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UNIVERSITY OF CAMBRIDGE

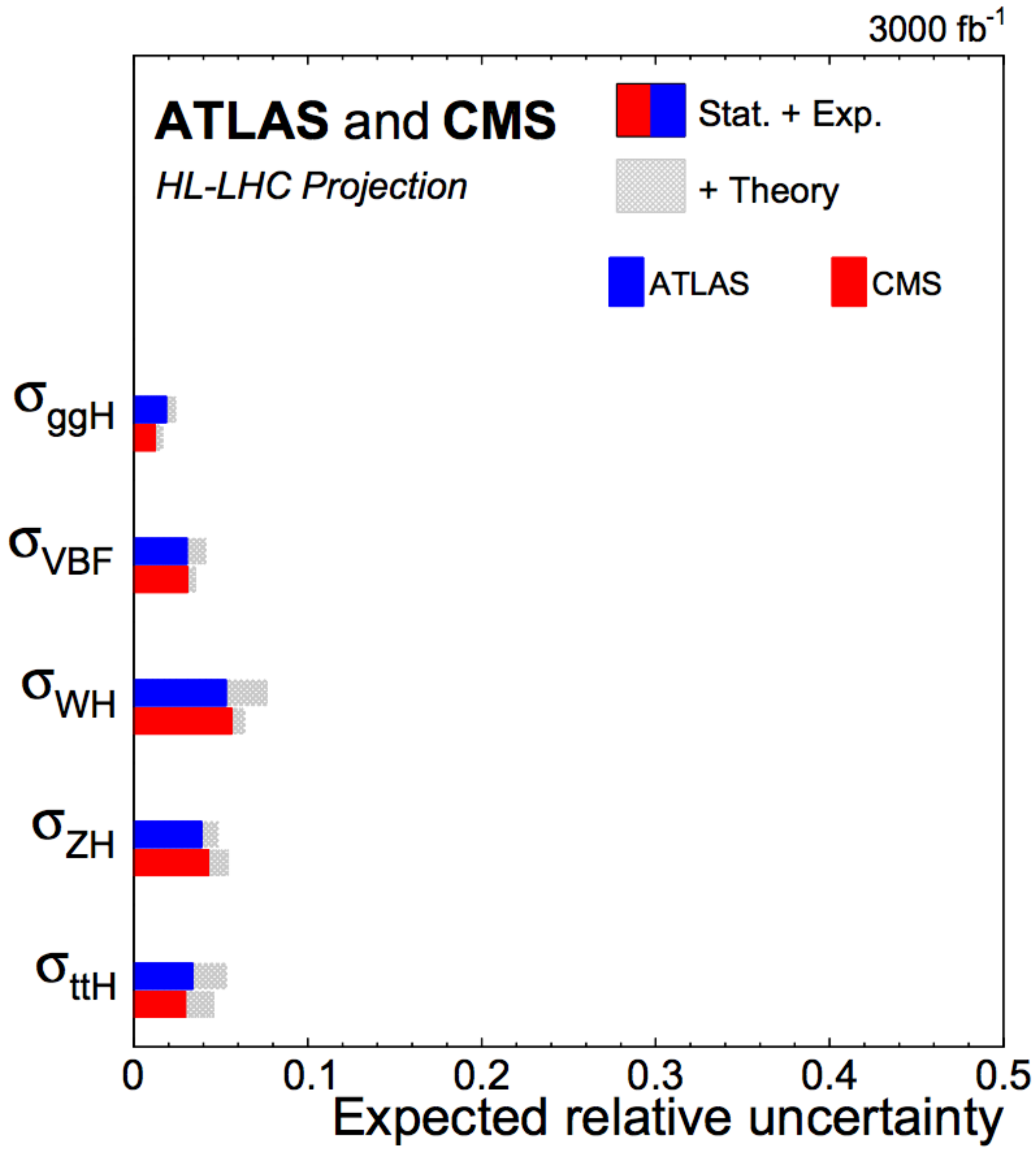
PARTON DISTRIBUTION FUNCTIONS FOR HIGGS PHYSICS

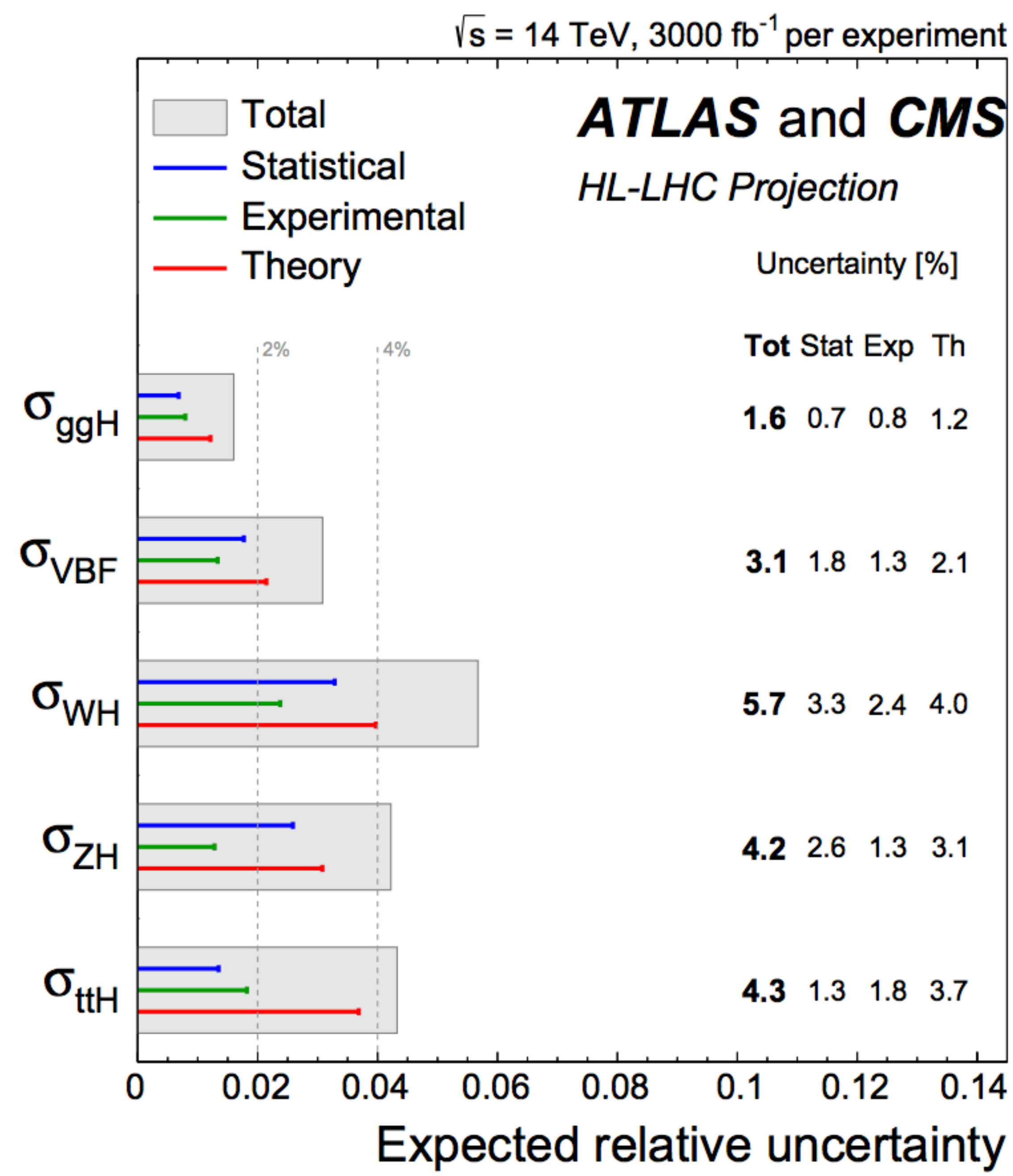
ULTIMATE PRECISION AT HADRON COLLIDERS WORKSHOP, INSTITUT PASCAL, PARIS

2ND DECEMBER 2019

PRECISION CHALLENGE FOR HIGGS PHYSICS

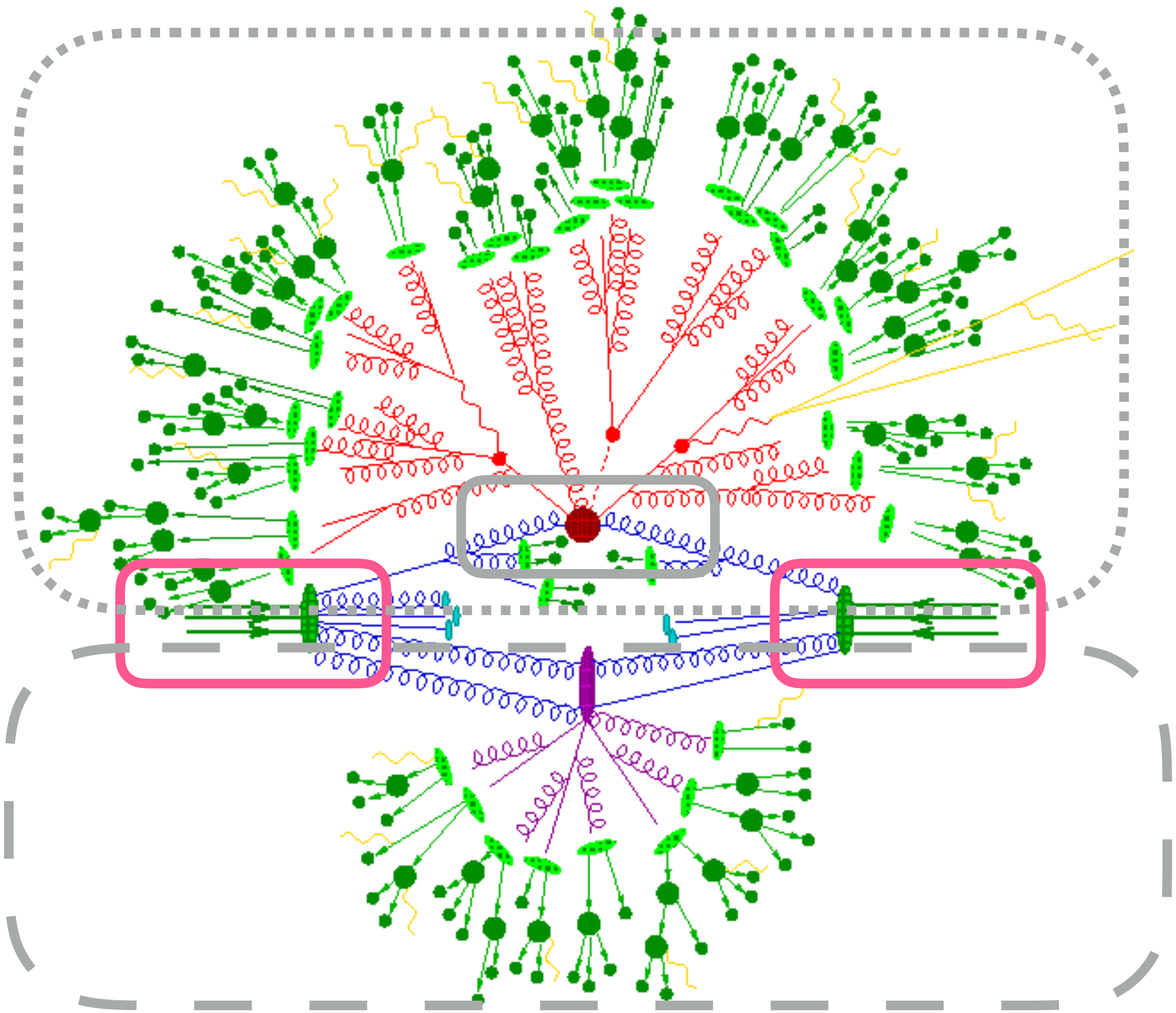
- LHC: discovery → discovery through precision
- To interpret HL-LHC data substantial progress from theory calculations is needed





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

PRECISION INGREDIENTS

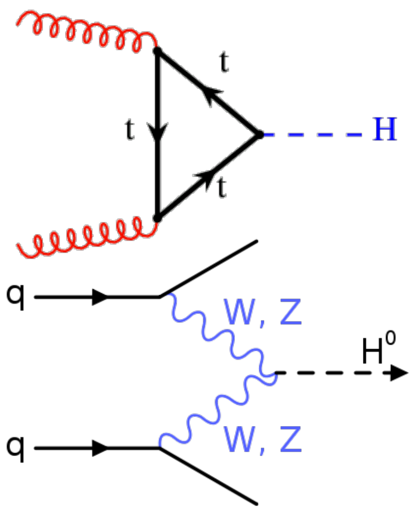


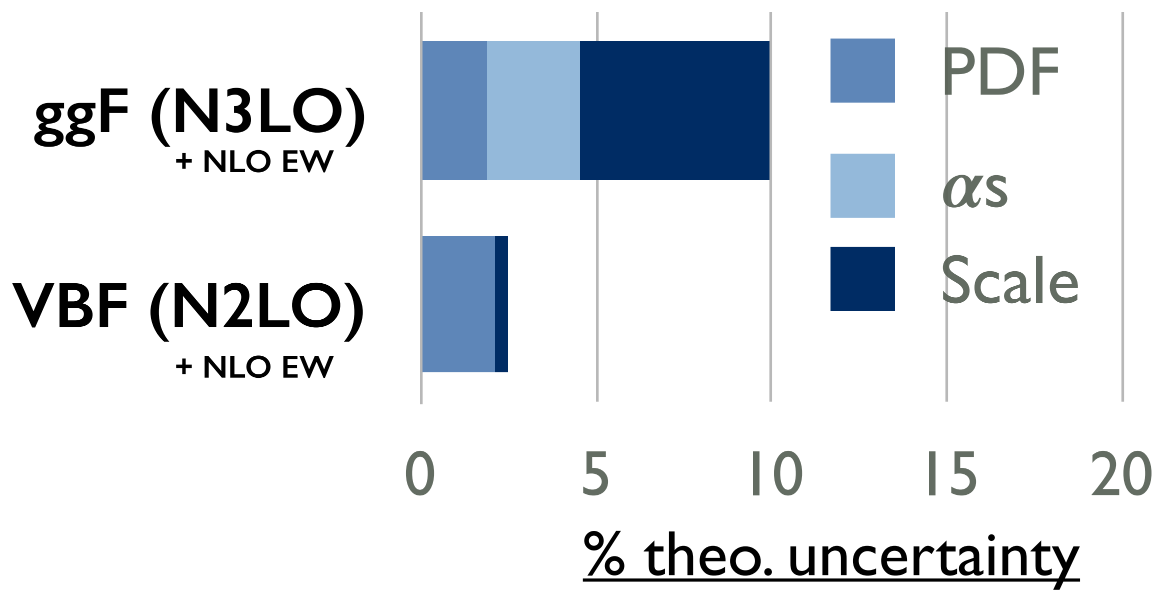
- Hard scattering of partons (Perturbative QCD+EW)
- Parton Distribution Functions
- Parton Showering and Hadronization
- Multiple Parton Interaction, Underlying Events

SHERPA artist

THE ROLE OF PDF UNCERTAINTIES

Higgs

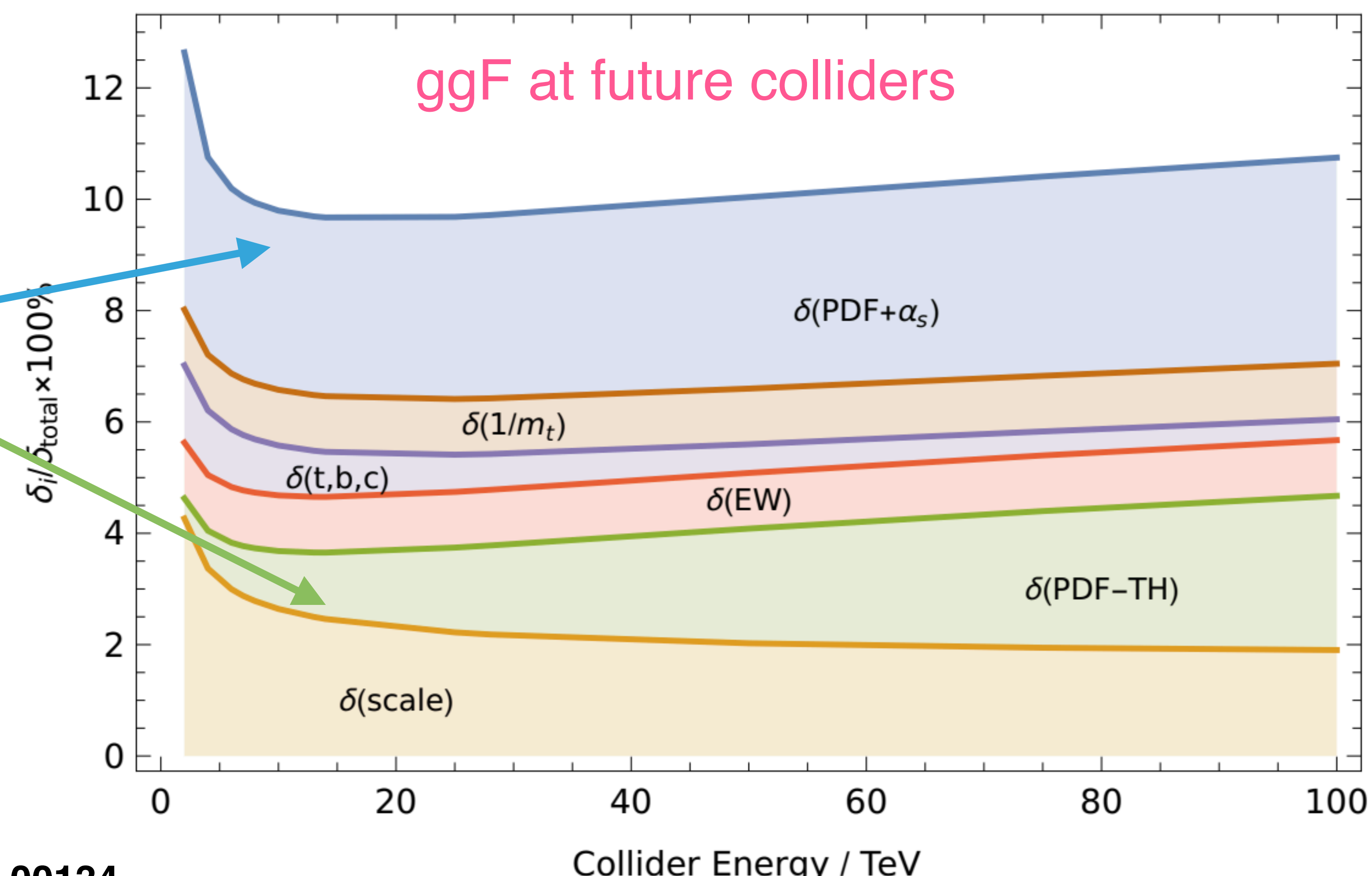




48.6 pb
3.77 pb

σ@13 TeV

PDF uncertainty significantly limitation to theory accuracy



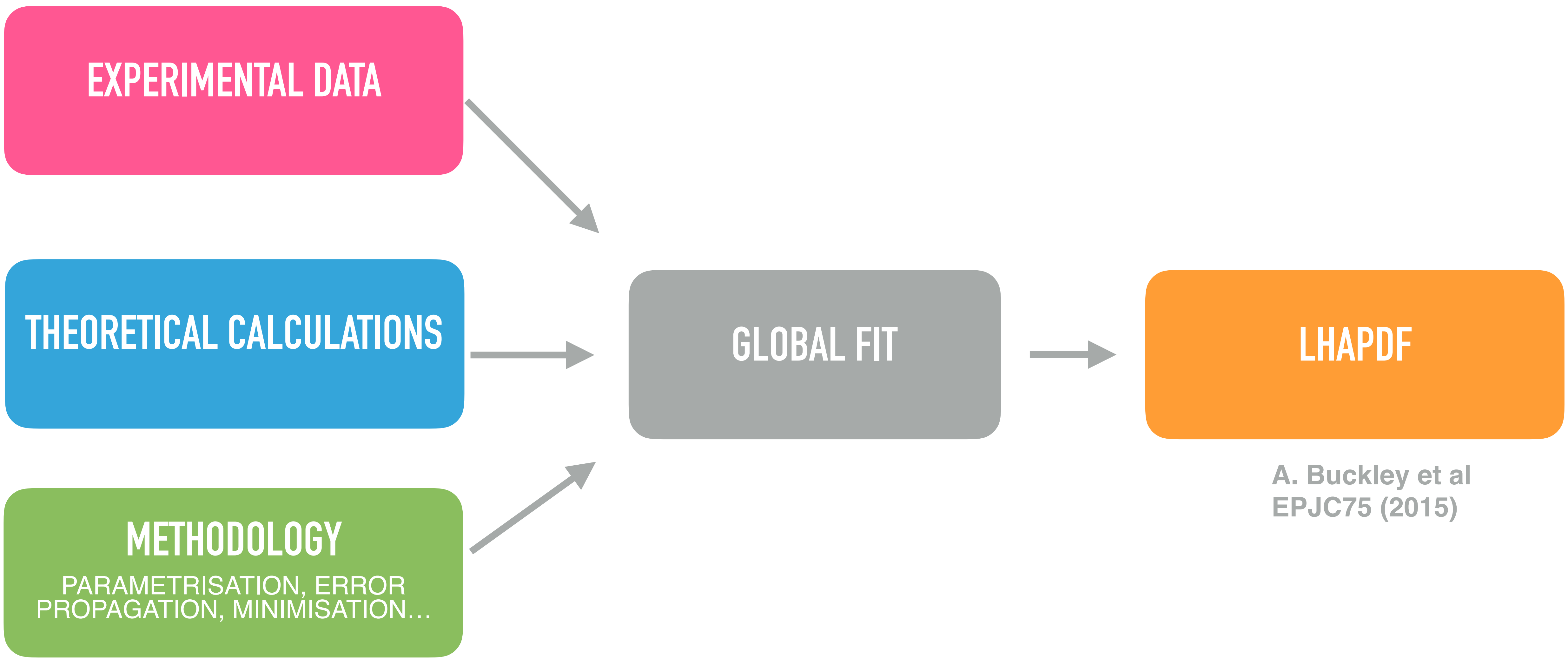
M. Cepeda et al. [HL/HE WG2 group], arXiv:1902.00134

PDF DETERMINATION

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

Data

Perturbative QCD
DGLAP evolution equations



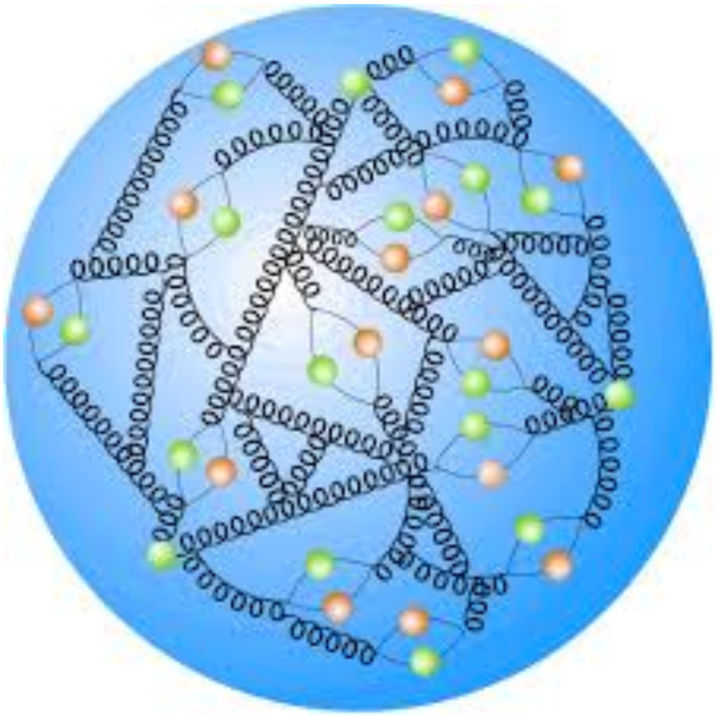
OUTLINE

- Challenges and updates in PDF determinations

  ➡ **Part I : Experimental data**

  ➡ Intermission: Methodological issues

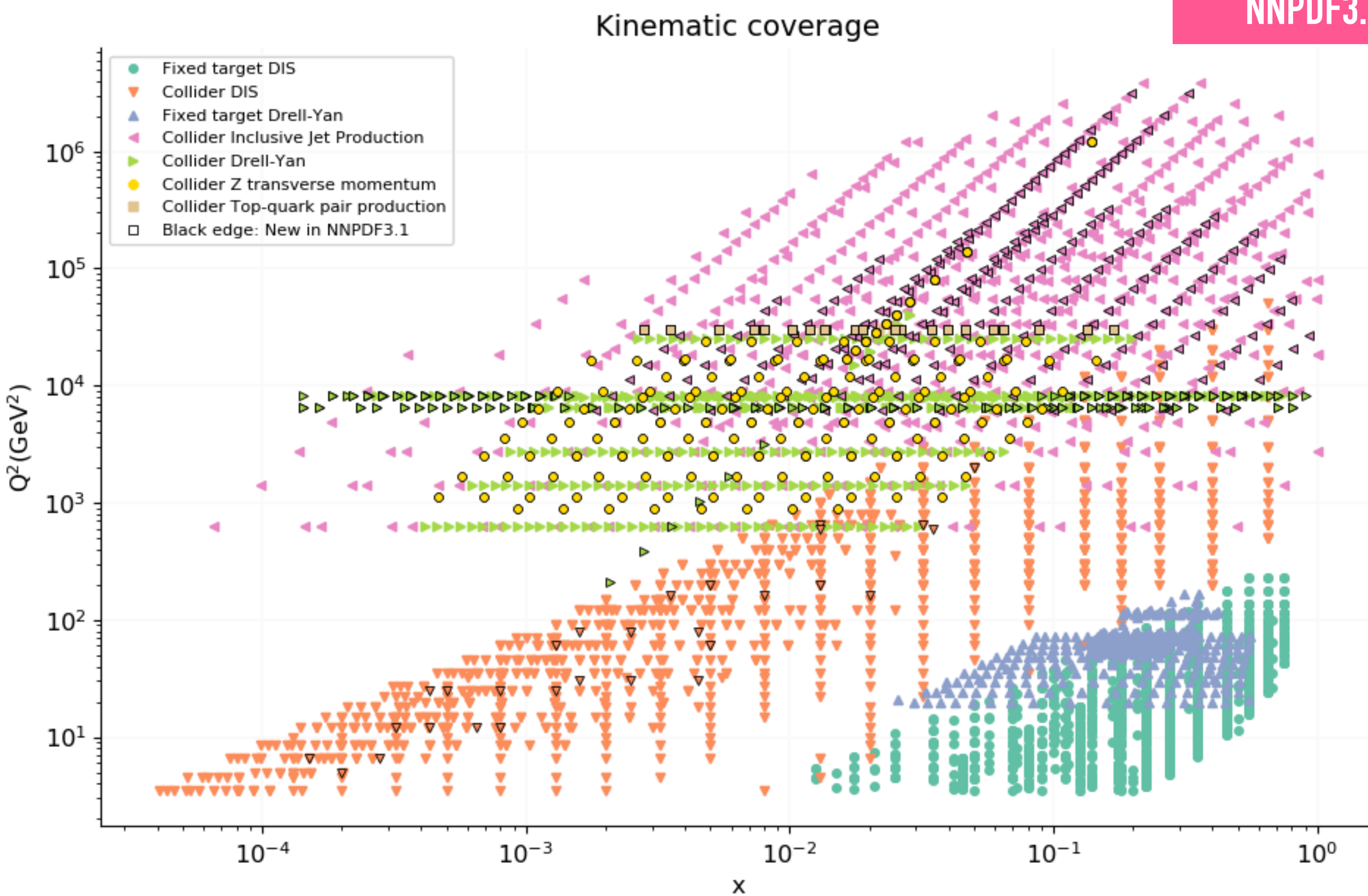
  ➡ Part II: Theoretical aspects



- 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
* 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
* 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)

prompt photons (at NNLO)

Dijets (at NNLO)

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
* 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

single top (at NNLO)

Upgrades

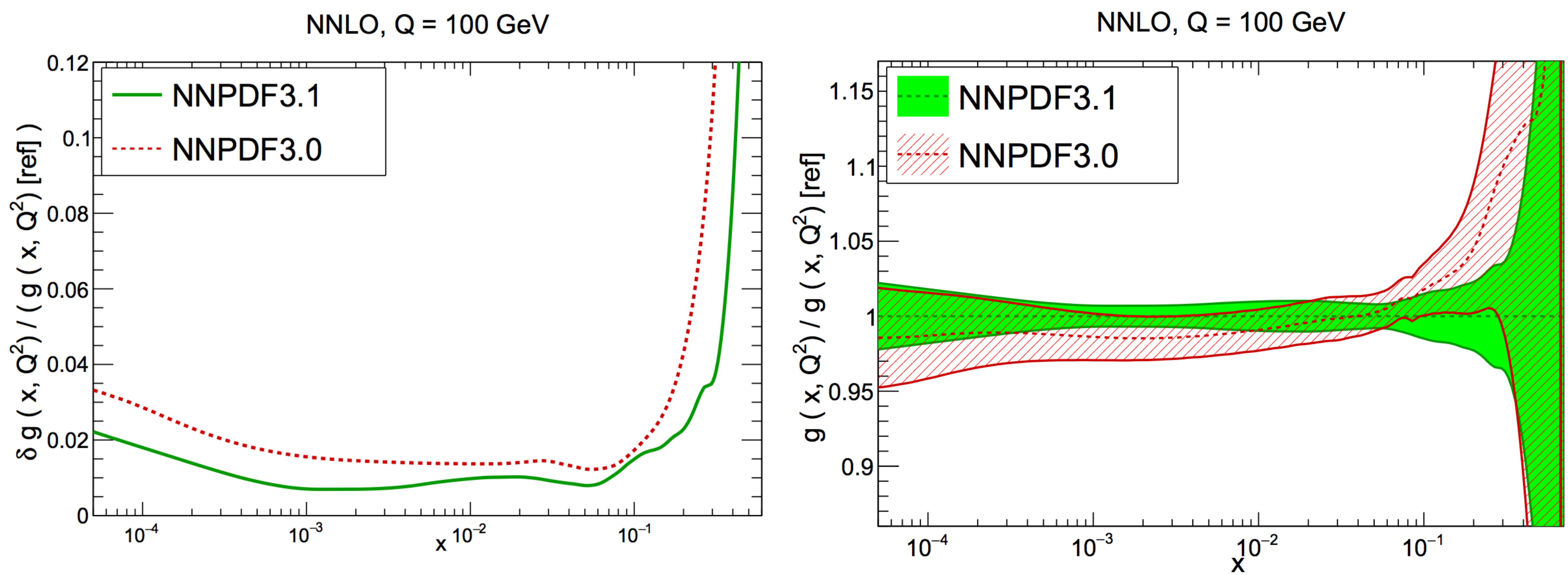
* ATLAS W/Z production, 7 TeV (4.6 fb-1) => added the off-peak and forward Z prod bins
* Final combination of charm and beauty str fns from HERA (Runs I+II): replaces HERA-I charm comb and H1, ZEUS structure functions

Cutoff date for new data:
end of 2019

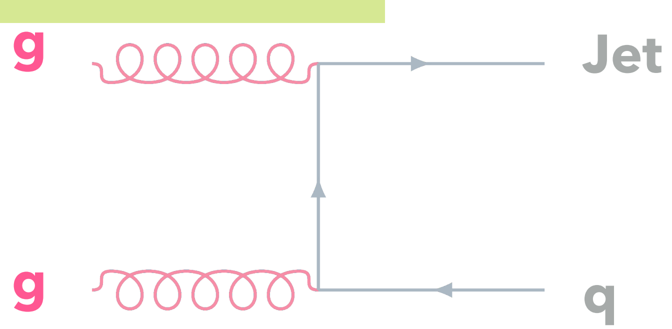
R. Ball, PDF4LHC September 2019

IMPACT OF THE LHC DATA – GLUON PDF

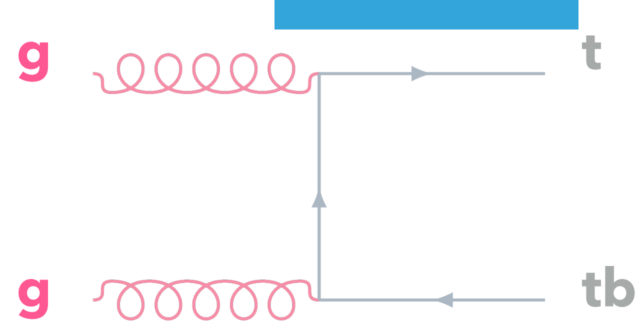
- Large-x gluon constrained by (at least) three independent processes
- Consistent picture and uncertainty reduction



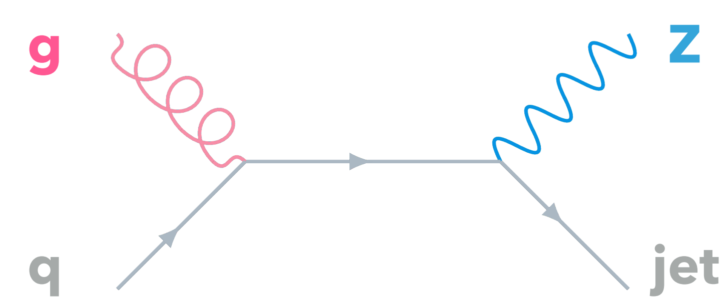
INCLUSIVE JETS



TOP PAIR

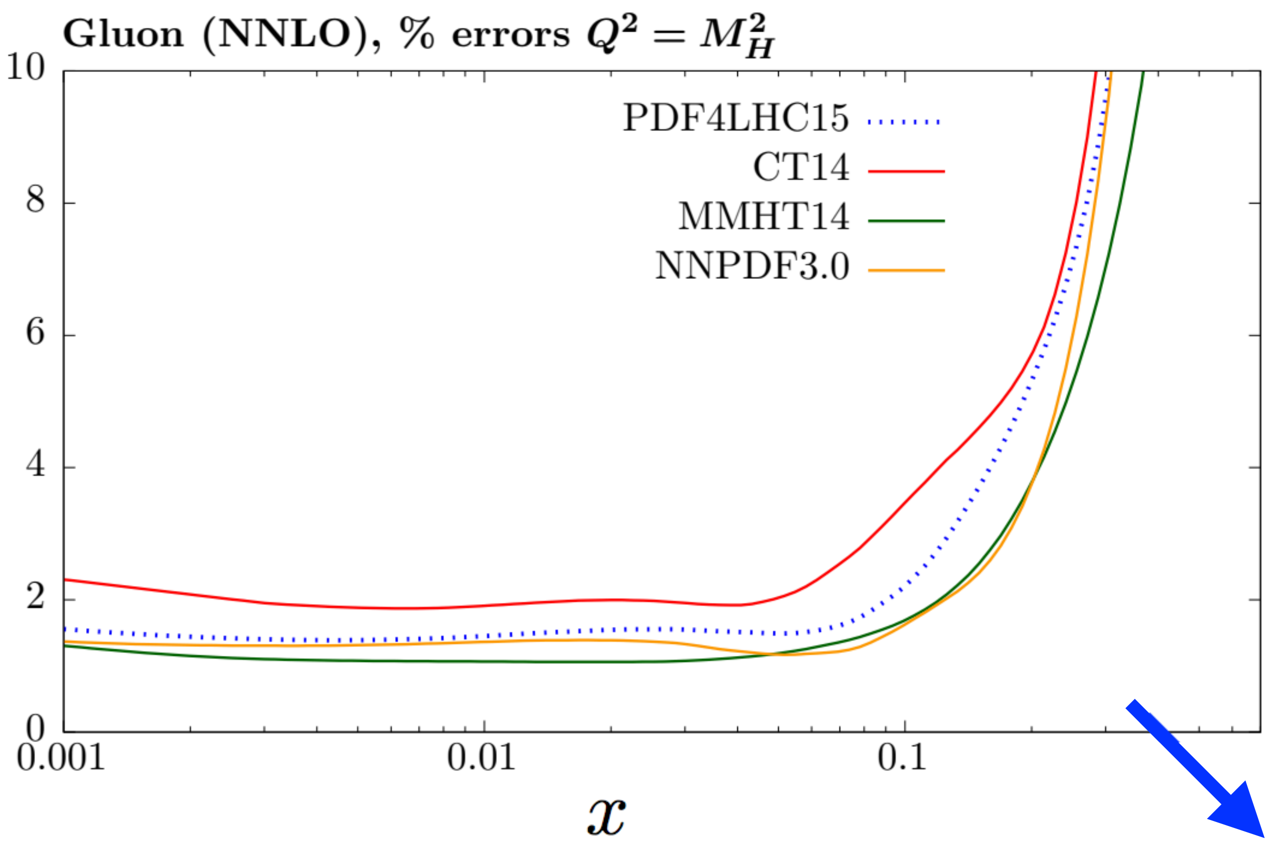


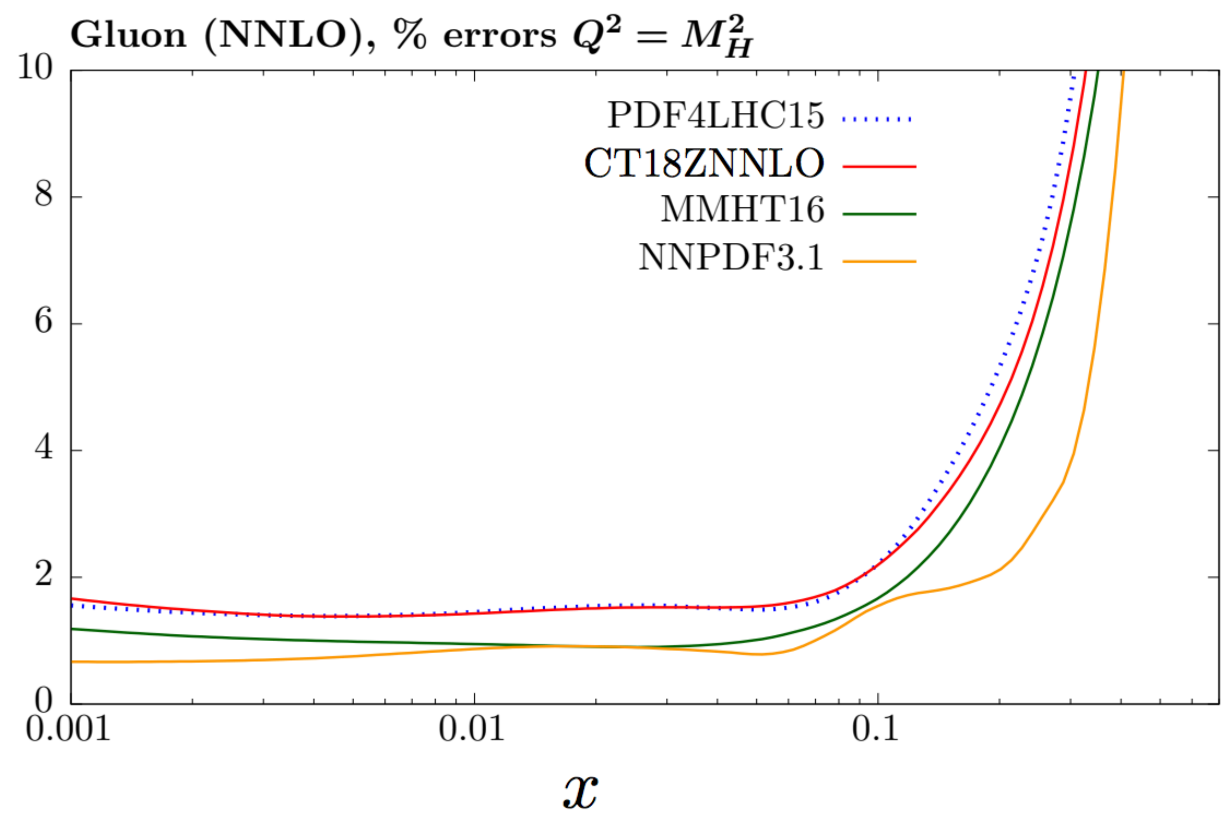
Z P_T



The NNPDF collaboration, EPJC 77 (2017)

FUTURE COMBINATIONS





Decrease in relative uncertainty…

L. Harland-Lang's talk

E. Nocera's talk

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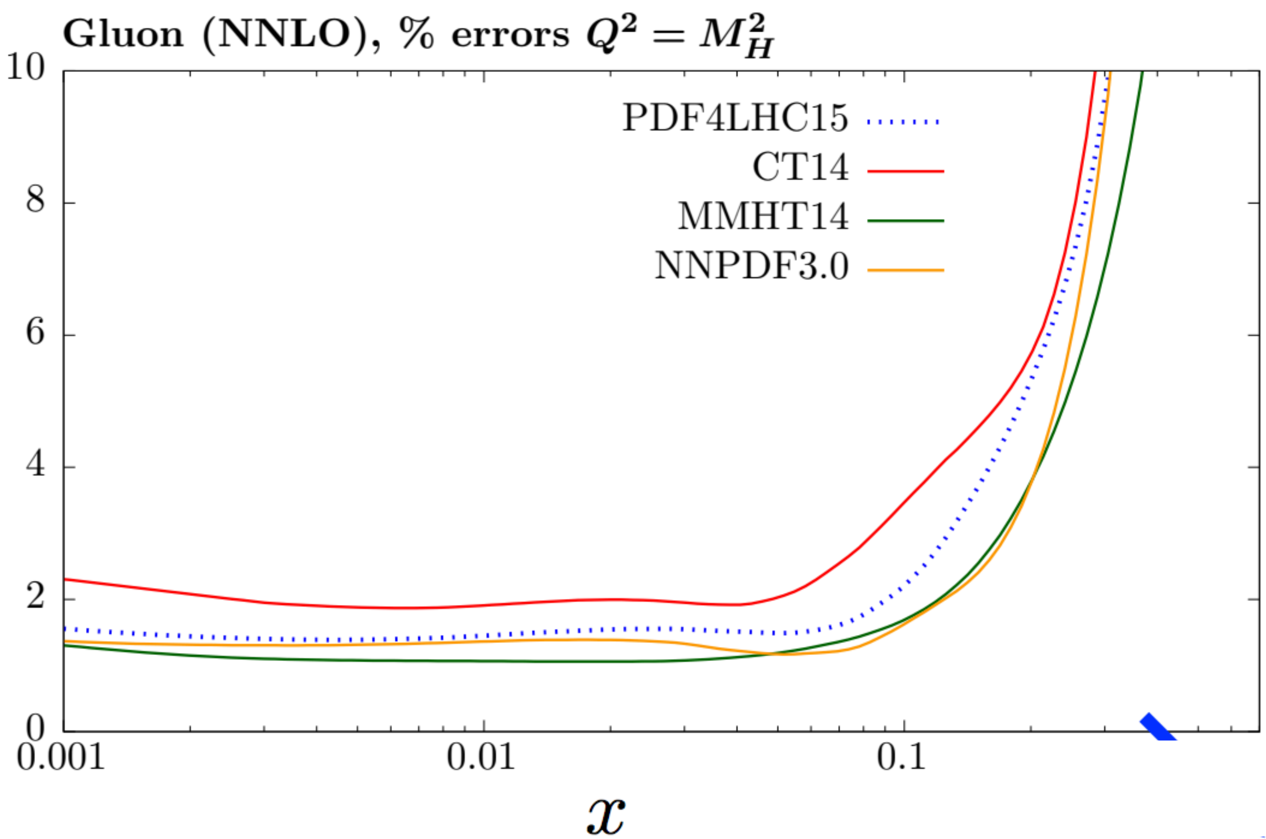
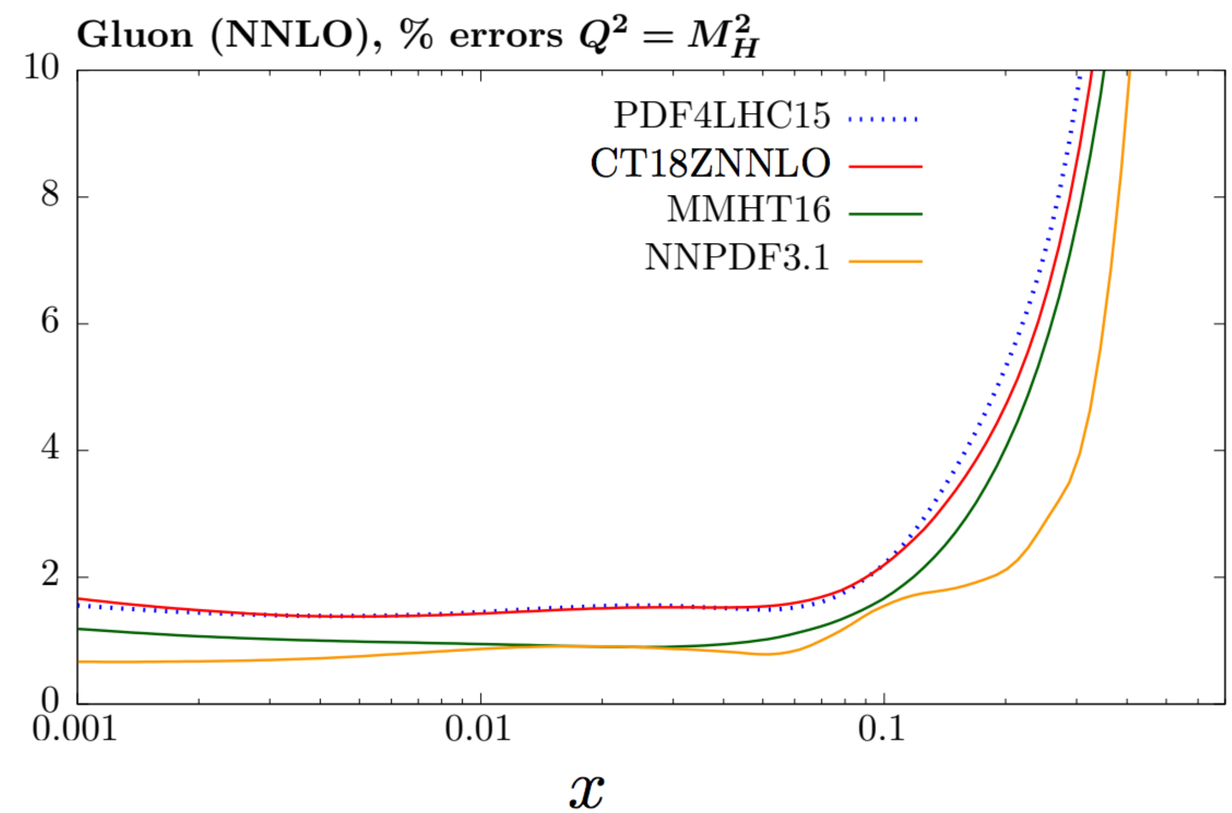
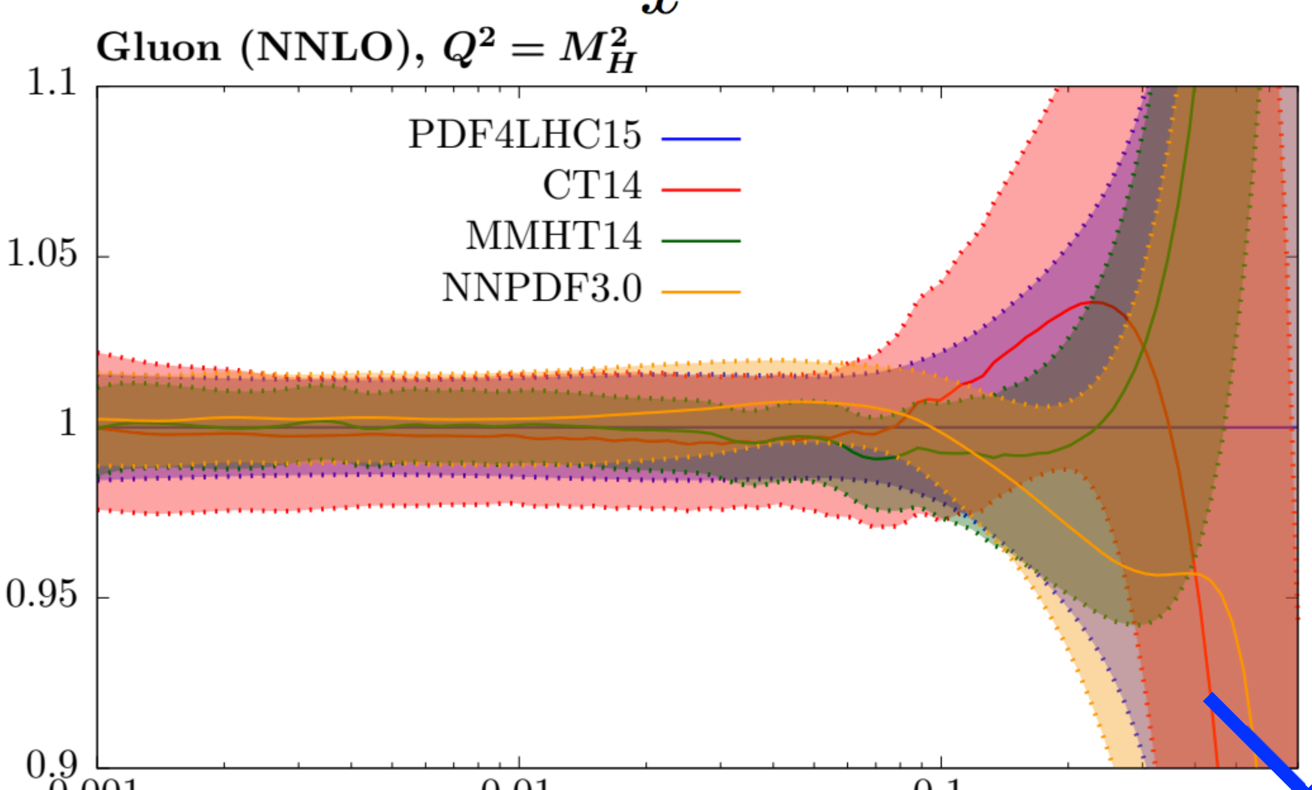
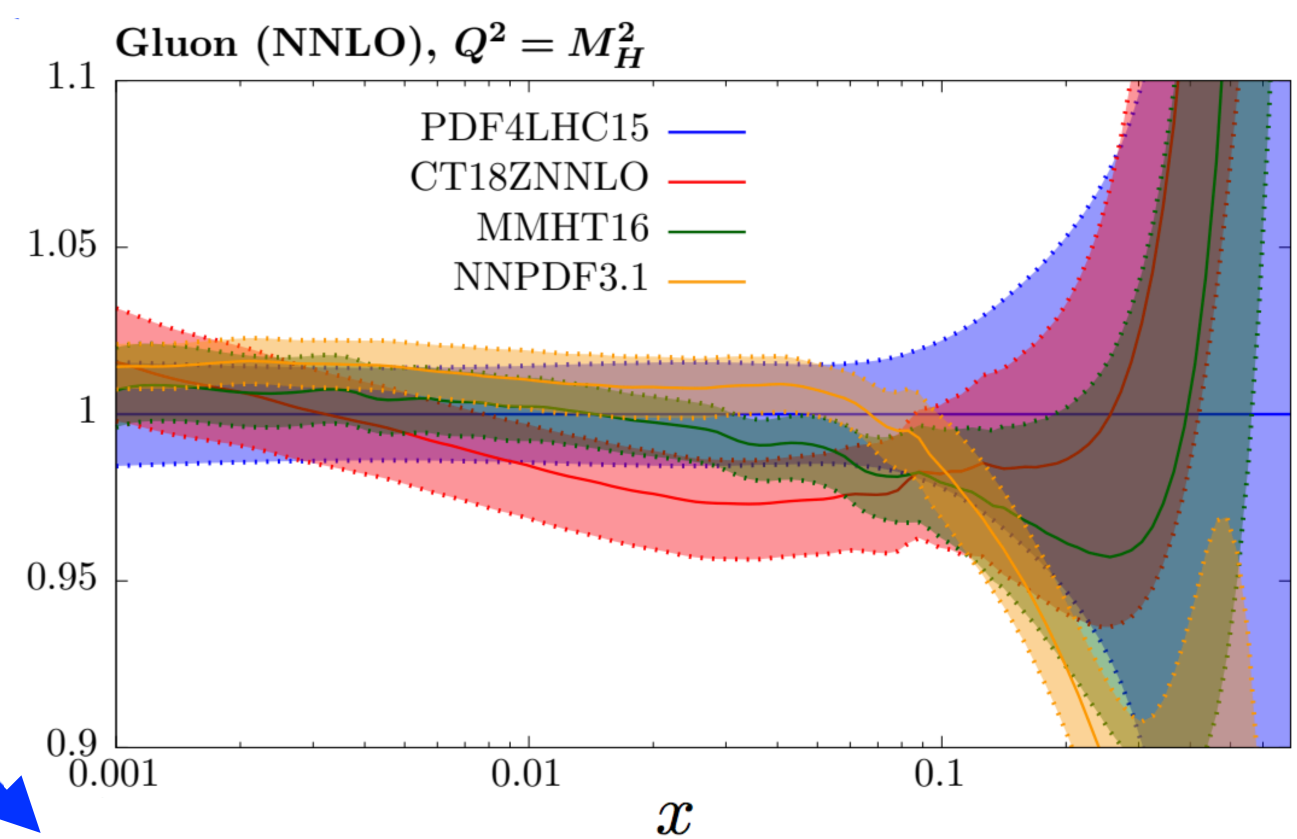








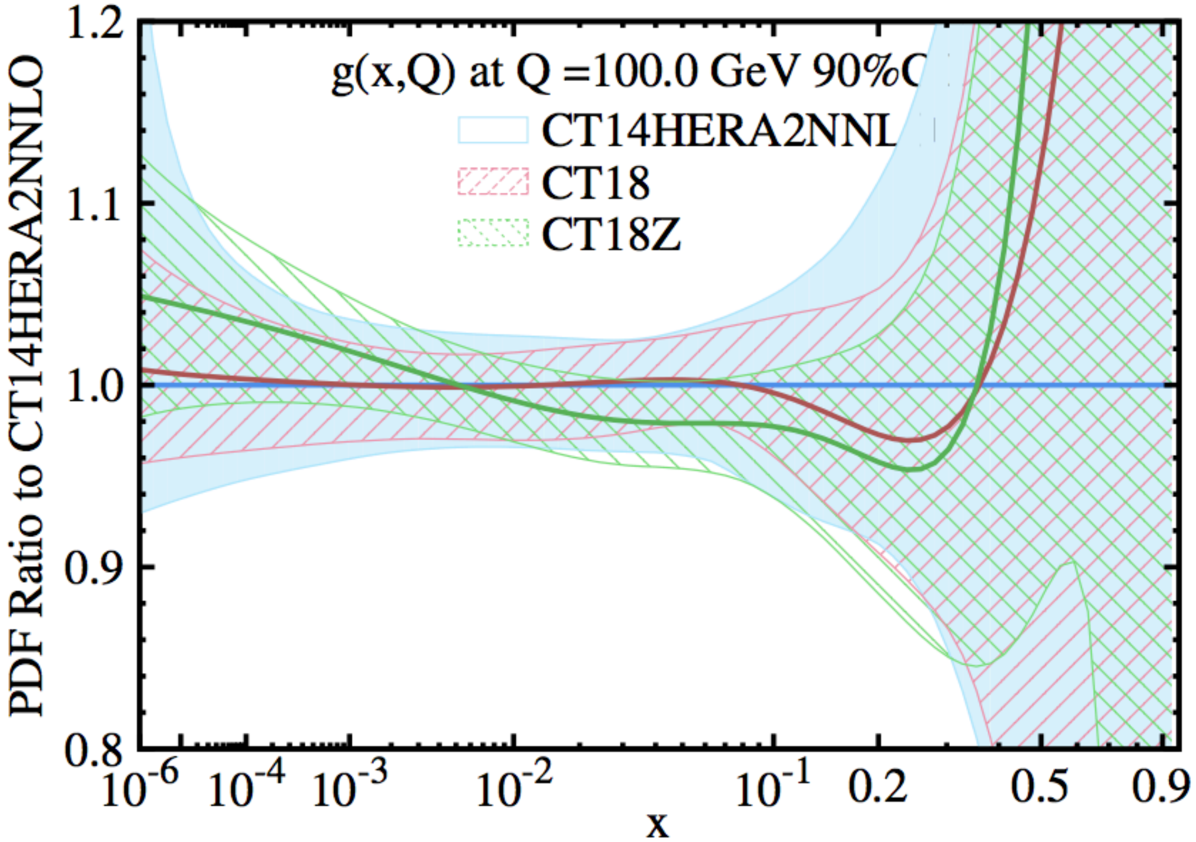
x

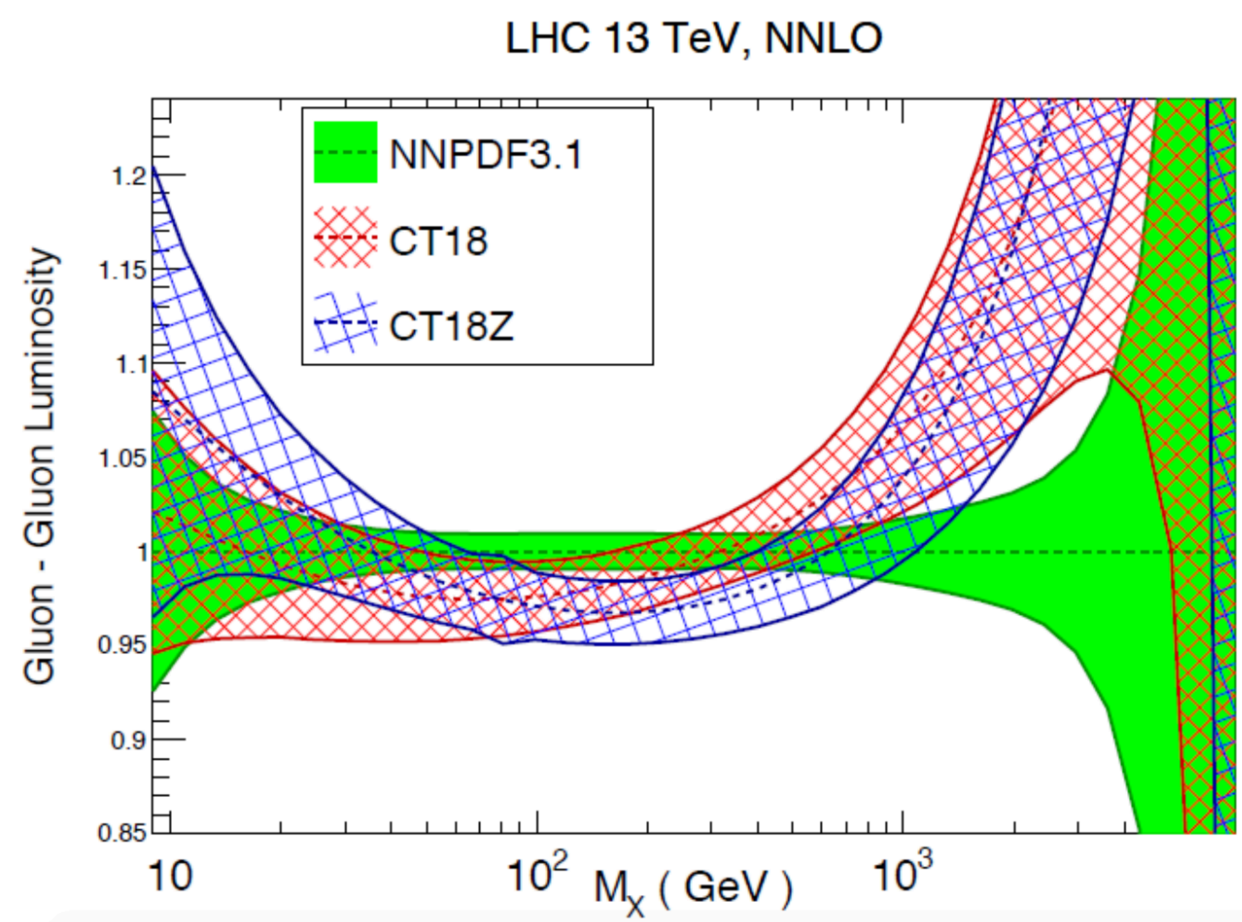
L. Harland-Lang’s talk

E. Nocera’s talk

… but spread between groups in some regions has increased

A COMPARISON AMONG GLOBAL FITS





CTEQ-TEA collaboration, arXiv: 1908.11394

P. Nadolsky's talk

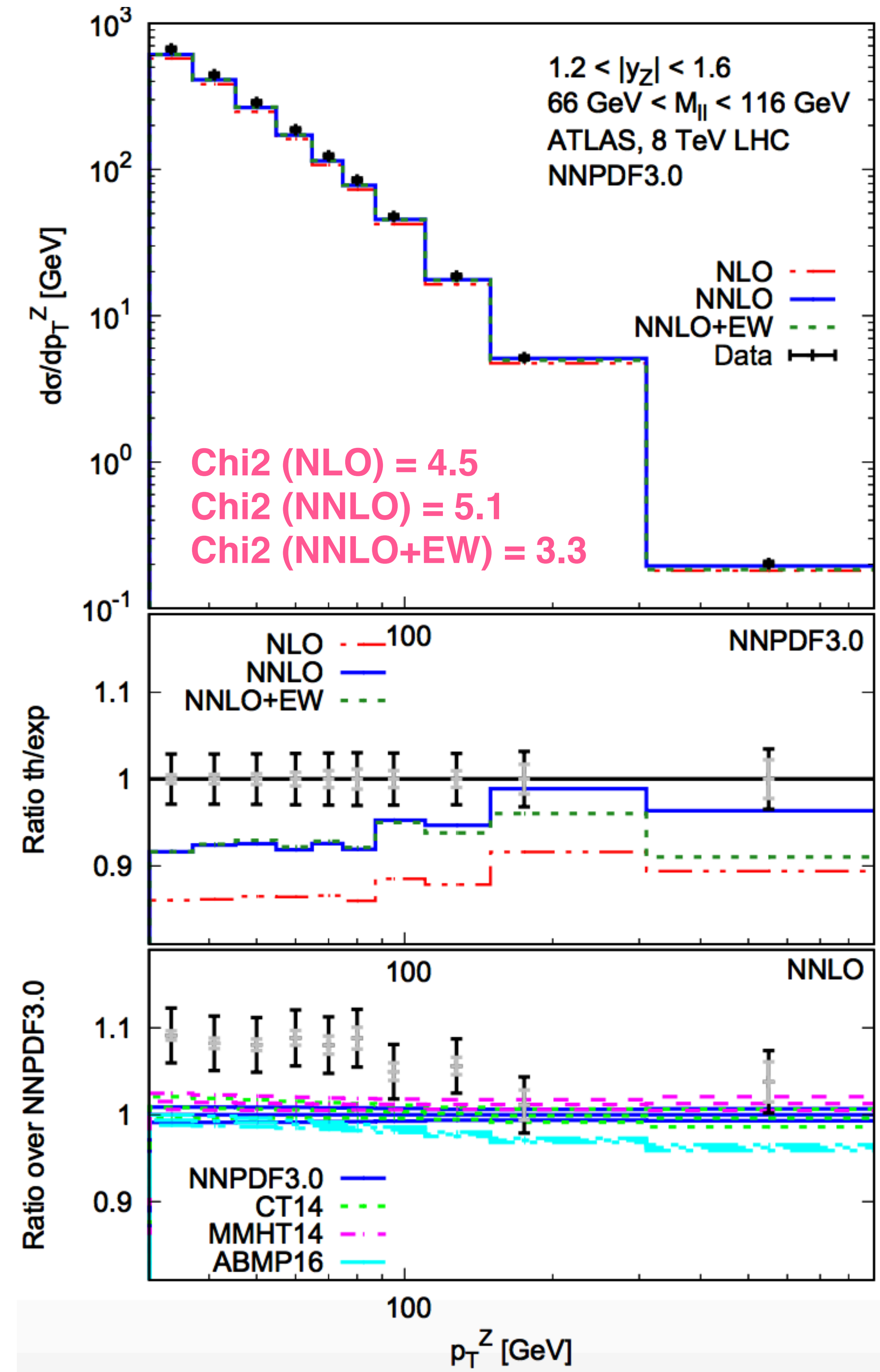
- **NNPDF3.1 (2017)** - gluon softer at large x and with ~30% uncertainty reduction
- **CT18 (2019)** - gluon harder at large x and milder uncertainty reduction

- CT18 releases separate CT18Z set that includes W and Z precision measurements at 7 TeV due to data tension
- Differences in datasets? Or theory: fitted versus perturbative 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, MMHT 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 recently put forward



Boughezal, Guffanti, Petriello, MU, JHEP 1707 (2017) 130

DEALING WITH HIGHLY CORRELATED DATA

TOP

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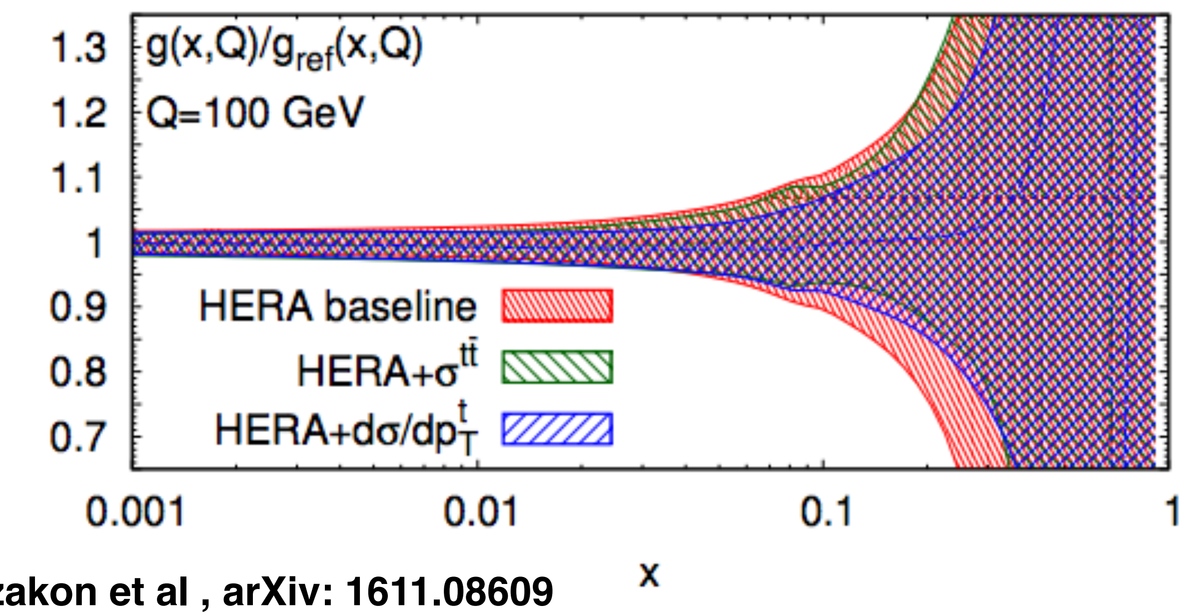
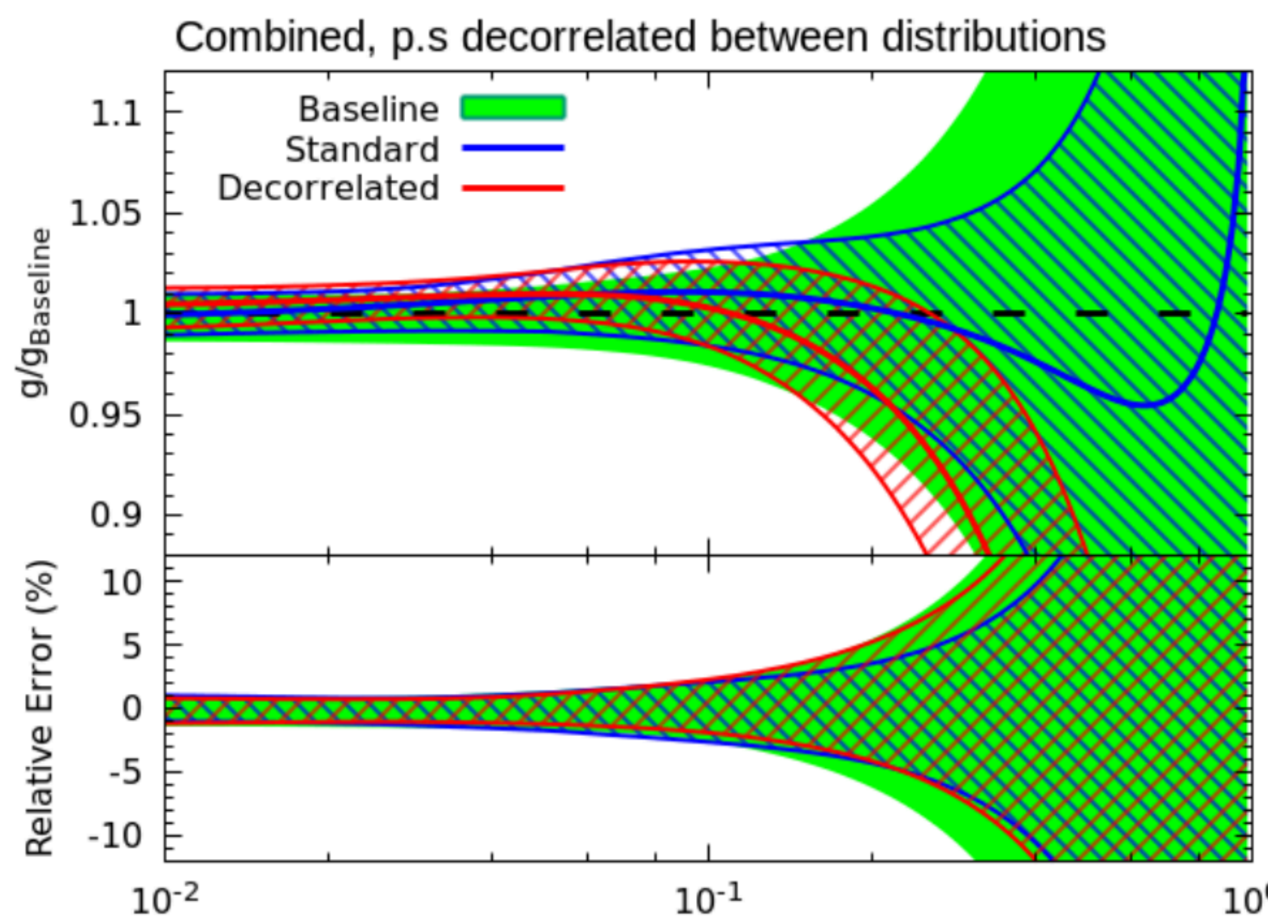


Czakon et al , arXiv: 1611.08609



Bailey, Harland-Lang, arXiv: 1909.10541

DEALING WITH HIGHLY CORRELATED DATA

JETS

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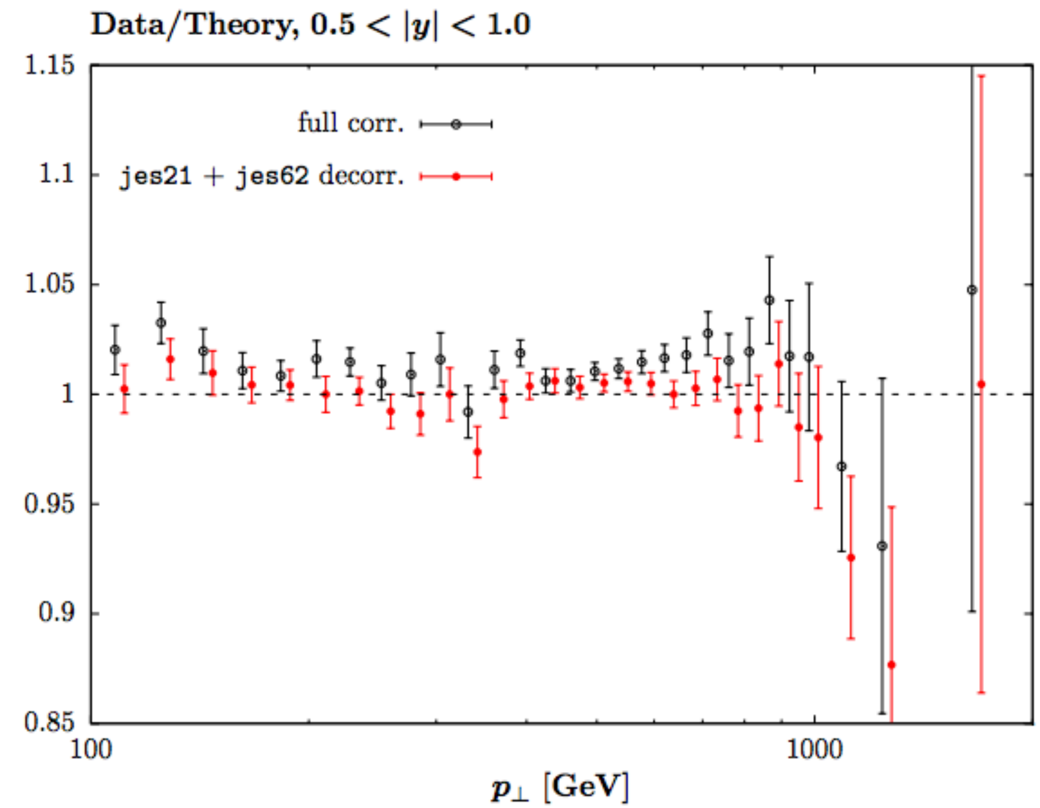
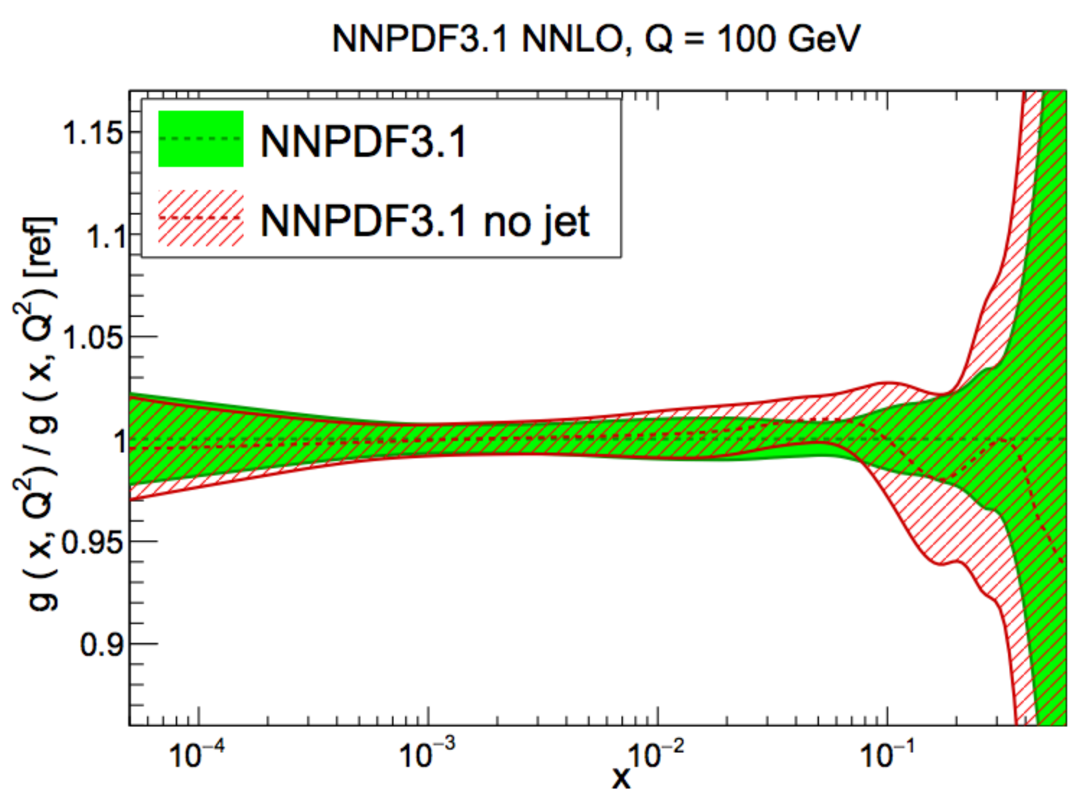


Harland-Lang, Martin, Thorne arXiv:1909.10541



The NNPDF collaboration, EPJC 77 (2017)

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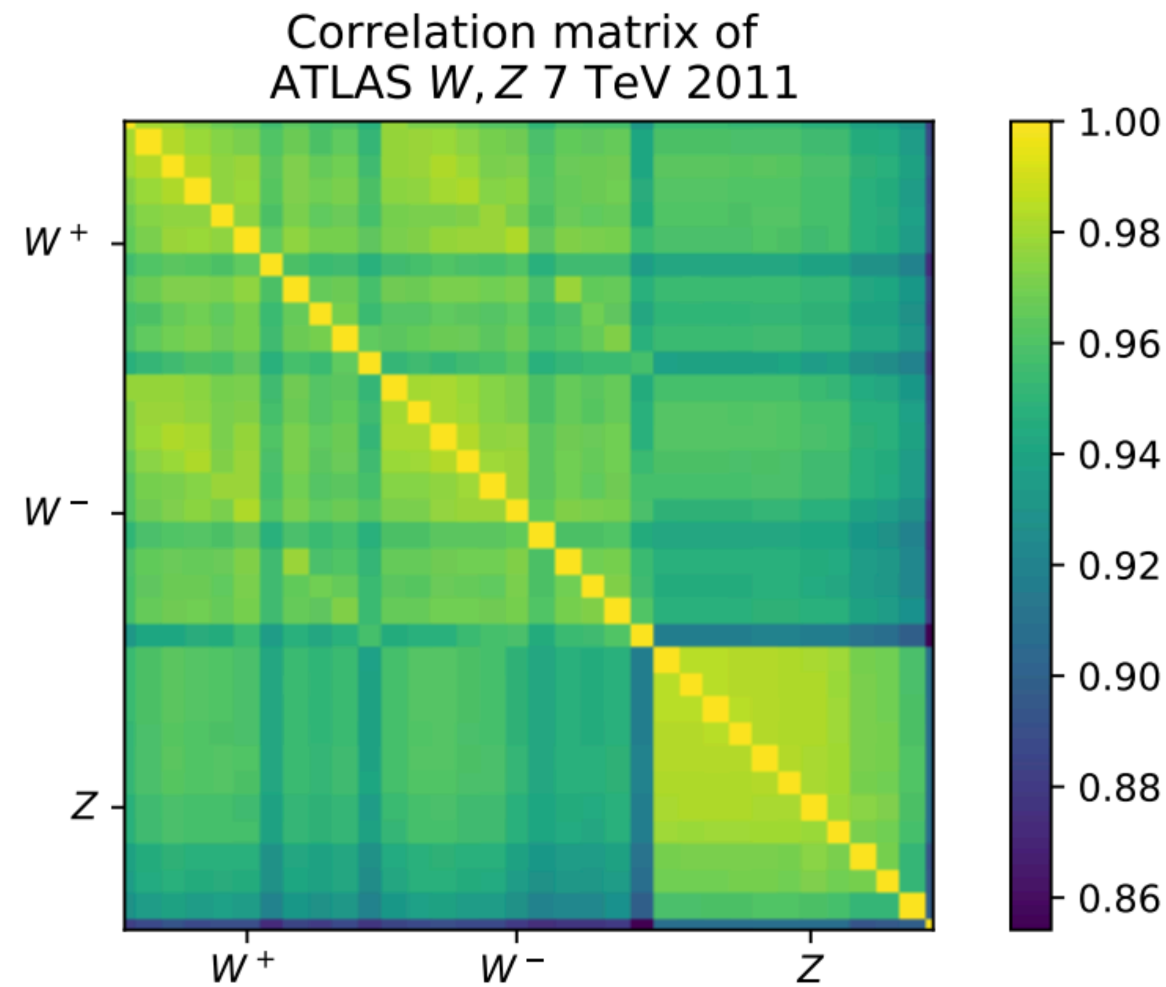
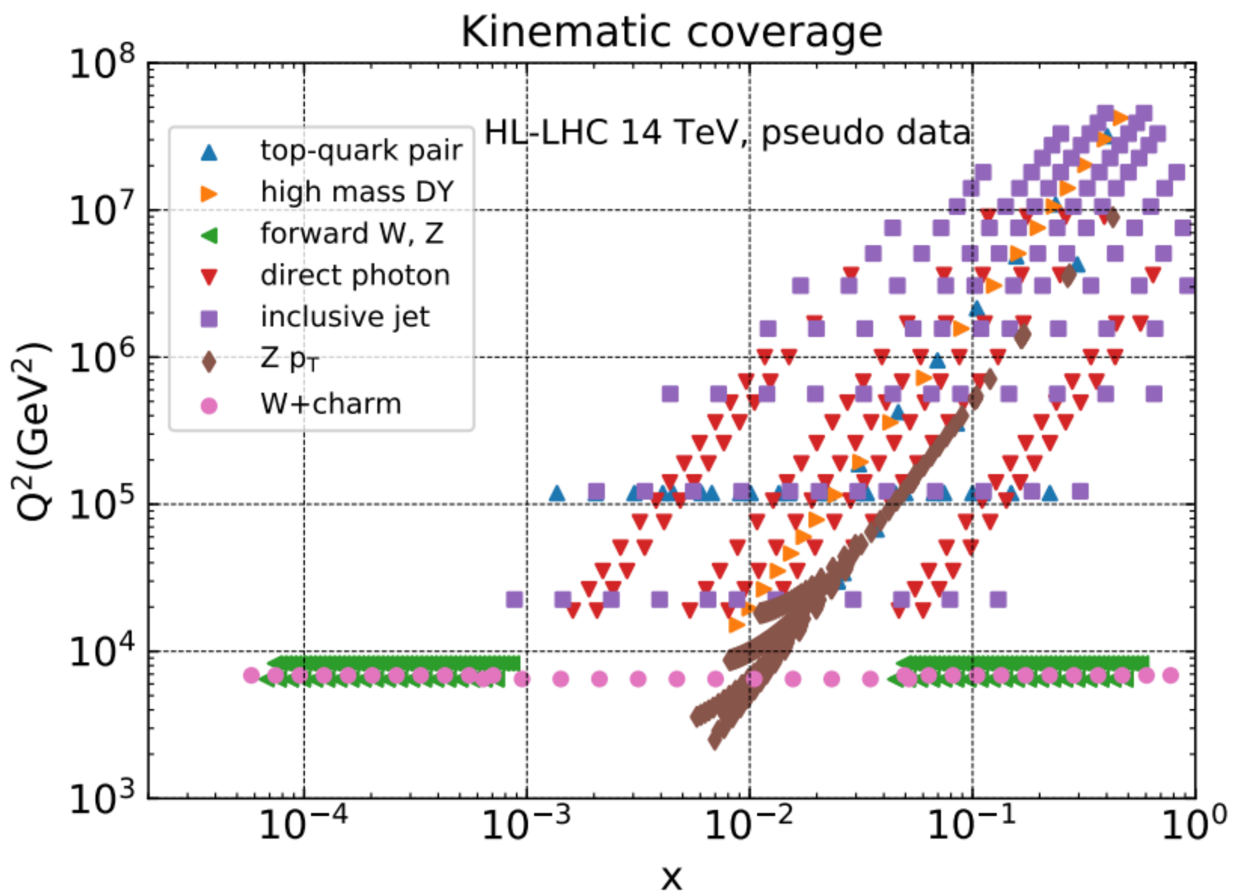


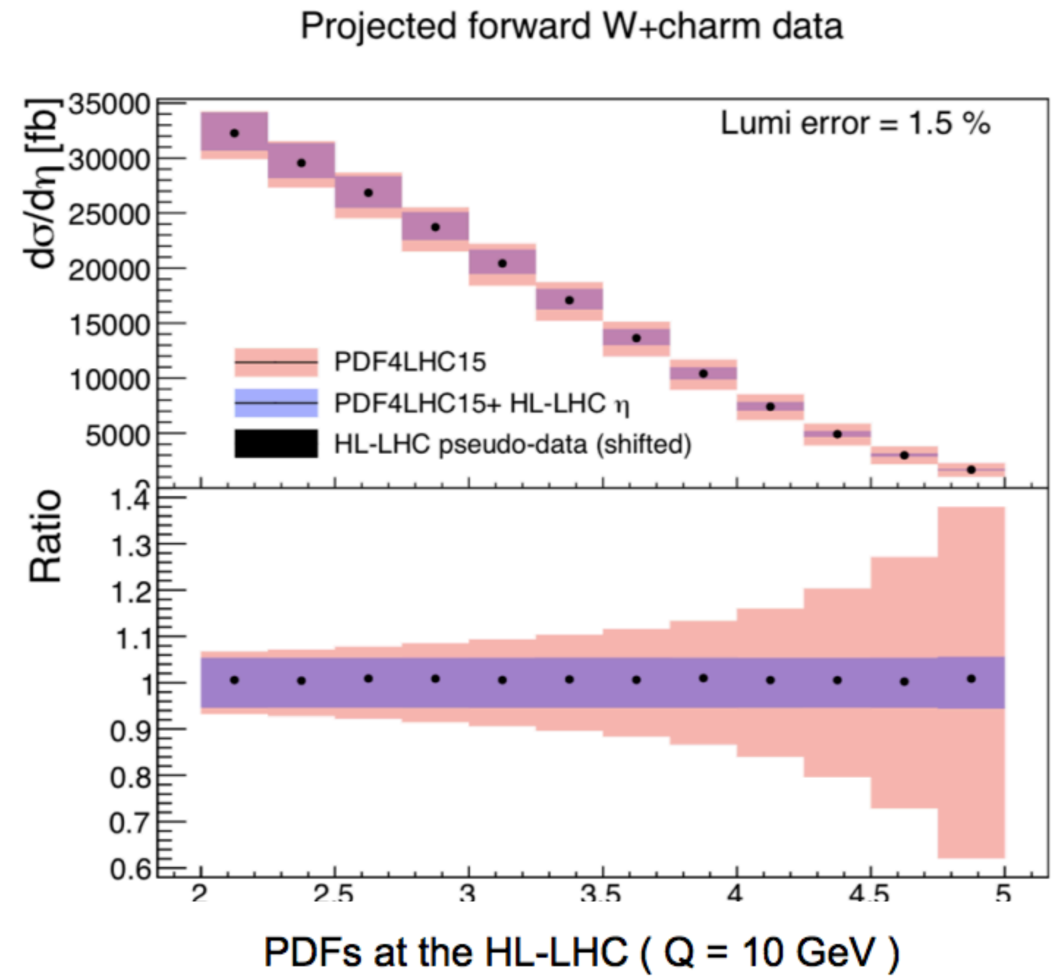
Correlation matrix for precise ATLAS WZ production dataset

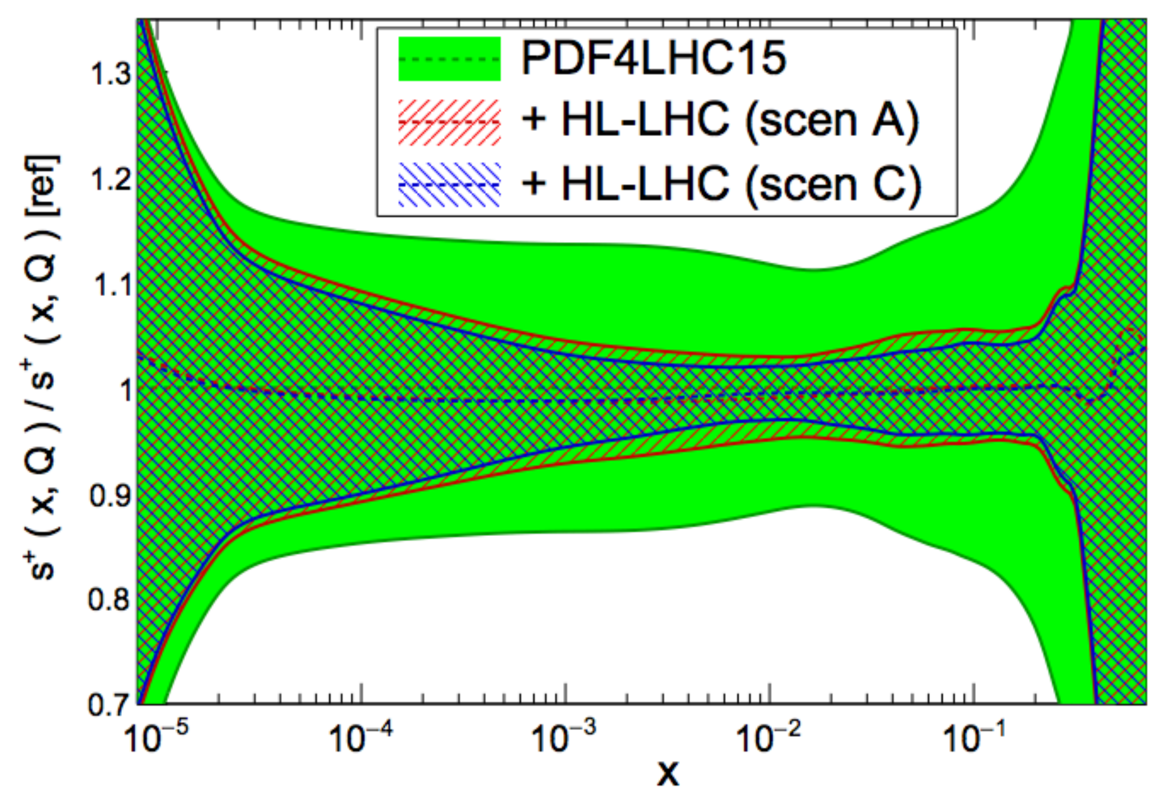
δ	χ^2/N (NNPDF3.1)	Max change in diagonal uncertainties
∞	2.2	0
5	1.6	2%
4	1.2	4%
3	0.77	8.5%

Z. Kassabov's talk

PERSPECTIVES AT HL-LHC





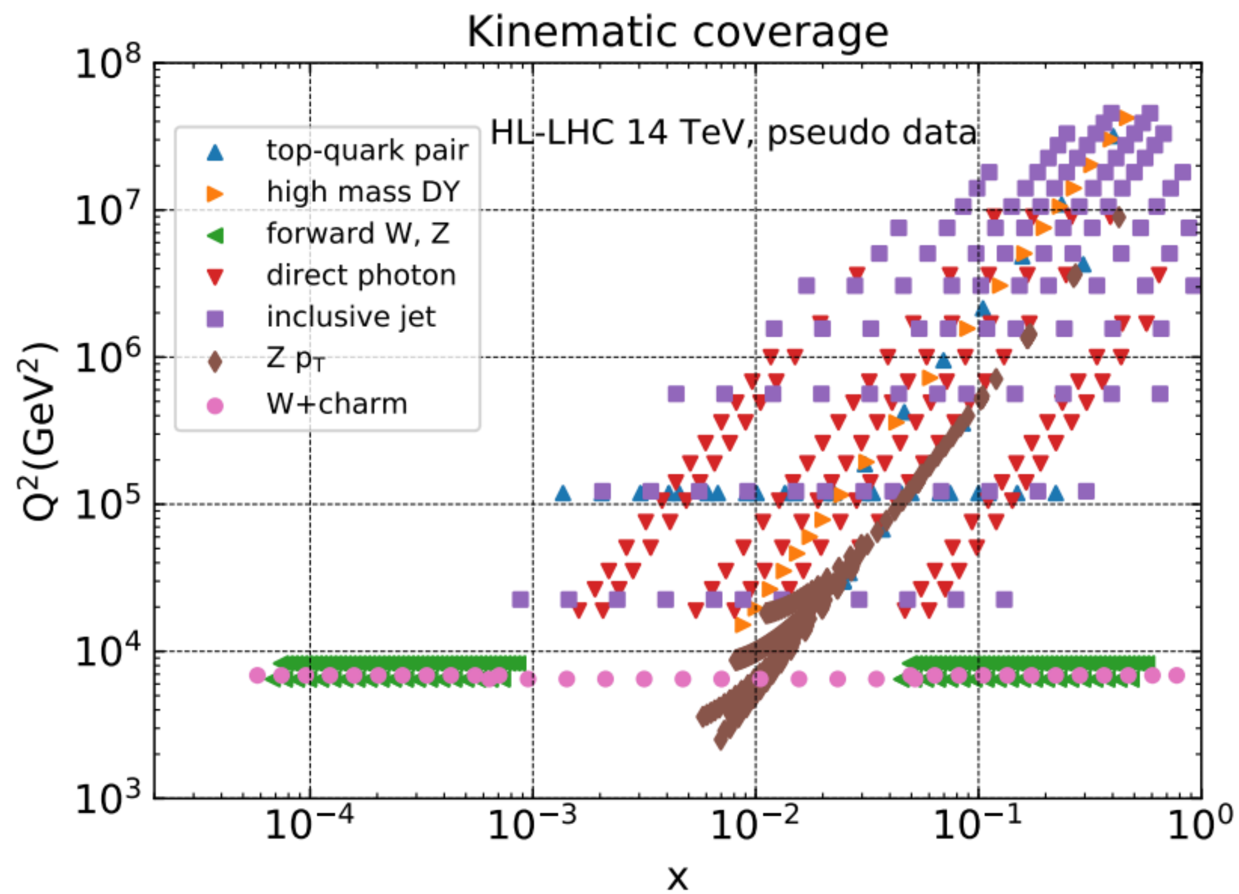


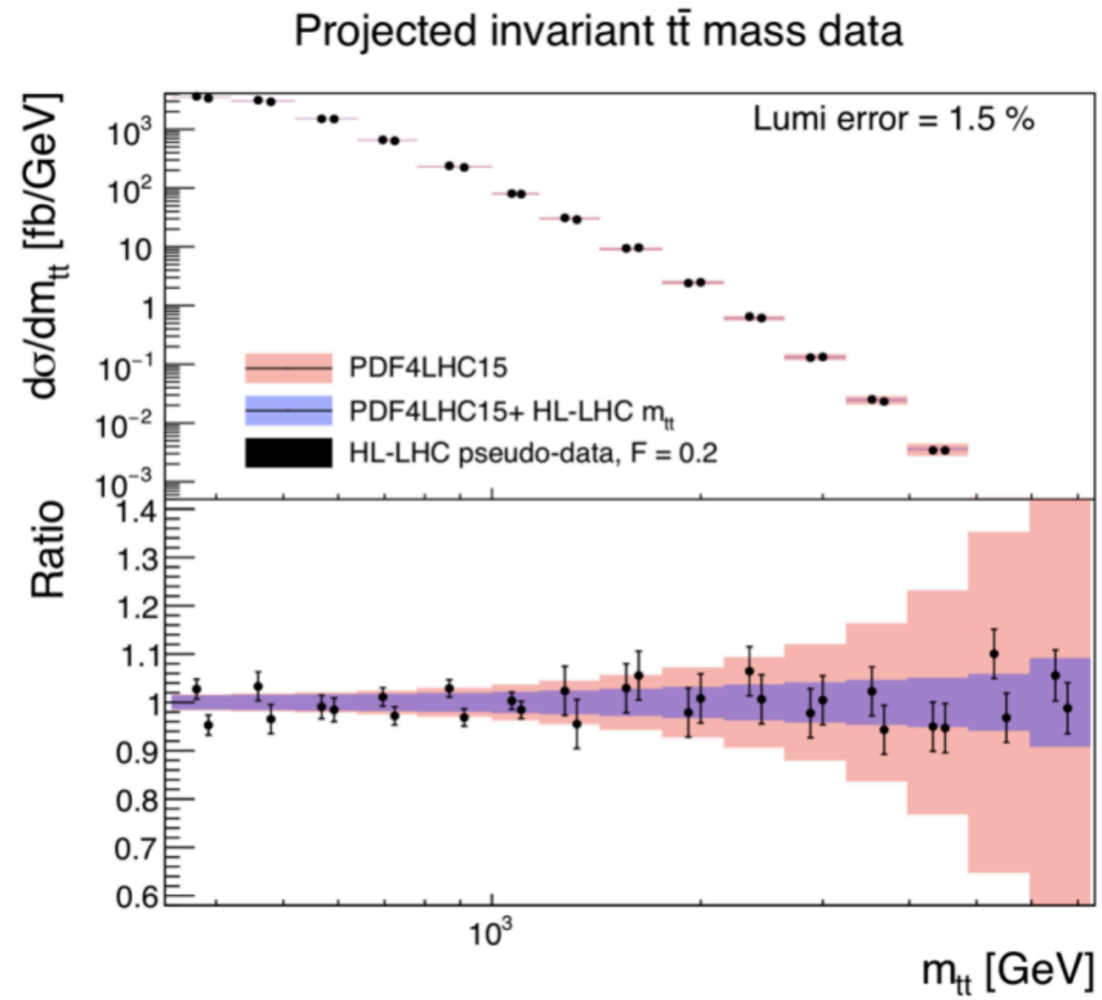
- W, Z handle on quarks
- **W+c on strangeness**
- Z pT on quarks and gluons
- Top and Jets on gluons

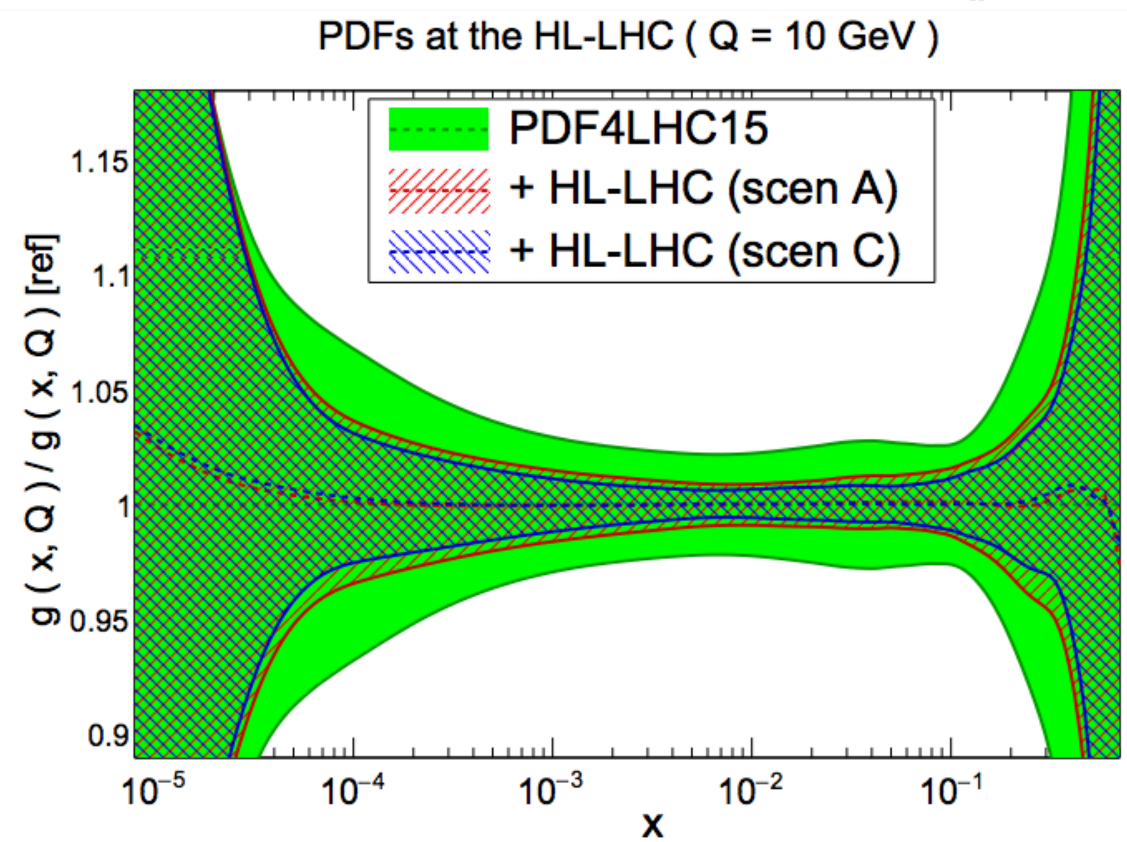
S. Bailey's talk

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

PERSPECTIVES AT HL-LHC







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

S. Bailey's talk

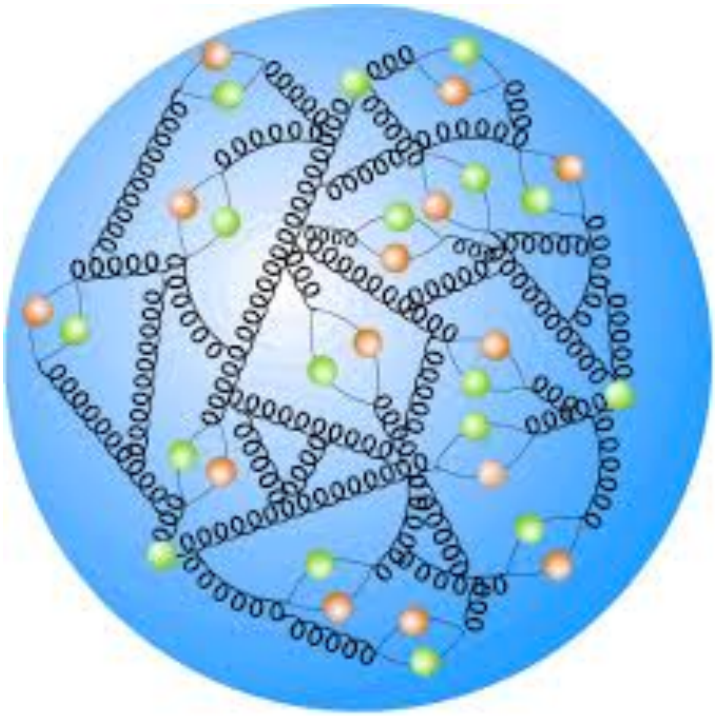
M. Cepeda et al. [HL/HE WG2 group], arXiv:1902.00134

- Challenges and updates in PDF determinations

  ➡ Part I : Experimental data

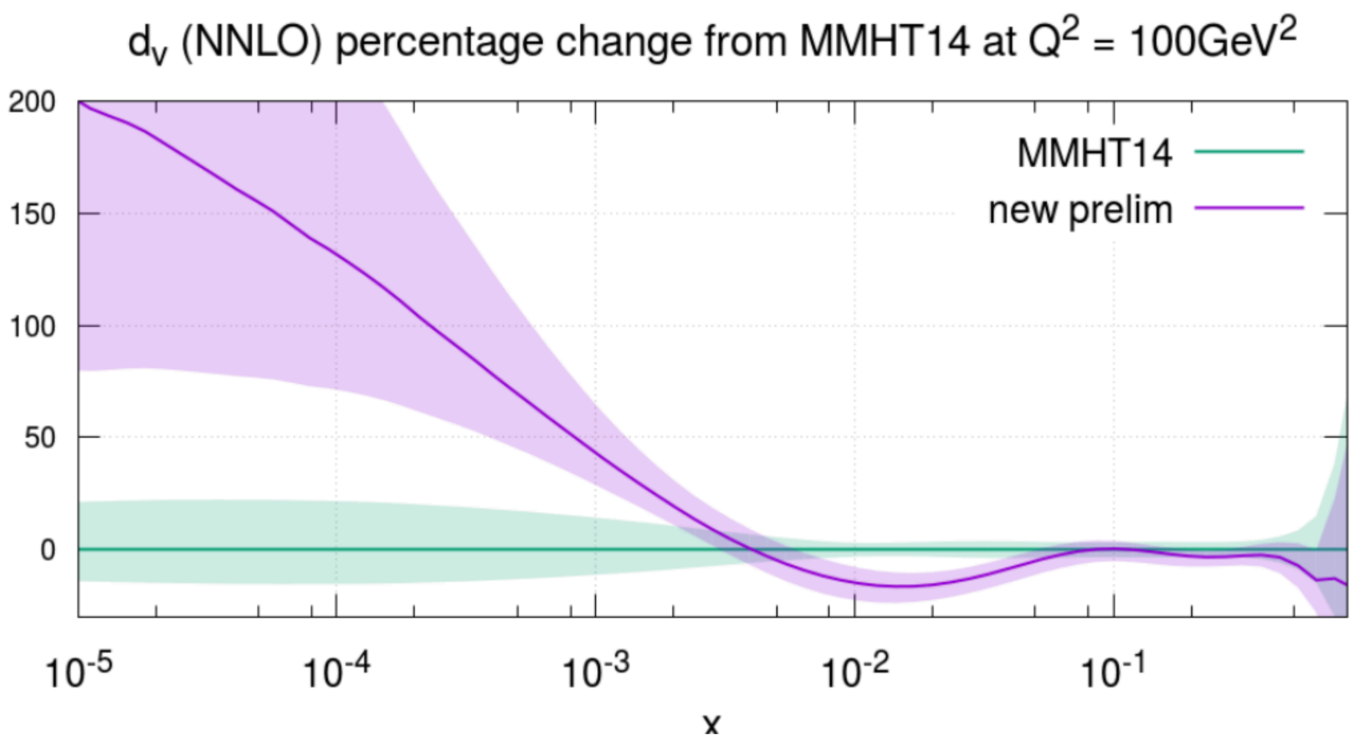
  ➡ **Intermission: Methodological issues**

  ➡ Part II: Theoretical aspects



- Conclusions and outlook

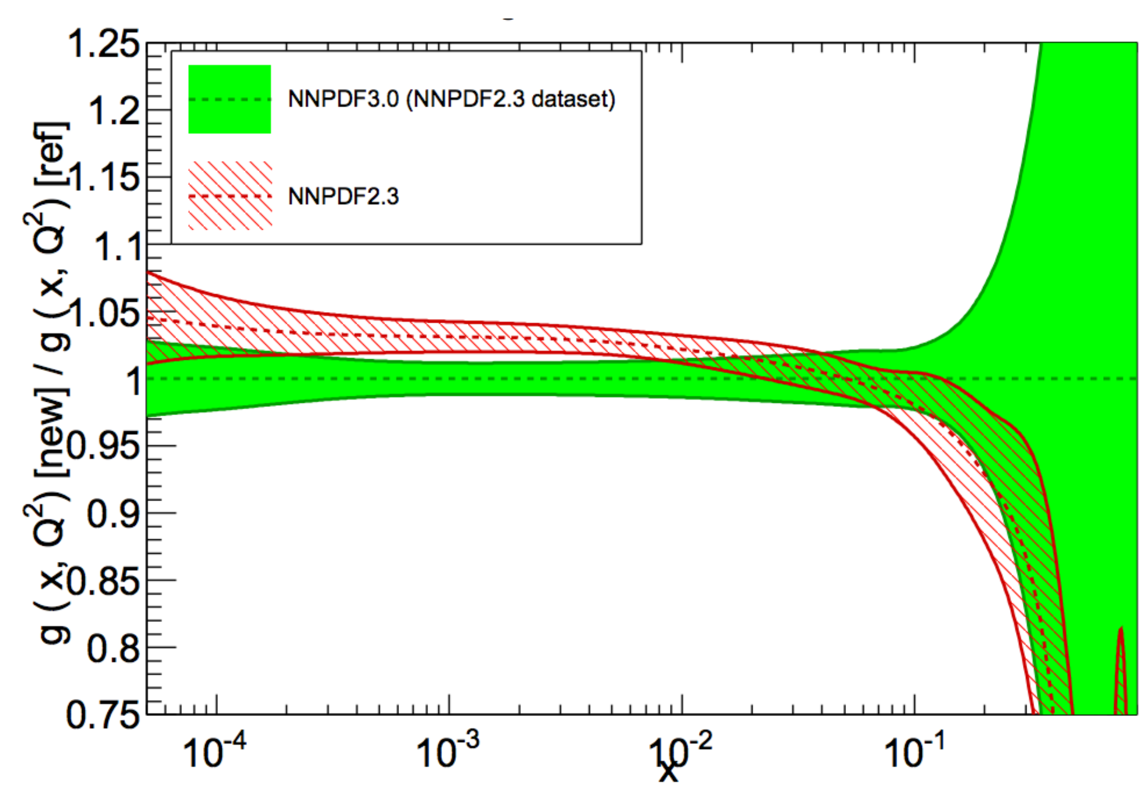
PARAMETRISATION & METHODOLOGY



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

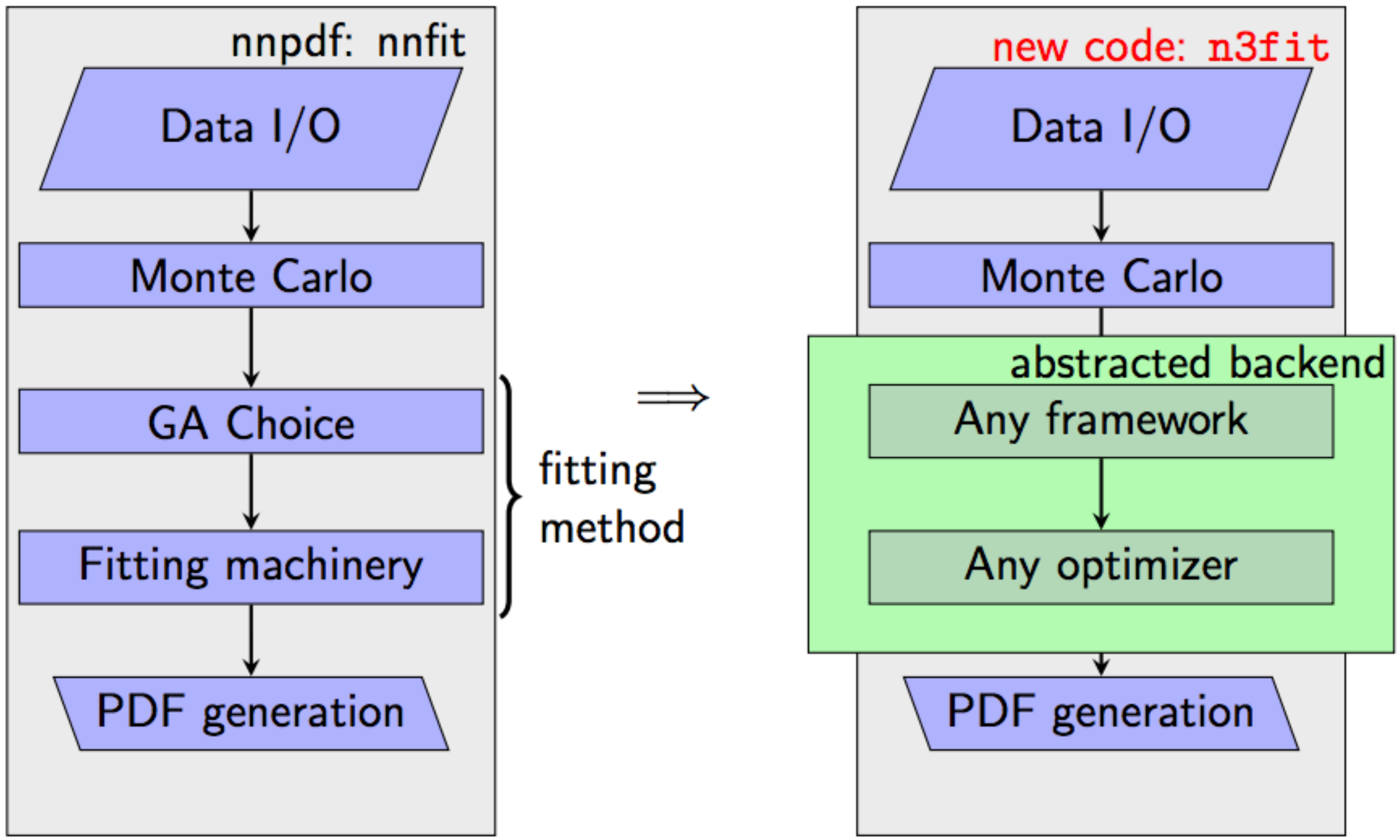
R. Thorne, PDF4LHC September 2019

- 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, JHEP 1504 (2015) 040

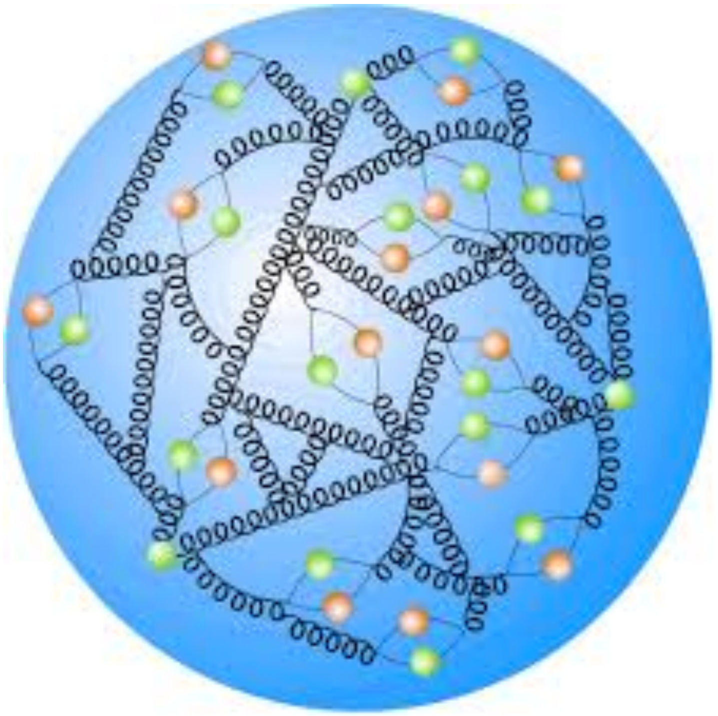
NEW: FITTING THE METHODOLOGY ITSELF



S. Carrazza, J. Cruz-Martinez, Eur.Phys.J. C79 (2019) no.8, 676

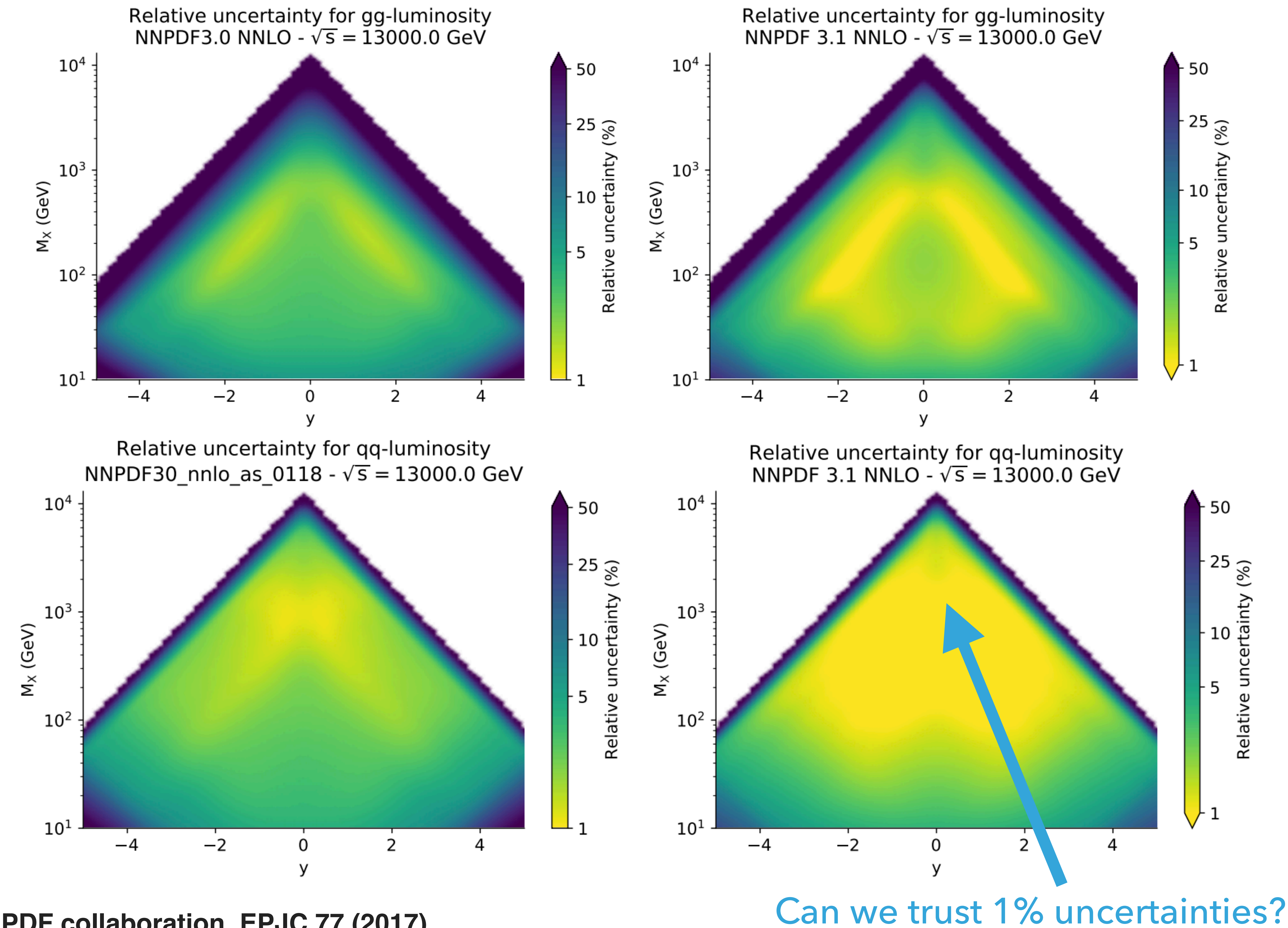
Fitting the whole methodology => Implement a hyperparameter scan: let the computer decide automatically the best methodology and PDF parametrisation by scanning over thousands of hyperparameter combinations and define a reward function to grade the methodology

- Challenges and updates in PDF determinations
  - ➡ Part I : Experimental data
  - ➡ Intermission: Methodological issues
  - ➡ **Part II: Theoretical aspects**



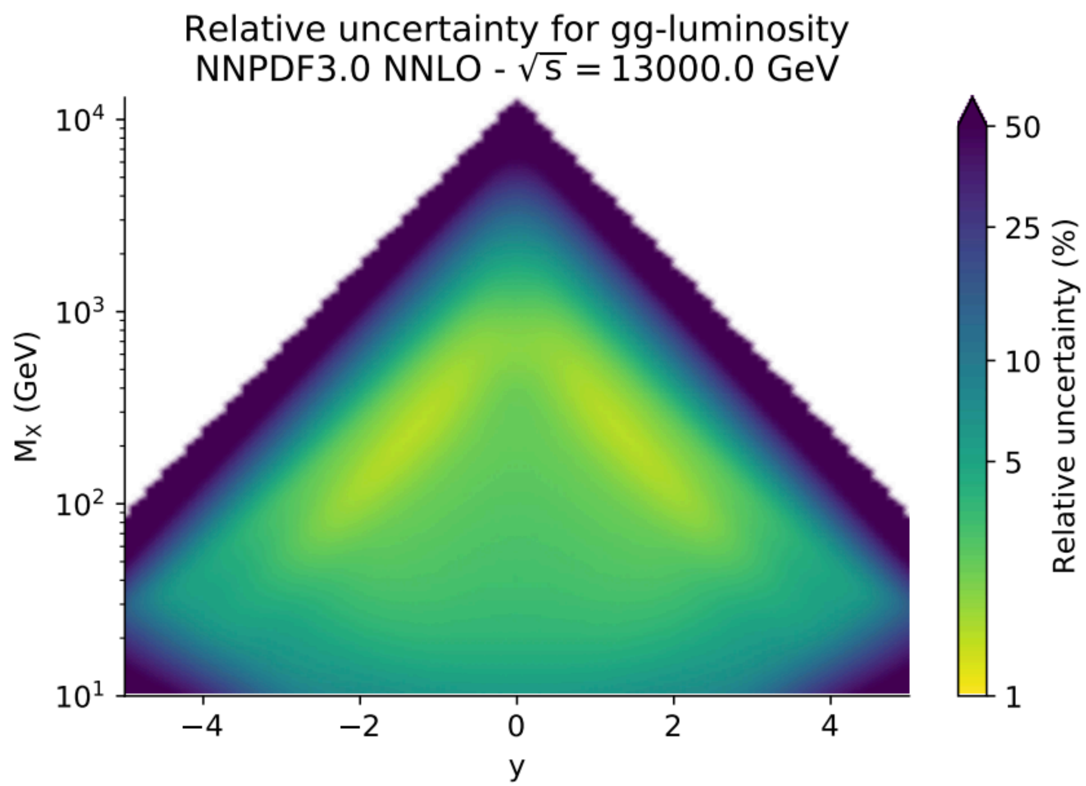
- Conclusions and outlook

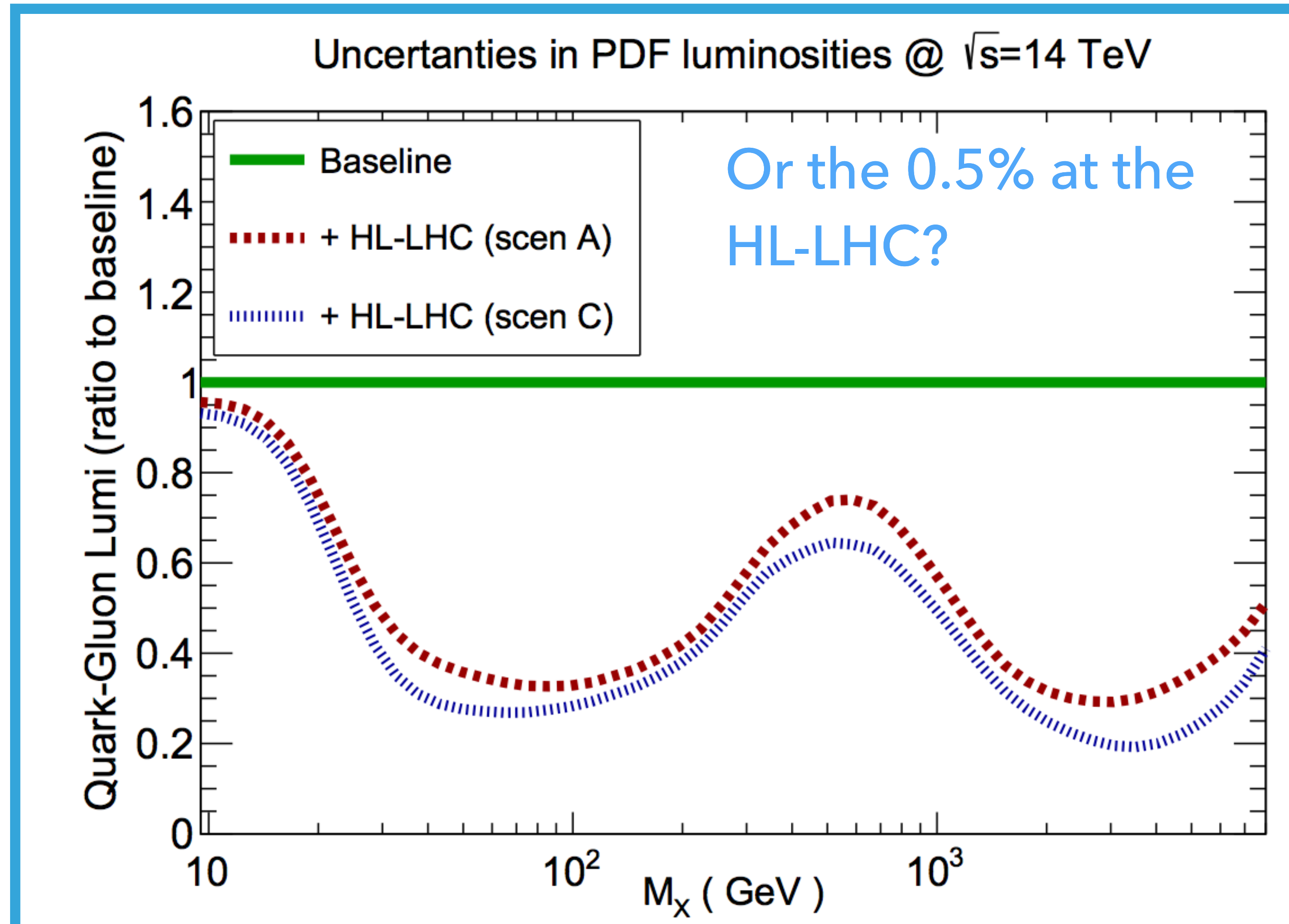
THE PRECISION VS ACCURACY CHALLENGE



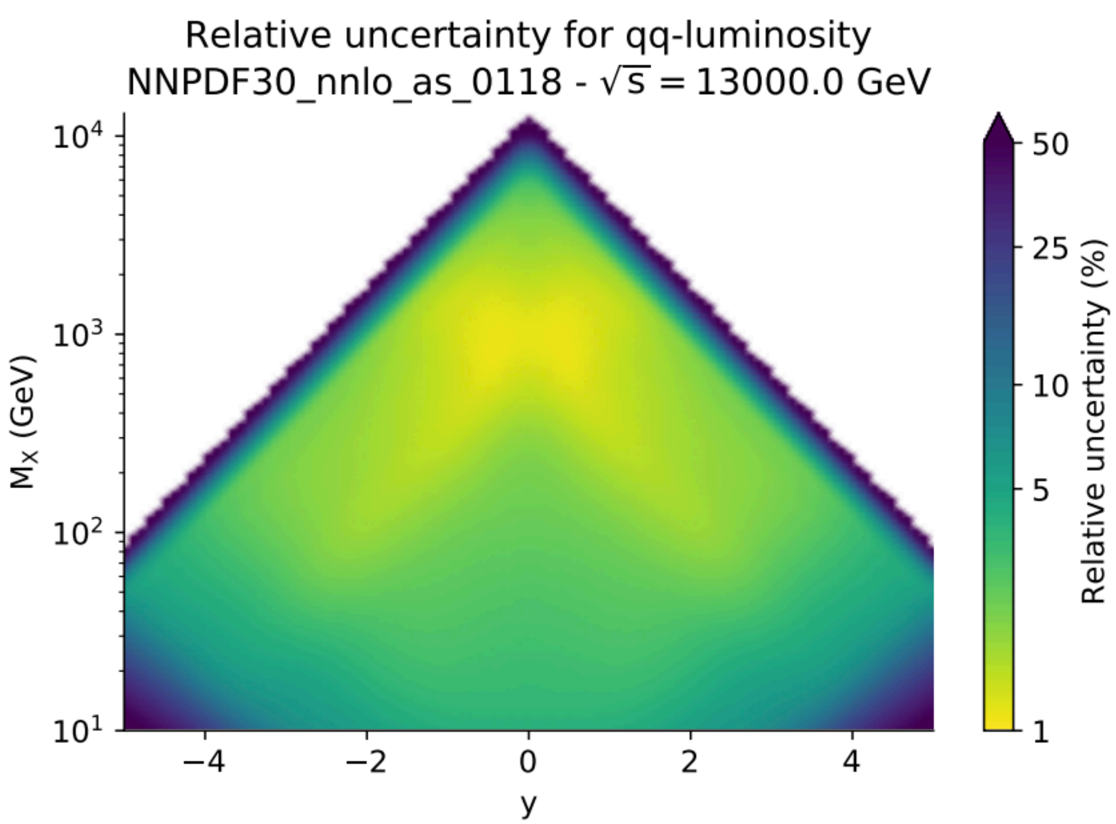
The NNPDF collaboration, EPJC 77 (2017)

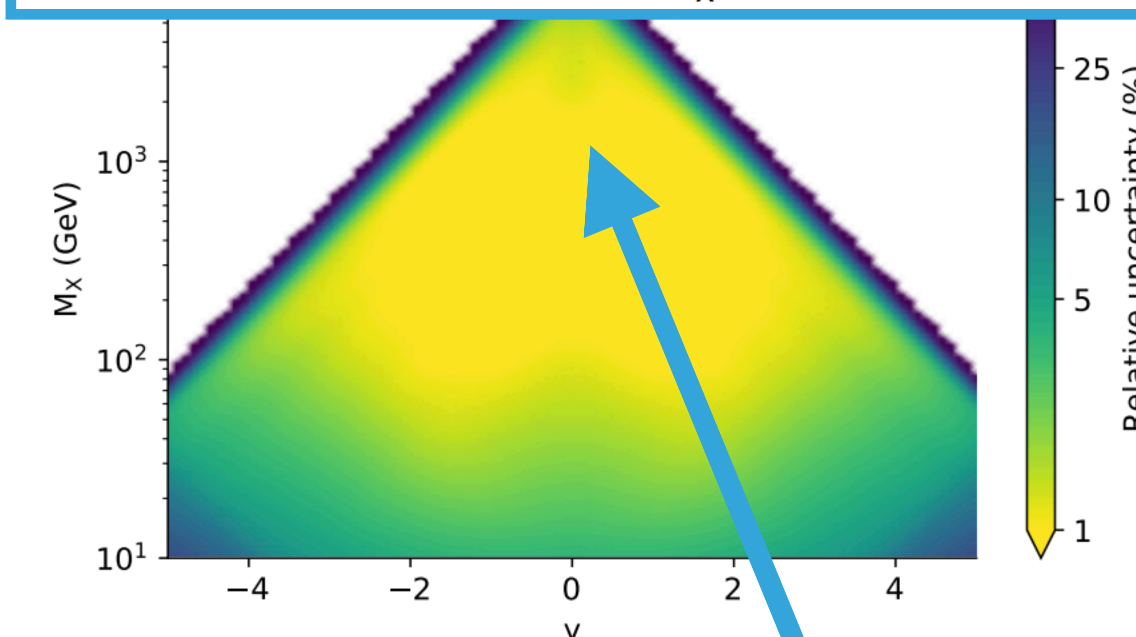
THE PRECISION VS ACCURACY CHALLENGE





Or the 0.5% at the HL-LHC?





Can we trust 0.4% uncertainties?

The NNPDF collaboration, EPJC 77 (2017)

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)]

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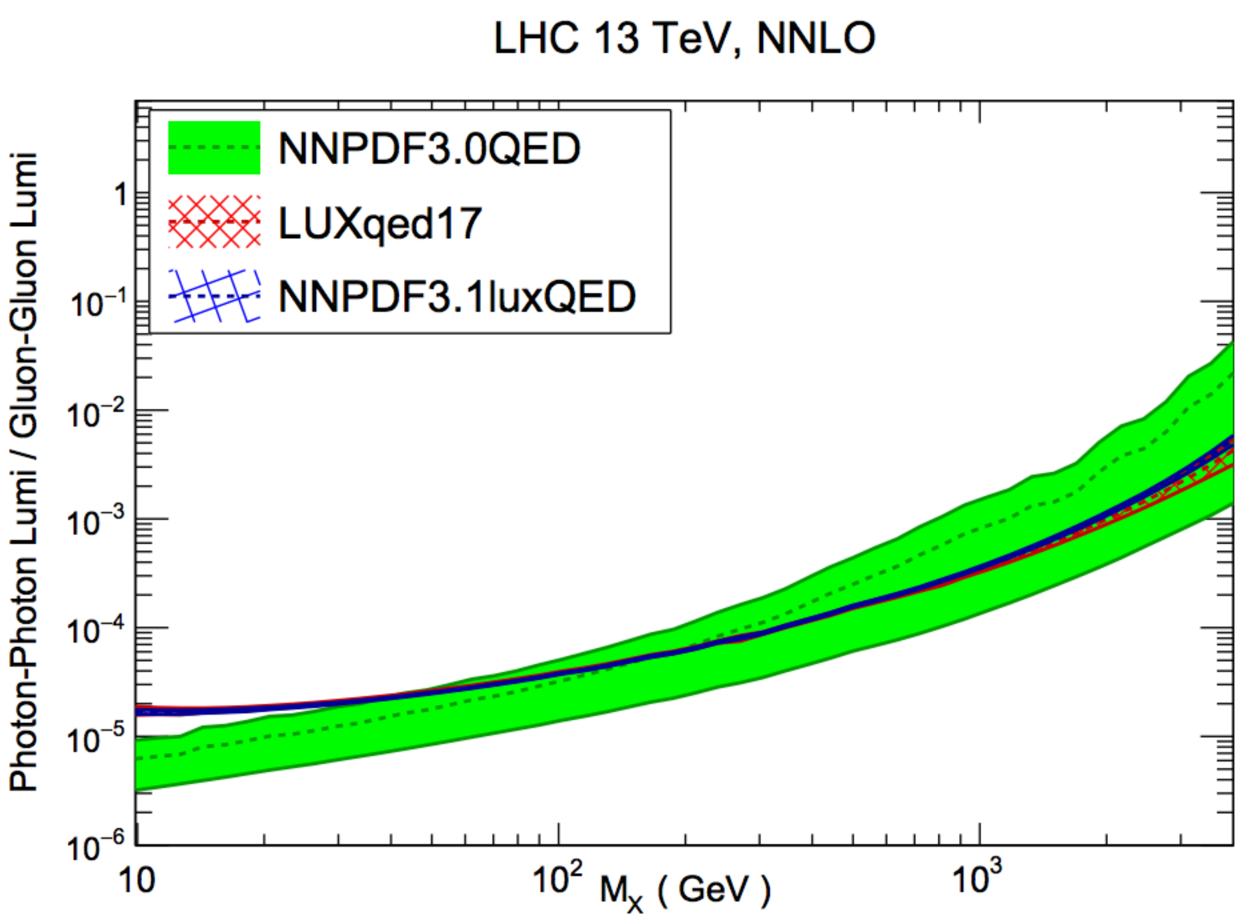
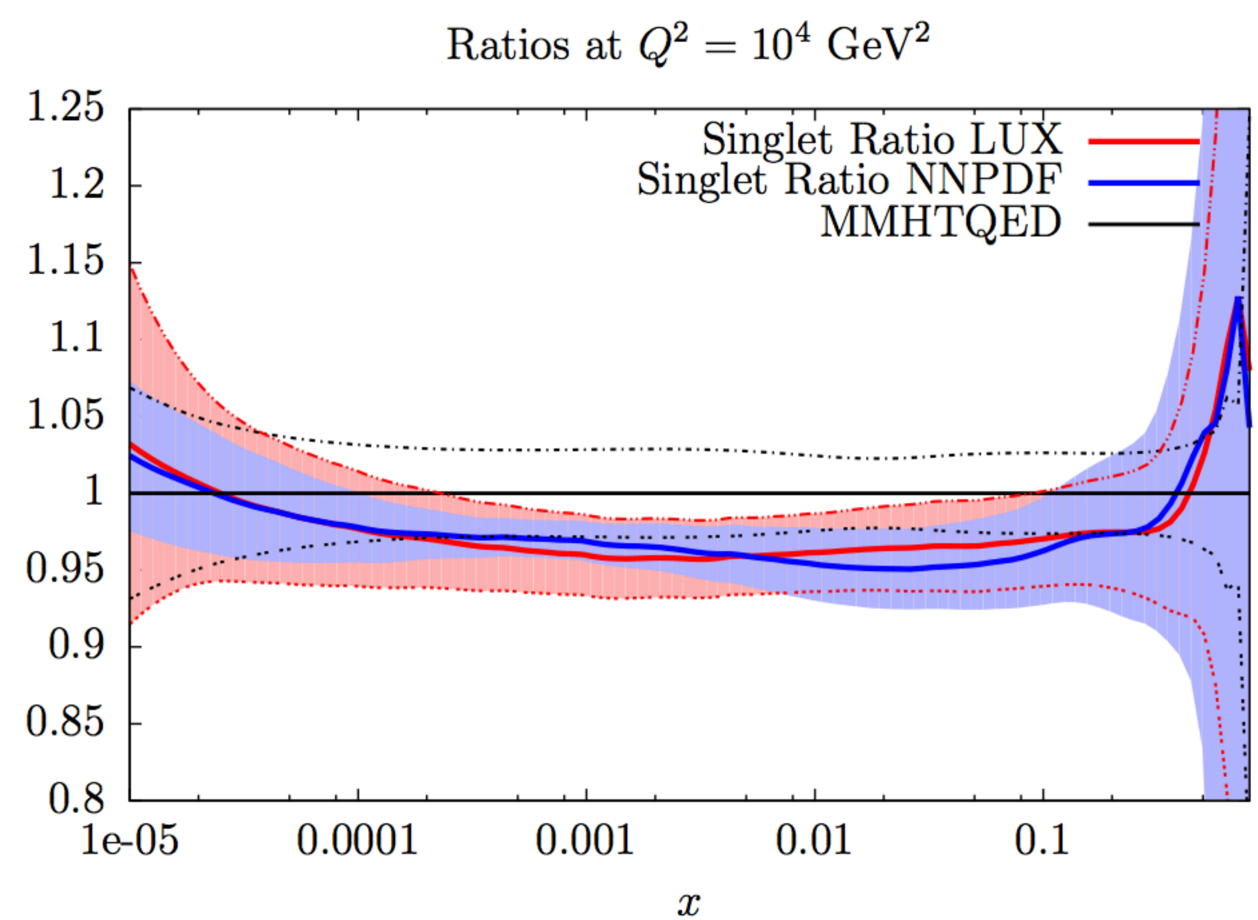
➡ **NNLO theoretical predictions for observables entering PDF fits**

➡ **Fast interface with NNLO codes**

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

L. Harland-Lang's talk
C. Schwan's talk





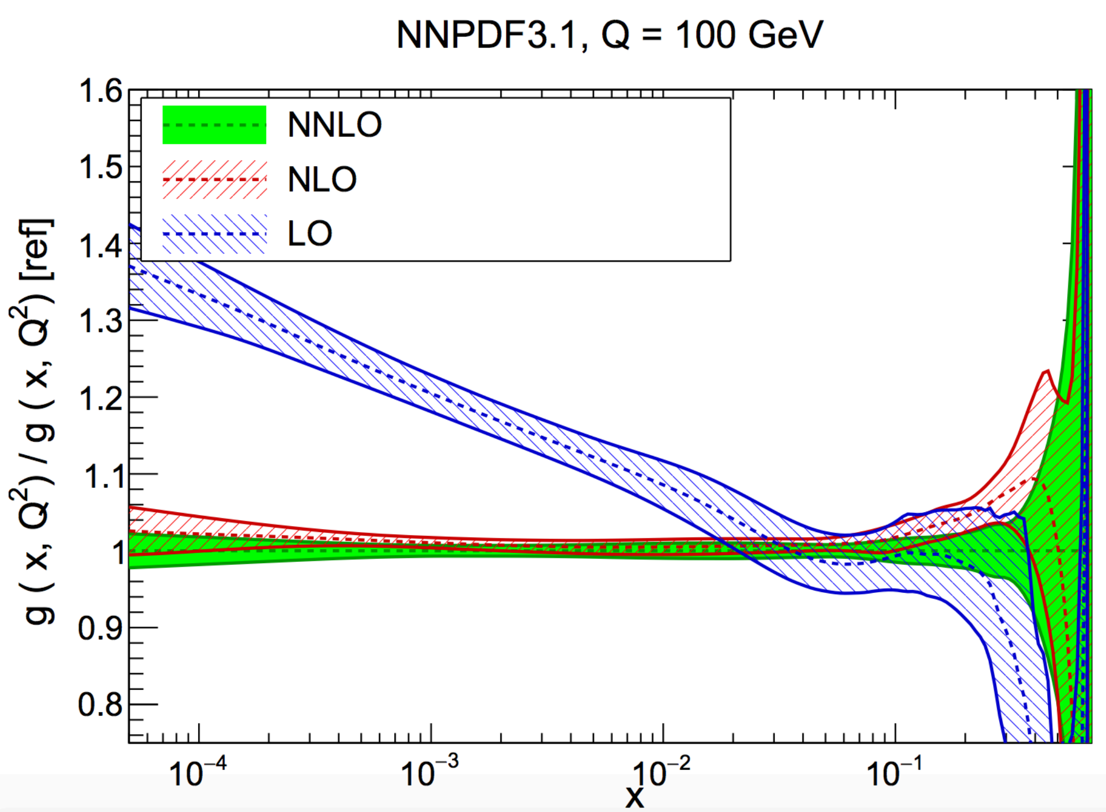
Manohar et al, arXiv: 1604.04266 + Carrazza et al, arXiv:1712.07053 + Harland-Lang et al, arXiv:190702750

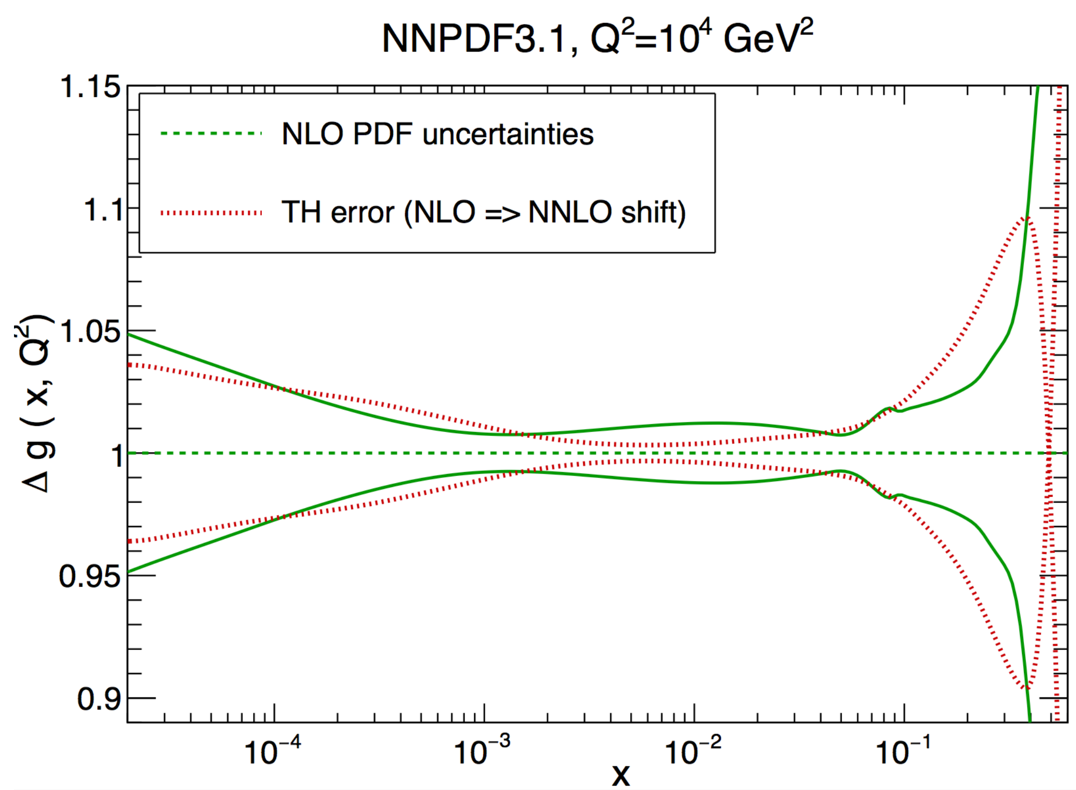
HOW TO MAKE PDFS MORE ACCURATE?

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

- 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** **C. Voisey's talk**
➡ **Inclusion of theory uncertainties**



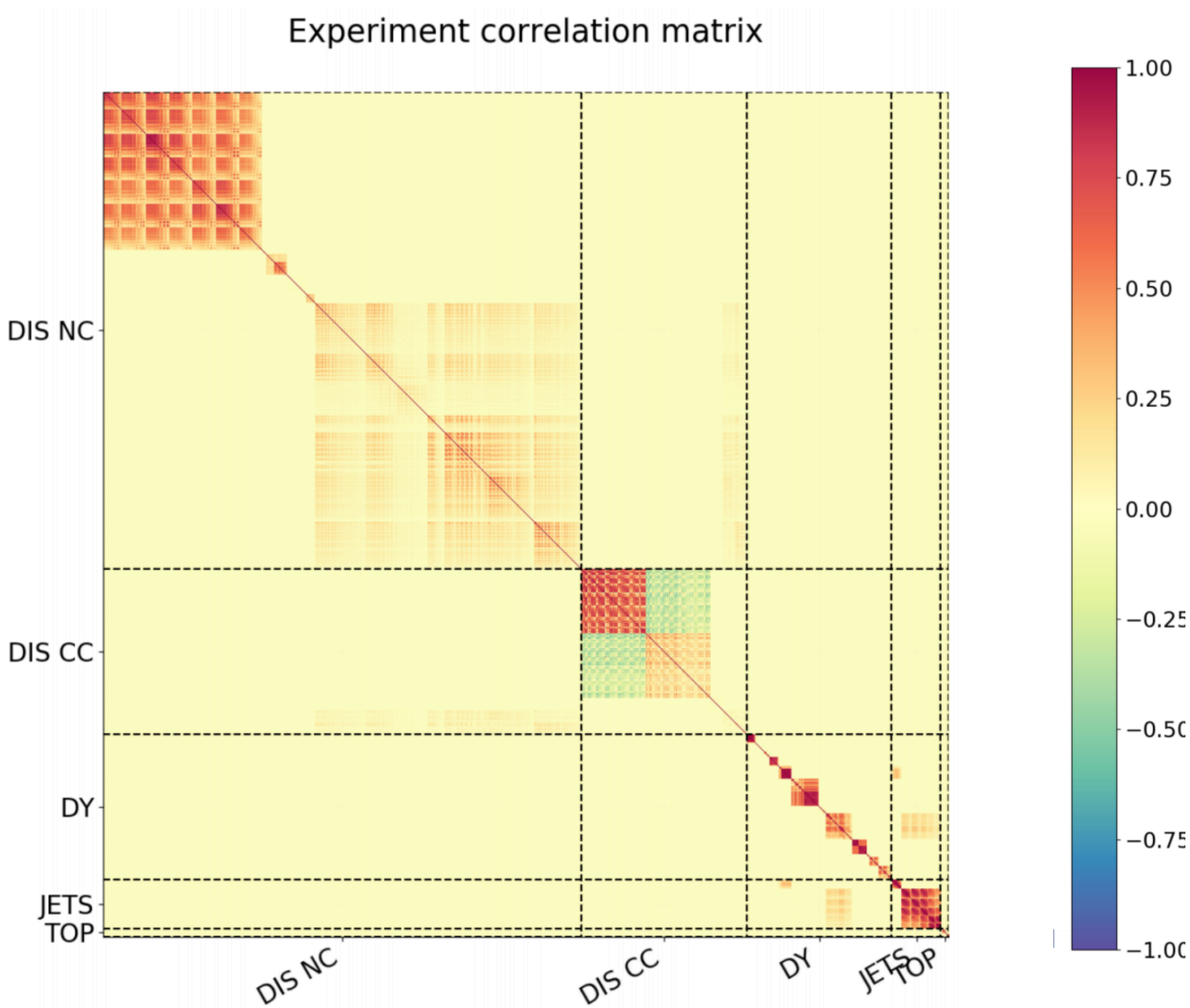


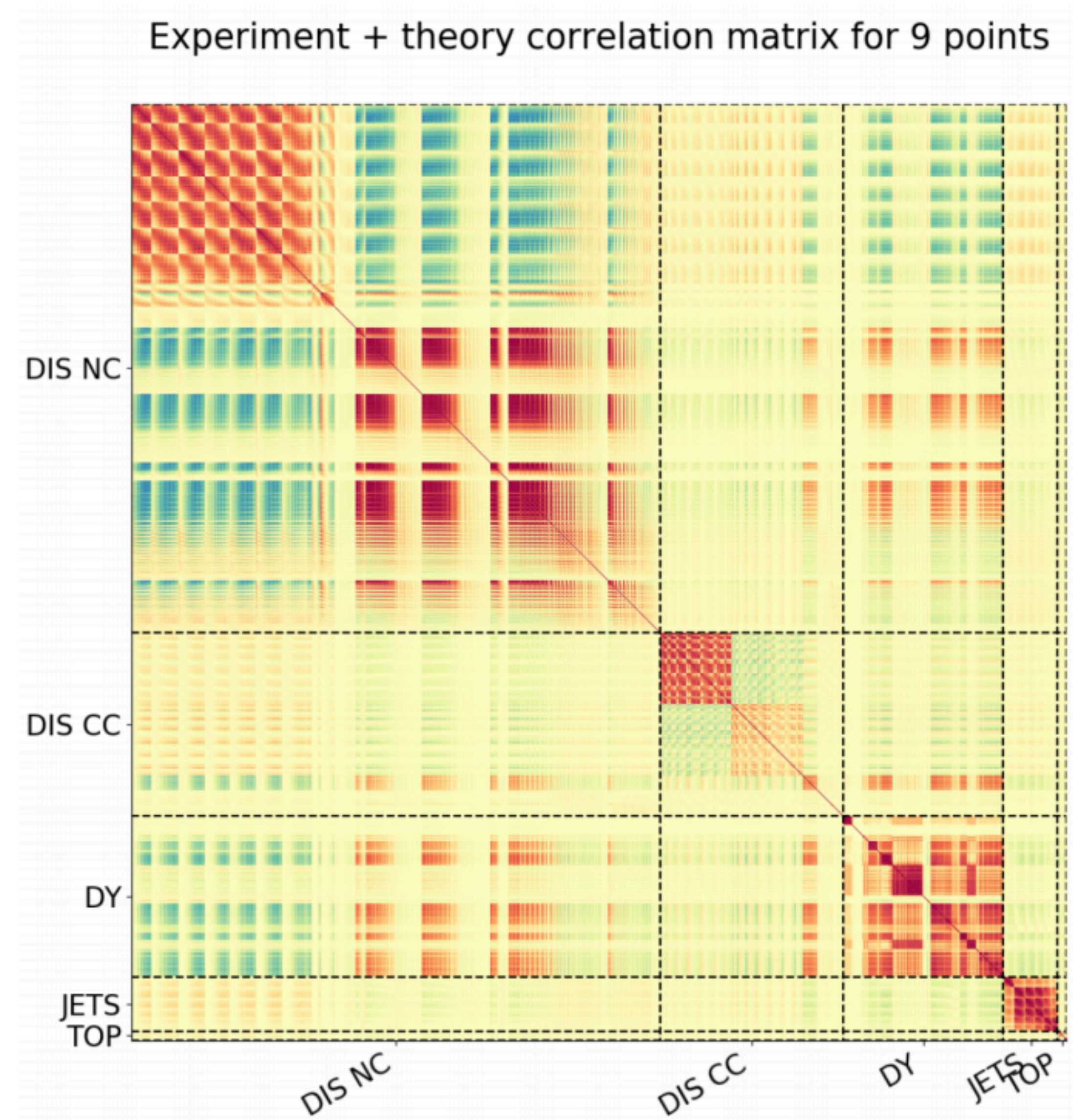
How much are we underestimating PDF uncertainties by ignoring it?

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

THE THEORY COVARIANCE MATRIX

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

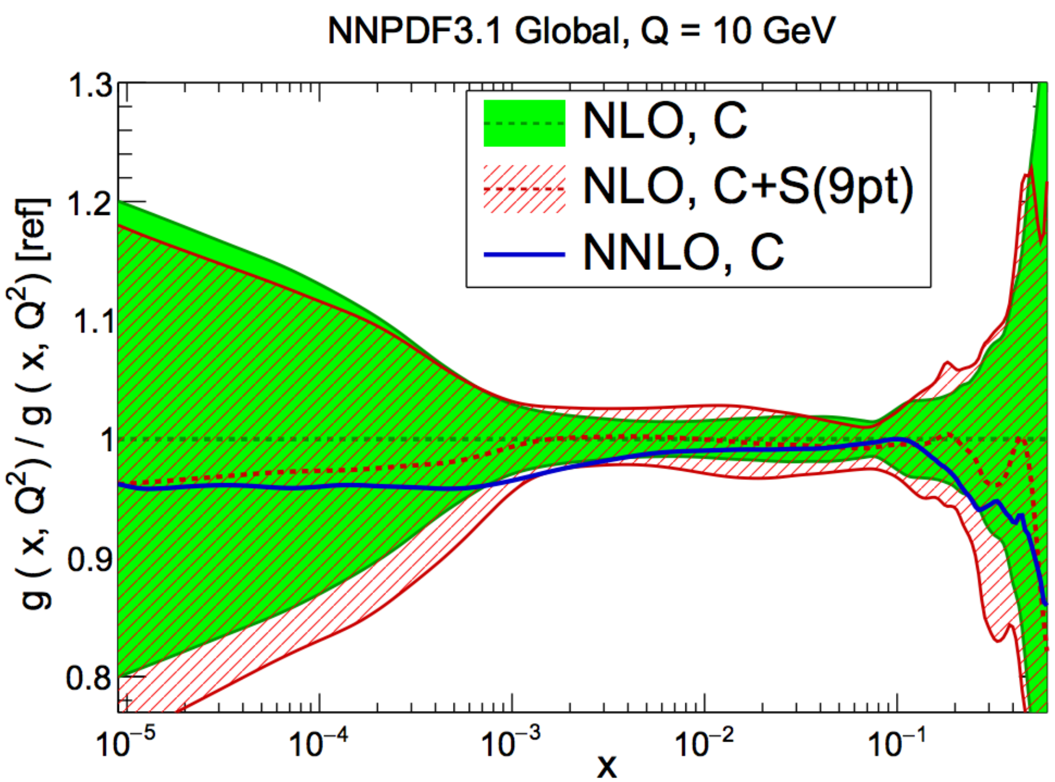
$$\chi^2 = \sum_{m,n=1}^{N} (d_m - t_m)(\mathrm{cov}_{\mathrm{exp}} + \mathrm{cov}_{\mathrm{th}})^{-1}_{mn}(d_n - t_n)$$

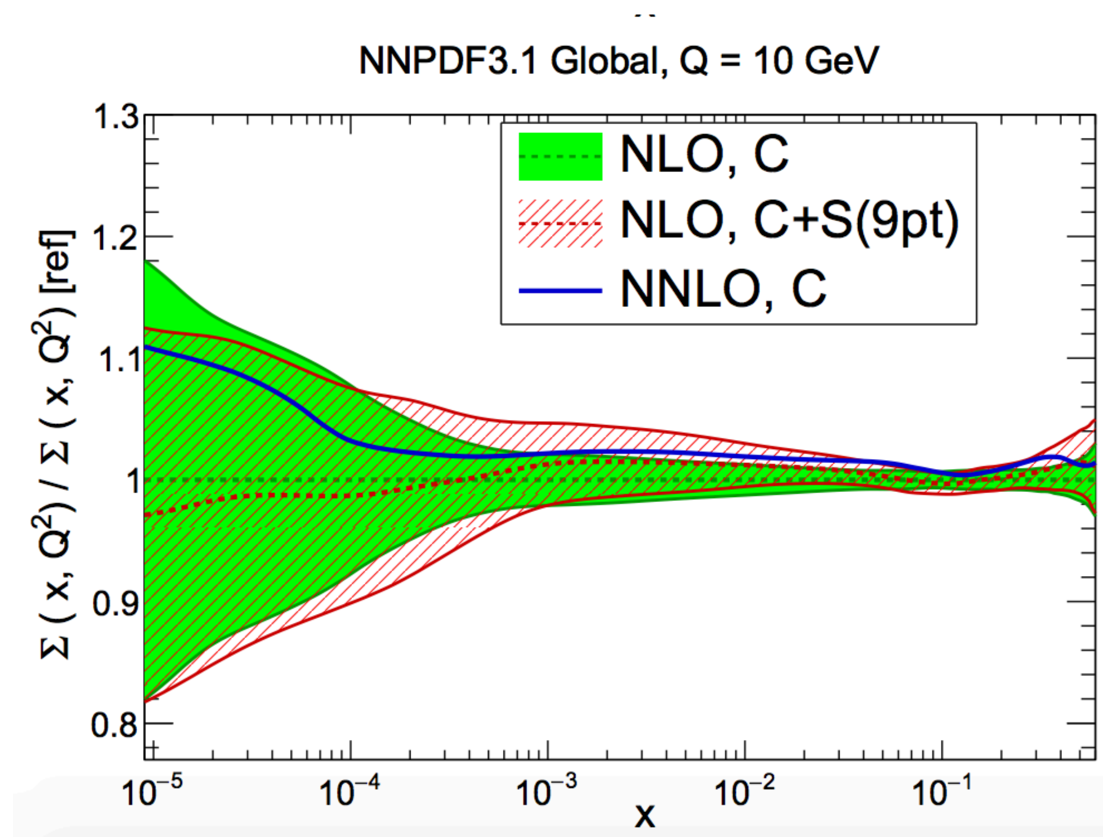
- ➡ Theory covariance matrix built from scale-varied cross sections

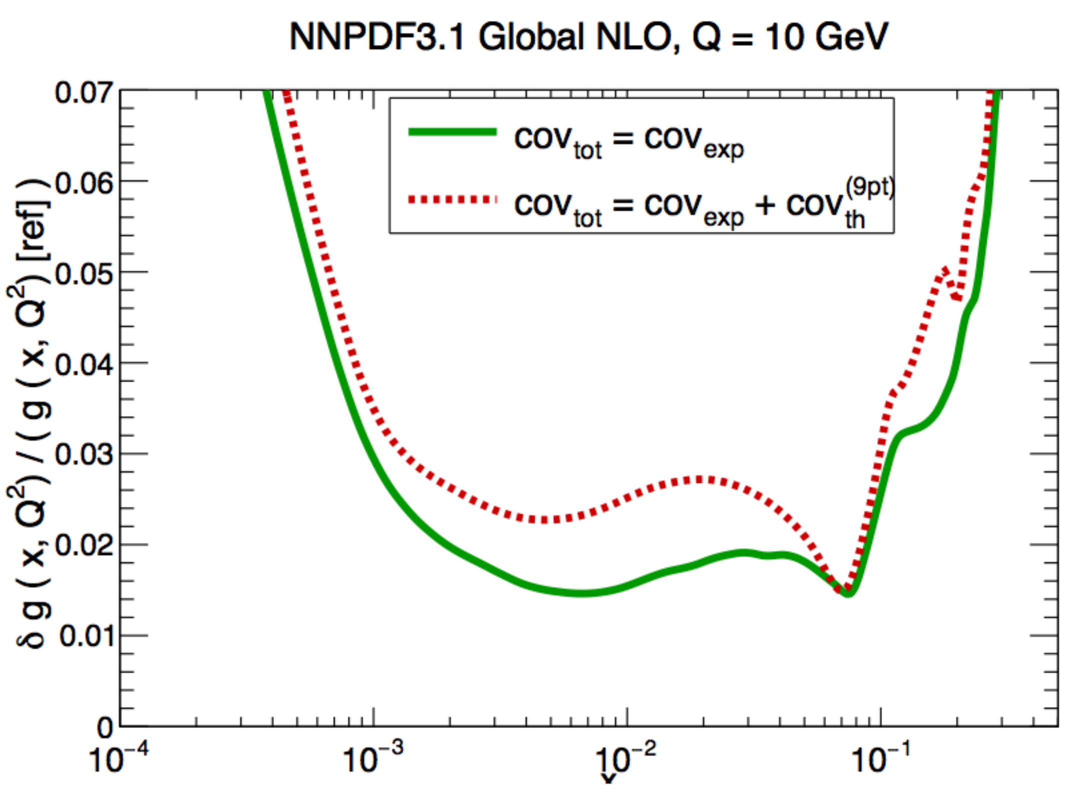
$$\mathrm{cov}^{(\mathrm{th})}{}_{ij} = \frac{1}{N}\sum_k \Delta_i^{(k)}\Delta_j^{(k)} \qquad \Delta_i^{(k)} \equiv T_i^{(k)} - T_i$$

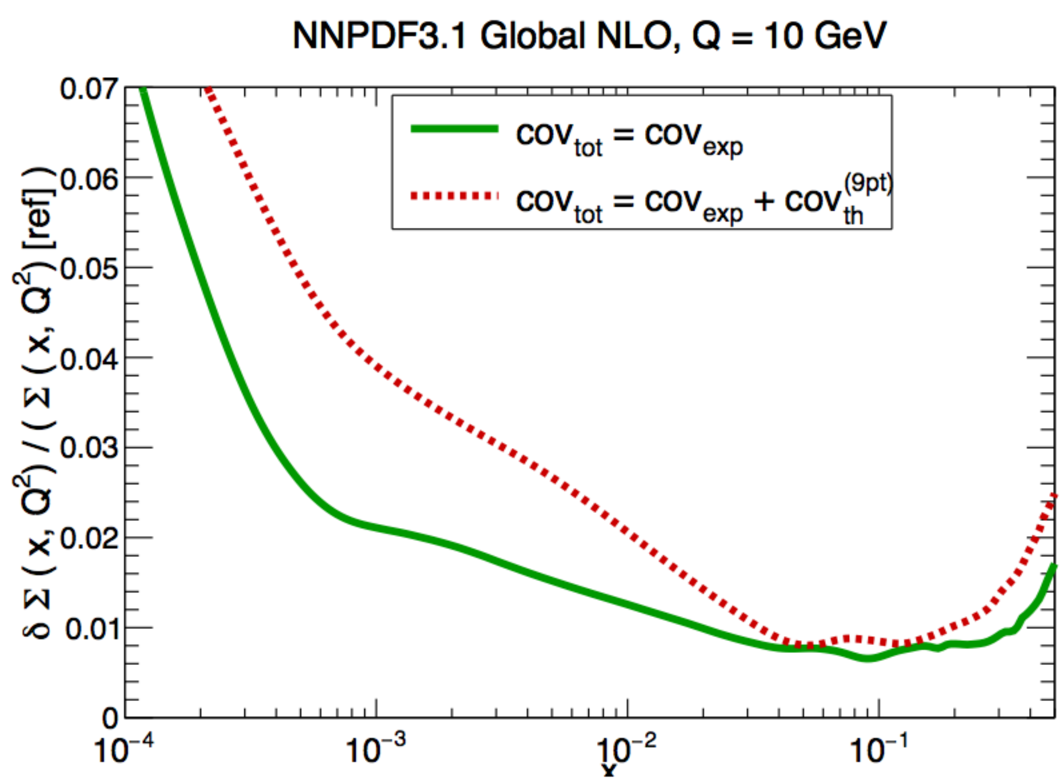
- ➡ Assumptions: experimental and theoretical errors independent and Gaussian
- ➡ Accounting for the theory covariance matrix will modify the relative weight that each of the datasets carries in the global fit: processes with higher MHOUs will be ``de-weighted"
- ➡ How to build it?
  - Specific form will depend on number of variation and assumption on correlations
  - μ_F variations correlated across all processes by PDF evolution
  - μ_R variation correlated by process (hard cross section)
  - Validation of diagonal elements and correlations against NLO=>NNLO shift matrix ✅

PDFS WITH THEORY UNCERTAINTIES



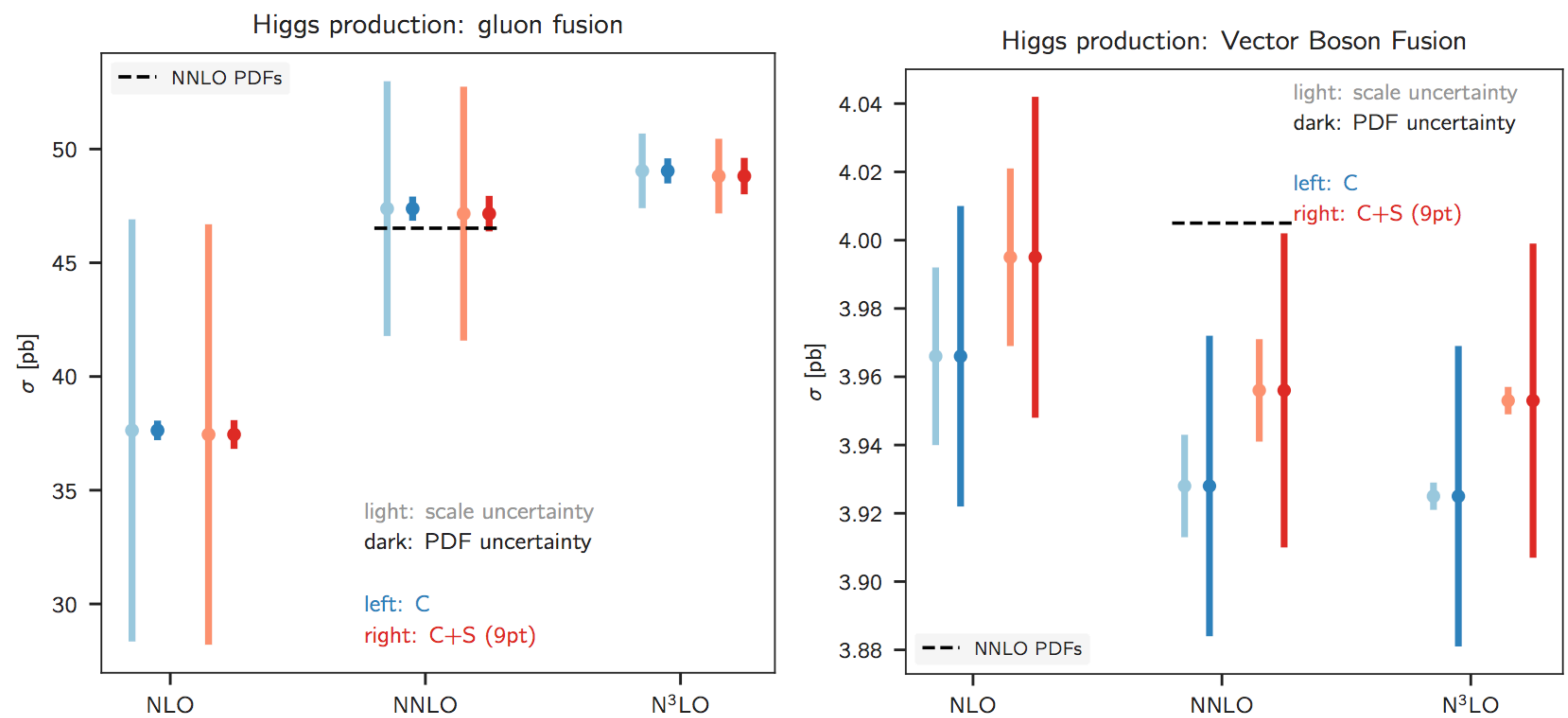






The NNPDF collaboration, Eur.Phys.J. C79 (2019) no.11, 931

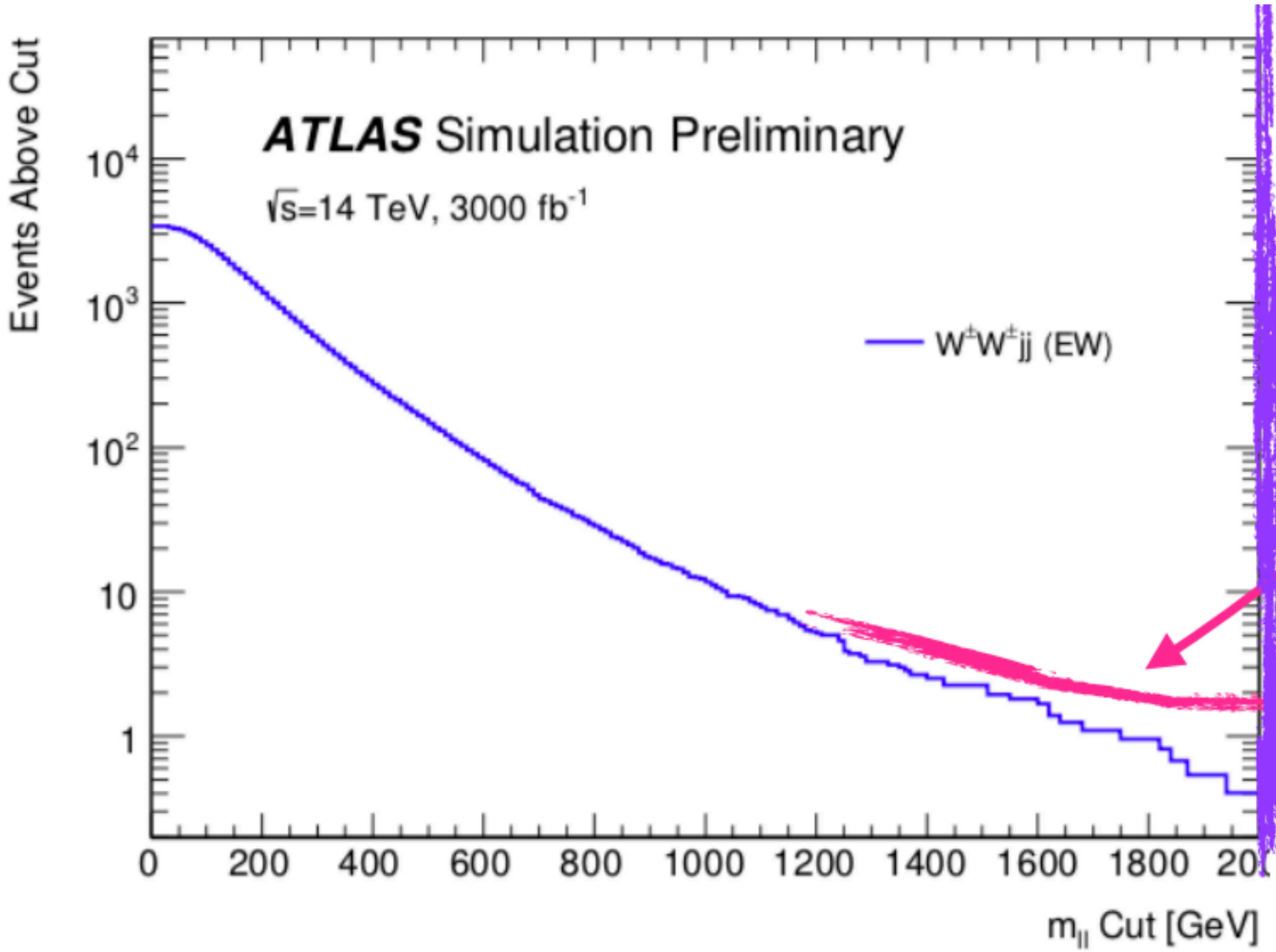
EFFECT ON HIGGS PHYSICS



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

The NNPDF collaboration, Eur.Phys.J. C79 (2019) no.11, 931

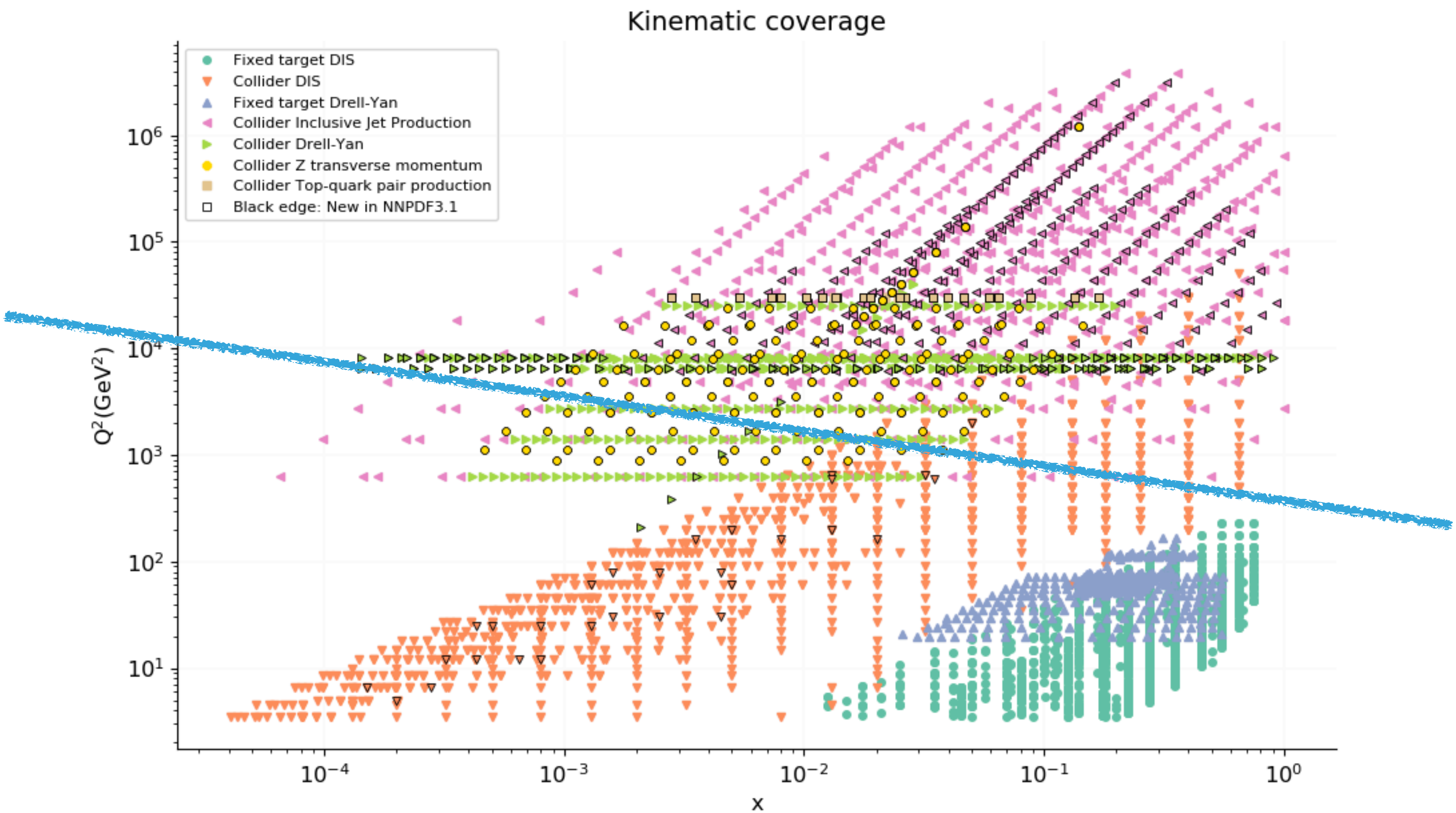
TOWARDS GLOBAL INTERPRETATIONS



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

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

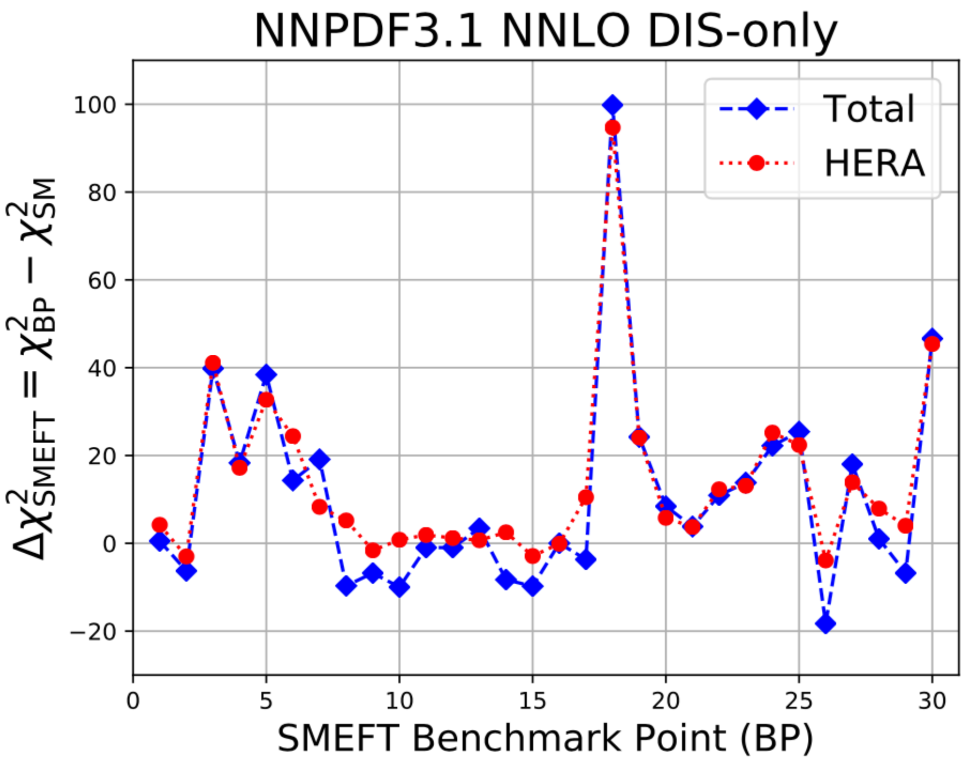
PDFS AND BSM INTERPLAY

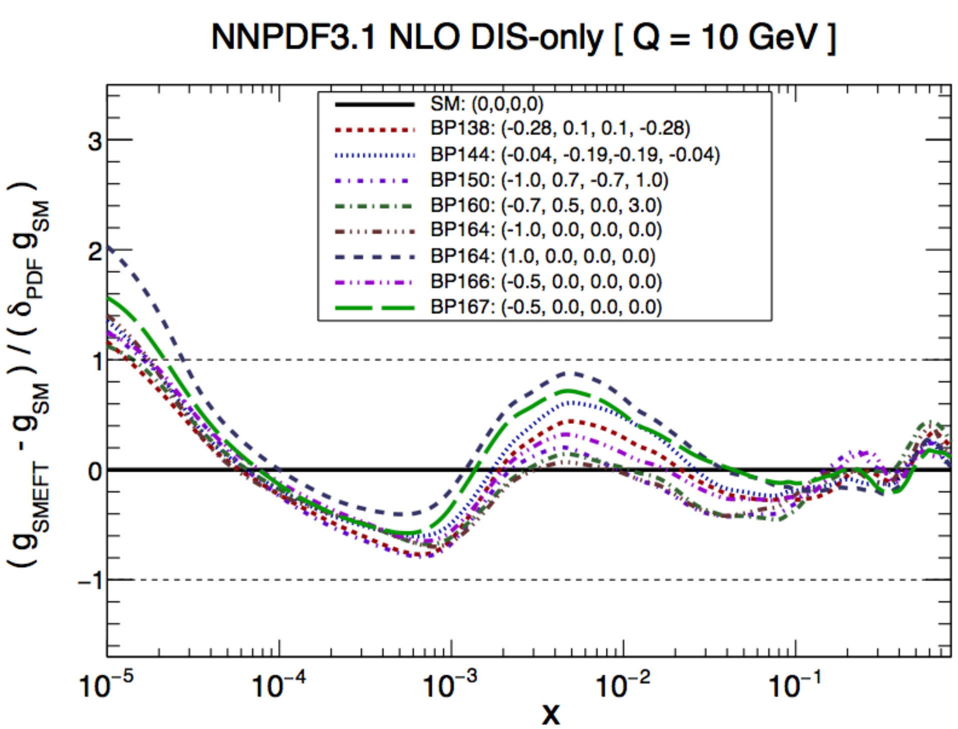


- How to disentangle potential BSM effects?
- How to make sure that BSM effects are not fitted away by flexible parametrisation?
- Conservative partons?

PDFS AND BSM INTERPLAY

S. Iranipour's talk





- 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**

C. Degrande's talk
E. Rizvi's talk

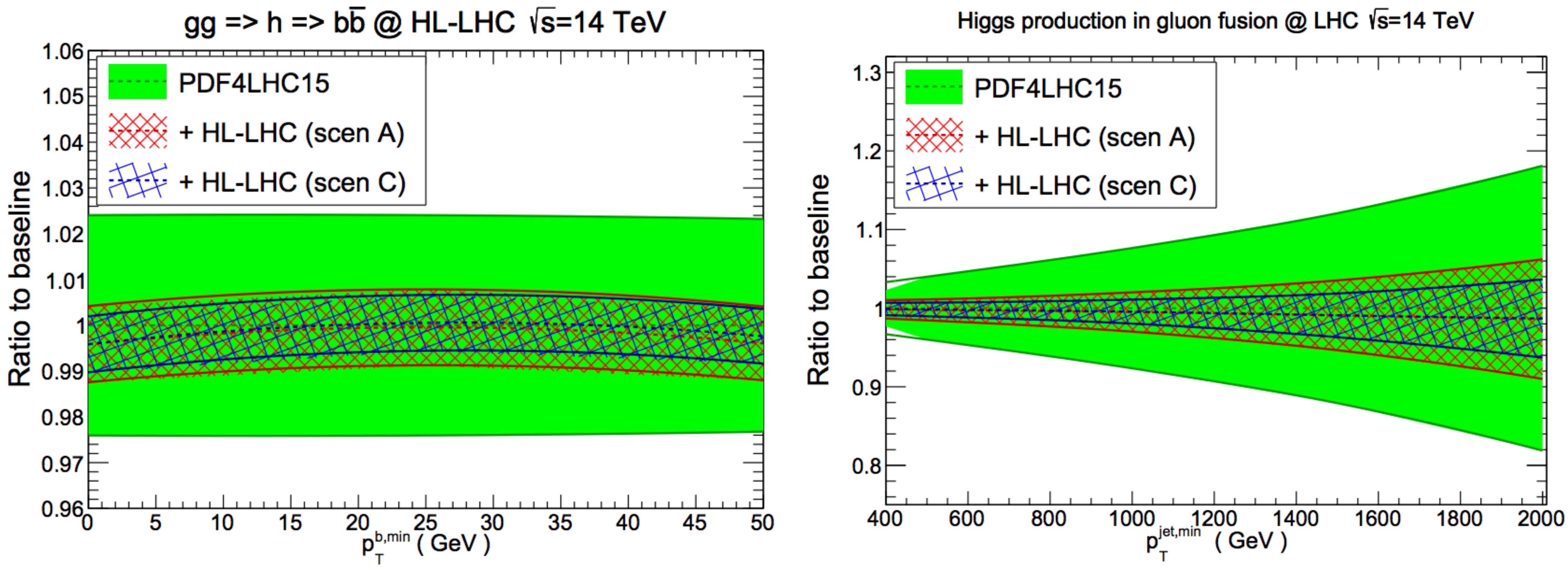
Carrazza, Degrande, Iranipour, Rojo, MU, Phys.Rev.Lett. 123 (2019) no.13, 132001

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, but need to benchmark and understand incompatibilities. Also great projections from LHeC and EIC (see M. Cooper-Sarkar's and T. Hobbs's talk)
- Need: robust methodology and precise theory (higher orders, EW corrections, photon)
- News: estimate of theoretical uncertainties associated with missing higher order in PDF fits & fit of the methodology
- News: lots of progress from lattice (see S. Zafeiropoulos's talk)
- Towards global fits (PDFs + αs, PDFs + EW parameters, PDFs + BSM parametrisation…)

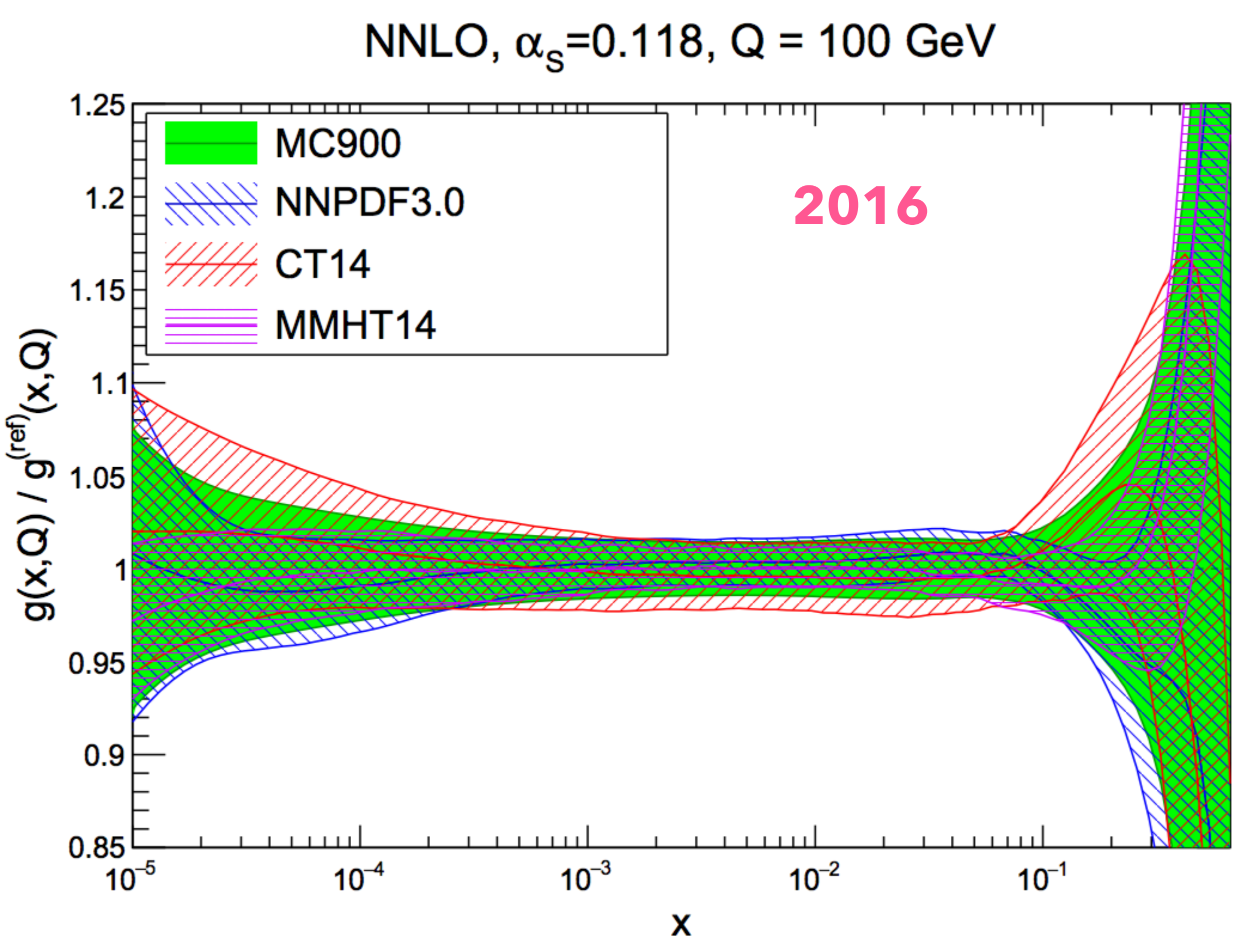
ADDITIONAL MATERIAL

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