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THE STRUCTURE OF THE PROTON IN THE LHC HERA

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)

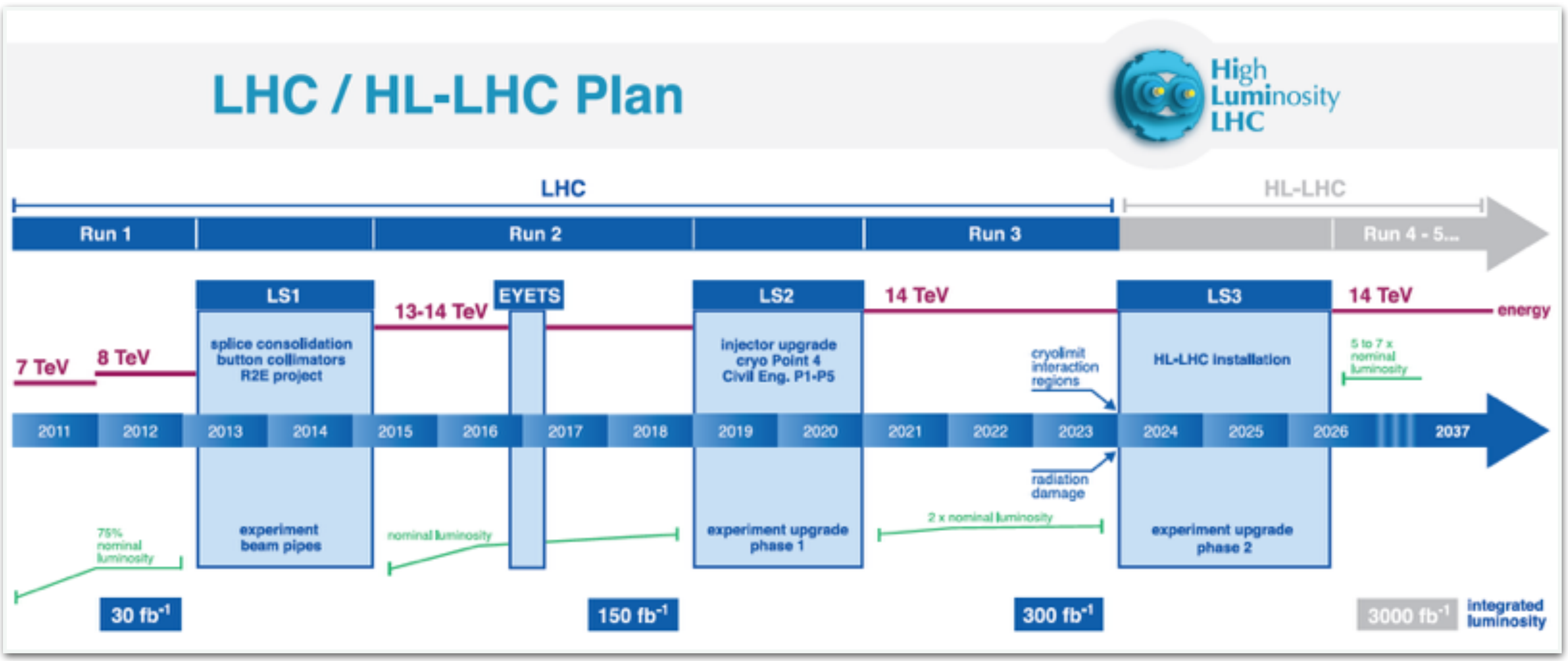
NNPDF

Outline

- Motivation
- What PDFs are
- The NNPDF approach
- Experimental constraints on PDFs and theoretical accuracy
- Beyond the state of the art

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

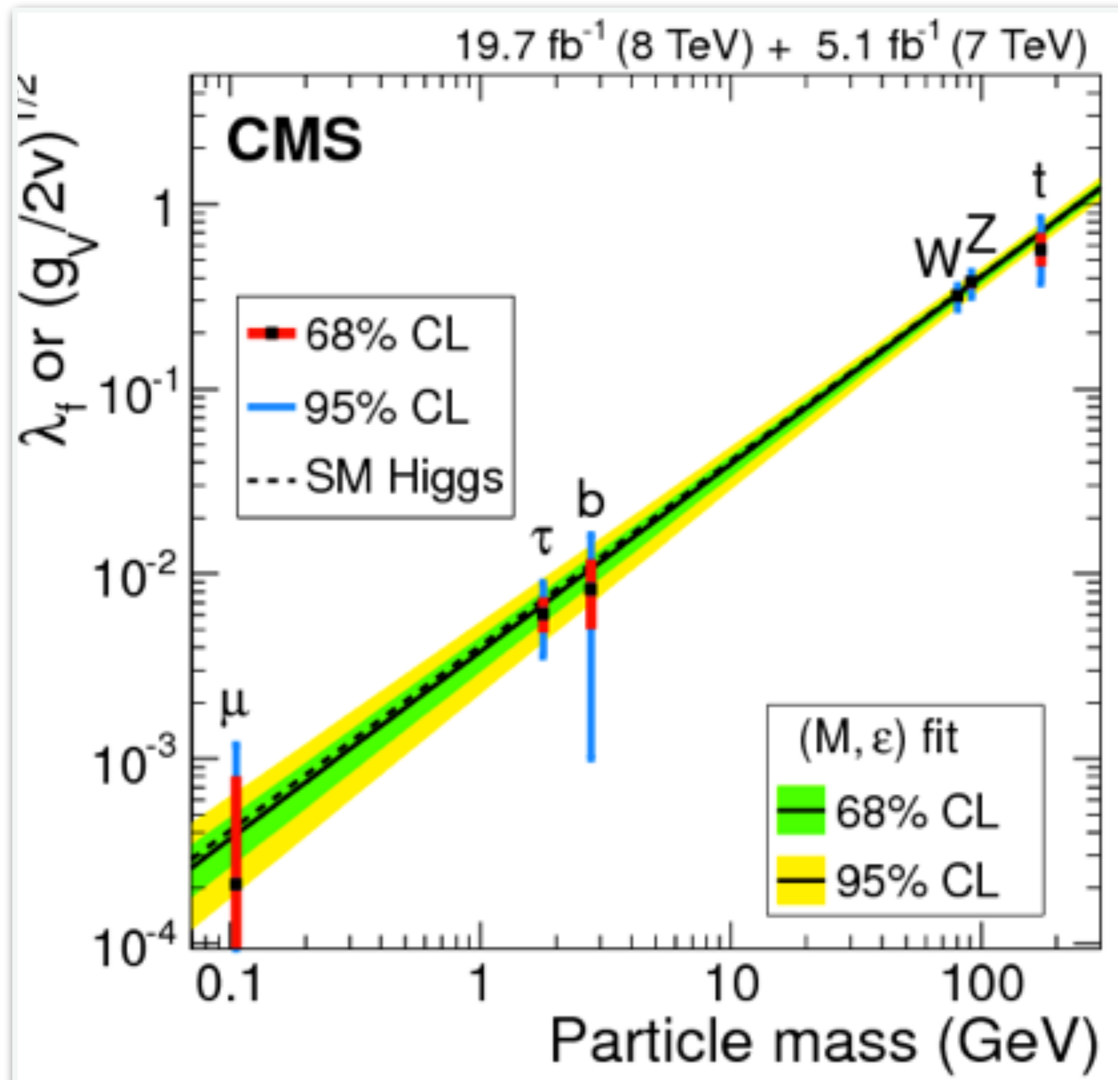


LHC physics at Run II

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

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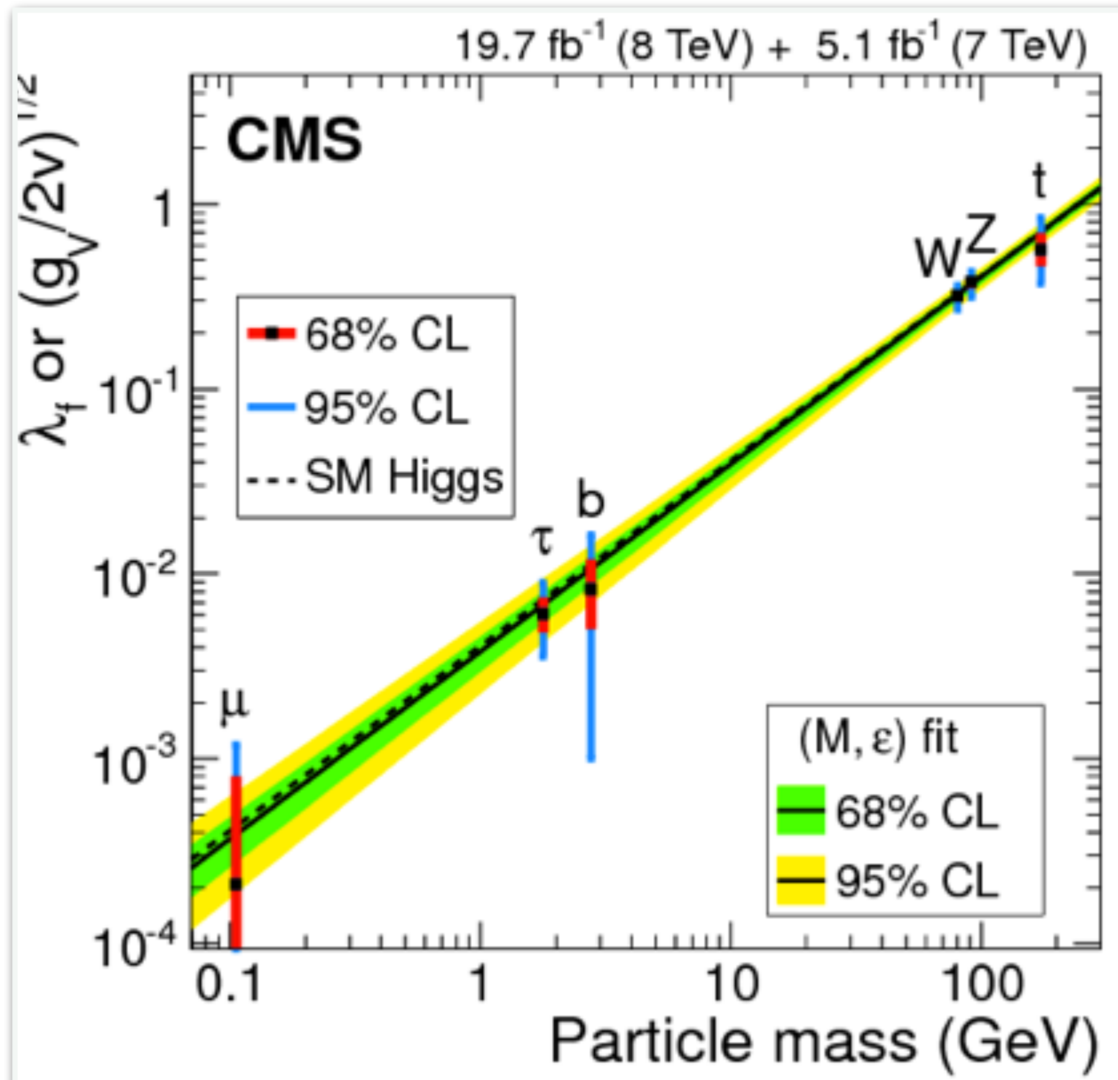
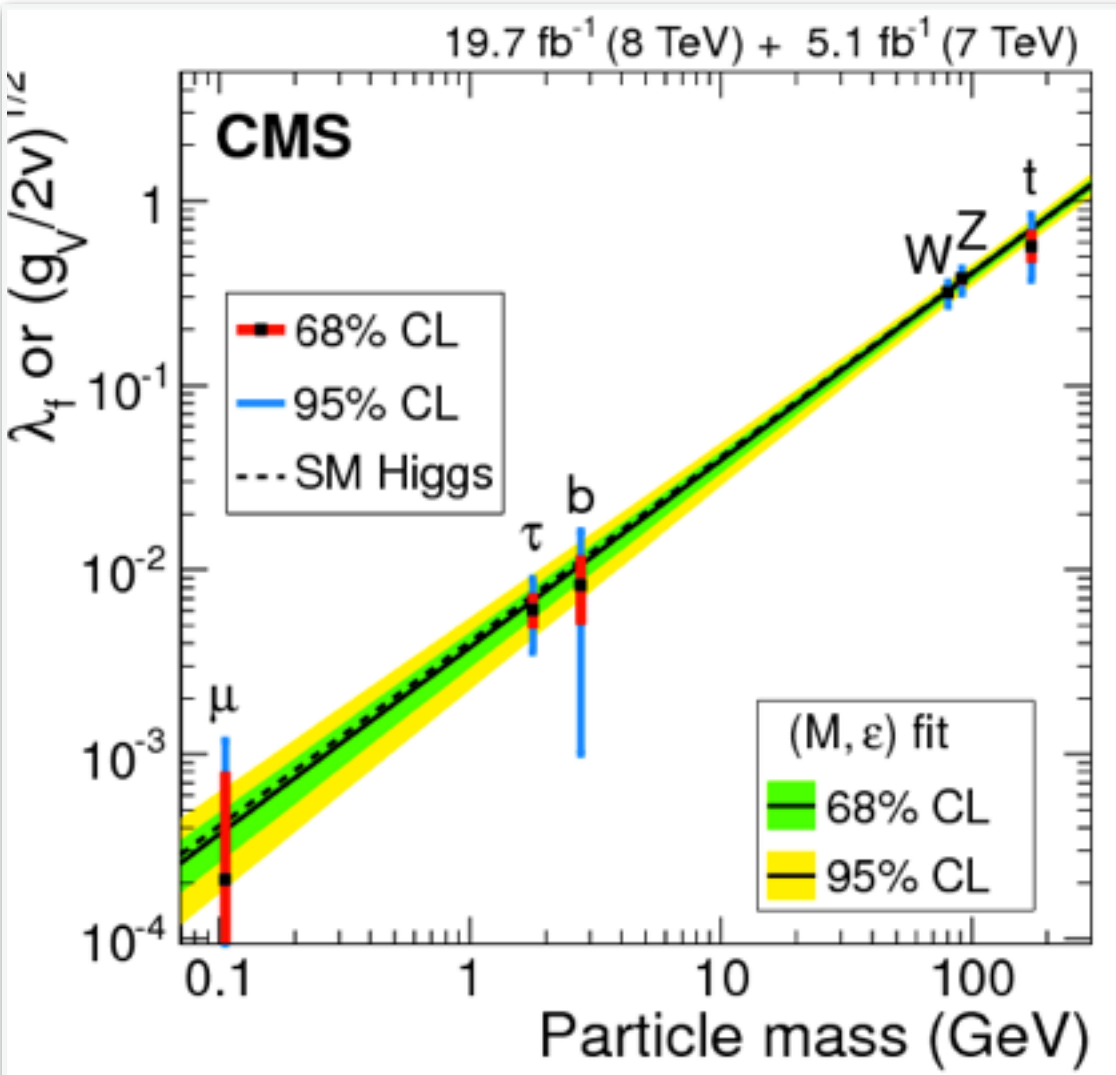
Are there new particles within the reach of LHC Run-II?

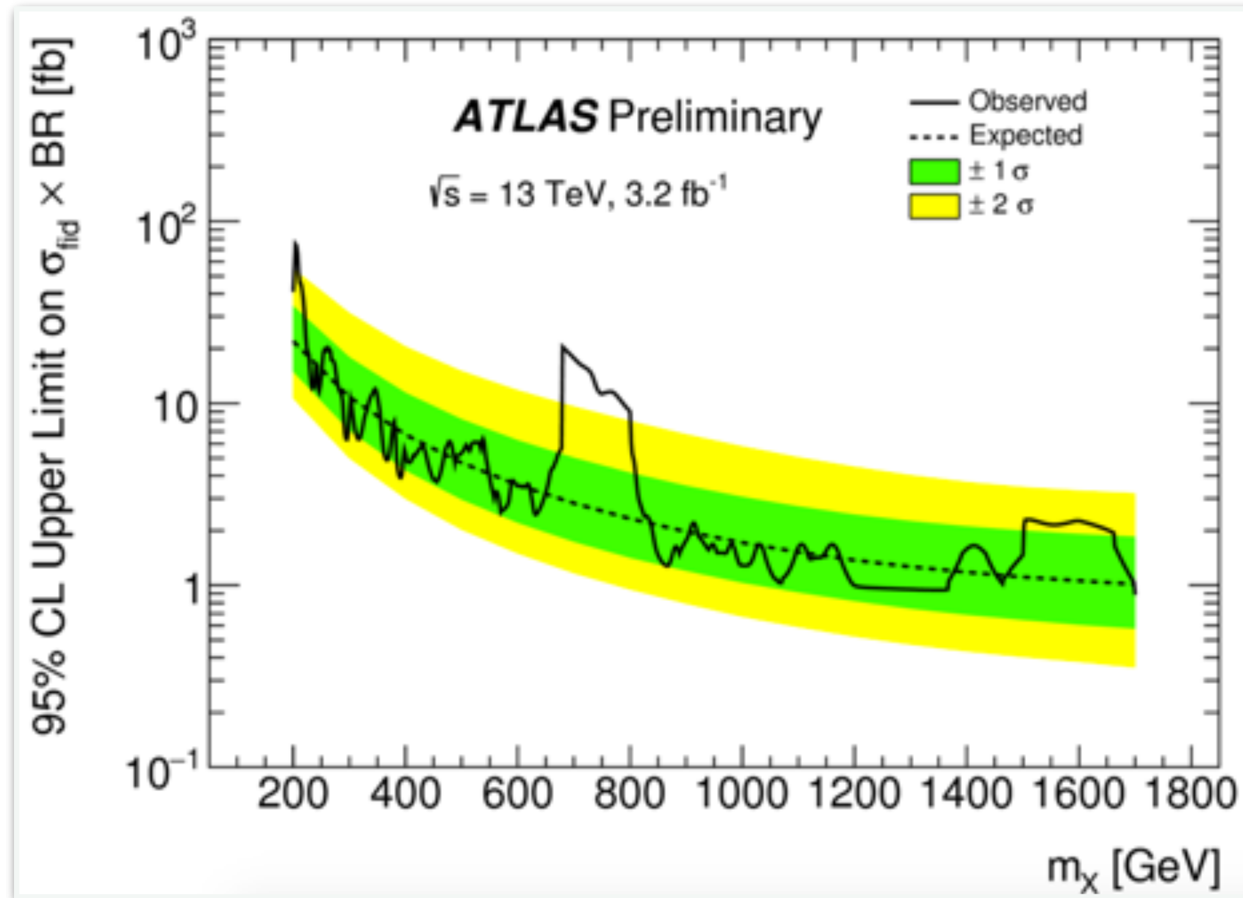
➡ Need robust search strategies not to miss any signal

➡ Need solid predictions for SM background to establish significance and characterise it



LHC physics at Run II





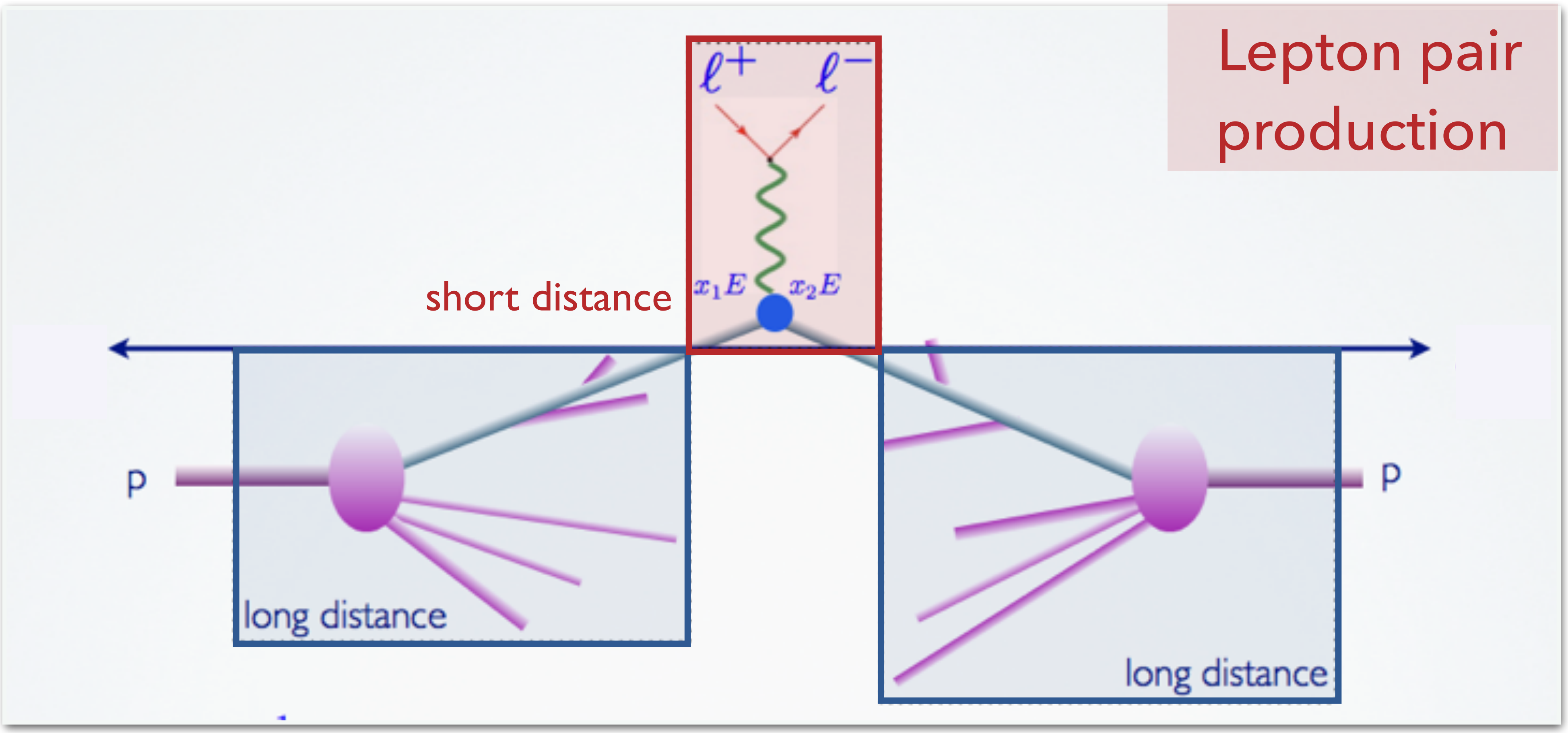
Beyond state-of-the-art theoretical predictions are the key for success

Why PDFs?

Motivation

1) PDFs are ubiquitous

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



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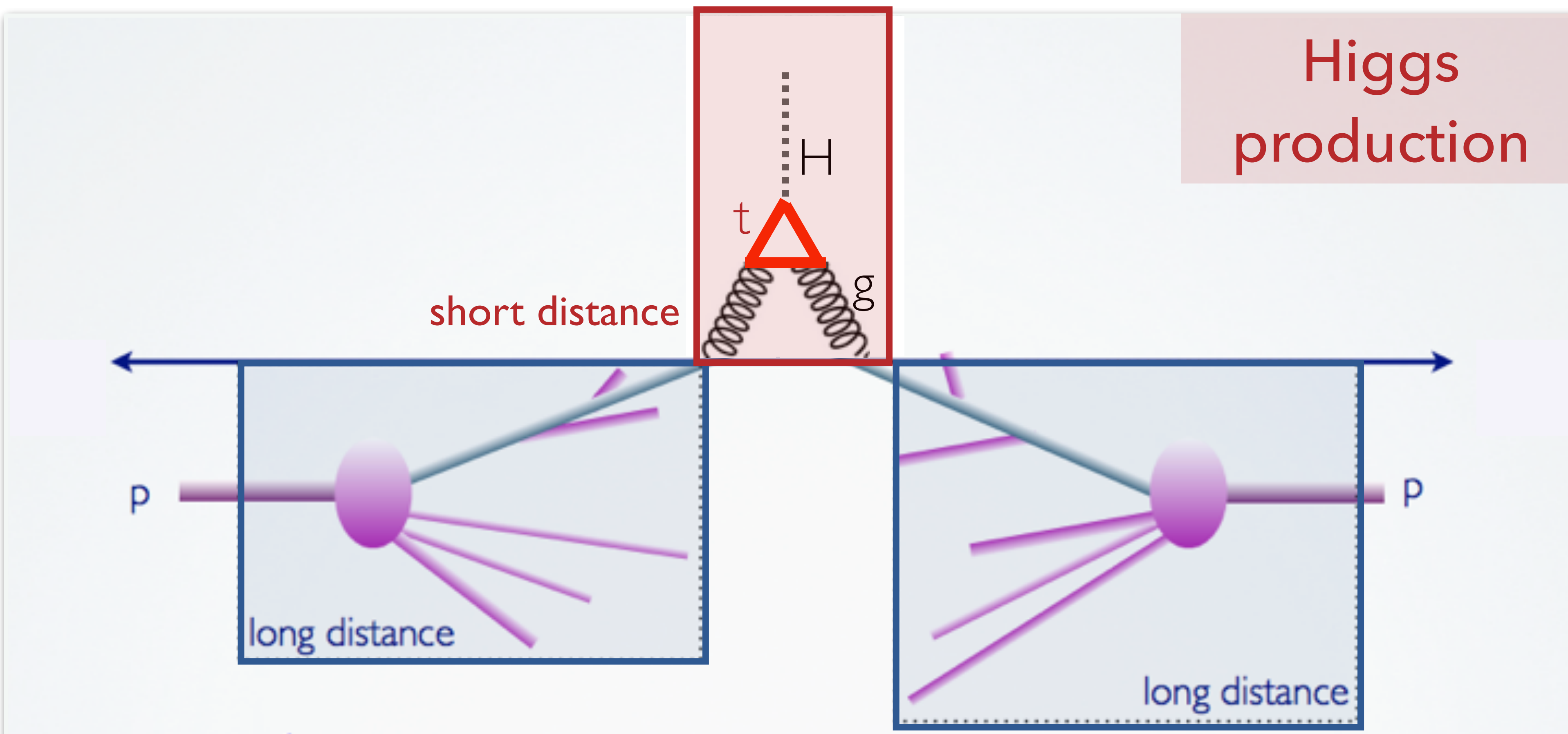
Proton Proton X-section = Parton Distribution Functions $\otimes$ Partonic X-section



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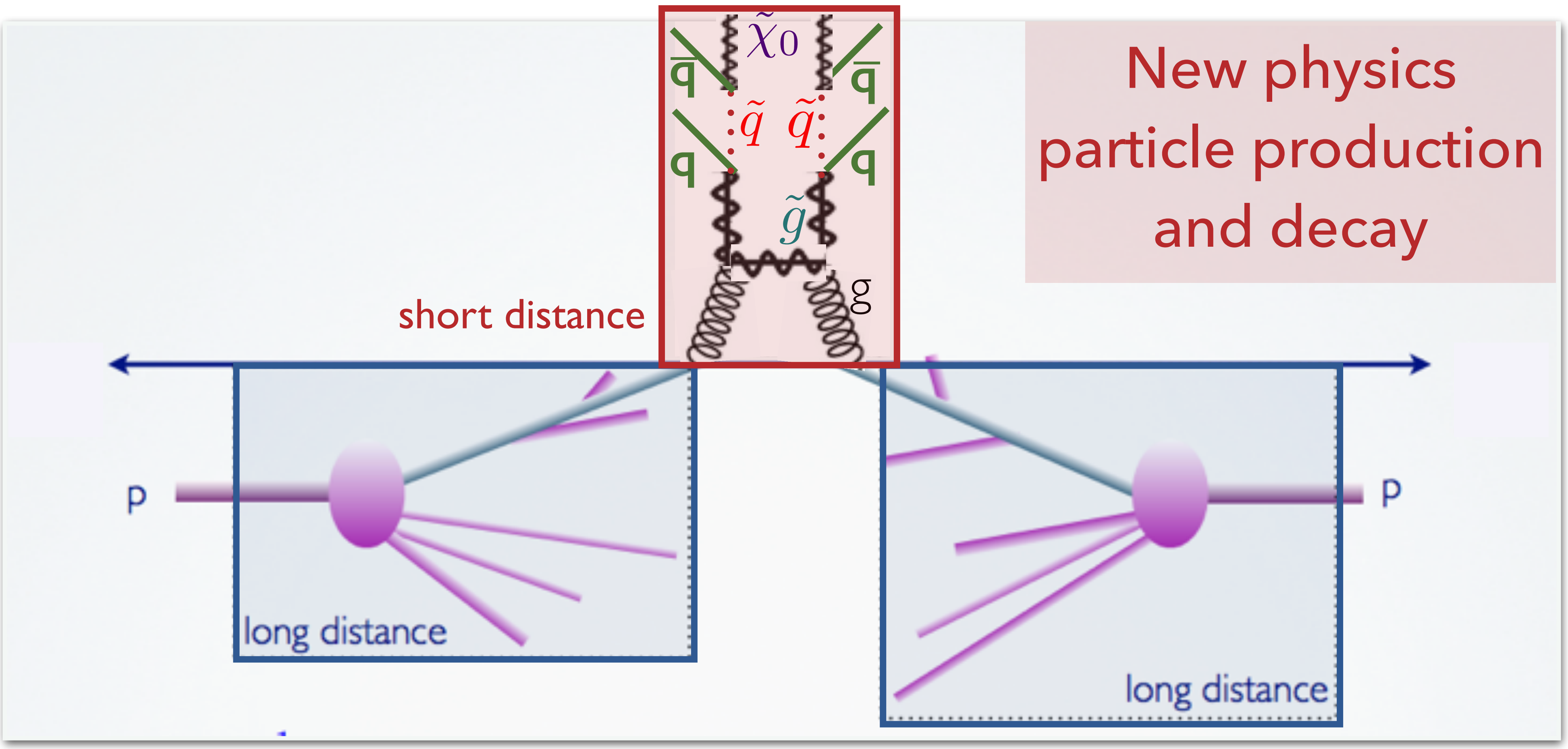
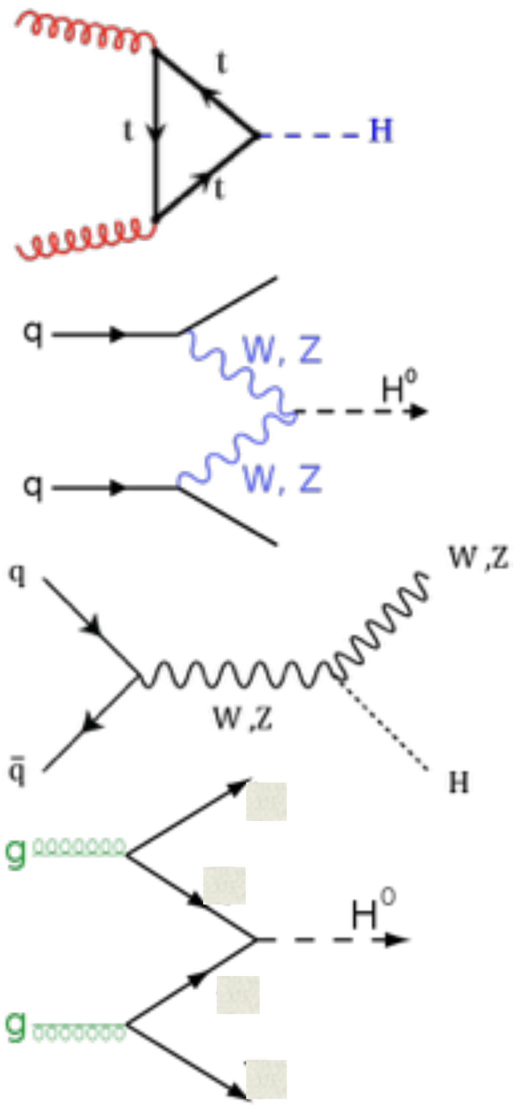
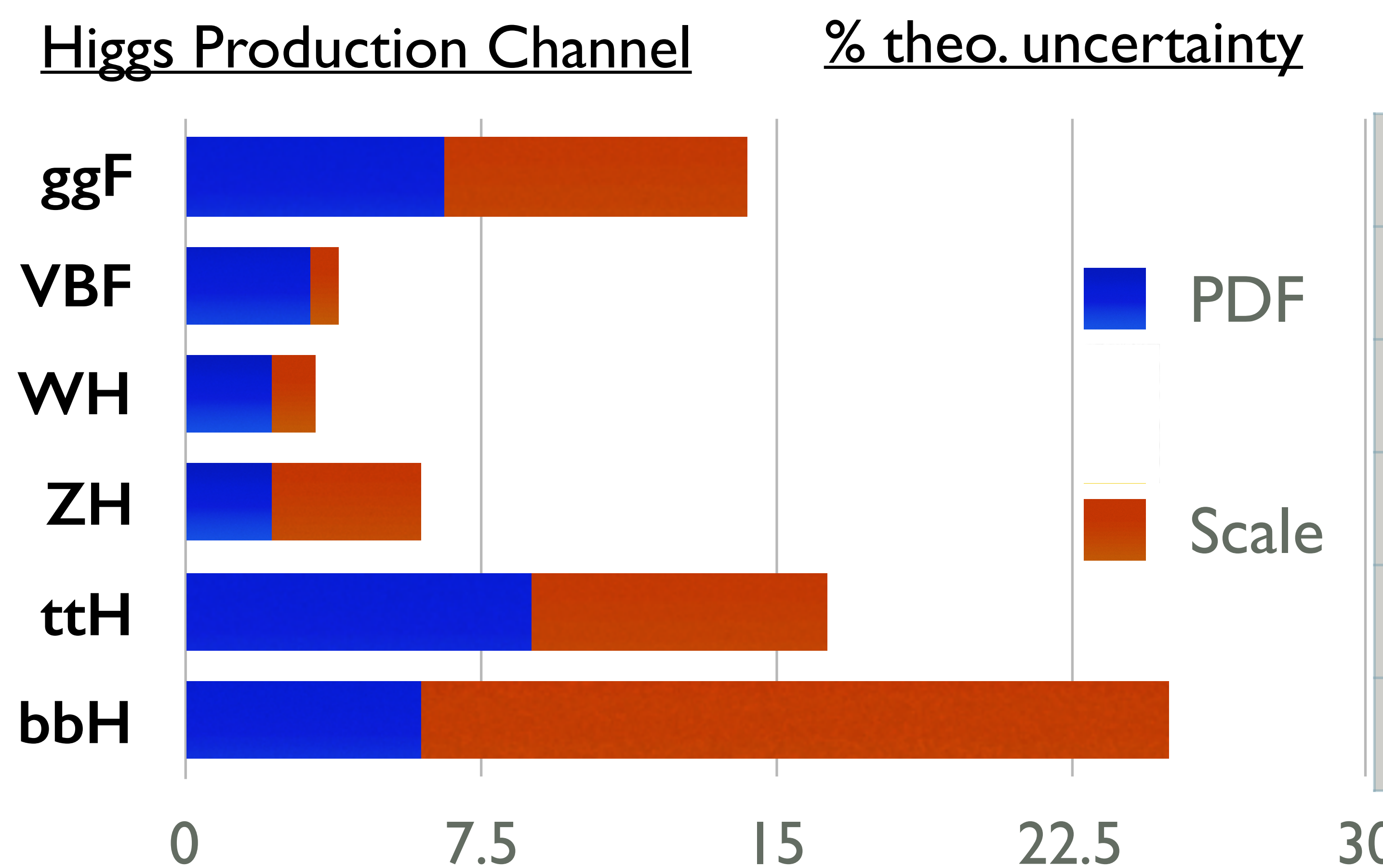


2a) The role of PDF uncertainty

Example in Higgs physics…



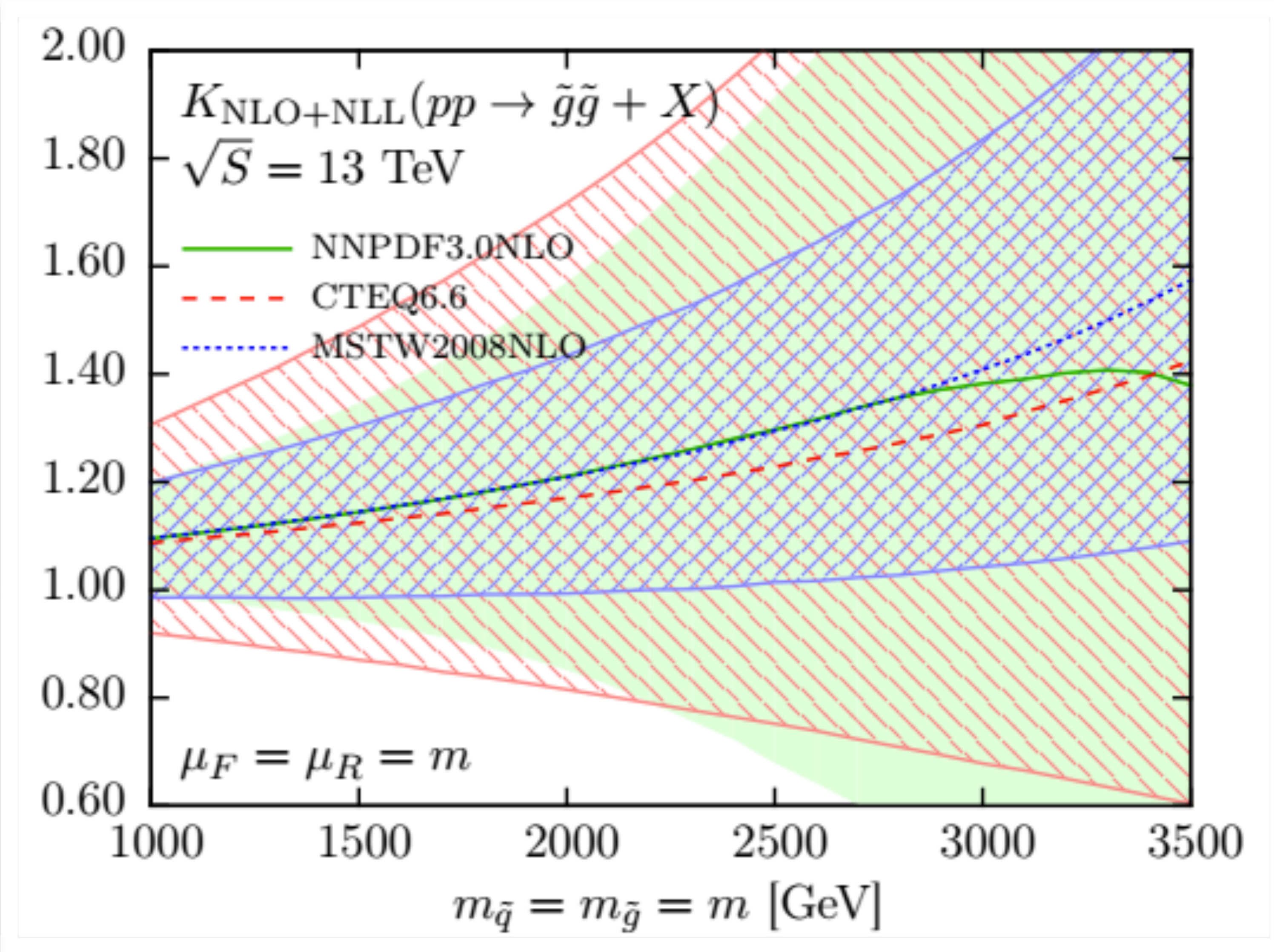


xsec @13 TeV
43.9 pb
3.75 pb
1.38 pb
0.87 pb
0.51 pb
0.51 pb

Most recent numbers from HXSWG Wiki for mH = 125 GeV

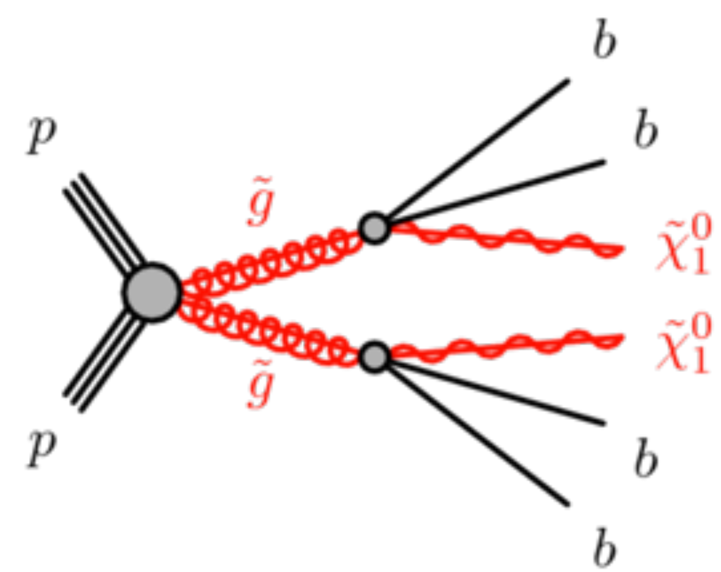
PDF uncertainties are a limiting factor in the accuracy of theoretical predictions, both within **SM** and **beyond**

2b) The role of PDF uncertainty



Beenakker et al. arXiv 1510.00375

Example in BSM physics…



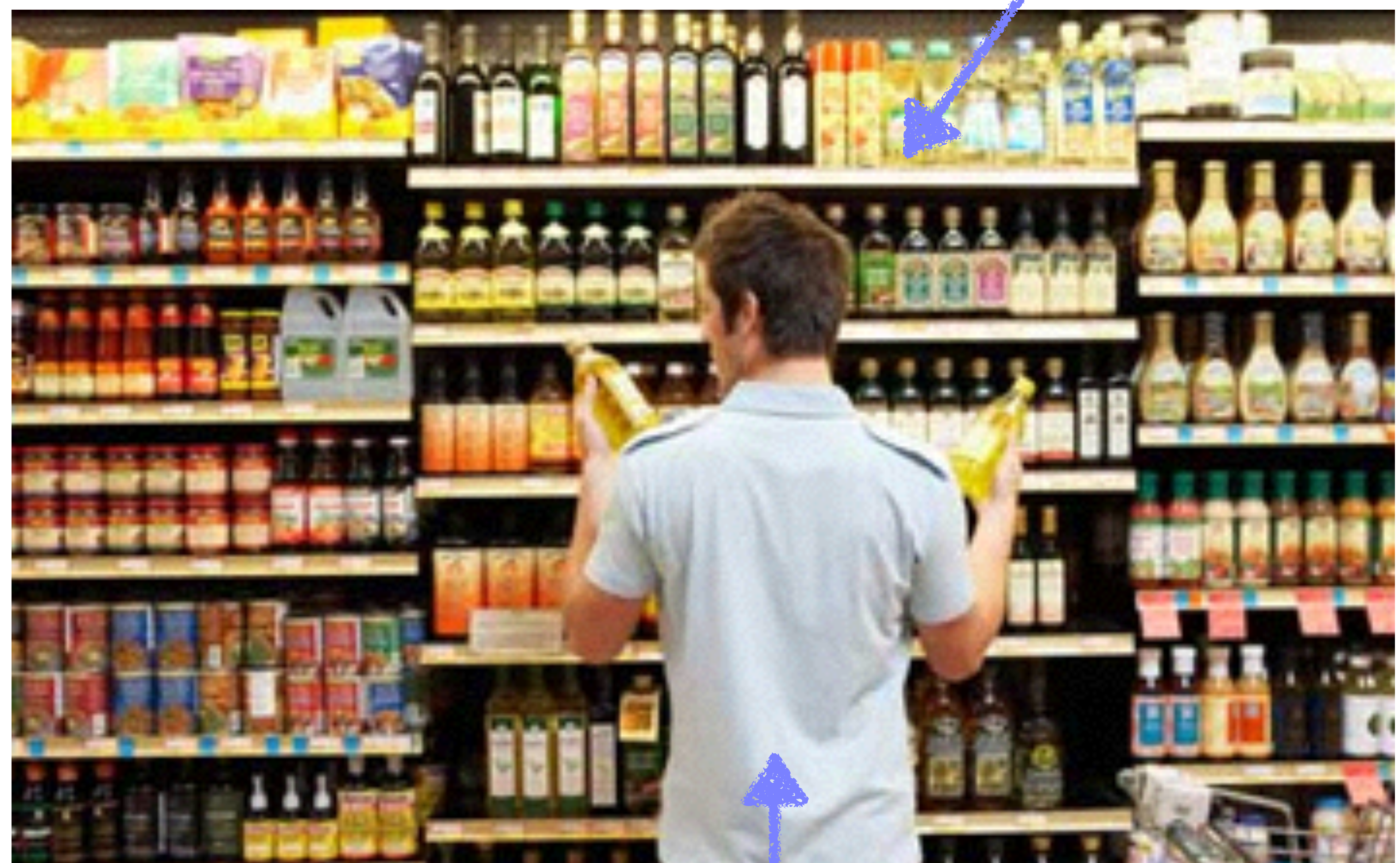
PDF uncertainties are a limiting factor in the accuracy of theoretical predictions, both within **SM** and **beyond**

3) The choice of PDFs matters

- A reliable understanding of PDF uncertainties plays a <u>crucial</u> 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?



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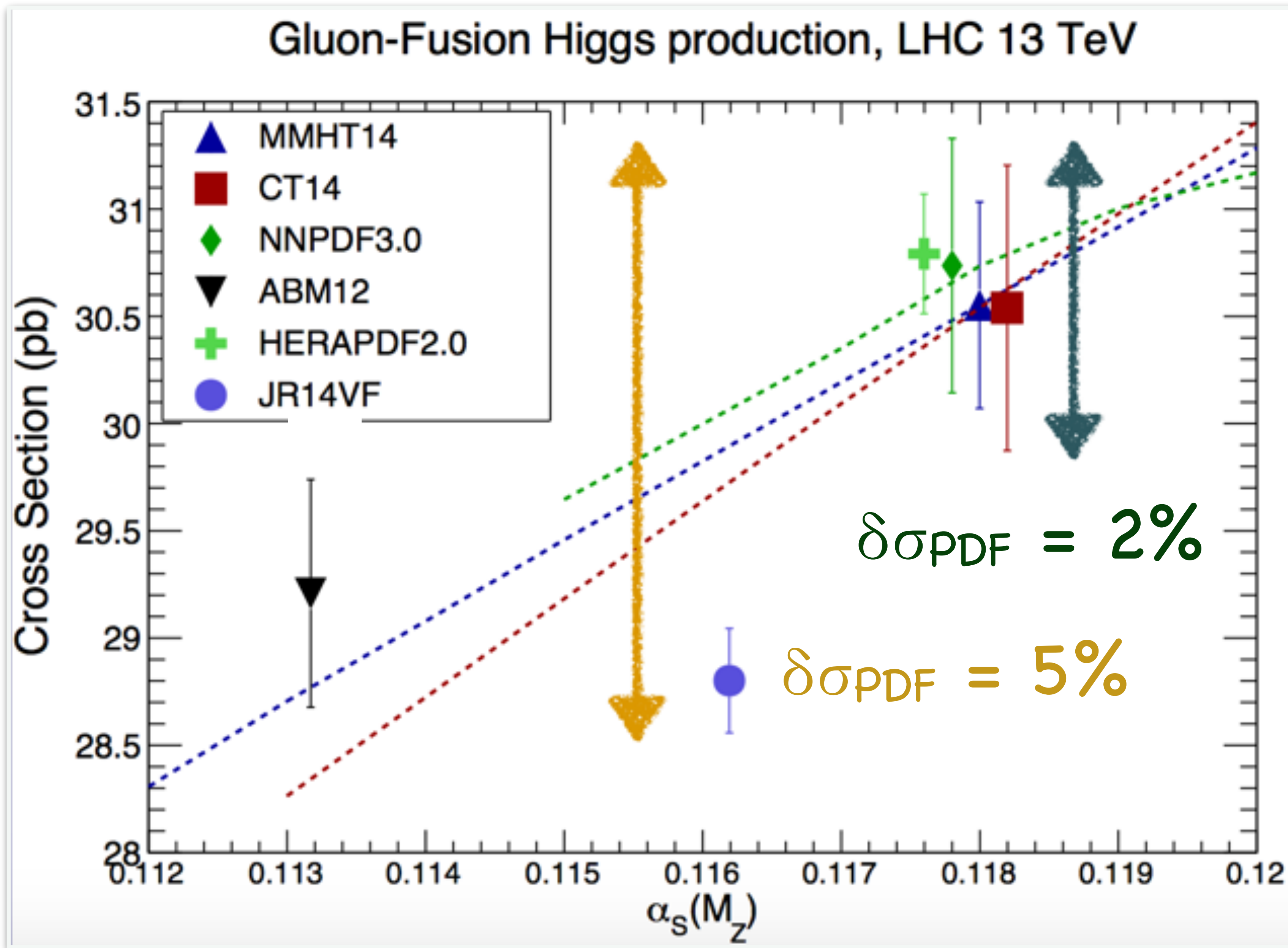

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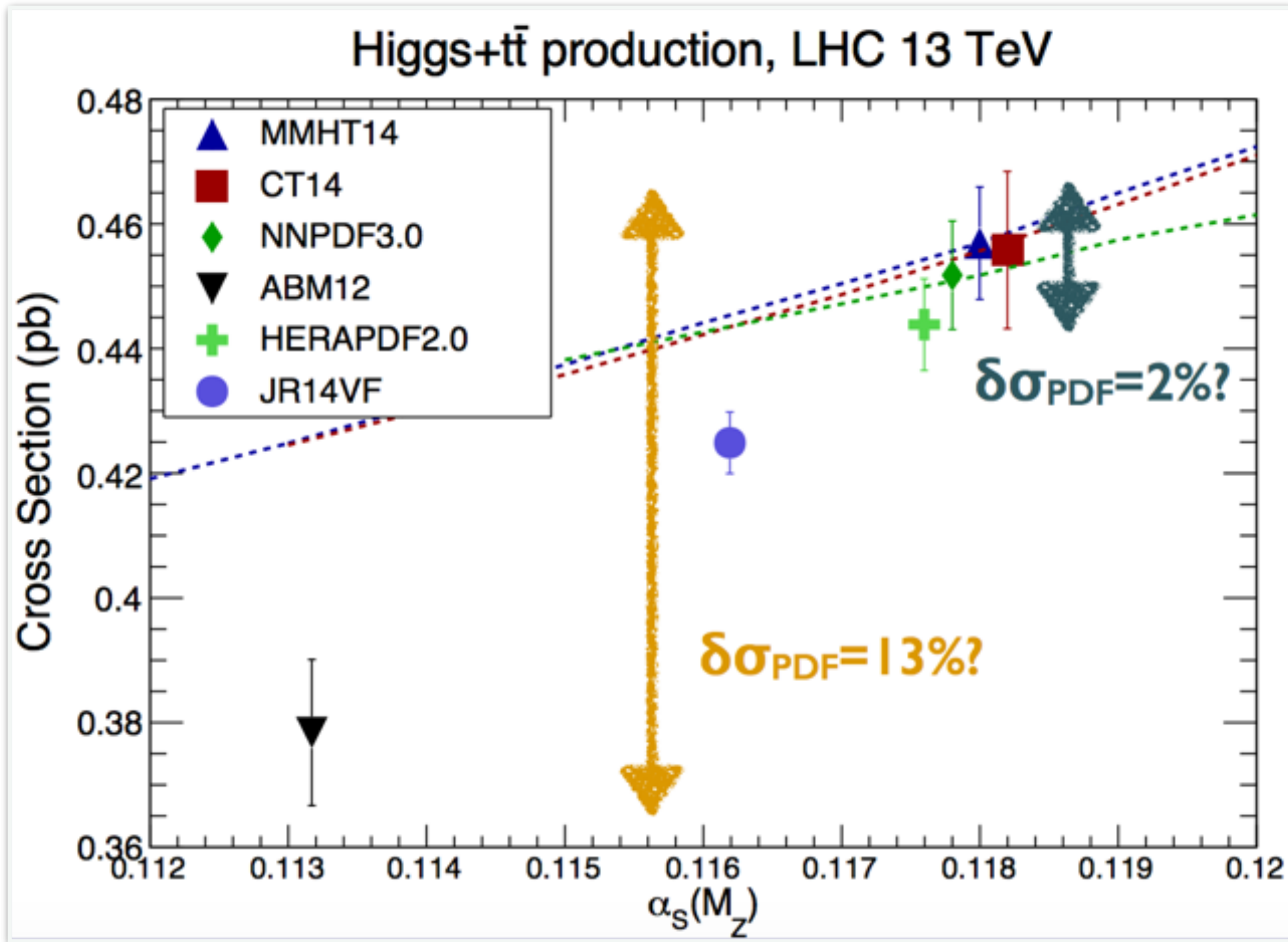
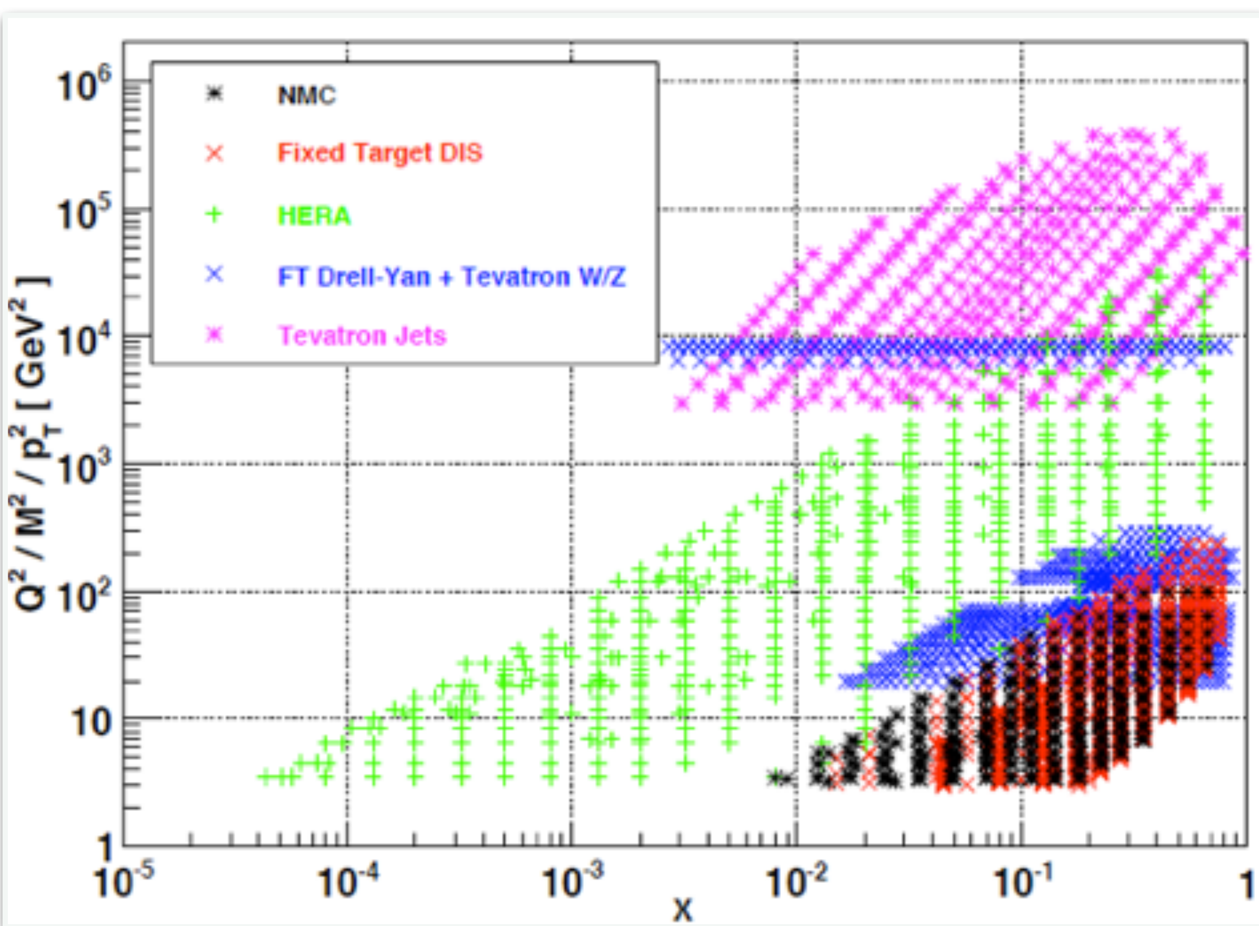


What PDFs are

Collinear Factorisation Theorem

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

Q-dependence: pert. theory



x-dependence: from data

- PDFs cannot be computed in perturbative QCD but they are universal and their evolution with Q^2 is predicted by pQCD by mean of DGLAP evolution equations
- They can be extracted from available experimental data and used as a phenomenological input for theory predictions

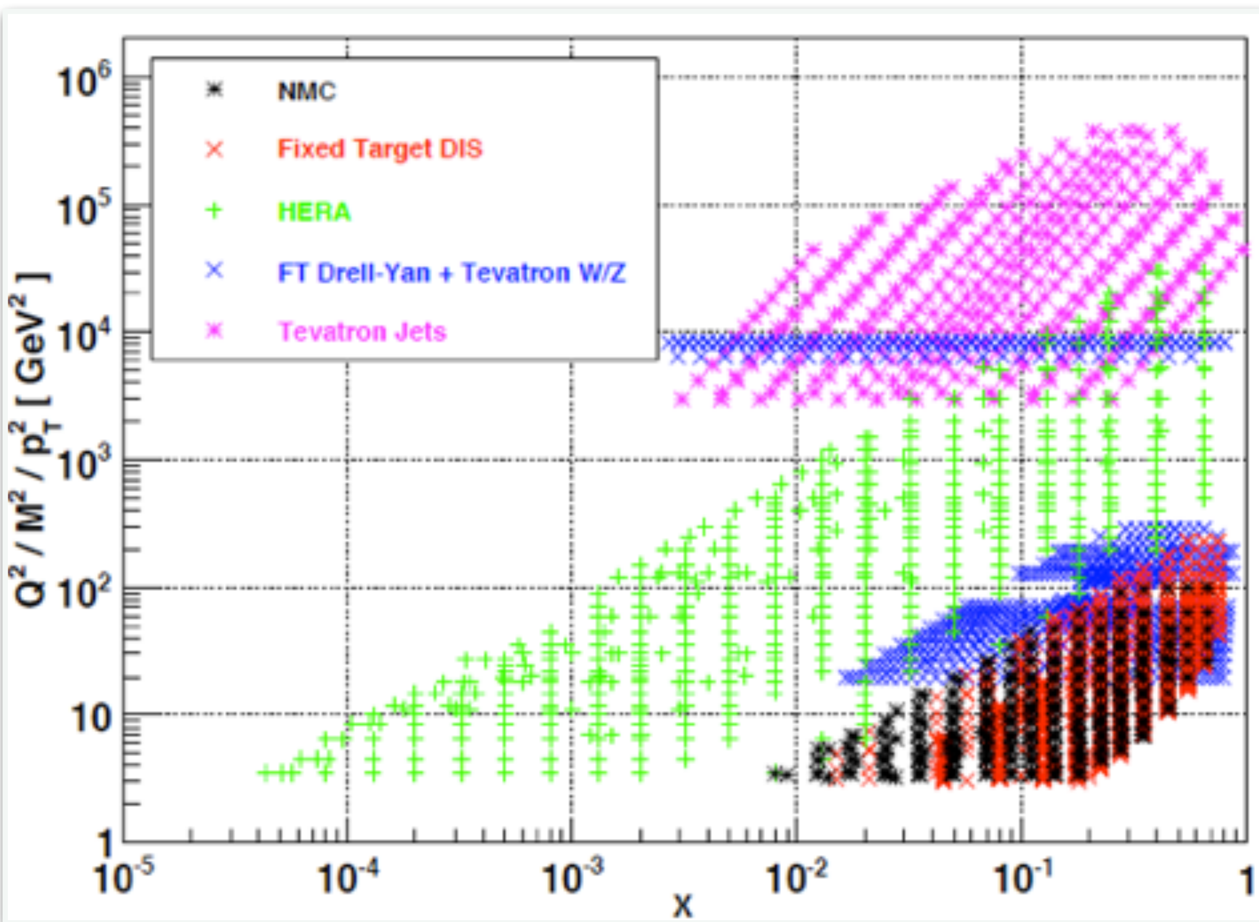
DGLAP evolution equations

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

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

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

μ-dependence: pert. theory



x-dependence: from data

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

NLO - Floratos,Ross,Sachrajda; Floratos,Lacaze,Kounnas, Gonzalez-Arroyo,Lopez,Ynduráin; 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

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

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

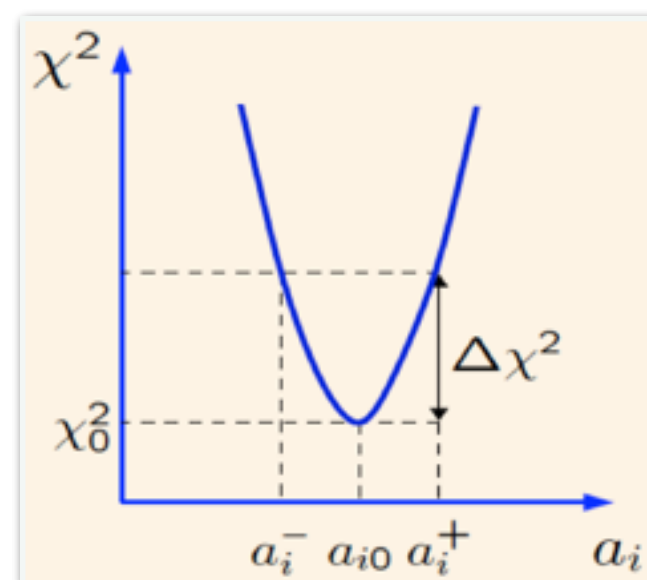
Not as simple as it may look (I)

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

- Given a finite number of experimental point want a set of functions with error
- Standard approach: project into a n-dimensional space of parameters and use linear approximation around the minimum of the χ^2 (Hessian method)

$$f_i(x, Q_0^2) = a_0\, x^{a_1}\, (1-x)^{a_2}\, P(x, a_3, a_4, \ldots)$$

- Possible issues:
  - (I) Linear approximation and Gaussian assumption
  - (II) Tolerance > 1 equivalent to blow up uncertainties



- $\Delta\chi^2 = 1$, ABKM fits and HERA (non global)
- $\Delta\chi^2 = 10$ [CT10], $\Delta\chi^2 \sim 7.5$ [MRST2001], dynamical tolerance [MSTW08], $3 < \Delta\chi^2 < 5$
- Uncertainty inflated by a factor 2/5?

Not as simple as it may look (II)

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

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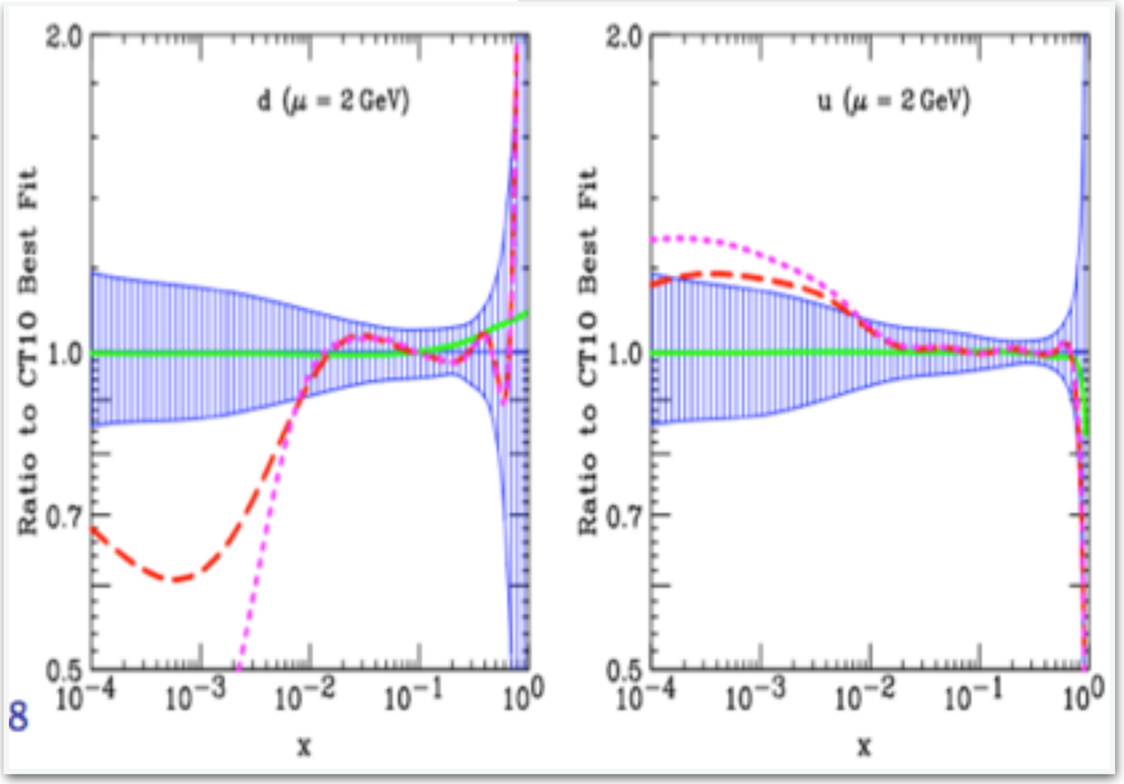
- Possible issues:

  (III) Parametrisation: what is the error associated to a given functional form? If it is not flexible enough PDFs may be not able to adapt to new data or present unrealistically small errors where data do not constrain PDF uncertainties



J. Pumplin ArXiv:0909.0268

A steady progress

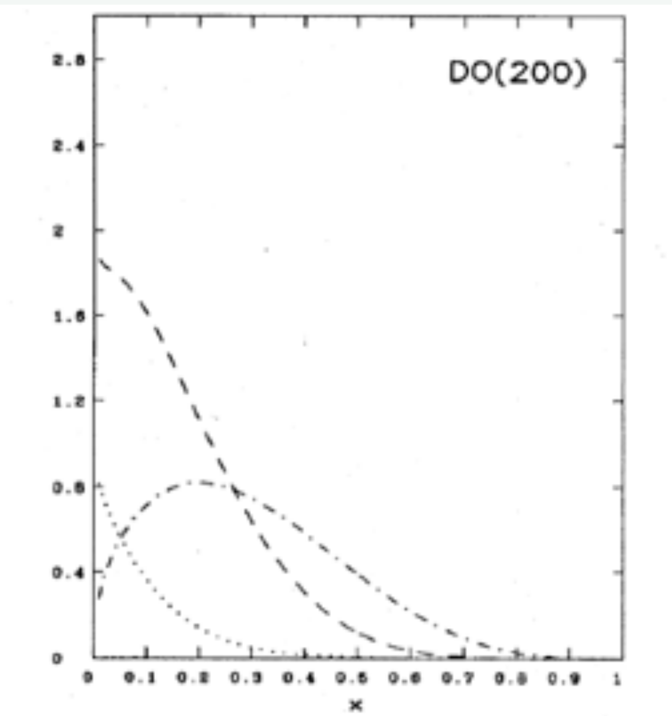
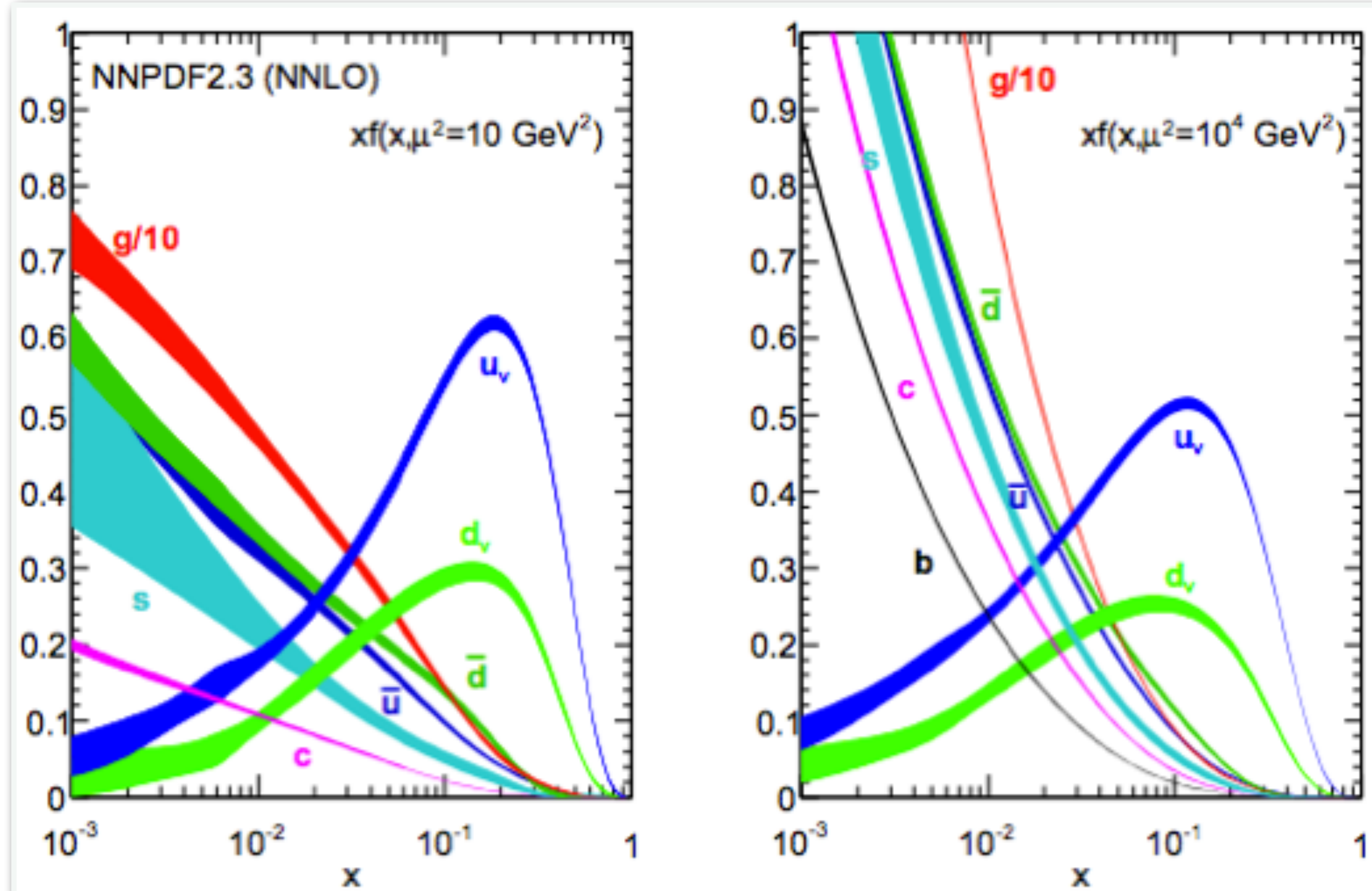


FIG. 27. "Soft-gluon" ($\Lambda = 200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2 = 5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_s(x)$ (dotted line).



PDG "Structure Functions"2013

- **< 2002**: sets without uncertainty

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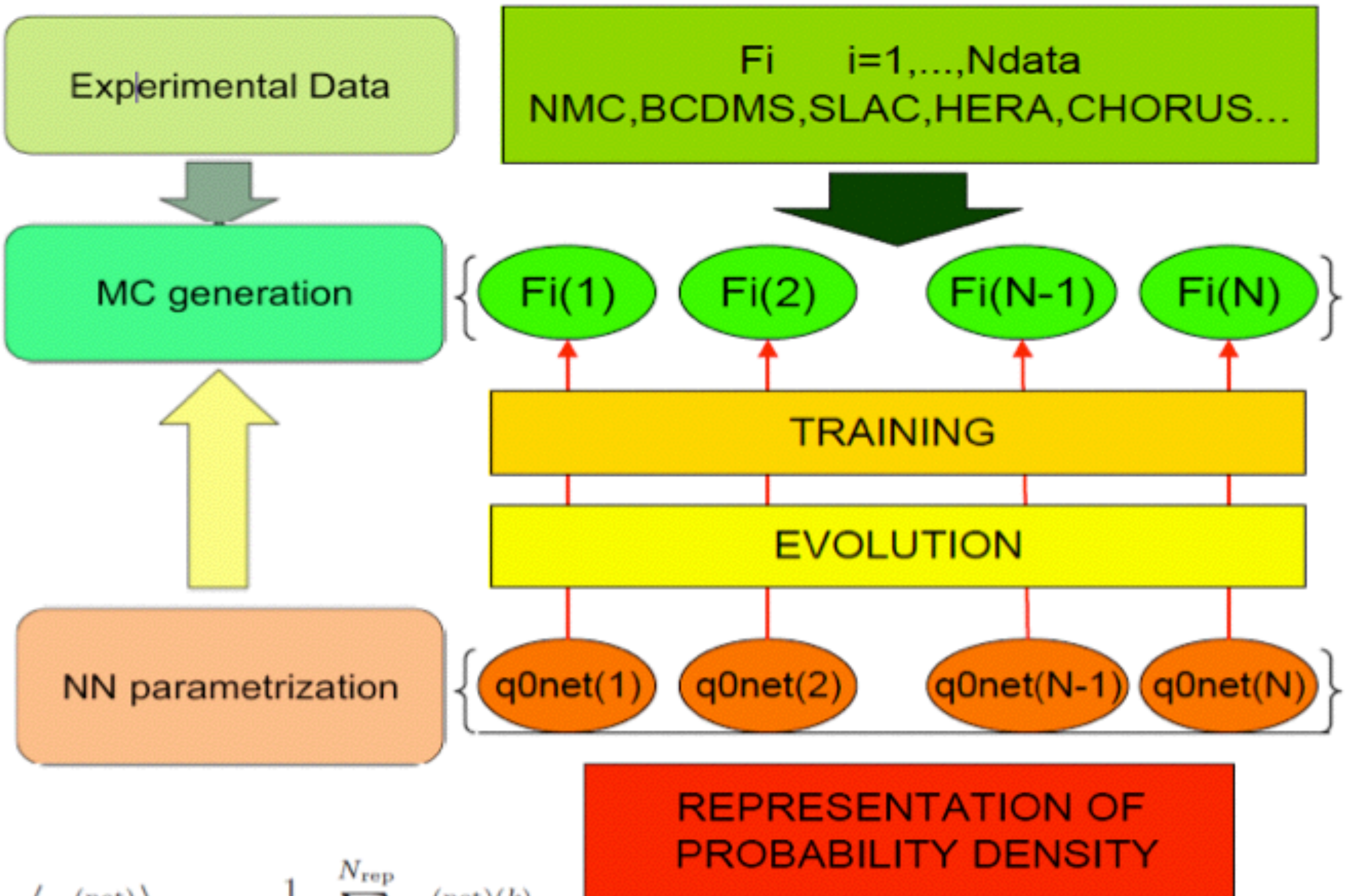
- **2003-2004:** first MRST, CTEQ, Alekhin sets with uncertainties
- **2004-now:** huge progress made in statistical and theoretical understand, new players

The NNPDF approach

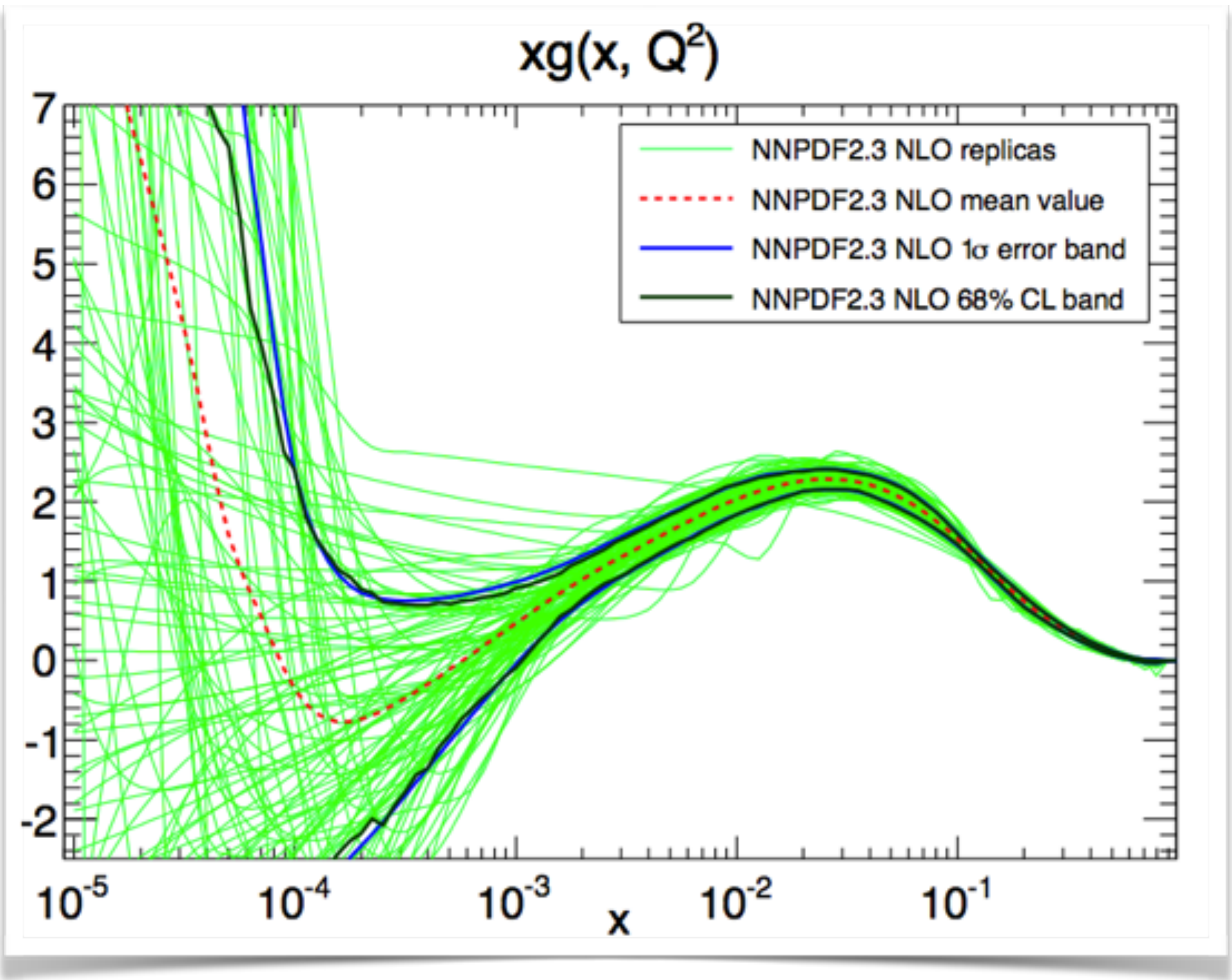
The NNPDF approach



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

Ball, Del Debbio, Forte, Guffanti, Latorre, Rojo, MU, ArXiv:0808.1231

The NNPDF approach

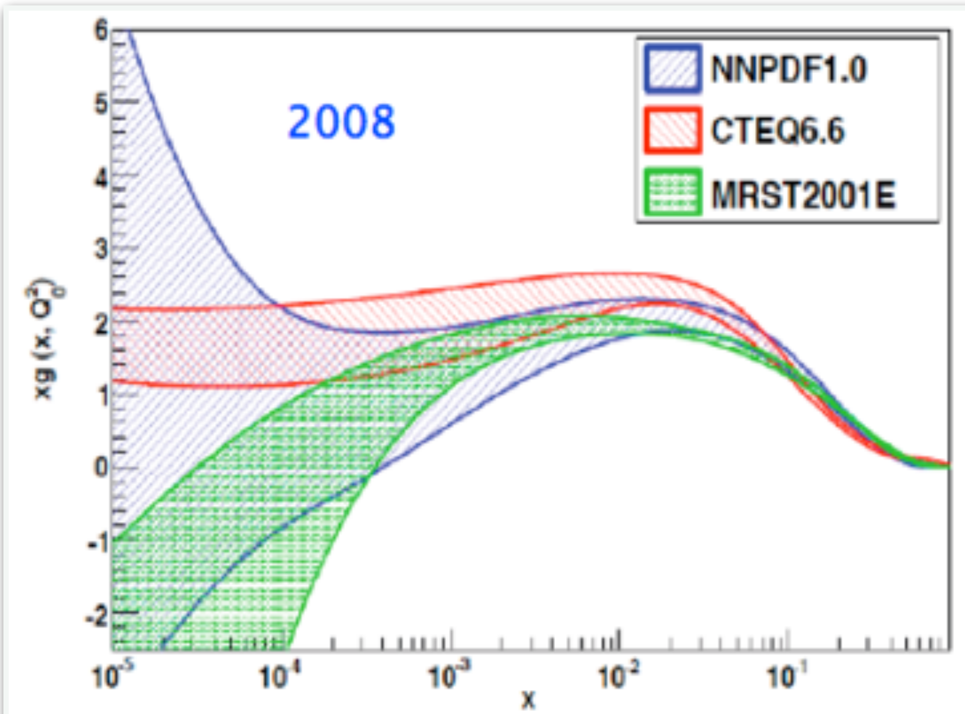


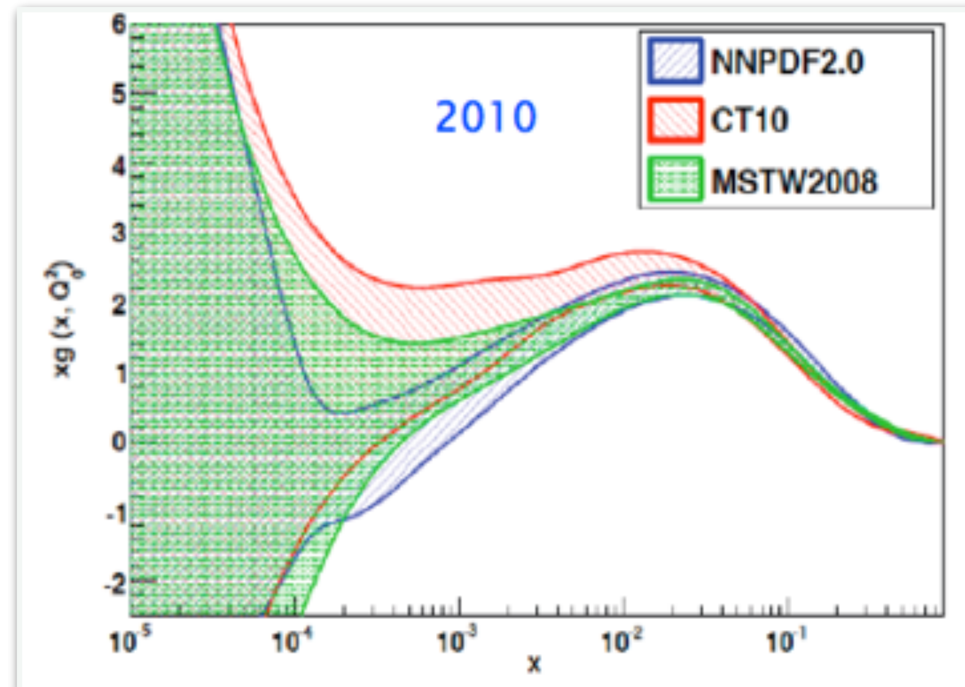
The N(eural)N(etwork)PDFs:

- 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

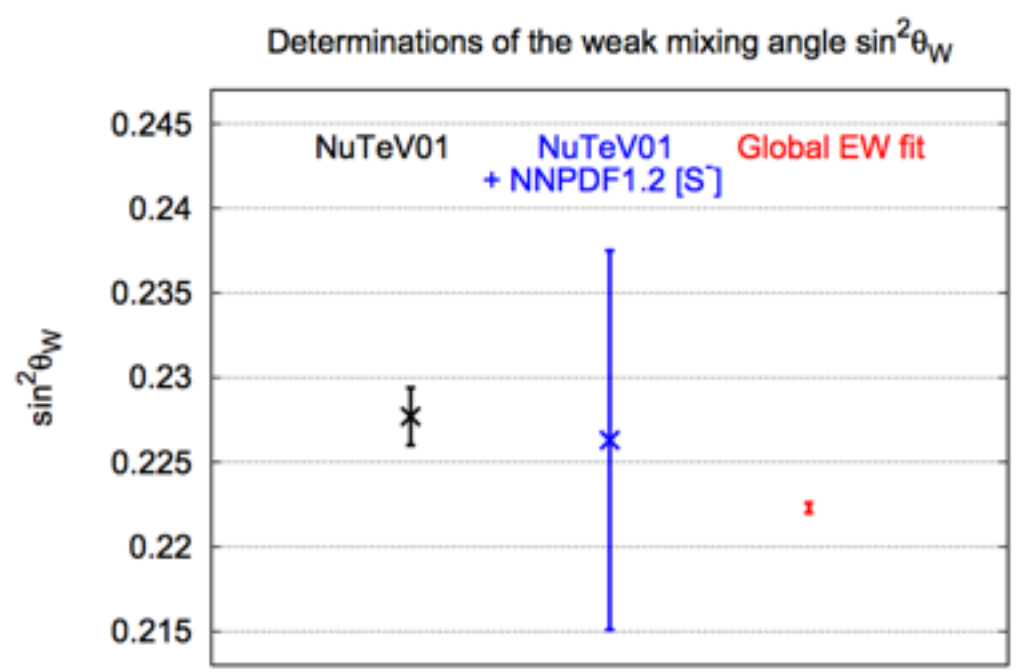
✓ Precise error estimate not driven by theoretical prejudice
✓ Statistical interpretation of uncertainty bands

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



A fast-pace growth

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

Example: resummed PDFs

fixed order

$$\frac{\sigma}{\sigma_0} = 1 \quad \text{LO}$$
$$+ c_1\alpha \quad \text{NLO}$$
$$+ c_2\alpha^2 \quad \text{NNLO}$$
$$+ \dots$$

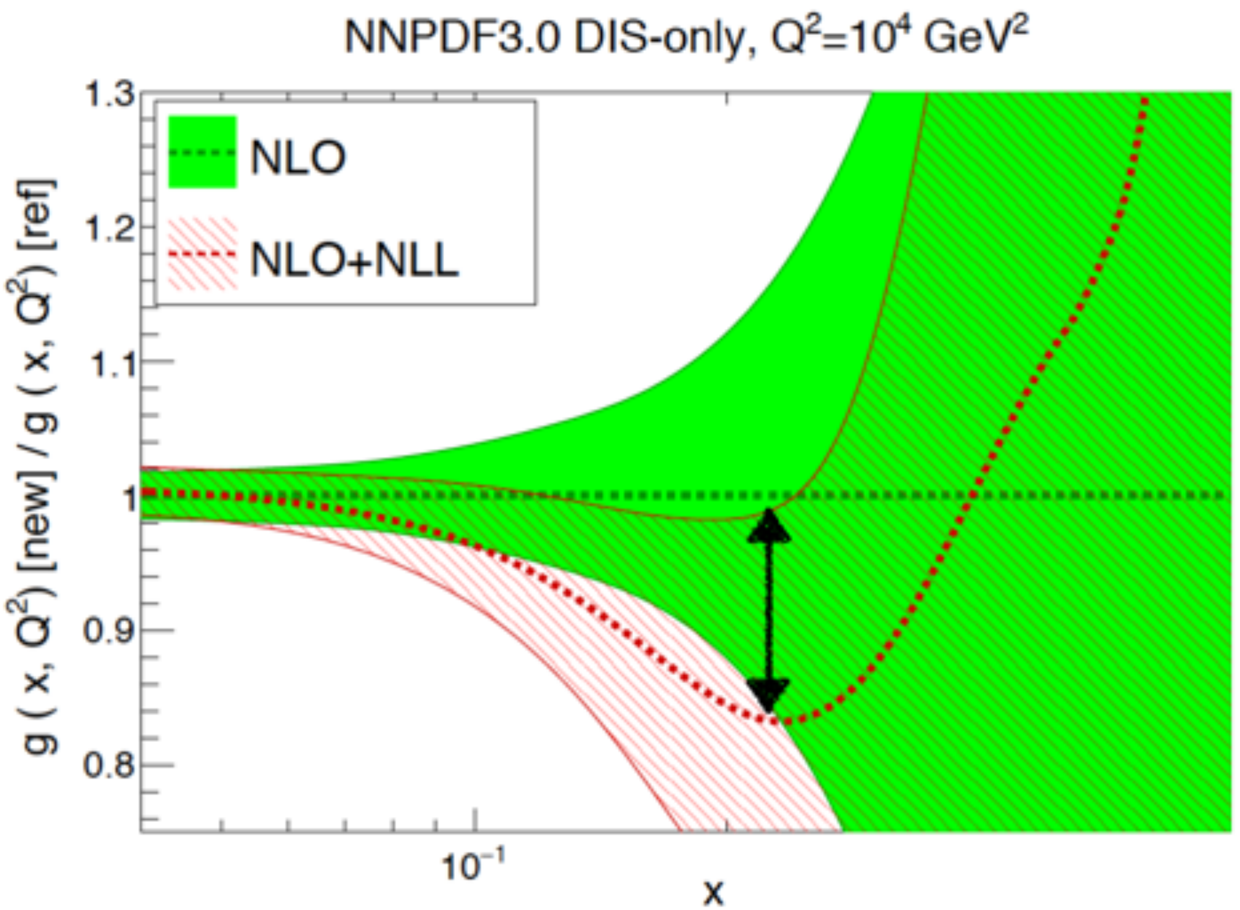
all order (L = some large logarithm)

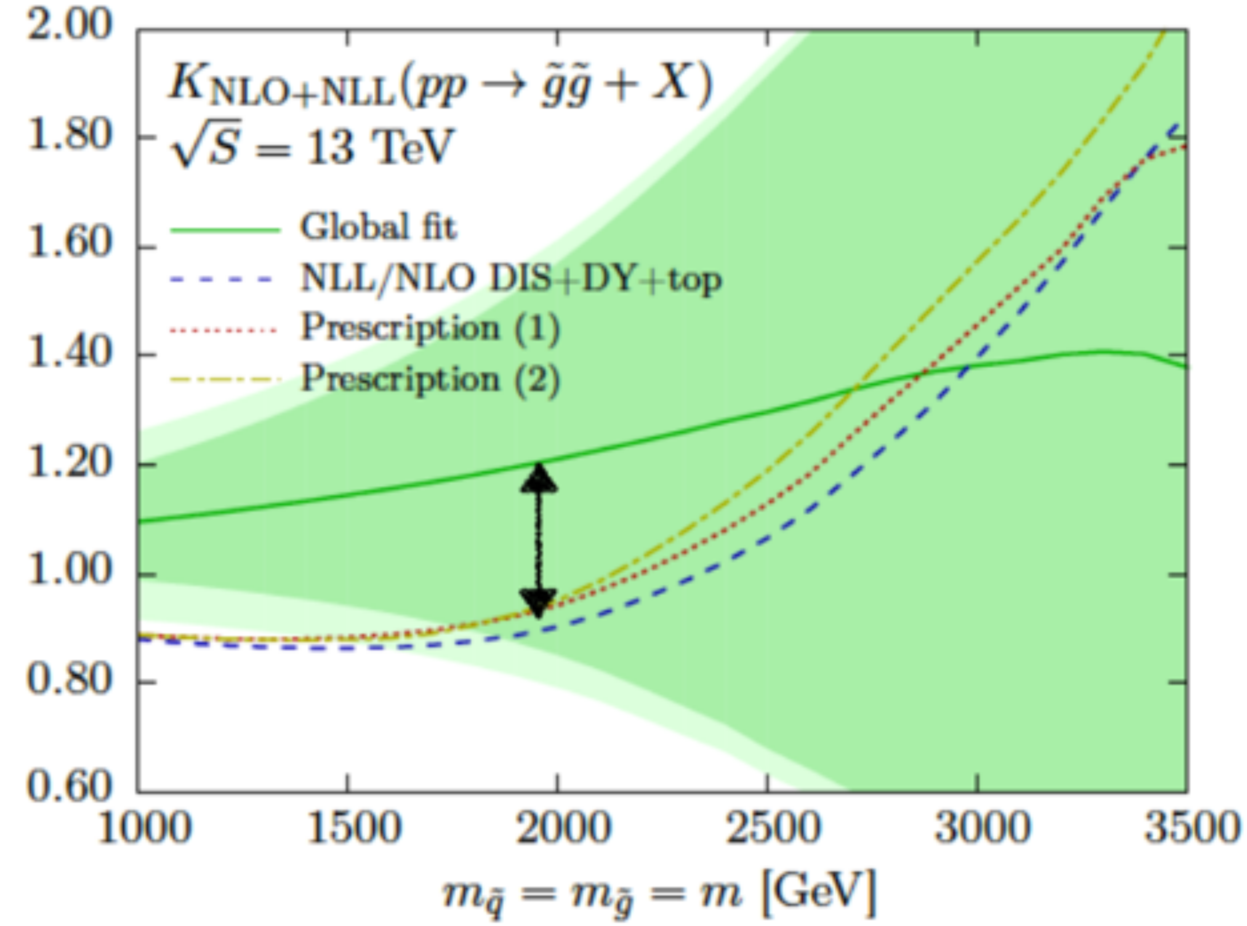
$$\ln\frac{\sigma}{\sigma_0} = \alpha^n L^{n+1} \quad \text{LL}$$
$$+ \alpha^n L^n \quad \text{NLL}$$
$$+ \alpha^n L^{n-1} \quad \text{NNLL}$$
$$+ \dots$$

- 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
L = log (pT/M) transverse momentum resummation

Example: resummed PDFs

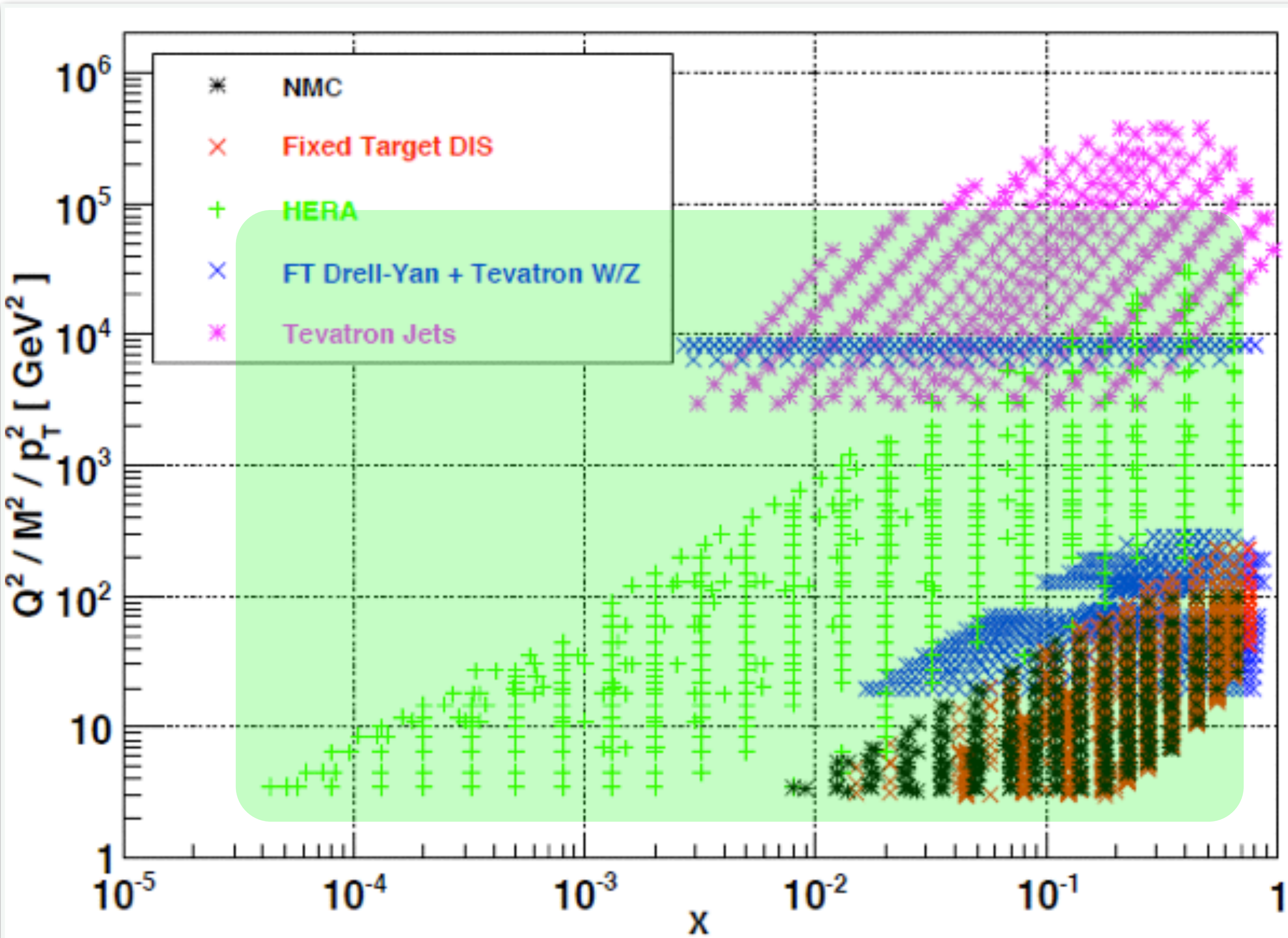




- Threshold-resummed PDFs will be suppressed as compared to fixed-order PDFs
- Mostly due to enhancement of NLO+NLL xsecs used in the fir of DIS structure functions and DY distributions
- This suppression partially or totally compensates enhancements in partonic cross sections
- Phenomenologically relevant for new physics processes

Experimental constraints and theoretical accuracy

The data (before LHC)



NC $\quad F_1^{\gamma,Z} = \sum_i e_i^2 (q_i + \bar{q}_i)$

CC $\quad F_1^{W^+} = \bar{u} + d + s + \bar{c}$

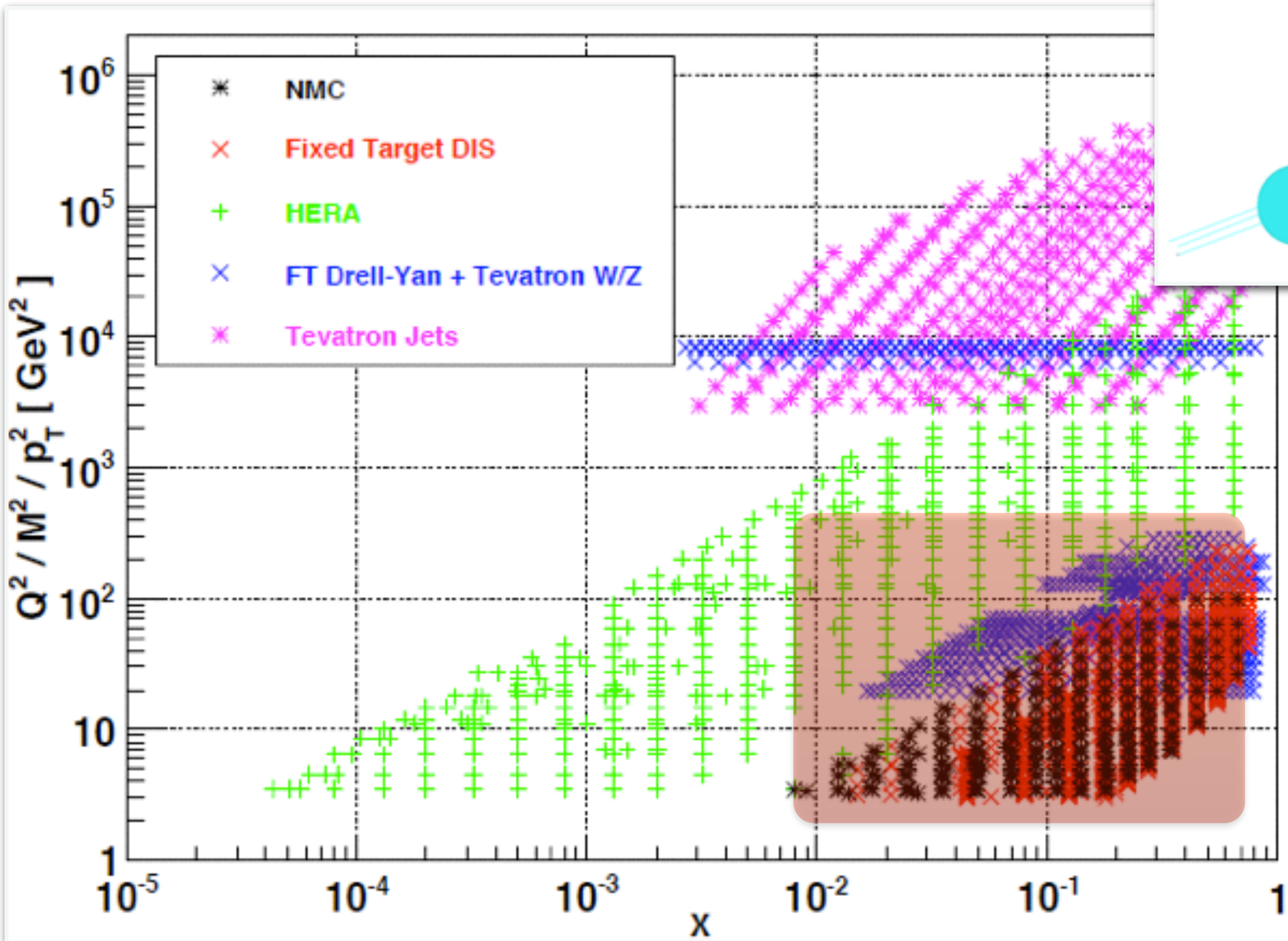
CC $\quad -F_3^{W^+}/2 = \bar{u} - d - s + \bar{c}$

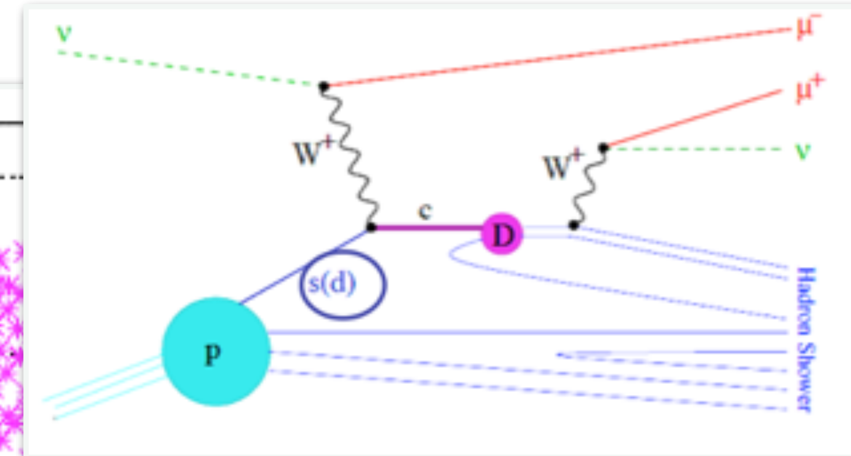
$$F_2 = 2xF_1$$

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)

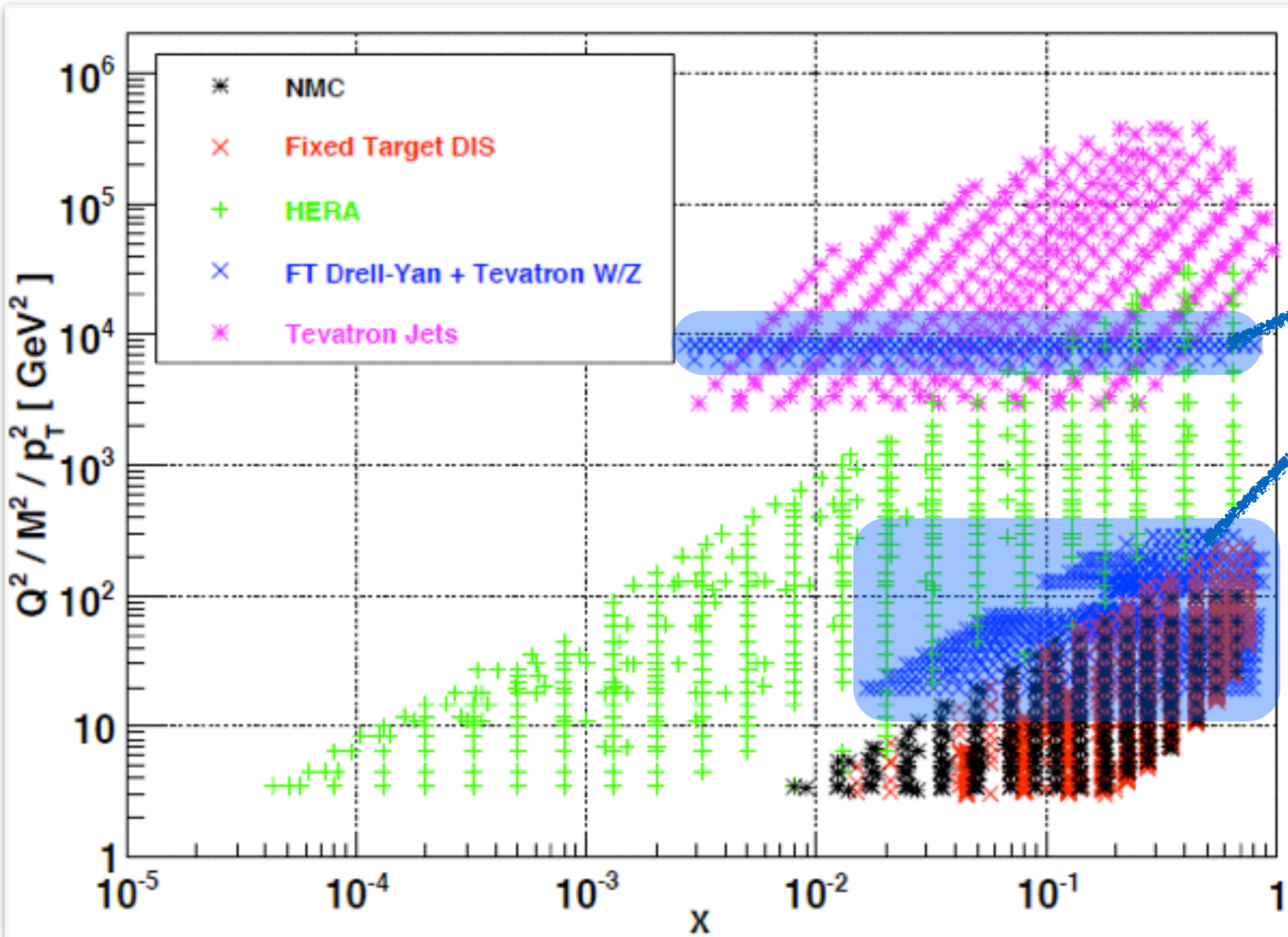


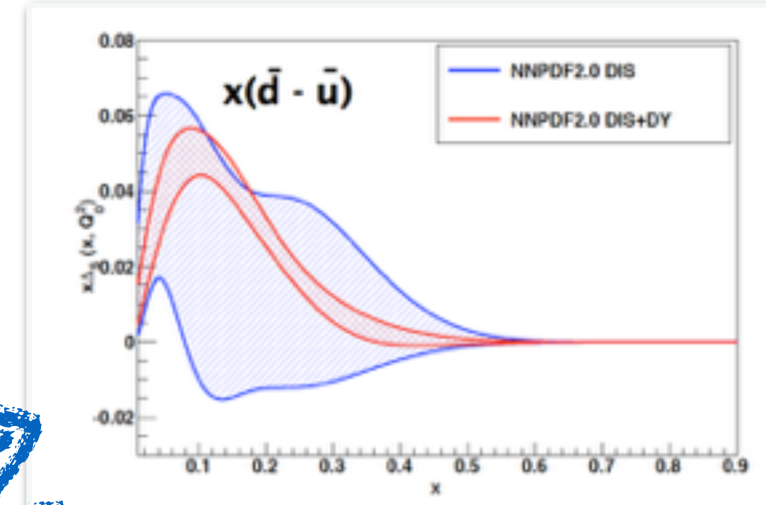


Fixed Target DIS data

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

The data (before LHC)





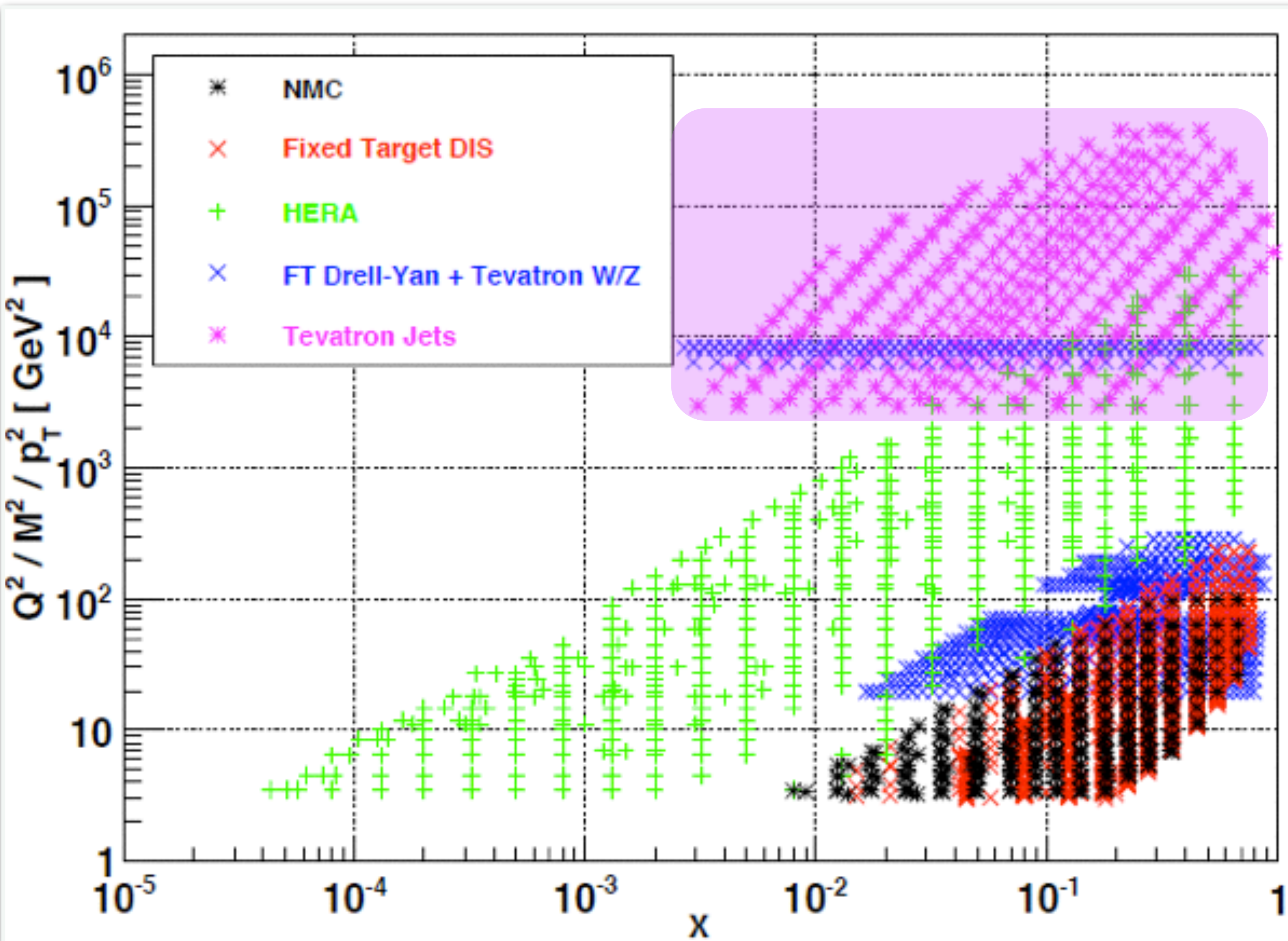
[NNPDF2.0, Ball et al, ArXiv: 1002.4407]

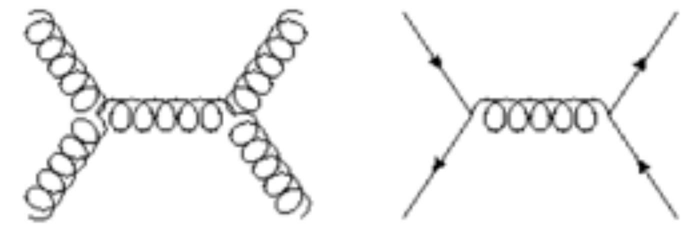
$$\sigma^{\mathrm{DY},p} \propto u(x_1)\bar{u}(x_2) + d(x_1)\bar{d}(x_2)$$
$$\sigma^{\mathrm{DY},d} \propto u(x_1)(\bar{u}+\bar{d})(x_2) + d(x_1)(\bar{u}+\bar{d})(x_2)$$

DY and EW vector boson data

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

The data (before LHC)

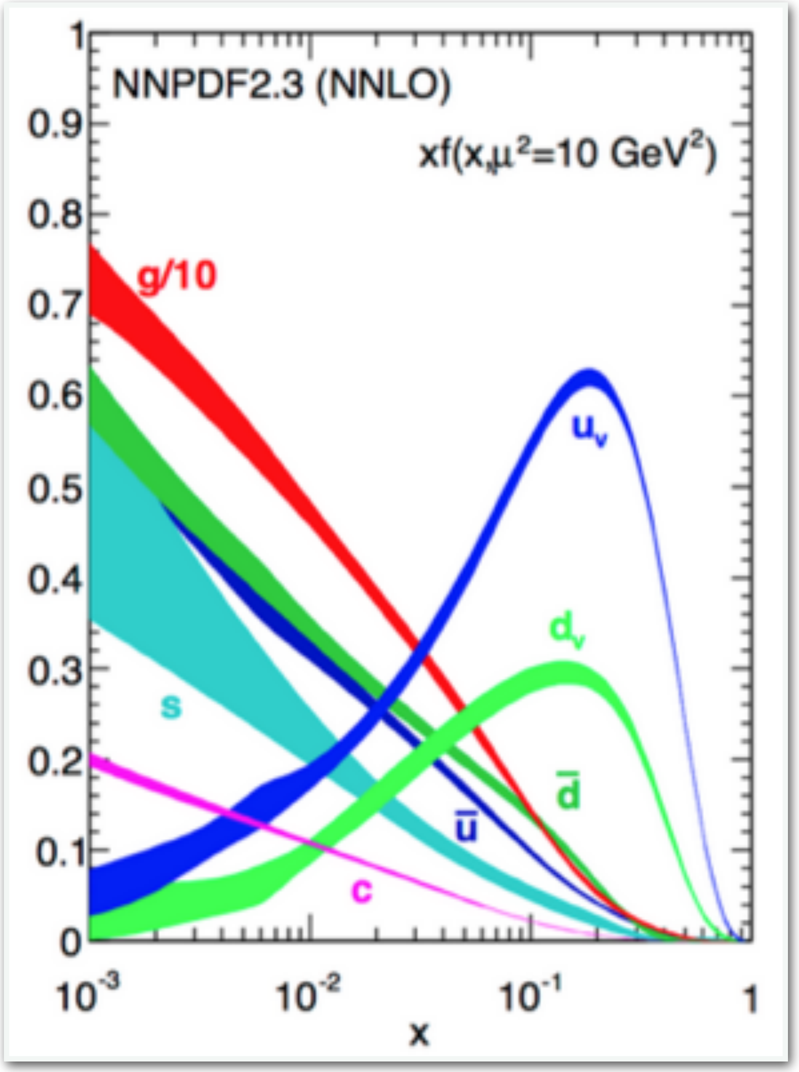


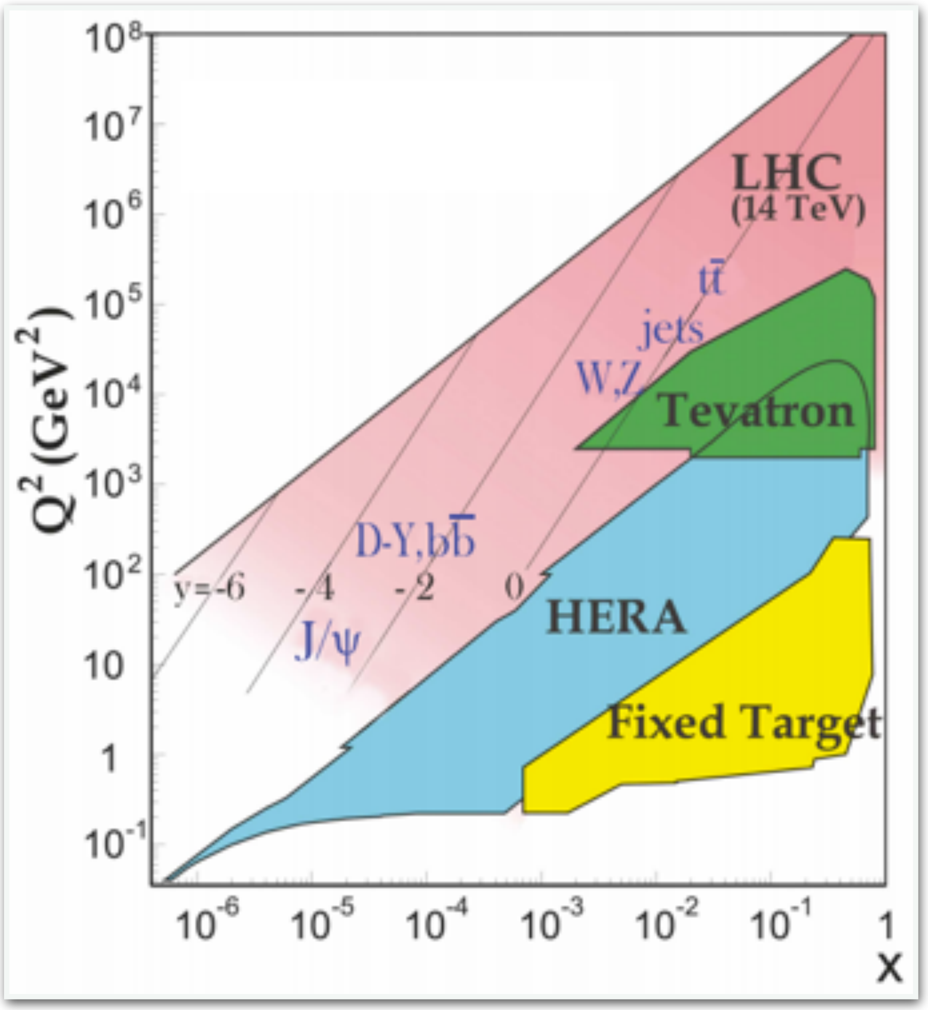


Jet data

- 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

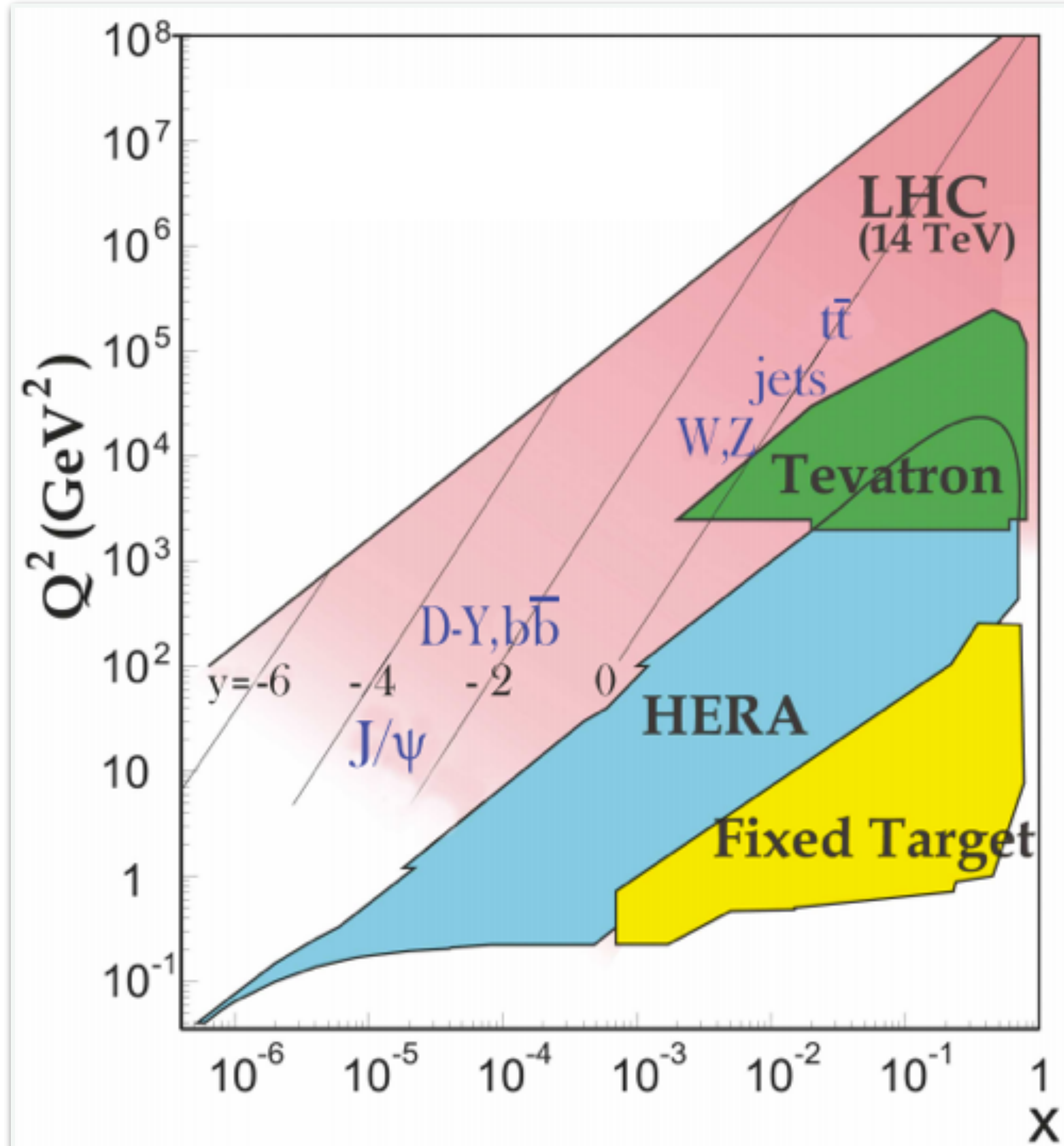
- Inclusive jets and dijets
  (medium/large x)
- Isolated photon and γ+jets
  (medium/large x)
- Top pair production **(large x)**
- High p_T V(+jets) distribution
  (small/medium x)

QUARKS

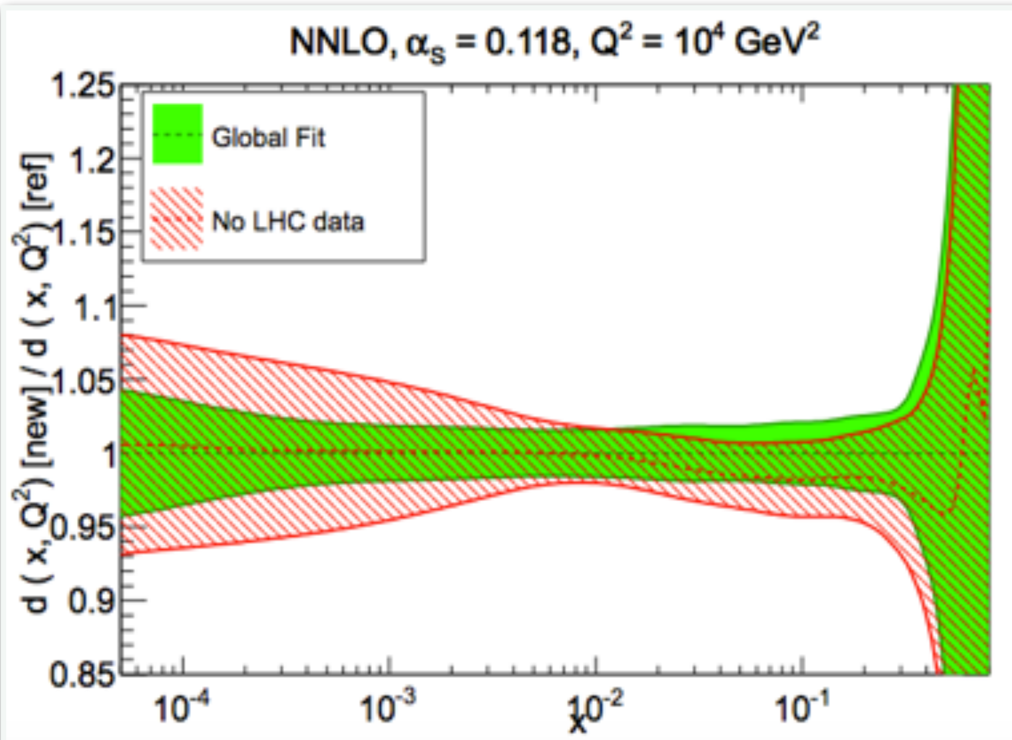
- High p_T W(+jets) ratios
  (medium/large x)
- W and Z production
  (medium x)
- Low and high mass Drell-Yan
  (small and large x)
- Wc **(strangeness at medium x)**

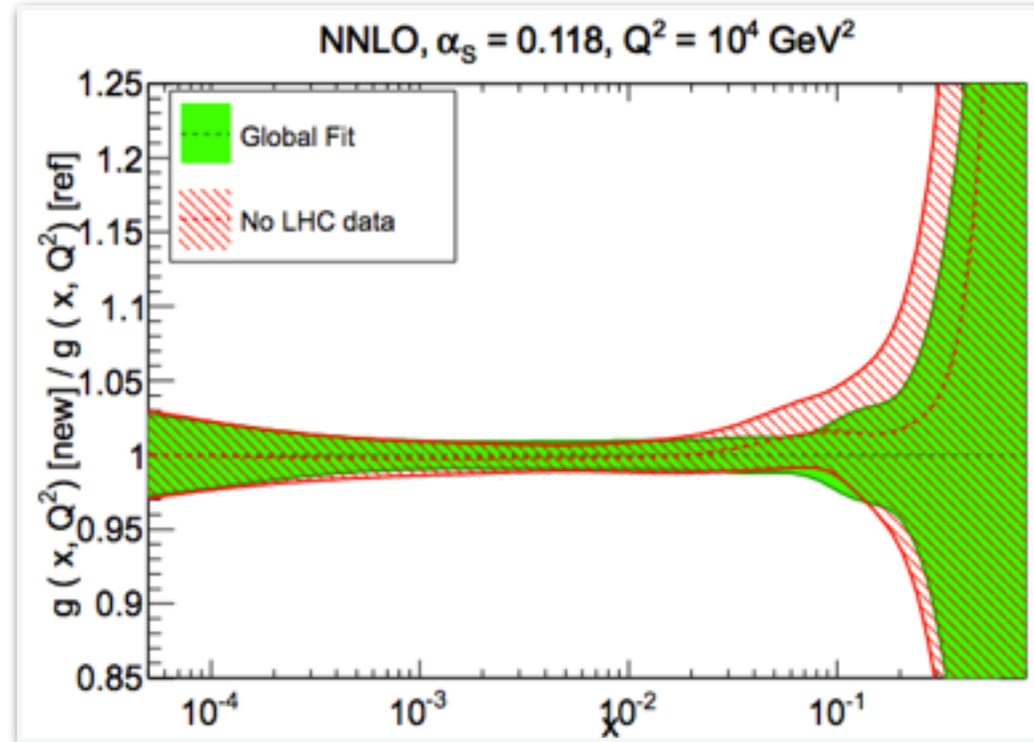
PHOTON

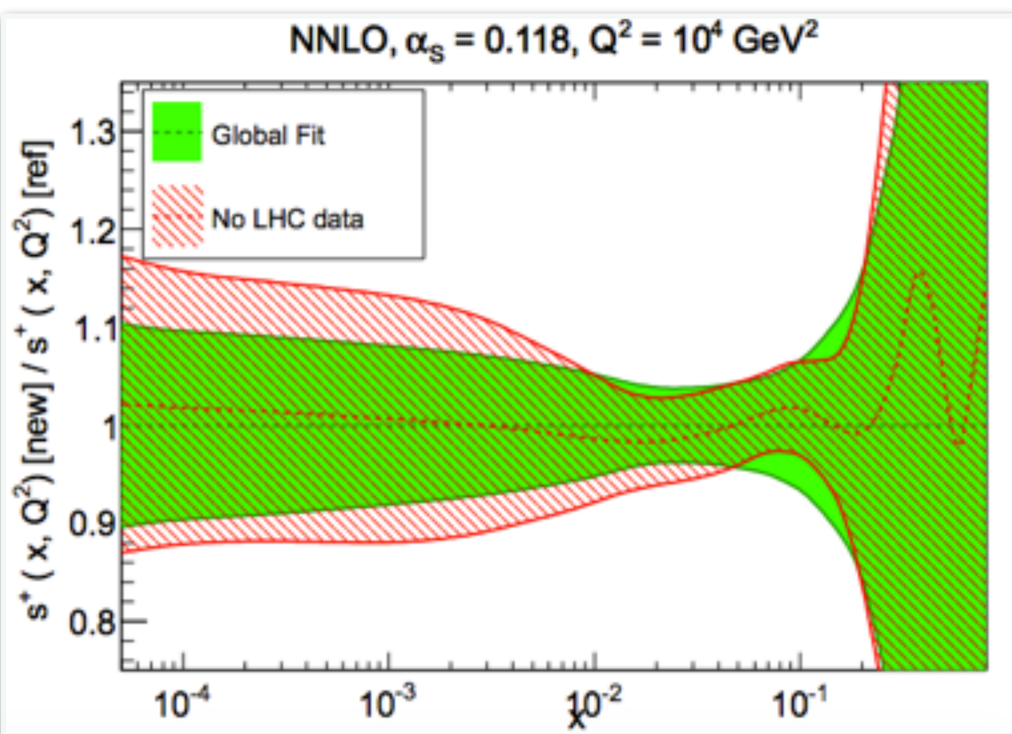
- Low and high mass Drell-Yan
- WW production



New constraints on PDFs







- PDF uncertainty of large-x gluon reduced by inclusion of jet and top data
- Uncertainty of light quarks at small x reduced by DY data and W+c

NNPDF collaboration, JHEP04(2015)040

The NNLO frontier

- NNLO calculations are essential to reduce theoretical uncertainties in PDF analyses
- Recently important progress has been made on some key processes

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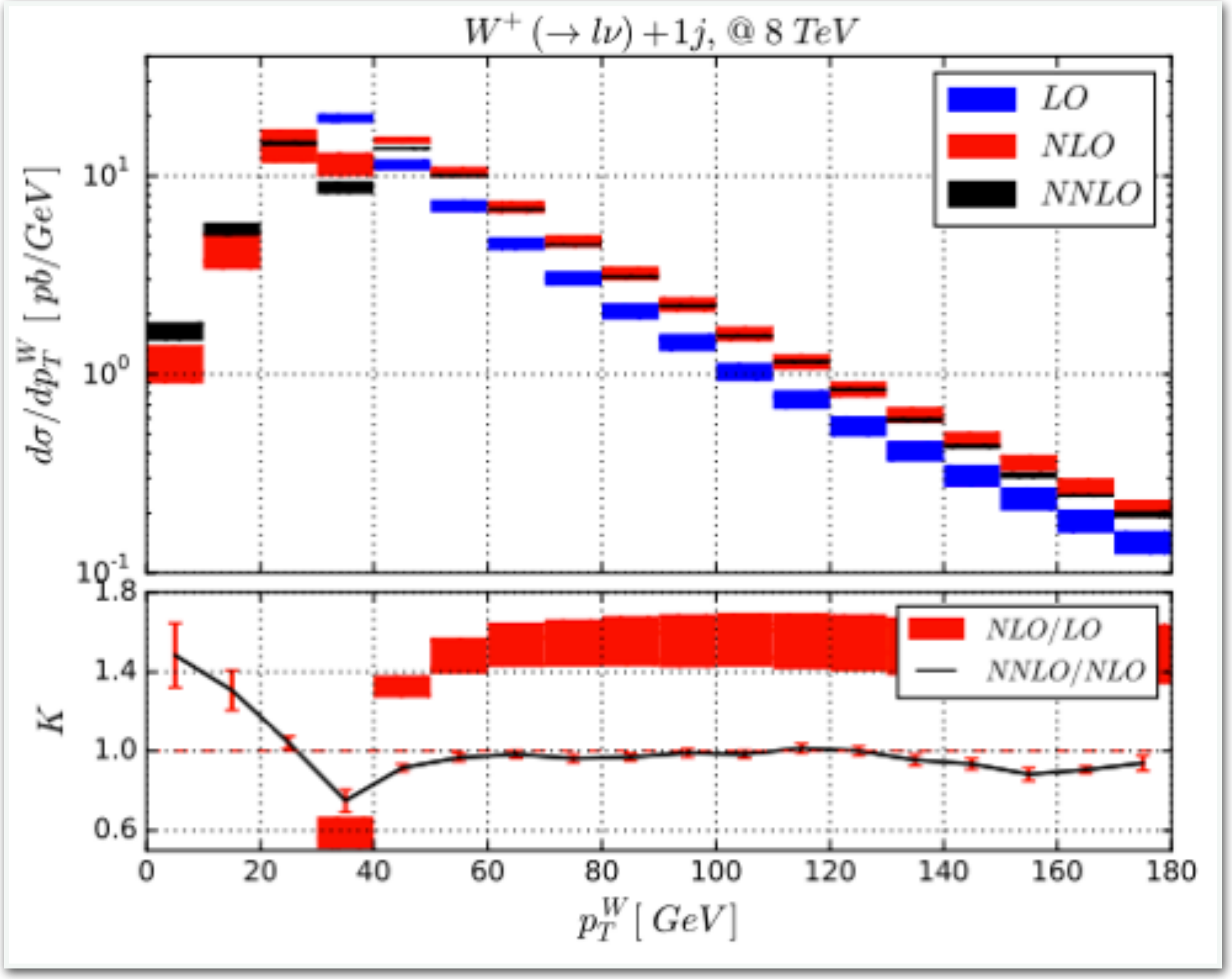

Czakon, Fiedler, Mitov PRL 110 (2013) 25
Boughezal et al, 1504.02131
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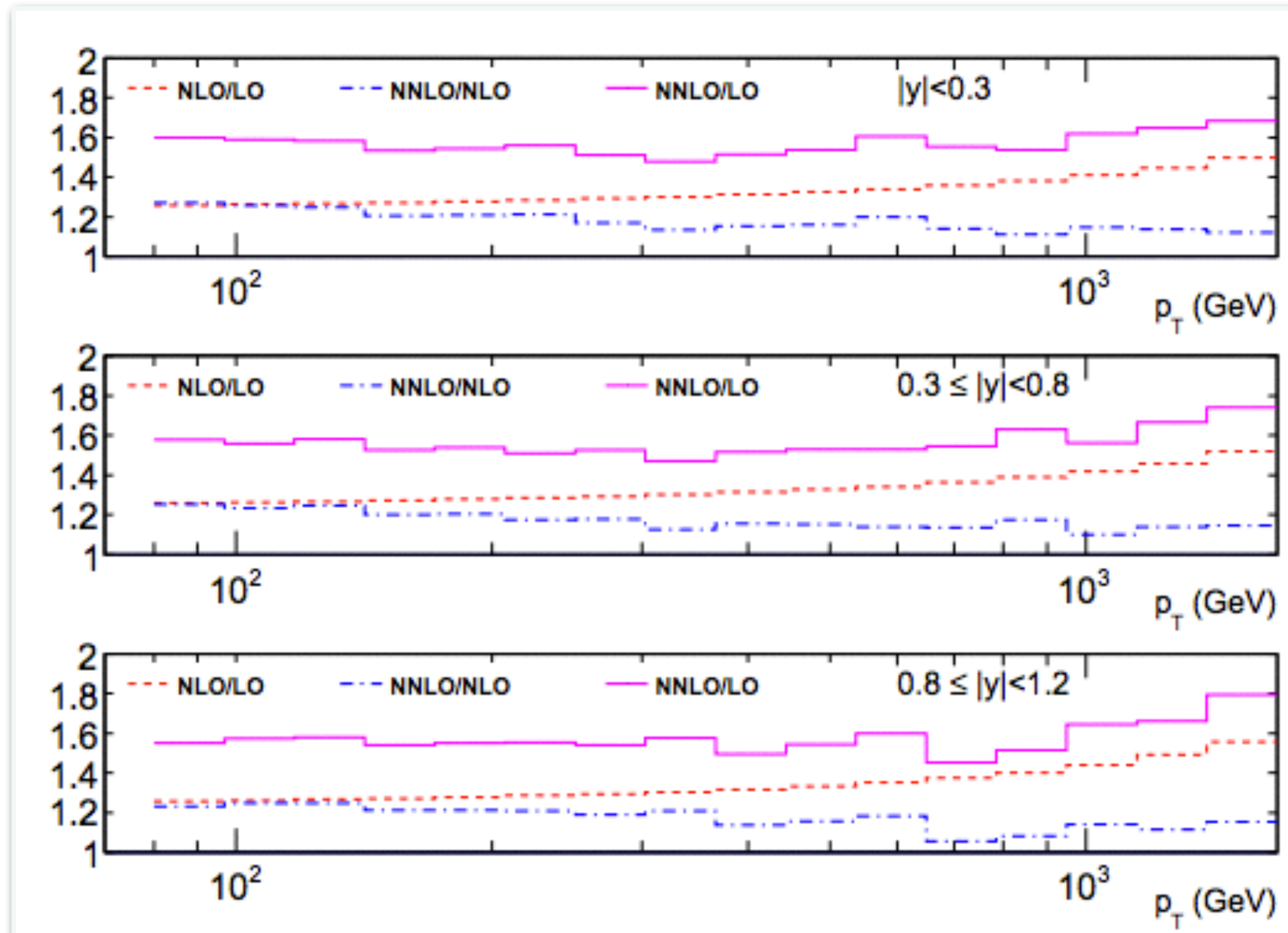

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EW corrections matter

- EW corrections become relevant at the current precision level
- Several tools to compute them along with QCD correction [FEWZ3.1, Phys.Rev. D86 (2012) 094034]
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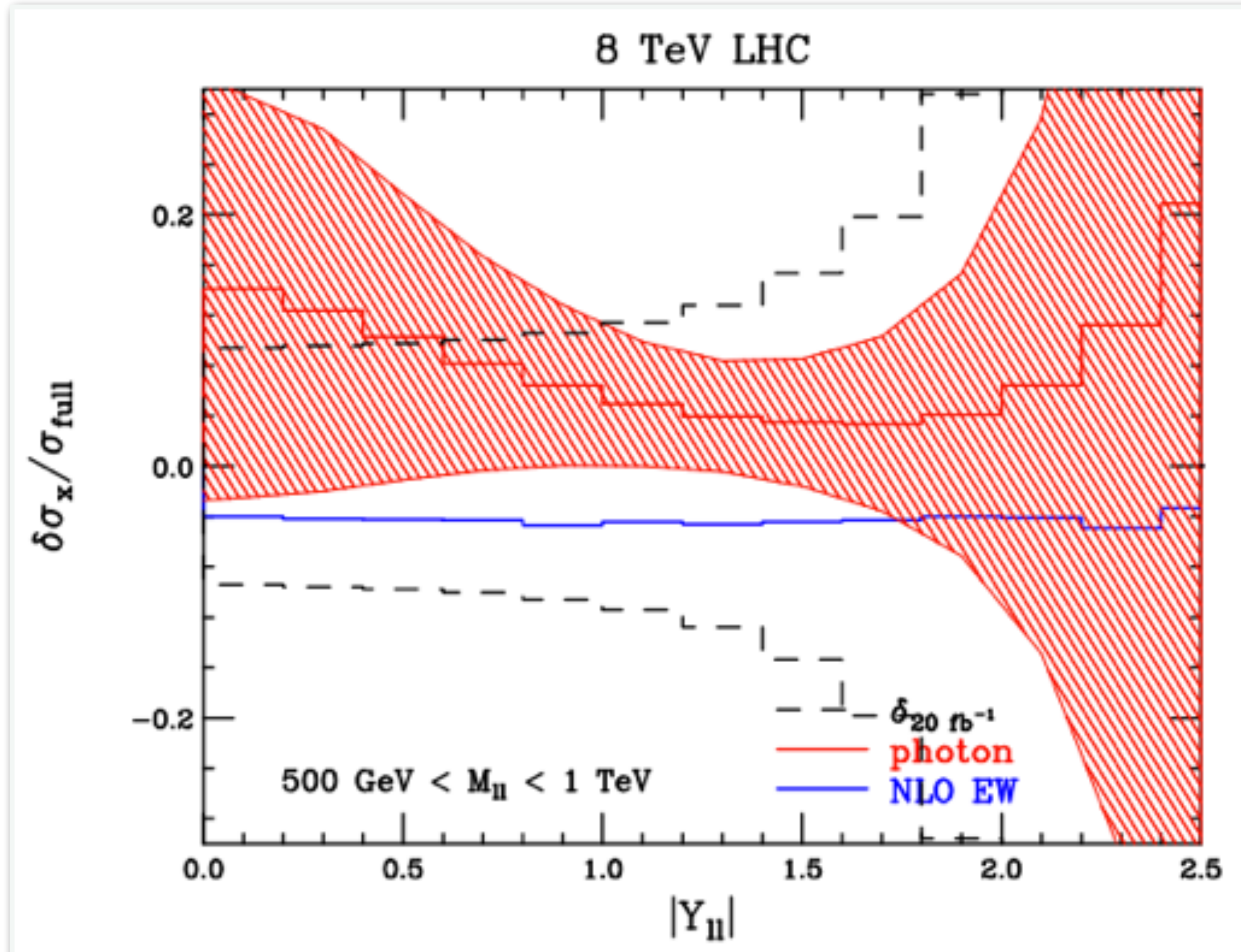

Boughezal, Li, Petriello, Phys.Rev. D89 (2014) 3, 034030

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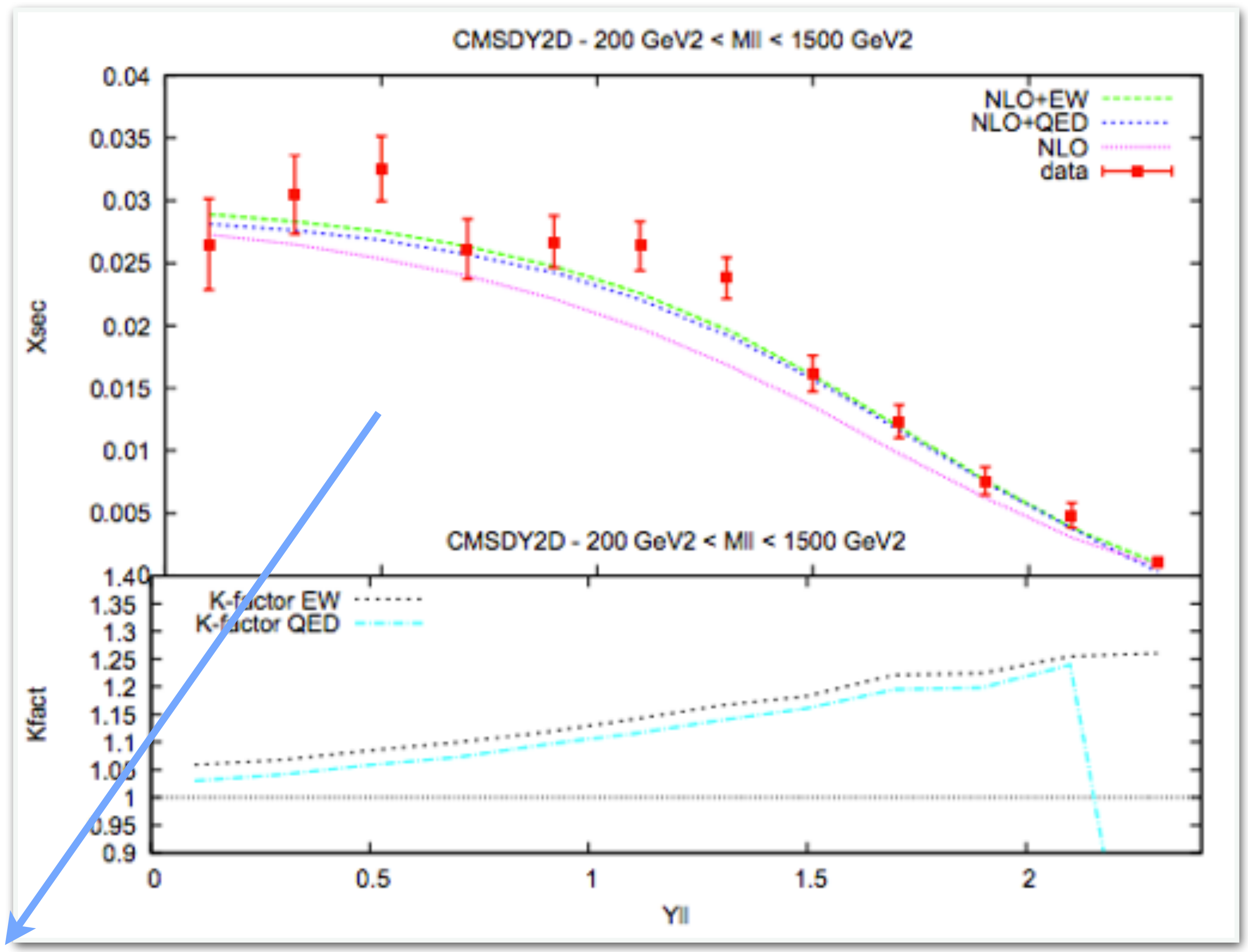

Pure EW C-factors included in theoretical predictions at NLO and NNLO in NNPDF30 fit

$$C_{\rm fact}^{\rm NNLO} = \frac{\hat{\sigma}_{\rm NNLO} \otimes f^i_{\rm NNLO}}{\hat{\sigma}_{\rm NLO} \otimes f^i_{\rm NNLO}}$$

$$C_{\rm fact}^{\rm EW} = \frac{\hat{\sigma}_{\rm NLO+EW} \otimes f^i_{\rm NLO}}{\hat{\sigma}_{\rm NLO} \otimes f^i_{\rm NLO}}$$

The photon PDF

- The inclusion of EW corrections requires PDF with QED effects
- **NNPDF23QED** is a recent PDF set with uncertainties which incorporates (N)NLO QCD + LO QED effects. MMHT QED set and CT14 sets expected soon
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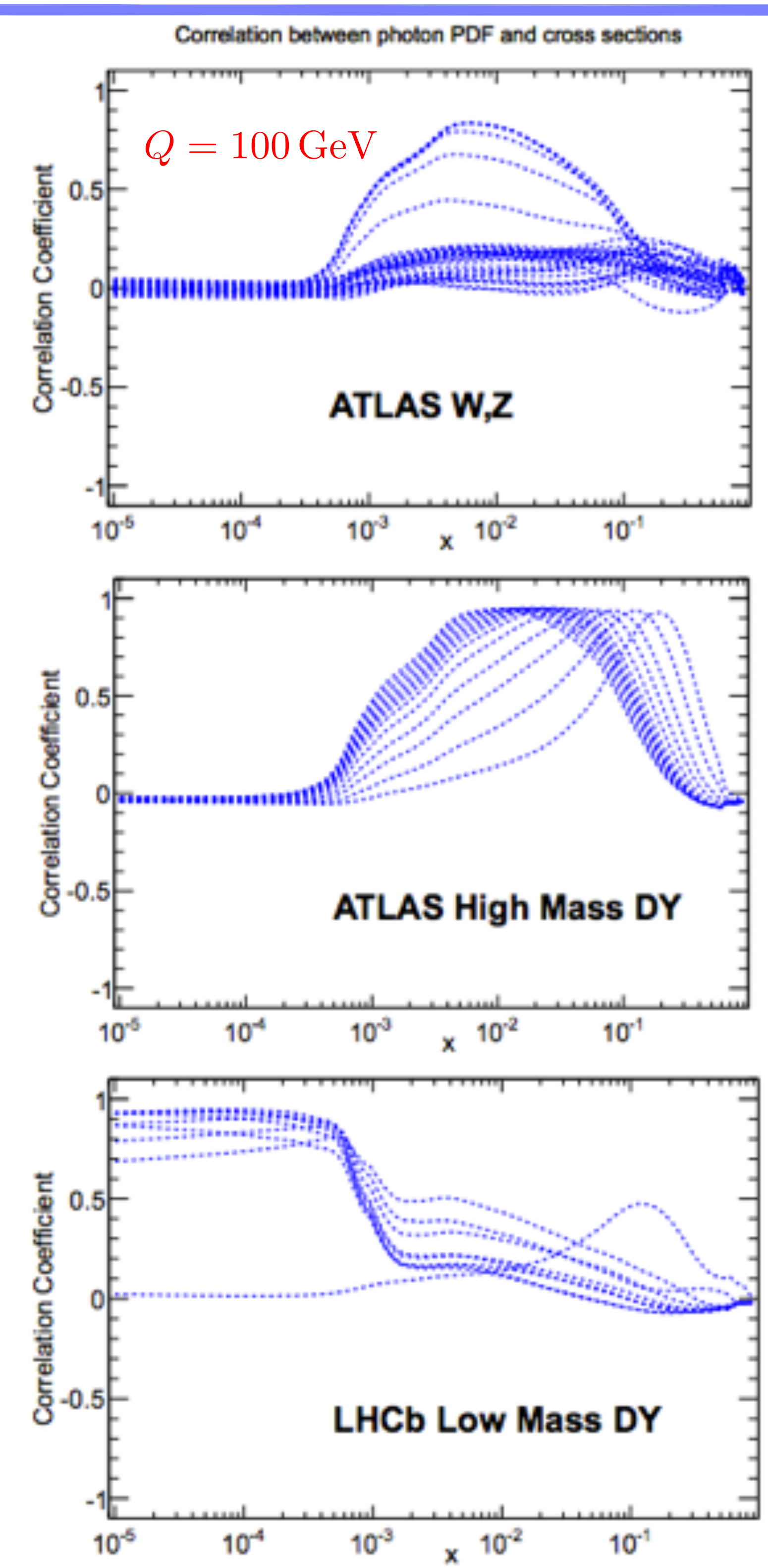

Ball et al, Nucl.Phys. B877 (2013) 290-320

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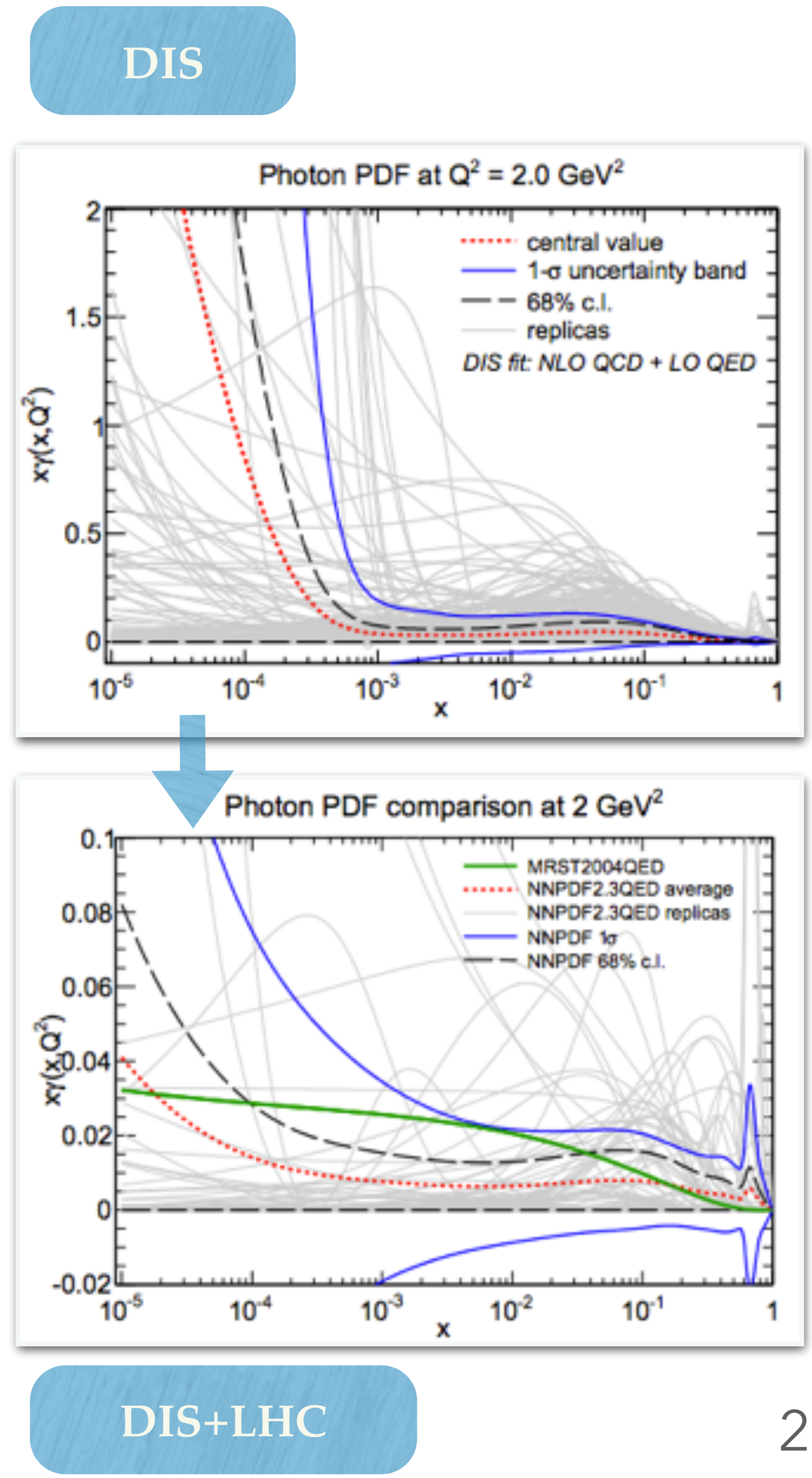
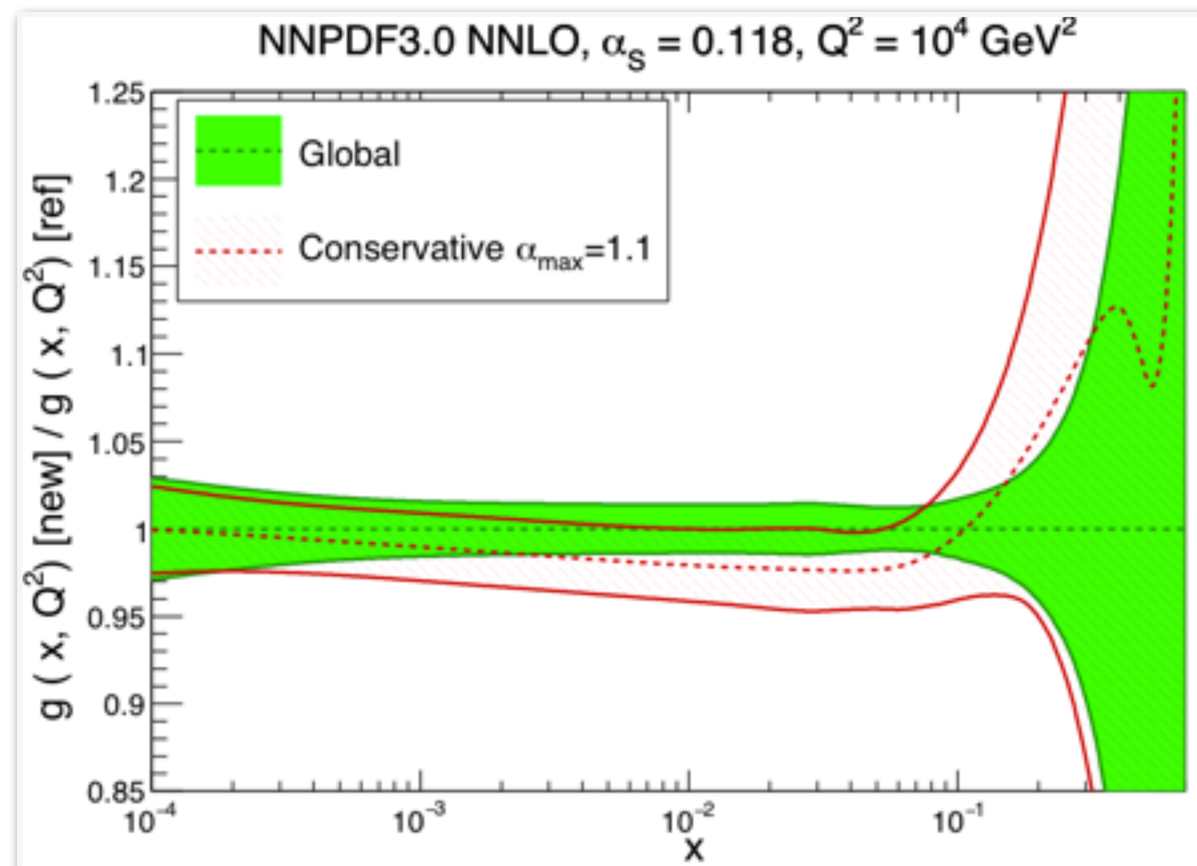


A final remark

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 the state of the art

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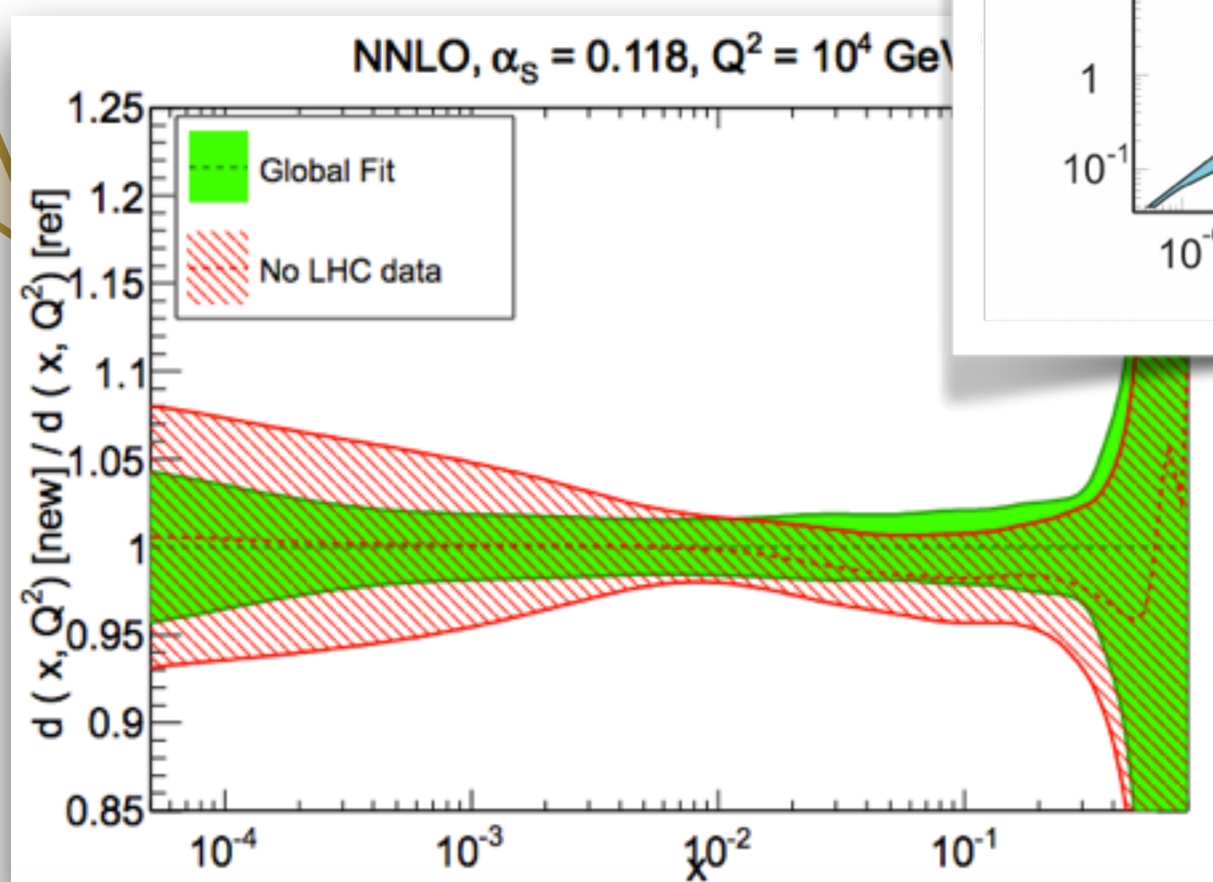
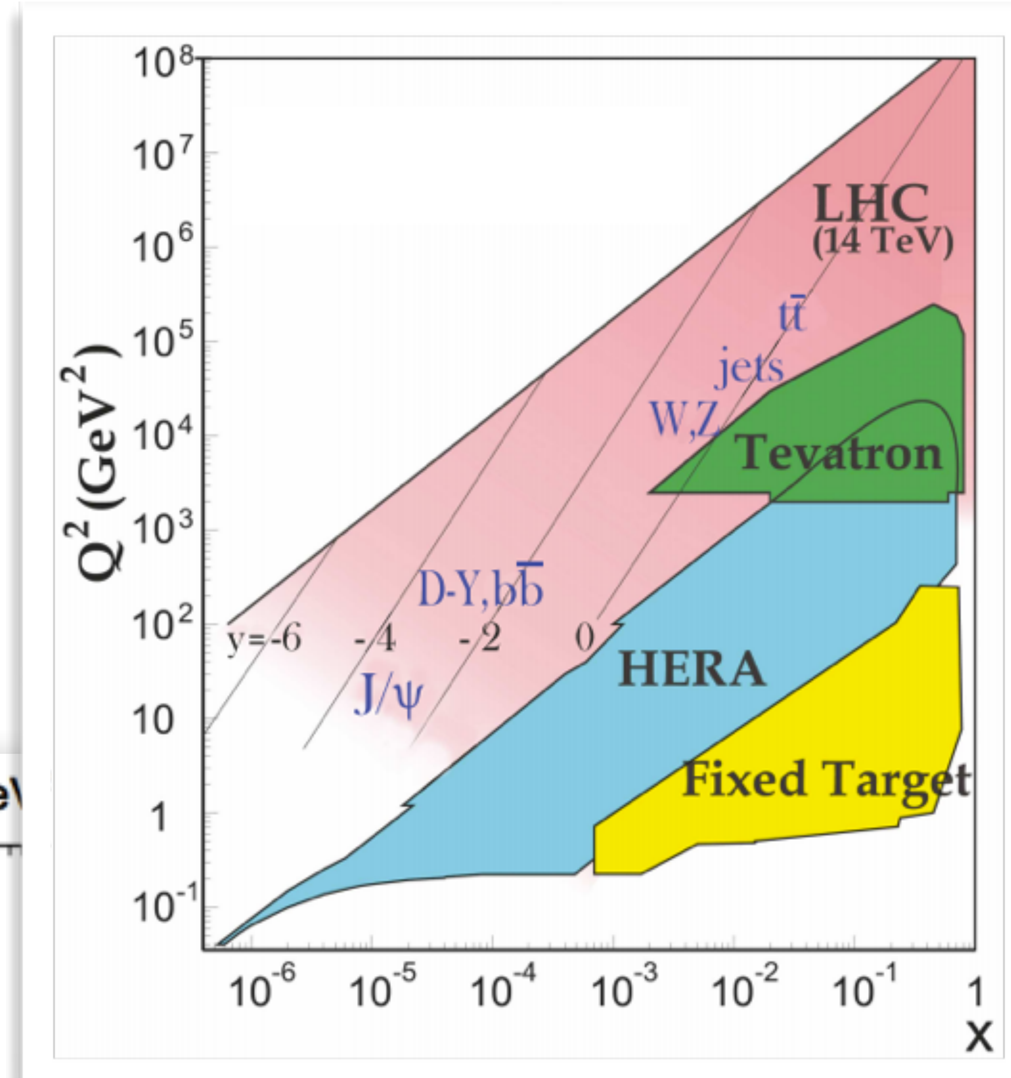
Exploit precise **LHC data** to reduce PDF uncertainties

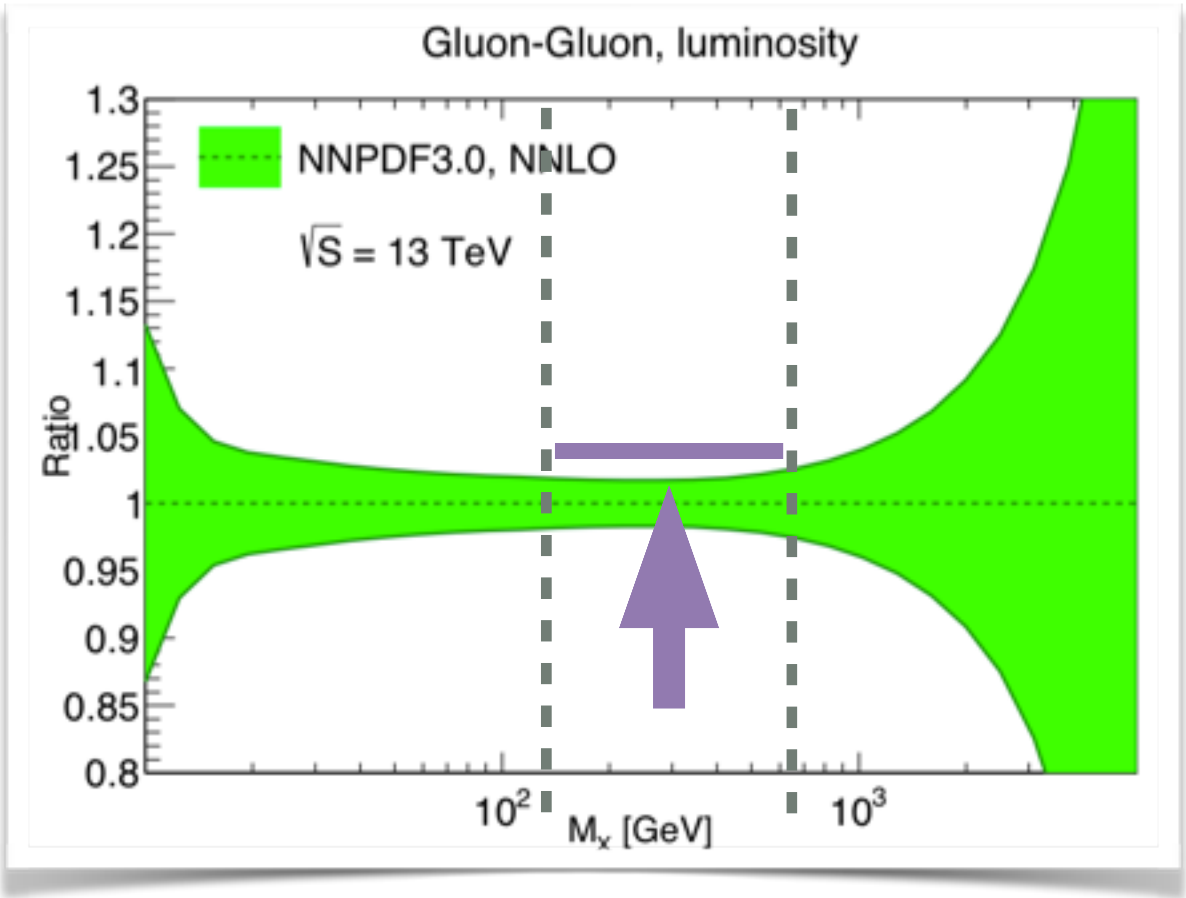
Explore potential constraints from **future colliders**

EXPER.





Beyond the state of the art



Theory boundaries

Precision Physics

Discovery region

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

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

- PDF fits are all made at a given theoretical accuracy (fixed order perturbative QCD)
- PDF uncertainties only reflect lack of information from data given the theory
- Changes in theory may cause shifts outside the error band: lack of accuracy!
- No longer an option!

Beyond the state of the art

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

Explore potential constraints from **future colliders**

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

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

Conclusions

- Parton Distribution Functions are an essential ingredient for LHC phenomenology
- Accurate PDFs are required for precision SM measurements, Higgs characterisation and New Physics searches
- Fast progress in recent months, new PDF sets, inclusion of new data, more solid theory and methodology
- The NNPDF approach provides parton distributions based on a robust, unbiased methodology, the most updated theoretical information and all the relevant hard scattering data including LHC data
- Still a lot of work ahead!

* Fast interface to NNLO observables
* N(N)LO+NLO EW fits with initial photon
* Effect of parton shower resummation in PDF fits
* Small-x resummation
* Definition of theoretical uncertainties in PDF fits

* Statistically-sound PDF combination
* Closure tests and measure of data consistency

* HERA I+II combination
* Loads of new data from LHC and new observables to be investigated