IMPACT OF PRECISE DATA AND ACCURATE THEORETICAL PREDICTIONS ON PDFS

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Outline of the talk

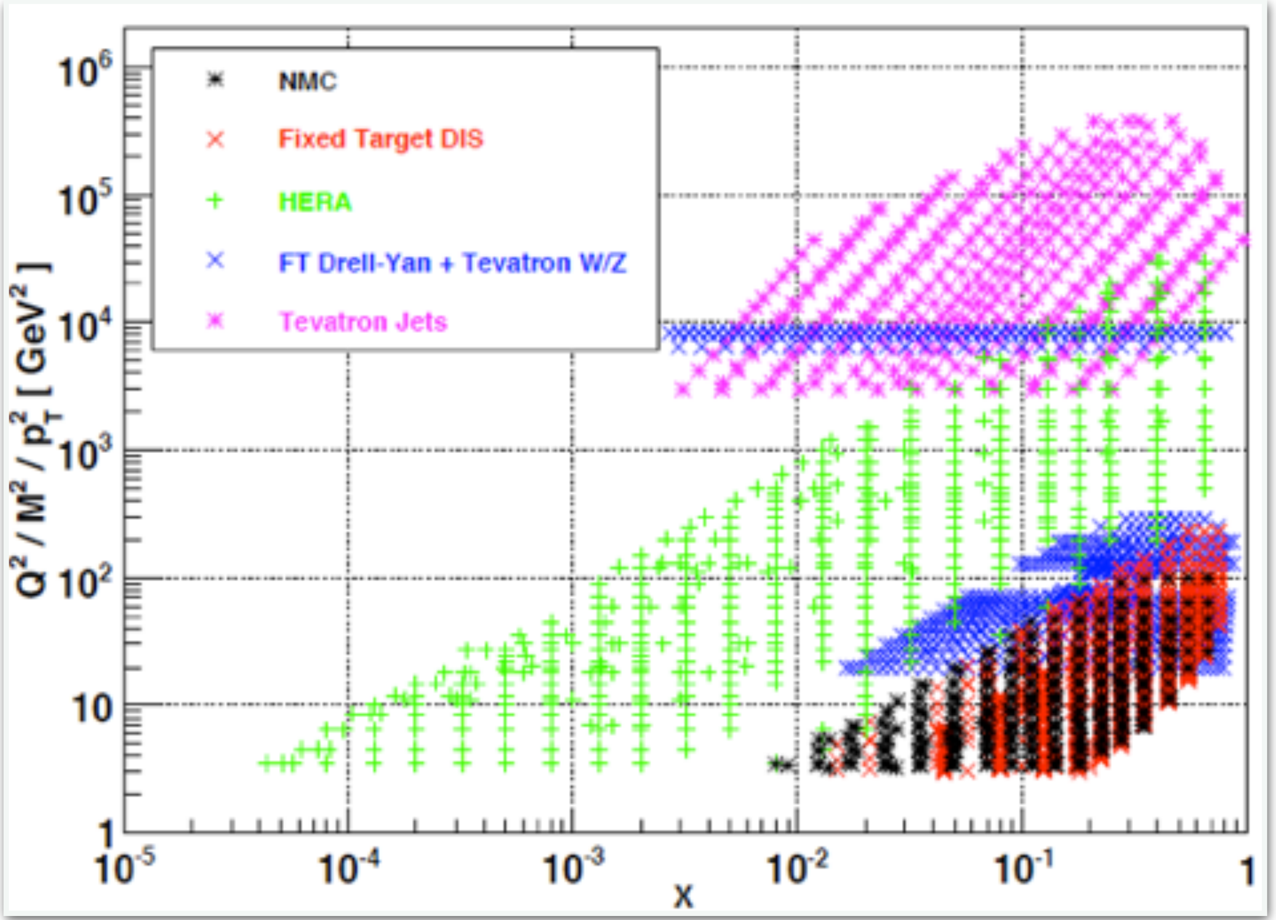
- Introduction
- Interplay between data and LHC
    - Data-driven progress
    - New constraints from LHC: challenges and opportunities (top, Z pT)
- Implications for theory
    - Reduce theoretical uncertainty
    - Measure residual theoretical uncertainty
- Conclusions and outlook

Collinear Factorisation Theorem

$$\frac{d\sigma_H^{pp\to ab}}{dX} = \sum_{i,j=1}^{N_f} f_i(x_1,\mu_F)\, f_j(x_2,\mu_F)\, \frac{d\sigma_H^{ij\to ab}}{dX}(x_1 x_2 S_{\text{had}}, \alpha_s(\mu_R), \mu_F) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^{2n}}{S_{\text{had}}^{n}}\right)$$

$$\boxed{\mu^2 \frac{\partial f(x,\mu^2)}{\partial \mu^2} = \int_z^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z)\, f\left(\frac{x}{z},\mu^2\right)}$$

Dokshitzer, Gribov, Lipatov, Altarelli, Parisi renormalization group equations



Q-dependence: pert. theory

x-dependence: from data

LO - Dokshitzer; Gribov, Lipatov; Altarelli, Parisi, 1977

NLO - Floratos,Ross,Sachrajda; Floratos,Lacaze,Kounnas, Gonzalez-Arroyo,Lopez,Yndurain; Curci,Furmanski Petronzio, 1981

NNLO - Moch, Vermaseren, Vogt, 2004

The PDF extraction process

- 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
- **Parametrize** 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
- Provide **error sets** to compute PDF uncertainties

PDF uncertainty

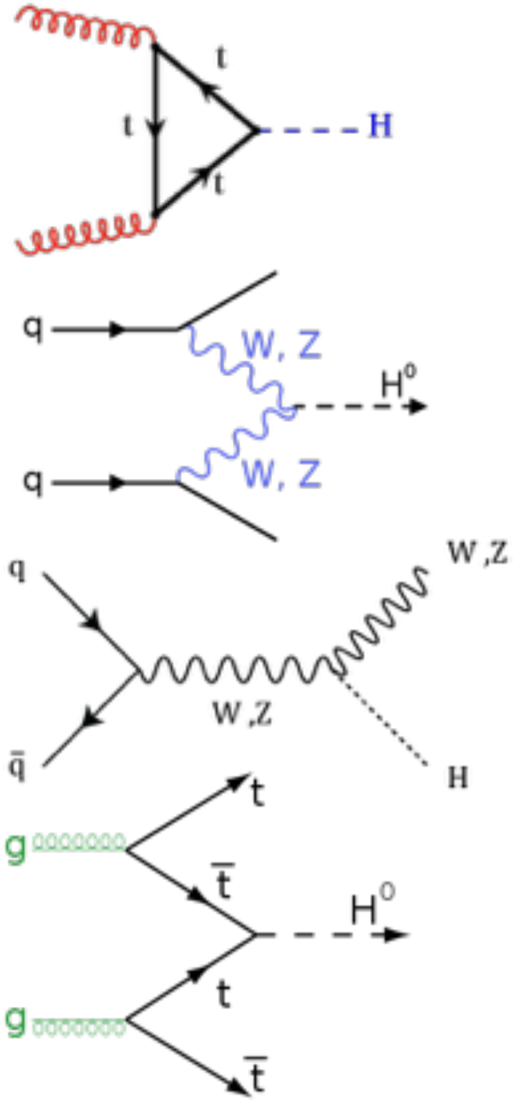
Hidden uncertainty

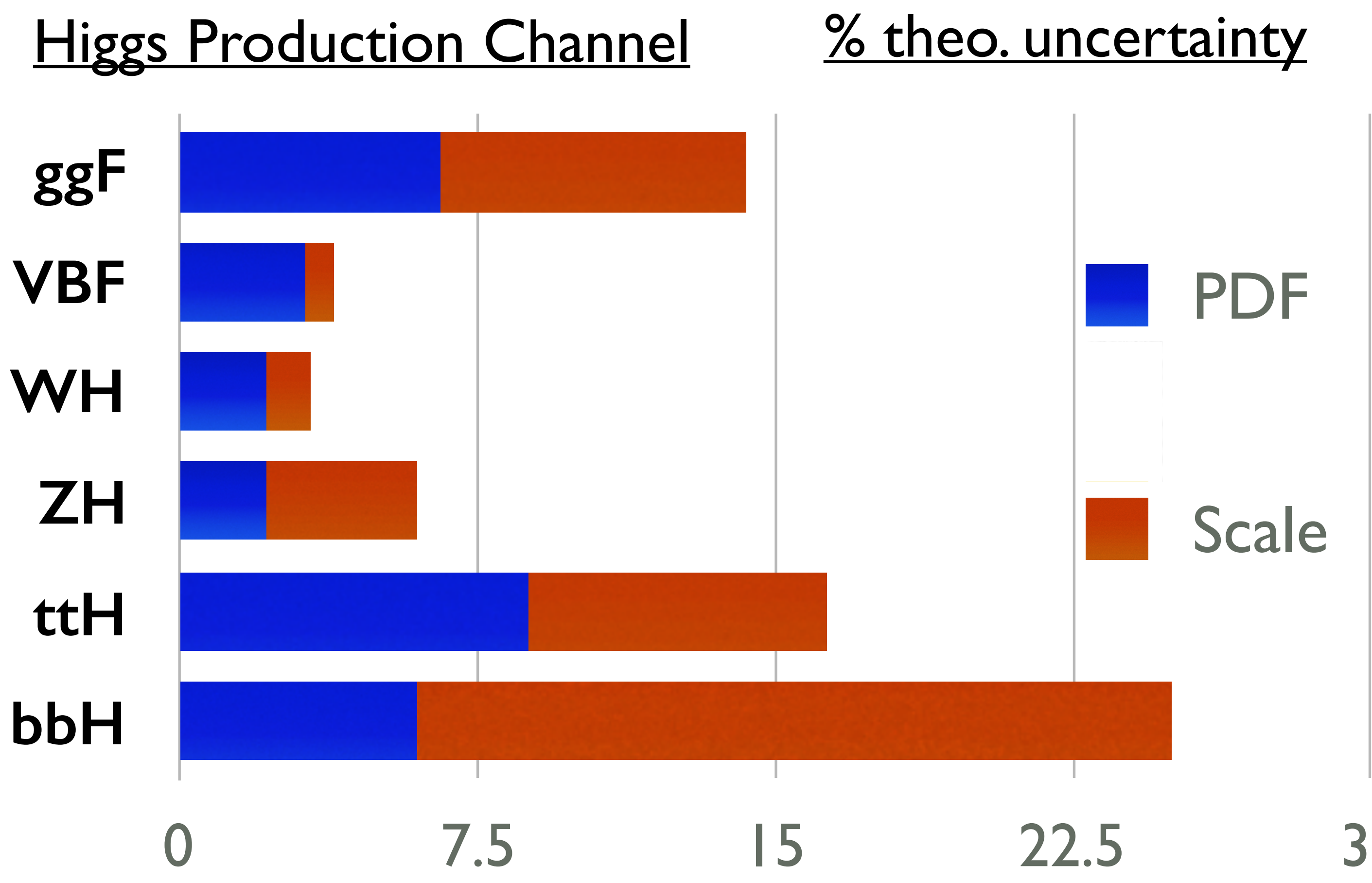
Parametric versus non-parametric approach

Hessian versus MC approach

PDFs and LHC interplay

Higgs physics





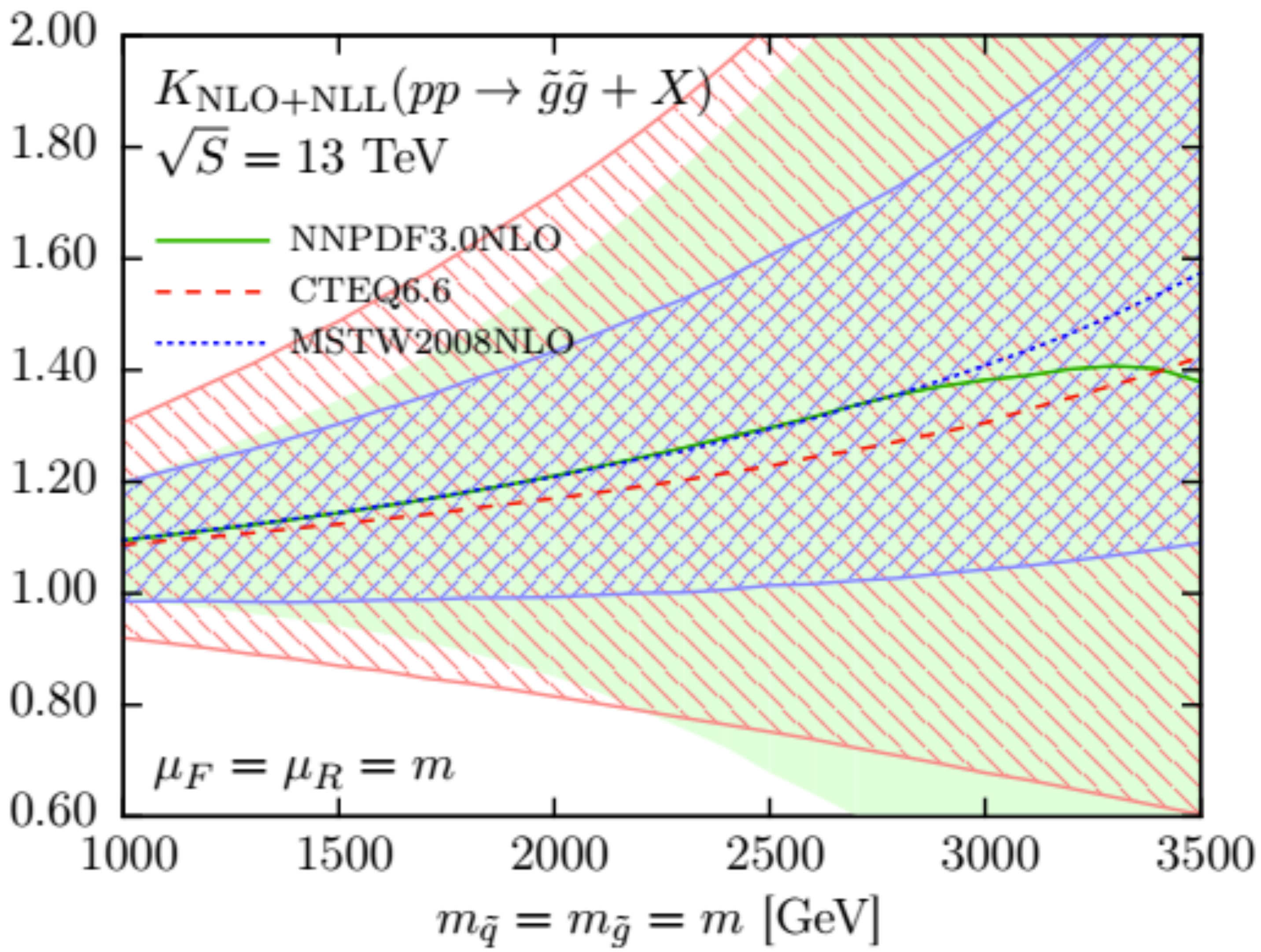
Higgs Production Channel	xsec @13 TeV
ggF	43.9 pb
VBF	3.75 pb
WH	1.38 pb
ZH	0.87 pb
ttH	0.51 pb
bbH	0.51 pb

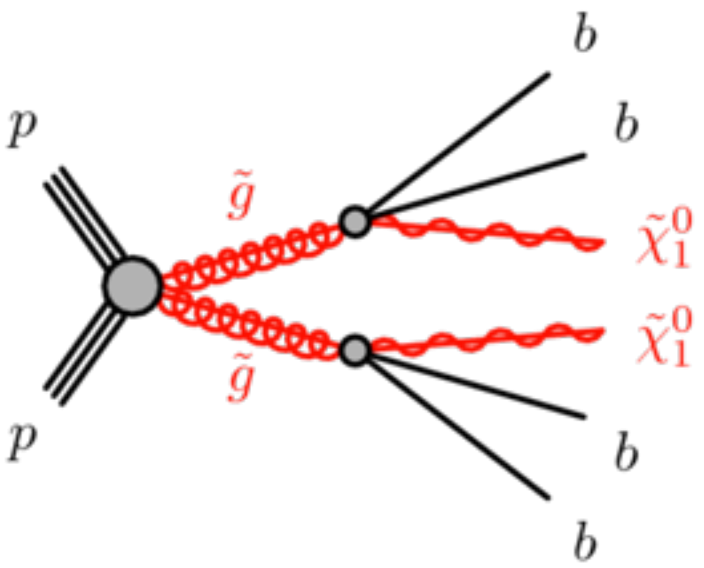
Pre-YR4 numbers from HXSWG Wiki for mH = 125 GeV

PDF uncertainties are a limiting factor in the accuracy of theoretical predictions, both within **SM** and **beyond**

PDFs and LHC interplay

BSM physics





Beenakker et al. arXiv 1510.00375

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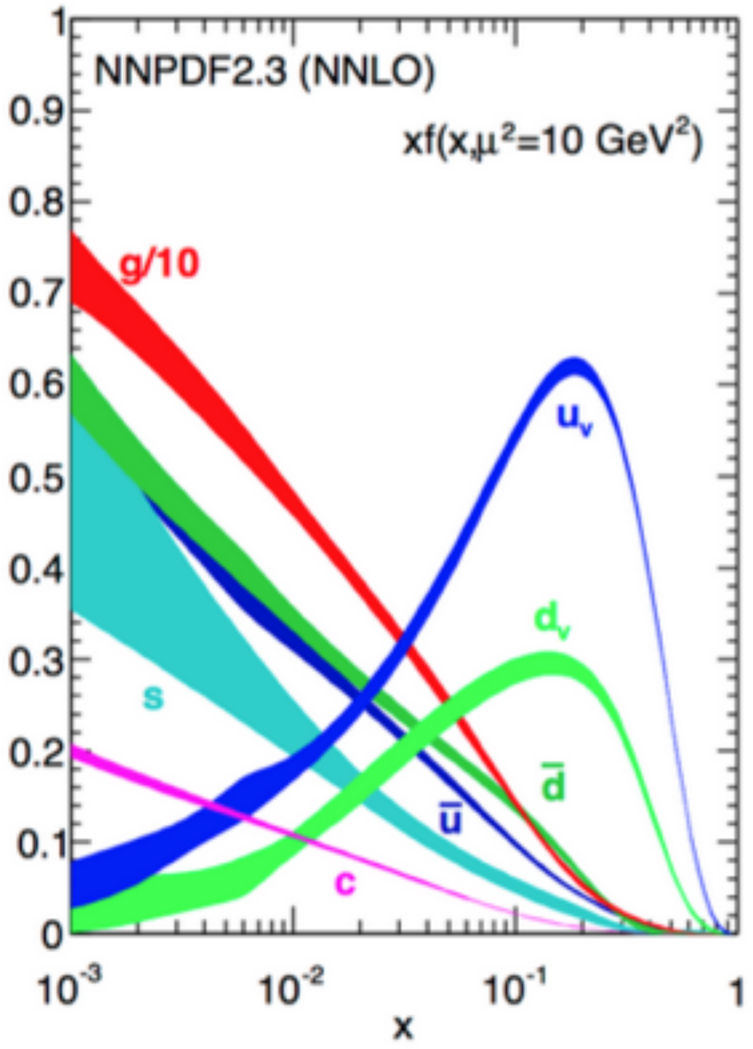
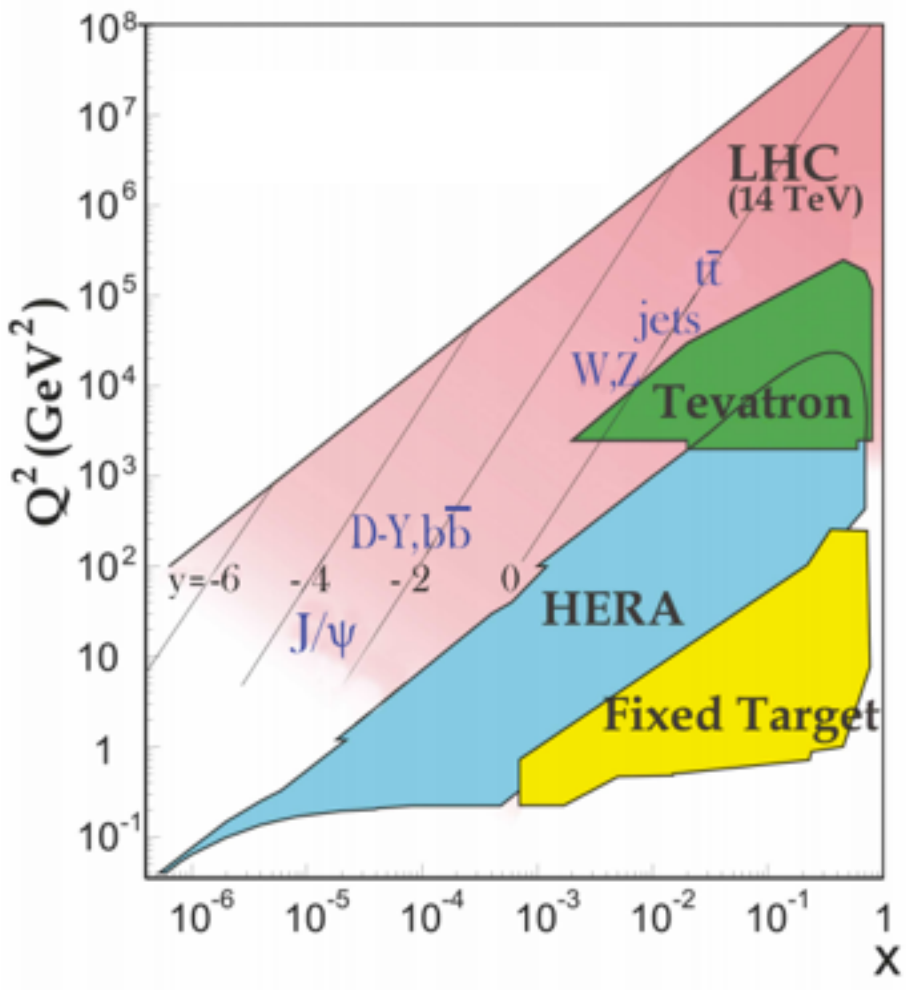
PDFs and LHC interplay



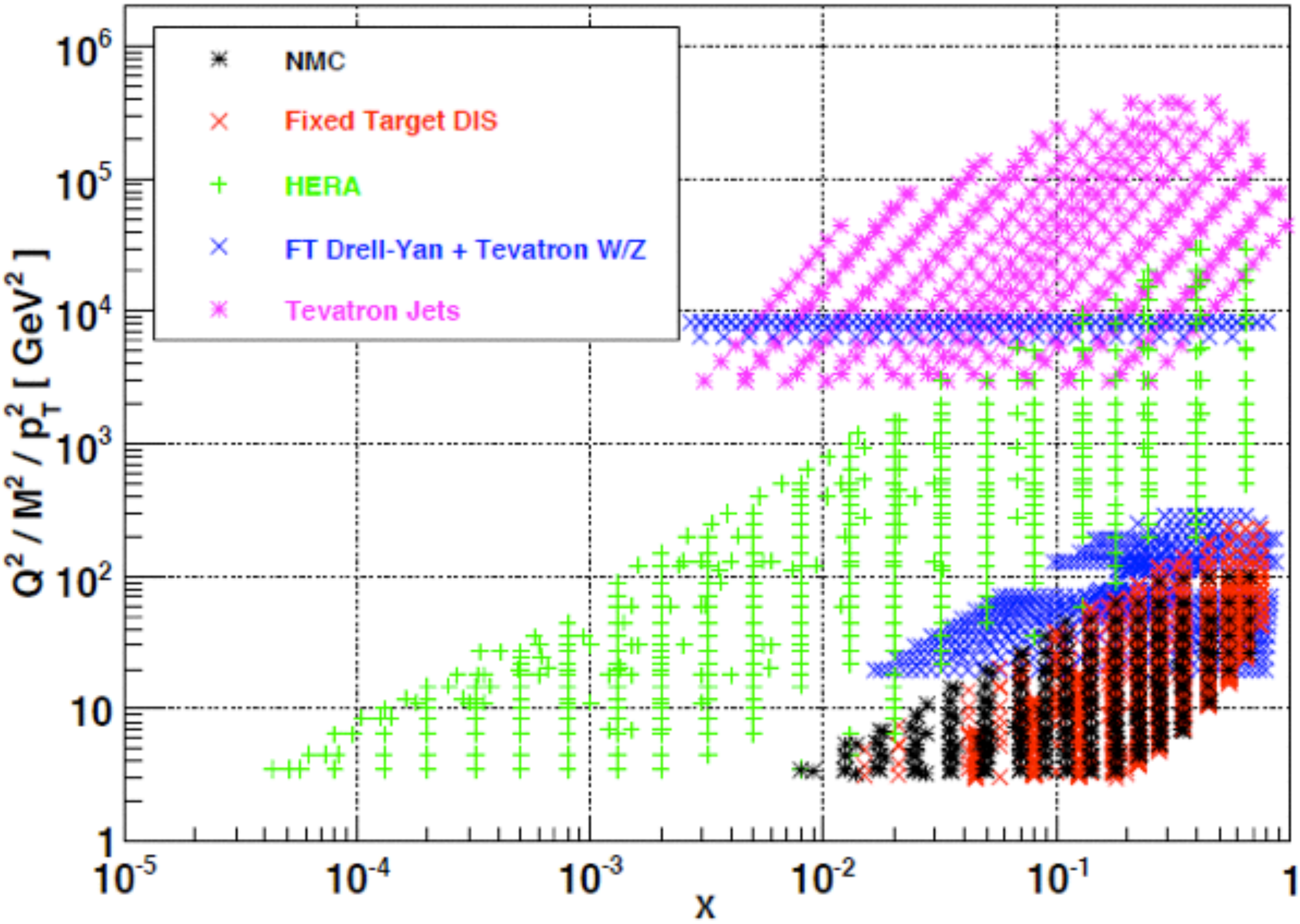


PDF uncertainties are a limiting factor in the accuracy of theoretical predictions, both within **SM** and **beyond**

Exploit the power of precise LHC data to reduce PDF uncertainties and discriminate among PDF sets

Experimental data

The data (before LHC)



large-x gluon

u/d u~/d~ separation

small/moderate-x
gluon and light
quarks

u/d separation
& strangeness

Data inclusion timeline

- Increasingly wide dataset used in PDF analyses: from DIS structure functions only to global analyses including jets, top, W/Z, HQ observables
- HERA PDFs based on maximally consistent set of data, others have to deal with inconsistencies

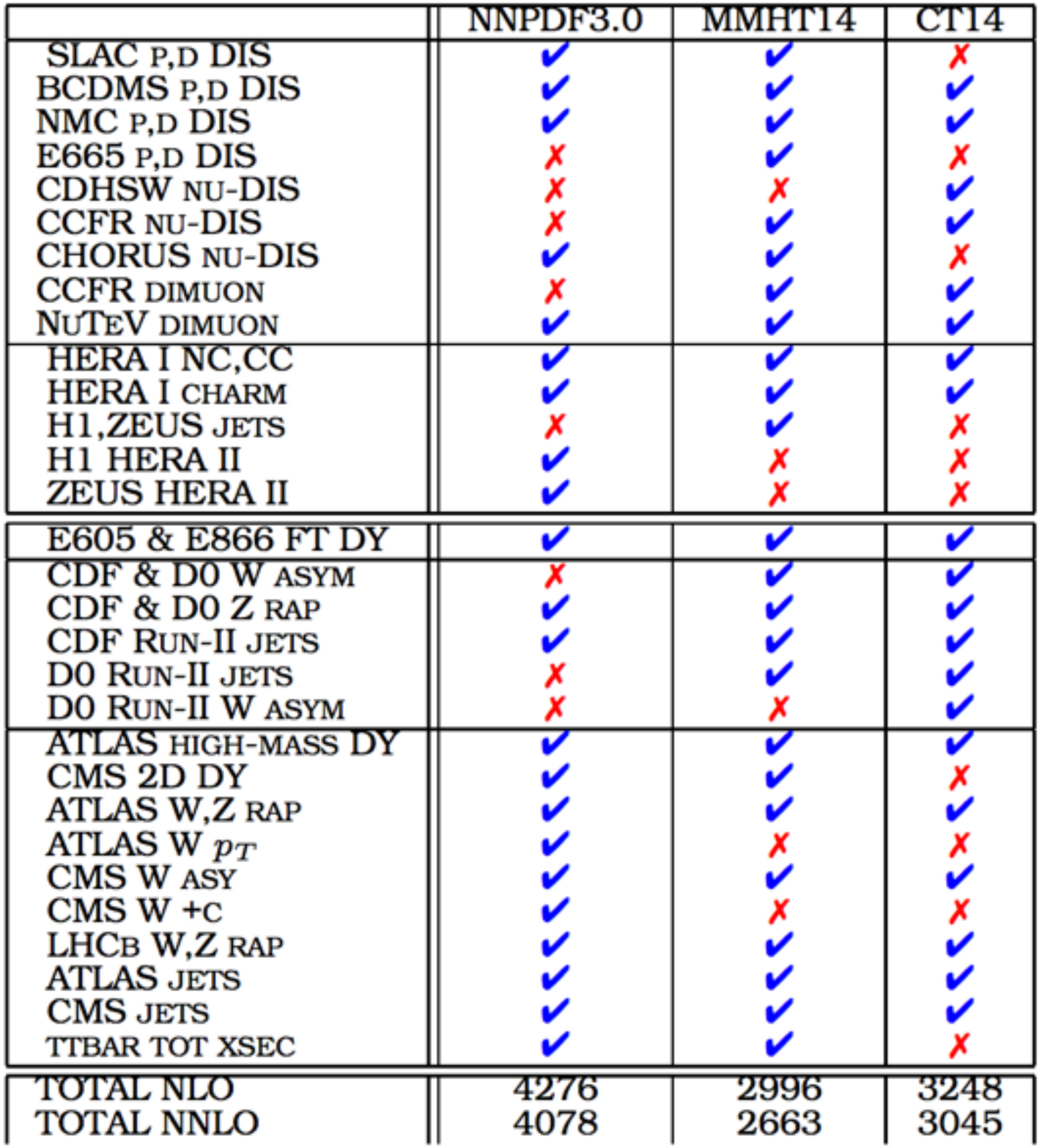
	2008		2009		2010		2011	2012		2013		2014		2015
SET MONTH	CT6.6 (02)	NN1.0 (08)	MSTW (01)	ABKM09 (08)	NN2.0 (02)	CT10(N) (07)	NN2.1(NN) (07)	ABM11 (02)	NN2.3 (07)	CT10(NN) (02)	ABM12 (10)	NN3.0 (10)	MMHT (12)	CT14 (06)
F. T. DIS	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ZEUS+H1-HI	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
COMB. HI	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✓	✗	✗
ZEUS+H1-HII	✗	✗	✗	✗	✗	✗	some	✗	✗	some	✗	✓	✗	✗
HERA JETS	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗
F. T. DY	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
TEV. W+Z	✓	✗	✓	✗	✓	✓	✓	✗	✓	✓		✓	✓	✓
TEV. JETS	✓	✗	✓	✗	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
LHC W+Z	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	some	✓	✓	✓
LHC JETS	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓
TOP	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗
W+C	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
W p_T	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗

pre-LHC

post-LHC

S. Forte, talk in Durham

The global PDF sets



	NNPDF3.0	MMHT14	CT14
SLAC p,d DIS	✓	✓	✗
BCDMS p,d DIS	✓	✓	✓
NMC p,d DIS	✓	✓	✓
E665 p,d DIS	✗	✓	✗
CDHSW nu-DIS	✗	✗	✓
CCFR nu-DIS	✗	✓	✓
CHORUS nu-DIS	✓	✓	✗
CCFR dimuon	✗	✓	✓
NuTeV dimuon	✓	✓	✓
HERA I NC,CC	✓	✓	✓
HERA I charm	✓	✓	✓
H1,ZEUS jets	✗	✓	✗
H1 HERA II	✓	✗	✗
ZEUS HERA II	✓	✗	✗
E605 & E866 FT DY	✓	✓	✓
CDF & D0 W asym	✗	✓	✓
CDF & D0 Z rap	✓	✓	✓
CDF Run-II jets	✓	✓	✓
D0 Run-II jets	✗	✓	✓
D0 Run-II W asym	✗	✗	✓
ATLAS high-mass DY	✓	✓	✓
CMS 2D DY	✓	✓	✗
ATLAS W,Z rap	✓	✓	✓
ATLAS W p_T	✓	✗	✗
CMS W asy	✓	✓	✓
CMS W +c	✓	✗	✗
LHCb W,Z rap	✓	✓	✓
ATLAS jets	✓	✓	✓
CMS jets	✓	✓	✓
ttbar tot xsec	✓	✓	✗
TOTAL NLO	4276	2996	3248
TOTAL NNLO	4078	2663	3045

DATA CONVERGENCE

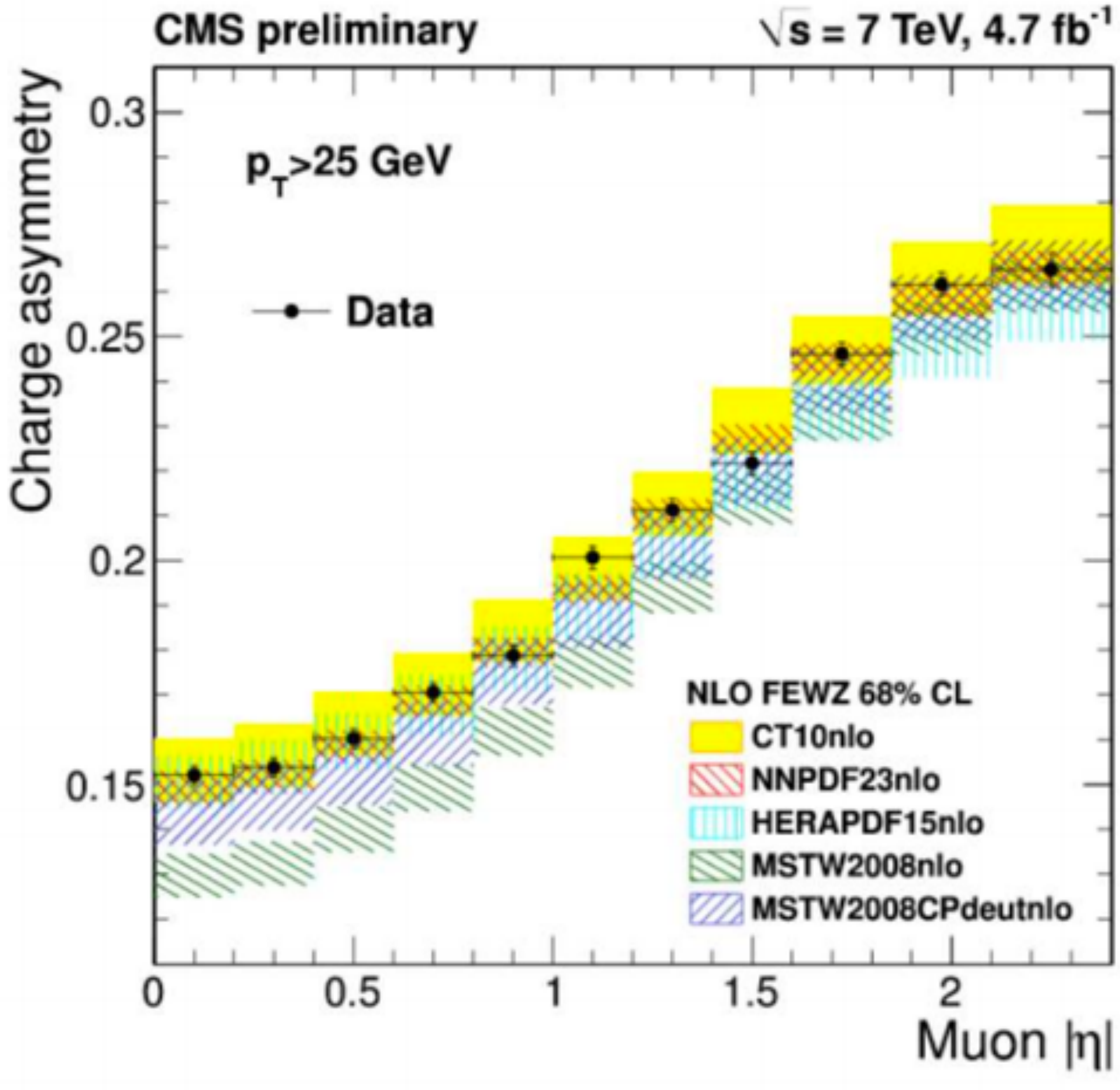
- Global sets: inclusion of O(4000) experimental data
- PDF uncertainties tuned to data (CT,MMHT: tolerance, NN: closure tests)
- Fixed parametrisation (MMHT,CT) made more flexible

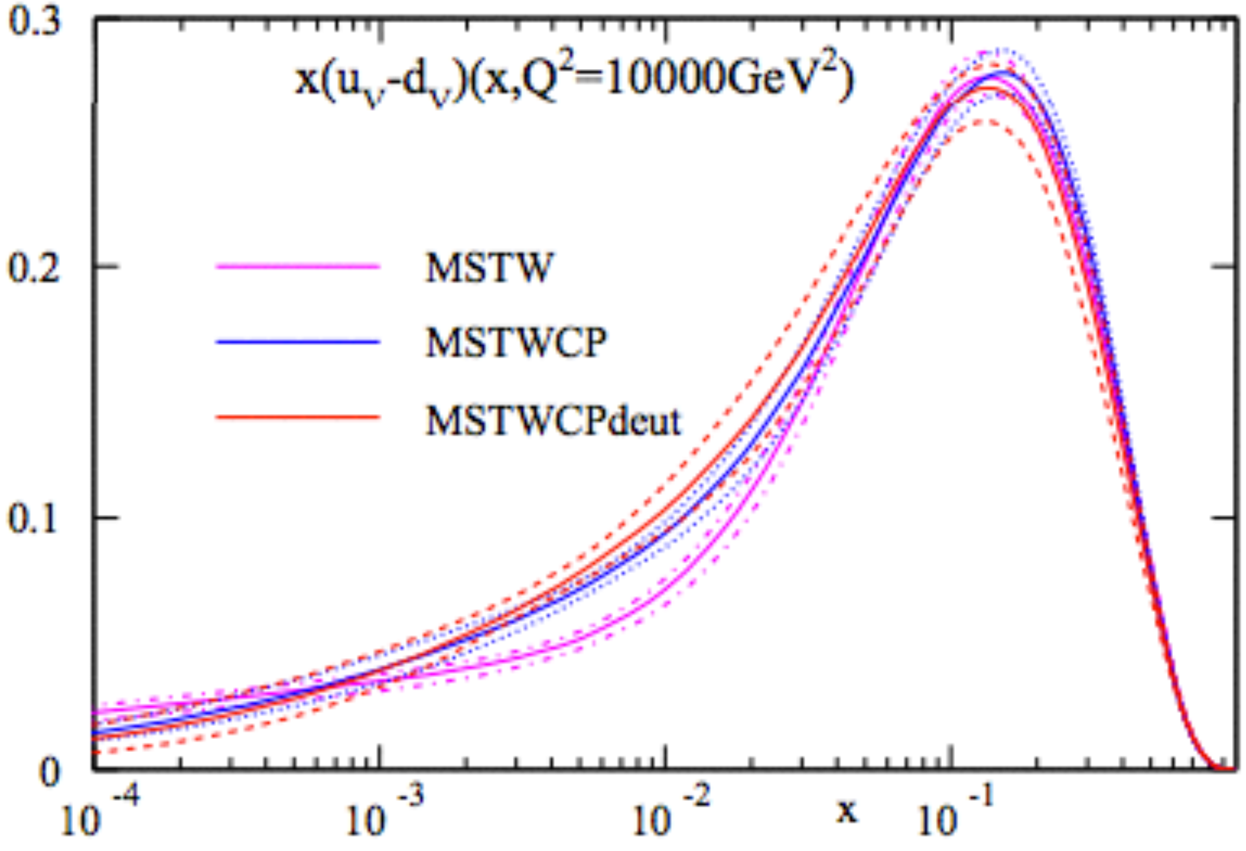
THEORY CONVERGENCE

- Common $\alpha_S(M_Z) = 0.118$
- Comparable GM-VFN schemes for inclusion of HQ masses (ABM uses FFNS)
- NNLO (although with some caveat)
- Extensive benchmarking

S. Forte, talk in Durham

Data-driven progress



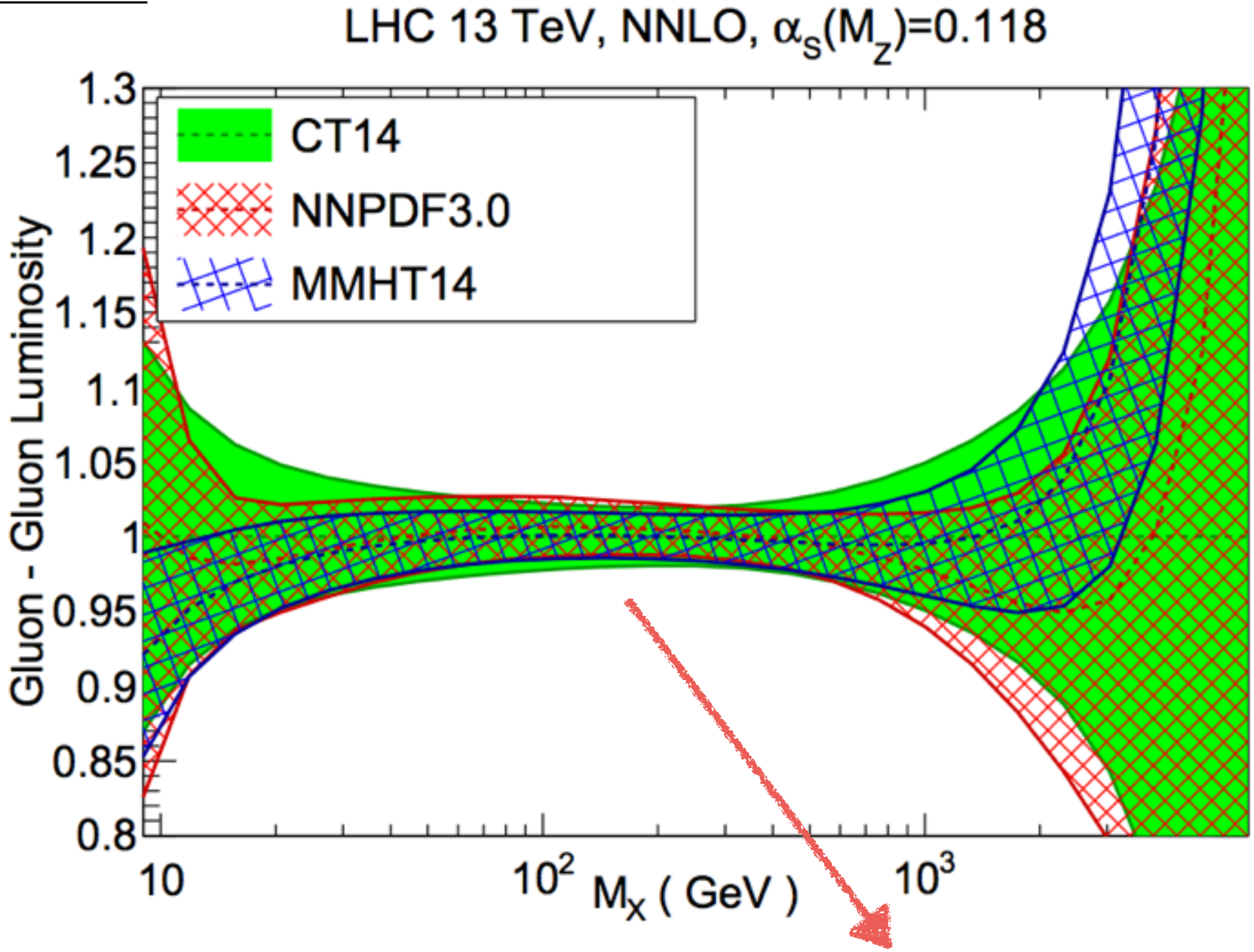


Martin et al
EPJC73 (2013) 2, 2318

- Parametric approach: lot of progress in recent years in achieving a less biased parametrisation form (data-driven)
- Non-parametric approach: methodology tested via closure test studies

Convergence of global analyses

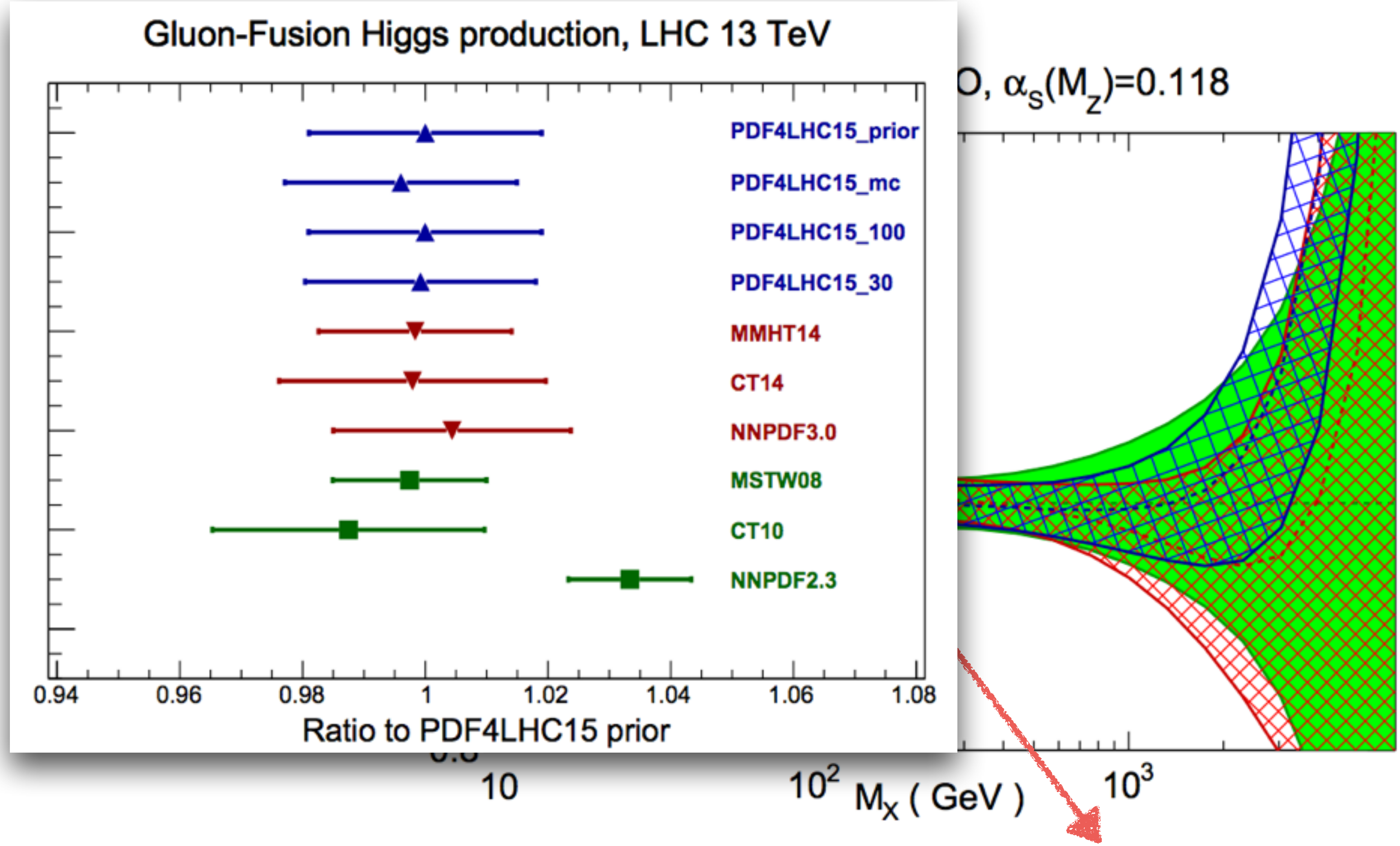
NNPDF3.0 / CT14 / MMHT



Impact on Higgs physics

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

Convergence of global analyses



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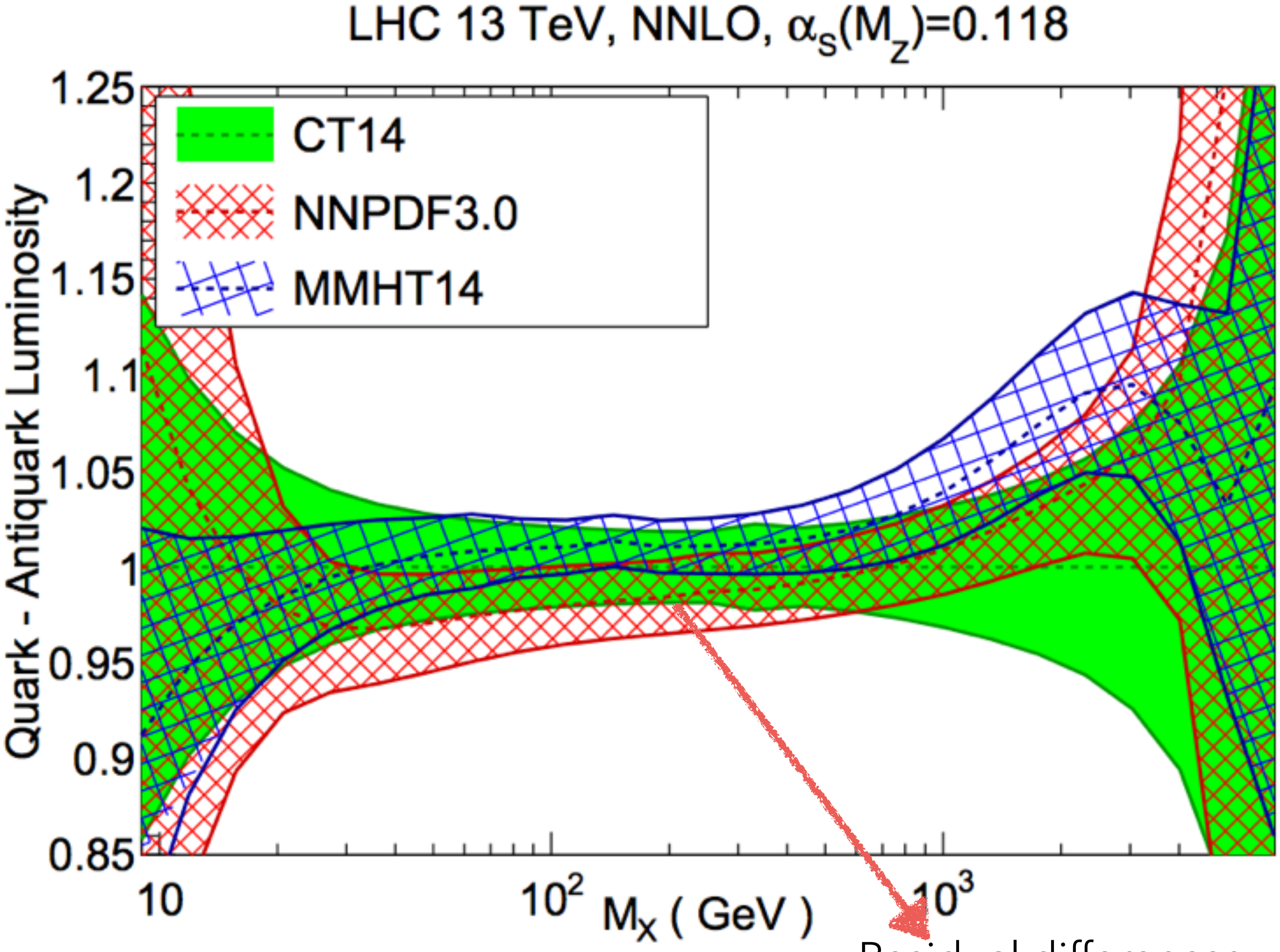

Residual differences

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

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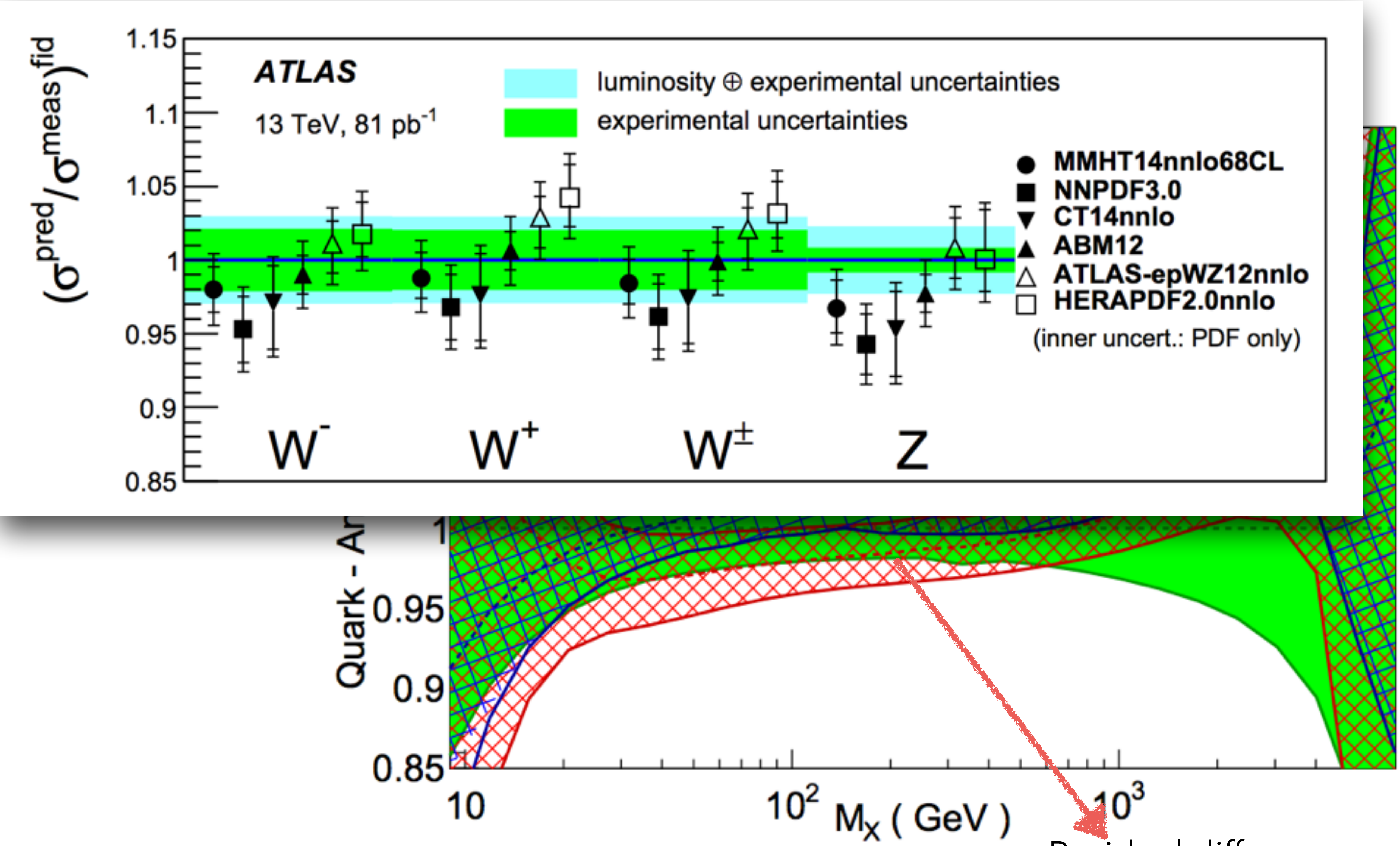
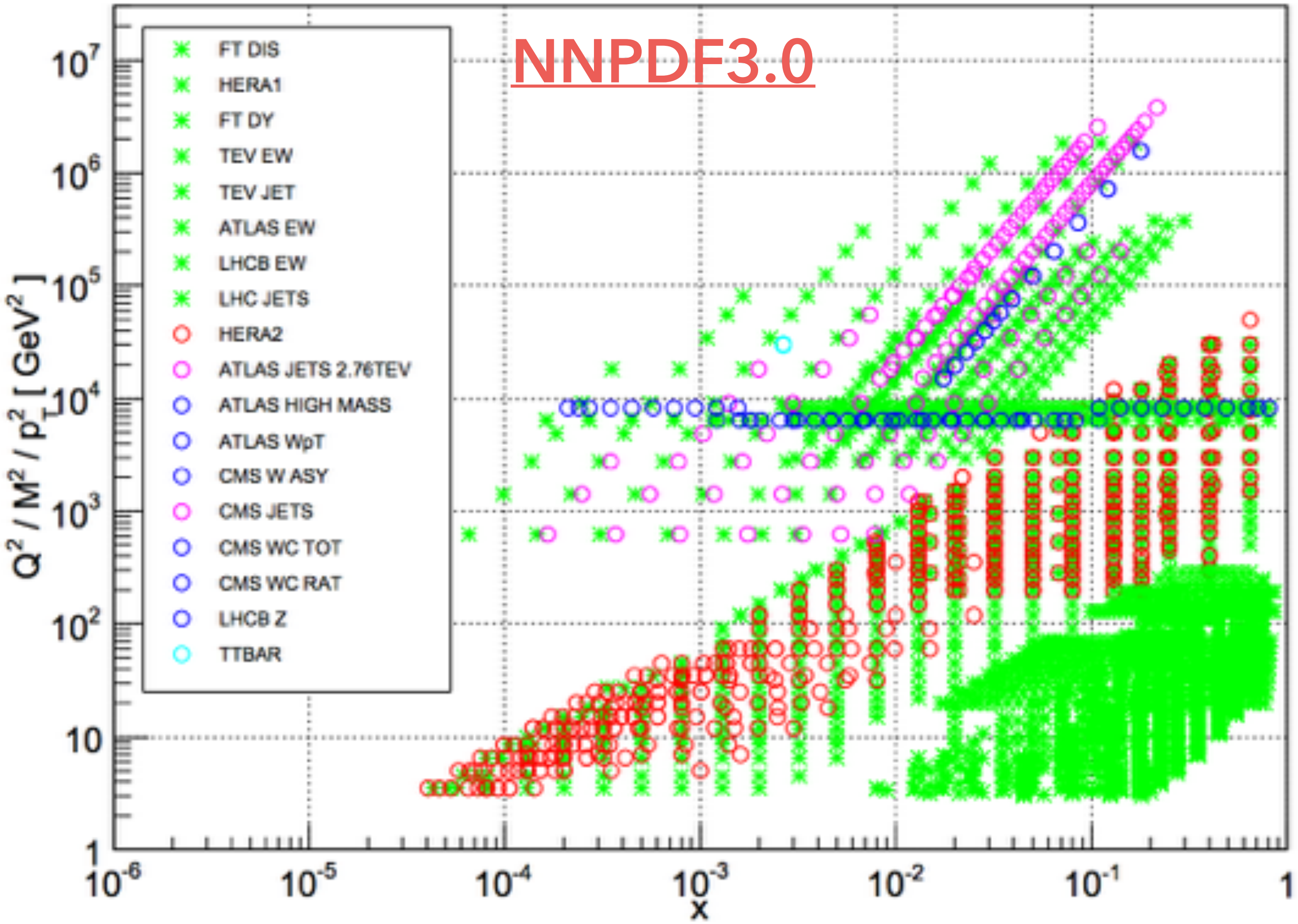


Residual differences

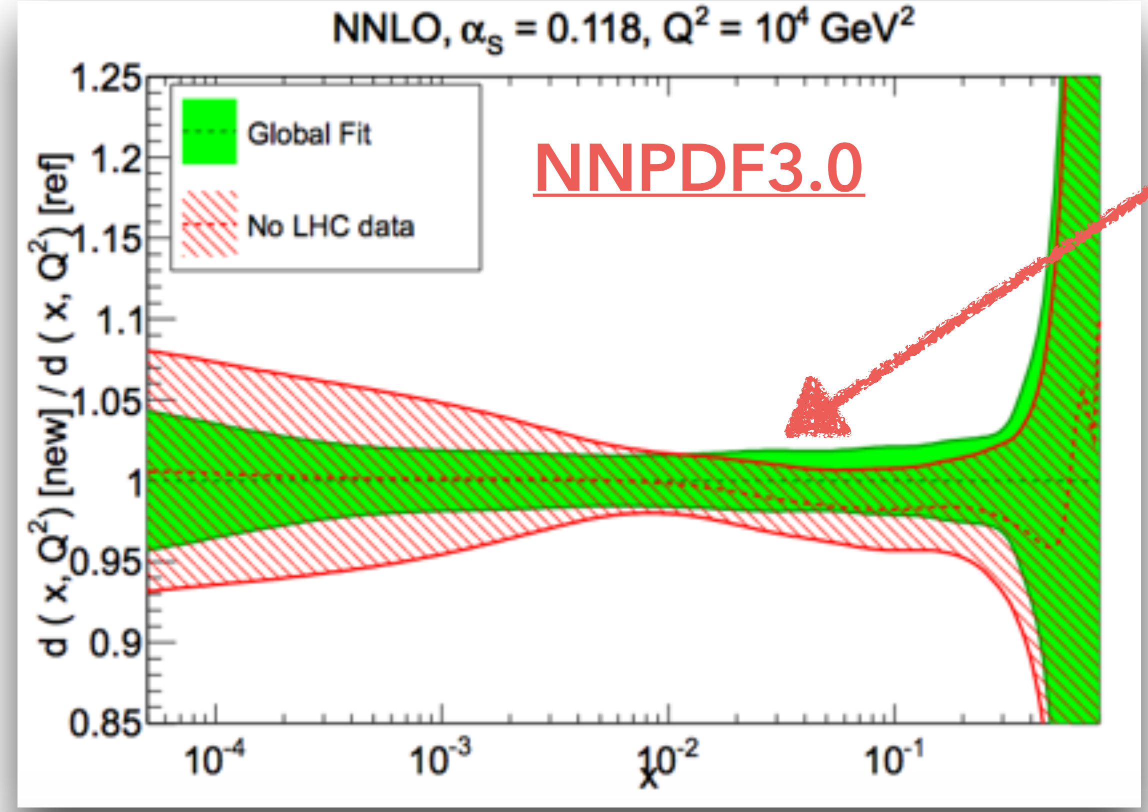
ATLAS, 1603.09222

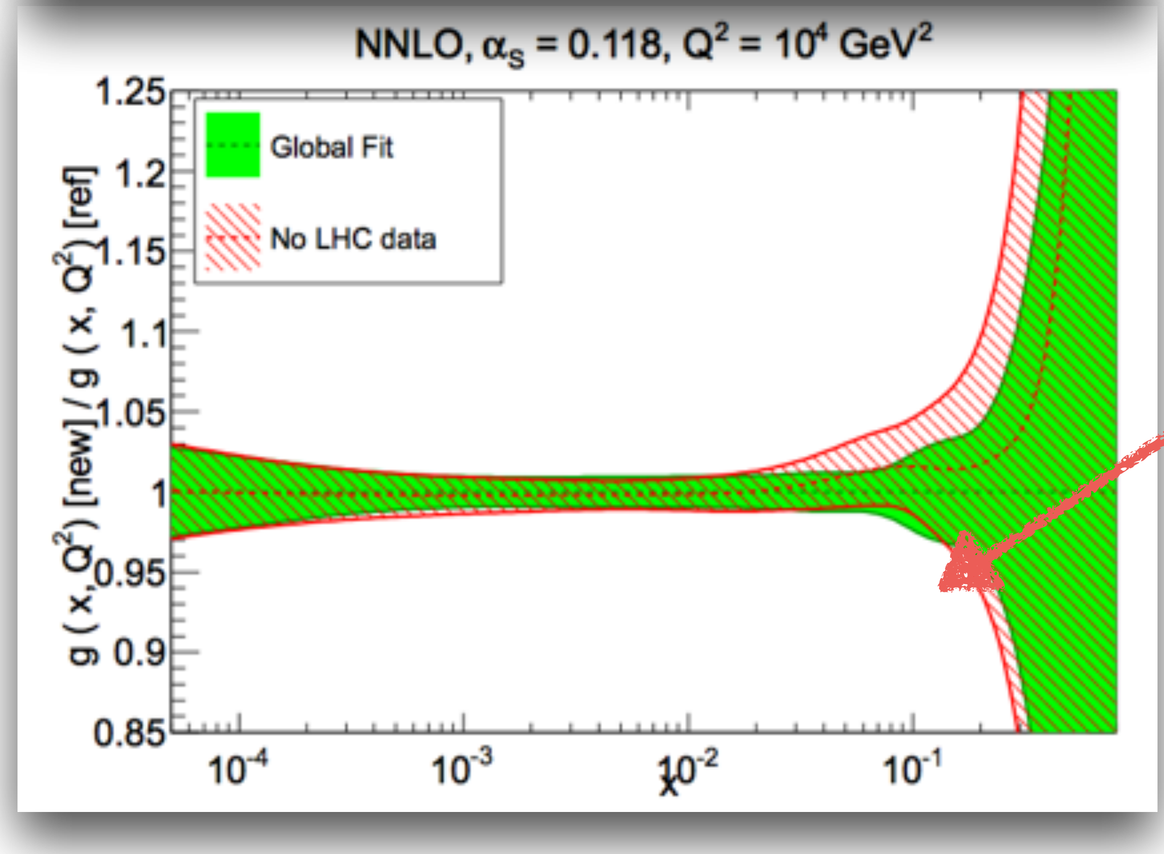
Effect of LHC data on PDFs



ATLAS jets 2.76 TeV and 7 TeV	g at large x
ATLAS high-mass DY at 7 TeV	q/q~ sep.
ATLAS W pT data at 7 TeV	g and q at med. x
CMS (Y,M) double diff distributions 7 TeV	q/q~ sep.
CMS jets at 7 TeV	g at large x
CMS muon charge asymmetry at 7 TeV	q/q~ sep.
CMS W+c at 7 TeV	strange
LHCb Z rapidity distribution at 7 TeV	small/large x q
ATLAS+CMS tt total xsec at 7/8 TeV	g at large x

Effect of LHC data on PDFs





ATLAS jets 2.76 TeV and 7 TeV	g at large x
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CMS (Y,M) double diff distributions 7 TeV	q/q~ sep.
CMS jets at 7 TeV	g at large x
CMS muon charge asymmetry at 7 TeV	q/q~ sep.
CMS W+c at 7 TeV	strange
LHCb Z rapidity distribution at 7 TeV	small/large x q
ATLAS+CMS tt total xsec at 7/8 TeV	g at large x

More data from the LHC

NNPDF3.1

ATLAS jets 2.76 TeV and 7 TeV **+ 2011 data 7 TeV**	gluon large x
ATLAS high-mass DY at 7 TeV **+ low mass**	q/q~ separation
ATLAS W pT data at 7 TeV **+ ATLAS & CMS double diff Z pT**	g and q at moderate x
CMS (Y,M) double diff distributions 7 TeV **+ 8 TeV**	flavour separation
CMS jets at 7 TeV **+ 2.76 and 8 TeV jet data**	gluon large x
CMS muon charge asymmetry at 7 TeV **+ 8 TeV**	quark separation
CMS W+c at 7 TeV	strangeness
LHCb Z rapidity distribution at 7 TeV **+ 8 TeV (legacy data)**	small/large x quarks
ATLAS+CMS tt total xsec at 7/8 TeV **+ differ. distributions**	gluon large x
D0 legacy W asymmetry data	q/q~ separation

The NNLO frontier

- NNLO calculations are essential to reduce theoretical uncertainties in PDF analyses

- Stunning progress has been made on some key processes for PDF determination

✓ NNLO top pair production

Czakon, Fiedler, Mitov [PRL 116(2016) 082003]
Czakon, Mitov [JHEP 1301(2015)]

✓ 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]

✓ Inclusive jet cross section

Currie et al [JHEP 1401 (2014) 110]
Gehrmann-De Ridder et al [PRL 110 (2016) 162003]

The NNLO frontier

- NNLO calculations are essential to reduce theoretical uncertainties in PDF analyses

- Stunning progress has been made on some key processes for PDF determination

- Great progress also in tools to interface NLO (NNLO?) codes to PDF fitting code

$$\sigma = \sum_{i,j}^{n_f} \sum_{\alpha,\beta}^{n_x} W_{ij\alpha\beta}\, f_i(x_\alpha, Q_0^2) f_j(x_\beta, Q_0^2)$$

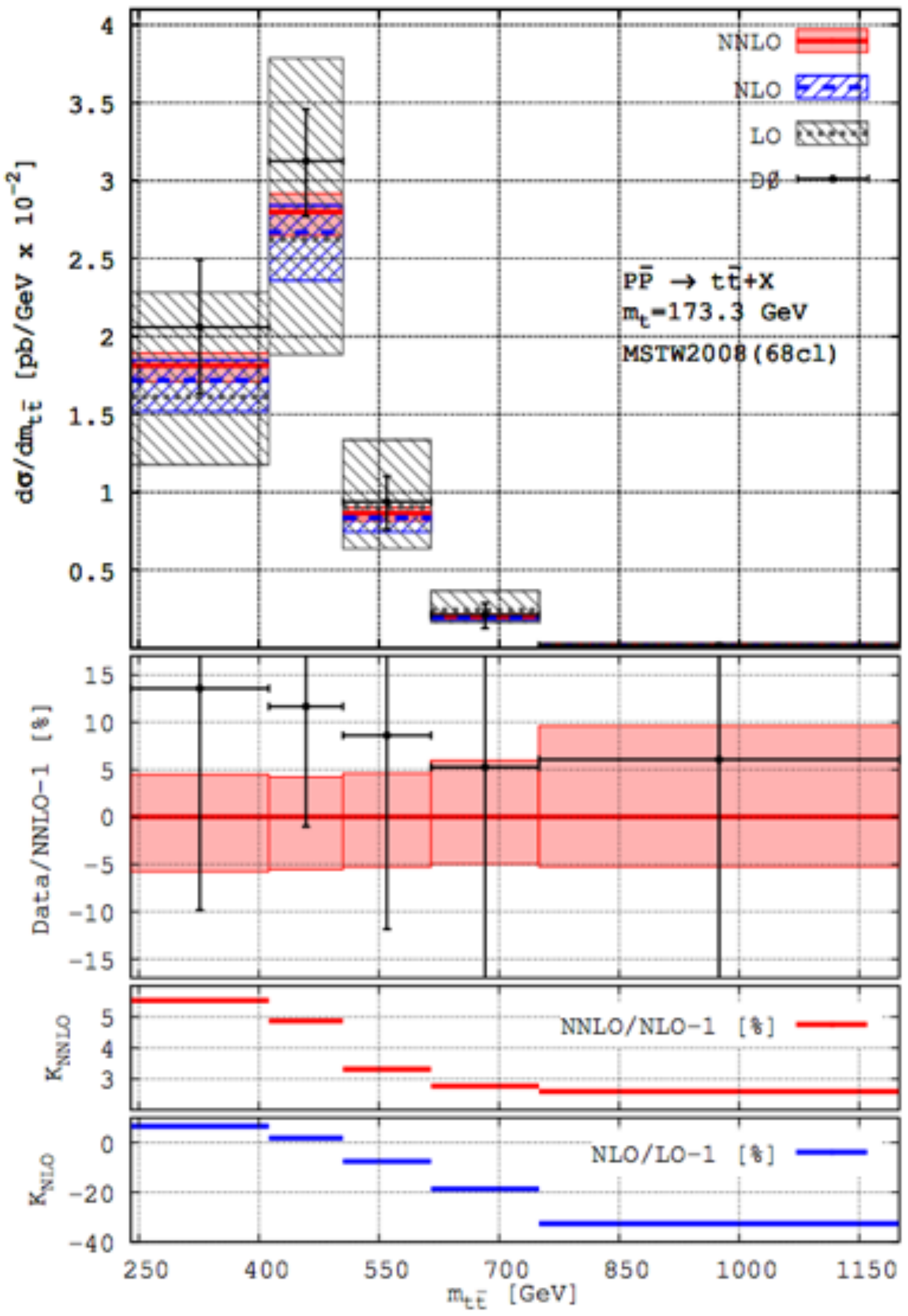
APFEL

the APPLgrid project

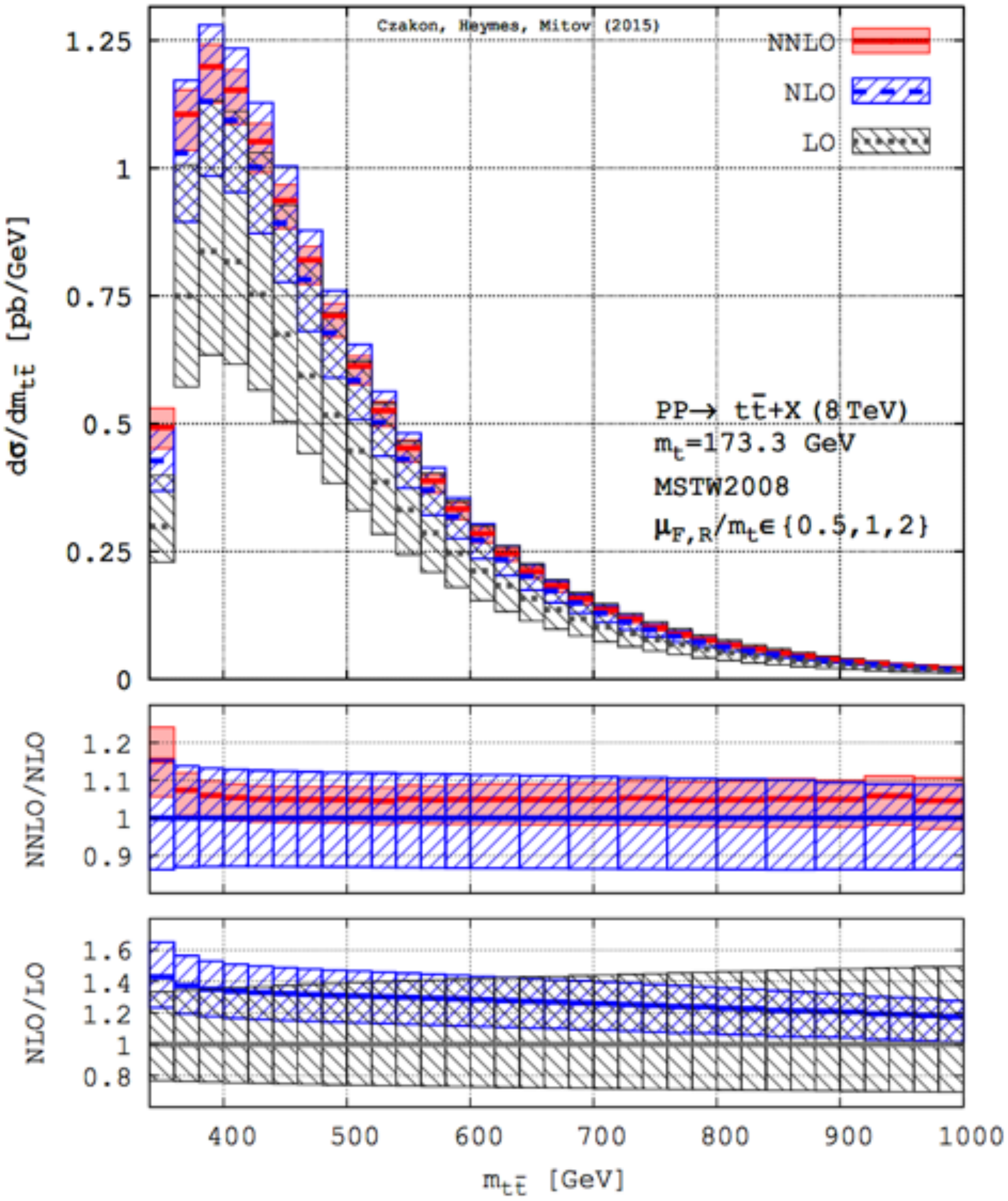
Observable	APPLGRID	**APFELcomb**
W^+ production	1.03 ms	0.41 ms (2.5x)
Inclusive jet production	2.45 ms	20.1 μs (120x)

APPLgrid, Carli et al EPJC66 (2010) 503-524 & FASTNLO, Kluge et al
APFELgrid, Bertone et al 1605.02070
aMCfast, Berton et al JHEP 1408 (2014) 166
MCgrid, Del Debbio et al Comput.Phys.Commun. 185 (2014) 2115-2126

The NNLO frontier - top data



Czakon, Fiedler, Mitov [PRL 116(2016) 082003]

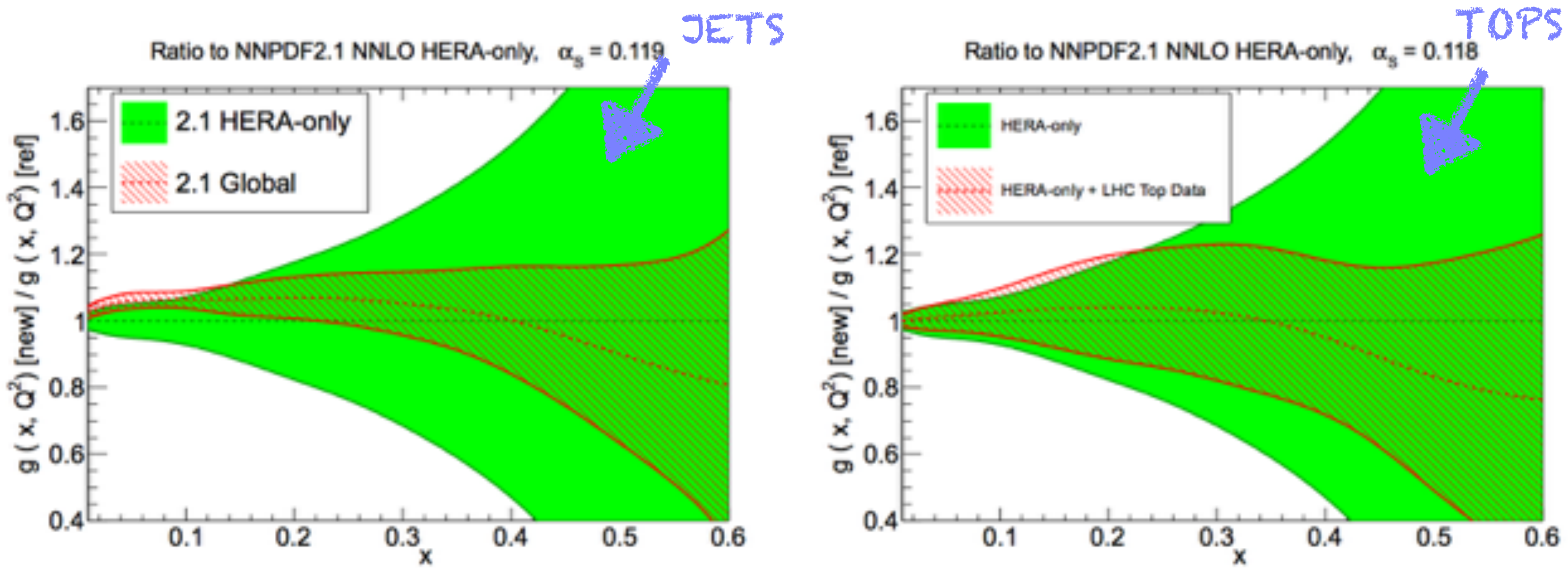


The NNLO frontier - top data

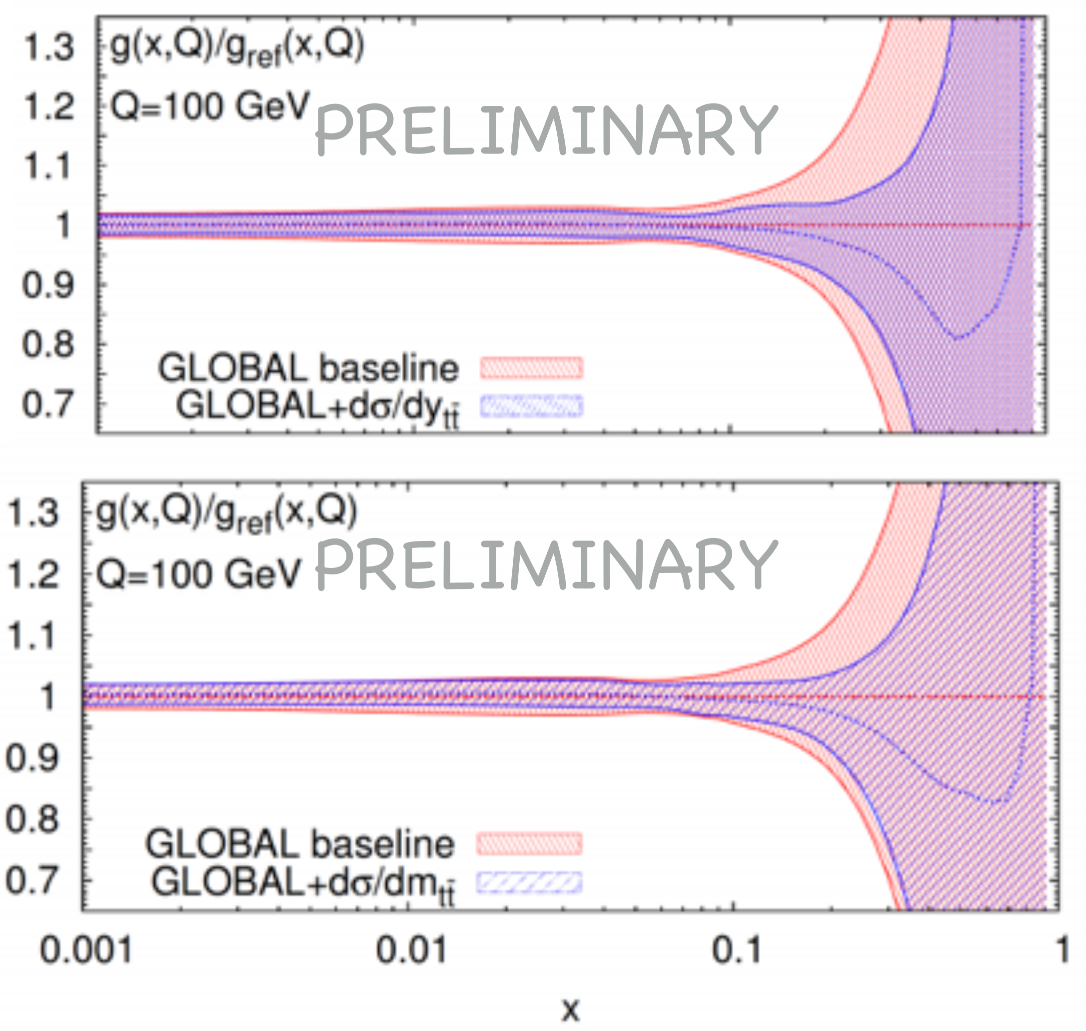
Total cross section →

Differential cross section

↓



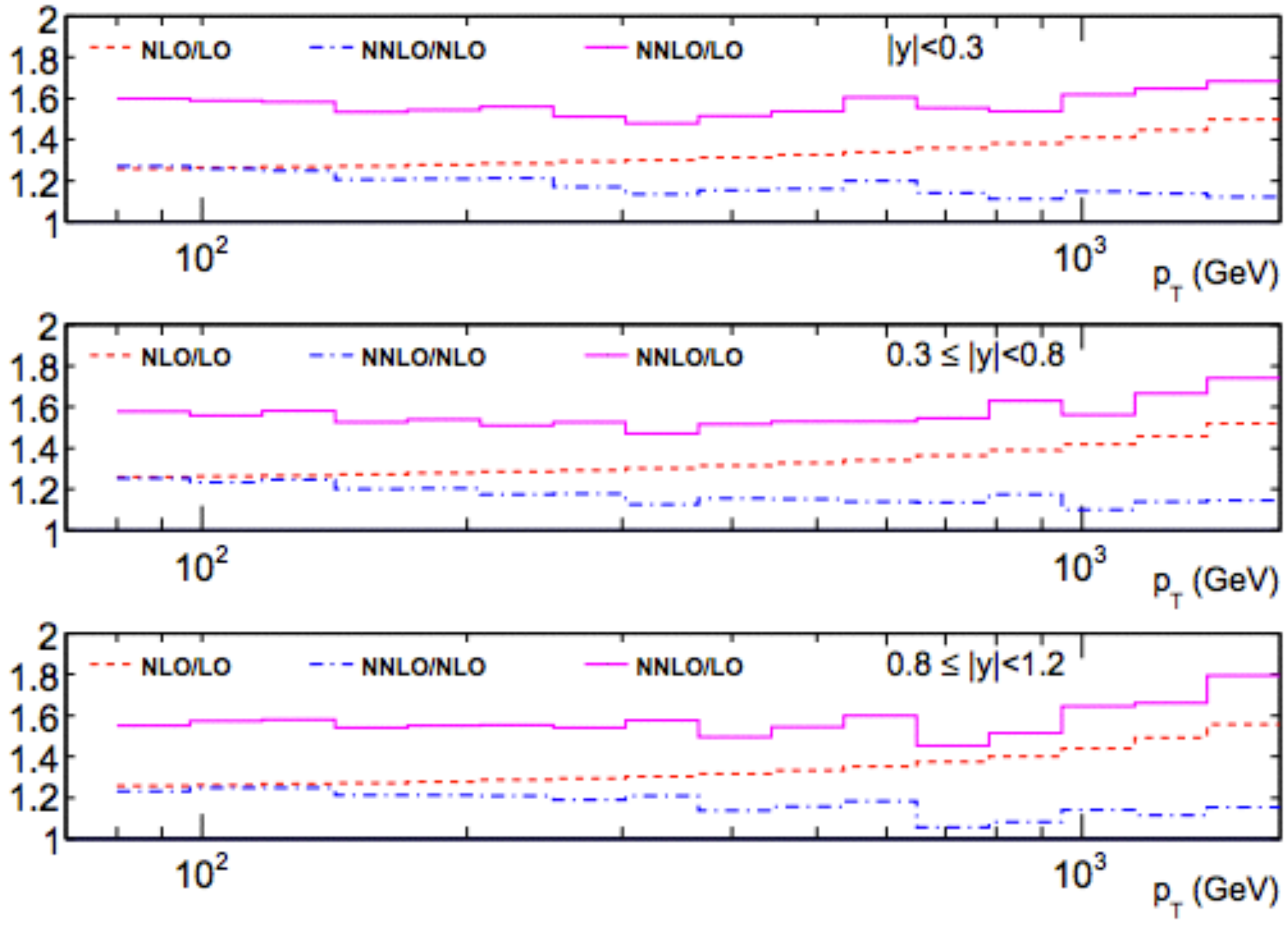
Czakon et al [JHEP 1307 (2013) 167]
Beneke et al [JHEP 1207 (2012) 194]



- Inclusion of top pair production data (total cross section and differential distributions) competitive to jets data and cleaner from non-perturbative effects
- Some tensions between ATLAS and CMS invariant mass distributions & difficulties in fitting pT distribution

Courtesy of J. Rojo
Czakon, Hartland, Mitov, Nocera and Rojo, in preparation

The NNLO frontier - jets data

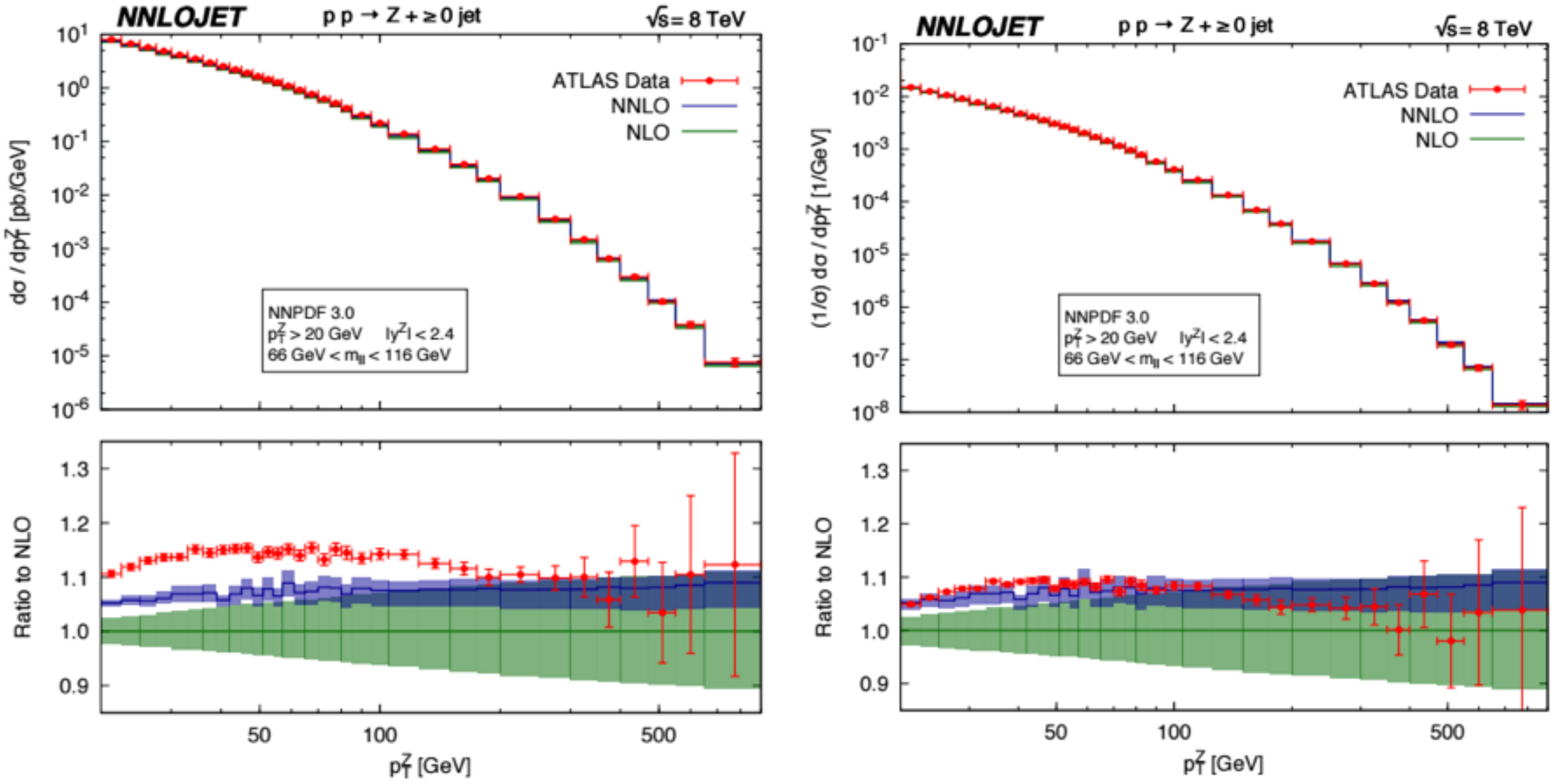


- NNLO corrections only partially known (gg channel)
- Several PDF groups make different choices: CT14 includes all jet data in NNLO fit assuming overall C-factor small, MMHT14 and ABM12 do not include LHC jet data at NNLO, NNPDF3.0 include some jet data based on goodness of threshold approximation
- These choices affect precision of the gluon, full NNLO calculation is very much needed

Gehrmann-De Ridder et al [PRL 110 (2016) 162003]

The NNLO frontier - Z pT data

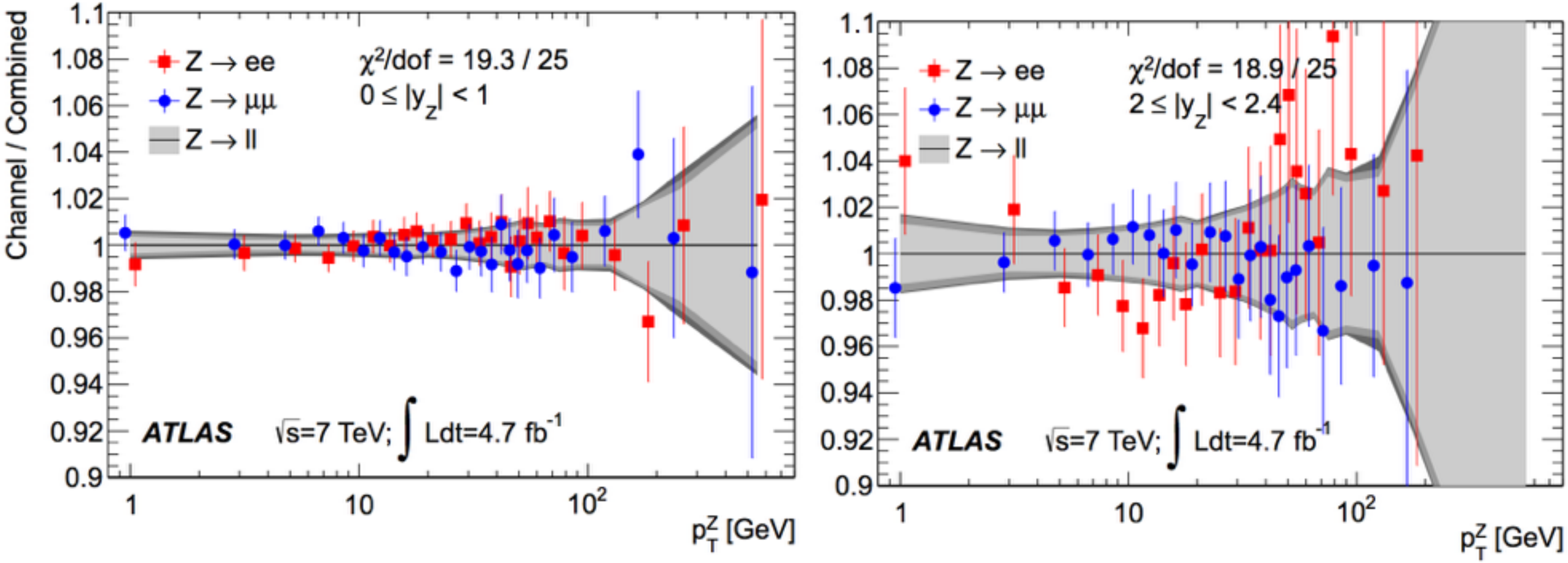
- Experimental precision < 1% up to pT~200 GeV
- Expect a great impact on the quark-gluon luminosity
- Interesting case-study to probe current theory-experiment frontier



Gerhmann-De Ridder et al., 1605.04295

Z pT data

ATLAS 7 TEV

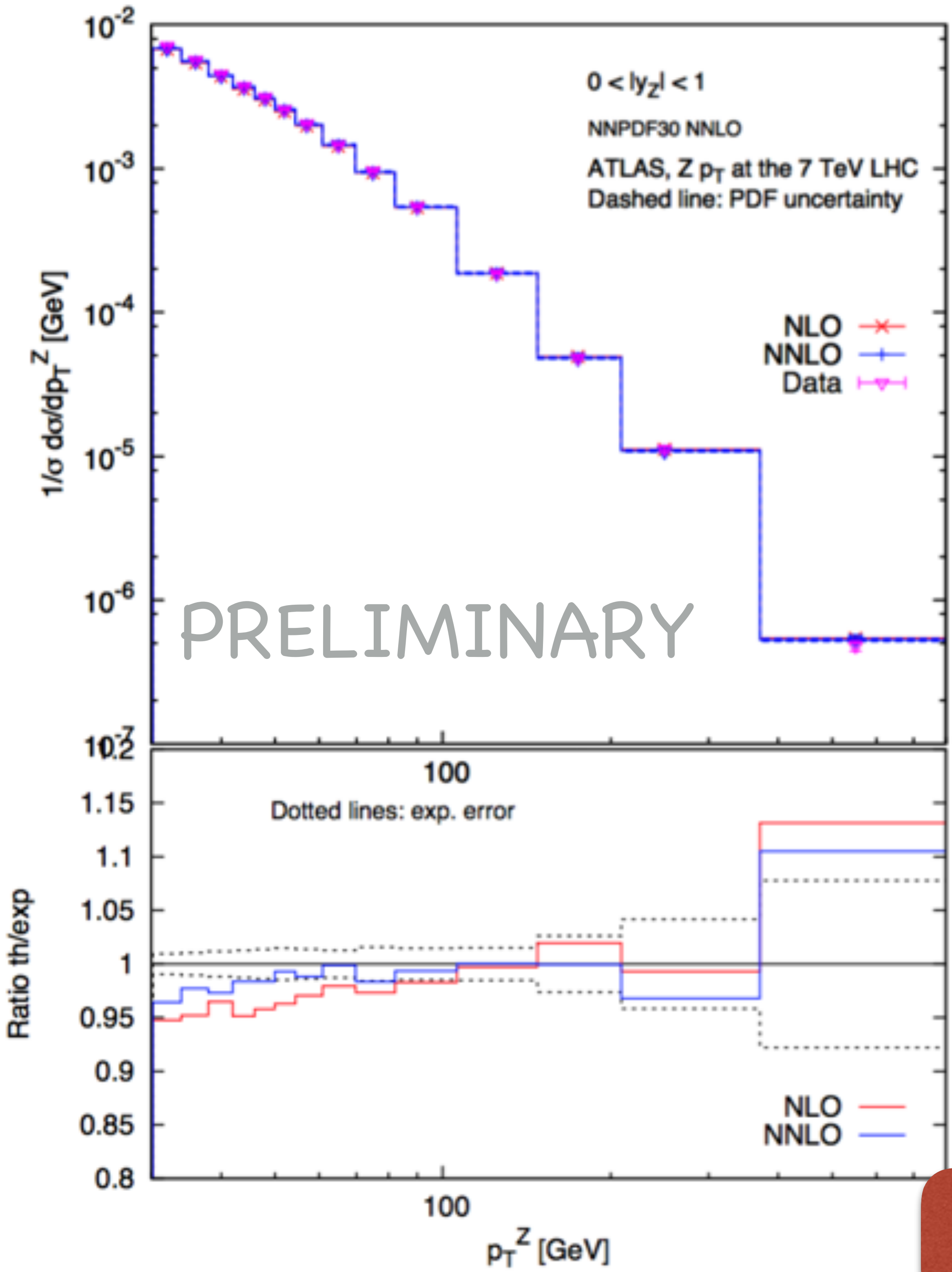


- Normalised distributions
- Three rapidity bins
  - 0.0 < Y <1.0
  - 1.0 < Y < 2.0
  - 2.0 < Y < 2.4
- O(50) data points with pT > 30 GeV

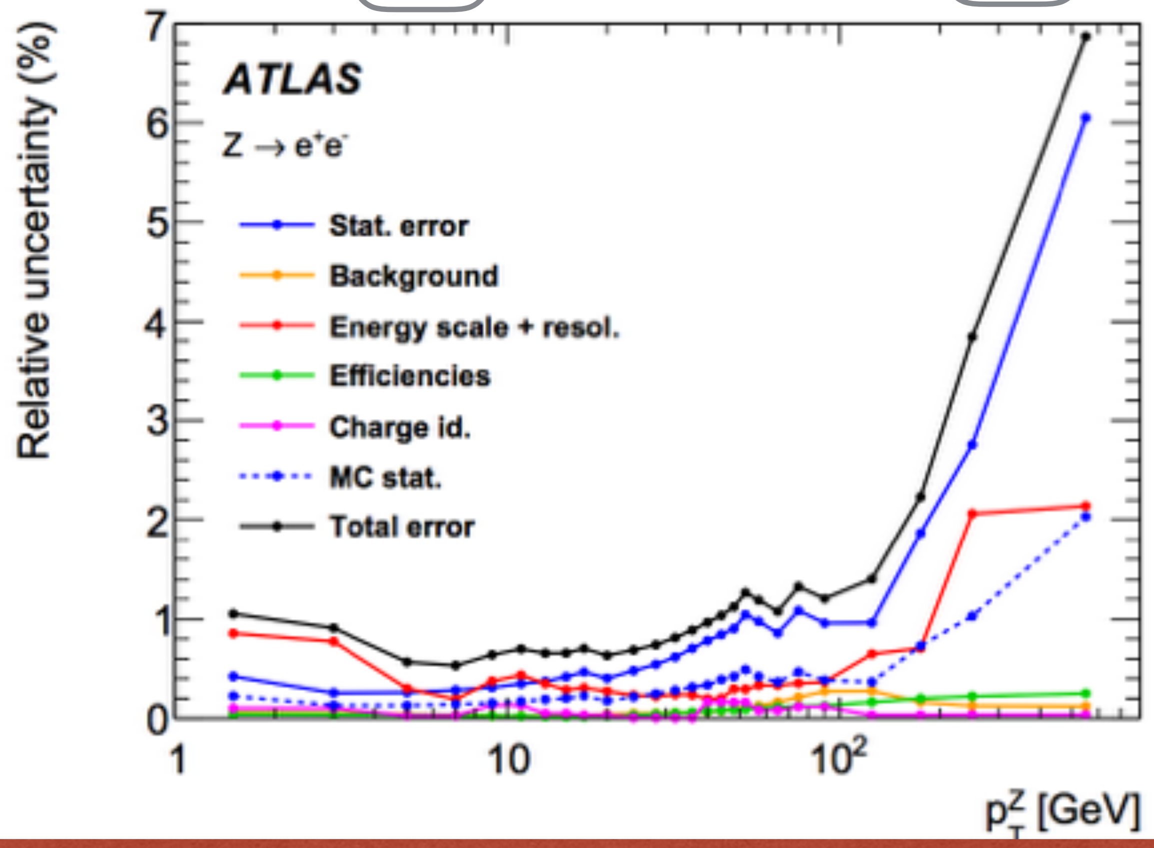
ATLAS 7 TeV measurements [1406.3660]

Z pT data

ATLAS 7 TEV



NLO	NNLO	
$\chi^2_{\rm stat} = 10.$	$\chi^2_{\rm stat} = 1.3$	/d.o.f.
$\chi^2_{\rm uncor} = 7.3$	$\chi^2_{\rm uncor} = 0.9$	
$\chi^2_{\rm diag} = 6.0$	$\chi^2_{\rm diag} = 0.7$	
$\chi^2_{\rm full} = \boxed{16.}$	$\chi^2_{\rm full} = \boxed{1.9}$	

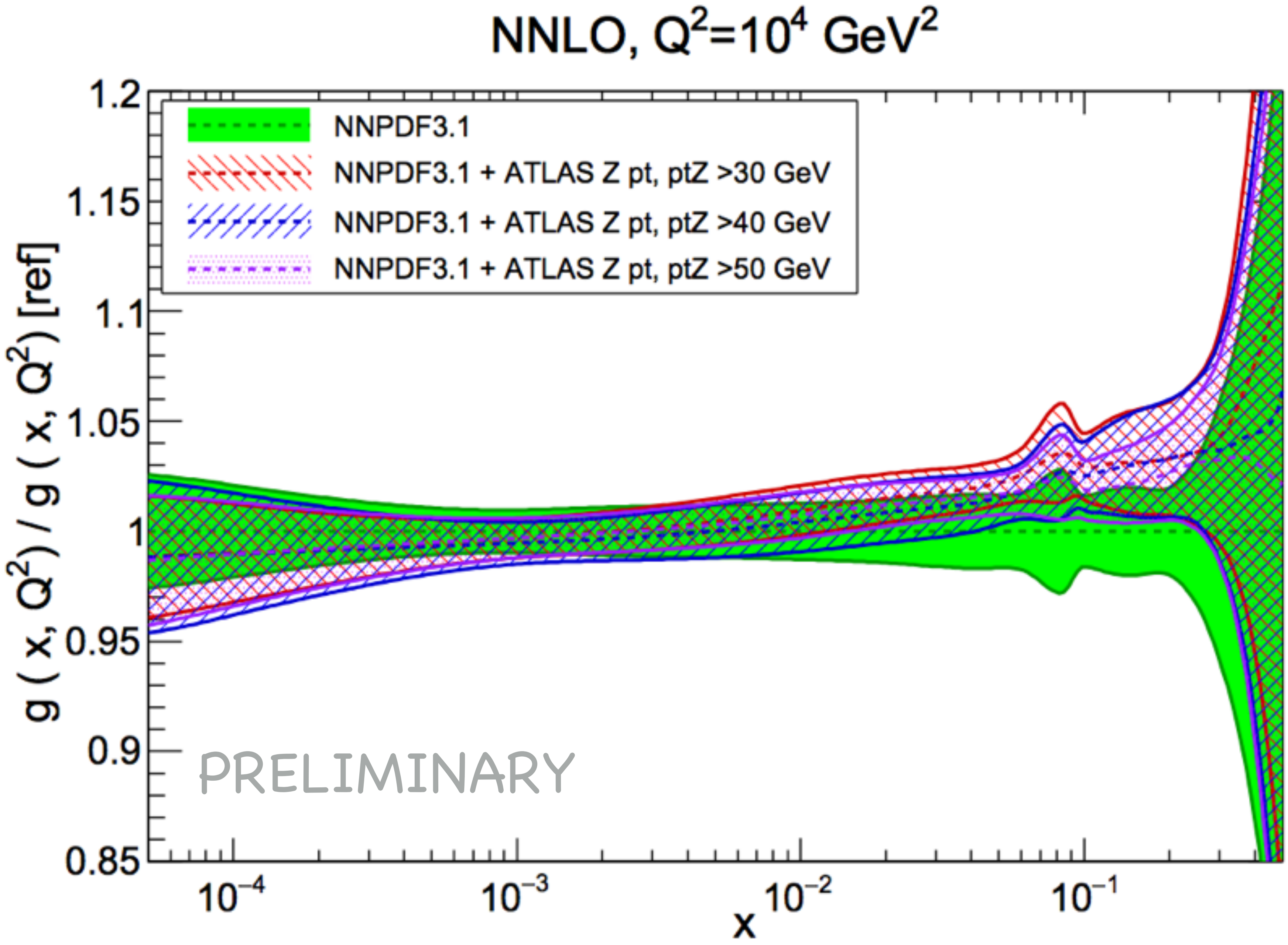


NNLO correction crucial to get the right shape!

Boughezal, Guffanti, Petriello, MU, in preparation

Z pT data

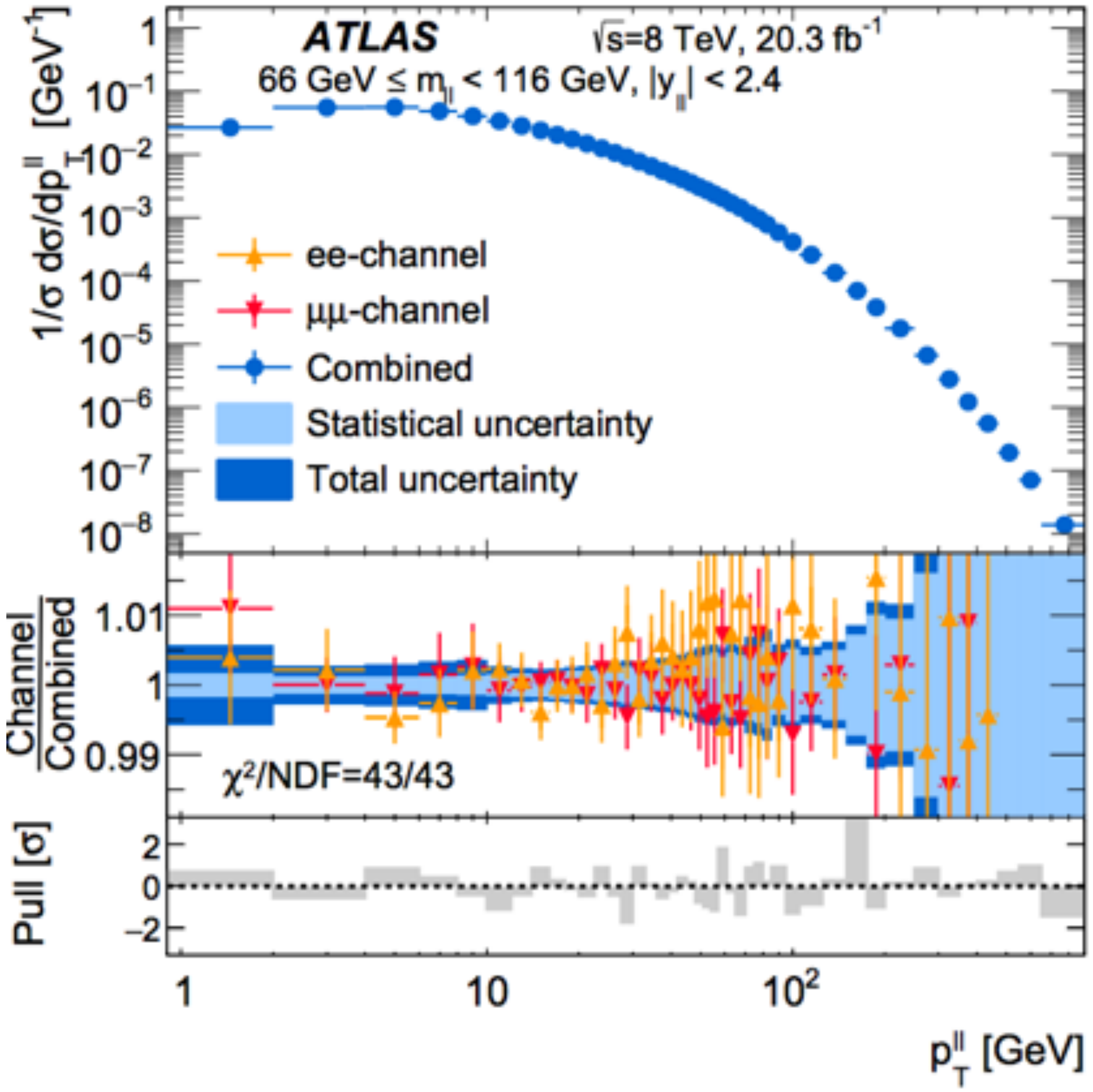
ATLAS 7 TEV

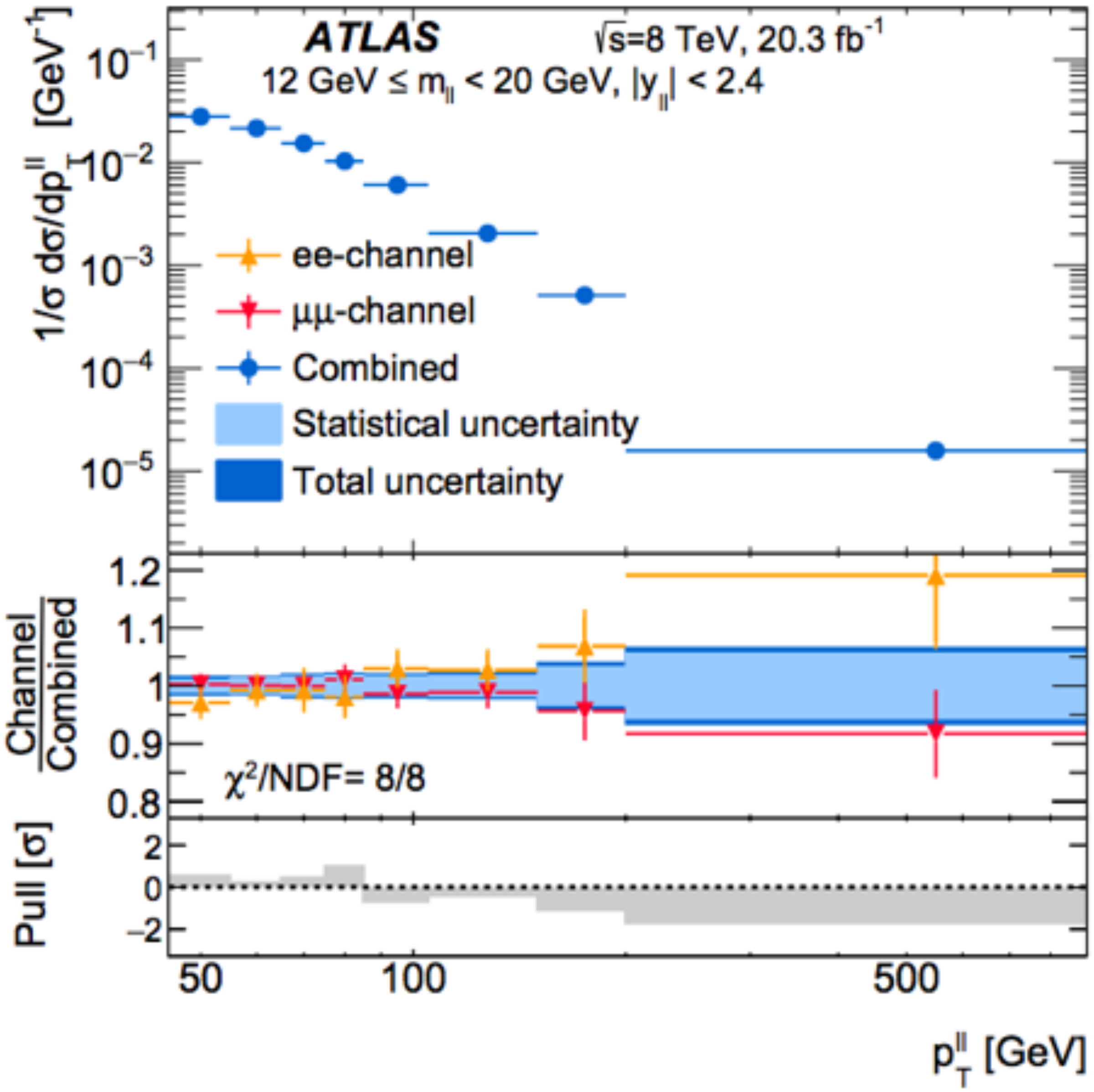


Boughezal, Guffanti, Petriello, MU, in preparation

Z pT data

ATLAS 8 TEV





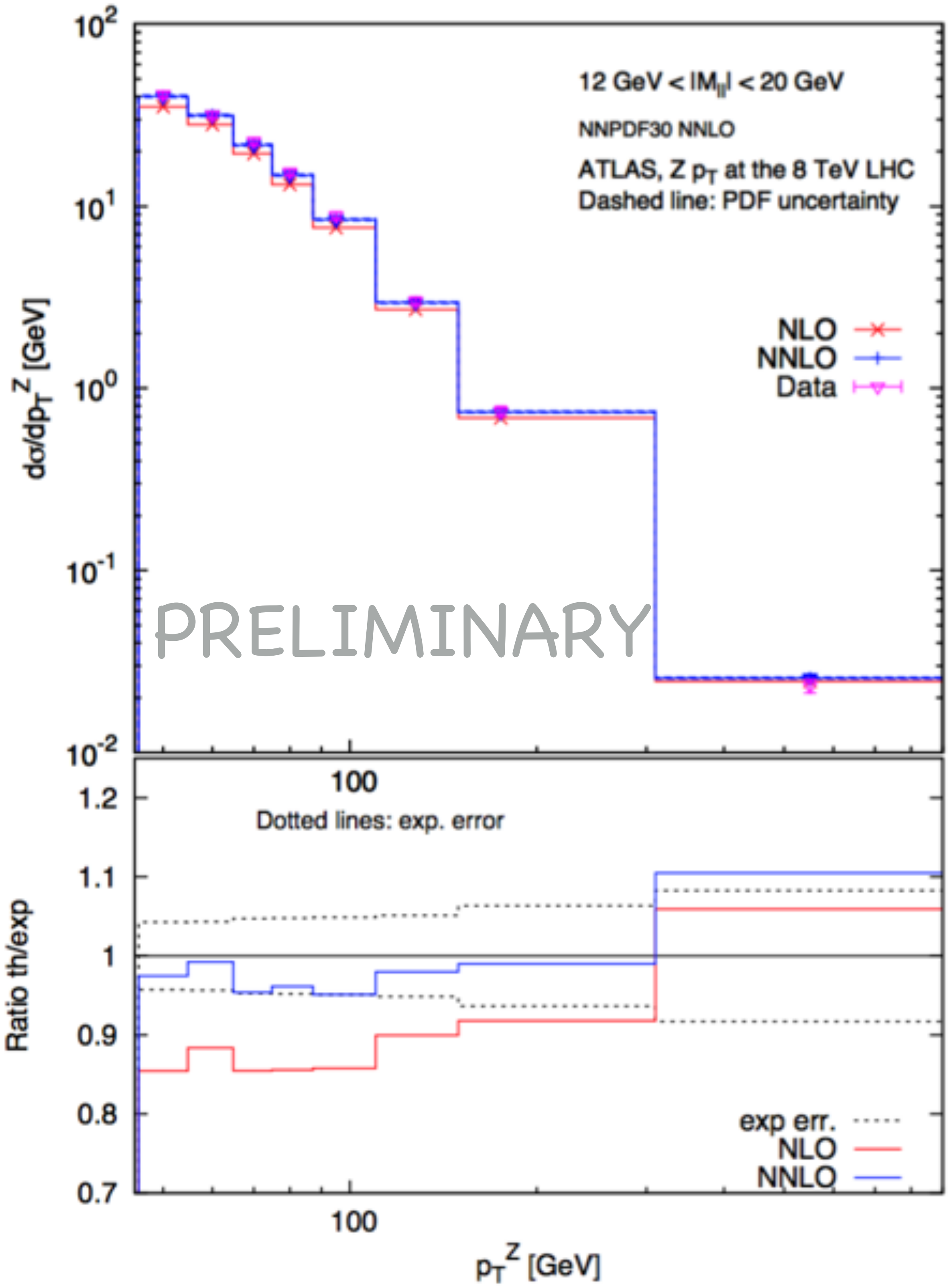
ATLAS 8 TeV measurements [1512.02192]

- Normalised and un-normalised
- Six rapidity bins in Z peak region
  0.0 < Y < 0.4 - 0.4 < Y < 0.8
  0.8 < Y < 1.2 - 1.2 < Y < 1.6
  1.6 < Y < 2.0 - 2.0 < Y < 2.4

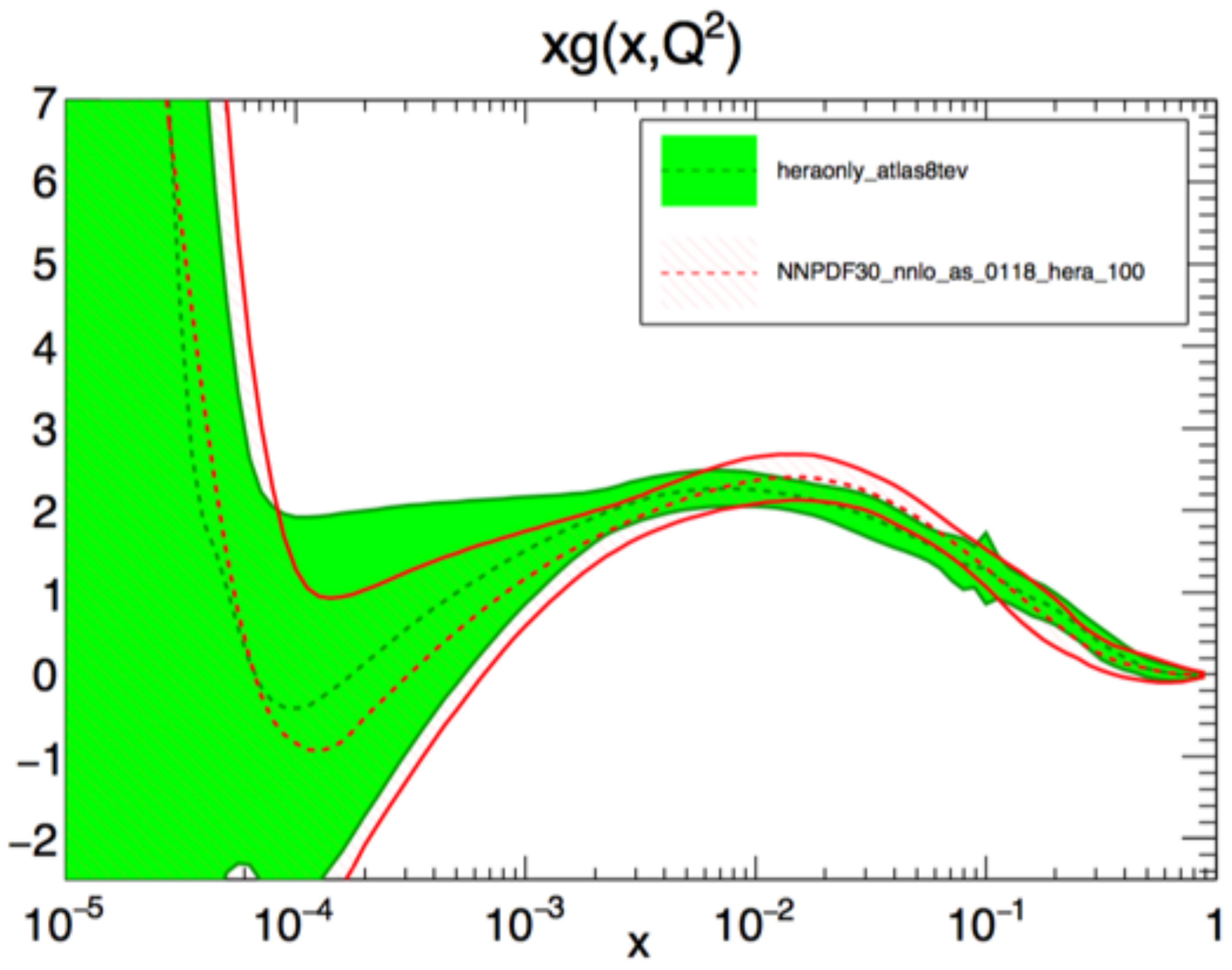
- Four low-invariant mass bins
  (12,20) (20,30)(30,46)(46,66) GeV
- One high-invariant mass bin
  (116,150) GeV
- O(150) datapoints with pT > 30 GeV

Z pT data

ATLAS 8 TEV



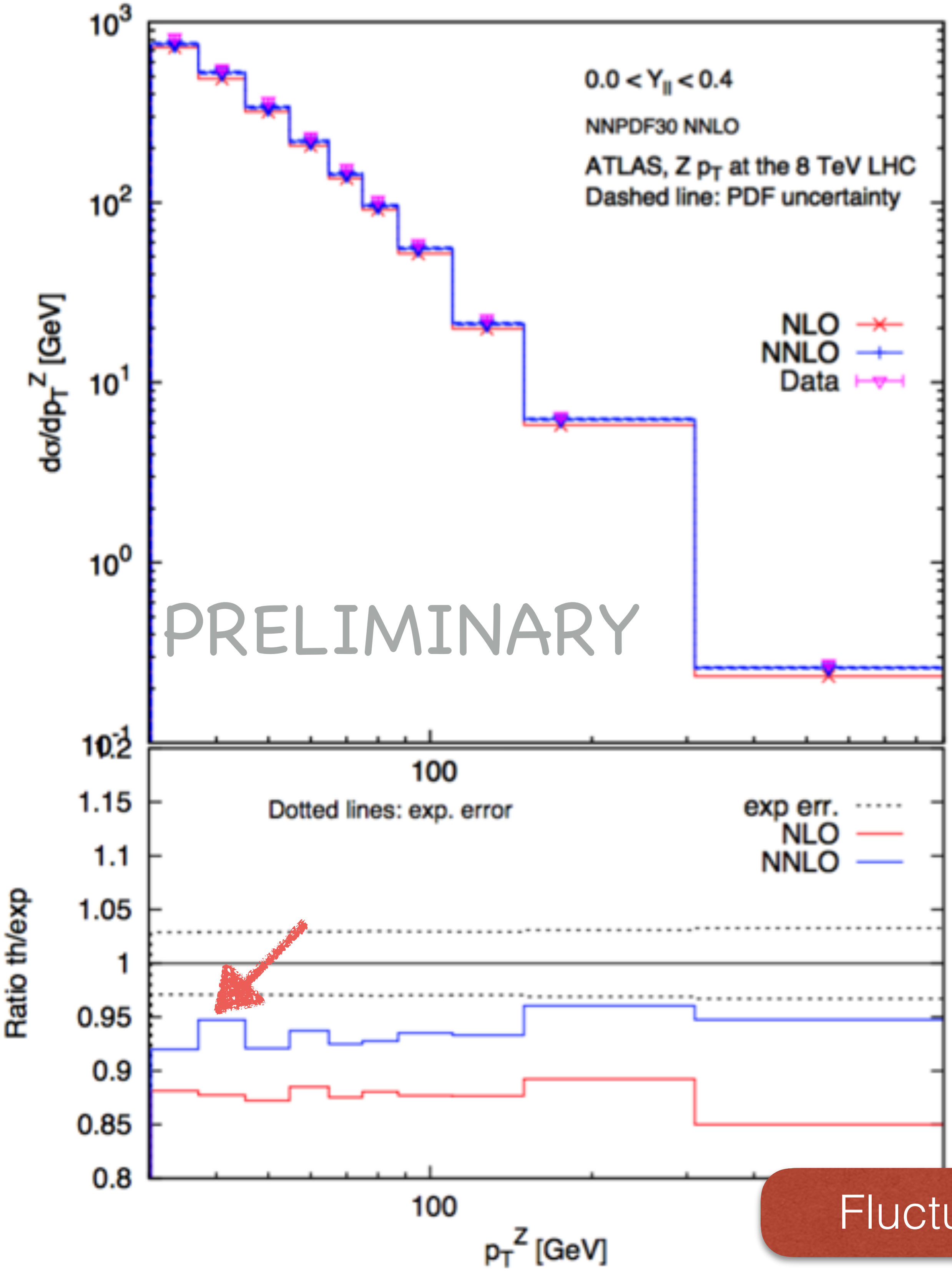
- Low- and high-invariant mass distributions well described at NNLO (shape and normalisation)
- Inclusion in DIS-only fit shows similar trend as the 7 TeV data



Boughezal, Guffanti, Petriello, MU, in preparation

Z pT data

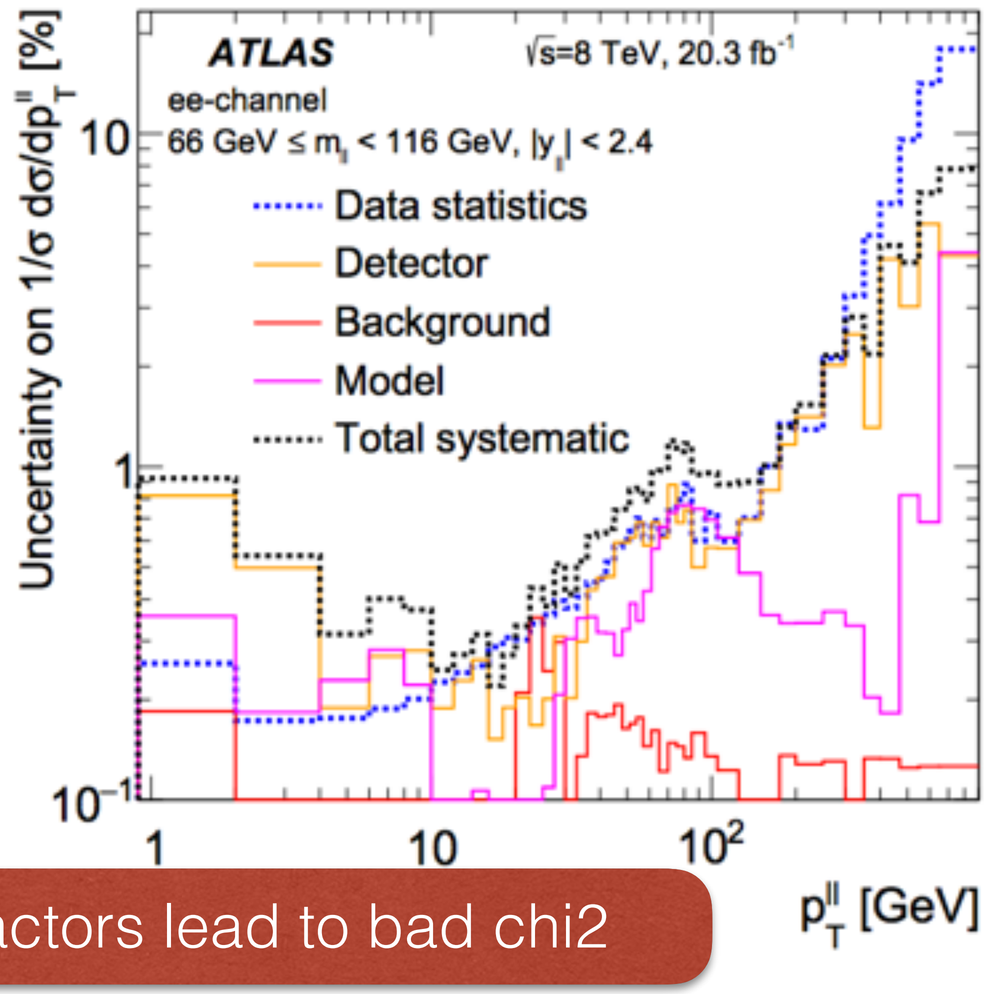
ATLAS 8 TEV



- What about Z-peak, double diff y-pT distns?

	NLO	**NNLO**
$\chi^2_{\rm stat}$	$= 140$	$= 51.$
$\chi^2_{\rm uncor}$	$= 115$	$= 42.$
$\chi^2_{\rm diag}$	$= 1.70$	$= 0.62$
$\chi^2_{\rm full}$	$= \boxed{2.80}$	$= \boxed{5.61}$

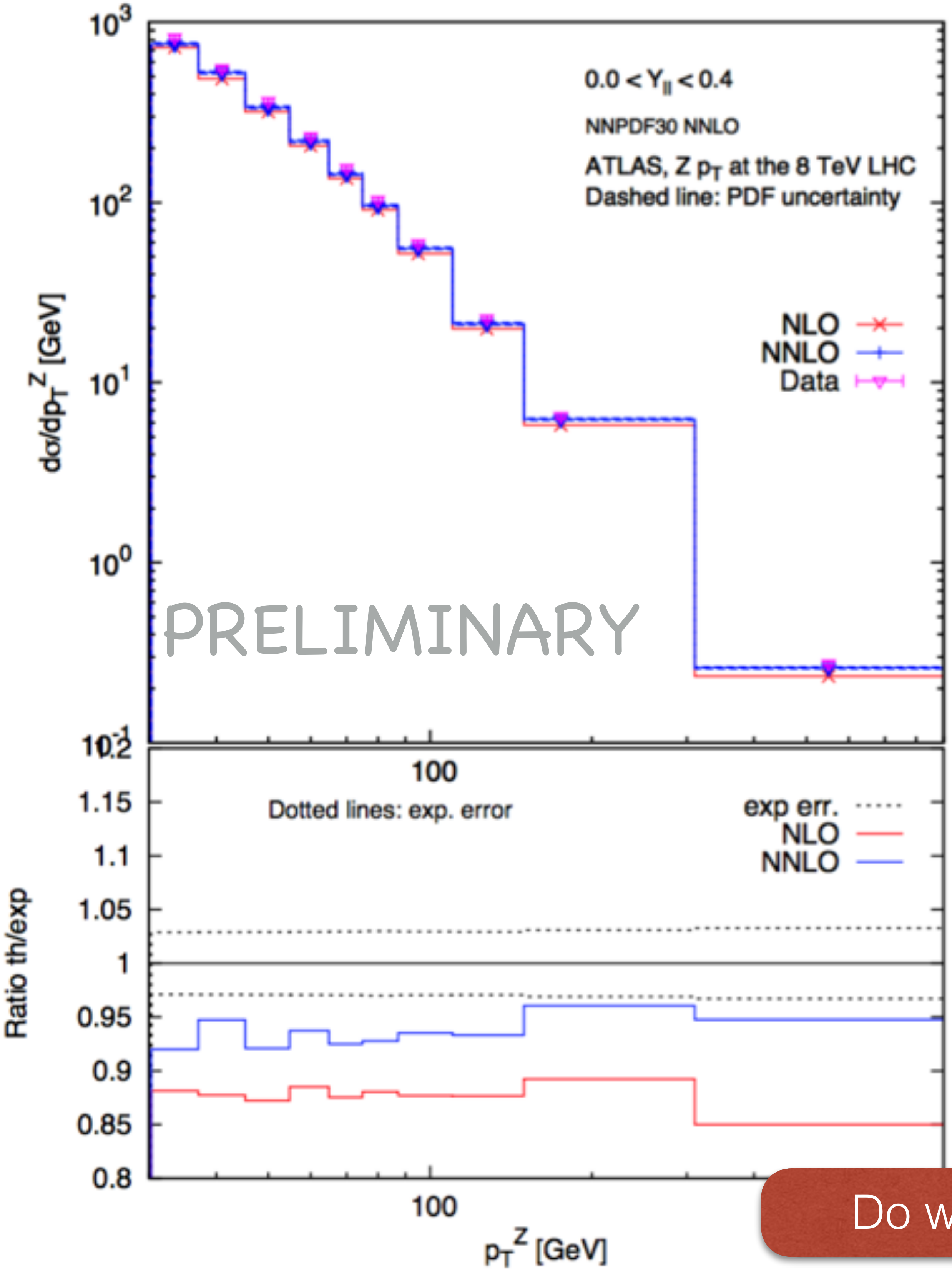
/d.o.f.



Fluctuations in K-factors lead to bad chi2

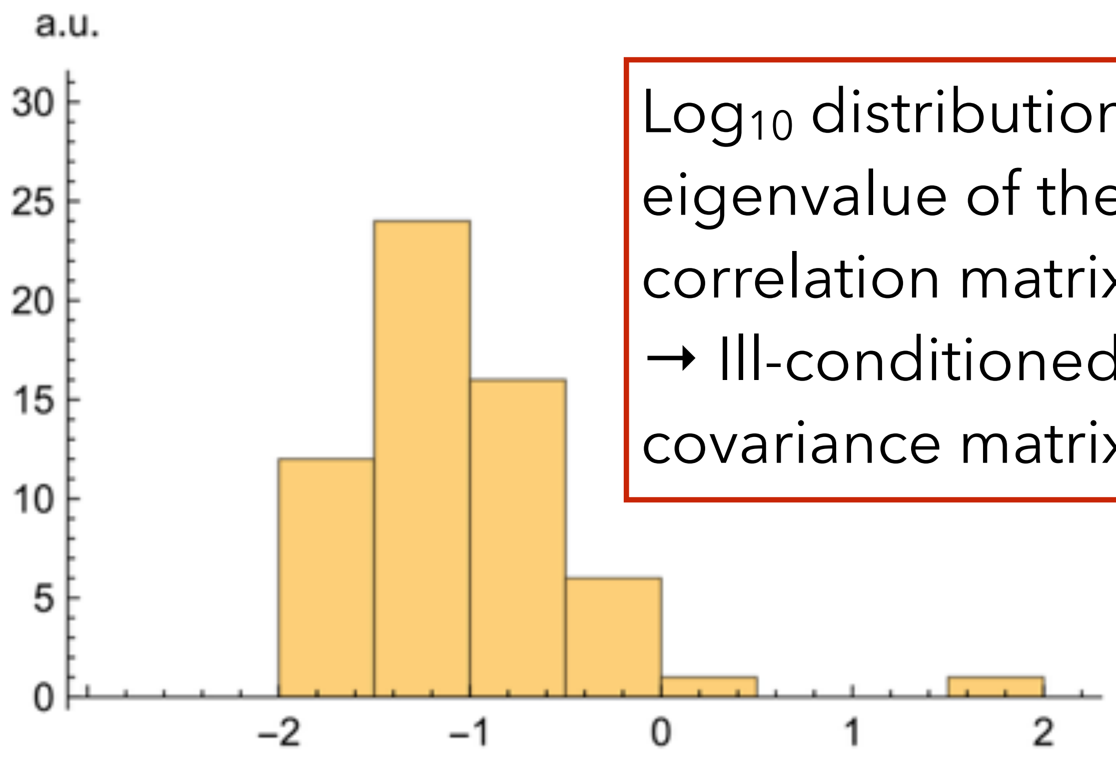
Z pT data

ATLAS 8 TEV



- What about Z-peak, double diff y-p_T distns?

NLO	**NNLO**	
$\chi^2_{\rm stat} = 140$	$\chi^2_{\rm stat} = 51.$	**/d.o.f.**
$\chi^2_{\rm uncor} = 115$	$\chi^2_{\rm uncor} = 42.$	
$\chi^2_{\rm diag} = 1.70$	$\chi^2_{\rm diag} = 0.62$	
$\chi^2_{\rm full} = \boxed{2.80}$	$\chi^2_{\rm full} = \boxed{5.61}$	

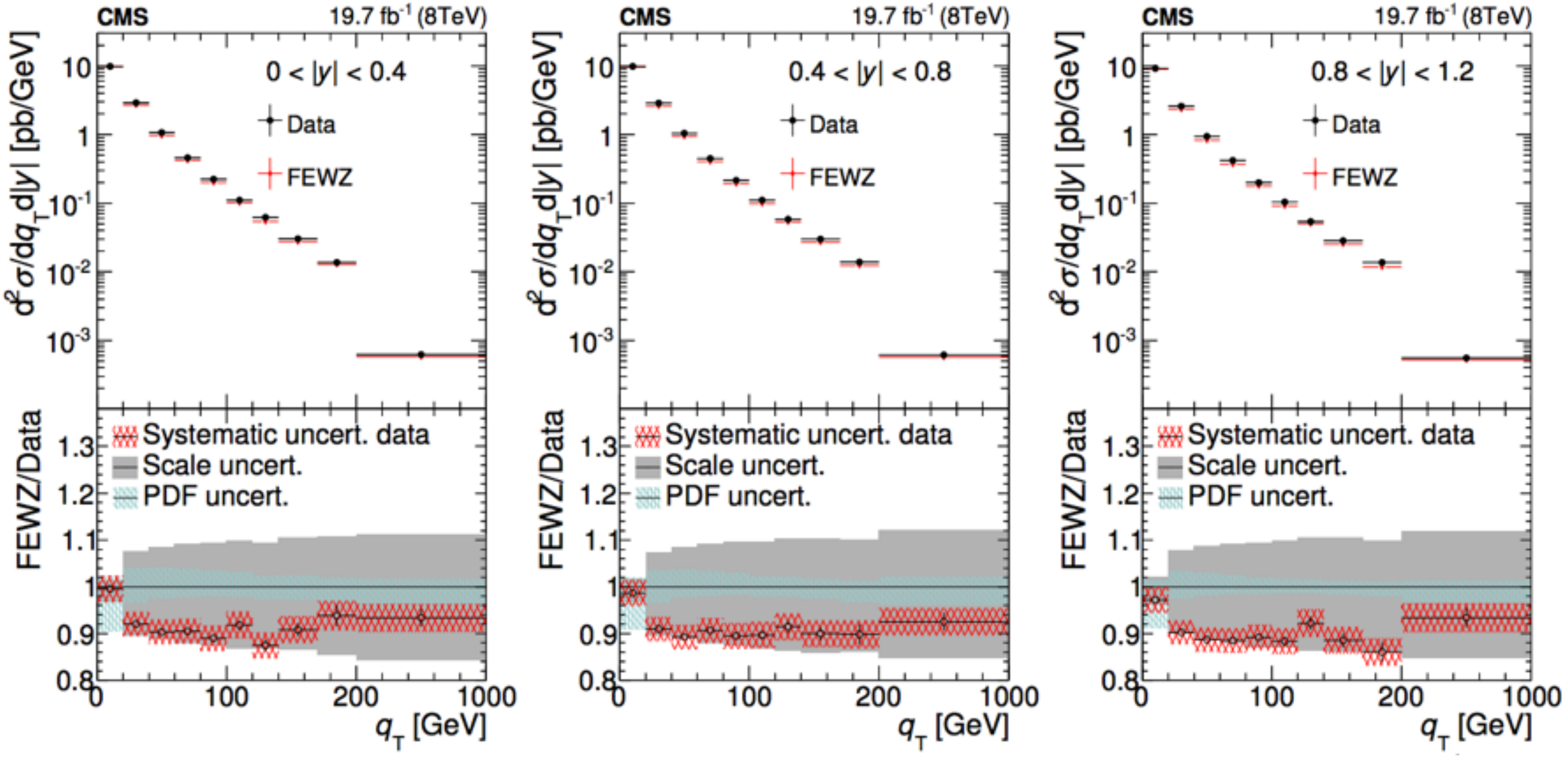


Log$_{10}$ distribution of eigenvalue of the correlation matrix → Ill-conditioned covariance matrix

Do we need uncertainty on covariance matrix?

Z pT data

CMS 8 TEV



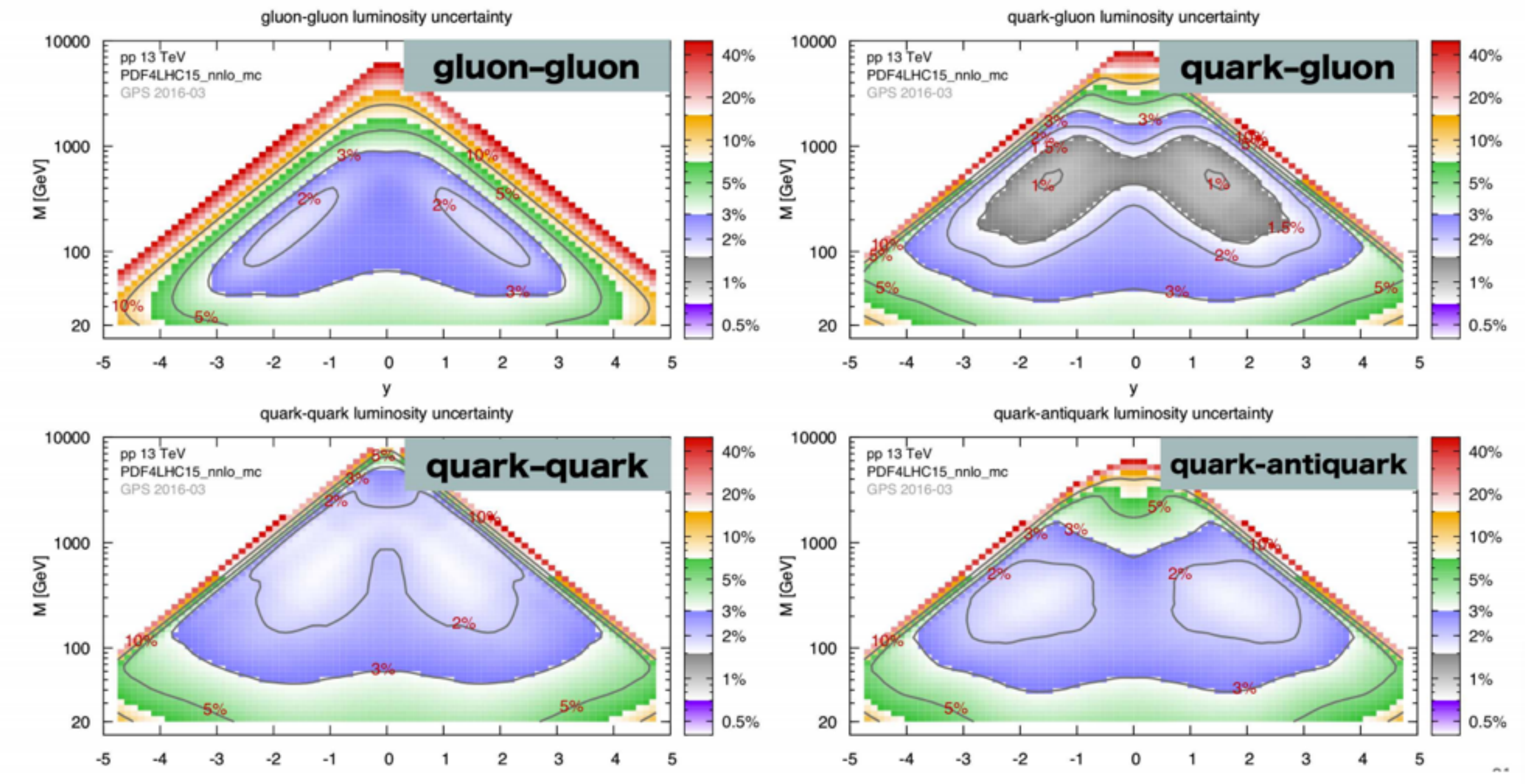
CMS 8 TeV measurements [1504.03511]

- Normalised and un-normalised
- Five rapidity bins in Z peak region
  0.0 < Y < 0.4 - 0.4 < Y < 0.8
  0.8 < Y < 1.2 - 1.2 < Y < 1.6
  1.6 < Y < 2.0
- O(50) datapoints with pT > 30 GeV

NLO prediction theoretical uncertainty reduced in NNLO correction

Implications for theory

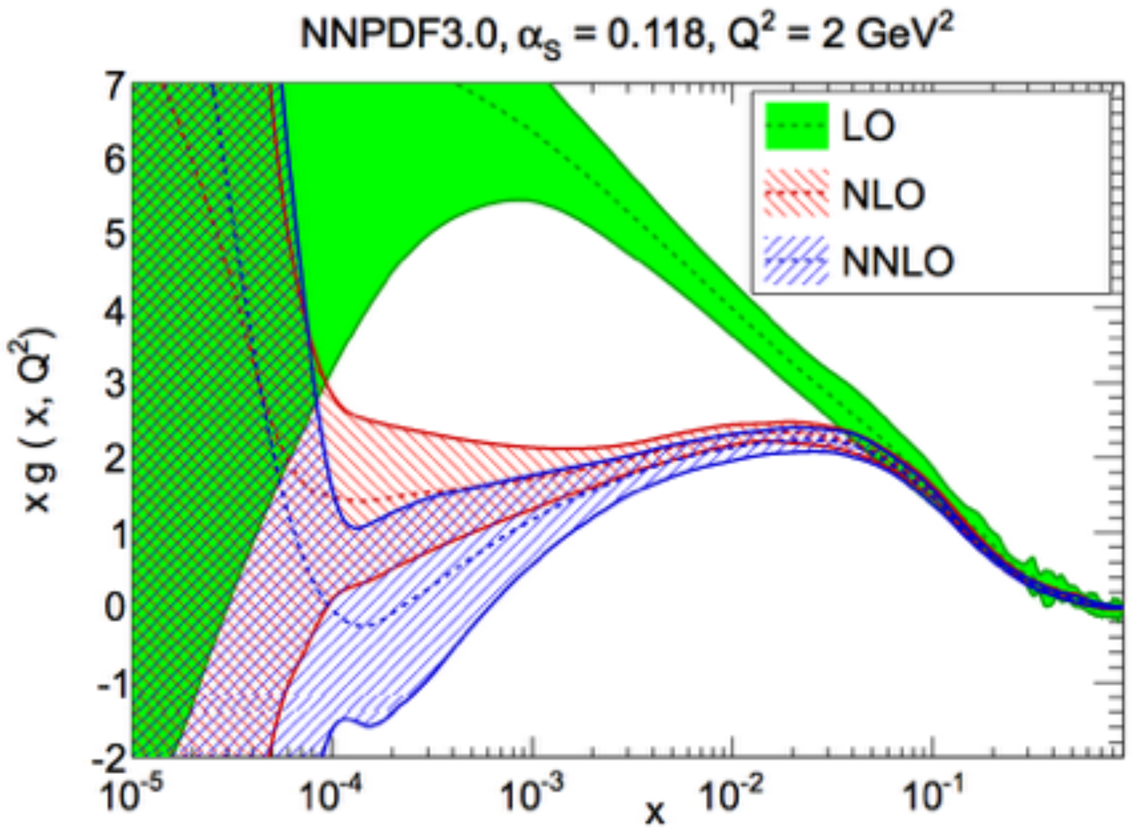
PDF uncertainties

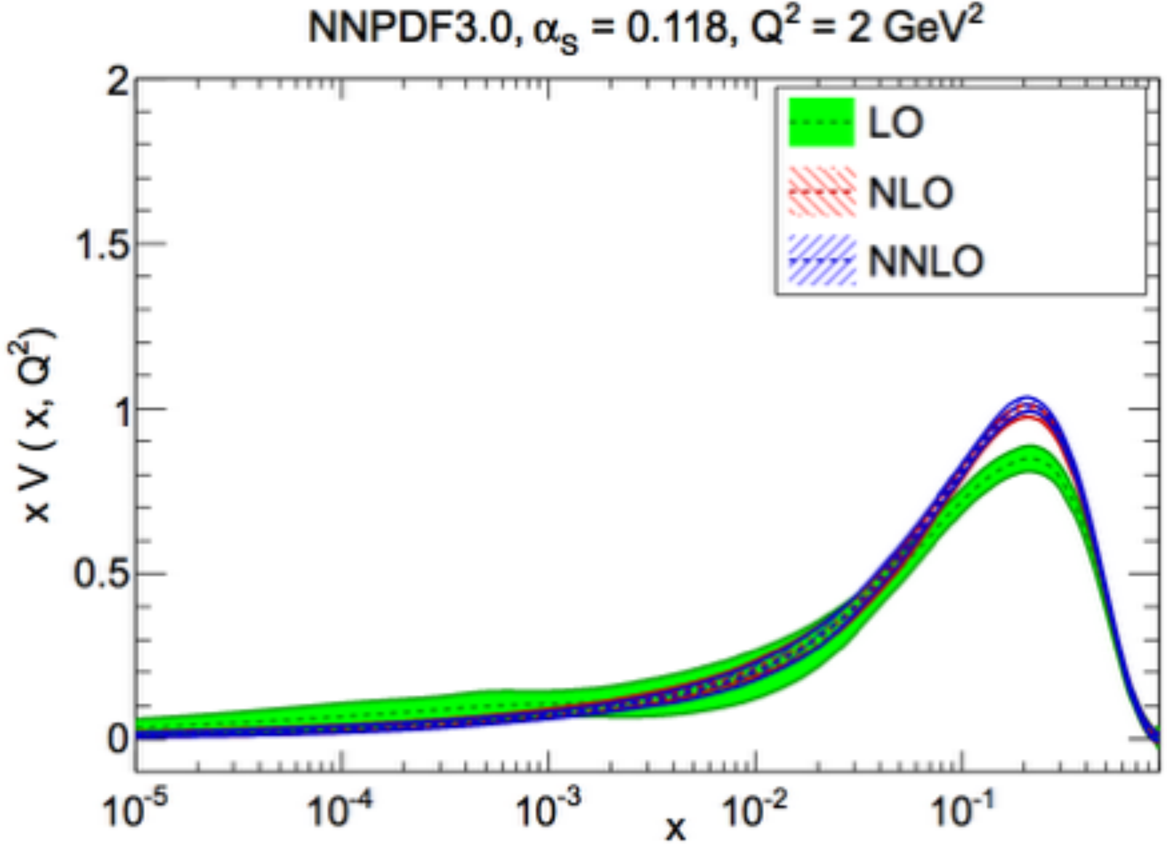


G. Salam, LHCP

Do we trust 1% accuracy in parton luminosities?

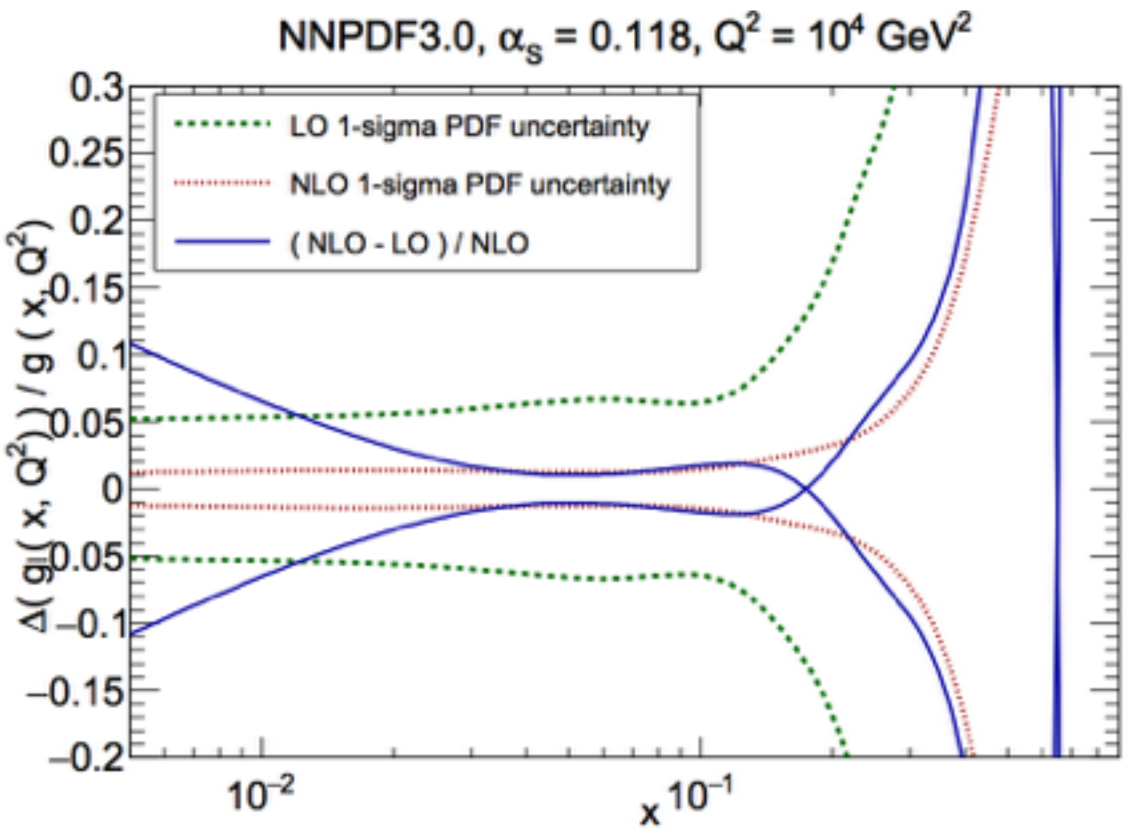
Fixed-order accuracy

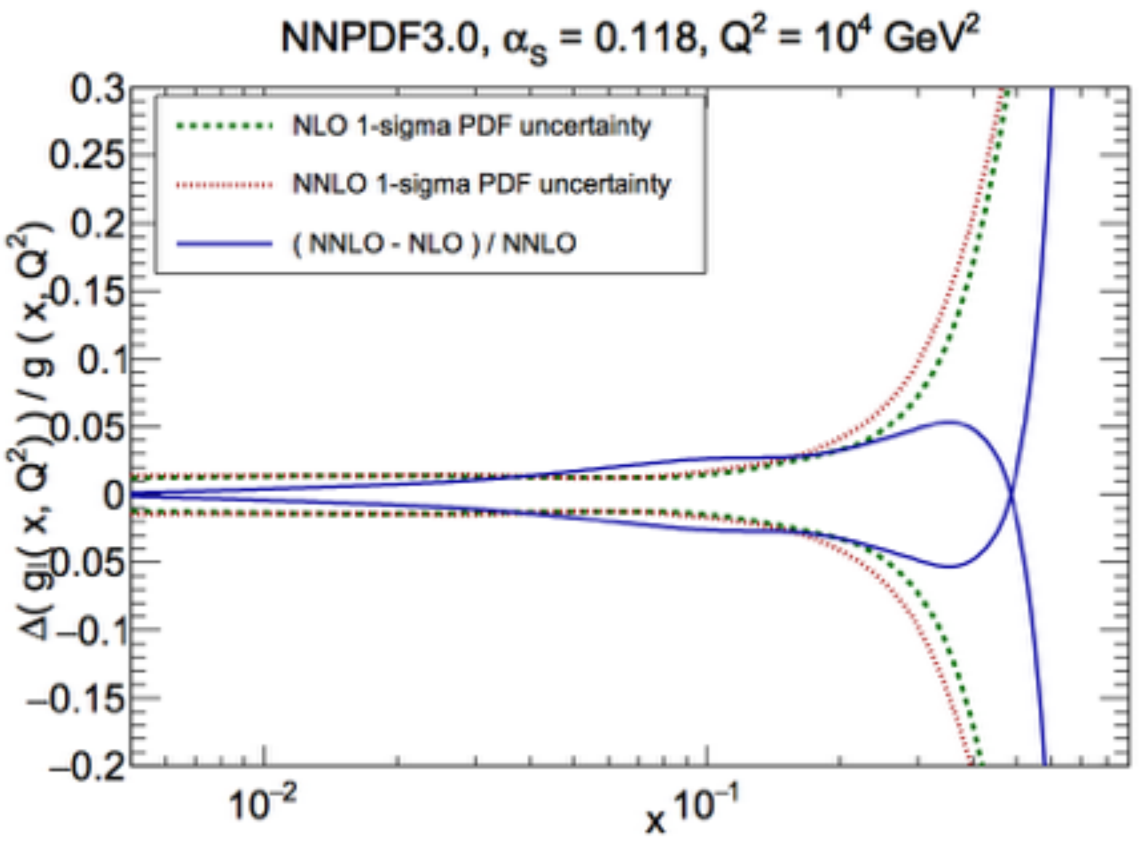




- PDF fits performed with given fixed perturbative order, value of α_S and heavy quark masses (estimated by combining PDF sets determined with different values)
- PDF uncertainties only reflect lack of information from data given the theory
- Changes in theory may cause shifts outside the error band,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

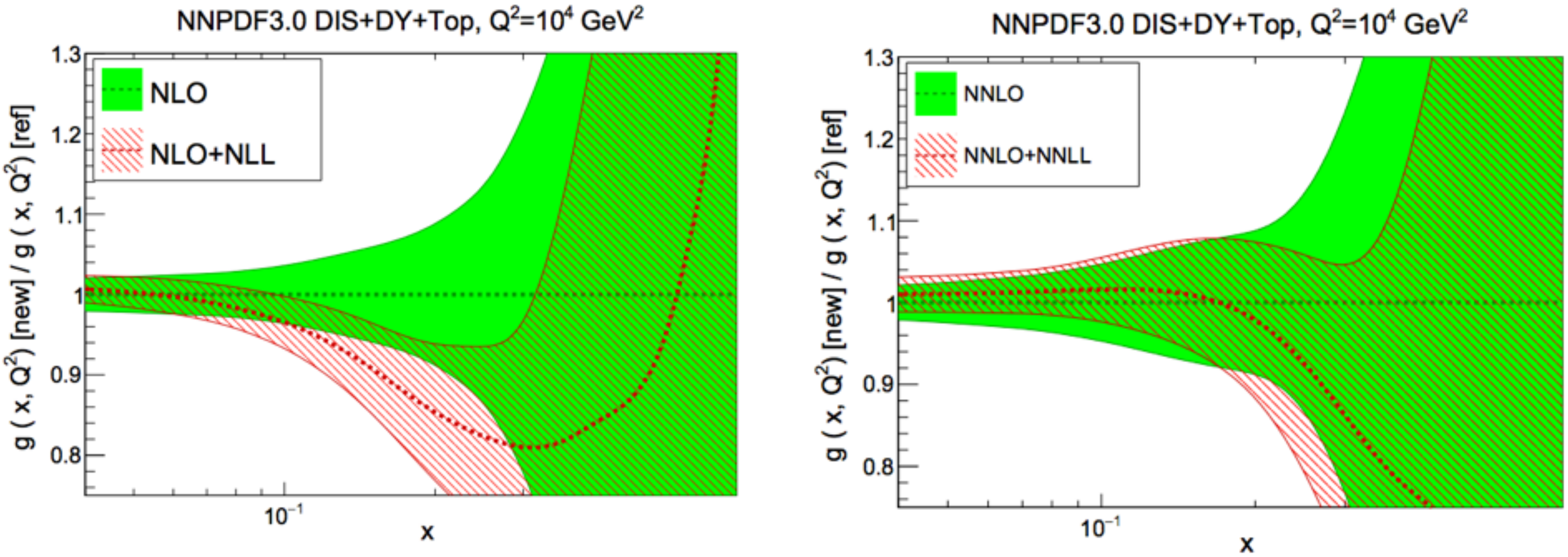
Fixed-order accuracy





- If we knew the next order we could compute the shift: at NLO theory uncertainty is comparable to the experimental one
- NNLO subdominant
- Cacciari Houdeau method [JHEP 1109 (2011) 039] look at the behaviour of perturbative expansion promising
- What about NNNLO PDFs? Main bottleneck is missing anomalous dimensions

Beyond fixed-order accuracy

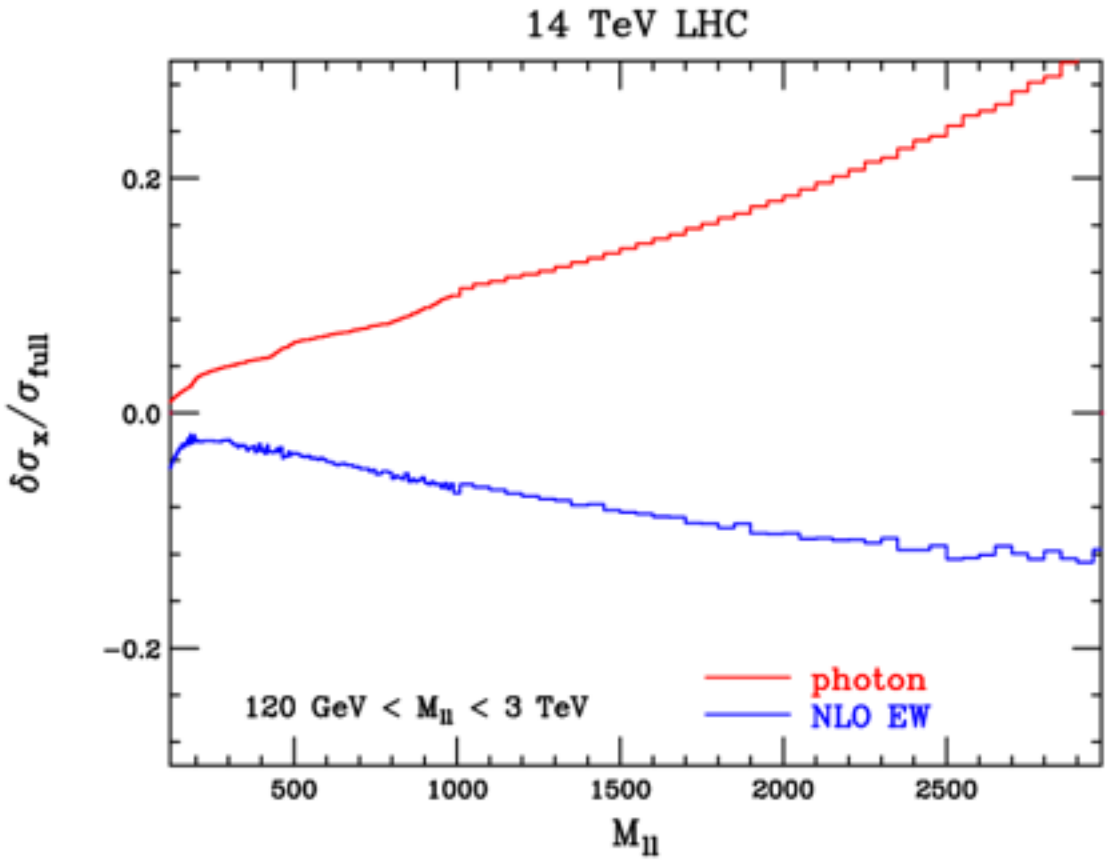


Bonvini et al, JHEP 1509 (2015) 191

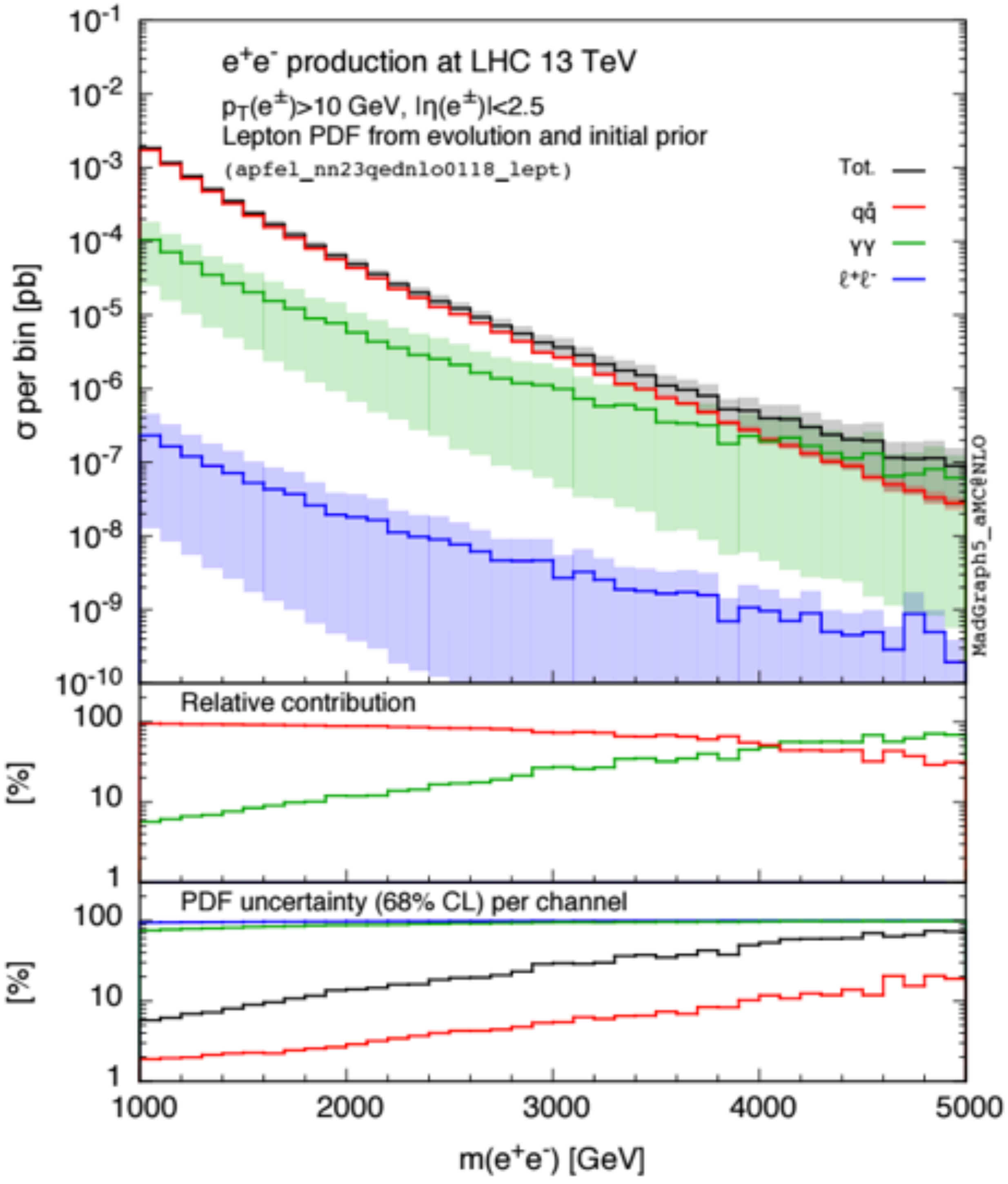
- Threshold-resummed PDFs made recently available **[Bonvini et al, JHEP 1509 (2015) 191]**
- Gluon suppressed as compared to fixed-order PDFs mostly due to enhancement of NLO+NLL xsecs used in the fit of DIS structure functions and DY distributions
- This suppression partially or totally compensates enhancements in partonic cross sections. Phenomenologically relevant for new physics processes **[Beenakker et al. EPJC76 (2016)2, 53]**
- Work in progress on small-x, pT resummation **[Simone's talk]**

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, which we thought induced large uncertainty



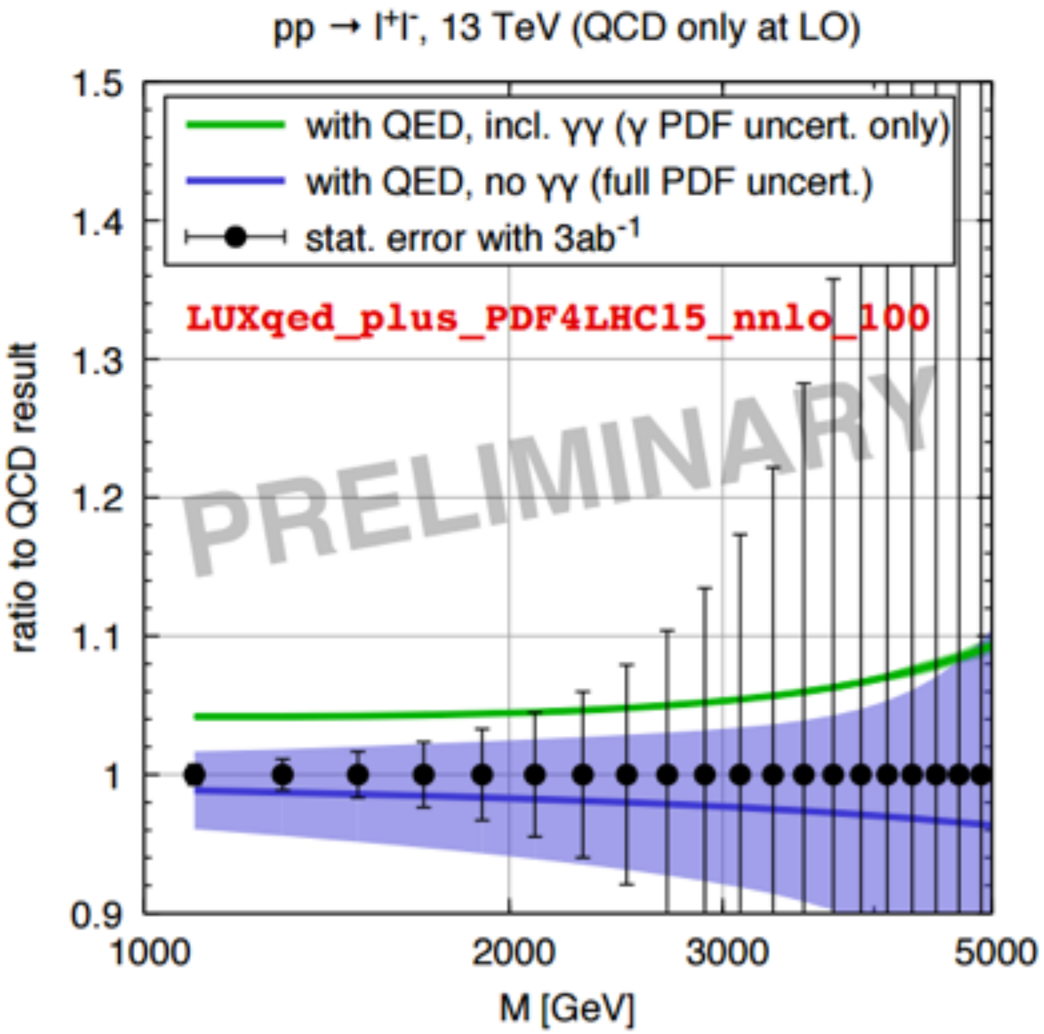
Boughezal et al [Phys.Rev. D89 (2014)3, 034030]

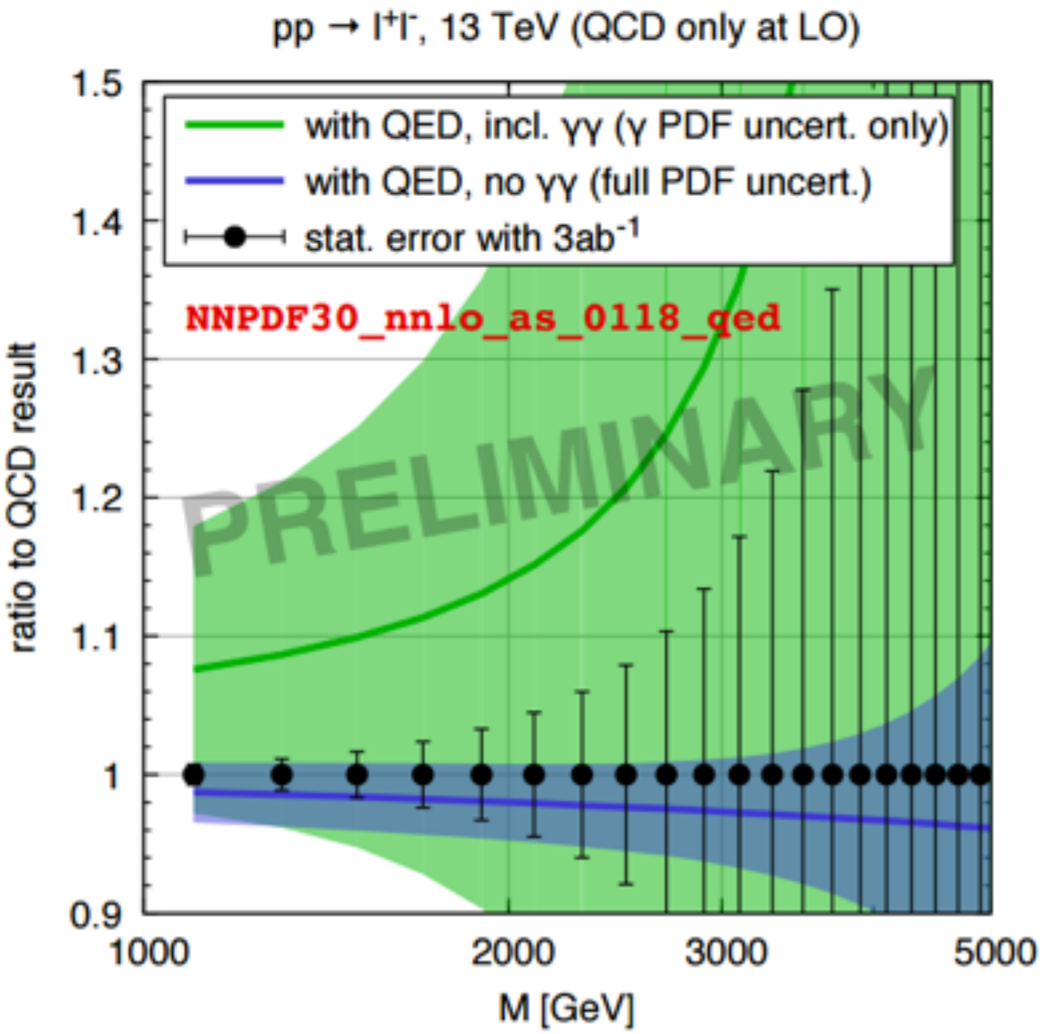


Bertone et al [JHEP 1511 (2015) 194]

Photon PDF

- Data-driven NNPDF approach inducing a large uncertainty on photon PDF
- Breakthrough: LUX PDF [Manohar, Nason, Salam, Zanderighi,1607.04266]
- 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





P. Nason, talk in Durham

Data-Theory interplay

Exploit precise **LHC data** to reduce PDF uncertainties

Experimental **correlations** bound to be dominant errors

Reduce **theoretical uncertainty** in PDF fits: resummation, EW effects, HQ masses, intrinsic HQ, parton shower

Introduce a way to measure residual **theoretical uncertainty** in PDF fits

The higher the energy regime, the more theory boundaries are probed
The smaller the experimental uncertainty, the more crucial is theory uncertainty

Conclusions and Outlook

- Parton Distribution Functions essential ingredient for LHC phenomenology
- Accurate PDFs are required for precision SM measurements

THEORY

- pQCD loop revolution - PDF and theory predictions in PDF fits must keep up
- Large invariant mass & large rapidity - EW and photon-initiated processes become important
- Closer to kinematic boundaries - resummation in PDFs

DATA

- Precision of LHC data starts being challenging!
- Correlated systematics increasingly dominant!
- Many new accurate LHC data - collider-only fit?

METHODOLOGY

- Closure tests to establish methodology
- Combination of different PDF sets
- Inclusion of hidden uncertainties in PDF error bands (especially theory uncertainties)
- How not to absorb new physics in PDFs?

Back-up slides

Threshold resummation

- Threshold resummation: initial energy just enough to produce final state with mass M, so emissions forced to be soft and logs at each order in PT are enhanced

$$x = \frac{M^2}{\hat{s}} \qquad \text{NLO}: \; M^2 = z\hat{s} \qquad \left[\frac{\log^k(1-z)}{(1-z)}\right]_+$$

- Transform factorised cross section into Mellin space

$$\sigma(x,Q^2) = x\sum_{a,b}\int_x^1 \frac{dz}{z}\mathcal{L}_{ab}\left(\frac{x}{z},\mu_{\mathrm{F}}^2\right)\frac{1}{z}\hat{\sigma}_{ab}\left(z,Q^2,\alpha_s(\mu_{\mathrm{R}}^2),\frac{Q^2}{\mu_{\mathrm{F}}^2},\frac{Q^2}{\mu_{\mathrm{R}}^2}\right)$$

$$\sigma(N,Q^2) = \int_0^1 dx\, x^{N-2}\sigma(x,Q^2) = \sum_{a,b}\mathcal{L}_{ab}(N,Q^2)\hat{\sigma}_{ab}\left(N,Q^2,\alpha_s\right)$$

- In the MSbar scheme PDF evolution does not contain large-x logs and the effect of resummation can be included in resummed coefficient functions

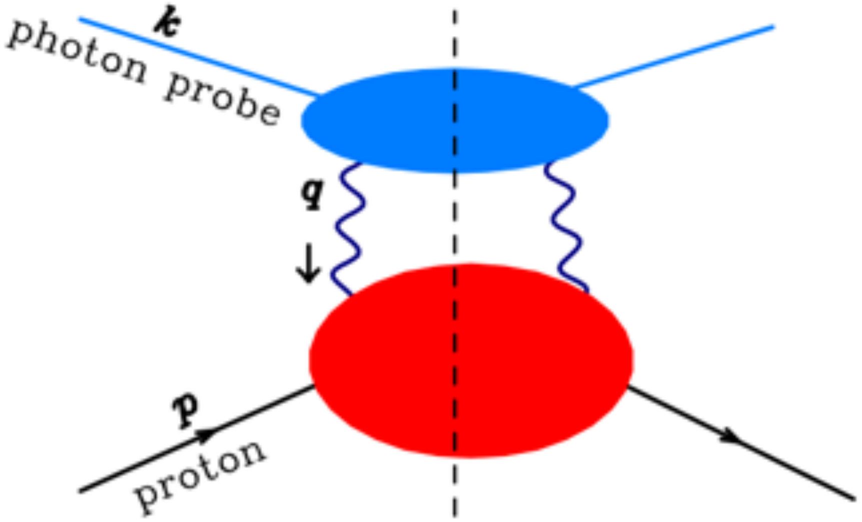
$$\hat{\sigma}_{ab}^{(\mathrm{res})}(N,Q^2,\alpha_s) = \sigma_{ab}^{(\mathrm{born})}(N,Q^2,\alpha_s)\,C_{ab}^{(\mathrm{res})}(N,\alpha_s).$$

$$C^{(N\text{-soft})}(N,\alpha_s) = g_0(\alpha_s)\exp\mathcal{S}(\ln N,\alpha_s),$$

$$\mathcal{S}(\ln N,\alpha_s) = \left[\frac{1}{\alpha_s}g_1(\alpha_s\ln N) + g_2(\alpha_s\ln N) + \alpha_s g_3(\alpha_s\ln N) + \ldots\right]$$

LUX, master equation

The Master Equation



$$\begin{aligned}\sigma &= \int \frac{\mathrm{d}^4 q}{(2\pi)^4} \frac{e^4_{\mathrm{phys}}(q^2)}{q^4} \\ &\quad \times \langle k|\tilde{J}_p{}^{\mu}(-q) J^{\nu}_p(0)|k\rangle \\ &\quad \times \langle p|\tilde{J}_{\mu}(q) J_{\nu}(0)|p\rangle\end{aligned}$$

Kinematics constraints:

$$Q^2 = -q^2 > 0,$$
$$0 < x_{\mathrm{bj}} = Q^2/(2p\cdot q) \leq 1.$$

- Same kinematic restrictions as in DIS.
- $\frac{1}{4\pi}\langle p|\tilde{J}_{\mu}(q)J_{\nu}(0)|p\rangle = -g_{\mu\nu}F_1(Q^2, x_{\mathrm{bj}}) + \frac{p^{\mu}p^{\nu}}{p\cdot q}F_2(Q^2, x_{\mathrm{bj}}) + \ldots$ (Notice: full F_1 and F_2, not only inelastic)
- Photon induced process can be given in terms of F_1, F_2
- Hence: the photon PDF must be calculable in terms of F_1, F_2.

P. Nason, talk in Durham

The photon PDF

- **NNPDF23QED** provides γ PDF and its uncertainty at (N)NLO QCD + LO QED, by reweighting photon PDF
  Ball et al [Nucl.Phys. B877 (2013)]

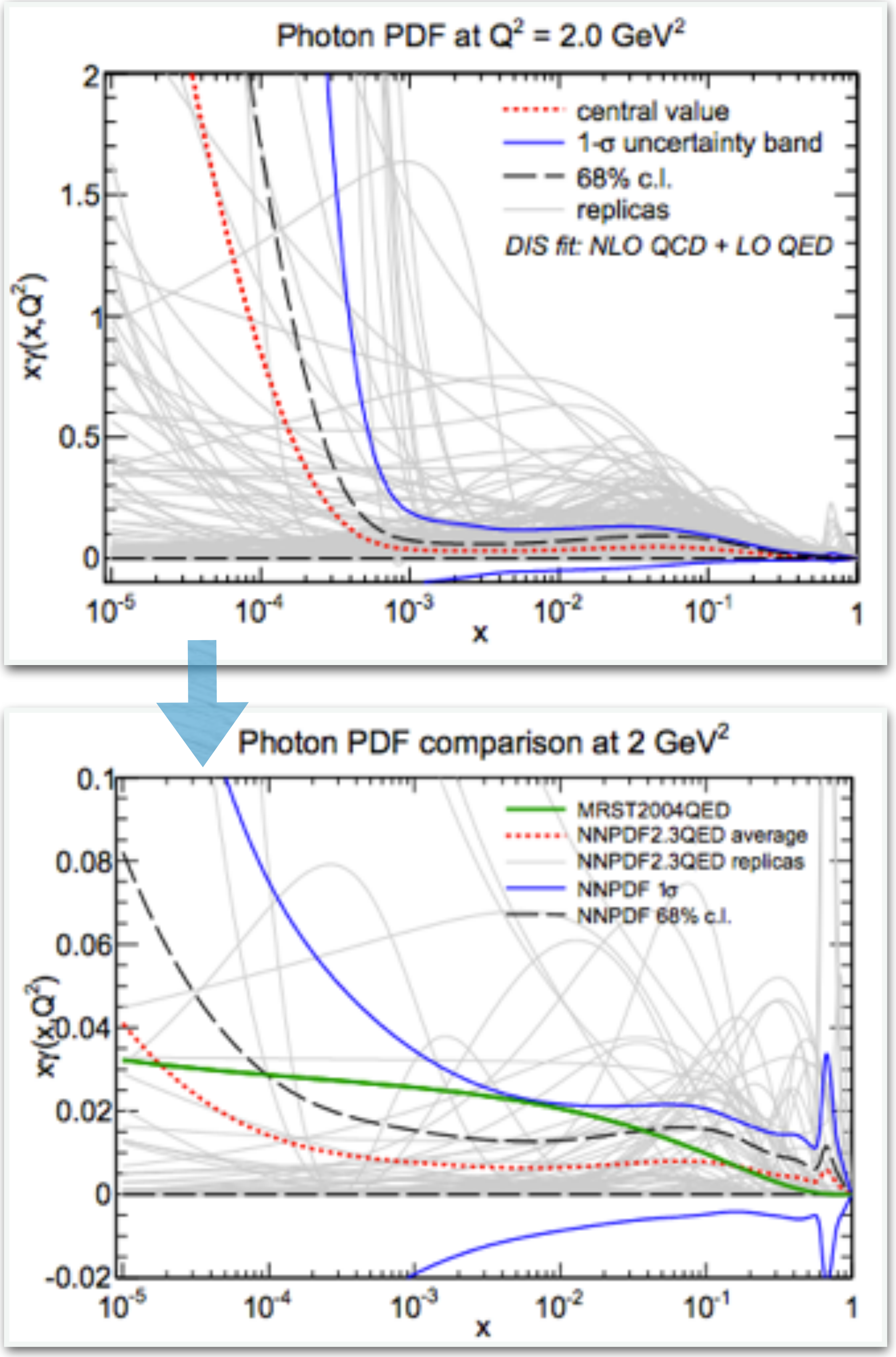
- **CT14QED** set based on two-parameter ansatz from model of photon radiate from valence quarks (extension to MRST2004QED model)
  Schmidt et al [1509.02905]

$$
\begin{aligned}
f_{\gamma/p}(x,Q_0) &= \frac{\alpha}{2\pi}\left(A_u e_u^2 \tilde{P}_{\gamma q}\circ u^0(x) + A_d e_d^2 \tilde{P}_{\gamma q}\circ d^0(x)\right)\\
f_{\gamma/n}(x,Q_0) &= \frac{\alpha}{2\pi}\left(A_u e_u^2 \tilde{P}_{\gamma q}\circ d^0(x) + A_d e_d^2 \tilde{P}_{\gamma q}\circ u^0(x)\right)
\end{aligned}
$$

- γ PDF poorly determined by DIS data. Need hadron collider processes where γ contributes at LO (on-shell W,Z production and low/high mass DY)

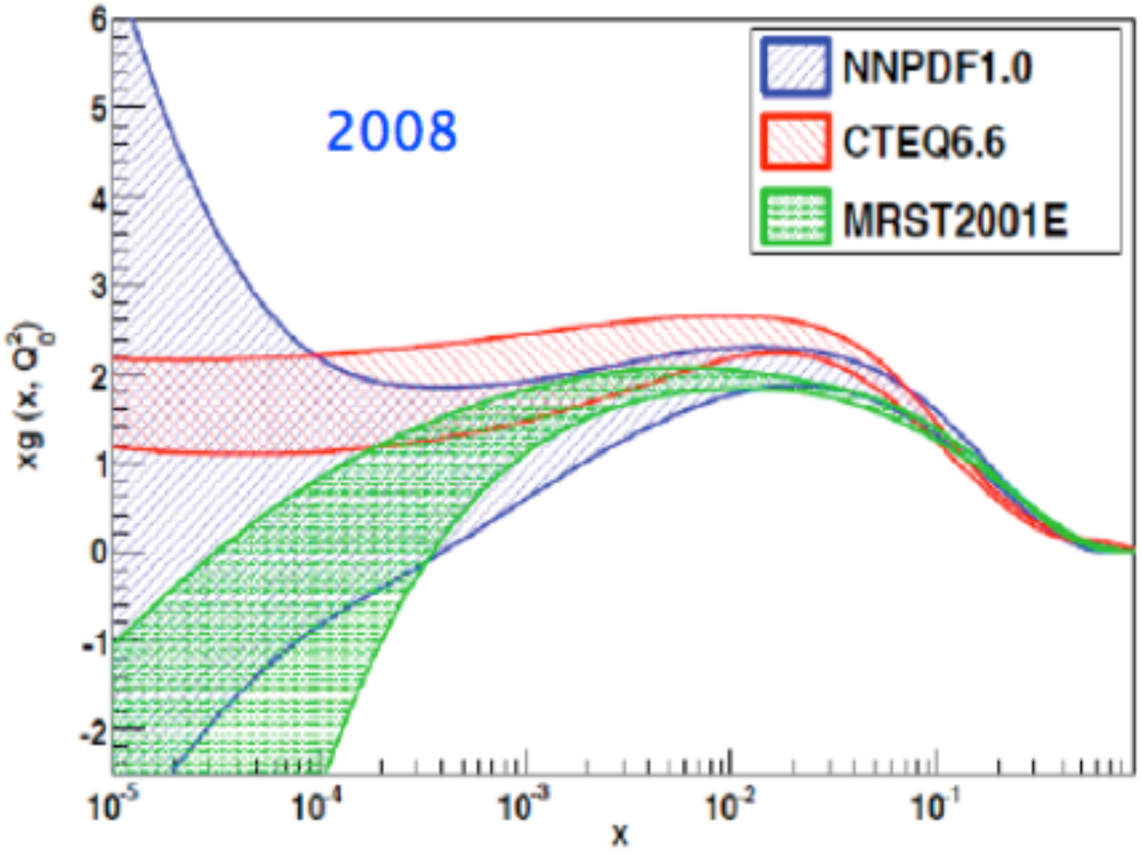
- NNPDF plan: fit photon along with other PDFs (thanks to upgrade of APFEL - simultaneous diagonalization of QCD and QED evolution matrices - and APFELgrid - now includes photon-induced processes)

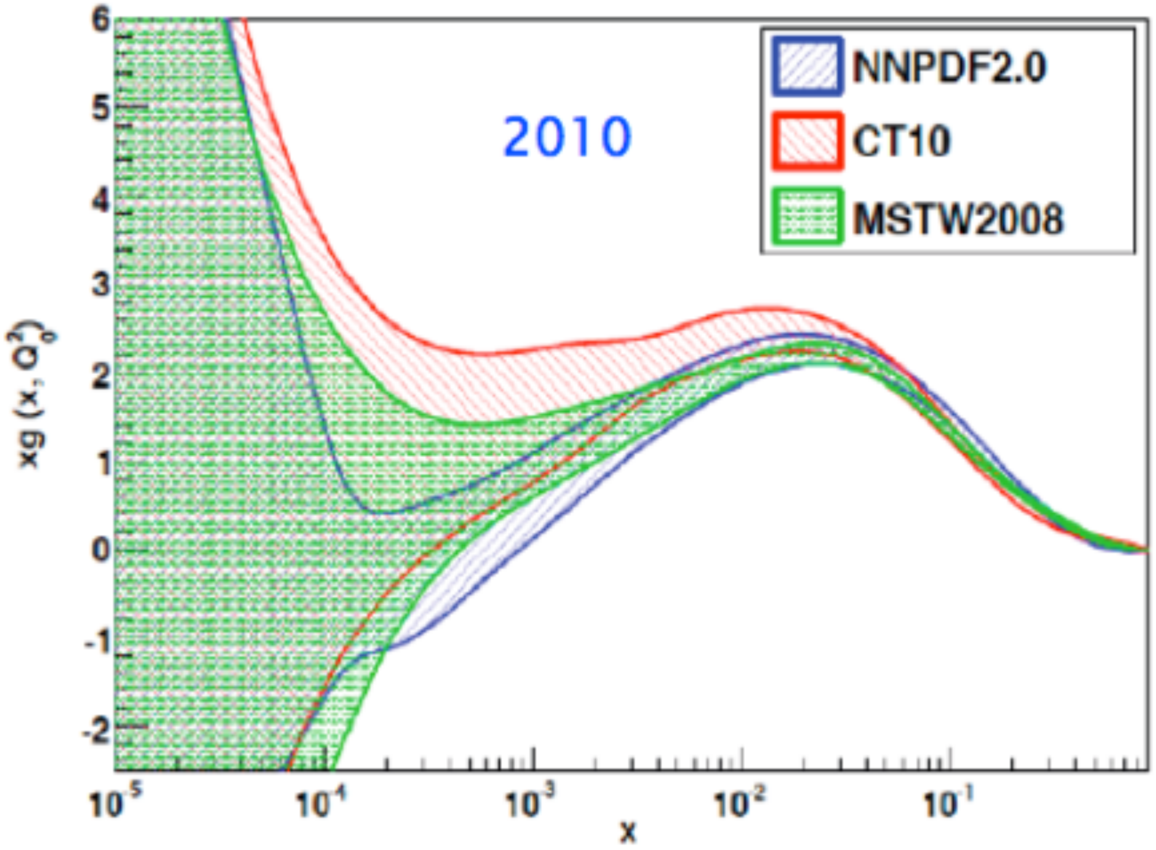
DIS



DIS+LHC

PDF parametrisation





- What is the error associated to a given choice of functional form?
  If too rigid PDFs may not adapt to new data or present small errors where data do not constrain PDFs
- Neural Networks: all independent PDFs are associated to an unbiased and flexible parametrisation: O(300) parameters versus O(20) in polynomial parametrisation

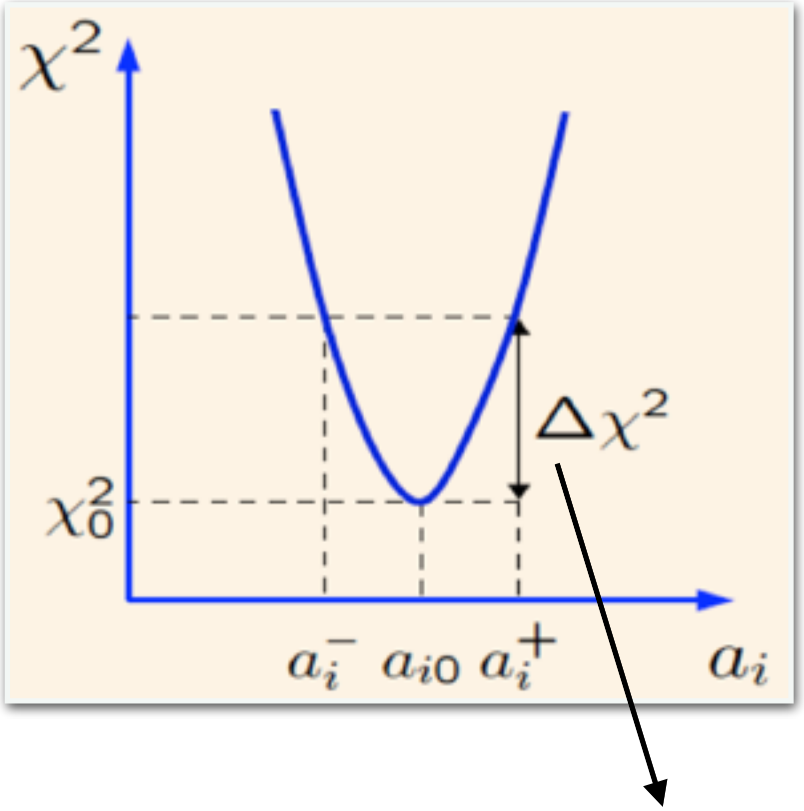
Hessian versus MC

Given a finite number of experimental point want a set of functions with error

$$\langle \mathcal{F}[f_{\{i\}}(x)]\rangle = \int [\mathcal{D}f]\,\mathcal{F}[f_{\{i\}}(x)]\,\mathcal{P}[f_{\{i\}}(x)]$$

Hessian approach: project into a N_{par}-dimensional space of parameters and use linear approximation around the minimum of the χ^2

$$F_0 = F(S_0), \quad \sigma_F = \sqrt{\sum_{i=1}^{N_{\mathrm{par}}} [F(S_i) - F(S_0)]^2}$$



Tolerance

Hessian versus MC

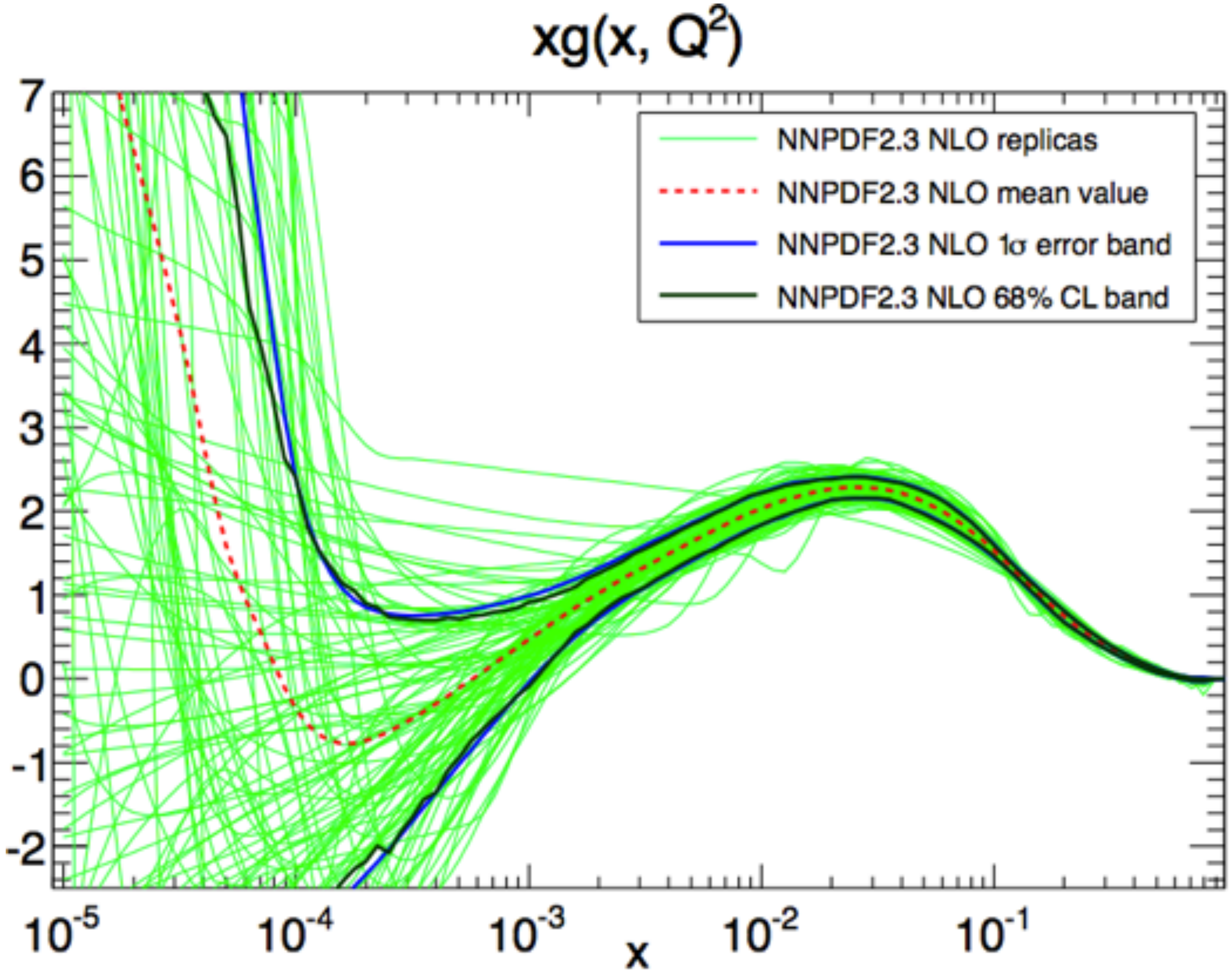
Given a finite number of experimental point want a set of functions with error

$$\langle \mathcal{F}[f_{\{i\}}(x)] \rangle = \int [\mathcal{D}f]\, \mathcal{F}[f_{\{i\}}(x)]\, \mathcal{P}[f_{\{i\}}(x)]$$

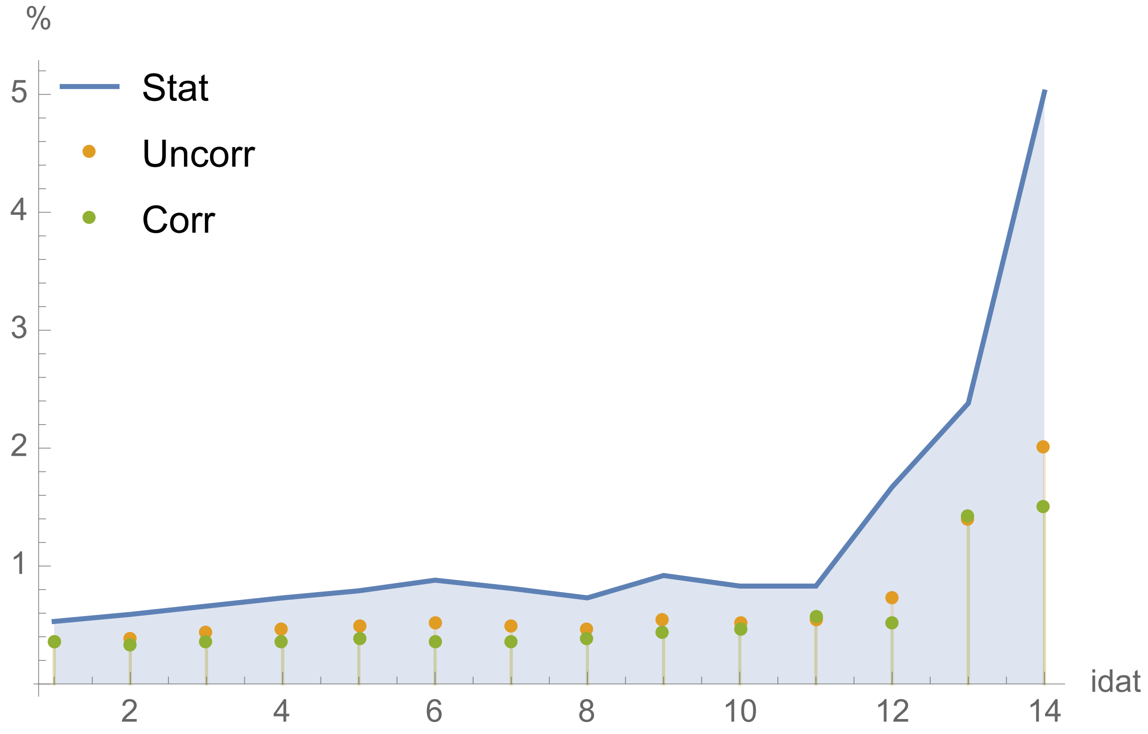
Monta Carlo (NNPDF) approach: Sampling the probability measure in PDF space by projecting down from probability density in data space

$$F_0 = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} F(S^k)$$

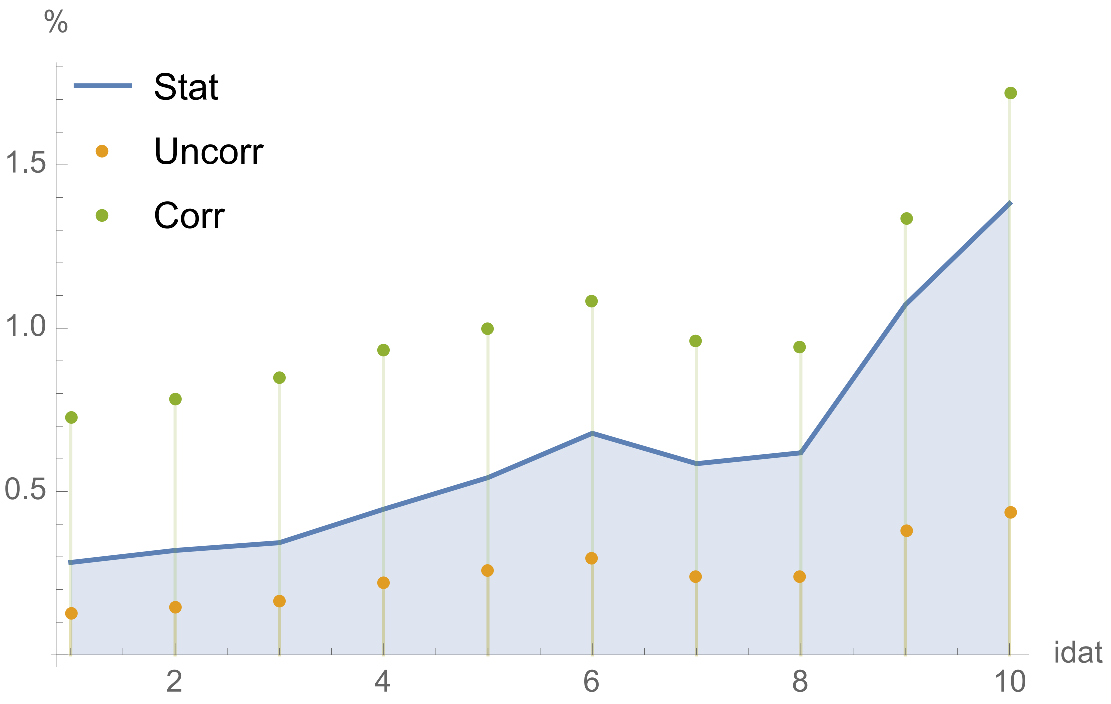
$$\sigma_F = \sqrt{\frac{1}{N_{\rm rep}-1} \sum_{k=1}^{N_{\rm rep}} \left[F(S^k) - F_0\right]^2}$$



Z pT data



ATLAS 7 TeV, Z peak, 0 < Y < 0.4



ATLAS 8 TeV, Z peak, 0 < Y < 1