Top-antitop measurements for PDF fits

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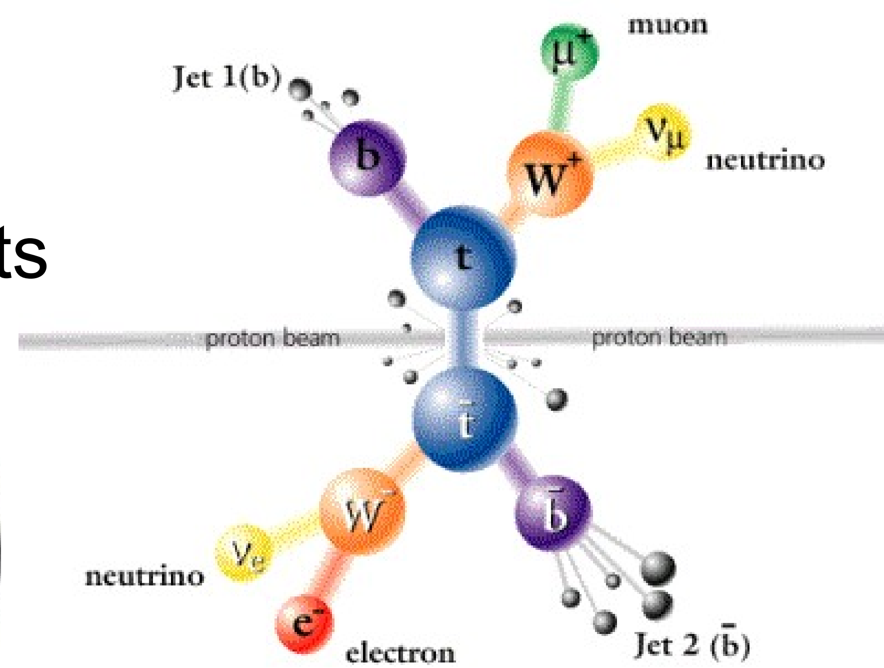
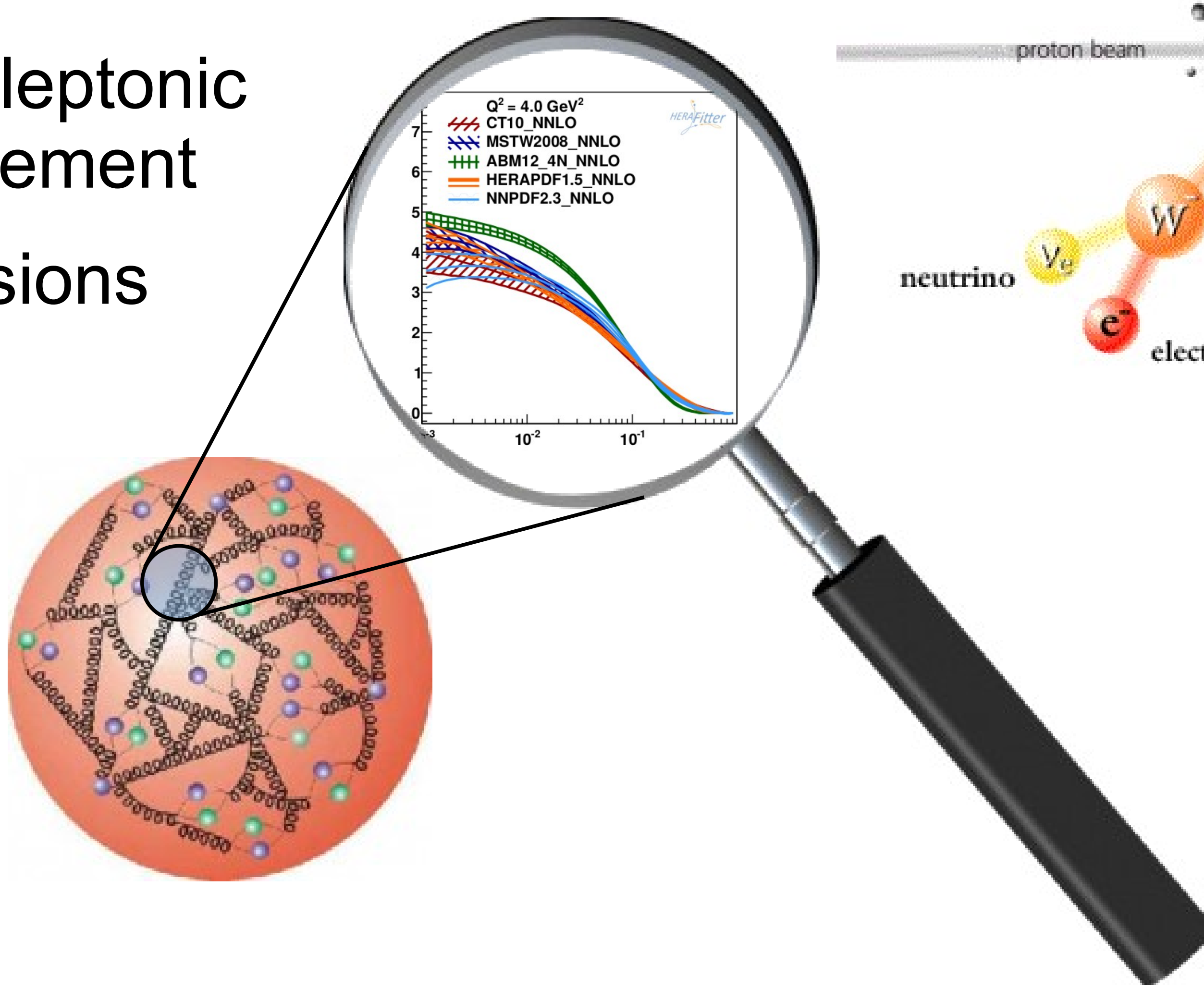
$t\bar{t}$ measurements for constraining PDFs

- Introduction and motivation
- Inclusive measurements
- Partonic differential measurements
- ATLAS leptonic measurement
- Conclusions





PDFs in the LHC era

Any prediction of physics observable at hadron colliders requires knowledge of the PDFs

PDFs

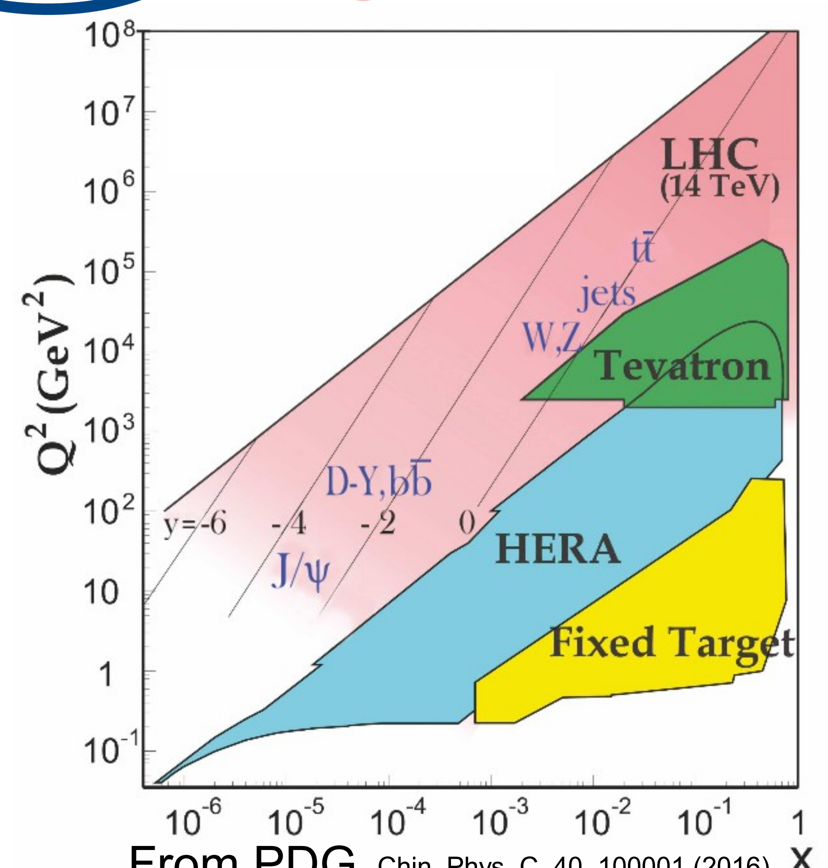
Partonic cross sections

Factorisation theorem*:

$$\sigma_{p\,p\to X} = \Sigma_{i,j} \int dx_1\, dx_2\, f_i^p(x_1,\mu)\, f_j^p(x_2,\mu) \times \sigma_{i,j}$$

- Cross section are calculated by convoluting short distance partonic reactions with Parton Distribution Functions (PDFs)
- Discovery of new exciting physics relies on precise knowledge of proton structure
- PDFs are among the dominant uncertainties for the W mass, weak-mixing angle, and gg → H production

**The factorisation theorem is proven rigorously only for DIS and inclusive DY, predictions and PDF fits of other semi-inclusive processes in hadron-hadron collisions are based on the assumption that the factorization holds also there*

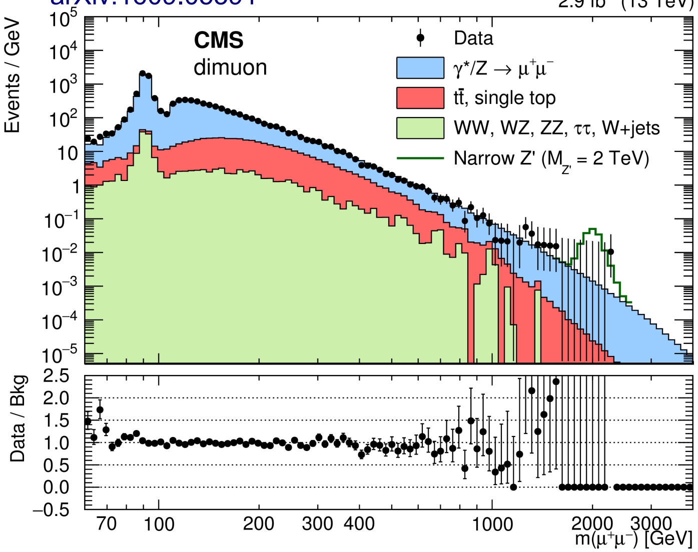


From PDG Chin. Phys. C, 40, 100001 (2016)

PDFs in the LHC era

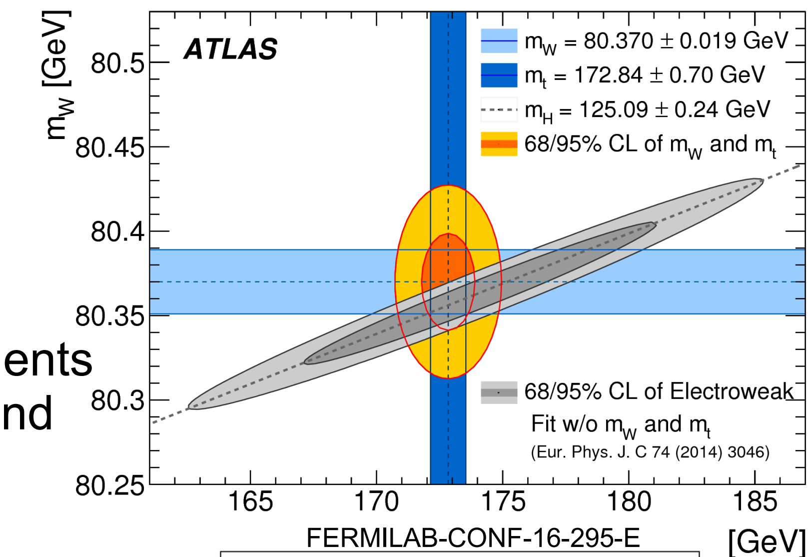
Accurate knowledge of the PDFs is crucial for direct searches of new physics, as well as for indirect searches through precision measurements

arXiv:1609.05391



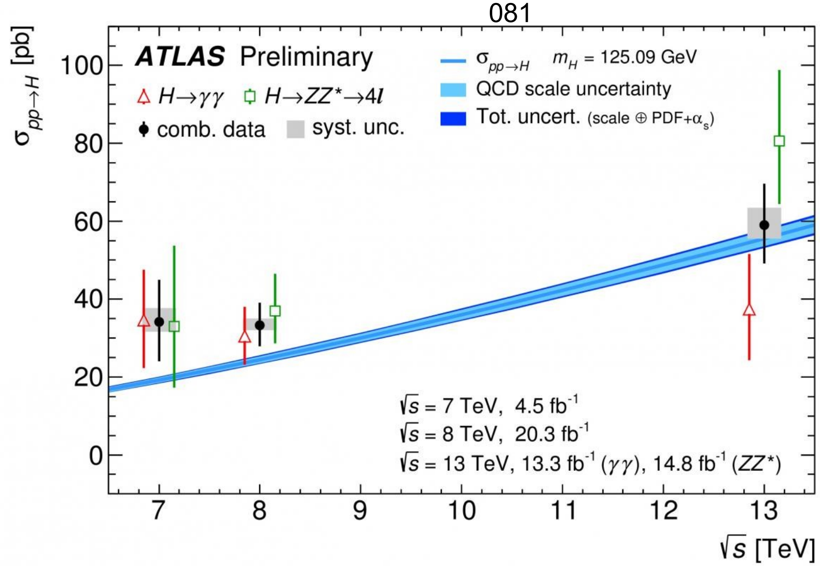
Direct searches

arXiv:1701.07240



Precise measurements of cross sections and EW observables

ATLAS-CONF-2016-081



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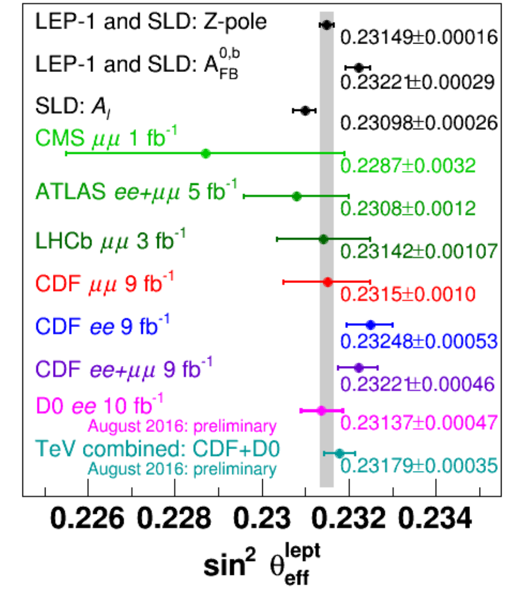
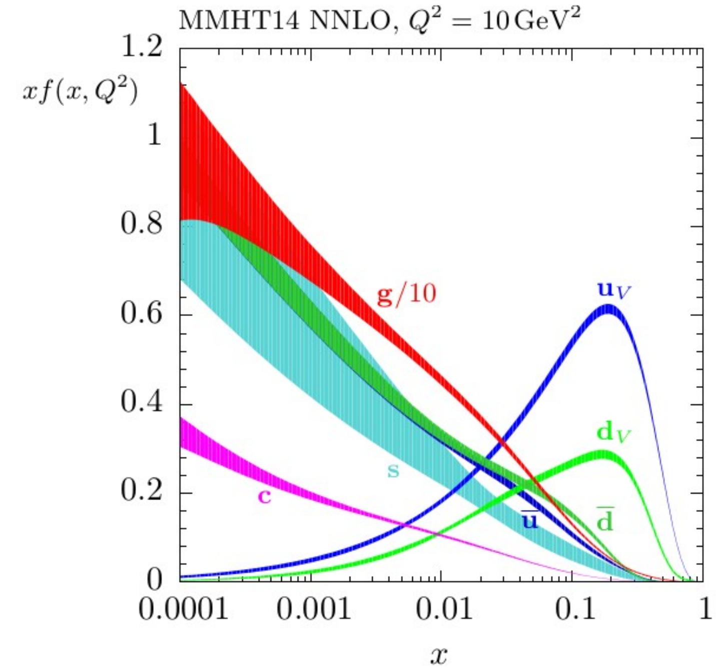


Parton distribution functions

- In a naive leading-order perspective, PDFs can be seen as the probability of finding a parton in a hadron which carries a momentum fraction x



  - In the collinear factorization, PDFs are a function of Bjorken-x, the momentum fraction, and Q^2, the “factorization” scale of the process

    - PDFs cannot (yet) be predicted by first principles with non-perturbative QCD calculations (lattice)
    - However, perturbative QCD accurately predicts the evolution of PDFs in Q^2
    - It is necessary and sufficient to use experimental inputs to determine the boundary conditions, i.e. the PDFs $f(x,Q0^2)$ at a given starting scale of the order $Q0^2 \sim 1$ GeV^2

Schematic of PDF determination

PDF determination is a complex problem, with a variety of solutions, namely PDF sets

Input data

Theory predictions

Partonic cross sections ⊗ **PDF evolved at all scales**

χ^2 test

Minimisation (Fit) of the PDF parameters at the starting scale

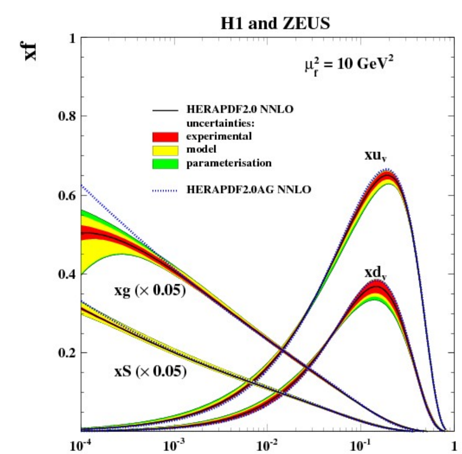
DGLAP evolution

PDF parametrisation at the starting scale ~ 1 GeV with ~ 20 free parameters

Standard and open source framework for PDF fits

xFitter

Result: $f(x,Q^2)$ at all scales



arXiv:1506.06042

Variety of PDF sets

V. Radescu *A complex problem leads to a variety of solutions...*

	CT14	MMHT15	NNPDF3.0	HERAPDF2.0	ABM12	CJ12	JR14
HQ scheme	VFNS (ACOT-χ)	VFNS (TR opt)	VFNS (FONLL)	VFNS (TR opt)	FFNS Run mc (ABM)	VFNS (ACOT)	FFNS (JR)
orders	LO, NLO, NLLO	LO, NLO, NLLO	LO, NLO, NLLO	LO, NLO, NLLO	NLLO	NLO	NLO, NLLO
α(Mz)	fixed (fitted)	fixed (fitted)	fixed	fixed	fitted	fixed	fitted
α(Mz) LO α(Mz) NLO α(Mz) NNLO	0.1300 0.1180 (0.117) 0.1180 (0.115)	0.1350 0.1180 (0.1201) 0.1180 (0.1172)	0.1180 0.1180 0.1180	0.1300 0.1180 0.1180	- - 0.1132	- 0.118 -	- 0.1158 0.1136
Nr param.	Pol. Bernst. 28	Pol. Cheb. 25	NN (259)	Pol. 14	Pol. 24	Pol. 22	Pol.25
PDF assumptions	ubar/dbar=1(x->0) u/d=1 (x->0)	s-sbar=fit. dbar-ubar=fit.	dbar-ubar=fit	ubar=dbar (x->0) sbar=0.67* dbar	s=sbar dbar-ubar=fit	dv/uv=const s+sbar=k(ubar+dbar)	dbar-ubar=fit
Stat. treatm.	Hessian $\Delta\chi$2=100 (90% CL)	Hessian $\Delta\chi$2 Dynamical (68% CL)	Monte Carlo (68% CL)	Hessian $\Delta\chi$2=1 (68% CL)	Hessian $\Delta\chi$2=1 (68% CL)	Hessian $\Delta\chi$2=1 (68% CL)	Hessian $\Delta\chi$2=1 (68% CL)
Q2min	2	2	3.5	3.5	2.5	1.69	2
HERA data	HERA I+ charm	HERA I charm jets	HERA I+ H1 and ZEUS II charm	HERA I+II	HERA I charm	HERA I	HERA I charm jets
Fix. Target DIS	✓	✓	✓	N/A	✓	JLAB, high x ✓	JLAB, high x ✓
Tevatron W,Z	✓	✓	✓	N/A	✗	✓	✗
Tevatron Jets	✓	✓	✓	N/A	✗	✗	✓
Fix. Target DY	✓	✓	✓	N/A	✓	✓	✓
LHC WZ	✓	✓	✓	N/A	✓	✗	✗
LHC jets	✓	✓	✓	N/A	✗	✗	✗
LHC top	✗	✓	✓	N/A	✓	✗	✗
LHC charm	✗	✗	✓	N/A	✗	✗	✗
References	arXiv:1506.07443	arXiv:1412.3989	arXiv:1410.8849	arXiv:1506.06042	arXiv:1310.3059	arXiv:1212.1702	arXiv:1403.1852

Limitation of DIS measurements

- PDFs are most precisely determined from DIS data, and the currently most precise dataset is the combined HERA-II inclusive DIS measurement
- However, DIS structure functions probe only particular combinations of PDFs: DIS data leads to a very precise determination of valence PDFs and total sea.
- Limitations:
  - d_v is less precisely determined than u_v
  - We miss precise knowledge of the flavour decomposition of the light sea, i.e. “How strange is the proton?”
  - The gluon PDF is determined only through scaling violation in DIS, leading to larger uncertainties, especially in the high-x region, which is crucial for searches

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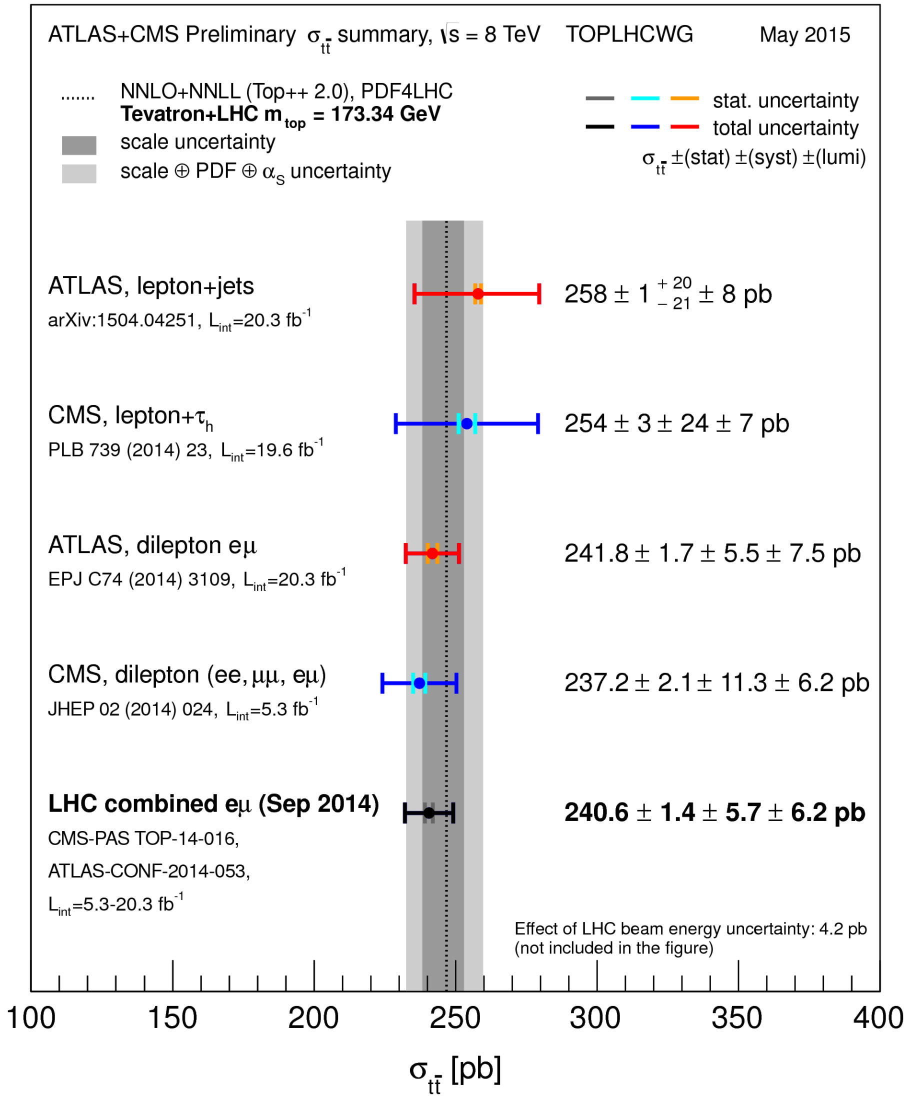
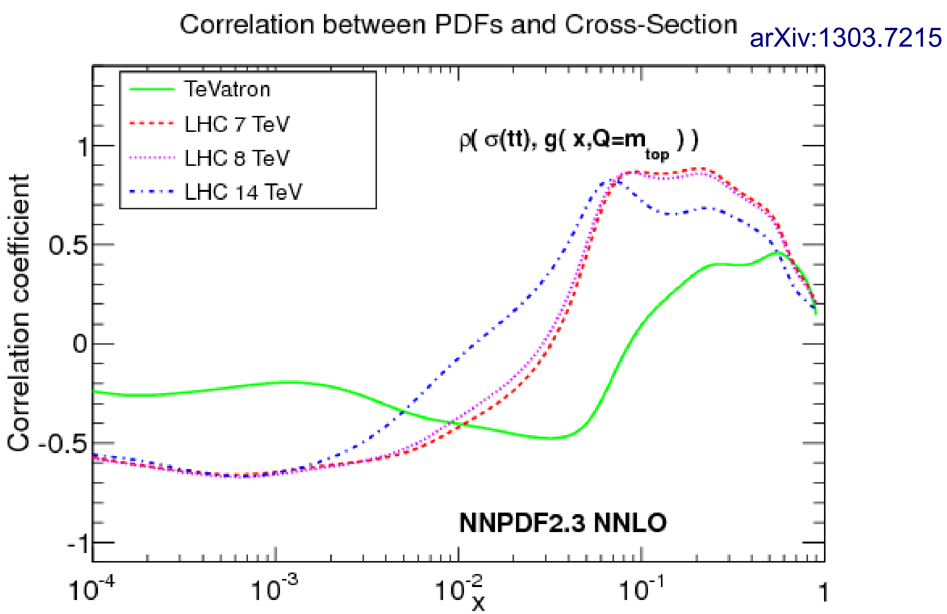
The ttbar cross section measurements can help to improve the determination of the gluon PDF in the medium- and high-x region

Top pair inclusive cross section measurements

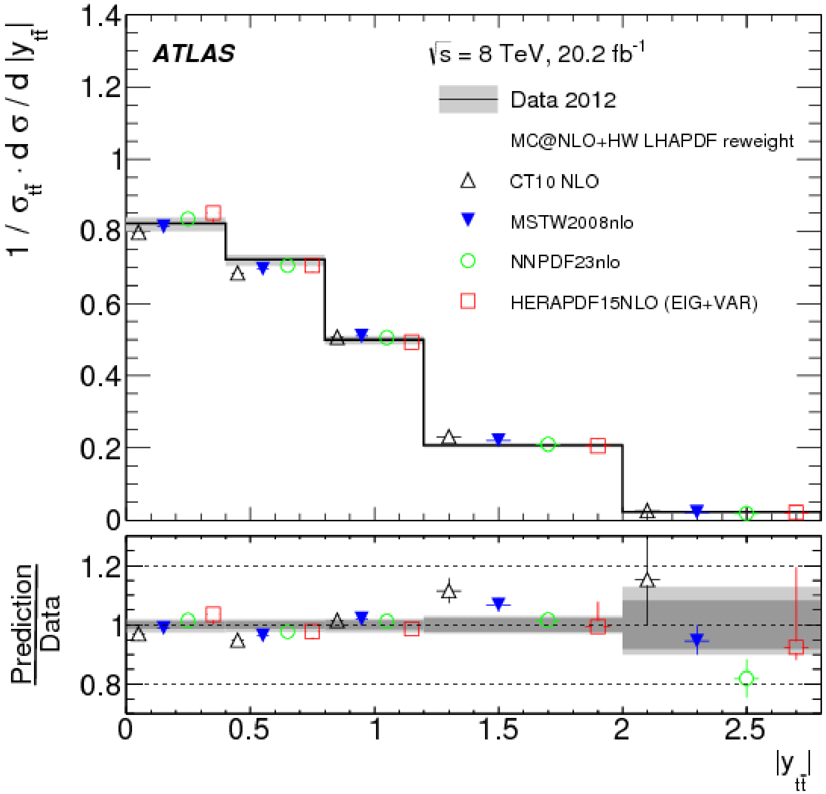


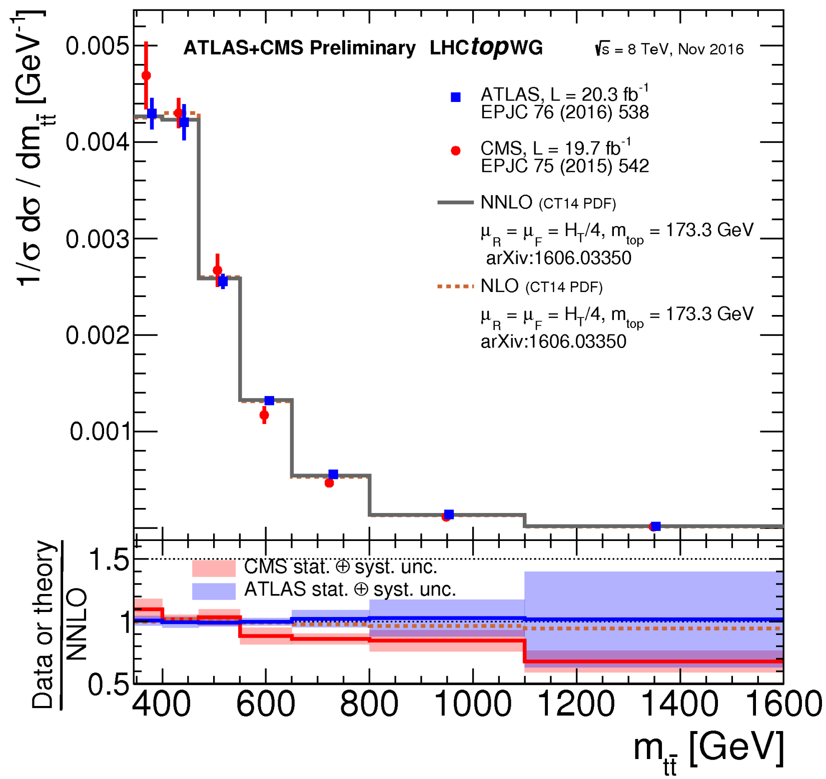
- $t\bar{t}$ inclusive cross sections are included in the latest global PDF fits, as MMHT and NNPDF
- Provide constraints on the medium- and high-x gluon



Top differential cross sections

arXiv:1607.07281

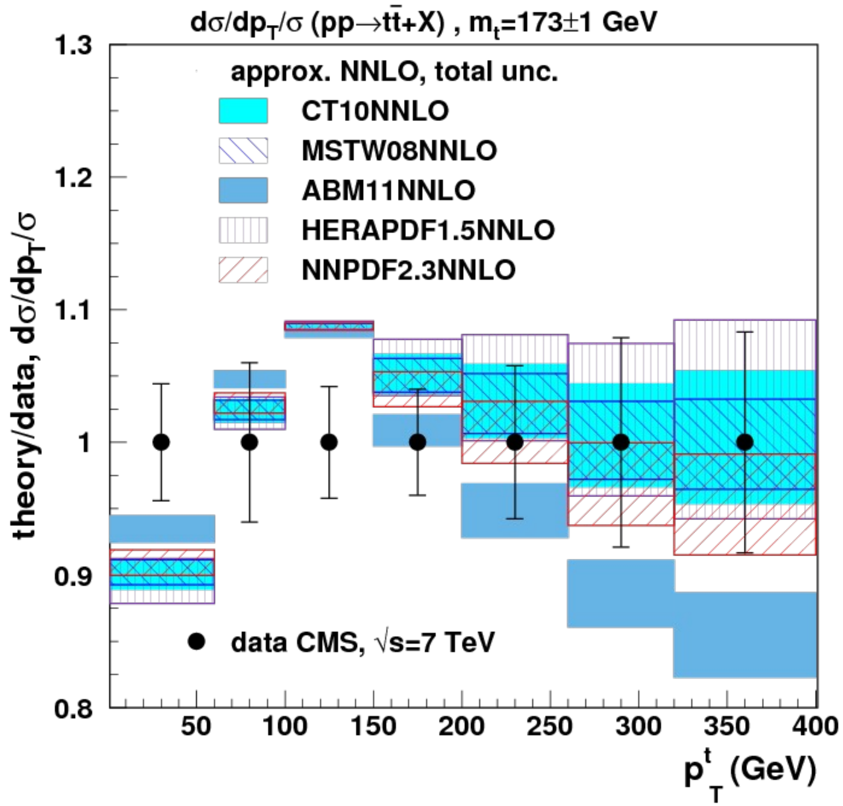


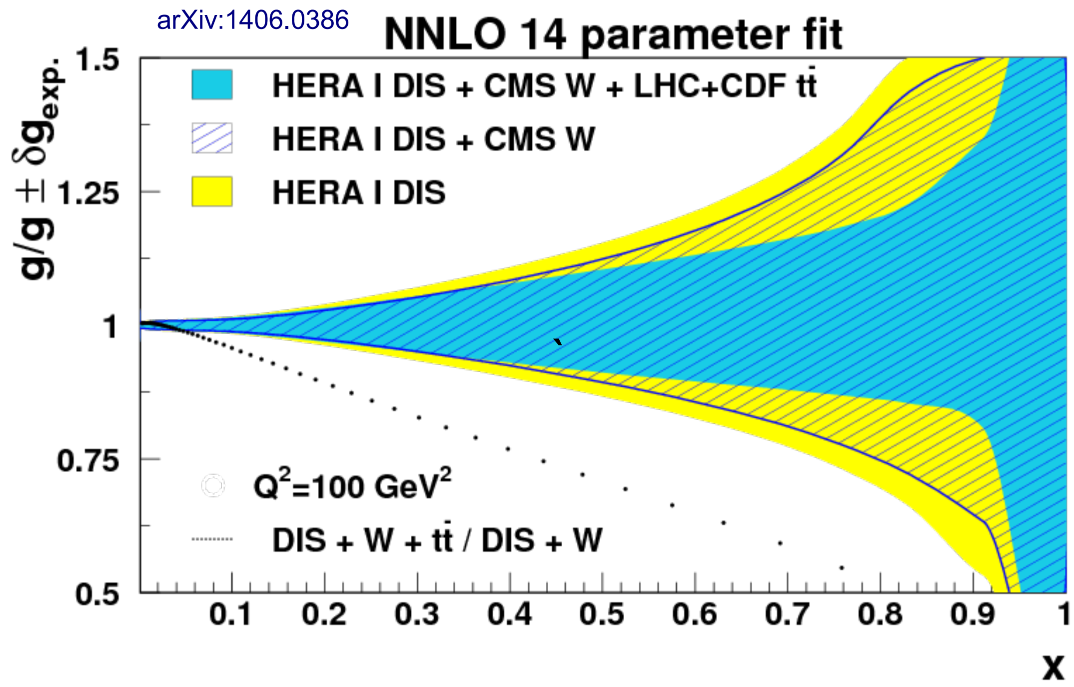


- Differential cross section measurements allows probing the gluon PDFs at even higher Bjorken-x
- NNLO predictions of $t\bar{t}$ differential cross sections are now available, which makes it possible to include this data in PDF fits at NNLO

PDF fits to $t\bar{t}$ differential cross sections

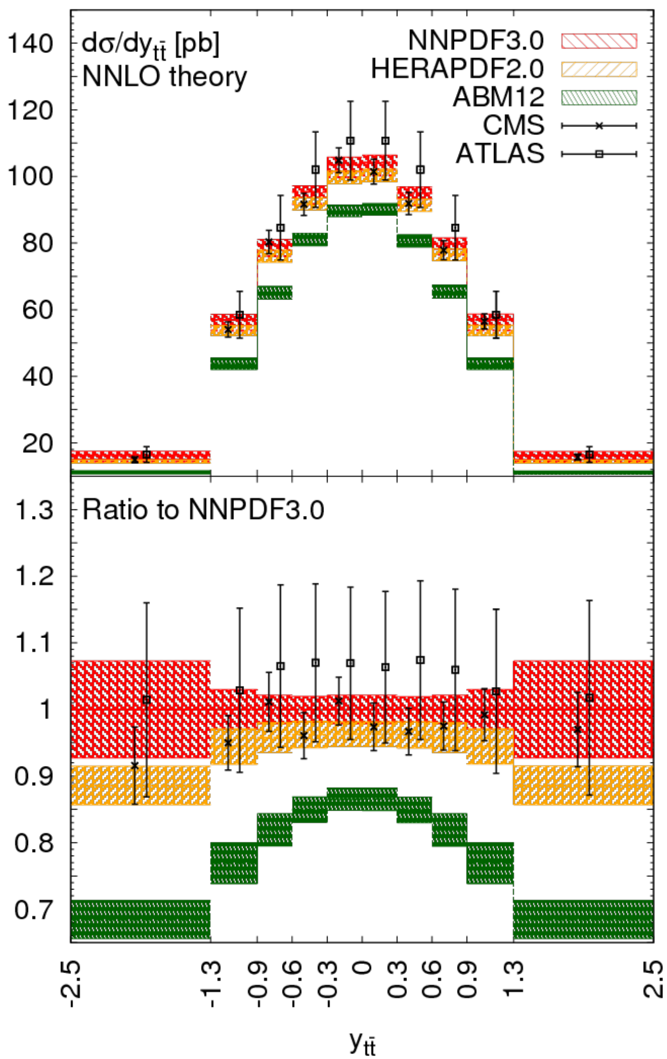
- First studies of PDF fits to top pair differential cross sections were performed with approx NNLO predictions
- Significant improvement of the gluon PDF at high-x



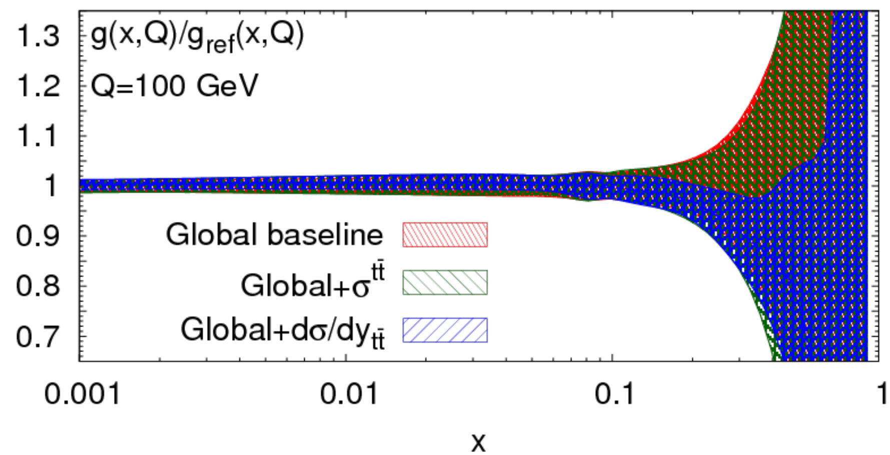


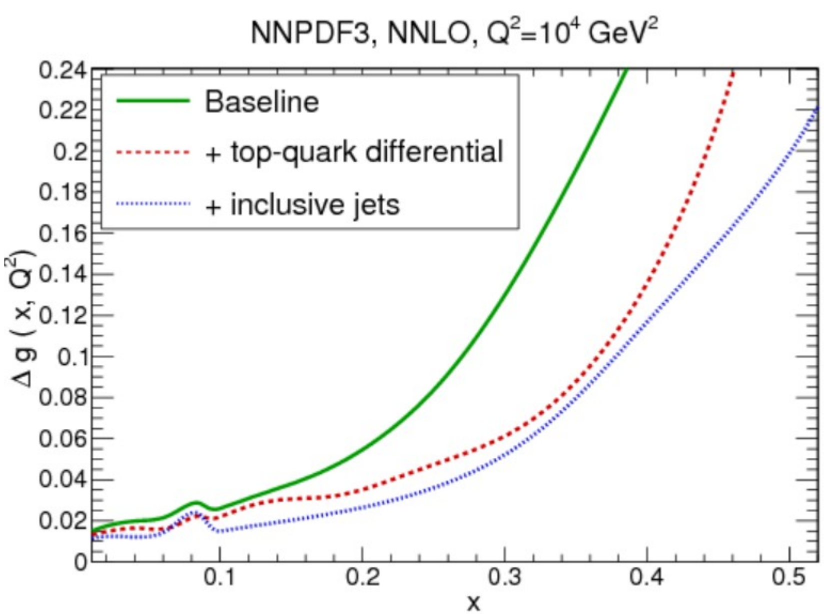
PDF fits to $t\bar{t}$ differential cross sections

arXiv:1611.08609



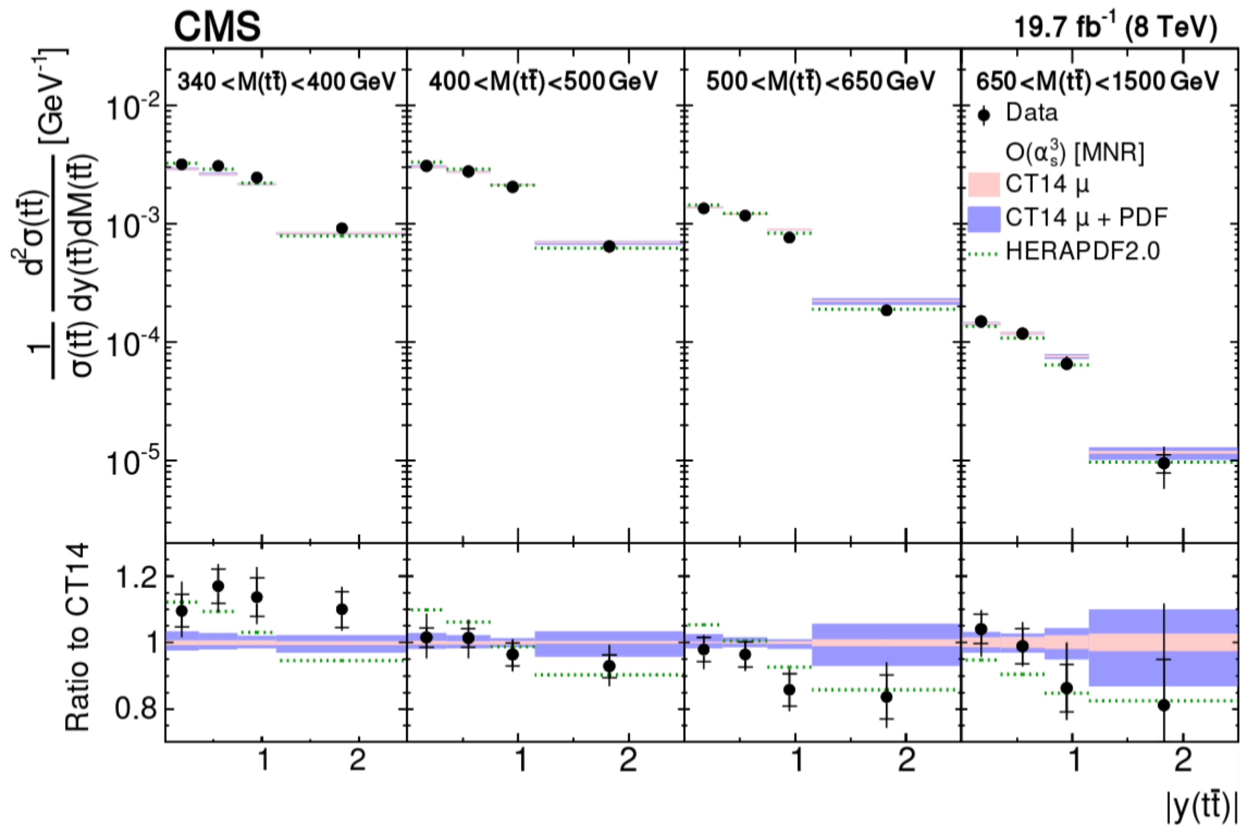
- A recent analysis performed the first PDF fit to $t\bar{t}$ differential cross sections at NNLO
- Significant improvement of the gluon PDF at high-x





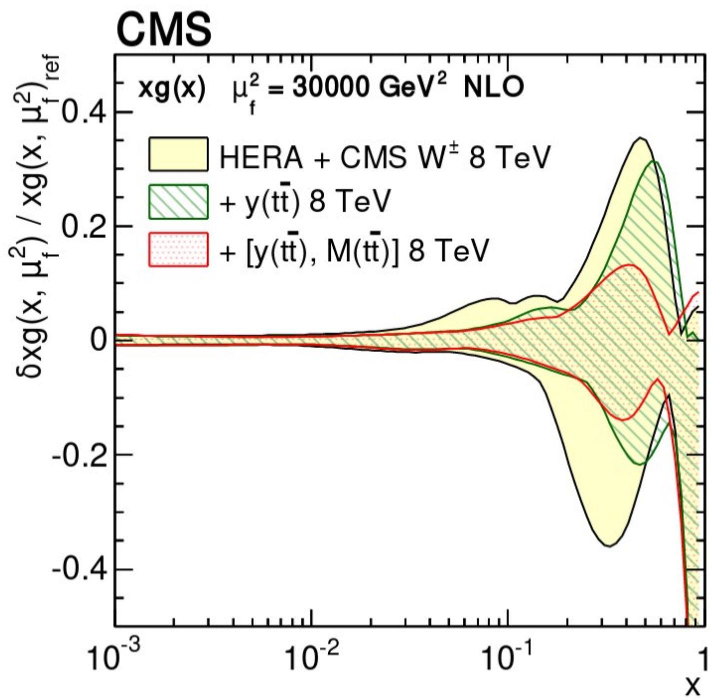
- Reduction in the gluon PDF uncertainty comparable to jet data

PDF fits to 2D $t\bar{t}$ differential cross sections



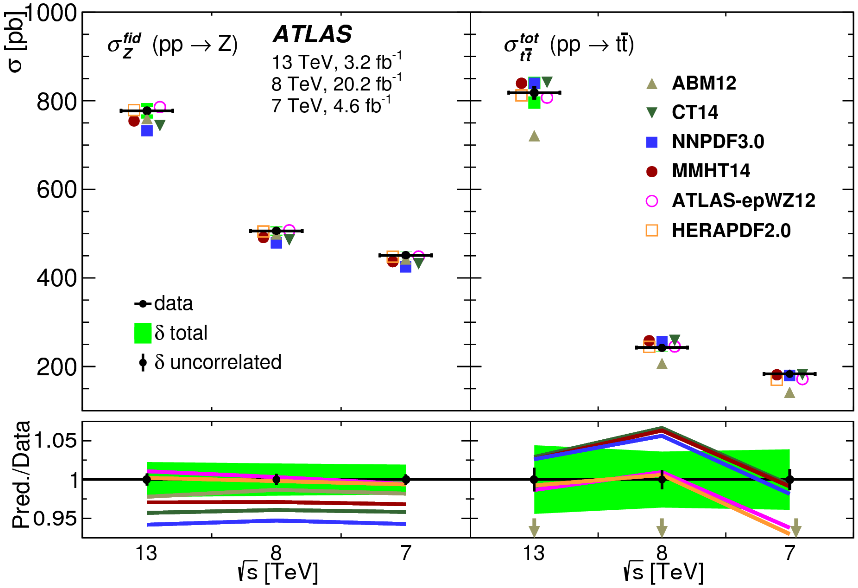
- CMS measured $t\bar{t}$ double differential cross sections
- Significant sensitivity to PDFs, larger than NLO scale variations

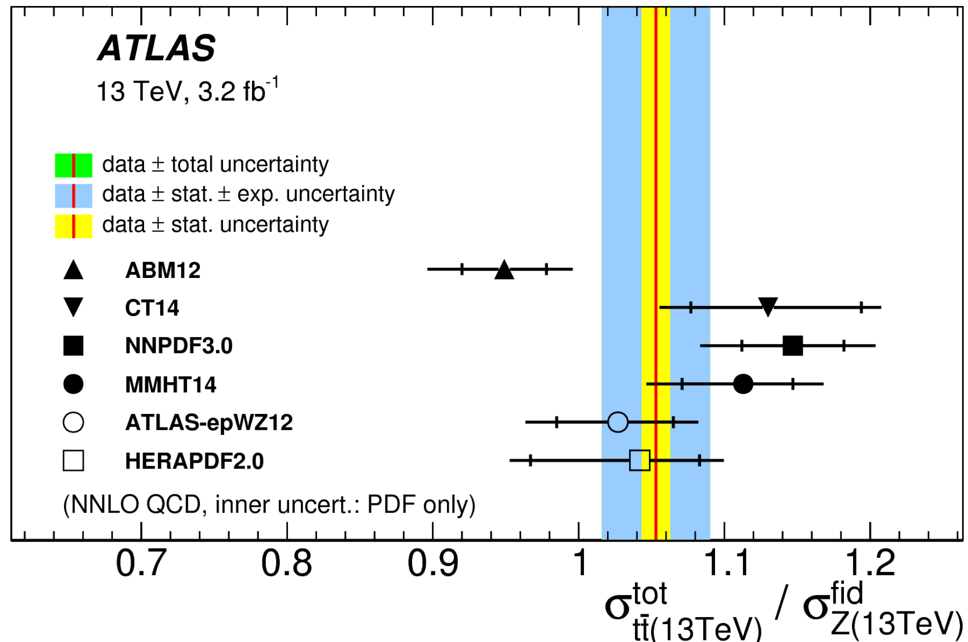
- The 2D cross section measurement is more sensitive than 1D measurement to the gluon PDF
- Good compatibility with the gluon PDF determined from HERA DIS data



$t\bar{t}$ / Z ratio measurement

arXiv:1612.03636



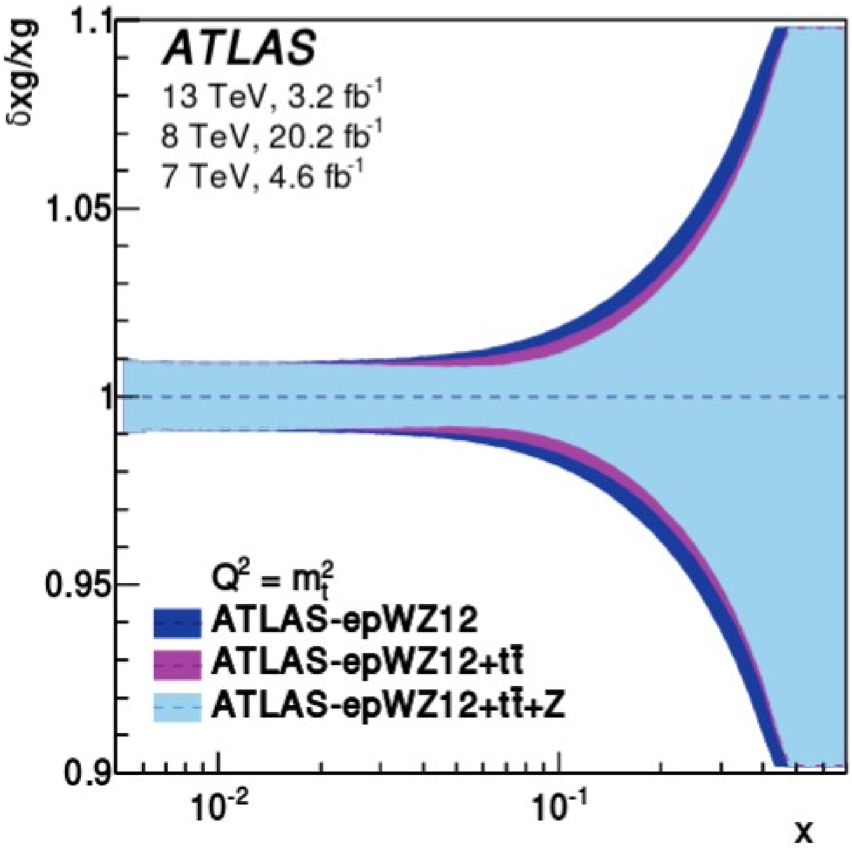


- Measurement of $t\bar{t}$ / Z ratio at 7, 8, and 13 TeV
- Single and double ratio measurements are not affected by luminosity uncertainties
- Best agreement with PDF sets based on DIS or DIS+Drell-Yan data

	ATLAS-epWZ12	CT14	MMHT14	NNPDF3.0	HERAPDF2.0	ABM12
χ^2/NDF	8.3 / 6	15 / 6	13 / 6	17 / 6	10 / 6	25 / 6
p-value	0.22	0.02	0.05	0.01	0.11	< 0.001

$t\bar{t}$ / Z ratio measurement

arXiv:1612.03636



- The measurement is used to constrain the gluon PDF
- The inclusion of the Z cross section as luminometer gives even better constraints on the gluon PDF at high x

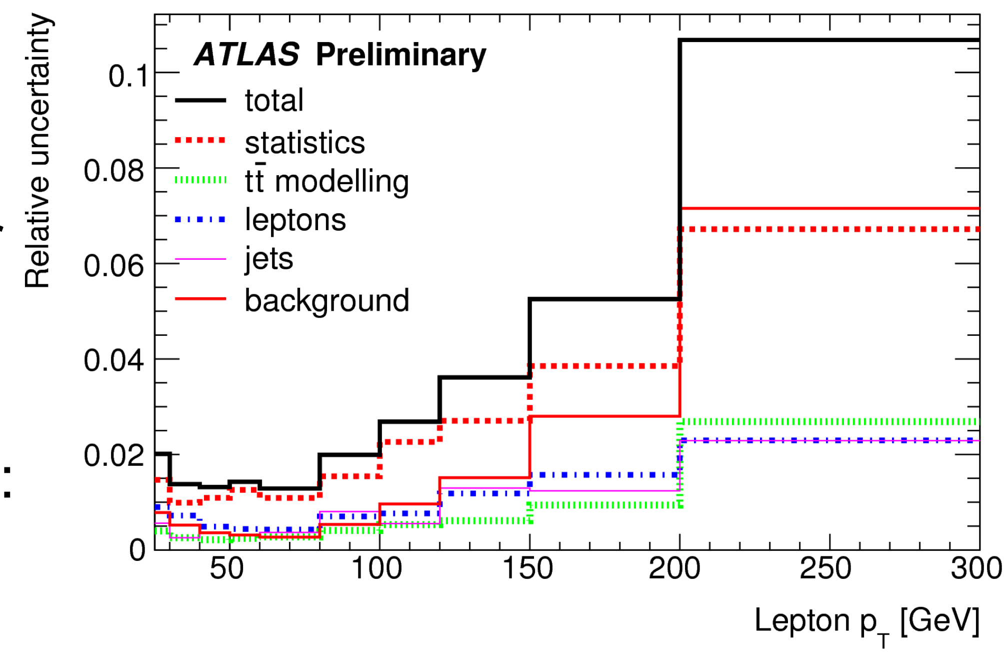
$t\bar{t}$ leptonic differential cross sections – methodology

- Measurement of $t\bar{t}$ leptonic differential cross sections in the $e\mu b\bar{b}\nu\bar{\nu}$ final states with L = 20.2 fb^{-1}, at sqrt(s) = 8 TeV
- Clean experimental signature, little sensitivity to JES and QCD modelling
- Methodology: count 1 and 2 b-tags in bins of differential variables

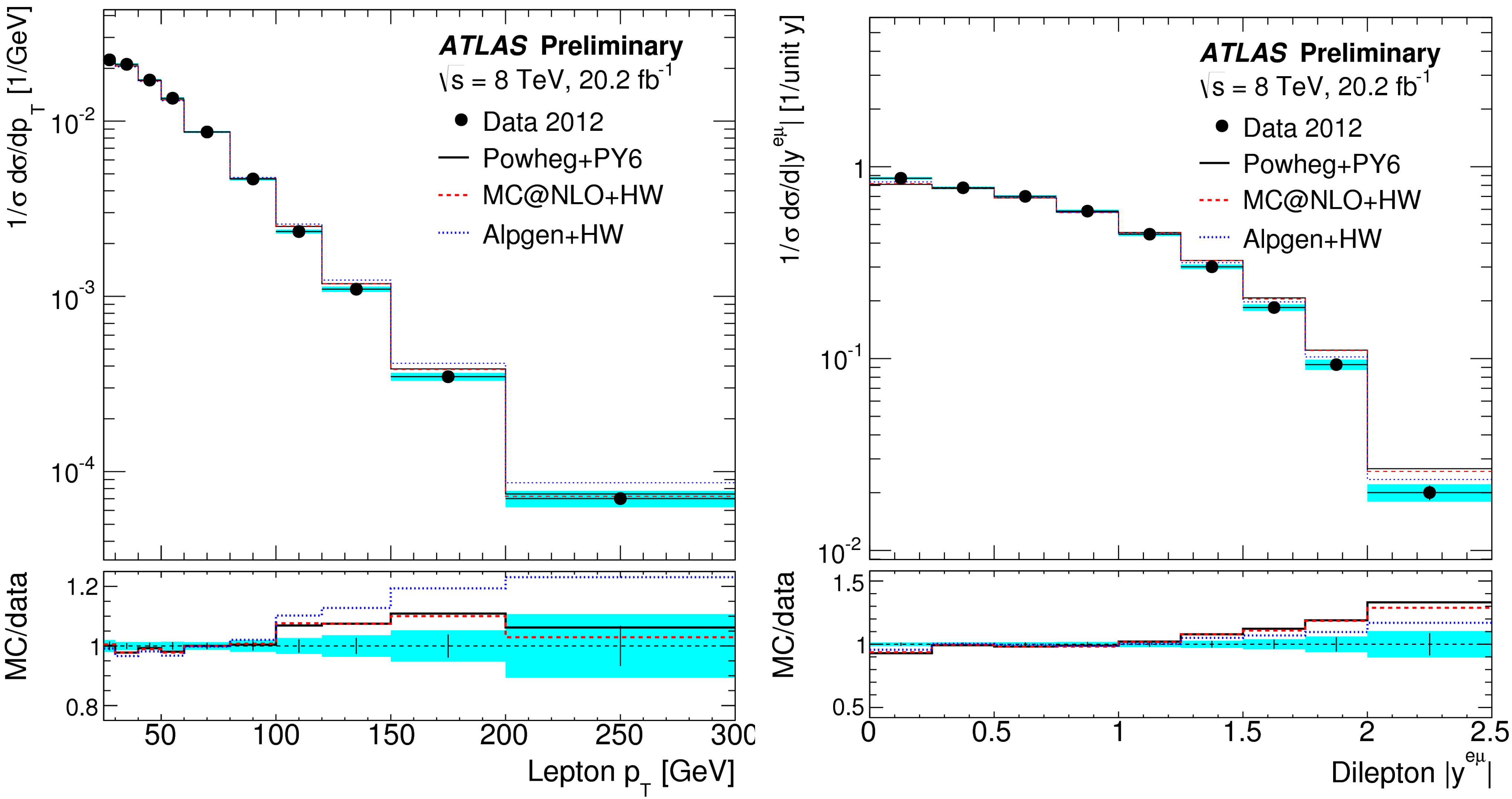
$$
\begin{aligned}
N_1^i &= L\sigma_{t\bar{t}}^i G_{e\mu}^i 2\epsilon_b^i (1 - C_b^i \epsilon_b^i) + N_1^{i,\mathrm{bkg}} \\
N_2^i &= L\sigma_{t\bar{t}}^i G_{e\mu}^i C_b^i (\epsilon_b^i)^2 + N_2^{i,\mathrm{bkg}},
\end{aligned}
$$

- Solve tagging equations and measure ε_b and $\sigma^i_{t\bar{t}}$ simoultaneously → yields a particle-level fiducial measurement for $p_T(l) > 25$ GeV and $|\eta(l)| < 2.5$, with no requirements on jets
- Measured 8 differential cross sections: $p_T(l)$, $\eta(l)$, $p_T(e\mu)$, $m(e\mu)$, $y(e\mu)$, $\Delta\phi(e\mu)$, $p_T(e)+p_T(\mu)$, $E(e)+E(\mu)$

ATLAS-CONF-2017-044



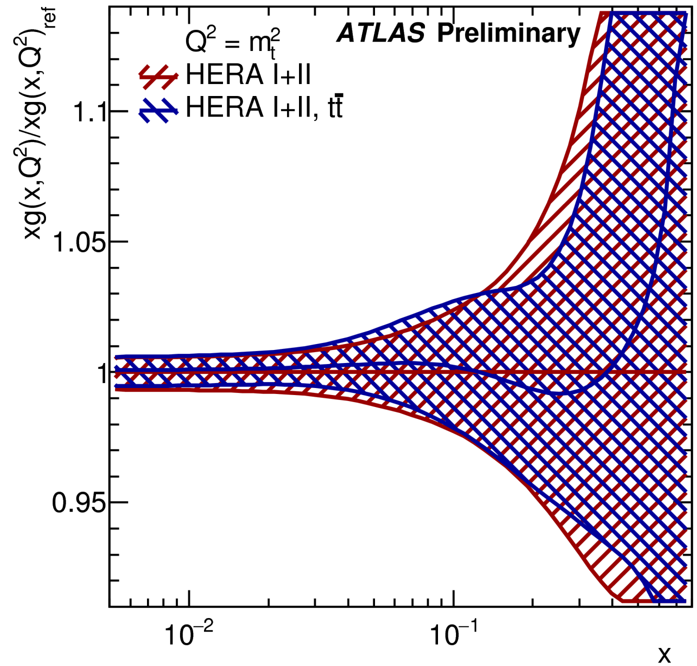
Measured cross sections

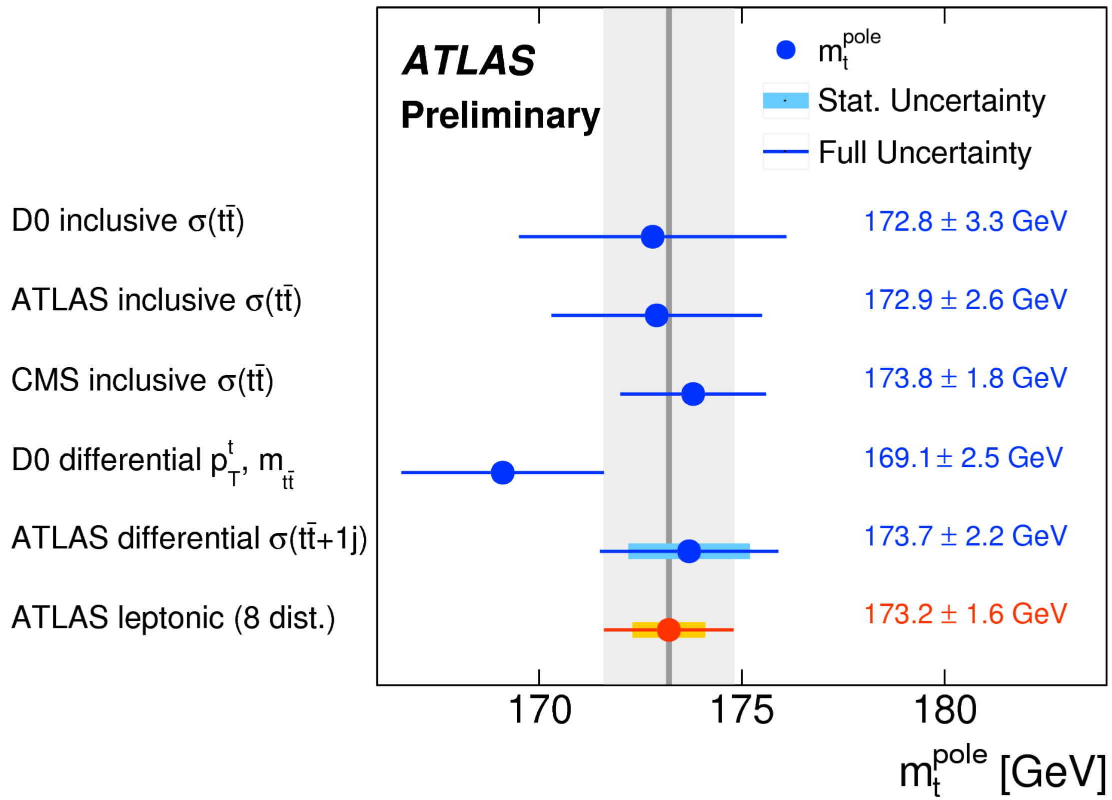


- Measured absolute and normalised differential cross sections
- Total uncertainties for the normalised cross sections at the level of 1-2% at low p_T, and 10-20% at high p_T

Interpretation – Gluon PDF and m_t^{pole}

- Explored the sensitivity to the gluon PDF through a QCD analysis including DIS data
- Gluon PDF uncertainties reduced from 4% to 2.5% at high Bjorken-x ~ 0.1
- Very good compatibility between DIS and tt data

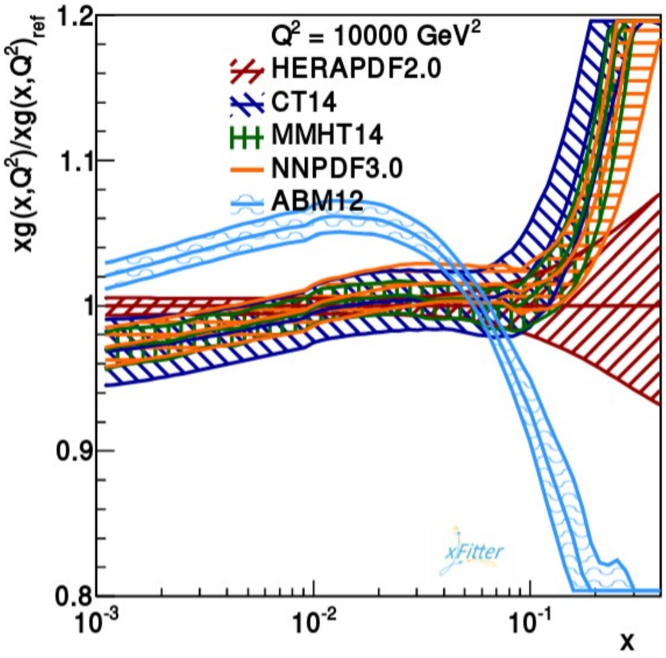




- Top-quark pole-mass determined from a combined fit to all measured distributions using NLO QCD
- Current m_t^{pole} determination with the smallest uncertainty
- Uncertainty dominated by QCD scale variations (1.1 GeV)

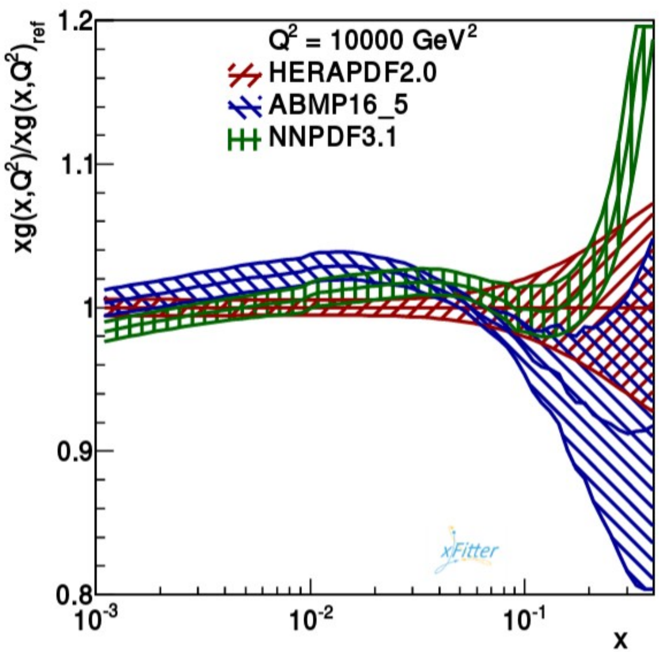
$$m_t^{\text{pole}} = 173.2 \pm 0.9(\text{stat}) \pm 0.8(\text{exp.syst}) \pm 1.2(\text{theory})\ \text{GeV}$$

Prospects for gluon PDF constraints with $t\bar{t}$ data



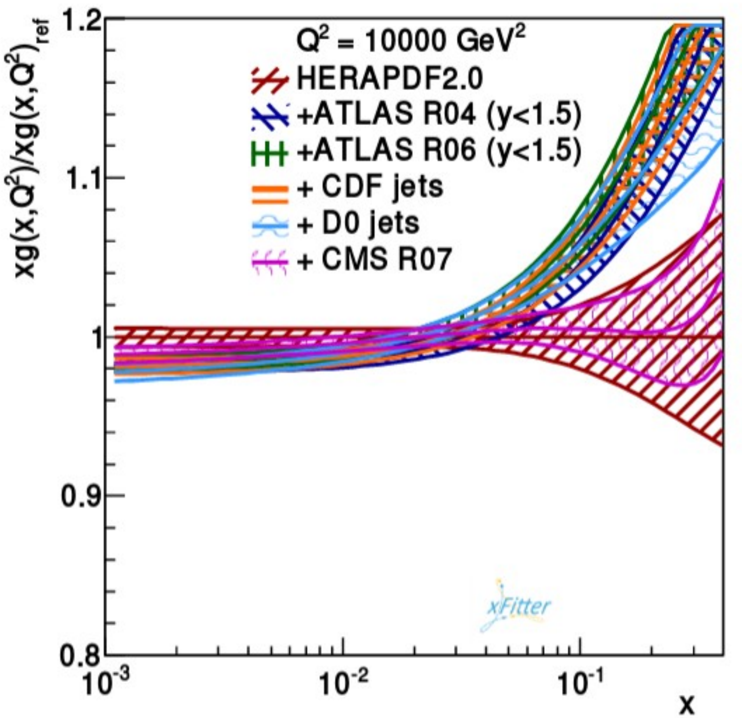
What is the current knowledge of the gluon PDF?

- Gluon at x ~ 0.01 important for Higgs
- Gluon at x > 0.3 important for searches
- Gluon at x ~ 0.1 important for tt



- The VFNS global PDF sets CT14, MMHT14, NNPDF3.0 are in very good agreement for the gluon PDF
- The gluon PDF of HERAPDF at high-x is softer than the VFNS global PDF sets
- The ABM12 gluon PDF (FFNS) is significantly softer than the others, less so the more recent ABMP16 PDF

Prospects for gluon PDF constraints with $t\bar{t}$ data



- As shown in previous slides, the gluon PDF constraints of $t\bar{t}$ data are usually in very good agreement with the gluon PDF determined from HERA DIS data
- On the contrary, the inclusion of jets data lead in general to harder gluon distribution (see talk of S. Glazov at EPS)
- Is this an indication of tension between jet and $t\bar{t}$ data for the gluon PDF?
- More precise $t\bar{t}$ cross section measurements and their QCD analysis at NNLO could answer these questions in the near future

Summary and conclusions

- PDFs are an essential ingredient for the physics programme at the LHC. PDF extraction is a complex problem with a variety of solutions
- $t\bar{t}$ measurements already provide important constraints to the PDFs, complementary to DIS and jets data, especially for the medium- and high-x gluon PDF
- More precise $t\bar{t}$ cross section measurements and their inclusion in PDF fits at NNLO will allow to further improve our knowledge of the gluon PDF, and shed light on possible tensions with jets data

BACKUP

Variety of PDF sets

A complex problem leads to a variety of solutions.

- PDF sets differ by:
  - Input data: all or part of DIS, Tevatron, LHC, fixed target, neutrino data
  - Determination of PDF uncertainties: hessian, MC replica
  - Parametrization of the PDF functional form: polynomials, NN
  - QCD perturbative order: LO, NLO, NNLO
  - Heavy flavour scheme for the DIS cross section: Variable flavour number scheme (VFNS), Fixed flavour number scheme (FFNS)
  - Choice of $\alpha_s(M_Z)$, top, charm, and bottom masses
  - χ^2 definition and χ^2 tolerance criteria

Motivation for LHC measurements for PDFs

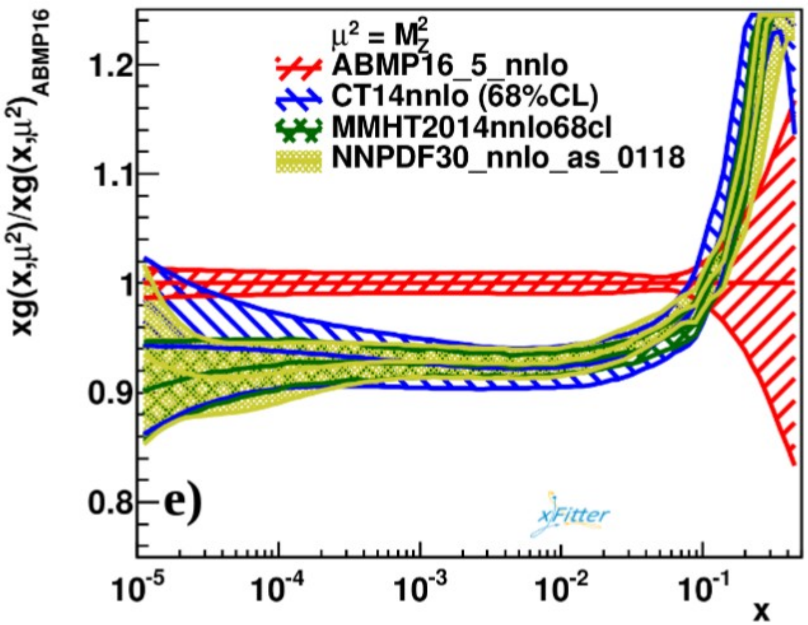
- Cross section measurements at hadron colliders cannot replace the invaluable ep DIS data
- Nevertheless they can provide important complementary information in the corners of the phase space not well covered by other datasets
- The LHC data can also help to resolve some of the disagreement between datasets and PDF groups, e.g. on the strange and gluon PDFs

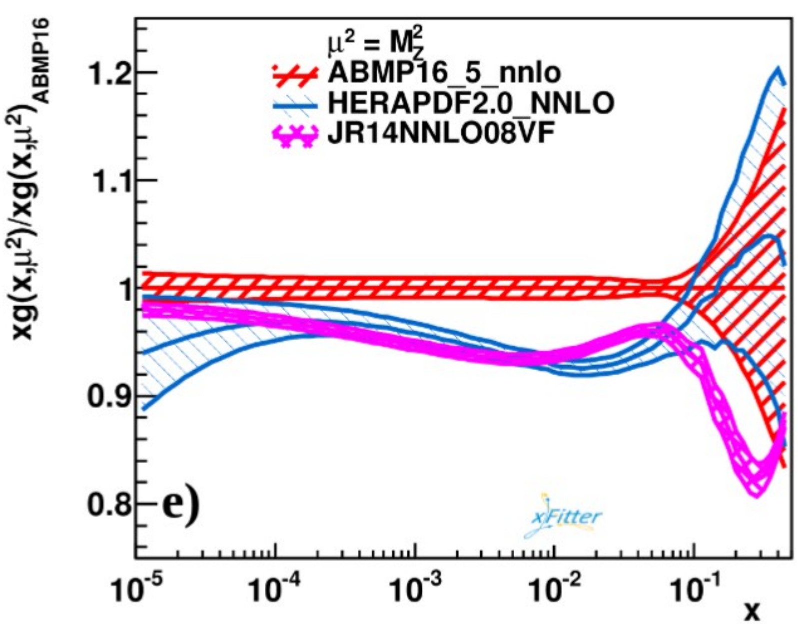
Process	Sensitivity
Drell-Yan	Flavour decomposition of the sea, u_v, d_v, γ PDF
W+charm	Strange PDF
Jets	High-x gluon PDF
Photon	Medium-x gluon PDF
Top pair	Medium- and high-x gluon PDF

- Other measurements not yet fully exploited: diboson, single top, W/Z+jet
- Precise data requires precise theory:NNLO QCD, NLO EW, non-pQCD, and PS corrections

Including LHC measurements into a QCD analysis for PDF determination allows stress testing QCD and the factorisation theorem

Prospects for the gluon PDF





- Similar picture for the latest ABMP16 Fixed-Flavour-Number scheme PDF set