PDF Prospects at the HL-LHC

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arXiv: 1810.03639, 1906.10127

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- Data sets and errors
- Hessian profiling
- HL-LHC results
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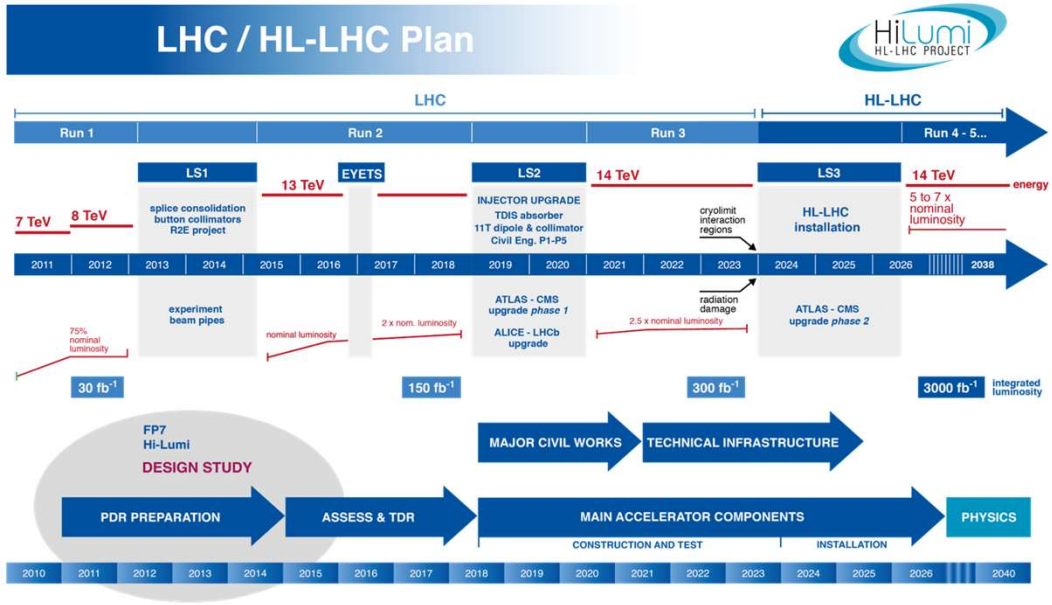
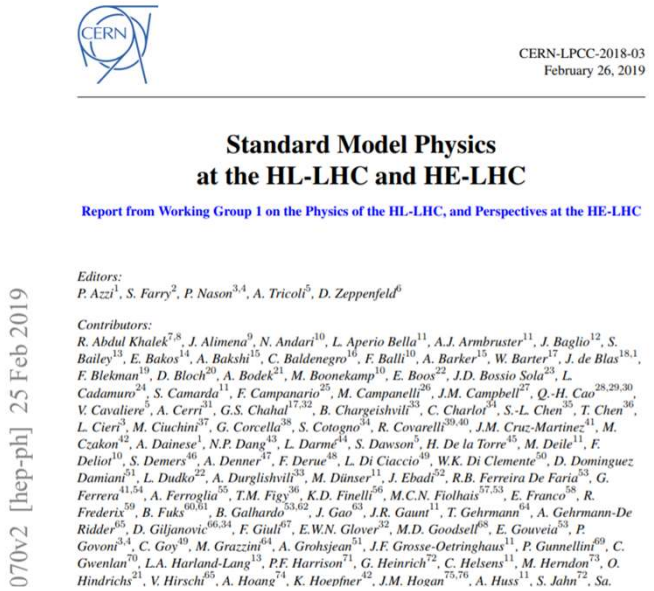
HL-LHC



- A new phase of the LHC starting in 2025
- Increased luminosity results in improved statistics
- Question: What will PDFs look like after this phase?

ATLAS + CMS: $\mathcal{L} = 3\ \mathrm{ab}^{-1}$

LHCb: $\mathcal{L} = 0.3\ \mathrm{ab}^{-1}$



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Standard Model Physics at the HL-LHC and HE-LHC

Report from Working Group 1 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

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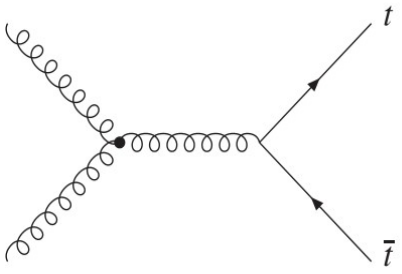
arXiv: 1902.04070

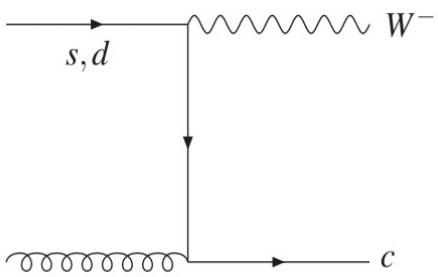
Data Sets

Top quark pair production



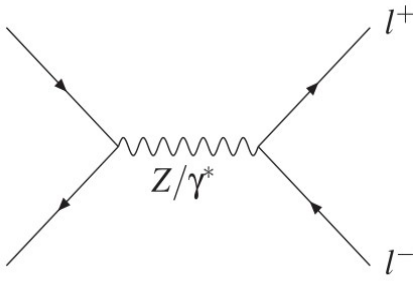
High x gluon

$W + c$ production



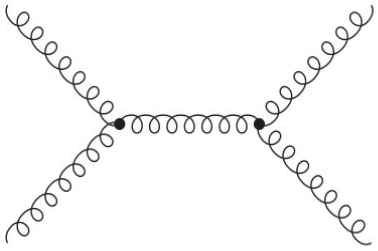
Strange quark

Drell–Yan production



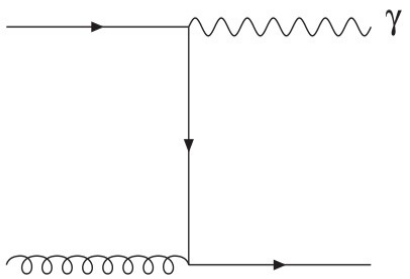
Flavour separation

Jet production



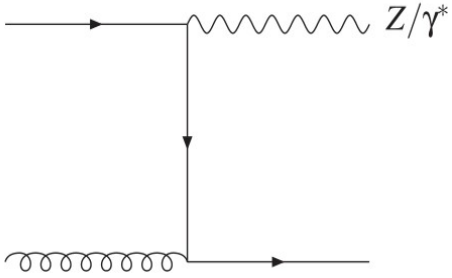
High x gluon + valence quarks

Direct photon production



Mid x gluon

$Z\ p_T$



Mid x gluon + antiquarks

- Concentrating on mid – high x for a variety of pdfs
- Not systematic dominated
- Low number of observed events (W + charm)
- Benefit from extended kinematic reach ($t\bar{t}$)

Data Sets

- Central value determined by NLO theory and then shifted according to errors
- No need for NNLO theory due to closure test
- Acceptance, a, accounts for detector effects /branching ratio/…
- Acceptance taken from existing experimental data set (nearest bin)

Statistics:

$$\text{stat} \sim \sqrt{N_{\text{obs}}}$$

$$N \sim a\mathcal{L}\frac{\partial\sigma^{\text{th}}}{\partial x}\Delta x$$

$$a = Br \times \frac{N_{obs}}{N_{predicted}}$$

Data Sets

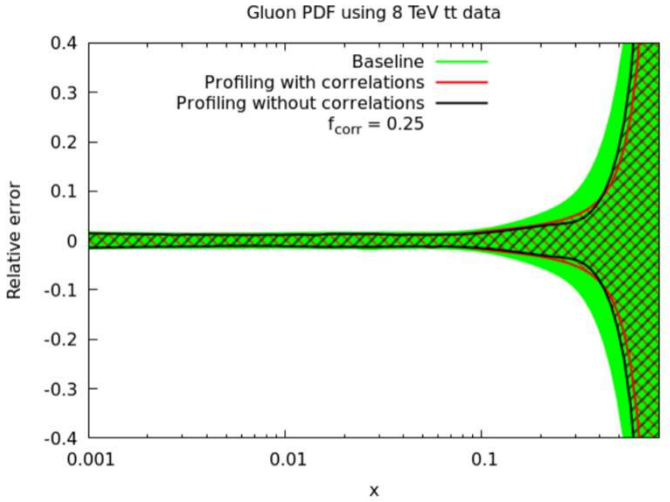
- Systematics taken from existing data set
- Treated as uncorrelated, with a factor f_{corr} to account for this
- A variable factor, f_{red}, used to estimate improvement to systematics
- Exception: Luminosity error

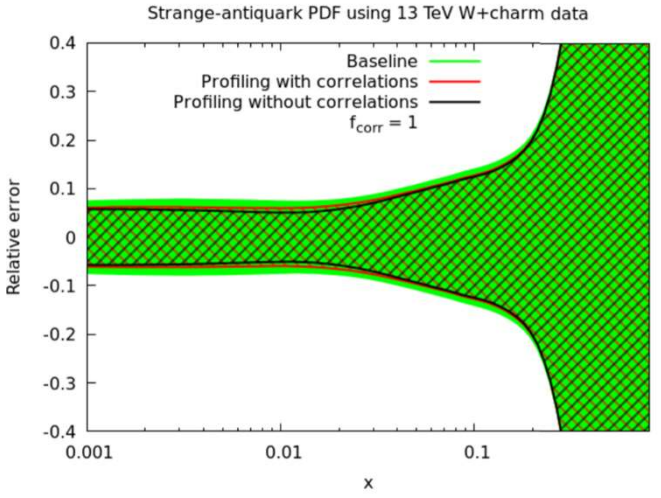
$$\mathrm{sys}(14\ \mathrm{TeV}) \sim f_{\mathrm{corr}} \times f_{\mathrm{red}} \times \mathrm{sys}(8/13\ \mathrm{TeV})$$

$$f_{corr} = 0.5$$

Scenario A: (Conservative)
$$f_{red} = \begin{cases} 1.0\ (8\ \mathrm{TeV}) \\ 0.5\ (13\ \mathrm{TeV}) \end{cases}$$

Scenario C: (Optimistic)
$$f_{red} = \begin{cases} 0.2\ (8\ \mathrm{TeV}) \\ 0.1 (13\ \mathrm{TeV}) \end{cases}$$





Hessian Profiling

- Estimates the effect of adding new data sets to a Hessian PDF set
- We will be using PDF4LHC for this study
- Hessian PDF set described by eigenvectors of the Hessian matrix.
- Tolerance, T, takes into account data/theory inconsistencies, parameterisation effects..
- We take $T = 3$, roughly in line with MMHT and CT

Hessian: $H_{ij} = \frac{\partial^2 \chi^2}{\partial z_i \partial z_j}$

Expand: $\chi^2 = \chi_0^2 + T^2 \sum_\alpha \beta_\alpha^2$

β_α along Hessian's eigenvector directions

At $\beta_\alpha = 1$ define error PDF: $f_{S_\alpha}(x)$

Error on PDF: $\delta f(x) = \sqrt{\sum_\alpha \left(f_{S_\alpha}(x) - f_0(x)\right)^2}$

Hessian Profiling

- Can add in new data set with typical χ^2 formula
- Theory values parametrised using error PDFs
- χ^2 minimised with respect to Hessian parameters → new central PDF
- Calculate new Hessian → new error PDFS

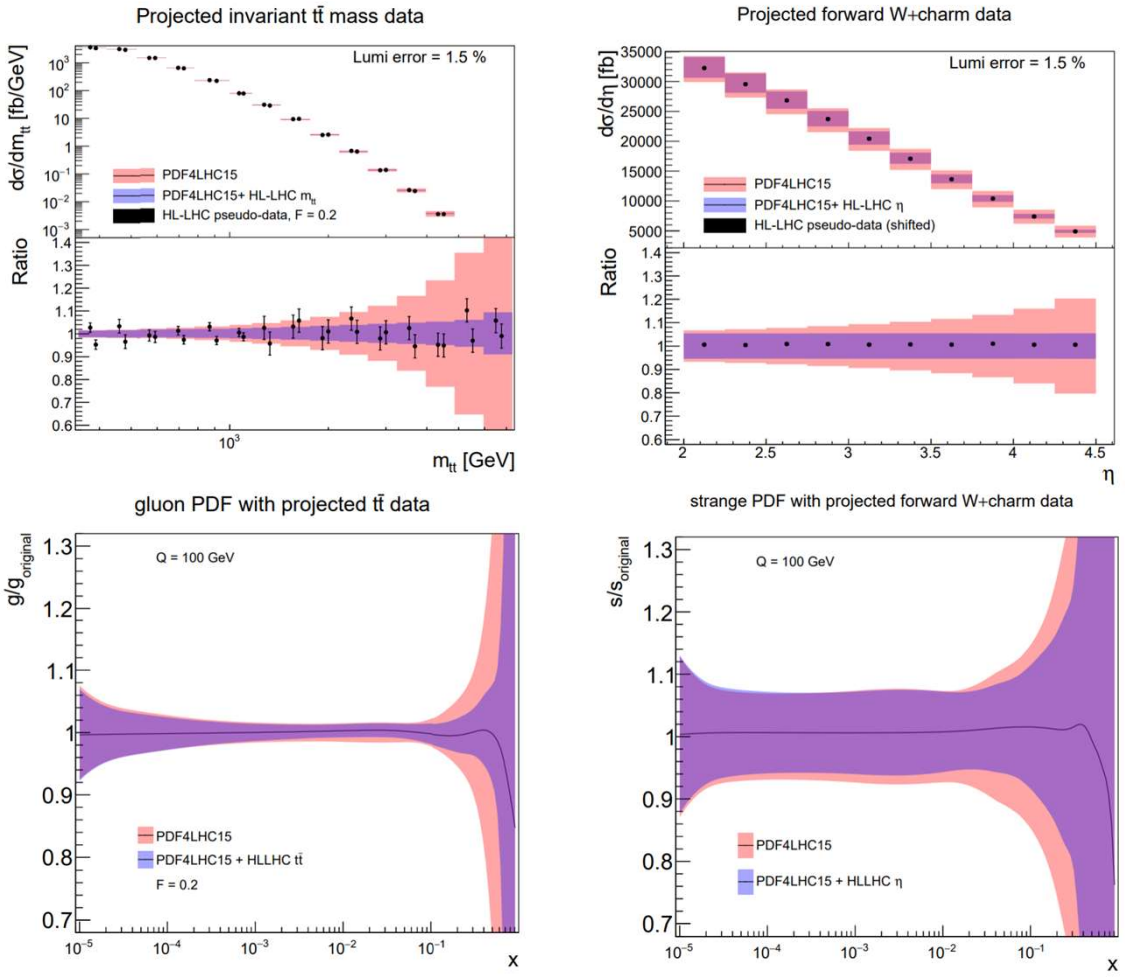
$$\sigma_i^{\text{th}} \to \sigma_i^{\text{th}} + \sum_\alpha \Gamma_{i\alpha}\beta_\alpha$$

$$\Gamma_{i\alpha} = \sigma_i^{\text{th}}(S_\alpha) - \sigma_i^{\text{th}}(S_0)$$

$$\Delta\chi^2 = \sum_{ij}\left(\sigma_i^{\text{exp}} - \sigma_i^{\text{th}} + \sum_\alpha \Gamma_{i\alpha}\beta_\alpha\right)(\text{cov})_{ij}^{-1}\left(\sigma_j^{\text{exp}} - \sigma_j^{\text{th}} + \sum_\gamma \Gamma_{j\gamma}\beta_\gamma\right) + T^2\sum_\alpha \beta_\alpha^2$$

New Hessian: $H_{\alpha\gamma} = \dfrac{\partial^2\chi^2}{\partial\beta_\alpha\partial\beta_\gamma}$

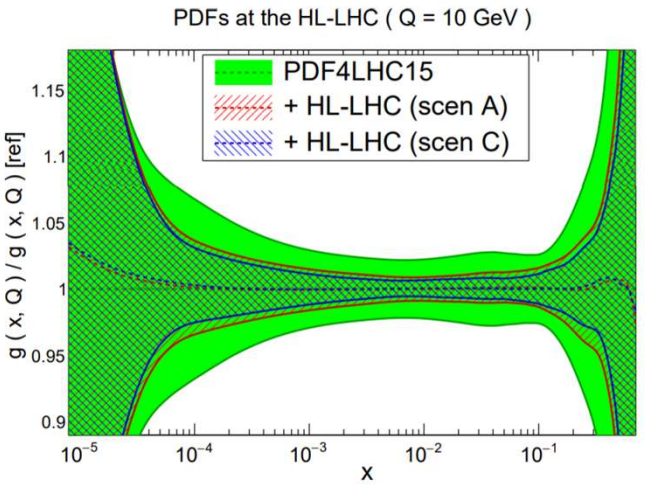
Individual Data Sets

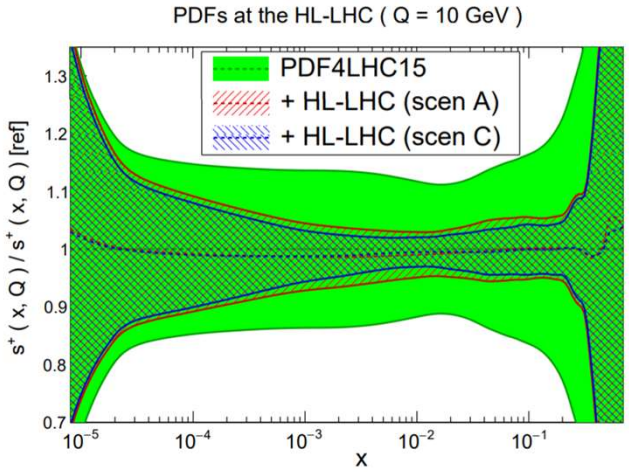


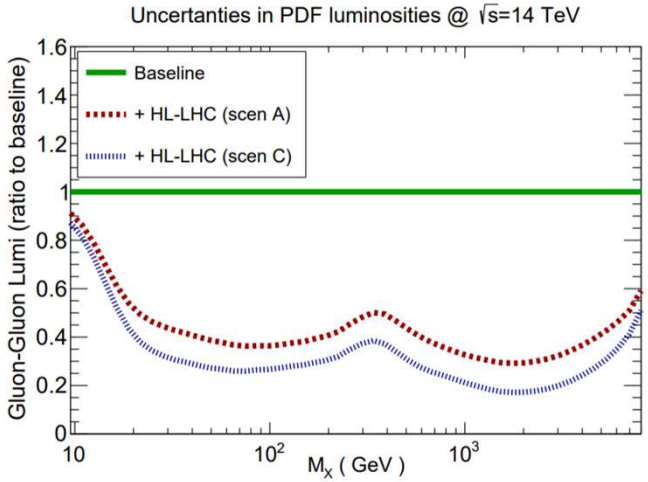
- $t\bar{t}$ has good constraints on high-x gluon
- Results from extended kinematic region

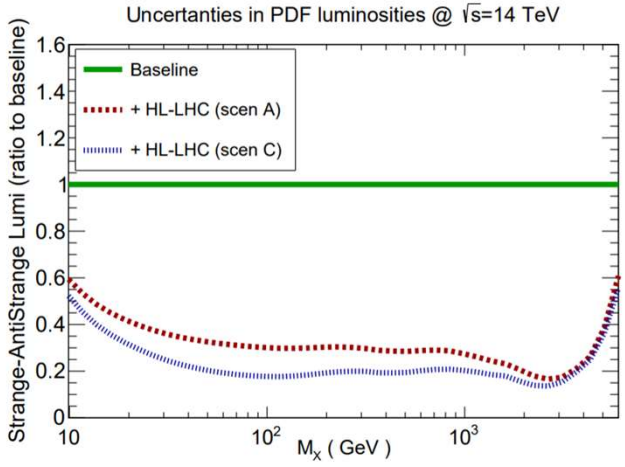
- Forward W + charm data constrains the strange PDF
- Limited by overall normalisation error

Parton Distributions and Luminosities









Scenario A:

$$f_{red} = \begin{cases} 1\ (8\ \text{TeV}) \\ 0.5\ (13\ \text{TeV}) \end{cases}$$

Scenario C:

$$f_{red} = \begin{cases} 0.2\ (8\ \text{TeV}) \\ 0.1\ (13\ \text{TeV}) \end{cases}$$

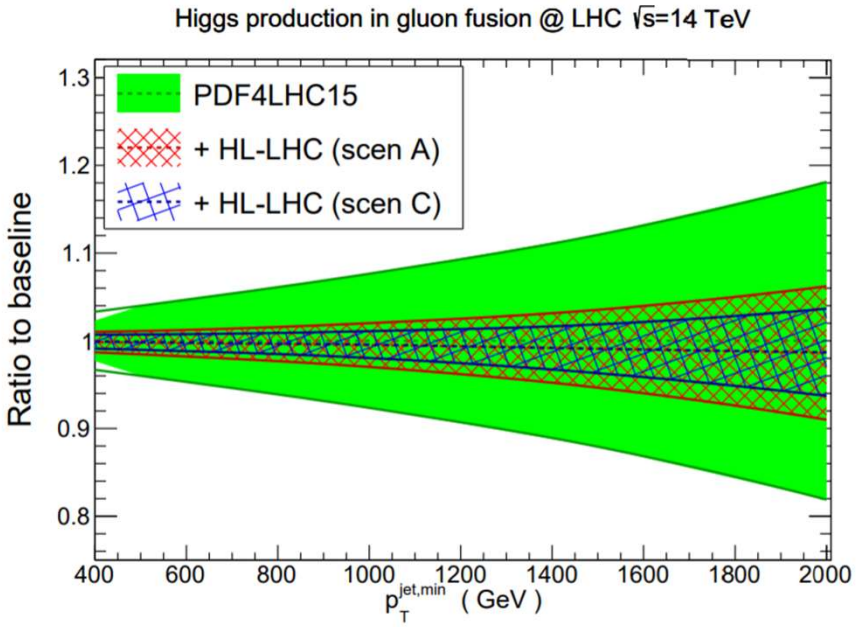
- Good reduction overall
- Not much difference between scenarios

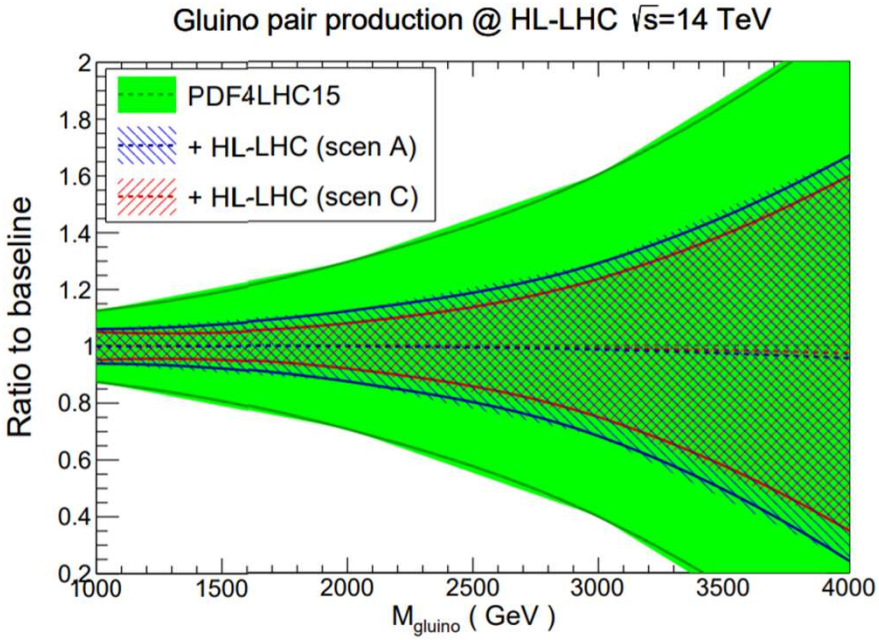
Luminosities

- Overall factor of ~2-4 improvement over a wide range of kinematics
- Not much difference between optimistic and conservative (in brackets) scenarios

Ratio to baseline	$10\ \text{GeV} \leq M_X \leq 40\ \text{GeV}$	$40\ \text{GeV} \leq M_X \leq 1\ \text{TeV}$	$1\ \text{TeV} \leq M_X \leq 6\ \text{TeV}$
gluon–gluon	0.50 (0.60)	0.28 (0.40)	0.22 (0.34)
gluon–quark	0.66 (0.72)	0.42 (0.45)	0.28 (0.37)
quark–quark	0.74 (0.79)	0.37 (0.46)	0.43 (0.59)
quark–antiquark	0.71 (0.76)	0.31 (0.40)	0.50 (0.60)
strange–antistrange	0.34 (0.44)	0.19 (0.30)	0.23 (0.27)
strange–antiup	0.67 (0.73)	0.27 (0.38)	0.38 (0.43)

Higgs and BSM

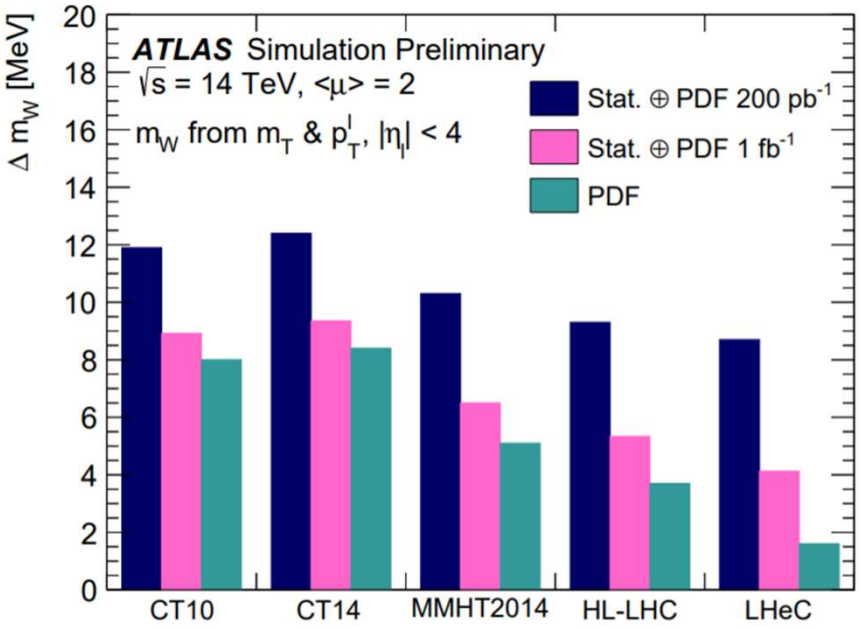




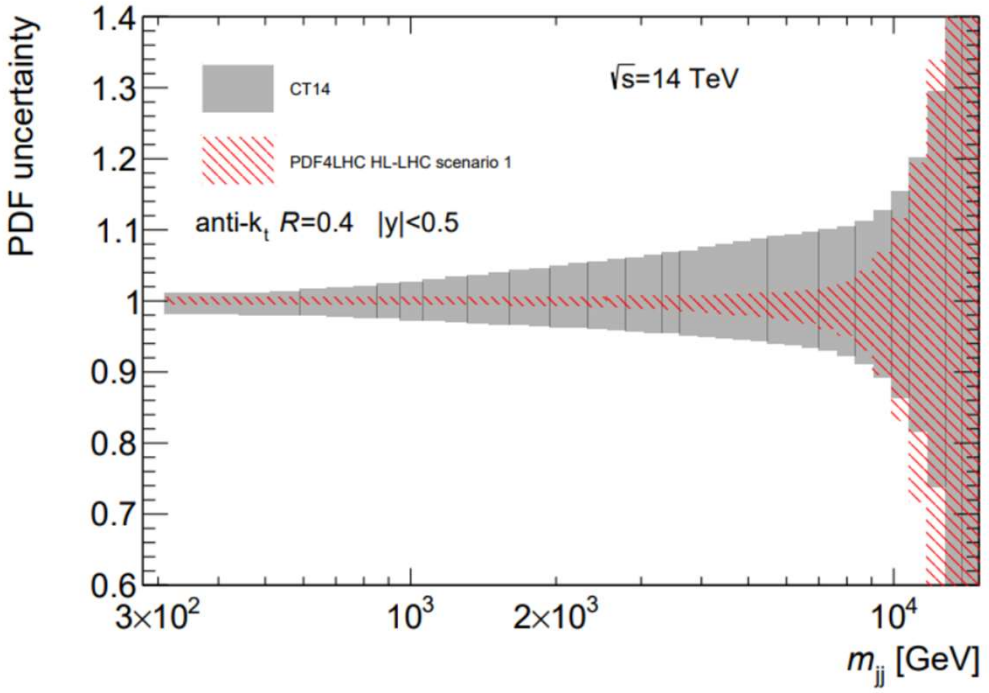
- PDF errors down to ~ 2%
- Potential for new heavy particles at high p_T

- Example BSM theory with good reduction
- Will help constrain parameter space

Yellow Report Studies



- W mass measurement
- Up to a factor of 2 improvement



- Dijet theory
- Significant error reduction over a broad range of m_{jj}

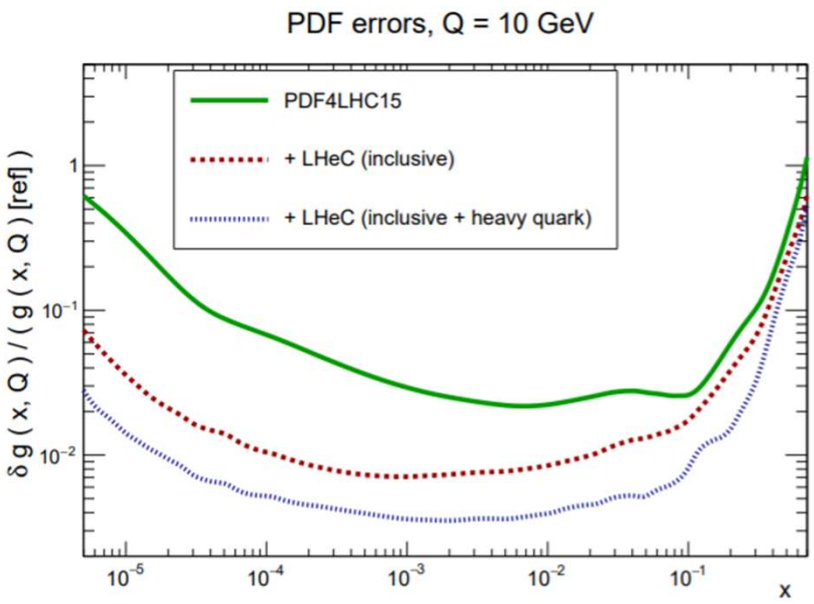
LHeC

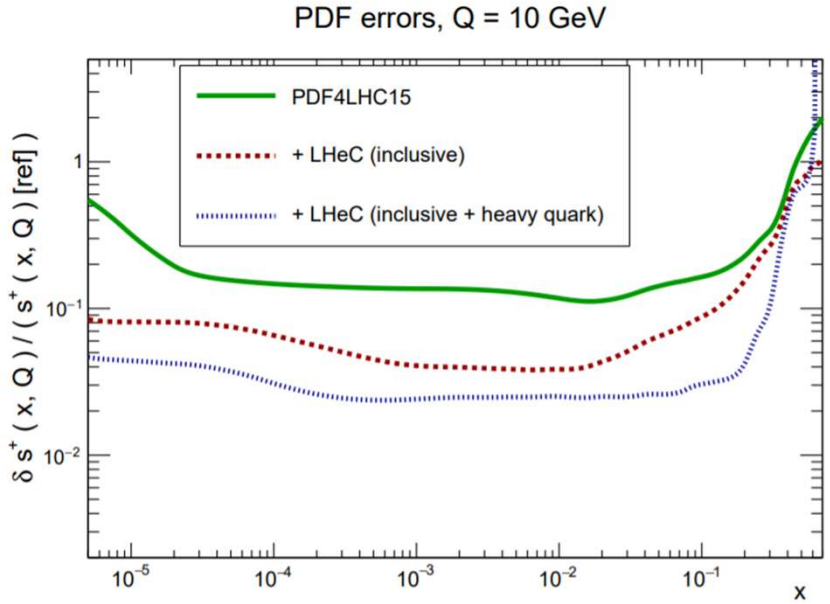
- Proposed electron-proton collider
- Much cleaner results, expected significant improvement to PDF errors, all the way down to low x
- What happens when applying the same formalism?
- See talk by A. Cooper Sarkar for further details

	Observable	E_p	Kinematics	N_{dat}	$\mathcal{L}_{\text{int}}$ [ab^{-1}]
Inclusive	$\tilde{\sigma}^{\text{NC}}\ (e^-p)$	7 TeV	$5 \times 10^{-6} \leq x \leq 0.8,\ 5 \leq Q^2 \leq 10^6$ GeV^2	150	1.0
	$\tilde{\sigma}^{\text{CC}}\ (e^-p)$	7 TeV	$8.5 \times 10^{-5} \leq x \leq 0.8,\ 10^2 \leq Q^2 \leq 10^6$ GeV^2	114	1.0
	$\tilde{\sigma}^{\text{NC}}\ (e^+p)$	7 TeV	$5 \times 10^{-6} \leq x \leq 0.8,\ 5 \leq Q^2 \leq 5 \times 10^5$ GeV^2	148	0.1
	$\tilde{\sigma}^{\text{CC}}\ (e^+p)$	7 TeV	$8.5 \times 10^{-5} \leq x \leq 0.7,\ 10^2 \leq Q^2 \leq 5 \times 10^5$ GeV^2	109	0.1
	$\tilde{\sigma}^{\text{NC}}\ (e^-p)$	1 TeV	$5 \times 10^{-5} \leq x \leq 0.8,\ 2.2 \leq Q^2 \leq 10^5$ GeV^2	128	0.1
	$\tilde{\sigma}^{\text{CC}}\ (e^-p)$	1 TeV	$5 \times 10^{-4} \leq x \leq 0.8,\ 10^2 \leq Q^2 \leq 10^5$ GeV^2	94	0.1
Heavy quark	$F_2^{c,NC}\ (e^-p)$	7 TeV	$7 \times 10^{-6} \leq x \leq 0.3,\ 4 \leq Q^2 \leq 2 \times 10^5$ GeV^2	111	0.1
	$F_2^{b,NC}\ (e^-p)$	7 TeV	$3 \times 10^{-5} \leq x \leq 0.3,\ 32 \leq Q^2 \leq 2 \times 10^5$ GeV^2	77	0.1
	$F_2^{c,CC}\ (e^-p)$	7 TeV	$10^{-4} \leq x \leq 0.25,\ 10^2 \leq Q^2 \leq 10^5$ GeV^2	14	0.1
	Total			945	

Ignore polarisation: not expected to have a large effect

LHeC

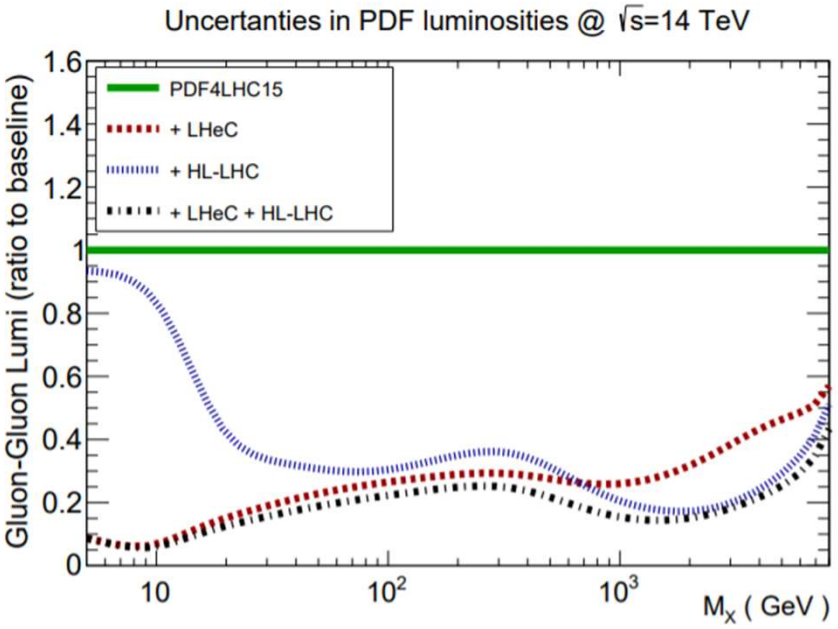


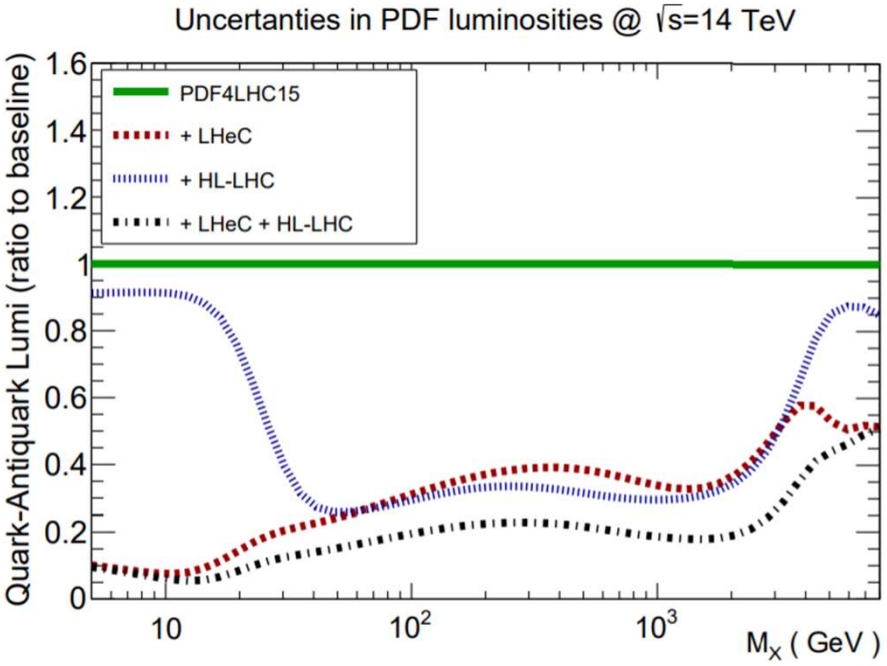


- Very good reduction overall, particularly at low x
- Heavy quark data had good improvement over a broad range of x, especially around x = 0.1-0.3

- Fits have also been done with T =1, with a factor of 2 improvment

LHeC + HL-LHC





- HL-LHC and LHeC complementary, reducing errors in different regions
- e.g. HL-LHC reduces high-x gluon, while LHeC reduces low-x gluon
- However, not all data-sets chosen to concentrate on these regions and others such as jets at LHeC can constrain high-x gluon

Conclusions

- HL-LHC will have significant constraining power, reducing luminosity errors by 2-4 over a wide range of kinematics
- Reduced errors on SM measurements and BSM searches
- Caveats:
  - Ignored issues such as difficulties in data/theory comparisons and data incompatibilities
  - Not included all possible data sets
- HL-LHC and LHeC are complementary in their PDF constraining abilities

LHAPDF Sets

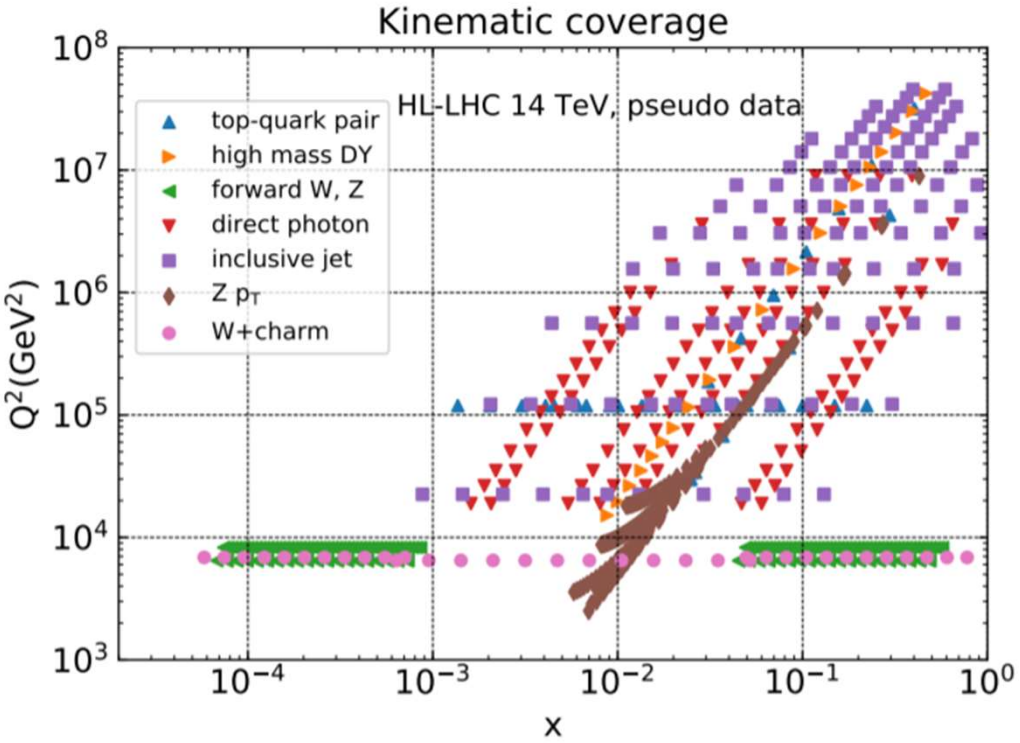
https://data.nnpdf.science/HLLHC_YR/PDF4LHC15_nnlo_hllhc_scen1.tgz
https://data.nnpdf.science/HLLHC_YR/PDF4LHC15_nnlo_hllhc_scen2.tgz
https://data.nnpdf.science/HLLHC_YR/PDF4LHC15_nnlo_hllhc_scen3.tgz

Thank you for listening
Any questions?

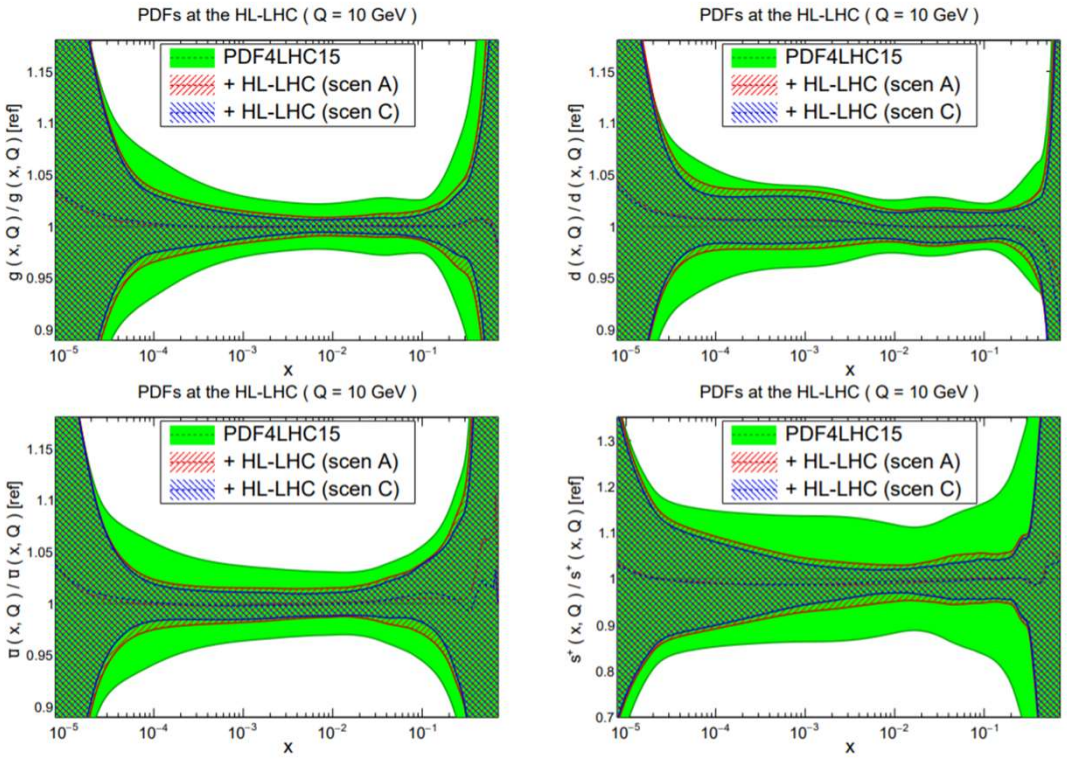
Data Sets

Process	Kinematics	$N_{\rm dat}$	$f_{\rm corr}$	$f_{\rm red}$	Baseline
$Z\ p_T$	$20\,\text{GeV} \le p_T^{ll} \le 3.5\ \text{TeV}$ $12\,\text{GeV} \le m_{ll} \le 150\ \text{GeV}$ $\lvert y_{ll}\rvert \le 2.4$	338	0.5	(0.4, 1)	[52] (8 TeV)
high-mass Drell-Yan	$p_T^{l1(2)} \ge 40(30)\,\text{GeV}$ $\lvert\eta^l\rvert \le 2.5,\ m_{ll} \ge 116\,\text{GeV}$	32	0.5	(0.4, 1)	[47] (8 TeV)
top quark pair	$m_{t\bar{t}} \simeq 5\ \text{TeV},\ \lvert y_t\rvert \le 2.5$	110	0.5	(0.4, 1)	[50] (8 TeV)
W+charm (central)	$p_T^{\mu} \ge 26\,\text{GeV},\ p_T^{c} \ge 5\,\text{GeV}$ $\lvert\eta^{\mu}\rvert \le 2.4$	12	0.5	(0.2, 0.5)	[24] (13 TeV)
W+charm (forward)	$p_T^{\mu} \ge 20\,\text{GeV},\ p_T^{c} \ge 20\,\text{GeV}$ $p_T^{\mu+c} \ge 20\,\text{GeV}$ $2 \le \eta^{\mu} \le 4.5,\ 2.2 \le \eta^{c} \le 4.2$	10	0.5	(0.4, 1)	LHCb projection
Direct photon	$E_T^{\gamma} \lesssim 3\ \text{TeV},\ \lvert\eta_{\gamma}\rvert \le 2.5$	118	0.5	(0.2, 0.5)	[55] (13 TeV)
Forward W, Z	$p_T^{l} \ge 20\,\text{GeV},\ 2.0 \le \eta^{l} \le 4.5$ $60\,\text{GeV} \le m_{ll} \le 120\,\text{GeV}$	90	0.5	(0.4, 1)	[49] (8 TeV)
Inclusive jets	$\lvert y\rvert \le 3,\ R = 0.4$	58	0.5	(0.2, 0.5)	[61] (13 TeV)
Total		768			

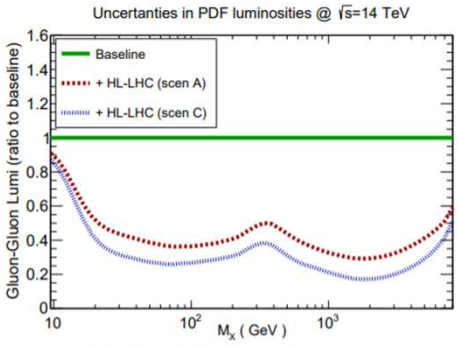
Kinematic coverage

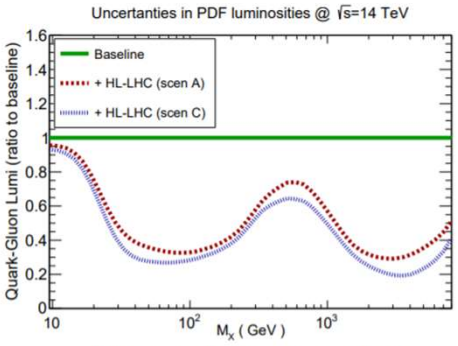


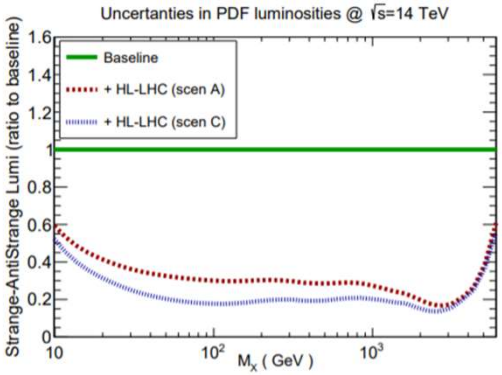
Parton Densities

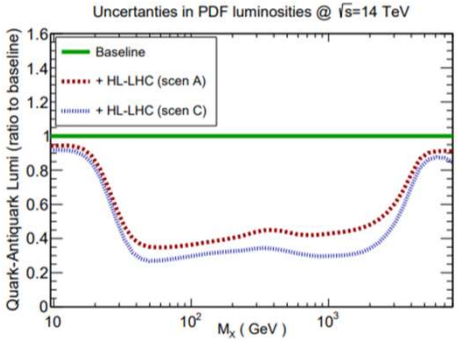


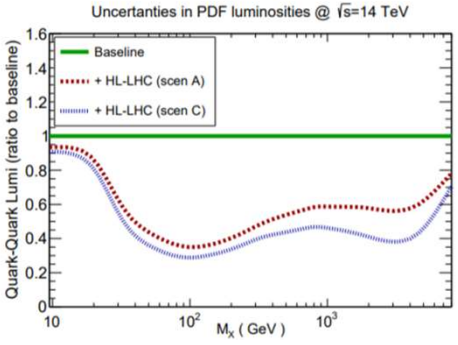
Luminosities

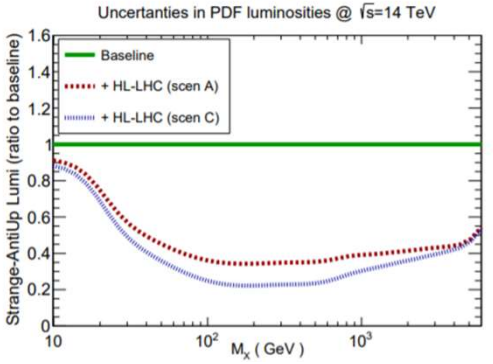




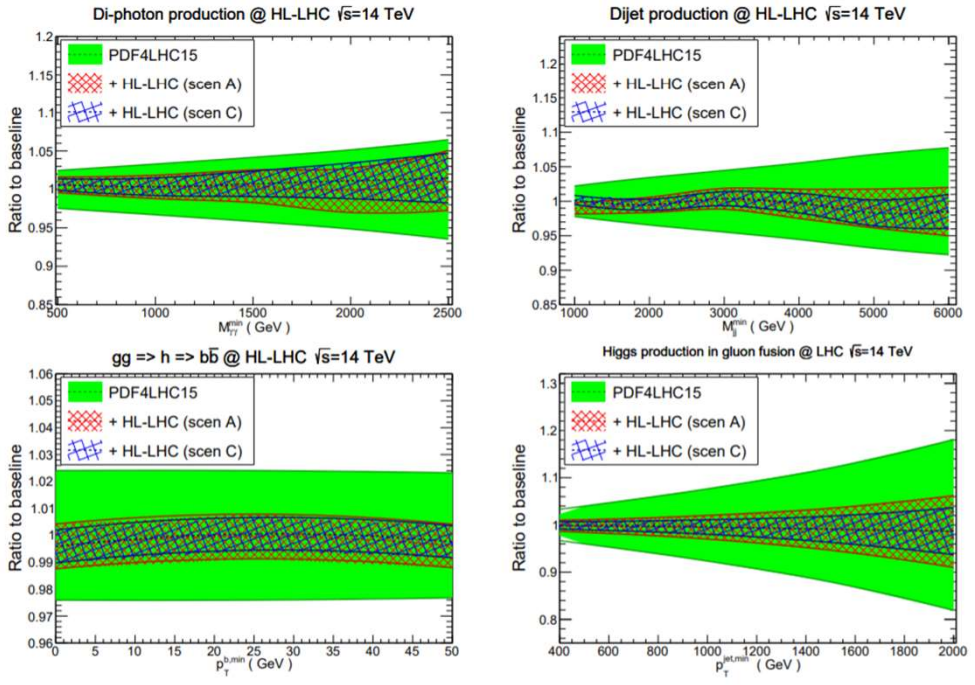




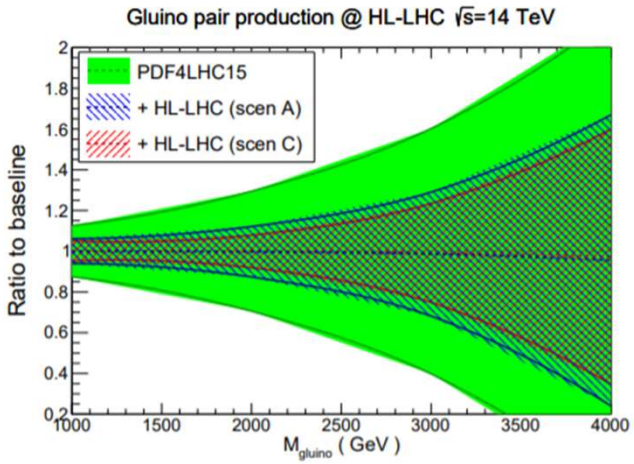


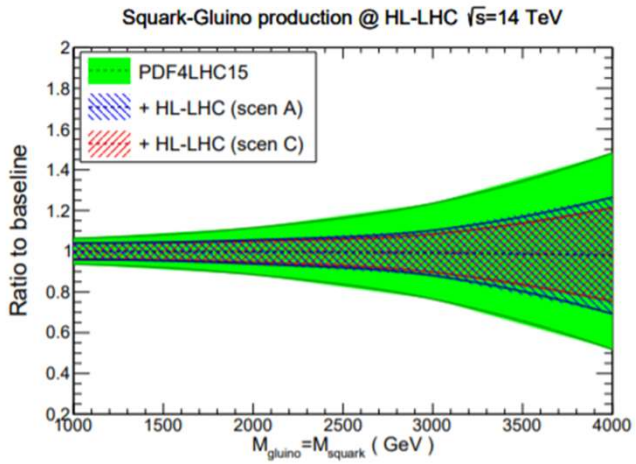


SM Cross Sections



BSM Cross Sections





Hessian Profiling

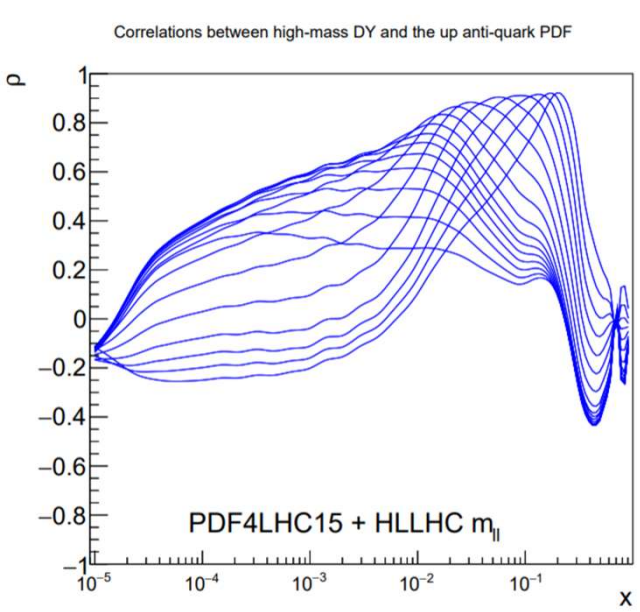
$$H_{\alpha\beta} = \Gamma_{i\alpha}(\mathrm{cov})^{-1}_{ij}\Gamma_{j\beta} + T^2\delta_{\alpha\beta}$$

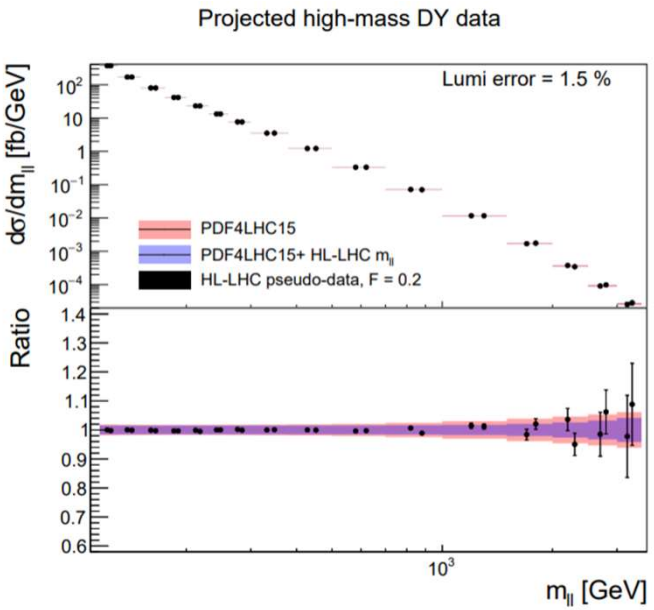
$$f'_{S'_i} = \sum_{k}^{N_{\mathrm{eig}}} \left(f_{S_k} - f_0\right) v_k^{(i)} \sqrt{\frac{1}{\epsilon_i}} T$$

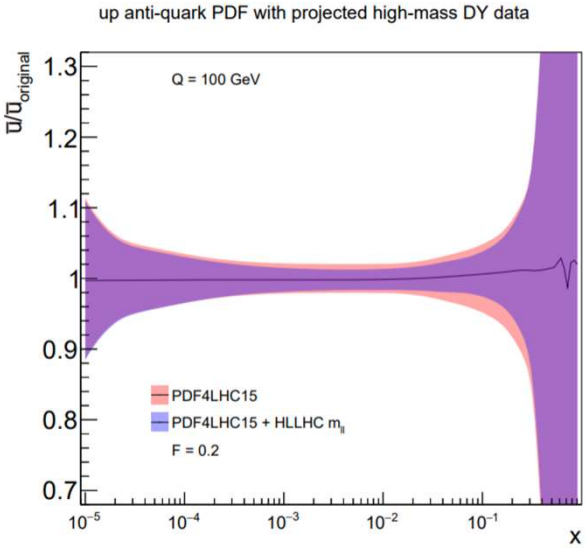
Data dominant -> ϵ independent of T -> $\delta f \sim T$

Data not constraining -> $\epsilon \sim T$ -> δf independent of T

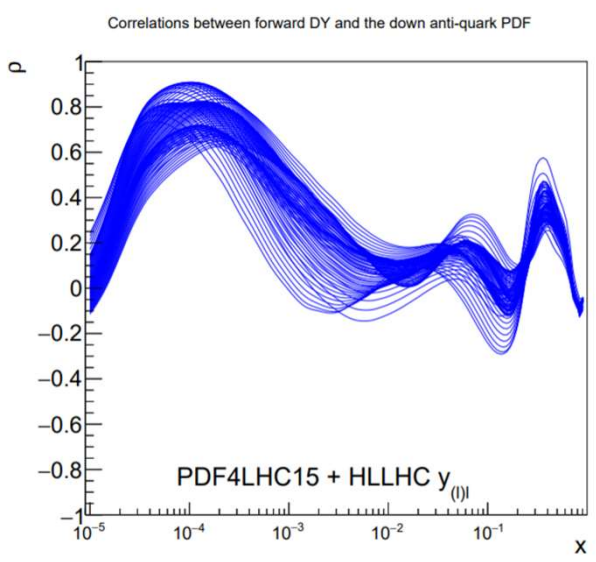
High Mass DY

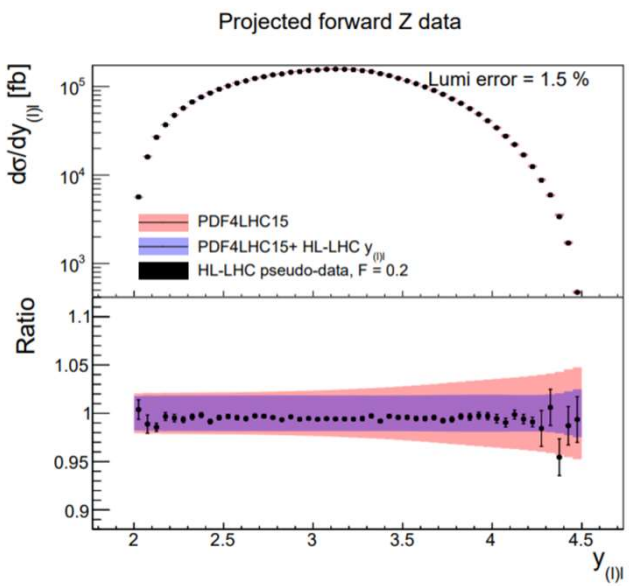

Correlations between high-mass DY and the up anti-quark PDF
ρ
x
PDF4LHC15 + HLLHC m_ll

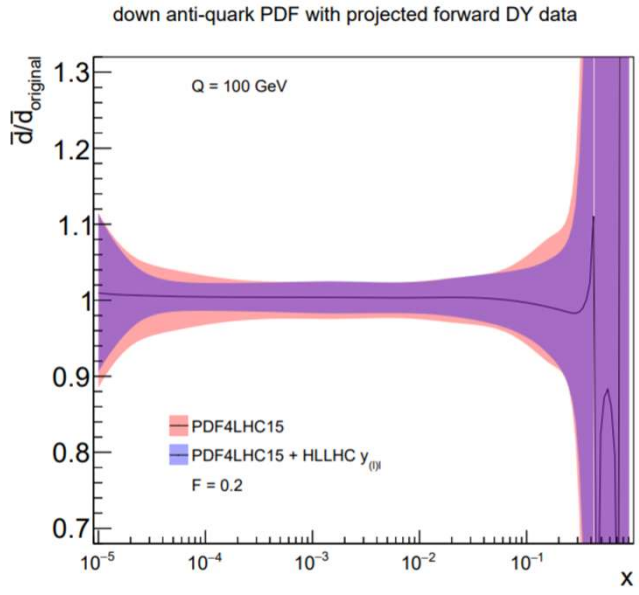

Projected high-mass DY data
dσ/dm_ll [fb/GeV]
Lumi error = 1.5 %
PDF4LHC15
PDF4LHC15+ HL-LHC m_ll
HL-LHC pseudo-data, F = 0.2
Ratio
m_ll [GeV]


up anti-quark PDF with projected high-mass DY data
ū/ū_original
Q = 100 GeV
PDF4LHC15
PDF4LHC15 + HLLHC m_ll
F = 0.2
x

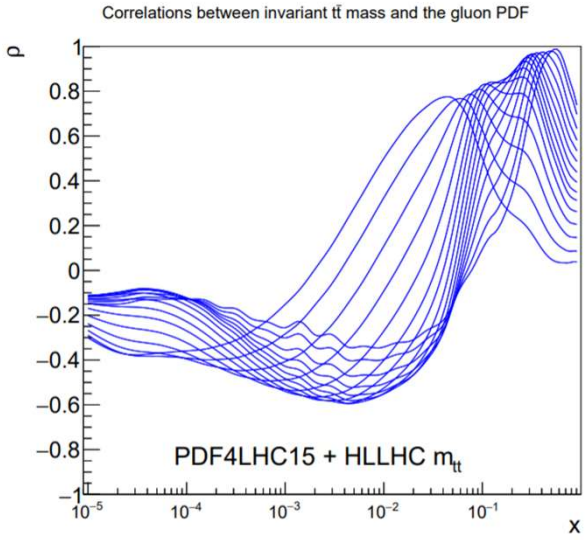
Forward DY

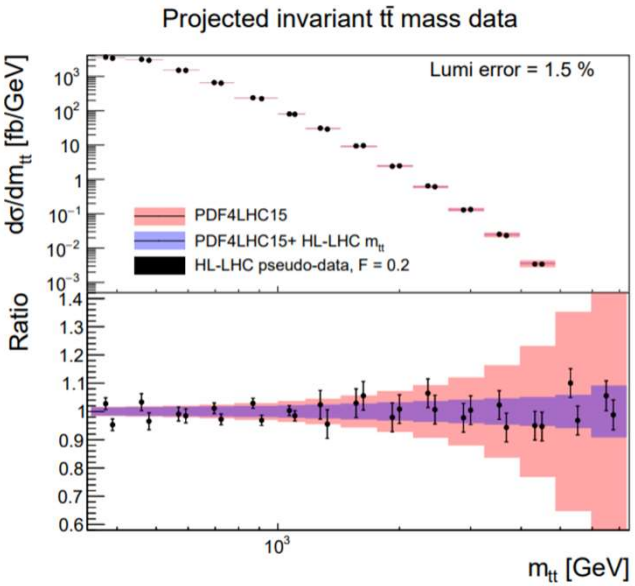

Correlations between forward DY and the down anti-quark PDF
ρ
PDF4LHC15 + HLLHC y(l)l
x

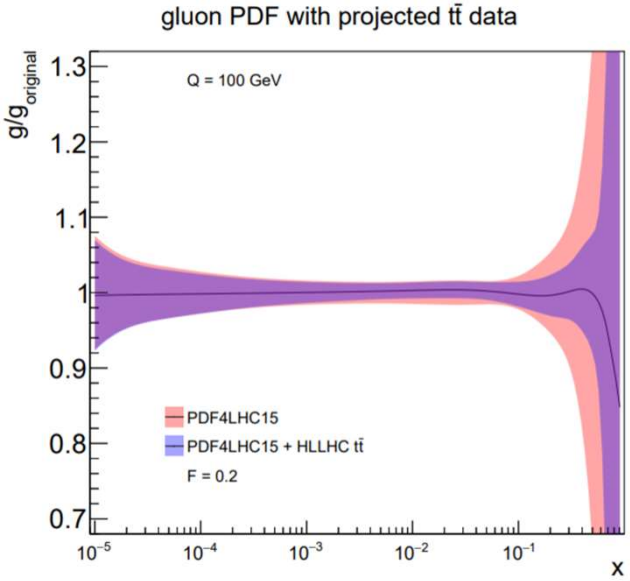

Projected forward Z data
dσ/dy(l)l [fb]
Lumi error = 1.5 %
PDF4LHC15
PDF4LHC15+ HL-LHC y(l)l
HL-LHC pseudo-data, F = 0.2
Ratio
y(l)l


down anti-quark PDF with projected forward DY data
d̄/d̄original
Q = 100 GeV
PDF4LHC15
PDF4LHC15 + HLLHC y(l)l
F = 0.2
x

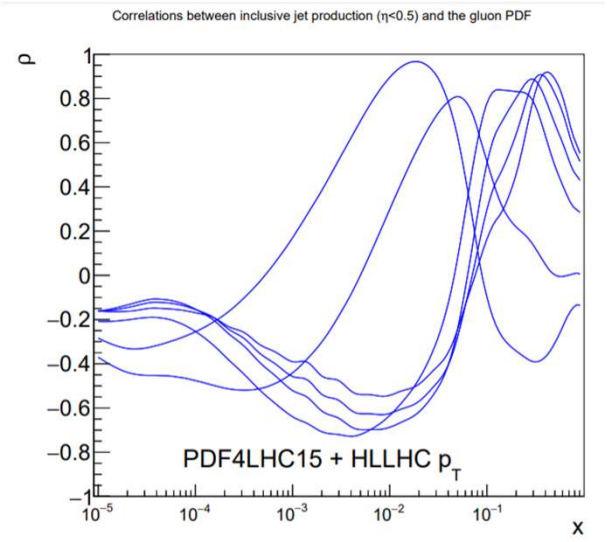
$t\bar{t}$

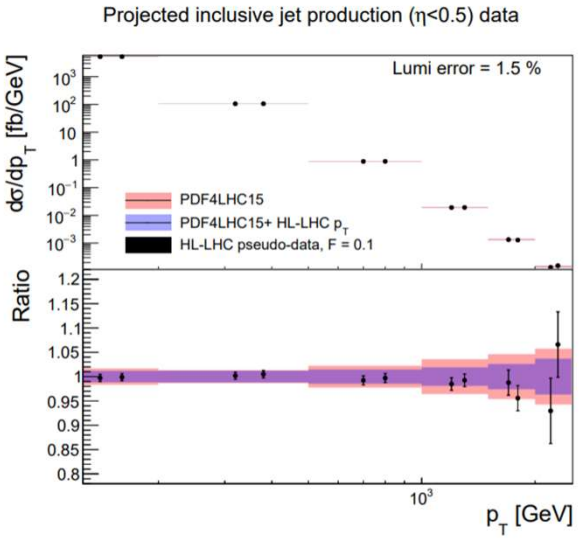

Correlations between invariant tt̄ mass and the gluon PDF
ρ
PDF4LHC15 + HLLHC m_tt
x

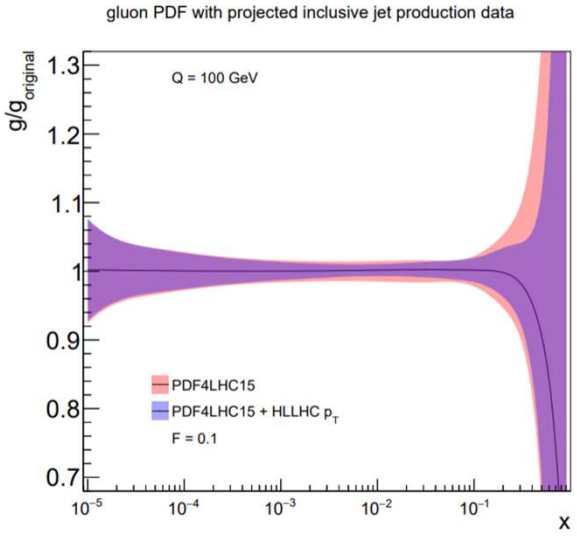

Projected invariant tt̄ mass data
Lumi error = 1.5 %
dσ/dm_tt [fb/GeV]
PDF4LHC15
PDF4LHC15+ HL-LHC m_tt
HL-LHC pseudo-data, F = 0.2
Ratio
m_tt [GeV]


gluon PDF with projected tt̄ data
g/g_original
Q = 100 GeV
PDF4LHC15
PDF4LHC15 + HLLHC tt̄
F = 0.2
x

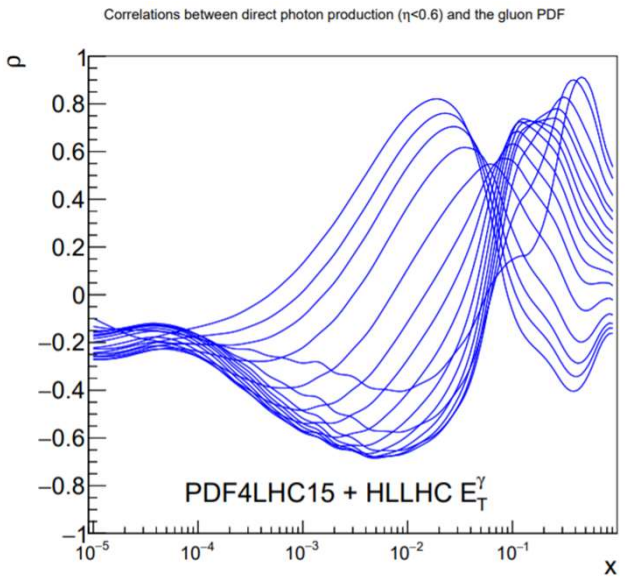
Inclusive Jet

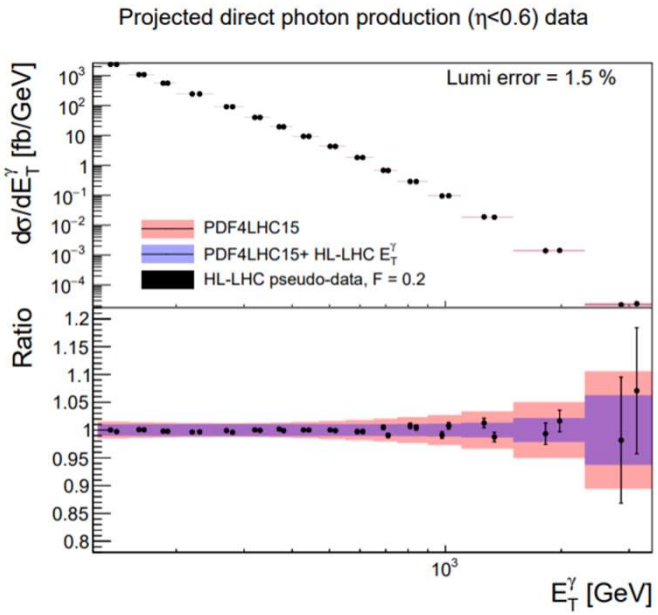


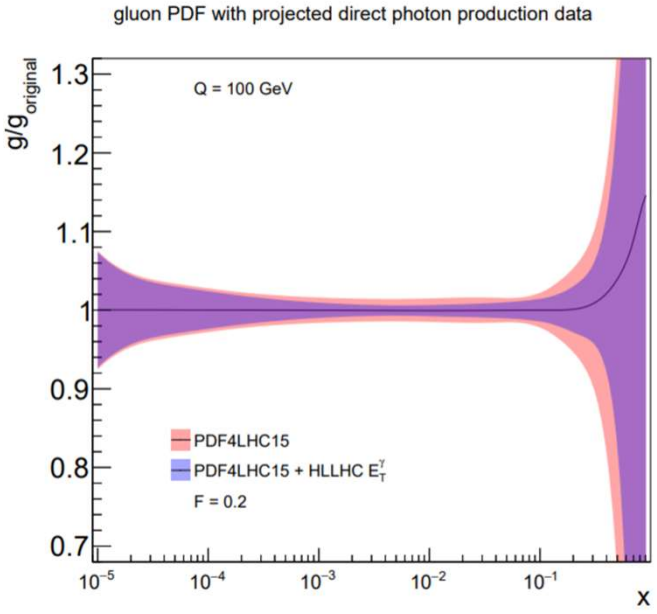




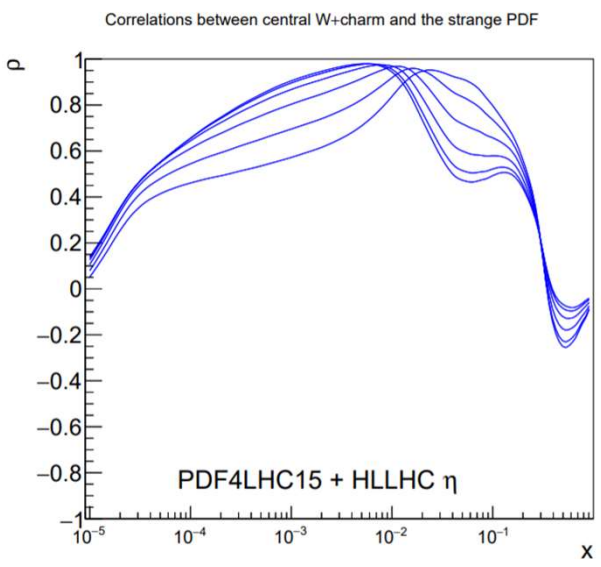
Direct Photon

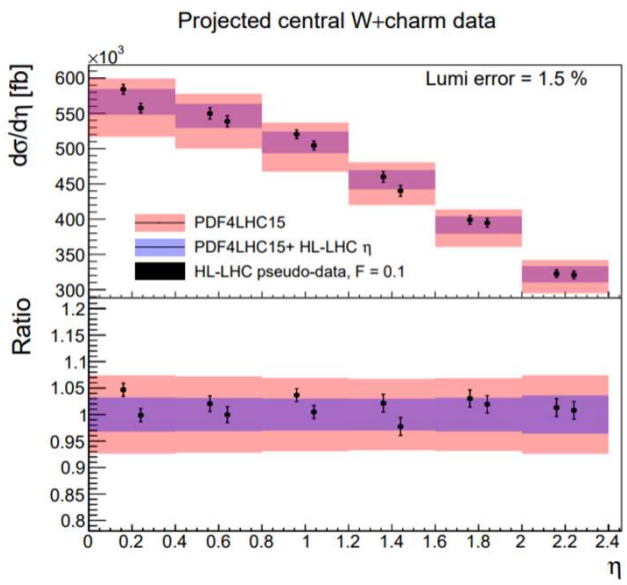


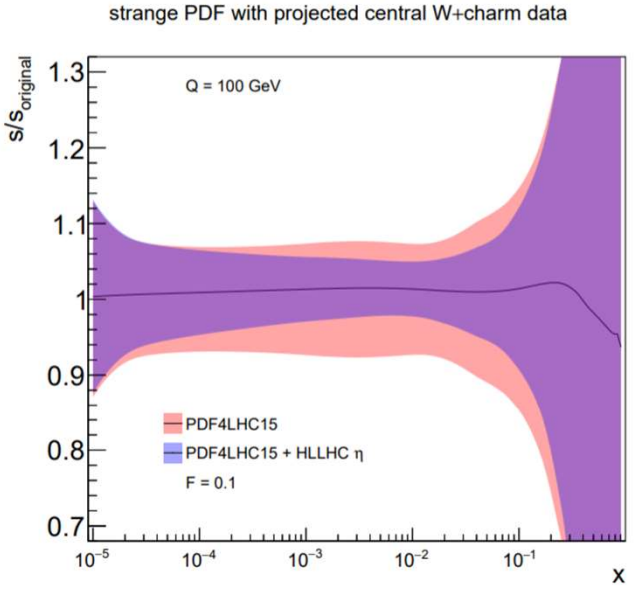




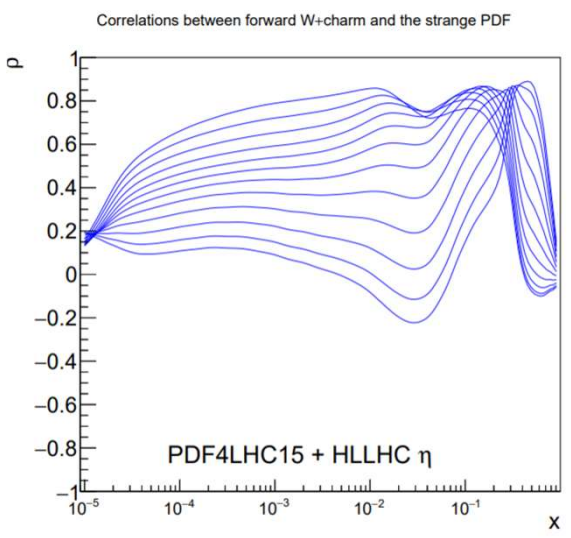
Central W + charm

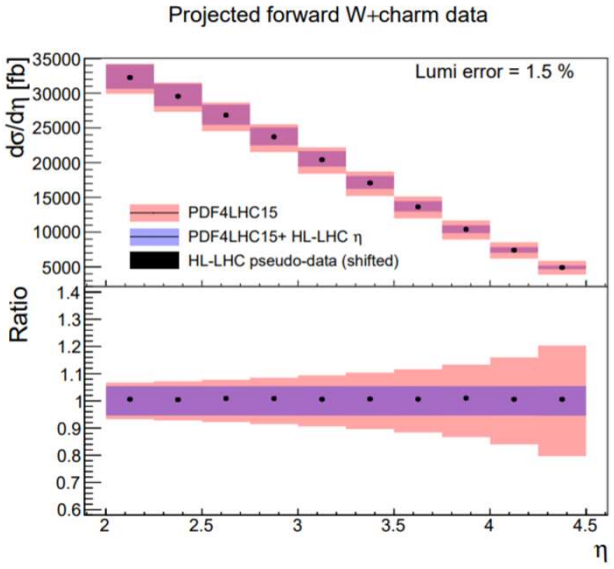


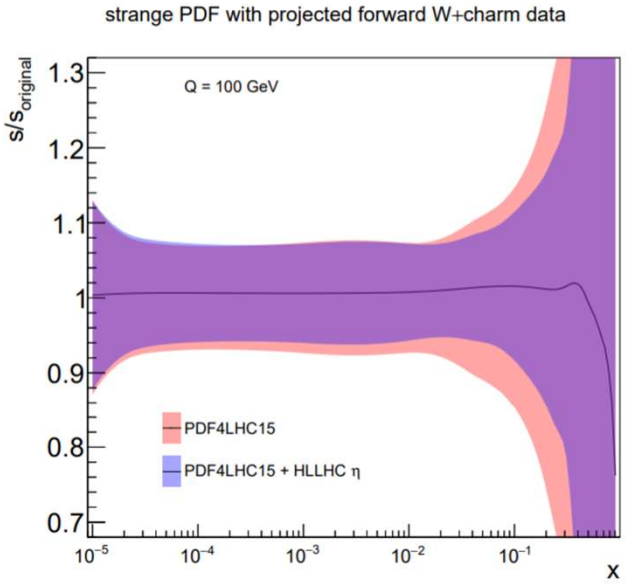




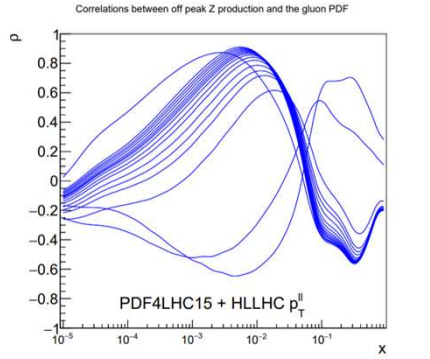
Forward W + charm

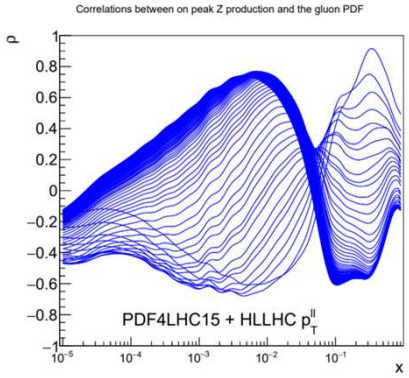


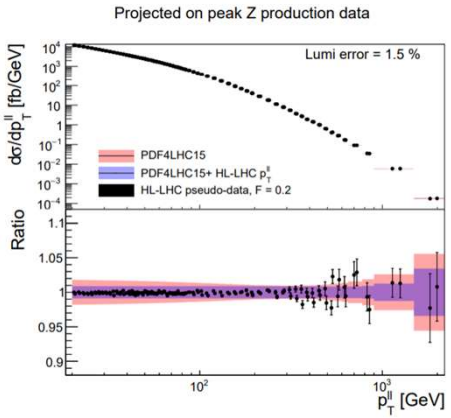


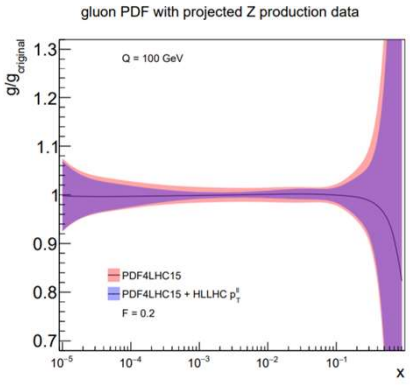


Z production

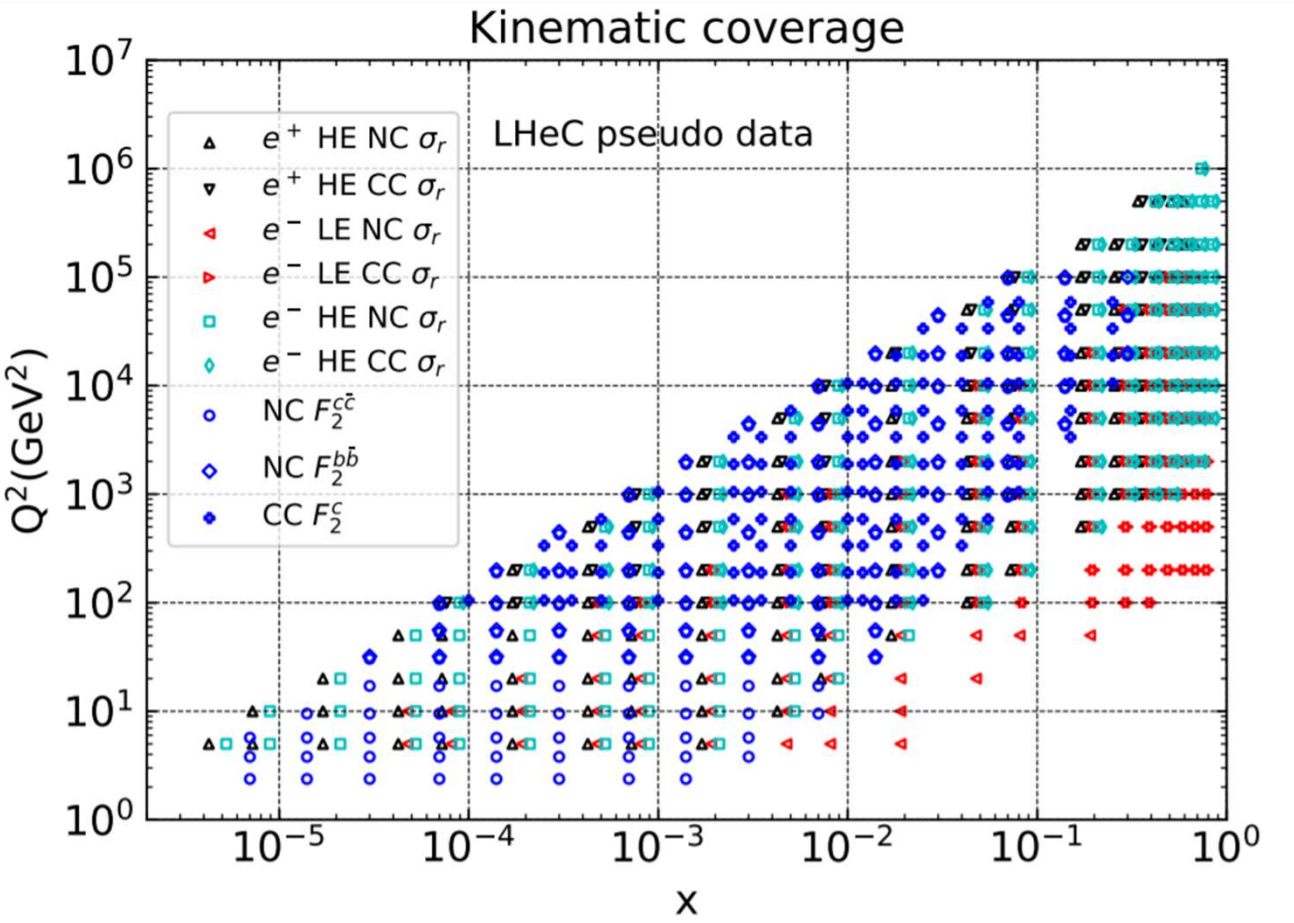




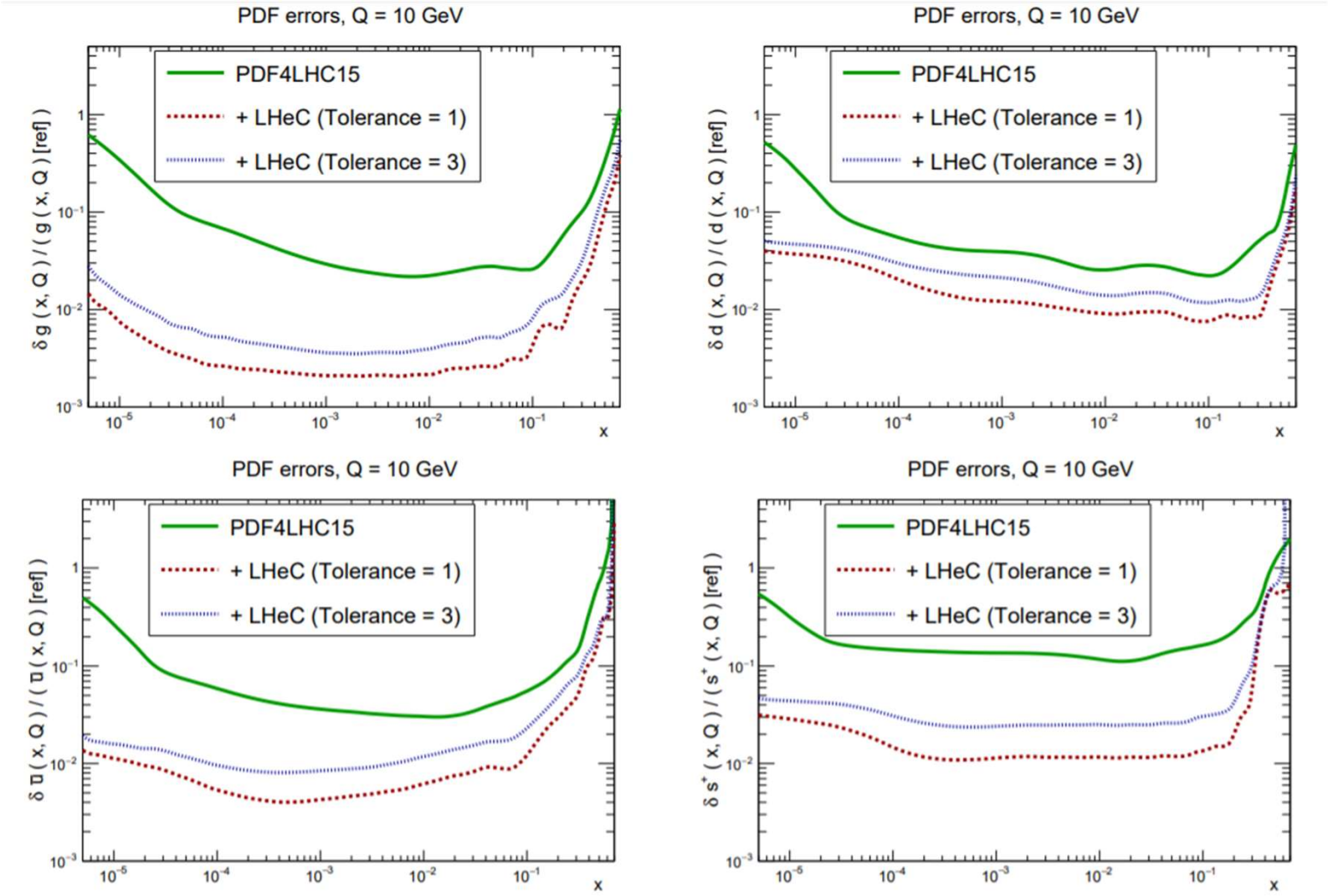




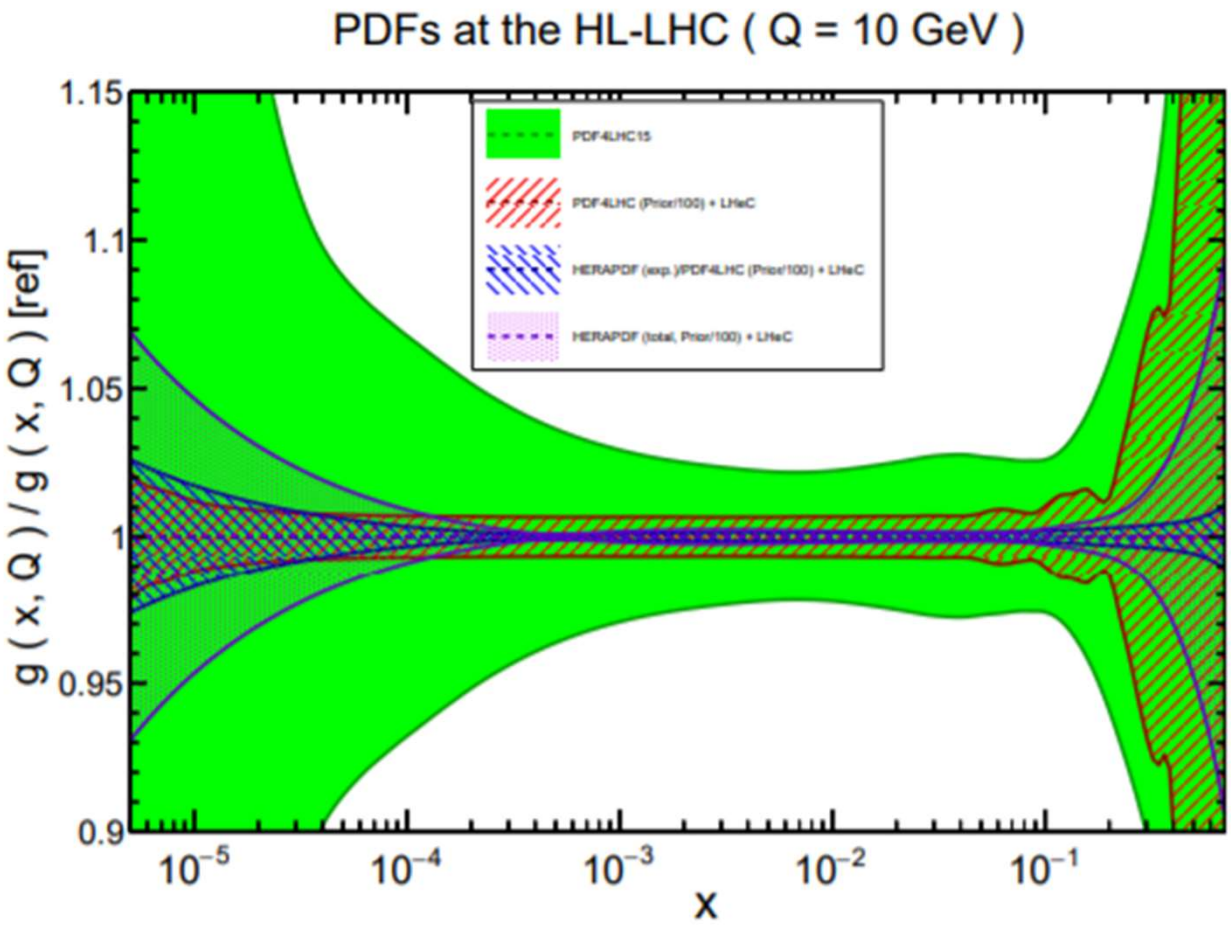
Kinematic coverage LHeC



LHeC - tolerance



Prue LHeC


PDFs at the HL-LHC (Q = 10 GeV)
PDF4LHC15
PDF4LHC (Prior/100) + LHeC
HERAPDF (exp.)/PDF4LHC (Prior/100) + LHeC
HERAPDF (total, Prior/100) + LHeC
g (x, Q) / g (x, Q) [ref]
1.15
1.1
1.05
1
0.95
0.9
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x

LHeC – HERAPDF