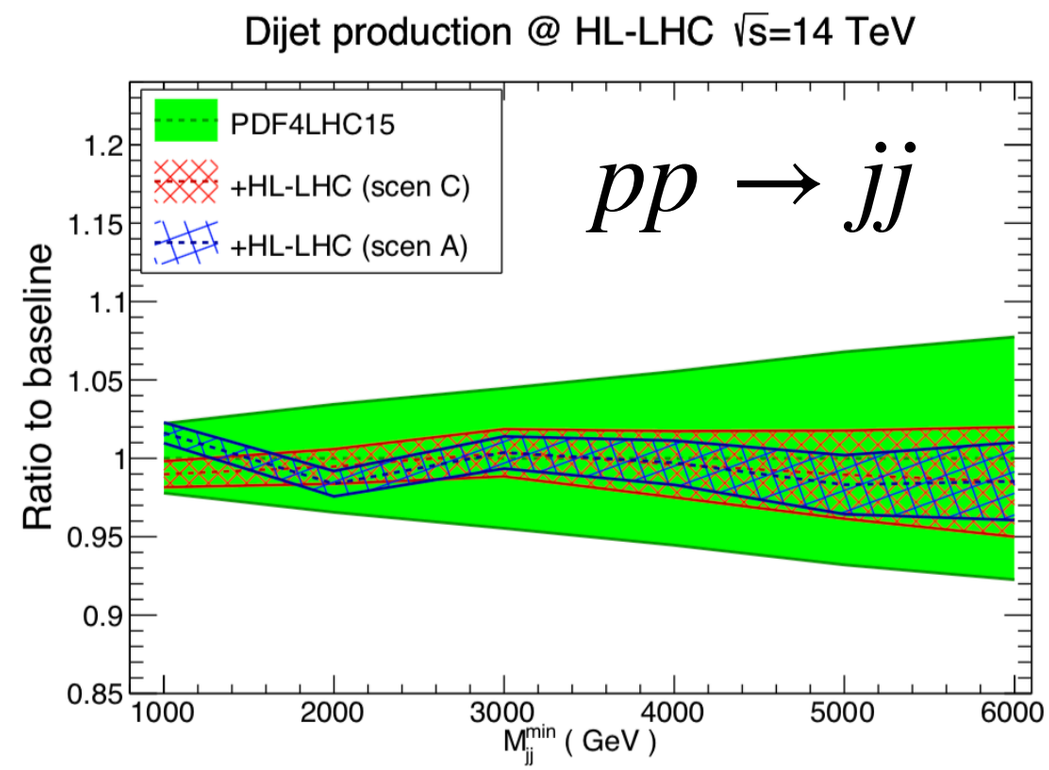
Uncertainty reduction in PDF luminosities as compared to the baseline (current situation)

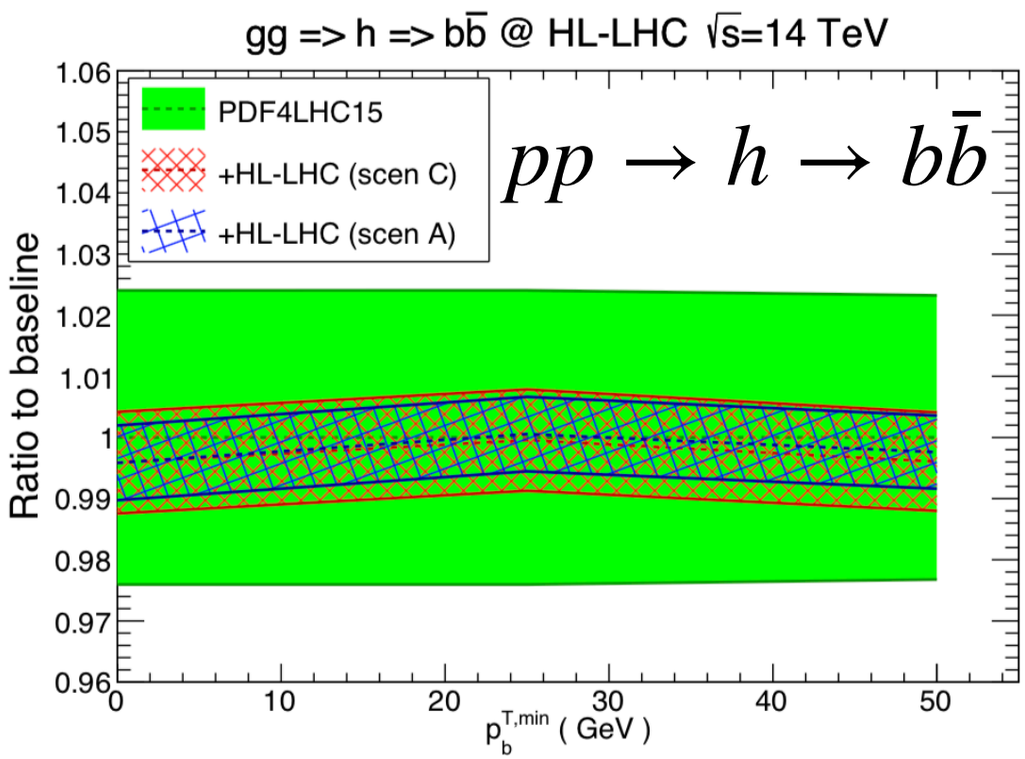
PDF uncertainties HLLHC / Current	10 GeV < M_X < 40 GeV	40 GeV < M_X < 1 TeV	1 TeV < M_X < 6 TeV
g-g luminosity	0.58 (0.49)	0.41 (0.29)	0.38 (0.24)
q-g luminosity	0.71 (0.65)	0.49 (0.42)	0.39 (0.29)
quark-quark luminosity	0.78 (0.73)	0.46 (0.37)	0.60 (0.45)
quark-antiquark luminosity	0.73 (0.70)	0.40 (0.30)	0.61 (0.50)
up-strange luminosity	0.73 (0.67)	0.38 (0.27)	0.42 (0.38)

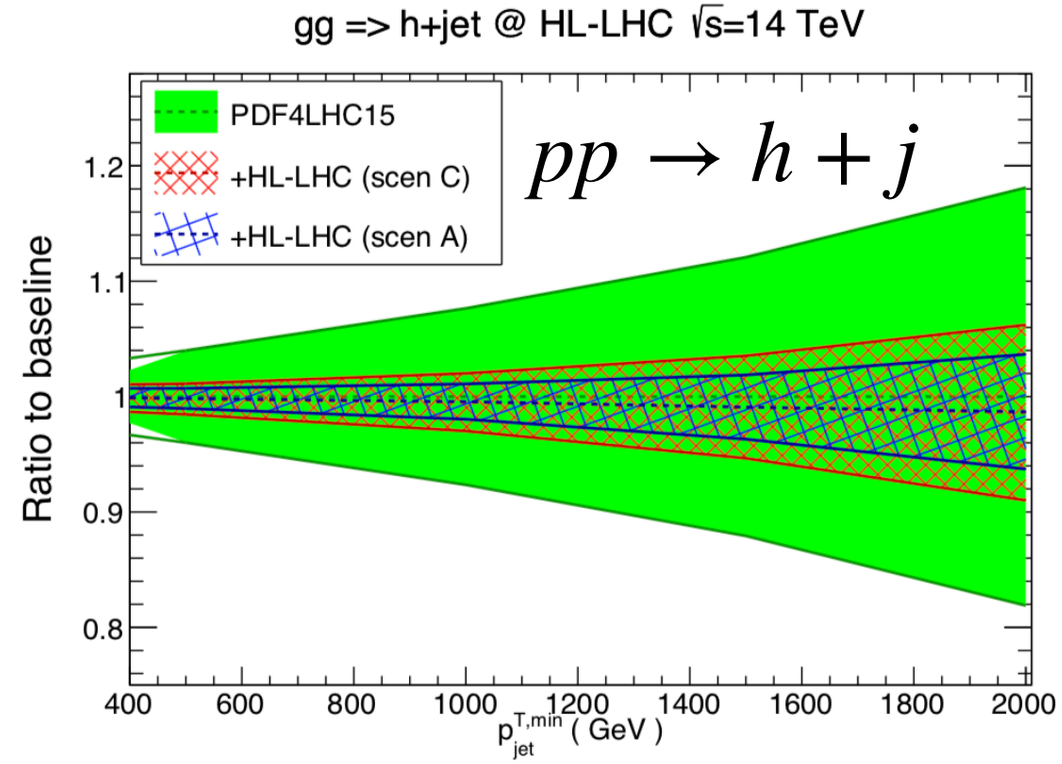
- In the region **M_X > 40 GeV**, the constraints from the HL-LHC can lead to a reduction of the PDF uncertainties in the partonic lumis of **up to a factor 4 in the optimistic scenario**
- Even with rather conservative assumptions, a **PDF error reduction between a factor 2 and 3** can be expected
- Moreover, these results are mostly likely **upper bounds** on the HL-LHC potential, since we have not included other PDF-sensitive processes (dijets, single top, low-mass DY, charged meson production, …)

Impact on QCD and Higgs processes



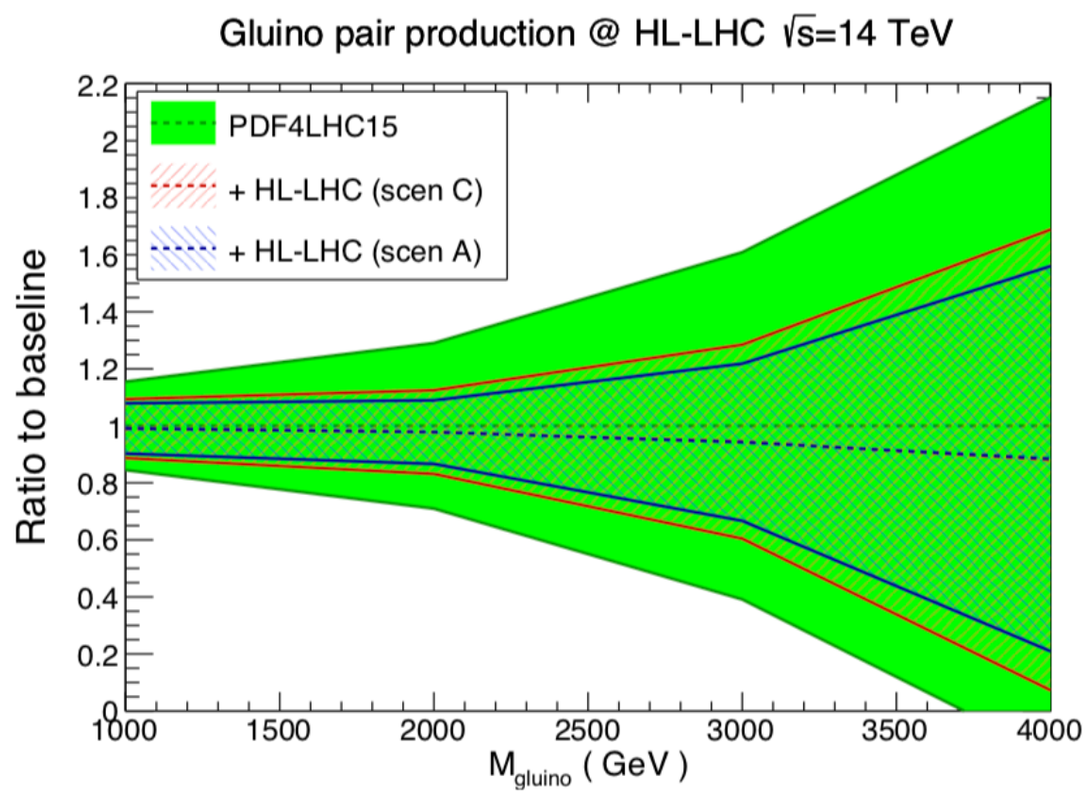


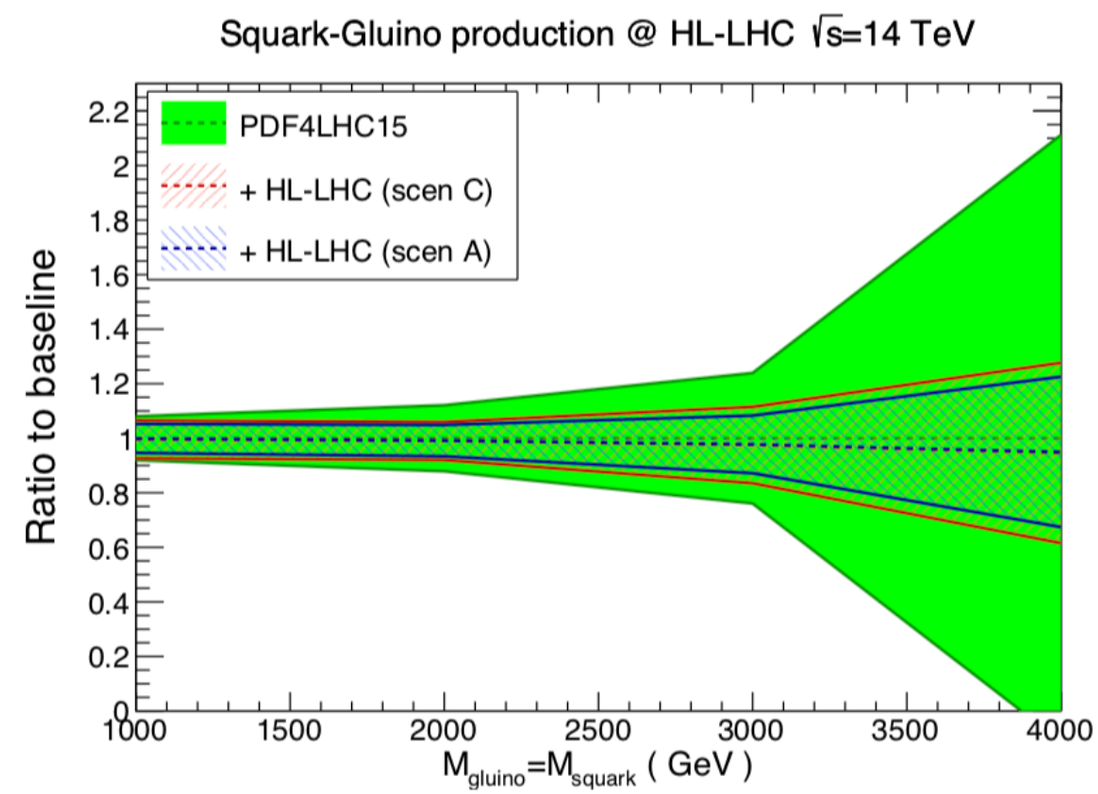


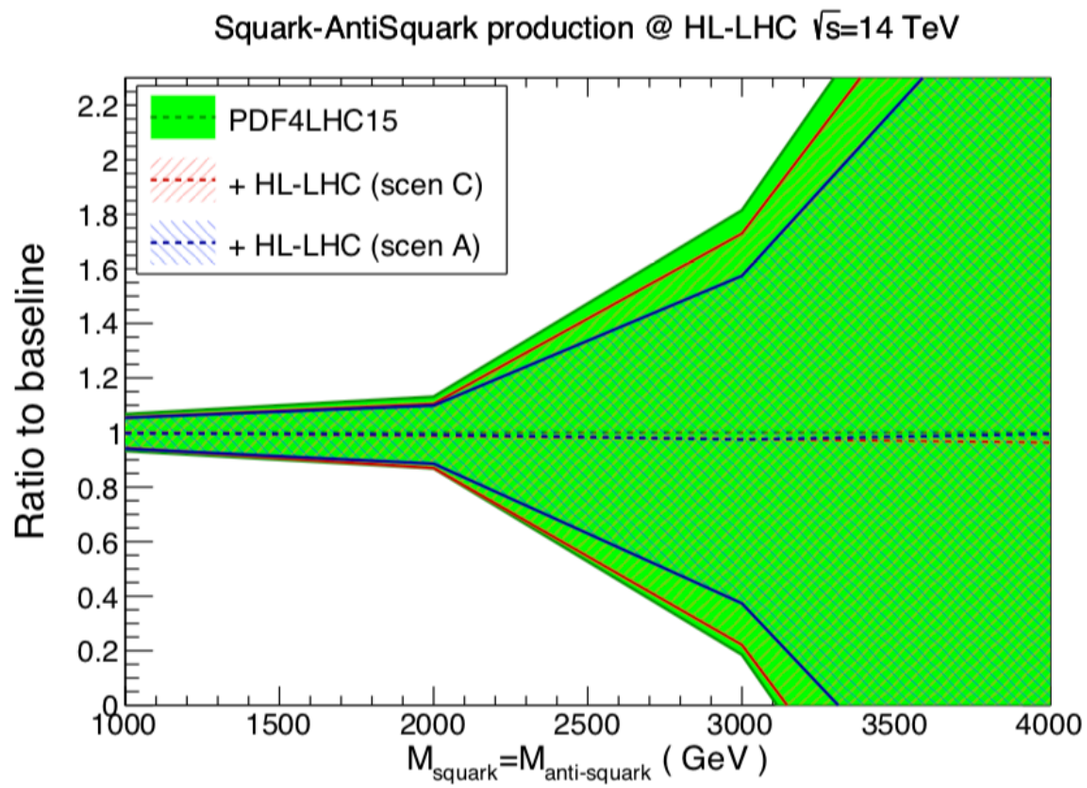


*PDF uncertainties in (gg) Higgs production down to the **1% level** at the HL-LHC*

Impact on high-mass BSM processes





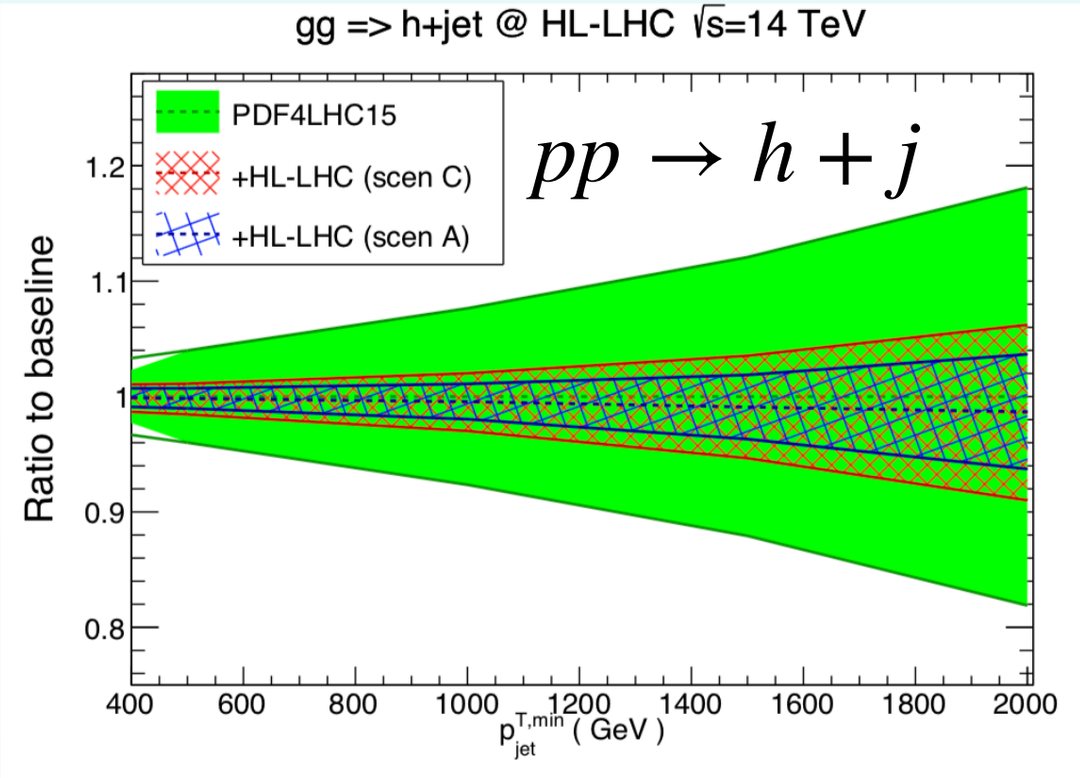


Marked improvement for gluon-initiated processes

- *A challenge seems to be pinning down the large-x antiquarks*
- *Include further processes, e.g. high-mass CC Drell-Yan?*

Summary and outlook

- We have presented a first systematic estimate of the **impact of HL-LHC measurements on the PDFs**
- We find that the **PDF uncertainty reduction** on LHC cross-sections ranges between **a factor 2 and a factor 4**, depending on the assumptions on the systematic errors and the specific mass region and partonic combination
- Our results are likely to represent an **upper bound only** on the potential impact of HL-LHC measurements, since only a subset of the possible PDF-sensitive measurements has been included
- The **PDF4LHC_HLLHC sets** will be sent to LHAPDF in the next days



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Thanks for your attention!