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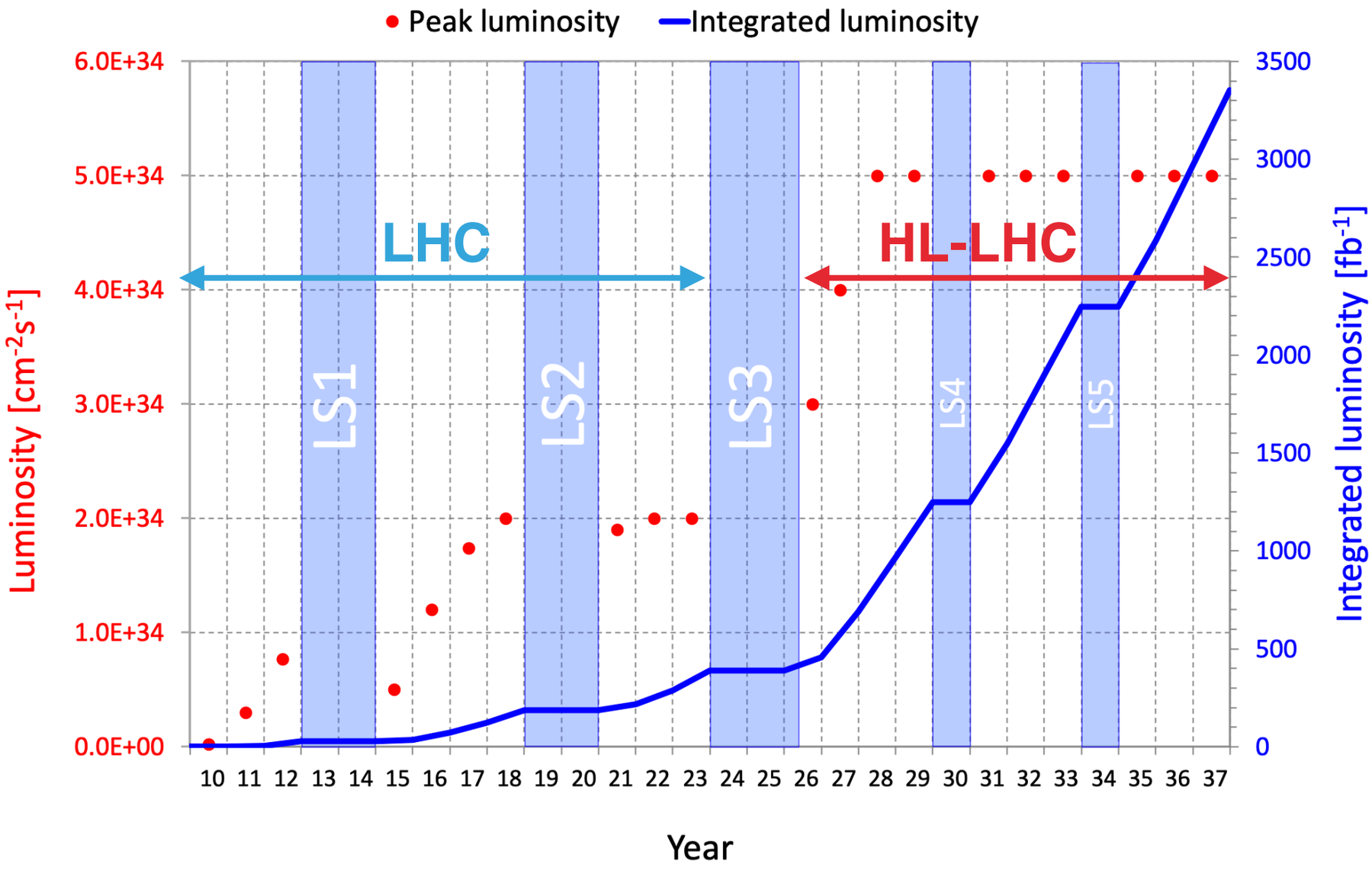
NEW FRONTIERS IN PDF ANALYSES IN THE HL-LHC ERA

SNOWMASS JOINT SESSION: OPEN QUESTIONS AND NEW IDEAS

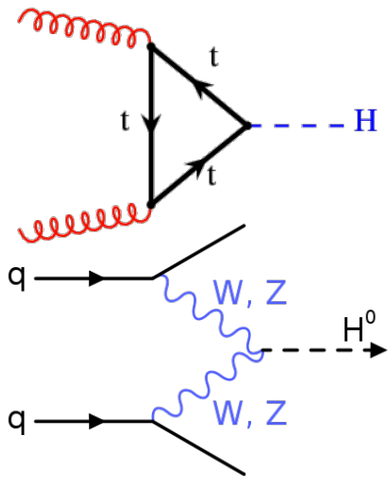
7-8 JULY 2020

PRECISION CHALLENGE AT THE HL-LHC

- LHC: discovery → discovery through precision
- With plethora of new precise data at HL-LHC and increased accuracy of experimental data theoretical predictions face unprecedented precision challenge
- In this talk focus on PDFs, which are an essential element of any theoretical prediction at hadron colliders

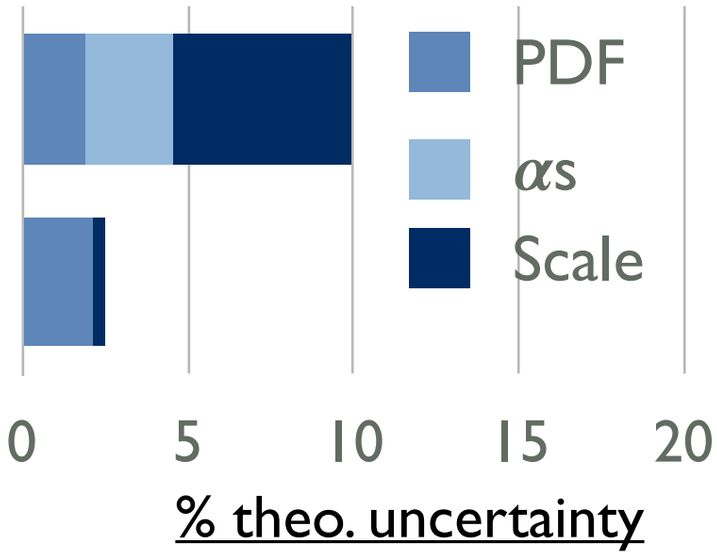


THE ROLE OF PDF UNCERTAINTIES



ggF (N3LO) + NLO EW

VBF (N2LO) + NLO EW



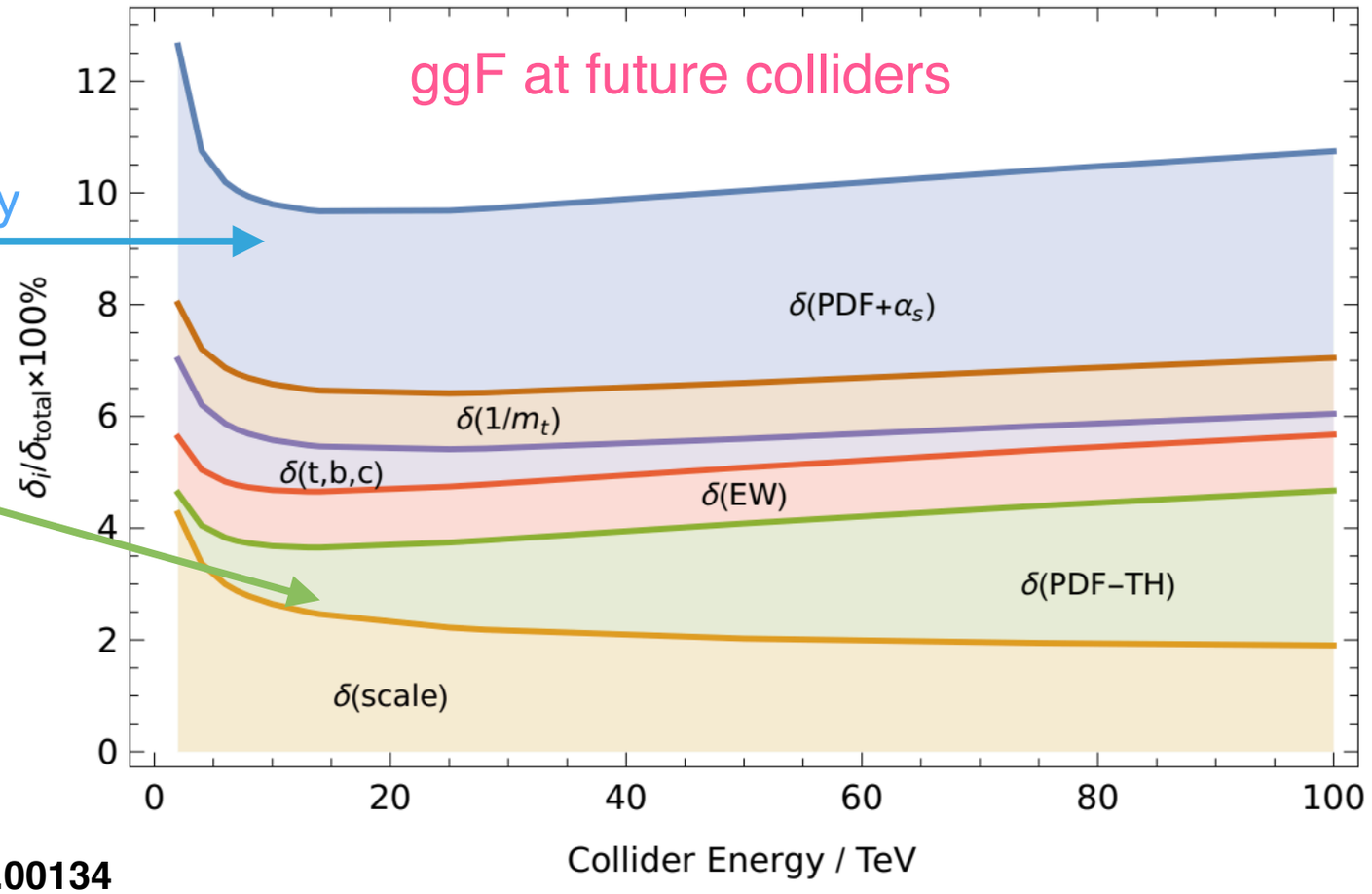
48.6 pb
3.77 pb

σ@13 TeV

PDF uncertainty significantly limitation to theory accuracy

PDF+as uncertainty

Th. mismatch



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

PDF DETERMINATION INGREDIENTS

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

Fit to global set of data

Perturbative QCD
DGLAP evolution equations

EXPERIMENTAL DATA

THEORETICAL CALCULATIONS

METHODOLOGY

PARAMETRISATION, ERROR PROPAGATION, MINIMISATION…

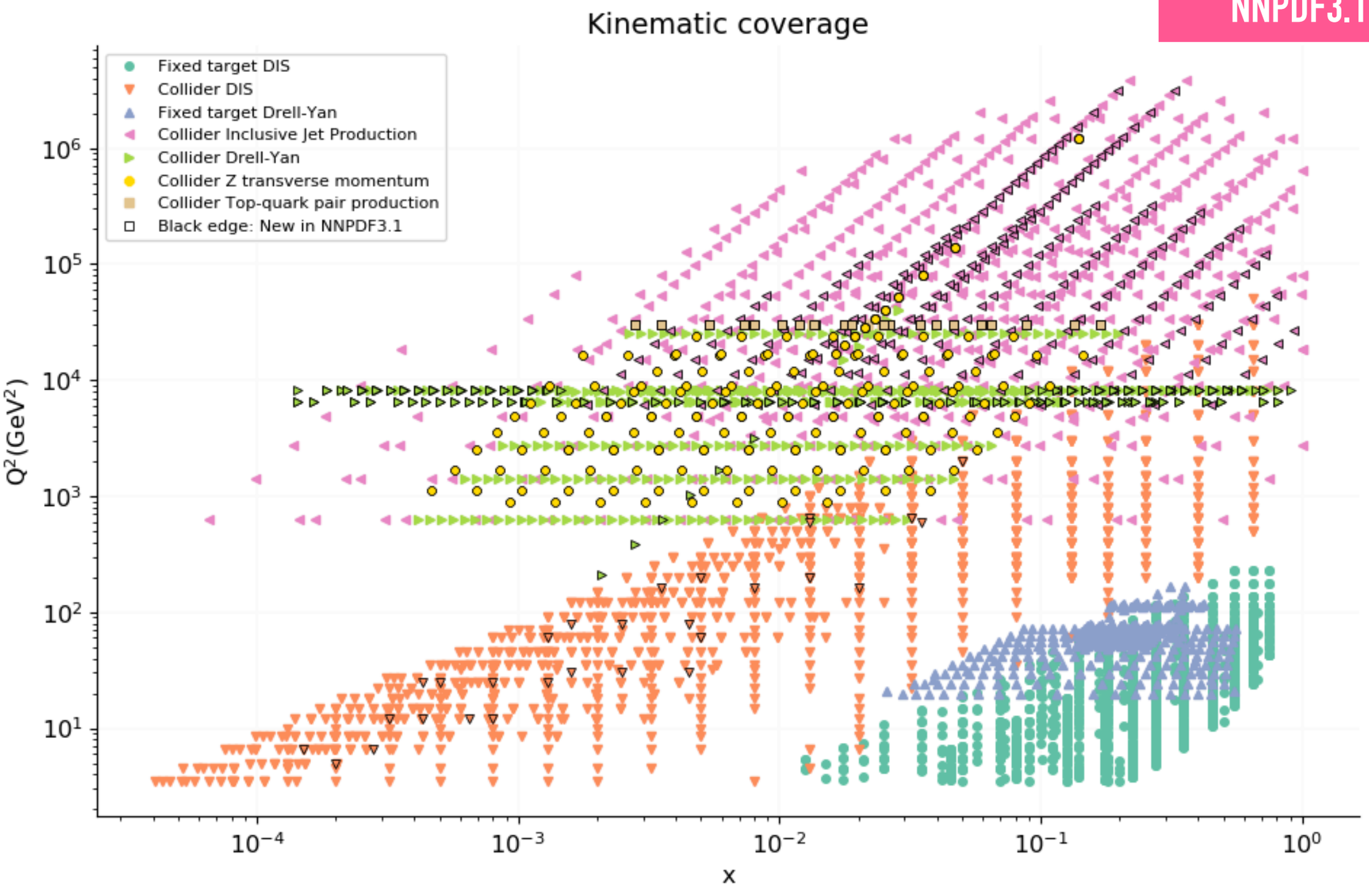
GLOBAL FIT

LHAPDF

A. Buckley et al
EPJC75 (2015)

THE EXPERIMENTAL DATA

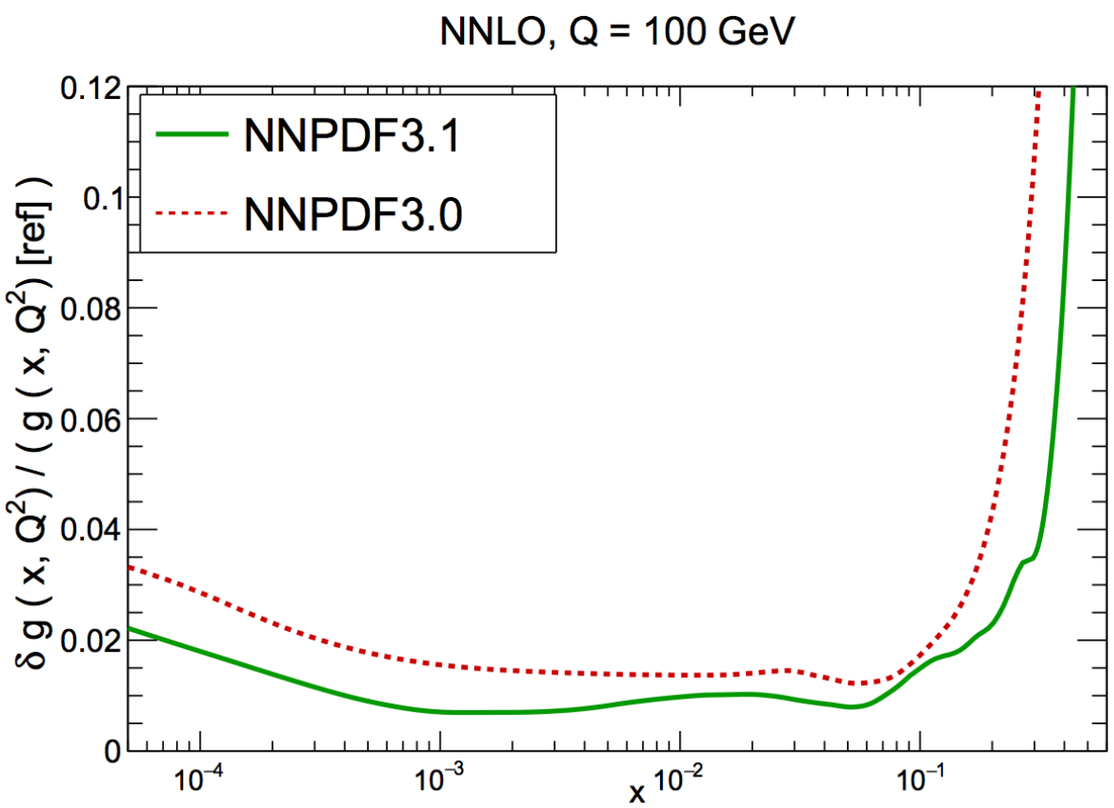
NNPDF3.1

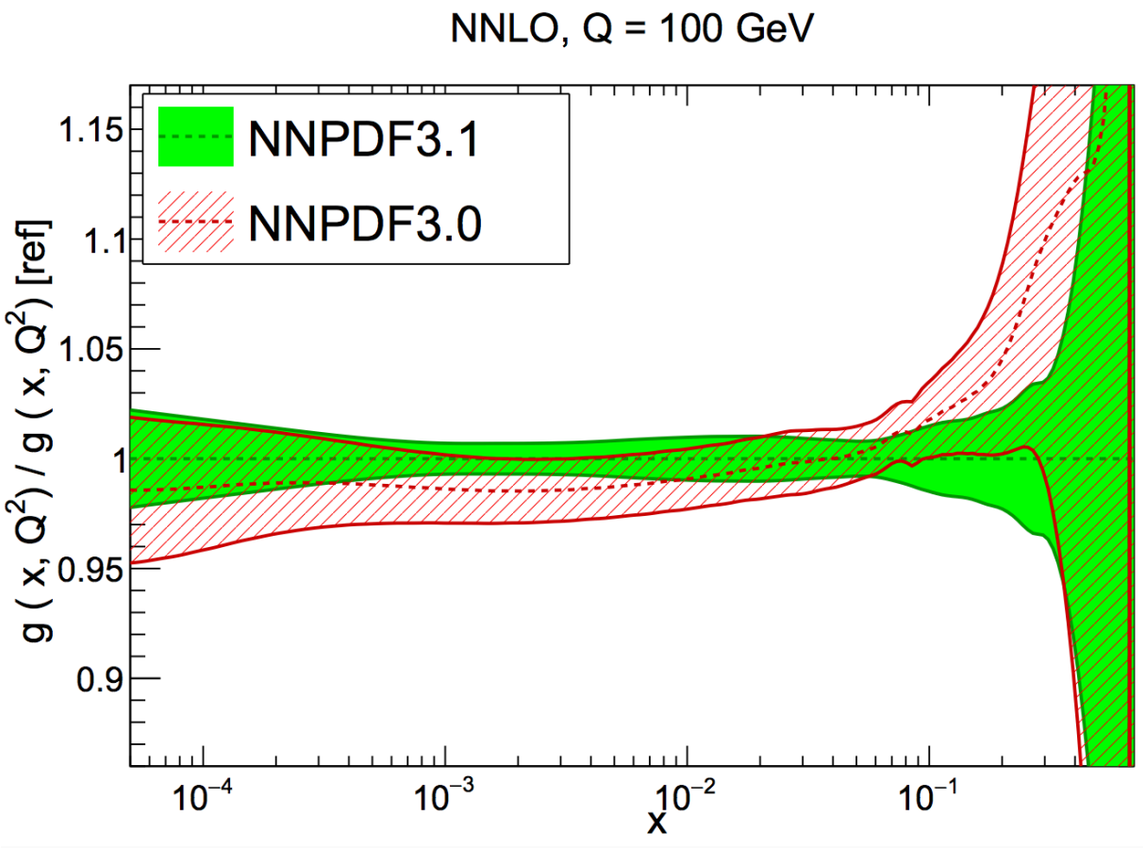


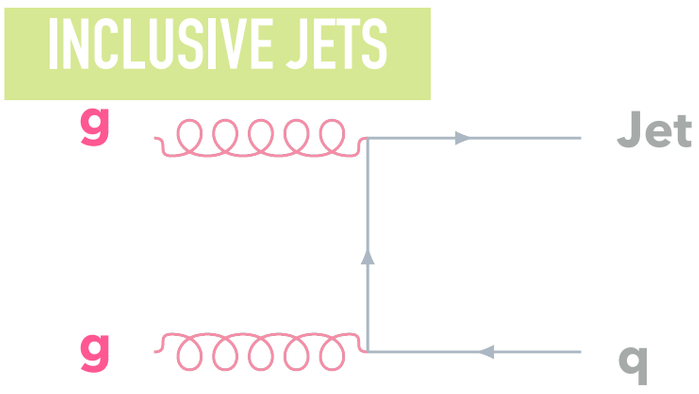
The NNPDF collaboration, EPJC 77 (2017)

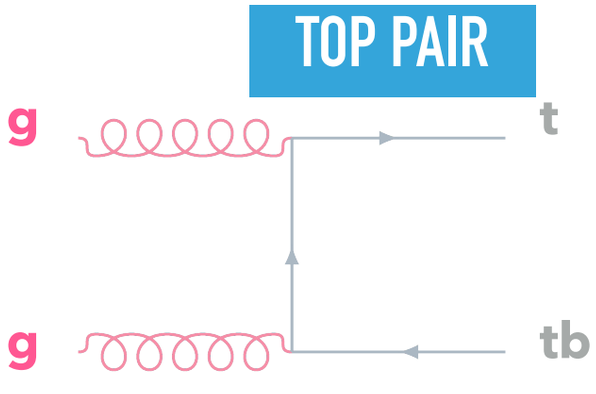
IMPACT OF THE LHC DATA – GLUON PDF

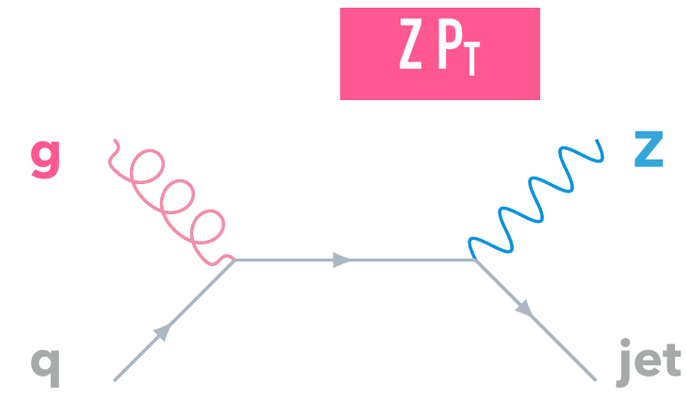
- Large-x gluon constrained by (at least) three independent processes
- Consistent picture and uncertainty reduction





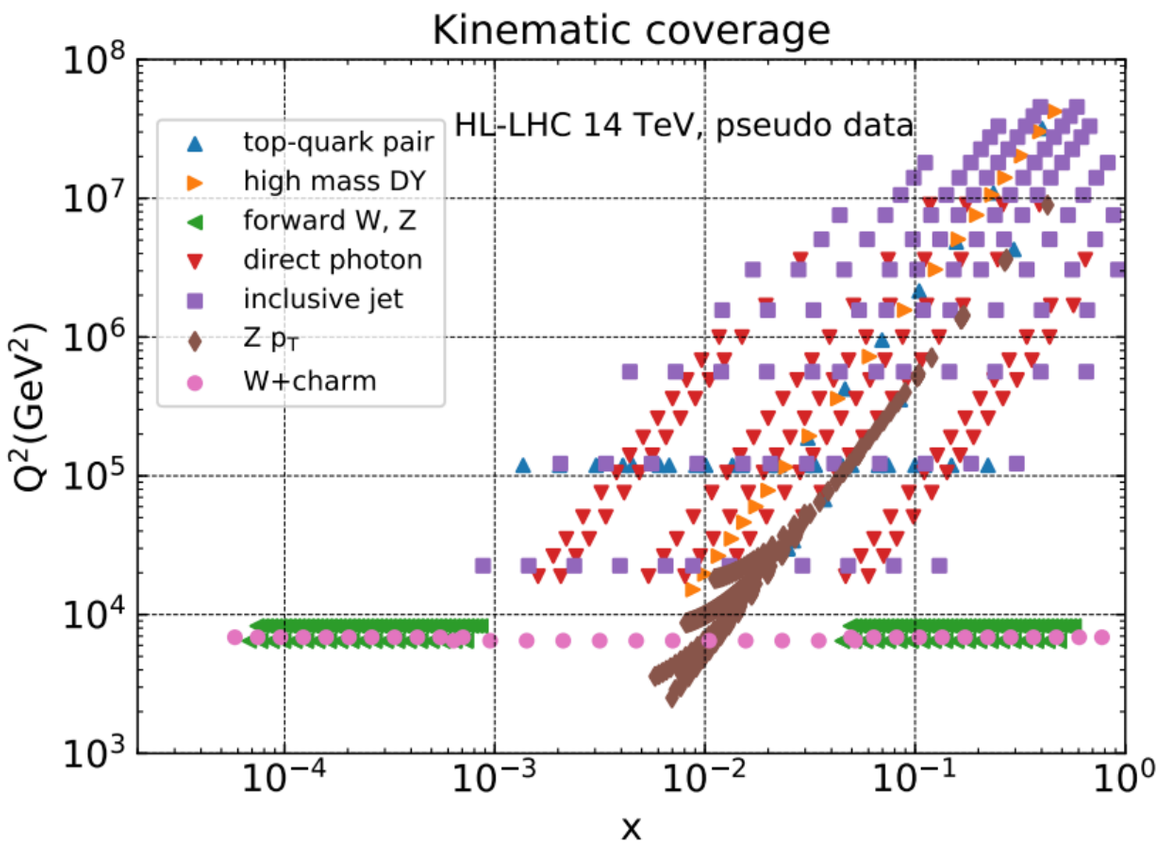




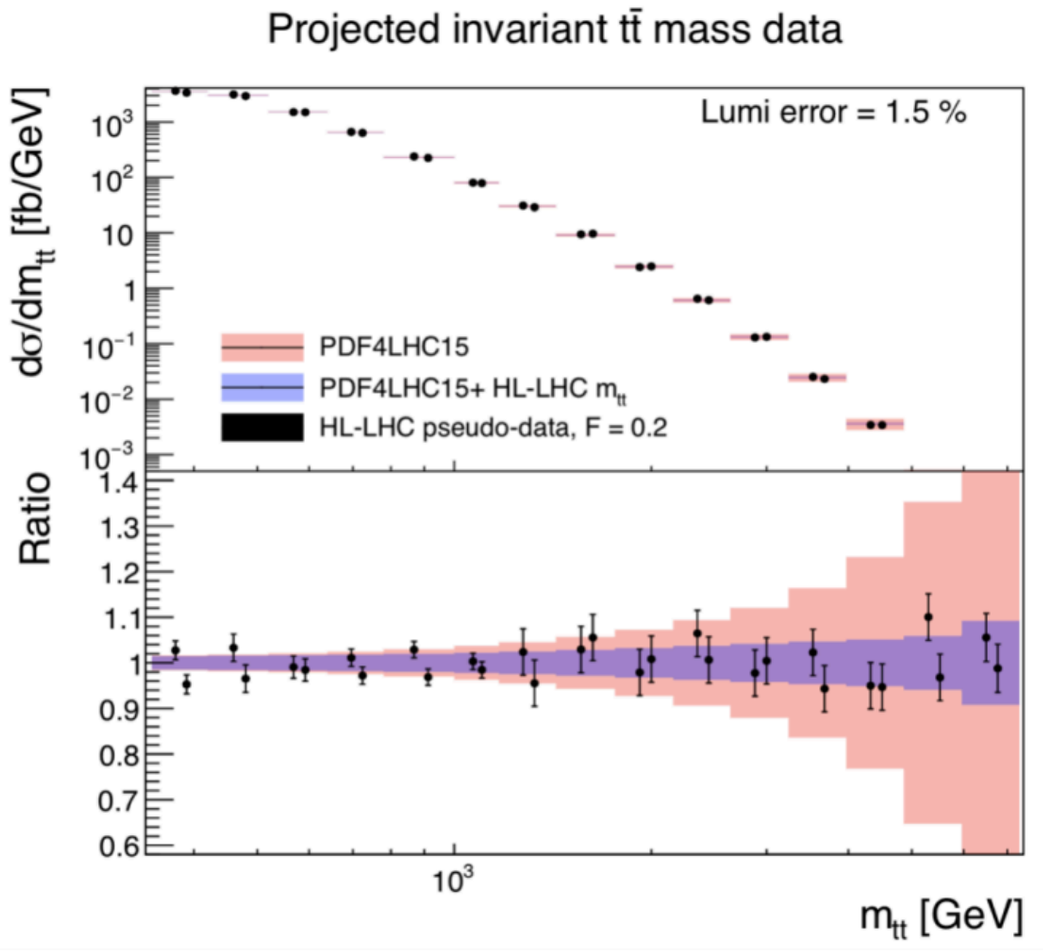


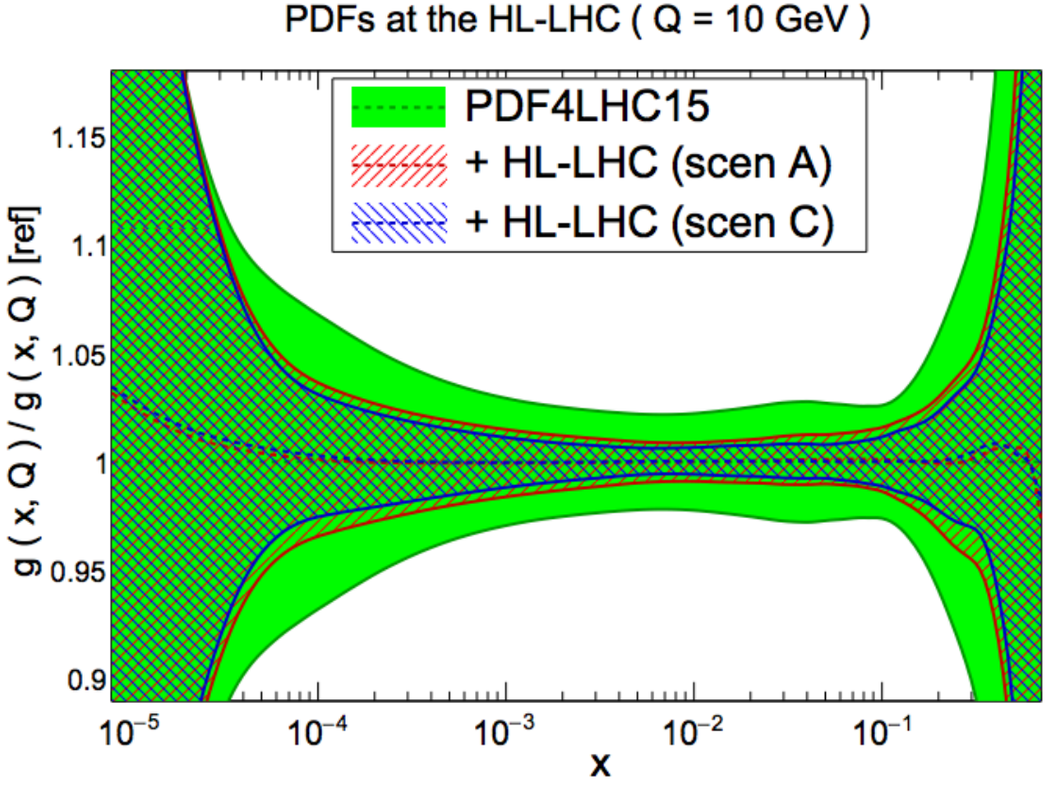
The NNPDF collaboration, EPJC 77 (2017)

PERSPECTIVES AT HL-LHC



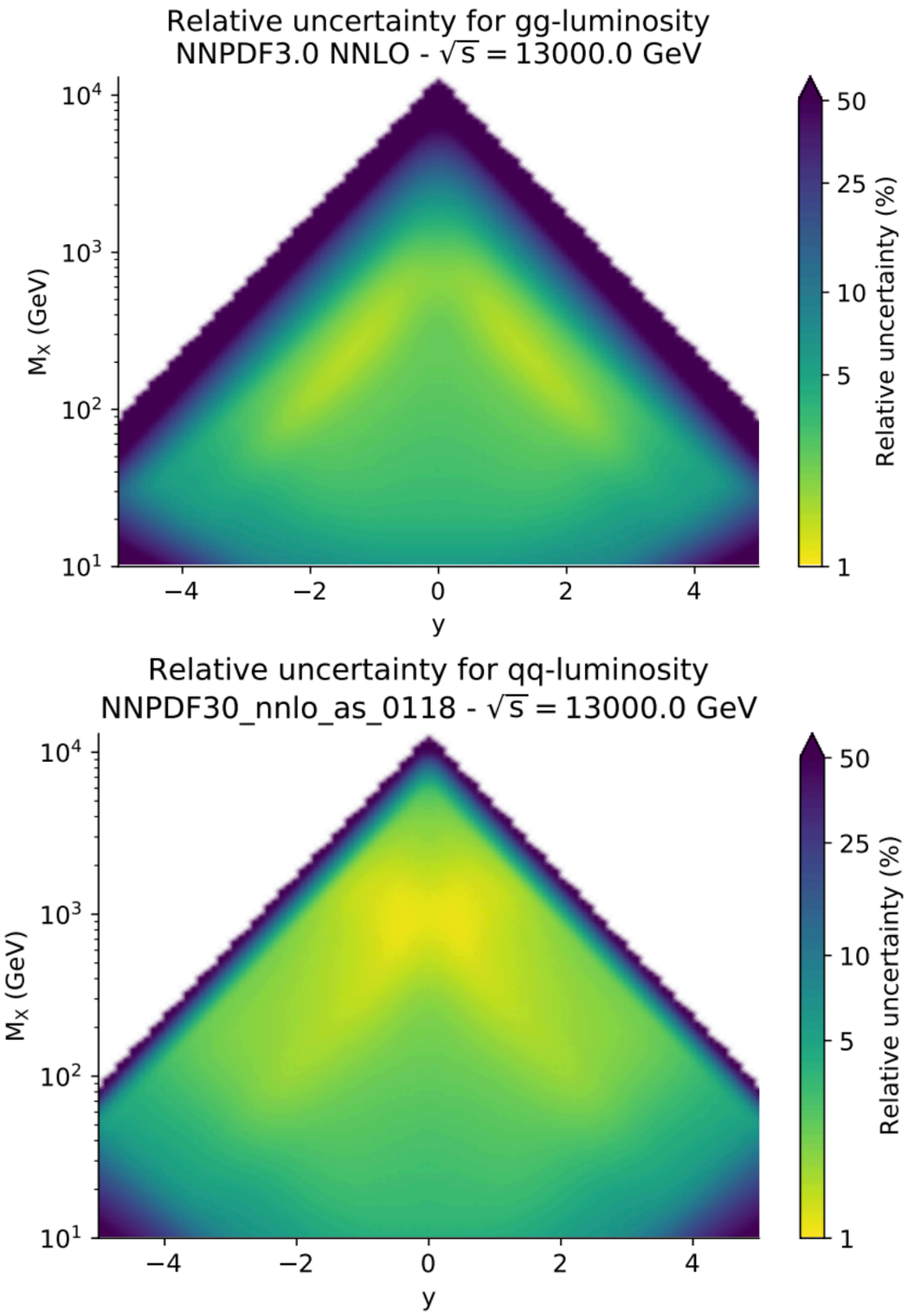
- W, Z handle on quarks
- W+c on strangeness
- Z pT on quarks and gluons
- Top and Jets on gluons

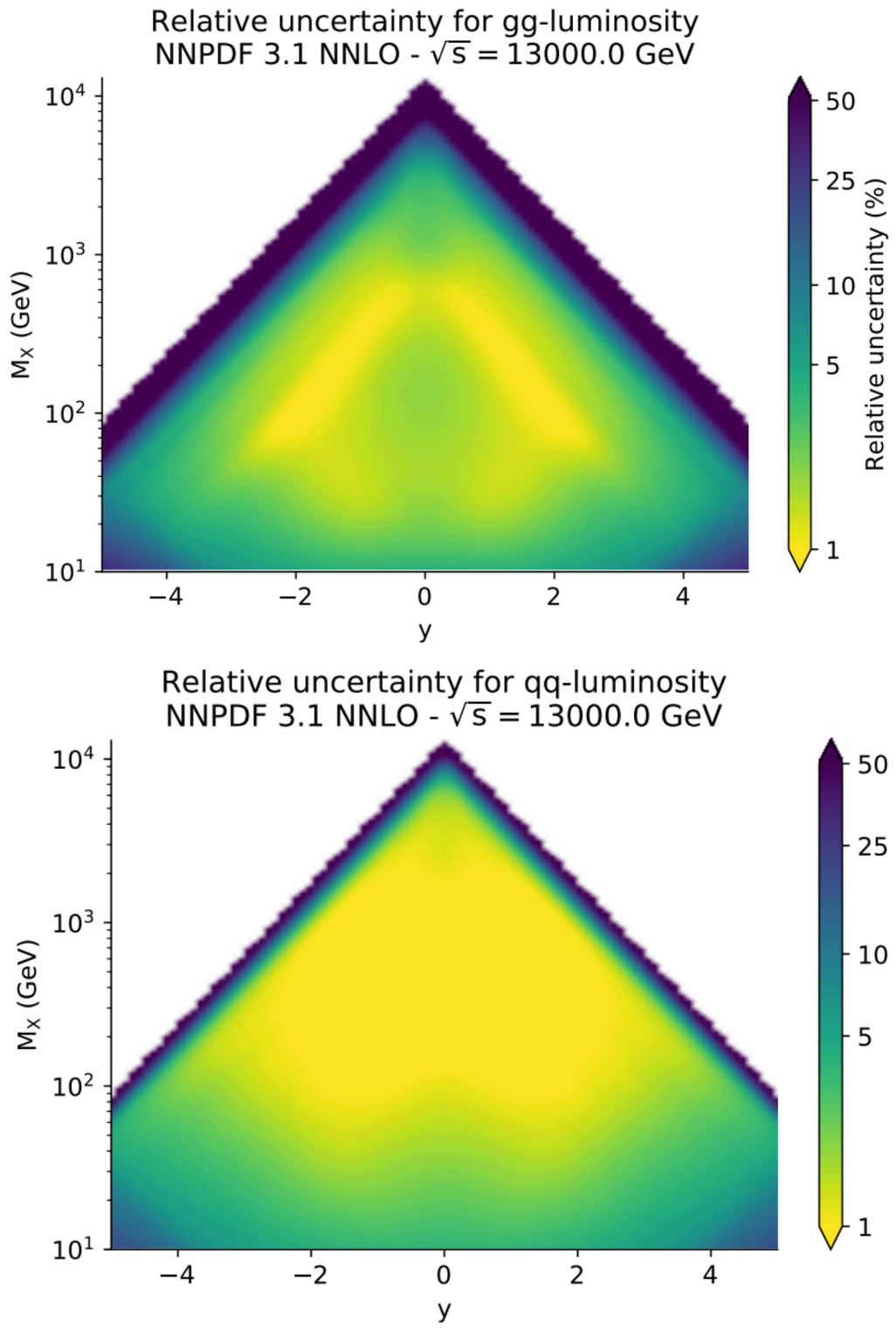




M. Cepeda et al. [HL/HE WG2 group], arXiv:1902.00134

THE PRECISION CHALLENGE





Ball et at, EPJC 77 (2017)

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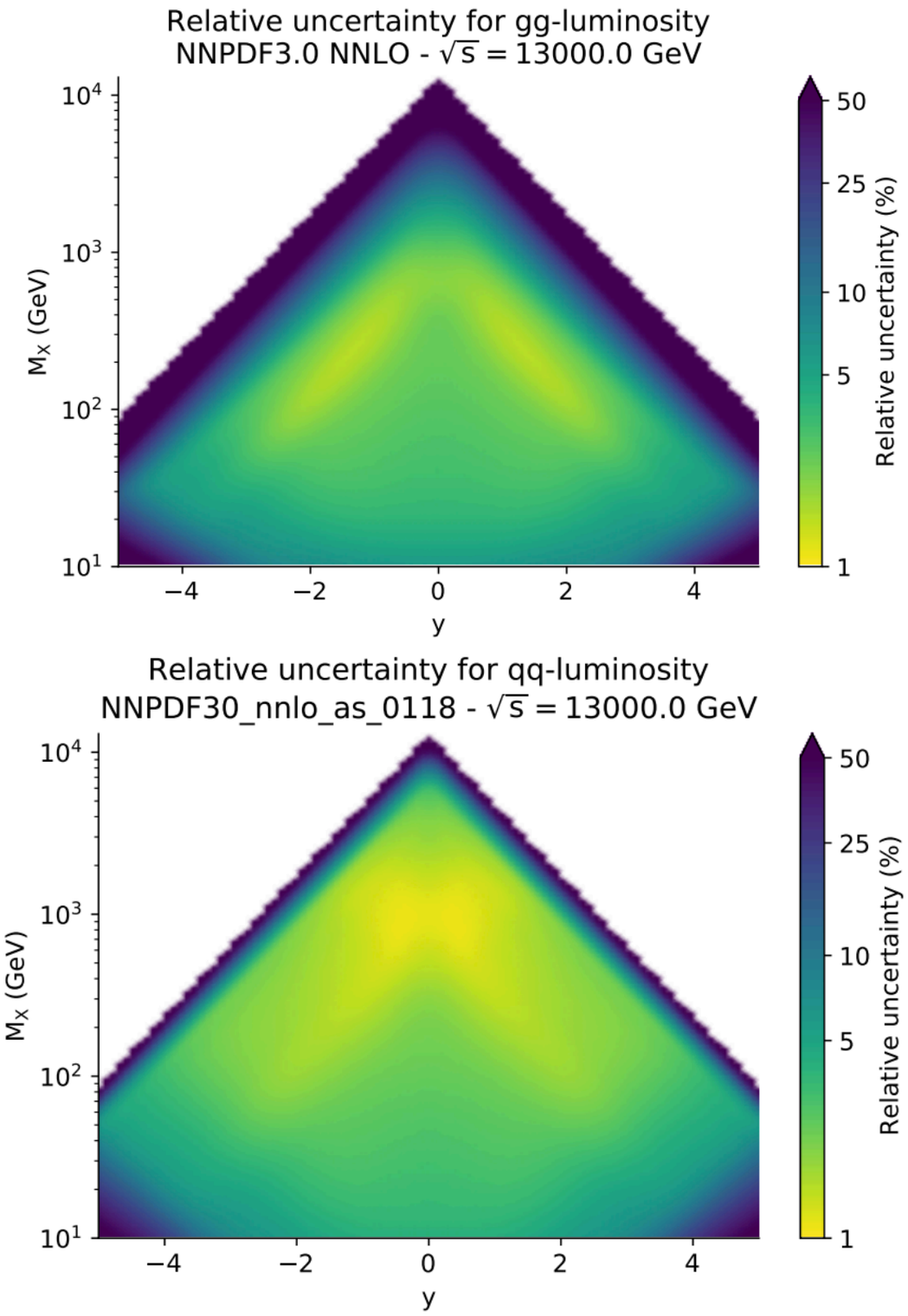
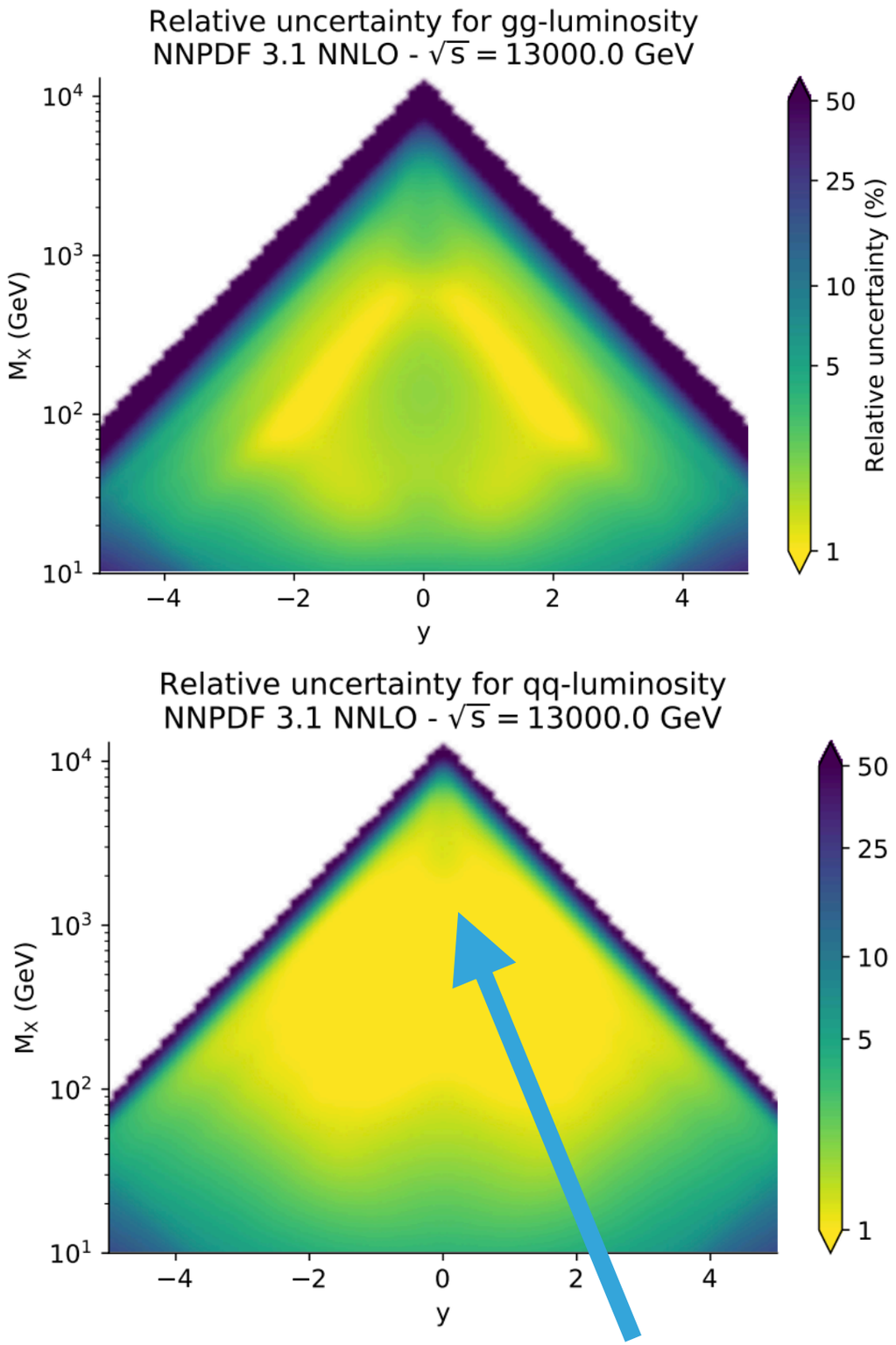
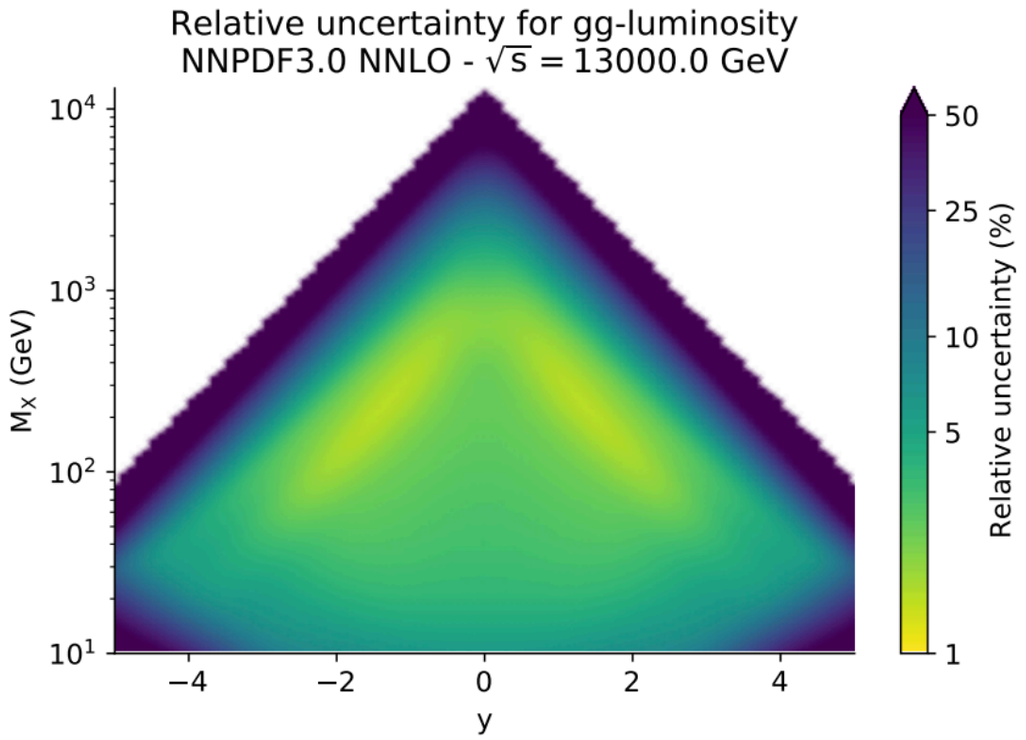


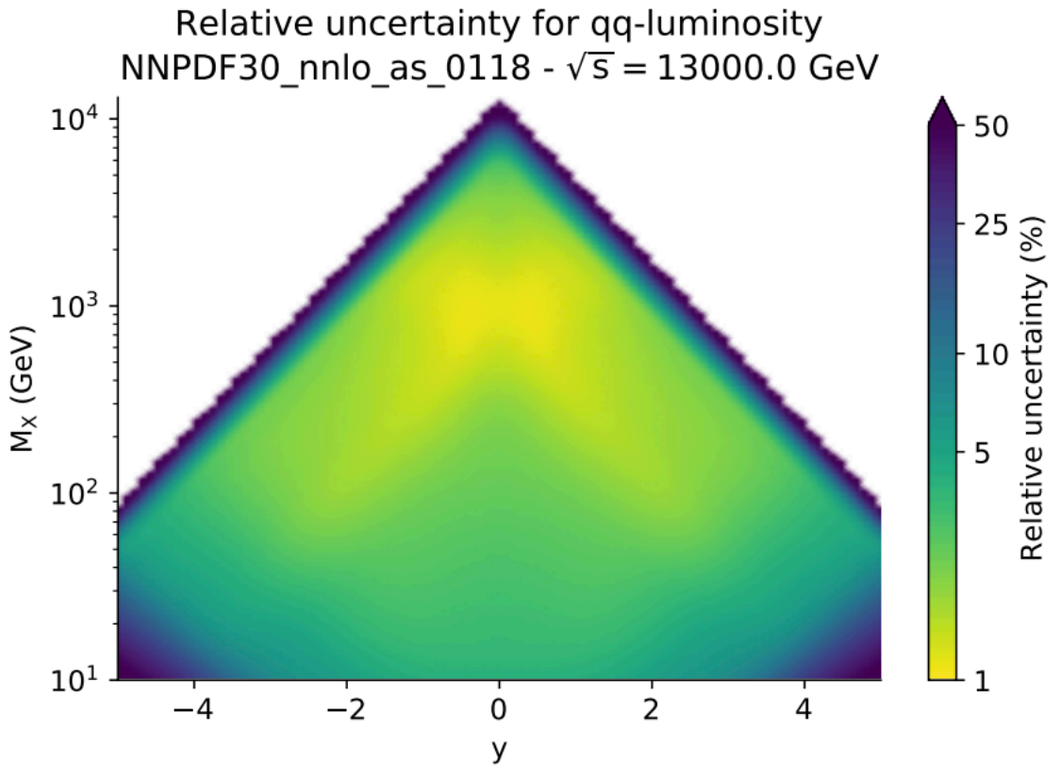


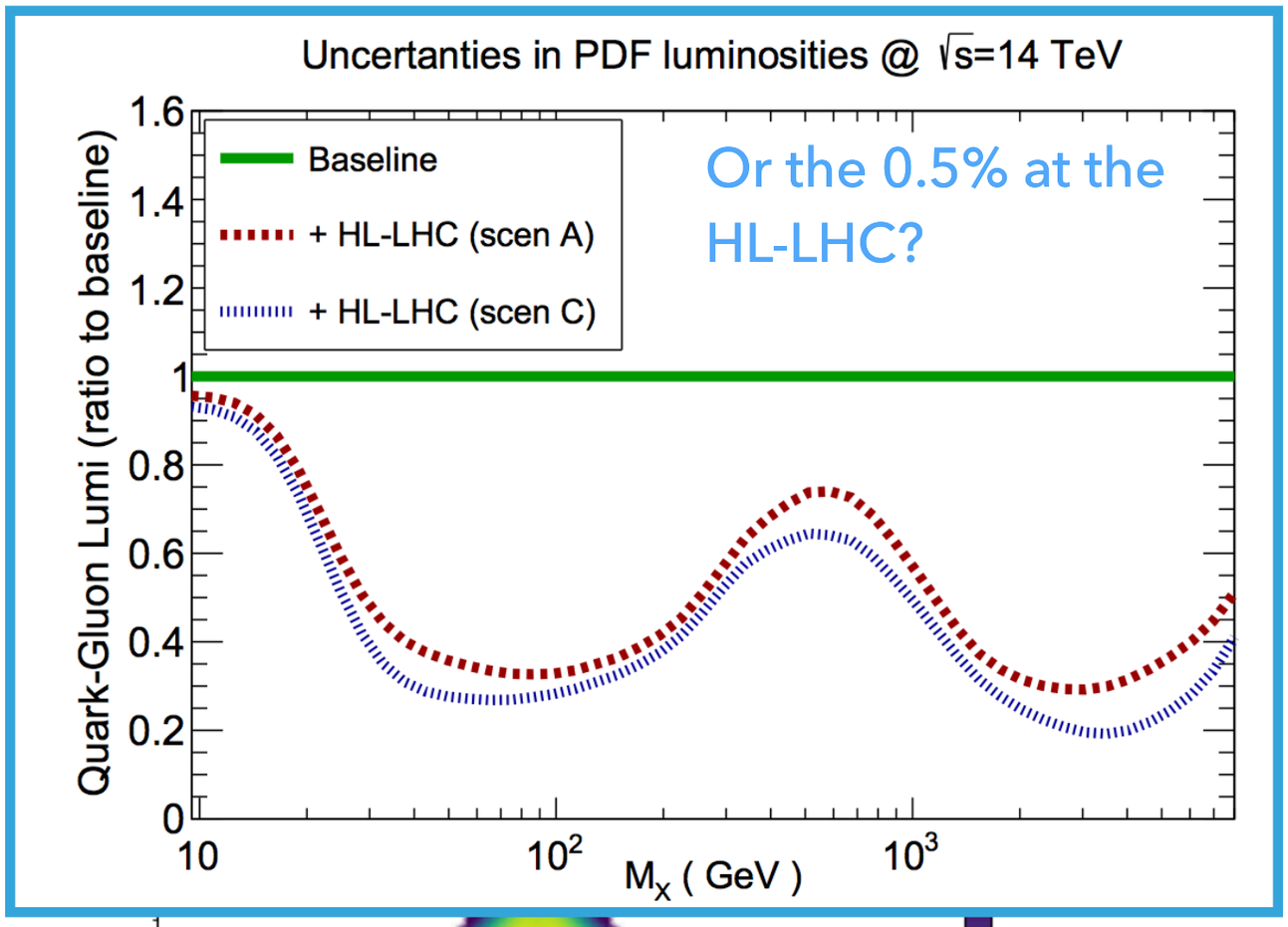
Ball et at, EPJC 77 (2017)

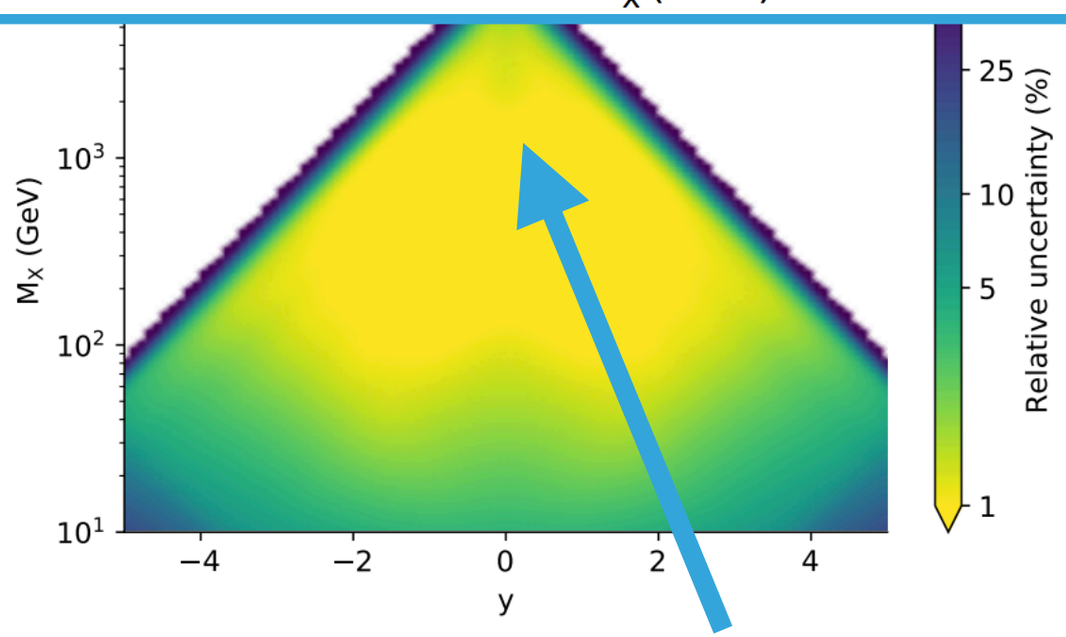
Can we trust 1% accuracy?

THE PRECISION CHALLENGE





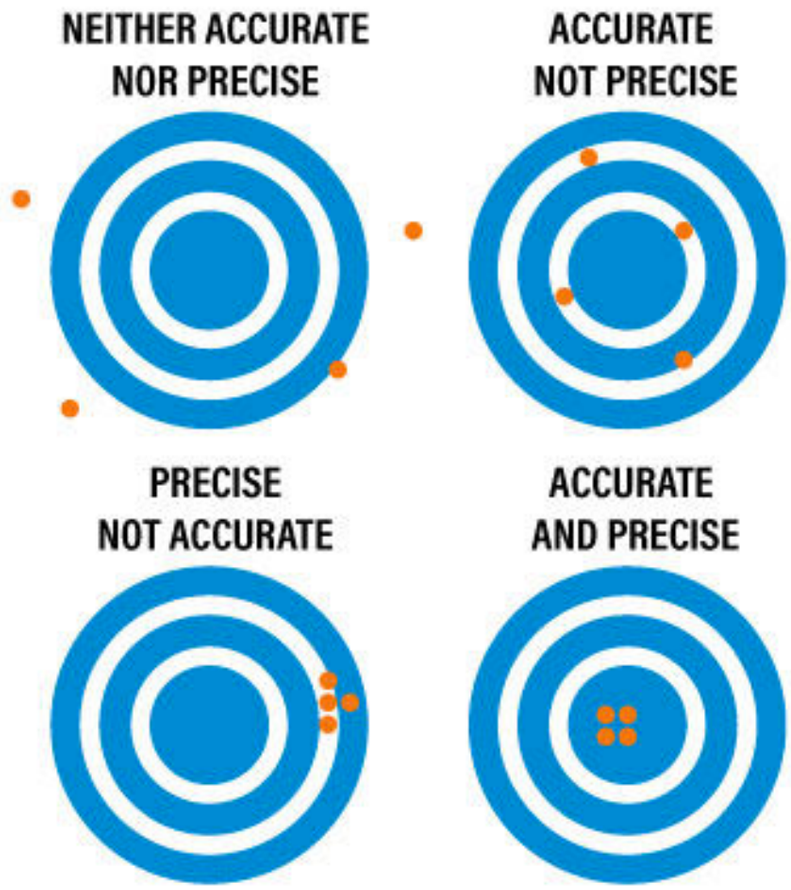


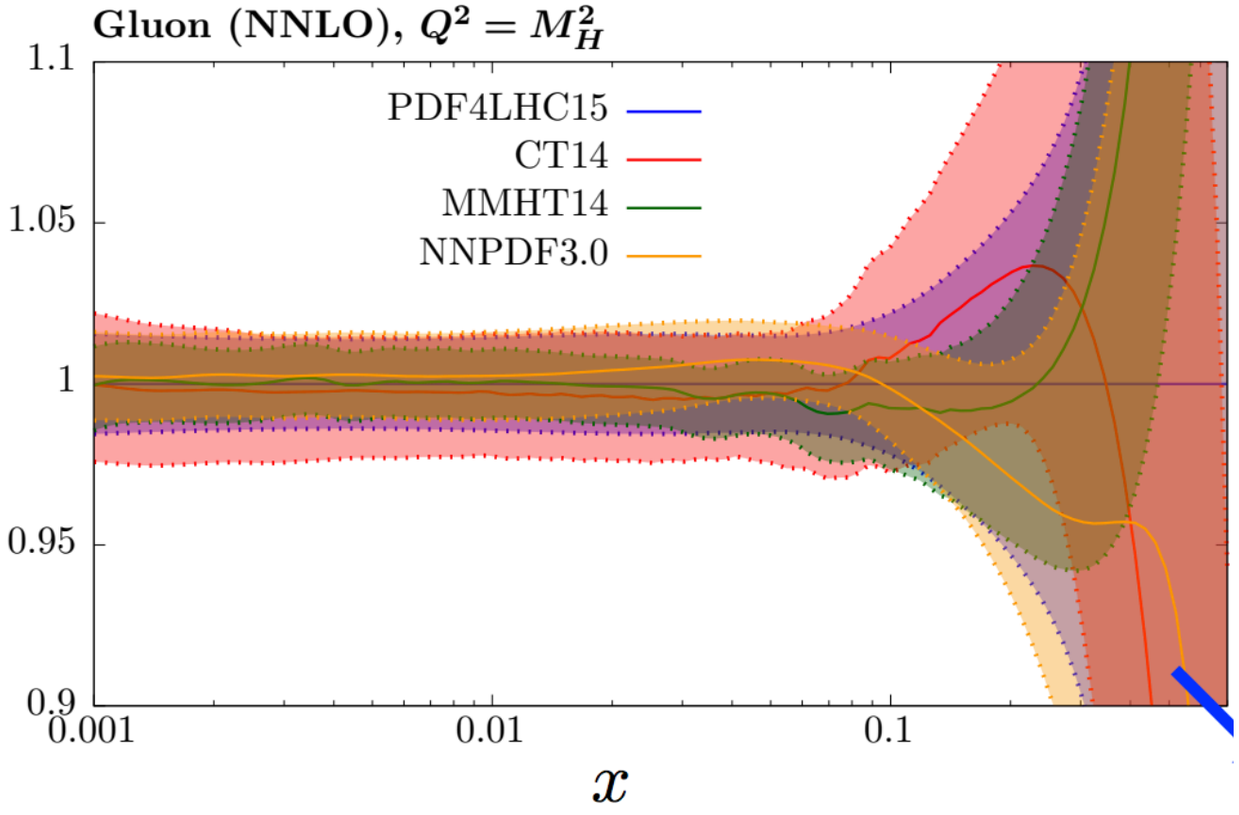


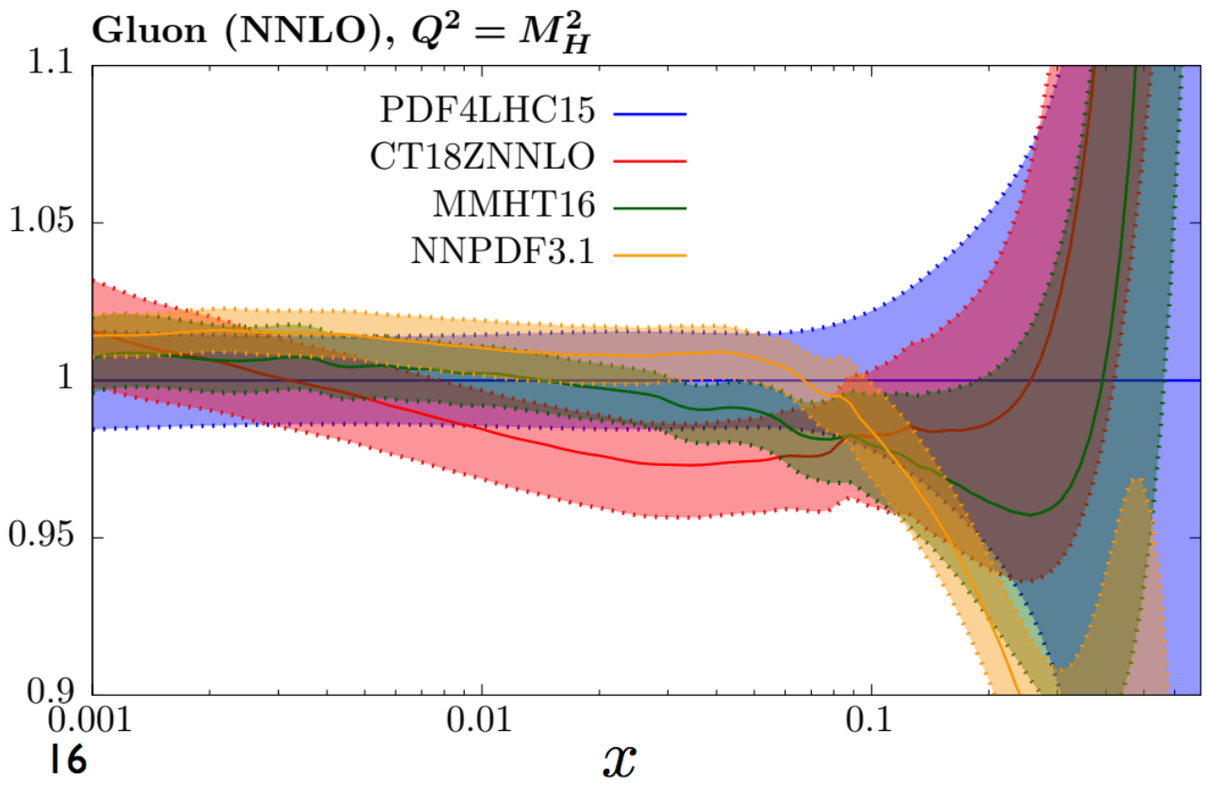
Ball et at, EPJC 77 (2017)

Can we trust 1% accuracy?

THE PRECISION VS ACCURACY CHALLENGE

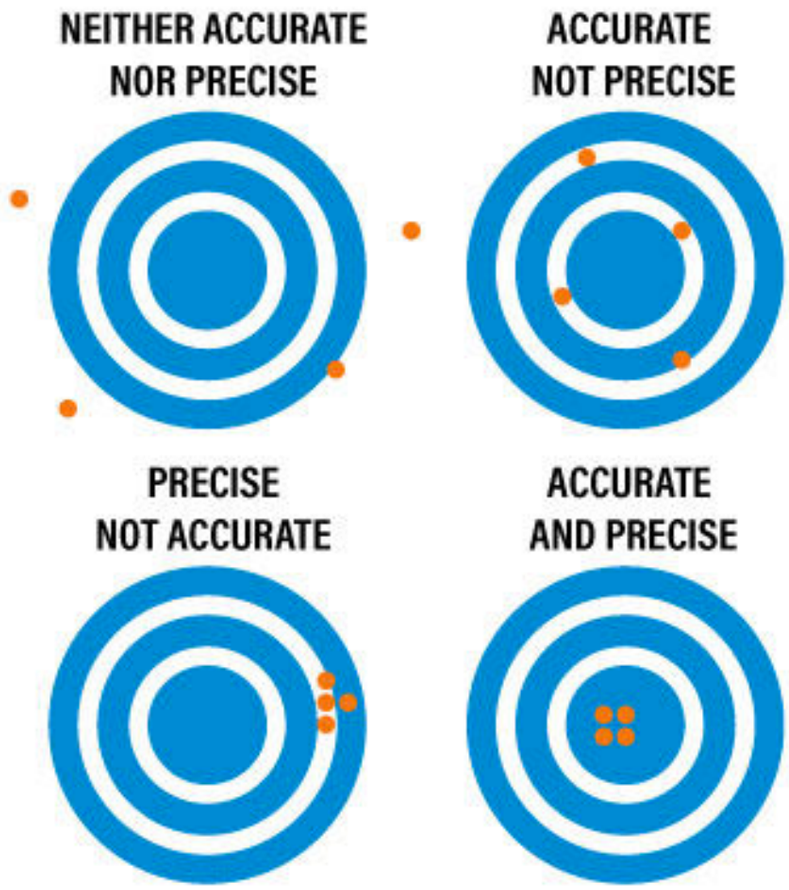


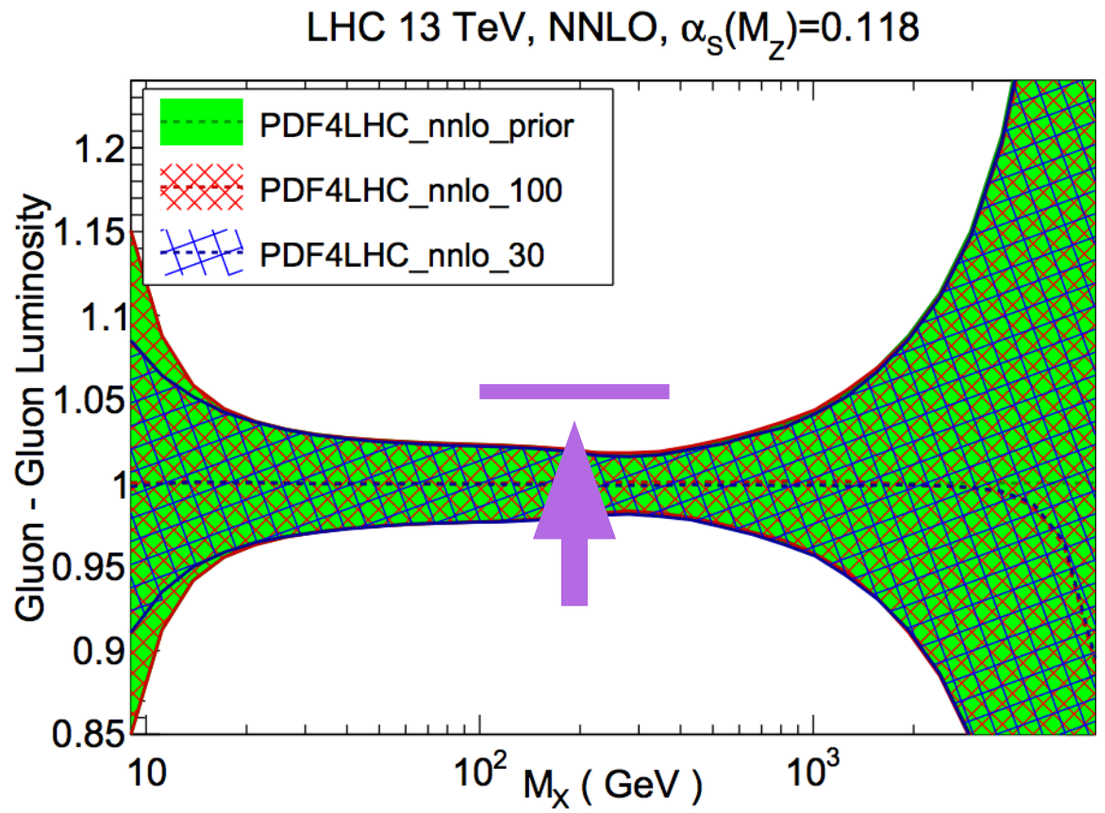




- CT18, "MMHT"2020 and NNPDF3.1 based on comparable data sets. Preliminary comparison of PDF sets suggests that differences among sets increased compared to 2015 combination => BENCHMARKING crucial!

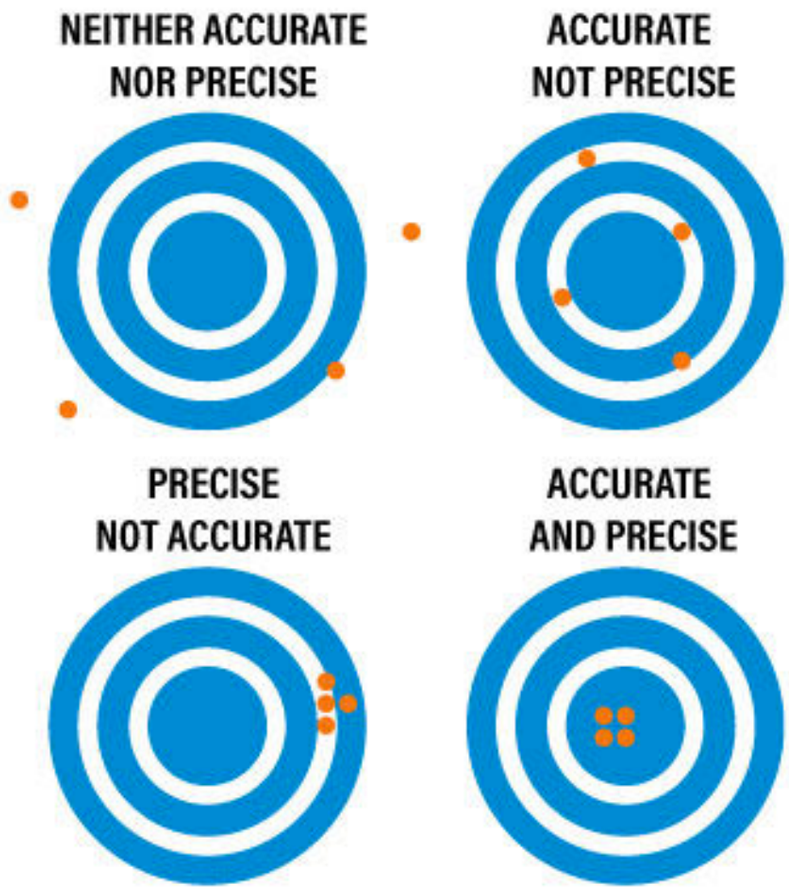
THE PRECISION VS ACCURACY CHALLENGE





➡ In updated PDF analysis, shift between old and new set may be larger than PDF uncertainties

THE PRECISION VS ACCURACY CHALLENGE



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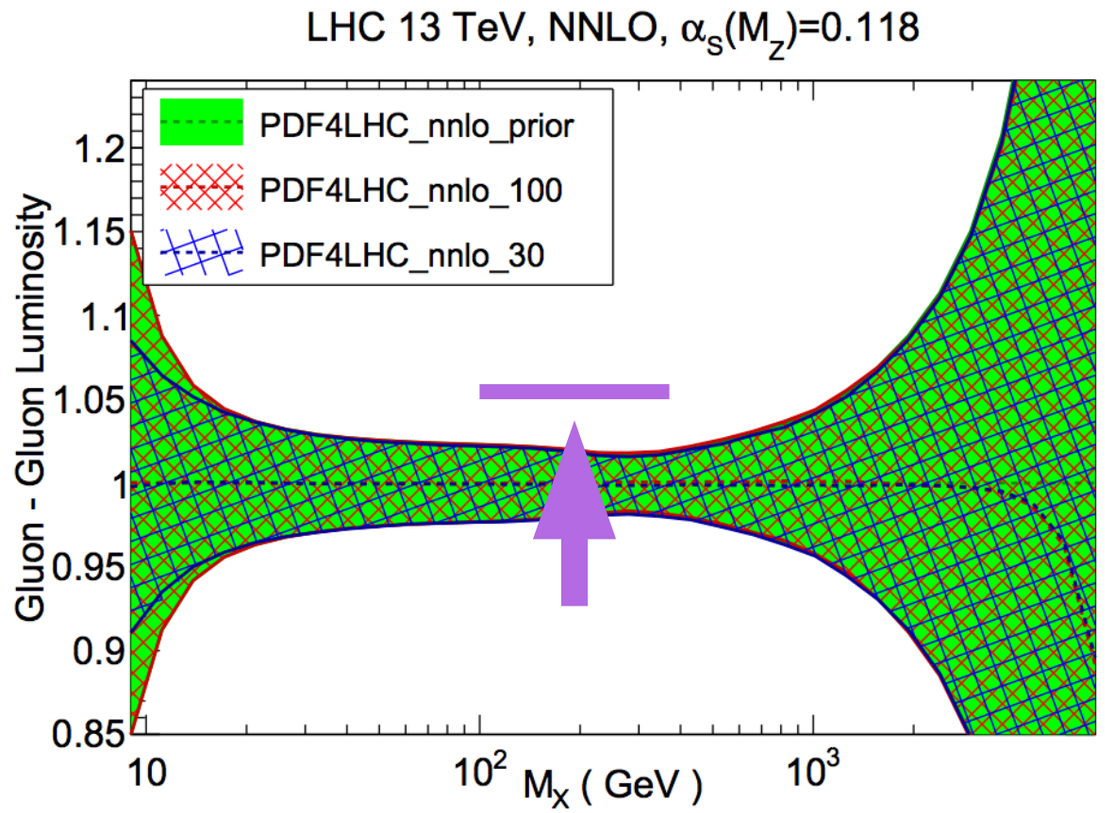
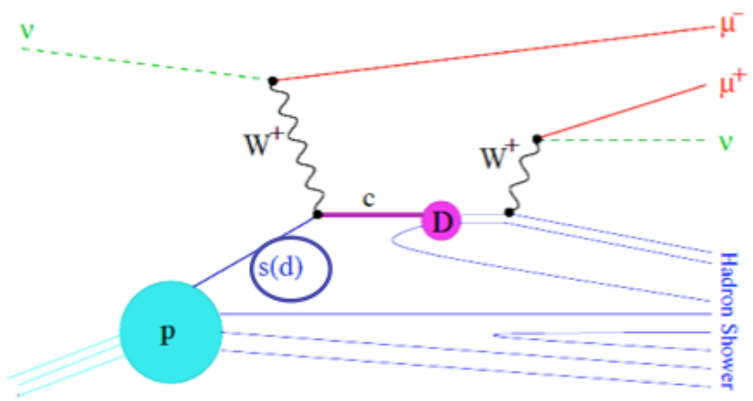


- Experimental data:
  - Inconsistency or tension
  - Highly correlated data
- Methodology:
  - Data-driven parametrisation change
  - Improvements in fitting methodology/minimisation
- Theoretical framework
  - Missing higher order uncertainties
  - BSM effects
  - Other corrections (nuclear)

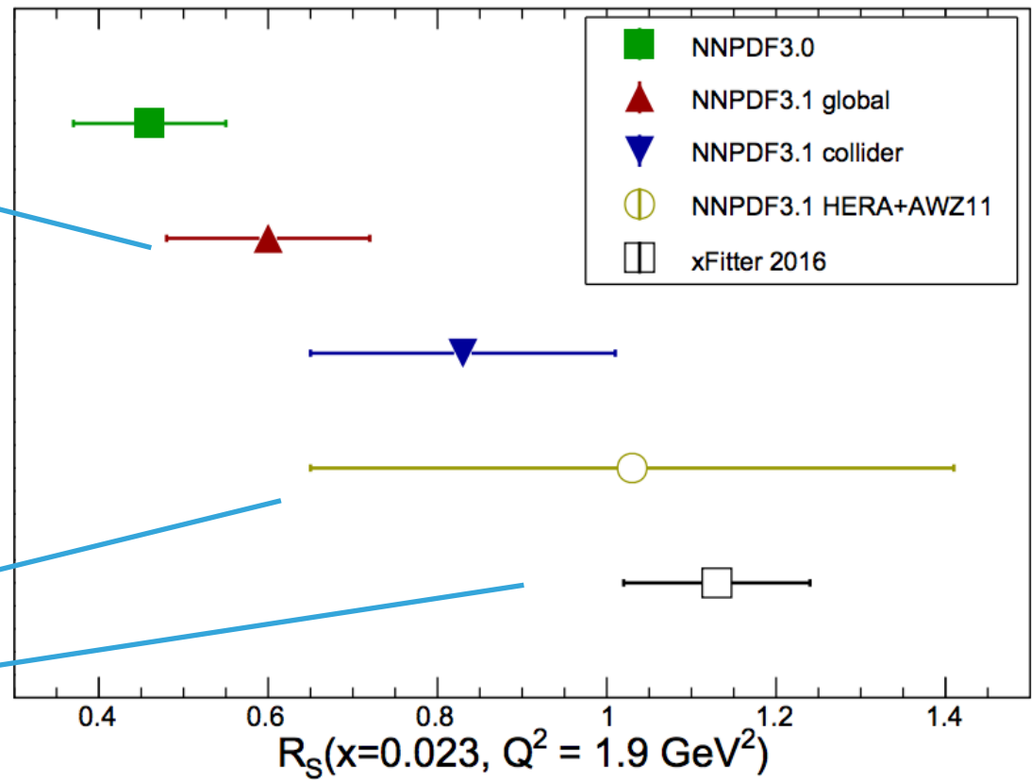
INCONSISTENCY OR TENSION IN DATA

Dominated by NuTeV data

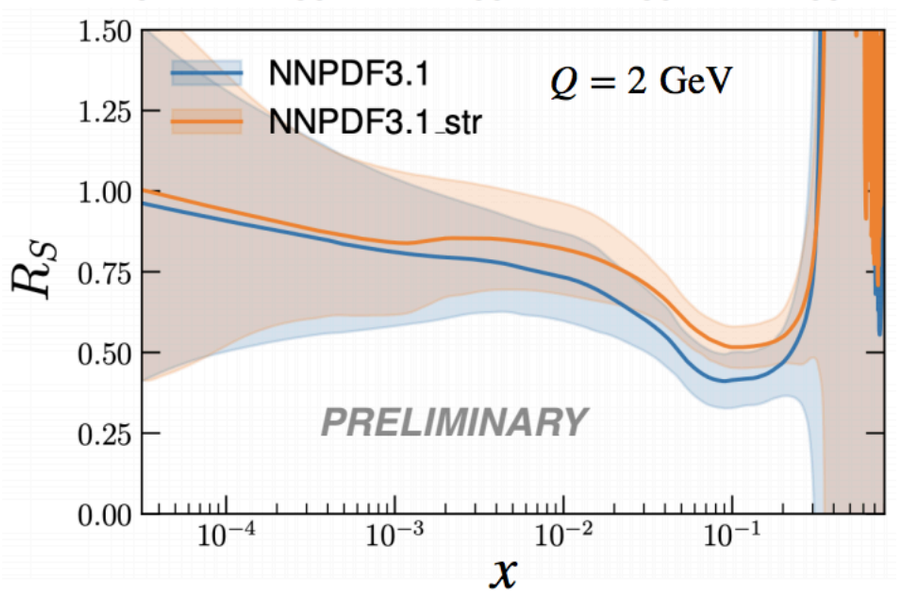


Both include HERA & LHC precise W/Z data but use different parametrisation and methodologies

$R_S = (s + \bar{s}) / (\bar{u} + \bar{d})$ Ball et at, EPJC 77 (2017)



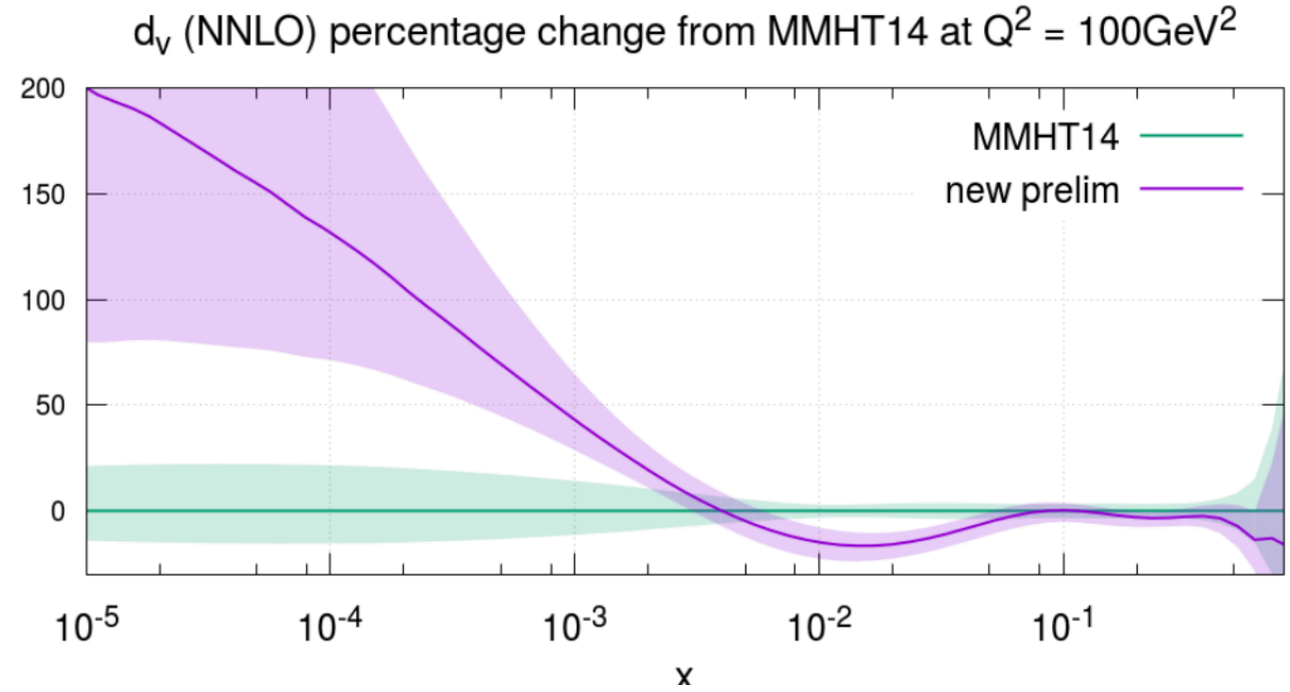
Work in progress towards including all strange-sensitive measurements in global fit: NuTeV and NOMAD DIS (with NNLO theory), LHC W,Z, ATLAS and CMS W+c production at 7 and 13 TeV shows no tension **[Faura, Iranipour, Nocera, Rojo, MU]**



METHODOLOGY: PARAMETRISATION

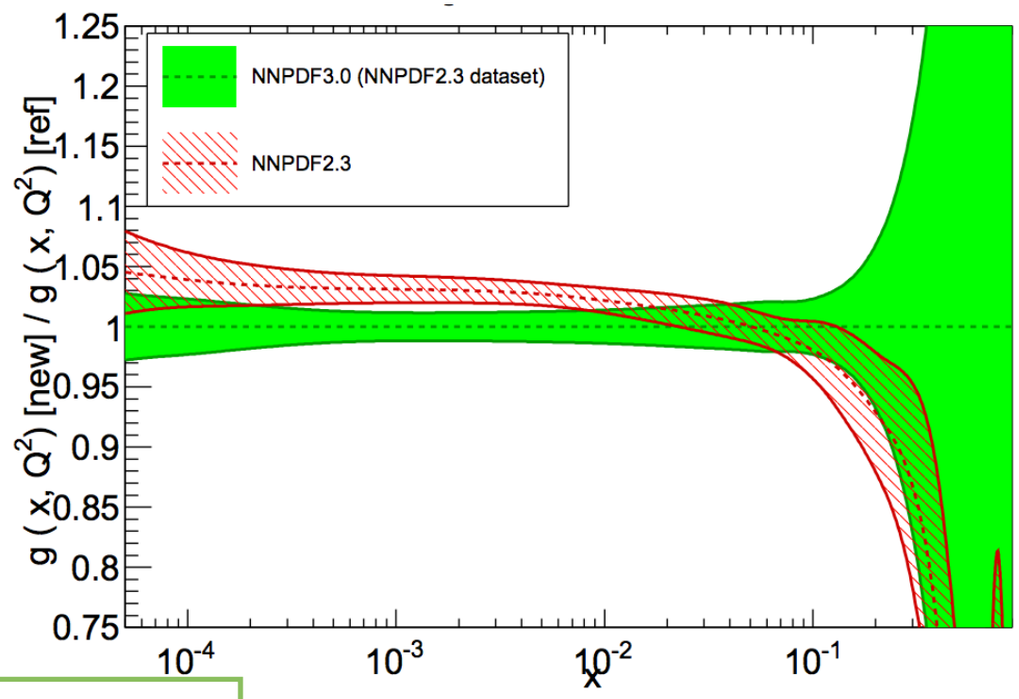
"MMHT"2020 analysis: Extended parametrisation of PDFs based on Chebyshev polynomials.
Down valence quark changes quite dramatically and reduces tension among data

R. Thorne, PDF4LHC September 2019

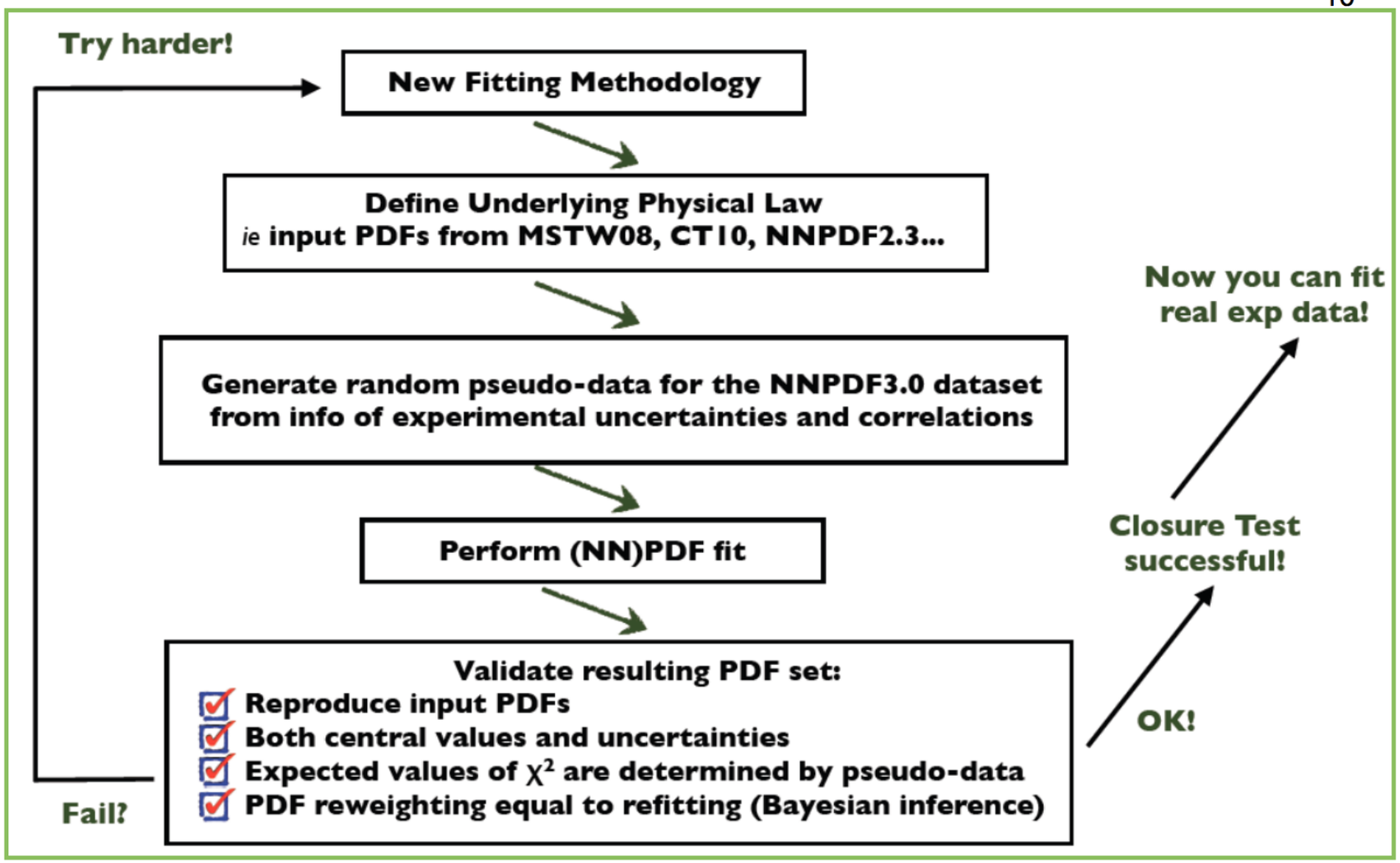


METHODOLOGY: FIT AND MINIMISATION

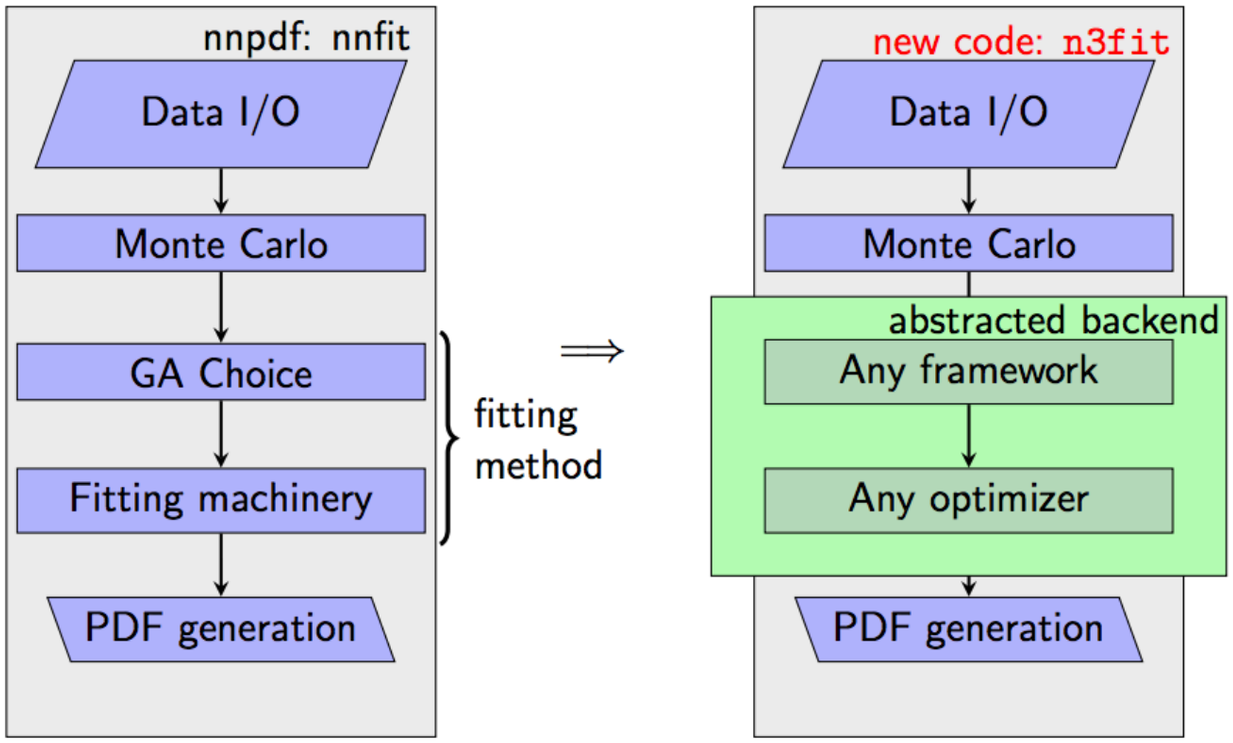
NNPDF2.3 to 3.0 shift due to change in methodology!



Crucial for PDF methodology to be validated by closure test!



METHODOLOGY: FIT AND MINIMISATION



New: Methodology fitting itself via hyper-parameter scan to let the computer decide automatically the best methodology by scanning over thousands of hyper-parameter combinations and define a reward function to grade the methodology

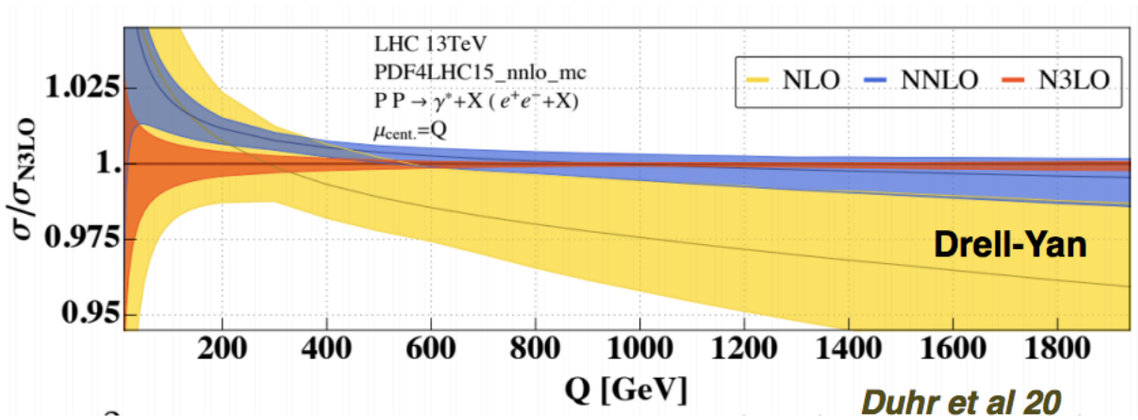
S. Carrazza, J. Cruz-Martinez, Eur.Phys.J. C79 (2019) no.8, 676

MISSING HIGHER ORDER UNCERTAINTIES

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

- Standard global PDF fits based on fixed-order NNLO QCD calculations
- **N3LO is now the precision frontier for theoretical predictions in PDF fits**

- N3LO splitting functions and DIS coefficient functions available but not yet implemented in evolution codes.
- N3LO partonic cross sections not yet available for most pp processes (apart from Drell-Yan) but some approximations available.



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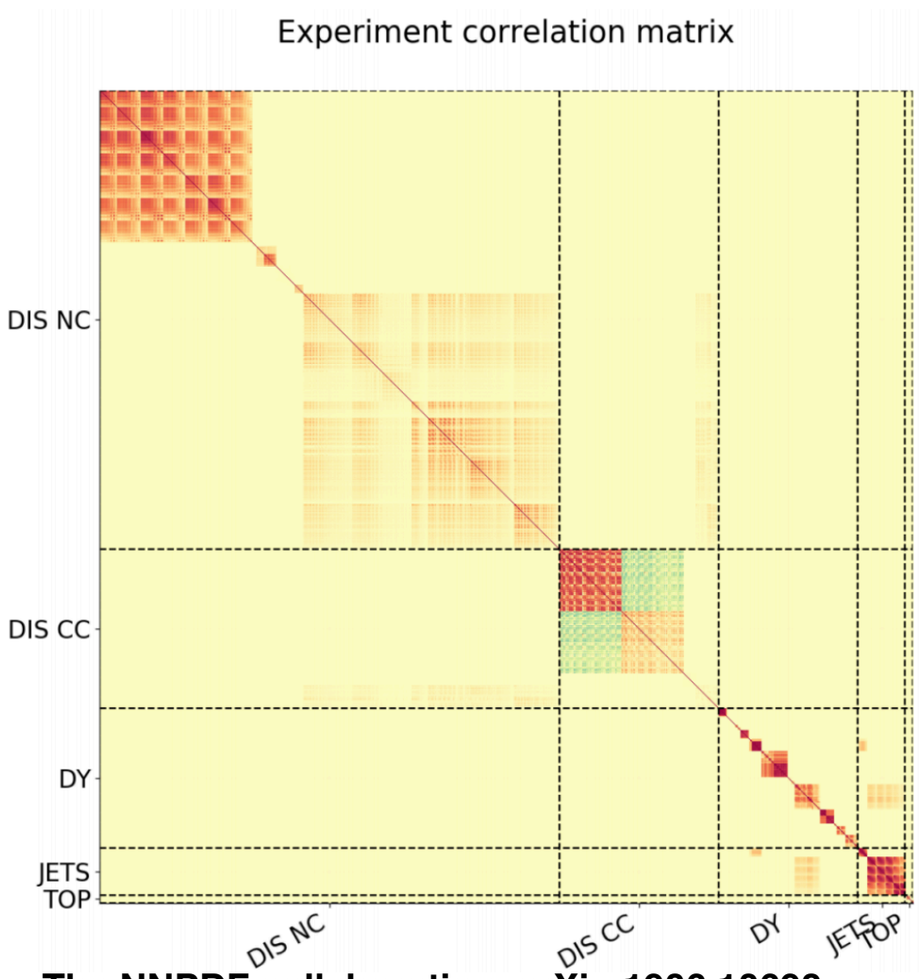
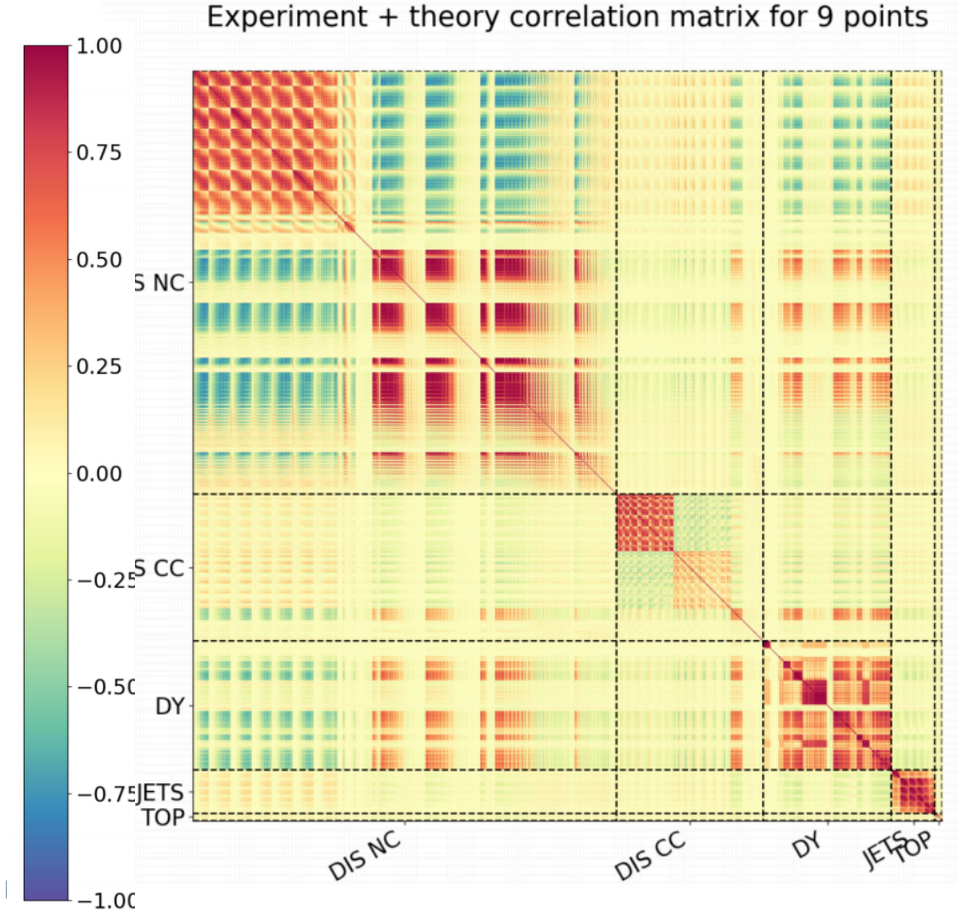
- Standard global PDF fits based on fixed-order NNLO QCD calculations
- **N3LO is now the precision frontier for theoretical predictions in PDF fits**
- **Global fits including MHOU reveal impact of missing higher orders in PDF fits**

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





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

The NNPDF collaboration, arXiv:1906.10698

MISSING HIGHER ORDER UNCERTAINTIES

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

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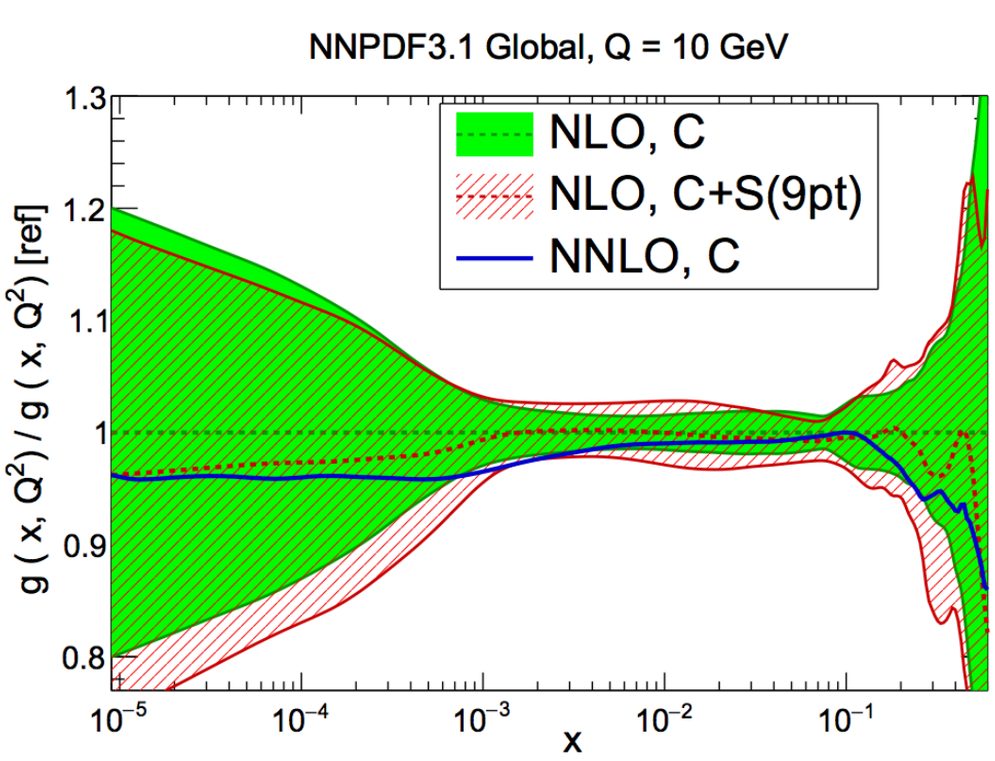
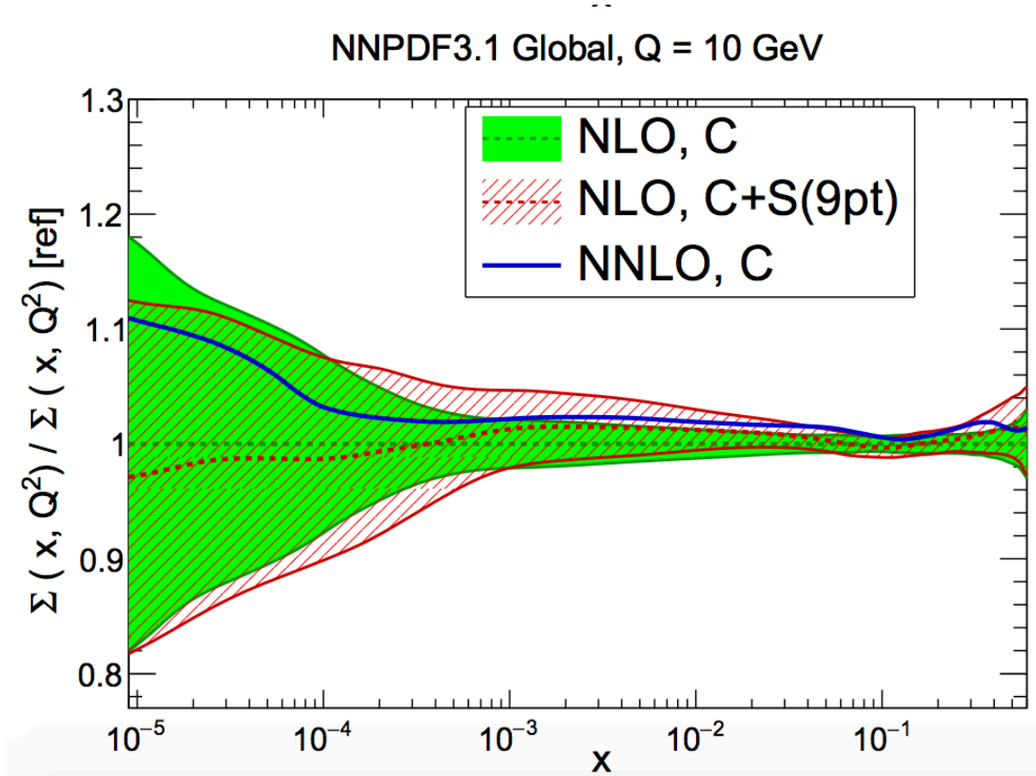
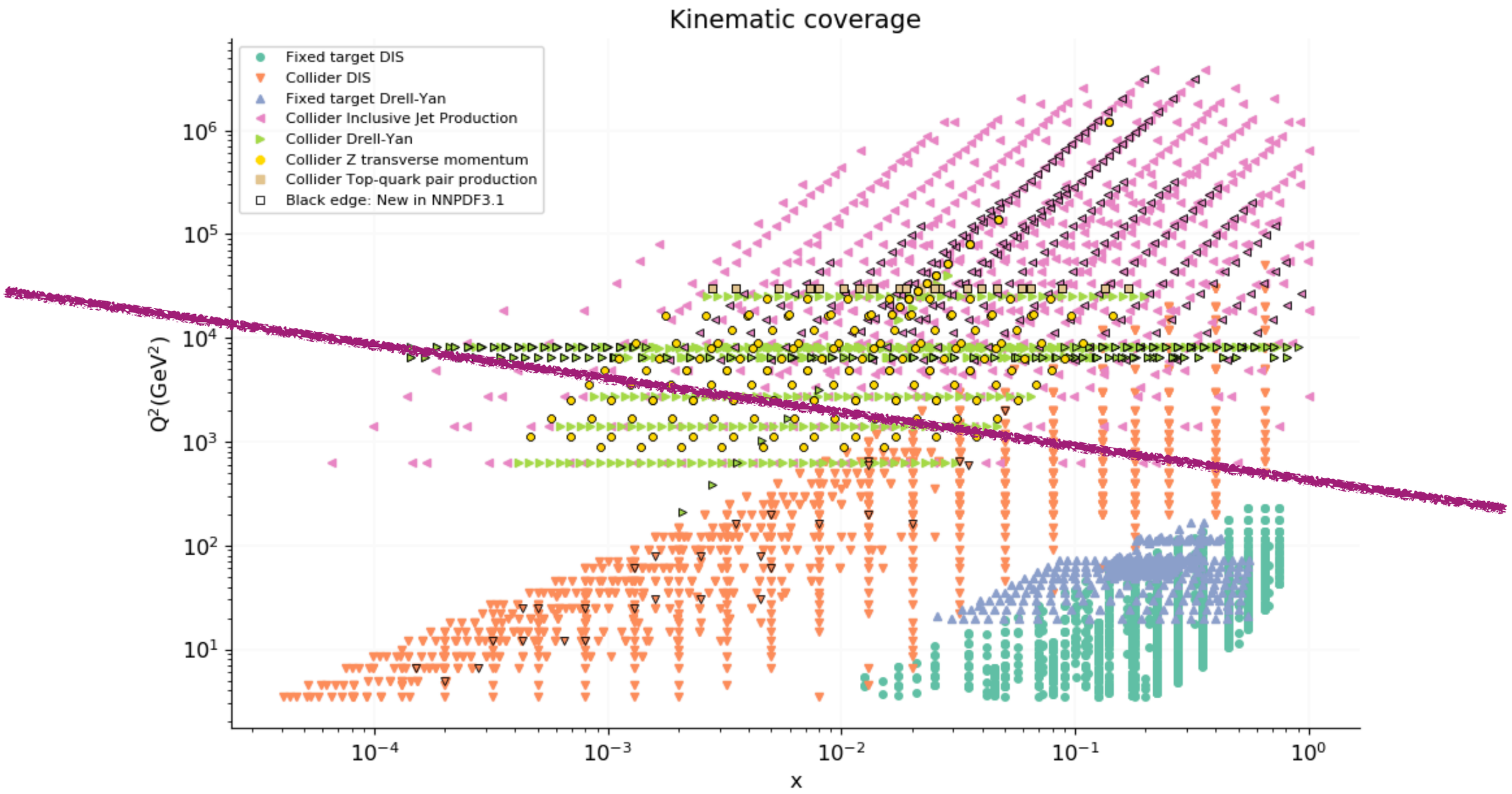




BSM EFFECTS



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

Carrazza, Degrande, Iranipour, Rojo, MU, Phys.Rev.Lett. 123 (2019) no.13, 132001
Greljo, Iranipour, Moore, Rojo, MU, Voisey in progress

Simultaneous determination of PDFs and dim-6 SMEFT Wilson coefficients in progress

CONCLUSIONS AND OUTLOOK

- Precision physics frontier at HL-LHC opens up new fascinating challenges also in the field of PDF determination
- Precise and accurate understanding of the proton structure is key to achieve accurate theoretical predictions
- HL-LHC projection: reduction of PDF uncertainties by factor 2-3, but to achieve this goal benchmark among PDF sets and thorough scrutiny of each PDF analysis is a must.
- Need: robust methodology (e.g. closure tests) and increased precision in theoretical predictions in PDF fits (N3LO, estimate of missing higher order uncertainties, EW corrections, photon and lepton PDFs)
- News: estimate of theoretical uncertainties associated with missing higher order and nuclear models in PDF fits, fit of the methodology, new tools to quantify the effects of new data.
- General aim towards global fits of all parameters that enter QCD analyses (PDFs + α_S, PDFs + EW parameters, PDFs + BSM EFT parametrisation…)
- Broad effort and cross-talk essential to advance and face these challenges

ADDITIONAL MATERIAL

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

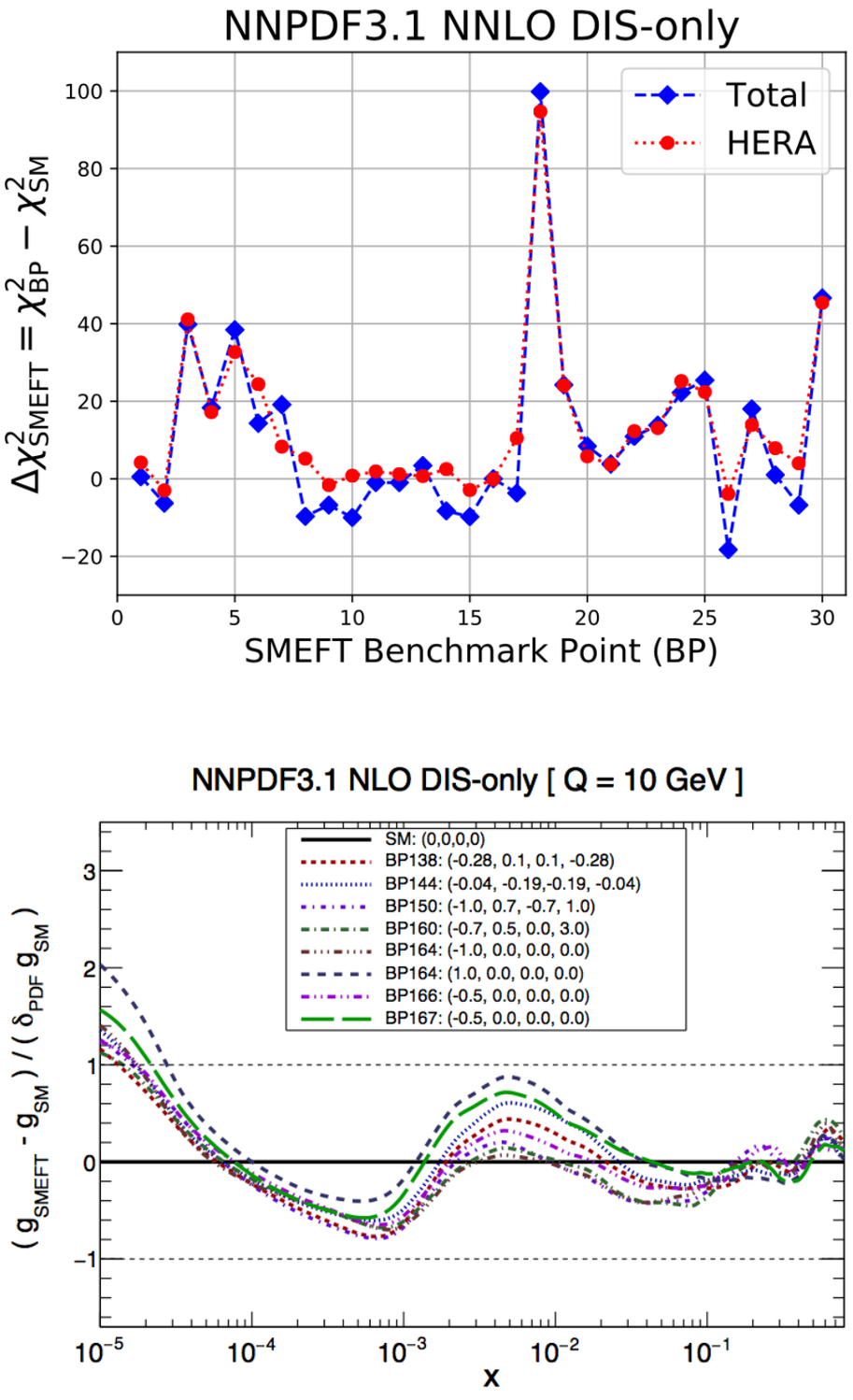
Upgrades

* 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

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

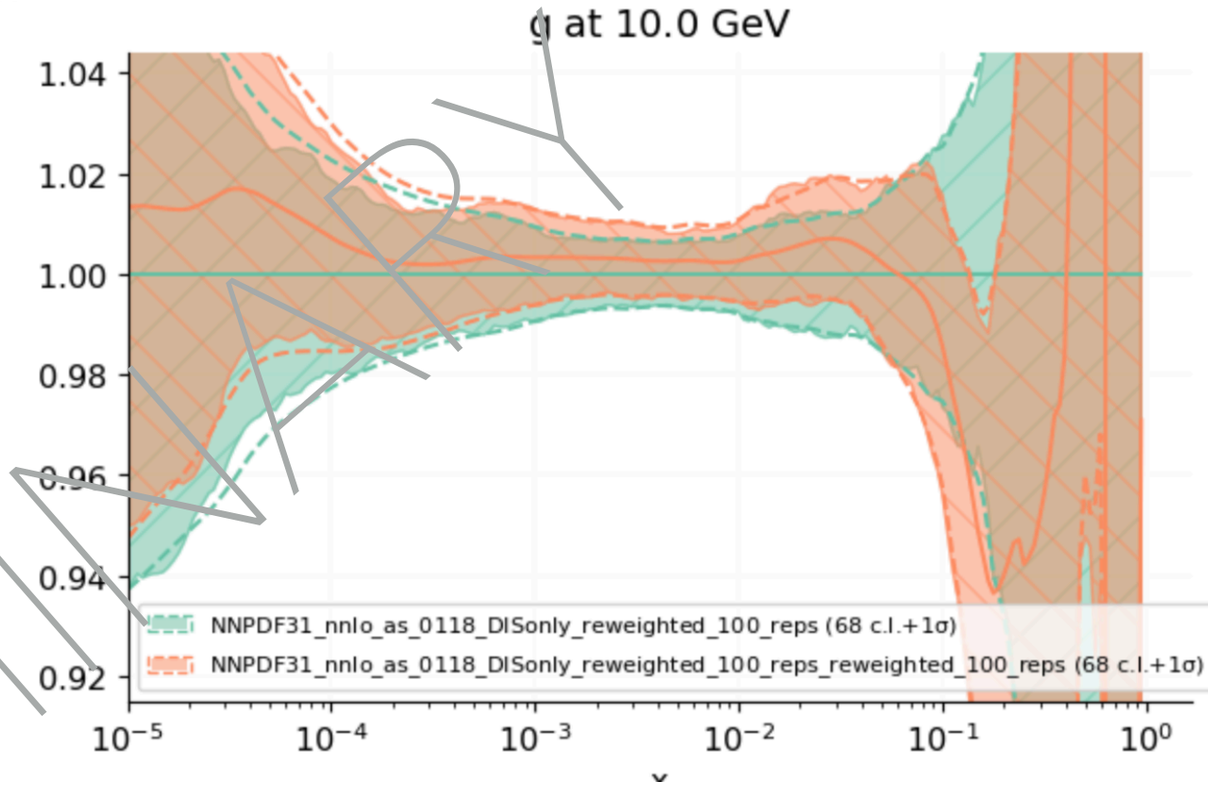
  - ✦ Q: (How) would the bounds change if I was using PDFs that include the same operators that I am fitting?

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

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

TOWARDS SIMULTANEOUS FITS

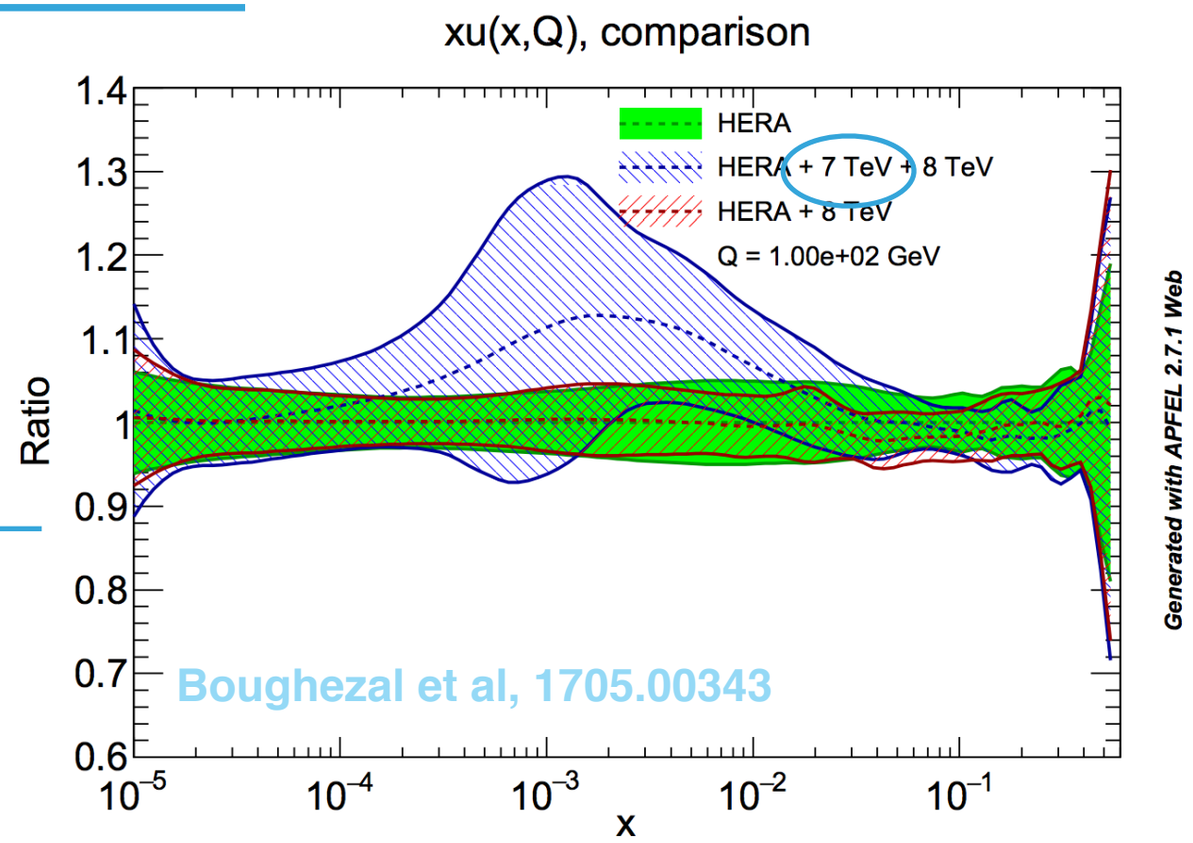
- Simultaneous parametrisation of modified PDFs and Wilson coefficients based on convex optimisation and linearisation displaying extremely promising results
- Could be the basis for global fits of SMEFT coefficients giving the opportunity to fit them along PDFs and other parameters of the SM.



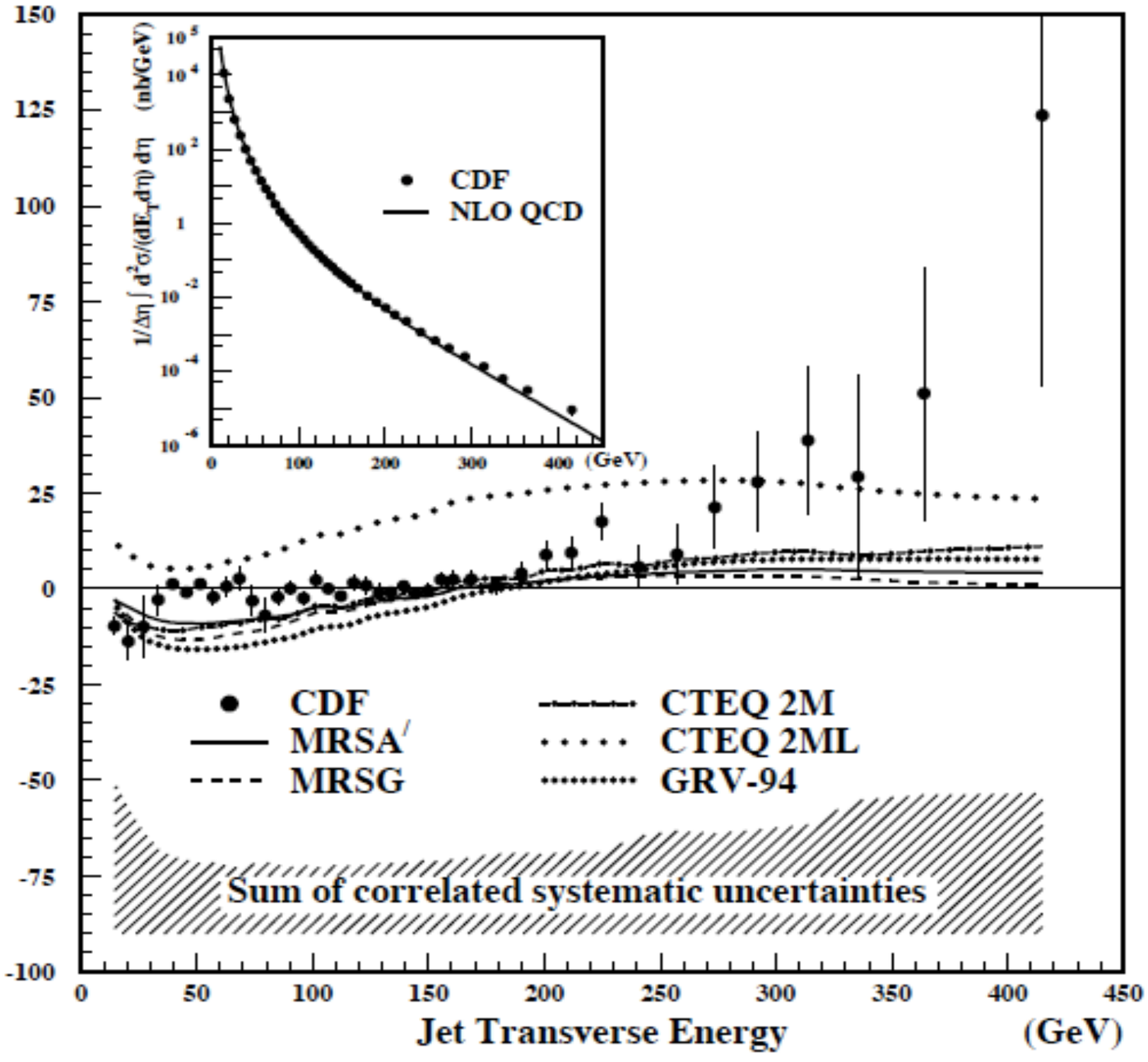
Flavour	Bounds
up	(-0.6997467104050734, 0.4796822557531577 6)
down	(-5.5843429714279536, -0.6417132759778587)
strange	(-9.930852611950987, 0.3698107553888288)
charm	(-10.705650270152223, -3.5562328427918866)

THE PRECISION VS ACCURACY CHALLENGE

Normalised Z pT distribution at 7 TeV inconsistent with other data



THE ROLE OF PDF UNCERTAINTIES



Fake BSM signals

Historia magistra vitae est

Discrepancy between QCD calculations and CDF jet data (1995)

At that time there was no information on PDF uncertainties
and the theoretical prediction strongly depends on gluon shape at x>0.1

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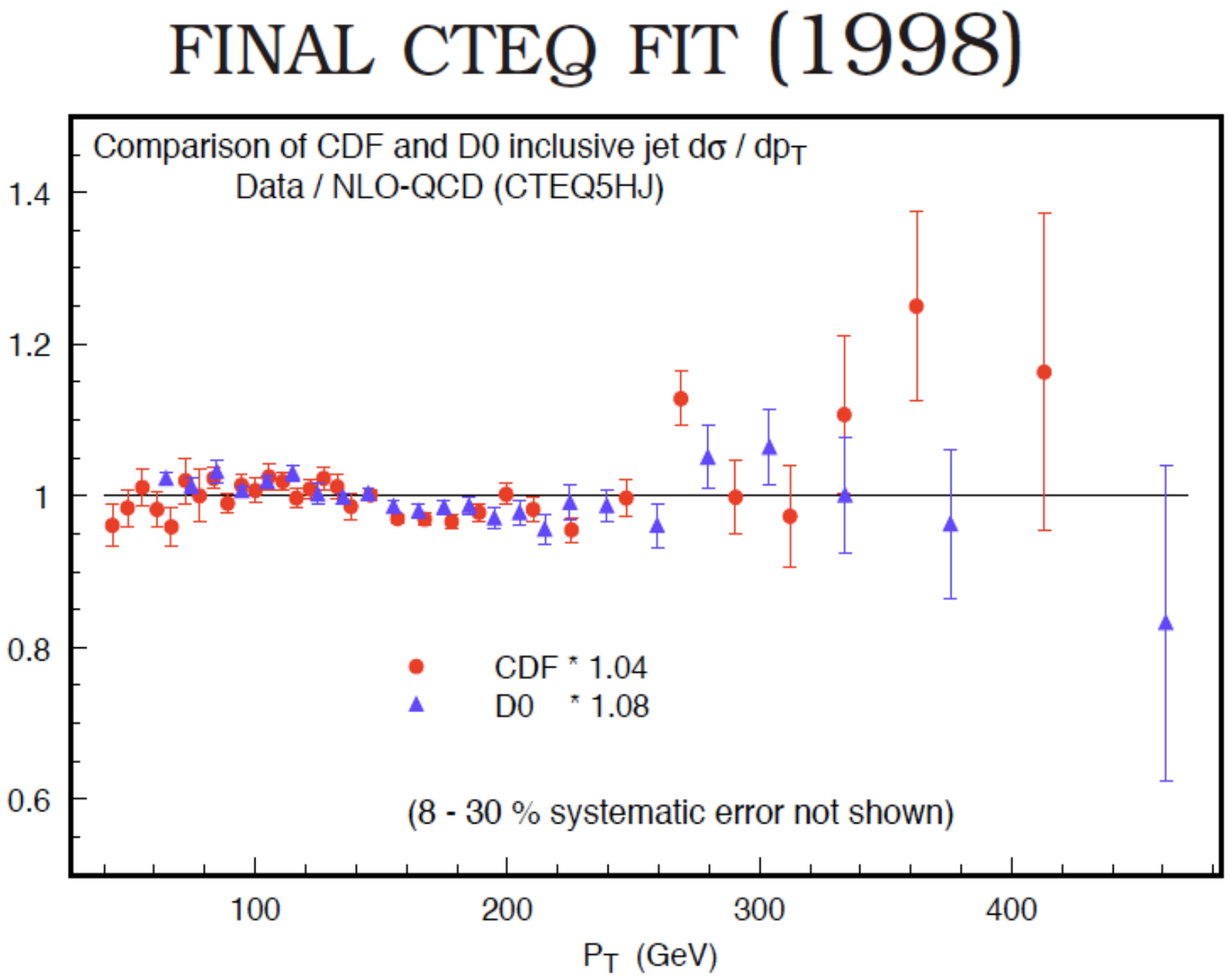

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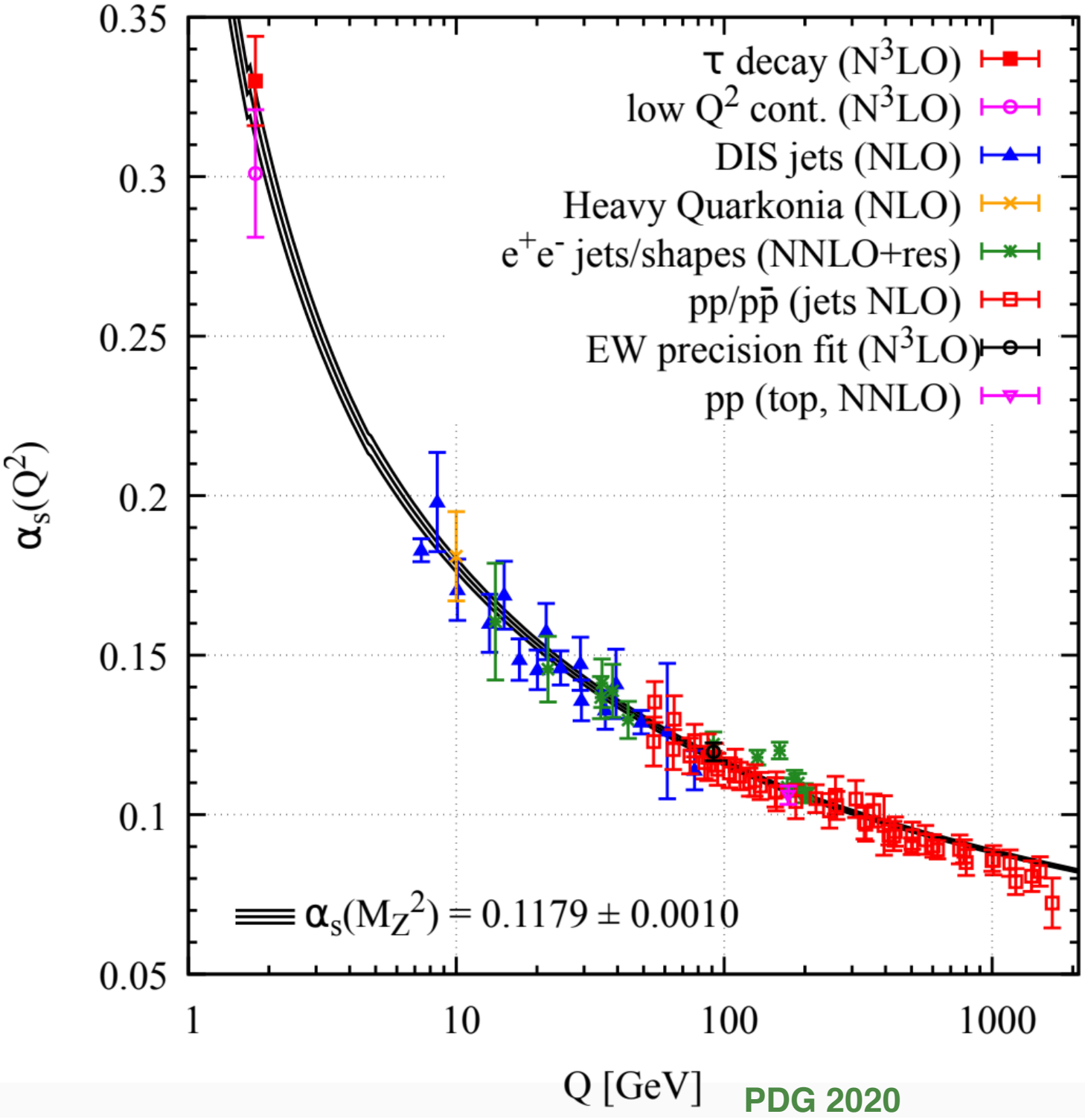
CTEQ re-performed the parton fit by including the jet data and the discrepancy was removed.

A QUICK DIGRESSION: PDFS AND ALPHA$_S$

- PDFs and α_s strongly correlated (PDF evolution with the scale and hard cross sections)
- Cleanest determinations of α_s from processes that do not require knowledge of the PDFs
- A determination of α_s jointly with the PDFs has advantage that it is driven by the combination of many experimental measurements from several different processes.



PDG 2020

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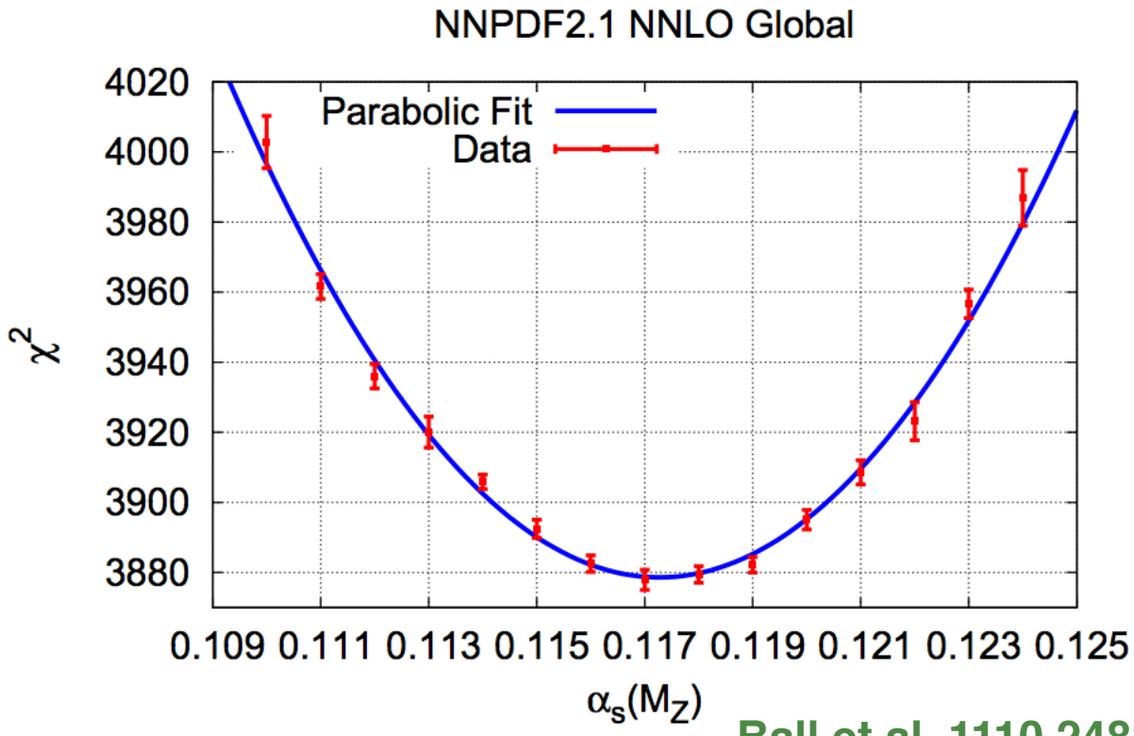
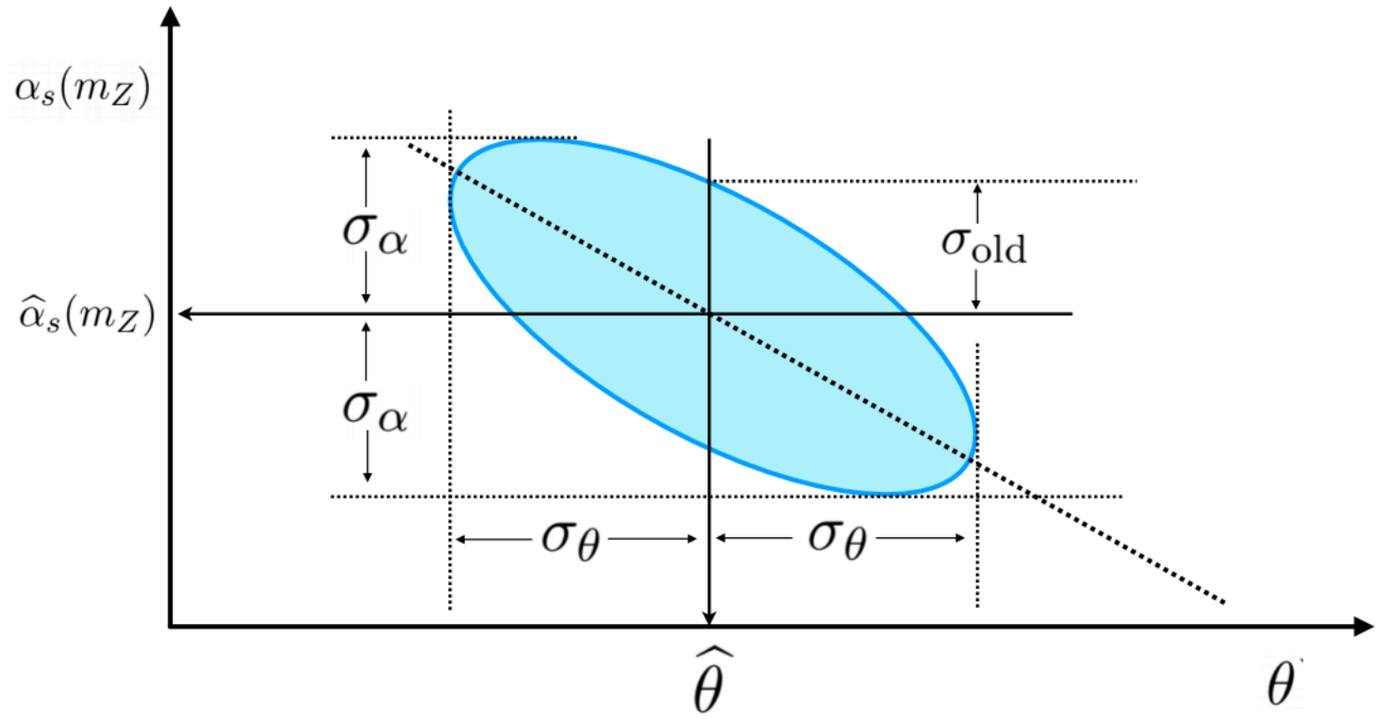


Ball et al, 1110.2483



- Early determinations involve a scan over α_s
- Recent simultaneous determination of PDF and α_s using correlated replica method
- Many determination of α_s from analyses of specific LHC processes have been published recently (from tt~, Z and W production, jets)
- How reliable are such partial determination of α_s ?

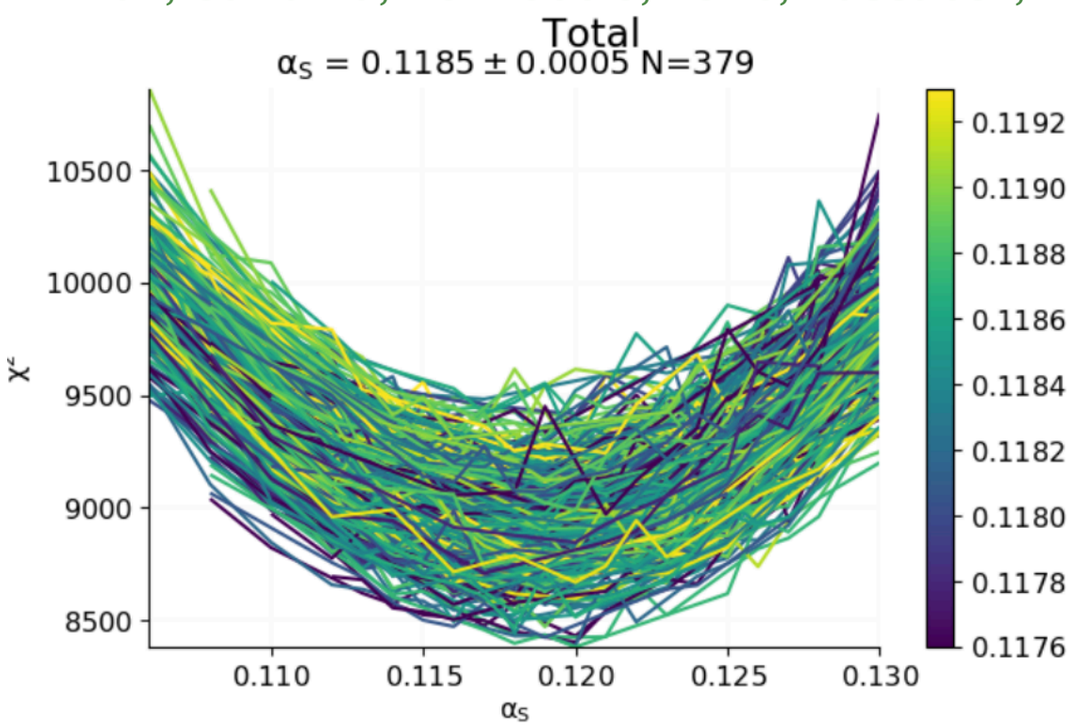
Ball, Carrazza, Del Debbio, Forte, Kassabov, Rojo, Slade, MU 1802.03398

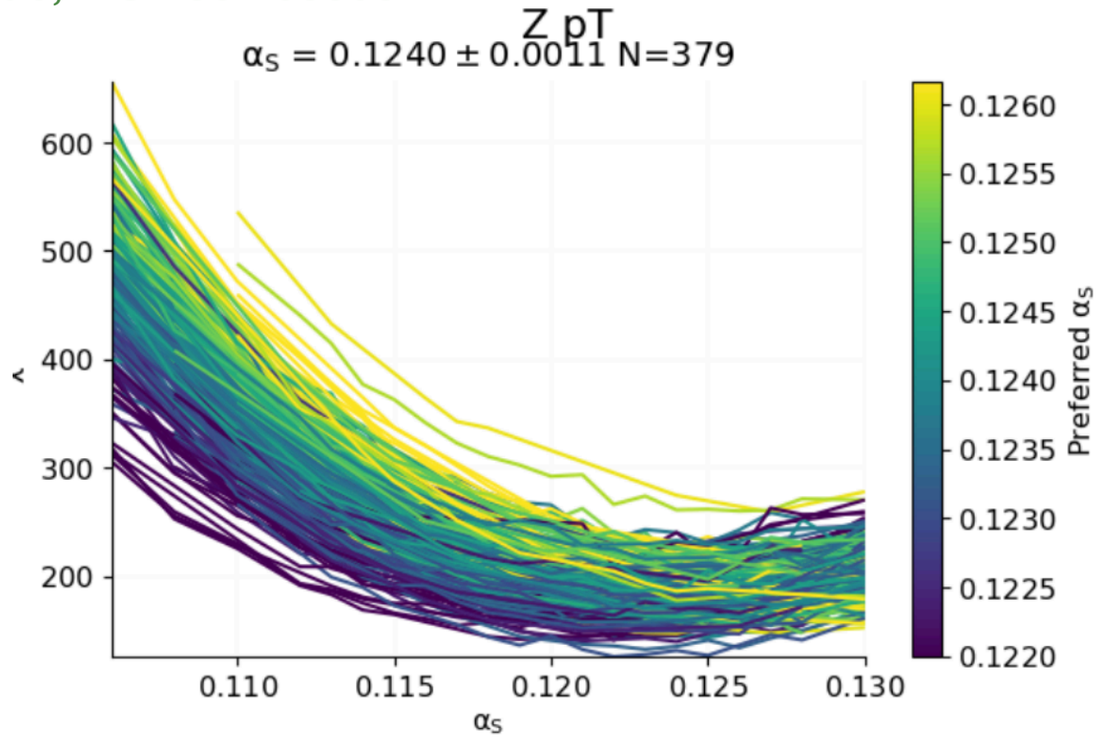
A QUICK DIGRESSION: PDFS AND ALPHA$_S$

Forte, Kassabov 2001.04986

We show that any determination of the strong coupling α_s from a process which depends on parton distributions, such as hadronic processes or deep-inelastic scattering, generally does not lead to a correct result unless the parton distributions (PDFs) are determined simultaneously along with α_s. We establish the result by first showing an explicit example, and then arguing that the example is representative of a generic situation which we explain using models for the shape of equal χ^2 contours in the joint space of α_s and the PDF parameters.

Ball, Carrazza, Del Debbio, Forte, Kassabov, Rojo, Slade, MU 1802.03398





These results point towards the need of new generation of global fits, in which all ingredients that enter theoretical predictions are treated consistently.