

PDF Theory Update: Tools & Ultimate PDF Study

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HL/HE-LHC Meeting - SM (WG1)

CERN, 20 June 2018

Outline

- Two PDF contributions to Yellow Report:
 - ❖ **PDF 'tools'** (3 pages): summary of PDF theory aspects of direct relevance to HL/HE-LHC.
 - ❖ **Ultimate PDFs** (10 pages): dedicated study to quantify expected impact of final HL-LHC dataset on PDF fits.
- Will provide updates on both contributions.

a. **PDF tools** (3 pages)

Contributors: Lucien Harland Lang, Jun Gao, Juan Rojo (TH)

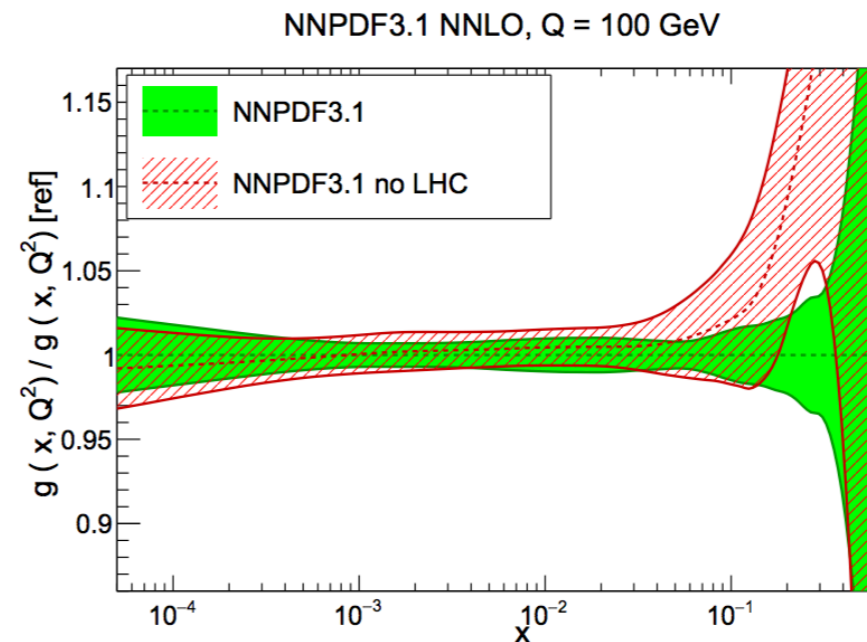
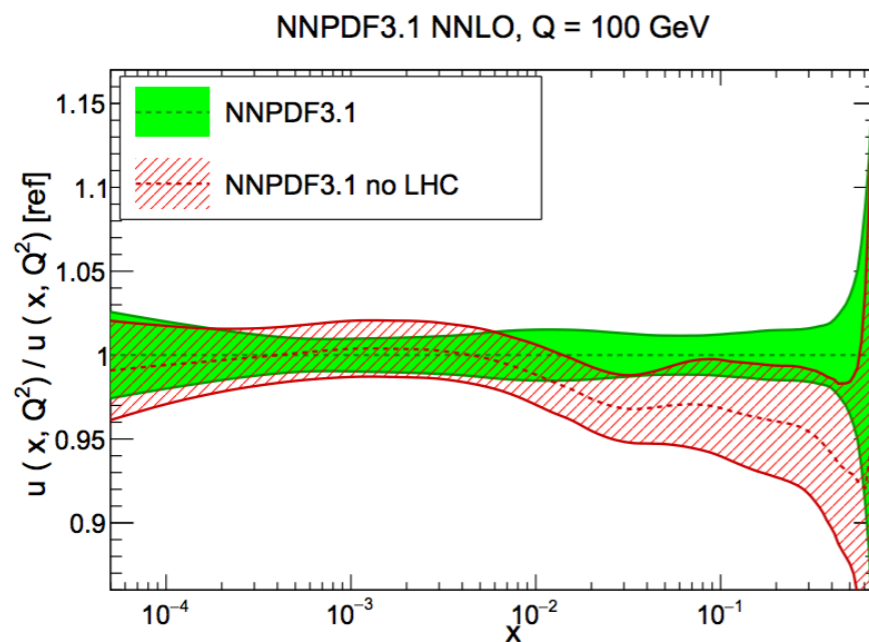
a. **Ultimate Parton Densities** (10 pages)

Contributors: Mario Campanelli (ATLAS), Claire Gwenlan (ATLAS), Katerina Lipka (CMS), Katerina Mueller (LHCb), Juan Rojo Chacon (TH), Jun Gao (TH), Lucian Harland-Lang (TH), Paolo Nason (TH)

PDF Tools

Tools section

- Six broad subtopics discussed. Will give (very) brief overview here:
 - ★ Quantifying the **impact** of LHC data.
 - ★ **Theory**: uncertainties and future improvements.
 - ★ **Fast interfaces** at NNLO.
 - ★ **EW** corrections and photon-initiated processes.
 - ★ Perspectives for the **HE-LHC**.



- **Impact of LHC** data: clear from Run I alone. Motivation for ultimate PDF study (more later).

Fast Interfaces

- **NNLO** the **standard** in PDF fits. Availability of fast tools for inclusion of NNLO theory essential, as in APPLgrid and FastNLO at NLO.
- Progress already made in this direction - differential $t\bar{t}$ at NNLO released via FastNLO grids. **Used in PDF fits** already.

M. Czakon, D. Heymes, A. Mitov, arXiv:1704.08551

- **APPLfast** will make fast **NNLOJET** (IPPP, Zurich, ETH et al.) calculation feasible for inclusive W, Z, Z + jet, H + jet, inclusive jets in ep and pp...

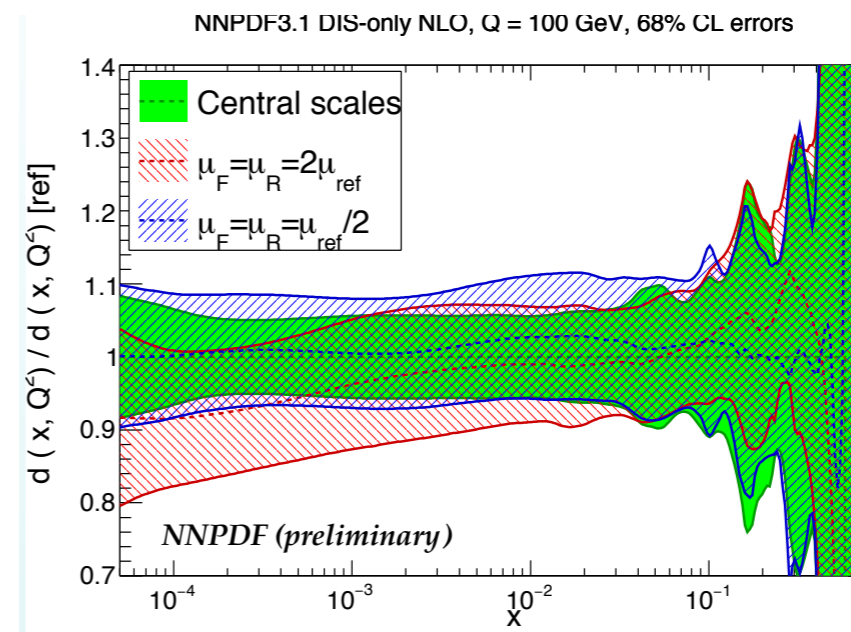
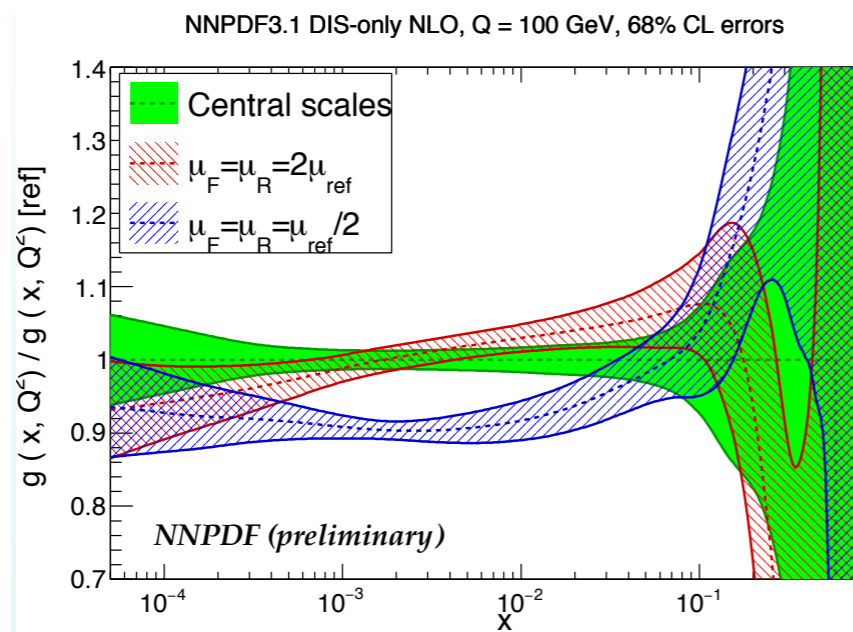
→ Fast interfaces for NNLO theory will be the standard by the HL era.

job type	# jobs	events/job	runtime/job	# events	total output	total runtime
LO	10	140 M	20.6 h	1.4G	24 MB	206 h
NLO-R	200	6 M	19.0 h	1.2G	1.3 GB	3800 h
NLO-V	200	5 M	21.2 h	1.0G	1.2 GB	4240 h
NNLO-RPa	5000	60 M	22.5 h	0.3G	26 GB	112500 h
NNLO-RPb	5000	40 M	20.3 h	0.2G	27 GB	101500 h
NNLO-RV	1000	200 M	19.8 h	0.2G	6.4 GB	19800 h
NNLO-WV	300	4 M	20.5 h	1.2G	2.0 GB	6150 h
total	11710	—	—	5.5G	64 GB	248196 h

3 × 11710 grids/tables + all NNLOJET output!
 Final 3 files for analysis are O(10MB) each

Theory: uncertainties and improvements

- **HL-LHC** - data errors \downarrow : must consistently quantify uncertainty from approx. fixed-order theory in fits. First estimates - could be significant.



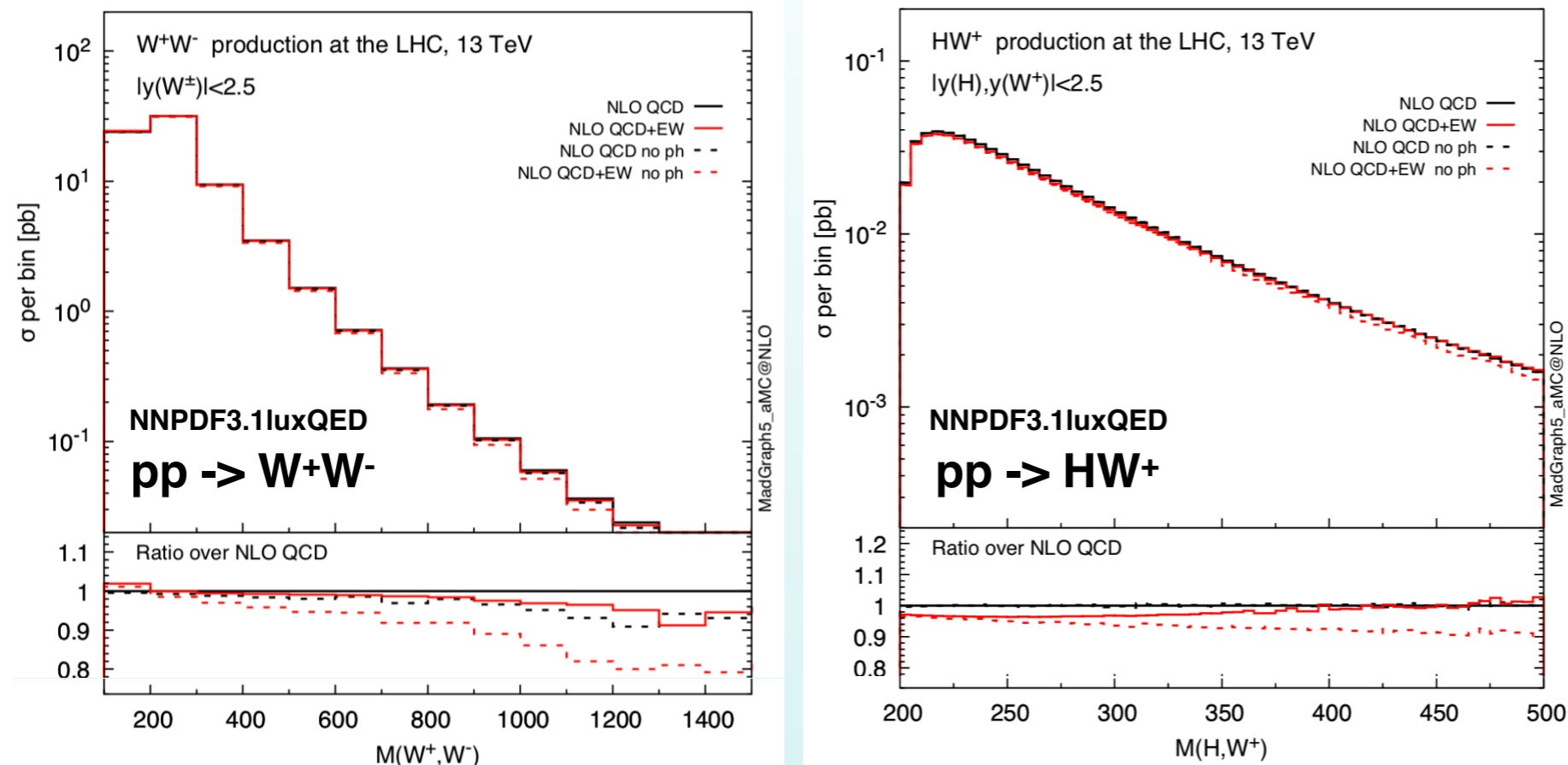
- Other anticipated improvements can reduce these uncertainties:
 - ▶ **N3LO** fits may be within reach: recent progress in splitting functions + cross section calculations. **S. Moch et al., JHEP 1710 (2017) 041**
F. Dulat et al., JHEP 1801 (2018) 145
 - ▶ Fits with low/high x **resummation** for relevant kinematic regions.

EW corrections

$$\alpha_s(M_Z)^2 \sim \alpha_{EM}(M_Z)$$

- **EW corrections** can contribute at same level as **NNLO QCD** corrections, particularly at large p_\perp /invariant mass due to Sudakov logs \Rightarrow **NLO EW** should be systematically accounted for in fits at HL-LHC (and before).
- This must include **photon-initiated** contributions with high precision (luxQED) determination. Cancellation with virtual EW often seen.

A. Manohar et al., Phys. Rev. Lett. 117 (2016) no.24, 100001

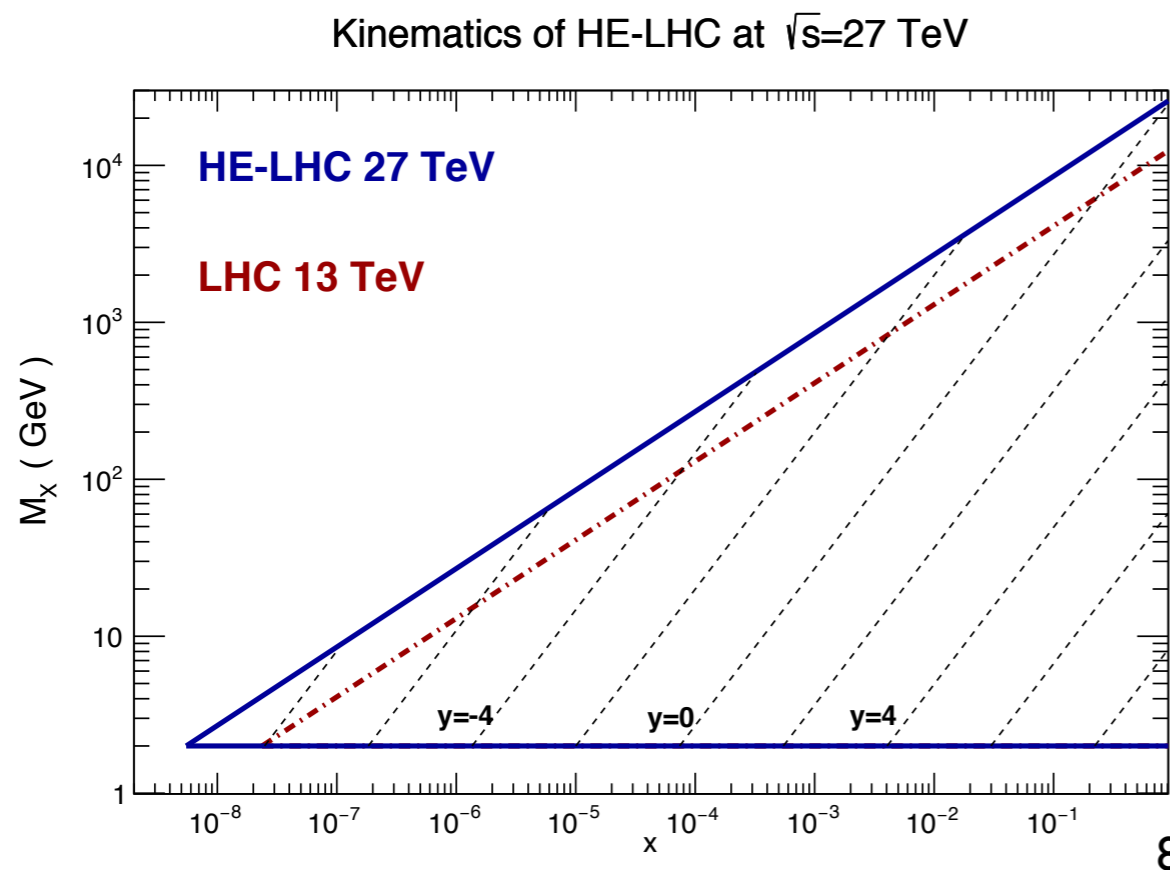


Bertone, Carazza,
Pagani, Rojo, Vicini,
Zaro, in progress.

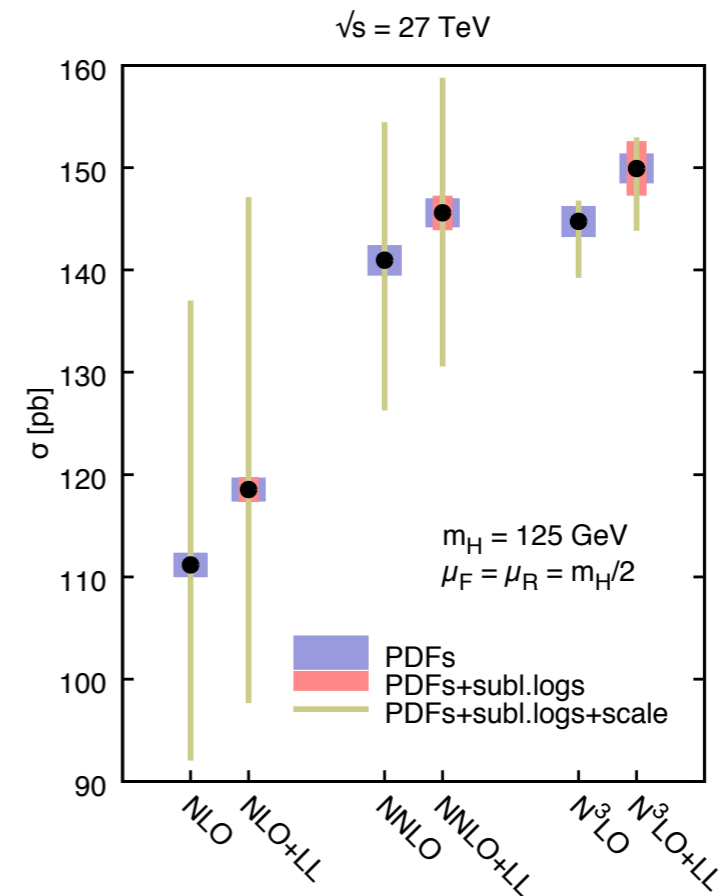
HE-LHC perspectives

- HE-LHC - new PDF relevant effects become important due to **increased phase space** (much already discussed in FCC context):
 - ★ Sensitivity to low x region increases for EW scale objects - BFKL **resummation** becomes more relevant.
 - ★ EW objects ~ effectively massless at high energy: **EW PDFs** more relevant: e.g. W, Z and top quark PDFs (latter with suitable matching).

M. Bonvini, arXiv:0805.08785



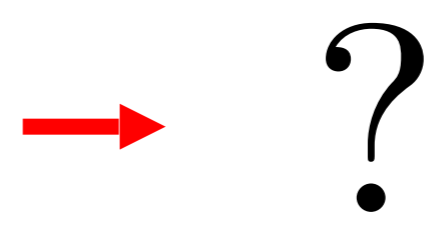
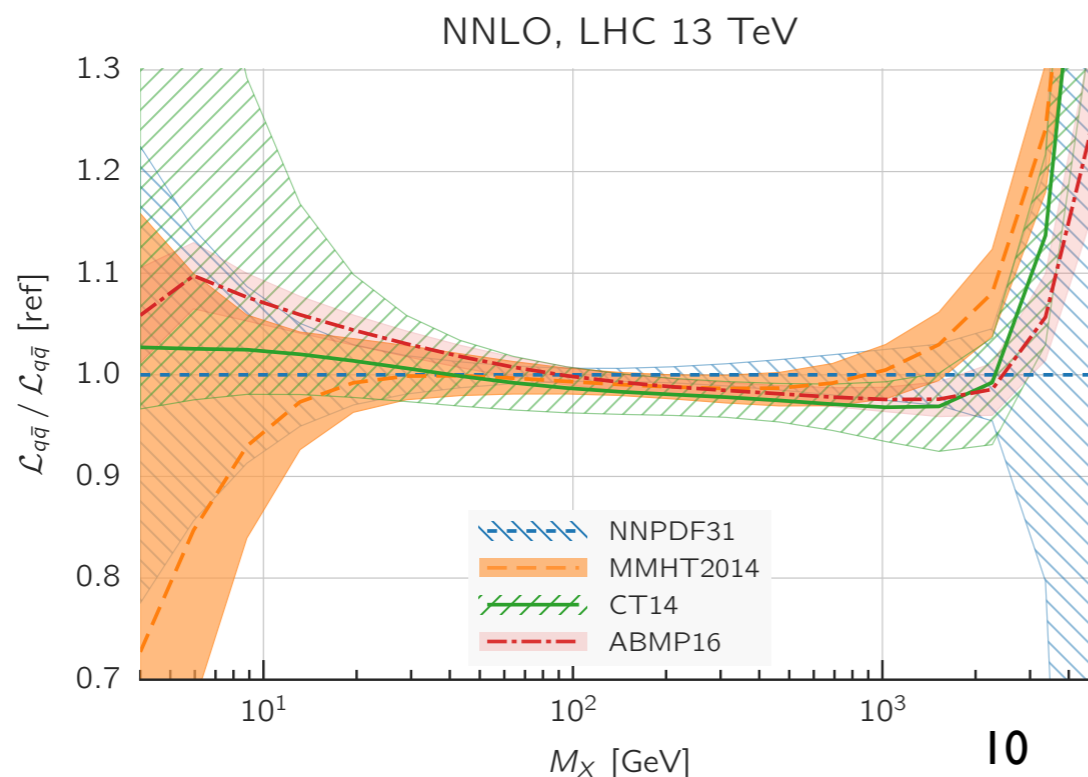
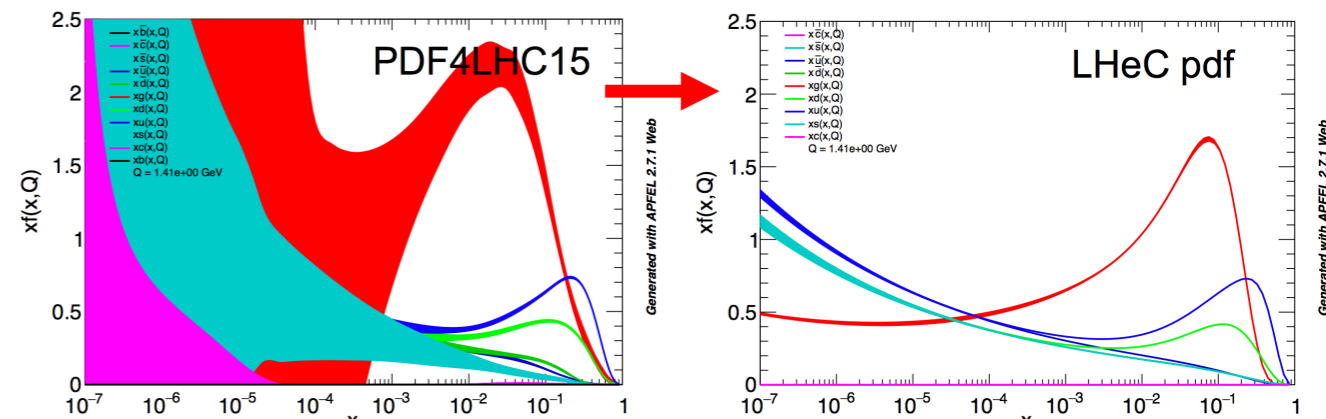
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Ultimate PDFs

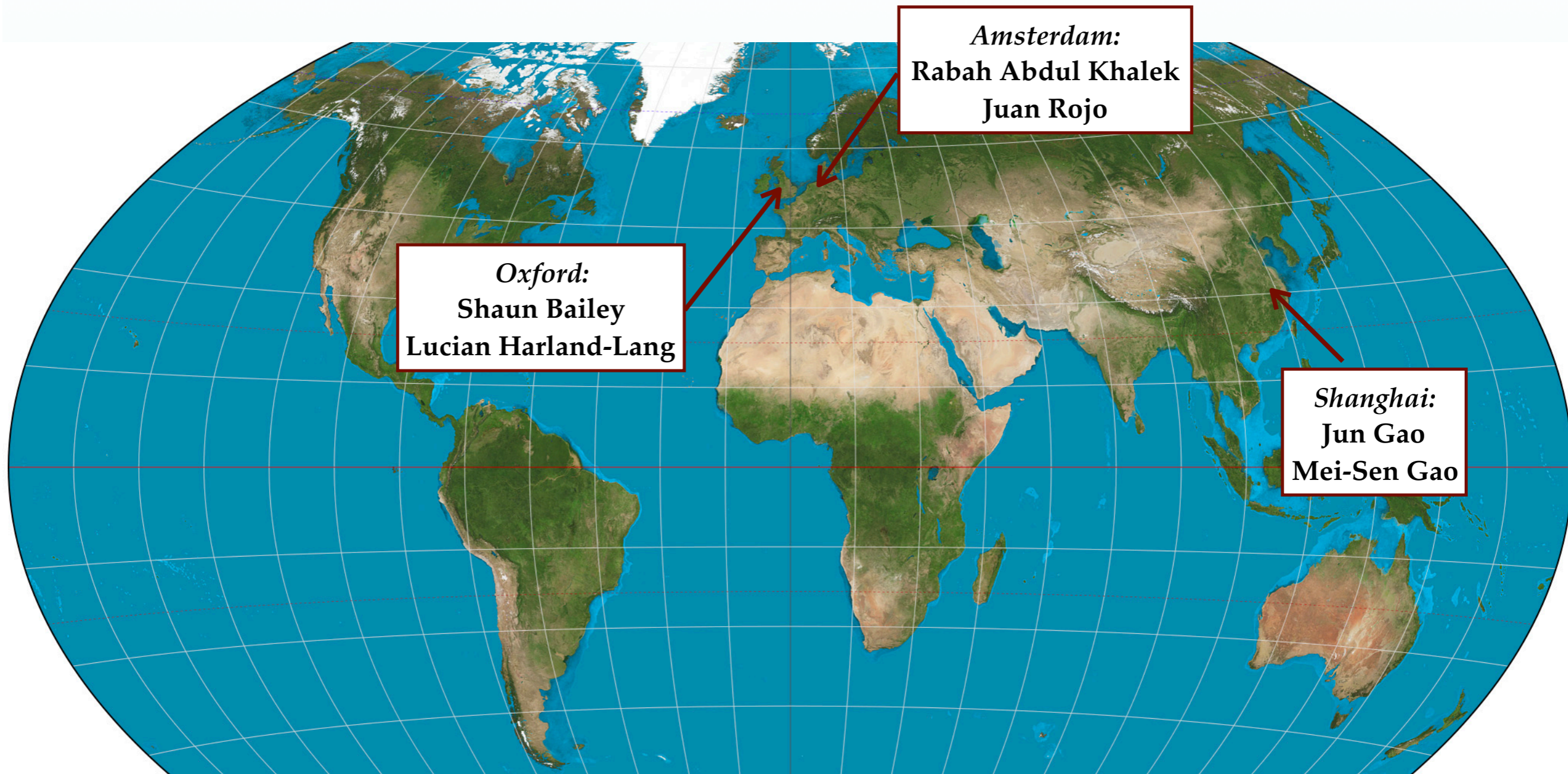
Ultimate PDFs - Motivation

- The HL-LHC will provide a vast range of data with a direct impact on the PDFs (in particular in poorly known high x region).
- **Question:** what exactly can we expect that impact to be?
- To address this, collaborative effort to produce '**Ultimate**' PDF set ongoing.
- Similar exercise has already been done for **LHeC**.



Generated with APFEL 2.7.1 Web

The team



Contact persons within the LHC experiments:
Mario Campanelli, Claire Gwenlan (ATLAS)
Katerina Lipka (CMS)
William Barter, Stephen Farry (LHCb)

Basic Idea

Produce theory predictions for relevant processes, in kinematic region probed by HL-LHC



Produce pseudodata - binned predictions, provided with corresponding statistical + systematic errors.



Perform initial profiling with PDF4LHC baseline to assess impact of HL-LHC pseudodata set



Perform full fits within global framework. Combination gives 'Ultimate PDF' set for public release.

The HL-LHC dataset

- Processes included so far (presented today):
 - ▶ **Drell-Yan** - high mass, central (flavour separation).
 - ▶ **Differential top** quark (gluon).
 - ▶ **Z transverse momentum** distribution (gluon, antiquarks).
- Processes to follow:
 - ▶ **Drell-Yan** - forward (flavour separation).
 - ▶ **W/Z + charm** (strange, charm).
 - ▶ **Prompt photon** production (gluon).
- Generate pseudo-data for these using PDF4LHC set. Take **NLO** QCD theory input.

In detail - errors and binning

- What will final datasets look like?

- ★ **Binning + statistical errors.** Base on existing measurements, latter scaled from data. Expected refinements in latter to be included.

- ★ **Systematics errors:** Base on existing data + expected reduction.

What about **correlations**?

- True systematics highly correlated between bins. Correlations non-trivial + experiment dependent. **Beyond scope** of study.

- Simply treat as **uncorrelated*** - decreases PDF sensitivity below realistic expectation.

- Idea: include uncorrelated systematics, but scaled by factor $f_{\text{sys}} < 1$

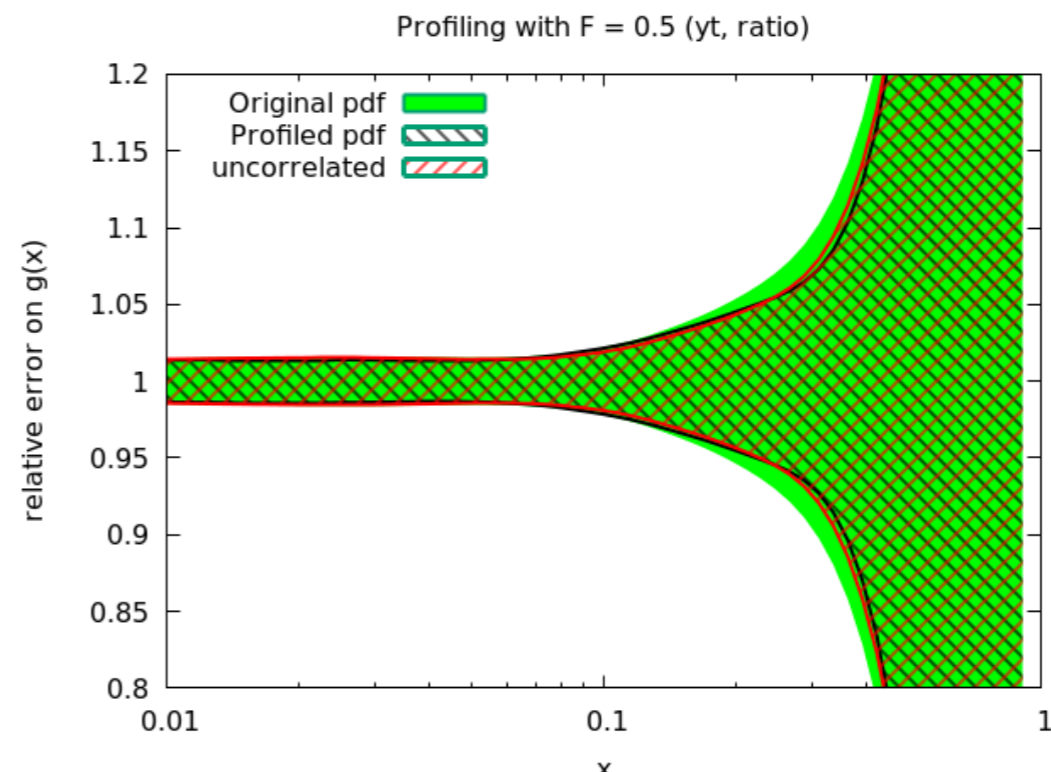
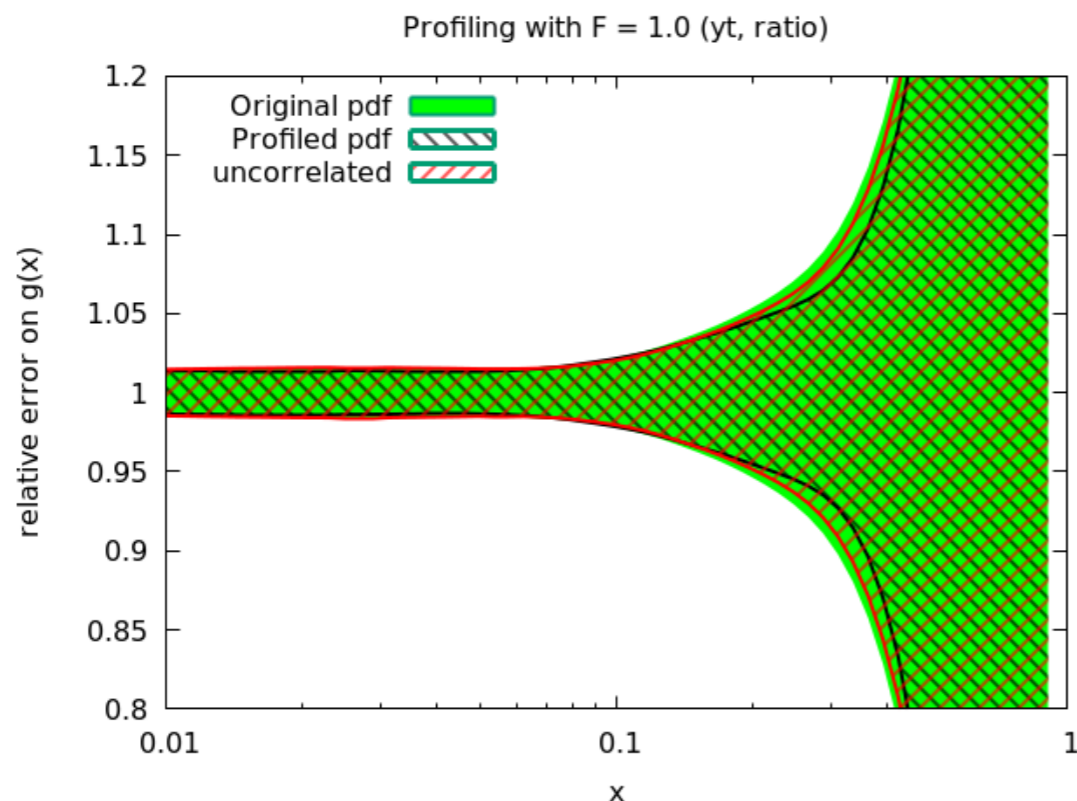
$$\sigma_i^{\text{sys,uncorr}} = f_{\text{sys}} \left(\sum_{k=1}^{N_{\text{corr}}} (\sigma_{k,i}^{\text{sys,corr}})^2 \right)^{1/2}$$

- Fix f_{sys} by requiring comparable PDF impact of existing data (w/ full corr.). Future improvement \Rightarrow further reduction in f_{sys} .

***Exception- luminosity correlation included.**

Systematic Errors

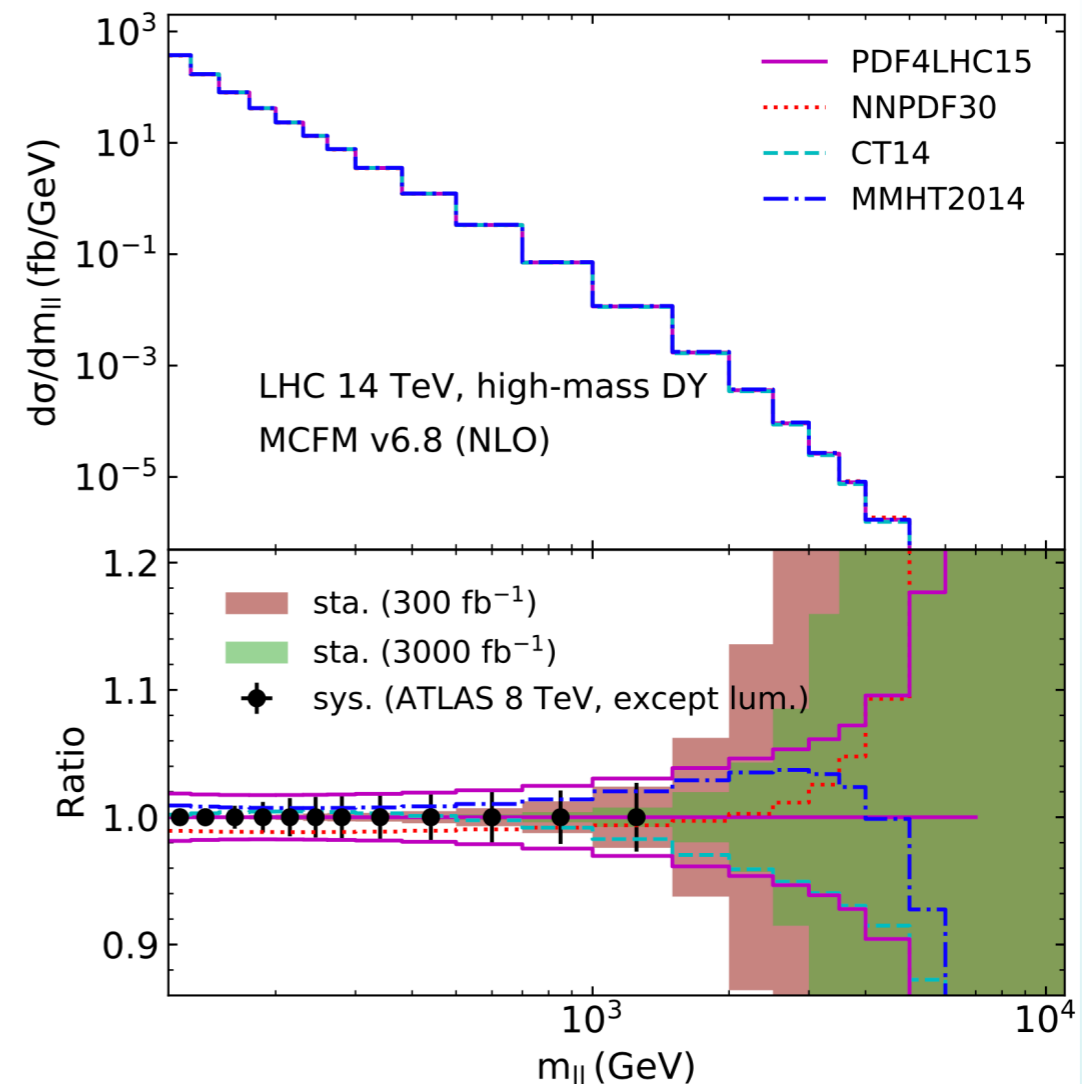
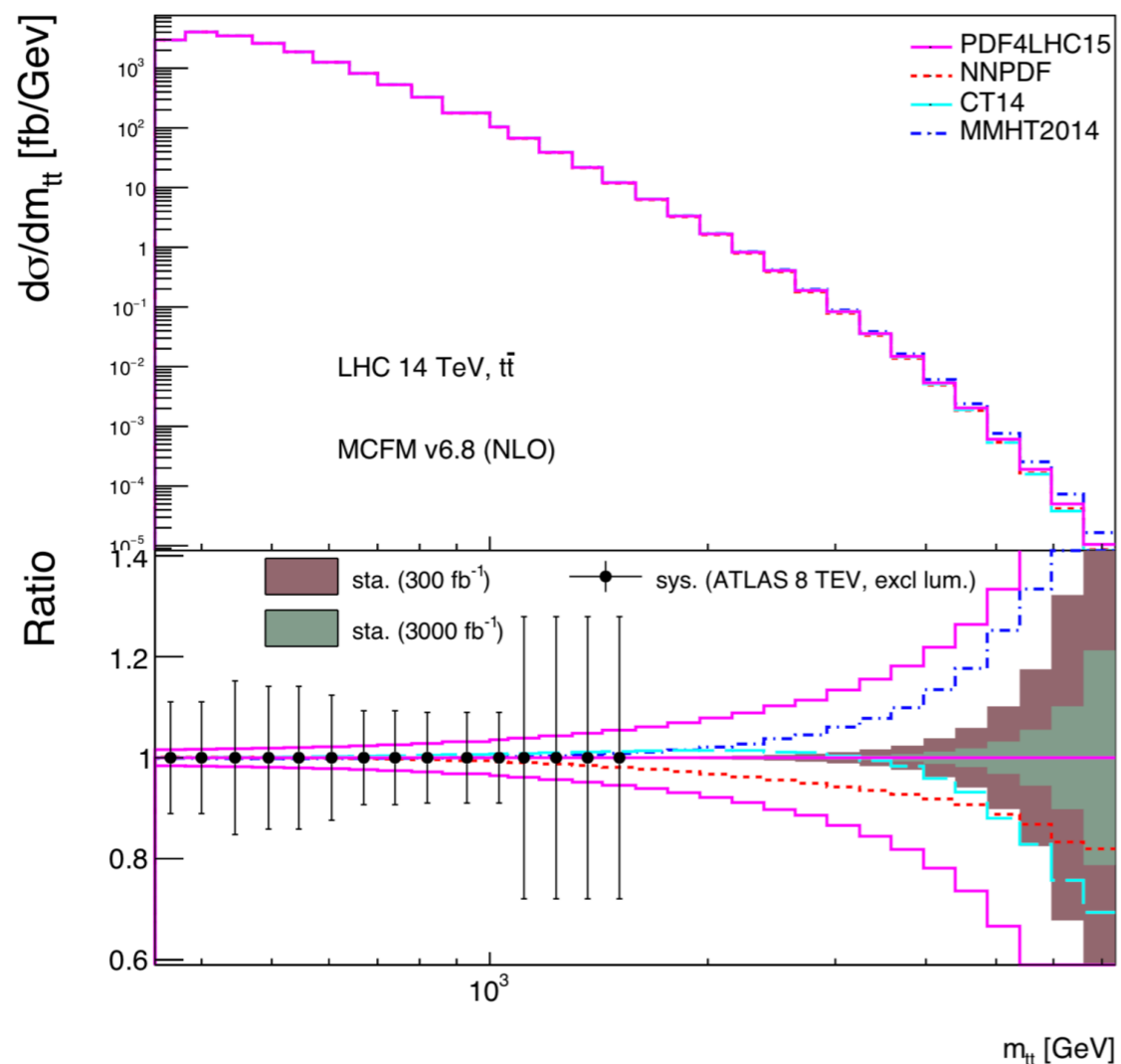
- Consider ATLAS 8 TeV differential $t\bar{t}$ data as example.
- Find that fitting* with $f_{\text{sys}} = 1$ indeed gives less reduction in uncertainties vs. fitting with full experimental correlations.
- A value of $f_{\text{sys}} \approx 0.25 - 0.5$ appropriate. Final choice to be fine-tuned.
- Note this only comes from (lack of) correlations. Must also include expected improvement at HL-LHC. To be finalised, but baseline - further reduction by factor of ~ 2 .



*To be precise, profiling.

Pseudodata - examples

- Two examples shown below - dilepton and $t\bar{t}$ invariant mass distributions.
- Extended reach out to $M \sim O(\text{TeV})$ clear \Rightarrow important constraints on e.g. high x gluon and antiquarks expected.



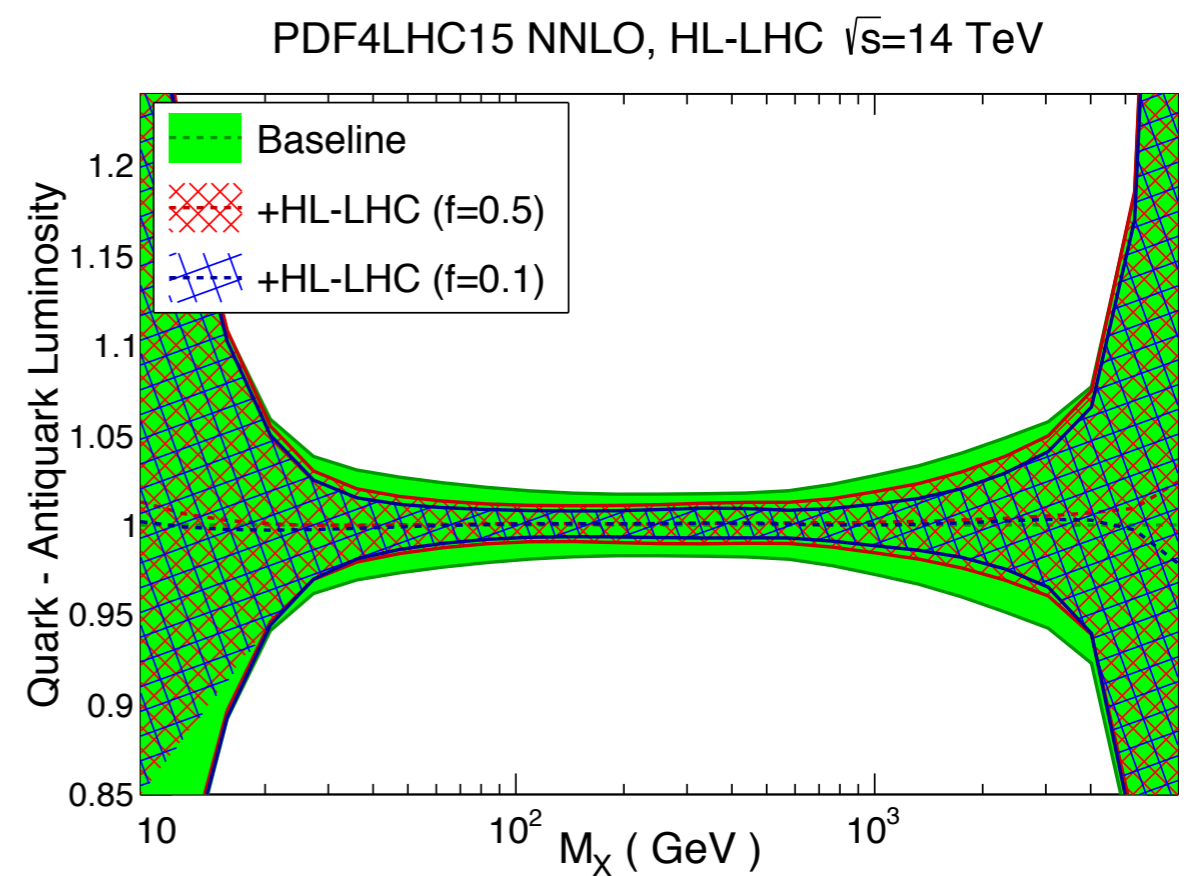
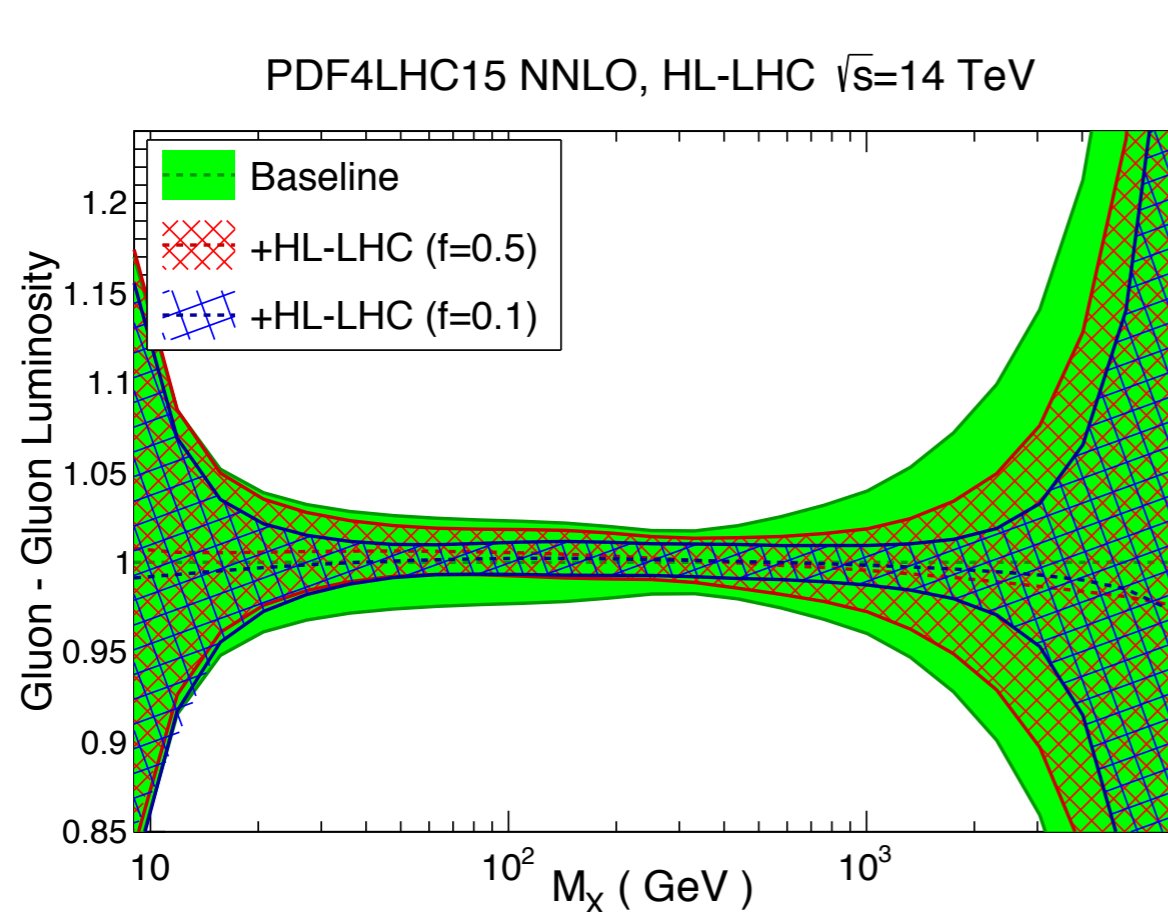
First Results

- What is impact? Three datasets considered (so far):
 - ▶ **Drell-Yan** - low to high mass, central (flavour separation).
 - ▶ **Differential top** quark (gluon).
 - ▶ **Z transverse momentum** distribution (gluon, antiquarks).
- Systematics: take $f_{\text{sys}} = 0.5$ vs. 0.1 ~ conservative vs. optimistic scenarios.
- This and other aspects (e.g. binning) to be refined, further data sets to be added.

→ First Look. More to come!

PDF Luminosities

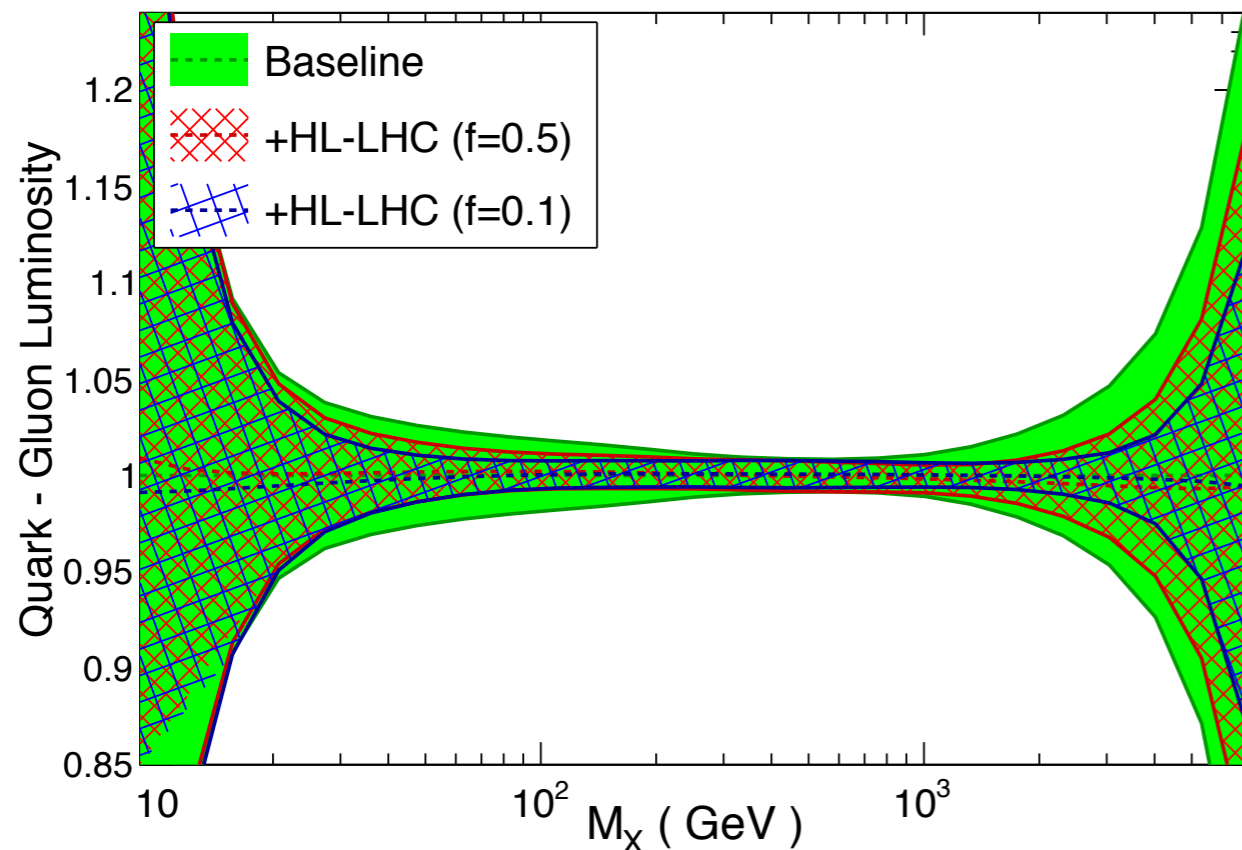
- Consider gg and $q\bar{q}$ luminosities:
 - ★ gg : large impact particularly at high mass, even with v. conservative systematics (\sim essentially no improvement in systematics).
 - ★ $q\bar{q}$: improvement over wide mass range.



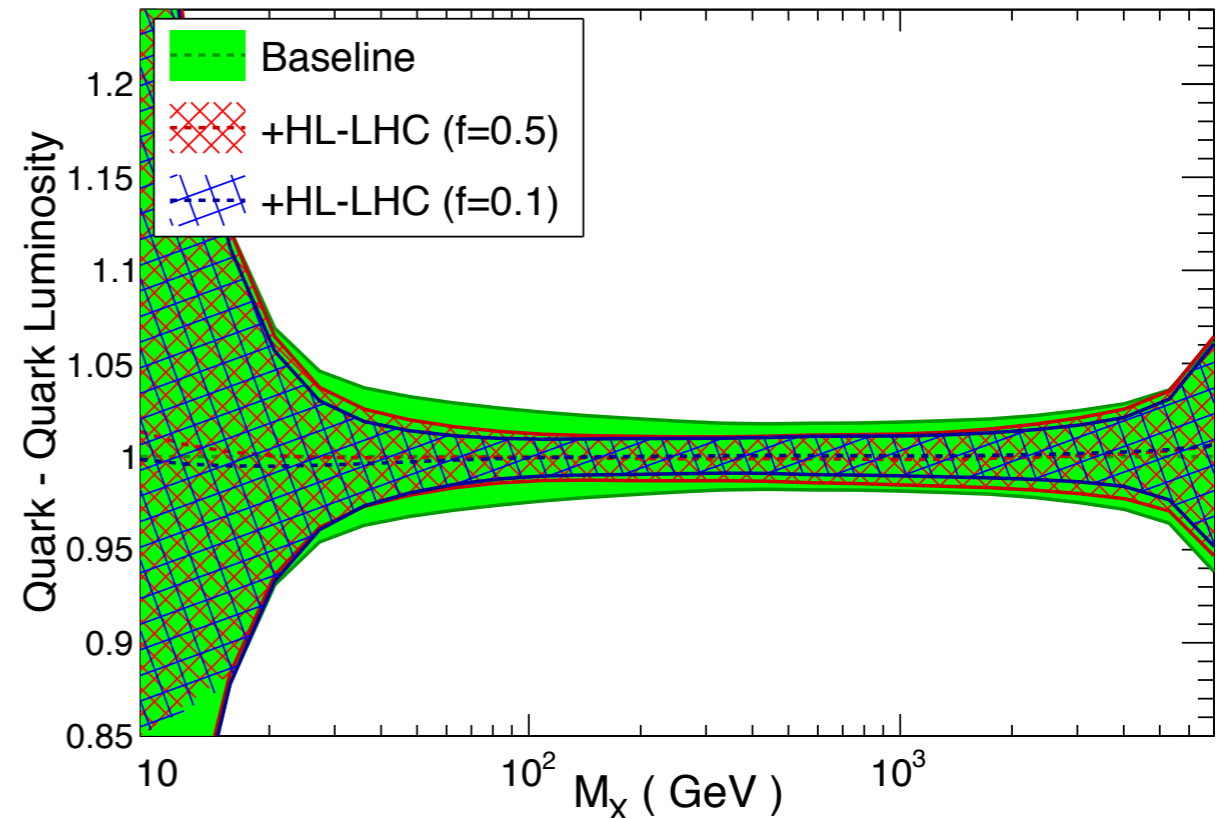
PDF Luminosities

- qg and qq luminosities:
 - ★ qg : again dramatic impact at high mass, even with v. conservative systematics - driven by improvement in gluon.
 - ★ qq : less significant (already constrained by DIS), but not negligible.

PDF4LHC15 NNLO, HL-LHC $\sqrt{s}=14$ TeV

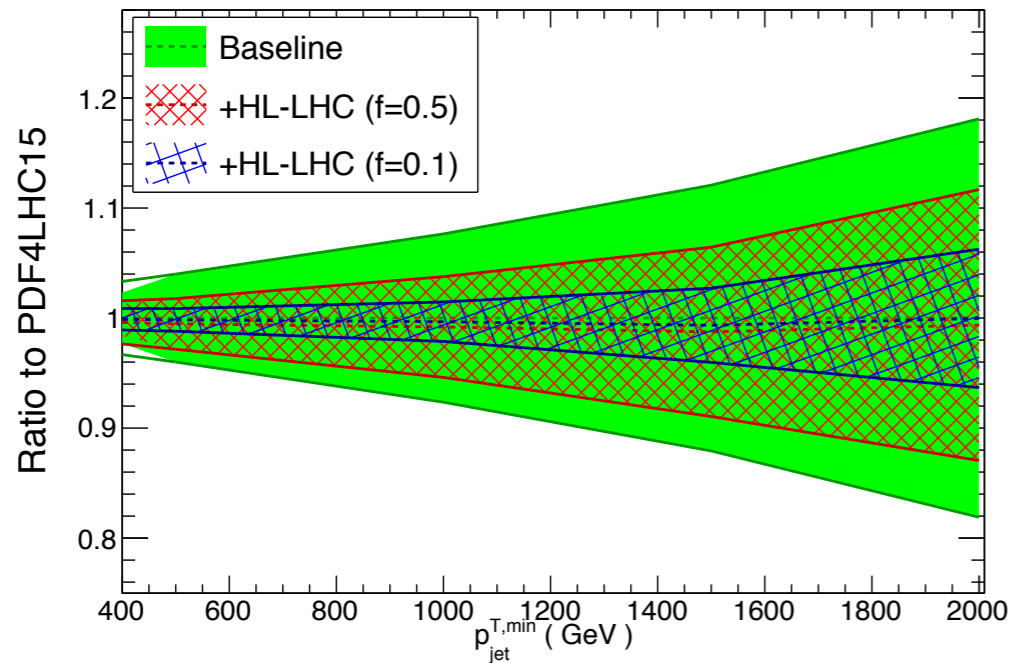


PDF4LHC15 NNLO, HL-LHC $\sqrt{s}=14$ TeV

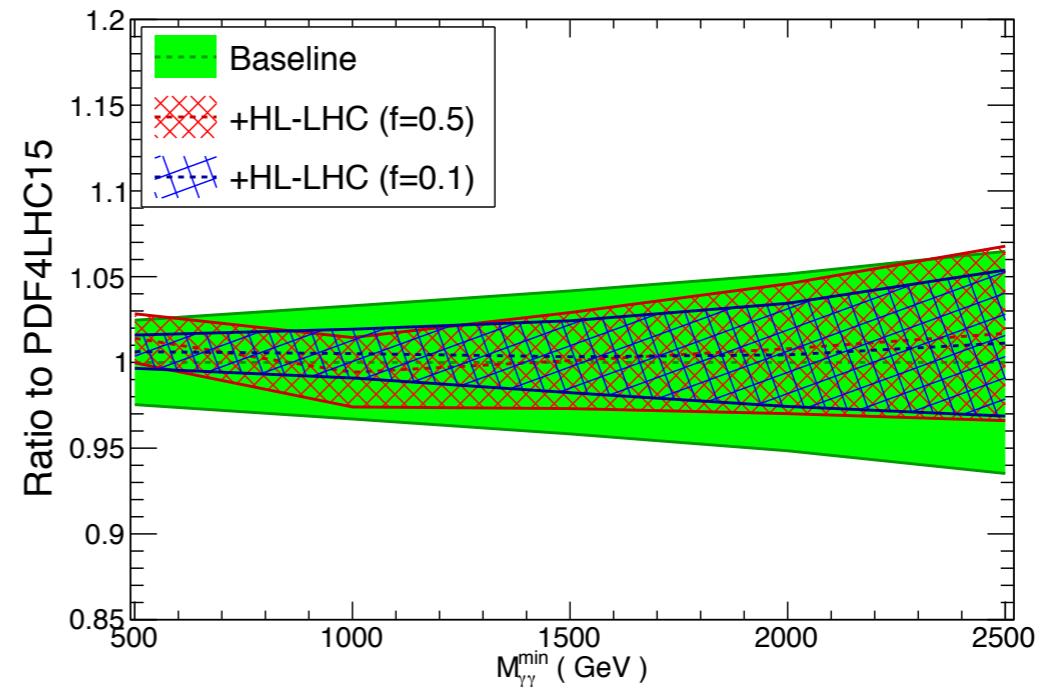


Cross sections

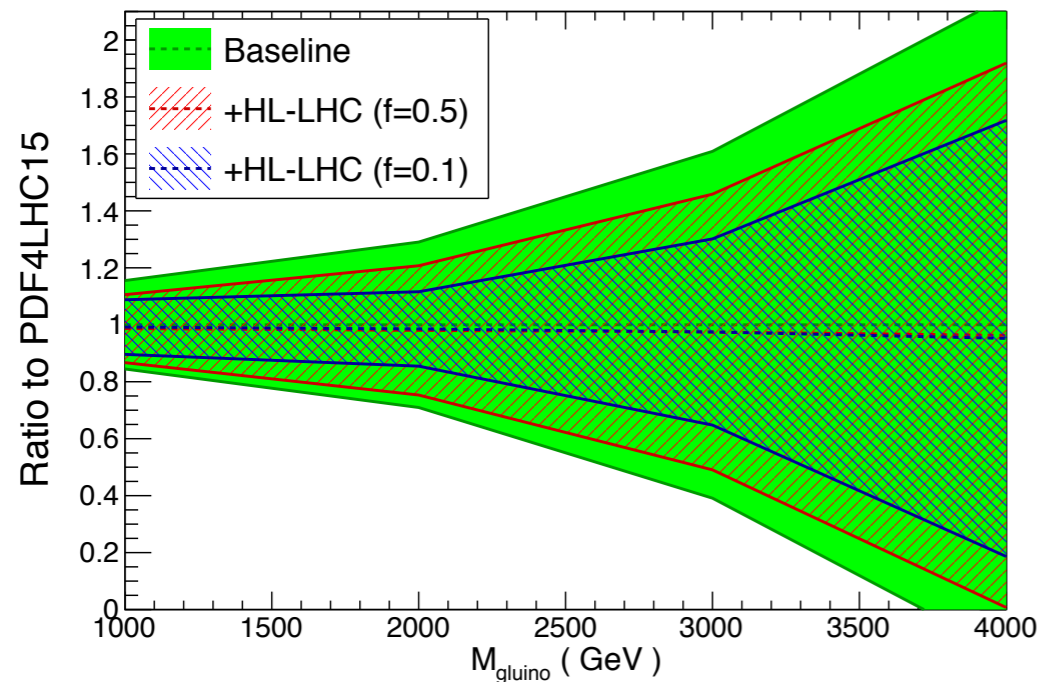
gg => h+jet at the HL-LHC $\sqrt{s}=14$ TeV



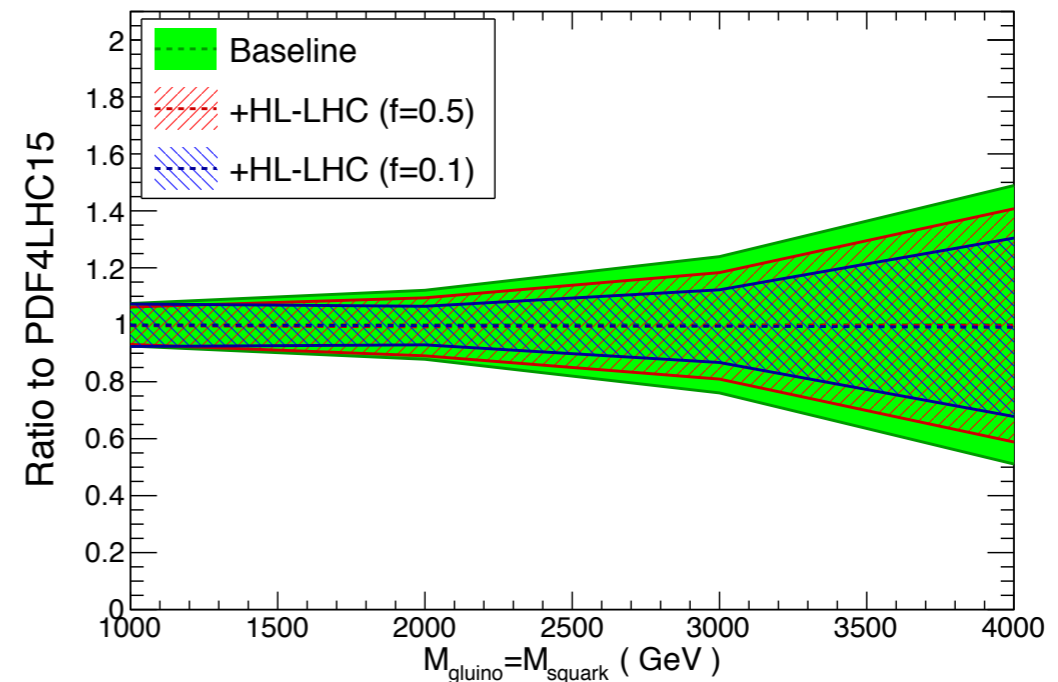
Di-photon production at the HL-LHC $\sqrt{s}=14$ TeV



Glauino pair production at the HL-LHC $\sqrt{s}=14$ TeV



Squark-Gluino production at the HL-LHC $\sqrt{s}=14$ TeV



- Improvement in parton luminosities feeds through to impact on LHC cross sections, in particular gluon-initiated.

Preliminary

Conclusion - next Steps

- Projected impact already promising, but further datasets to add:
 - ▶ **Drell-Yan** - forward (flavour separation).
 - ▶ **W/Z + charm** (strange, charm).
 - ▶ **Prompt photon** production (gluon).
- Other elements of study to be refined:
 - ▶ Final systematics. Plan - consider factor of ~ 2 improvement as reasonable assumption \rightarrow three baselines ($f_{\text{sys}} = (0.1, 0.25, 0.5)$).
 - ▶ Binning - how will this be refined at HL-LHC? In many cases to be discussed/finalised.
 - ▶ After profiling exercise: full fits and combination. Public release of Ultimate PDF sets via LHAPDF.

Thank you for listening