PARTON DISTRIBUTIONS
AND THE PRECISION FRONTIER AT THE LHC

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DIS2017, Birmingham

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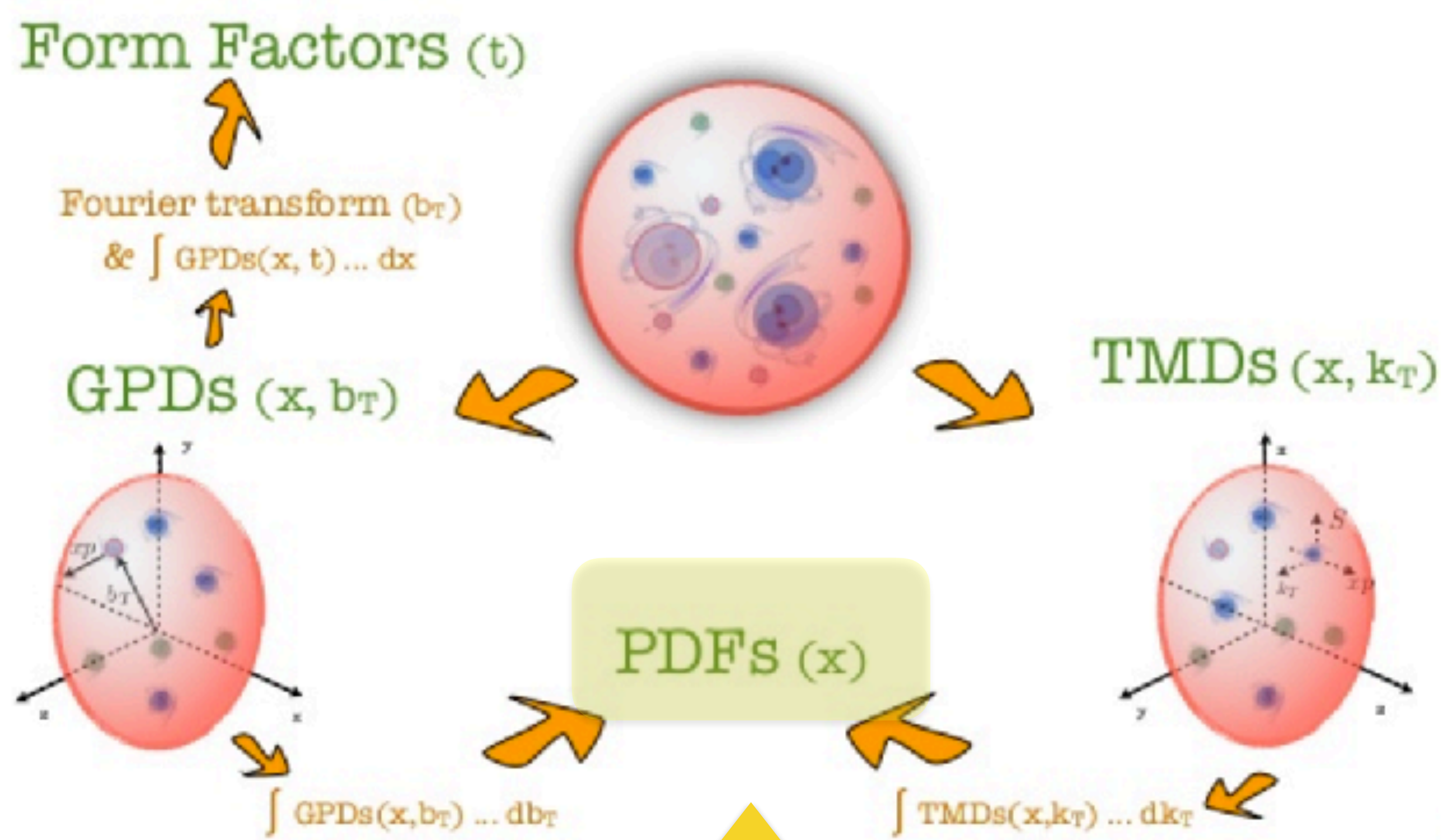
Disclaimer

- ☑ Not a systematic review of recent developments in PDF analyses, rather a personal review of most compelling issues and challenges in determination of unpolarised collinear Parton Distribution Functions of the proton
- ☑ Apologies for all interesting recent developments that I won't have time to mention!



E.-M. Kabuss talk
A. Bacchetta's talk

This talk

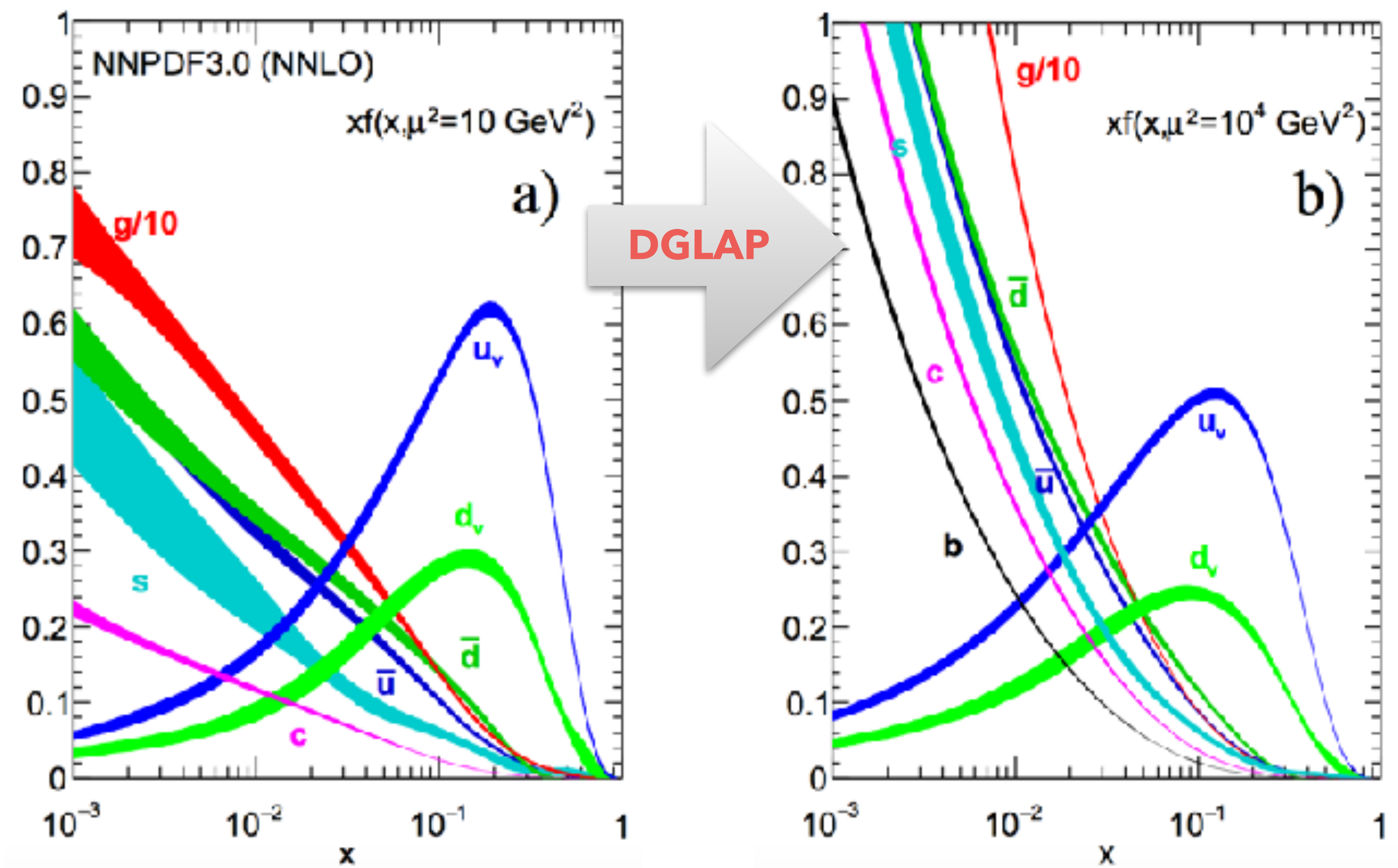
Collinear Factorisation Theorem

$$\frac{d\sigma_H^{ep\to ab}}{dX} = \sum_{i=-n_f}^{+n_f} \int_{x_B}^{1} \frac{dz}{z} \boxed{f_i(z,\mu_F)} \frac{d\hat{\sigma}_i^{ei}}{dX}(zS, \alpha_s(\mu_R), \mu_F) + \mathcal{O}\left(\frac{\Lambda^n}{S^n}\right)$$

$$\frac{d\sigma_H^{pp\to ab}}{dX} = \sum_{i,j=-n_f}^{+n_f} \int_{\tau_0}^{1} \frac{dz_1}{z_1} \frac{dz_2}{z_2} \boxed{f_i(z_1,\mu_F)\, f_j(z_2,\mu_F)} \frac{d\hat{\sigma}_i^{ij}}{dX}(zS, \alpha_s(\mu_R), \mu_F) + \mathcal{O}\left(\frac{\Lambda^n}{S^n}\right)$$

Hadronic scale: global fit of PDFs

High scale: input to the LHC



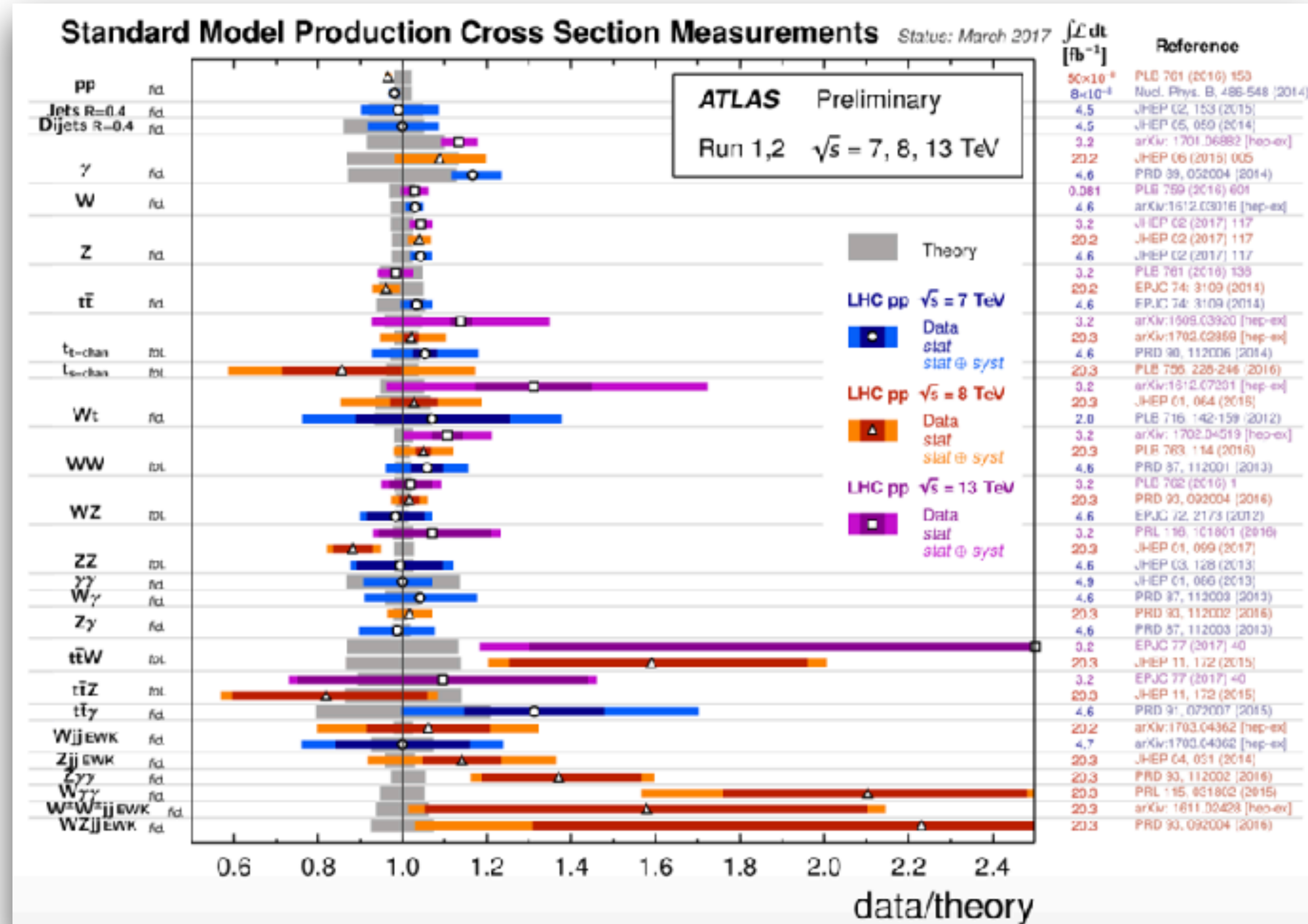
PDG 2016

Outline of the talk

- Introduction
  - The name of the game
  - The players
- New developments & new frontiers
  - Data: opportunities and challenges
  - Theory/Methodology: new frontiers and hidden uncertainties
- Conclusions and outlook

Introduction

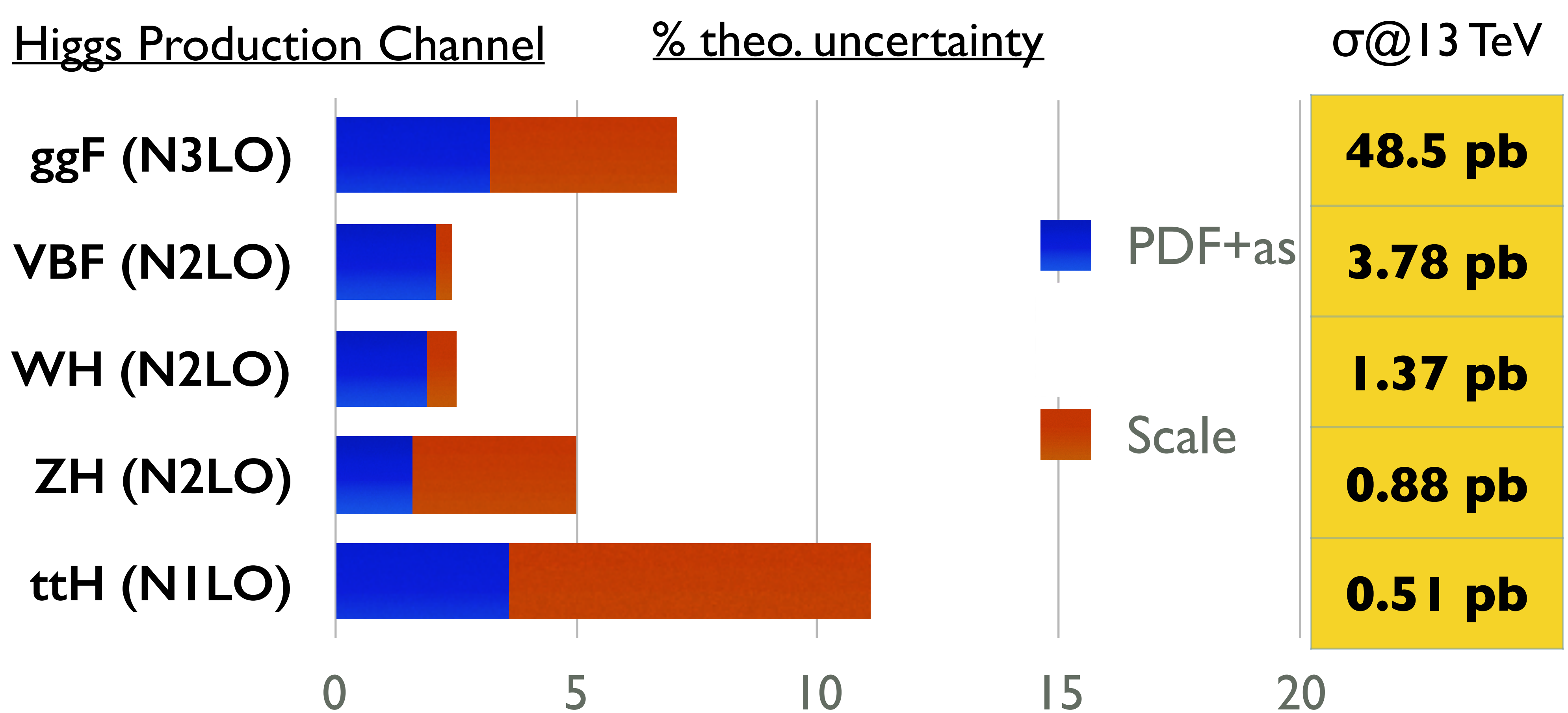
The precision frontier

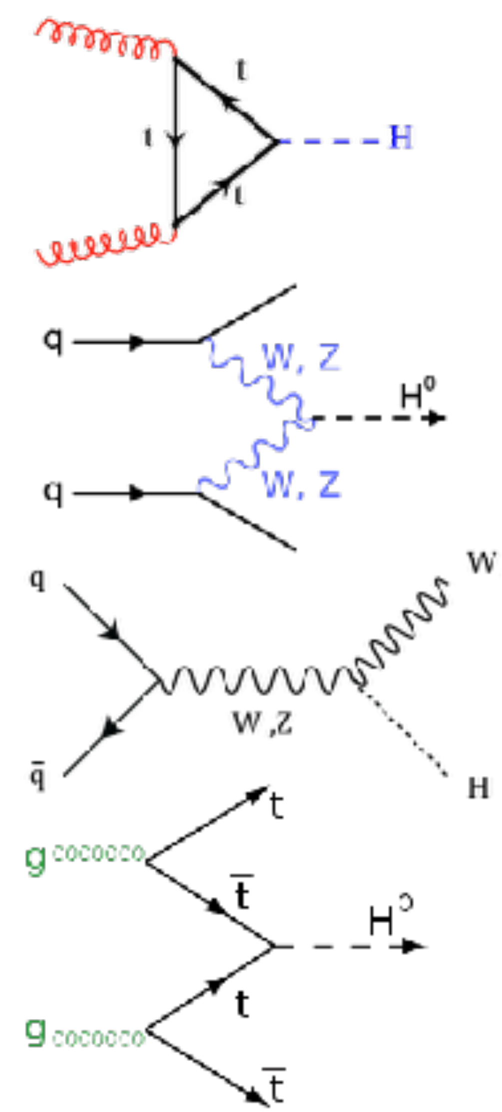


- LHC: a **discovery** machine & a **precision** machine
- **PDFs** are a key ingredient in achieving the level of precision that is needed to fully exploit the LHC potential

The role of PDF uncertainties

Higgs Physics





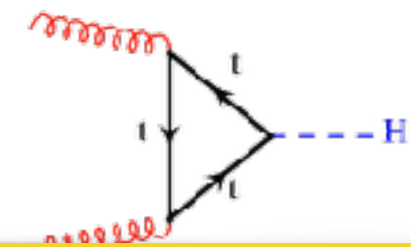
PDF uncertainty often dominant contribution to theory uncertainty

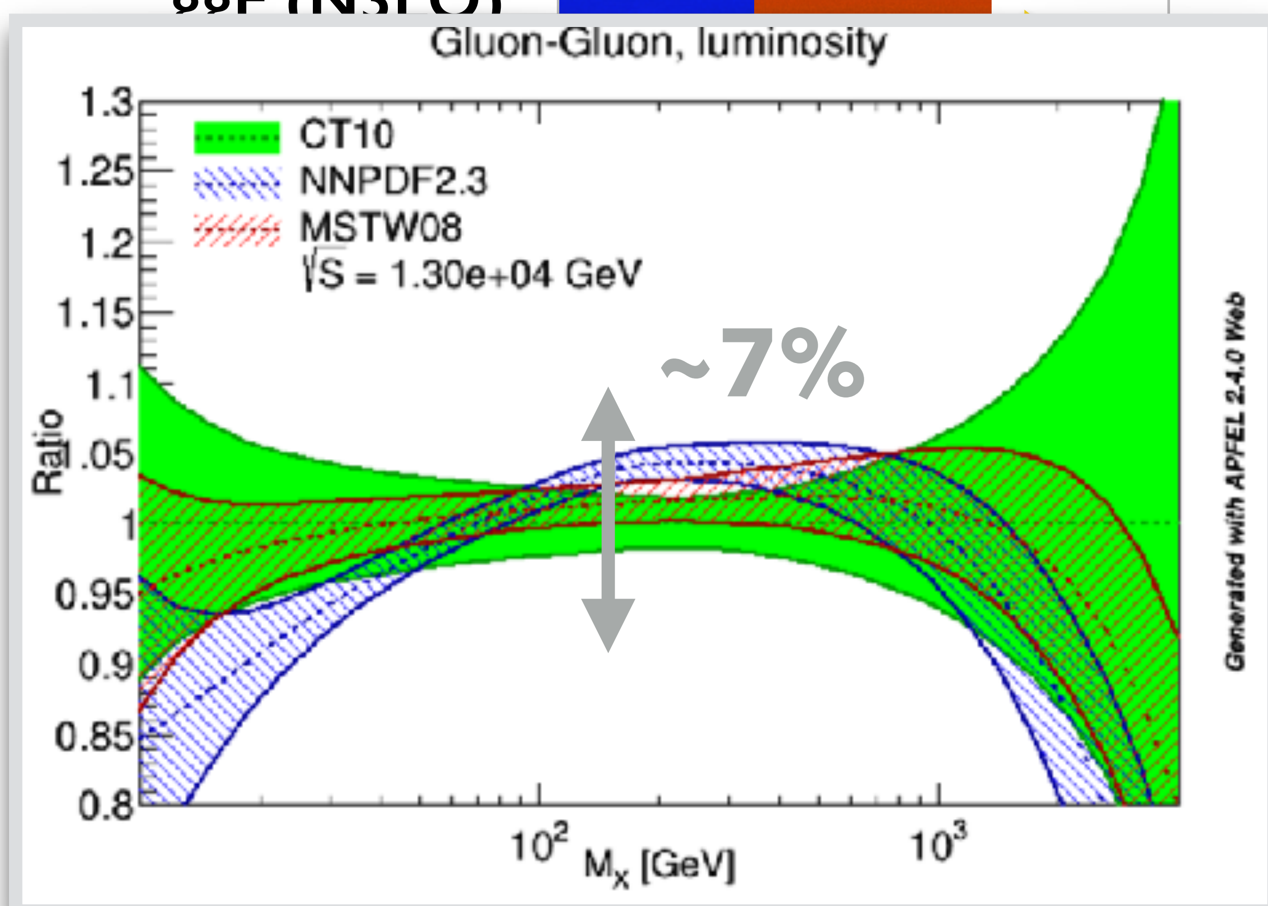
Yellow Report 4 (2016)

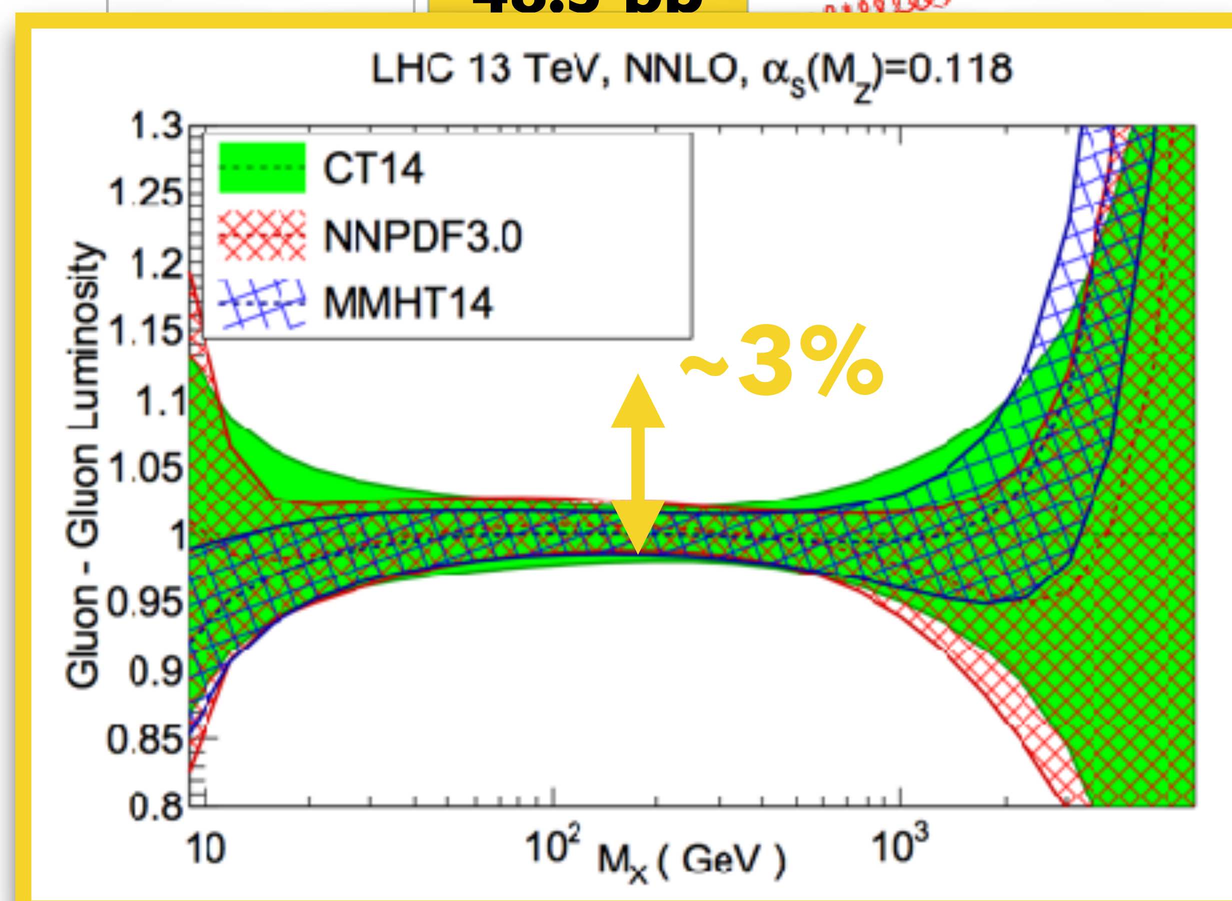
The role of PDF uncertainties

Higgs Physics

Higgs Production Channel	% theo. uncertainty	σ@13 TeV
ggF (N3LO)		48.5 pb





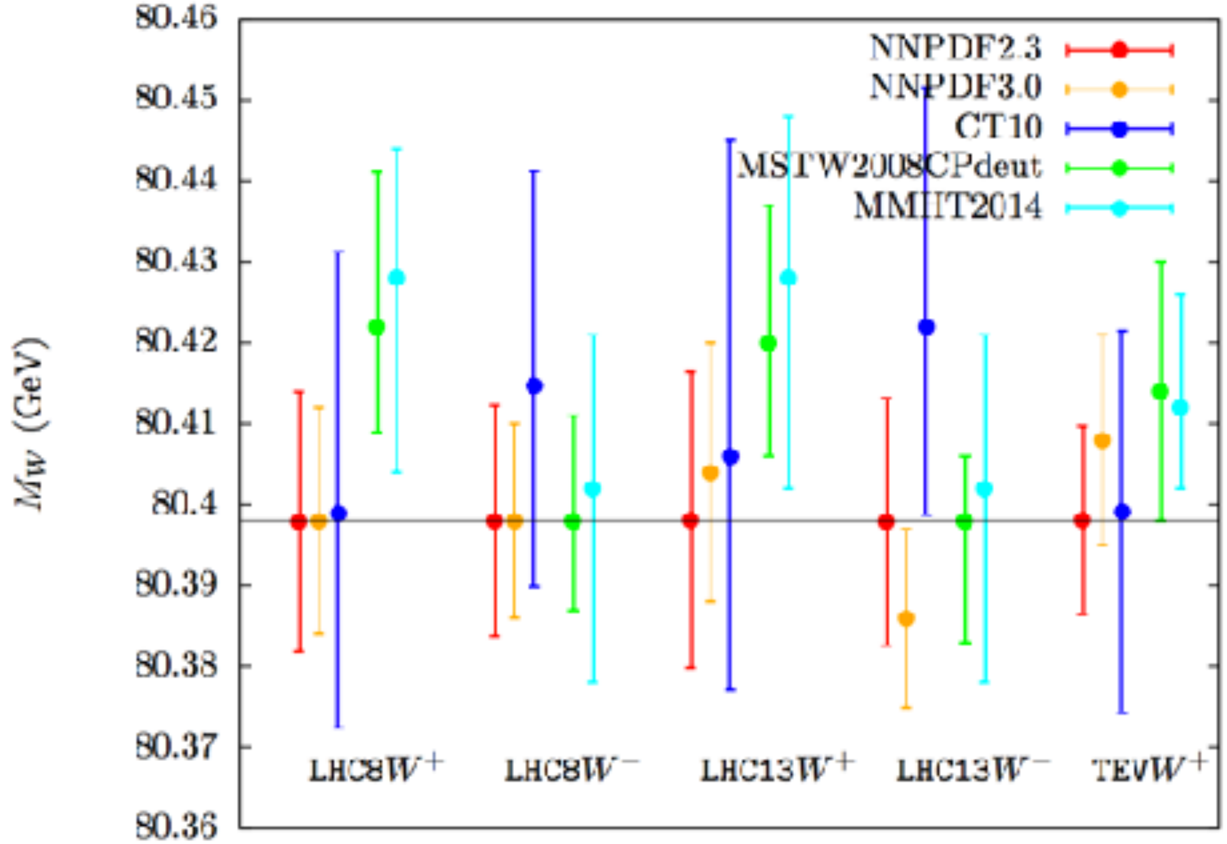


Yellow Report 3 (2013)

Yellow Report 4 (2016)

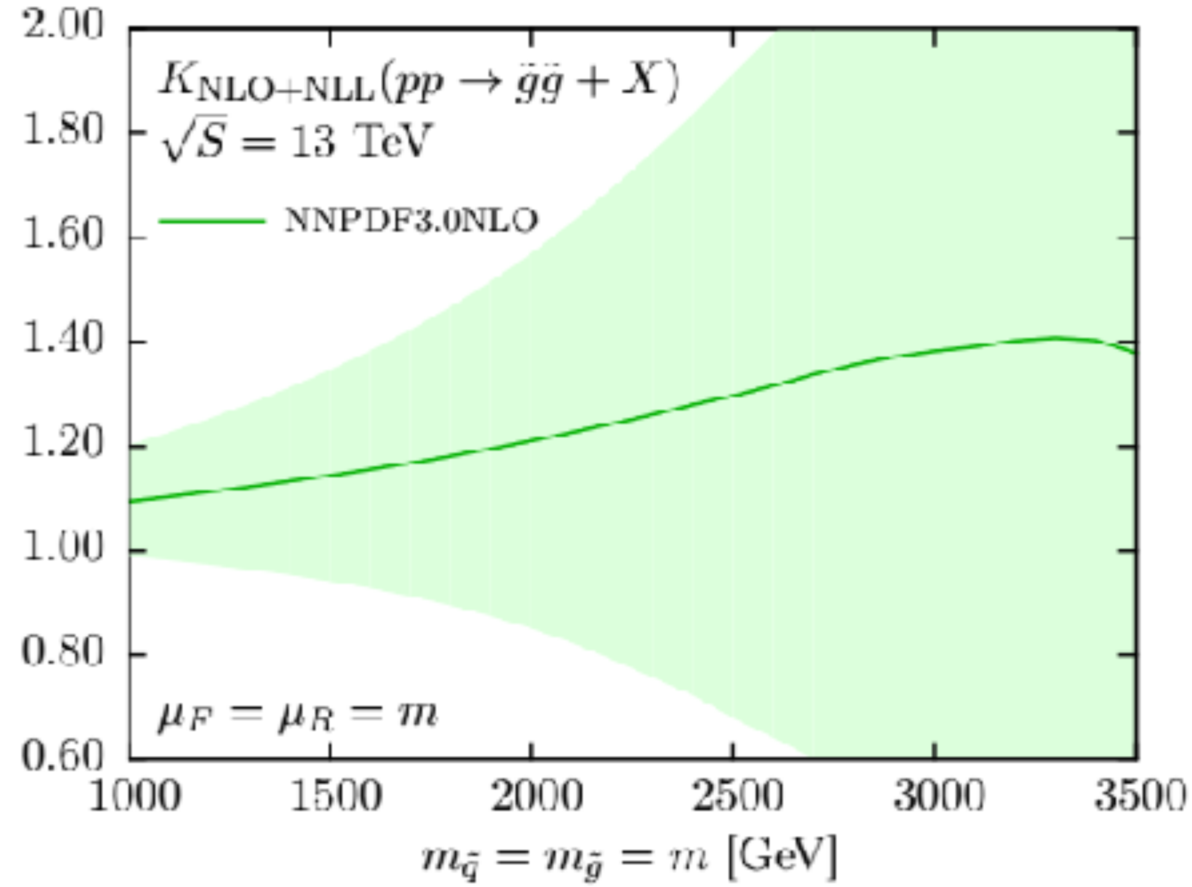
The role of PDF uncertainties

M_W determination



Bozzi et al, 2015

Gluino production



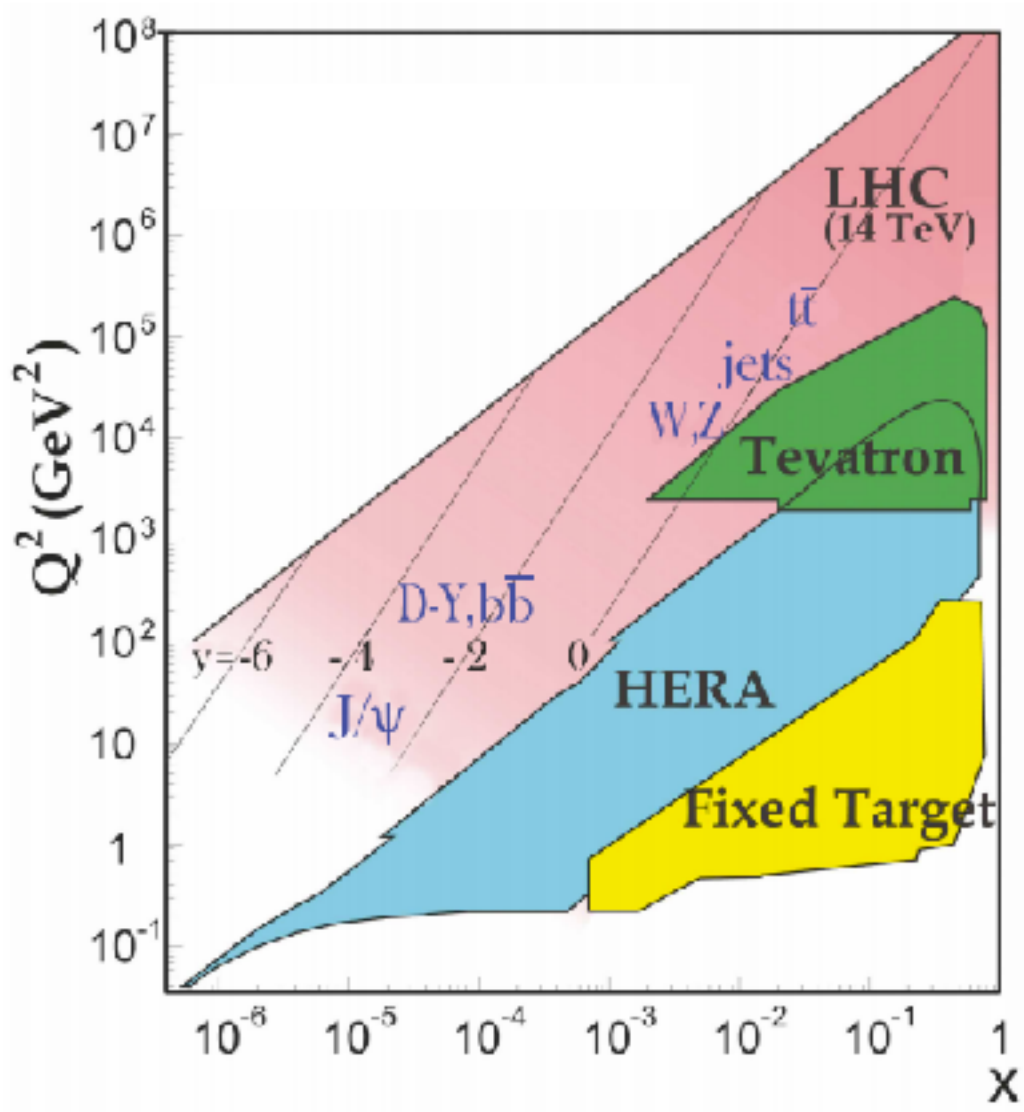
Beenakker et al. , 2016

PDF uncertainties the largest theoretical systematic uncertainty that enters Mw determination

The larger the mass of the produced final state, the larger are PDF uncertainties

The name of the game

- Choose **experimental data** to fit and include all info on correlations
- **Theory settings**: perturbative order, heavy quark mass scheme, EW corrections, intrinsic heavy quarks, α_s, quark masses value and scheme
- Choose a starting scale Q_0 where pQCD applies
- **Parametrise** independent quarks and gluon distributions at the starting scale
- Solve **DGLAP equations** from initial scale to scales of experimental data and build up observables
- **Fit** PDFs to data



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- **Fit** PDFs to data
- Provide **error sets** to compute **PDF uncertainties**

Must propagate data uncertainty into PDF uncertainty. How to deal with inconsistencies?

Hidden uncertainty: still an option?

Is parametrisation flexible enough (too flexible)?

Methodology

Hessian versus MC approach

The players

April 2017	NNPDF3.0 (10/2014)	MMHT2014 (12/2014)	CT14 (06/2015)	HERAPDF2.0 (06/2015)	CJ15 (06/2016)	ABMP16 (01/2017)
Fixed Target DIS	✔	✔	✔	✘	✔	✔
JLAB	✘	✘	✘	✘	✔	✘
HERA I+II	✔	✔	✔	✔	✔	✔
HERA jets	✘	✔	✘	✘	✘	✘
Fixed Target DY	✔	✔	✔	✘	✔	✔
Tevatron W,Z	✔	✔	✔	✘	✔	✔
Tevatron jets	✔	✔	✔	✘	✔	✘
LHC jets	✔	✔	✔	✘	✘	✘
LHC vector boson	✔	✔	✔	✘	✘	✔
LHC top	✔	✘	✘	✘	✘	✔
Stat. treatment	Monte Carlo	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2$ dynamical	Hessian $\Delta\chi^2=1$	Hessian $\Delta\chi^2=1.645$	Hessian $\Delta\chi^2=1$
Parametrization	Neural Networks (259 pars)	Chebyshev (37 pars)	Bernstein (30-35 pars)	Polynomial (14 pars)	Polynomial (24 pars)	Polynomial (15 pars)
HQ scheme	FONLL	TR'	ACOT-χ	TR'	ACOT-χ	FFN (+BMST)
Order	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO/NNLO	NLO	NLO/NNLO

New developments and new challenges

New opportunities & challenges

DATA

- Many new accurate data and precise computations: a great <u>opportunity</u>
- Dominating correlated uncertainties <u>challenge</u> both theorists and for experimentalists
- Do data indicate need to fit charm?

- Large invariant mass & large rapidity: EW corrections and photon-initiated processes become crucial
- Closer to kinematic boundaries: need resummation in PDFs?
- Time to quantify hidden PDF uncertainties

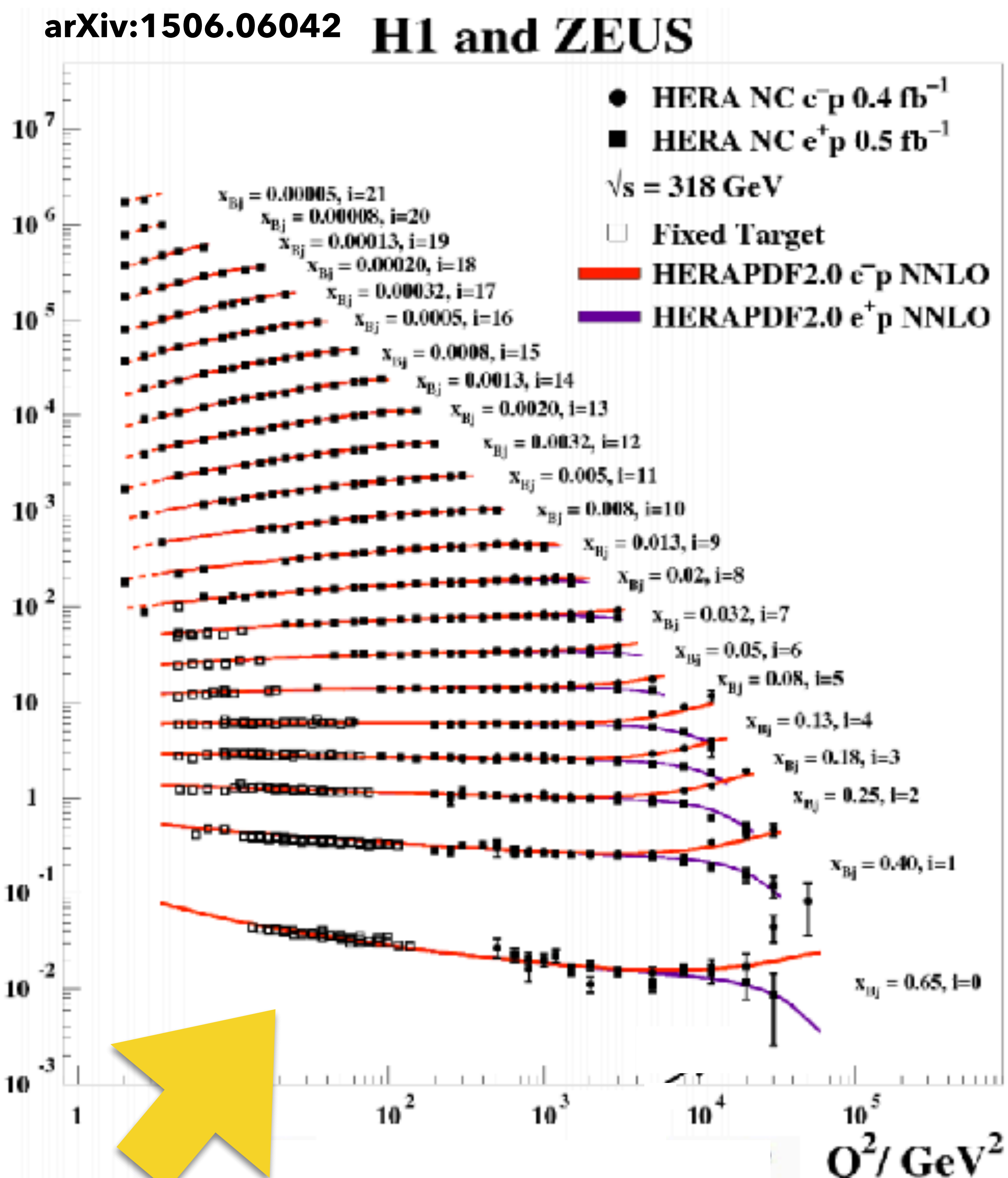
THEORY/ METHODOLOGY

DATA

- Many new accurate data and precise computations: a great opportunity
- Dominating correlated uncertainties challenge both theorists and for experimentalists
- Do data indicate need to fit charm?

A plethora of new data: HERA

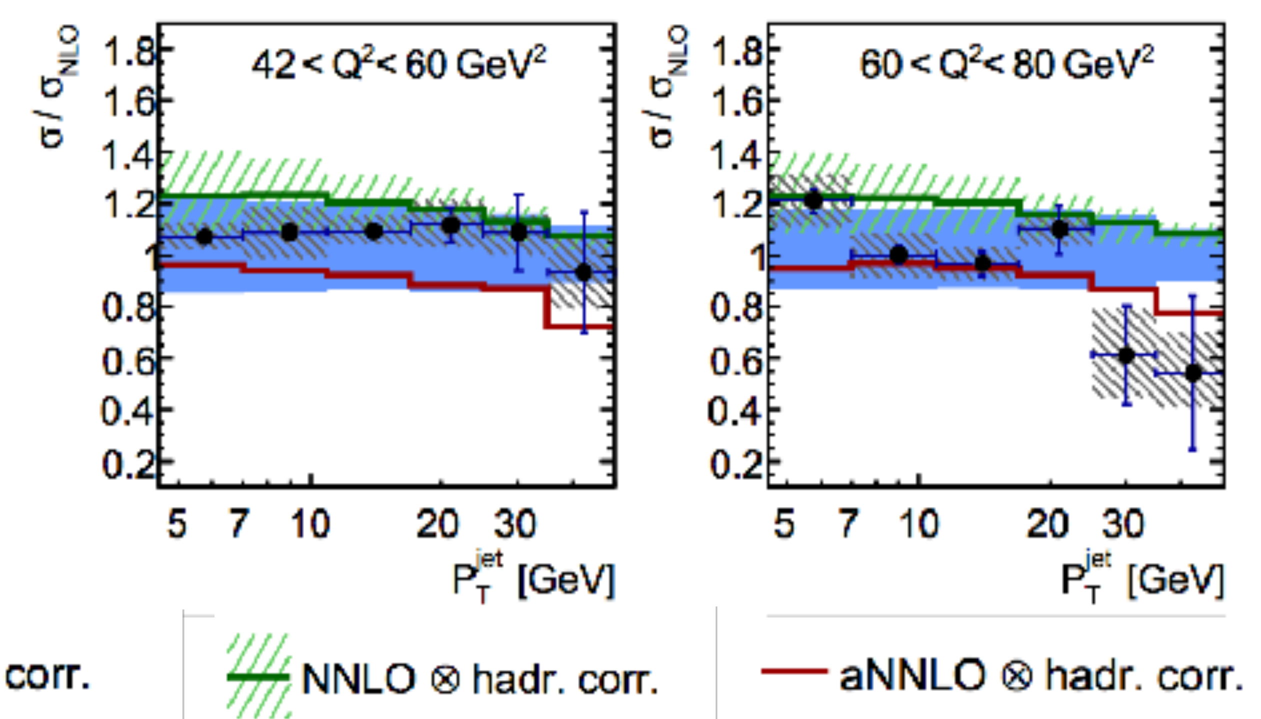
arXiv:1506.06042



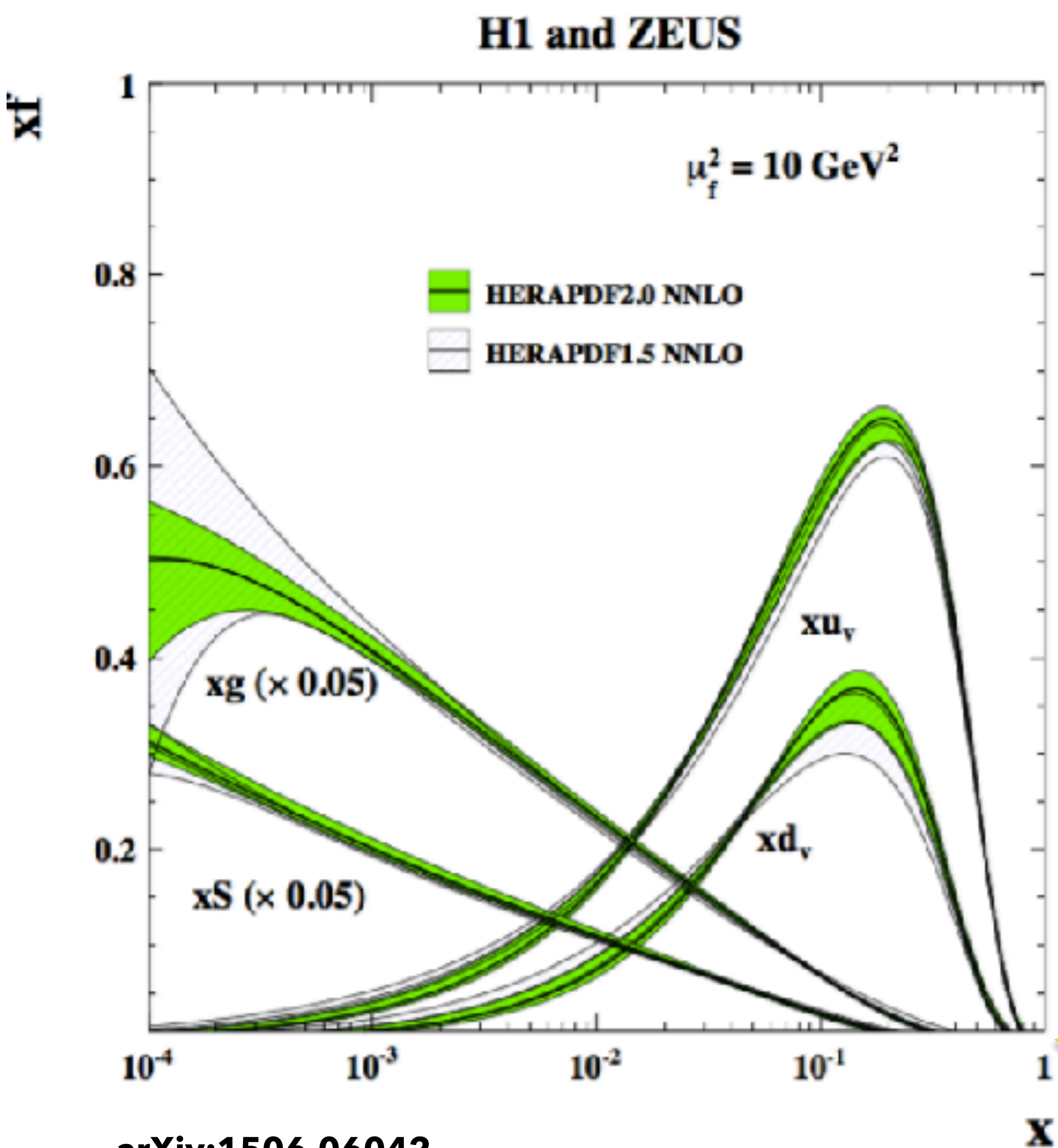
M. Wing

- HERA I + II : 2927 data-points combined to 1309 averaged measurements with 169 sources of systematical uncertainties
- Upcoming combinations of F2b and F2c
- New e±p jets measurements by H1 over a large number of Q2 bins, 0.2 < y < 0.6

arXiv:1611.03421



Highlights: HERAPDF2.0



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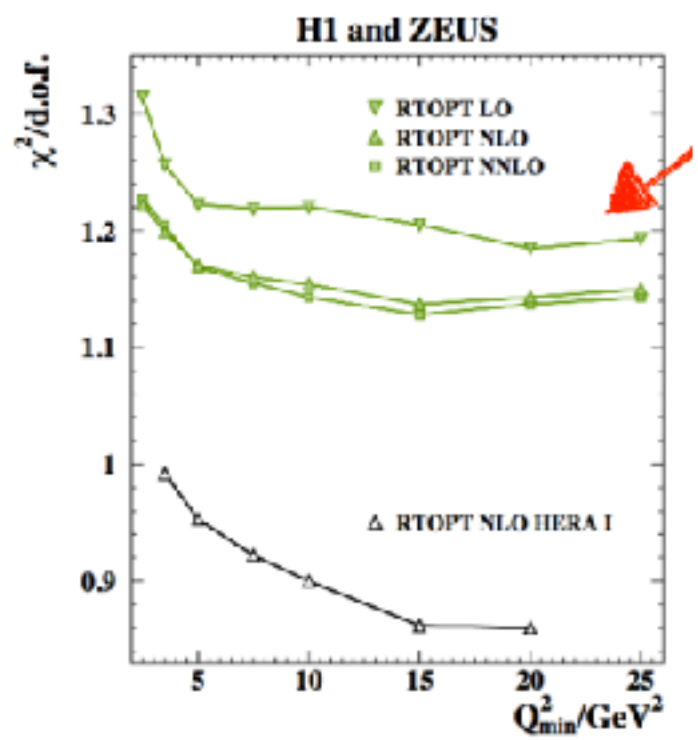
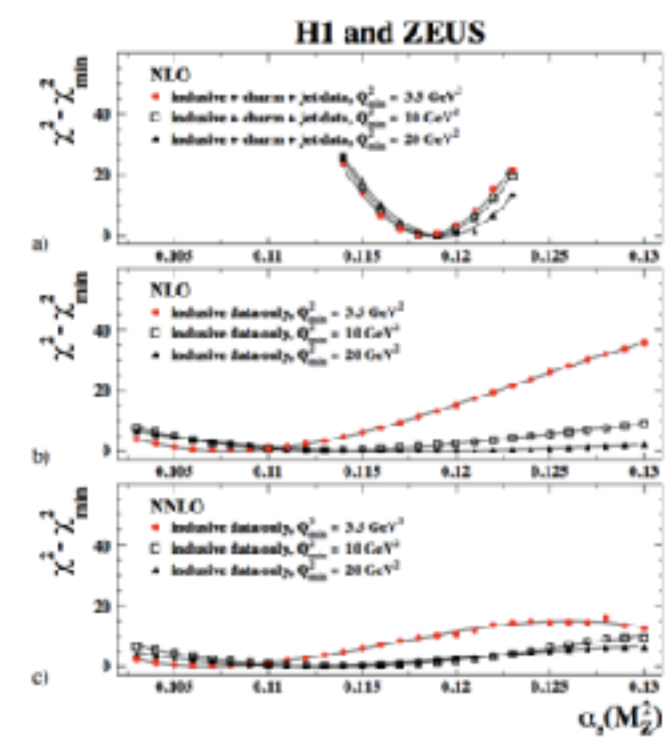
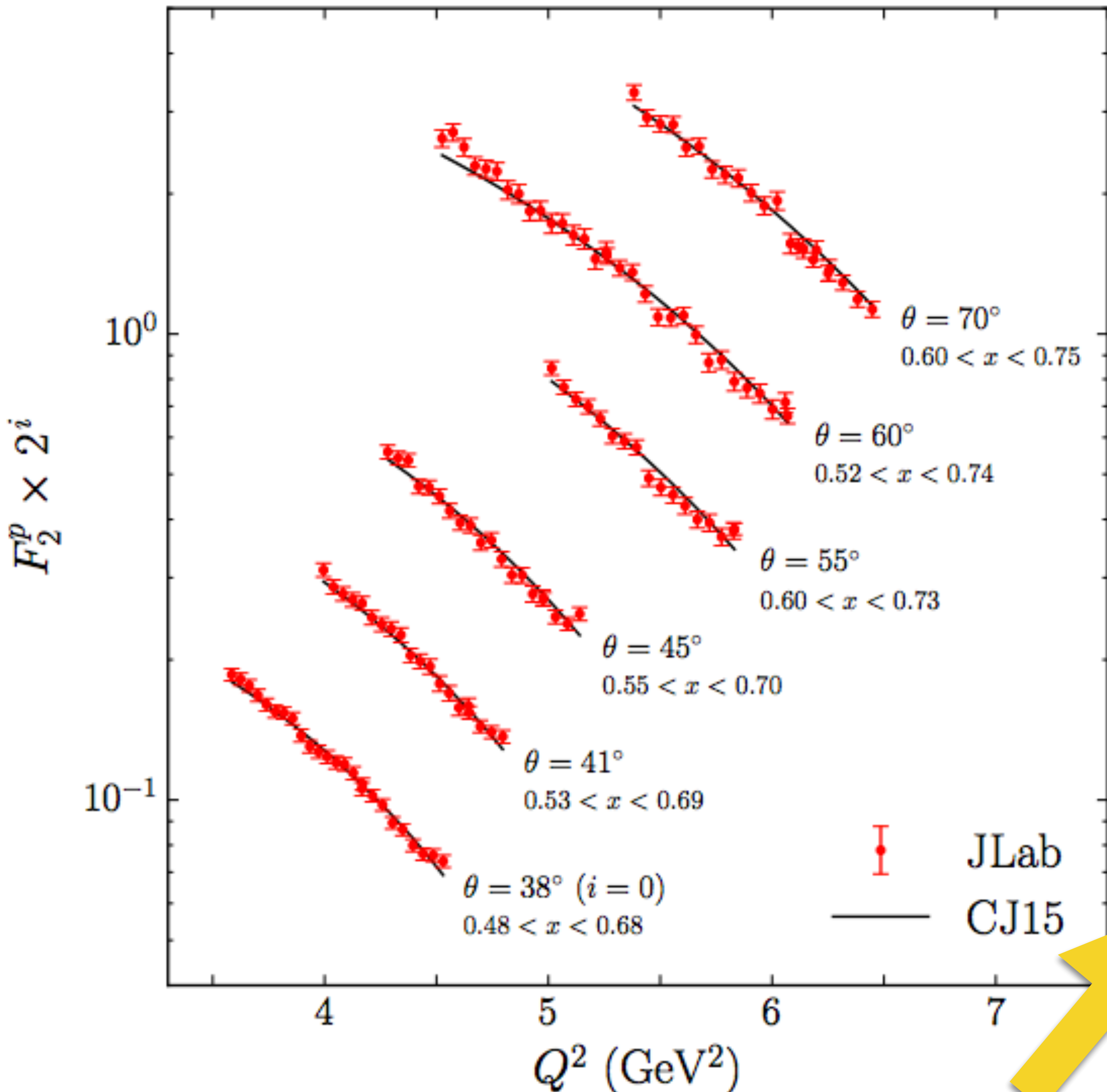




K. Wichmann

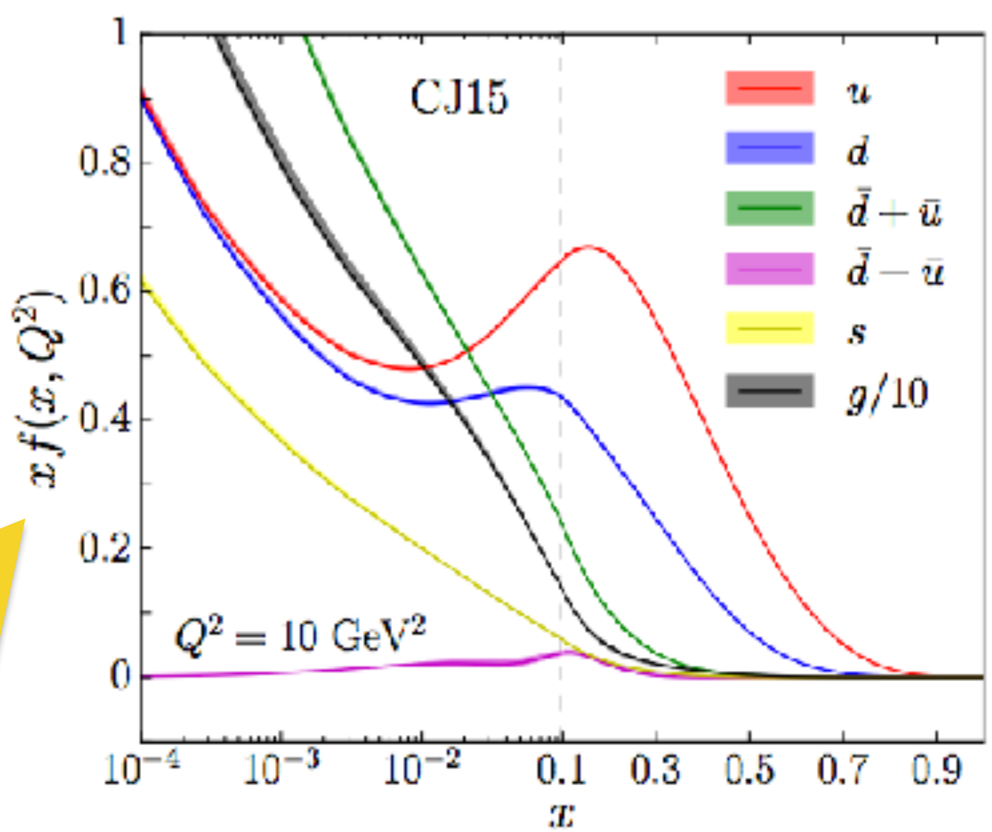
- HERAPDF2.0 based on combined structure function data
- Many interesting studies
  - Dependence of the chi2 of combined HERA data with Q2cut
  - Inclusion of ep jet data and constraints on alphas

Highlights: CJ15



Accardi et al., 2016

- CJ15 is NLO PDF determination with focus on large-x and small-Q^2 region (higher twists, nuclear effects, deuteron models)
- HERA + JLAB + HERMES + Tevatron data allow to constrain large-x region



W. Melnitchouk

A plethora of new data: LHC

GLUON

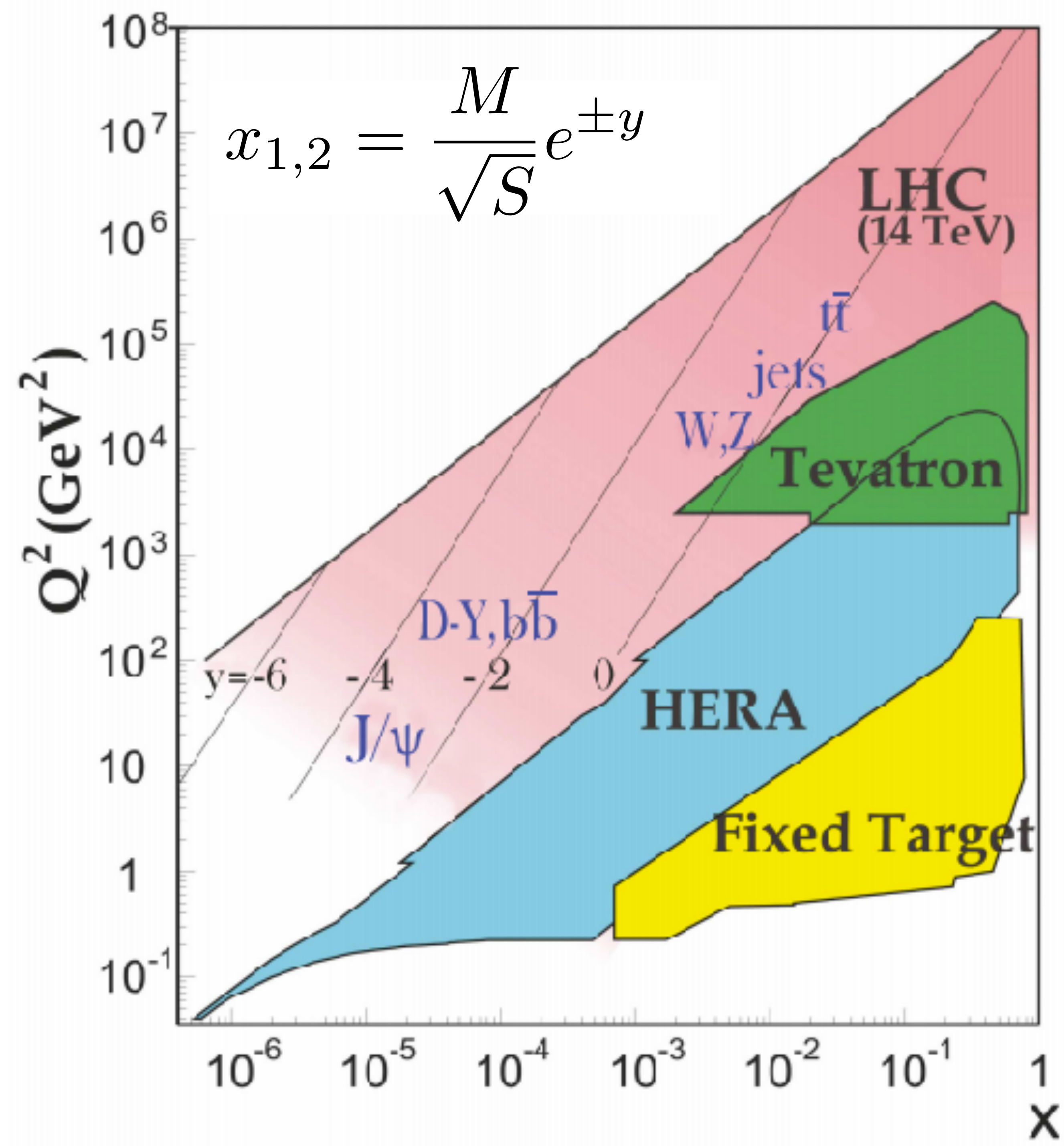
- Inclusive jets and dijets **(medium/large x)**
- Isolated photon and γ+jets **(medium/large x)**
- Top pair production **(large x)**
- High p_T V(+jets) distribution **(small/medium x)**

QUARKS

- High p_T W(+jets) ratios **(medium/large x)**
- W and Z production **(medium x)**
- Low and high mass Drell-Yan **(small and large x)**
- Wc **(strangeness at medium x)**

PHOTON

- Low and high mass Drell-Yan
- WW production



PDG 2016

A wealth of new NNLO calculations

- NNLO calculations essential to reduce theory uncertainty in PDF analyses
- Stunning progress made on key processes for PDF determination
- Great progress also in tools to interface NLO (NNLO) codes to PDF fitting code

APPLgrid, Carli et al EPJC66, 2010
FASTNLO, Kluge et al 2010
aMCfast, Berton et al , 2014
MCgrid, Del Debbio et al, 2014
APFELgrid, Bertone et al , 2016
APPLfast, 2017 (?)

C. Gwenlan

✓ NNLO top pair production (total and differential)
Czakon, Fiedler, Mitov [PRL 116(2016) 082003]
Czakon, Mitov [JHEP 1301(2015)]

E. Nocera

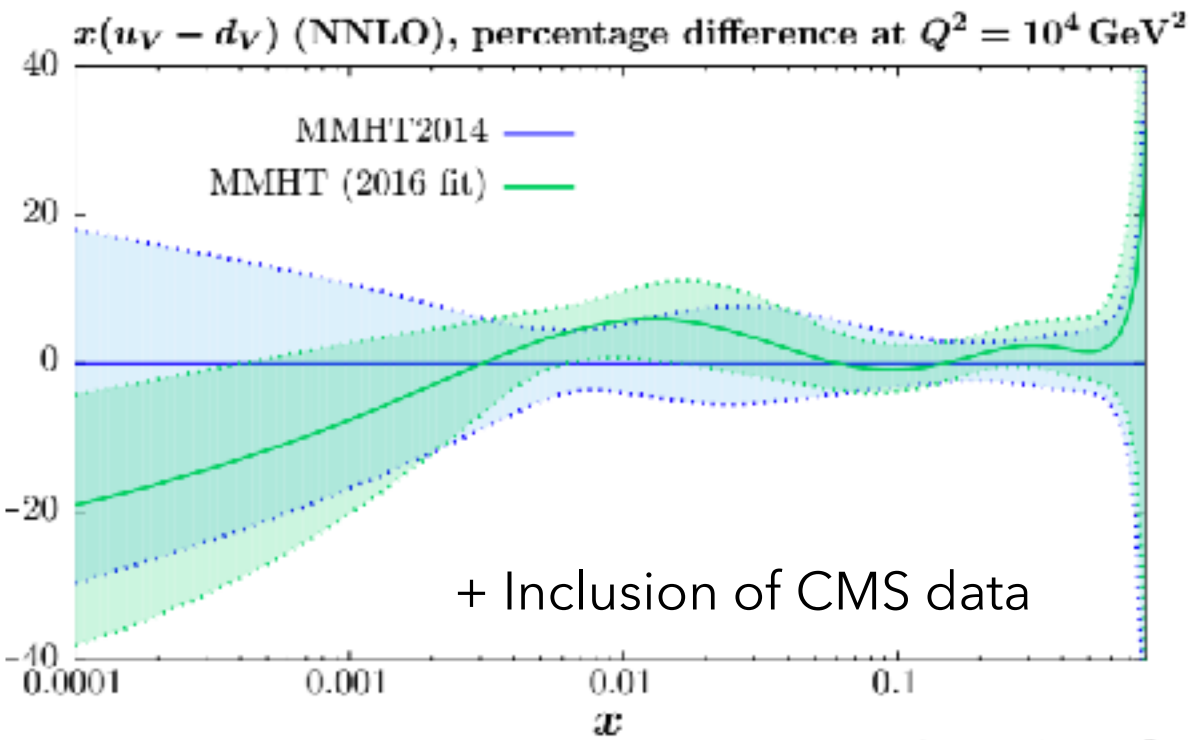
✓ W/Z+j and W/Z transverse momentum distributions
Gehrmann-De Ridder et al [1605.04295]
Boughezal, Liu, Petriello [1602.08140]
Boughezal, Liu, Petriello [1602.06965]
Boughezal et al [PRL 116(2016) 152001 & 062002]
Gehrmann-De Ridder et al [1507.02850]

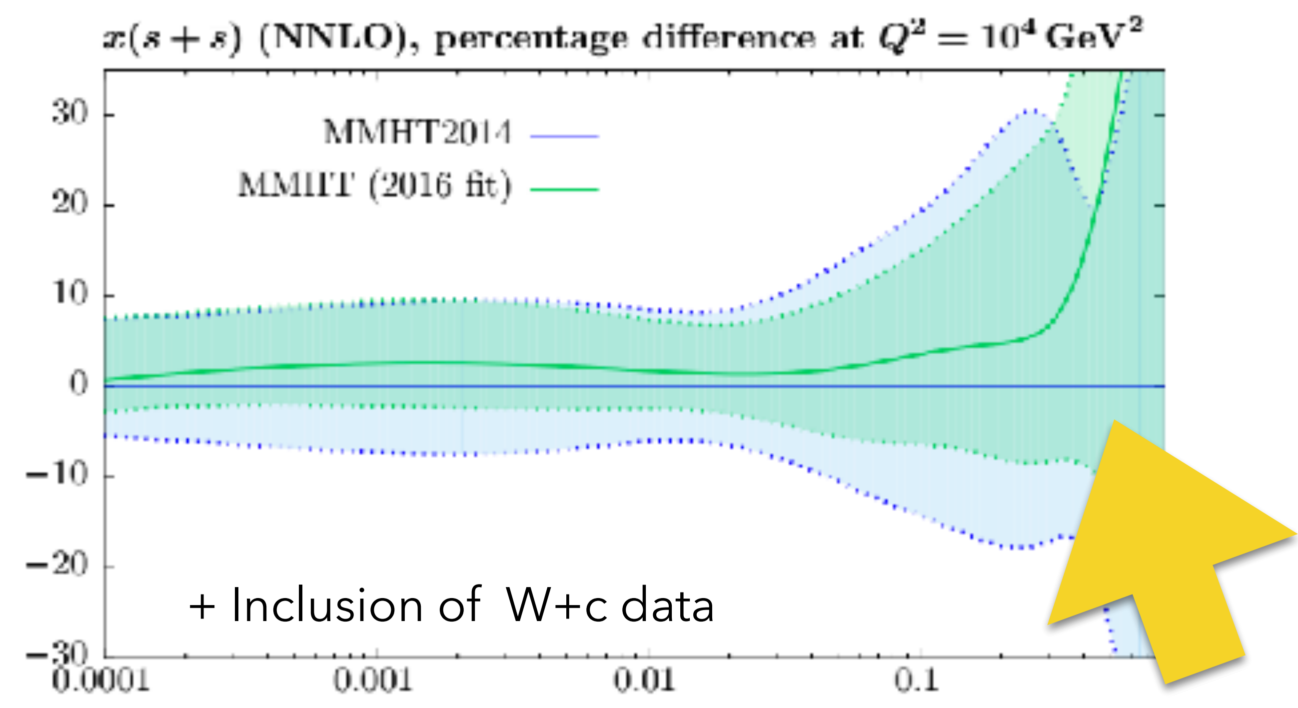
M. Ubiali

✓ Inclusive jet cross section
Currie et al [JHEP 1401 (2014) 110]
Gehrmann-De Ridder et al [PRL 110 (2016) 162003]

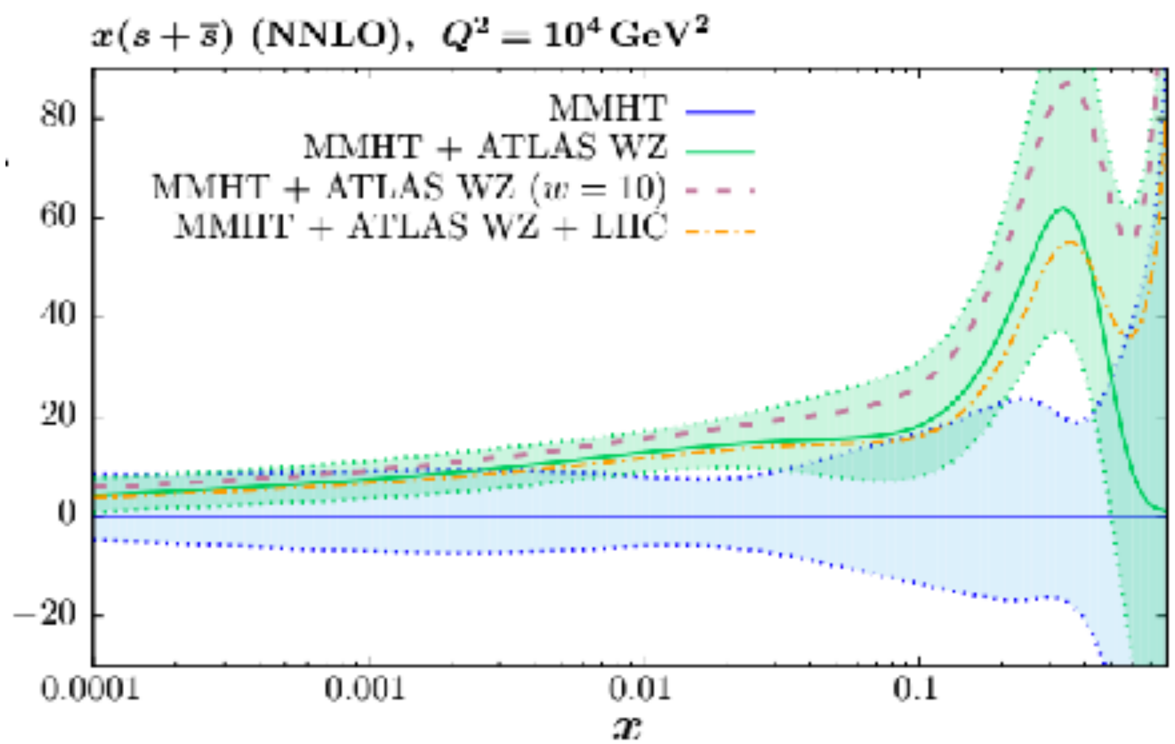
✓ Direct photon production
Campbell, Ellis, Williams [1612.04333]

Highlights: MMHT17





R. Thorne



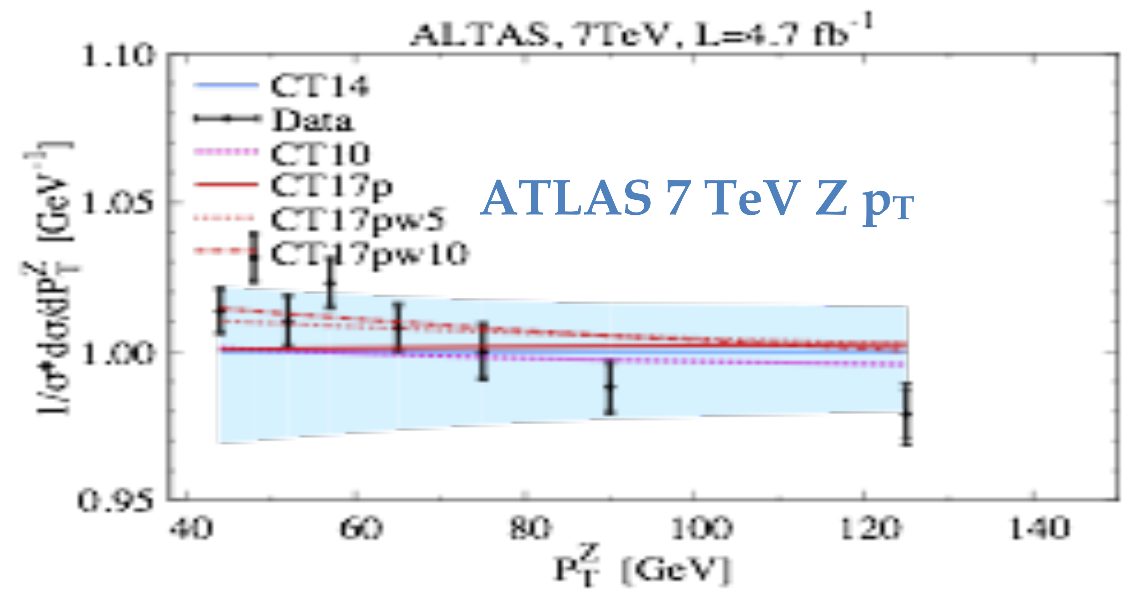
- Inclusion of LHC data: W+c, tT total xsec, LHCb combination, CMS W asymmetry
- Tension between old DY data and precise ATLAS W/Z 2011 data alleviated by extending (U-D) parametrisation, data cause important shift in strangeness

Highlights: CT17

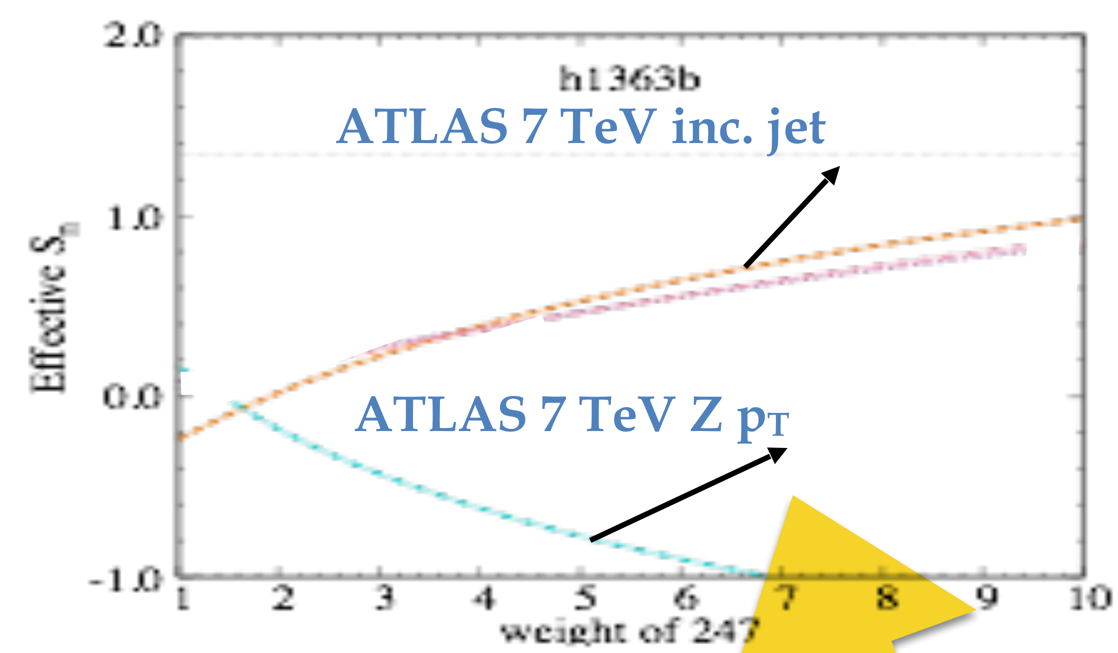
Included experiments:

- Combined HERA1+2 DIS
- LHCb 7 TeV Z, W muon rapidity dist.
- LHCb 8 TeV Z rapidity dist.
- ATLAS 7 TeV inclusive jet
- CMS 7 TeV inclusive jet (extended y range)
- ATLAS 7 TeV Z pT dist.
- LHCb 13 TeV Z rapidity dist.
- CMS 8 TeV Z pT and rapidity dist. (dble diff.)
- CMS 8 TeV W, muon asymmetry dist.
- ATLAS 7 TeV W/Z, lepton(s) rapidity dist.
- CMS 7,8 TeV tT differential dist.
- ATLAS 7,8 TeV tT differential dist.

Predictions vs. LHC data



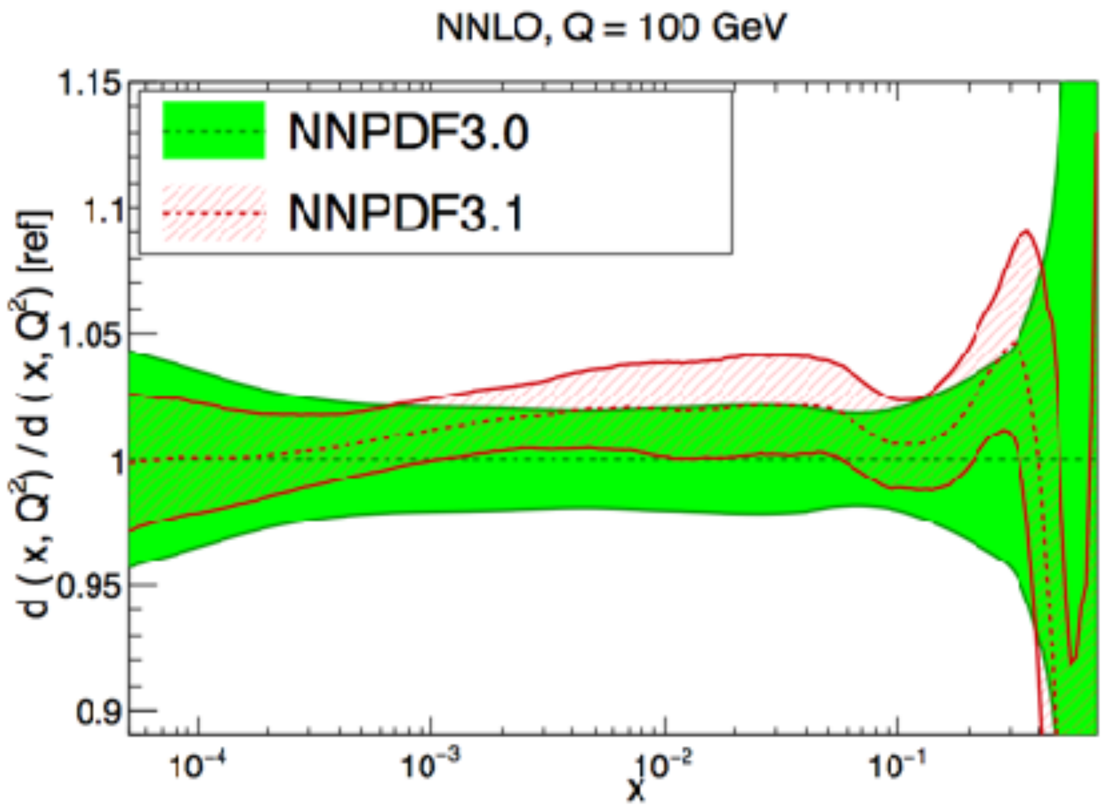
Study agreement between the LHC experiments

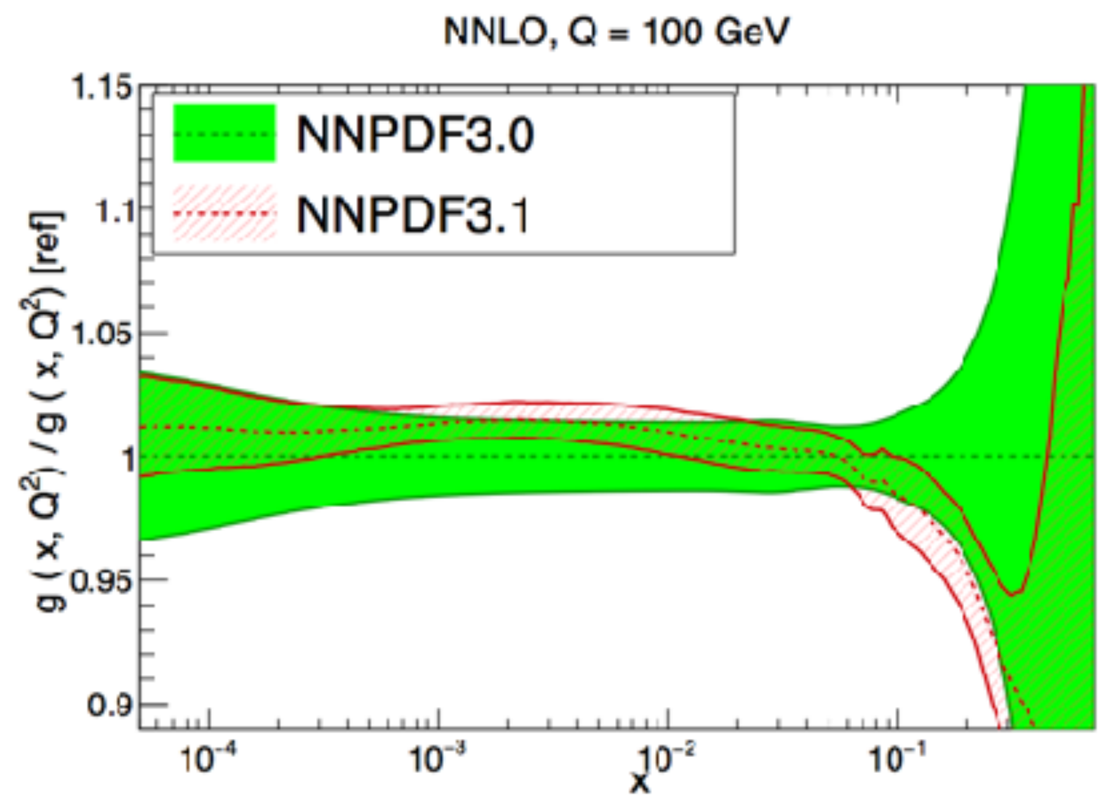


Weight of ZpT data

J. Gao

Highlights: NNPDF3.1



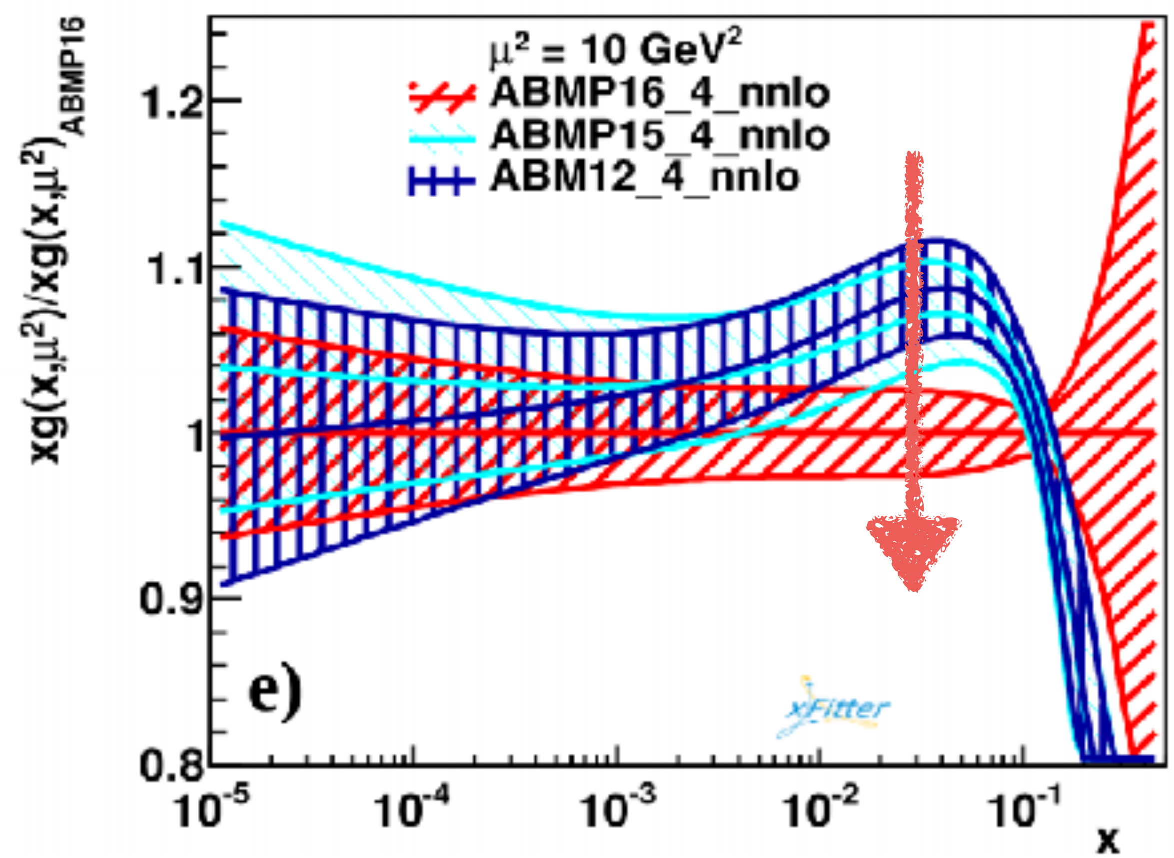


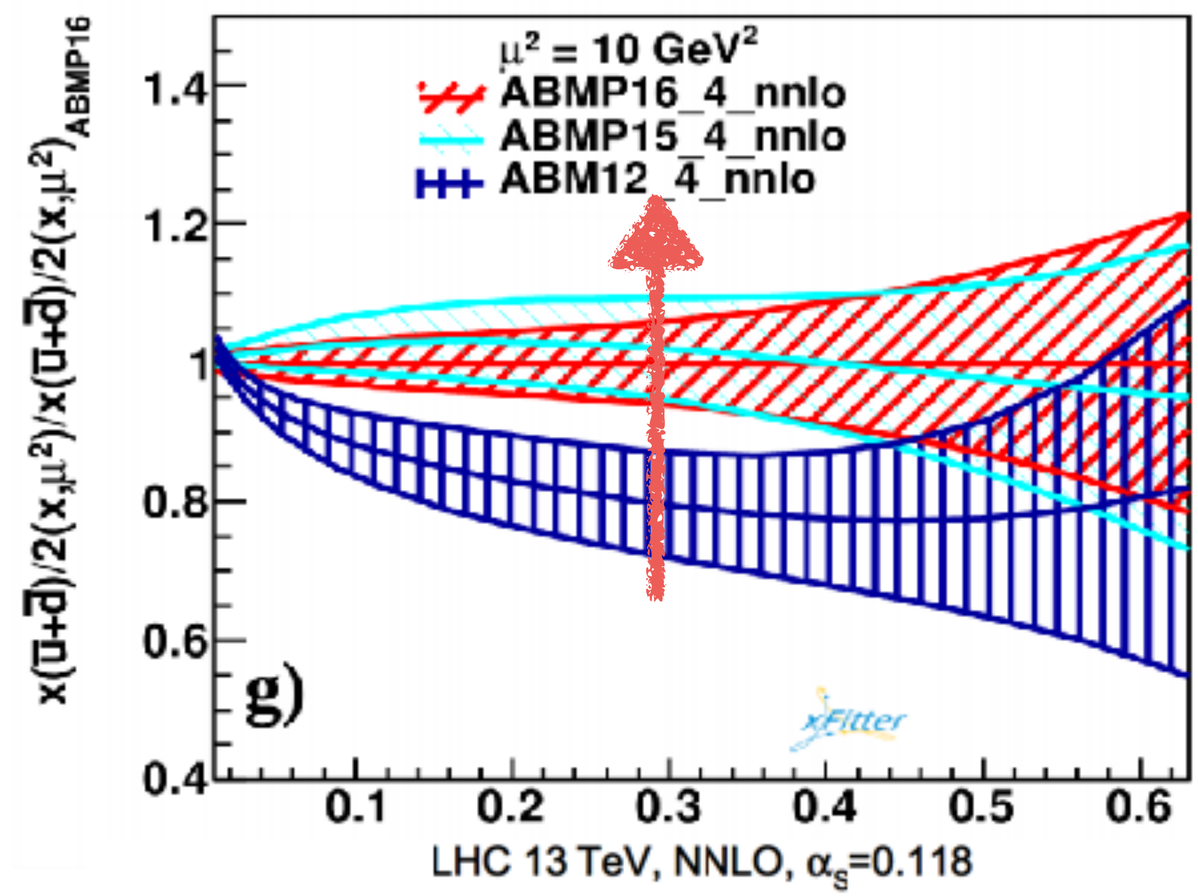
Combined HERA inclusive data	Run I+II	quark singlet and gluon
D0 legacy W asymmetries	Run II	quark flavor separation
ATLAS inclusive W, Z rap 7 TeV	2011	strangeness
ATLAS inclusive jets 7 TeV	2011	large-x gluon
ATLAS low-mass Drell-Yan 7 TeV	2010+2011	small-x quarks
ATLAS Z pT 7,8 TeV	2011+2012	medium-x gluon and quarks
ATLAS and CMS tt differential 8 TeV	2012	large-x gluon
CMS Z (pT,y) 2D xsecs 8 TeV	2012	medium-x gluon and quarks
CMS Drell-Yan low+high mass 8 TeV	2012	small-x and large-x quarks
CMS W asymmetry 8 TeV	2012	quark flavor separation
CMS 2.76 TeV jets	2012	medium and large-x gluon
LHCb W,Z rapidity dists 7 TeV	2011	large-x quarks
LHCb W,Z rapidity dists 8 TeV	2012	large-x quarks

- Many new LHC data included: reduced gluon uncertainty within 1σ band (tT diff distributions, ZpT data), quarks harder (W/Z 2011 rapidity data) and harder strangeness
- Thorough study of fitted charm

J. Rojo

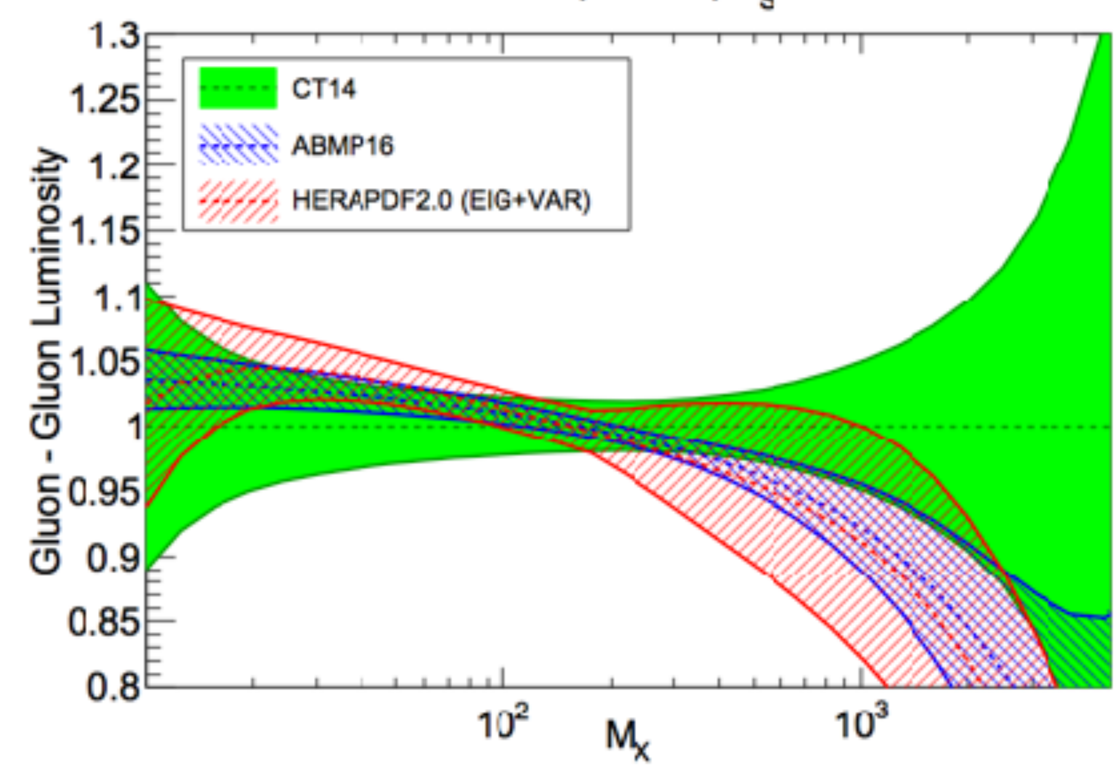
Highlights: ABMP16





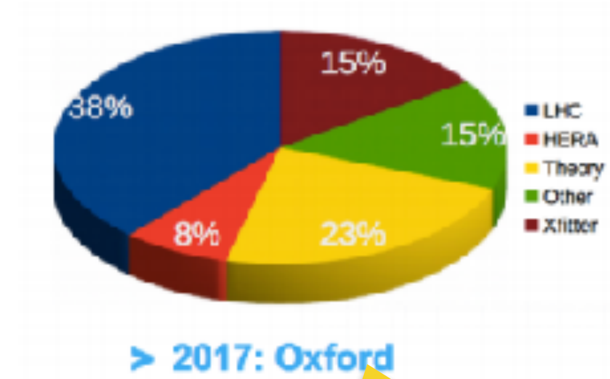
Alekhin et al, 2017

- New LHC data and included: LHCb W and Z data, CMS and ATLAS W,Z data, top pair and single top total xsec [decrease gluon]
- Combined HERAI+II data, new CHORUS and NOMAD data, Tevatron legacy data
- Excluded deuteron data
- Extended parametrisation of (u~ - d~)

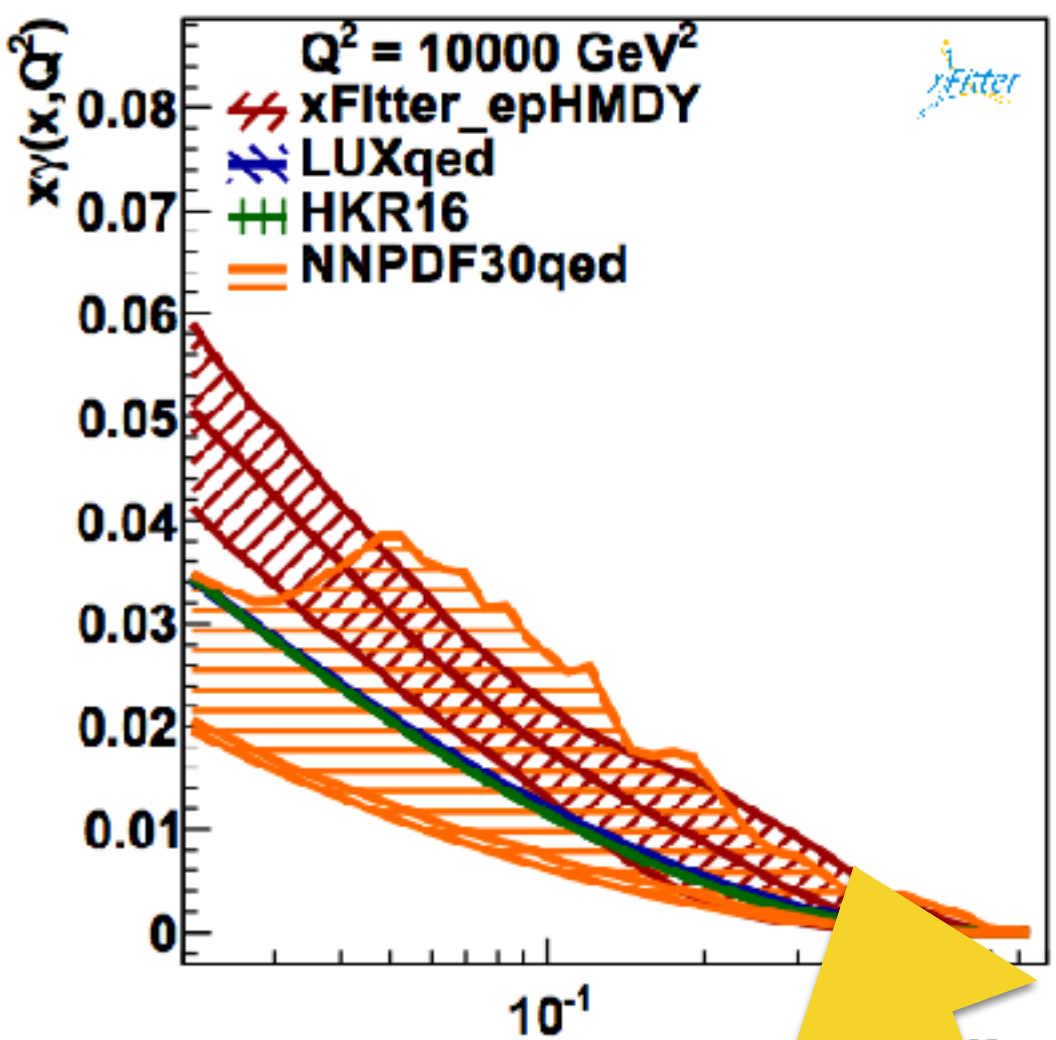


Updates: xFitter

- Open source QCD framework for PDF fitting
- Theory benchmarking (comparison of the use of different data sets and different methodology, e.g. choice of heavy flavour scheme)
- Analysis of the impact of the data from the experimentalists

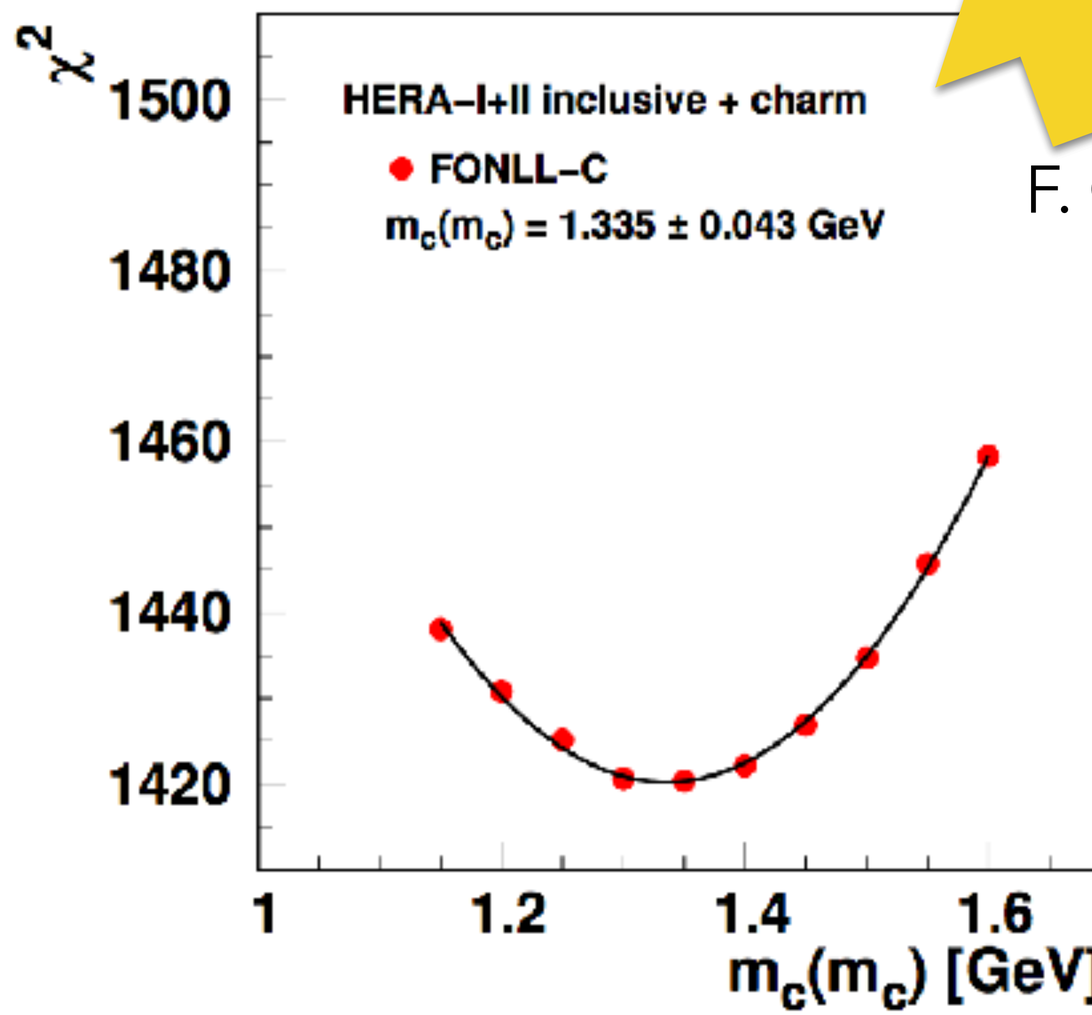


F. Olness



arXiv: 1701.08553

F. Giuli

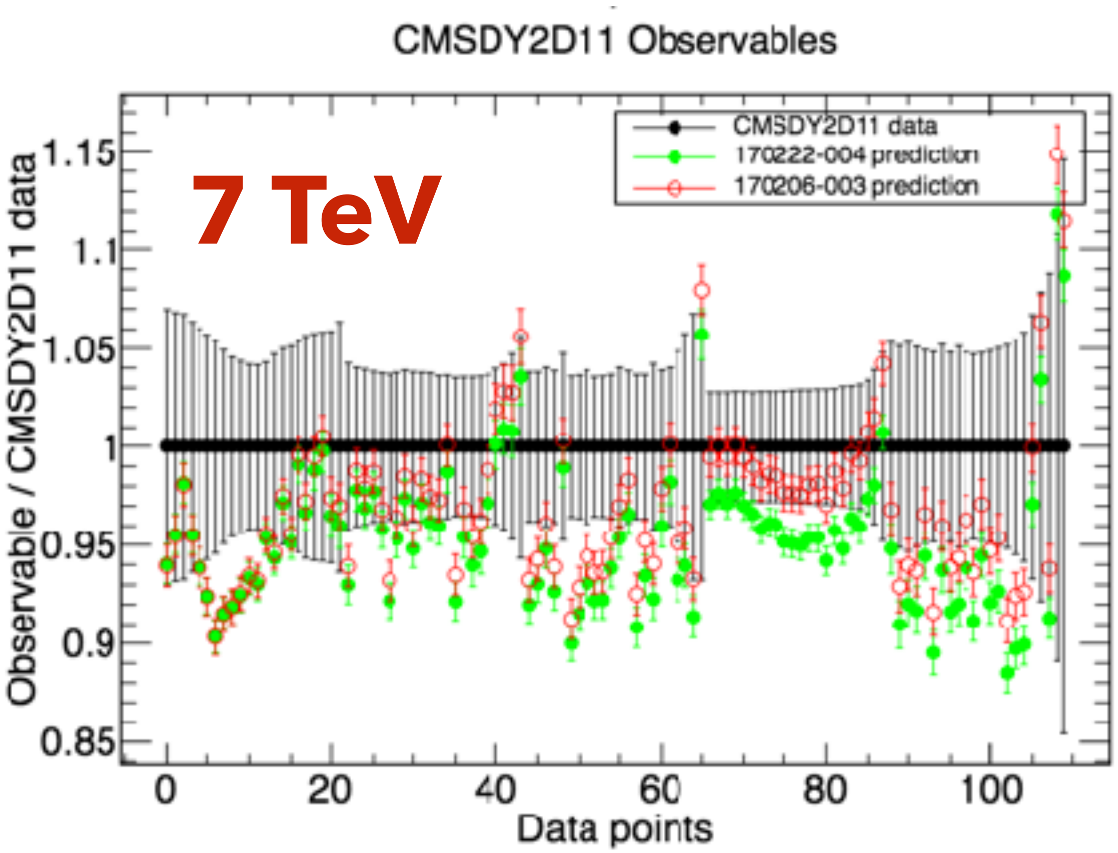


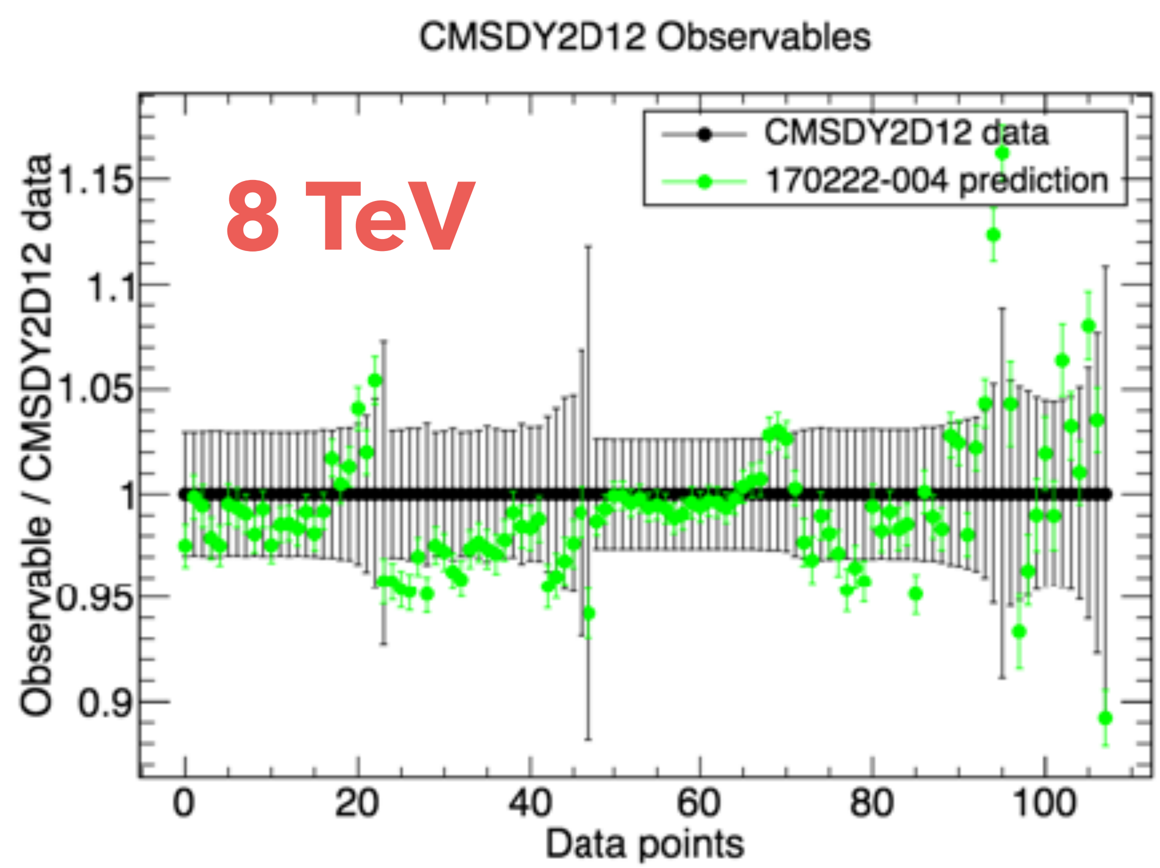
arXiv: 1605.01946

DATA

- Many new accurate data and precise computations: a great opportunity
- Dominating correlated uncertainties challenge both theorists and for experimentalists
- Do data indicate need to fit charm?

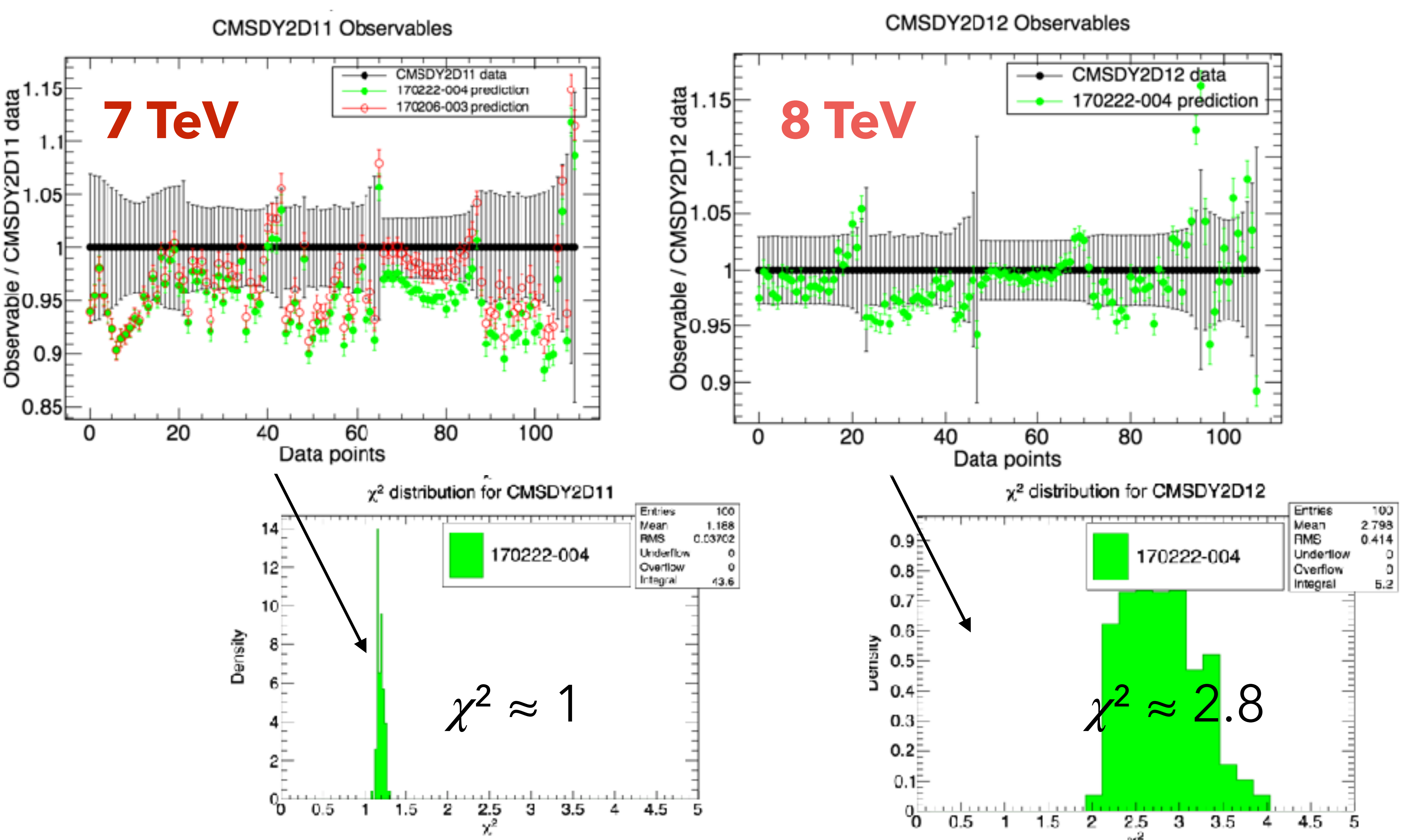
Correlated uncertainties dominance





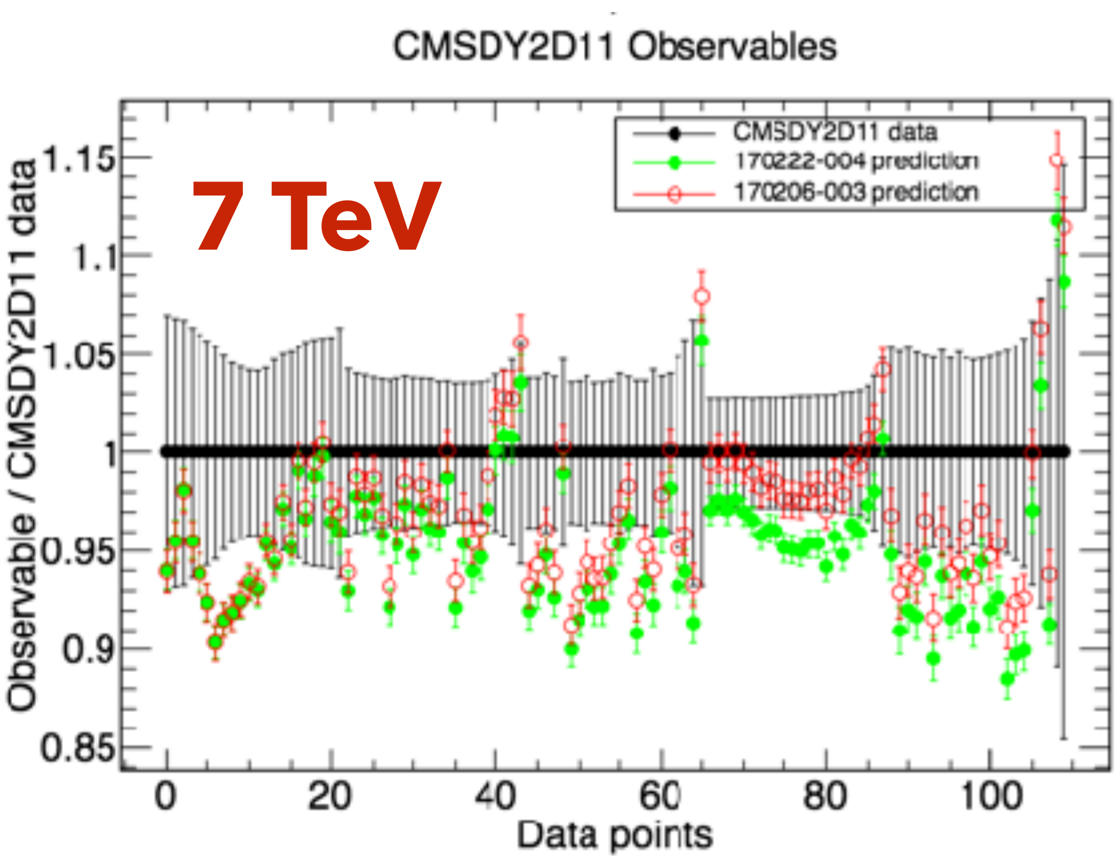
- Many new data drive PDF convergence
- However for the first time precision of the data represents a huge challenge given that for some sets uncorrelated and statistical uncertainties << 1%
- Example: $d^2\sigma / (dM\, dY)$ measured by CMS at 7 TeV and 8 TeV
- Theory data agreement (average distance between experimental points in **black** and theory predictions after the fit in **green**) seems the better for 8 TeV data

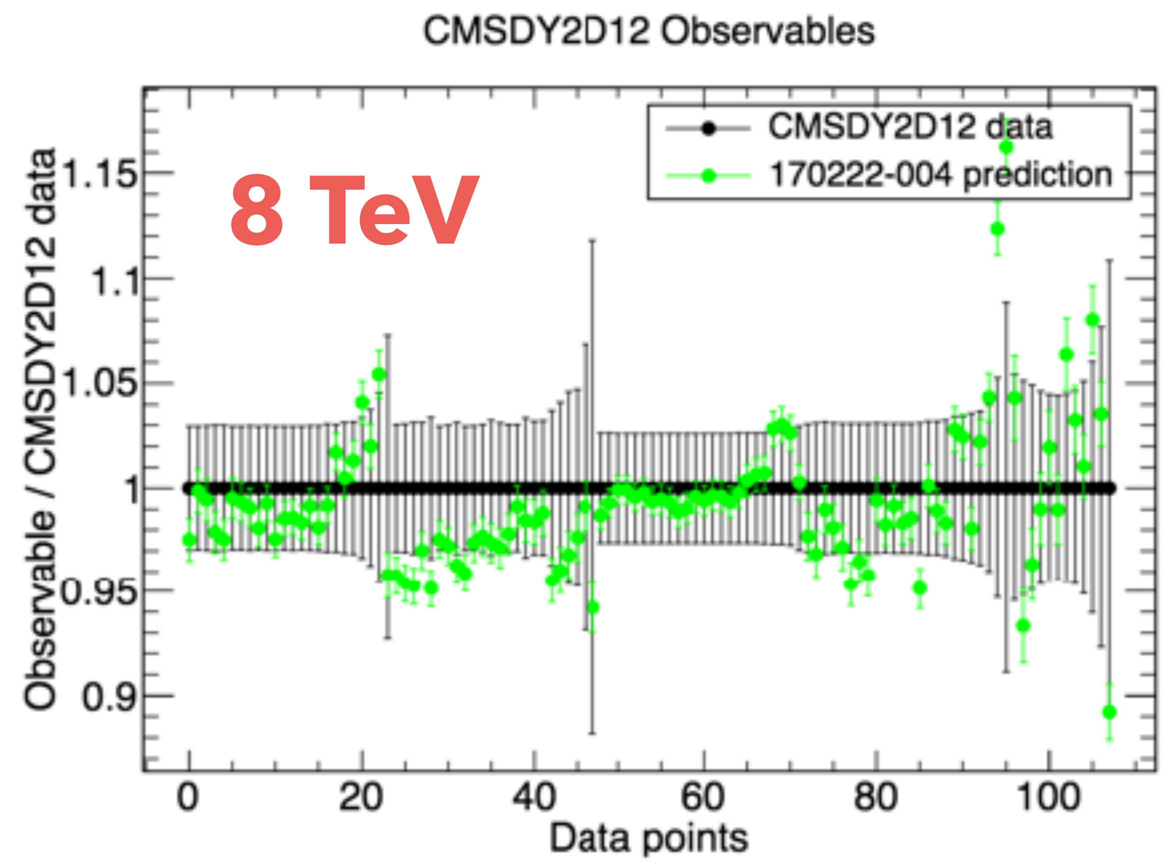
Correlated uncertainties dominance

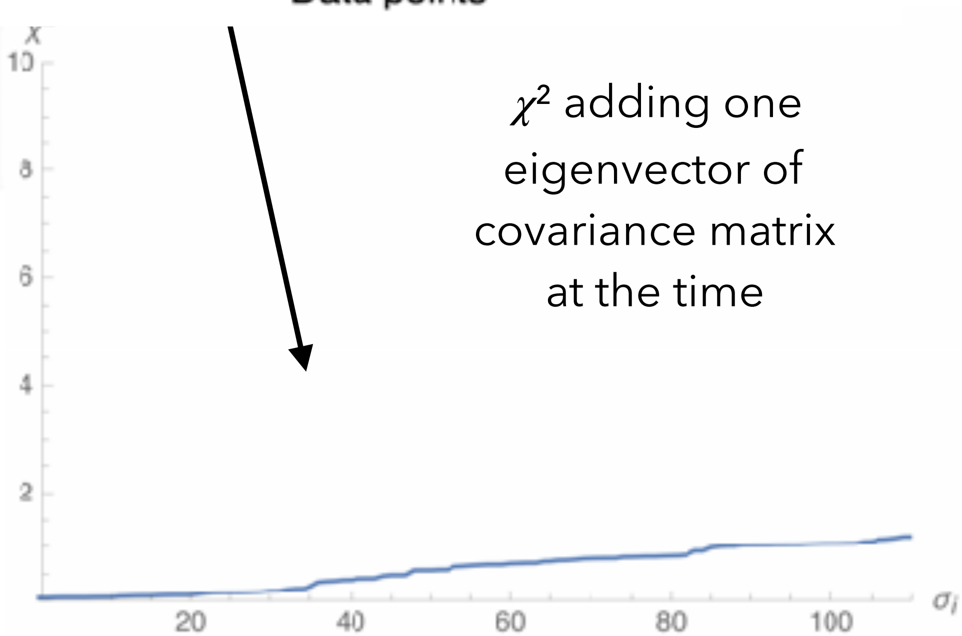


How comes?

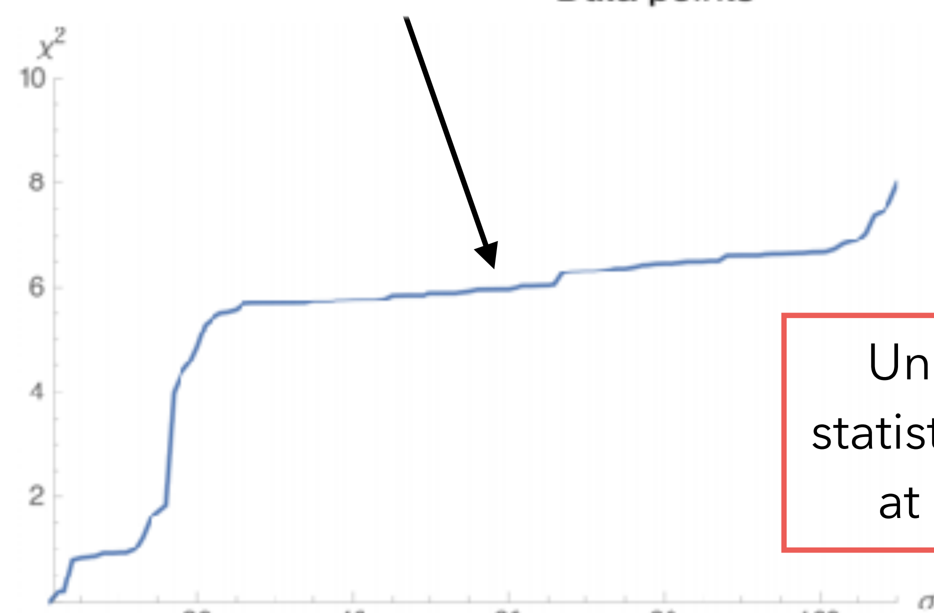
Correlated uncertainties dominance







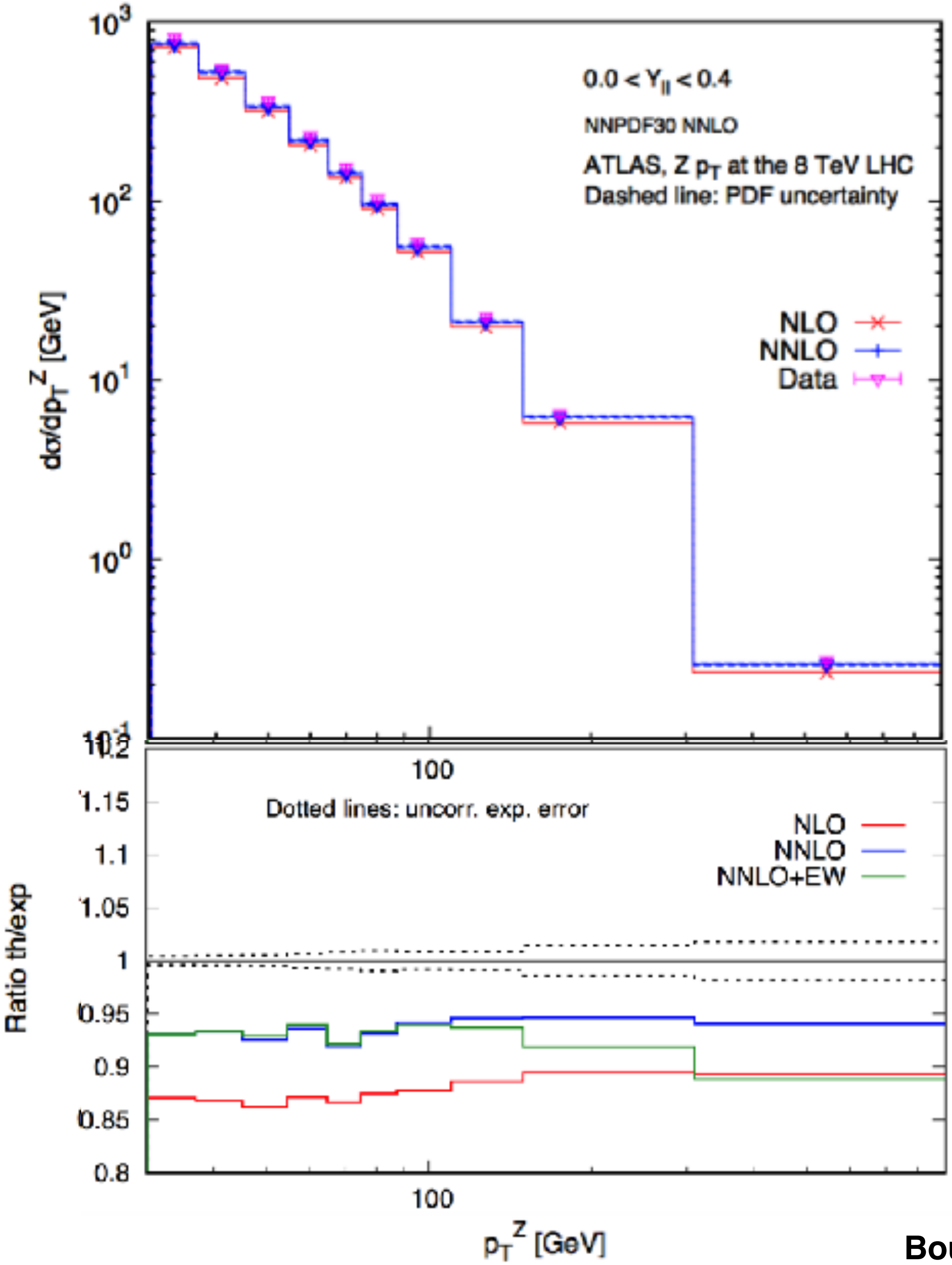
χ^2 adding one eigenvector of covariance matrix at the time

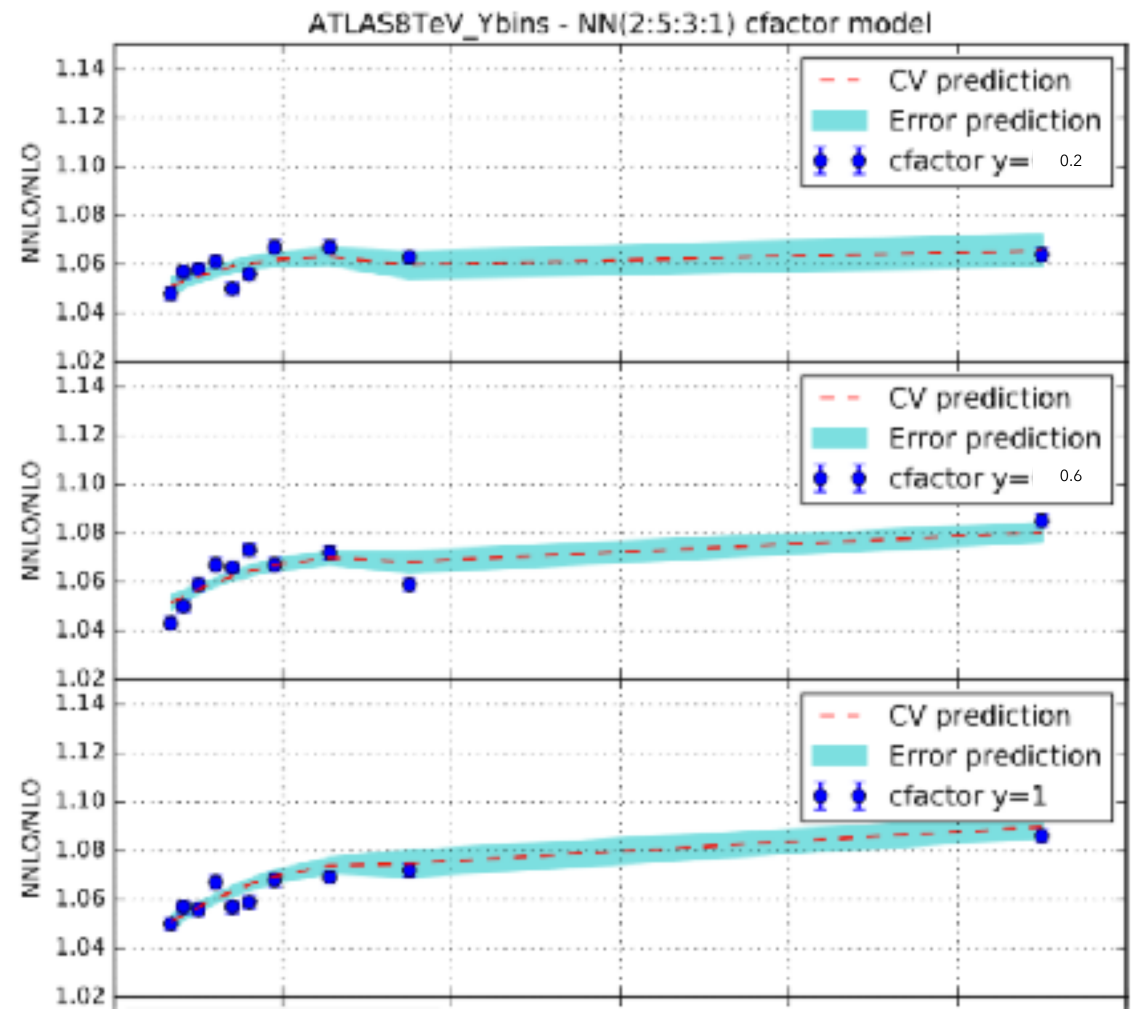


Uncorrelated and statistical uncertainties at per-mille level

- Do we need an uncertainty on the covariance matrix?

Correlated uncertainties dominance

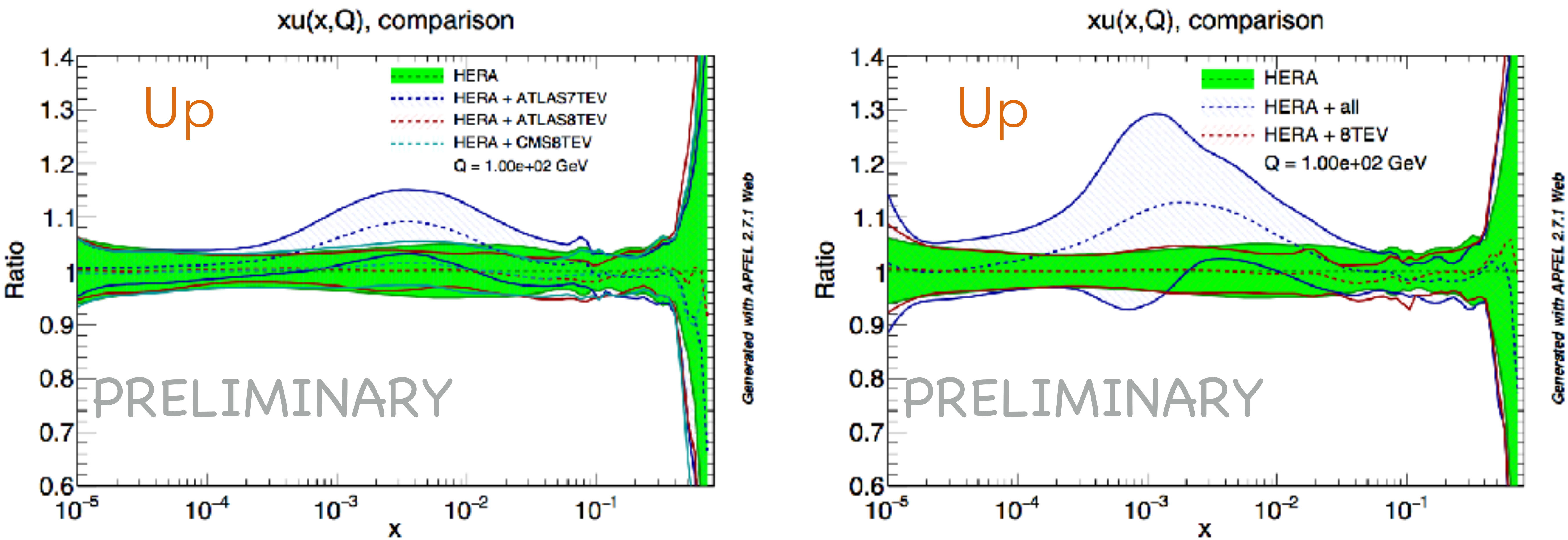




- NNLO theory predictions have Monte Carlo uncertainties
- Fit only possible if uncertainties in theoretical predictions are reliably estimated (fluctuation with respect to smooth interpolation)

Boughezal, Guffanti, Petriello, MU - in progress

Correlated uncertainties dominance



- Impact of Z pT distributions is significant, they increase the singlet and decrease the gluon in regions in which we expect them to be correlated with measurement
- ATLAS and CMS data at 8 TeV (unnormalised) decrease uncertainty of gluon and light quark distributions at both in HERA-only fits and in global fits.
- ATLAS 7 TeV data (normalised) can be fitted individually but point to a different minimum.

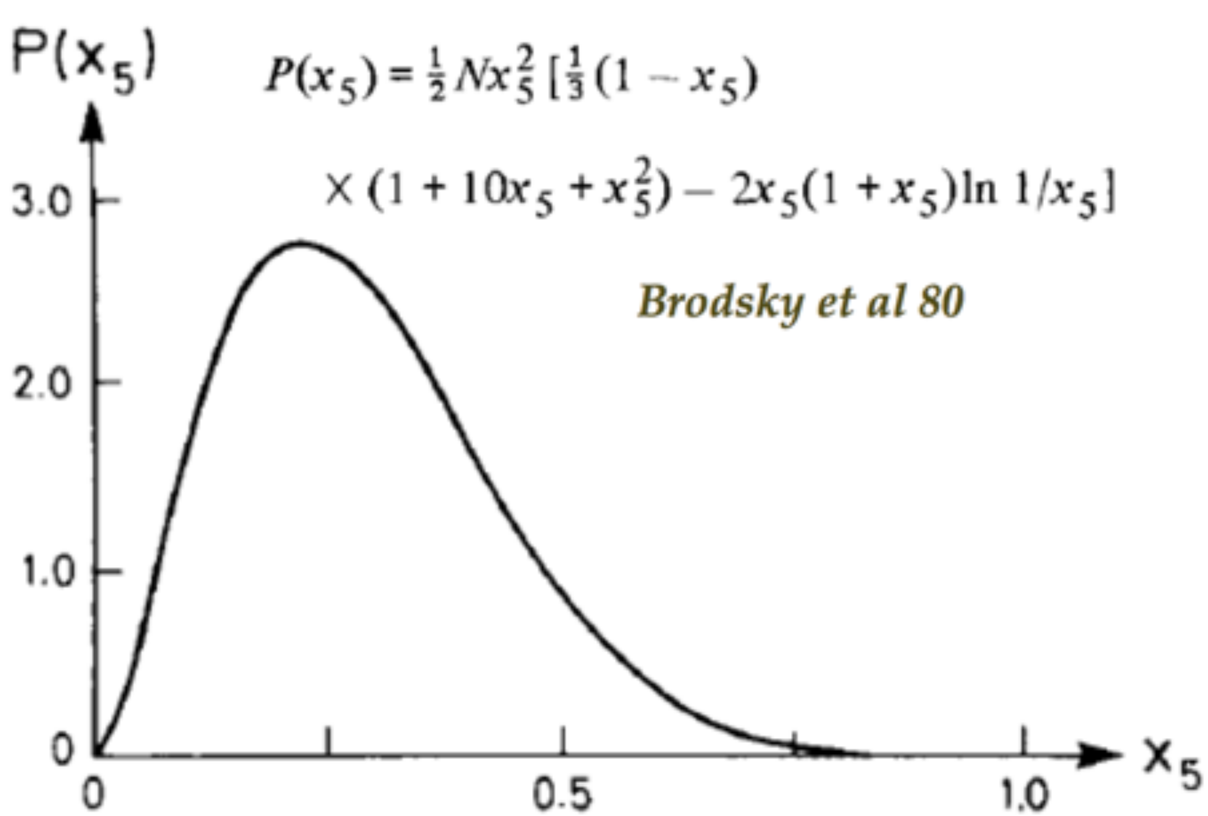
Boughezal, Guffanti, Petriello, MU - in progress

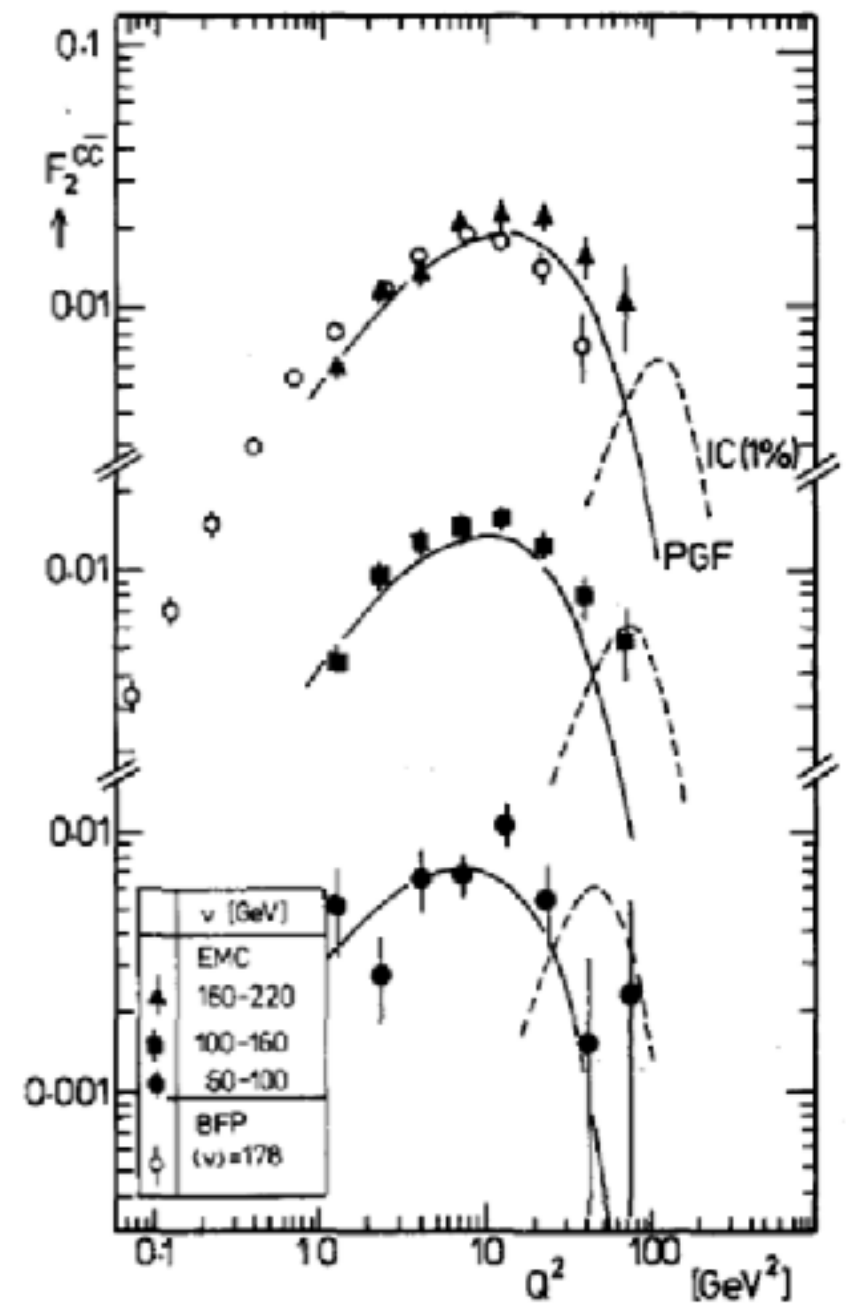
DATA

- Many new accurate data and precise computations: a great opportunity
- Dominating correlated uncertainties challenge both theorists and for experimentalists
- Do data indicate need to fit charm?

Intrinsic/Fitted charm?

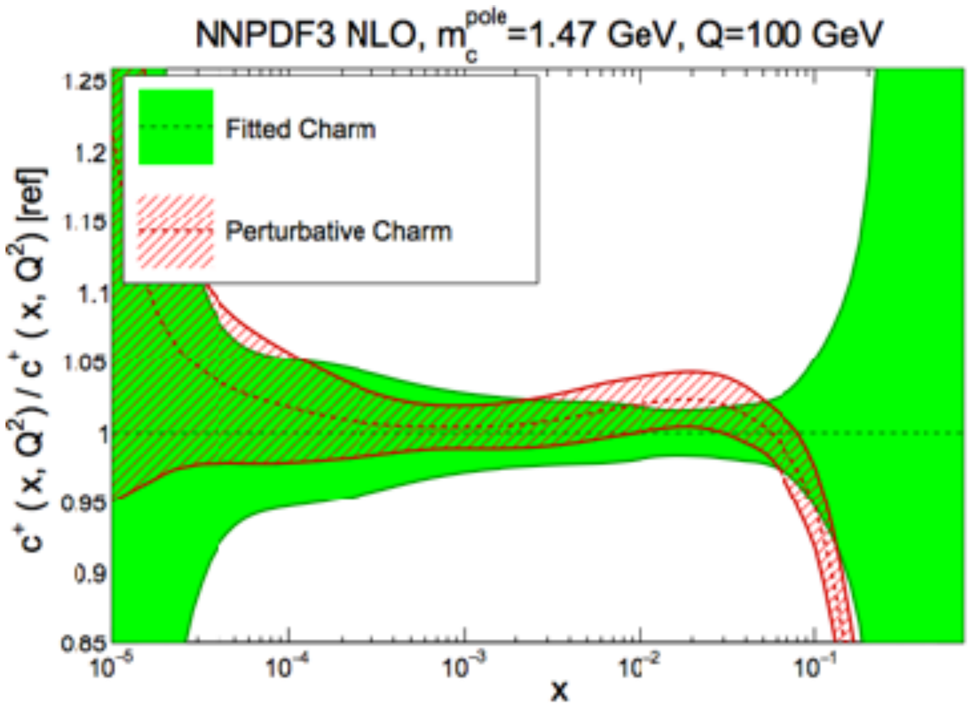
- Do the LHC data point to presence of a non-perturbative component of the charm quark? Interesting because
  - ➡ It would compare to available models
  - ➡ Stabilise fit dependence on mc

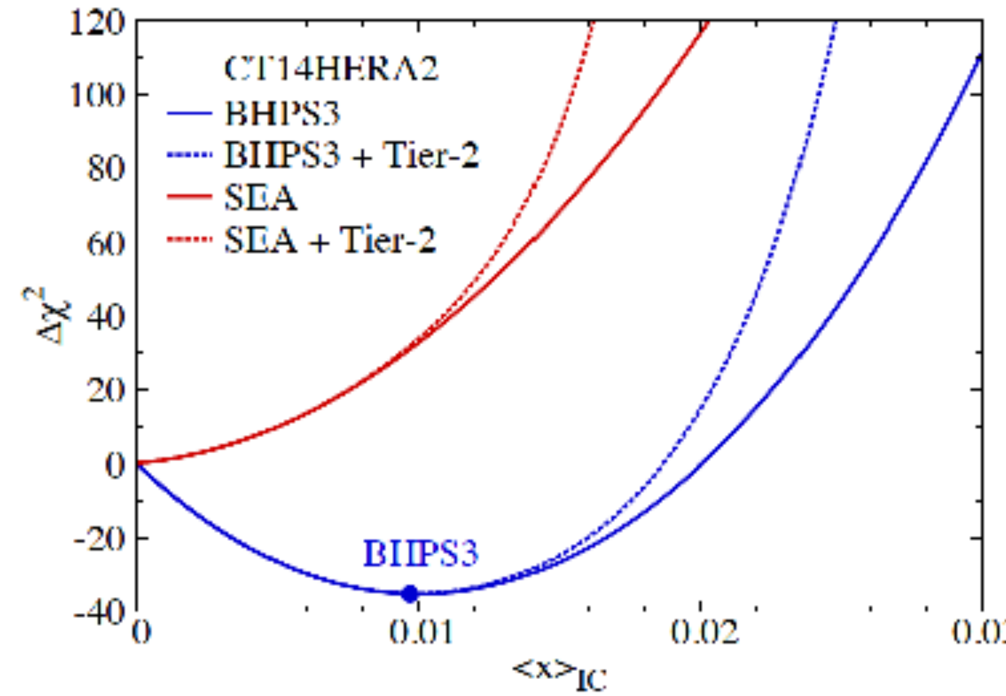




EMC data, 1981

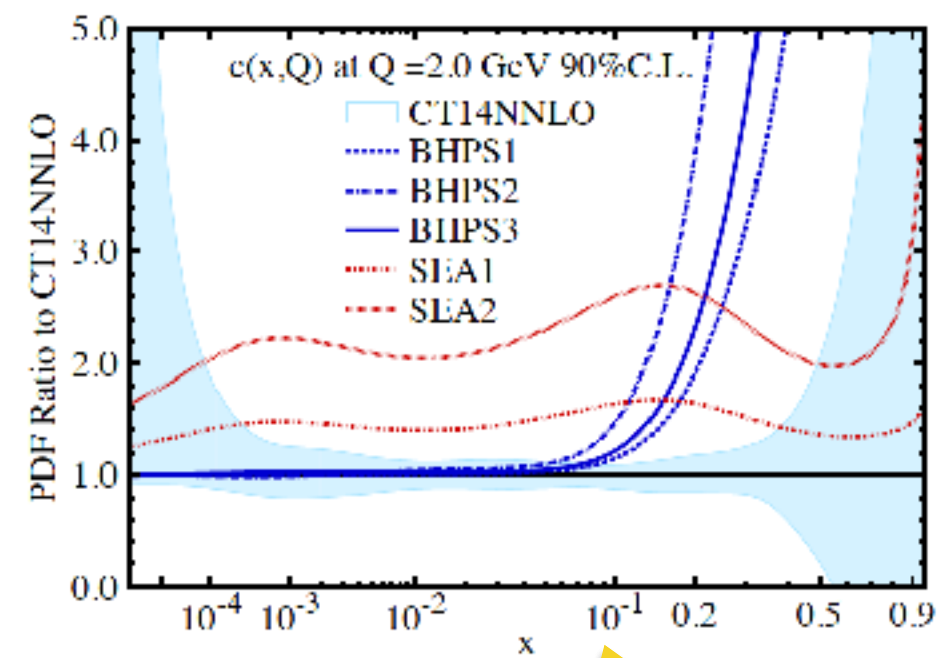
Intrinsic/Fitted charm?





$$C(Q = 1.65\ \mathrm{GeV})_{\mathrm{FC}} - C(Q = 1.65\ \mathrm{GeV})_{\mathrm{PC}} = (0.24 \pm 0.16)\ \%$$

PDF set	$C(Q = 1.65$ GeV$)$	$C(Q = 100$ GeV$)$
NNPDF3.1PC	$(0.360 \pm 0.007)\%$	$(4.48 \pm 0.03)\%$
NNPDF3.1FC	$(0.3 \pm 0.4)\%$	$(4.4 \pm 0.2)\%$
NNPDF3.1FC no ATLAS W, Z 2011	$(0.8 \pm 0.5)\%$	$(4.7 \pm 0.3)\%$
NNPDF3.1FC with EMC	$(0.60 \pm 0.16)\%$	$(4.6 \pm 0.1)\%$



- NNPDF3.1: fitted charm improves fit quality
- Fit more stable wrt to charm threshold
- Reduced dependence on EMC data
- With EMC data included in global fit 1.5σ evidence of presence of non-perturbative charm

J. Rojo

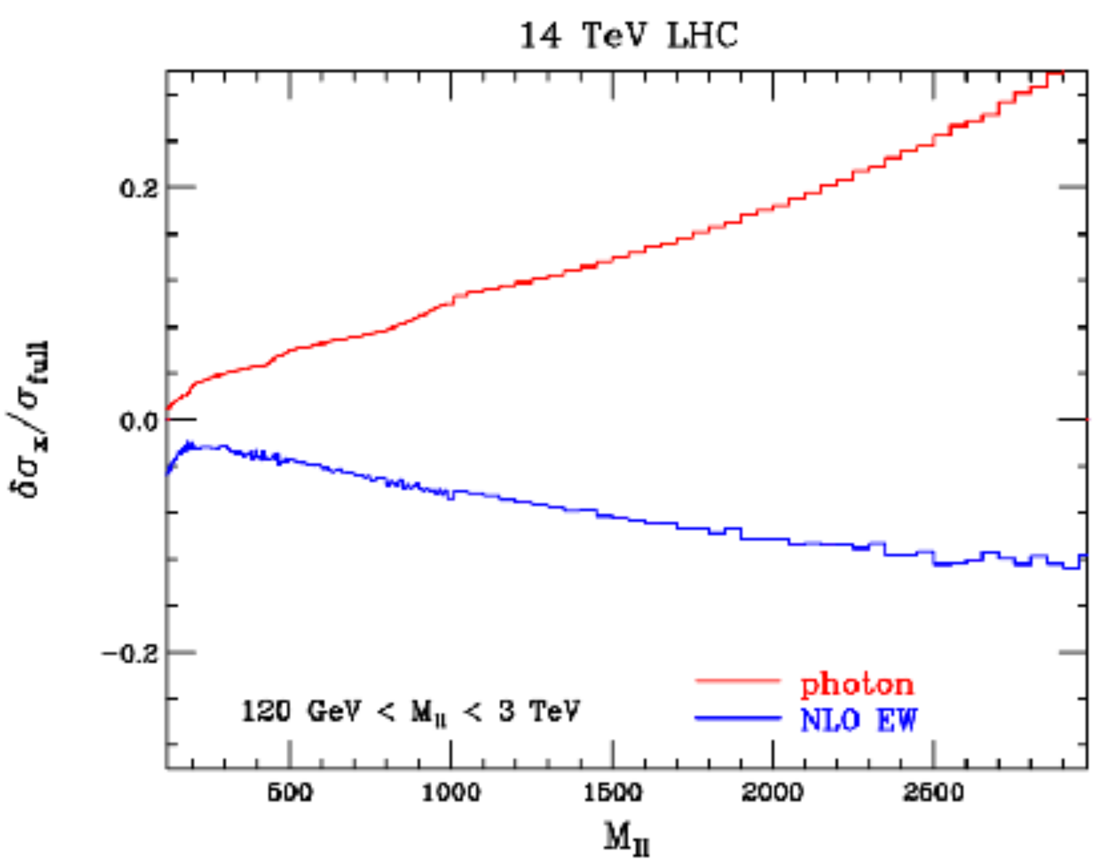
M. Guzzi

- Large invariant mass & large rapidity: EW and photon-initiated processes become crucial
- Closer to kinematic boundaries: need resummation in PDFs?
- Time to quantify hidden PDF uncertainties

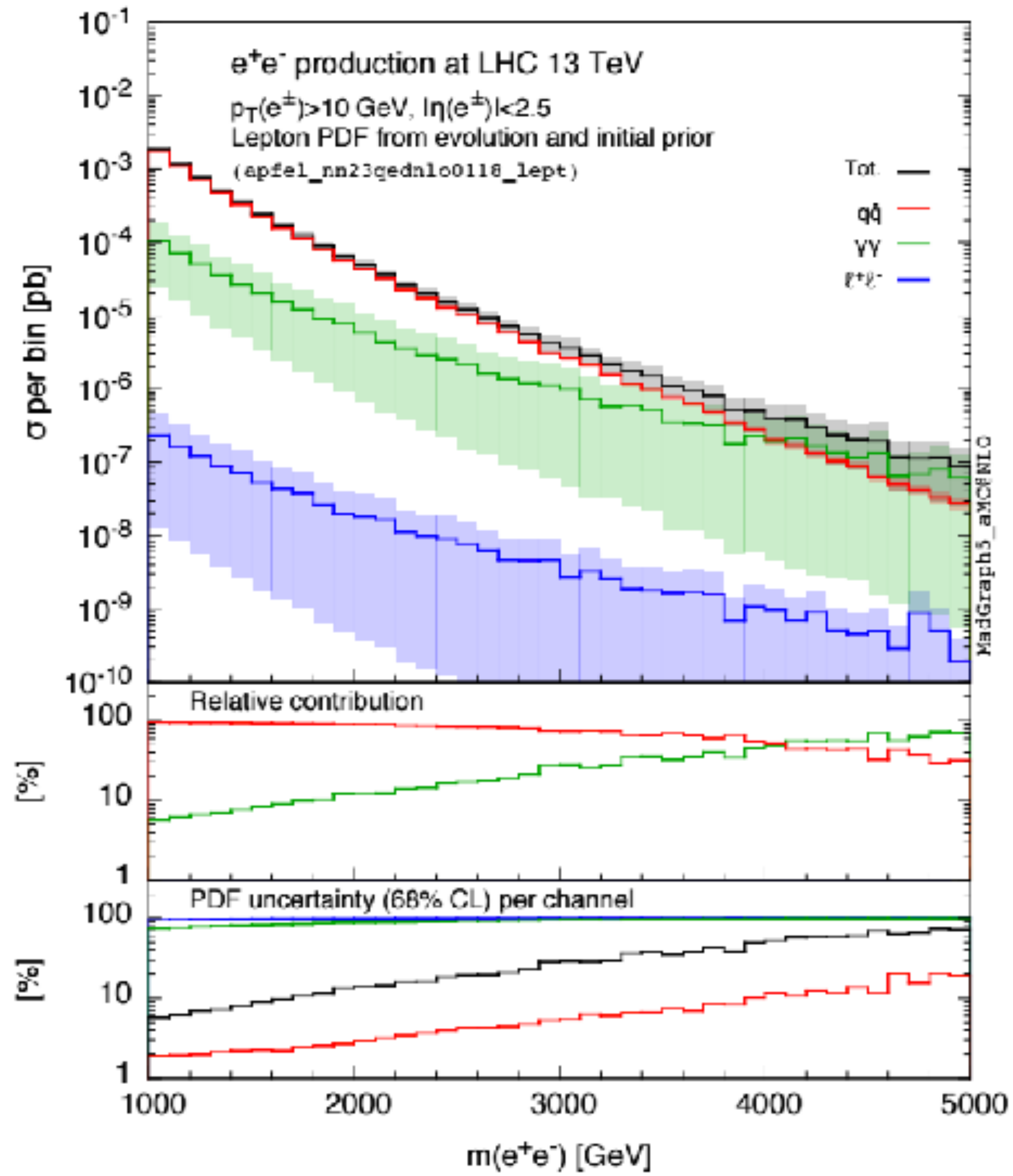
THEORY/ METHODOLOGY

EW corrections

- EW corrections become relevant at the current precision level as are sizeable at large invariant mass
- Full inclusion of EW corrections requires initial γ PDF



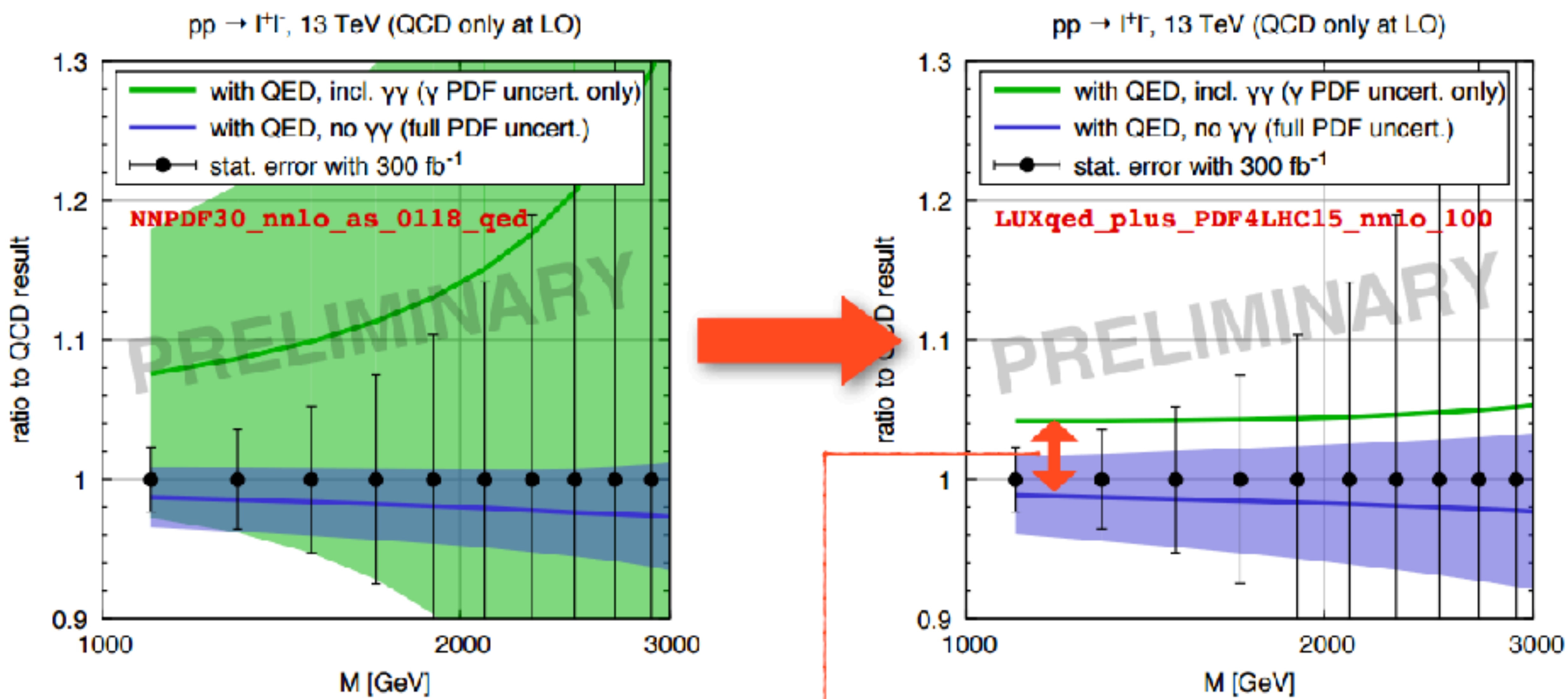
Boughezal et al, 2014



Bertone et al, 2015

Photon PDF

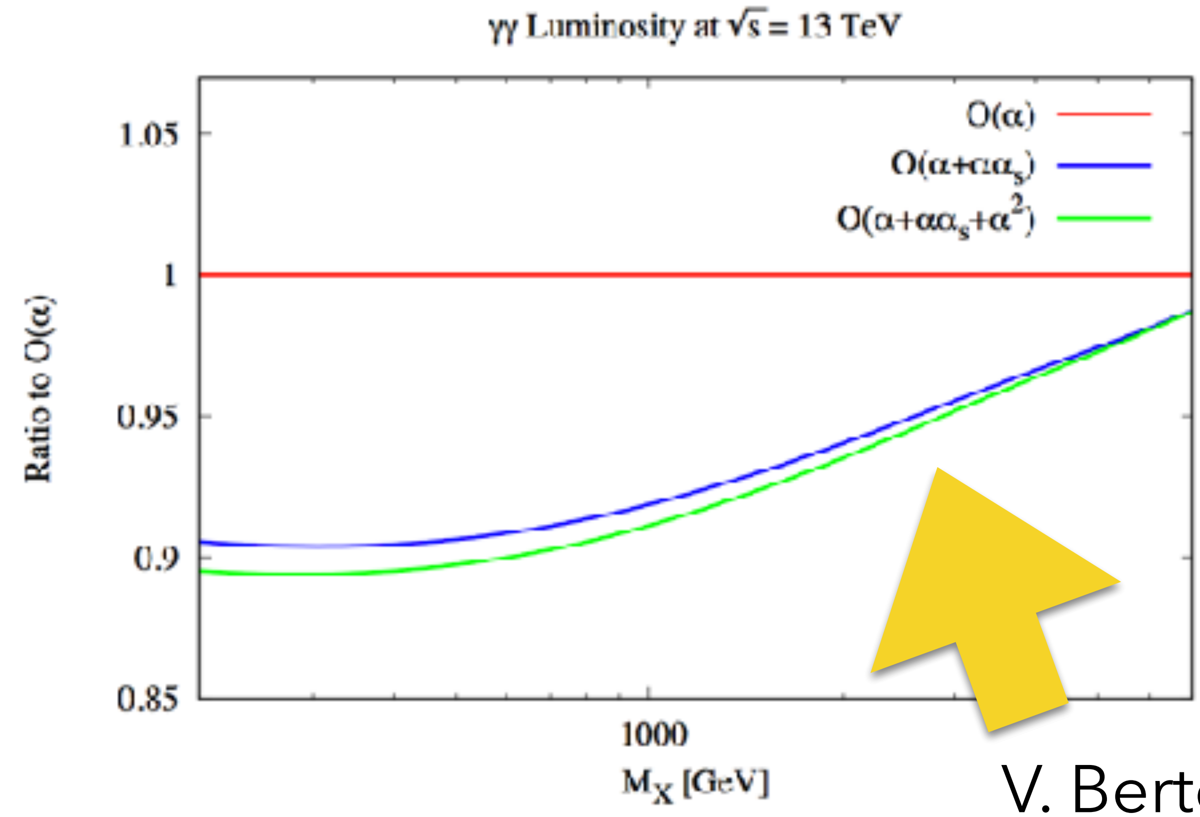
- Data-driven NNPDF approach inducing a large uncertainty on photon PDF
- Breakthrough: LUX PDF [Manohar, Nason, Salam, Zanderighi,2016]
- Take a BSM interaction, compute the cross section with the Master Formula or with the Parton Model formula. Extract photon PDF by identifying the two cross sections.
- Theory constraint reduces uncertainty by a huge factor



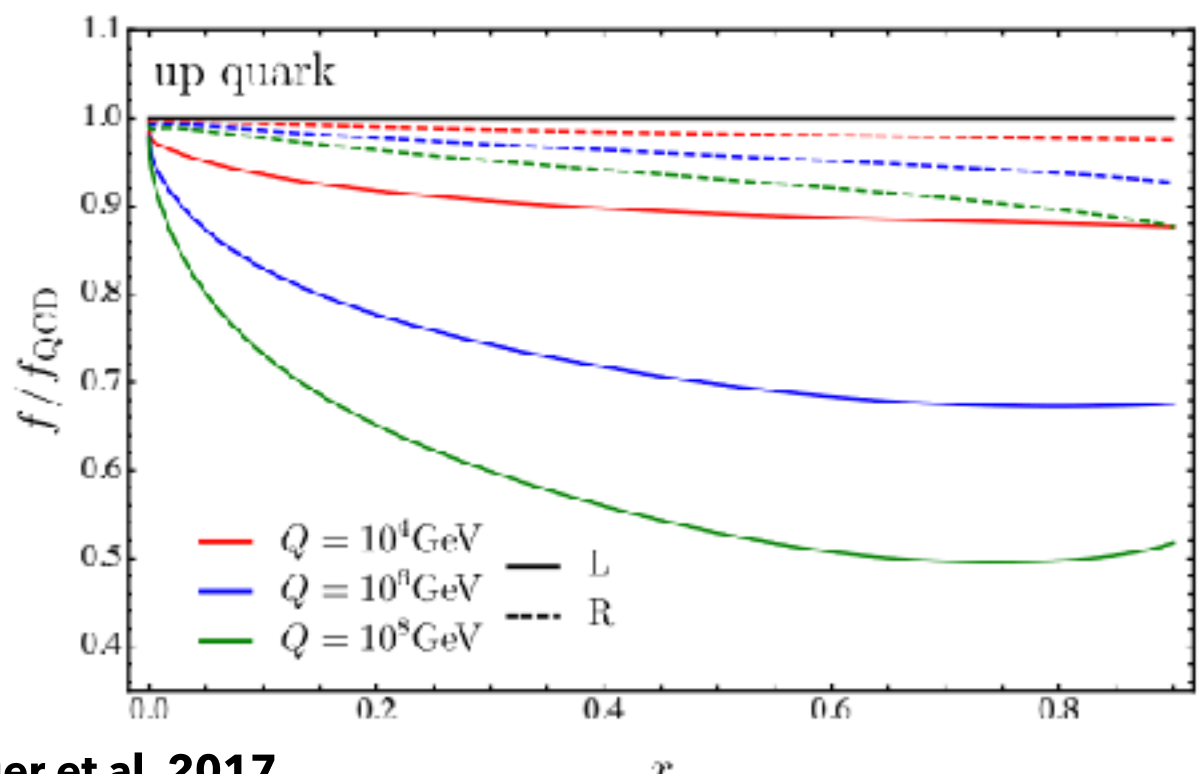
G. Salam, Moriond EWK 2017

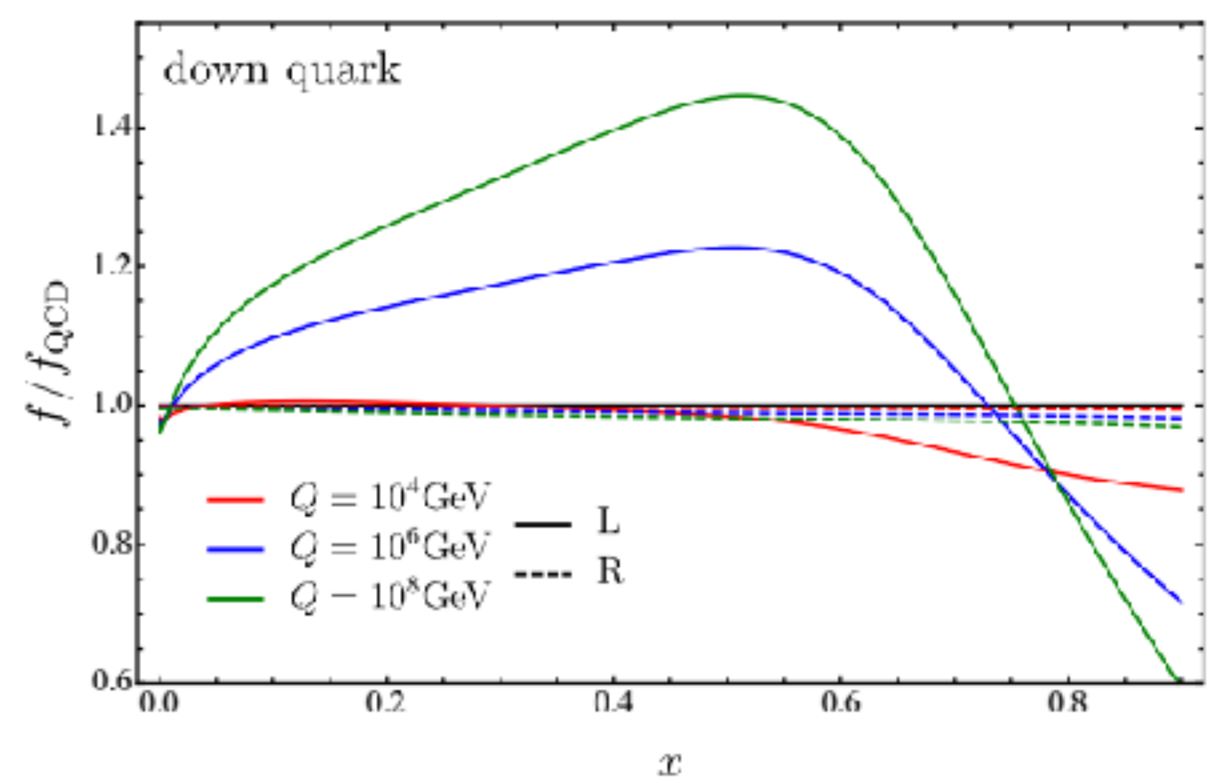
Beyond pure QCD evolution

- Need NNLO QCD and NLO EW coupled evolution
- Recent progress in APFEL full inclusion of coupled NNLO QCD and NLO QED
- At scales much beyond LHC reach full unbroken SM evolution must be considered (γ, l, W, Z, h, ν…)



V. Bertone





Bauer et al, 2017

Beyond fixed-order accuracy

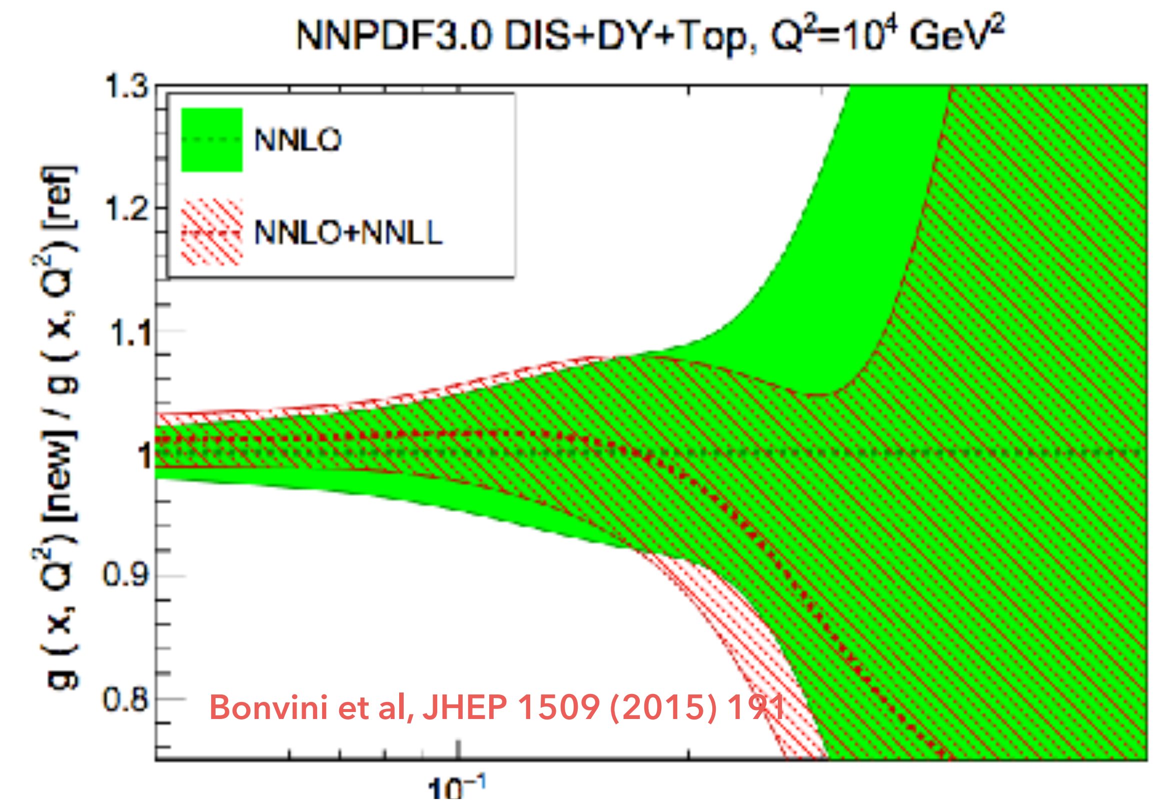
- Multi-scale processes: log(Qi/Qj) = L arise, which may spoil perturbative expansion
- If (α_S * L) ~ O(1) fixed order perturbative QCD is no longer justified
- Resummation effectively rearranges perturbative series

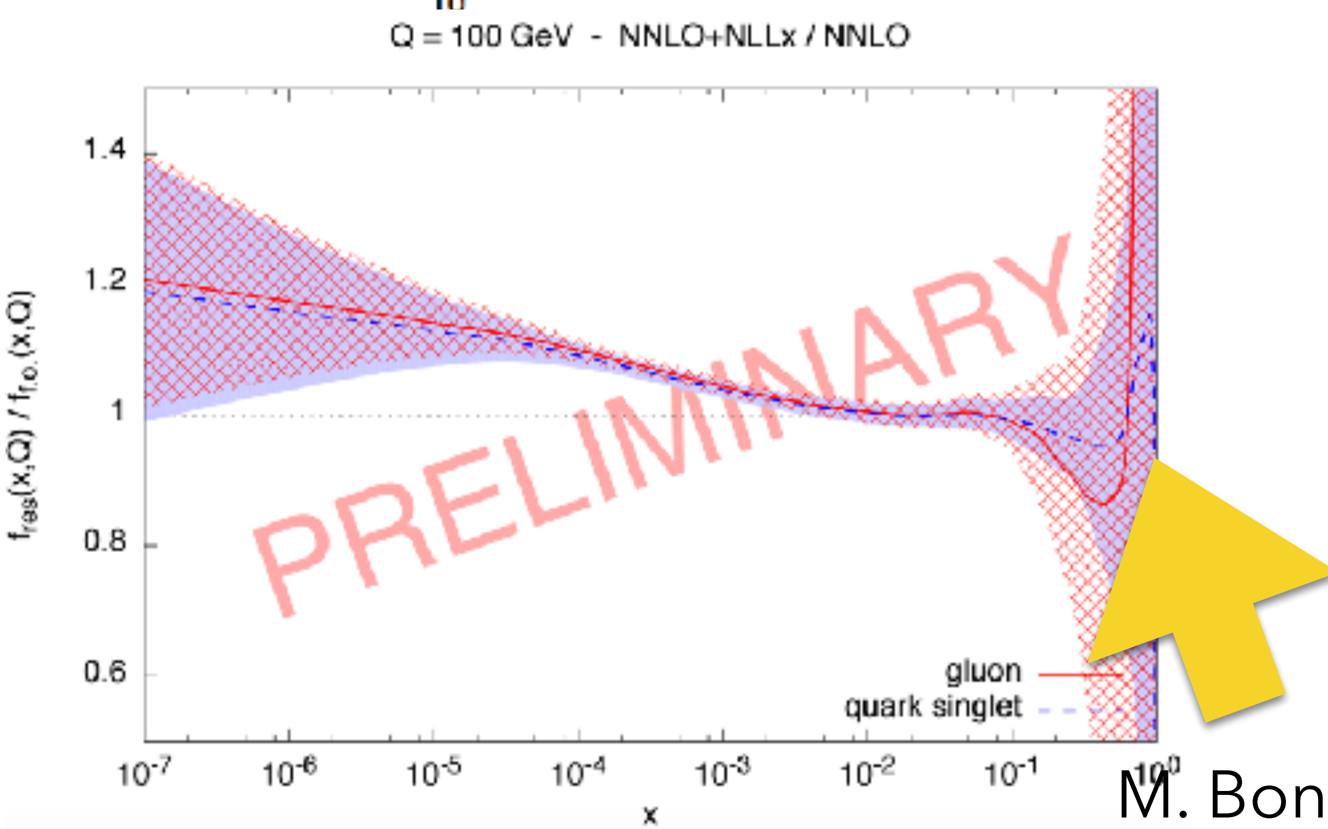
fixed order		all order (L = some large logarithm)	
$\frac{\sigma}{\sigma_0} = 1$	LO	$\ln \frac{\sigma}{\sigma_0} = \alpha^n L^{n+1}$	LL
$+ c_1 \alpha$	NLO	$+ \alpha^n L^n$	NLL
$+ c_2 \alpha^2$	NNLO	$+ \alpha^n L^{n-1}$	NNLL
$+ \ldots$		$+ \ldots$	

- Various kinds of logs:

L = log (1-x)   threshold (soft-gluon) resummation
L = log (1/x)   high-energy (small-x) resummation
L = log (pT/M) transverse momentum resummation

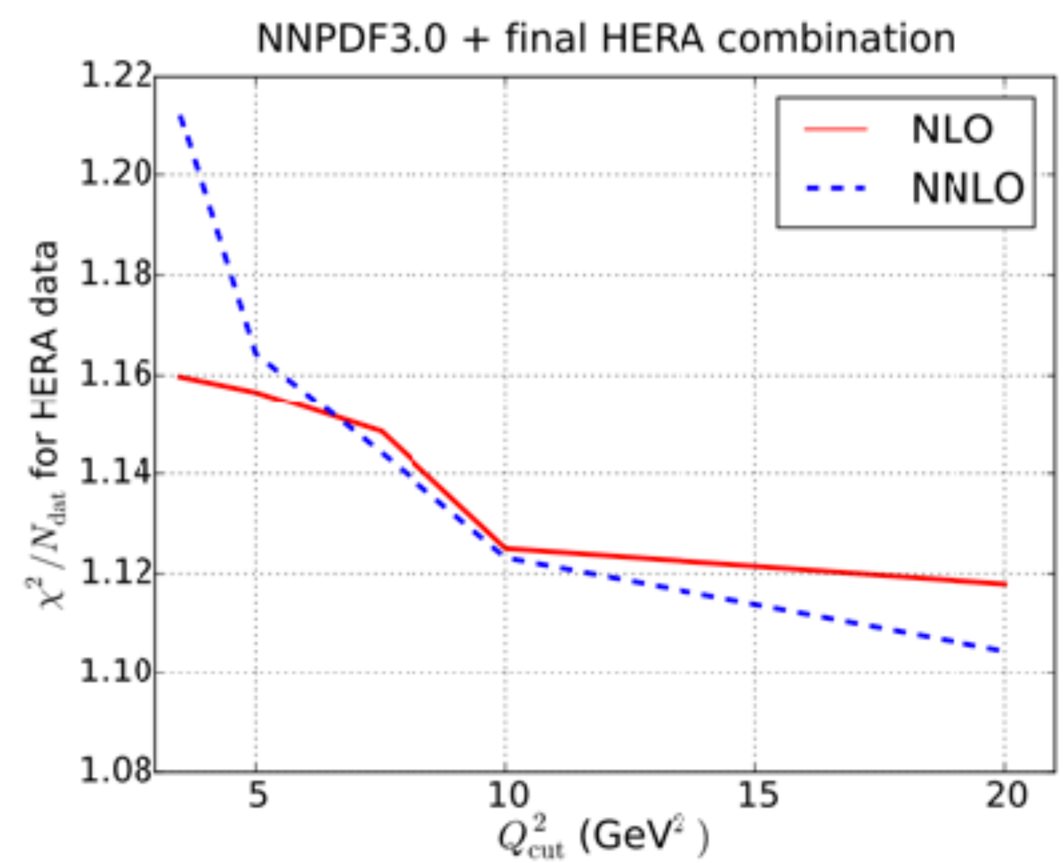
Beyond fixed-order accuracy





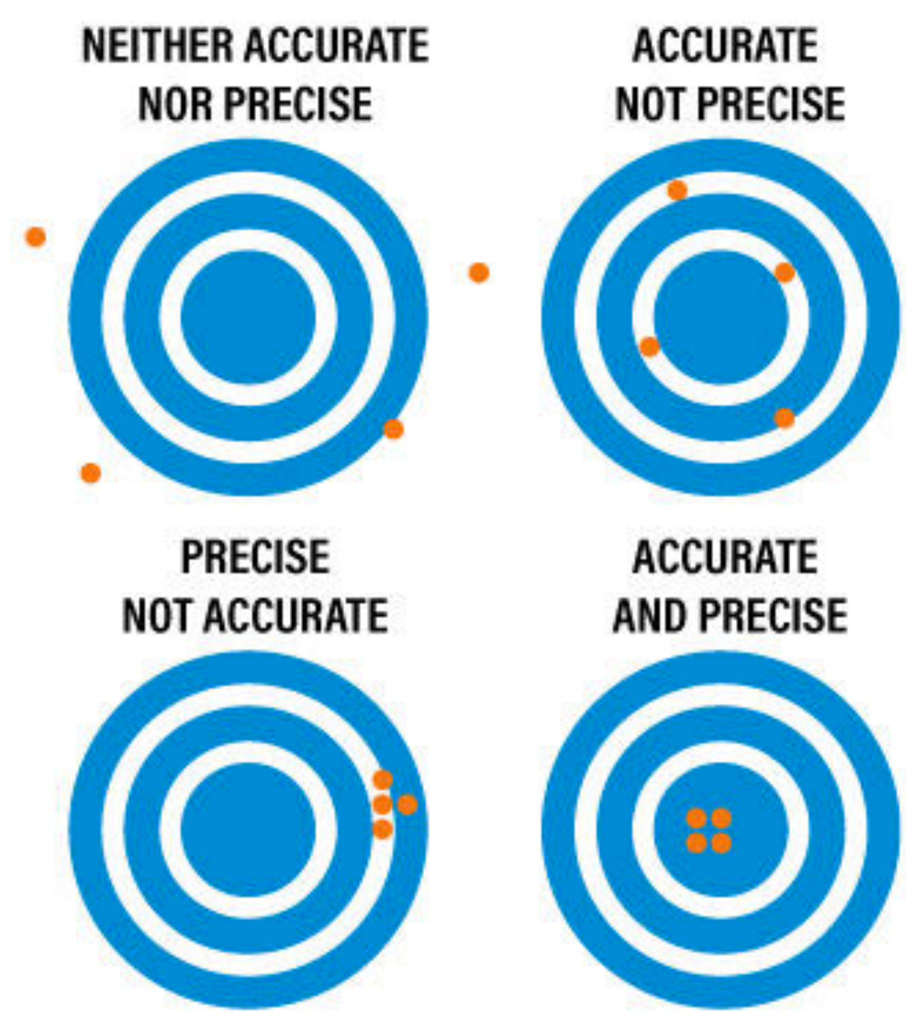
M. Bonvini

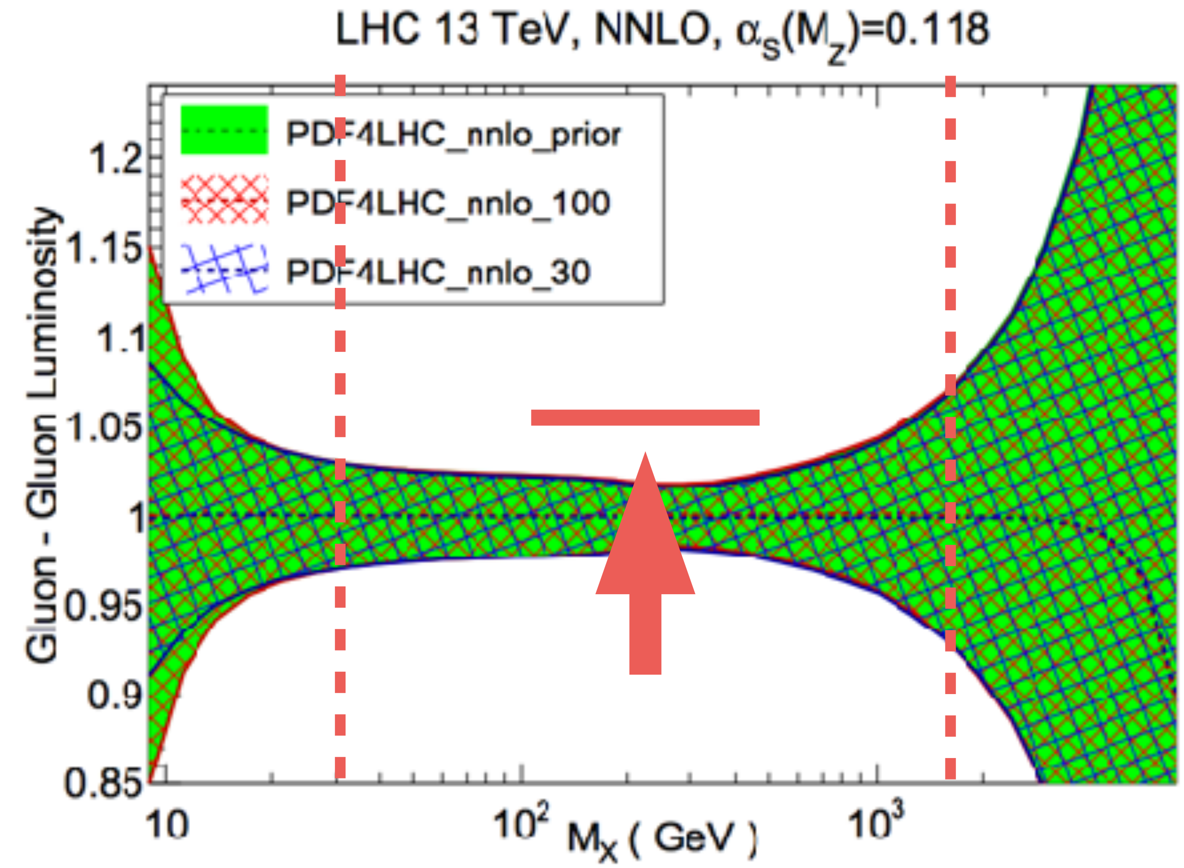
- First threshold-resummed PDFs made recently available **[Bonvini et al,2015]**
- Suppression in PDFs partially or totally compensates enhancements in partonic cross sections.
- Progress in inclusion of small-x resummation in PDF fits (may explain χ^2 of precise HERA data?)



Are PDFs accurate enough?

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

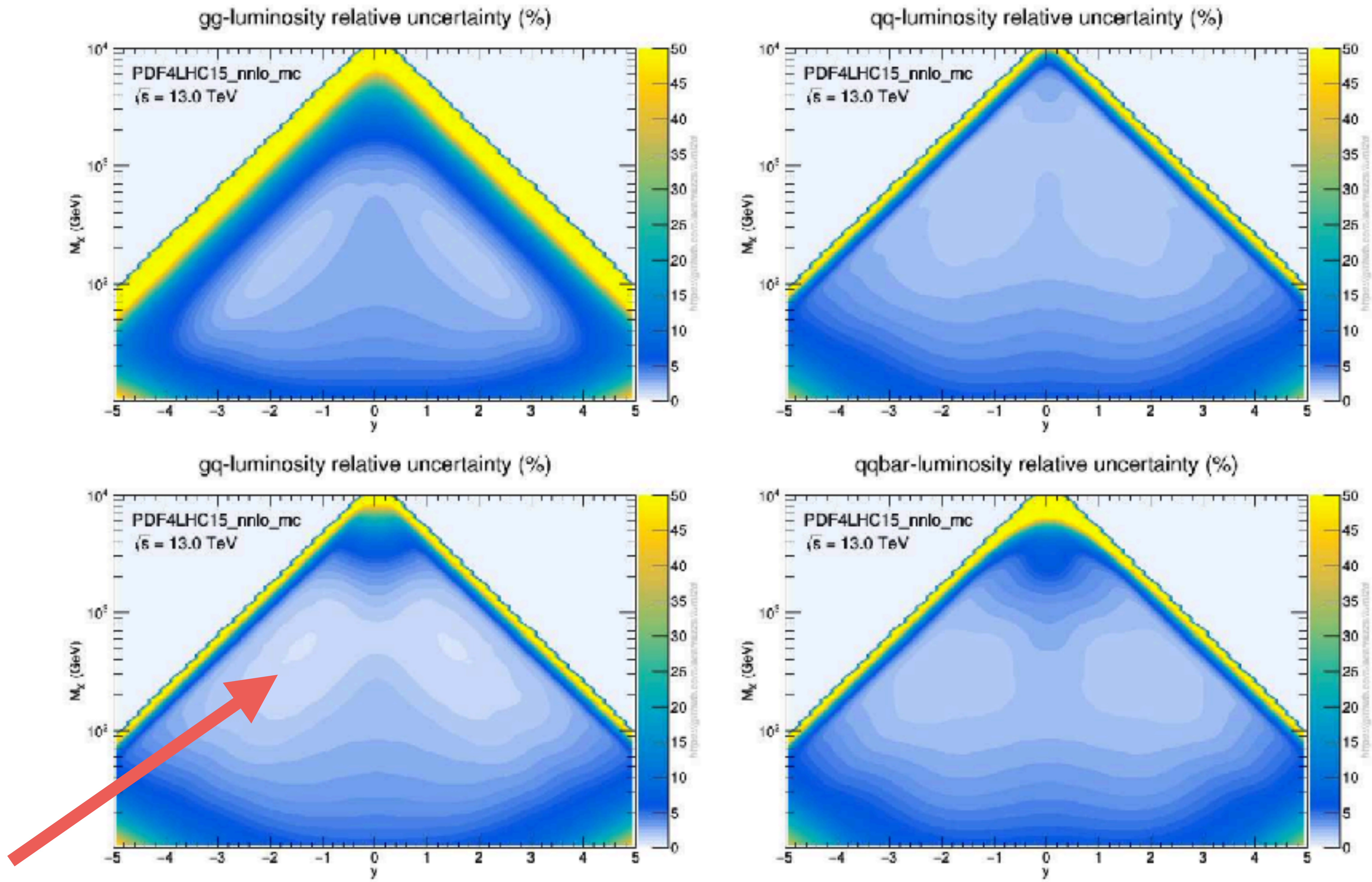




Theory boundaries | Precision Physics | Discovery region

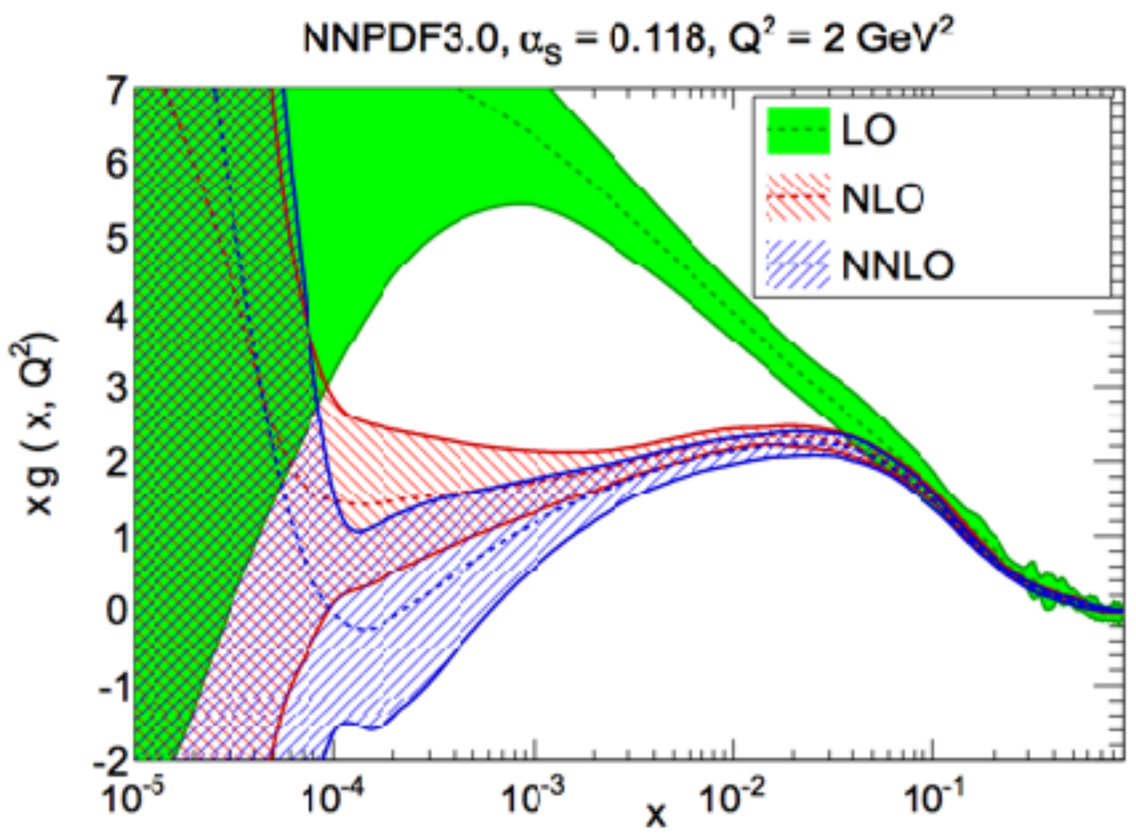
- Inconsistent data → Tolerance
- **Changes in theory**
- Updated parametrization
- Differences in fitting methodology/minimisation? → Closure Test

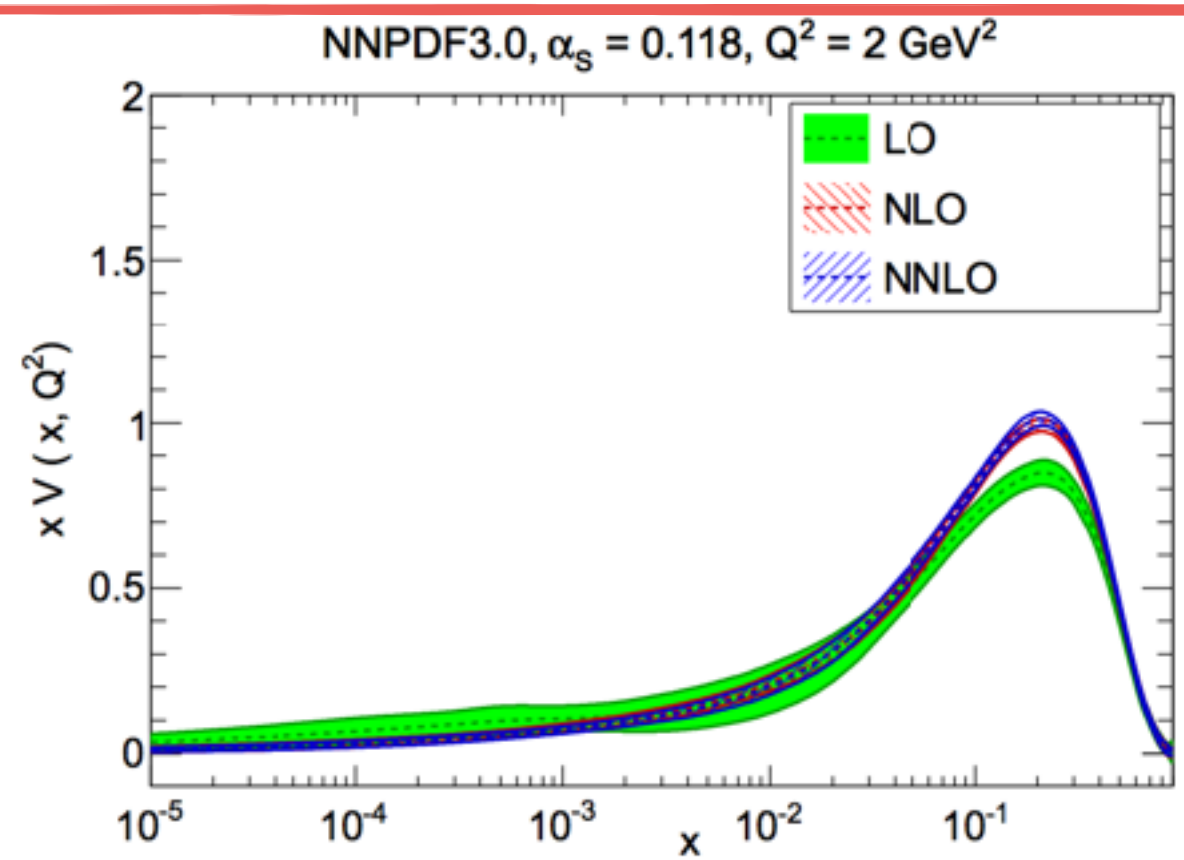
Are PDFs accurate enough?



Gluon better known at small-x, valence quark at large x and sea quark in between. Do we trust 1% uncertainty in parton luminosities?

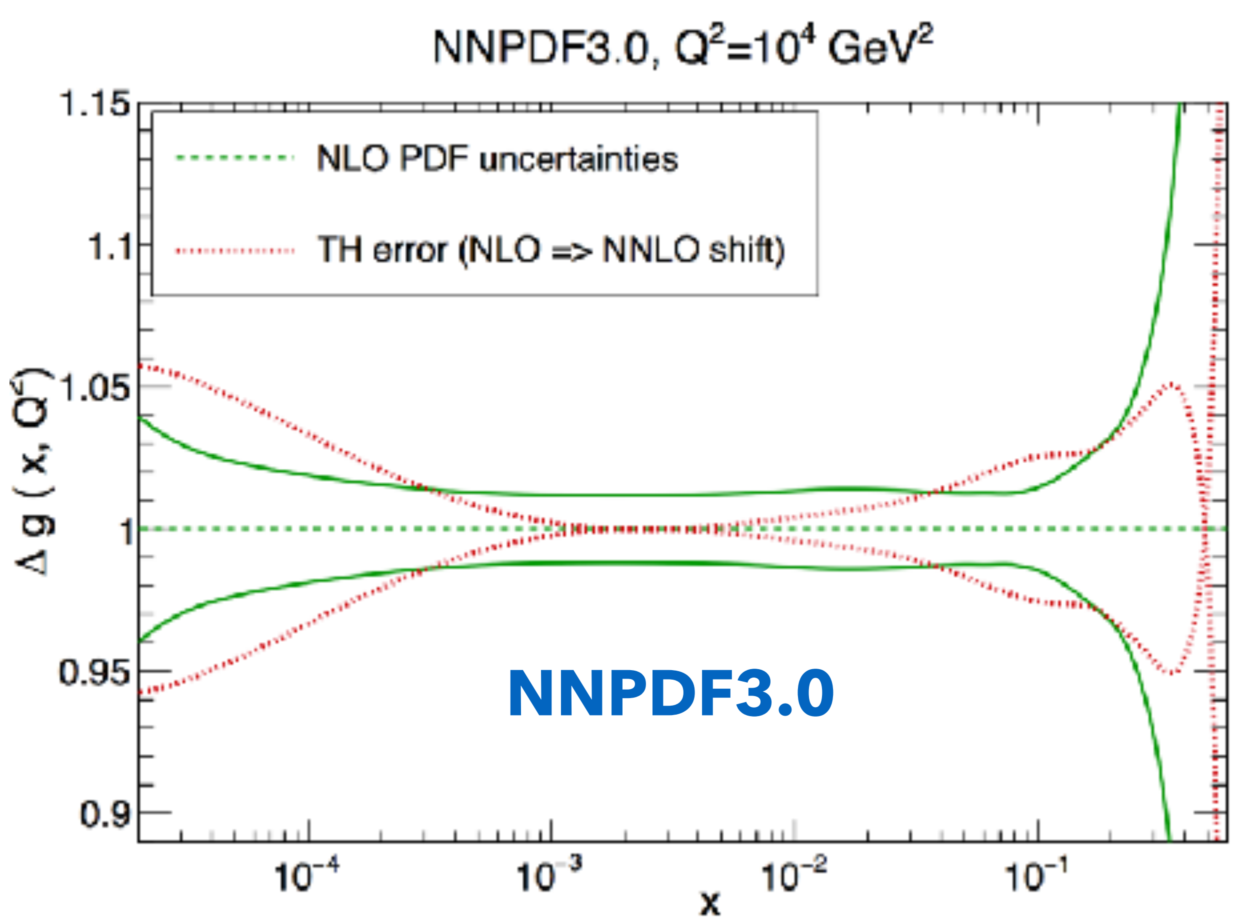
PDF hidden uncertainties

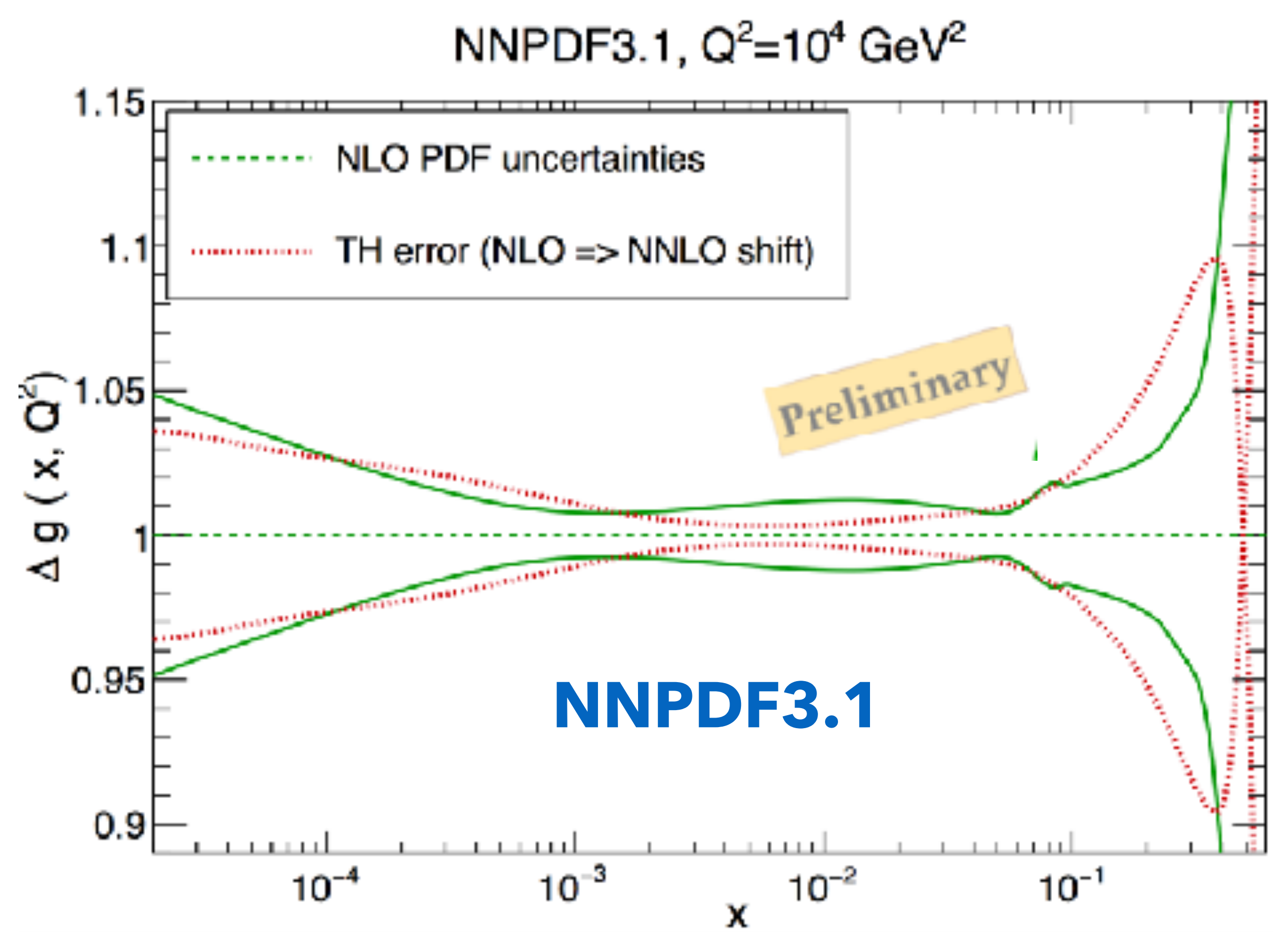




- PDF fits performed with given fixed perturbative order, value of α_S and heavy quark masses
- PDF uncertainties only reflect lack of information from data given the theory
- Changes in theory may cause shifts outside the error band, can we estimate that?
- LO fits are merely qualitative, NLO quantitative and NNLO precise, but how much?

PDF hidden uncertainties





- As PDF uncertainties get smaller the role of theoretical uncertainties becomes increasingly crucial, especially for well-constrained PDF combinations
- Time to explore fits with scale variations
- How to keep into account theoretical correlations between different processes?
- How to combine PDF theory uncertainties and hard process theory uncertainties?

(March 2017: SCALES workshop in Cambridge)

Conclusions

- Parton Distribution Functions essential ingredient for LHC phenomenology
- New precise data from the HERA and LHC drive convergence among PDF sets & push collaborations to clarify the origin of residual differences & hint to deeper understanding of proton structure
- The very precision of the data starts making life hard for both theorists and PDF fitters: Need uncertainty on the correlation? Uncertainty of theory predictions?
- Precision pushing to new frontiers: closure tests, theoretical uncertainties, resummations and coupled QCD and EWK evolution
- Not time to mention
  - Moving heavy quark thresholds (see F. Olness talk)
  - Relation with Lattice QCD (see E. Nocera's talk)
  - As higher invariant mass is fitted, can PDFs hide new physics?

Outlook

[…] Global QCD Analysis of available hard processes critically tests the validity of the PQCD framework, allows the determination of the non-perturbative parton distribution functions, thereby provides the necessary input to calculate and predict most Standard Model and New Physics processes for future, higher, energy interactions. **After two decades of steady progress in this venture, has global QCD analysis of parton distributions reached the End of the Road (as some have proclaimed); or, will the physics challenges of the next generation of colliders usher in the Dawn of a New Era, with fresh ideas and more powerful methodology (as some have promised)? That, is the question.**

Wu-Ki Tung - CERN-TH colloquium 2000

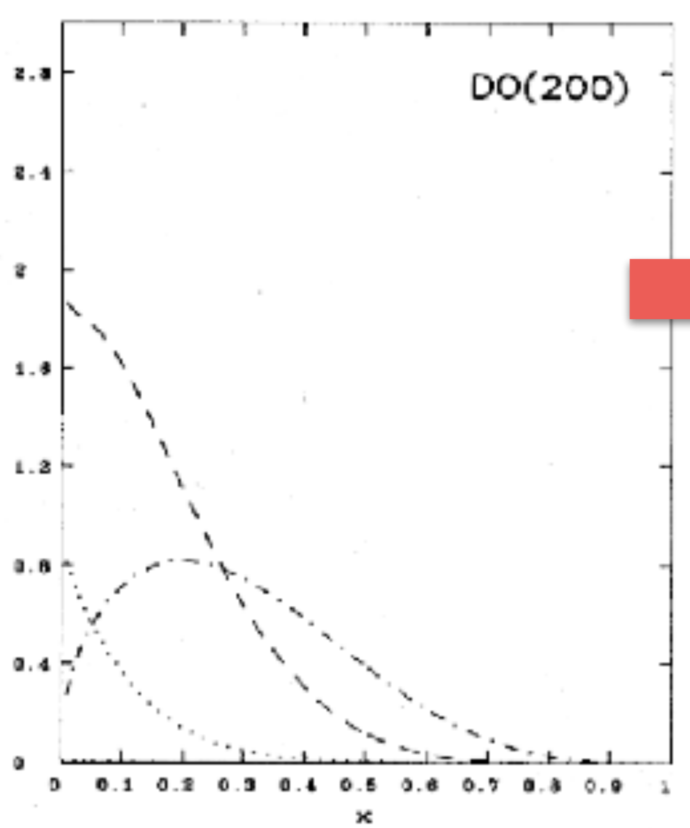


FIG. 27. "Soft-gluon" ($\Lambda = 200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2 = 5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).