Parton distribution functions

News from the front for the visionary frontier

Pavel Nadolsky

For CTEQ-TEA group

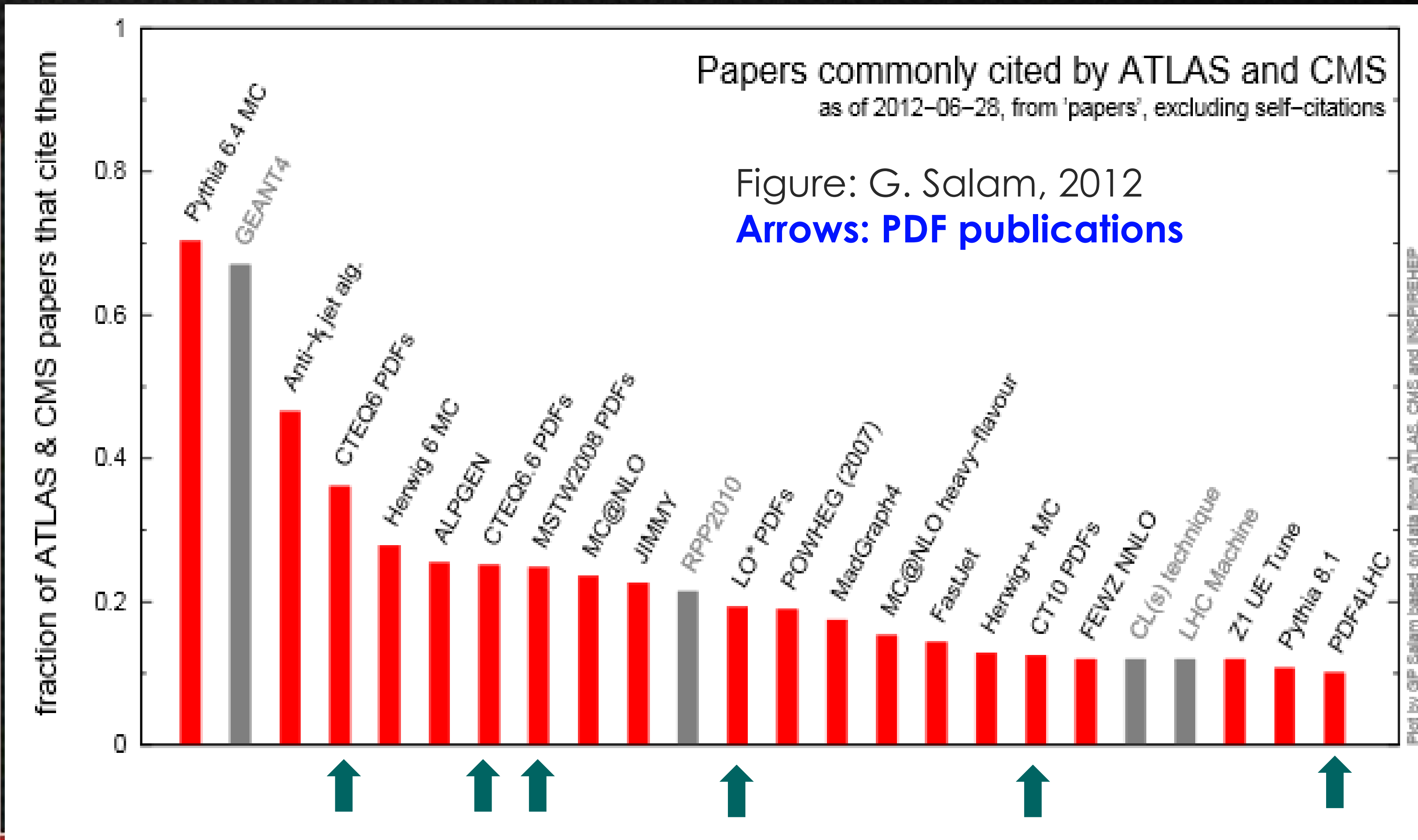
S. Dulat, J. Gao, J. Huston, M. Guzzi, T.J. Hou, H-L Lai, J. Pumplin, T.-J. Hou, D. Stump, C.-P. Yuan

APS DPF meeting, UC Santa Cruz, August 16, 2013

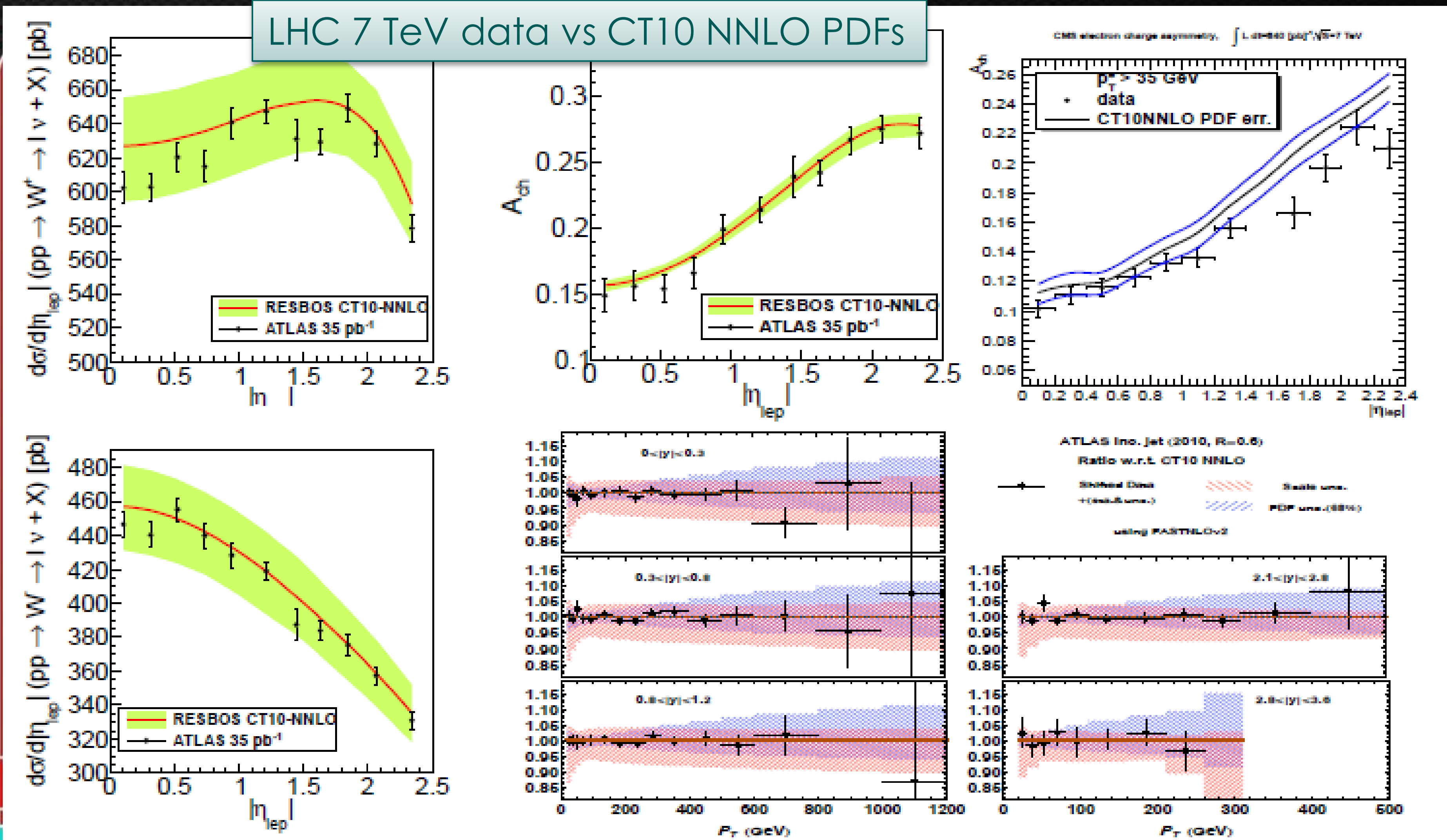
It is a payoff decade for the PDF analysis efforts!

1. A windfall of new data to compare with (LHC, HERA, Tevatron…)
2. Tests of QCD factorization at new $\sqrt{s}$, targeting 1% precision
3. Impact on a variety of electroweak precision measurements, new physics searches

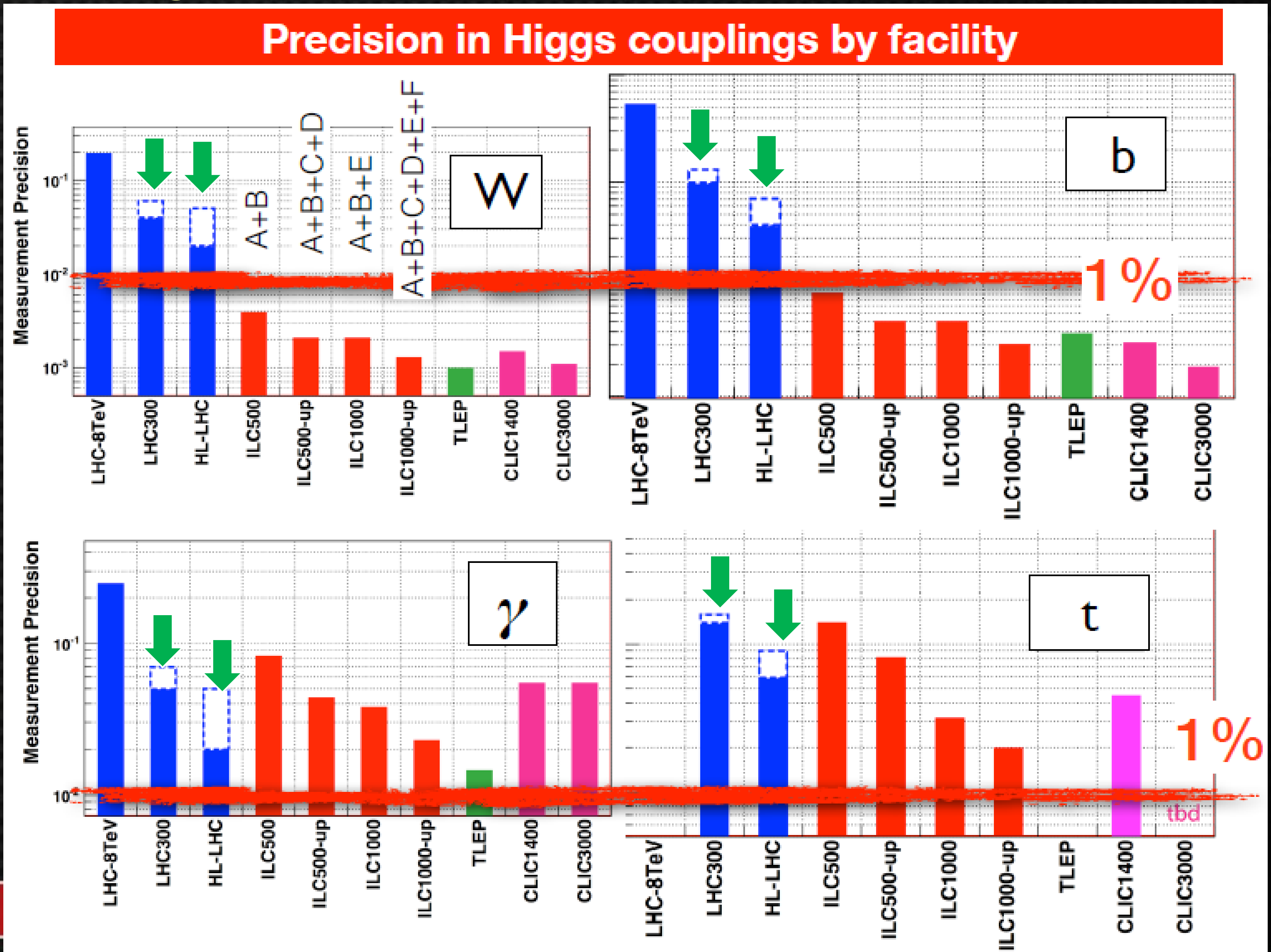
A large fraction of hadronic experiments relies on PDFs in theoretical simulations



PQCD based on pre-LHC PDFs successfully **predicted** early LHC cross sections within 3-10% accuracy

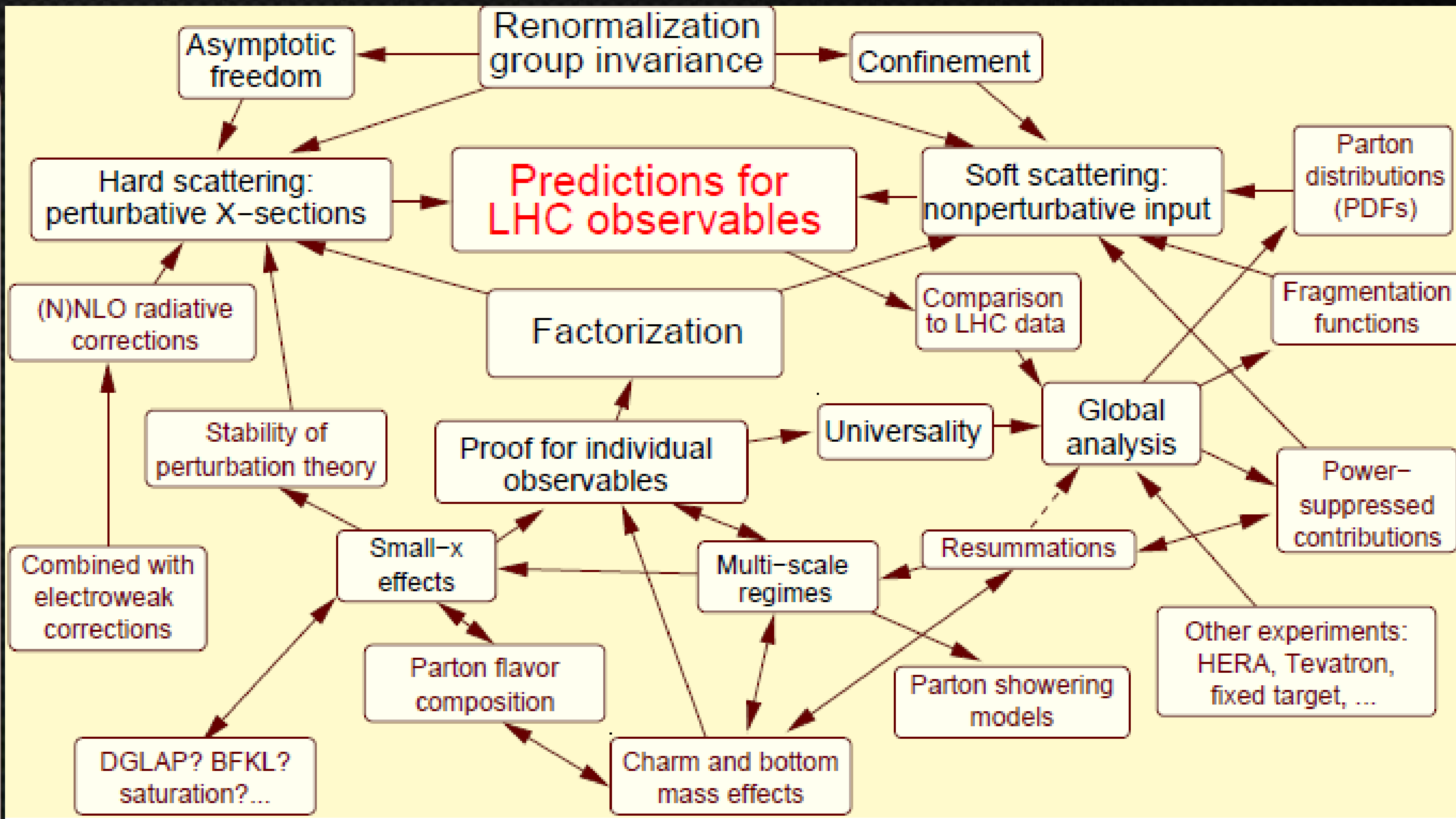


We now wish to know PDFs to within 1% to realize the LHC program of EWSB studies



C. Brock, Snowmass'2013

Full richness of QCD theory comes into play at 1% resolution



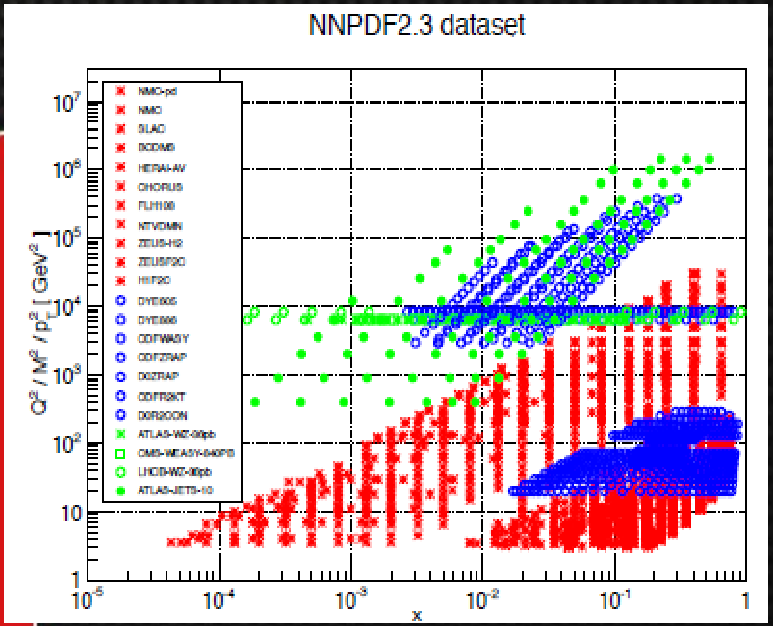
Concept map (c. 2007), even more relevant now

1% accuracy on PDFs demands major leaps beyond the present level

- **Experiment:** finding new clean measurements to probe unconstrained PDF combinations
- **Theory:** Computation of (N)NNLO QCD + NLO EW corrections and resummation. Total revision of computer codes for fits to bring their numerical accuracy from the current ~1% to >0.1%.
- **Statistics:** fast multivariate fits for unbiased PDF parametrizations with 100+ fitted parameters and multiple correlated nuisance parameters of experimental and theoretical origin

=> MC sampling, neural networks, PDF reweighting, meta-PDFs, …

Parton distribution functions in a nucleon



At NNLO QCD, general-purpose PDF parametrizations are available from ABM, CT, HERA, MSTW, NNPDF groups

Typical PDFs are constrained by

- DIS at HERA
- Vector boson production at low $\sqrt{s}$, Tevatron
- Inclusive jet production

- Any PDF set makes assumptions about poorly constrained PDF combinations, e.g., sea PDFs at $x < 0.01$ and $x > 0.3$. Photon PDF is largely unknown.
- Fixed-target data sets are critical at $x > 0.01$, but may be replaced in the future by collider measurements in $t\bar{t}$, direct-γ, Wc, … production

Our latest PDFs: CT10 and CT1X NNLO

- **CT10 NNLO** [**arXiv:1302.6246**] is an NNLO counterpart either to CT10 NLO or CT10W NNLO
  - In good agreement with early LHC data
- **CT1X NNLO** – a preliminary extension of CT10 NNLO that includes latest HERA data on $F_L(x,Q)$ and $F_2^c(x,Q)$, LHC 7 TeV data (ATLAS W & Z, ATLAS jets, CMS W asymmetry)
- The new data provide only minor improvements compared to the CT10 data set. We investigate its agreement with the CT10 data sets and await for more precise LHC data to be included in the CT1X public release

CT10 NNLO PDF vs CT10 NLO PDF

(1) gluon smaller at low x
(2) charm larger for x>0.01
(3) gluon smaller at large x

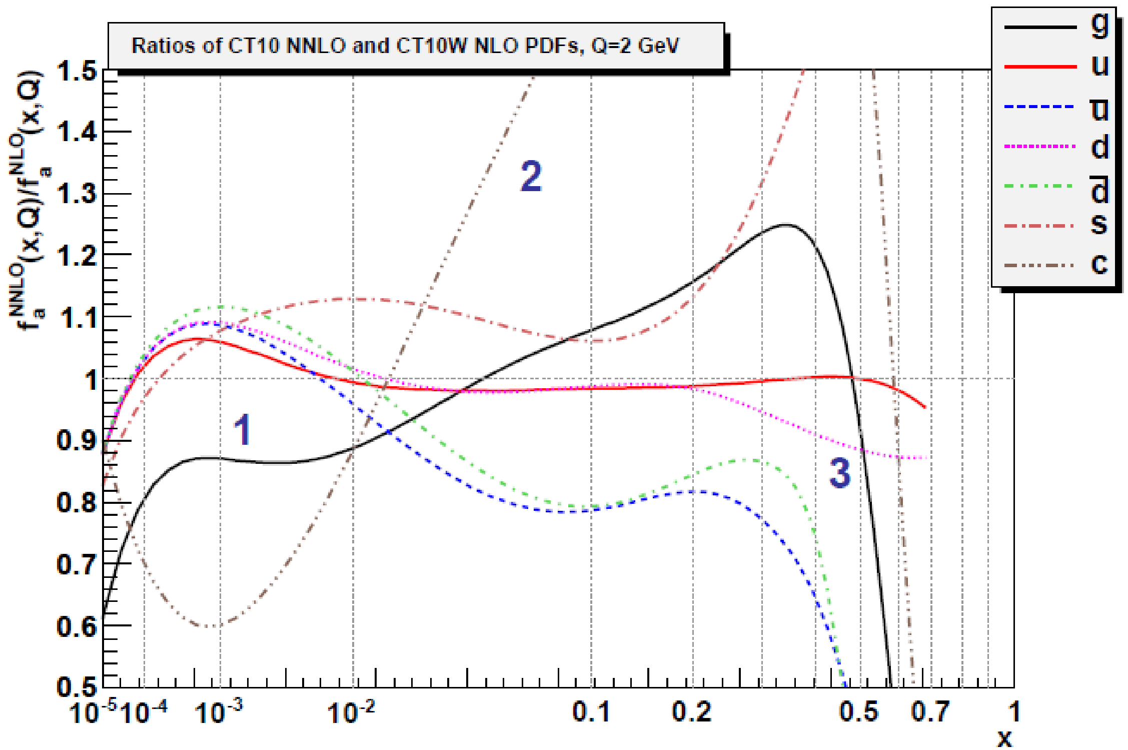
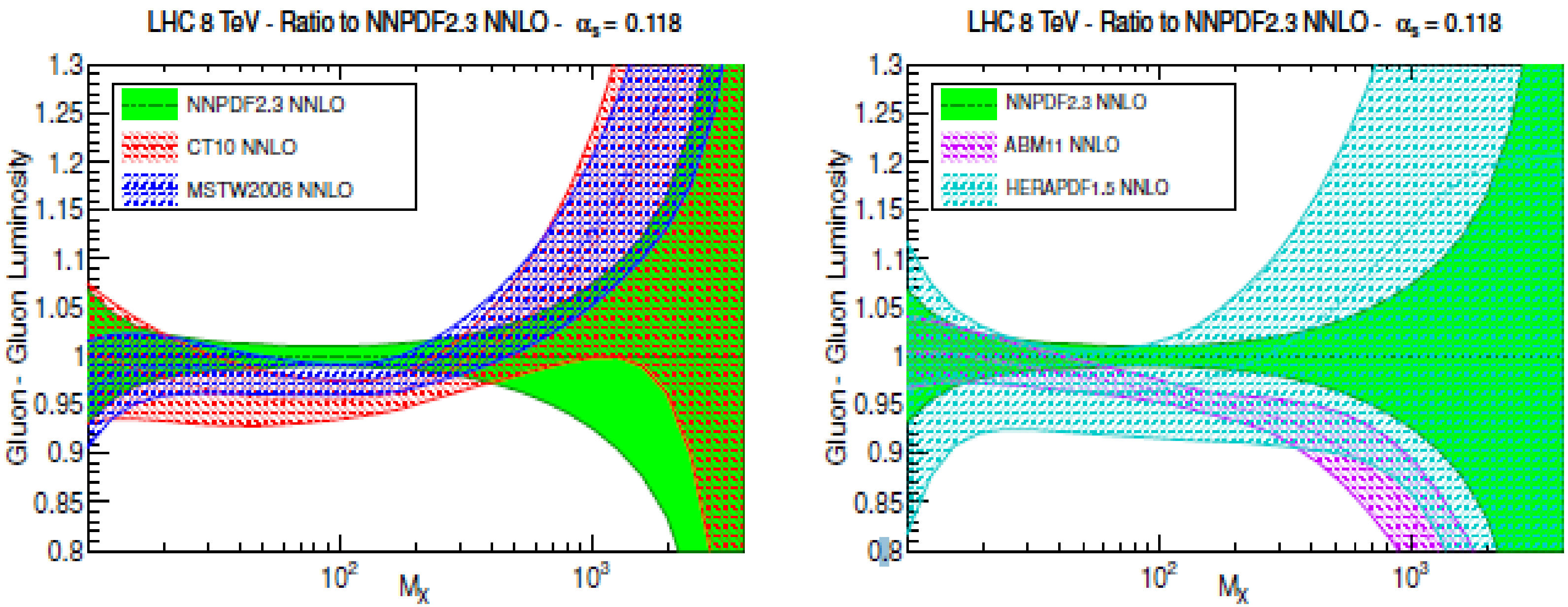


FIG. 3: Ratios of various CT10NNLO central fit parton distributions to those of the CT10W central fit, at $Q = 2\,\text{GeV}$.

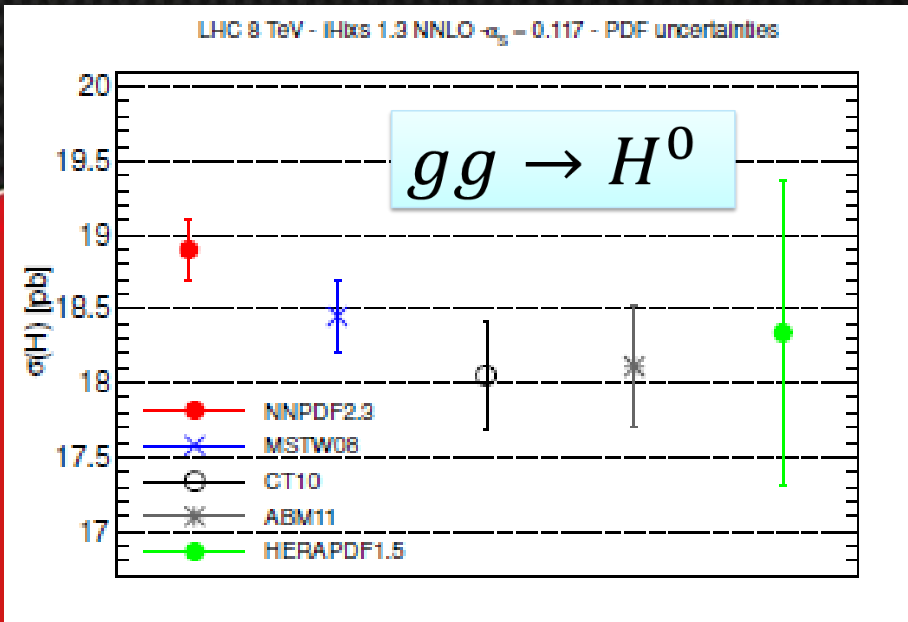
Parton distribution benchmarking with LHC data

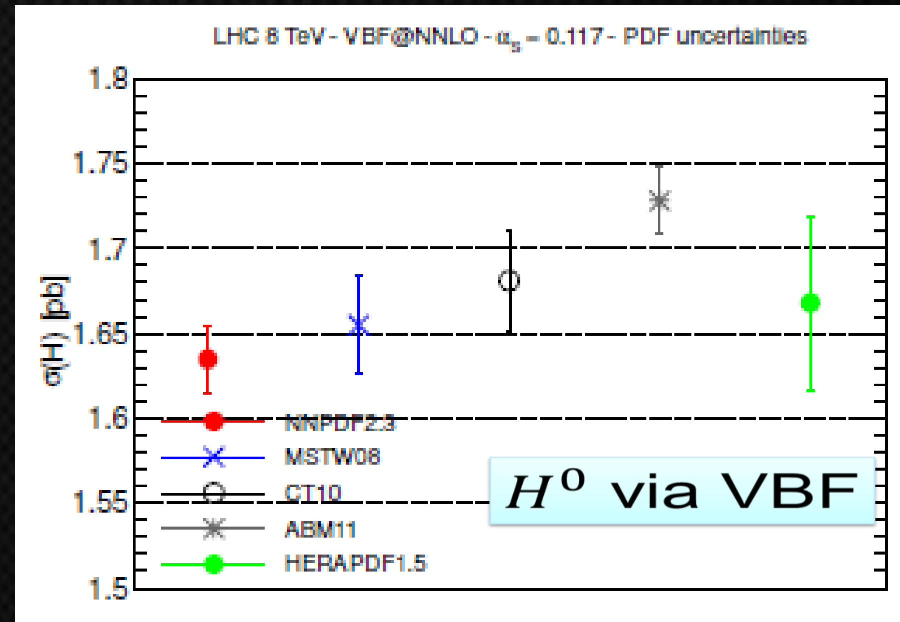
R. Ball et al., arXiv:1211.5142

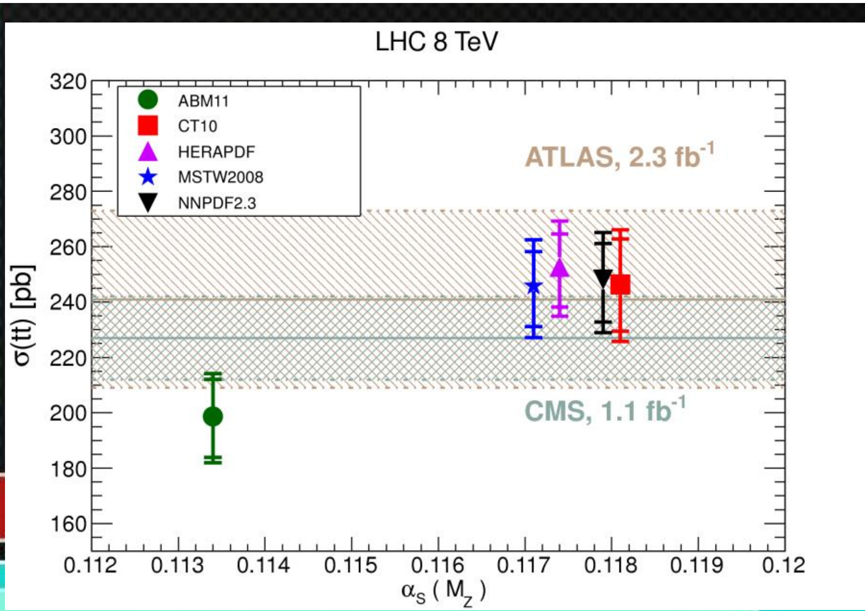


- A comparison of latest NNLO fits from 5 collaborations for a common $\alpha_s(M_Z)$ and their predictions for LHC observables
- CT10, MSTW'08, NNPDF2.1 PDFs are in good overall agreement
- Central PDFs of HERA1.5 agree well with other sets, but the PDF errors are larger because of fewer data sets included
- ABM has a smaller large-x gluon, larger quark PDFs

Predictions for benchmark LHC cross sections







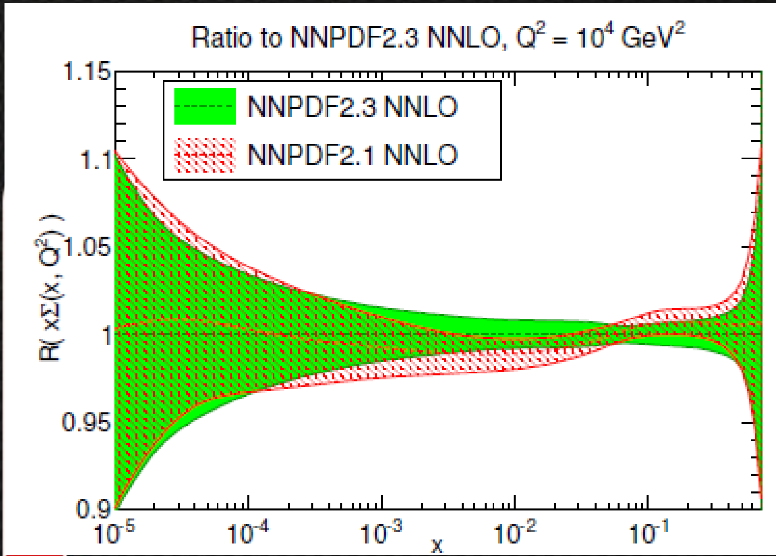
The ABM set is different from other sets, requires to reduce $\alpha_s(M_Z)$ and m_t^{pole} by ~ 3"σ" below PDG values to describe the LHC data

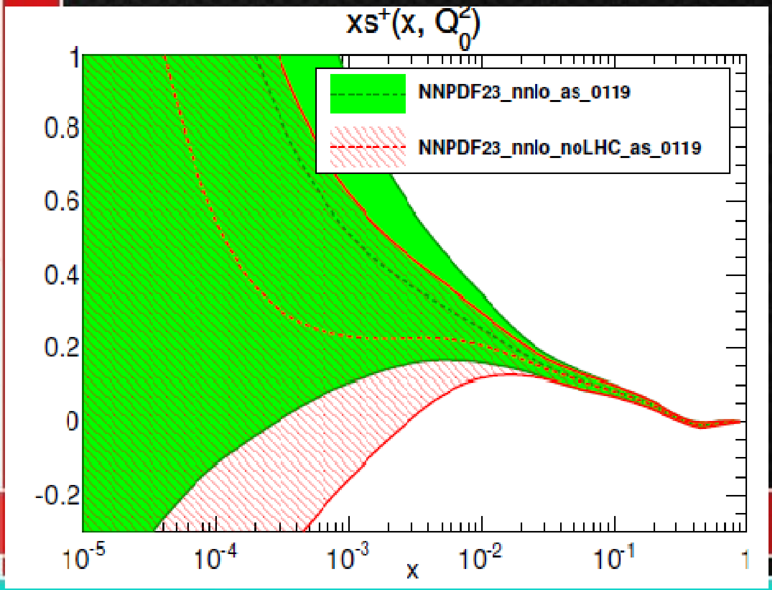
Differences are likely due to the ABM heavy-quark scheme

R. Ball etal., arXiv:1211.5142

Impact of LHC data on parton distributions

LHC data => new PDFs





NNPDF2.3: the first published PDF set that includes LHC 7 TeV data sets:

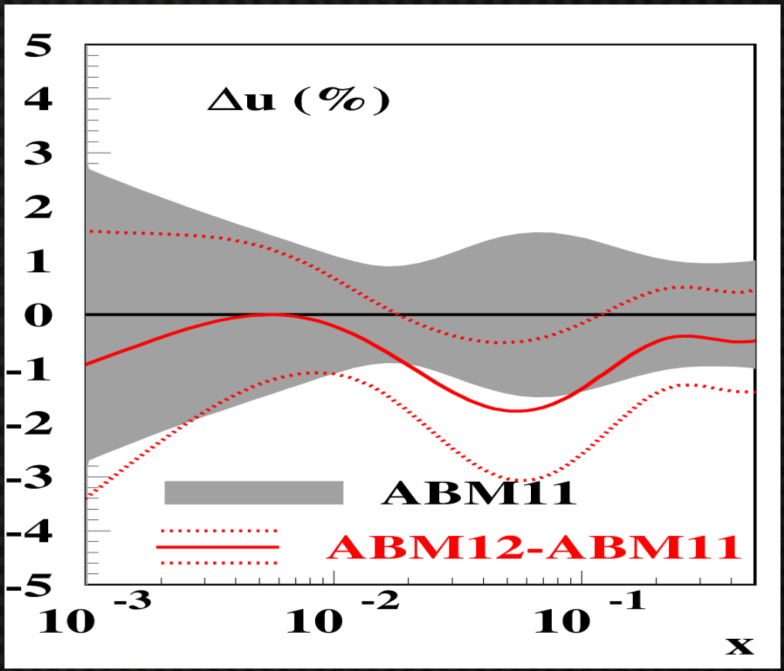
- ATLAS inc. jets and $W^{\pm}/Z$ rapidity distributions
- LHCb $W^{\pm}$ rapidity distributions
- CMS W asymmetry

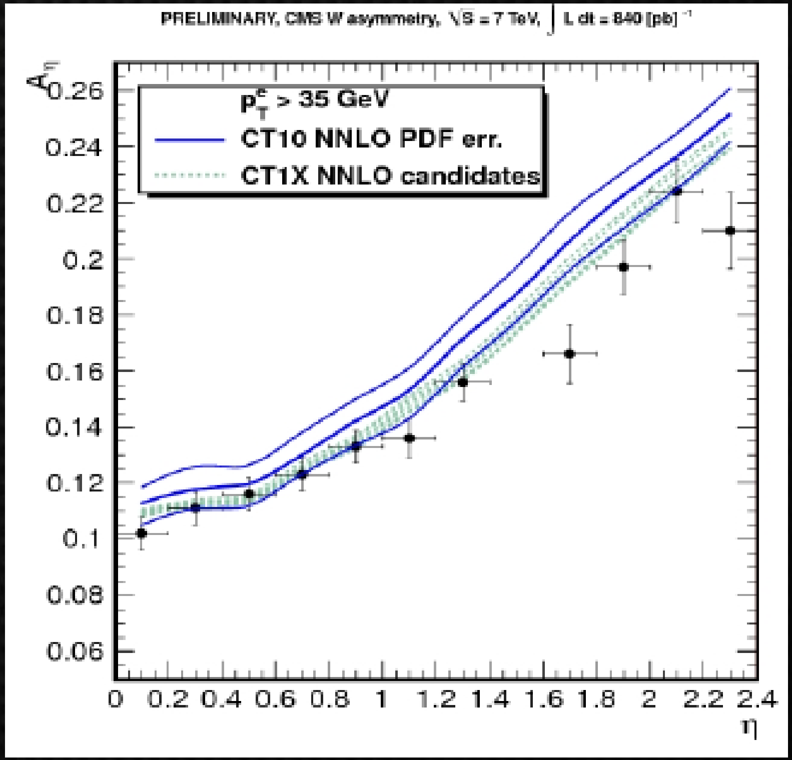
Some reduction in the PDF uncertainty compared to pre-LHC measurements

Reduced error on strangeness PDF

Large constraint for "collider only" PDFs

W/Z cross sections, W charge asymmetry





ABM: inclusion of ATLAS W/Z data modifies u and d PDFs

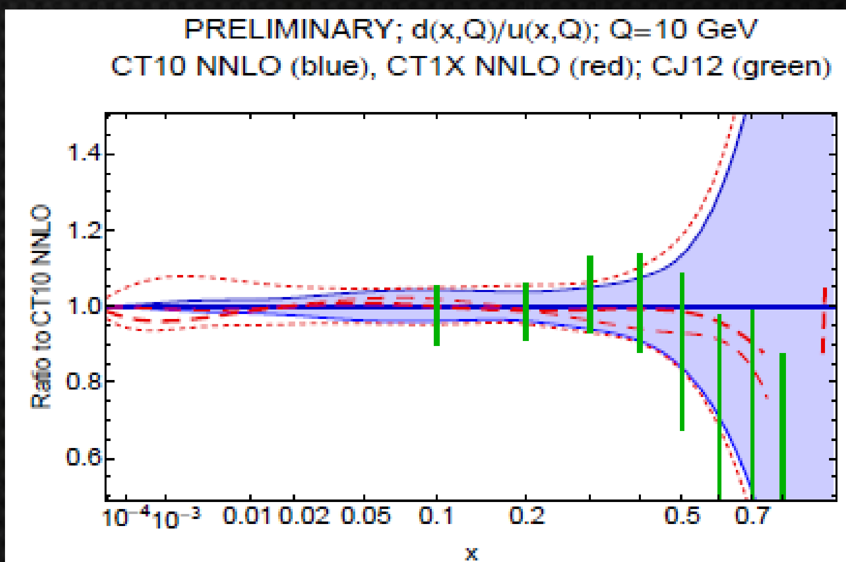
Preliminary fits CT1X and MMSTWW with LHC data

The CMS W asymmetry modifies separation between $u, \bar{u}, d, \bar{d}$ PDFs at $x \sim 0.01$ and d/u at $x > 0.1$

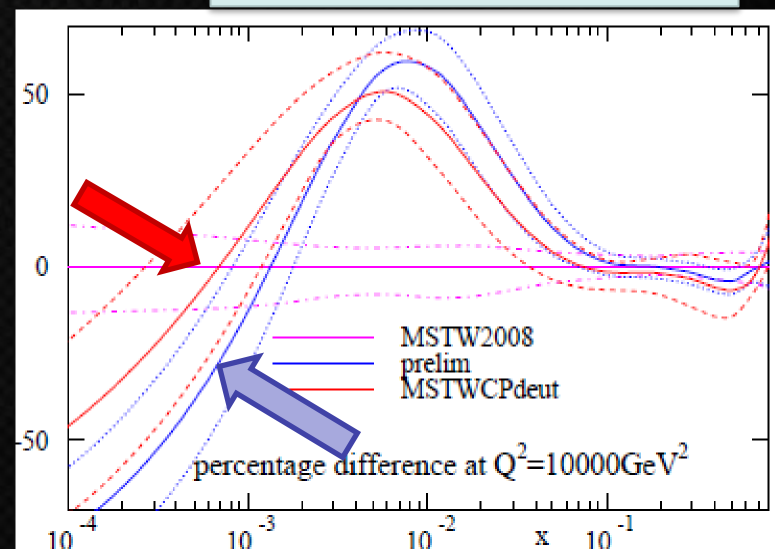
W/Z cross sections, W charge asymmetry

CT1X: modified d/u at x>0.1, increased uncertainties on d/u and $\bar{d}/\bar{u}$ at $x < 0.01$

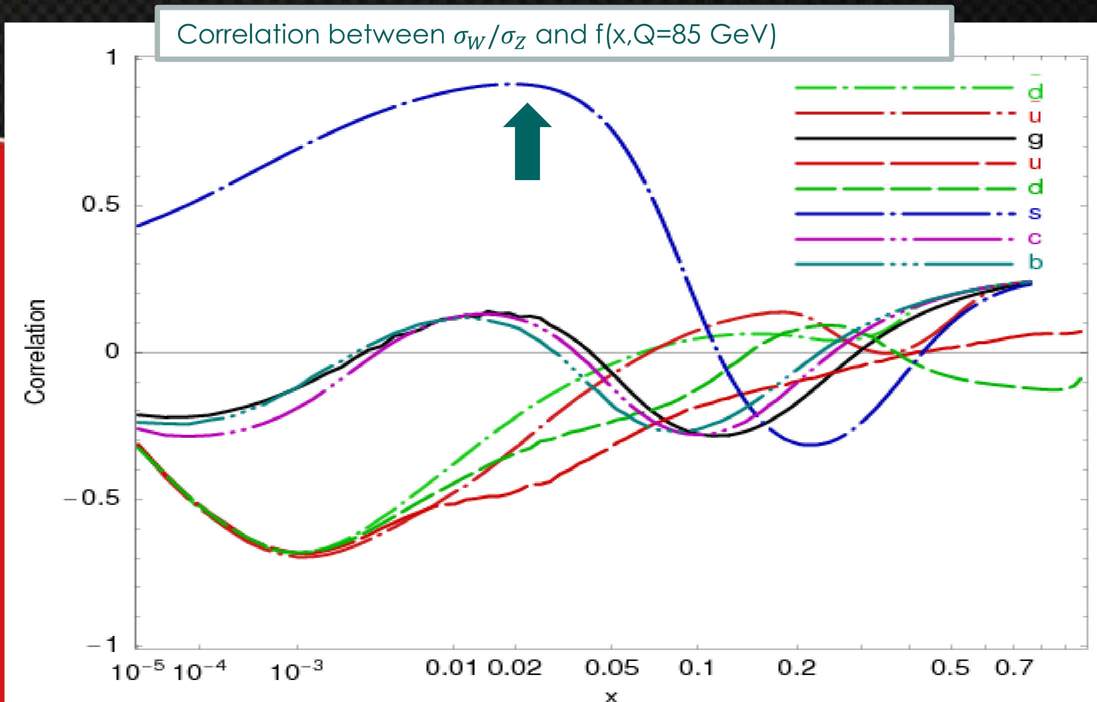
MMSTWW: $d(x,Q)$ is modified across all x, now in agreement with CMS W asy data



$x(u_v - d_v)$ at $Q = 100$ GeV

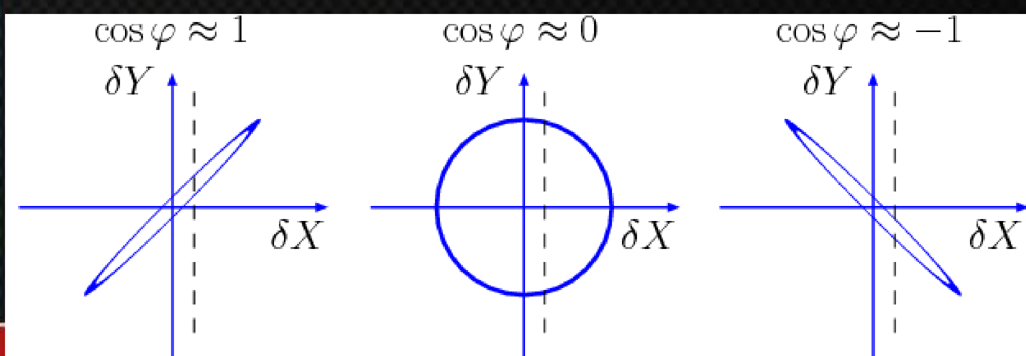


Constraining strangeness PDF by LHC W and Z cross sections



2008, CTEQ6.6 (arXiv:0802.0007): the ratio σ_W/σ_Z at LHC must be sensitive to the strange PDF $s(x,Q)$

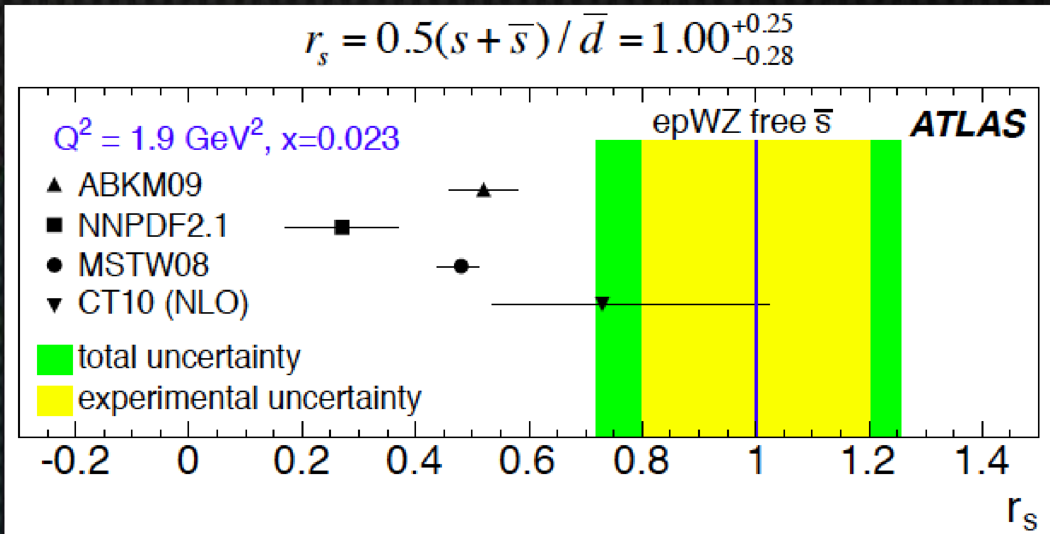
The uncertainty on $s(x,Q)$ limits the accuracy of the W boson mass measurement at the LHC



Correlation cosine $\cos\varphi \approx \pm 1$:

⇔ Measurement of X imposes tight constraints on Y

Constraining strangeness PDF by LHC W and Z cross sections

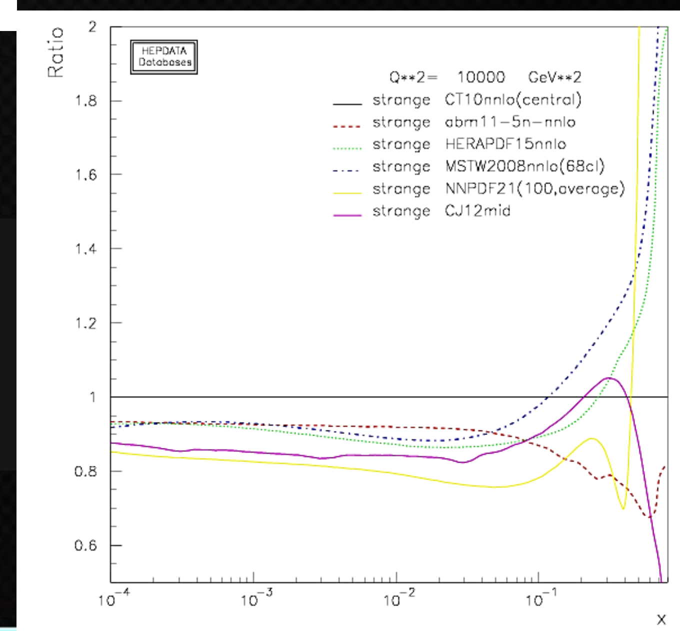


2012: the ATLAS analysis (arXiv:1203.4051) of W and Z production suggests

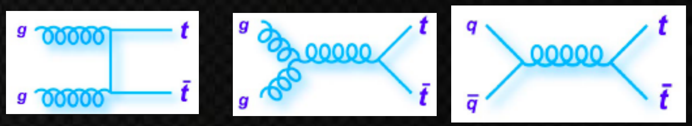
$\bar{s}(x,Q)/\bar{d}(x,Q) = 1.00^{+0.25}_{-0.28}$

at $x = 0.023$ and $Q^2 = 1.9$ GeV^2

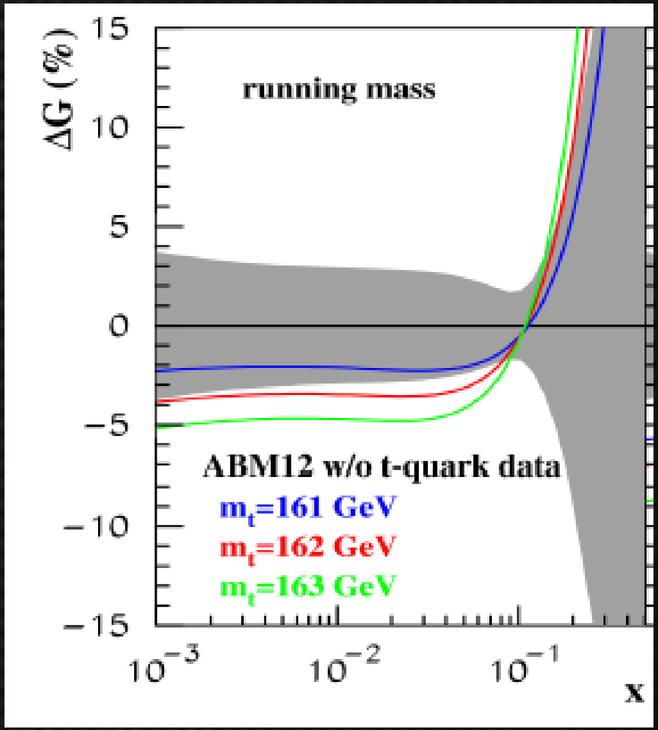
Similarly, $\sigma(W^+c)/\sigma(W^-c)$ cross section ratios show preference for $\frac{\bar{s}(x,Q)}{\bar{d}(x,Q)} \sim 1$, larger than in most pre-LHC PDF sets

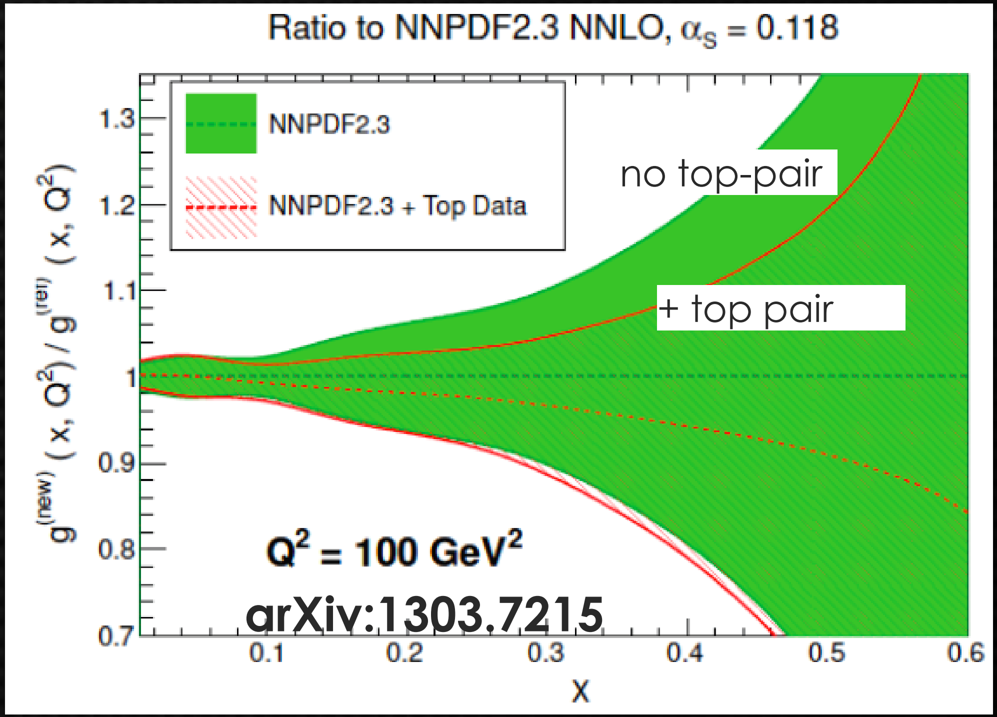


Inclusive $t\bar{t}$ production at the LHC



NNLO total cross sections computed by Czakon, Fiedler, Mitov





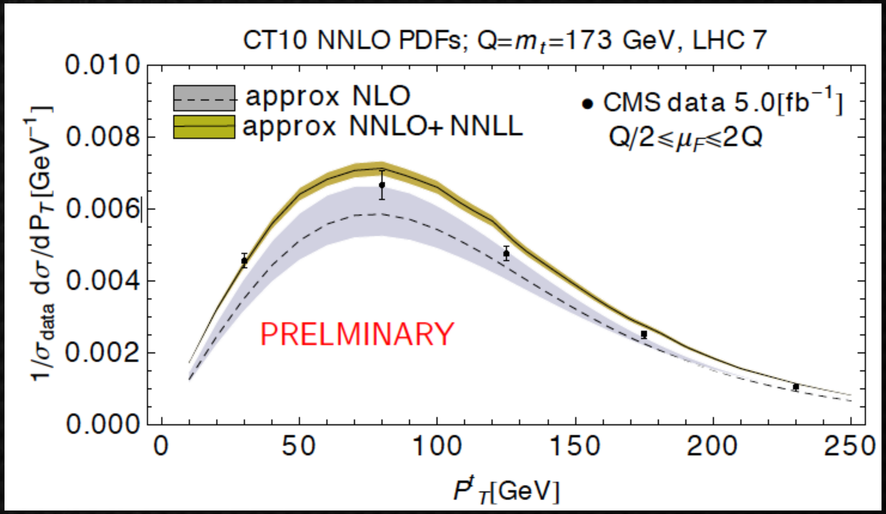
$t\bar{t}$ production may compete with inclusive jet production in constraining $g(x, Q)$ ... cf. arXiv:0802.0007
... but beware of strong dependence of $\sigma_{t\bar{t}}$ on m_t, α_s, and experimental systematics

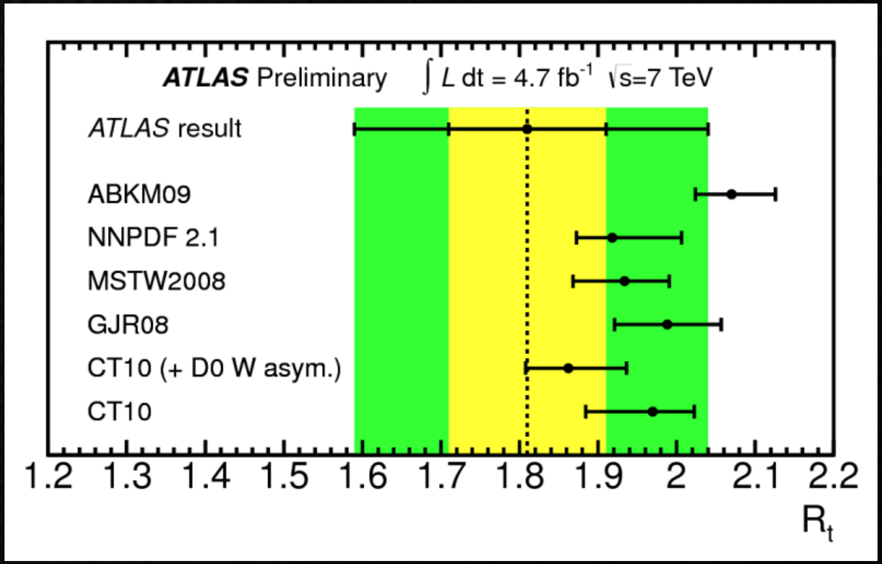
Differential $t\bar{t}$ and single-top production

Differential ttbar cross sections at 7 and 8 TeV reach precision ~ 8%

An open-source code for approx. NNLO+NNLL resummation is developed (Guzzi, Moch, Lipka)

Ratios $\sigma(pp \to tX)/\sigma(pp \to \text{tbar } X)$ in the t channel: sensitive to u/d





Some ongoing projects

- Constraints on the gluon PDFs in Higgs production
- A meta-analysis of parton distribution functions

In the backup:

- Constraints on charm mass from the PDF analysis
- PDFs for photon

Constraining the gluon PDF in the Higgs production region

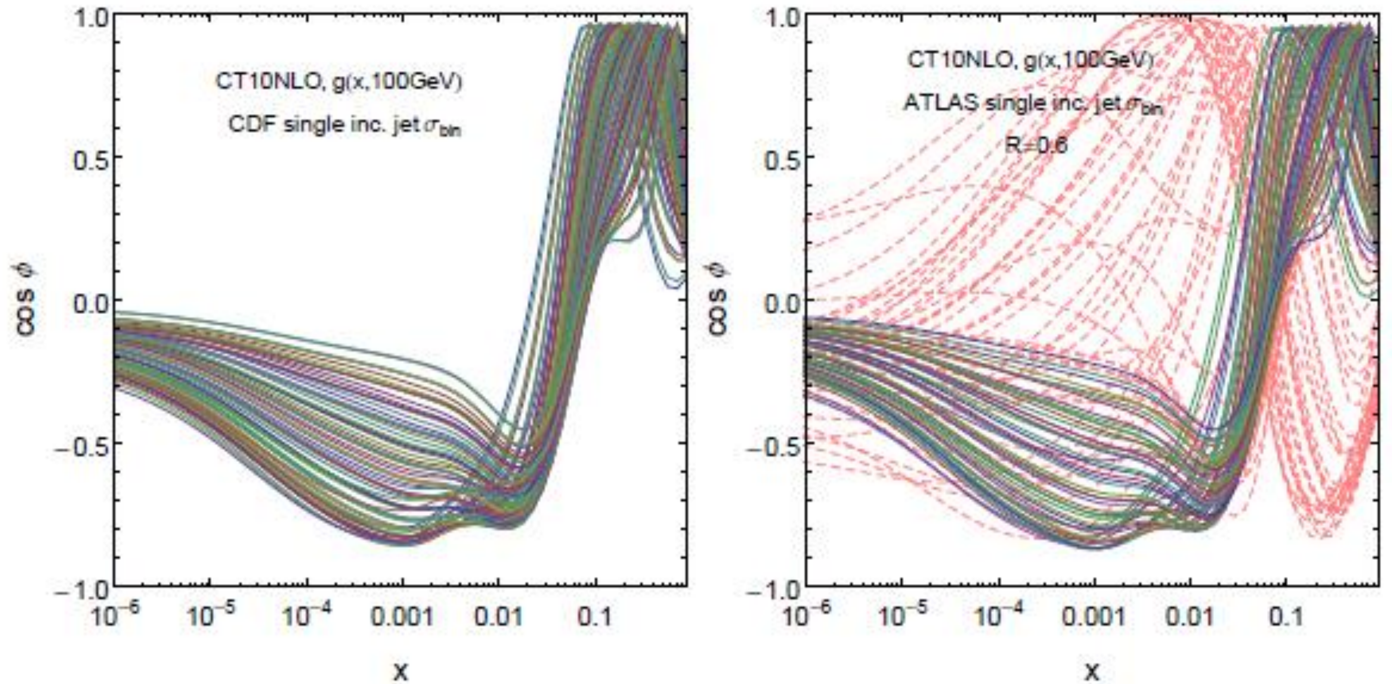
(S. Dulat, J. Gao, T.J. Hou, C. Schmidt, et al.)

The goal: find ways to reduce PDF uncertainty on $g(x, Q)$ at $x \sim 0.01$ relevant for Higgs production

- Determine experiments sensitive to $g(x, Q)$ at small x, besides the HERA DIS data
  - LHC jet production, to some extent $t\bar{t}$ production
- Obtain reliable (N)NLO predictions for these processes; benchmarking of MEKS, ApplGrid, FastNLO codes for NLO inclusive jet production
- Understand theoretical and experimental systematic errors on $g(x, Q)$

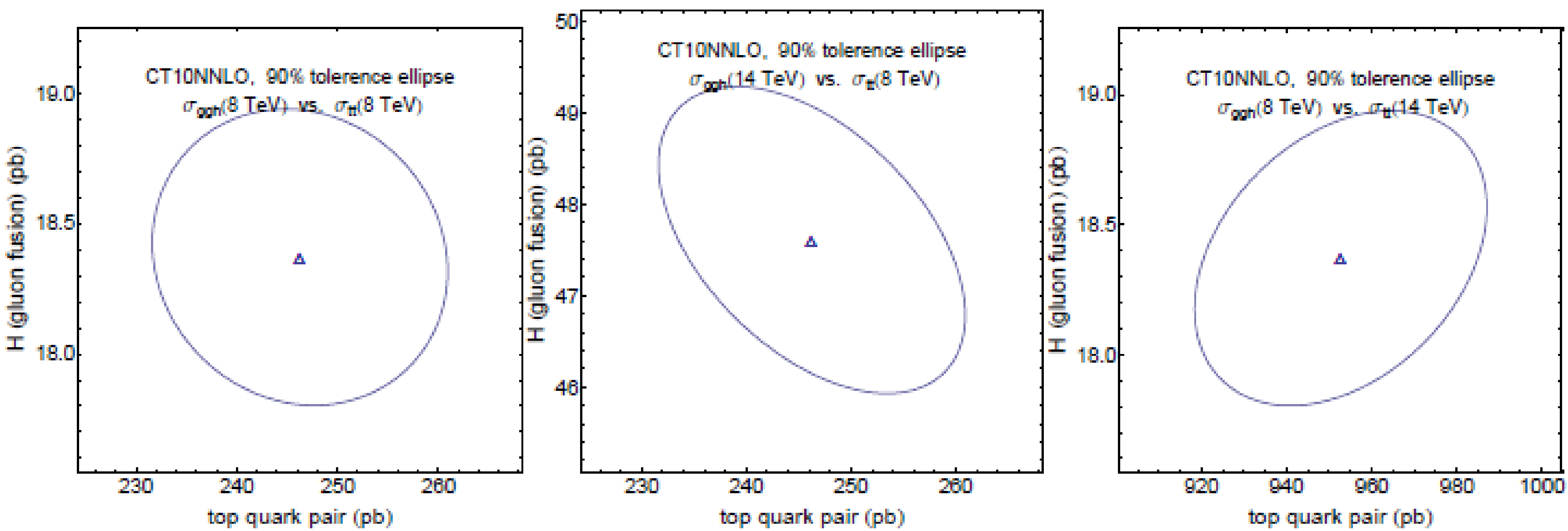
Correlations of $g(x,Q)$, Higgs, inclusive jet, and $t\bar{t}$ cross sections

PDF correlation analysis *(J. Gao, prelim.)*: LHC inclusive jet production directly probes $g(x,Q)$ at $x < 0.05$ (red lines), in contrast to the Tevatron that constrains this range by momentum sum rule

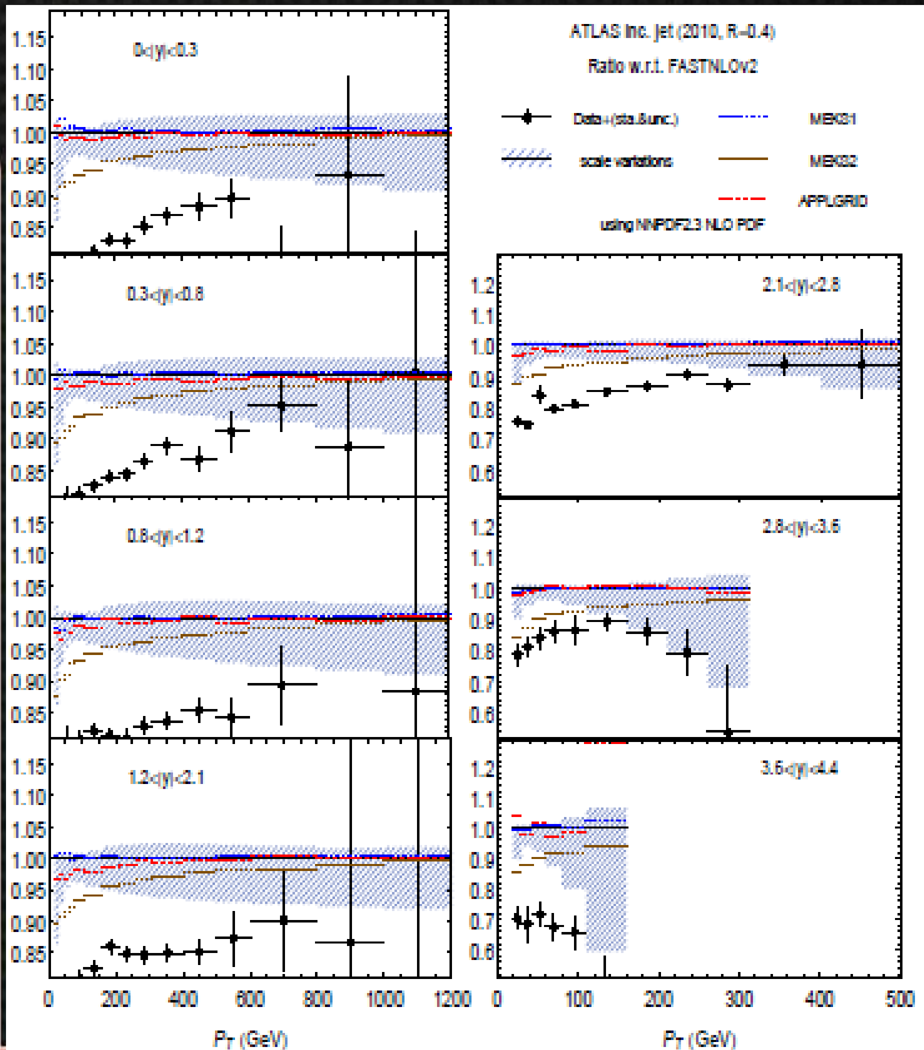


Correlations of $g(x,Q)$, Higgs, inclusive jet, and $t\bar{t}$ cross sections

$\sigma(t\bar{t})$ and $\sigma(ggH)$ at the LHC are not correlated at the same $\sqrt{s}$, mildly (anti-)correlated at different $\sqrt{s}$



Advanced NLO predictions for incl. jet production

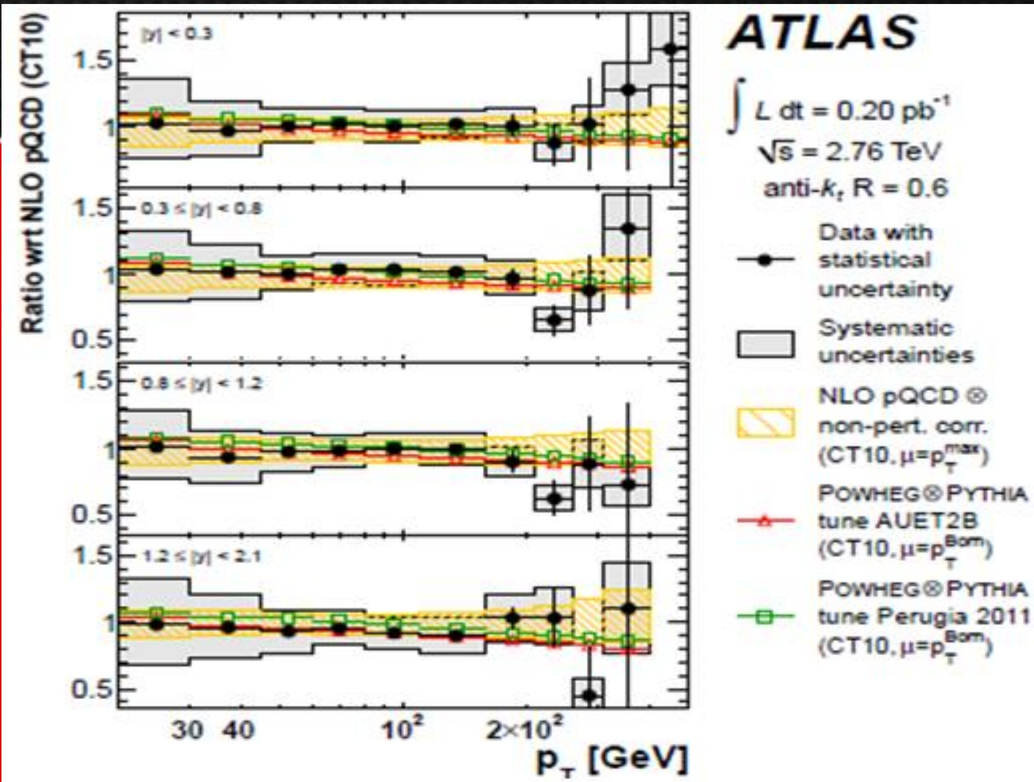


arXiv: 1207.0513, 1211.5142

The need to have reliable predictions for LHC (di)jet production for PDF analysis inspired revisions/tuning of NLO theory calculations.

Through various tests, two available families of NLO codes (**NLOJet++/ApplGrid/FastNLO** and **MEKS**) **AND** NLO event generators (**MC@NLO** and **Powheg, previous slide**) were brought into excellent agreement (non-trivial!)

Advanced NLO predictions for incl. jet production



P. Starovoitov, DIS'2013

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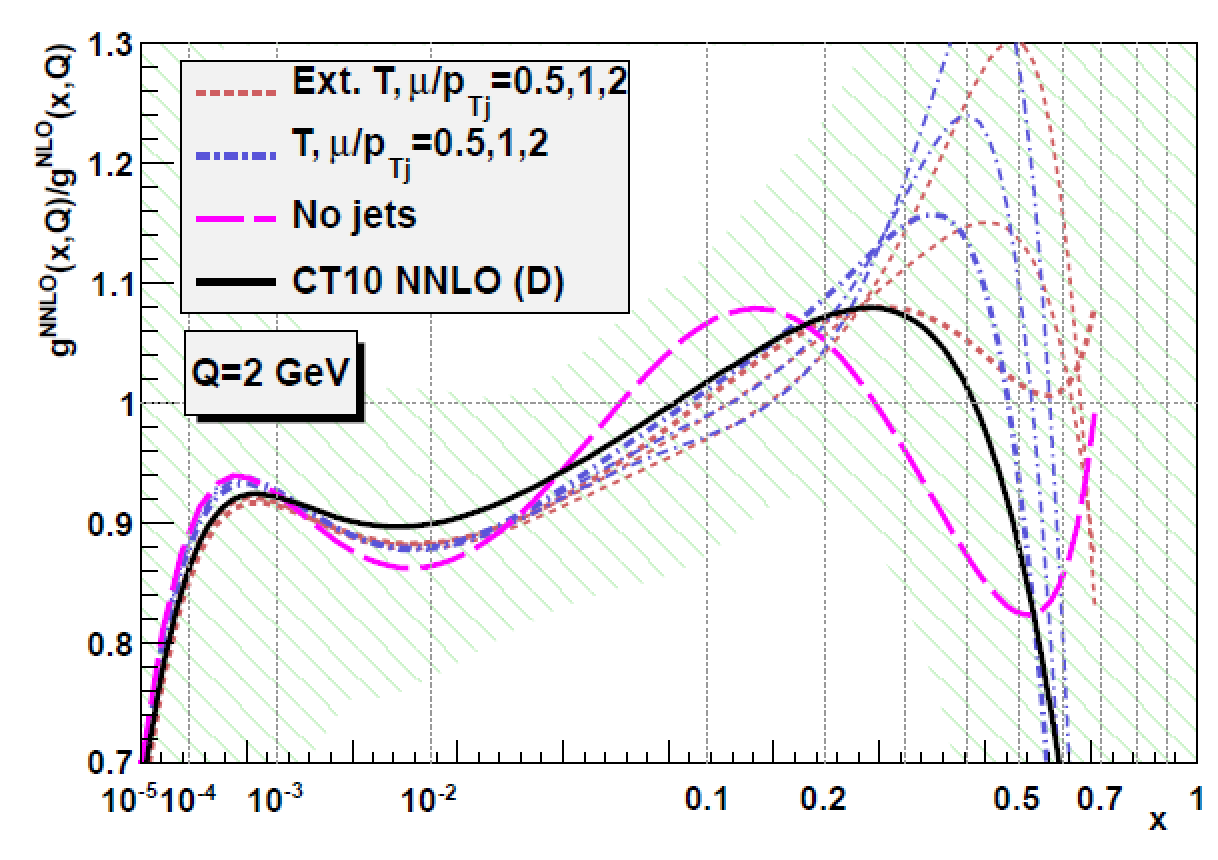
Role of correlated systematic errors



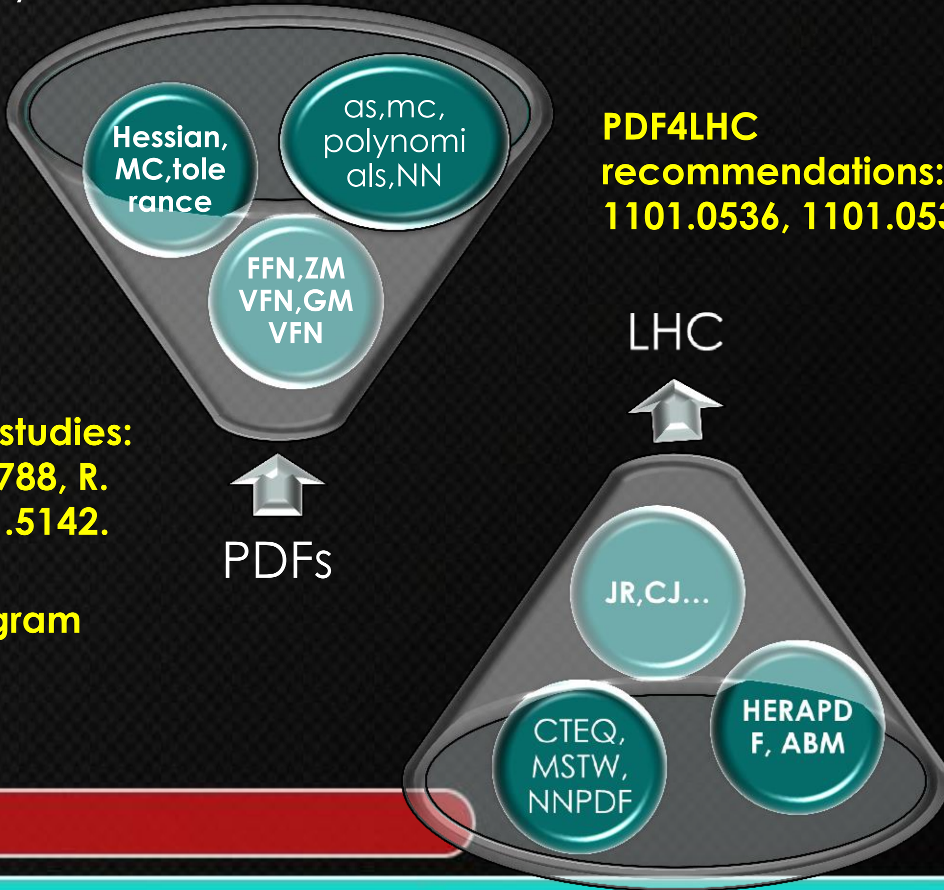
One of the objectives of the CT10 NNLO study was to investigate the role of correlated systematic errors and theoretical uncertainties

For example, the large-x g(x,Q) depends on the implementation of corr. syst. errors in Tevatron jet experiments, as well as on the assumptions about QCD scales. The CT10 NNLO gluon error sets are constructed so as to span the full range of uncertainty due to experimental errors, corr. syst. errors, and various scale choices

A meta-analysis of parton distribution functions

Jun Gao, PN, in progress

Often, it is necessary to provide a central PQCD prediction and PDF uncertainty using PDF sets from several groups. However, these PDF sets assume distinctly different physics inputs and cannot be combined in a simplistic way



PDF4LHC recommendations: 1101.0536, 1101.0538

Benchmarking studies: G. Watt, 1106.5788, R. Ball, et al., 1211.5142.

HERA Fitter program

Can we try a different path?

A meta-analysis of parton distribution functions

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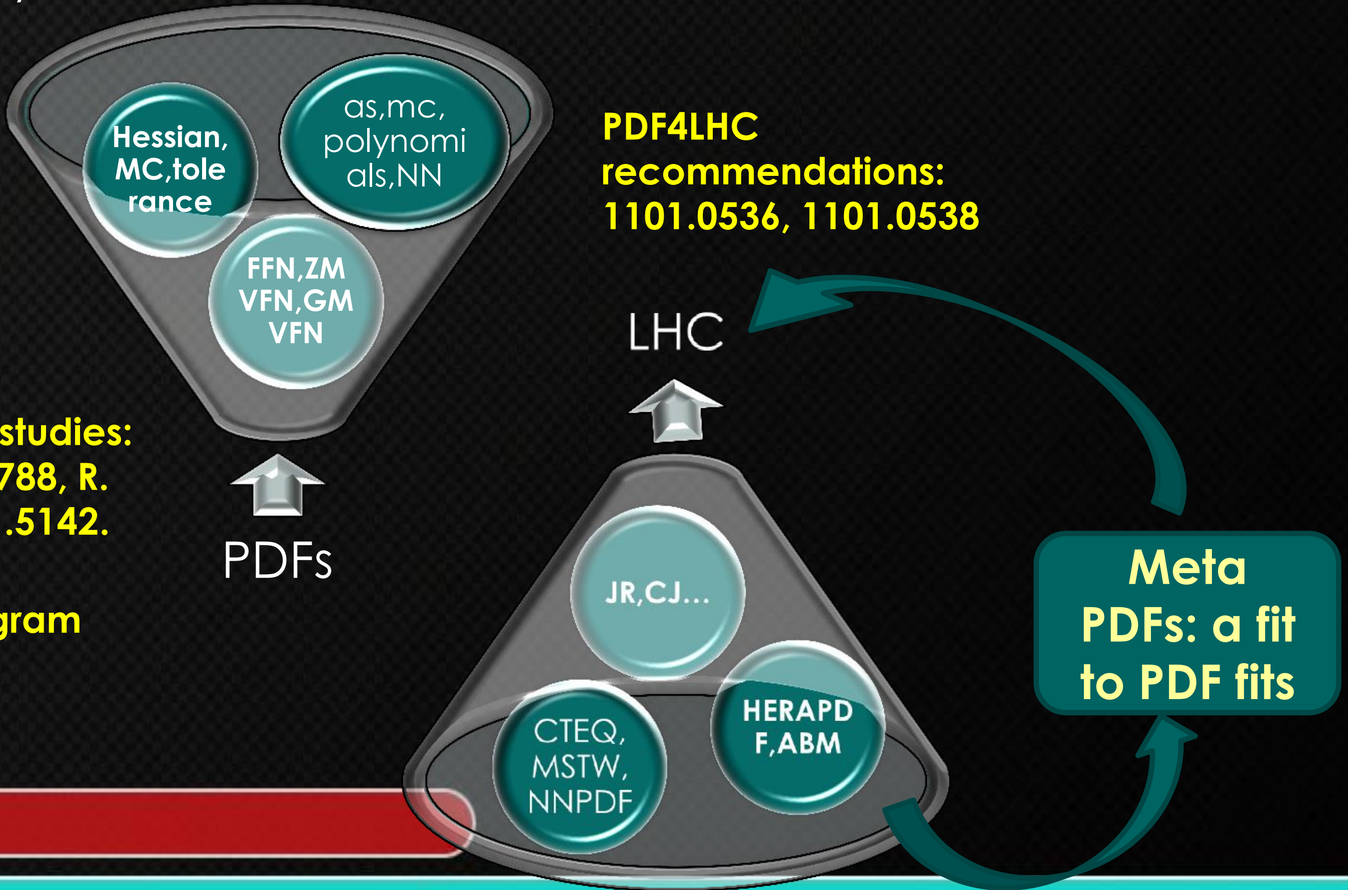


Benchmarking studies: G. Watt, 1106.5788, R. Ball, et al., 1211.5142.

HERA Fitter program

A meta analysis of parton distribution functions for the LHC

The META PDFs is found by the following procedure:

1. Select several groups of PDFs (CT, MSTW, NNPDF..)
2. Convert every input PDF at an initial scale Q_0 above the bottom quark mass into a shared parametrization form
3. Compute the central META PDF by averaging all META replicas. Eliminate redundant replicas using the Hessian or another method.

Benefits:

1. A natural way to compare and combine the LHC predictions from different PDF groups in most processes. Works similarly to the PDF4LHC prescription, but PDFs are combined directly in the PDF parameter space.

2. Especially desirable for combining a large number of PDF sets, in this case also minimizing numerical computation efforts for massive NNLO calculations.

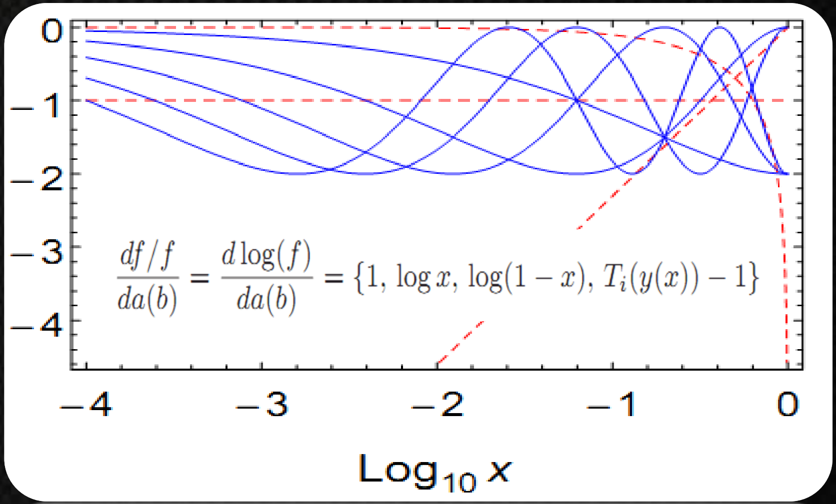
A functional form for META PDFs

We work with 9 PDF flavors, including strangeness asymmetry, and parametrize each of them as

$$f(x, Q_0) = a_1 x^{a_2} (1-x)^{a_3} e^{\sum_i b_i (T_i(y(x))-1)}$$

J. Pumplin, 0909.5176, A. Glazov, et al., 1009.6170, A. Martin, et al., 1211.1215

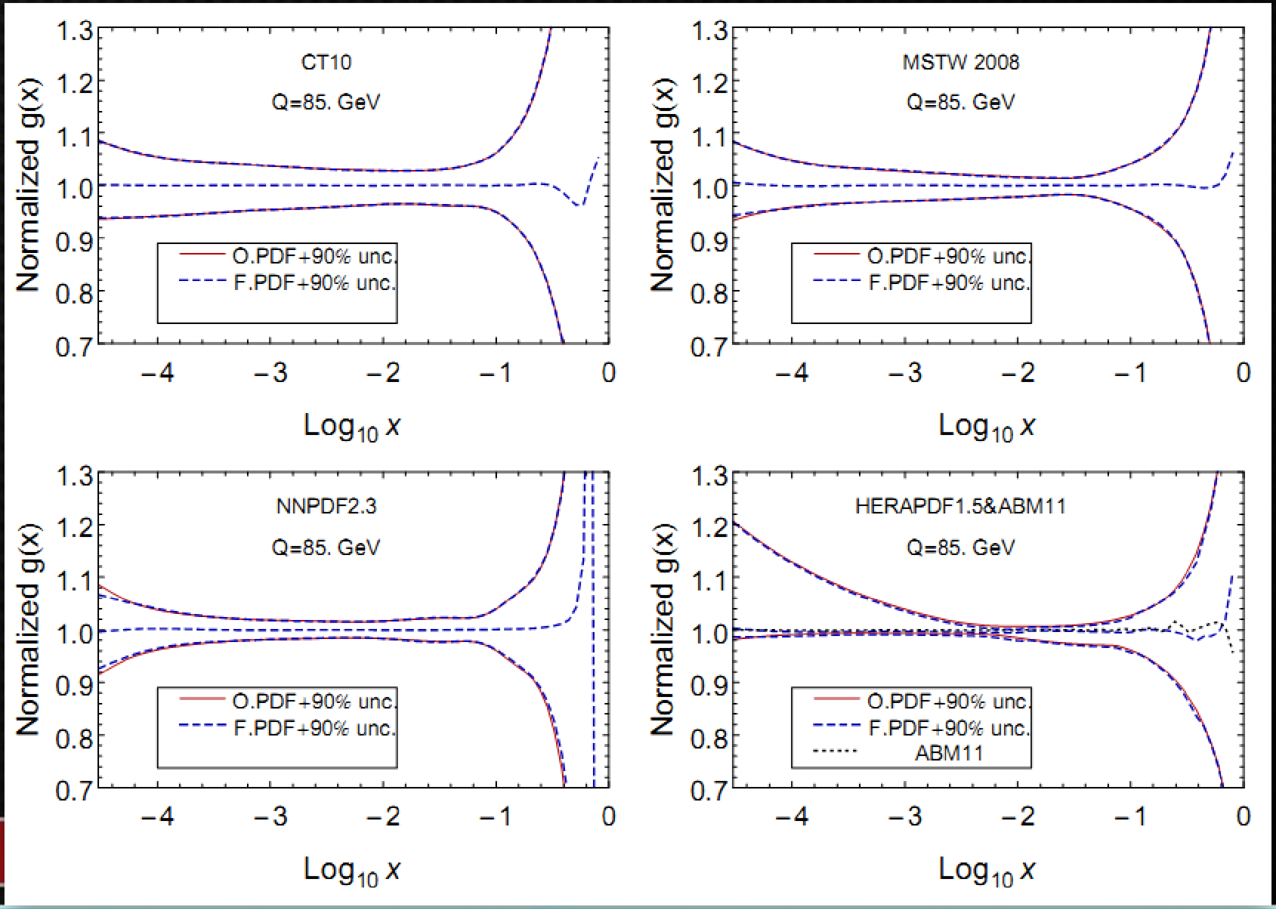
The input scale is set to be $Q_0 = 8$ GeV. The exponential contains Chebyshev polynomials $T(y)$ with $y(x)=\cos(\pi x^{\beta})$ and $\beta=1/4$.



We focus on the x range with the lower limit of 3×10^{-5} for all flavors and upper limits of 0.4 for ubar, dbar; 0.3 for s, sbar; and 0.8 for other flavors. PDFs outside these x regions are determined entirely by extrapolation.

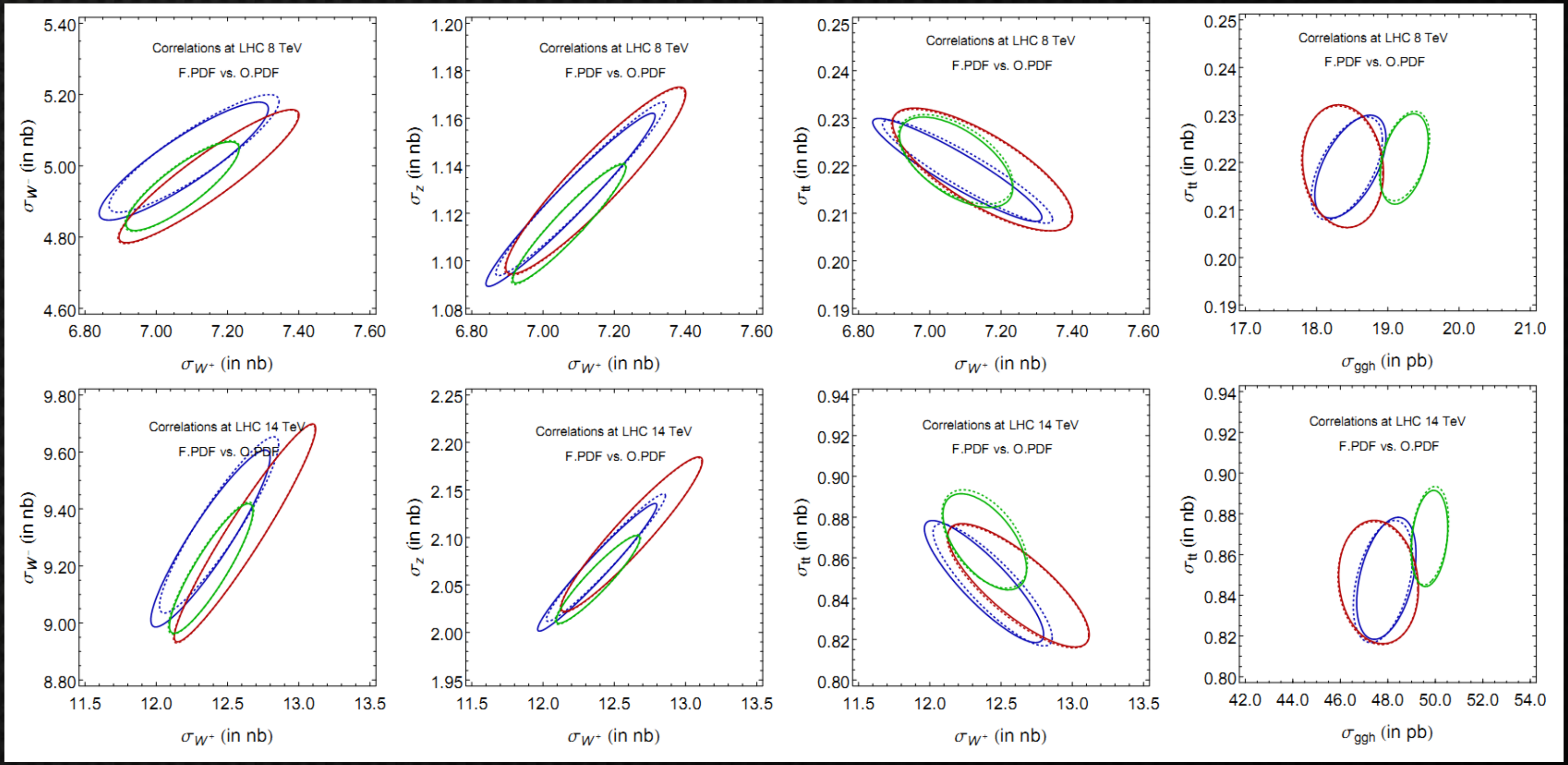
Agreement of the original and fitted PDFs at arbitrary Q

The meta PDFs are fitted at Q=8 GeV and evolved to higher Q using a common numerical program, HOPPET, then compared to the original PDFs at same scales. Excellent agreement, minor discrepancies at small x are further reduced by evolution.



META predictions for benchmark LHC processes

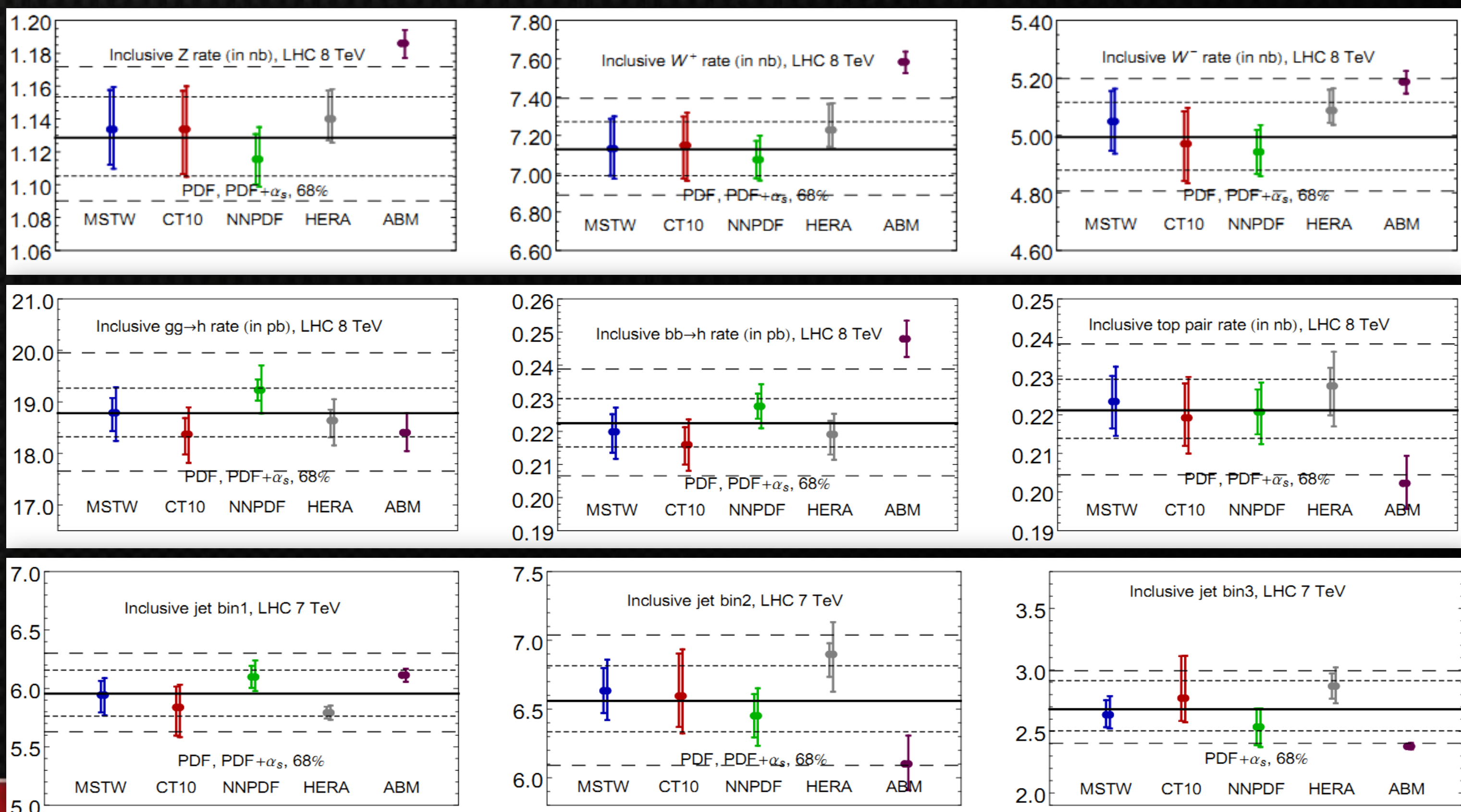
For NNLO inclusive rates of W, Z, Higgs, top quark pair production, NLO jet cross sections in different kinematic bins, at the LHC 8 and 14 TeV, the fitted PDFs can well reproduce predictions of the original PDFs, as well as their correlations.



red(CT10), blue(MSTW), green(NNPDF), solid(dotted) for original(fitted) PDFs

META predictions for the LHC

Comparisons of the LHC predictions, including central prediction, PDF uncertainties, and PDF+alphas uncertainties, at 68% C.L.. Similar results comparing to the envelope prescription in the benchmark study **(R. Ball, et al., 1211.5142)**, e.g., for gg→h, 18.75±1.24 pb there, while 18.78±1.15 pb here.

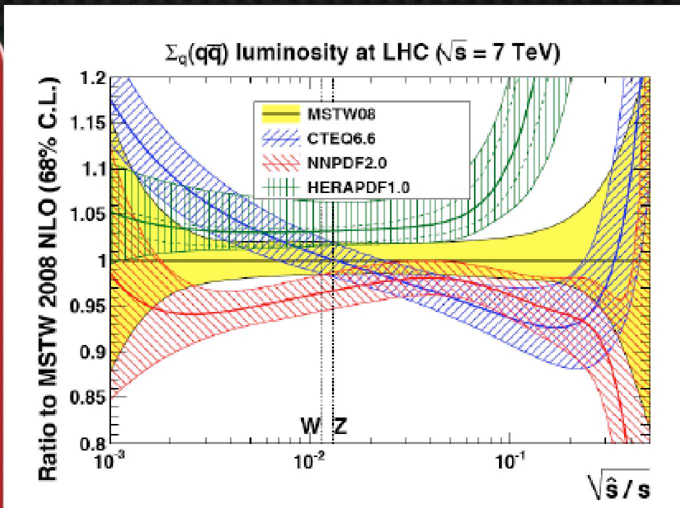


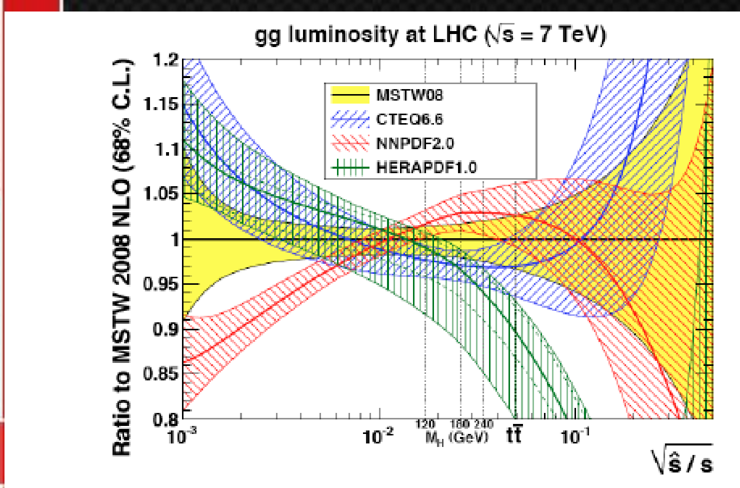
Summary

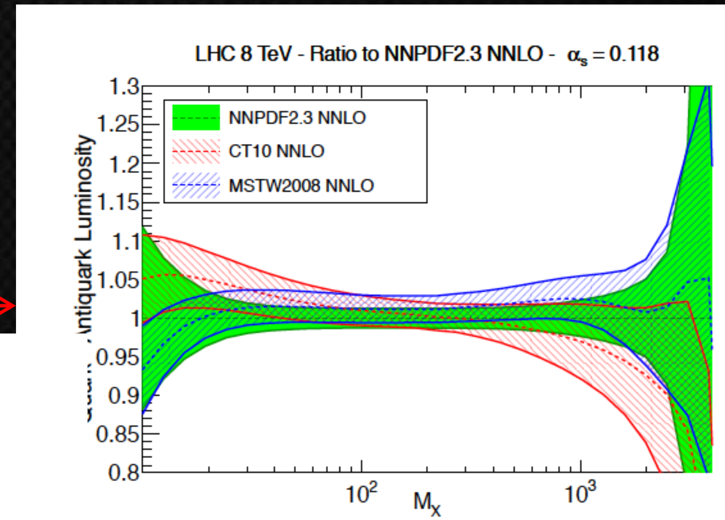
- CT1X under development; will include LHC data with correlated error information
- Bringing PDFs to 1% accuracy will require major advancements in PQCD calculations, statistical analysis, and development of numerical tools. I reviewed some ongoing efforts:
  - Implementation of NNLO QCD, NLO EW, massive quark contributions
  - Benchmarking of PDFs and theoretical computations
  - Development of methods for handling experimental and theoretical correlated uncertainties
  - A meta-analysis of PDFs provided by various groups

Backup slides

2010->2012: changes in the PDF luminosities (from J. Huston)





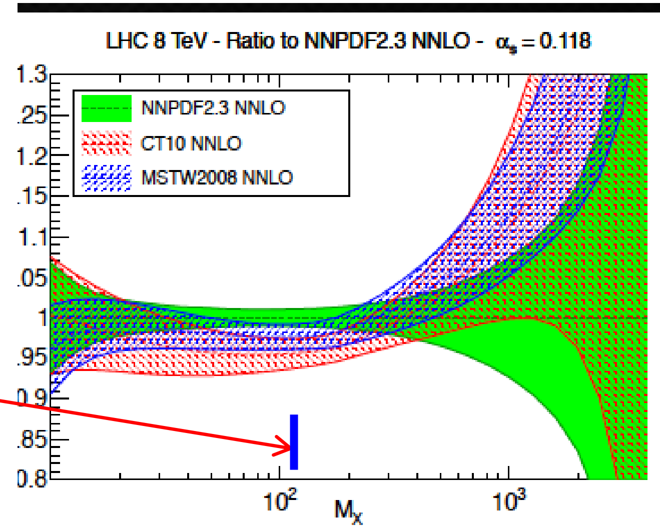


improvements from 2010 to 2012…

…and from NLO to NNLO

so Higgs PDF uncertainty under good control

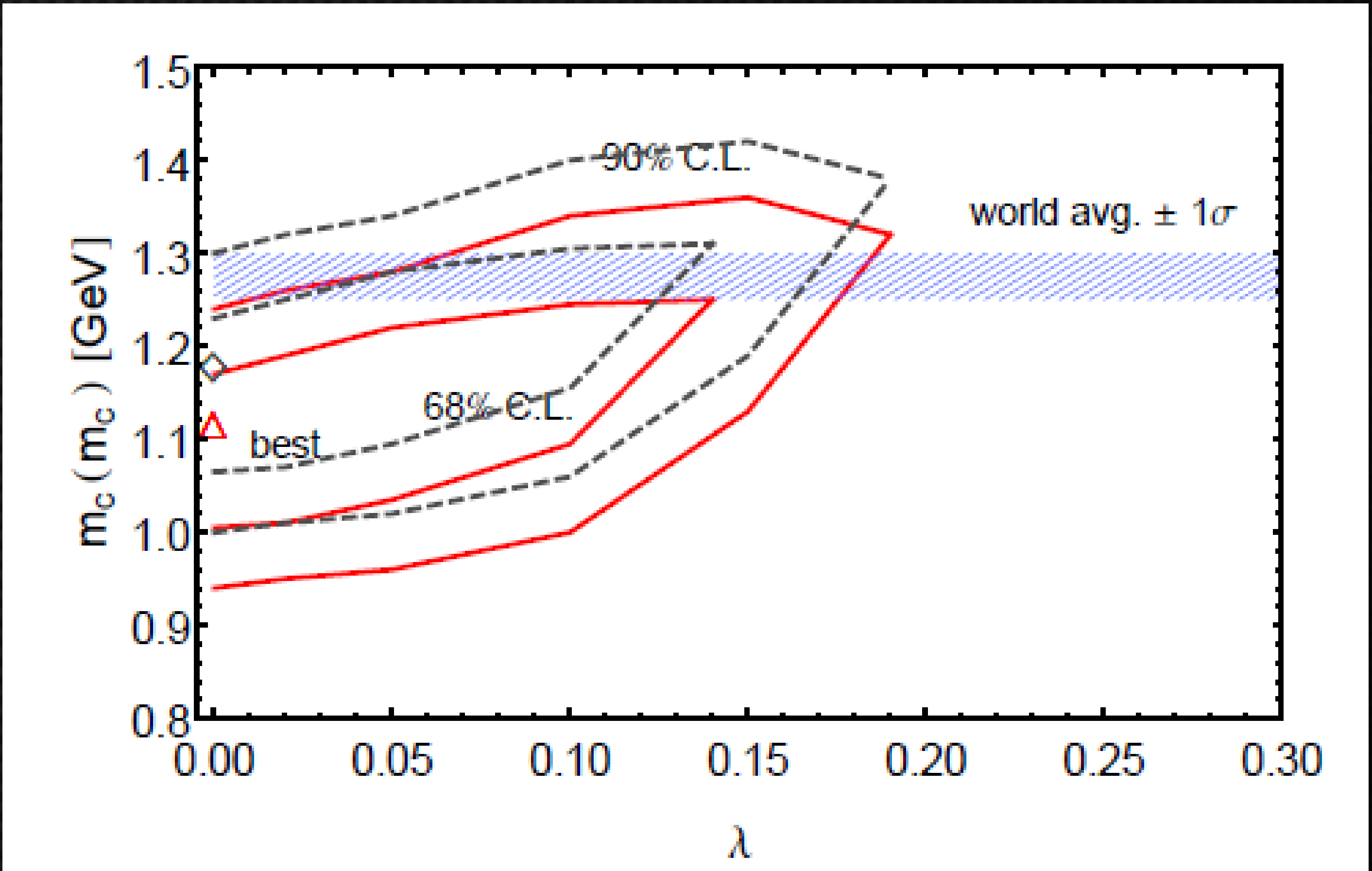
α_s uncertainty still +/-0.002



Charm quark mass dependence in a global QCD analysis J. Gao, M. Guzzi, P. Nadolsky, arXiv:1304.3494

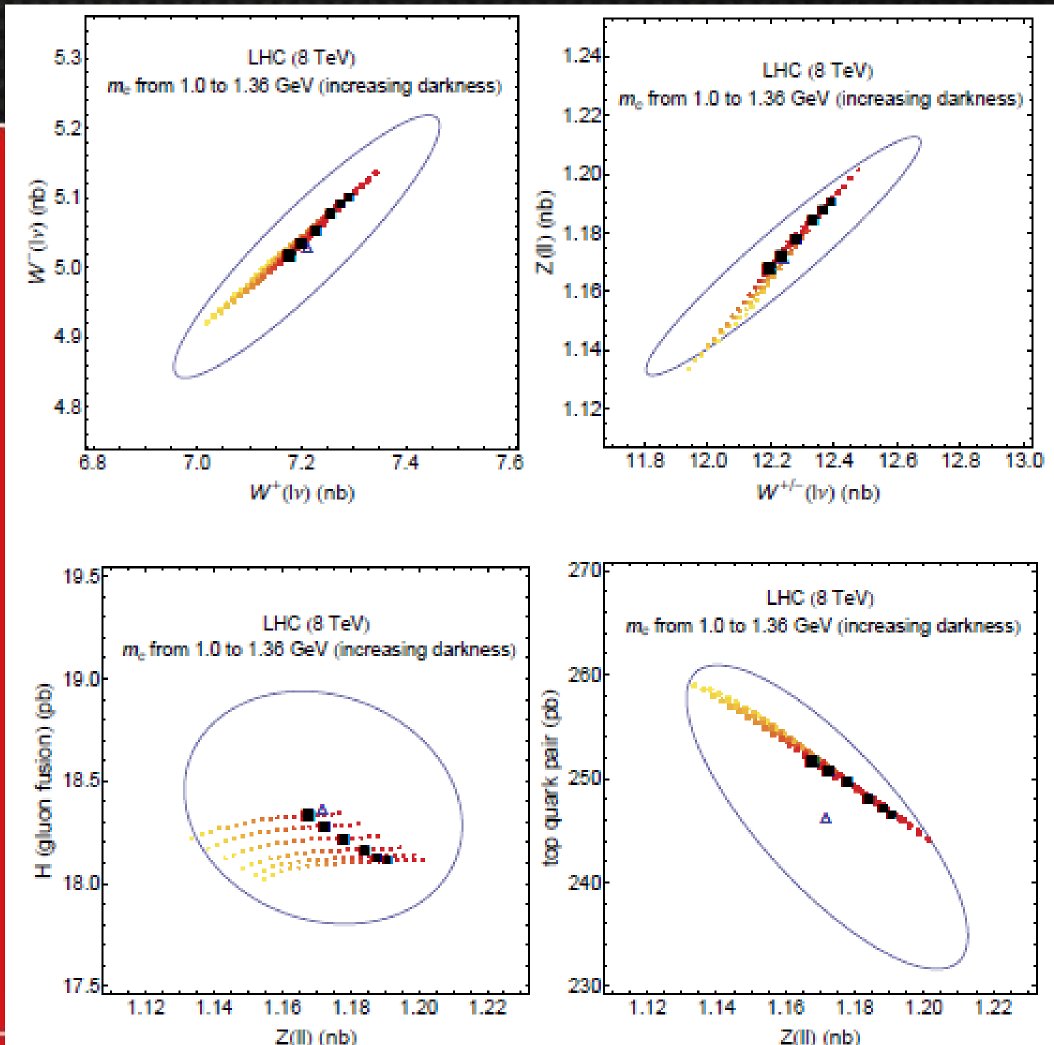
- The assumed value of m_c and the implementation of a particular general mass scheme affects precision LHC variables
- Constraints on the $\overline{MS}$ mass $m_c(m_c)$ from the CT10 NNLO data set were found to be $1.18^{+0.08}_{-0.15}$ GeV, including both PDF and theoretical errors
- The best-fit value of $m_c(m_c)$ is consistent with the world average 1.275+/-0.025 GeV within errors
- It has a significant dependence on the form of the rescaling parameter (controlled by a parameter l in the generalized re-scaling prescription by Nadolsky and Tung, 2009)

68% and 90%CL contours for $m_c(m_c)$ from the CT10 NNLO analysis



Preferred regions for $m_c(m_c)$ vs. the rescaling parameter . The best-fit values and confidence intervals are shown for two alternative methods for implementation of correlated systematic errors.

Uncertainty in LHC total cross sections due to $m_c(m_c)$ and rescaling parameter λ



Error ellipses: CT10 NNLO PDF errors

Yellow-red scattered points: both m_c and λ are varied

$1 \leq m_c(m_c) \leq 1.36$ GeV
$0 \leq \lambda \leq 0.2$

Black squares: only λ is varied
$m_c(m_c) = 1.275\ GeV$
$0 \leq \lambda \leq 0.2$

Using a fixed world-average $m_c(m_c)$ reduces the total uncertainty of the fit

Photon PDFs: include γ as a new parton

Important for EW precision physics (W mass measurements), require deep revisions in the PDF analysis

NNPDF (1308.0598) published NNLO QCD+LO QED PDFs with error sets

- An important step despite substantial limitations

CTEQ pursues a similar effort

The only previous existing QCD+QED PDF set is MRST'2004 QED, not updated for detailed studies