24th June 2016

LAL-Orsay

PARTON DISTRIBUTIONS FOR BSM SEARCHES AT THE LHC

Maria Ubiali

(University of Cambridge)

In collaboration with:

* J. I. Latorre (Barcelona)
* R. D. Ball, L. Del Debbio, P. Mermaid (Edinburgh)
* Z. Dim, S. Forte (Milano), A. Guffanti (Torino)
* V. Bertone, N. Hartland, J. Rojo, L. Rottoli (Oxford)

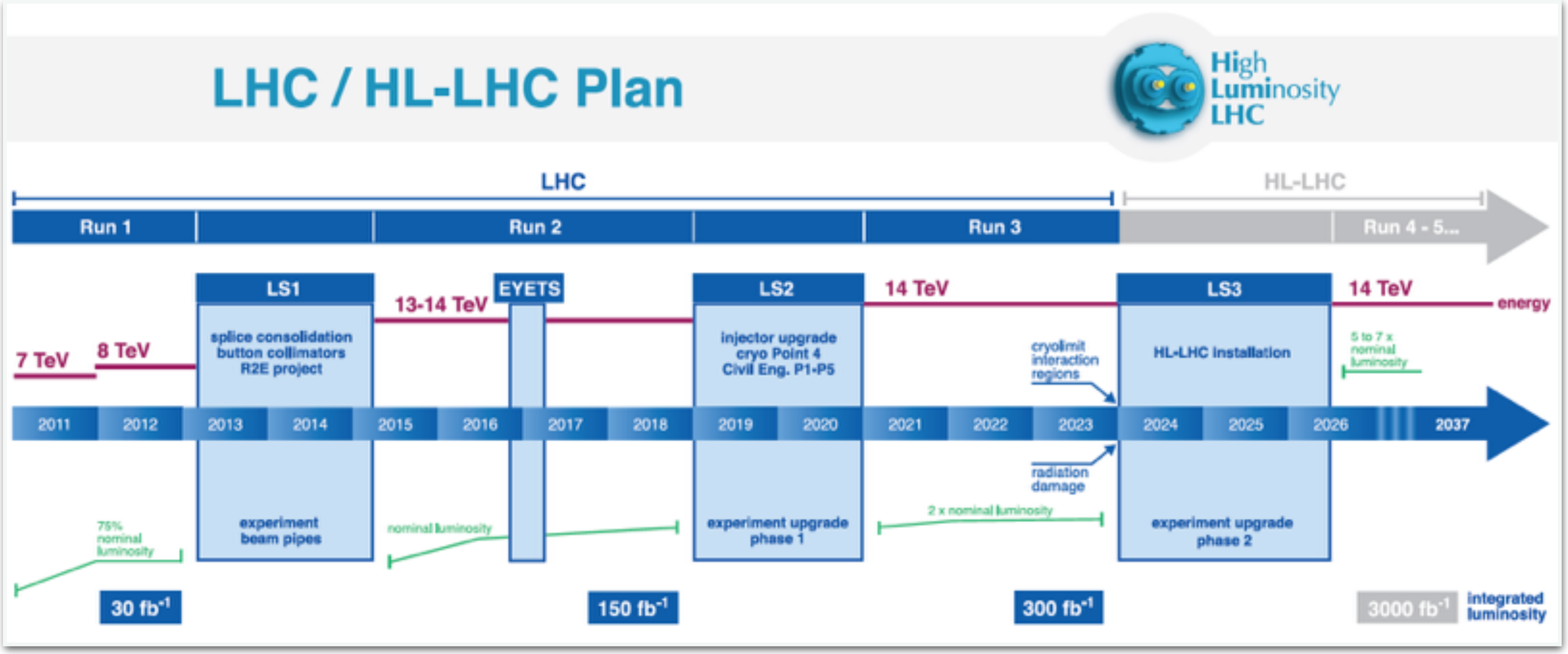
NNPDF

Outline

- Motivation
- What (NN)PDFs are
- Impact of LHC data on PDFs
- Needs for BSM searches
- Conclusion

LHC physics at Run II

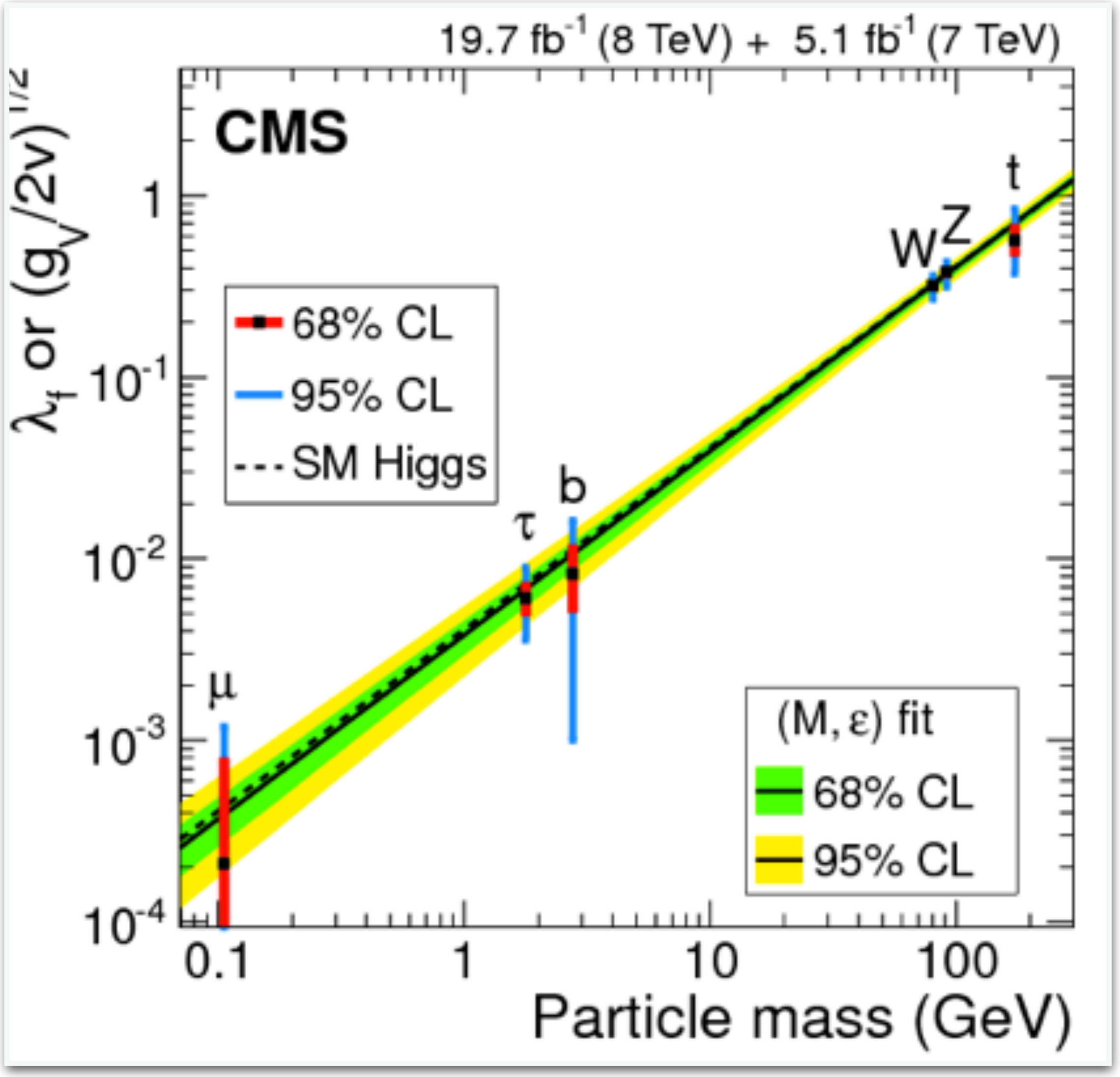
- Hadron colliders regarded as discovery machines, while lepton colliders seen as precision machines for characterisation
- <u>LHC:</u> change of paradigm, getting close to precision physics at pp collider, thanks to theoretical and experimental progress
- 20 years of exciting LHC physics in front of us and perturbative QCD could be the key for new discoveries



LHC physics at Run II

Is the discovered scalar truly the SM Higgs?

- ➡ Still substantial uncertainties
- ➡ Need accuracy for indirect detection of new particles



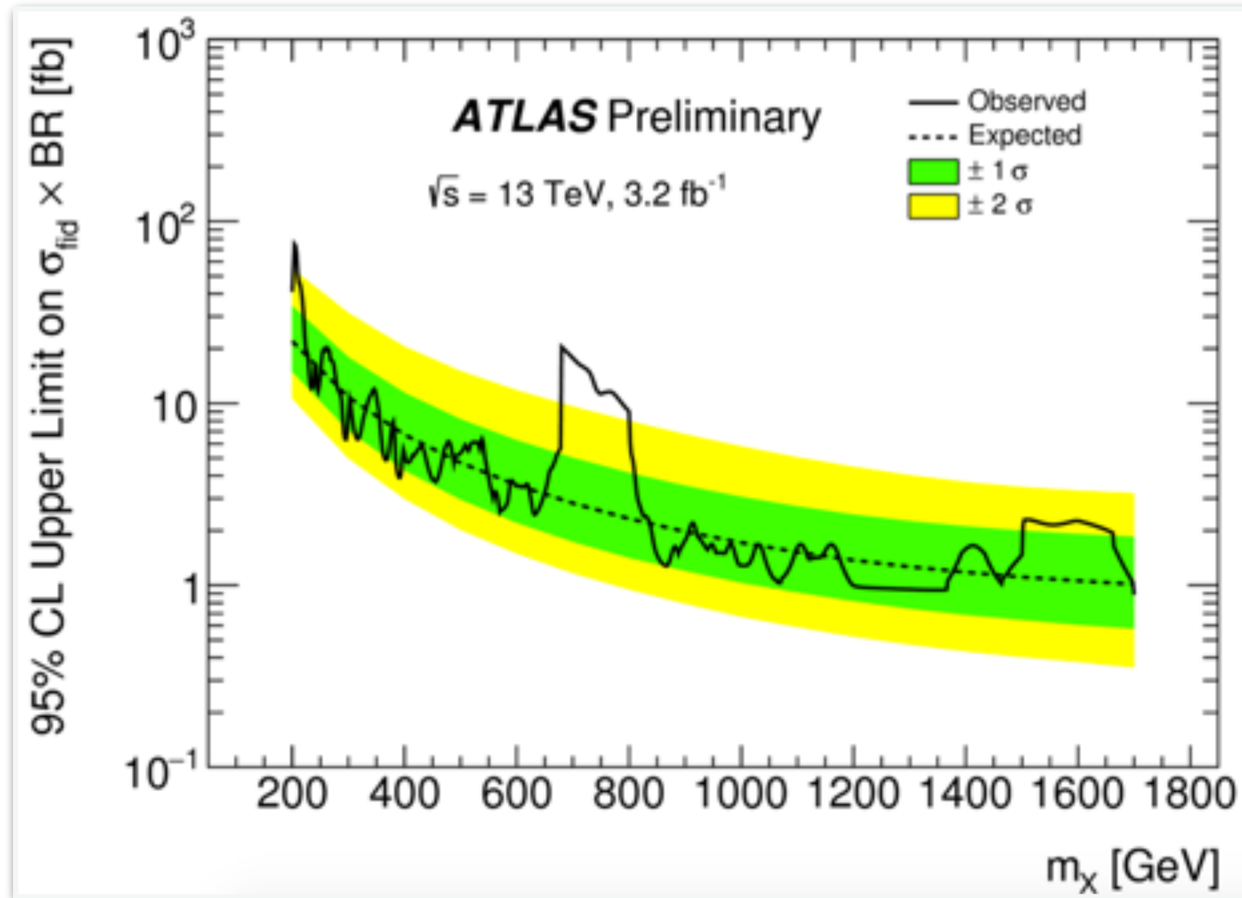
LHC physics at Run II

Is the discovered scalar truly the SM Higgs?

- ➡ Still substantial uncertainties
- ➡ Need accuracy for indirect detection of new particles

Are there new particles within the reach of LHC Run-II?

- ➡ Need robust search strategies not to miss any signal
- ➡ Need solid predictions for SM background to establish significance and characterise it

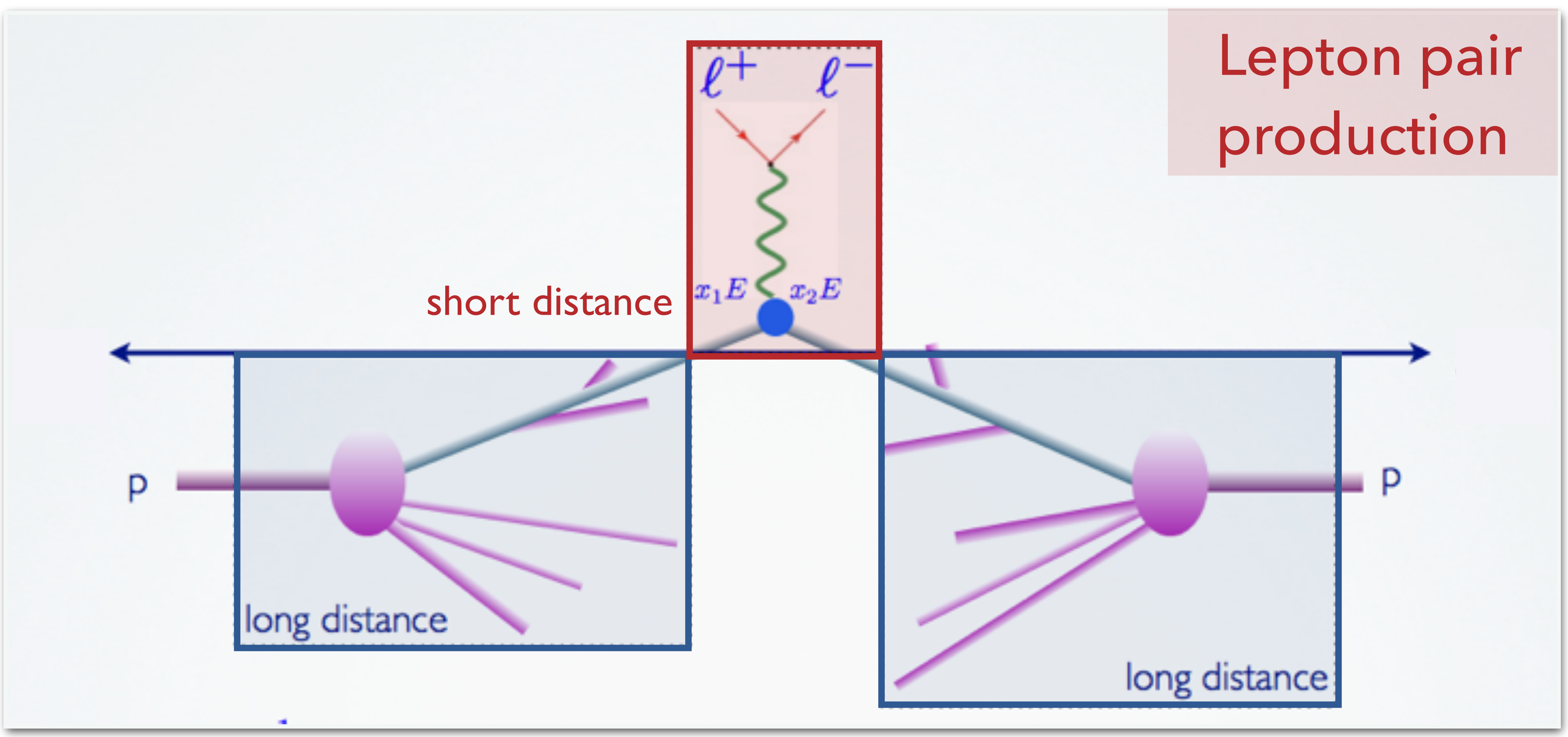


Why PDFs?

Motivation

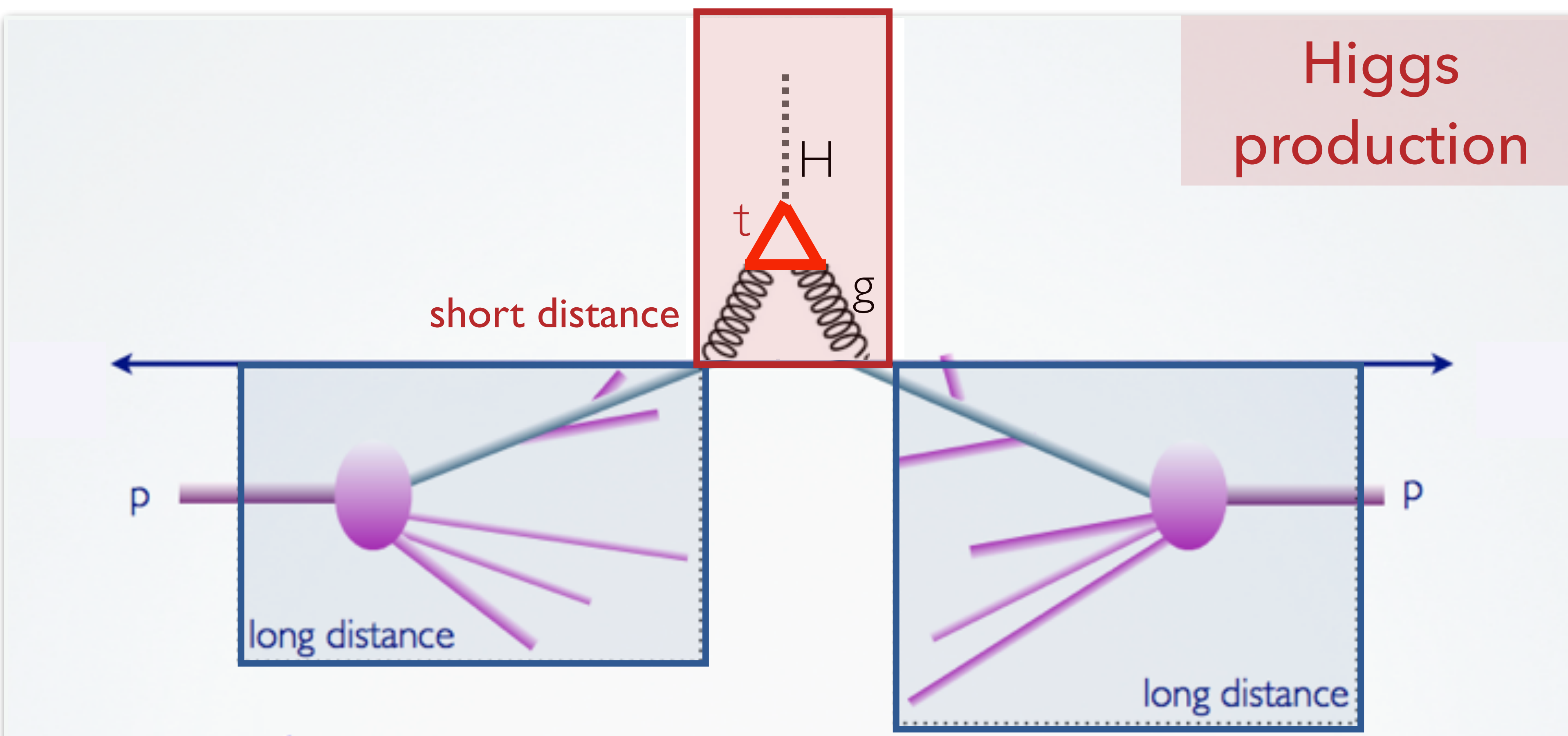
1) PDFs are ubiquitous

Proton Proton X-section = Parton Distribution Functions $\otimes$ Partonic X-section



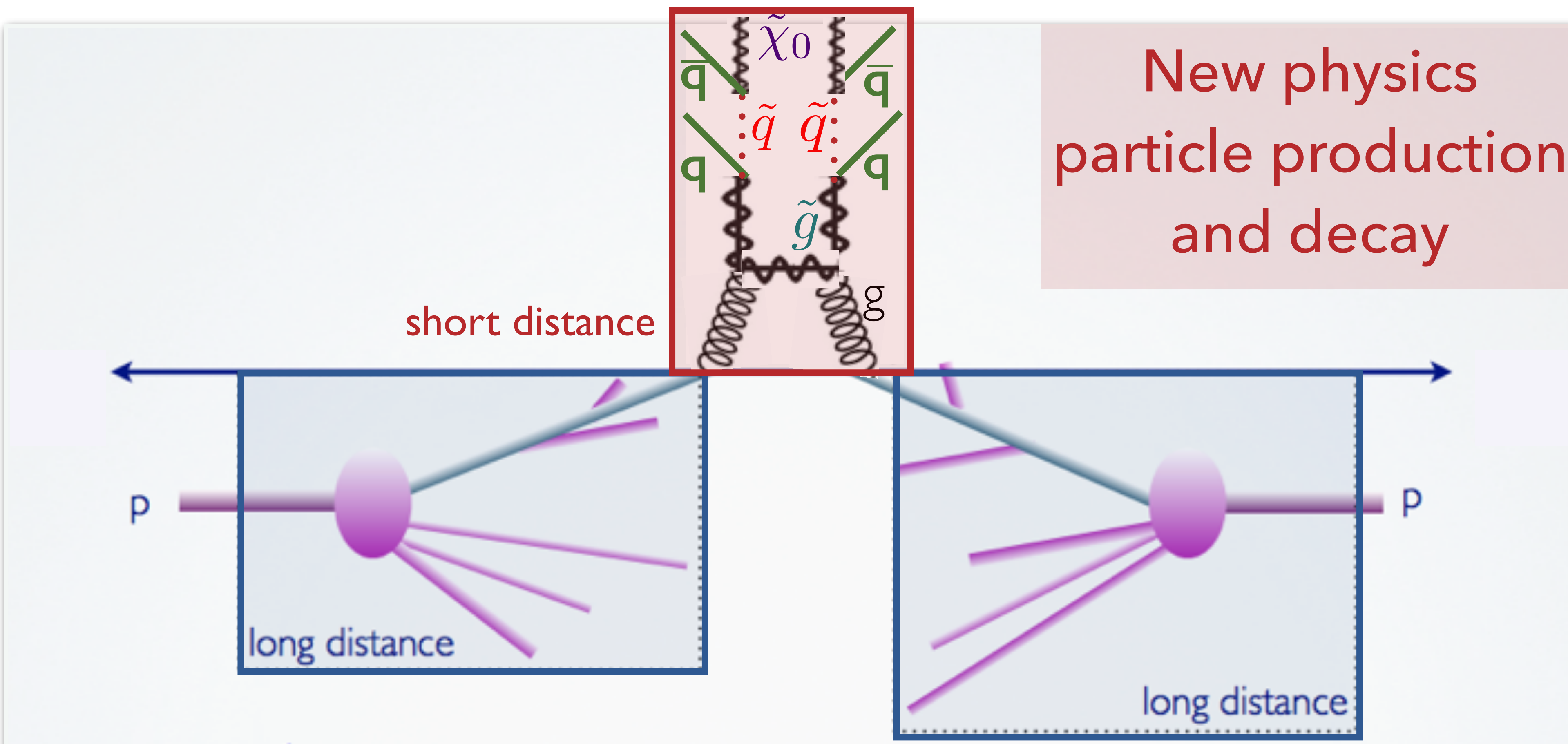
1) PDFs are ubiquitous

Proton Proton X-section = Parton Distribution Functions $\otimes$ Partonic X-section

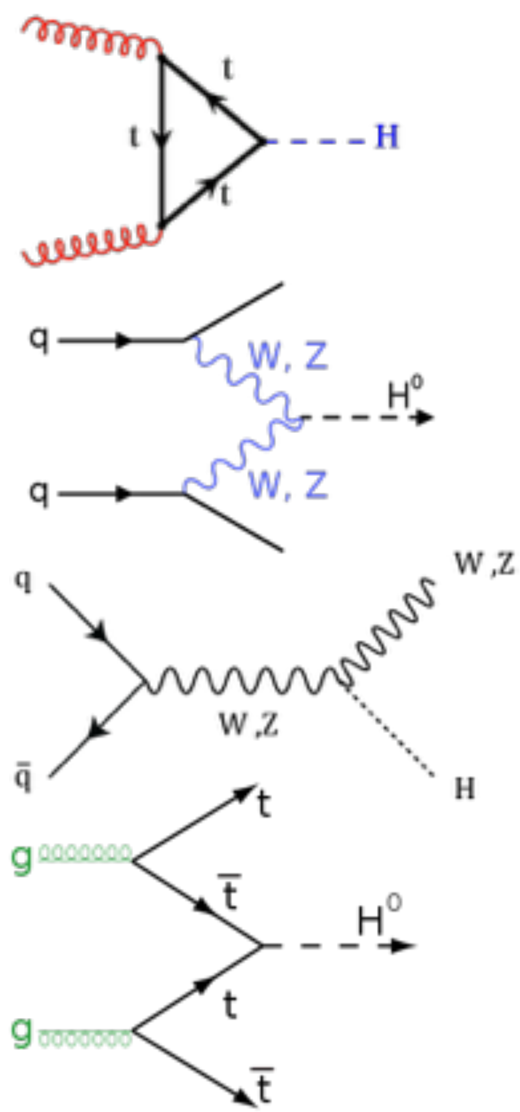


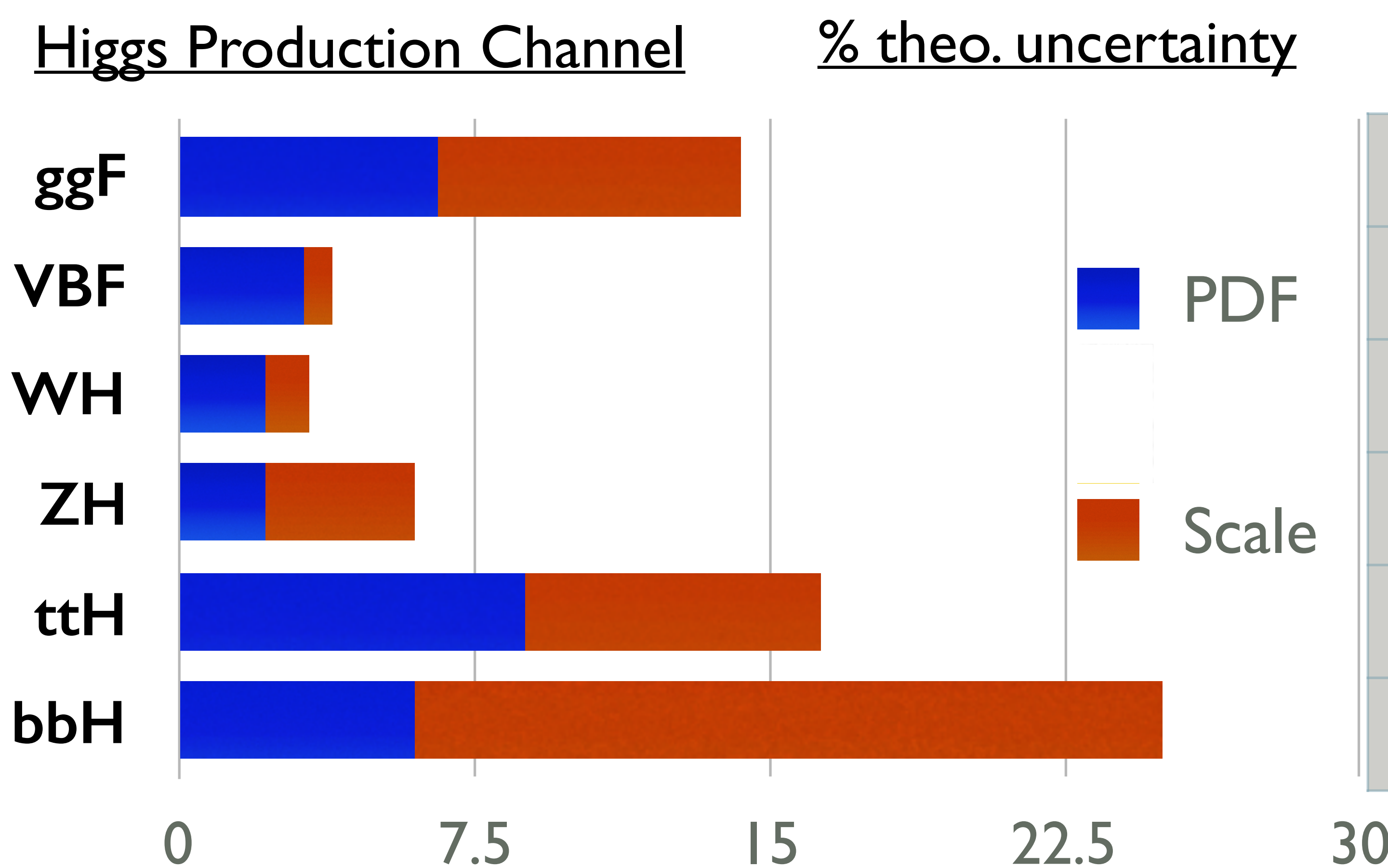
1) PDFs are ubiquitous

Proton Proton X-section = Parton Distribution Functions ⊗ Partonic X-section



2) The role of PDF uncertainty





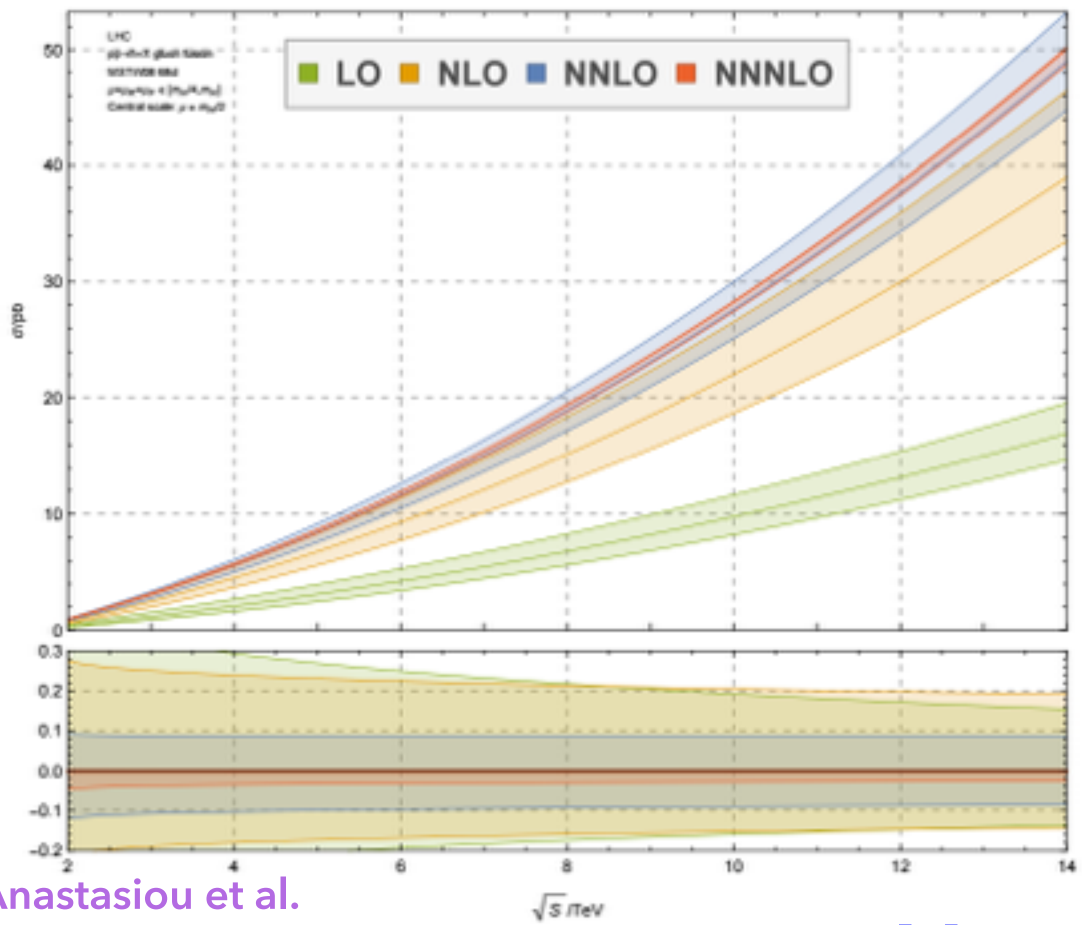
Higgs Production Channel	xsec @13 TeV
ggF	43.9 pb
VBF	3.75 pb
WH	1.38 pb
ZH	0.87 pb
ttH	0.51 pb
bbH	0.51 pb

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**

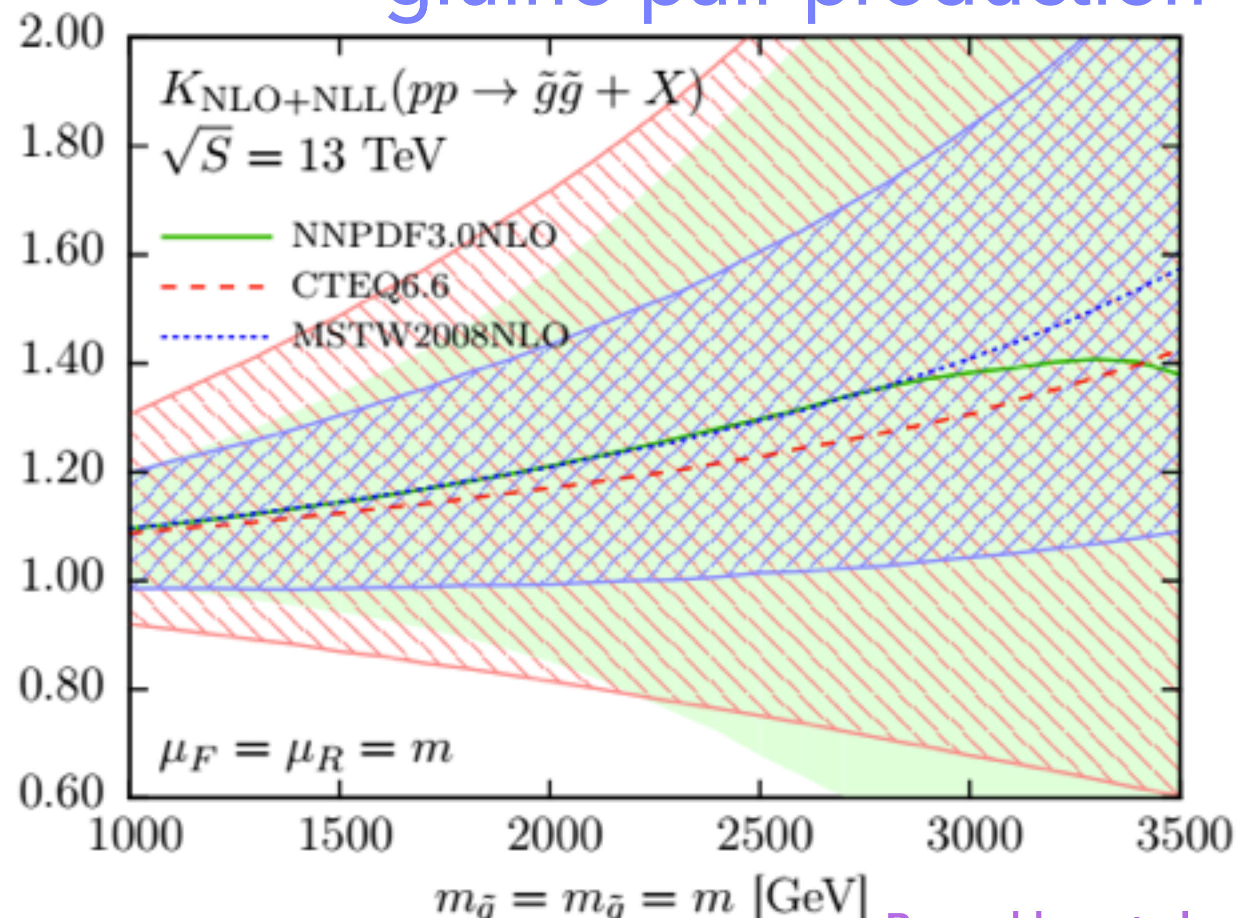
2) The role of PDF uncertainty

ggF @ NNNLO



Anastasiou et al.
PRL 114(2015) 212001

gluino pair production



Beenakker et al.
EPJC76 (2016)2, 53

Mw determination

ΔM_W [MeV]	present	CDF	D0	combined	LHC		
$\mathcal{L}$[fb]	7.6	10	10	20	20 (8 TeV)	300	3000
PDF	10	5	5	5	10	5	3
QED rad.	4	4	3	3	4	3	2
$p_T(W)$ model	2	2	2	2	2	1	1
other systematics	9	4	11	4	10	5	3
W statistics	9	6	8	5	1	0.2	0
Total	16	10	15	9	15	8	5

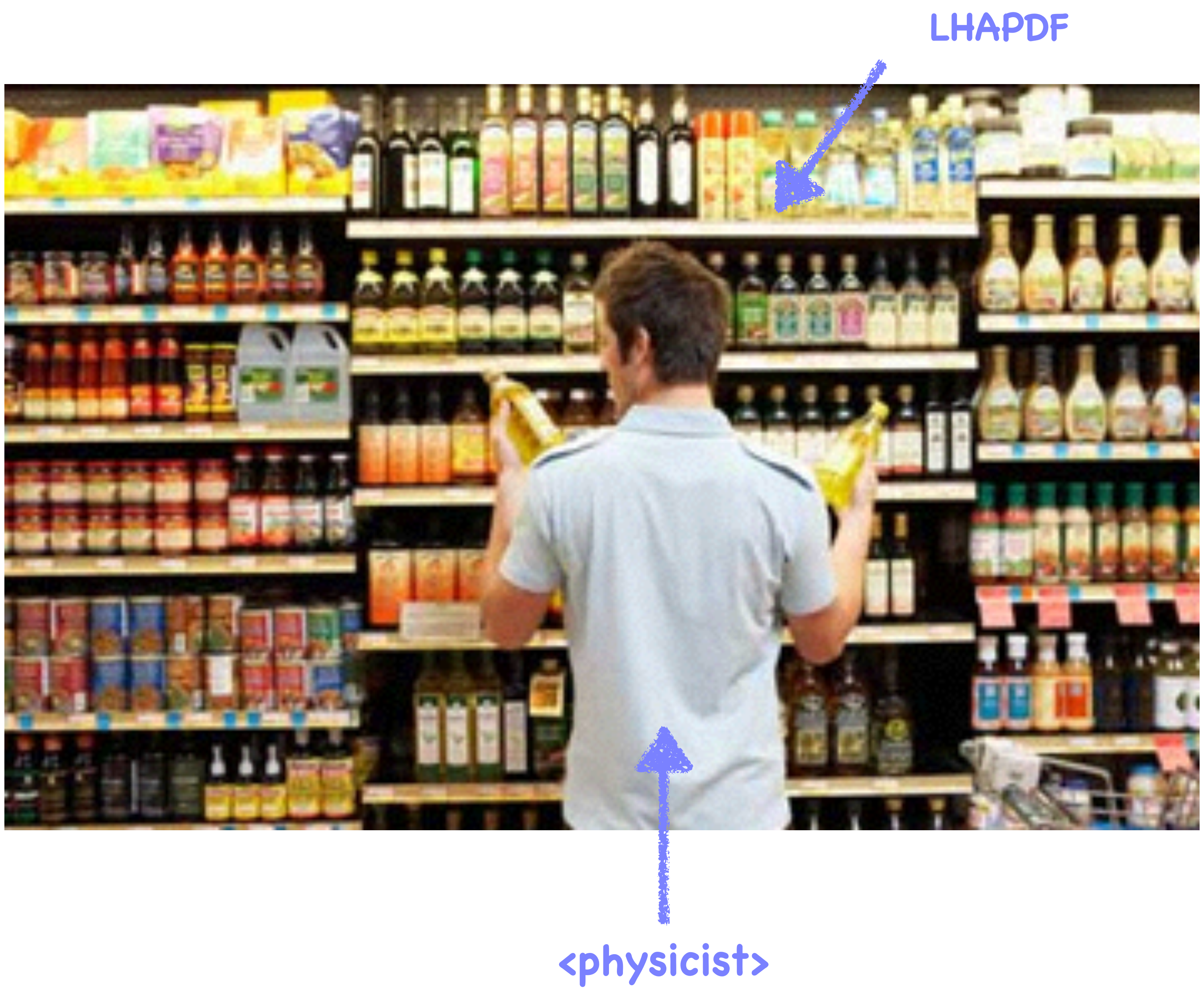
D. Wackeroth's
talk at KITP

3) The choice of PDFs matters

- A reliable understanding of PDF uncertainties plays a crucial role in precision physics

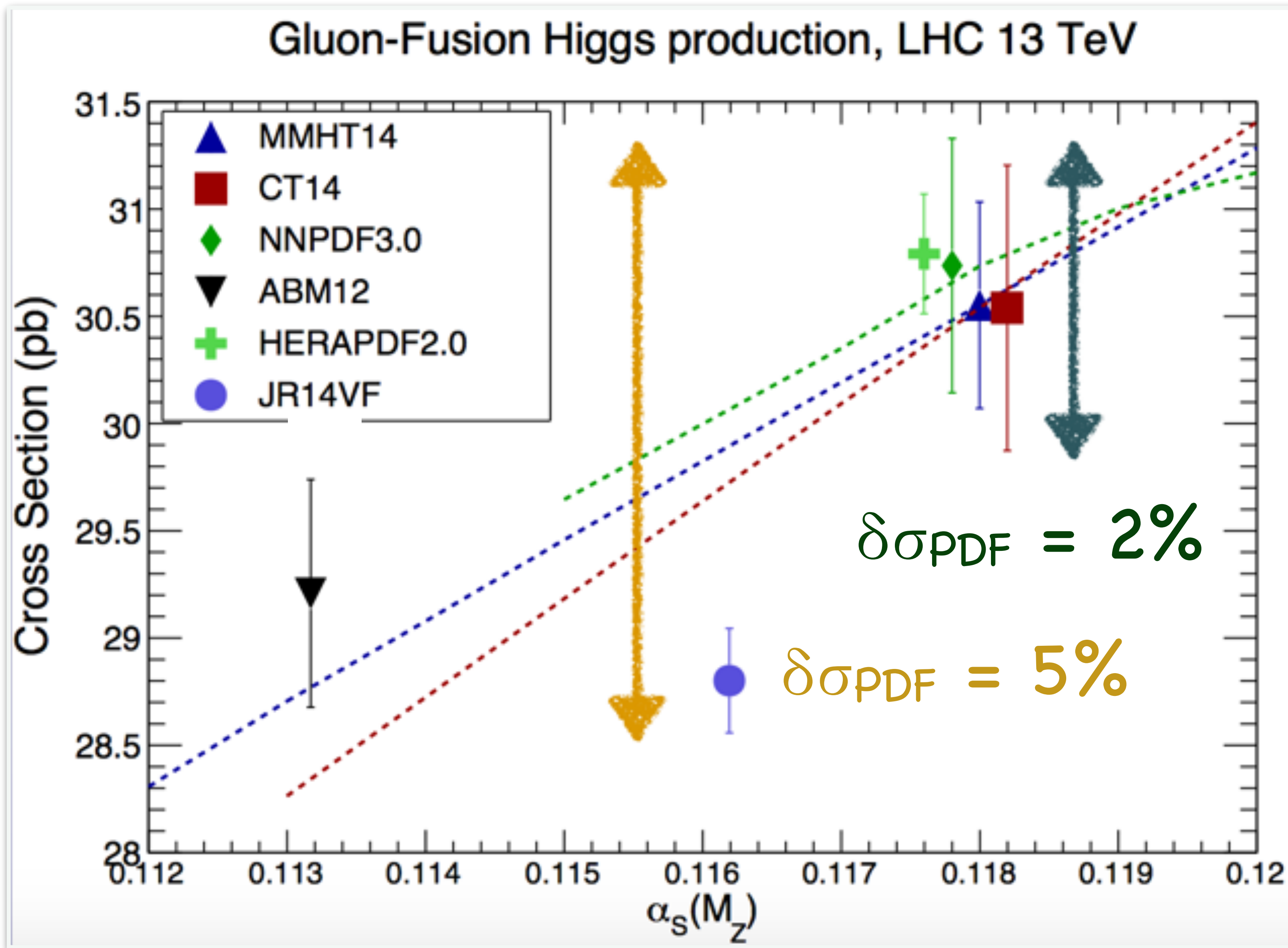
- How do we interpret the difference predictions using different PDF sets?

- Shall we just pick a set out of the PDFs “supermarket” shelf or take the envelope of ALL predictions?



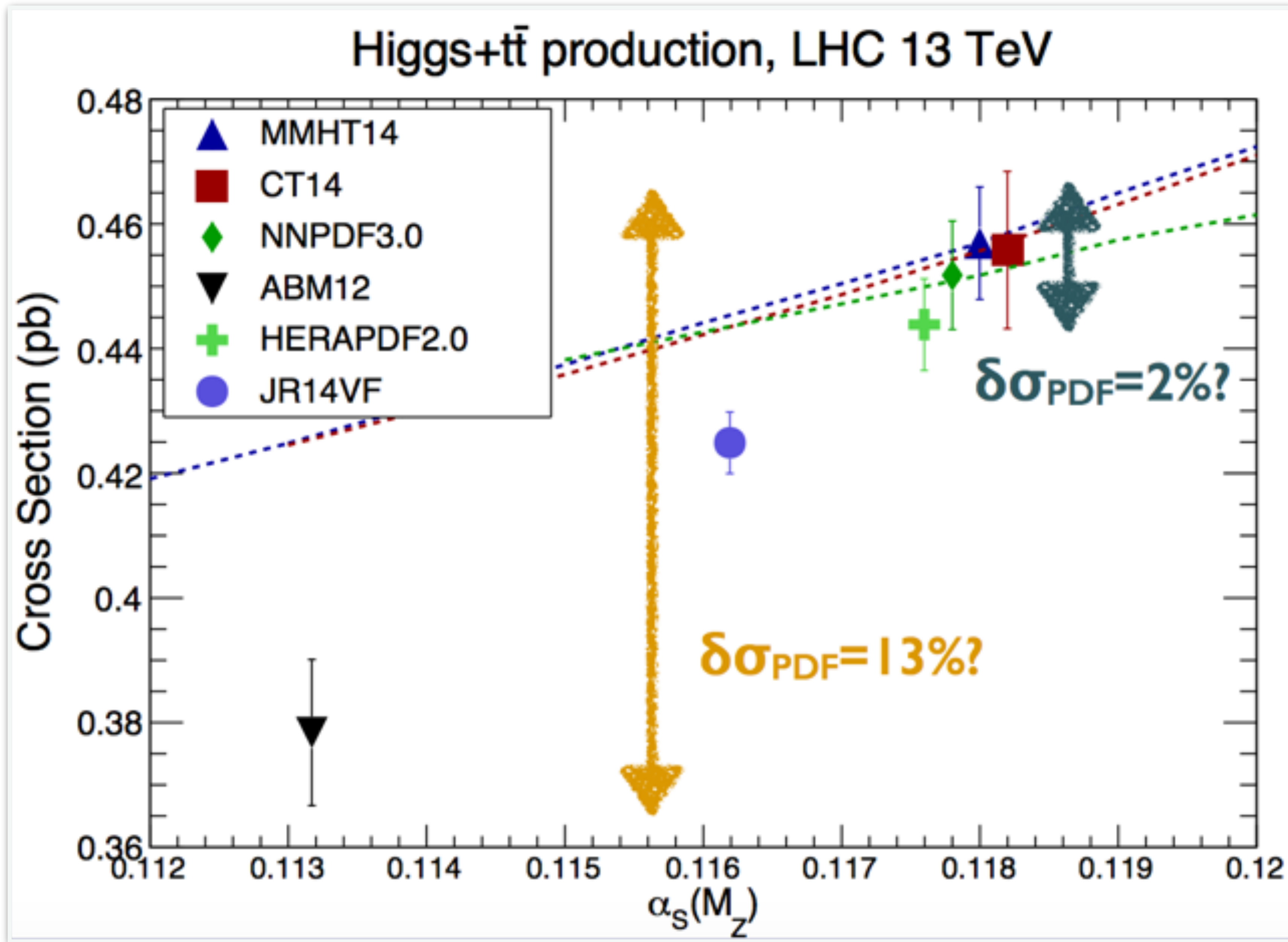
3) The choice of PDFs matters

- What does PDF uncertainty include? How reliable it is?
- How do we interpret the difference predictions using different PDF sets?
- Shall we just pick a set out of the PDFs "supermarket" shelf or take the envelope of ALL predictions?



3) The choice of PDFs matters

- What does PDF uncertainty include? How reliable it is?
- How do we interpret the difference predictions using different PDF sets?
- Shall we just pick a set out of the PDFs "supermarket" shelf or take the envelope of ALL predictions?



What PDFs are

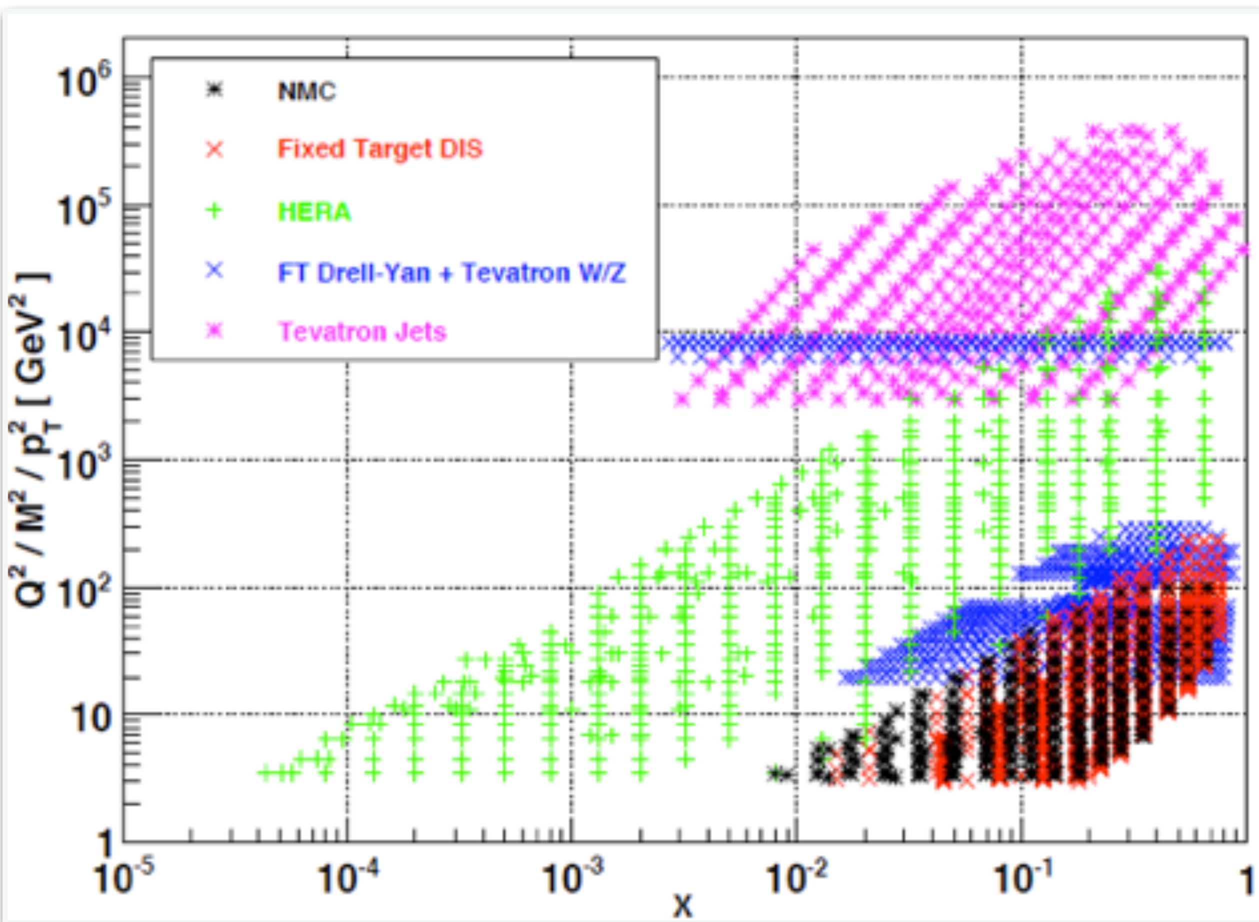
Collinear Factorisation Theorem

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

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

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
- **Theory settings**: factorization scheme, perturbative order, heavy quark mass scheme, EW corrections
- Choose a starting scale where pQCD applies Q_0
- **Parametrise** 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

$$\sigma_{\mathcal{F}} = \left(\sum_{k=1}^{N_{\rm set}} \left(\mathcal{F}[\{f^{(k)}\}] - \mathcal{F}[\{f^{(0)}\}] \right)^2 \right)^{1/2}$$

error sets
mem > 1

central set
mem = 0

```
call InitPDF(mem)

call evolvePDF(x,Q,f)
```

LHAPDF interface
http://lhapdf.hepforge.org

	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
Parton	tbar	bbar	cbar	sbar	ubar	dbar	g	d	u	s	c	b	t

A steady progress

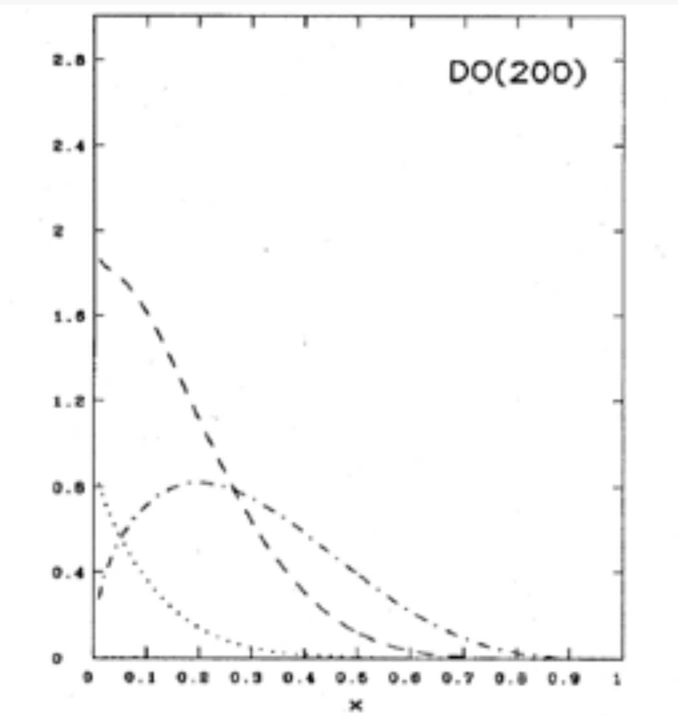
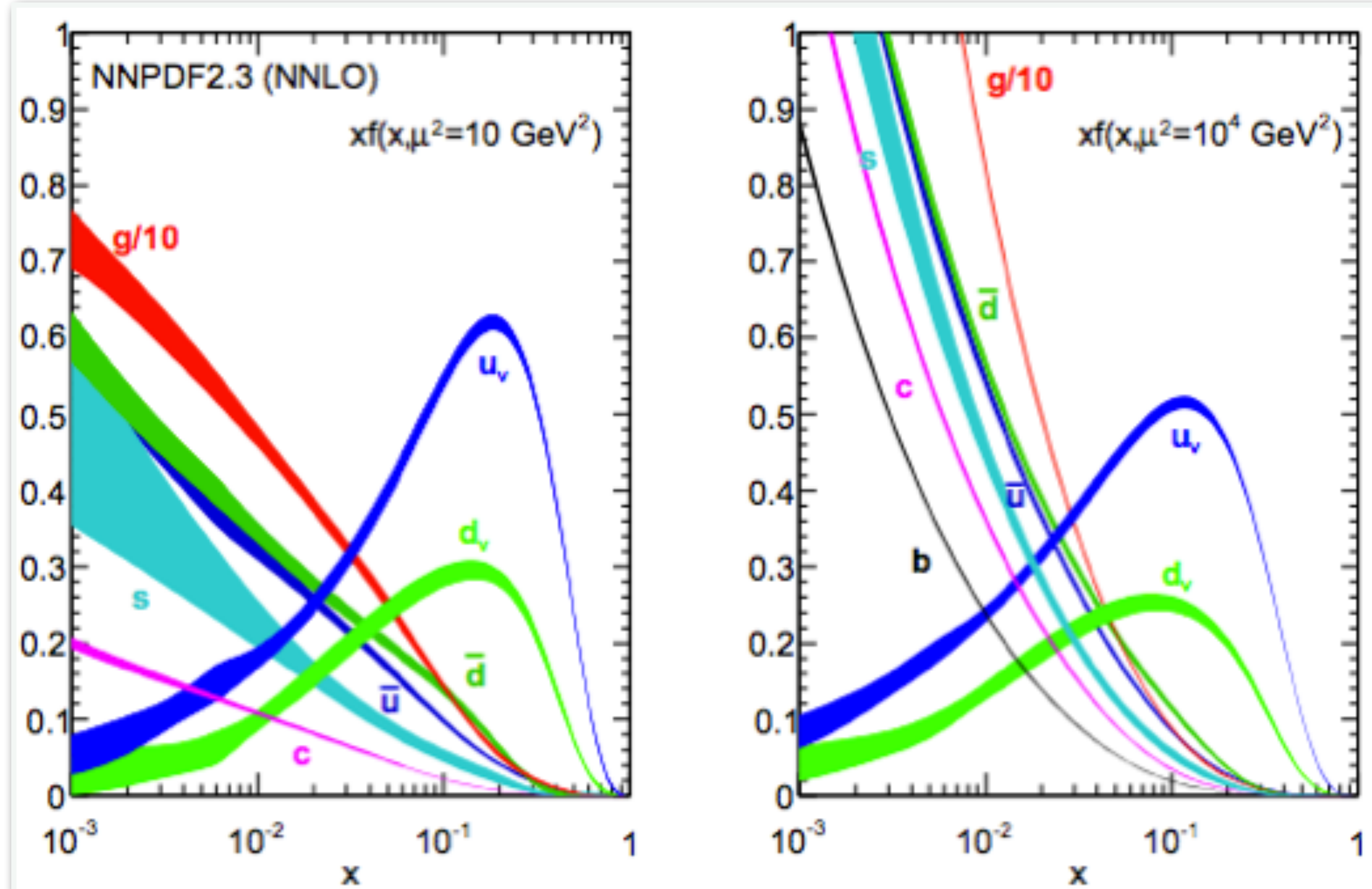


FIG. 27. "Soft-gluon" ($\Lambda = 200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2 = 5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).



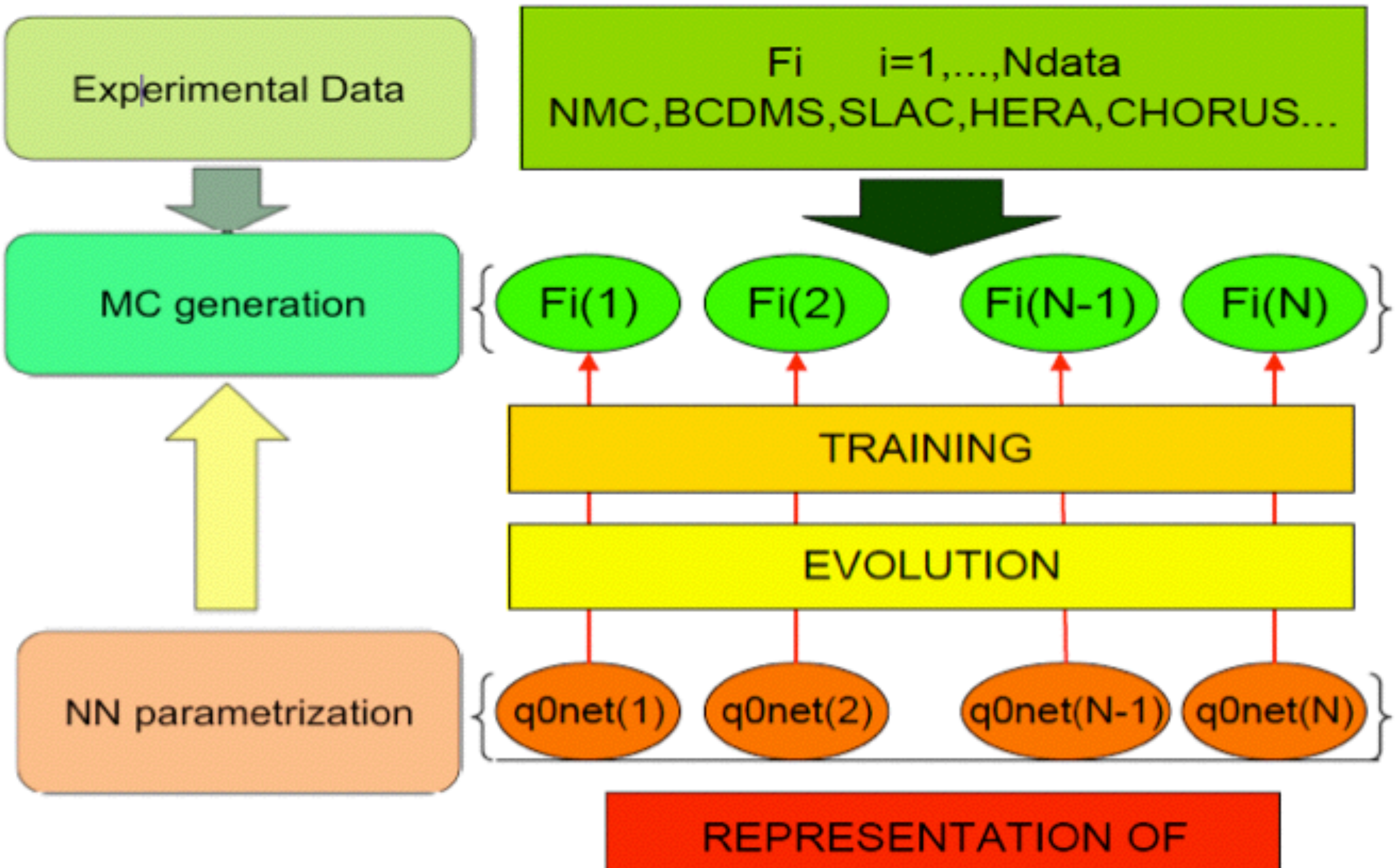
PDG "Structure Functions"2013

- **< 2002**: sets without uncertainty
- **2003-2004:** first MRST, CTEQ, Alekhin sets with uncertainties
- **2004-now:** huge progress made in statistical and theoretical understand, new players

4

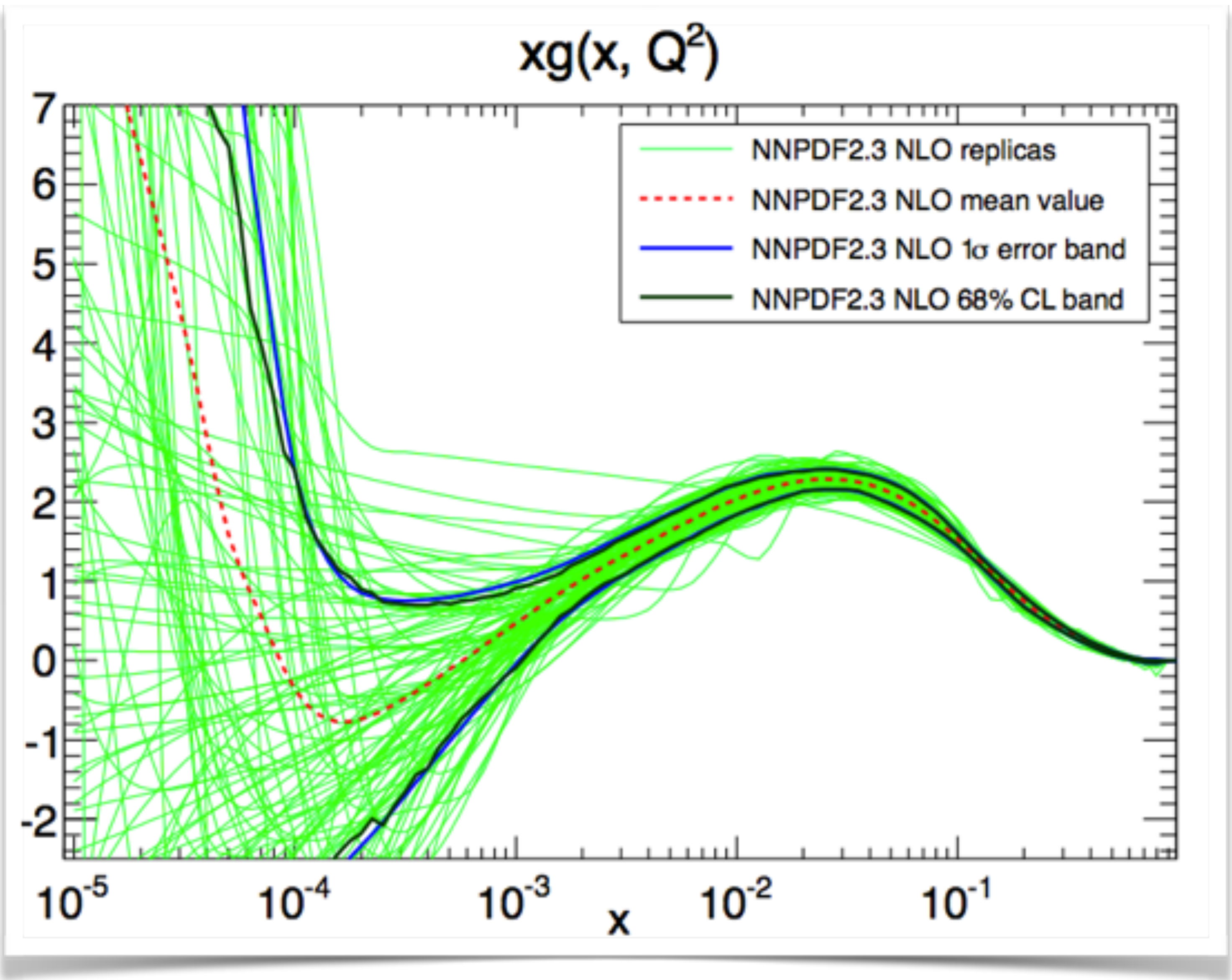
The NNPDF approach

The NNPDF approach



$$\left\langle F_i^{(\mathrm{net})} \right\rangle_{\mathrm{rep}} = \frac{1}{N_{\mathrm{rep}}} \sum_{k=1}^{N_{\mathrm{rep}}} F_i^{(\mathrm{net})(k)}$$

The NNPDF approach

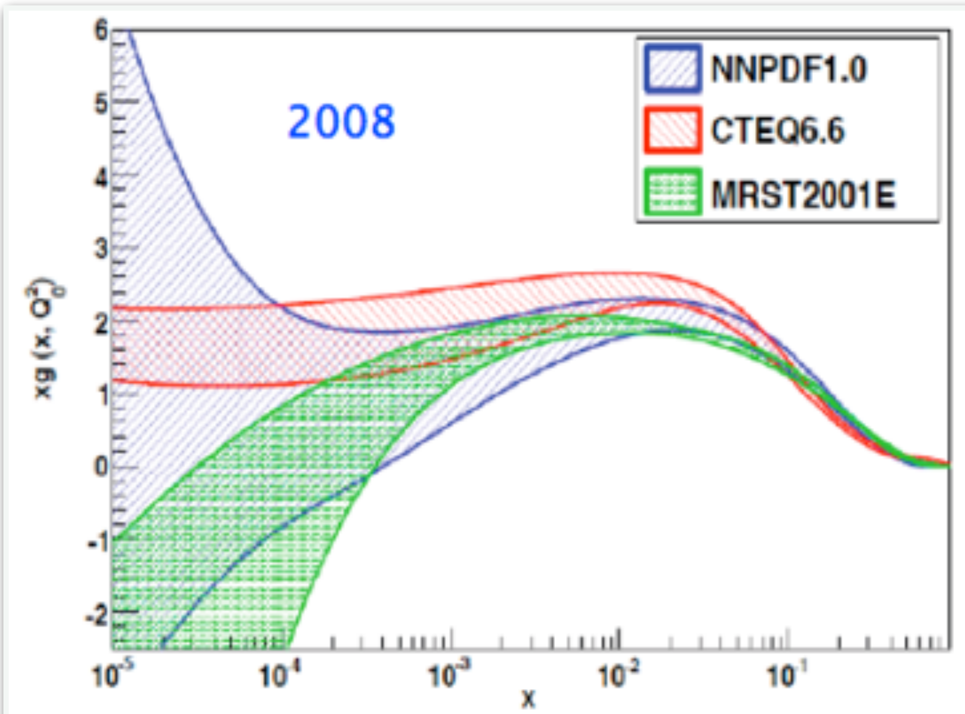


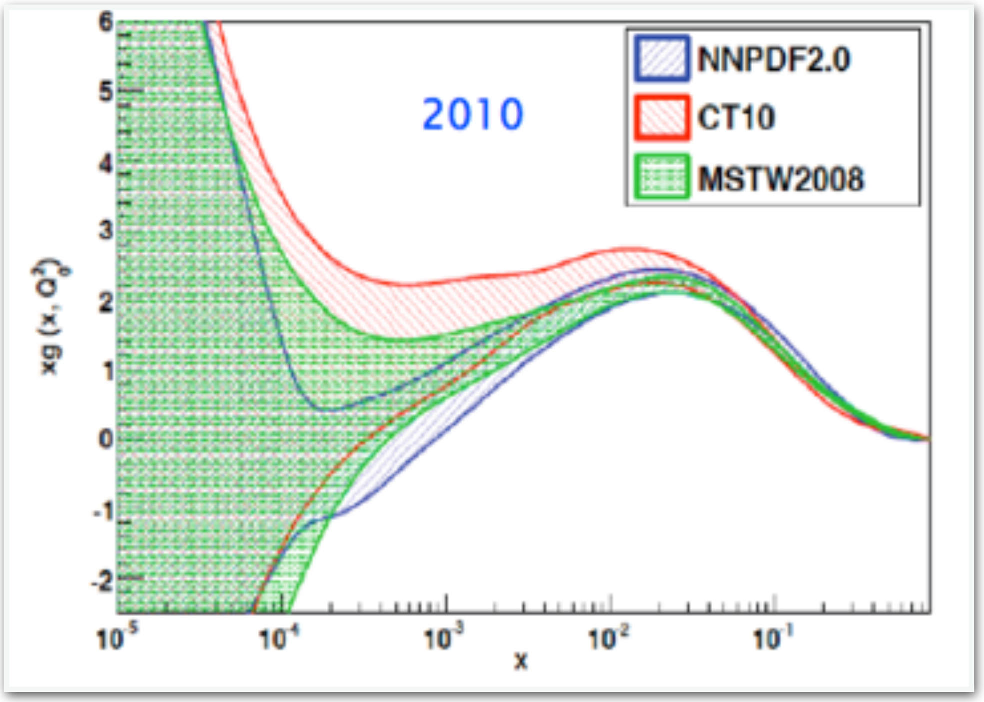
The N(eural)N(etwork)PDFs:

- Monte Carlo techniques: sampling the probability measure in PDF functional space
- Neural Networks: all independent PDFs are associated to an unbiased and flexible parametrization: O(300) parameters versus O(20) in polynomial parametrization

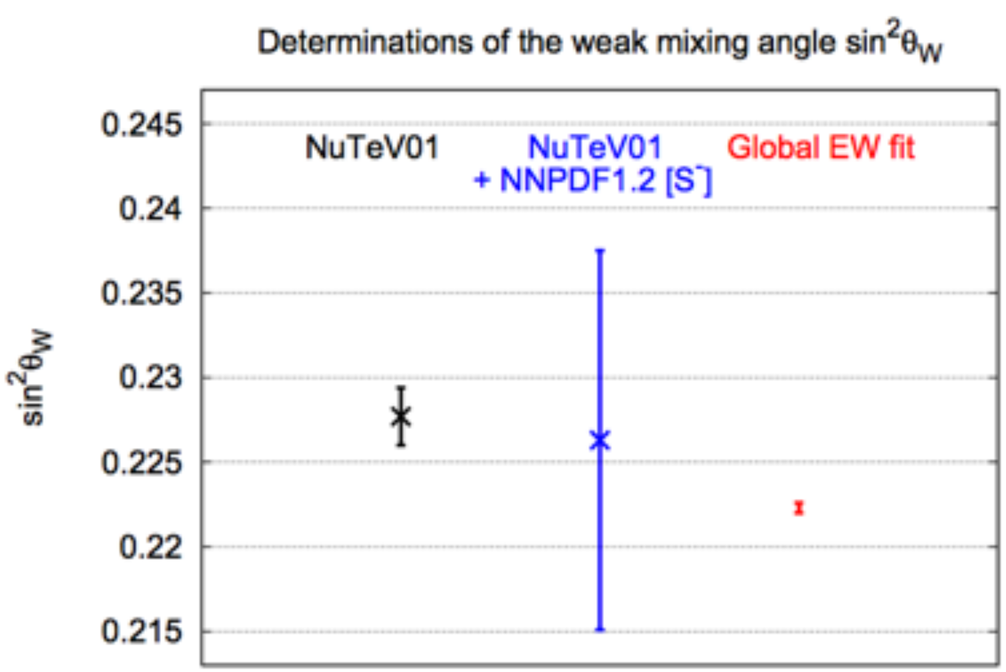
✓ Precise error estimate not driven by theoretical prejudice
✓ Statistical interpretation of uncertainty bands

Advantages





- No need to add new parameters when new data are included
- Reliable estimate of theoretical uncertainties not driven by parametrisation bias
- Possibility to include data via re-weighting: no need to refit



Past frontiers

2016 **First PDF set with fitted charm**

2015 **First PDF set with threshold resummation**

2014 **First PDF set with methodology validated with closure test**

2013 **First PDF set with fitted photon PDF**

First PDF set with LHC data

2012 **Reweighting PDFs**

2011 Heavy quark mass effects

Determination of α_S from PDF fit

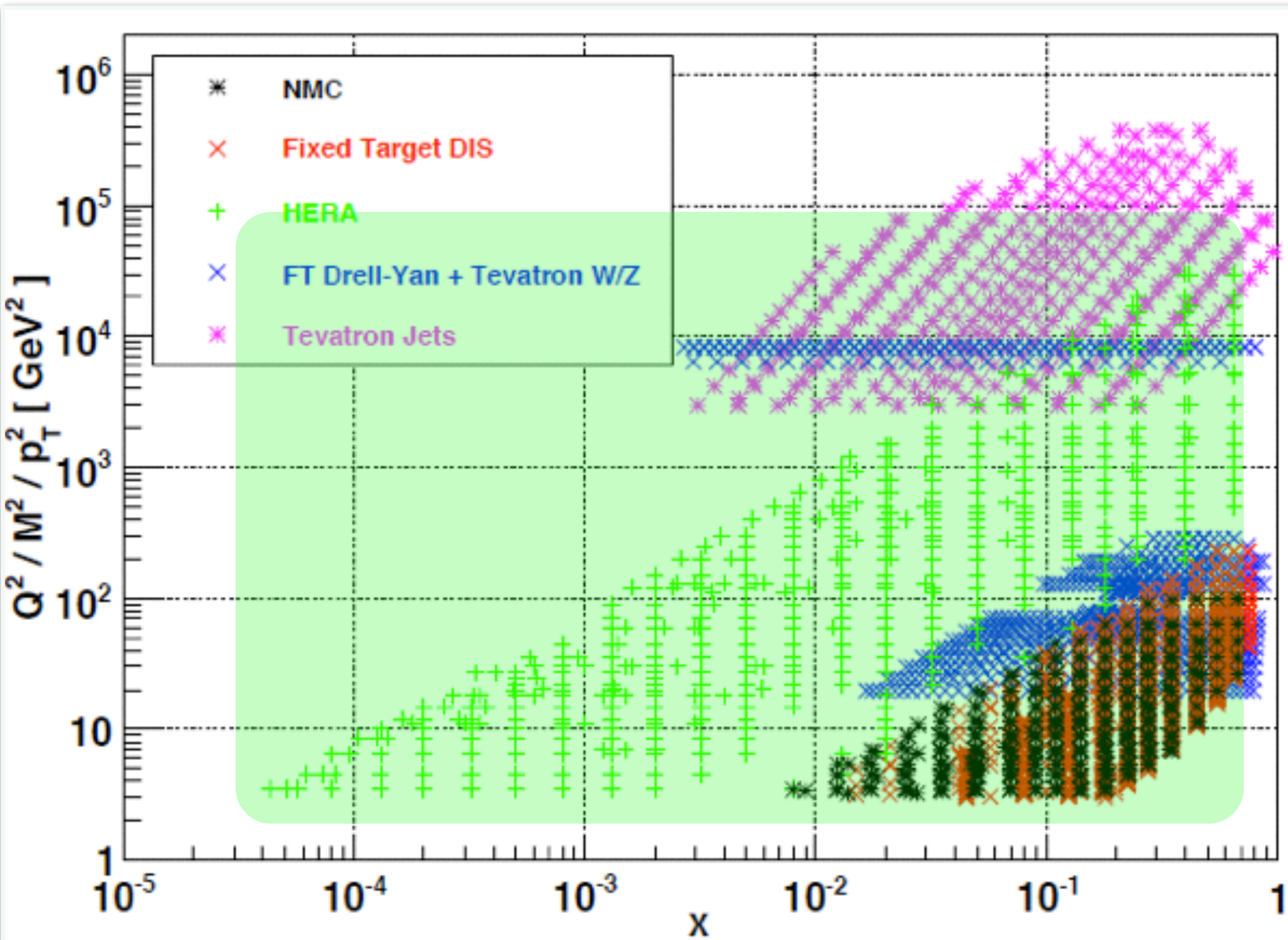
2010 First NNPDF global set

2009 Determination of the proton strangeness: solved NuTeV anomaly

2008 First NNPDF set - only DIS data

Experimental data

The data (before LHC)

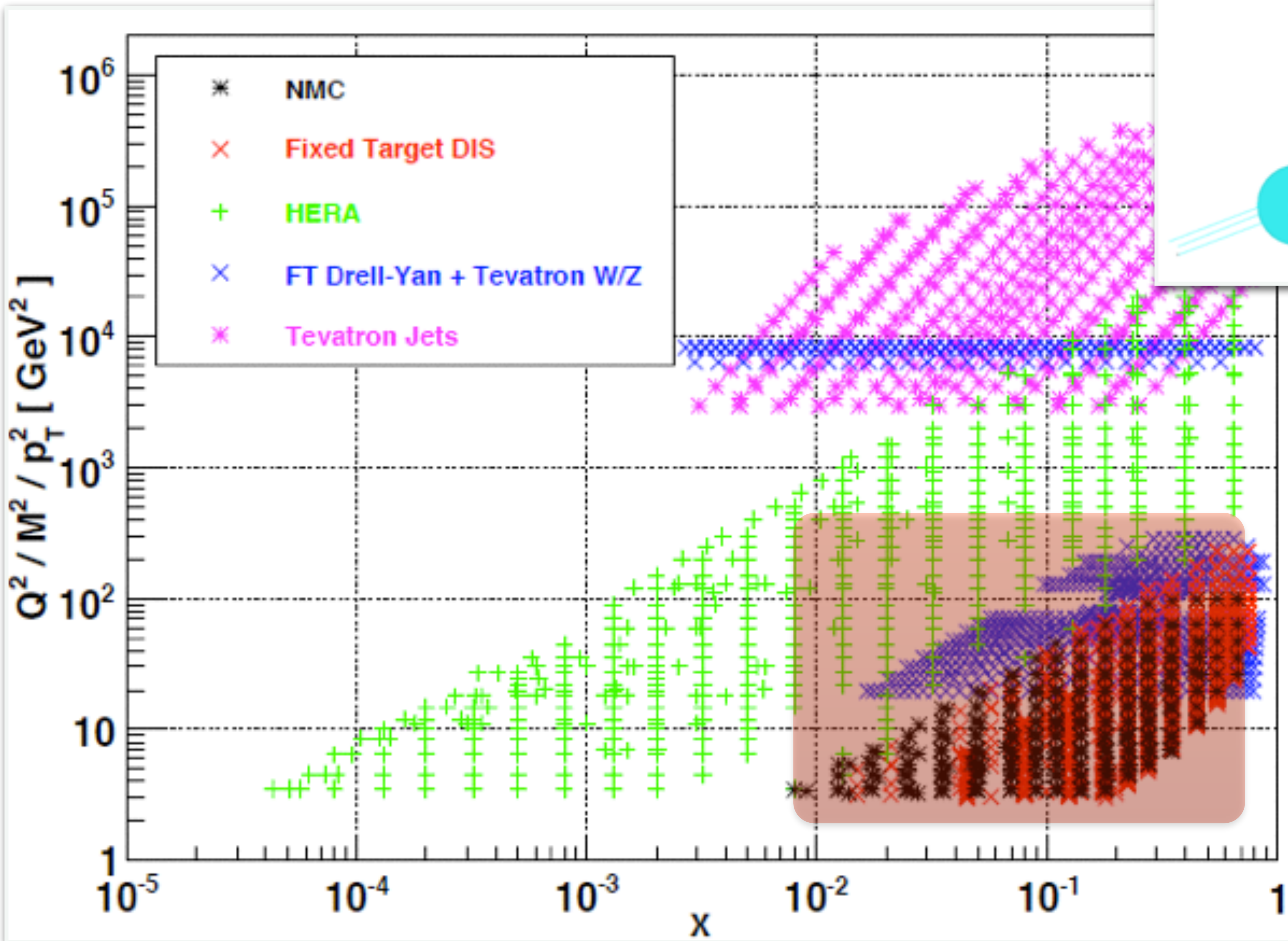


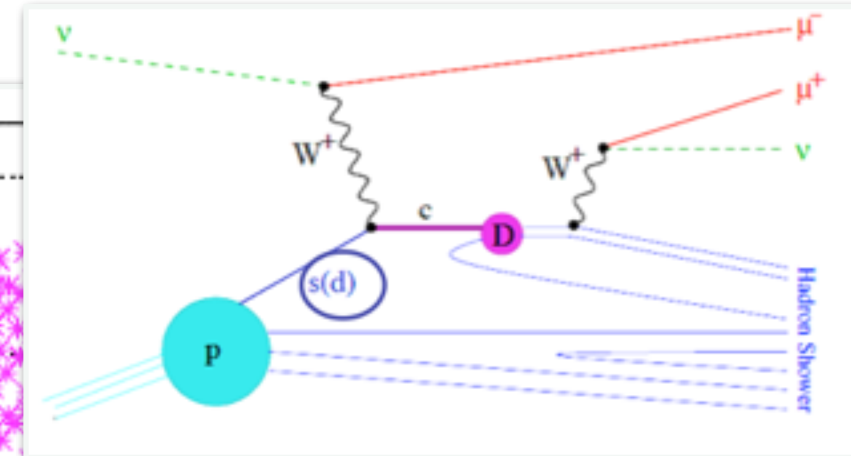
NC	$F_1^{\gamma, Z} = \sum_i e_i^2 (q_i + \bar{q}_i)$
CC	$F_1^{W^+} = \bar{u} + d + s + \bar{c}$
CC	$-F_3^{W^+}/2 = \bar{u} - d - s + \bar{c}$
	$F_2 = 2xF_1$

HERA DIS data

- Backbone of any PDF fit
- Structure functions known up to order α_S^3
- Constrain q, qbar at 10^{-4}
- Constrain g at small and moderate x

The data (before LHC)

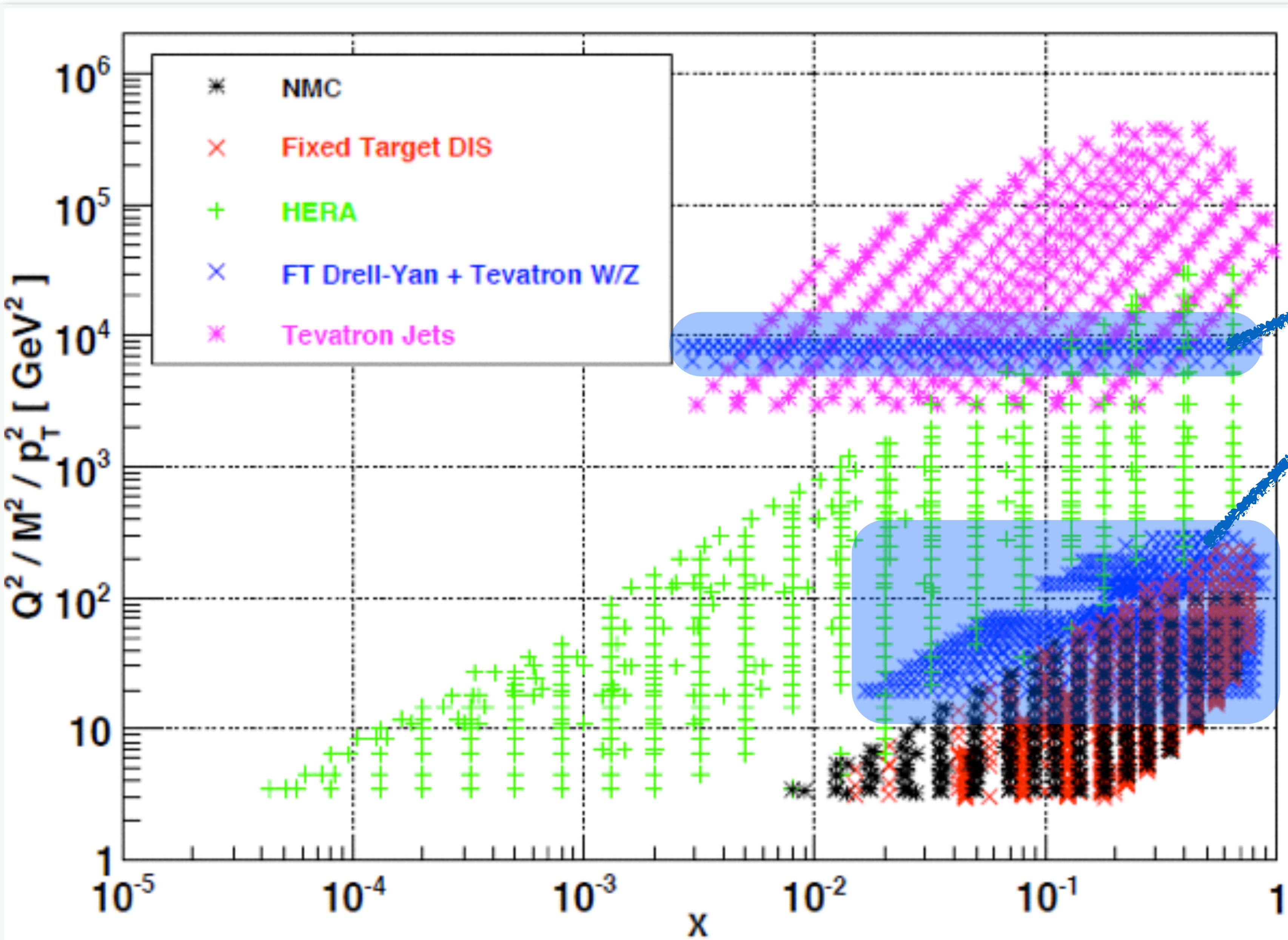


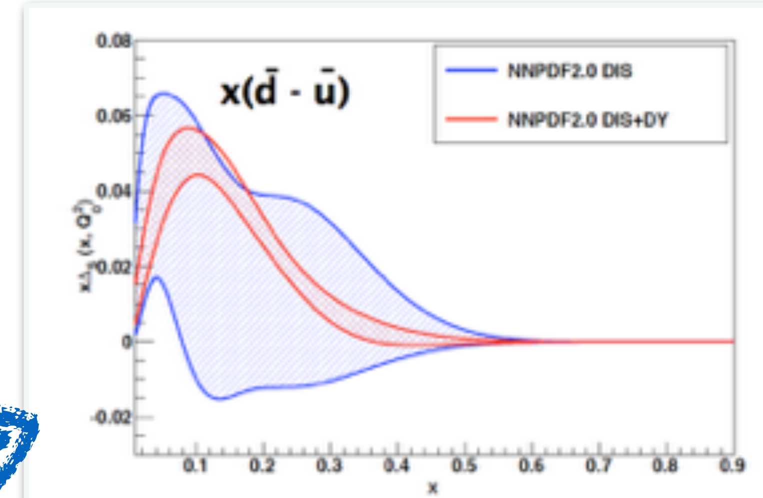


Fixed Target DIS data

- Deuteron data: disentangle isospin triplet and singlet contributions
- Constrain strange and anti-strange at moderate $x > 10^{-2}$

The data (before LHC)





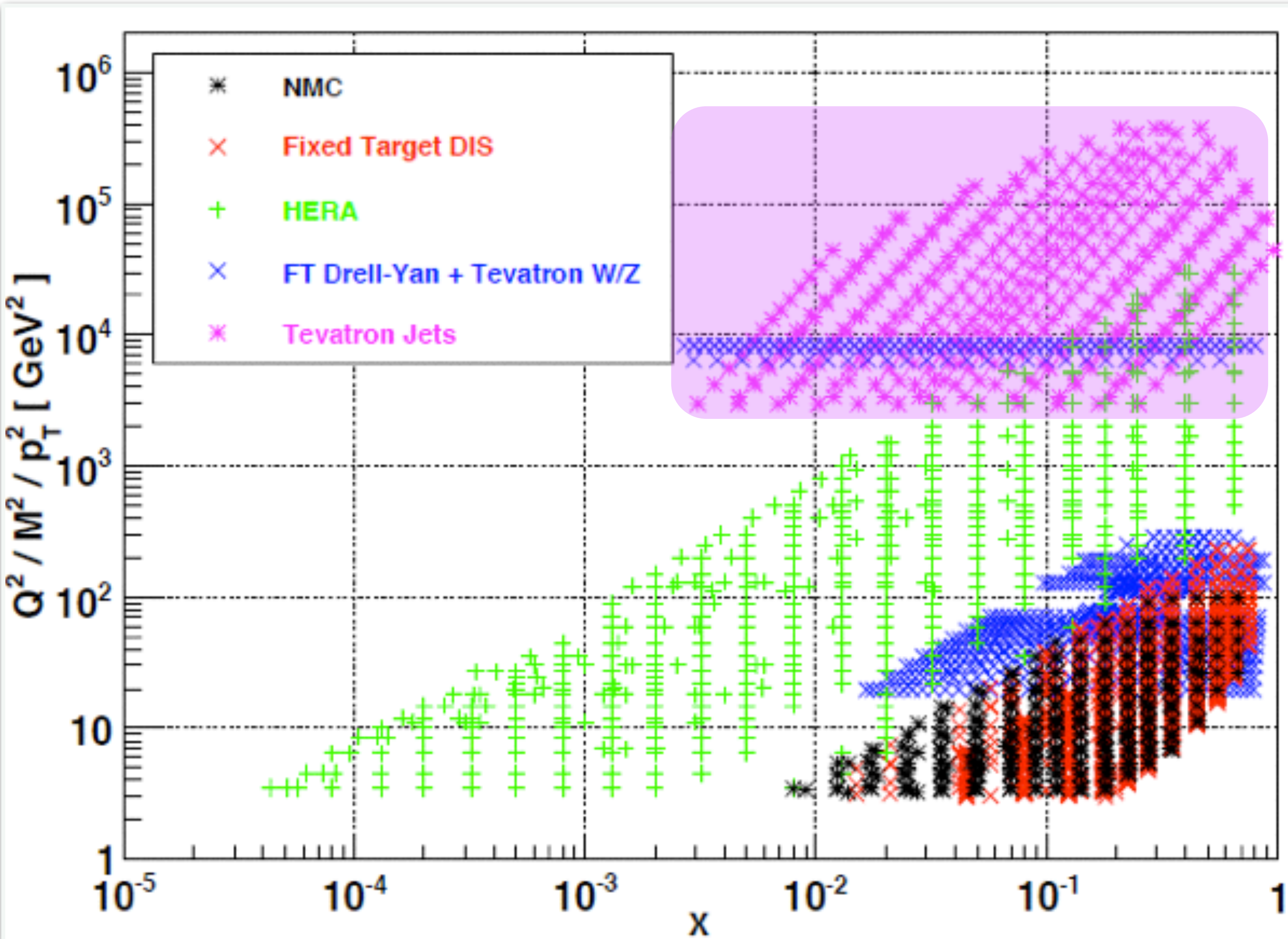
[NNPDF2.0, Ball et al, ArXiv: 1002.4407]

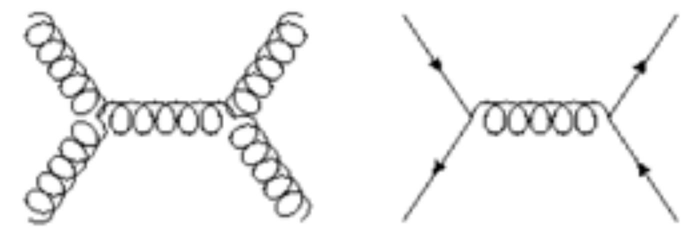
$$\sigma^{\mathrm{DY,p}} \propto u(x_1)\bar{u}(x_2) + d(x_1)\bar{d}(x_2)$$
$$\sigma^{\mathrm{DY,d}} \propto u(x_1)(\bar{u}+\bar{d})(x_2) + d(x_1)(\bar{u}+\bar{d})(x_2)$$

DY and EW vector boson data

- Constrain light quark and antiquark separation
- Up and down separation
- Ubar and Dbar separation

The data (before LHC)

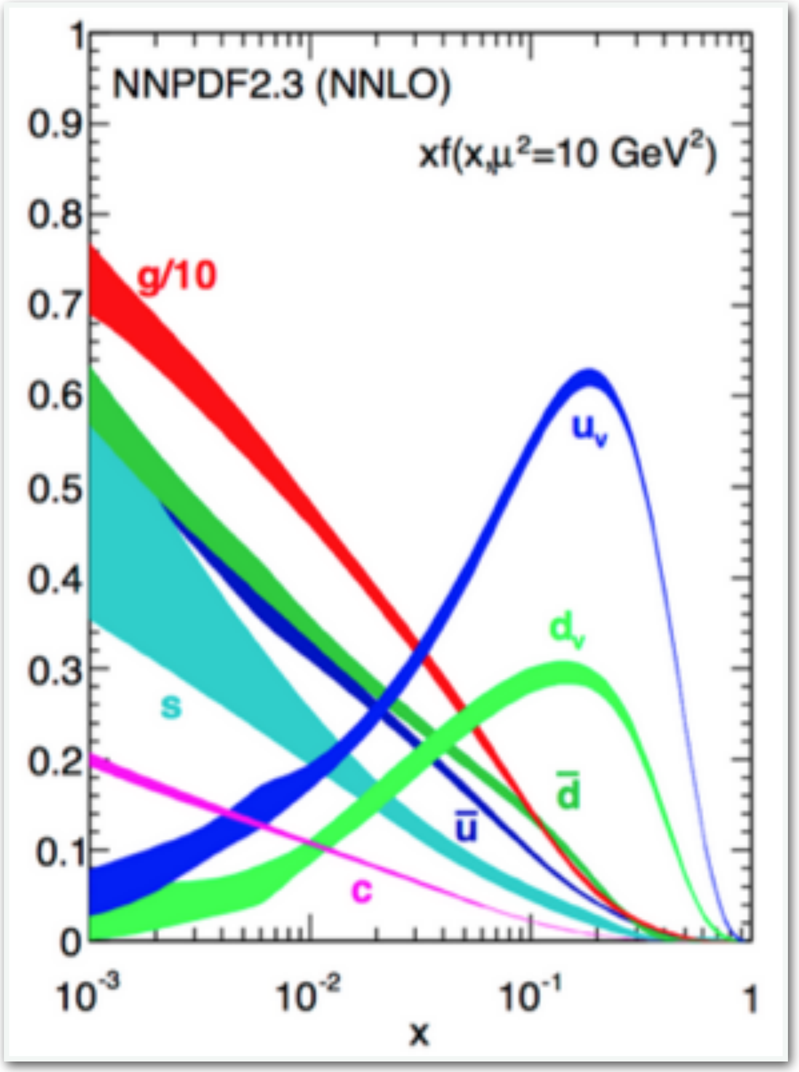


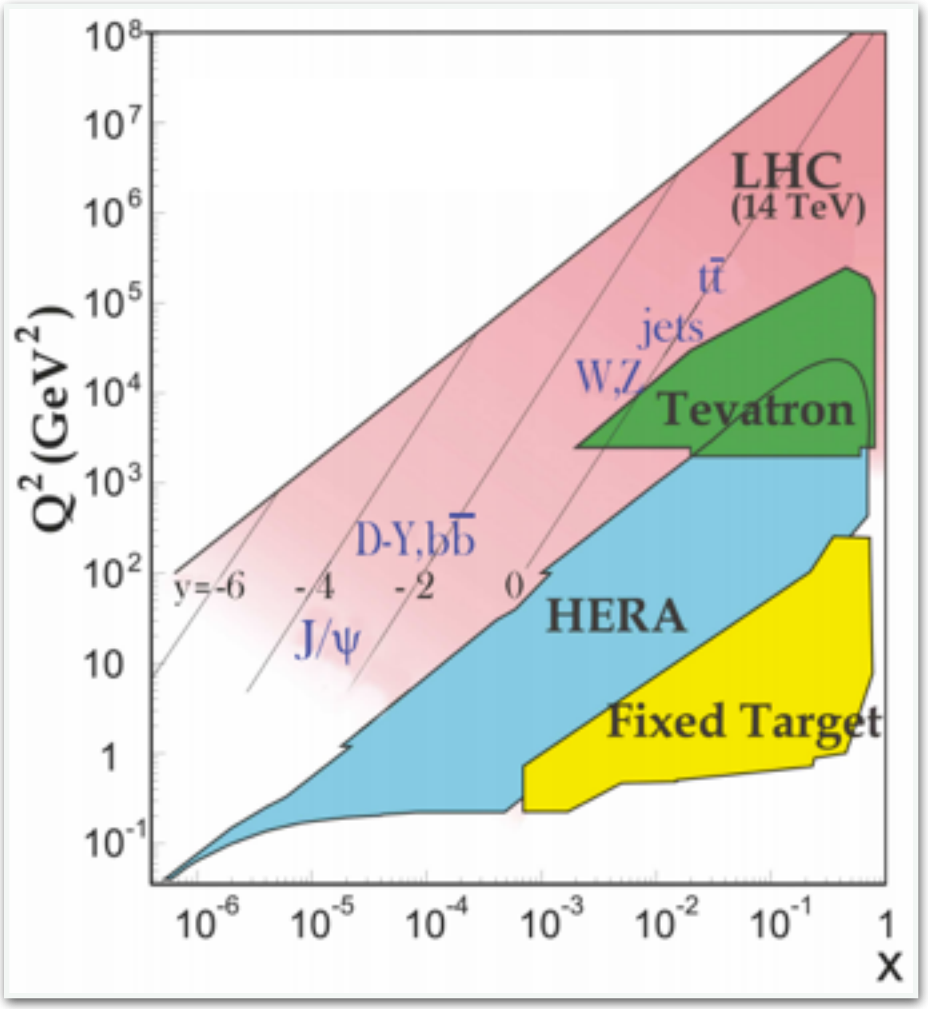


Jet data

- Constrain quarks and gluons at large x
- So far cross section known only at NLO + threshold approximation

The LHC data





PDFs

PDF uncertainties are a crucial input at the LHC, often being the limiting factor in the accuracy of theoretical predictions, both SM and BSM

LHC

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

The LHC data

GLUON

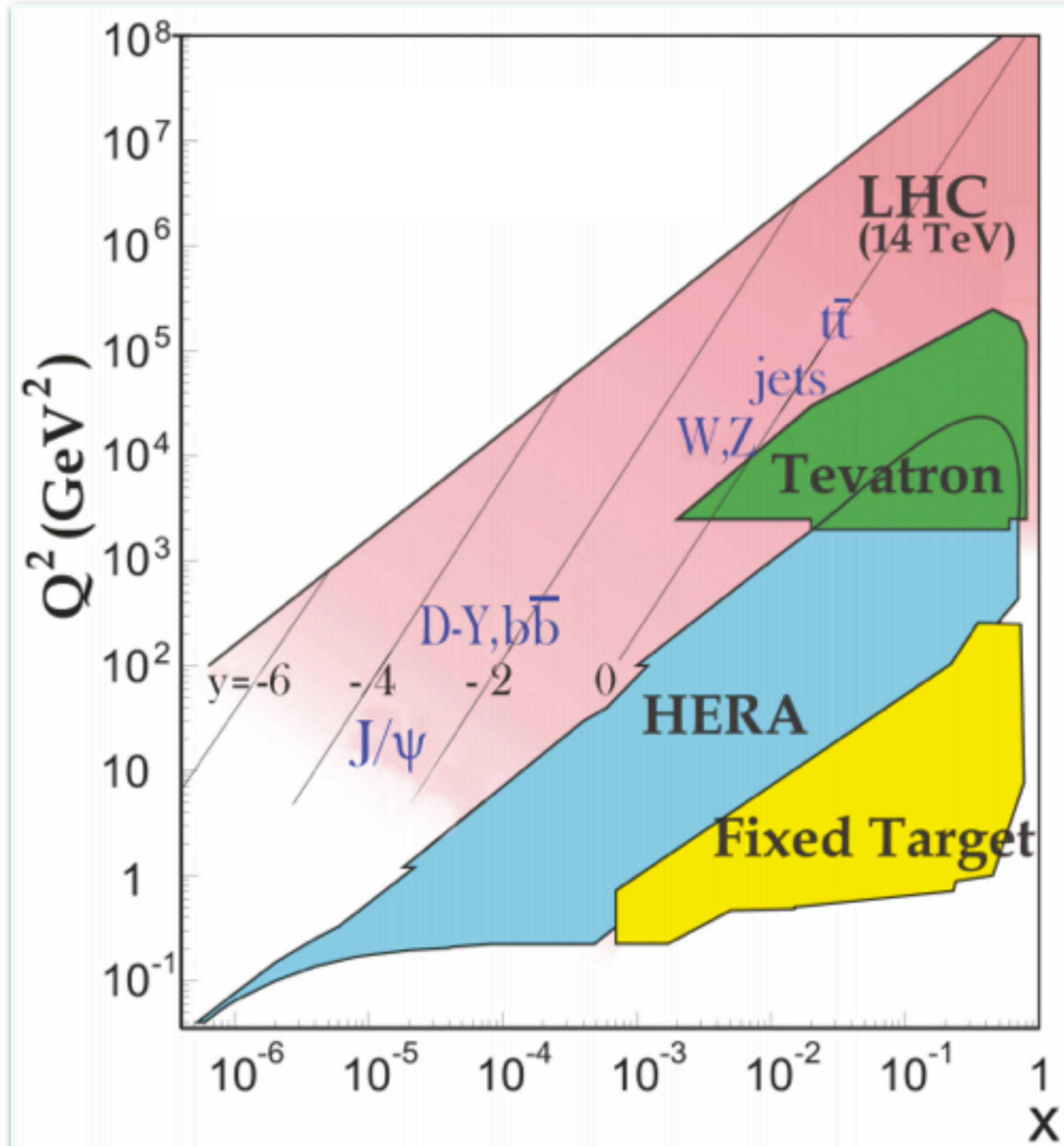
- Inclusive jets and dijets
  (medium/large x)
- Isolated photon and γ+jets
  (medium/large x)
- Top pair production **(large x)**
- High p_T V(+jets) distribution
  (small/medium x)

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



Effect of LHC data on PDFs

NNPDF3.0

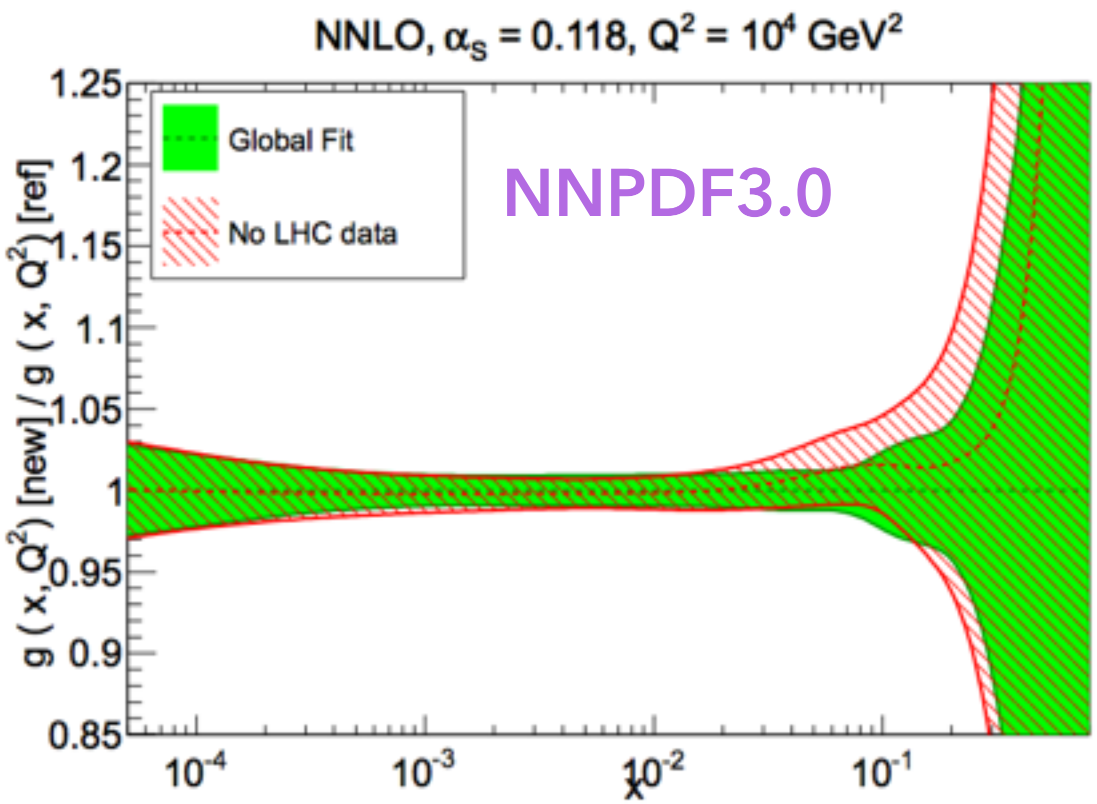
ATLAS jets 2.76 TeV and 7 TeV	gluon large x
ATLAS high-mass DY at 7 TeV	q/q~ separation
ATLAS W pT data at 7 TeV	g and q at moderate x
CMS (Y,M) double diff distributions 7 TeV	flavour separation
CMS jets at 7 TeV	gluon large x
CMS muon charge asymmetry at 7 TeV	quark separation
CMS W+c at 7 TeV	strangeness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

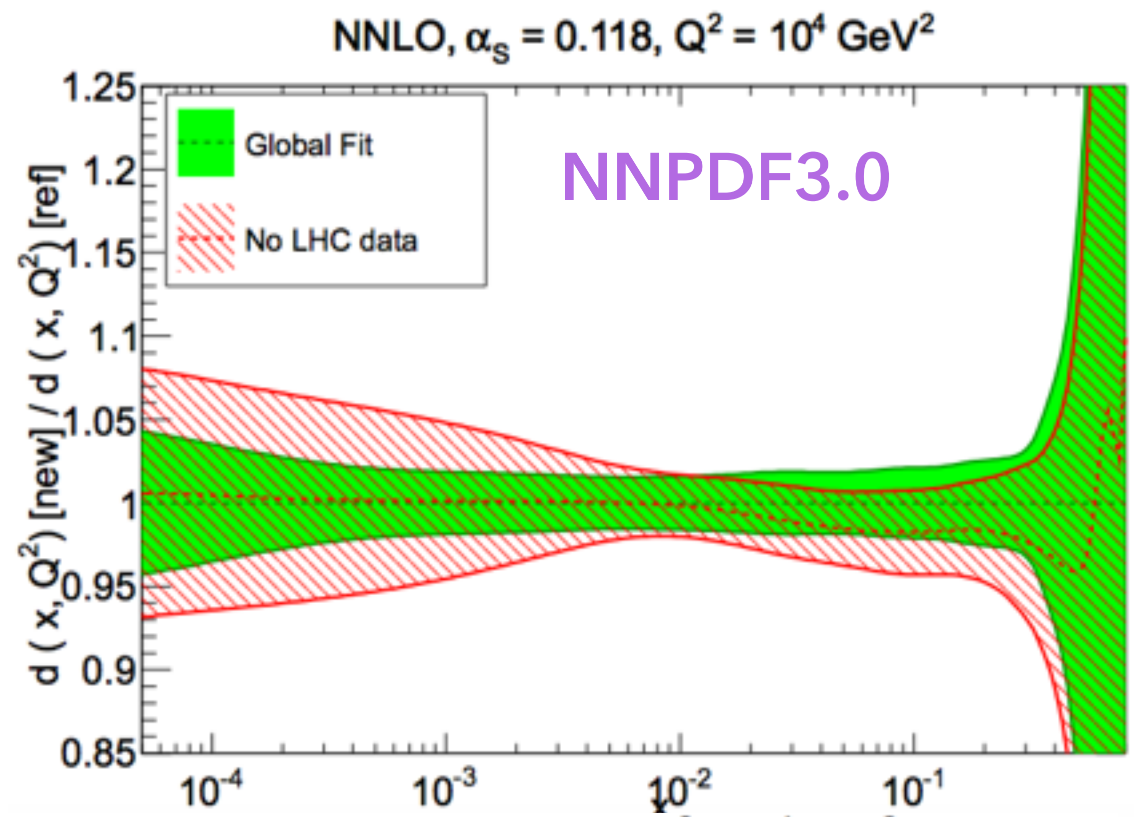
Effect of LHC data on PDFs

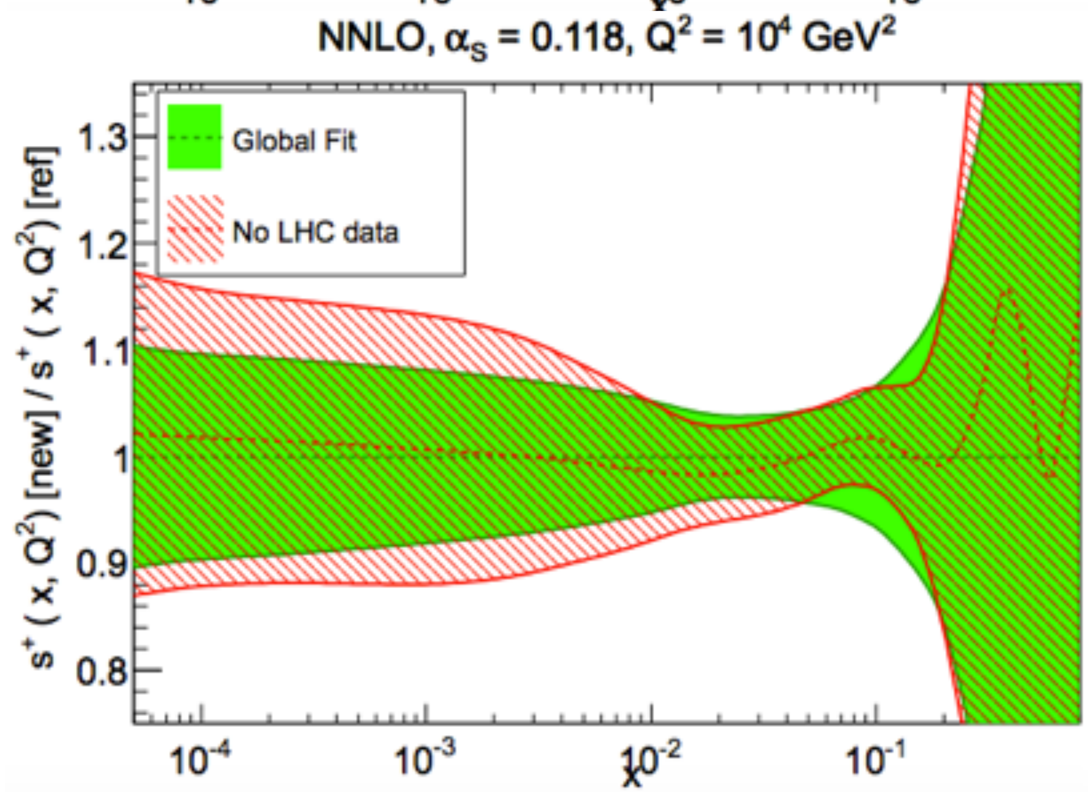
NNPDF3.1

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

Effect of LHC data on PDFs



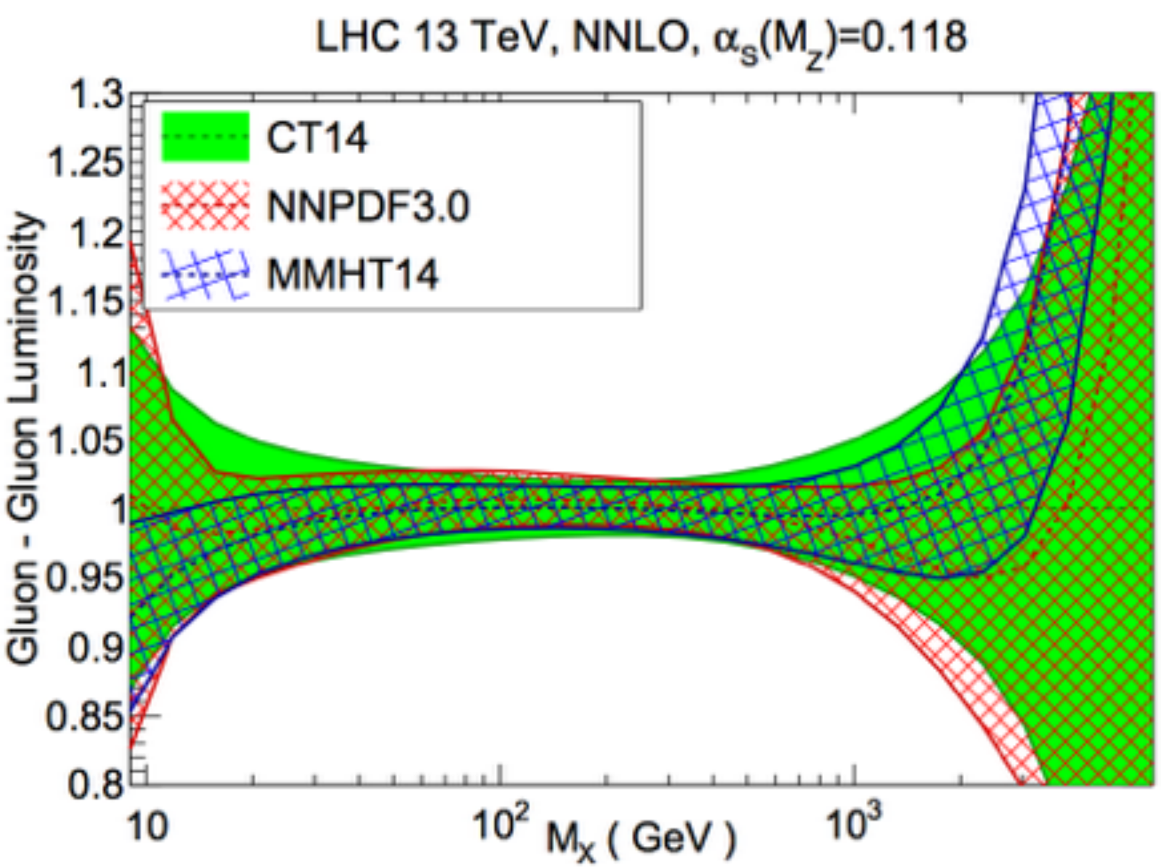


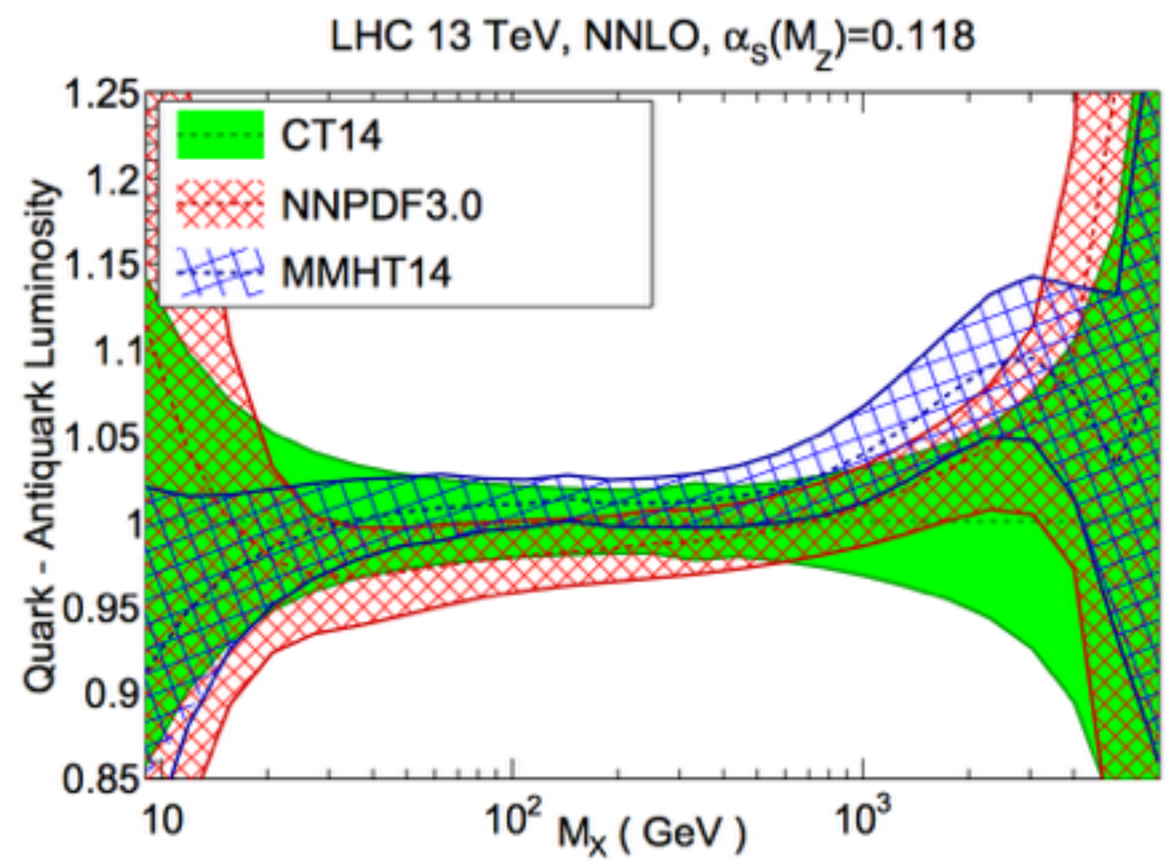


Ball et al.
JHEP 1504 (2015) 040

- Data give increasingly stronger constraints in known and less-known kinematic regions => PDF experimental uncertainties reduced
- In precision region are we keeping up with theory settings in PDF fits?
- Large x still affected by huge uncertainties

State of the art



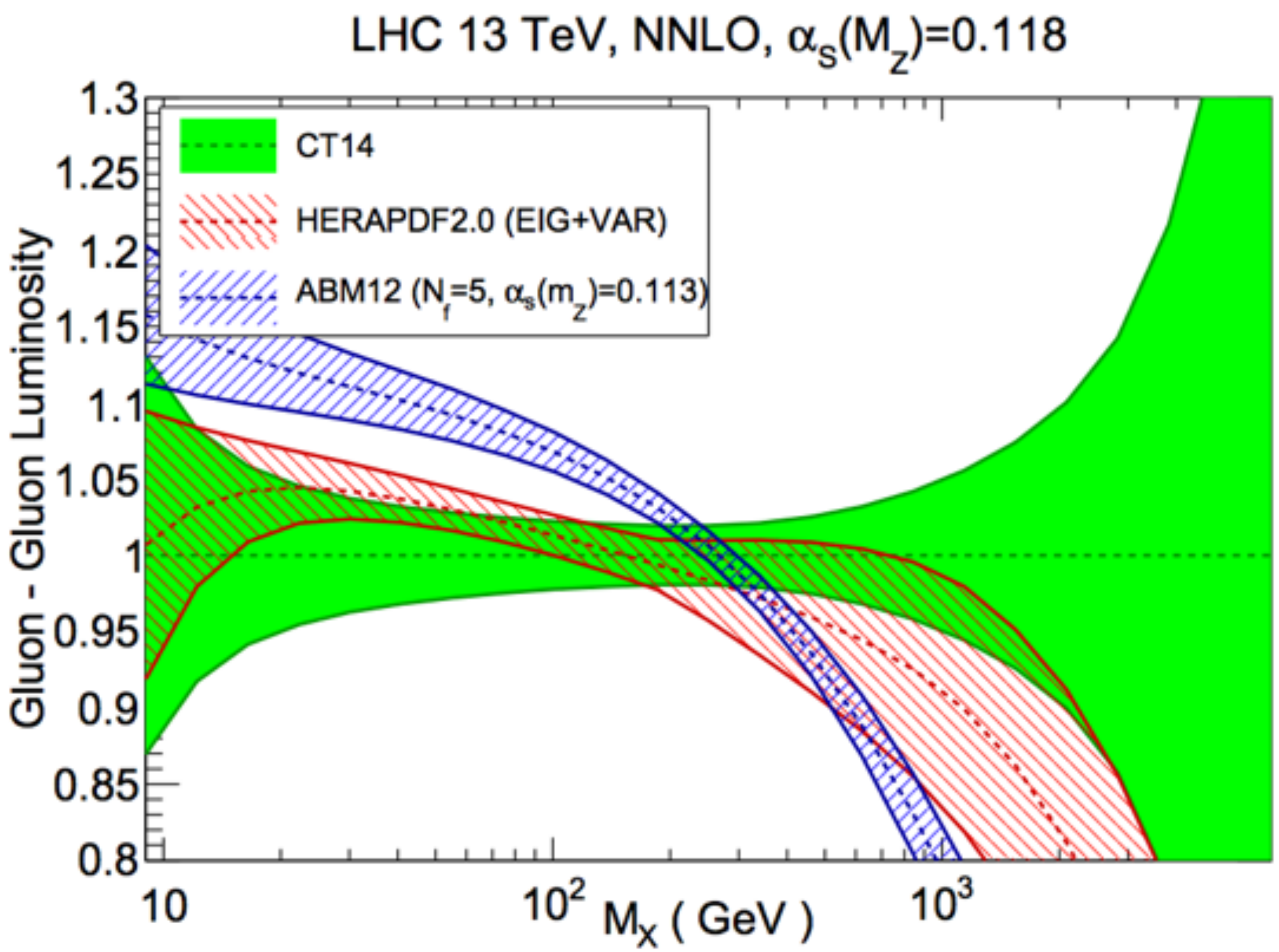


<u>NNPDF3.0 / CT14 / MMHT</u>

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

- common value of $\alpha_S(Mz) = 0.118$
- comparable GM-VFN schemes for inclusion of HQ masses
- global sets: inclusion of O(4000) experimental data
- extensive benchmarking

State of the art



ABM 12

- fitted $\alpha_S(Mz)$=0.1132
- Fixed-Flavour-Number scheme

HERAPDF2.0

- HERA-only data

Needs for BSM searches

Large-x gluon/quarks

- Large-x g/q uncertainty can be reduced thanks to inclusion of LHC data
- NNLO calculation now available for some key processes for PDF determination
- Great progress also in tools to interface NLO codes to PDF fitting code

✓ 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

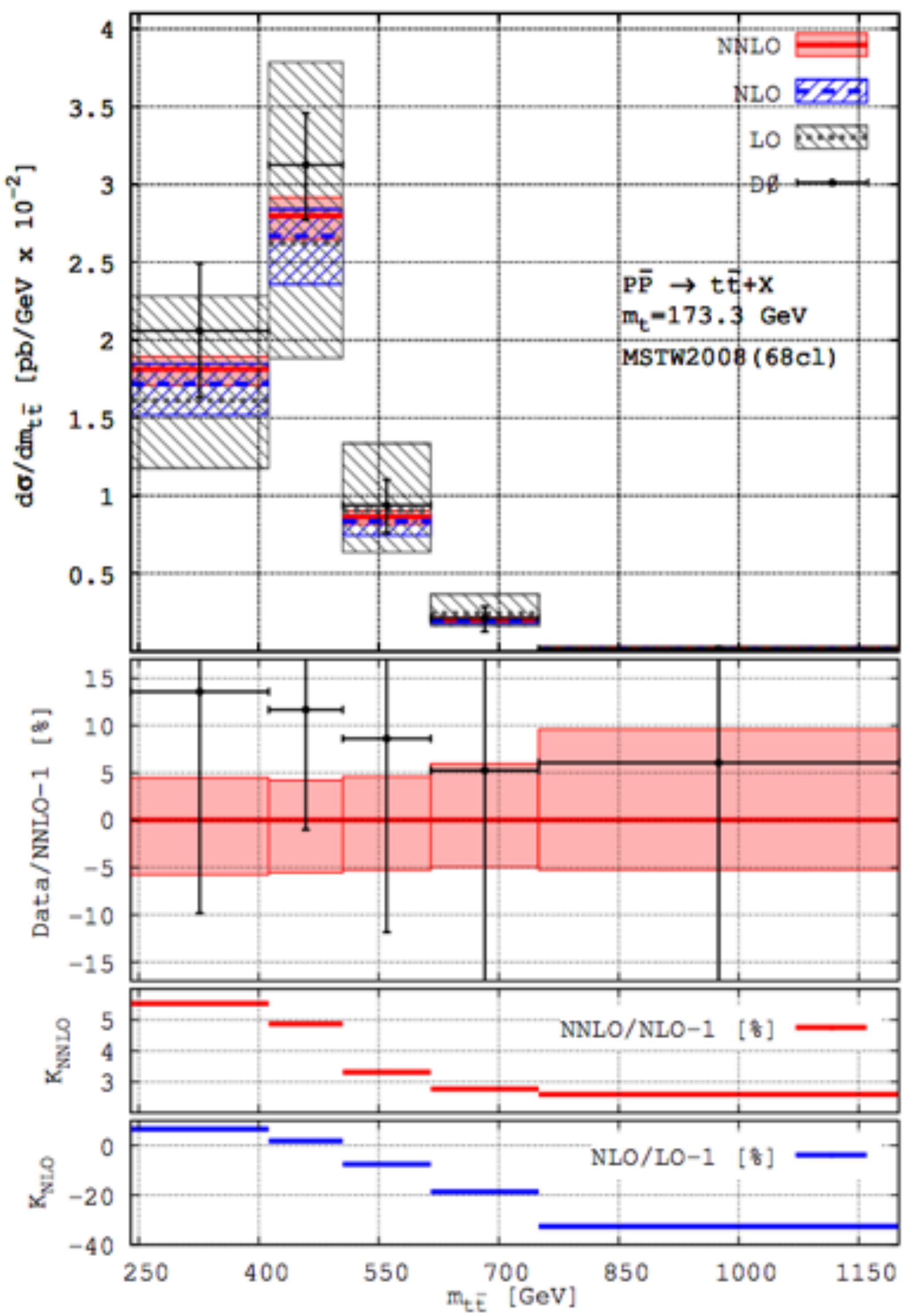
Gehrmann-De Ridder et al [1605.04295]
Boughezal, Liu, Petriello [1602.08140]
Boughezal, Liu, Petriello [1602.06965]
Boughezal et al [PRL 116(2016) 152001 & 062002]
Gehrmann-De Ridder et al [1507.02850]

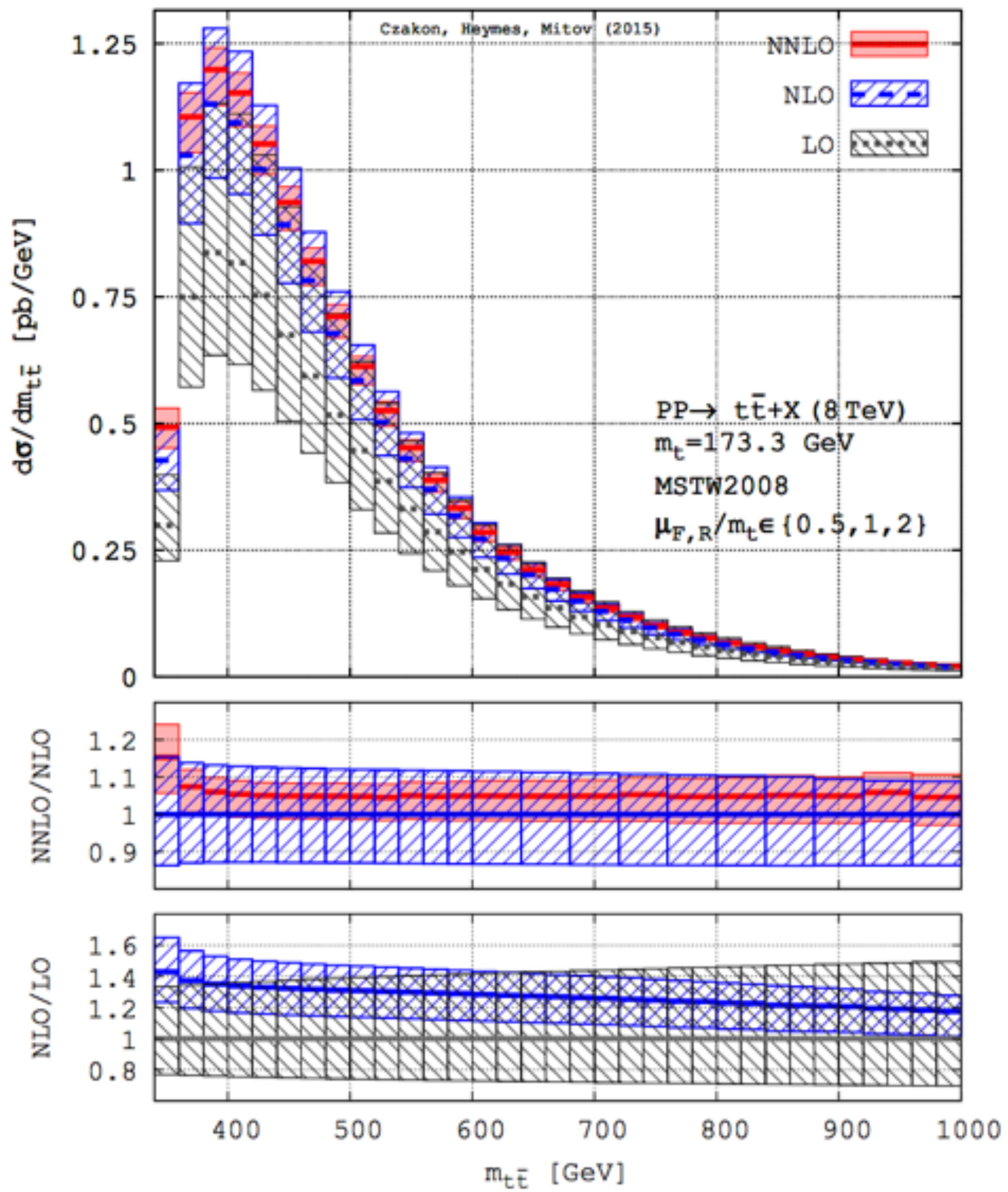
✓ Inclusive jet cross section

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

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
APPLgrid, Carli et al EPJC66 (2010) 503-524
FASTNLO, Kluge et al

Top data



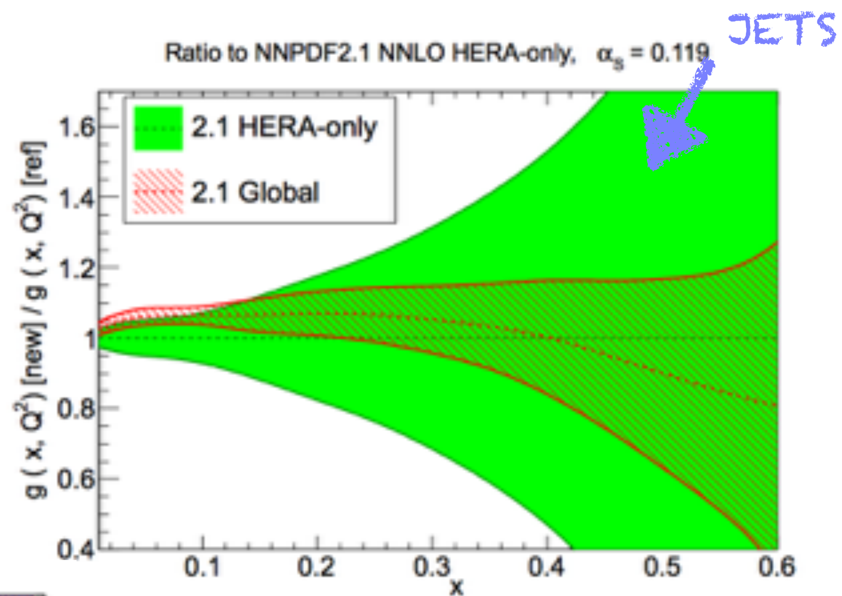


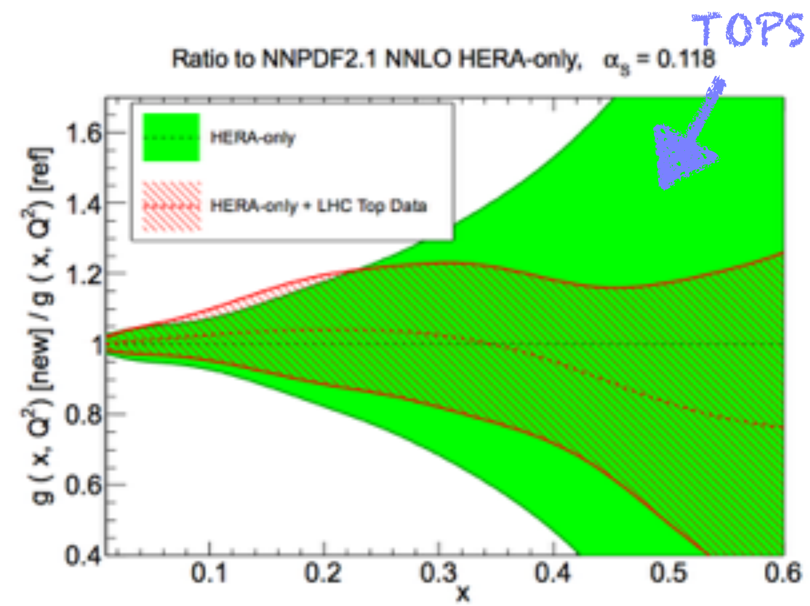
Czakon, Fiedler, Mitov [PRL 116(2016) 082003]

Top data

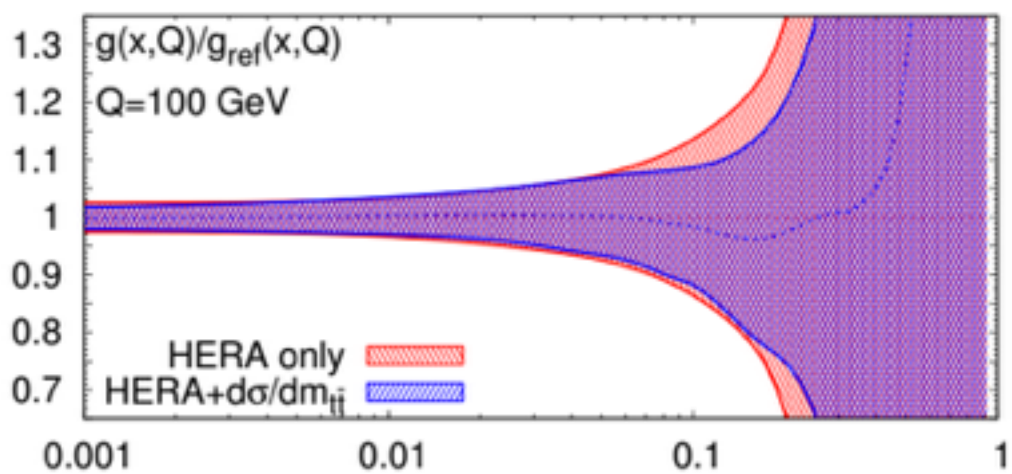
Total cross section →

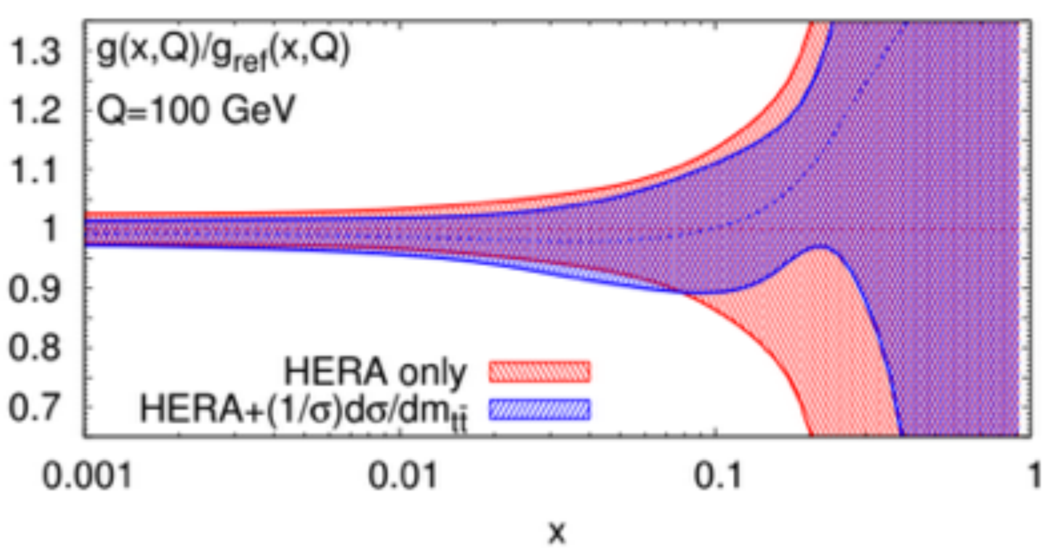
Differential cross section
↓





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



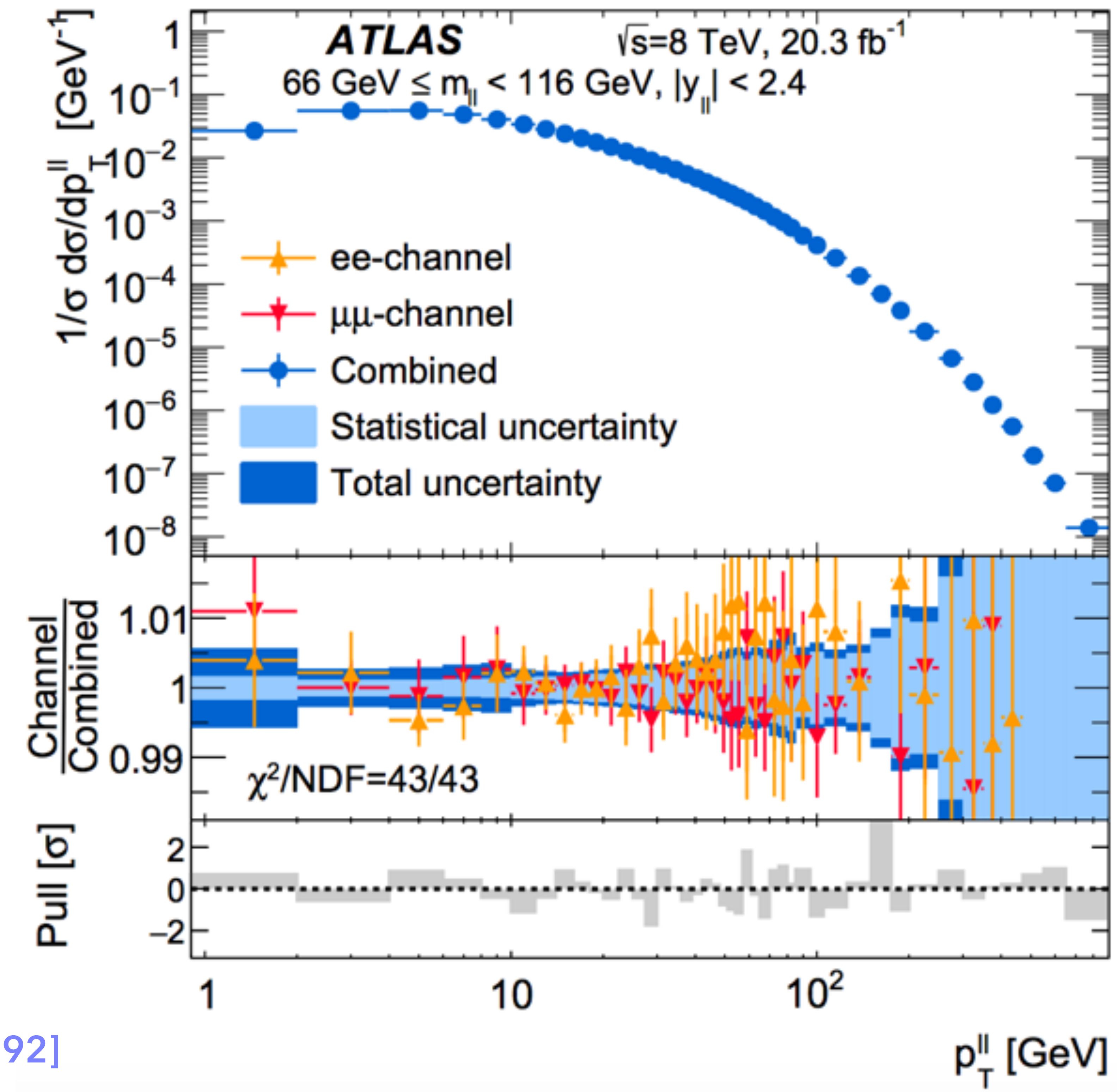


- Inclusion of top pair production data (total cross section and differential distributions) competitive to jets data and cleaner from non-perturbative effects

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

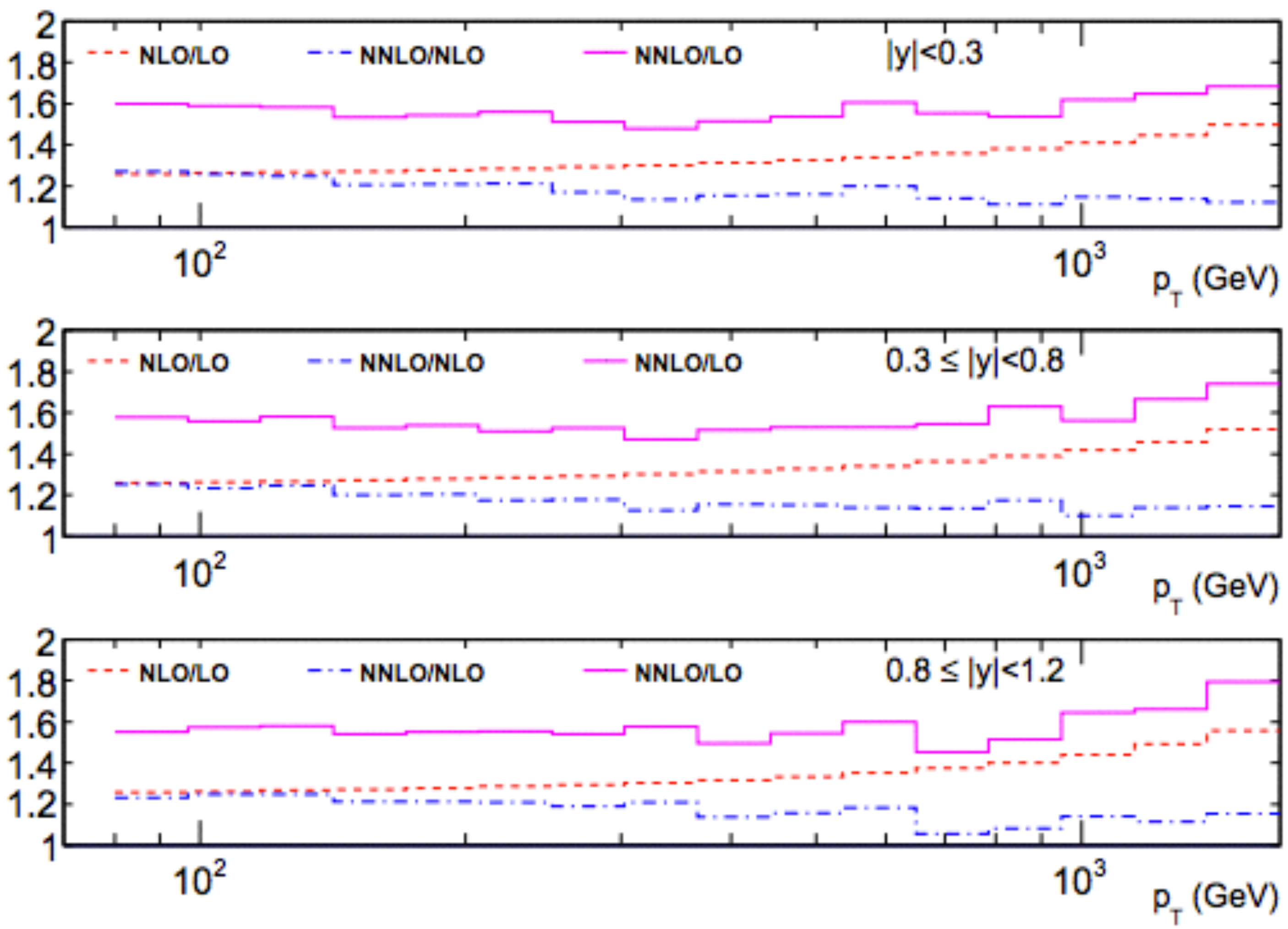
Z pT

- Experimental precision < 1% up to pT~200 GeV
- Expect a great impact on the quark-gluon luminosity
- To fit the data NNLO corrections are needed, discrepancies in non-normalised distributions



ATLAS collaboration [1512.02192]

Jets data

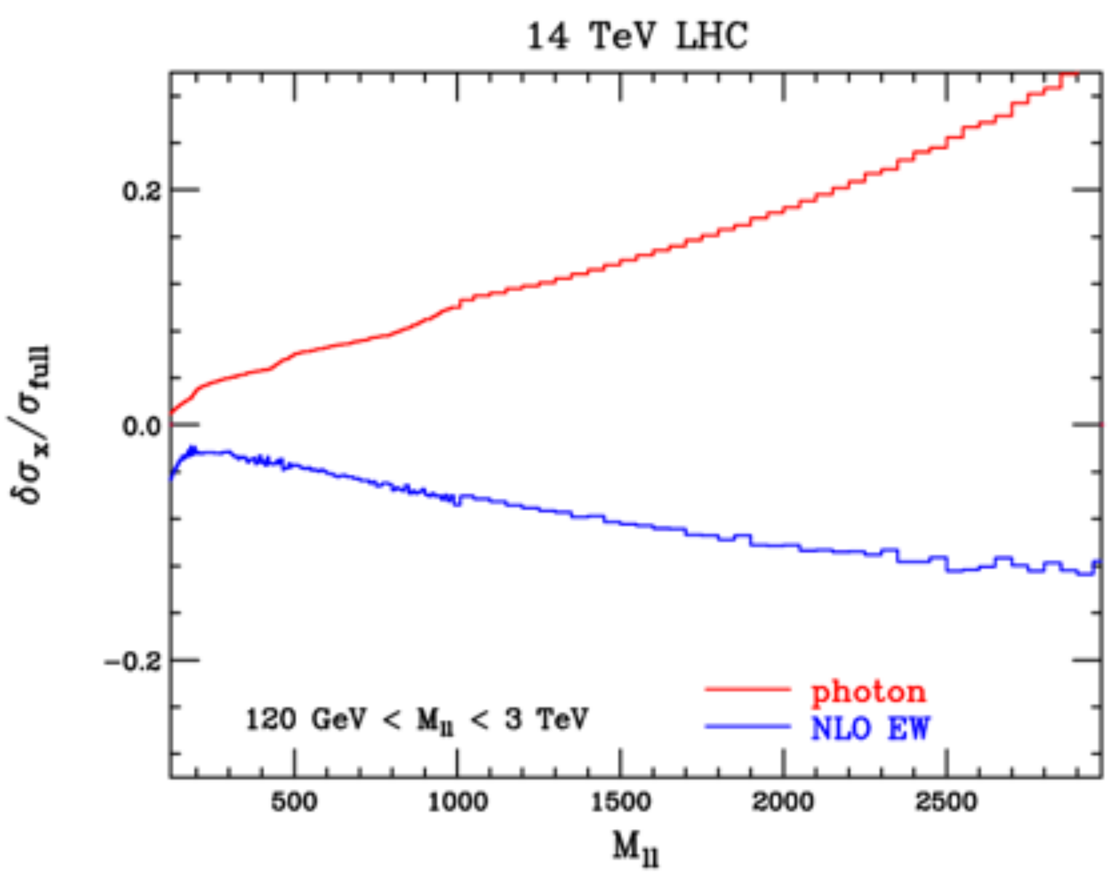


Gehrmann-De Ridder et al [PRL 110 (2016) 162003]

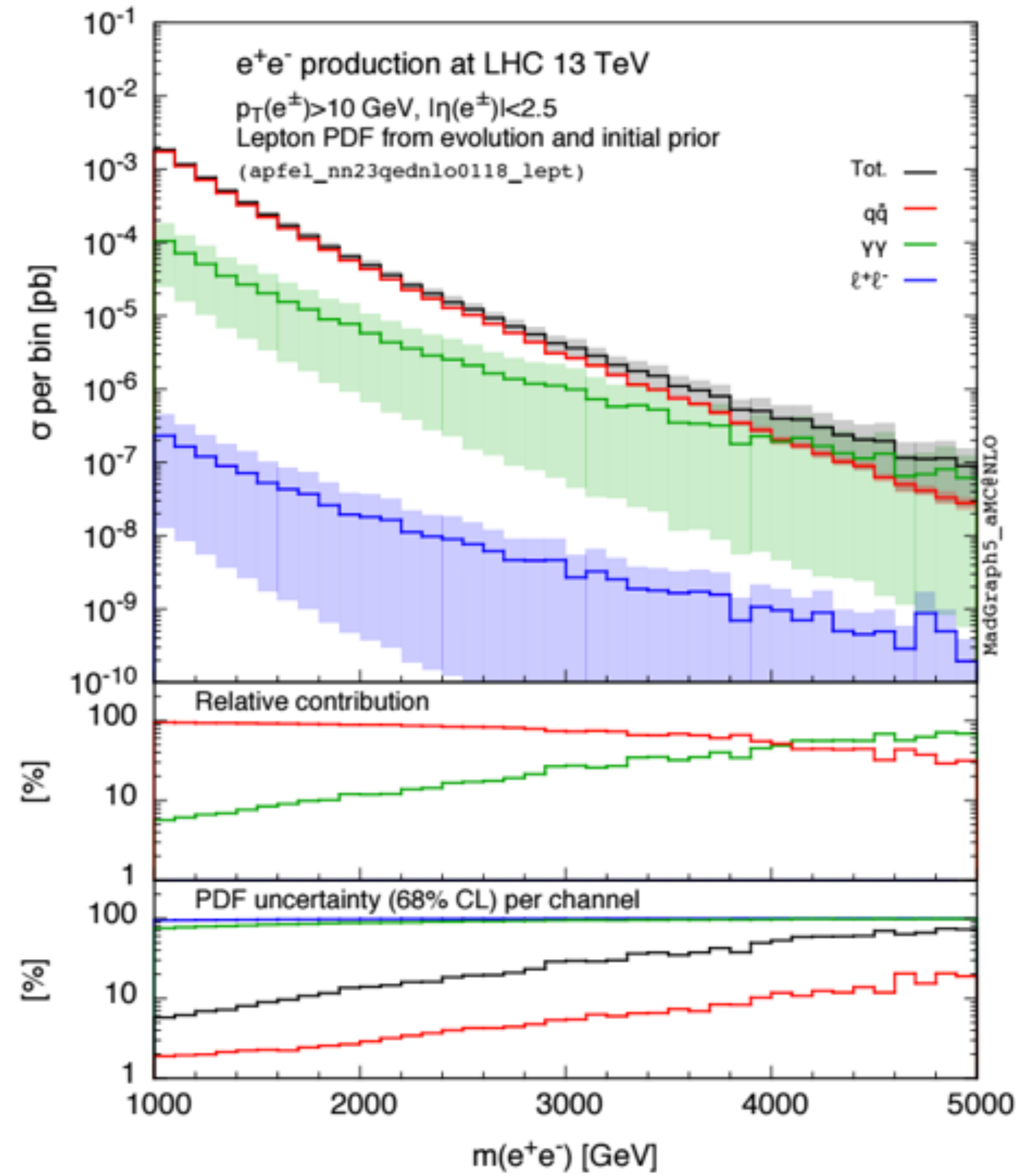
- Plenty of data from LHC
- NNLO corrections only partially known (gg channel)
- Several PDF groups make different choices: CT14 includes all jet data in NNLO fit assuming overall C-factor small, MMHT14 and ABM12 do not include LHC jet data at NNLO, NNPDF3.0 include some jet data based on goodness of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

EW corrections and photon PDF

- 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 induces large uncertainty



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



Bertone et al [JHEP 1511 (2015) 194]

The photon PDF

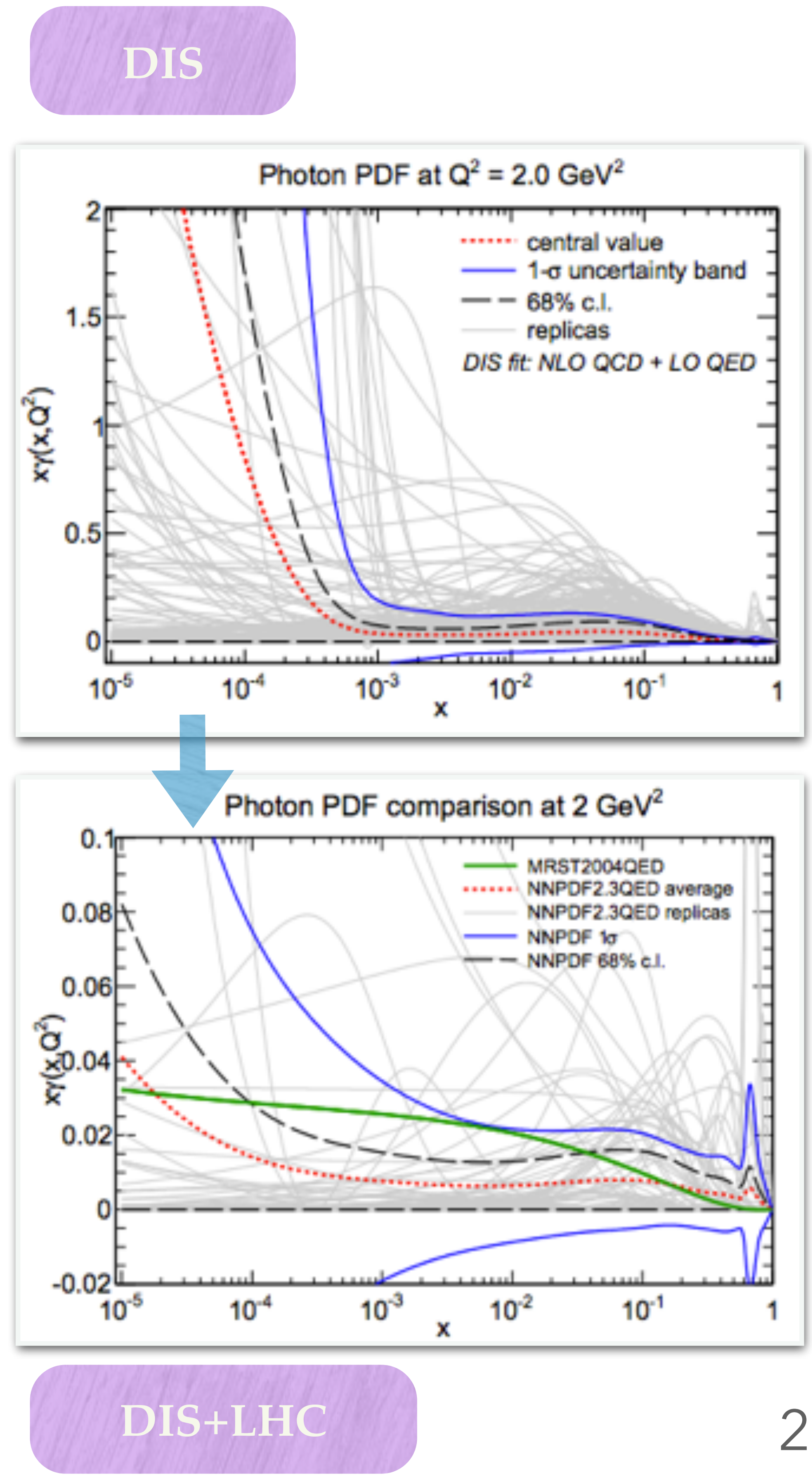
- **NNPDF23QED** provides γ PDF and its uncertainty at (N)NLO QCD + LO QED, by reweighting photon PDF
  Ball et al [Nucl.Phys. B877 (2013)]

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

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

- 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)



Large-x and resummation

- 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
$+ \ldots$		$+ \ldots$	

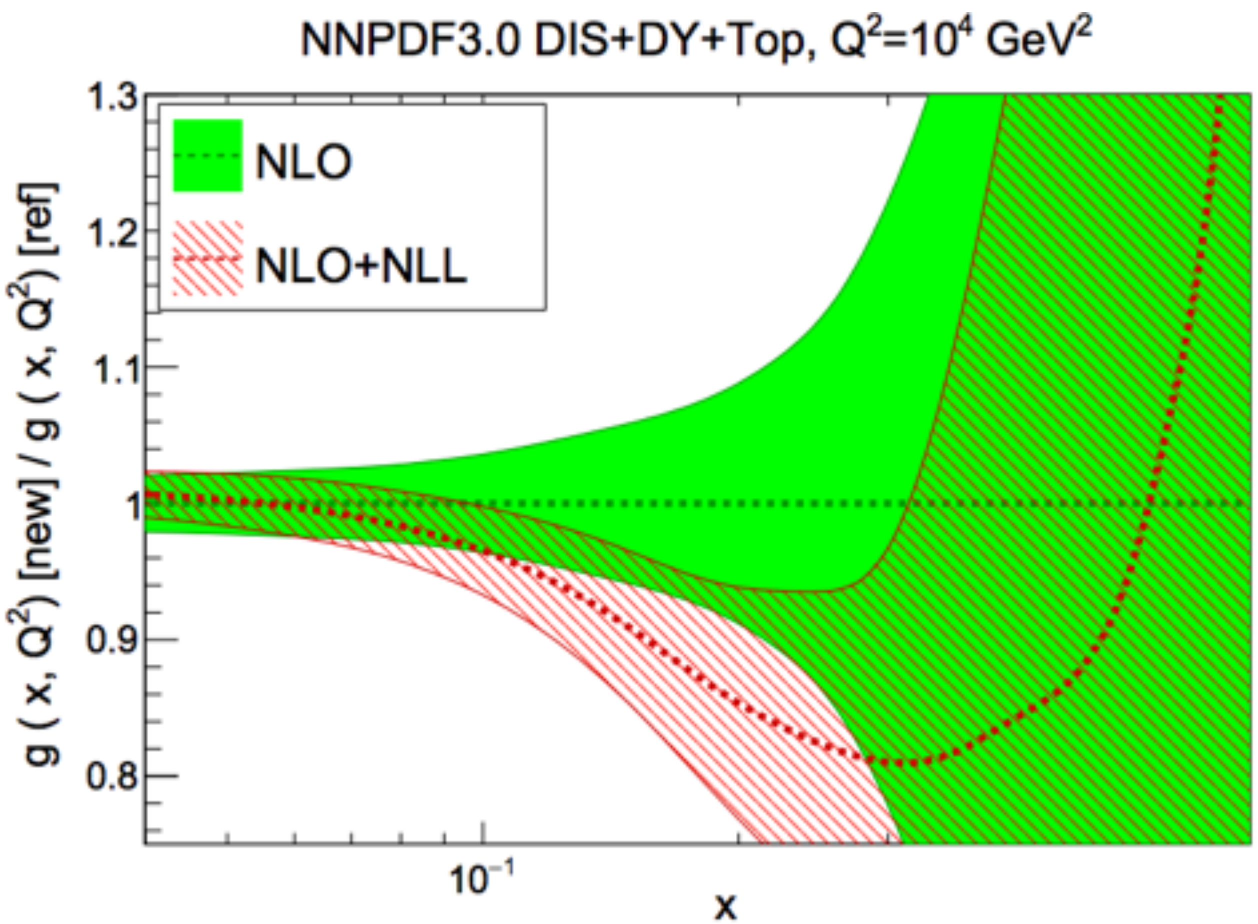
- Various kinds of logs:

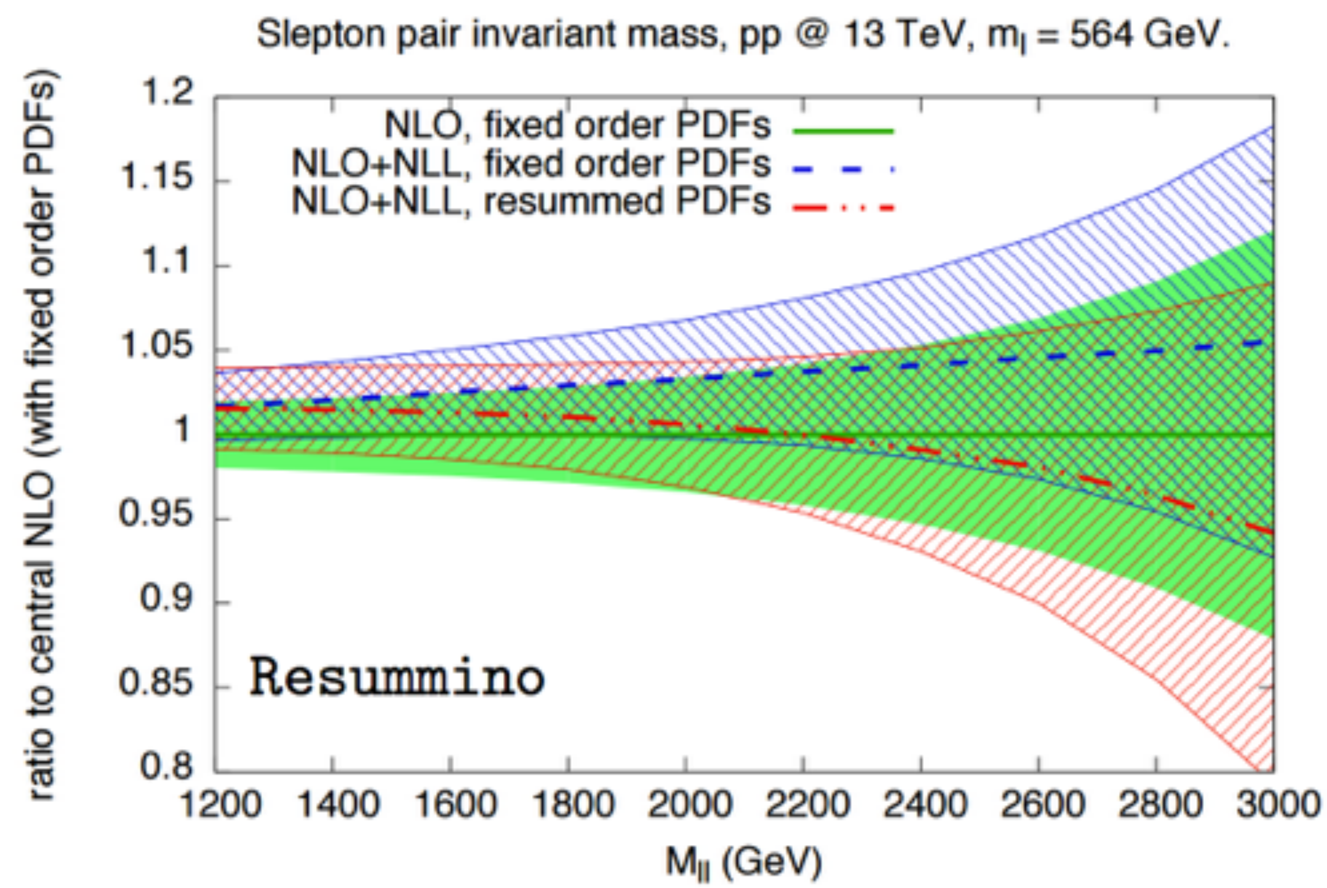
L = log (1-x) threshold (soft-gluon) resummation ⟵ Ball et al, JHEP09(2015)091

L = log (1/x) high-energy (small-x) resummation ⟵ in progress

L = log (pT/M) transverse momentum resummation

Resummed PDFs and BSM





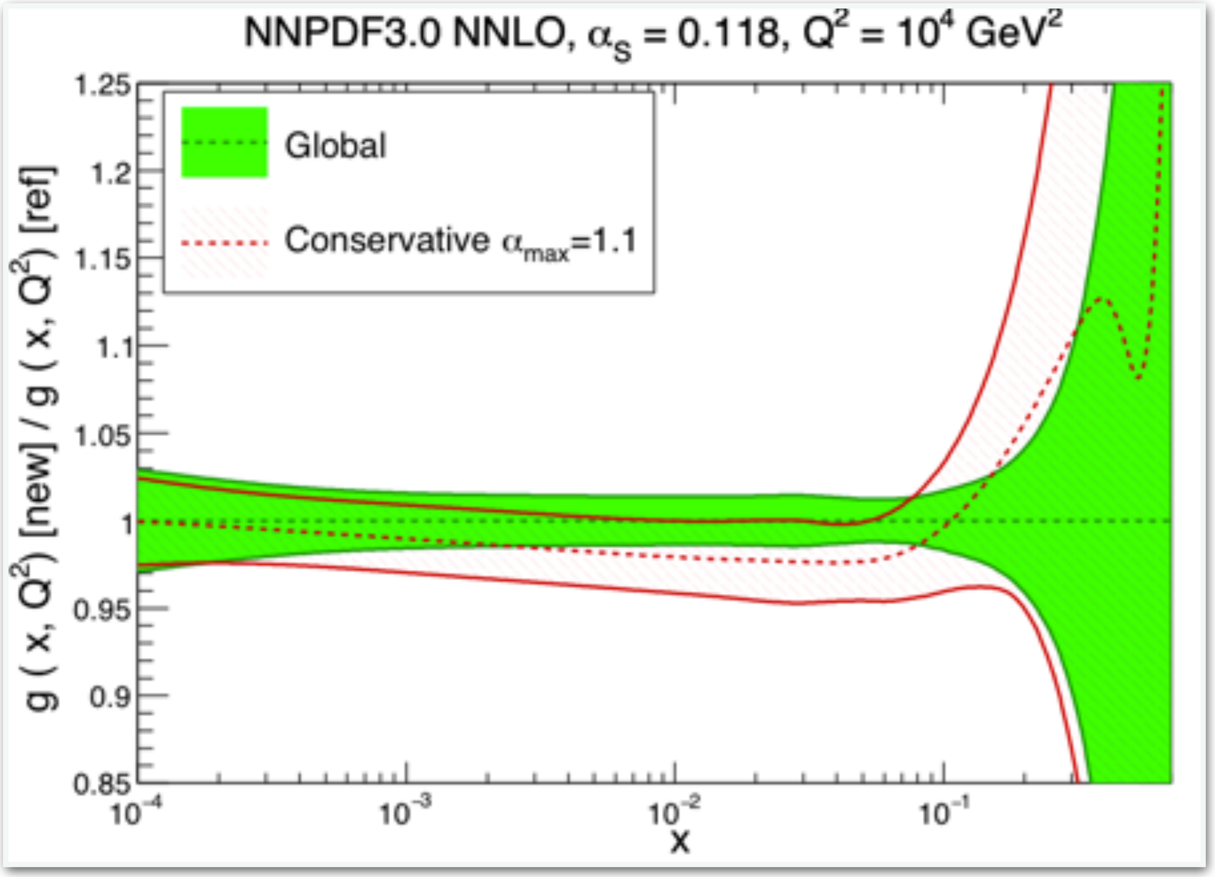
Bonvini et al, JHEP 1509 (2015) 191

- Threshold-resummed PDFs will be 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]

Absorbing New Physics?

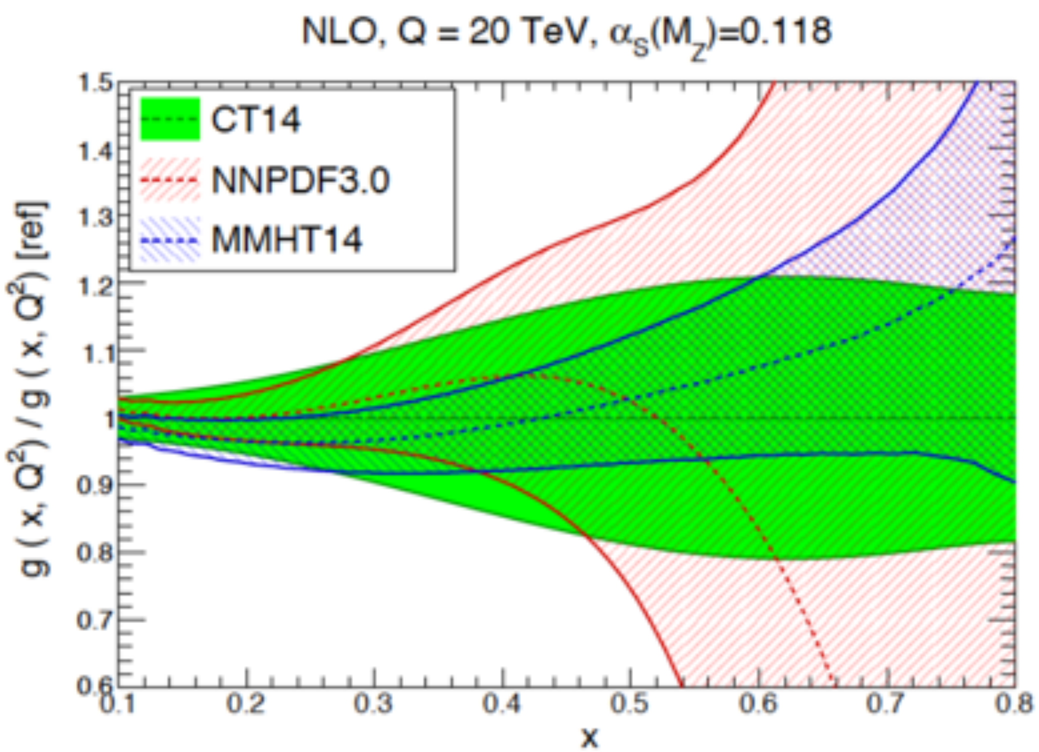
Q: As more data at higher energy will be released, how can we make sure that we will not absorb new physics in the PDFs?

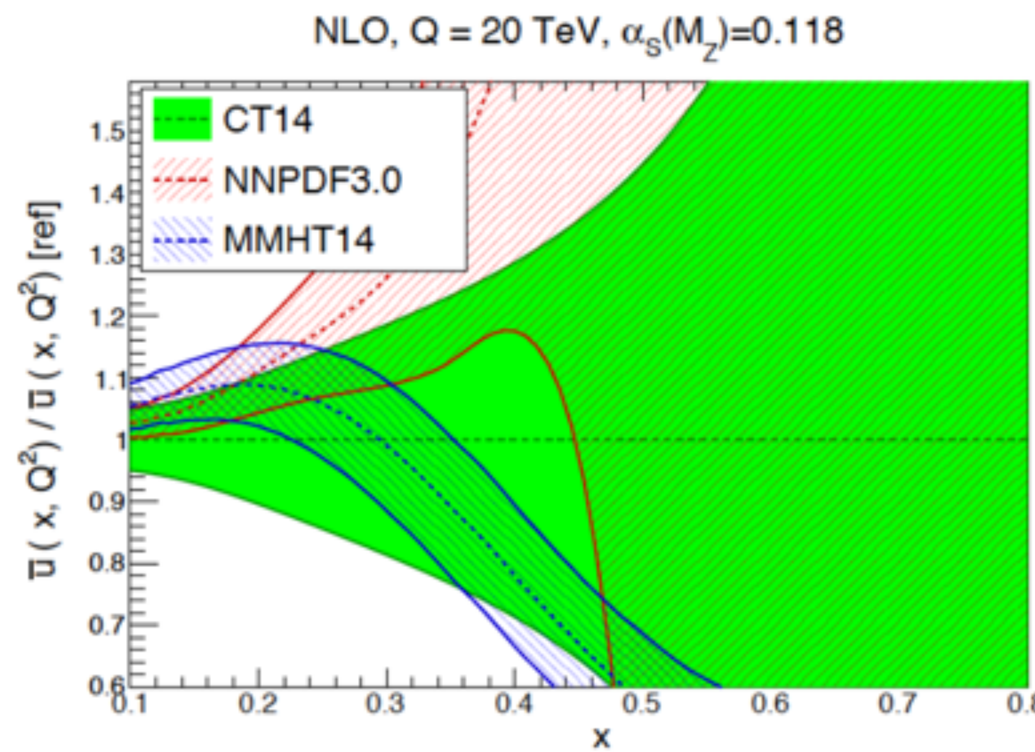
- Inconsistencies between data that enter a global PDF analysis can distort statistical interpretation of PDF uncertainties
- Inconsistency of any individual dataset with the bulk of global fit may suggest that its understanding (theory or experiment) is incomplete
- Set of **conservative partons** based on measure of consistency are crucial to systematically study inclusion of new data

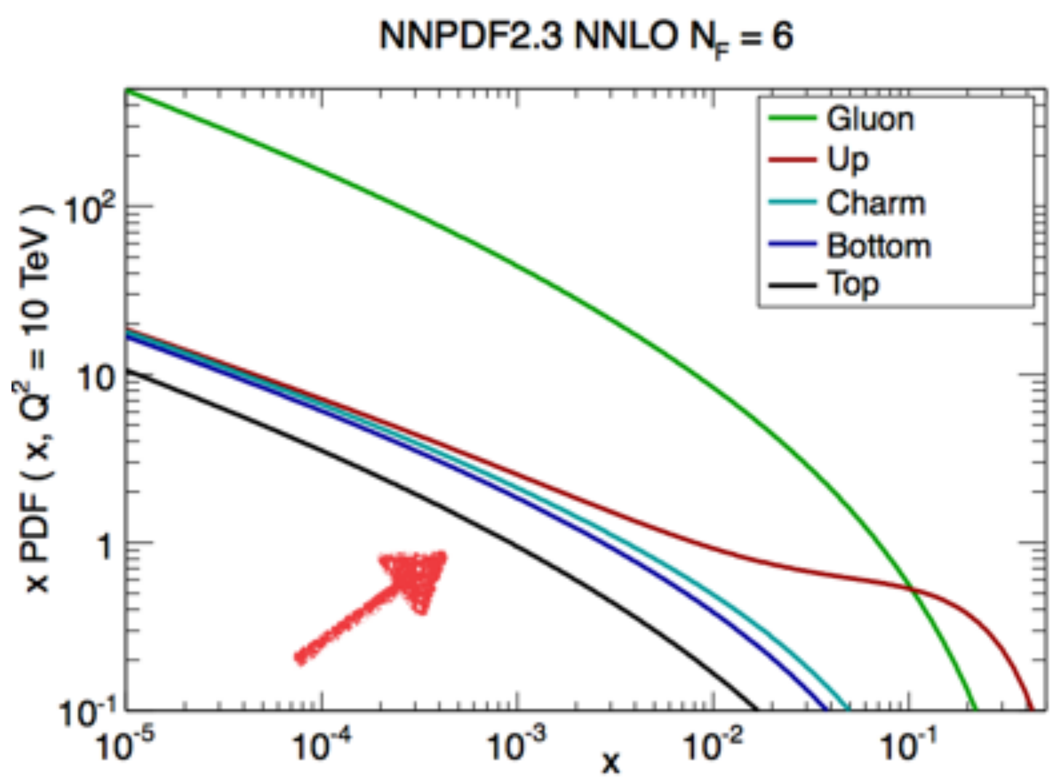


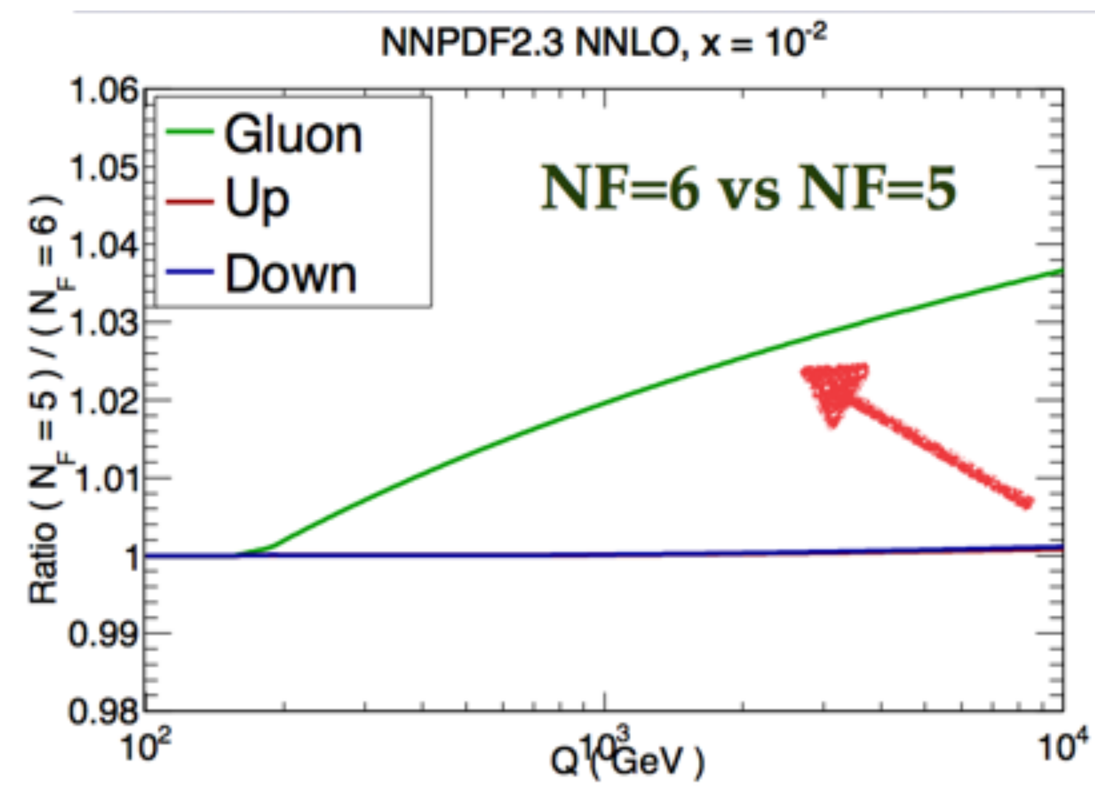
NNPDF collaboration, JHEP04(2015)040

Beyond LHC - 100 TeV









Conclusions

- Parton Distribution Functions essential ingredient for LHC phenomenology
- Accurate PDFs are required for precision SM measurements, Higgs characterisation and New Physics
- NNPDF approach provides parton distributions based on a robust, unbiased methodology, the most updated theoretical information and most relevant hard scattering data including LHC data
- Frontiers for PDFs and BSM searches:

  Bring down uncertainty of large-x gluon and quarks via inclusion of new data
  Bring the pQCD loop revolution & resummations into the PDF world
  How not to include effects that go beyond DGLAP/SM formalism into PDF fits?

- At 100 TeV collider big large-x uncertainties, top-quark, larger photon contribution, larger impact of large-x and small-x resummation
- Choice of heavy flavour schemes is also crucial: 4FS versus 5FS versus 6FS
- A challenging and exciting road ahead!

THANK YOU!