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UNIVERSITY OF CAMBRIDGE

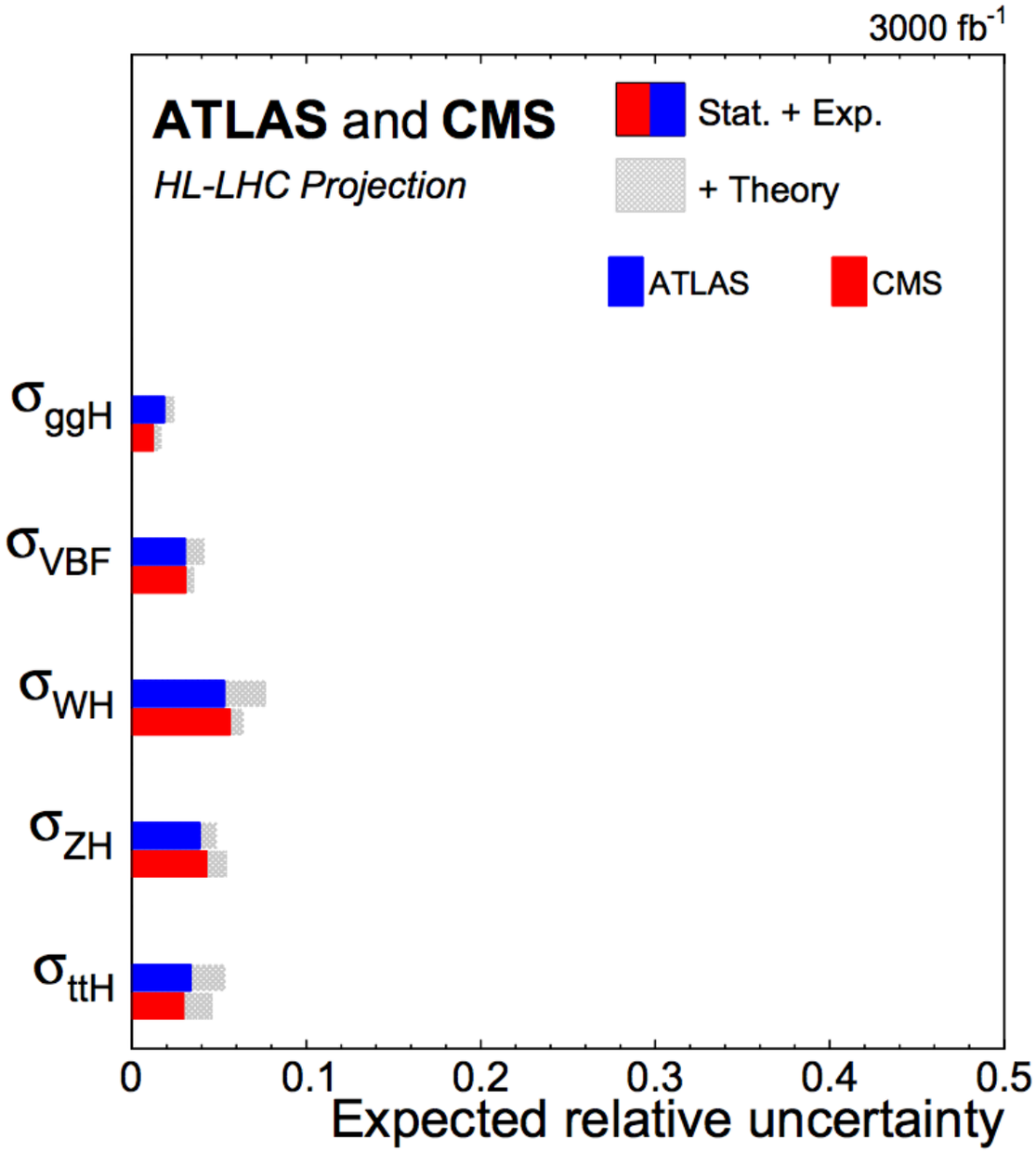
PARTON DISTRIBUTION FUNCTIONS FOR HIGGS PHYSICS

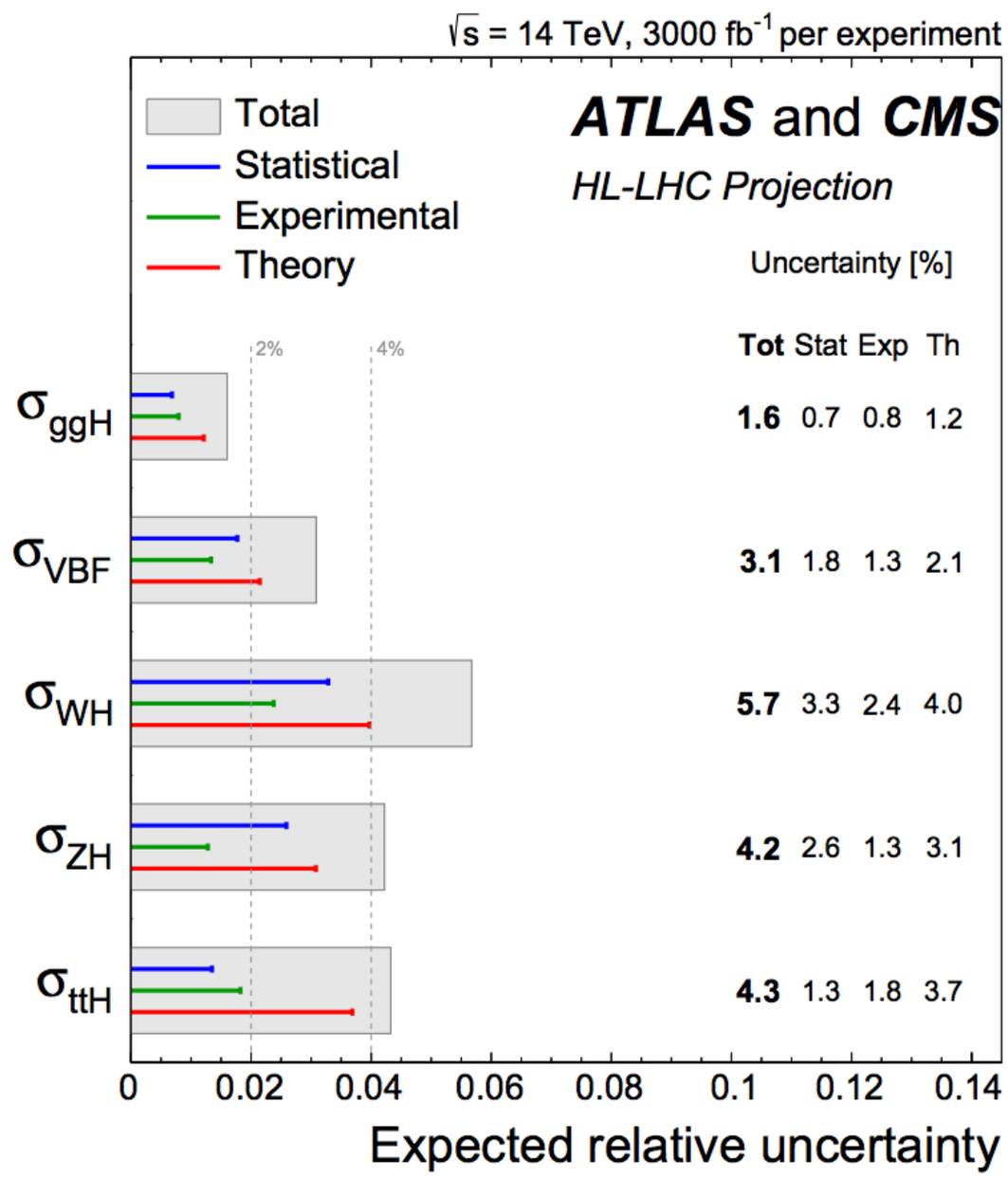
HIGGS COUPLINGS 2019, OXFORD

30TH SEPTEMBER 2019

PRECISION CHALLENGE FOR HIGGS PHYSICS

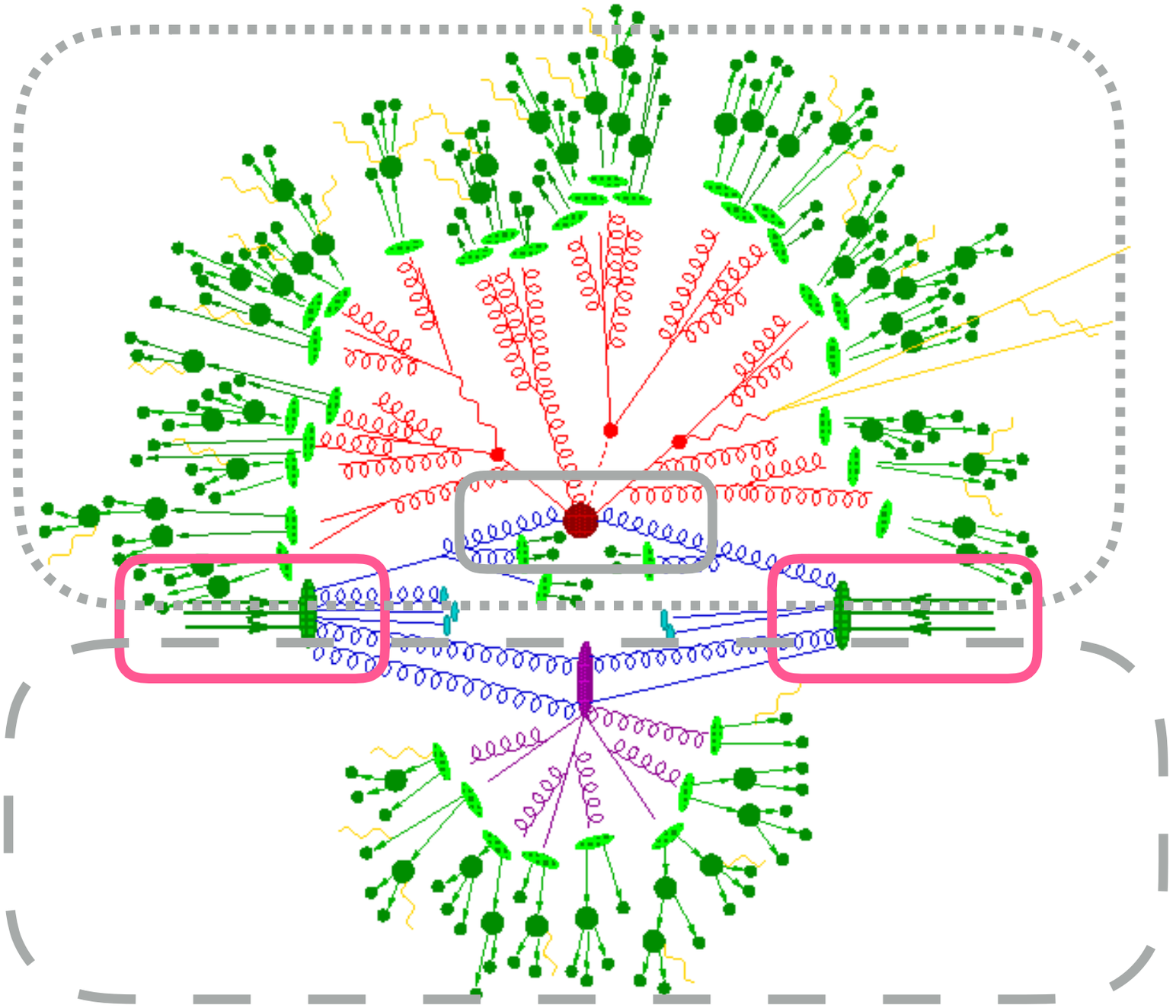
- LHC: discovery → discovery through precision
- To interpret HL-LHC data substantial progress from theory calculations is needed





M. Cepeda et al. [HL/HE WG2 group], arXiv:1902.00134

PRECISION INGREDIENTS

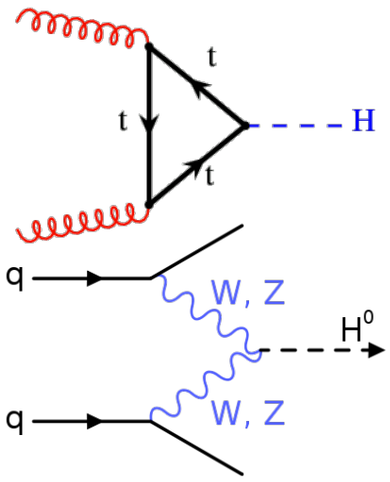


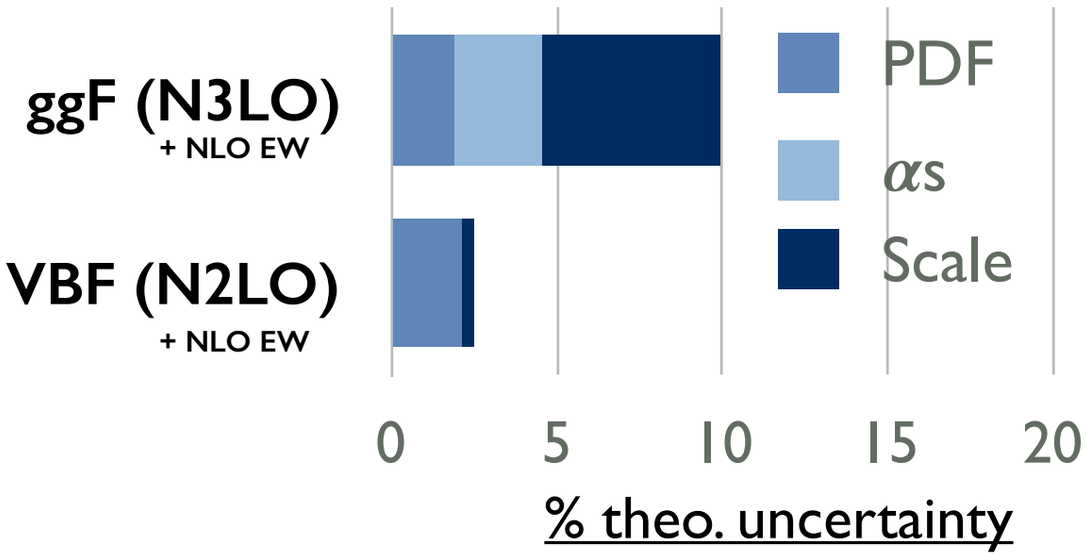
- Hard scattering of partons (Perturbative QCD+EW)
- Parton Distribution Functions
- Parton Showering and Hadronization
- Multiple Parton Interaction, Underlying Events

SHERPA artist

THE ROLE OF PDF UNCERTAINTIES

Higgs

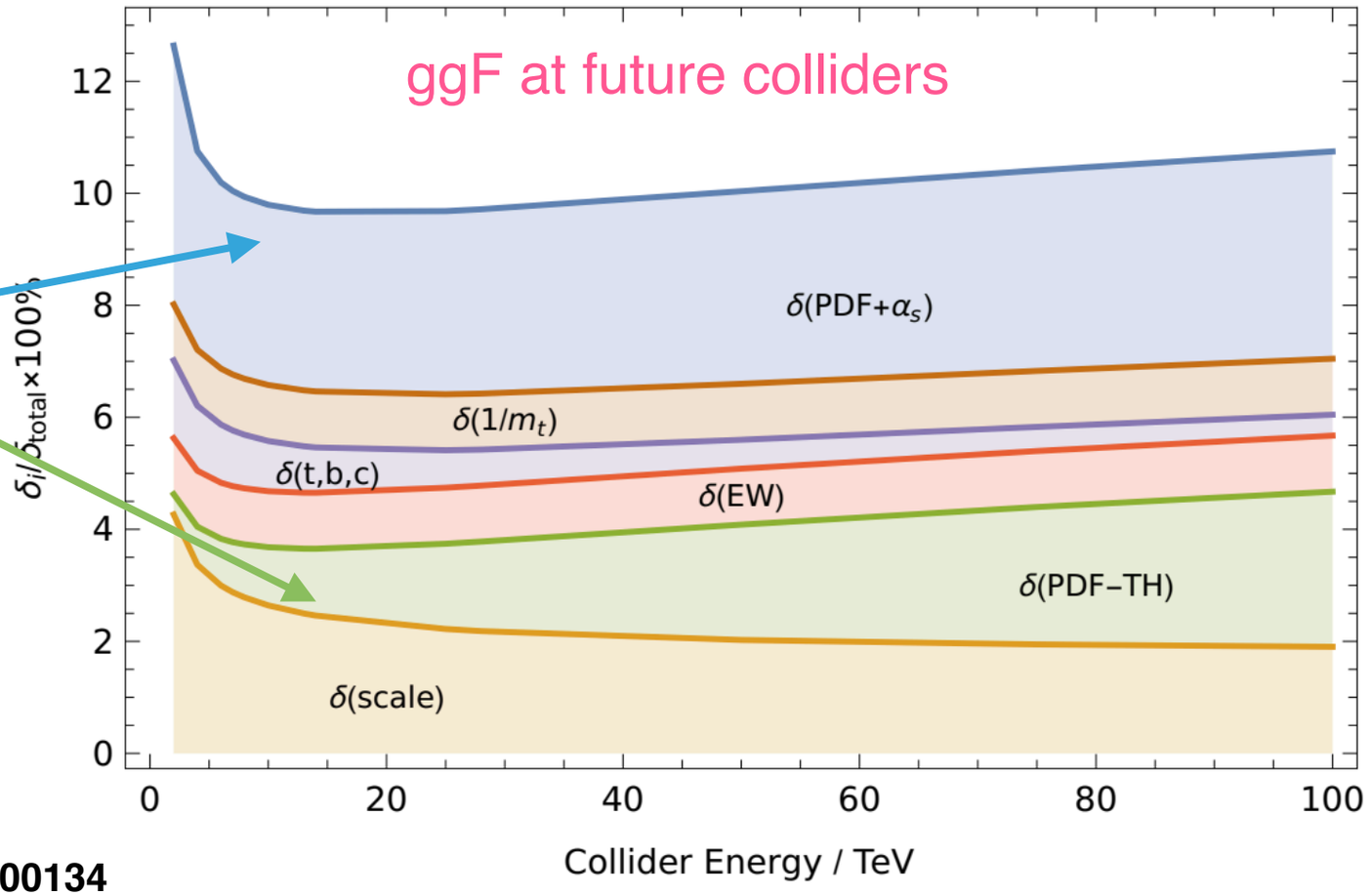




48.6 pb
3.77 pb

σ@13 TeV

PDF uncertainty significantly limitation to theory accuracy



M. Cepeda et al. [HL/HE WG2 group], arXiv:1902.00134

PDF DETERMINATION

$$f_i(x,\mu) \pm \Delta_i(x,\mu)$$

Data

Perturbative QCD
DGLAP evolution equations

EXPERIMENTAL DATA

THEORETICAL CALCULATIONS

METHODOLOGY

PARAMETRISATION, ERROR PROPAGATION, MINIMISATION…

GLOBAL FIT

LHAPDF

A. Buckley et al
EPJC75 (2015)

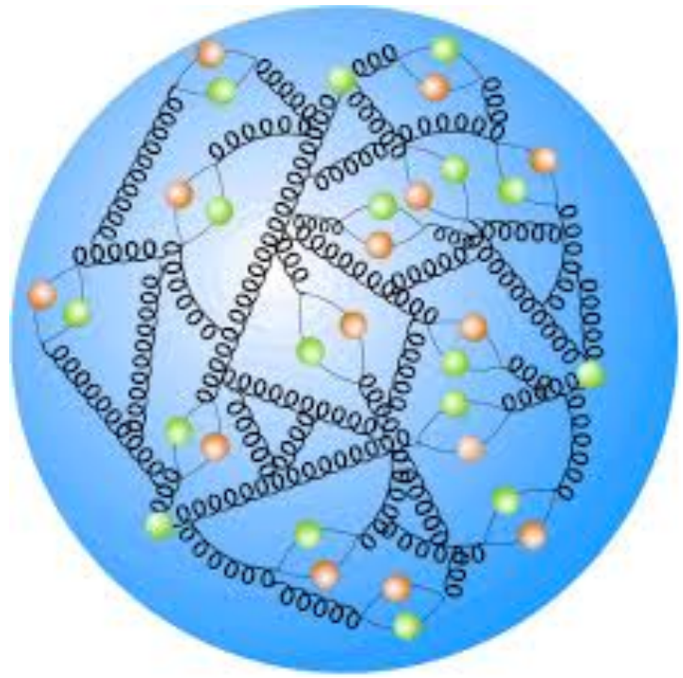
OUTLINE

- Challenges and updates in PDF determinations

  ➡ **Part I : Experimental data**

  ➡ Intermission: Methodological issues

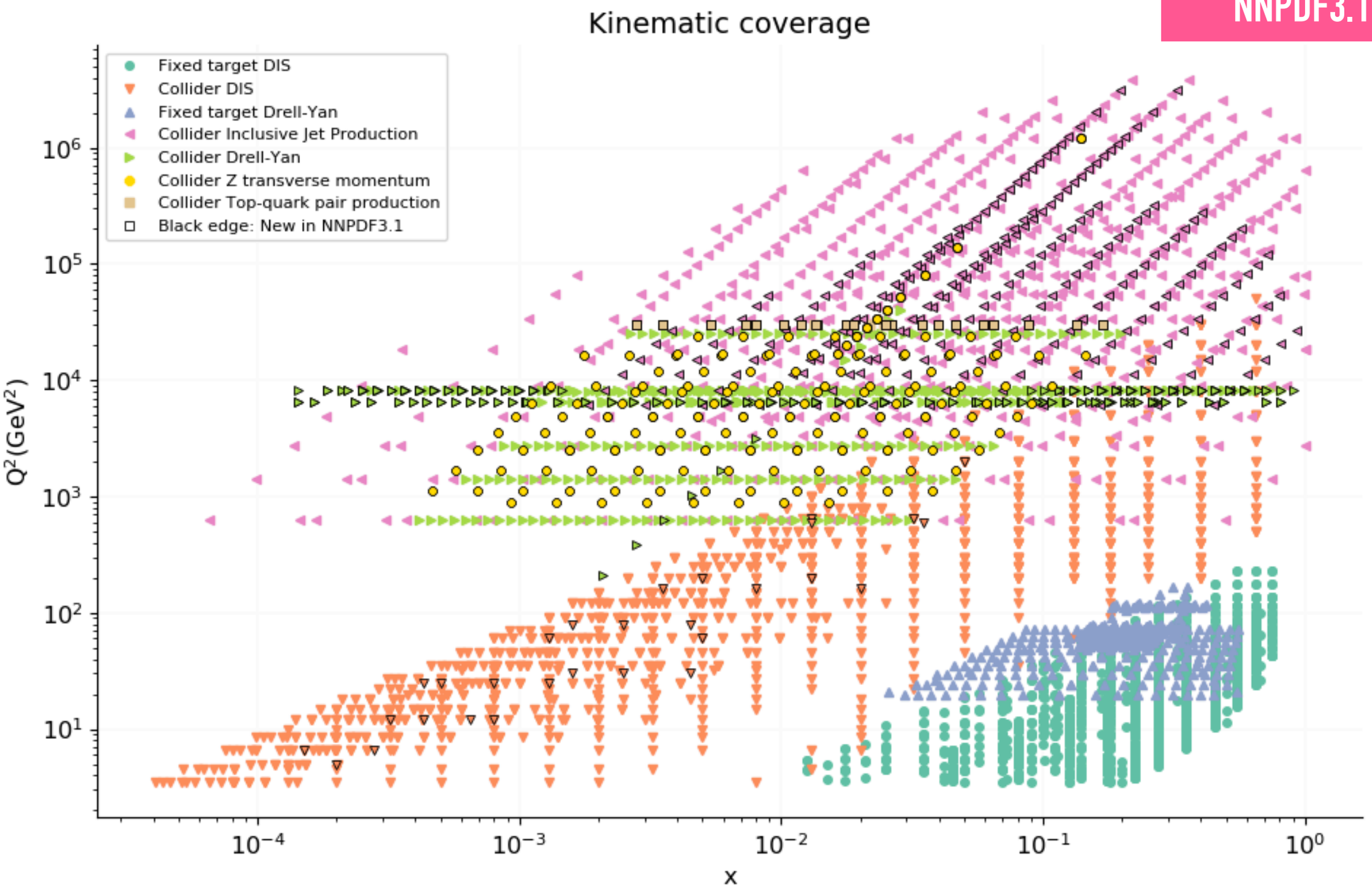
  ➡ Part II: Theoretical aspects



- Conclusions and outlook

THE EXPERIMENTAL DATA

NNPDF3.1



The NNPDF collaboration, EPJC 77 (2017)

THE EXPERIMENTAL DATA

New data for NNPDF4.0

ELECTROWEAK
* ATLAS high-mass Drell-Yan double-differential distributions at 8 TeV
* ATLAS W/Z total xsec at 13 TeV (81pb-1)
* ATLAS triple-differential Z production at 8 TeV (20.2 fb-1)
* ATLAS W+jets differential distributions at 8 TeV
* CMS differential distributions in Z production at 13 TeV
* LHCb W -> e nu rapidity dist, 8 TeV (2 fb-1)
* LHCb Z rapidity distribution, 13 TeV
* CMS W pt distribution, 8 TeV (18.4 fb-1)
* CMS Z+charm at 8 TeV, 19.7 fb-1
* CMS W+charm differential distributions at 13 TeV

JETS and PHOTONS
* ATLAS isolated photon production 8 TeV, 20 fb-1
* ATLAS isolated photon production, 13 TeV, 3.2 fb-1

prompt photons (at NNLO)

* ATLAS dijet cross-sections at 7 TeV
* ATLAS inclusive jet cross-sections at 8 TeV from the 2012 dataset
* CMS dijet cross-sections at 7 TeV

Dijets (at NNLO)

* CMS inclusive jet production at 8 TeV, 19.6 fb-1
* CMS triple differential dijet cross-sections at 8 TeV (19.6 fb-1)
* CMS double-differential dijet distributions at 5 TeV
* Inclusive jet and di-jet production in neutral-current DIS from H1 and ZEUS (HERA DIS jets)

DIS jets (at NNLO)

TOP QUARK
* CMS total xsec of top-pair production at 5.02 TeV, 27.4 pb-1
* CMS double differential distributions top-quark production 8 TeV, 19.7 fb-1
* CMS single differential distributions in top-pair production (lepton+jets) at 13 TeV, L=35.8 fb-1(2016)
* CMS single differential distributions in top-pair production (dilepton) at 13 TeV, 35.8 fb-1(2016)
* CMS single top t-channel total cross section ratio at 7 TeV
* CMS single top t-channel total cross section ratio at 8 TeV

single top (at NNLO)

* CMS single top t-channel total cross section ratio at 13 TeV
* ATLAS single top t-channel total cross section ratio and diff. distributions at 7 TeV
* ATLAS single top t-channel total cross section ratio at 8 TeV
* ATLAS single top t-channel total cross section ratio at 13 TeV

Upgrades

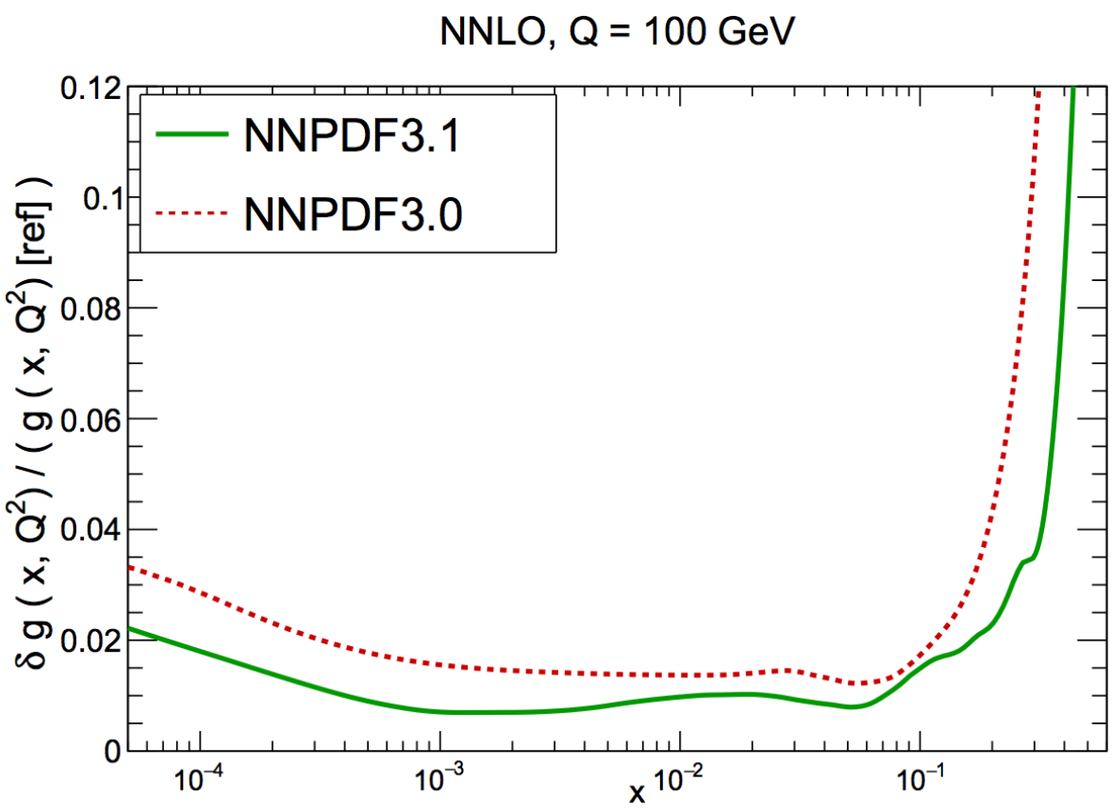
* ATLAS W/Z production, 7 TeV (4.6 fb-1) => added the off-peak and forward Z prod bins
* Final combination of charm and beauty str fns from HERA (Runs I+II): replaces HERA-I charm comb and H1, ZEUS structure functions

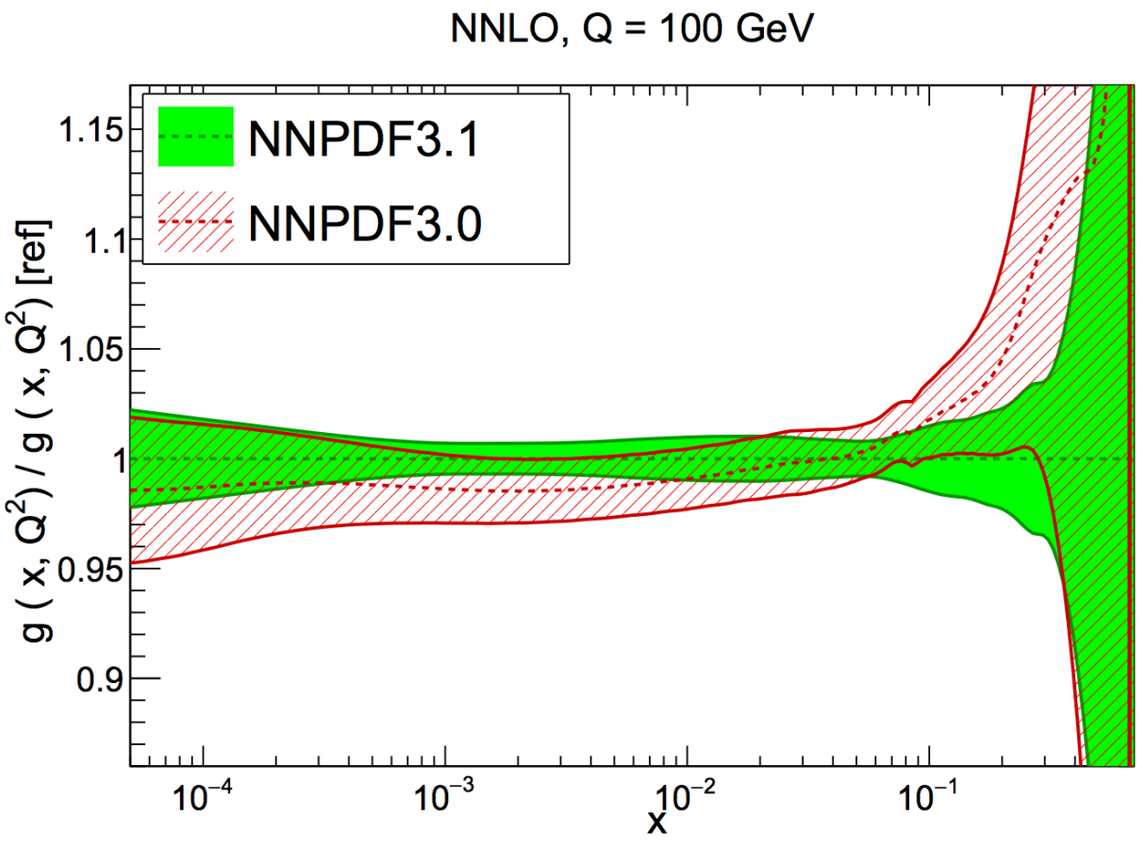
Cutoff date for new data: end of 2019

R. Ball, PDF4LHC September 2019

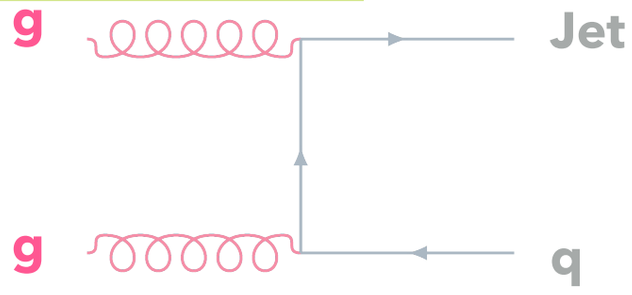
IMPACT OF THE LHC DATA – GLUON PDF

- Large-x gluon constrained by three independent processes
- Consistent picture and uncertainty reduction

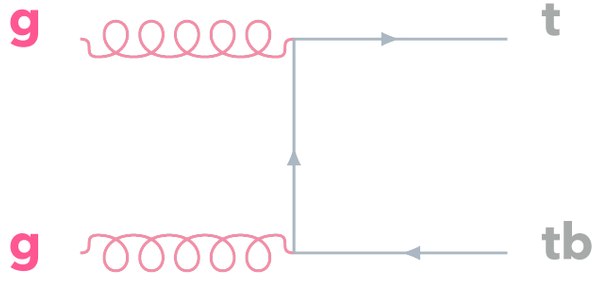




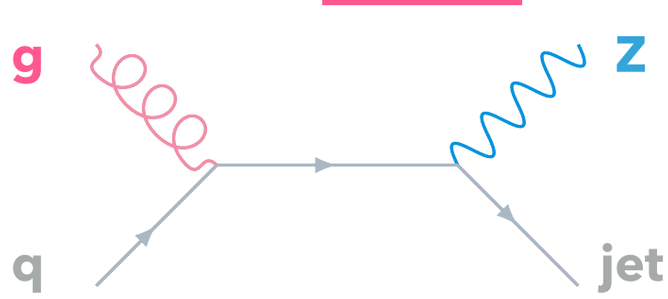
INCLUSIVE JETS



TOP PAIR

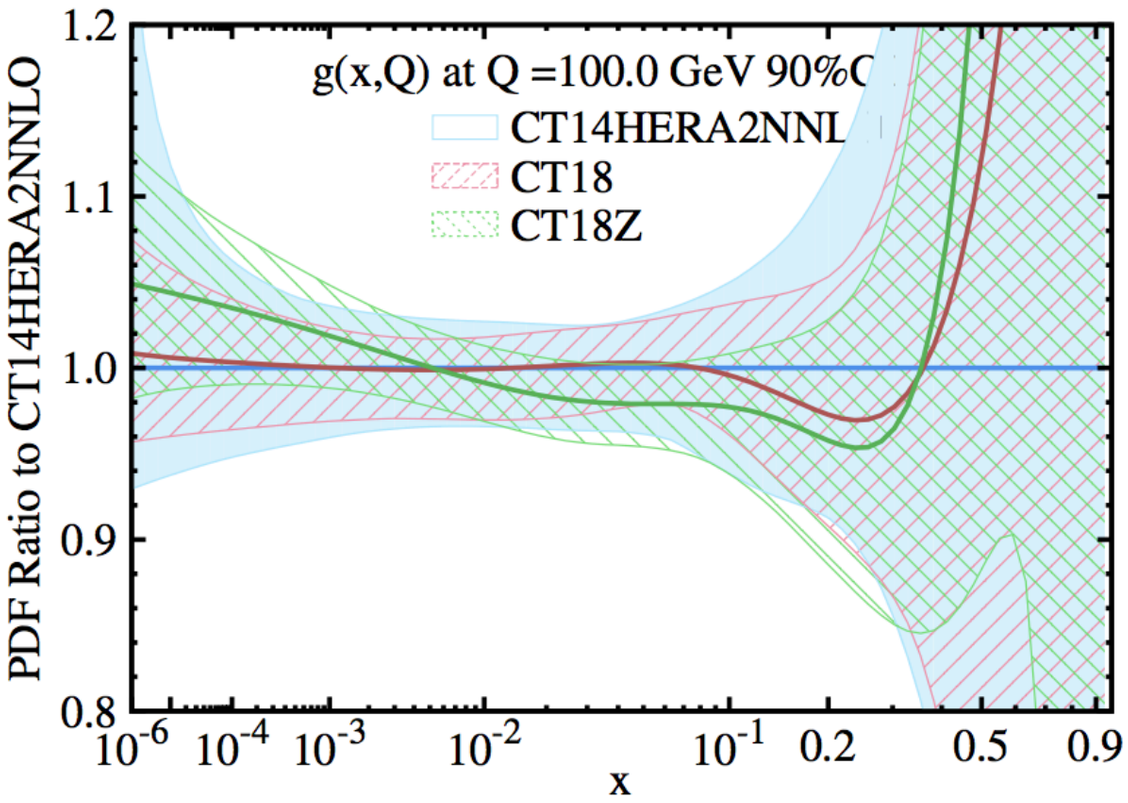


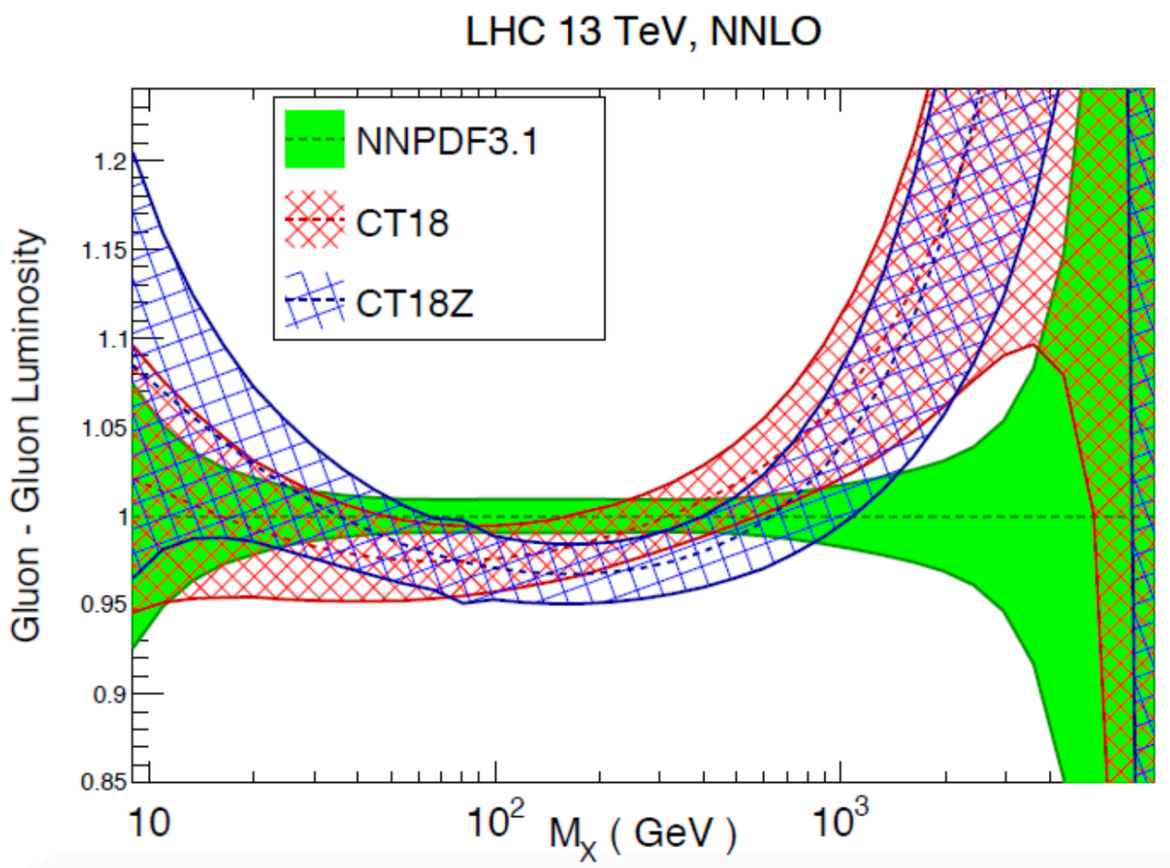
Z P_T



NNPDF collaboration, arXiv:1706.00428

IMPACT OF THE LHC DATA – GLUON PDF





CTEQ-TEA collaboration, arXiv: 1908.11394

- **NNPDF3.1** (2017) - gluon softer at large x and with ~30% uncertainty reduction
- **CT18** (2019) - gluon harder at large x and milder uncertainty reduction
- Agreement among global PDF determination deteriorates in the region relevant for ggF, CT18 gluon much harder than NNPDF3.1
- Datasets? Fitted charm? Methodology? To be investigated!

DEALING WITH HIGHLY CORRELATED DATA

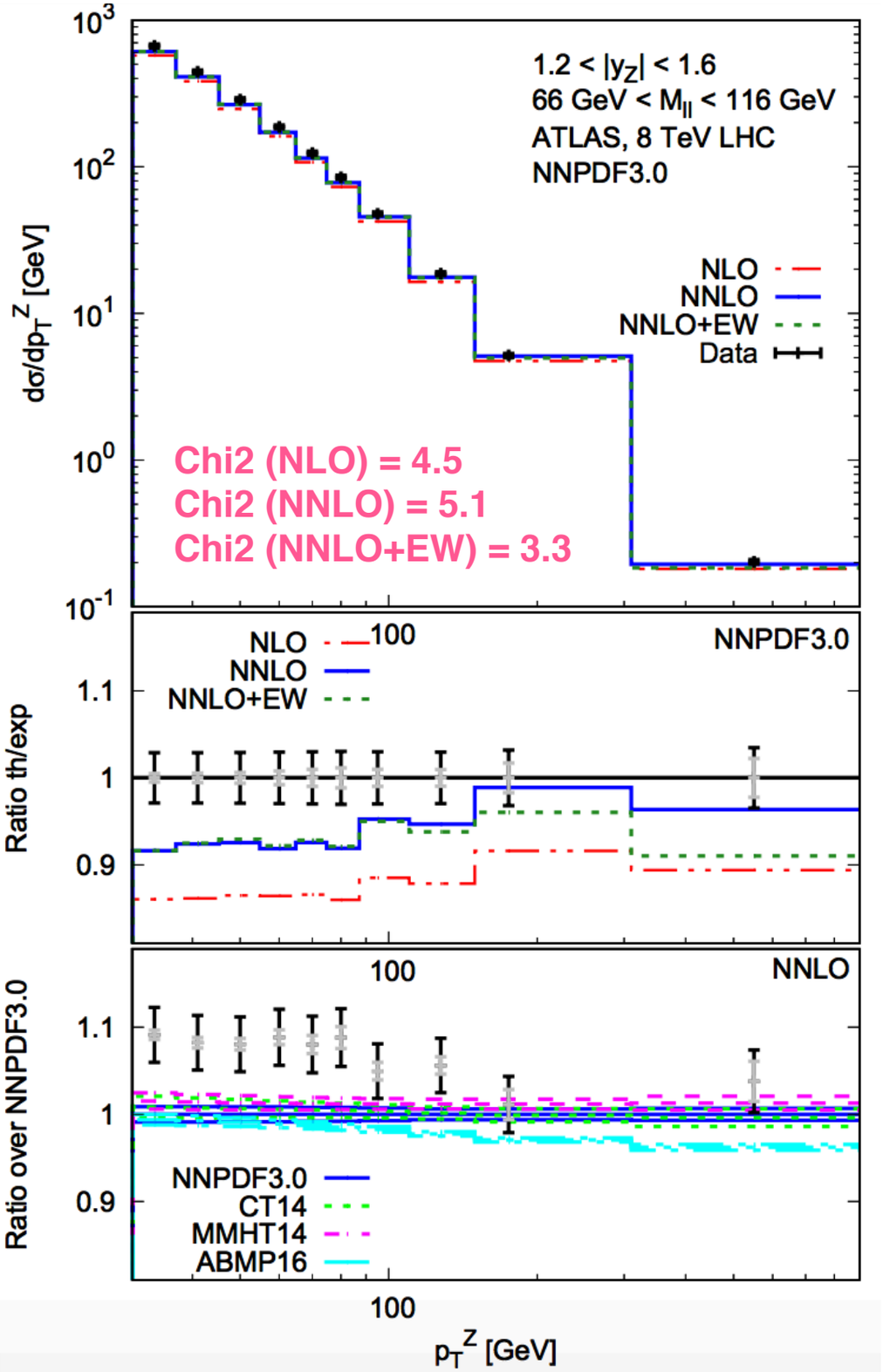
Z P_T

- **Z pT distributions** - challenge due to correlation-dominated observable, an uncorrelated uncertainty included to achieve a good fit

- **Top 8 TeV ATLAS data:** single distributions can be included and display consistency but for recent correlated differential distributions, must de-correlate uncertainties to have good fit (impact on the gluon)

- **Inclusive jet 7 TeV ATLAS data**: impossible to include all rapidity bins simultaneously unless de-correlate some systematics

- A more general approach such as regularisation of experimental covariance matrices based on stability was recently put forward



Boughezal, Guffanti, Petriello, MU 1705.00343

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TOP

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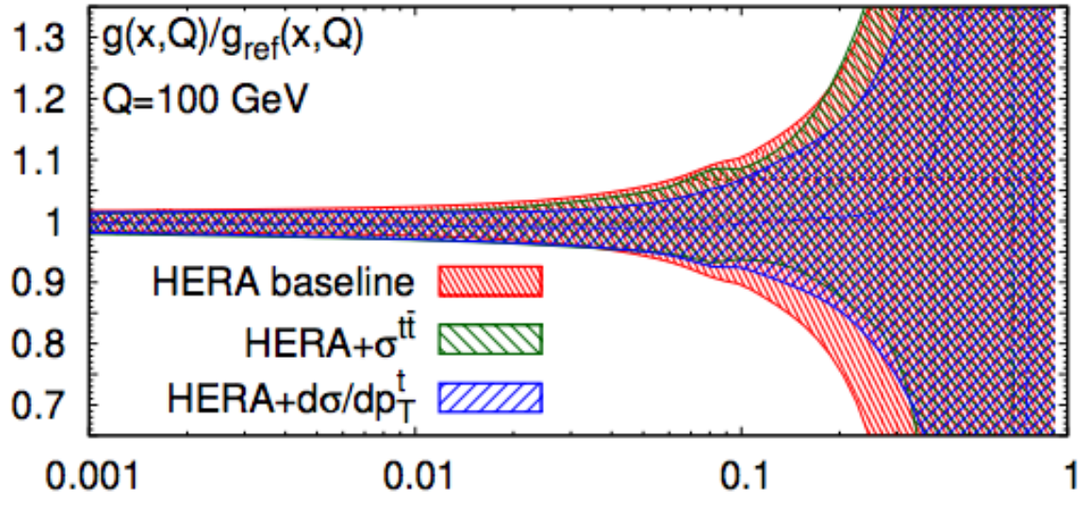
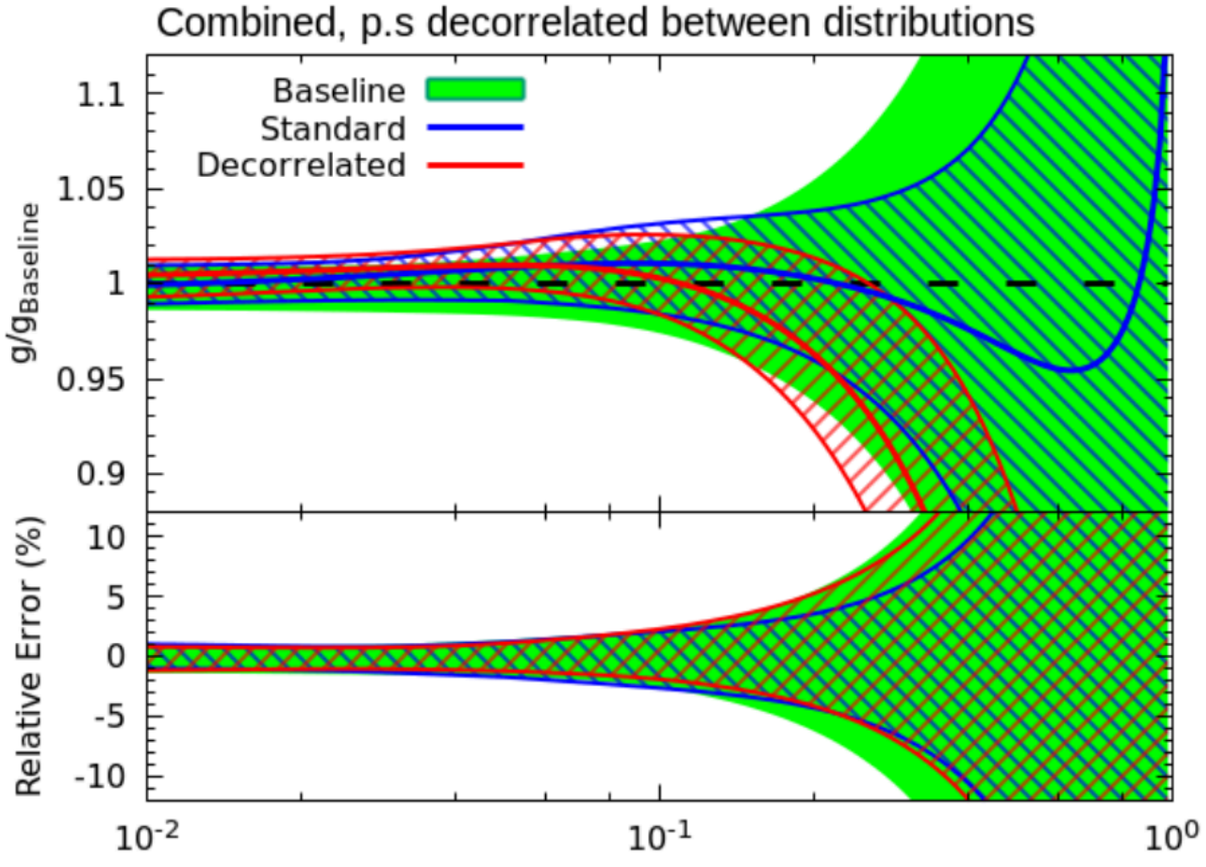


Czakon et al , arXiv: 1611.08609



Bailey, Harland-Lang, arXiv: 1909.10541

DEALING WITH HIGHLY CORRELATED DATA

JETS

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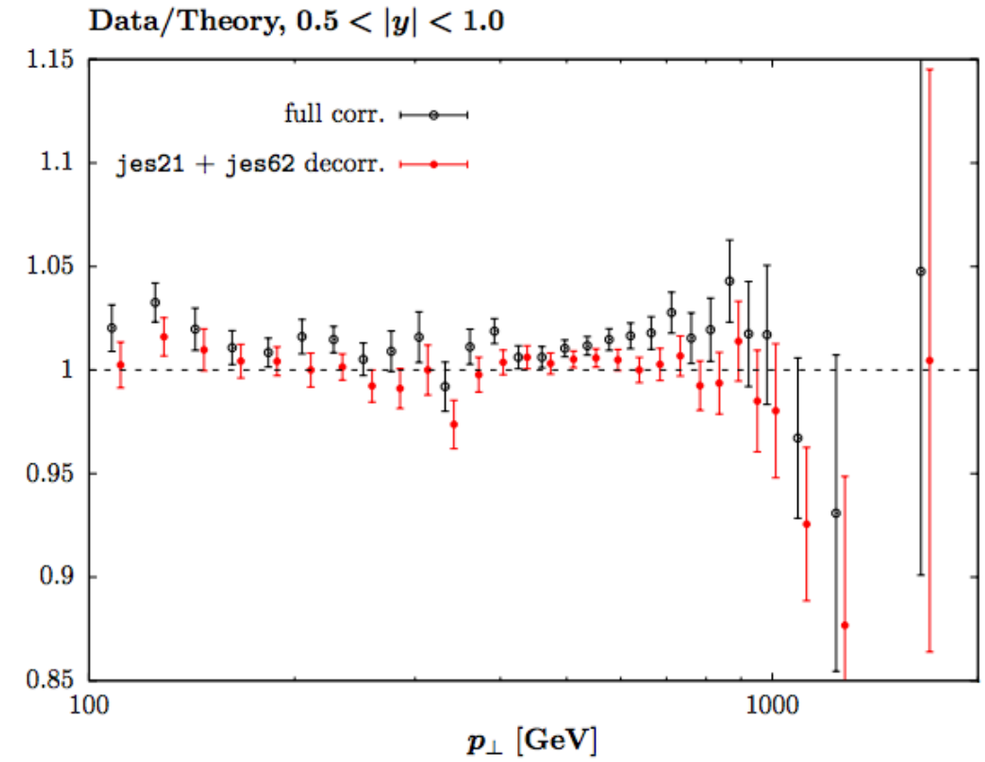
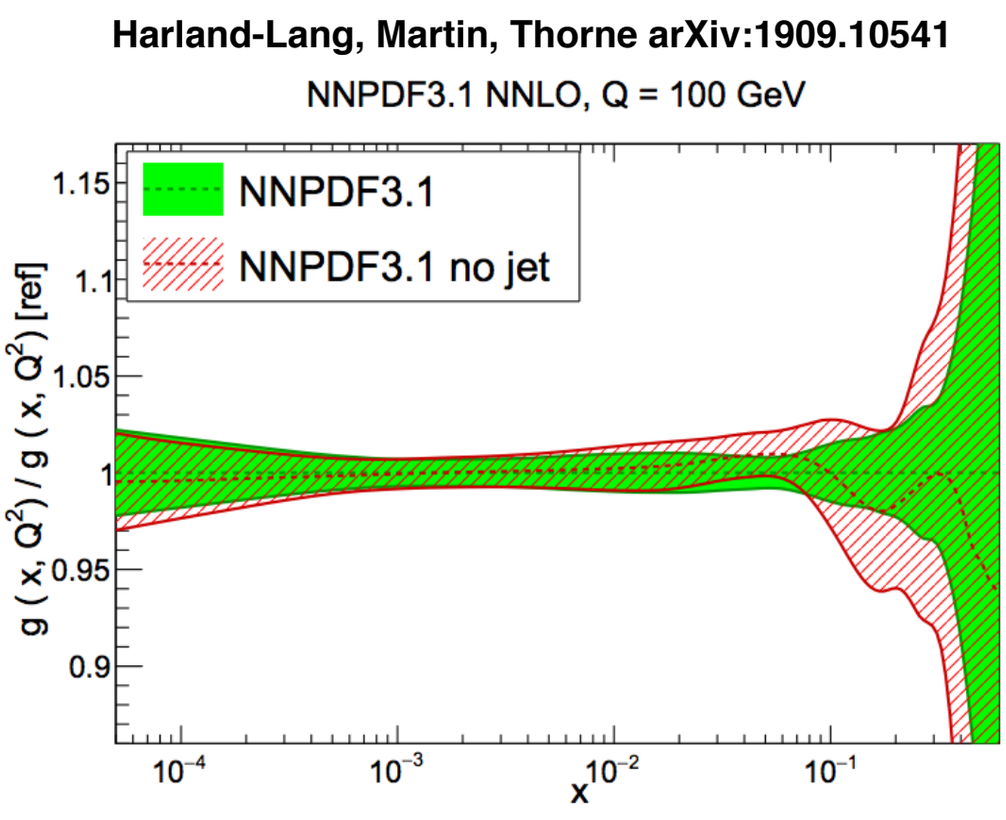


Harland-Lang, Martin, Thorne arXiv:1909.10541



NNPDF collaboration, arXiv:1706.00428

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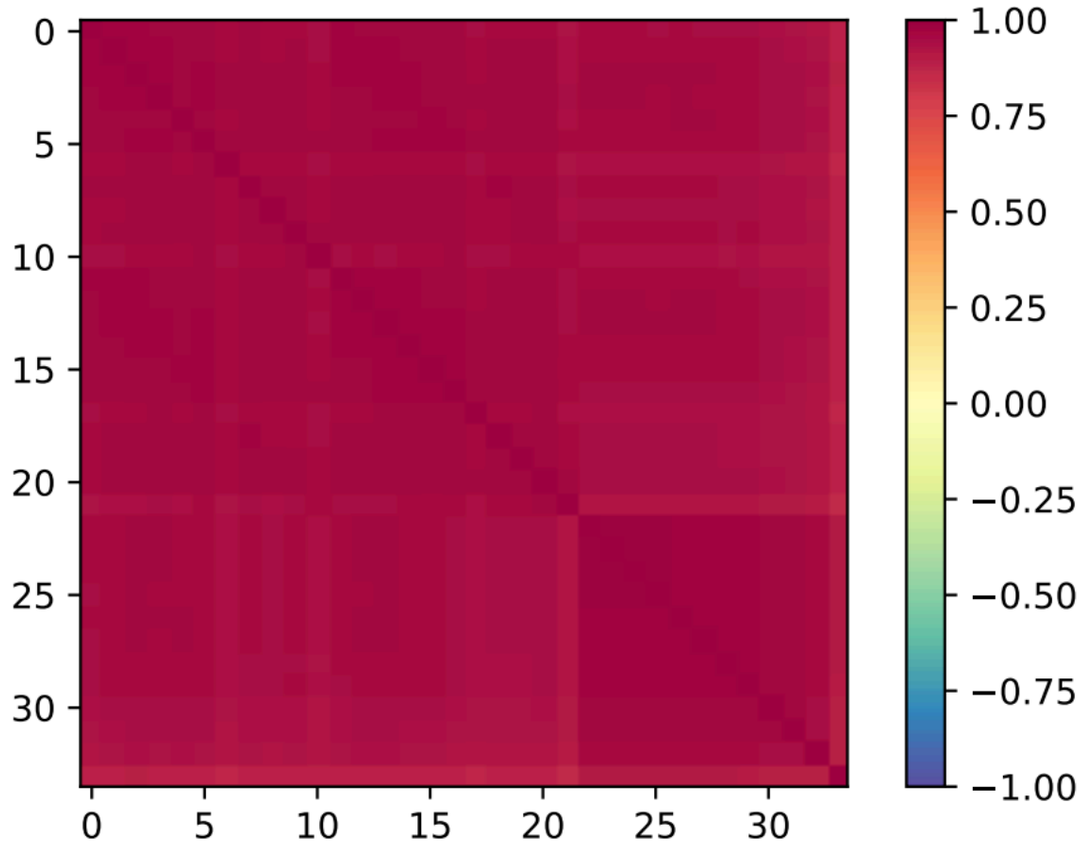
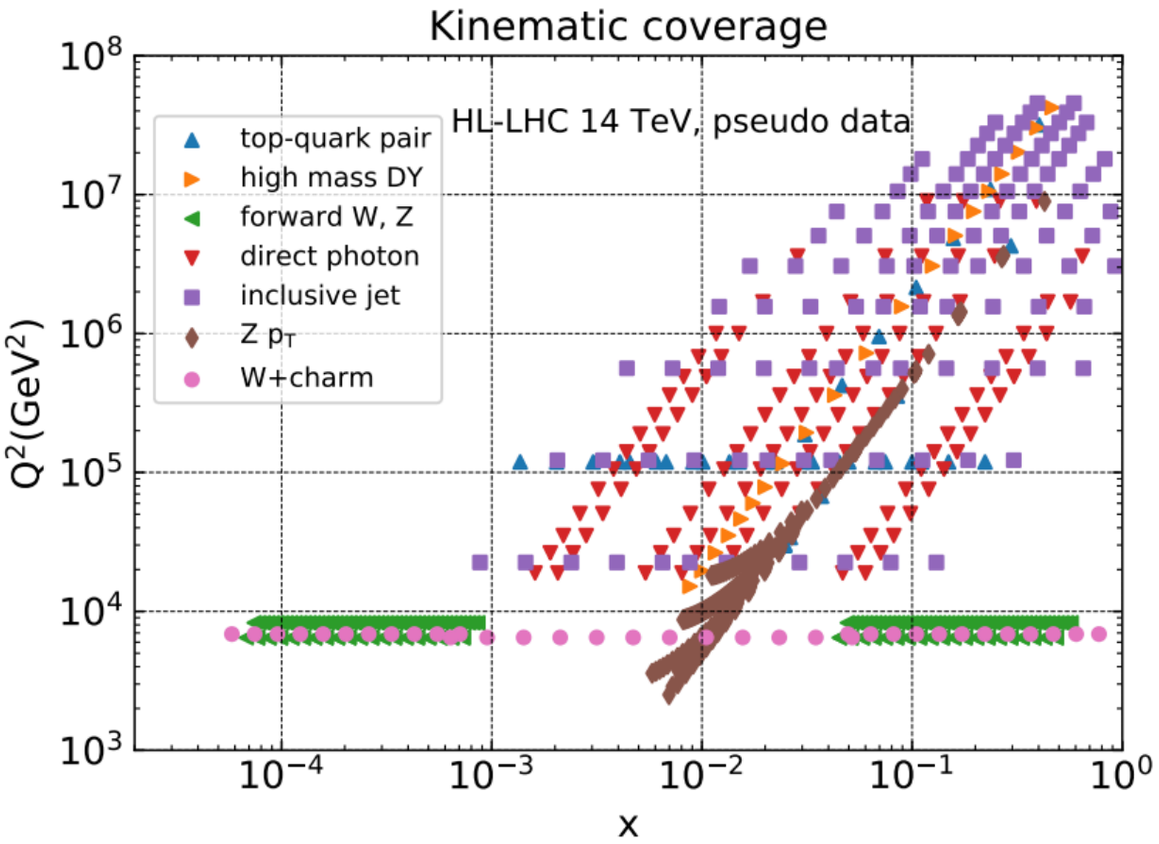


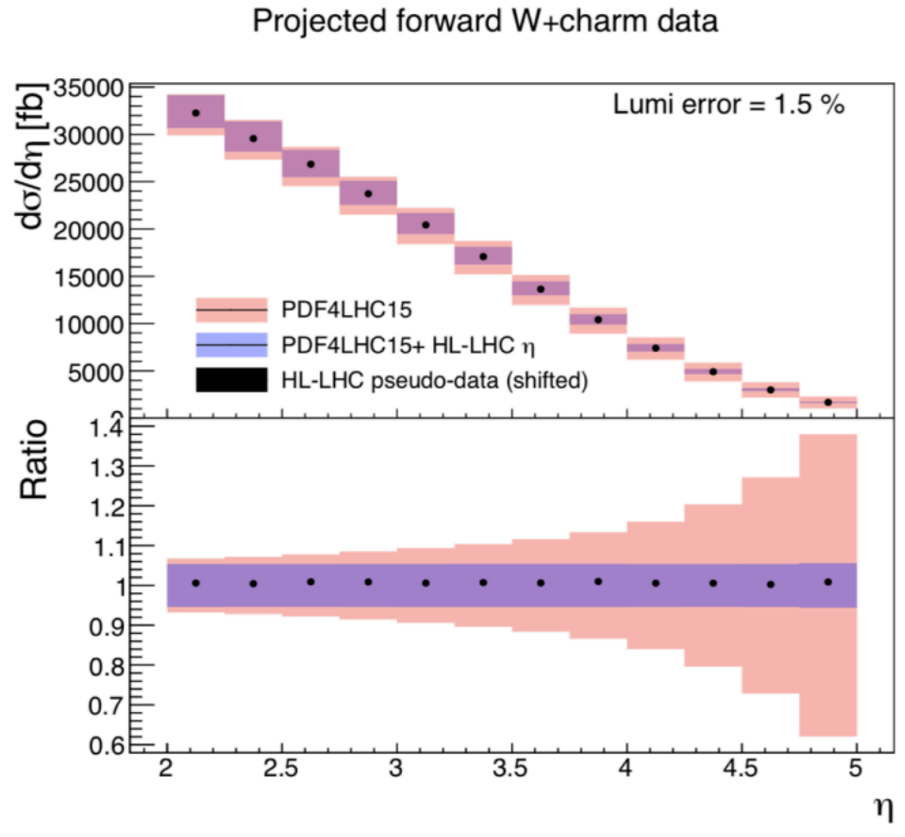
Correlation matrix for precise ATLAS WZ production dataset

Stat Estm.	Fit using $\tilde{\Sigma}\|_{k=500}$	fit using Σ
χ^2/N_{data}	1.00035	1.16328
$\langle\chi^2/N_{\text{data}}\rangle$	1.095 ± 0.038	1.253 ± 0.033

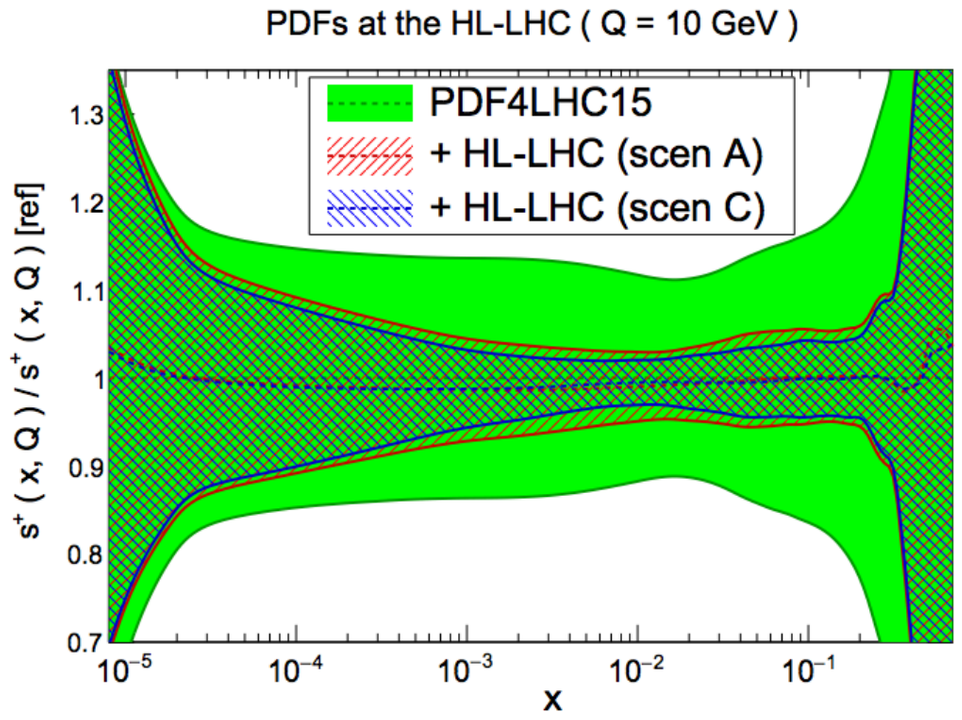
M. Wilson, PDF4LHC September 2019

PERSPECTIVES AT HL-LHC



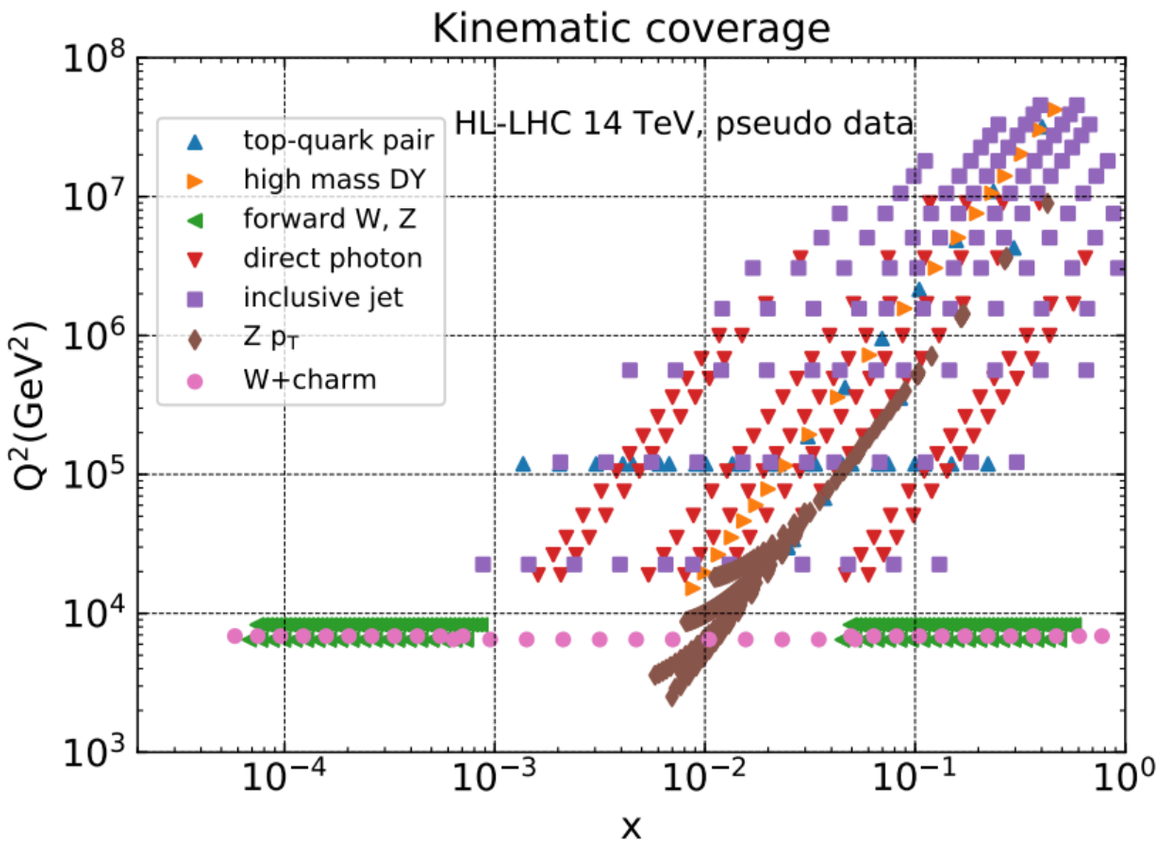


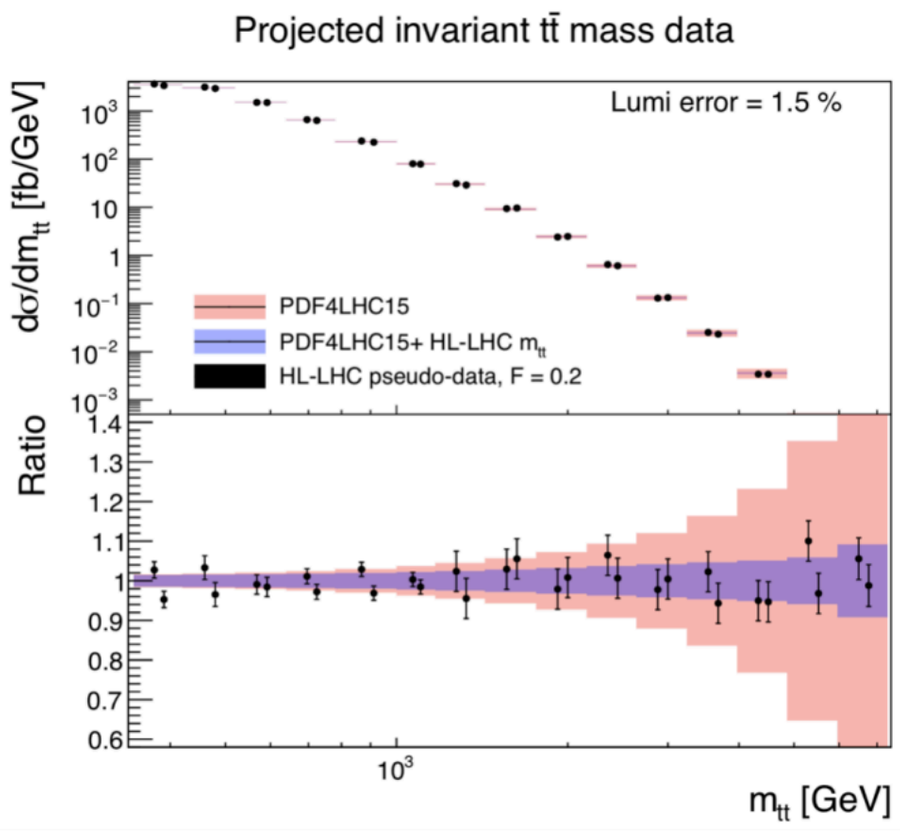
- W, Z handle on quarks
- **W+c on strangeness**
- Z pT on quarks and gluons
- Top and Jets on gluons



M. Cepeda et al. [HL/HE WG2 group], arXiv:1902.00134

PERSPECTIVES AT HL-LHC





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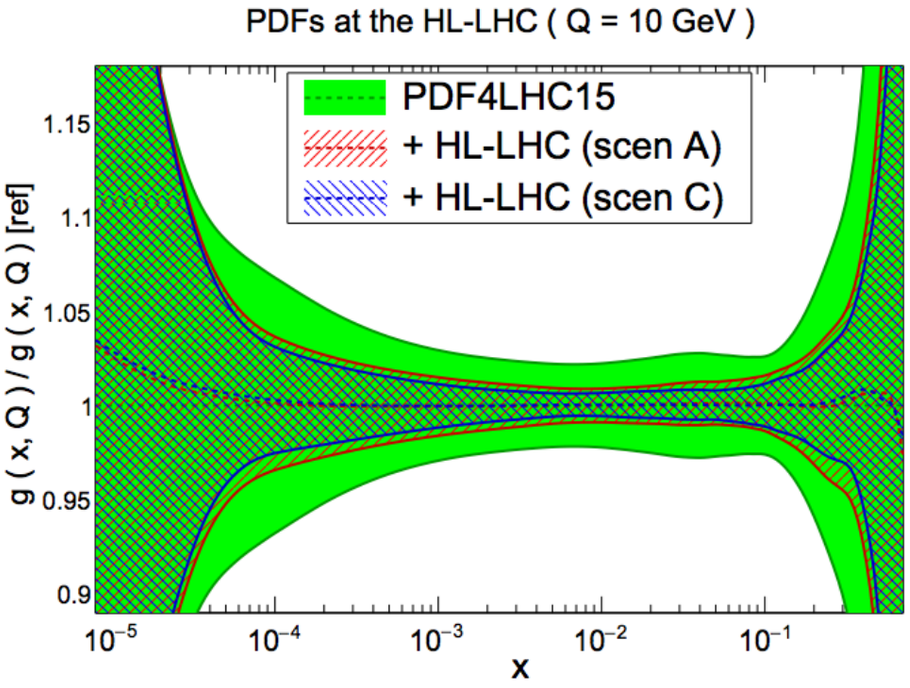


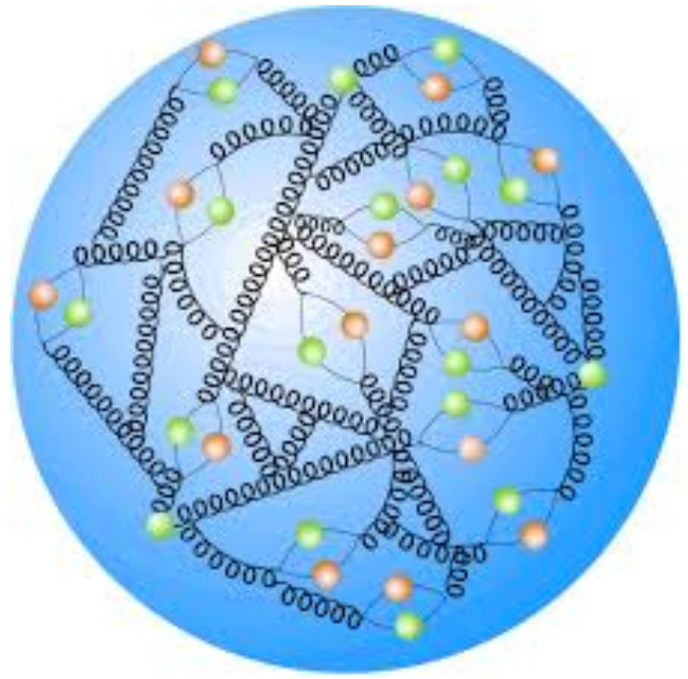
M. Cepeda et al. [HL/HE WG2 group], arXiv:1902.00134

- Challenges and updates in PDF determinations

  ➡ Part I : Experimental data

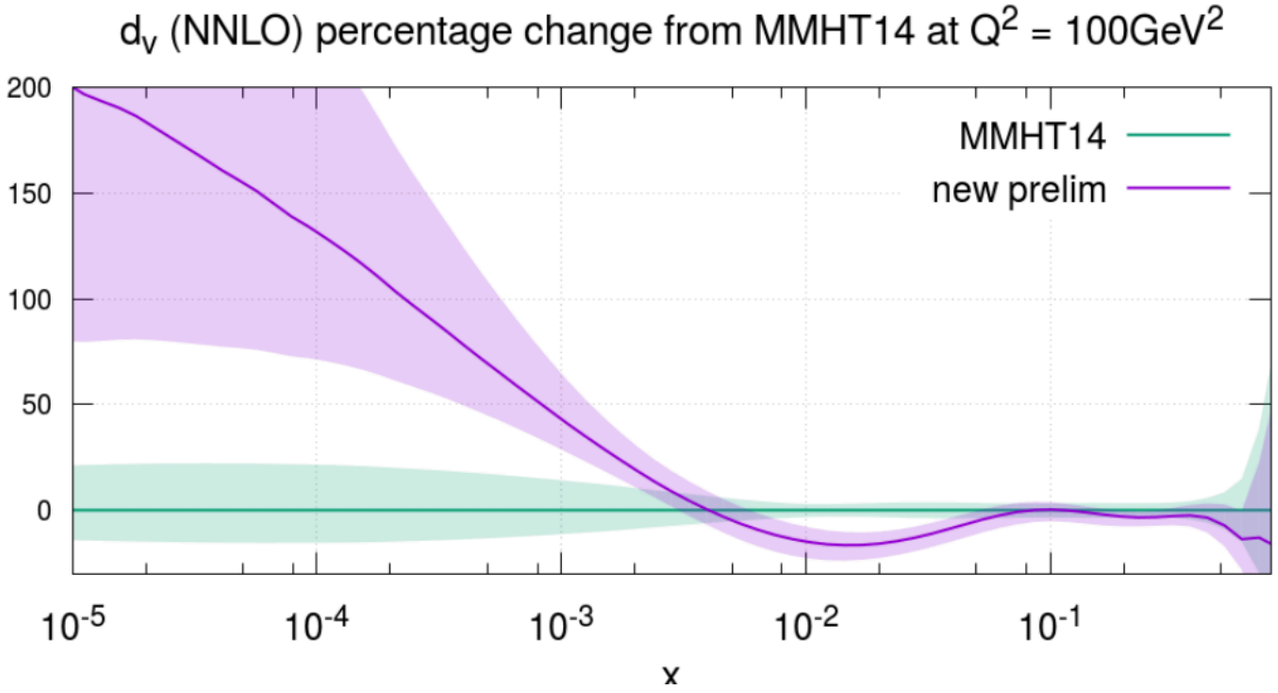
  ➡ **Intermission: Methodological issues**

  ➡ Part II: Theoretical aspects



- Conclusions and outlook

PARAMETRISATION & METHODOLOGY

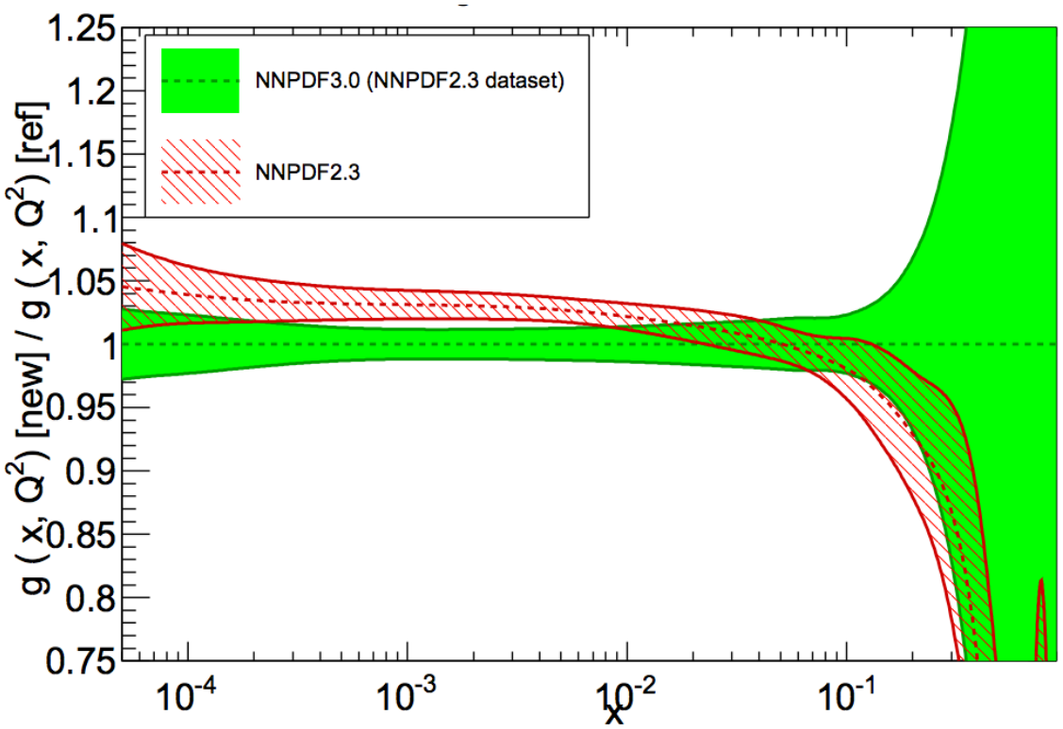


- Upcoming MMHT analysis: Extended parametrisation of PDFs based on Chebyshev polynomials
- Down valence quark changes quite dramatically and reduces tension among data

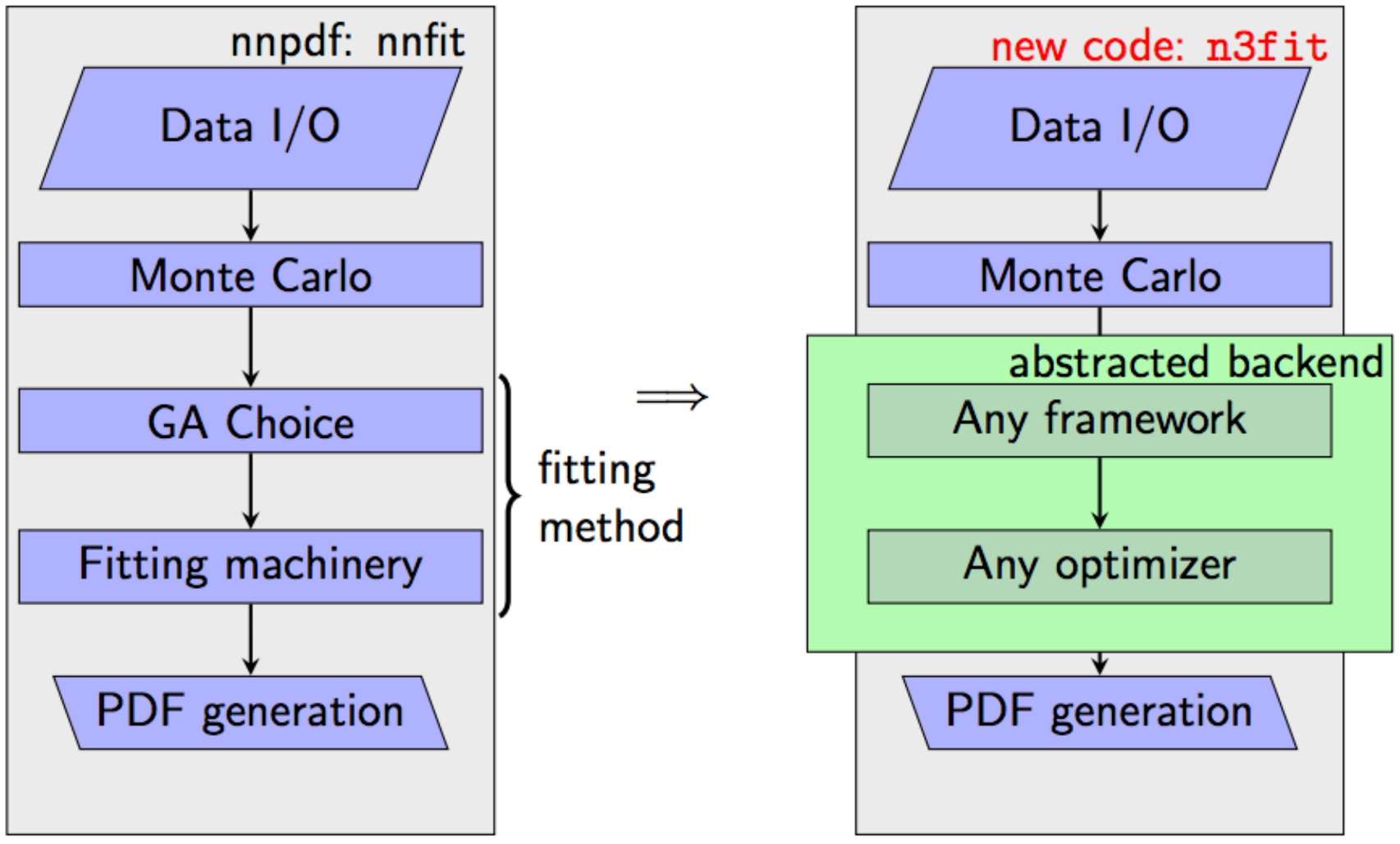
R. Thorne, PDF4LHC September 2019

- NNPDF2.3 to NNPDF3.0 significant shift due to changes in the generic algorithm minimisation
- From NNPDF3.0 introduces powerful closure tests to assess robustness of the fitting methodology

The NNPDF collaboration, arXiv: 1410.8849



NEW: FITTING THE METHODOLOGY ITSELF



J. Cruz-Martinez, PDF4LHC September 2019

Fitting the whole methodology => Implement a hyperparameter scan: let the computer decide automatically the best methodology and PDF parametrisation by scanning over thousands of hyperparameter combinations and define a reward function to grade the methodology

- Challenges and updates in PDF determinations

  ➡ Part I : Experimental data

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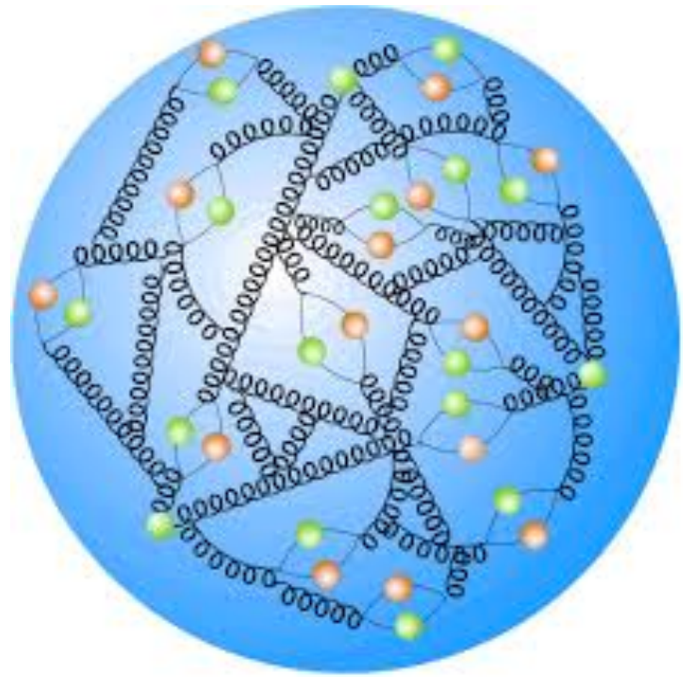
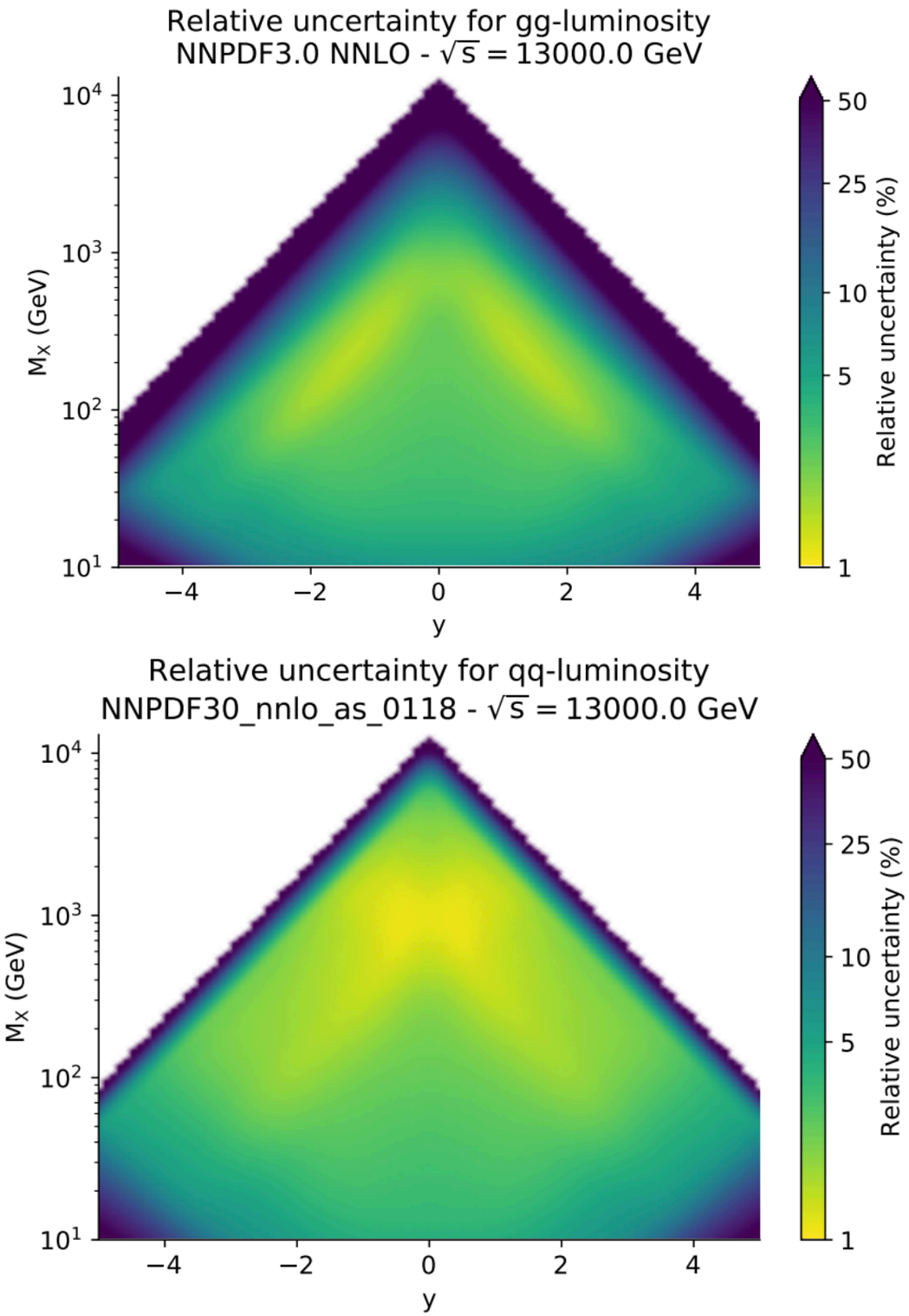
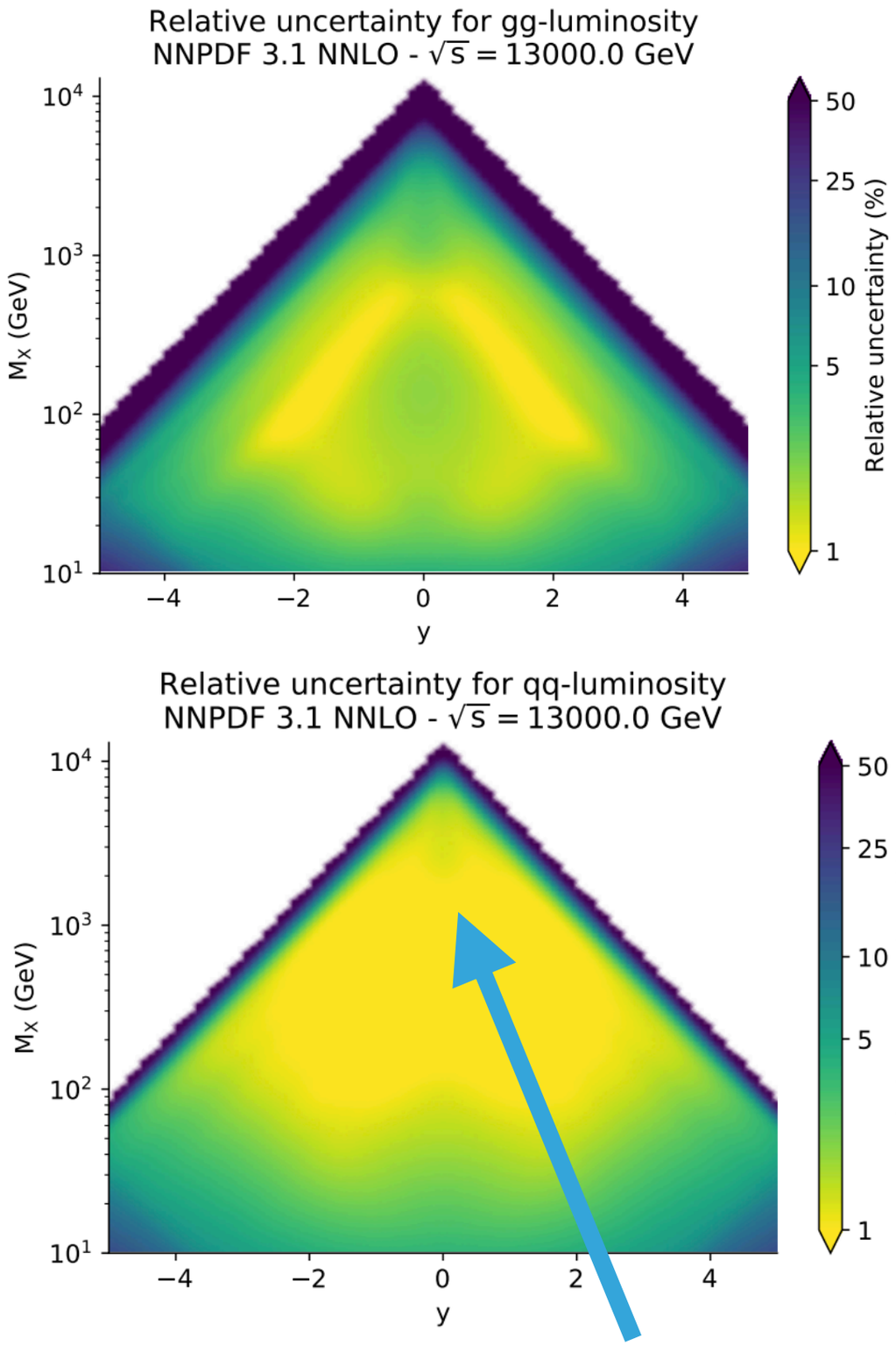


- Conclusions and outlook

THE PRECISION VS ACCURACY CHALLENGE

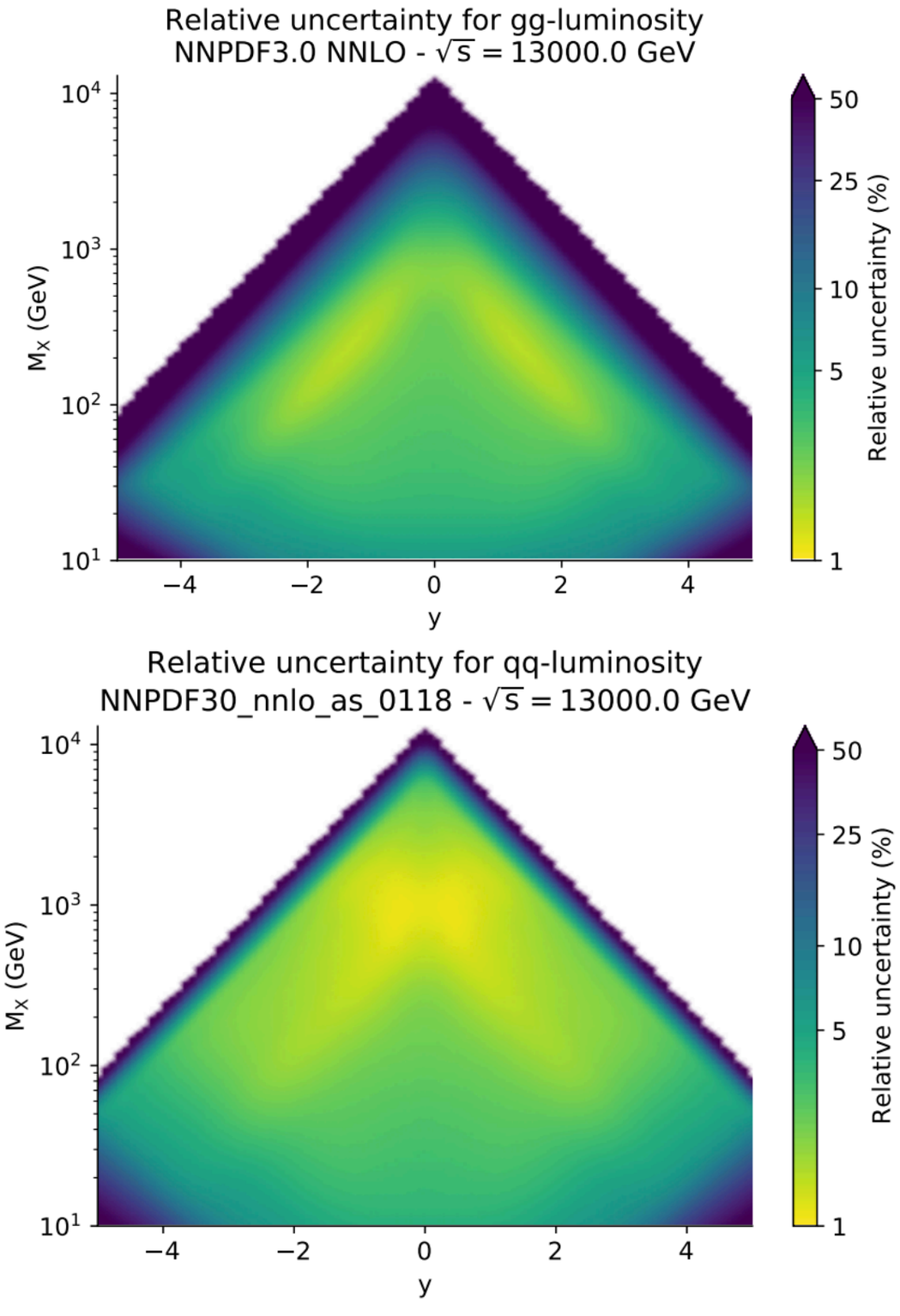


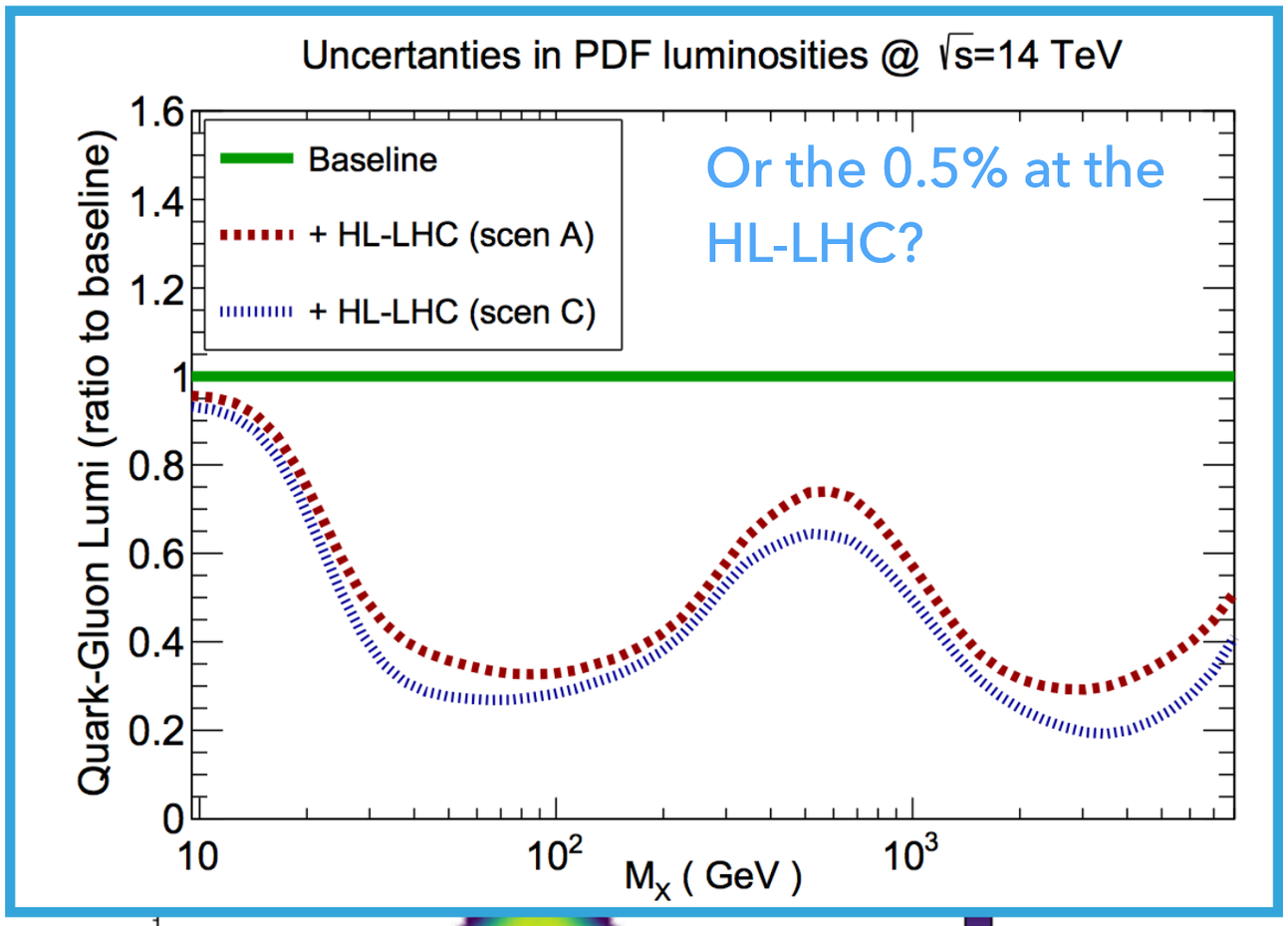


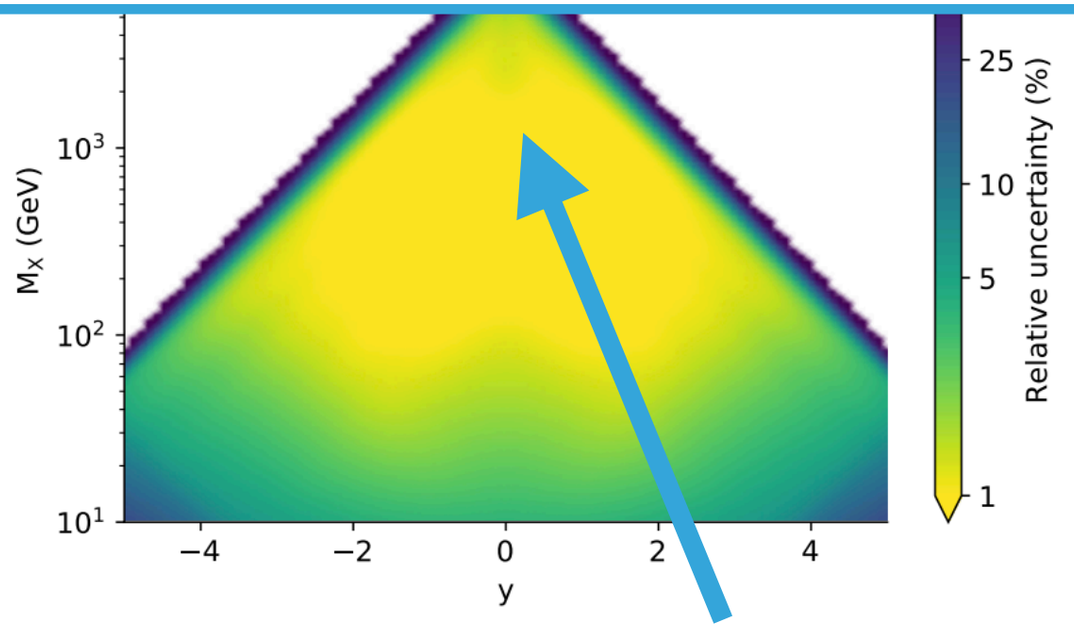
The NNPDF collaboration, arXiv:1706.00428

Can we trust 1% uncertainties?

THE PRECISION VS ACCURACY CHALLENGE







Can we trust 0.4% uncertainties?

The NNPDF collaboration, arXiv:1706.00428

HOW TO MAKE PDFS MORE ACCURATE?

$$\sigma = \alpha_s^p \sigma_0 + \alpha_s^{p+1} \sigma_1 + \alpha_s^{p+2} \sigma_2 + \mathcal{O}(\alpha_s^{p+3})$$

- Standard global PDF fits based on fixed-order QCD calculations
- So far PDF sets only account for experimental error. Error associated with truncation of perturbative series ignored

➡ **NNLO theoretical predictions for observables entering PDF fits**

✓ NNLO top pair production
Czakon et al [PRL 110(2013)], Czakon et al [JPCP (2014)], Czakon et al [JHEP 1301(2015)]

✓ W/Z+j and W/Z transverse momentum distributions
Gehrmann-De Ridder et al [JHEP 07 (2016)], Gehrmann-De Ridder et al [JHEP 11 (2016)]
Boughezal et al [PRL 16 (2016)], Boughezal et al [PRD 14 (2016)]

✓ Inclusive jet and di-jets
Currie et al [PRL 118 (2017)], Currie et al [PRL 119 (2017)], Gehrmann-De Ridder et al [PRL 110 (2016)

✓ Inclusive DIS jets
Currie et al [JHEP 17 (2017)]

✓ Direct photon
Campbell et al [PRL 118 (2017)]

✓ Single top
Bruchersfeier et al [PRB 736 (2014)]
Berger et al [PRD 94 (2016)]

HOW TO MAKE PDFS MORE ACCURATE?

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➡ **NNLO theoretical predictions for observables entering PDF fits**

➡ **Fast interface with NNLO codes**

- ✓ APPLgrid
  Carli et al (2010)
- ✓ FastNLO
  Kluge et al (2010)
- ✓ aMCfast
  Bertone et al (2014)
- ✓ FastNNLO
  Britzger, Kluge et al (2014)
- ✓ APPLfast
  Britzger et al (2019)

HOW TO MAKE PDFS MORE ACCURATE?

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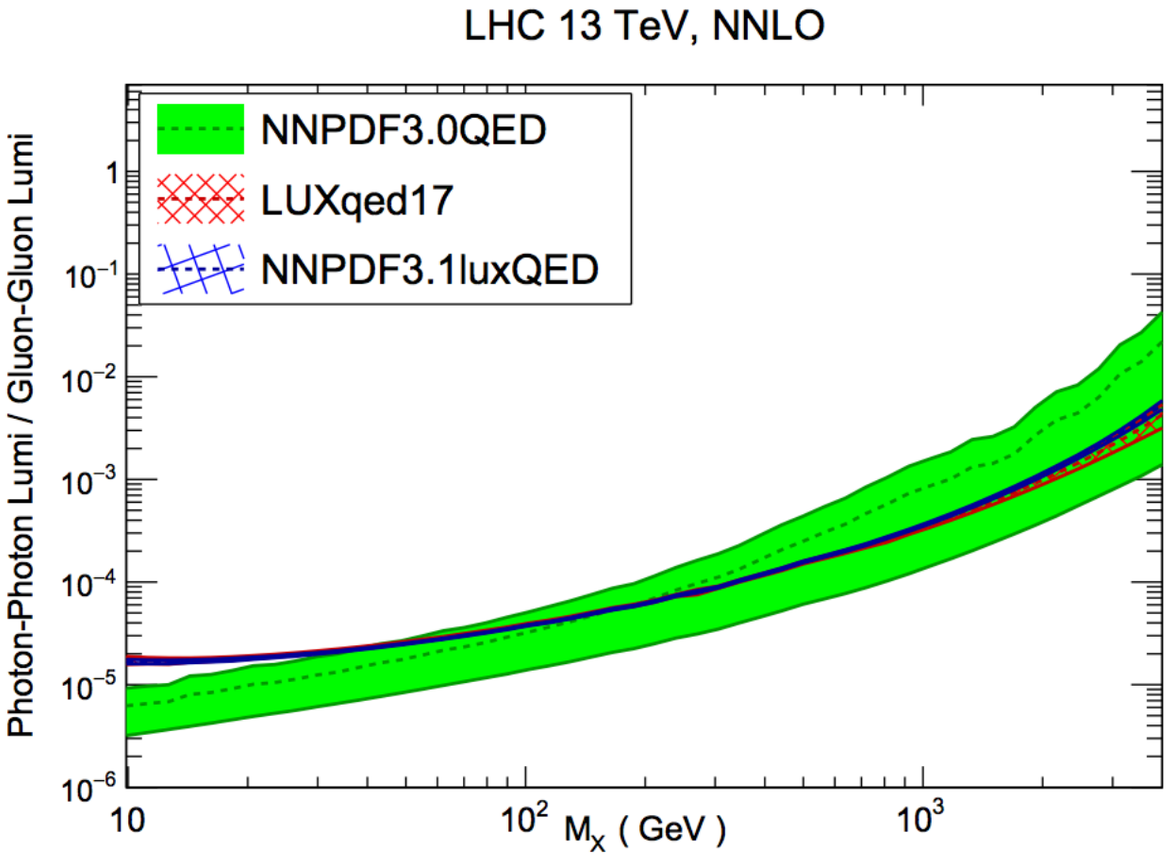
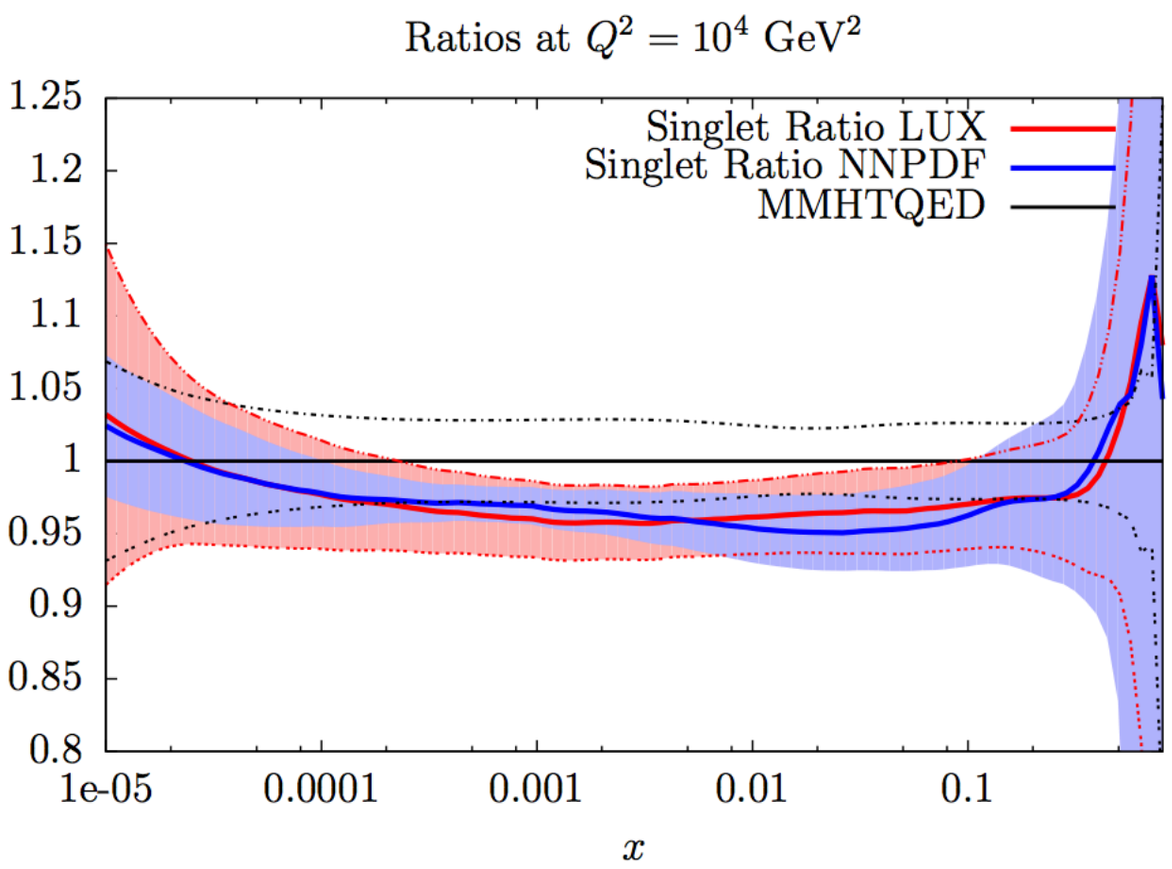
➡ **NNLO theoretical predictions for observables entering PDF fits**

➡ **Fast interface with NNLO codes**

➡ **Photon PDF and inclusion of EW corrections**





Manohar et al, arXiv: 1604.04266 + Carrazza et al, arXiv:1712.07053 + Harland-Lang et al, arXiv:190702750

HOW TO MAKE PDFS MORE ACCURATE?

$$\sigma = \alpha_s^p \sigma_0 + \alpha_s^{p+1} \sigma_1 + \alpha_s^{p+2} \sigma_2 + \mathcal{O}(\alpha_s^{p+3})$$

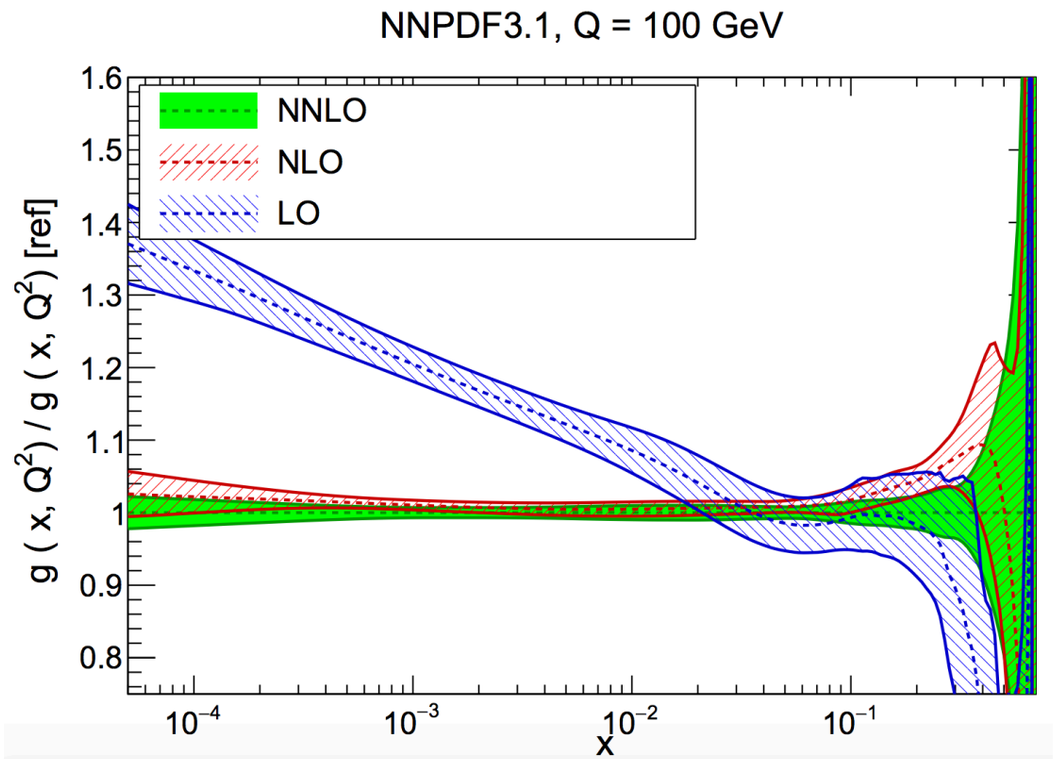
- Standard global PDF fits based on fixed-order QCD calculations
- So far PDF sets only account for experimental error. Error associated with truncation of perturbative series ignored

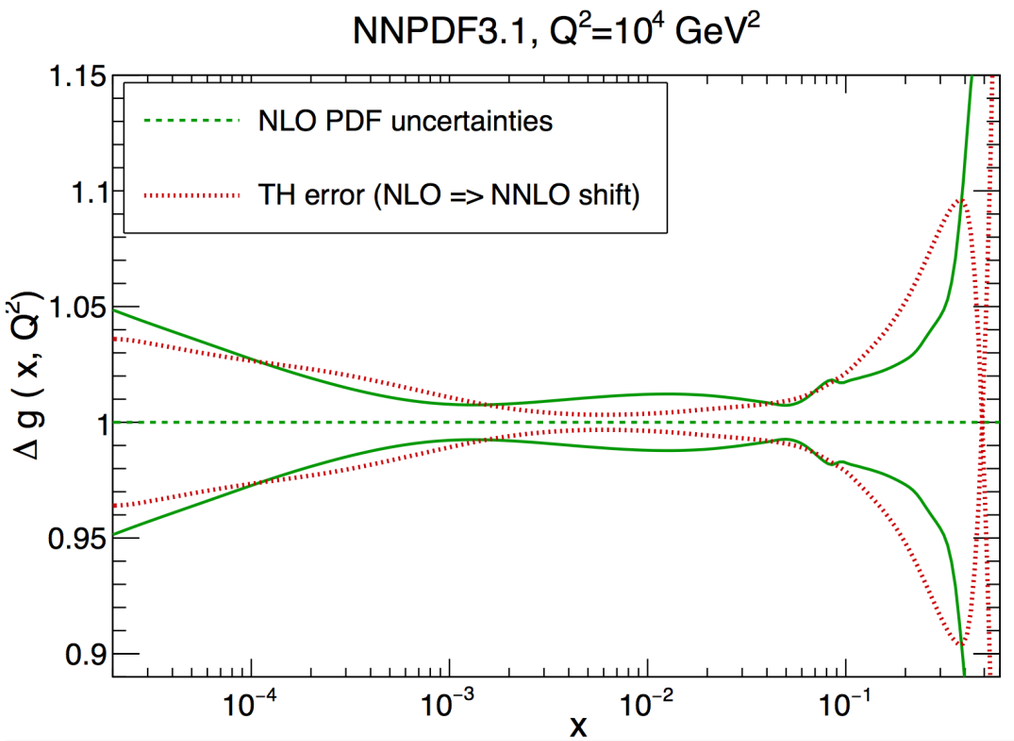
➡ **NNLO theoretical predictions for observables entering PDF fits**

➡ **Fast interface with NNLO codes**

➡ **Photon PDF and inclusion of EW corrections**

➡ **Inclusion of theory uncertainties**



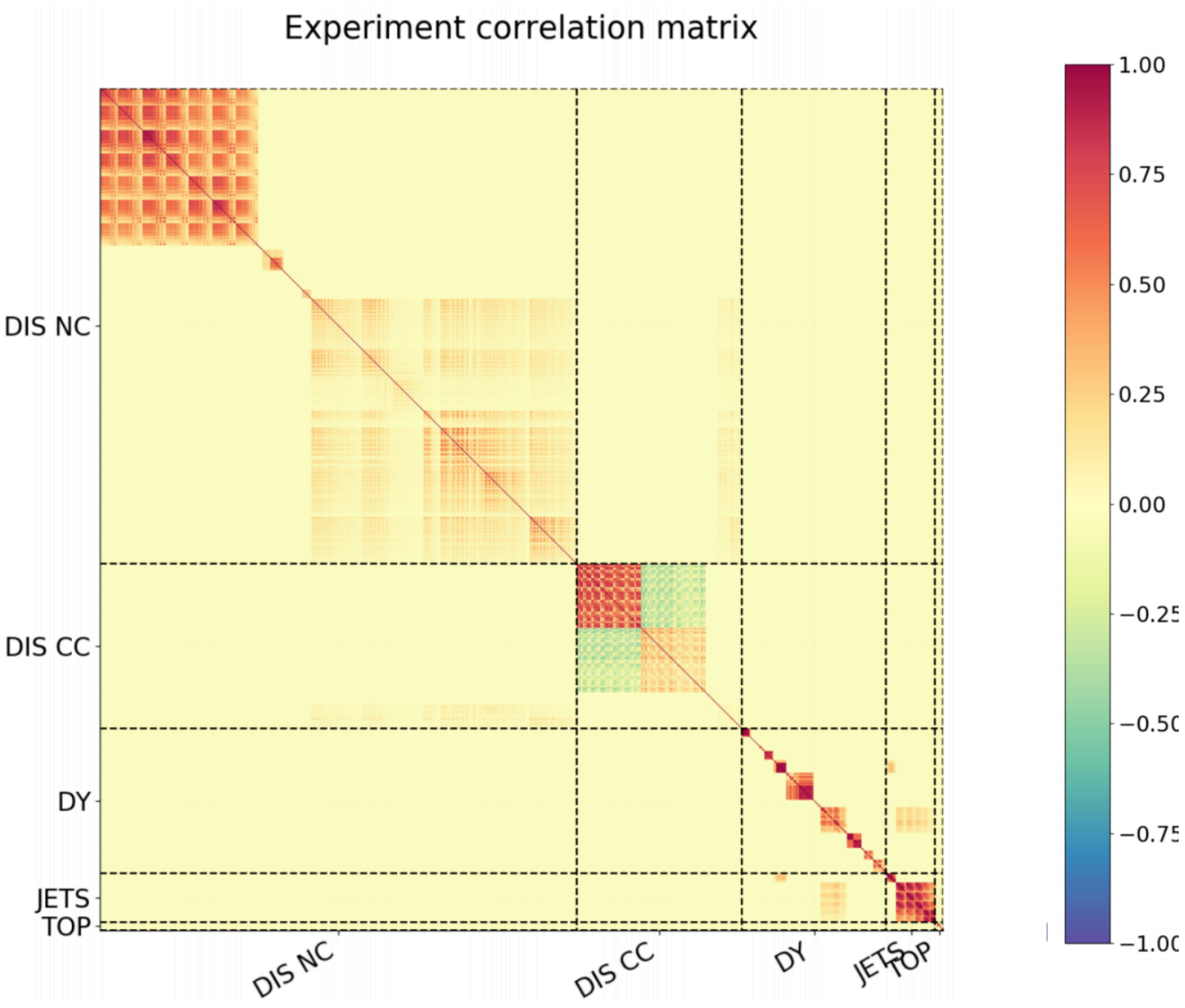


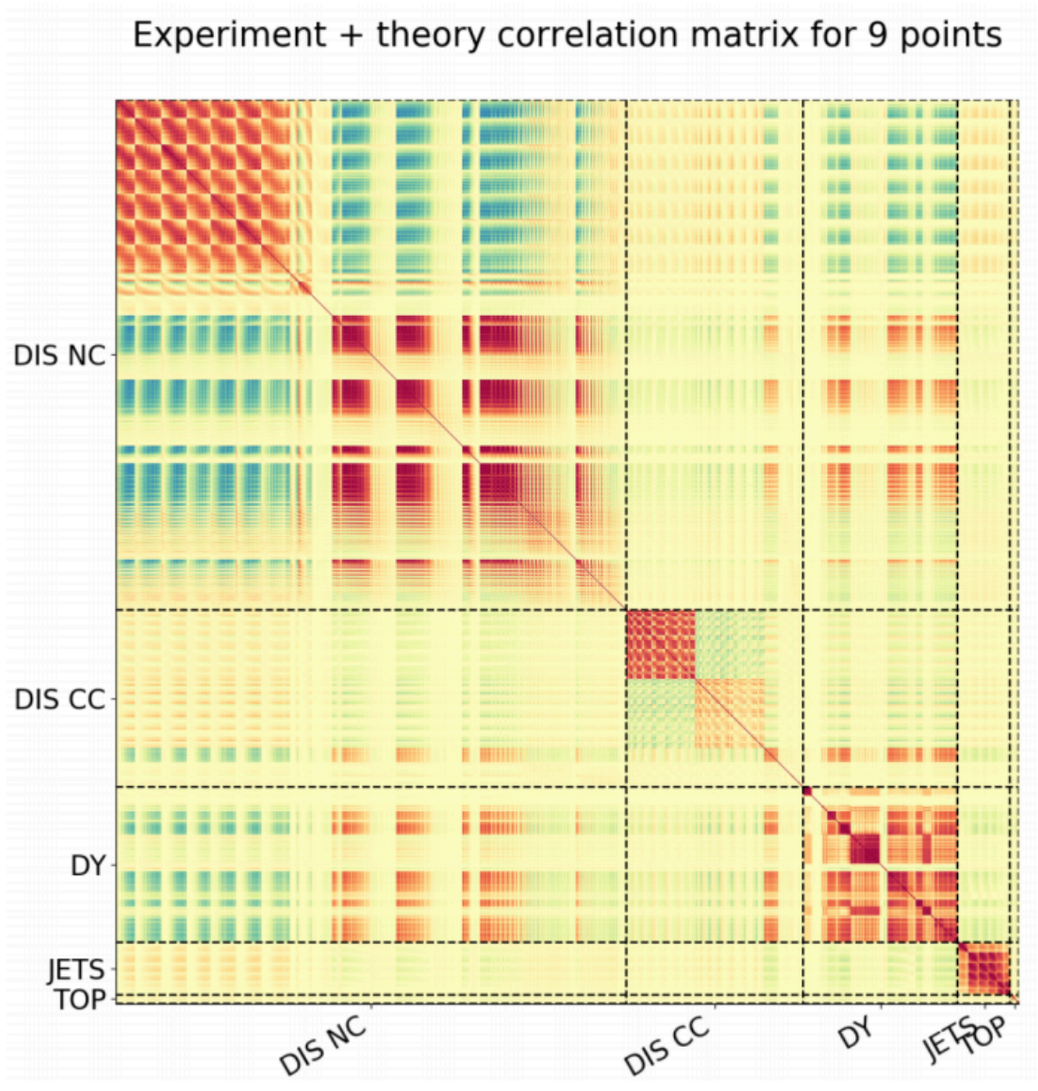
How much are we underestimating PDF uncertainties by ignoring it?

INCLUSION OF THEORY UNCERTAINTIES

- The idea: Construct a theory covariance matrix from scale-varied cross sections and combine it with the experimental covariance matrix

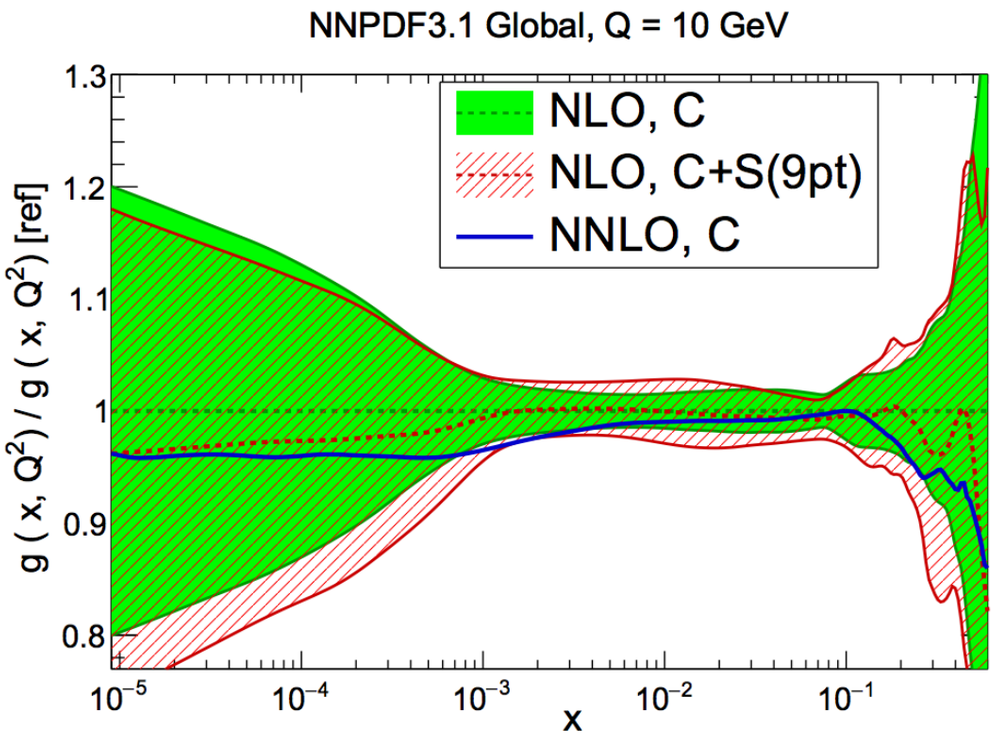
$$\chi^2 = \sum_{m,n=1}^{N} (d_m - t_m)(\mathrm{cov}_{\mathrm{exp}} + \mathrm{cov}_{\mathrm{th}})^{-1}_{mn}(d_n - t_n)$$

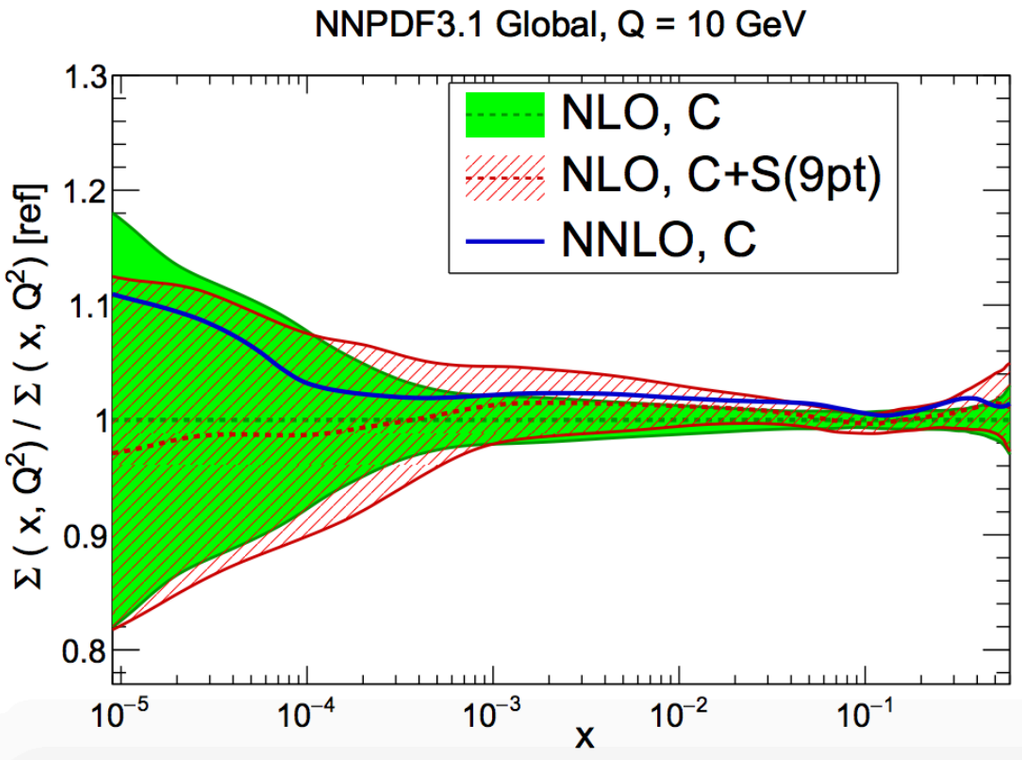


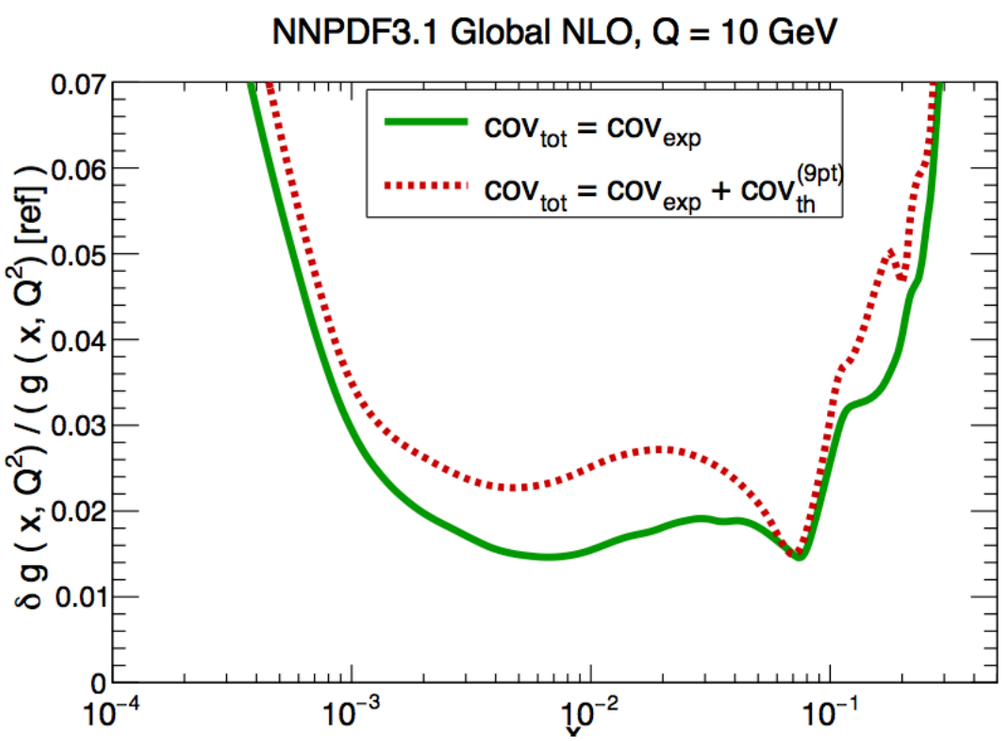


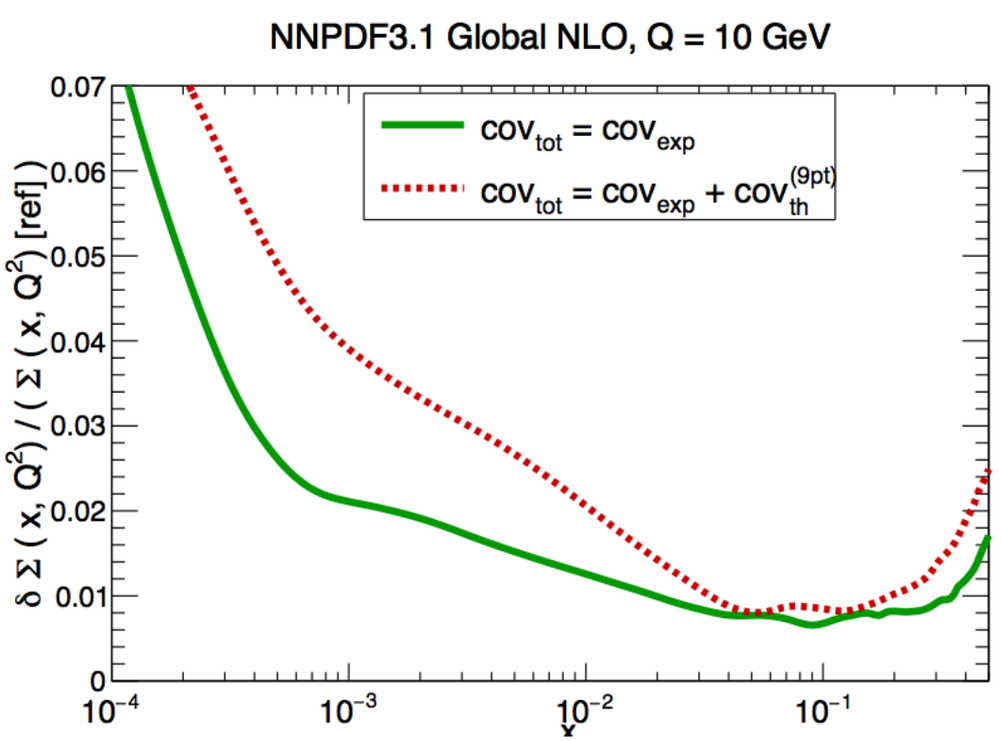
The NNPDF collaboration, arXiv:1906.10698

PDFS WITH THEORY UNCERTAINTIES



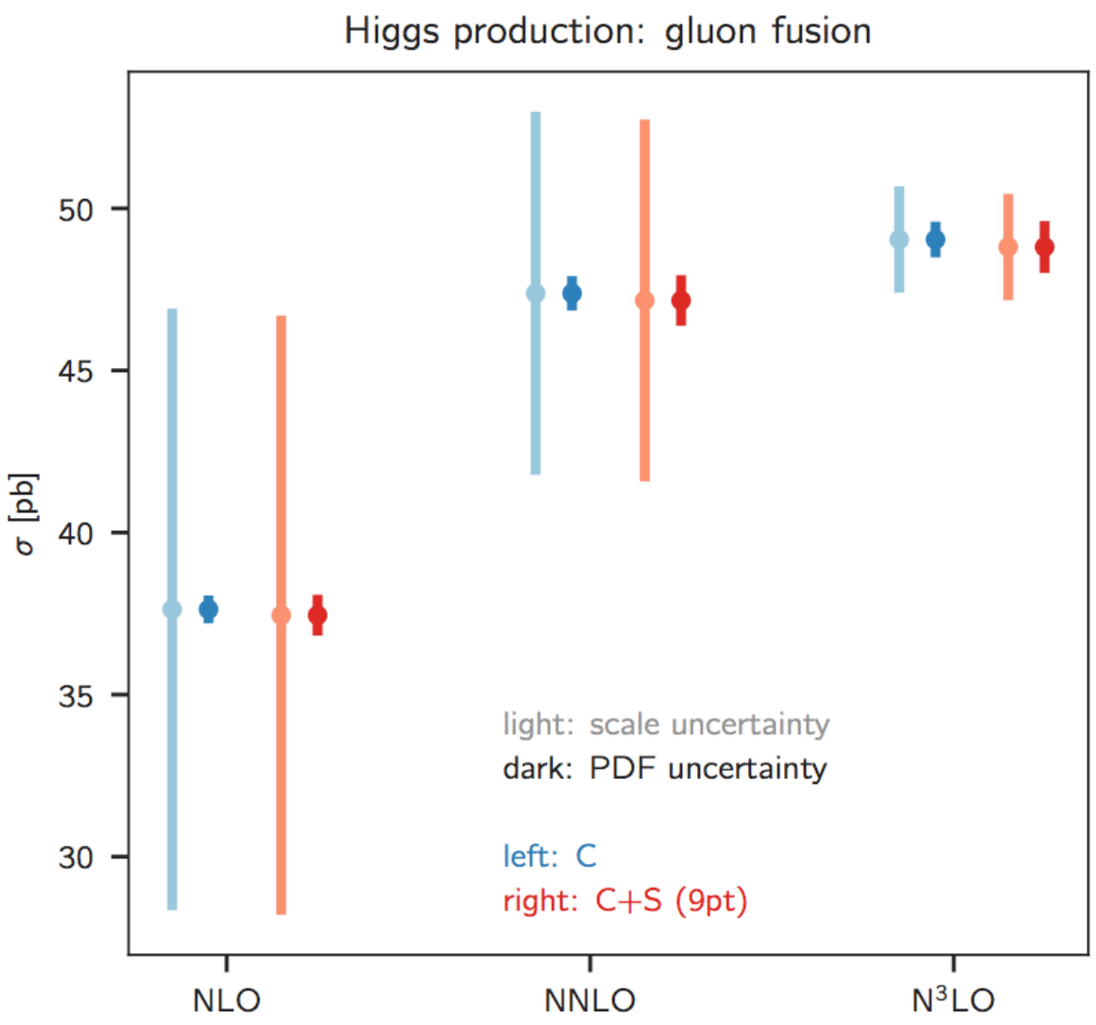


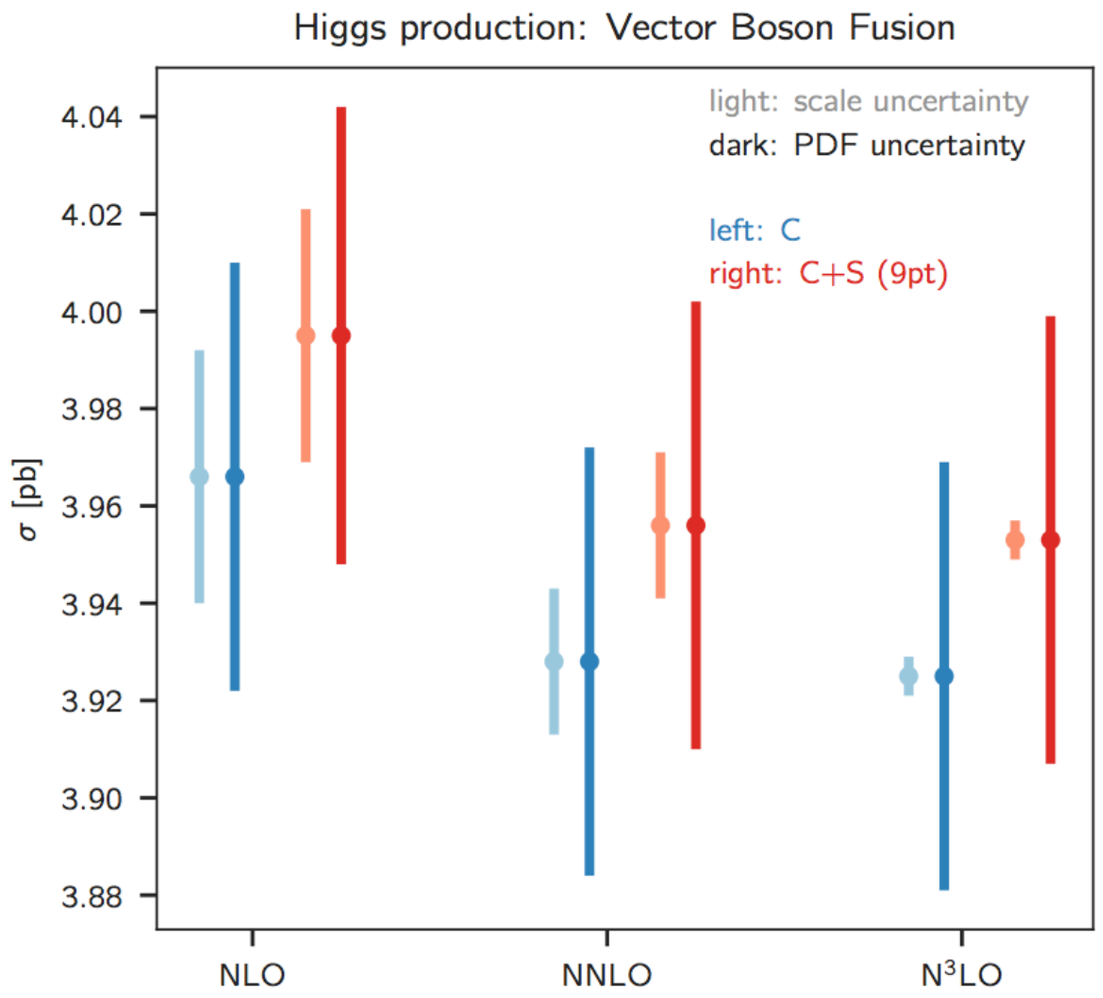




The NNPDF collaboration, arXiv:1906.10698

EFFECTS ON HIGGS PHYSICS

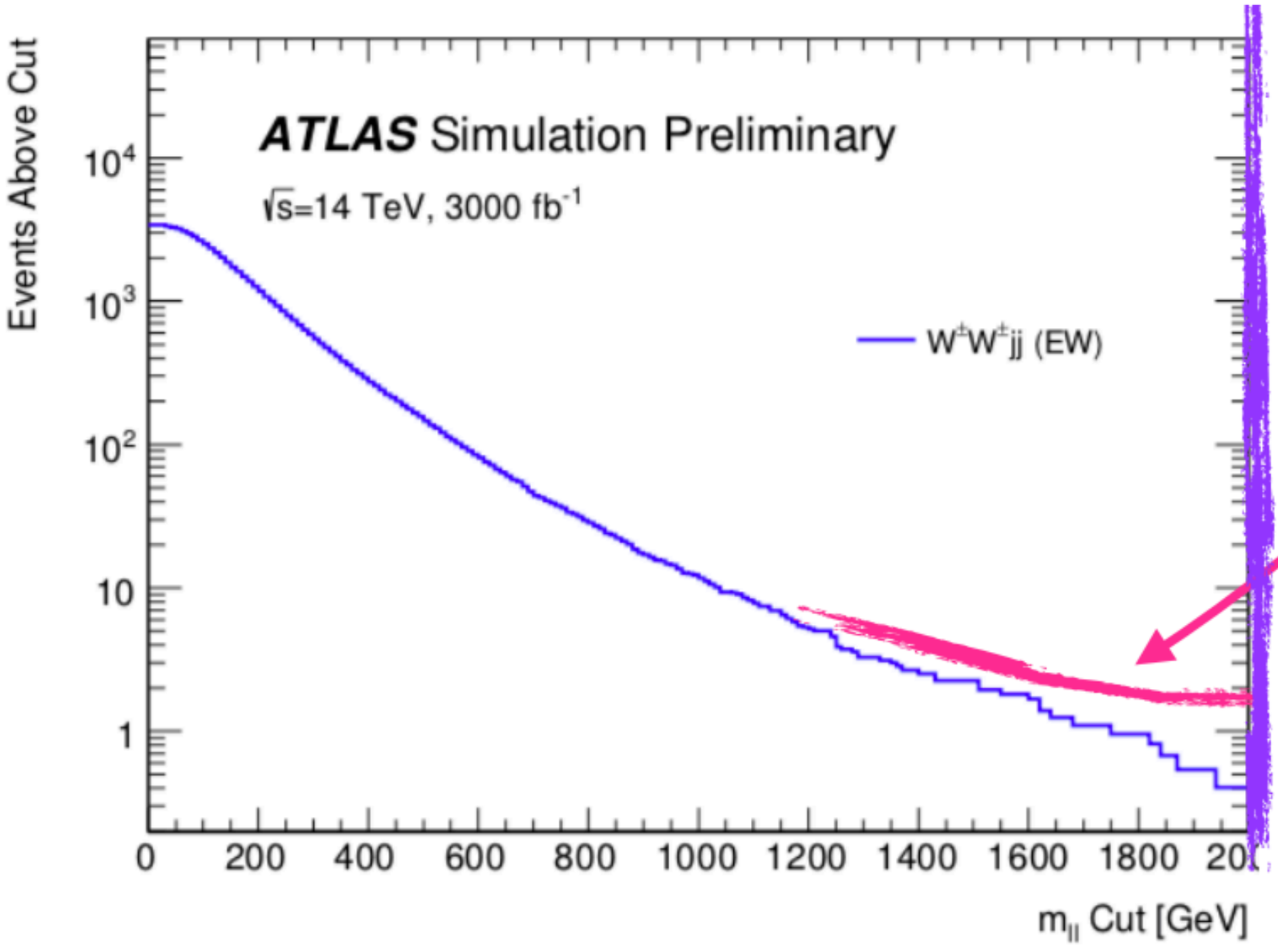




- Mild increase of PDF uncertainty
- Stable predictions for ggF
- Shift within 1σ error band for VBF

The NNPDF collaboration, arXiv:1906.10698

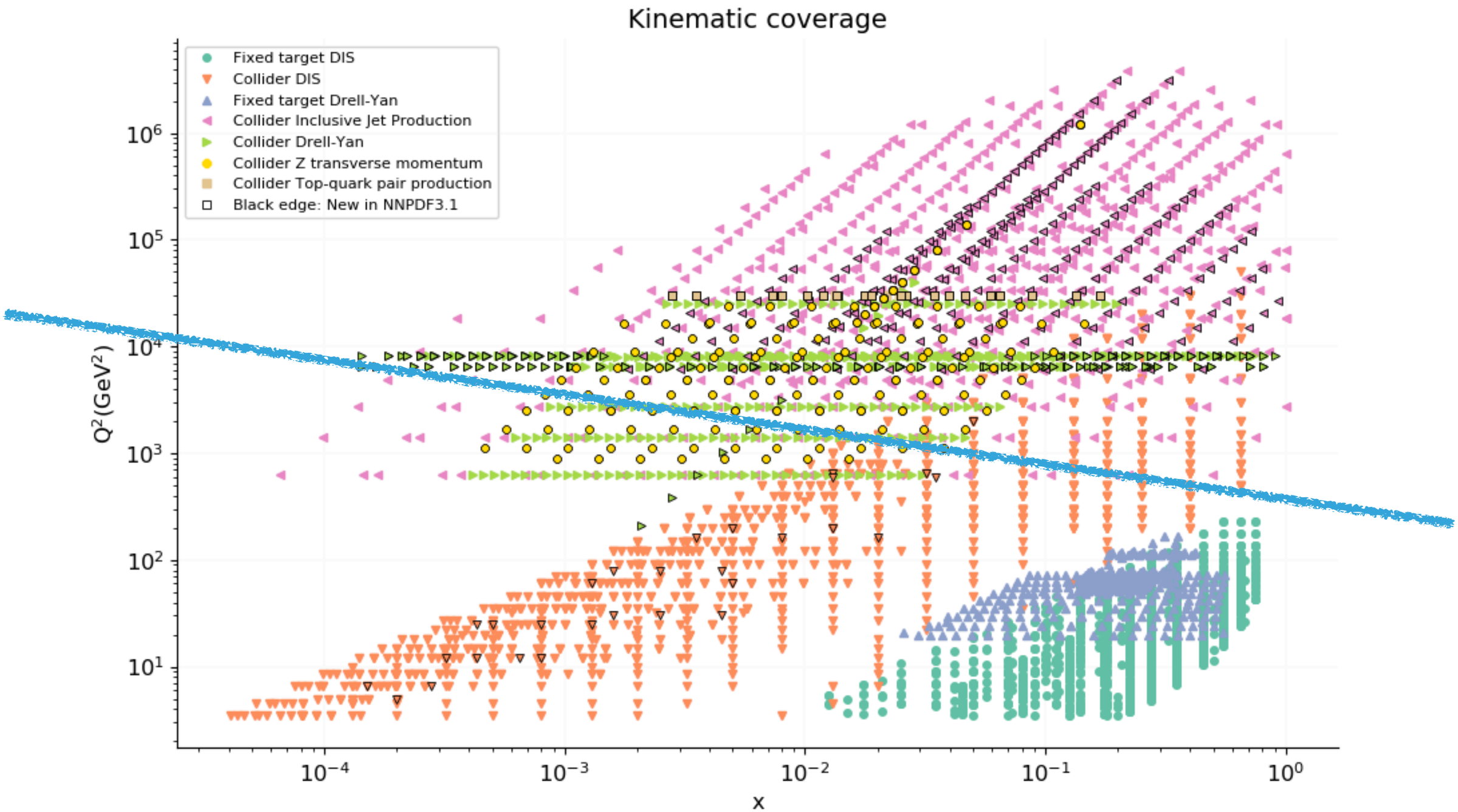
PDFS AND BSM INTERPLAY



Deviations from SM predictions in high energy tails: new physics or limited understanding of proton structure?

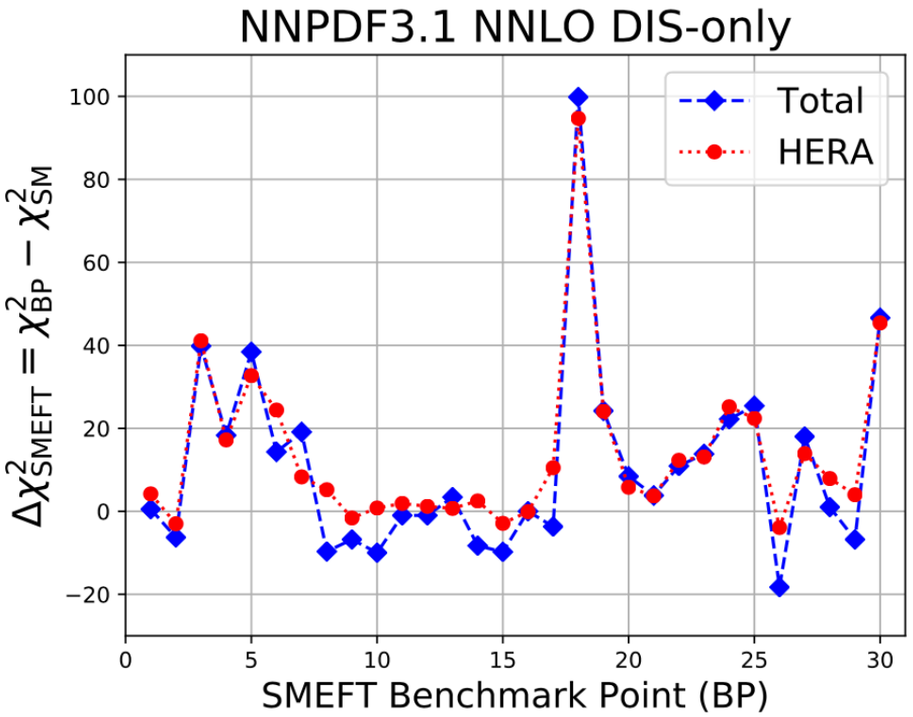
CA Lee, HL/HE-LHC Jamboree, 1 March 2019

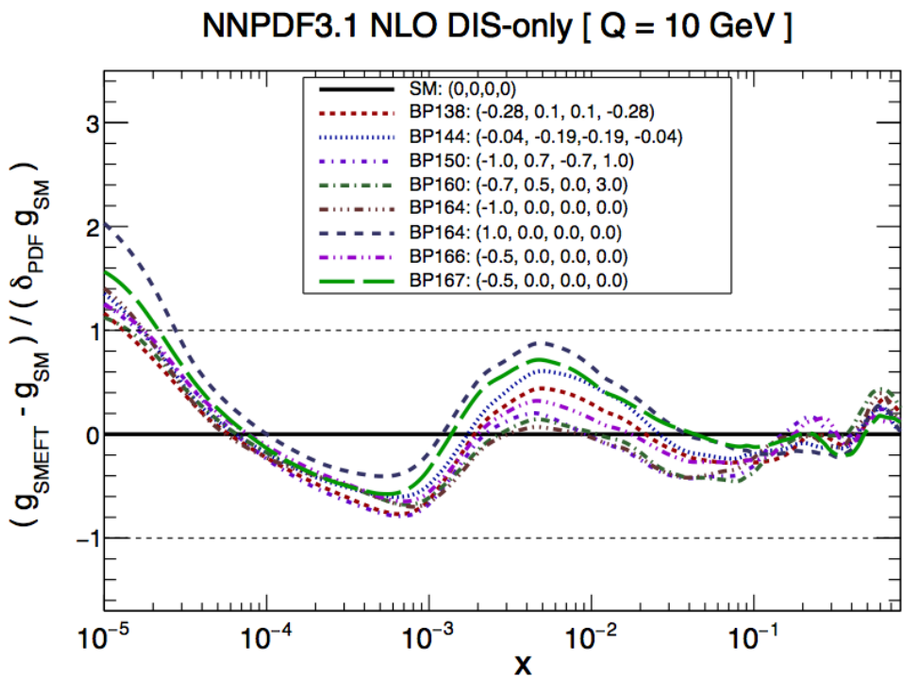
PDFS AND BSM INTERPLAY



- How to disentangle potential BSM effects?
- How to make sure that BSM effects are not fitted away by flexible parametrisation?
- Conservative partons?

PDFS AND BSM INTERPLAY





- Recent study on simultaneous determination of PDFs and SMEFT coefficients of four-fermion operators

  ➡ Q: How to make sure that we do not absorb new physics effects in the fit of proton structure?

  ➡ A: Allow PDFs to be fitted with higher dimensional coefficients and check PDF distortion versus changes in data description in a systematic way

  ➡ Q: (How) would the bounds change if I was using PDFs that include the same operators that I am fitting?

  ➡ A: Yes, even in a case - like DIS - where PDFs mildly change

- The way forward:

  ➡ Increase data sets (particularly DY tails and top) & operator space

  ➡ Ultimate goal: simultaneous fit of SMEFT and PDF degrees of freedom

Carrazza, Degrande, Iranipour, Rojo, MU 1905.05215

CONCLUSIONS AND OUTLOOK

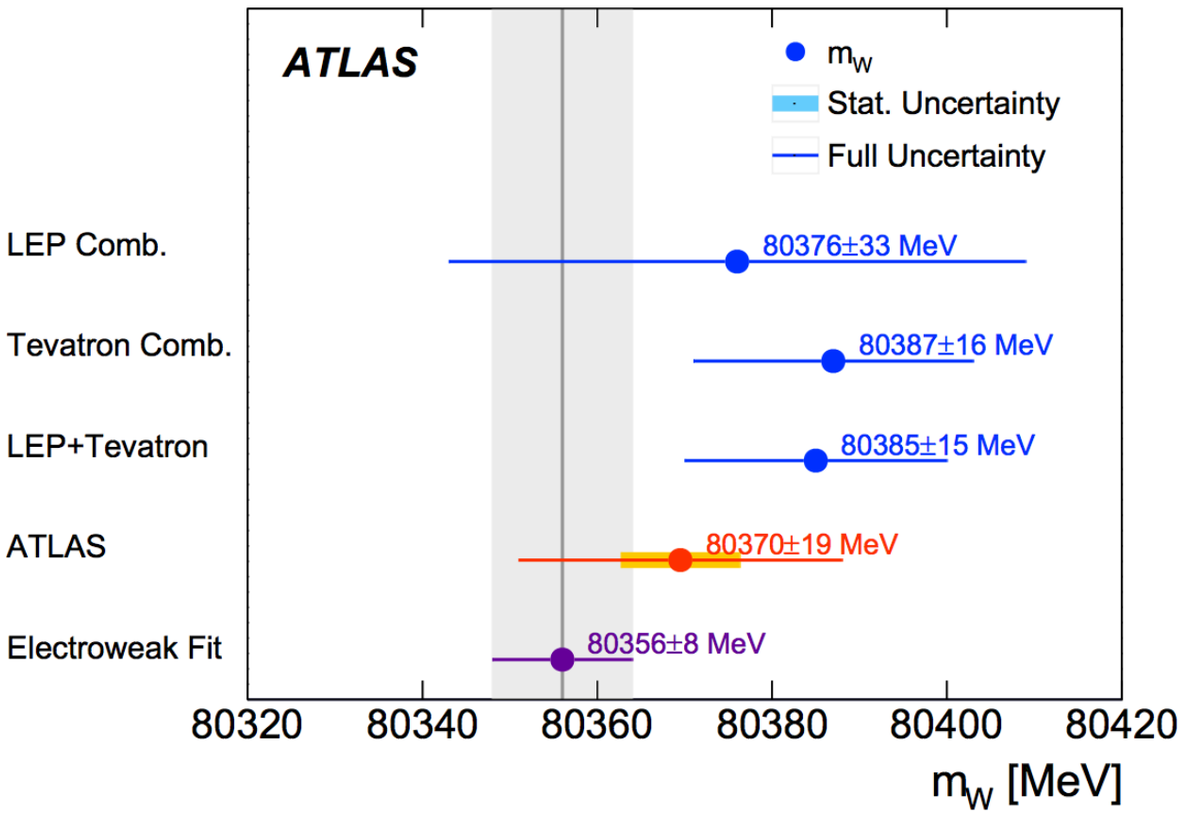
- Precision physics opens up new fascinating challenges also in the fields of PDF determination
- Precise and accurate understanding of the proton structure is key to achieve accurate theoretical predictions
- LHC data already provide strong handle on PDFs
- Challenging to include correlation-dominated data -
- HL-LHC projection: reduction of PDF uncertainties by factor 2-3
- Need: robust methodology and precise theory (higher orders, EW corrections, photons, resummations…)
- New: estimate of theoretical uncertainties associated with missing higher order in PDF fits & fit of the methodology
- Time to study the interplay within new physics and PDFs

THANK YOU!

ADDITIONAL MATERIAL

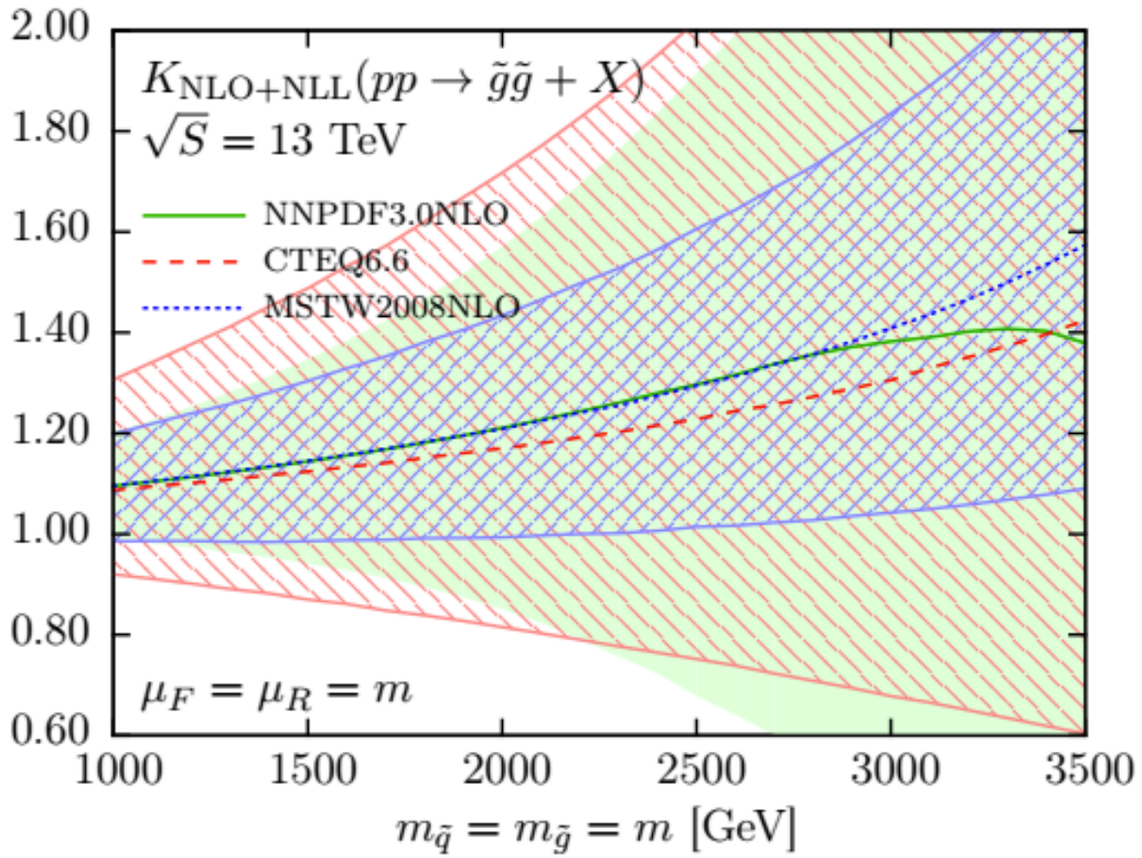
THE ROLE OF PDF UNCERTAINTIES

Determination of SM parameters



ATLAS collaboration, EPJC 78 (2018) 110

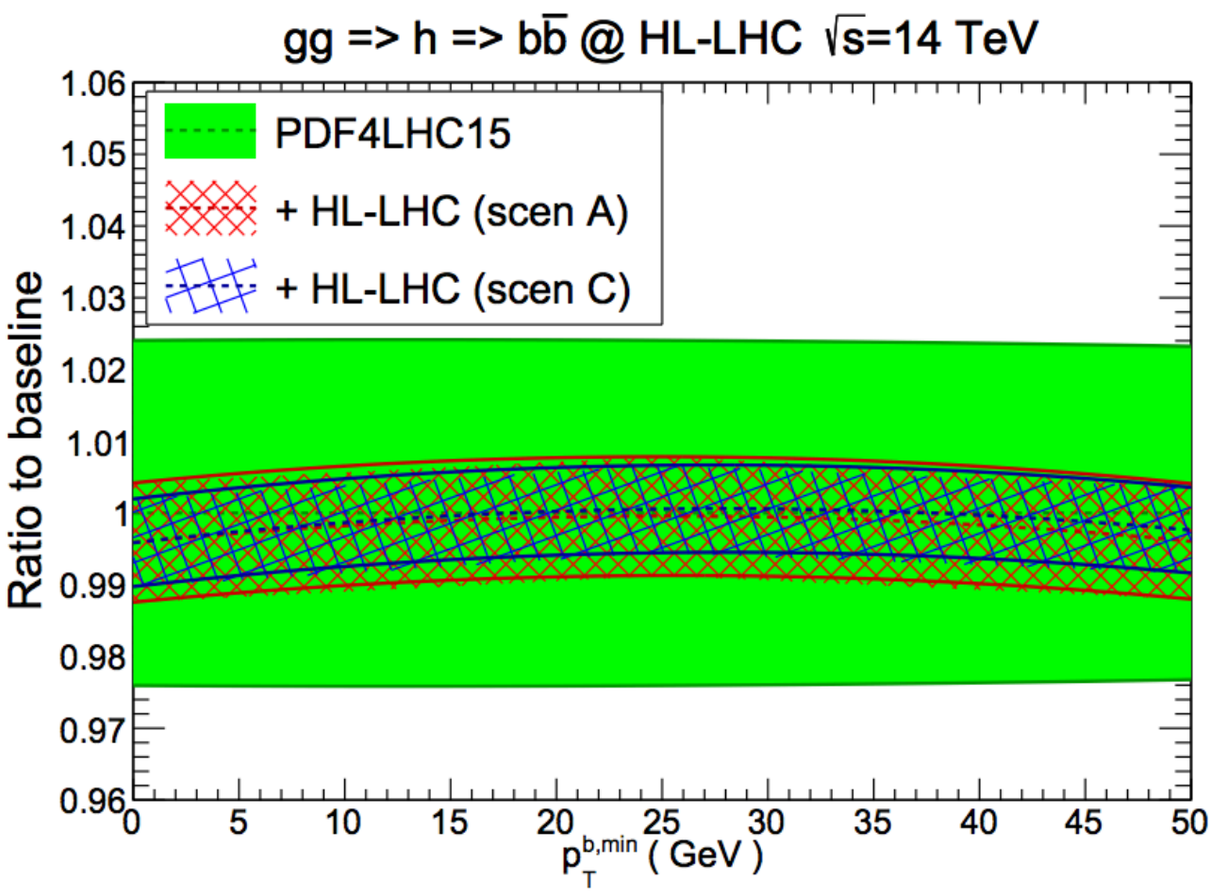
New Physics

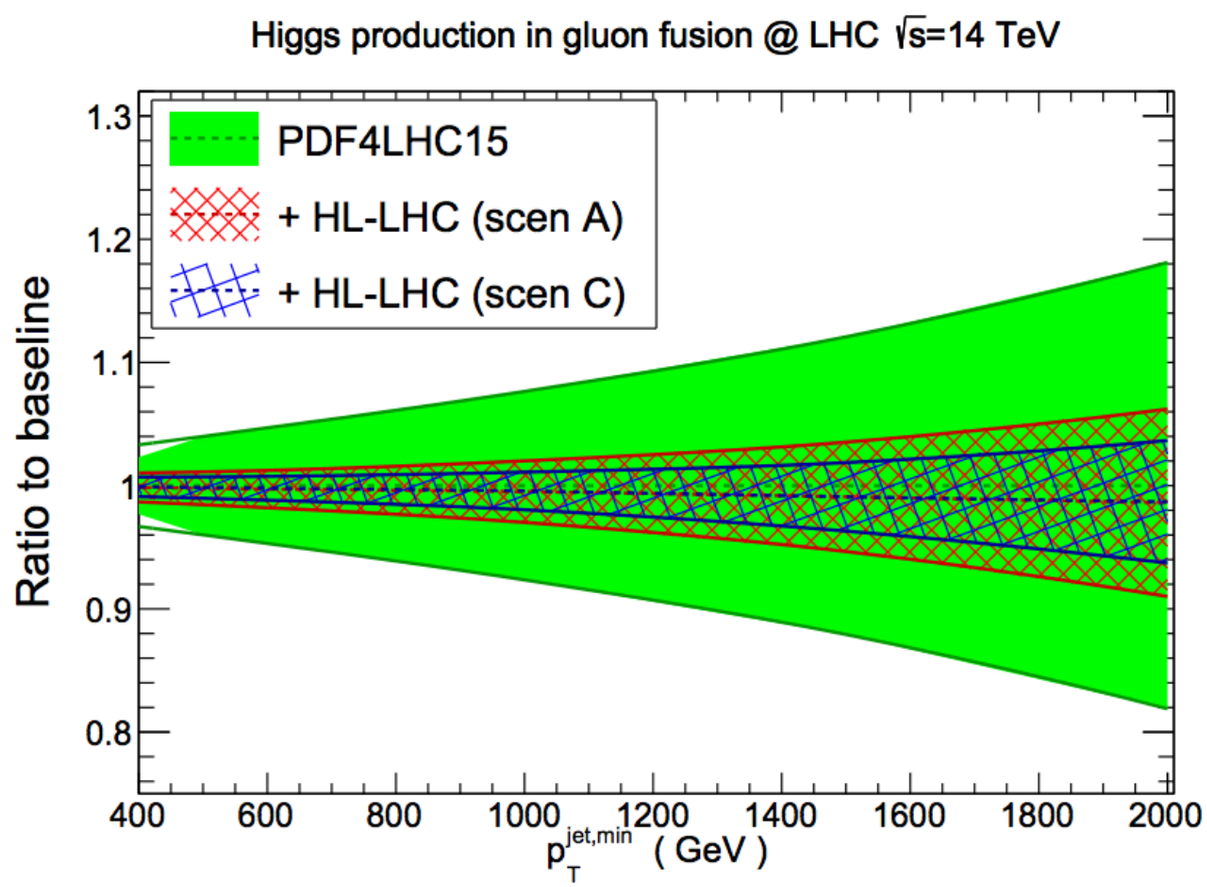


Beenakker et al.
EPJC76 (2016)2, 53

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

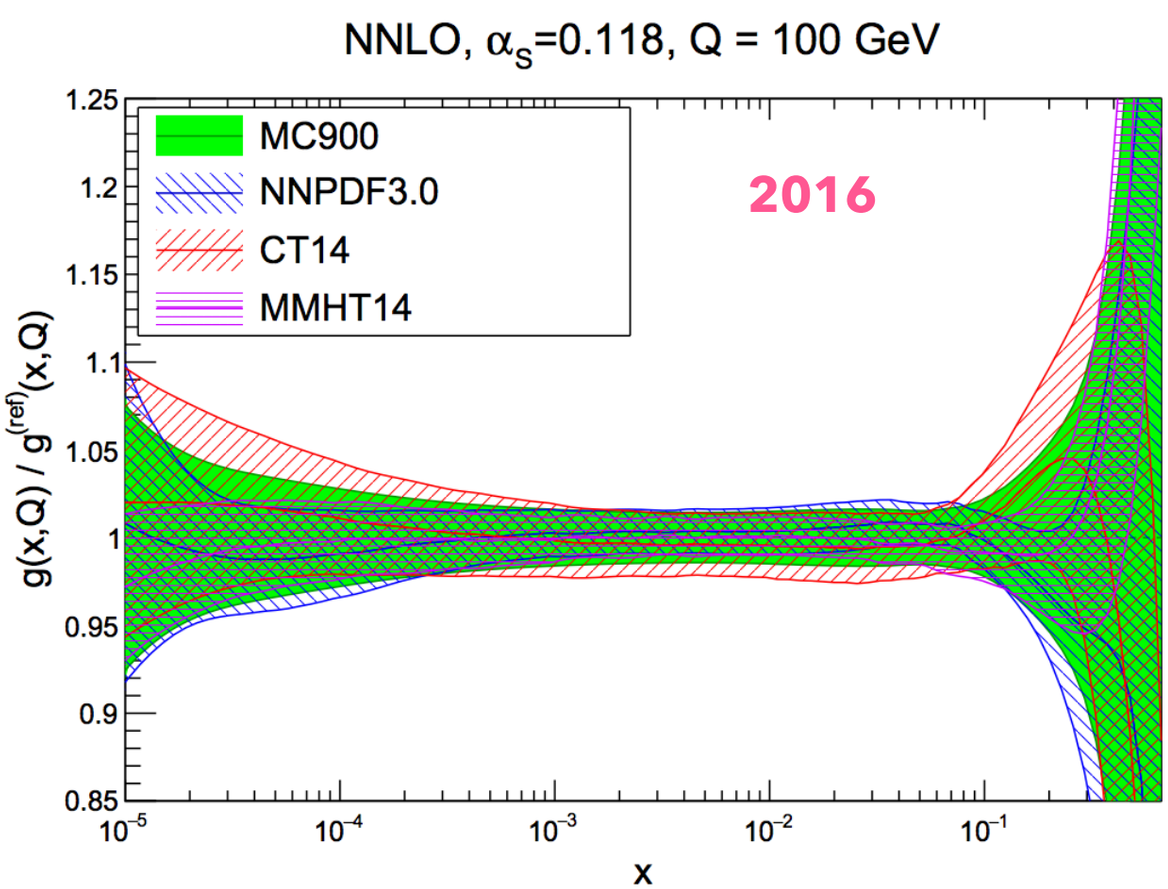
IMPLICATIONS FOR HIGGS PHYSICS



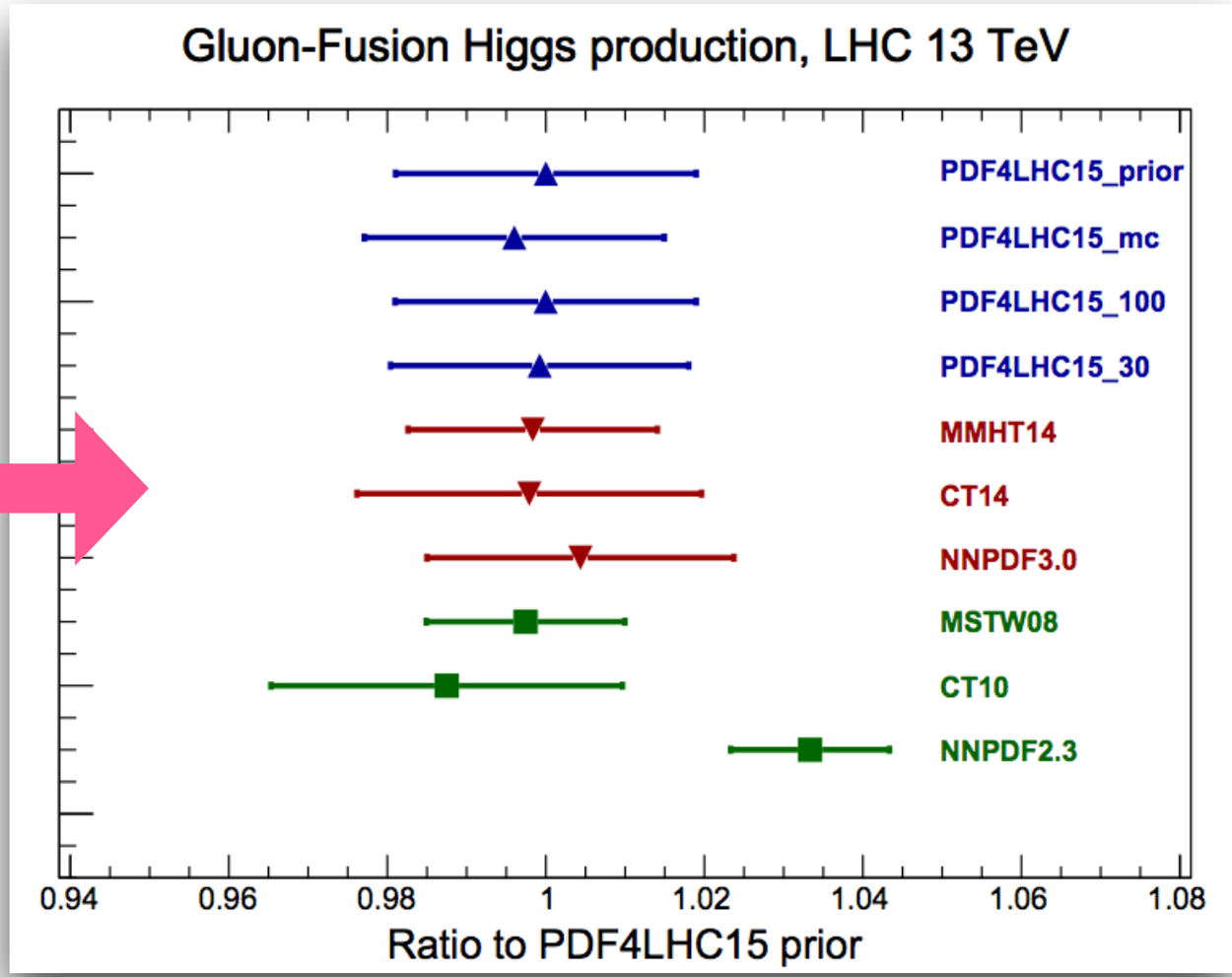


- Caveat N.1: only considered subset of measurements of relevance for HL-LHC
- Caveat N. 2: Possible data incompatibility not accounted for

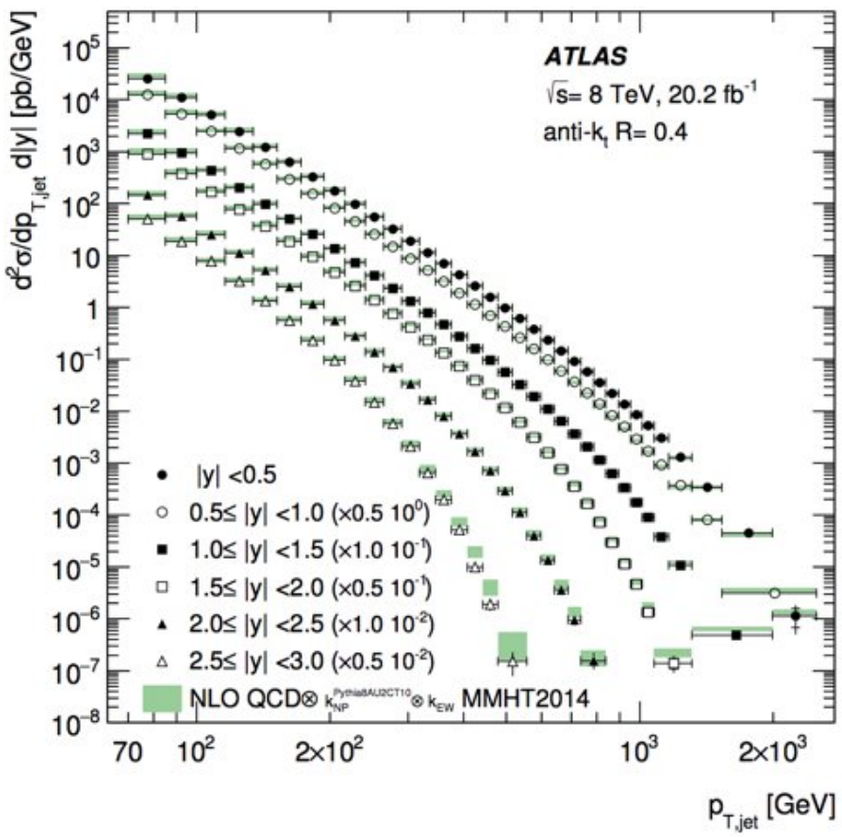
IMPACT OF THE LHC DATA – GLUON PDF

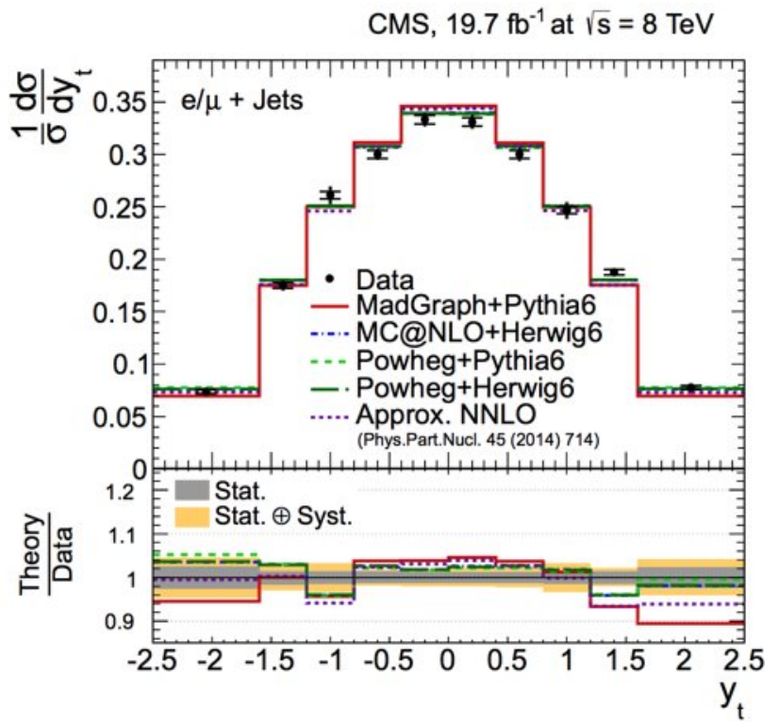


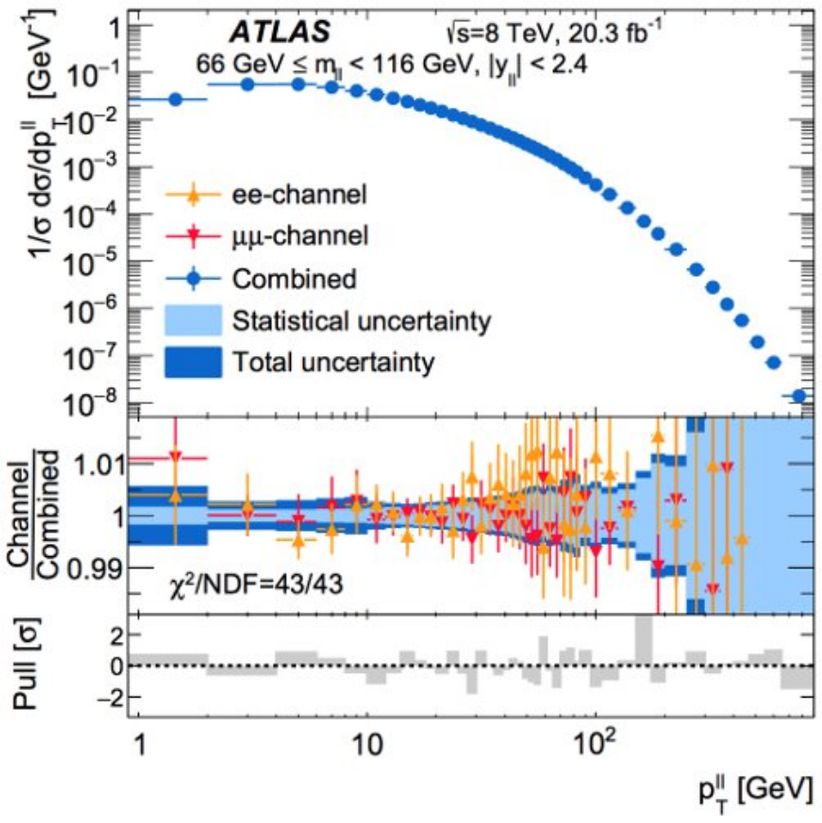
J. Butterworth et al, J.Phys. G43 (2016) 023001



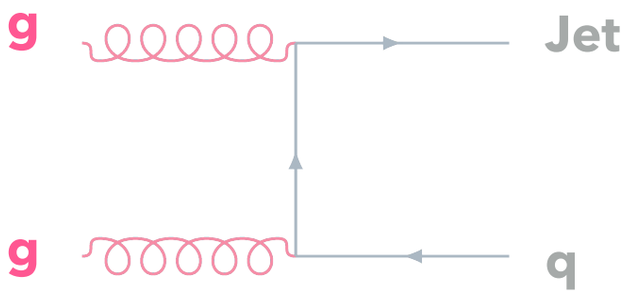
IMPACT OF THE LHC DATA – GLUON PDF



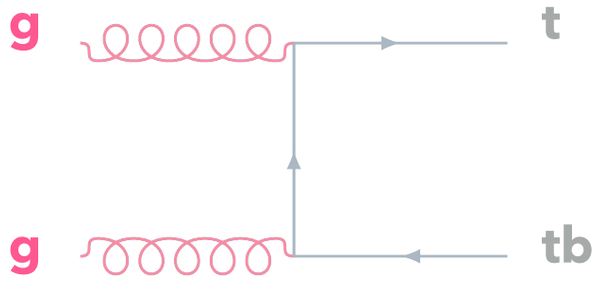




INCLUSIVE JETS



TOP PAIR



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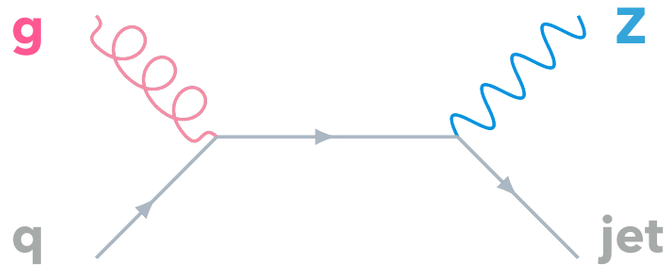

CLOSURE TESTS