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QCD and top at the LHC

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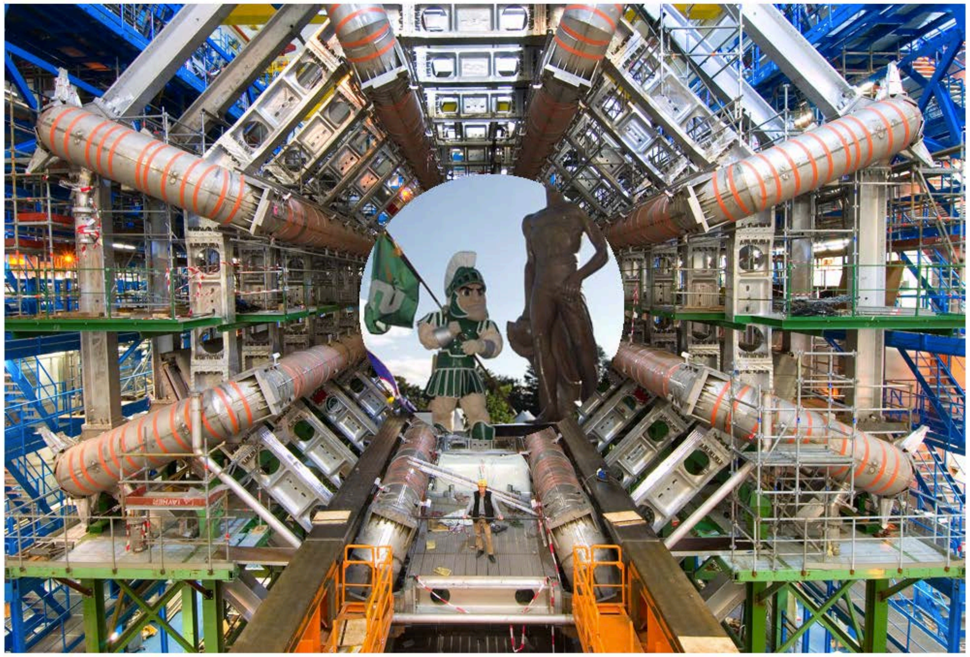
C T E Q

Introduction

- I will discuss several aspects of QCD phenomenology as it relates to top production measurements at the LHC
- The motivations for such measurements are well-known
- Much of the information in this talk was collected from contributions to the QCD@LHC2012 workshop in East Lansing, MI from Aug 20-24, 2012
  - especially the talks of Keith Ellis, Alex Mitov and Frank-Peter Schilling



www.pa.msu.edu/~huston/qcd2012/QCD_LHC.html

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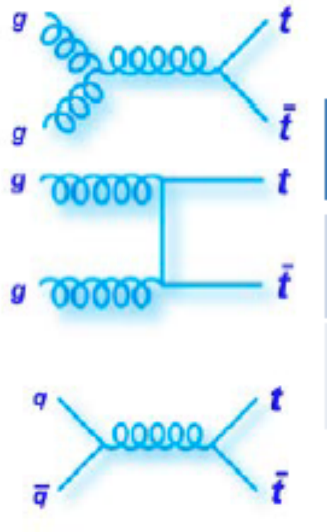
Top production

- Dominant initial state changes from Tevatron to LHC
  - due to a combination of the x-range of PDFs needed for tT production at the two accelerators and presence of valence anti-quarks at the Tevatron
- Note that this is a NLO picture; the percentages are different at LO (but similar at NNLO)
- Major theoretical uncertainties
  - value of α_s
  - PDF's
  - scales
  - top mass
- Major experimental uncertainties
  - luminosity
  - detector modelling (like selection efficiencies)
  - jet energy scale



Initial state	Tevatron	LHC (7 TeV)
qQ	85%	15%
gg	15%	85%

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PDF luminosities

- Define and compare PDF luminosities from the different PDF groups

$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\,\frac{1}{1+\delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)\right] . \tag{27}$$

The prefactor with the Kronecker delta avoids double-counting in case the partons are identical. The generic parton-model formula

$$\sigma = \sum_{i,j}\int_0^1 dx_1\,dx_2\,f_i(x_1,\mu)\,f_j(x_2,\mu)\,\hat{\sigma}_{ij} \tag{28}$$

can then be written as

$$\sigma = \sum_{i,j}\int\left(\frac{d\hat{s}}{\hat{s}}\right)\left(\frac{dL_{ij}}{d\hat{s}}\right)\left(\hat{s}\,\hat{\sigma}_{ij}\right) . \tag{29}$$

…from the 2010 PDF4LHC benchmarking exercise using NLO PDFs+matrix elements (MCFM)
arXiv:1101.0536

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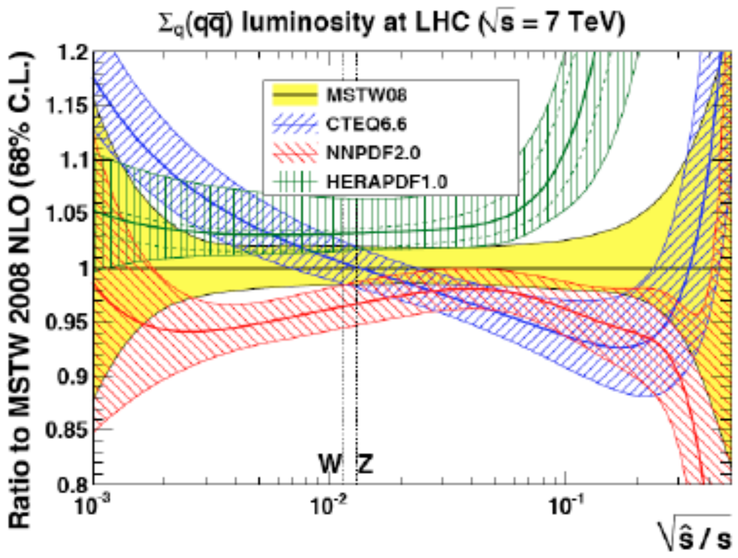
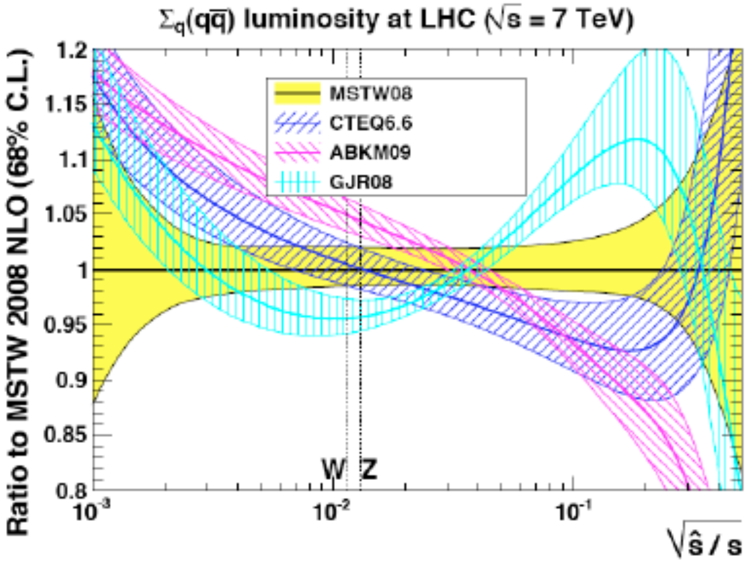
NLO PDF luminosities

- The qQ luminosities for the groups tend to have different behaviors at low mass and at high mass
- The reasons can often be understood
    - NNPDF2.0 does not use a heavy quark flavor scheme; this suppresses the low x quark and anti-quark distributions (NNPDF2.1 does use such a scheme)
    - HERAPDF uses the HERA combined Run 1 dataset that prefers a higher normalization
- The agreement tends to be much better in the W/Z region





Plots by G. Watt arXiv: 1106.5788

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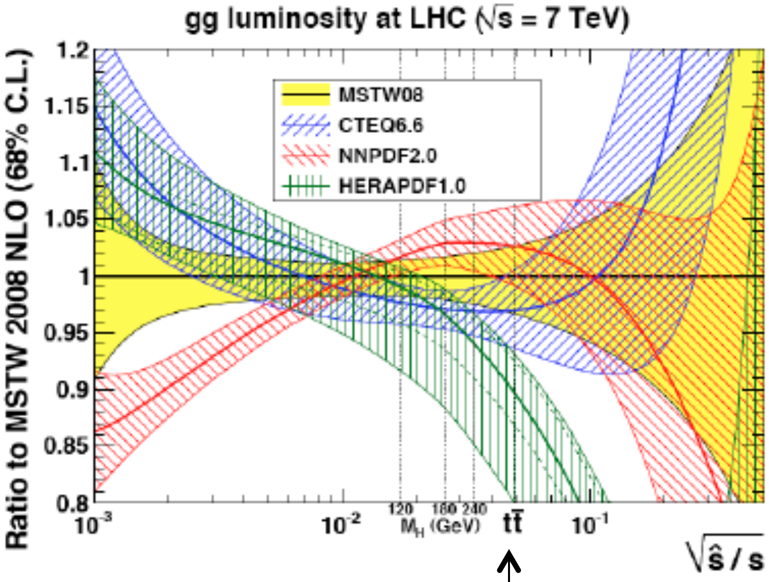
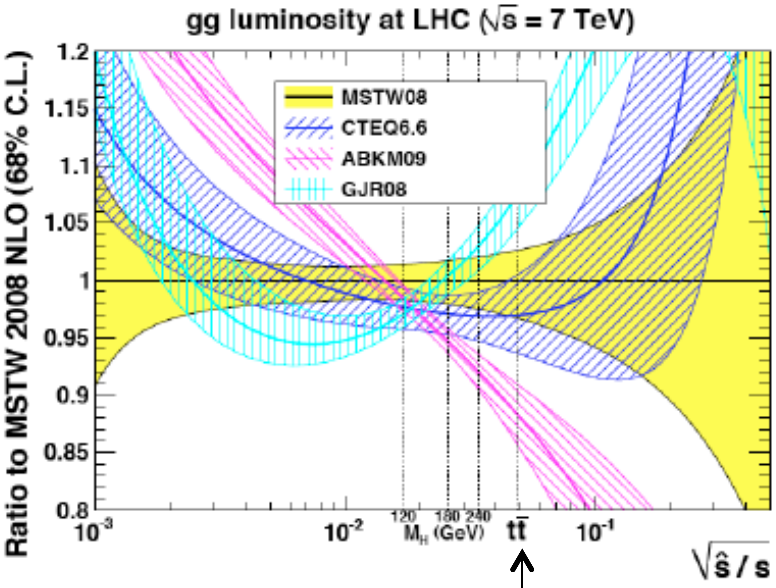
NLO PDFs

- Larger differences are observed for gg luminosities, especially at high mass
  - critically depends on whether Tevatron inclusive jet data have been used or not





even within the 3 global groups (CTEQ, MSTW, NNPDF), the uncertainty envelope for tT is a factor of 2 larger than any individual uncertainty; note that the uncertainty for tT within each group is comparable to that for W/Z production.

Plots by G. Watt arXiv: 1106.5788

NLO PDFs

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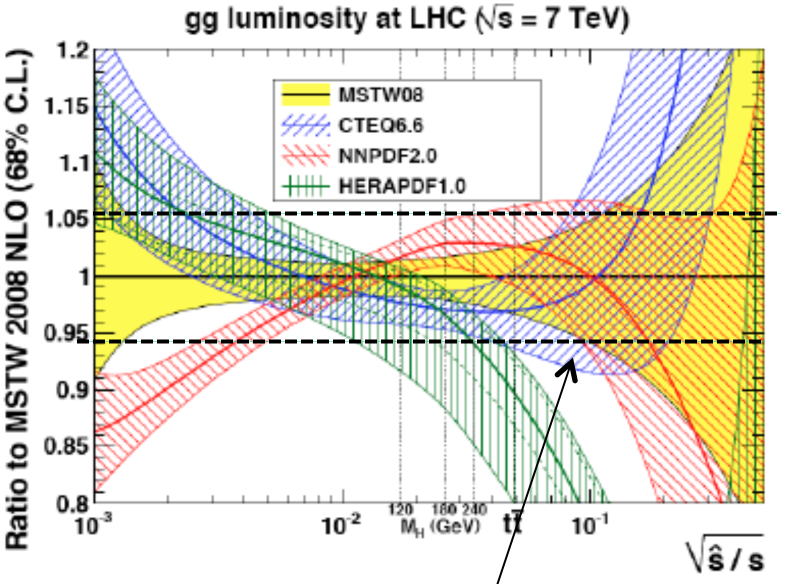
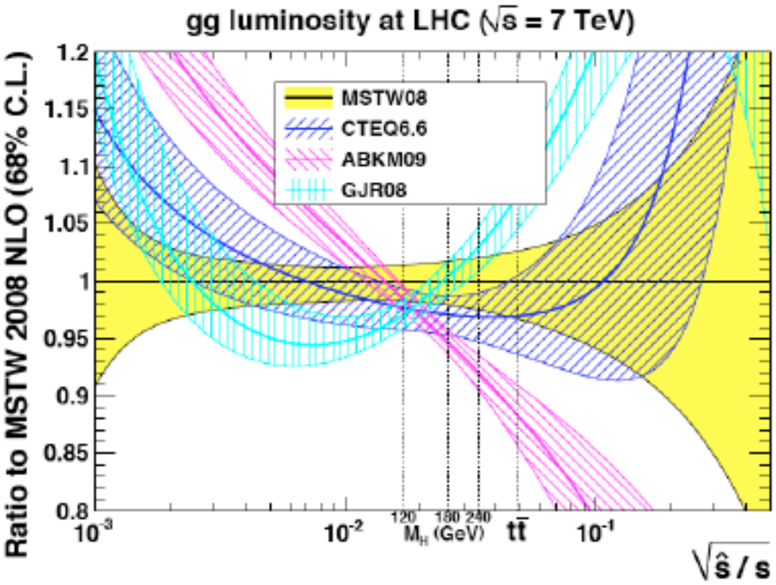


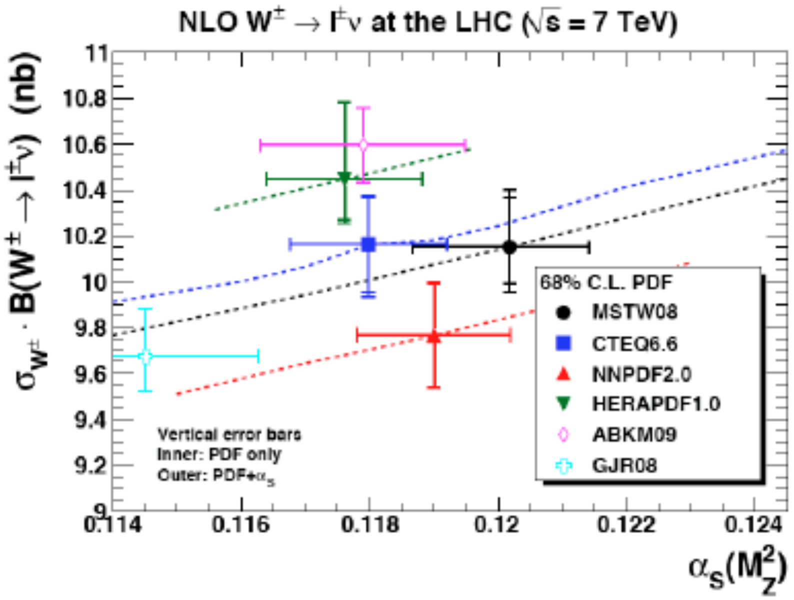


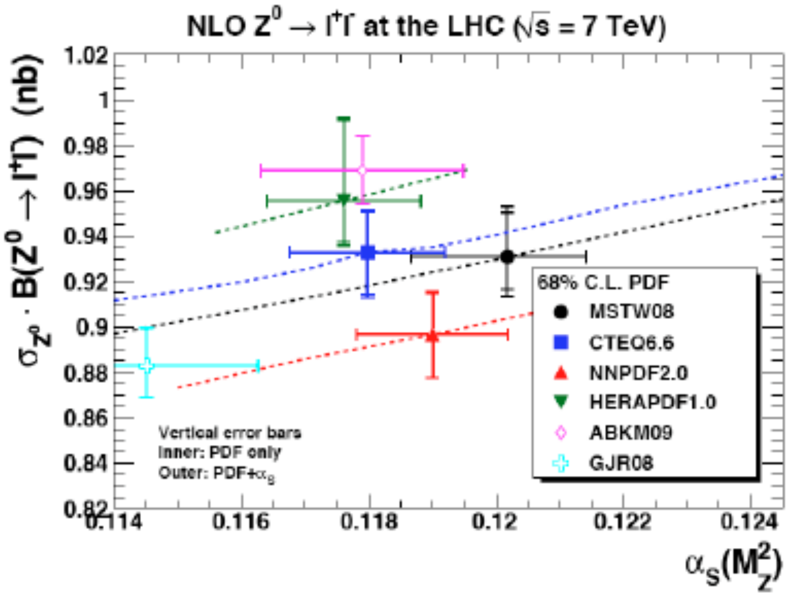
using the 3 global groups (CTEQ, MSTW, NNPDF), the PDF uncertainty envelope is about +/-6% (for a 1 sigma error) ⟶ PDF4LHC recommendation

arXiv: 1101.0538

NLO cross section comparisons

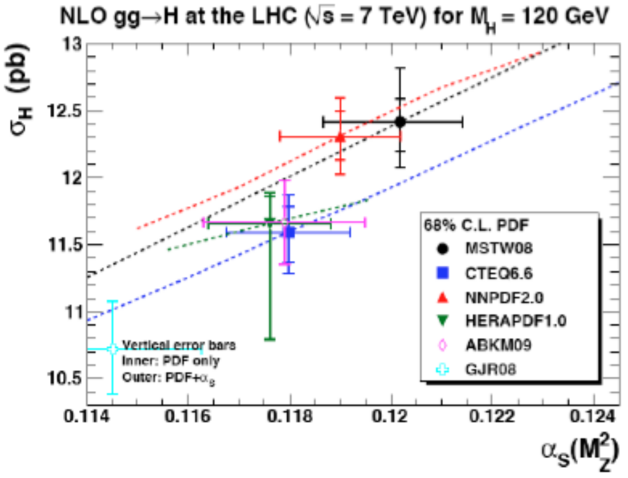
- Notice that the CTEQ and MSTW predictions for W/Z production are very close to each other
- Also, in general, there is very little dependence of the cross sections on the value of $\alpha_s(m_Z)$ (as expected)
- And of course, the higher qQ luminosities observed earlier lead to higher predictions for W/Z cross sections for HERAPDF

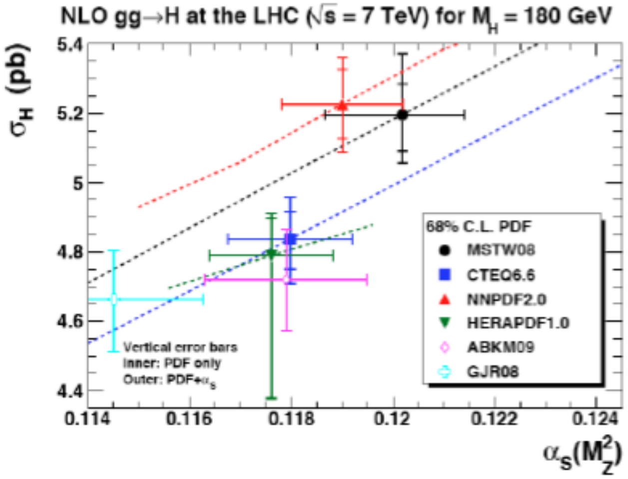




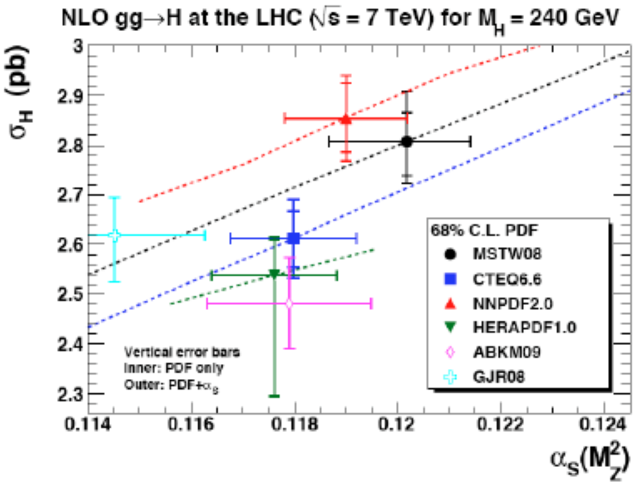
NLO cross section comparisons

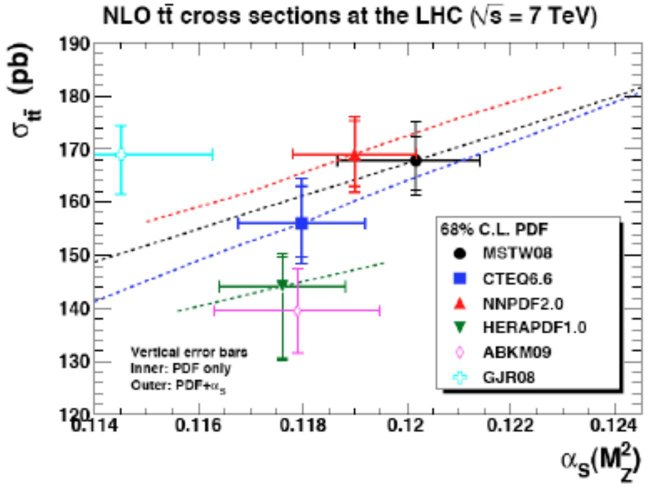
- Larger gg differences and greater dependence on α_s lead to larger differences in Higgs/tT cross section





Note that there tend to be two groupings





Plots by G. Watt arXiv: 1106.5788

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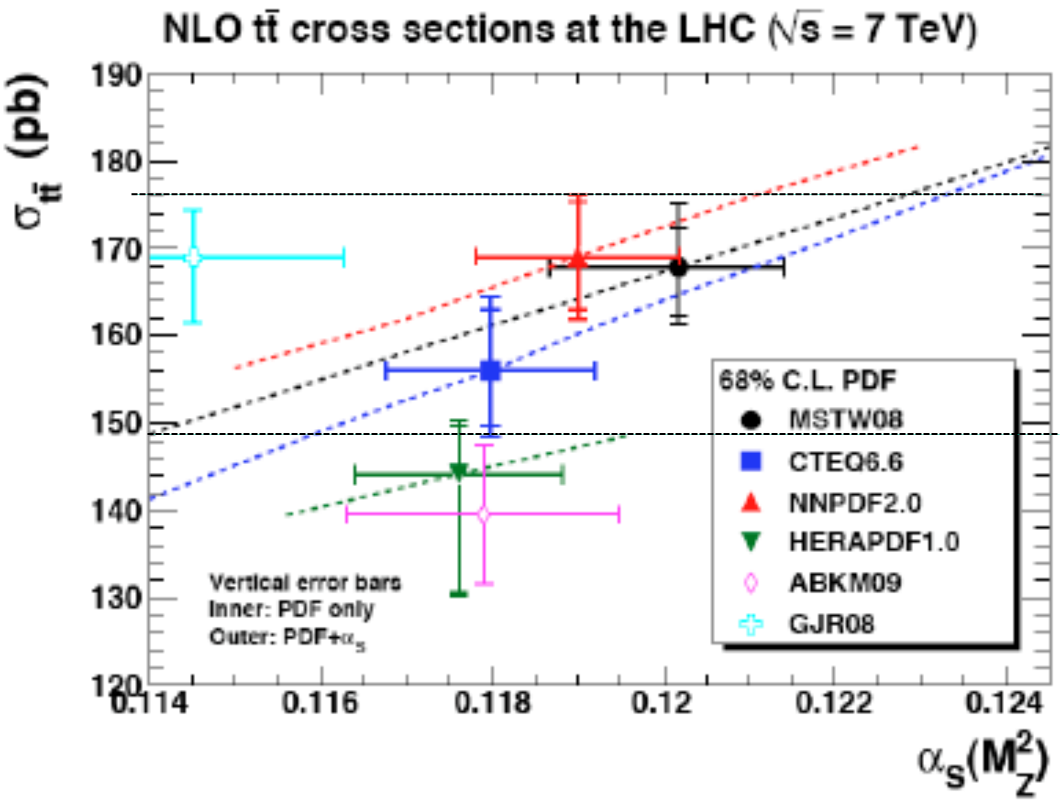
NLO cross section comparisons

- Larger gg differences and greater dependence on α_s lead to larger differences in Higgs/tT cross section



Note that there tend to be two groupings

Again, using the 3 global PDFs, the cross section range at NLO is from ~148 pb to 176 pb

The differences/range would be considerably smaller with a common value of α_s

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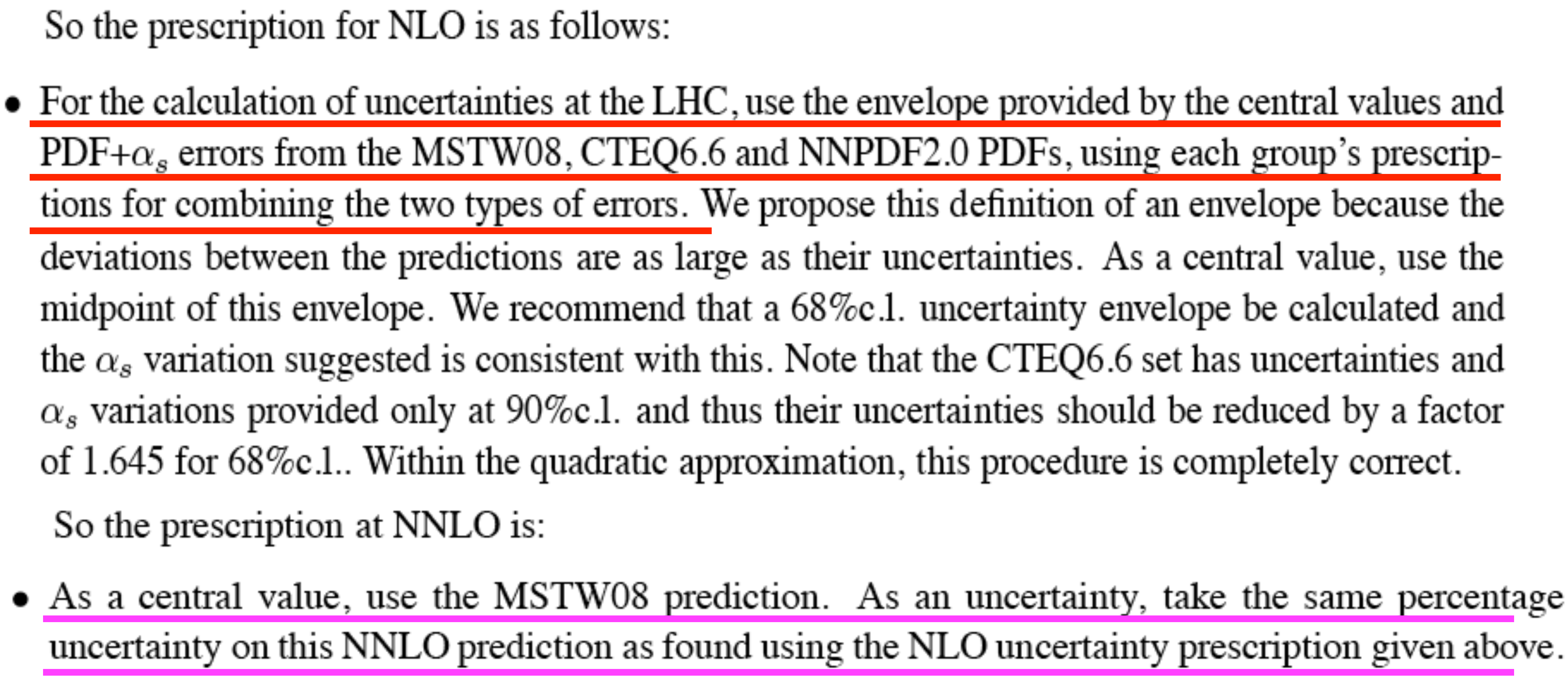
PDF4LHC recommendations(arXiv:1101.0538)



So the prescription for NLO is as follows:

- For the calculation of uncertainties at the LHC, use the envelope provided by the central values and PDF+α_s errors from the MSTW08, CTEQ6.6 and NNPDF2.0 PDFs, using each group's prescriptions for combining the two types of errors. We propose this definition of an envelope because the deviations between the predictions are as large as their uncertainties. As a central value, use the midpoint of this envelope. We recommend that a 68%c.l. uncertainty envelope be calculated and the α_s variation suggested is consistent with this. Note that the CTEQ6.6 set has uncertainties and α_s variations provided only at 90%c.l. and thus their uncertainties should be reduced by a factor of 1.645 for 68%c.l.. Within the quadratic approximation, this procedure is completely correct.

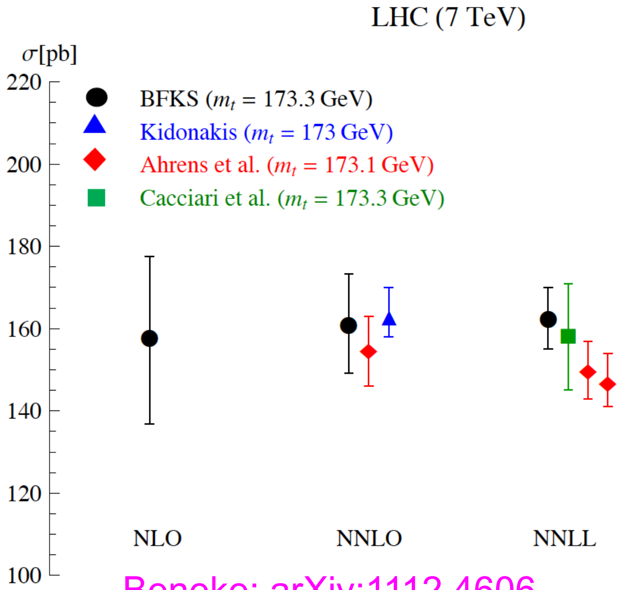
So the prescription at NNLO is:

- As a central value, use the MSTW08 prediction. As an uncertainty, take the same percentage uncertainty on this NNLO prediction as found using the NLO uncertainty prescription given above.

The NLO prescription is being somewhat conservative as each of the 3 NLO PDFs used has a different central value of α_s (and we are also includiing the α_s uncertainties within each group). In general, the PDF4LHC accepts using a value of α_s(mZ) of~ 0.118 with 1-sigma uncertainty of 0.0012.

Approximate NNLO

- There is still a sizeable scale uncertainty at NLO
- NNLL resummation used
- …but there is a considerable variation among the various authors
  - depending on the resummation formalism, whether the total cross section (or differential) is resummed…
  - an indication perhaps that the 2nd N in ~NNLO is not quite there yet
- Approximate NNLO used for most comparisons to experimental measurements of tT production
- Full NNLO needed
  - qQ finished (Barnreuther, Czakon, Mitov); ok for Tevatron
  - gg expected soon; needed for LHC
- Scale variations at ~NNLO quoted at the level of 3-8%
  - not sure I believe the 3% figure
- Might be reasonable to expect that full scale uncertainty at NNLO may be of the order of +/-2%



Beneke: arXiv:1112.4606

Approx. NNLO theory calculations

Authors	Cross Section @ 7 TeV [pb] (+-scale +-PDF)
NLO QCD (MCFM)	160 +20-21 +8-9
Kidonakis	163 +7-5 +9-9
Aliev et al. (HATHOR)	164 +5-9 +9-9
Ahrens et al.	155 +8-9 +8-9
Beneke et al.	163 +7-8 +15-14
Cacciari et al. (TOP++)	159 +12-14 +4-4
Moch et al.	175 +10-13 +5-5

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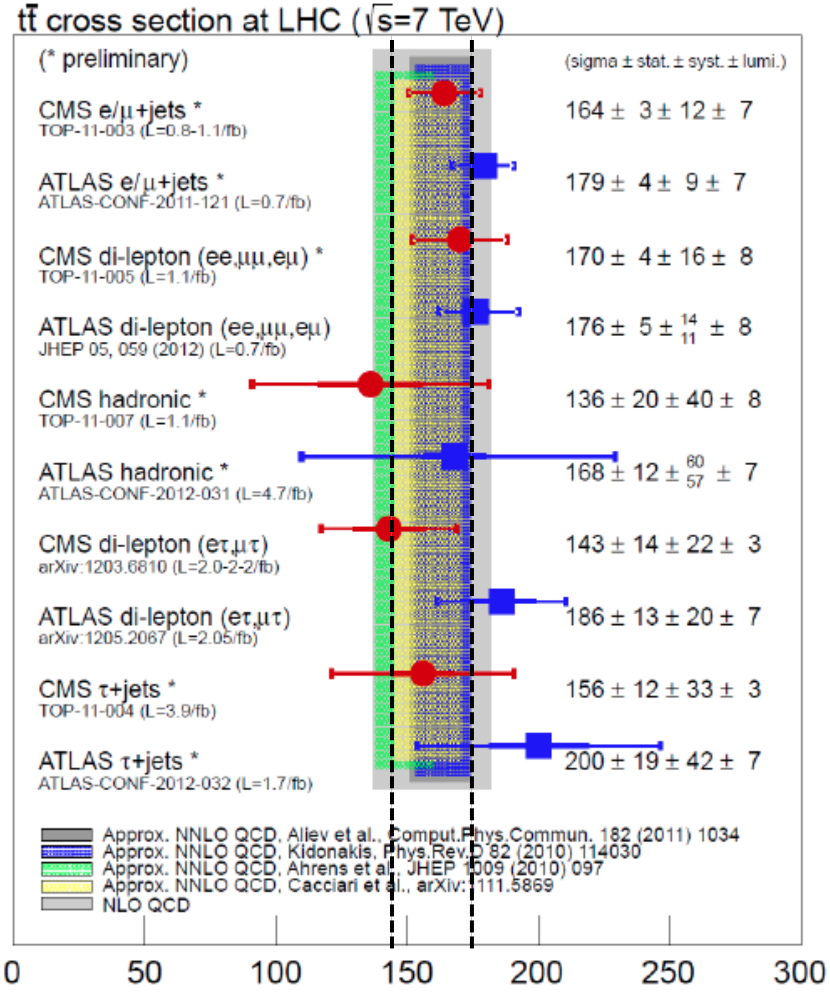
Cross sections at 7 TeV

- ATLAS and CMS combination cross sections are in reasonable agreement with the range provided by the PDF4LHC (given by dashed lines)
- Systematic errors (non-luminosity) are of the order of 5-6.5%
- Combined preliminary LHC cross section is 173.3+/-2.3(stat)+/-7.6 (syst)+/-6.3(lumi)
    - so combined non-lumi systematic error of ~4.5%
    - these will improve in future

	ATLAS	CMS	Correlation	LHC combination
Cross-section	177.0	165.8		173.3
Uncertainty				
Statistical	3.2	2.2	0	2.3
Jet Enegy Scale	2.7	3.5	0	2.1
Detector model	5.3	8.8	0	4.6
Signal model				
Monte Carlo	4.2	1.1	1	3.1
Parton shower	1.3	2.2	1	1.6
Radiation	0.8	4.1	1	1.9
PDF	1.9	4.1	1	2.6
Background from data	1.5	3.4	0	1.6
Background from MC	1.6	1.6	1	1.6
Method	2.4	n/e	0	1.6
W leptonic branching ratio	1.0	1.0	1	1.0
Luminosity				
Bunch current	5.3	5.1	1	5.3
Luminosity measurement	4.3	5.9	0	3.4
Total systematic	10.8	14.2		9.8
Total	11.3	14.4		10.1

Table 1: Table of uncertainties in the $t\bar{t}$ cross-section used in the BLUE combination. Cross-sections and uncertainties are in pb. Symbol "n/e" stands for "not evaluated".



CMS Combination (~8%)

$$\sigma_{t\bar{t}} = 165.8 \pm 2.2\ (\mathrm{stat.}) \pm 10.6\ (\mathrm{syst.}) \pm 7.8\ (\mathrm{lum.})\ \mathrm{pb}$$

ATLAS Combination (~6%)

$$\sigma_{t\bar{t}} = 177 \pm 3\ (\mathrm{stat.})^{+8}_{-7}\ (\mathrm{syst.}) \pm 7\ (\mathrm{lum.})\ \mathrm{pb}$$

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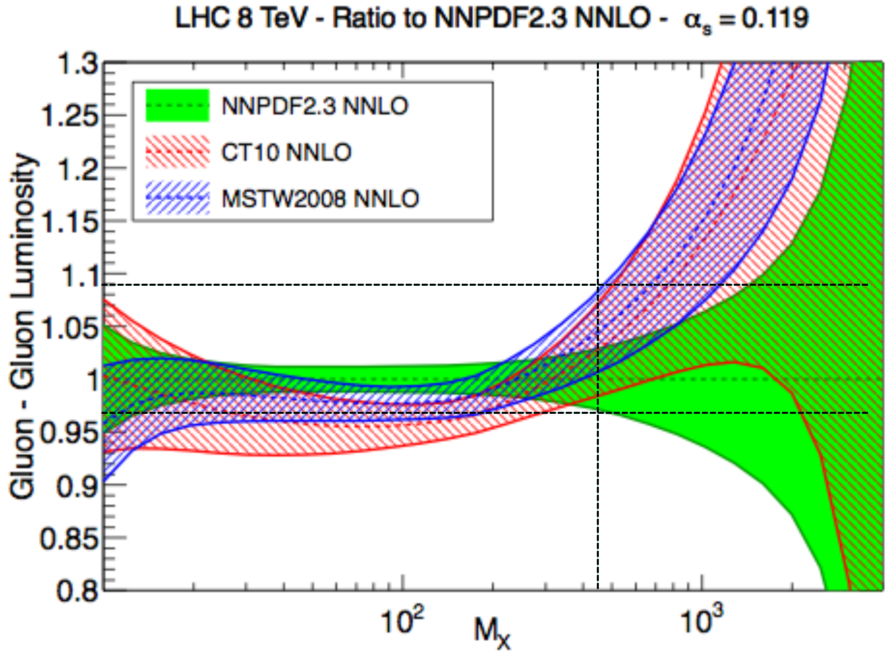
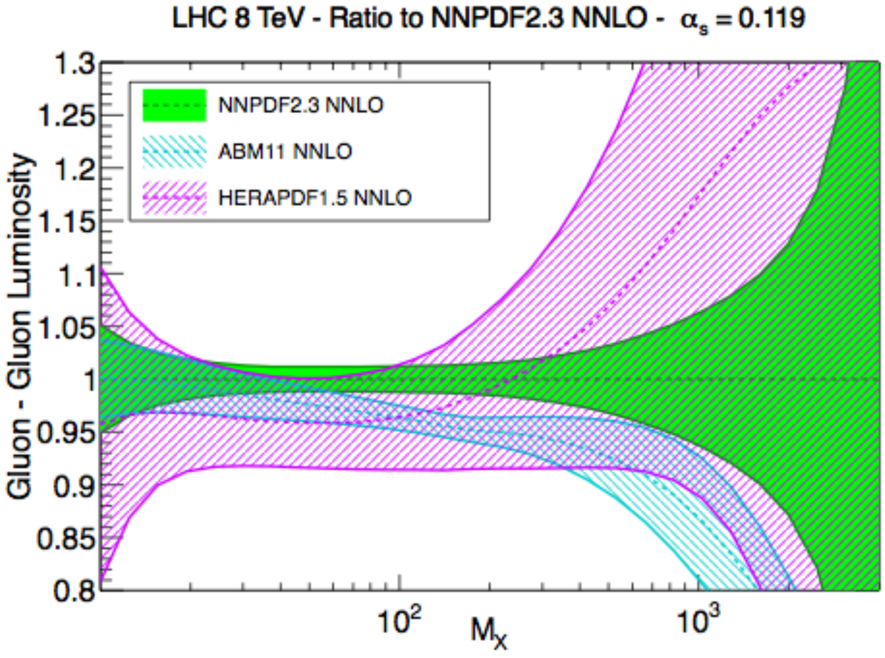
PDF luminosities: 2012 version*

- NNLO PDFs with a common value of α_s (0.117 or 0.119, to bracket 0.118) at a center of mass of 8 TeV





- PDF luminosity uncertainties haven't decreased near tT threshold
  - still somewhat diverging behavior for high mass
  - +/-6% for tT region (depend on inclusive jet data at Tevatron)
  - PDF uncertainties > scale uncertainties (that are expected at NNLO), and also > expt syst errors

*Pavel Nadolsky, Juan Rojo, JH et al, to be published

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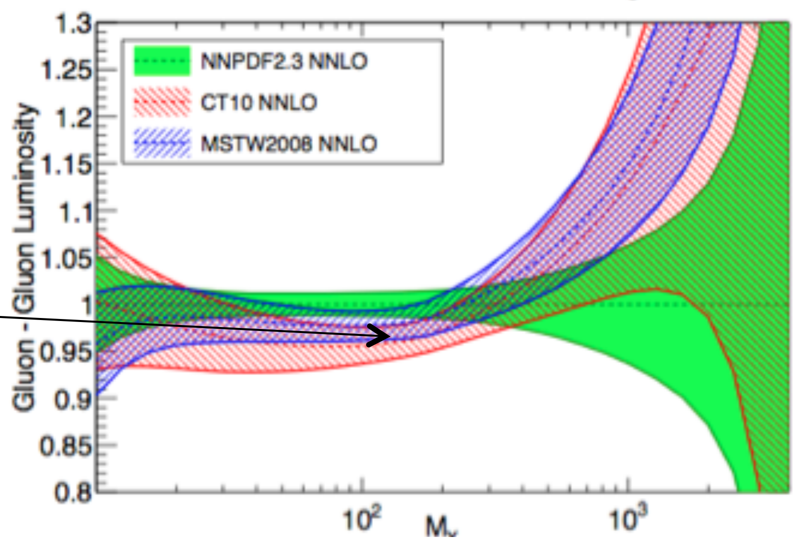
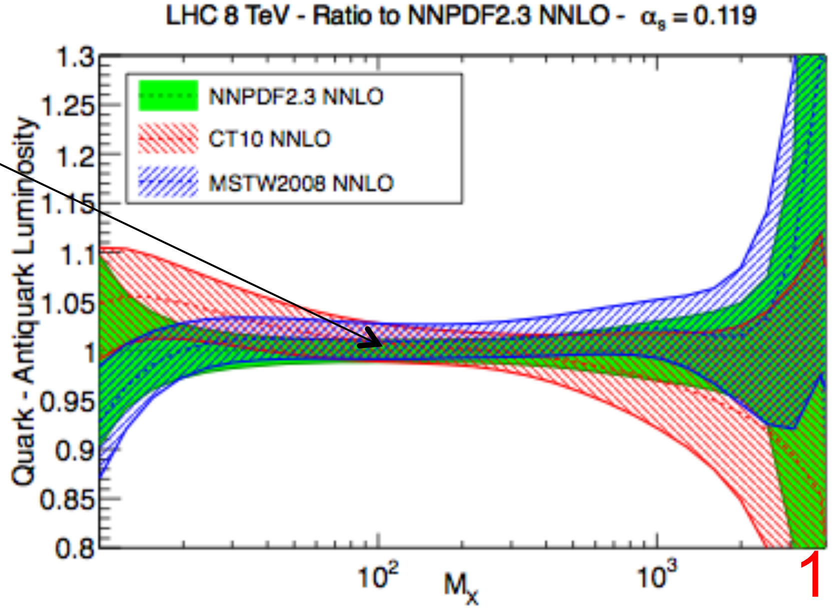
NNLO PDF uncertainties

- Recommended factor of 2 expansion of MSTW2008 error basically works for gg initial states (like 125 Higgs)
- …but maybe an overestimate for qQ initial states, at least in W/Z region
    - starting to see more of a spread in the tT region


LHC 8 TeV - Ratio to NNPDF2.3 NNLO - $\alpha_s = 0.119$


LHC 8 TeV - Ratio to NNPDF2.3 NNLO - $\alpha_s = 0.119$

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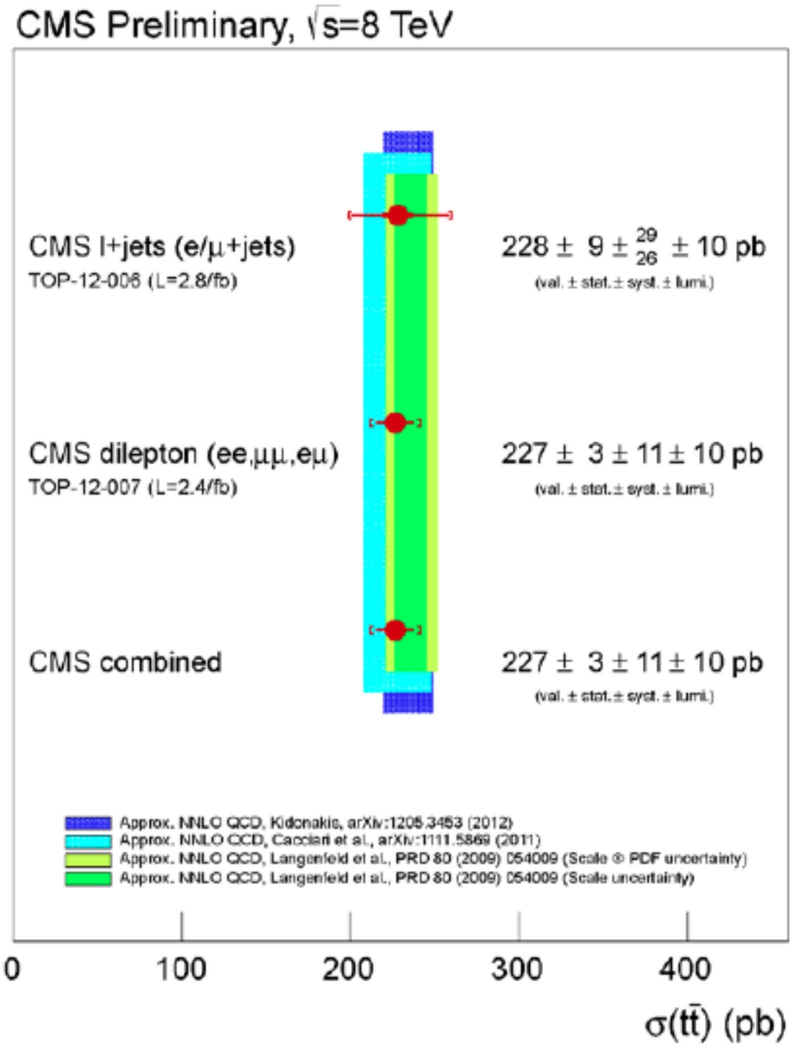
8 TeV measurements

- Larger cross section, as expected, due to the increase to 8 TeV
- Experimental errors comparable to 7 TeV
- Non-luminosity systematic error ~<5%



CMS PAS TOP-12-006/007

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8 TeV cross section predictions using NNLO PDFs

- Using ~NNLO from Czakon and Mitov
- The horizontal lines indicate the error range as given by CT10, MSTW2008 and NNPDF2.3
- Good agreement with CMS data

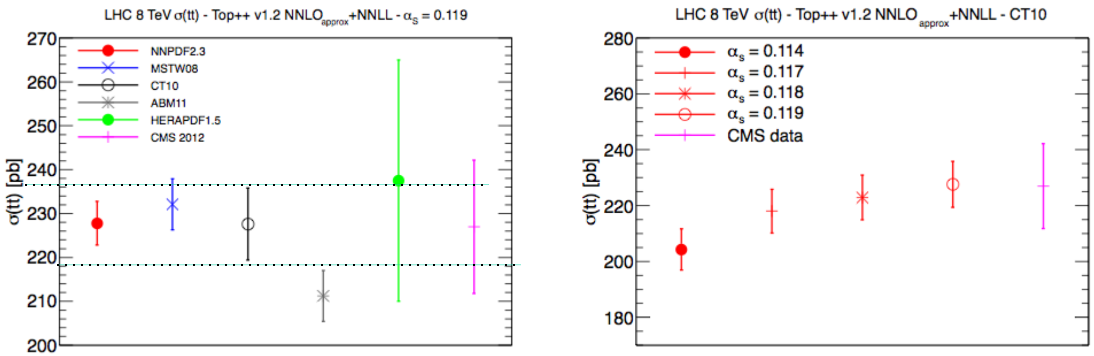

Figure 8: Comparison of the predictions for the top quark pair production at LHC 8 TeV between various NNLO PDF sets. Left plot: results for $\alpha_S(M_Z) = 0.119$. Right plot: the dependence on $\alpha_S(M_Z) = 0.119$ for the CT10 results. In both cases we also show the recent CMS 8 TeV measurement

$\alpha_S(M_Z)$	NNPDF2.3	MSTW08	CT10	ABM11	HERAPDF1.5
0.114	206.35 ± 4.5	208.8 ± 5.2	204.3 ± 7.4	181.4 ± 5.0	207.2 ± 24.0
0.117	217.9 ± 4.8	222.5 ± 5.5	218.0 ± 7.8	199.7 ± 5.5	225.1 ± 26.1
0.118	±	227.1 ± 5.7	222.9 ± 8.0	205.4 ± 5.6	228.8 ± 26.5
0.119	227.8 ± 5.0	232.1 ± 5.8	227.6 ± 8.2	211.2 ± 5.8	237.5 ± 27.5

Table 4: Same as Tab. 3 for the cross sections for top quark pair production at 8 TeV at NLO+NNL, using the settings described in the text. The cross sections are given in pb. We have assumed a top quark mass of $m_H = 173.3$ GeV.

α_s uncertainty for CT10 (0.117-0.119) ~4.5%, < PDF errors, ~same as syst errors (NB: PDF and α_s errors can be added in quadrature->uncorrelated)

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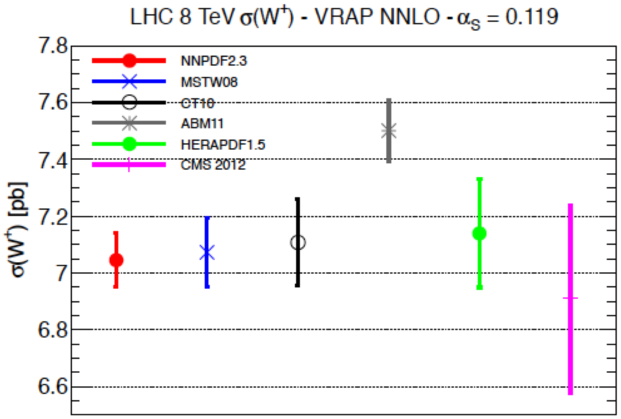
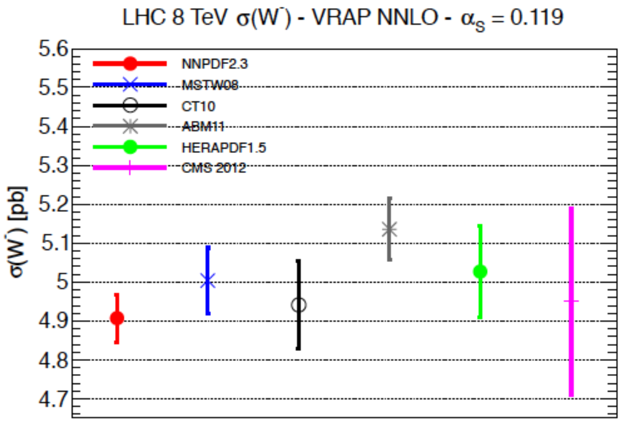
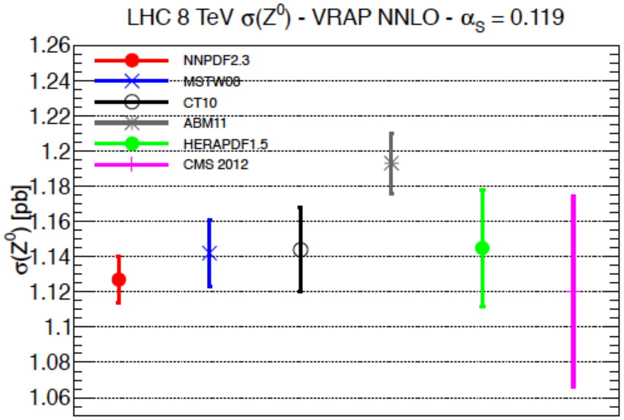
For comparison, W and Z at 8 TeV

CT10, MSTW08, NNPDF2.3 all agree (as you would expect from the PDF luminosity plots)

ABM11 gives a somewhat higher cross section prediction; it gave a somewhat lower cross section for tT







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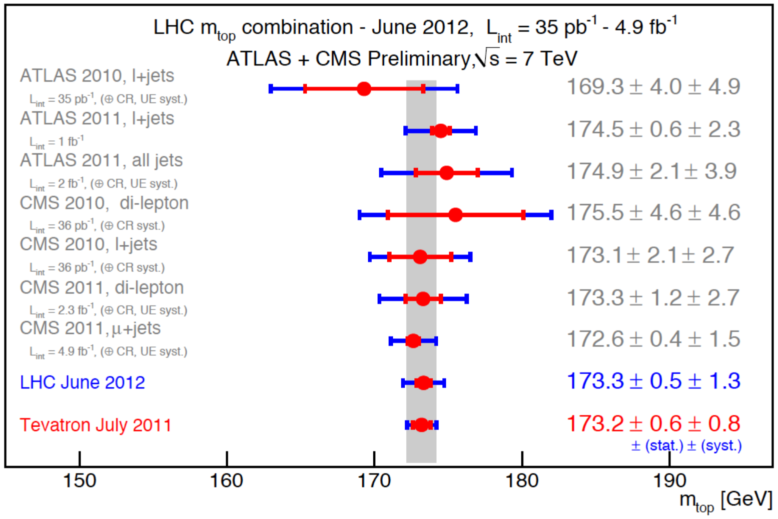
Top mass

- The LHC top mass average is very consistent with the Tevatron top mass average
  - ..and the total error is approaching that of the Tevatron (~1 GeV)
- The top cross section prediction depends strongly on the top quark mass
  - ~3% per GeV
- Further improvements to the top mass determination will lead to greater precision for the top cross section predictions
  - 0.5 GeV->1.5%
- Top production may become another precision benchmark, like W/Z production as the theory uncertainties (as, PDFs,scales, top mass) and experimental uncertainties improve

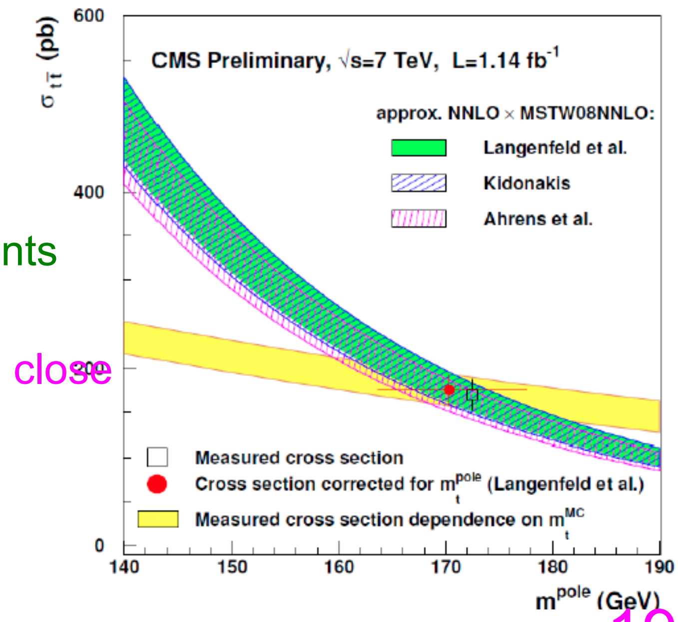
CMS PAS TOP-12-001

ATLAS CONF-2012-095



At this level of precision, we have to worry about effects such as color recombination, in addition to improvements of JES, UE, etc.

In fact, we may now be close to the point where we will be using the top cross section for determination of PDFs and/or α_s



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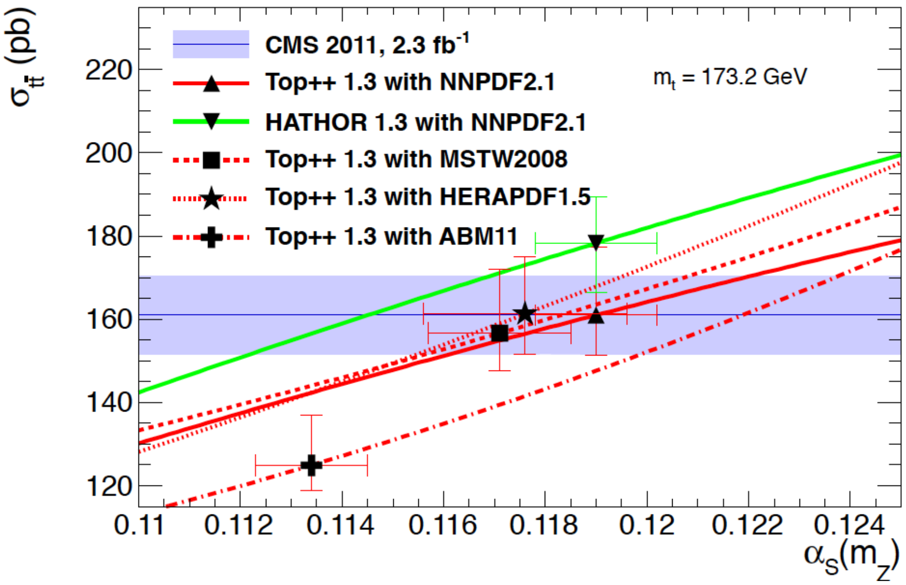
voila

- CMS PAS TOP-12-022
- $\alpha_s(m_Z)$=0.1178/+0.0046/-0.0040 is consistent with world average, although not competitive yet as a measurement



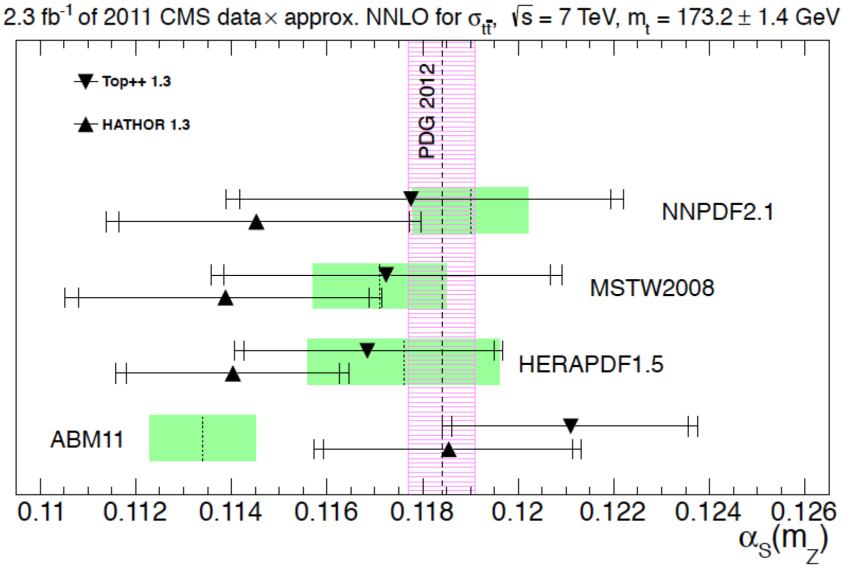


Figure 3: Comparison of the results obtained for $\alpha_S(m_Z)$ from the measured $t\bar{t}$ cross section using the approximate NNLO calculations implemented in Top++ 1.3 and HATHOR 1.3 together with four different PDF sets. The inner error bars include the uncertainties on the measured cross section as well as the PDF and scale uncertainties on the predicted cross section. The outer error bars additionally account for the uncertainty on m_t. The latest world average for $\alpha_S(m_Z)$, obtained by the Particle Data Group in June 2012, is also shown, using a dashed line together with a hatched uncertainty band. The filled bands with the dotted lines indicate the default $\alpha_S(m_Z)$ value of the corresponding PDF set.

What about PDFs?

Define a correlation cosine between two quantities

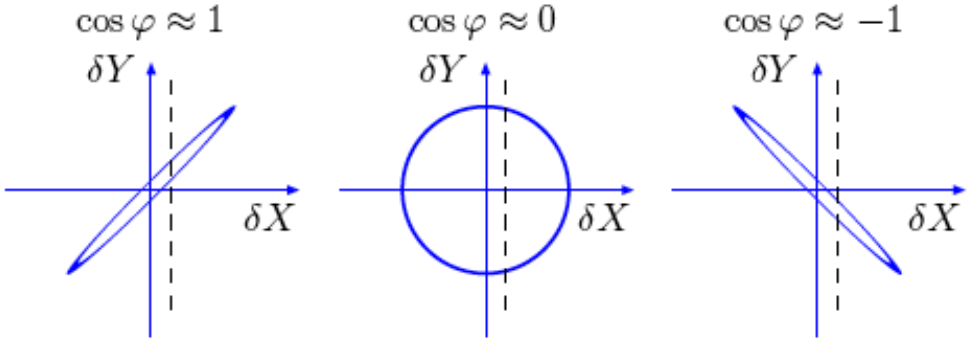
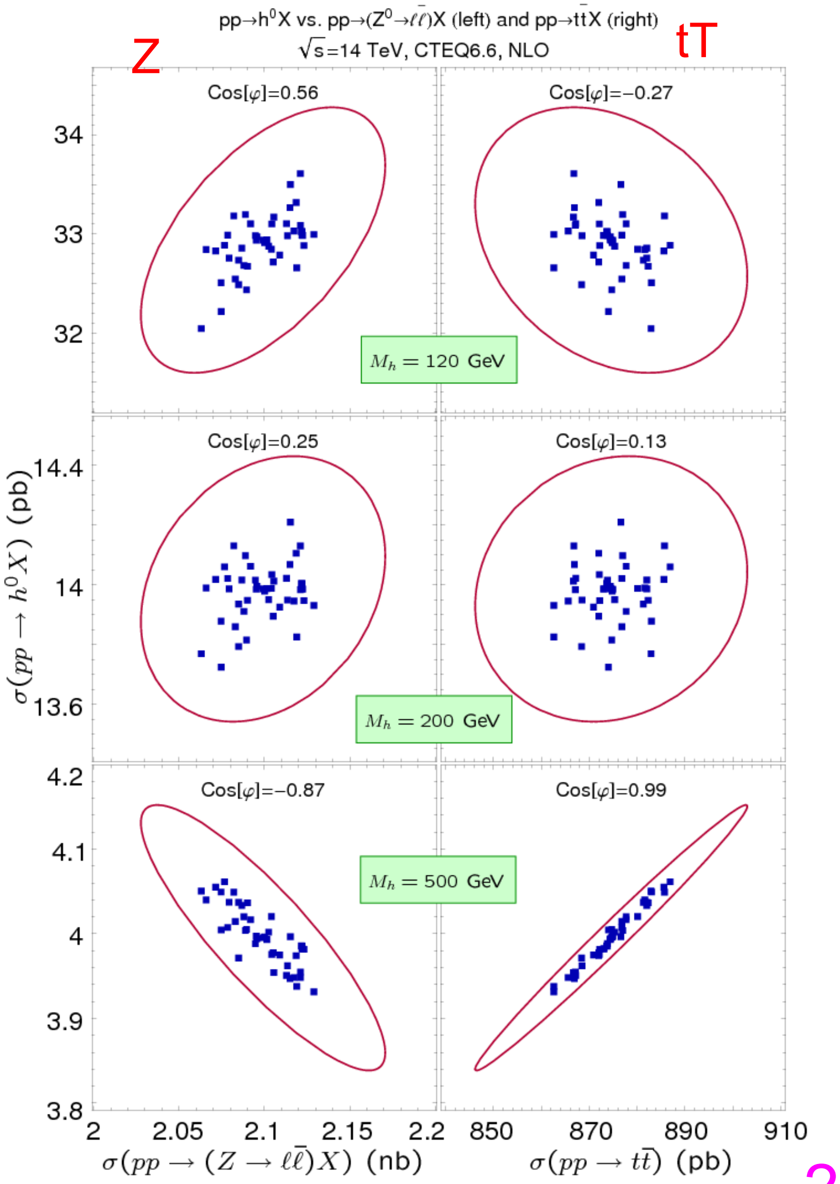


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

- If two cross sections are very correlated, then cosϕ~1
- …uncorrelated, then cosϕ~0
- …anti-correlated, then cosϕ~-1



Correlations with Z, tT: use tT production as a benchmark for gg initial states

Define a correlation cosine between two quantities

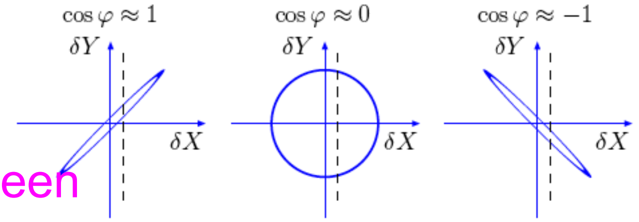
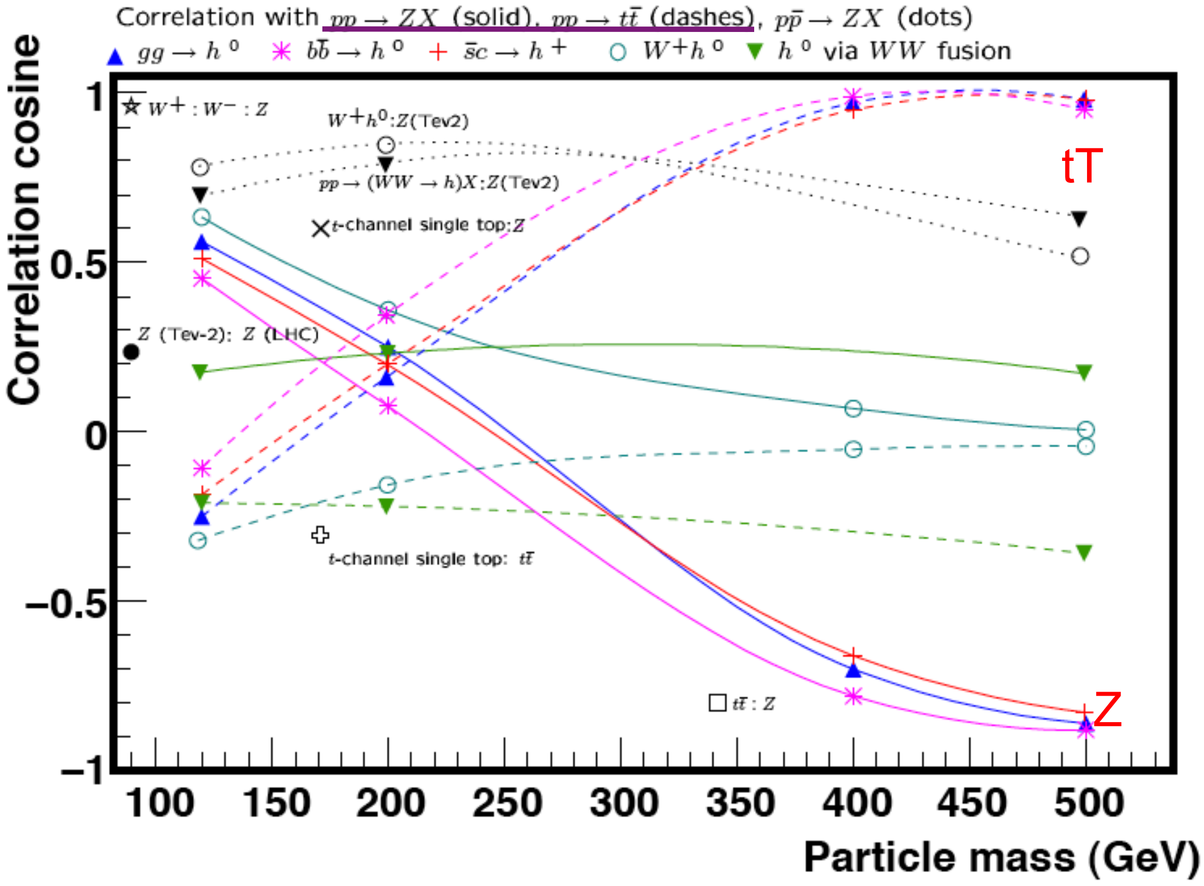


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

- If two cross sections are very correlated, then $\cos\phi \sim 1$
- …uncorrelated, then $\cos\phi \sim 0$
- …anti-correlated, then $\cos\phi \sim -1$



- Note that correlation curves to Z and to tT are mirror images of each other

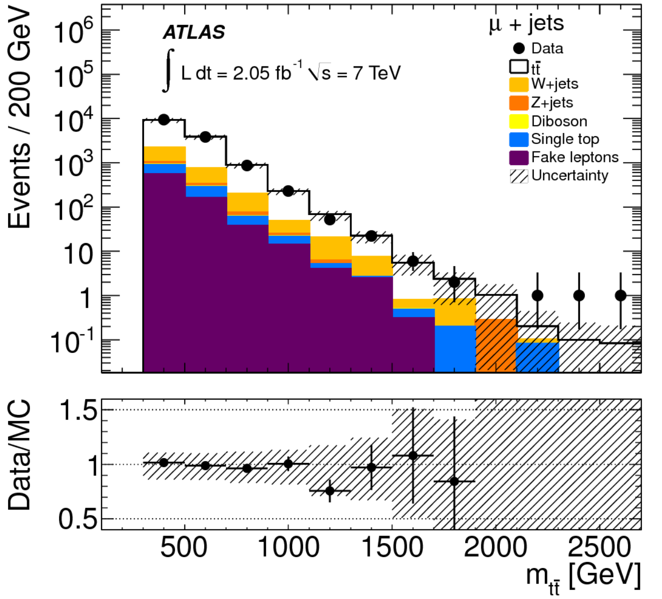
- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section **iff** $\cos\phi > 0$;e.g. $\Delta(\sigma_W+/\sigma_Z) \sim 1\%$

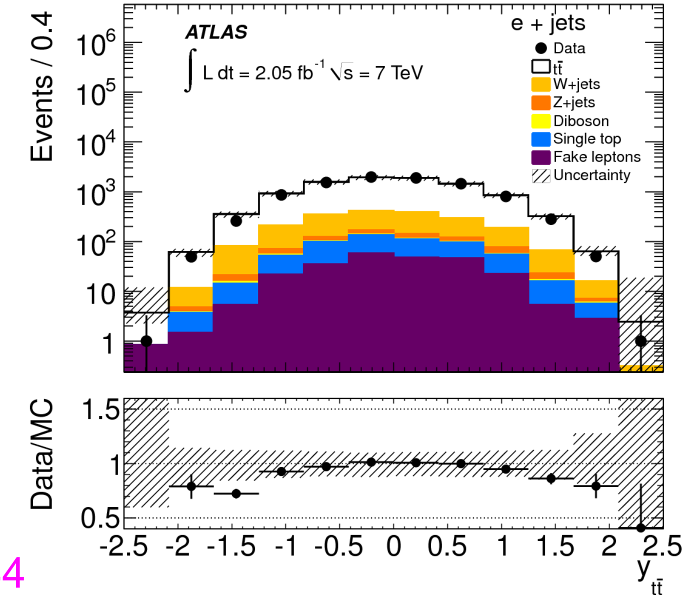
- If $\cos\phi < 0$, pdf uncertainty for one cross section normalized to a benchmark cross section is larger

- So, for gg->H(500 GeV); pdf uncertainty is 4%; $\Delta(\sigma_H/\sigma_Z) \sim 8\%$

Differential distributions

- More information about the production processes can be determined by examination of the differential distributions
- Both tT mass and rapidity distributions will be useful for PDF determination
- And of course high tT masses are a likely place to look for possible new physics in deviations from pQCD predictions



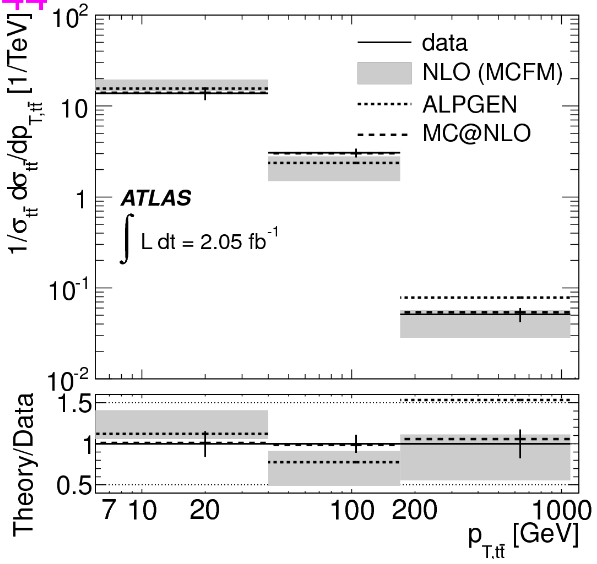


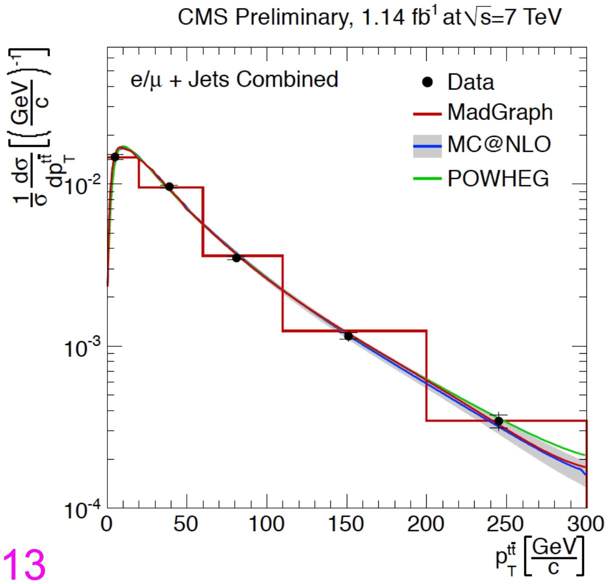
arXiv:1207.5644

Differential distributions-unfolded

- For easiest comparison of data to theory, best to have unfolding to hadron level (and clear indication of hadron to parton level conversions)
- Many systematic errors cancel in ratio
- Good agreement with predictions
- Future input for global PDF fits, especially once differential predictions are available at NNLO

arXiv:1207.5644





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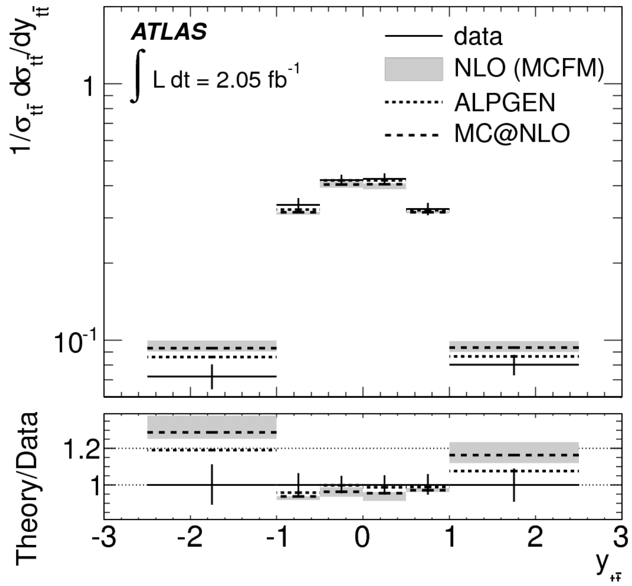
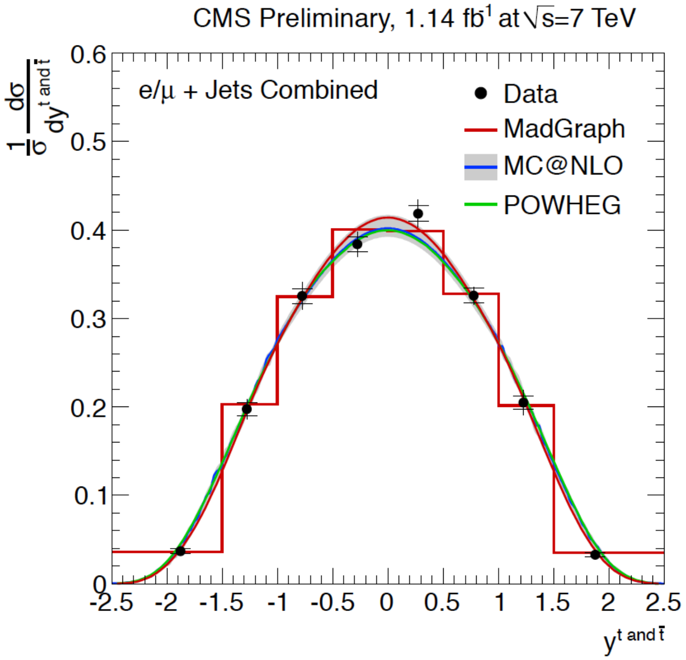
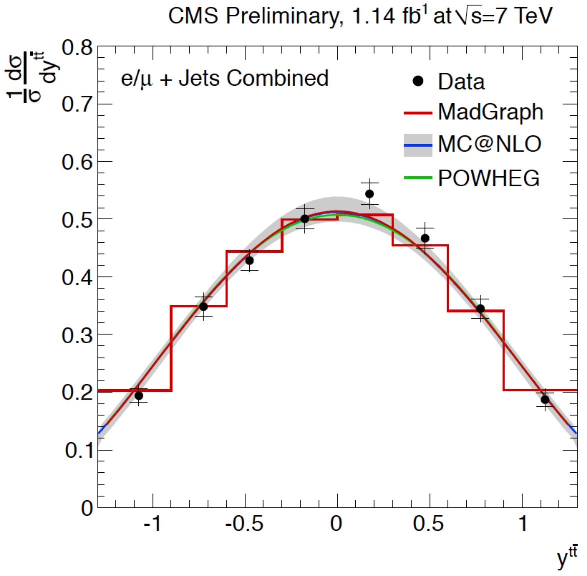
CTEQ

Differential distributions-unfolded

- For easiest comparison of data to theory, best to have unfolding to hadron level (and clear indication of hadron to parton level conversions)





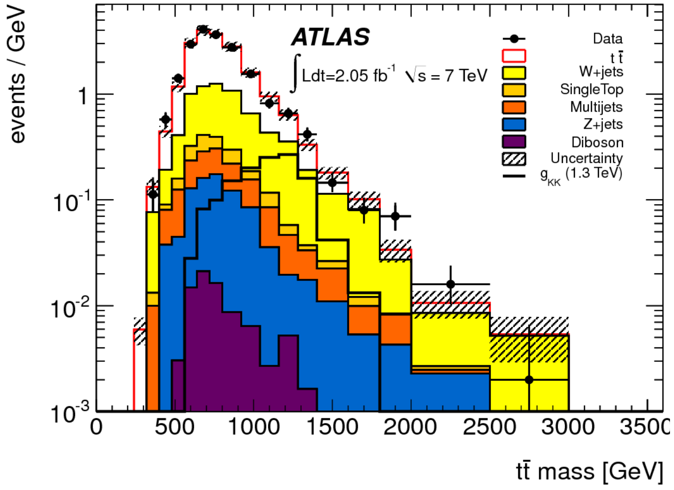


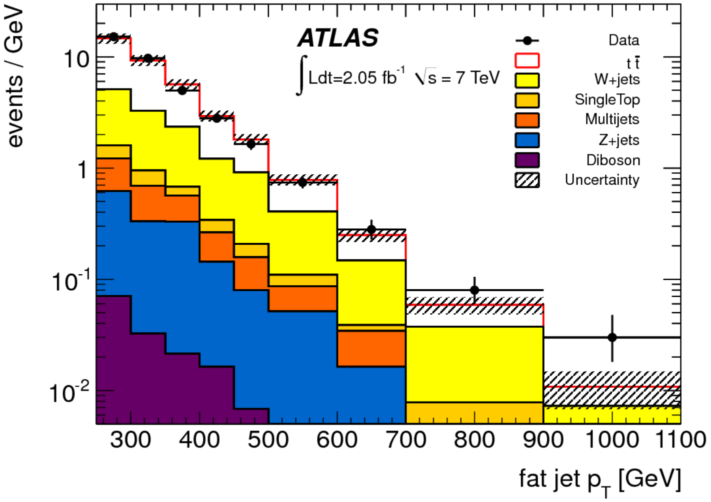
CTEQ

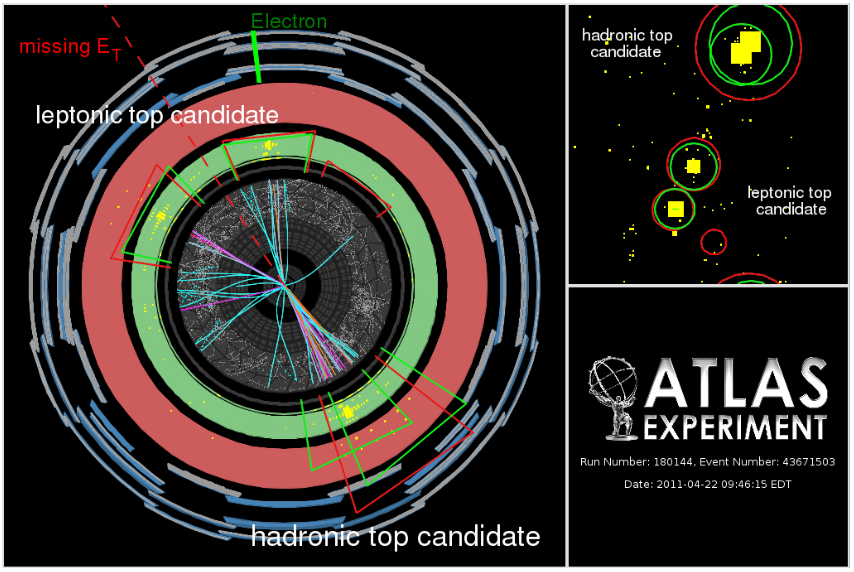
Boosted jets/fat jets

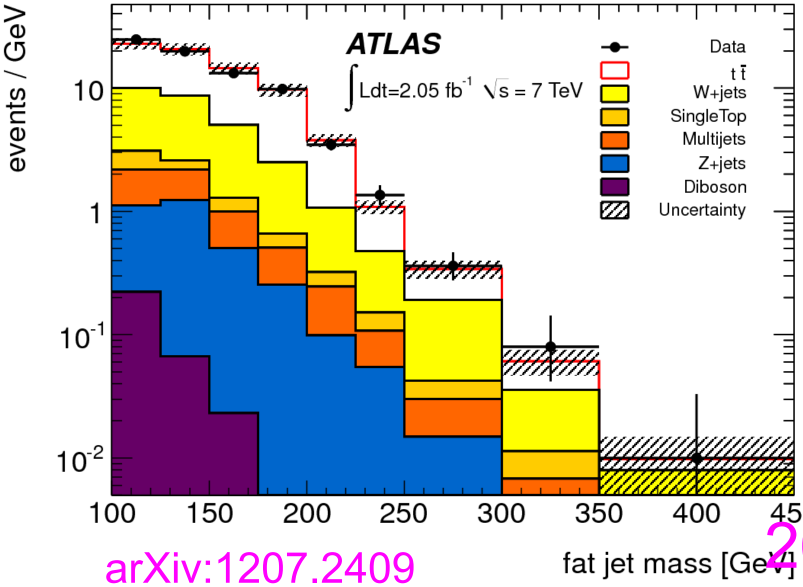
- There’s a whole growth industry now looking for new physics in boosted jets
- Many interesting QCD issues
- We know how to identify boosted top quarks in fat jets (R=1.0)

no new physics (yet)





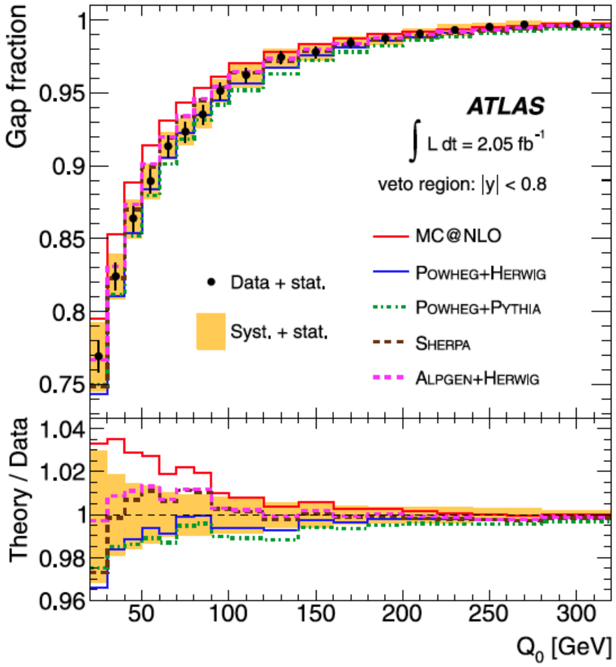




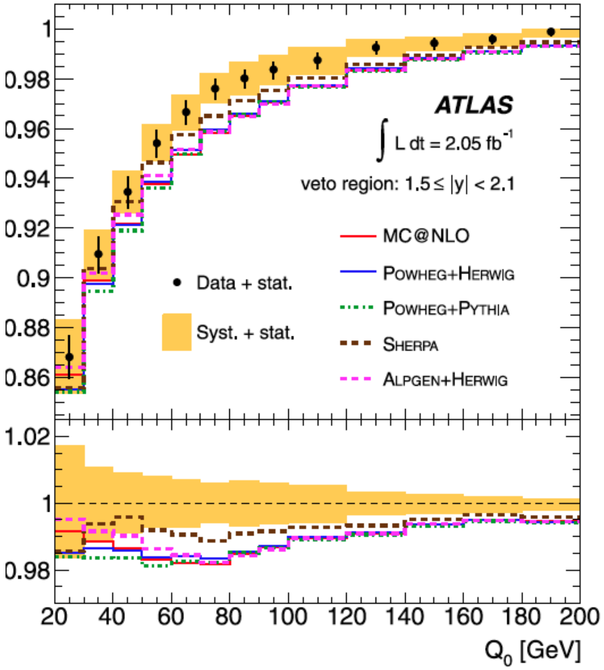
arXiv:1207.2409

tT with jet veto

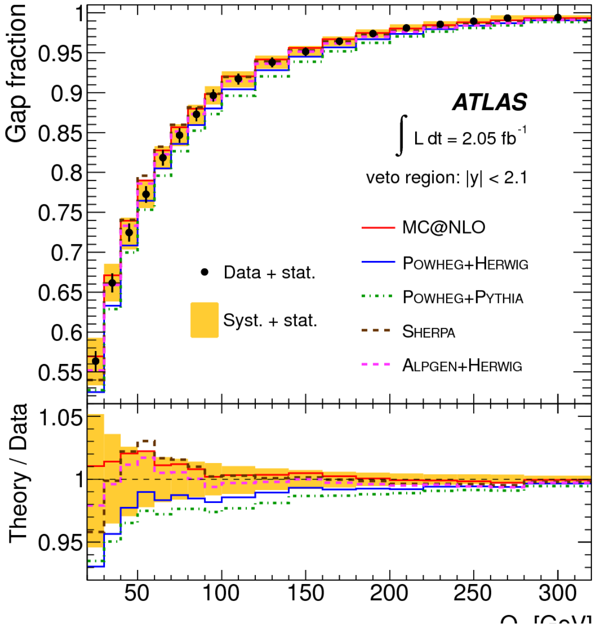
- Dilepton channel; measure fraction of tT events with no extra jet above a given p_T cut

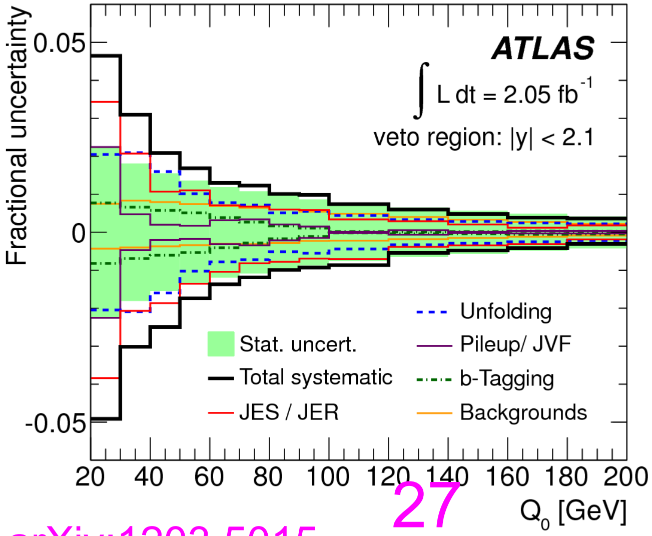


Central region: too few jets from MC@NLO



Forward region: all models produce too many jets





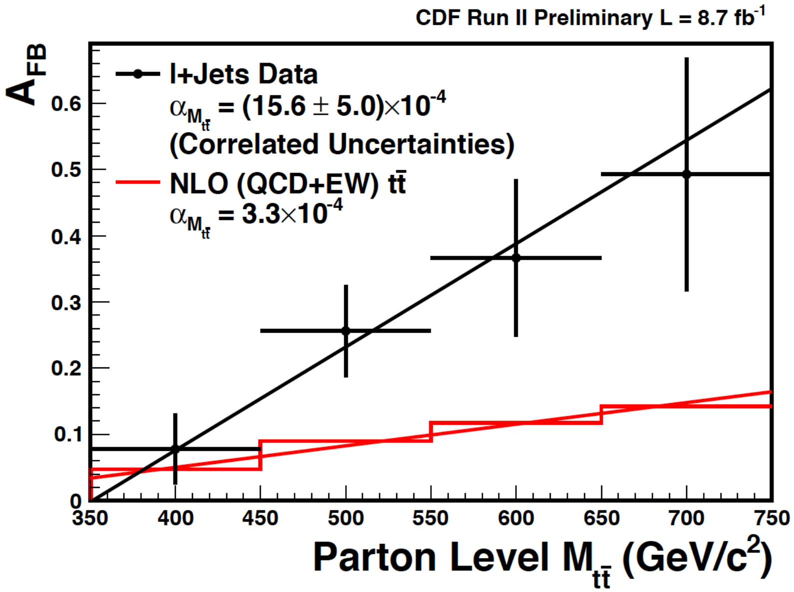
Good observable to develop more detailed understanding of hard gluon radiation at the LHC; 'CKKW-like' adding of NLO tT, tT+1 jet, tT+2 jets, etc (MEPS@NLO, aMC@NLO)

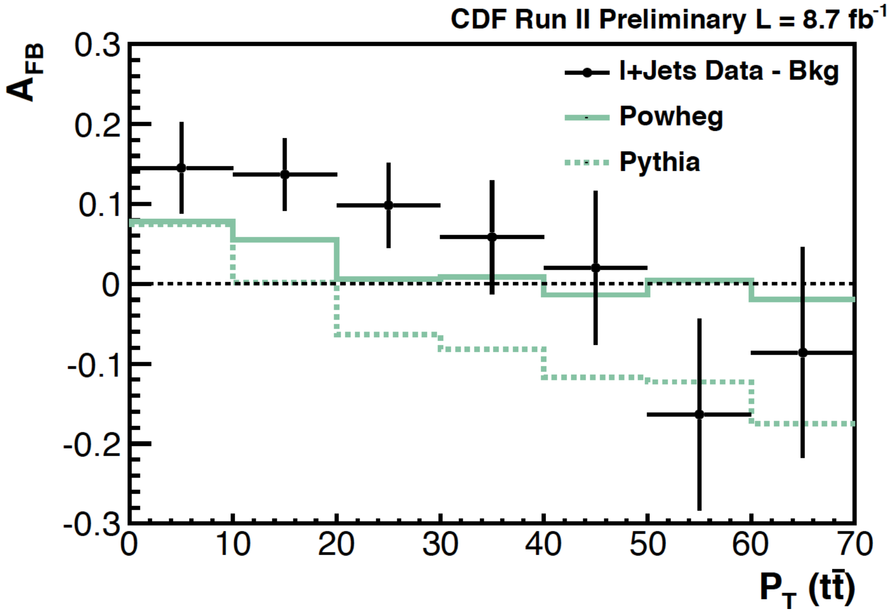
arXiv:1203.5015

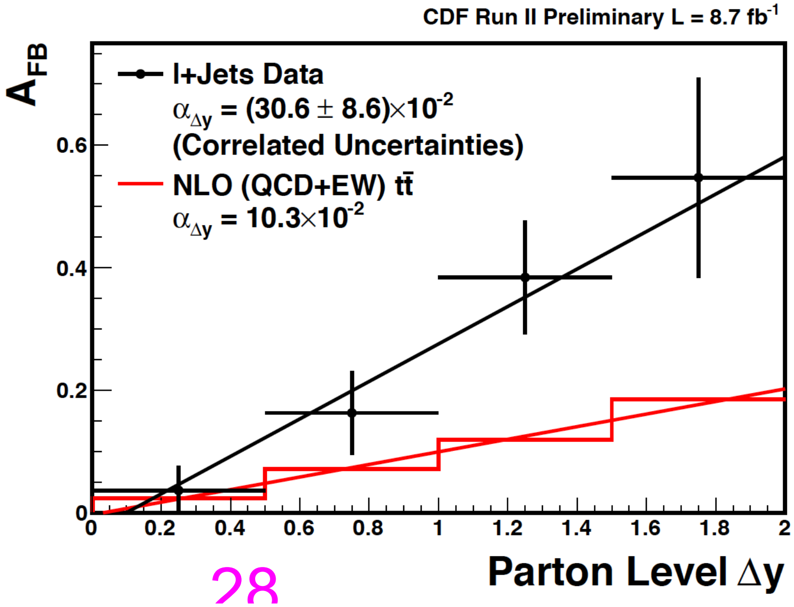
C T E Q

tT asymmetry

- At the Tevatron, the predicted asymmetry is sizeable
- The measured asymmetry is larger still
- It looks like QCD, but QCD on steroids (my phrase)





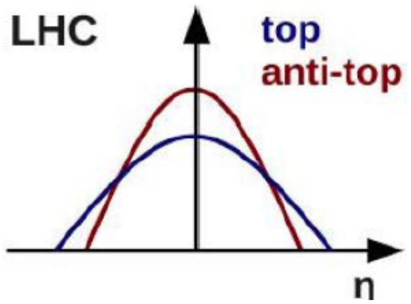


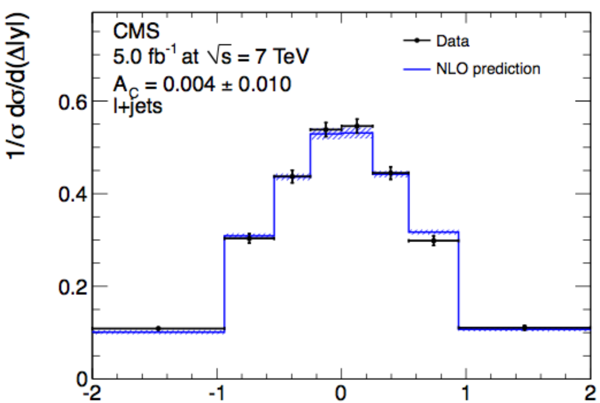
LHC

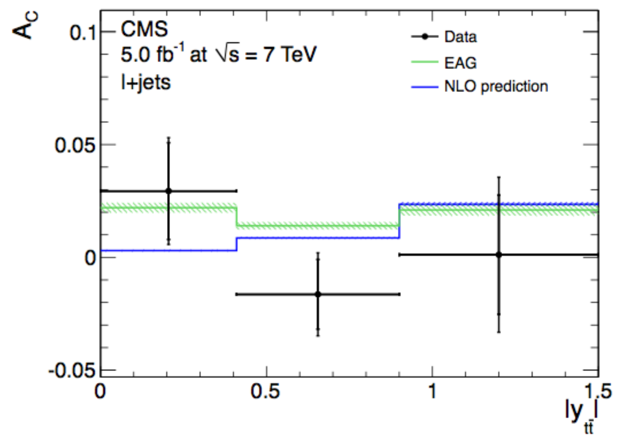
- Due to the symmetry of the initial state, the predicted asymmetry is much smaller than at the Tevatron, and has to be measured indirectly, by a broadening of the top distribution compared to the anti-top
- It's a lot more difficult to measure a few percent effect than the large asymmetries predicted/observed at the Tevatron: tension so far between Tevatron and LHC

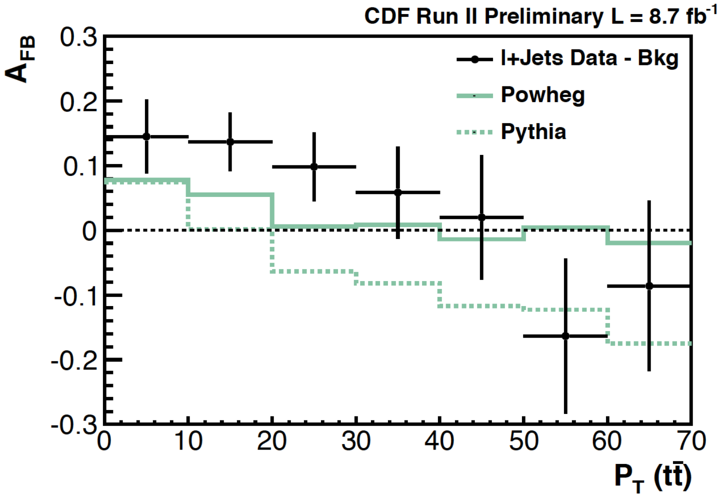
CMS PAS TOP-11-030

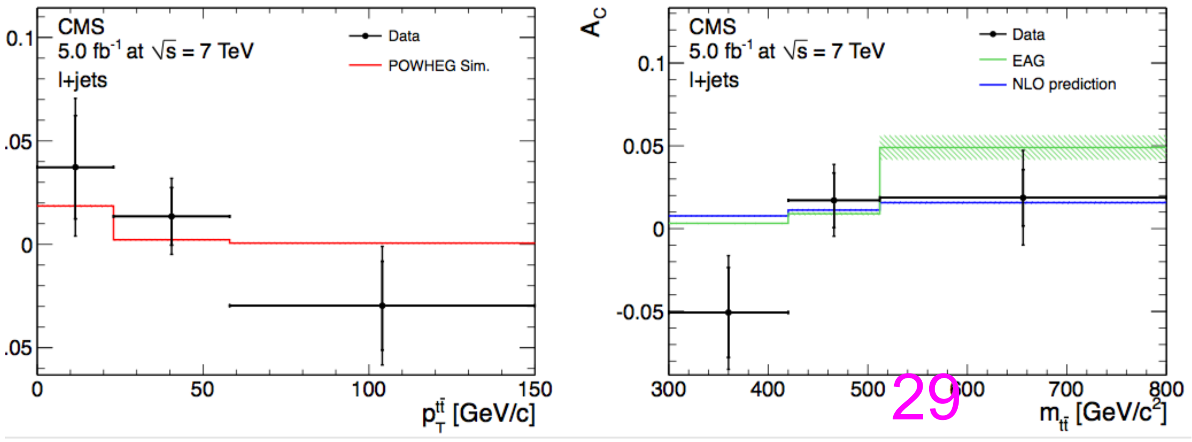
LHC: $\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$











C T E Q

Summary

- Due to its large mass, and its importance in the standard model, top quark production at the LHC plays an important role for improving our understanding of QCD, both perturbative and non-perturbative
- As data continues to flow in, the statistical errors are becomingly vanishingly small; as understanding of the detectors and reconstruction techniques improve, the systematic errors are improving past what was possible at the Tevatron
- We are close to a full NNLO tT inclusive cross section calculation; this calculation will allow for a new range of precision predictions
- Differential distributions at NNLO (the next step) will allow for even more detailed phenomenology, especially with regards to the tT asymmetry
- PDF uncertainties are still sizeable for gg initial states; with the advent of a full NNLO calculation, they will be the largest systematic error, either theoretical or experimental
    - the inclusion of precision LHC data from the 2011-2012 should serve to reduce that uncertainty
    - right now primary constraints are from Tevatron jets, HERA heavy flavor, HERA Run 1 cross section
- But tT cross sections may serve as a useful benchmark, esp for gg initial states
- (Unofficial) NNLO benchmarking paper should be posted to the archive in near future
- PDF4LHC should come out with an official recommendation for PDF uncertainties also in the near future

LHC jet data

- LHC jet data are in a kinematic region where there is a strong correlation with the gluons responsible for tT production
- Each curve shows the correlation for a specific data point

Jun Gao
preliminary