PDFs and the LHC

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Standard Model @ LHC

April 10, 2012

Some references

CERN-PH-TH/2011-149
28th June 2011

The PDF4LHC Working Group Interim Report

Sergey Alekhin[1,2], Simone Alioli[1], Richard D. Ball[3], Valerio Bertone[4], Johannes Blümlein[1], Michiel Botje[5], Jon Butterworth[6], Francesco Cerutti[7], Amanda Cooper-Sarkar[8], Albert de Roeck[9], Luigi Del Debbio[3], Joel Feltesse[10], Stefano Forte[11], Alexander Glazov[12], Alberto Guffanti[4], Claire Gwenlan[8], Joey Huston[13], Pedro Jimenez-Delgado[14], Hung-Liang Lai[15], José I. Latorre[7], Ronan McNulty[16], Pavel Nadolsky[17], Sven Olaf Moch[1], Jon Pumplin[13], Voica Radescu[18], Juan Rojo[11], Torbjörn Sjöstrand[19], W.J. Stirling[20], Daniel Stump[13], Robert S. Thorne[6], Maria Ubiali[21], Alessandro Vicini[11], Graeme Watt[22], C.-P. Yuan[13]

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Parton distribution function dependence of benchmark Standard Model total cross sections at the 7 TeV LHC

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ABSTRACT: We compare predictions for the W, Z, $gg \to H$ and $t\bar{t}$ total cross sections at the Large Hadron Collider (LHC), for a centre-of-mass energy of 7 TeV, using the most recent publicly available next-to-leading order and next-to-next-to-leading order parton distribution functions (PDFs) from all PDF fitting groups. In particular, we focus on the dependence on the different values of the strong coupling, $\alpha_S(M_Z^2)$, used by each group. We also perform a comparison of the relevant quark–antiquark and gluon–gluon luminosity functions. We make some comments on the recent PDF4LHC recommendations. Finally, we discuss the comparison of data and theory for W and Z cross sections at the LHC.

…and companion website at
http://mstwpdf.hepforge.org/pdf4lhc/

Some references

CERN–2011–002
17 February 2011

arXiv:1101.0593v3 [hep-ph] 20 May 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
1. Inclusive observables

Report of the LHC Higgs Cross Section Working Group

Editors: S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2011

arXiv:1201.3084v1 [hep-ph] 15 Jan 2012

Handbook of LHC Higgs cross sections:
2. Differential Distributions

Report of the LHC Higgs Cross Section Working Group

Editors: S. Dittmaier
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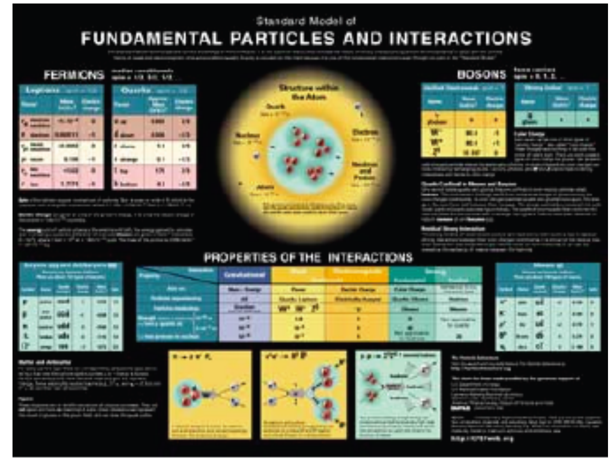
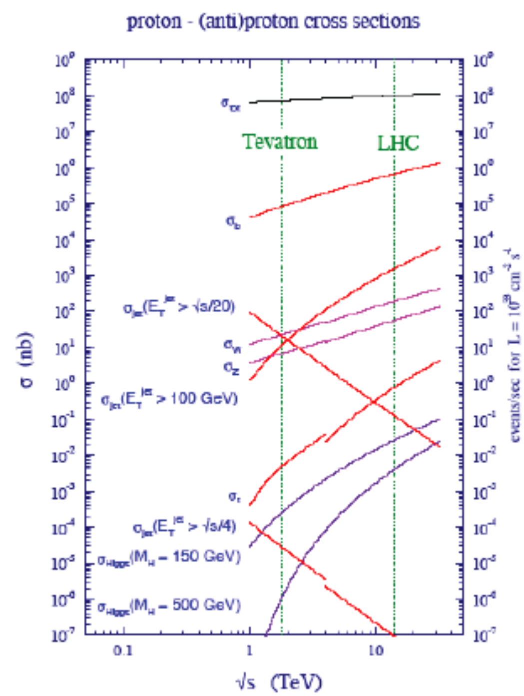
…and Pavel Nadolsky's talk at DIS2012

Understanding cross sections at the LHC

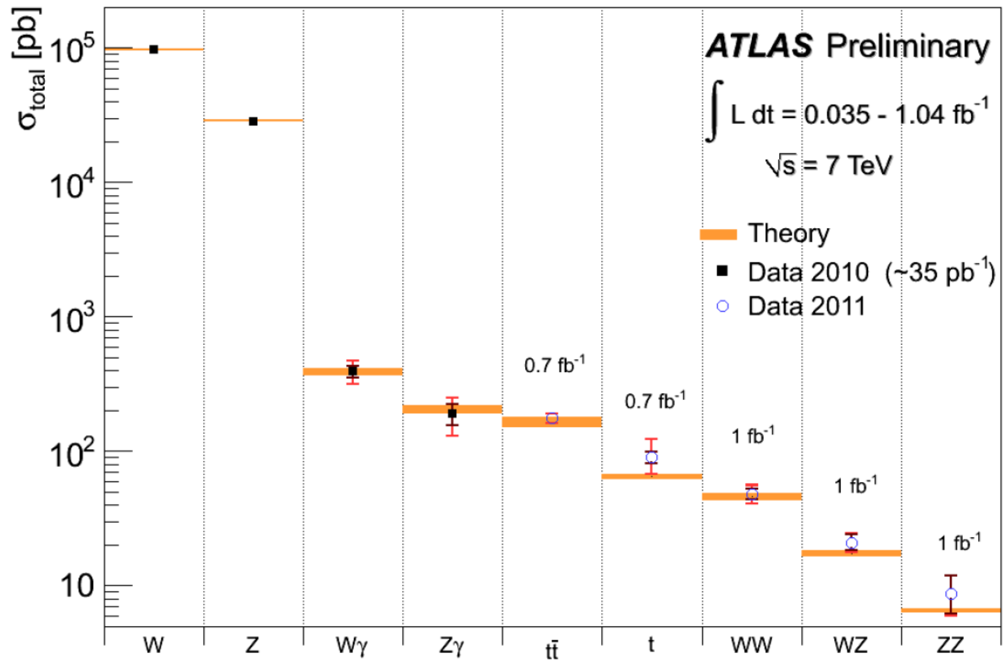
- We're all looking for Higgs/BSM physics at the LHC
- Before we publish Higgs/BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand the relevant cross sections
  - and this largely means understanding QCD at the LHC
  - in final states involving vector bosons, jets, photons, heavy quarks…
- 2010 was largely spent 'Re-discovering the Standard Model' at the LHC
  - my phrase by the way, so reference me if you use it
- 2011 was spent in extending the discovery reach beyond the Tevatron
- An important part of this understanding is related to our understanding of parton distribution functions and their uncertainties for LHC kinematics

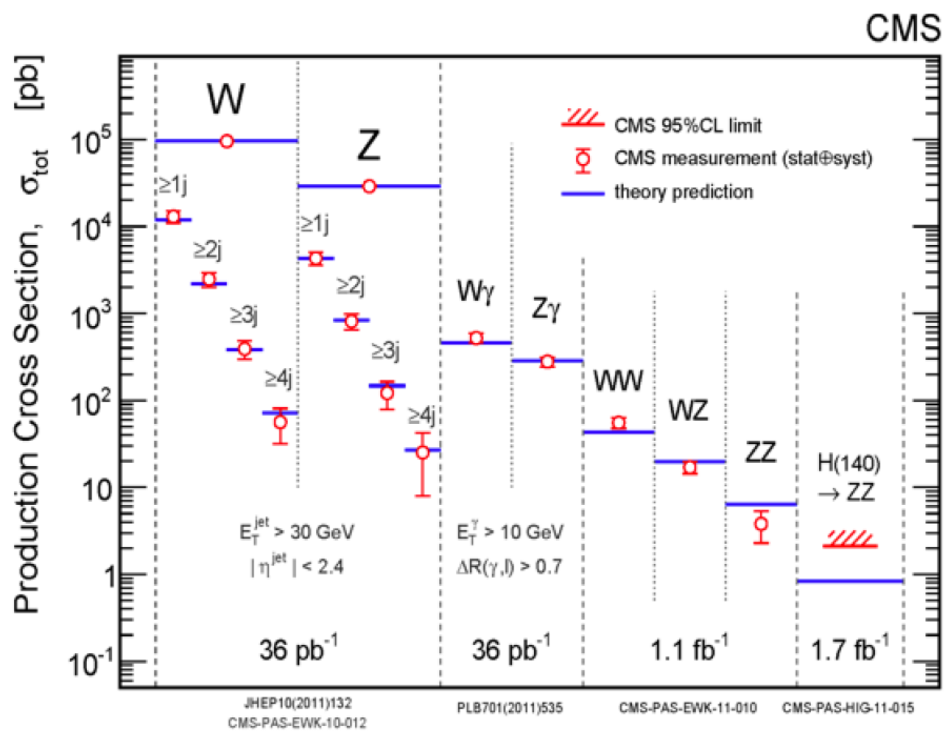




The re-discovery

- Each of these cross sections is compared to either NLO or NNLO predictions using current PDFs
- Many of these cross sections are being fed back into the global PDF fits providing information in a new kinematic regime
- …but only if the experiment provides the needed correlated systematic error info





Parton distribution functions and global fits

- Calculation of production cross sections at the LHC relies upon knowledge of PDF's in the relevant kinematic region
- PDF's are determined by global analyses of data from DIS, DY and jet production
- There are three major groups that provide semi-regular updates to global fits to parton distributions when new data/theory becomes available
  - MRS->MRST2004->MSTW2008
  - CTEQ->->CTEQ6.6->CT09->CT10->CT12
  - NNPDF->NNPDF2.0->NNPDF2.1
- There are three other groups that also provide updated PDF fits, that are not quite as fully global
  - HERAPDF
  - ABKM
  - (G)JR

1. BCDMS F_2^{proton} (339 data points)
2. BCDMS $F_2^{deuteron}$ (251 data points)
3. NMC F_2 (201 data points)
4. NMC F_2^d/F_2^p (123 data points)
5. F_2(CDHSW) (85 data points)
6. F_3(CDHSW) (96 data points)
7. CCFR F_2 (69 data points)
8. CCFR F_3 (86 data points)
9. H1 NC e^-p (126 data points; 1998-98 reduced cross section)
10. H1 NC e^-p (13 data points; high y analysis)
11. H1 NC e^+p (115 data points; reduced cross section 1996-97)
12. H1 NC e^+p (147 data points; reduced cross section; 1999-00)
13. ZEUS NC e^-p (92 data points; 1998-99)
14. ZEUS NC e^+p (227 data points; 1996-97)
15. ZEUS NC e^+p (90 data points; 1999-00)
16. H1 F_2^c e^+p (8 data points;1996-97)
17. H1 $R\sigma^c$ for ccbar e^+p (10 data points;1996-97)
18. H1 R_σ^b for bbbar e^+p (10 data points; 1999-00)
19. ZEUS F_2^c e^+p (18 data points; 1996/97)
20. ZEUS F_2^C e+p (27 data points; 1998/00)
21. H1 CC e^-p (28 data points; 1998-99)
22. H1 CC e^+p (25 data points; 1994-97)
23. H1 CC e^+p (28 data points; 1999-00)
24. ZEUS CC e^-p (26 data points; 1998-99)
25. ZEUS CC e^+p (29 data points; 1994-97)
26. ZEUS CC e^+p (30 data points; 1999-00)
27. NuTev neutrino dimuon cross section (38 data points)
28. NuTev anti-neutrino dimuon cross section (33 data points)
29. CCFR neutrino dimuon cross section (40 data points)
30. CCFR anti-neutrino cross section (38 data points)
31. E605 dimuon (199 data points)
32. E866 dimuon (13 data points)
33. Lepton asymmetry from CDF (11 data points)
34. CDF Run 1B jet cross section (33 data points)
35. D0 Run 1B jet cross section (90 data points)

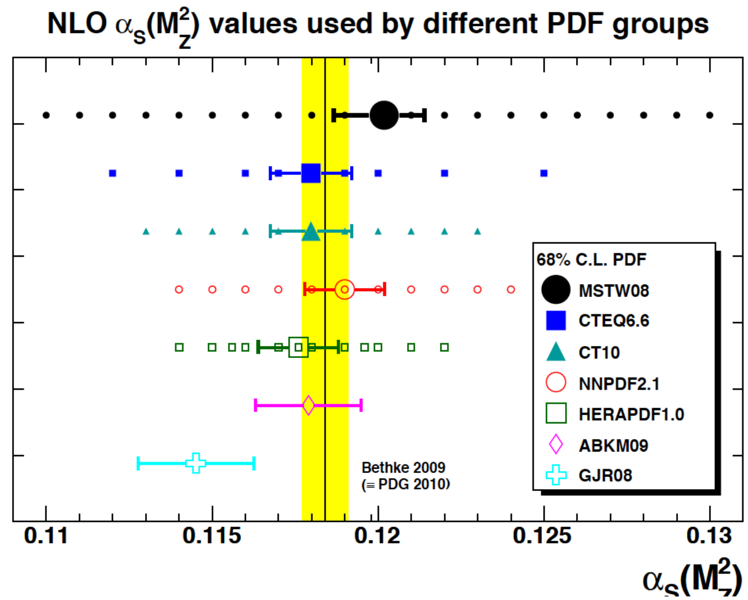
CTEQ6.6 data sets

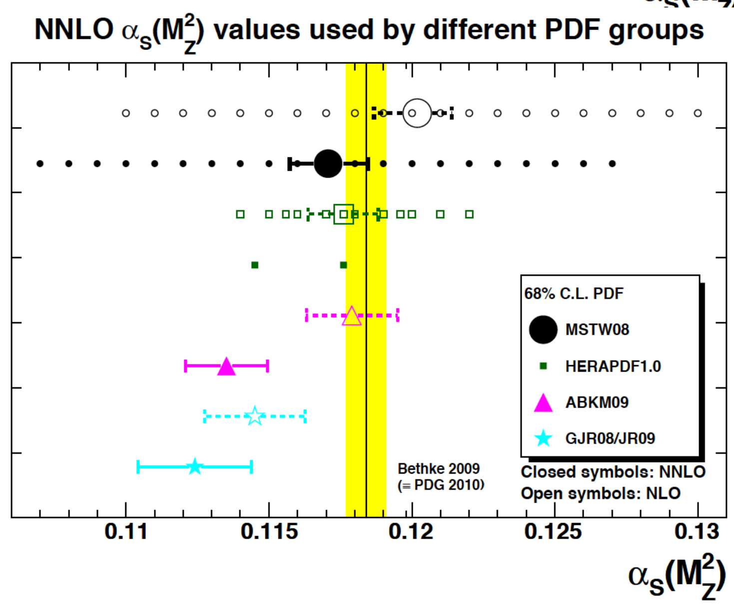
CT10 also includes Run 2 jets, HERA 1 combined data; CT12 uses LHC data in addition

Some of the PDF groups use a Hessian approach towards the estimation of errors; others use a Monte Carlo approach.
Some use a more limited parameterization for their PDFs.

α_s

- The value of $\alpha_s(m_Z)$ used in global fits can either be determined by the global fit (a la MSTW), or input as an external parameter (a la CTEQ-> world average)
- Global fits can not determine the value of $\alpha_s(m_Z)$ very precisely
- The world average in 2009 was 0.1184+/-0.0007
- In 2011, it is 0.1185+/-0.0008
- This is a mixture of analyses and calculations at different orders, including lattice calculations
  - perhaps $\alpha_s(m_Z)$ at NNLO should be smaller than at NLO
- For the PDF4LHC report, we have used a +/-0.002 variation as a 90% CL error (0.0012 as a 1-sigma error)
- The error in α_s can be added in quadrature with the PDF error, without approximation





G. Watt
arXiv:
1106.5788

PDF4LHC report

- We carried out an exercise to which all PDF groups were invited to participate
- A comparison of NLO predictions for benchmark cross sections at the LHC (7 TeV) using MCFM with prescribed input files
- Benchmarks included
  - W/Z production/rapidity distributions
  - ttbar production
  - Higgs production through gg fusion
    - masses of 120, 180 and 240 GeV
- PDFs used include CTEQ6.6, MSTW08, NNPDF2.0, HERAPDF1.0 ABKM09, GJR08
- In some of comparisons, updates to above PDFs may also be shown

The PDF4LHC Working Group Interim Report

Sergey Alekhin[1,2], Simone Alioli[1], Richard D. Ball[3], Valerio Bertone[4], Johannes Blümlein[1], Michiel Botje[5], Jon Butterworth[6], Francesco Cerutti[7], Amanda Cooper-Sarkar[8], Albert de Roeck[9], Luigi Del Debbio[3], Joel Feltesse[10], Stefano Forte[11], Alexander Glazov[12], Alberto Guffanti[4], Claire Gwenlan[8], Joey Huston[13], Pedro Jimenez-Delgado[14], Hung-Liang Lai[15], José I. Latorre[7], Ronan McNulty[16], Pavel Nadolsky[17], Sven Olaf Moch[1], Jon Pumplin[13], Voica Radescu[18], Juan Rojo[11], Torbjörn Sjöstrand[19], W.J. Stirling[20], Daniel Stump[13], Robert S. Thorne[6], Maria Ubiali[21], Alessandro Vicini[11], Graeme Watt[22], C.-P. Yuan[13]

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All of the benchmark processes were to be calculated with the following settings:

1. at NLO in the $\overline{MS}$ scheme
2. all calculation done in a the 5-flavor quark ZM-VFNS scheme, though each group uses a different treatment of heavy quarks
3. at a center-of-mass energy of 7 TeV
4. for the central value predictions, and for $\pm 68\%$ and $\pm 90\%$ c.l. PDF uncertainties
5. with and without the α_s uncertainties, with the prescription for combining the PDF and α_s errors to be specified
6. repeating the calculation with a central value of $\alpha_s(m_Z)$ of 0.119.

PDF luminosities

- As a first step, it's useful to define and to 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

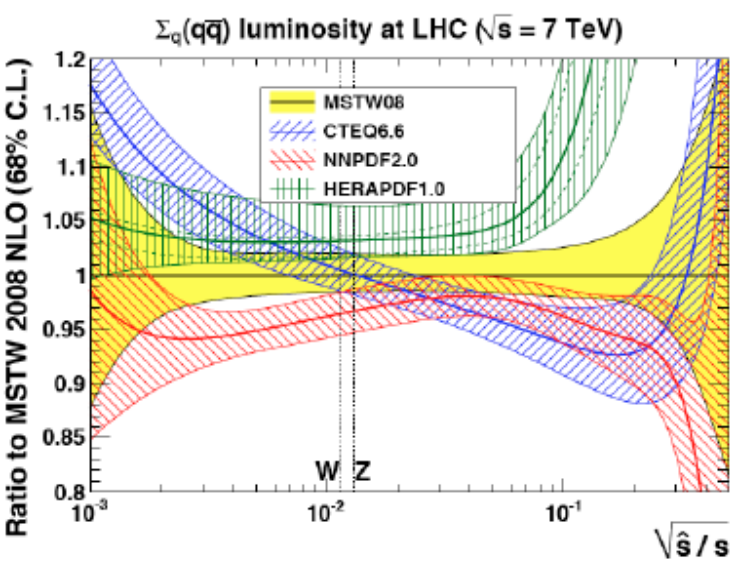
$$\sigma = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat{\sigma}_{ij} \tag{28}$$

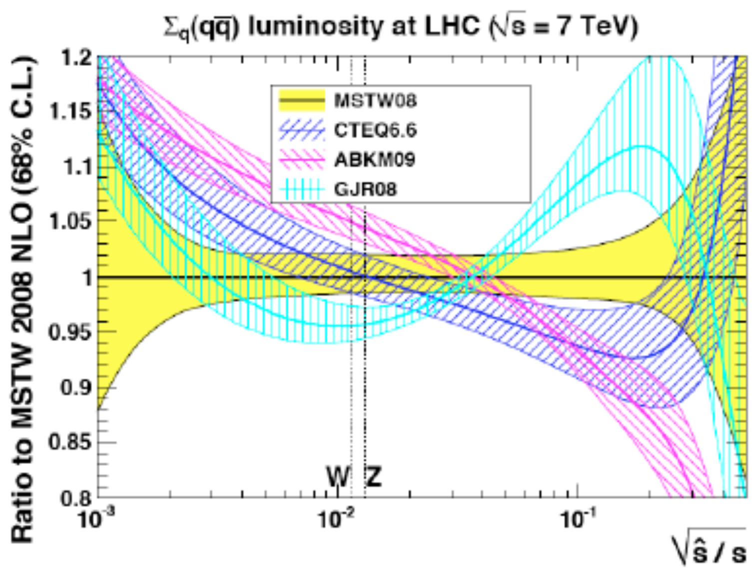
can then be written as

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

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

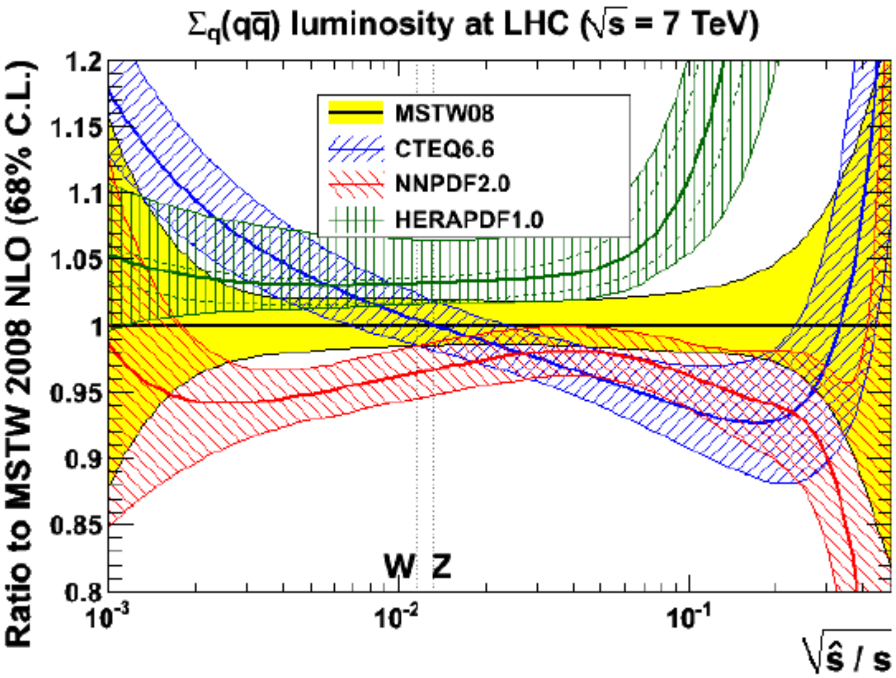




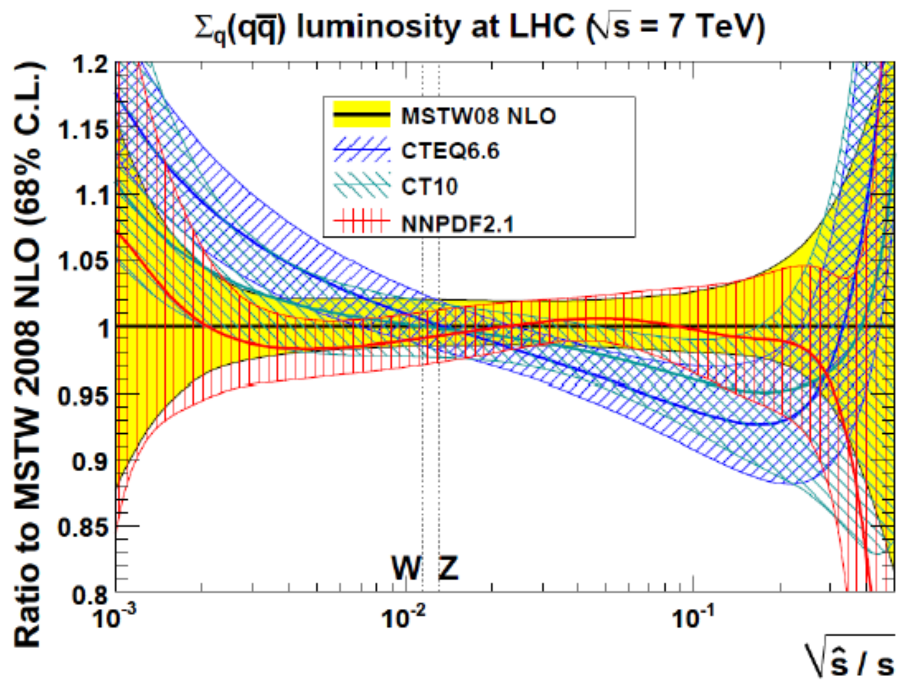
Plots by G. Watt arXiv: 1106.5788

PDFs are tending to get closer

plots from Graeme Watt



2010



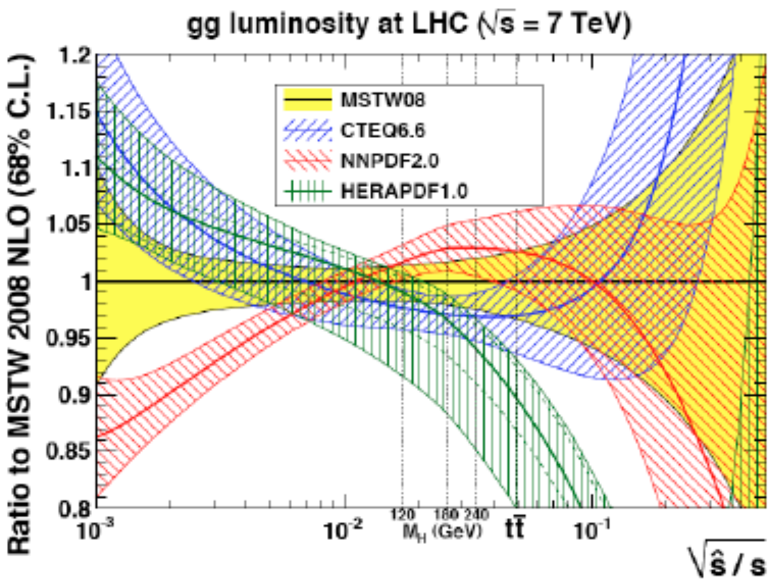
2011

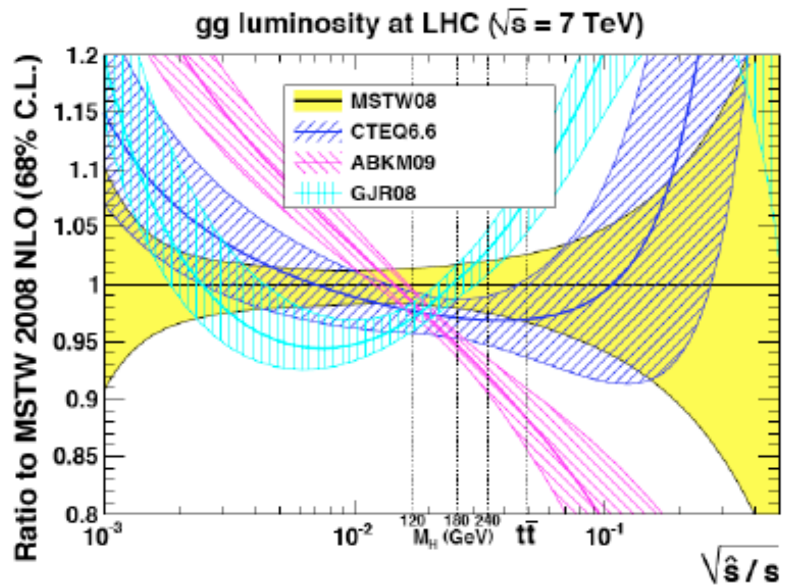
... although still some differences with ABKM, GJR, HERAPDF

NNPDF2.1 has a GM-VFNS treatment (FONLL) ->increase in low x quarks
CT10 includes Tevatron Run II jet data

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

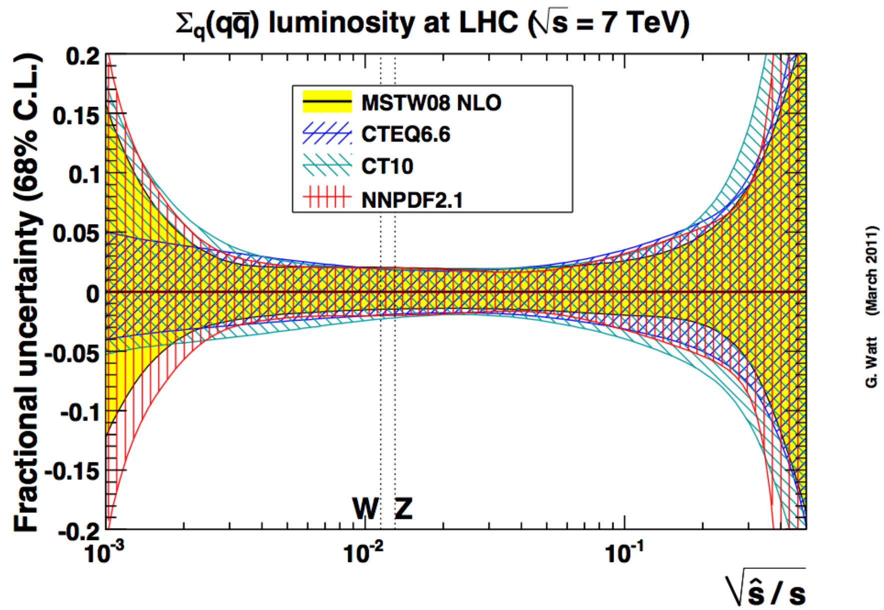


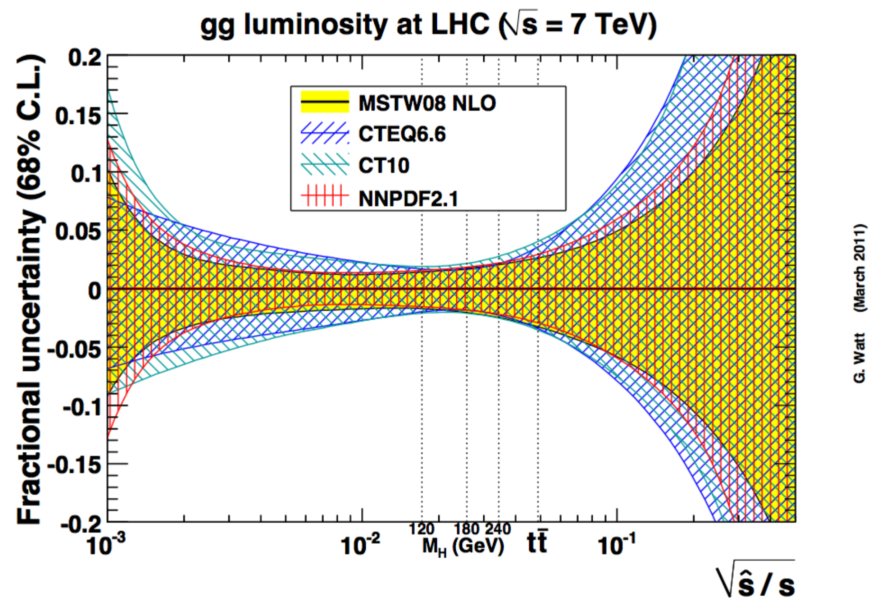


Plots by G. Watt arXiv: 1106.5788

Uncertainties

- Uncertainties, at least among the global PDF groups, agree amazingly well for qqbar, especially given different approaches/assumptions
- A bit larger spread for gg
- Unless otherwise stated, all PDF uncertainties are at 68% CL
  - some PDF groups produce uncertainties for both 68% and 90%CL
  - for others, a scaling of 1.645 is used (which works well)





Some cross section results

$\alpha_s(m_Z)$	$\sigma_{W^+} * BR(W^+ \to l^+\nu)$[nb]	$\sigma_{W^-} * BR(W^- \to l^-\nu)[nb]$	$\sigma_{Z^o} * BR(Z^o \to l^+l^-)[nb]$
0.116	5.957	4.044	0.9331
0.117	5.993	4.068	0.9384
0.118	**6.057**	**4.106**	**0.9469**
0.119	6.064	4.114	0.9485
0.120	6.105	4.139	0.9539

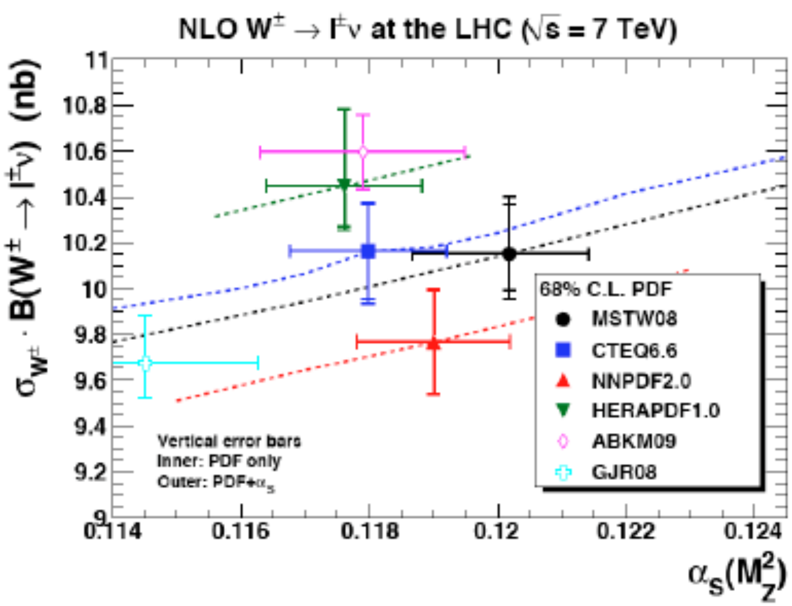
Table 3: Benchmark cross section predictions for CTEQ6.6 for $W^{\pm}, Z$ and $t\bar{t}$ production at 7 TeV, as a function of $\alpha_s(m_Z)$. The results for the central value of $\alpha_s(m_Z)$ for CTEQ6.6 (0.118) are shown in bold.

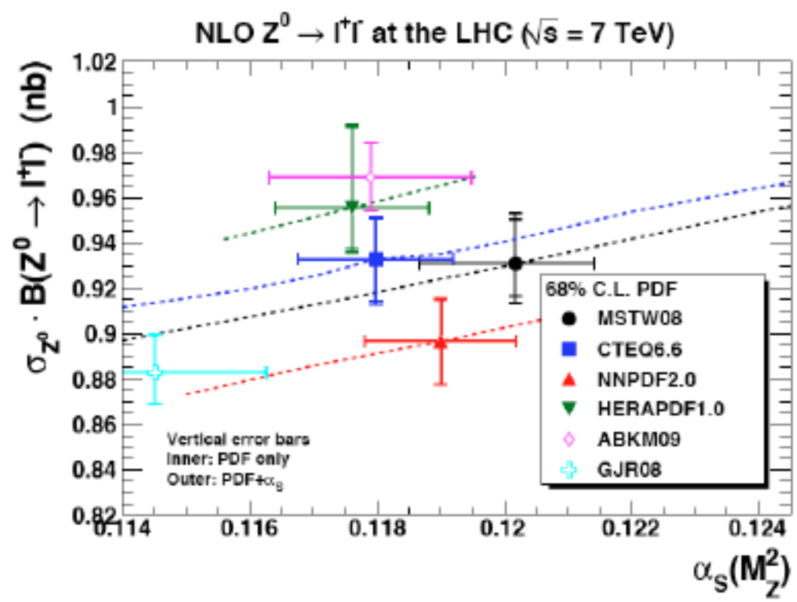
$\alpha_s(m_Z)$	$\sigma_{gg\to Higgs}(120\ GeV)[pb]$	$\sigma_{gg\to Higgs}(180\ GeV)[pb]$	$\sigma_{gg\to Higgs}(240\ GeV)[pb]$	$\sigma_{t\bar{t}}[pb]$
0.116	11.25	4.69	2.52	149.2
0.117	11.42	4.76	2.57	153.0
0.118	**11.59**	**4.84**	**2.61**	**156.2**
0.119	11.75	4.91	2.66	160.5
0.120	11.92	4.99	2.70	164.3

Table 4: Benchmark cross section predictions for CTEQ6.6 for $gg \to Higgs$ production (masses of 120, 180 and 240 GeV), and for $t\bar{t}$ production, at 7 TeV, as a function of $\alpha_s(m_Z)$. The results for the central value of $\alpha_s(m_Z)$ for CTEQ6.6 (0.118) are shown in bold. Higgs production ross sections have been corrected for the finite top mass effect (a factor of 1.06 for 120 GeV, 1.15 for 180 GeV and 1.31 for 240 GeV).

Cross section comparisons

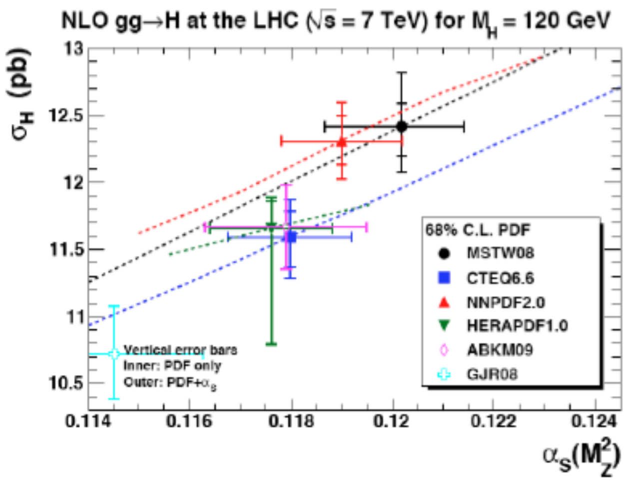
- Notice that the CTEQ and MSTW predictions for W/Z production are very close to each other
- Also, in general, there is very little dependence of the cross sections on the value of $\alpha_s(m_Z)$ (as expected)
- And of course, the higher qQ luminosities observed earlier lead to higher predictions for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

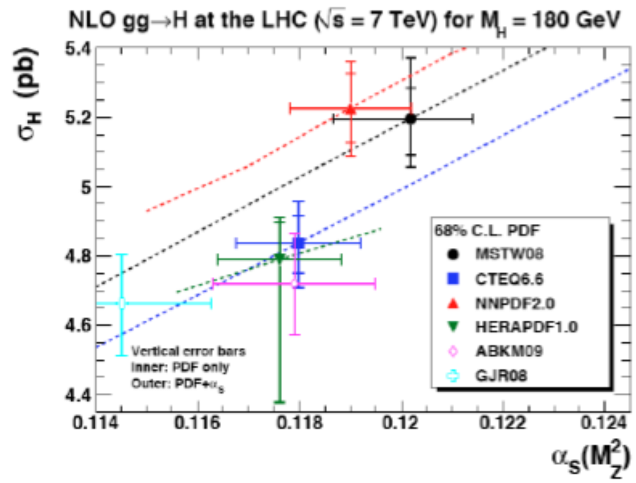




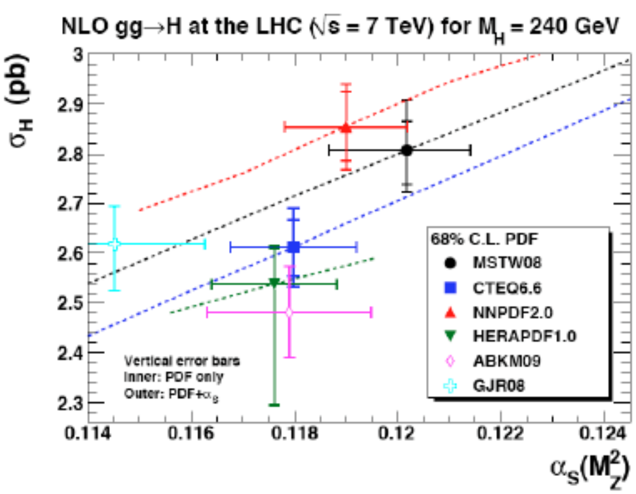
Cross section comparisons

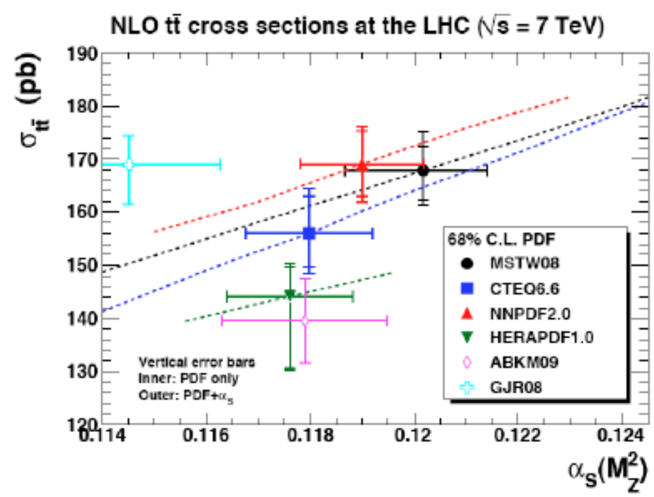
- Larger gg differences and greater dependence on α_s lead to larger differences in Higgs/tT cross section





Note that there tends to be two groupings

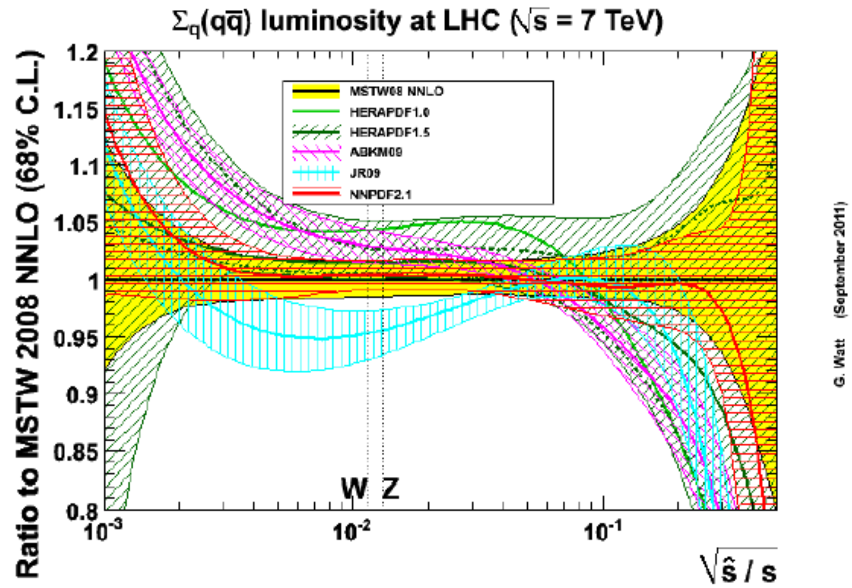


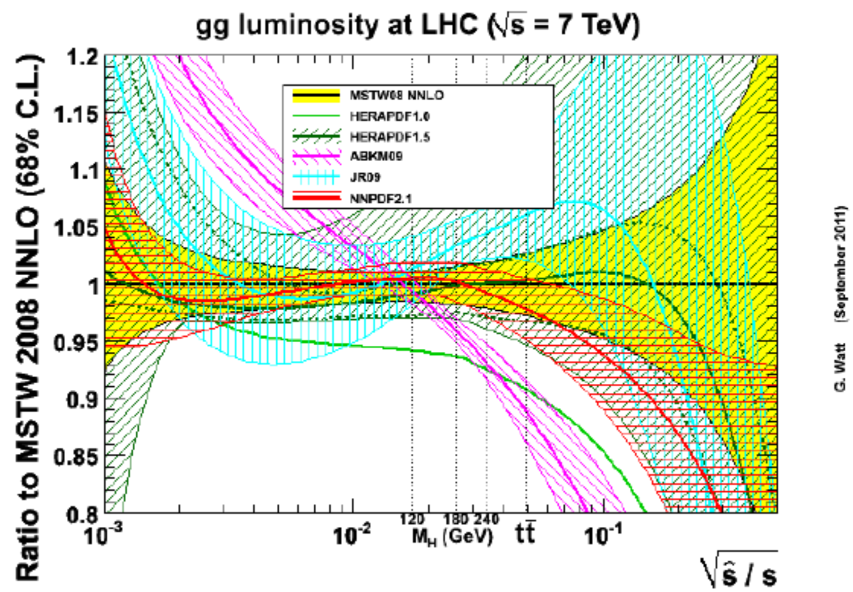


Plots by G. Watt arXiv: 1106.5788

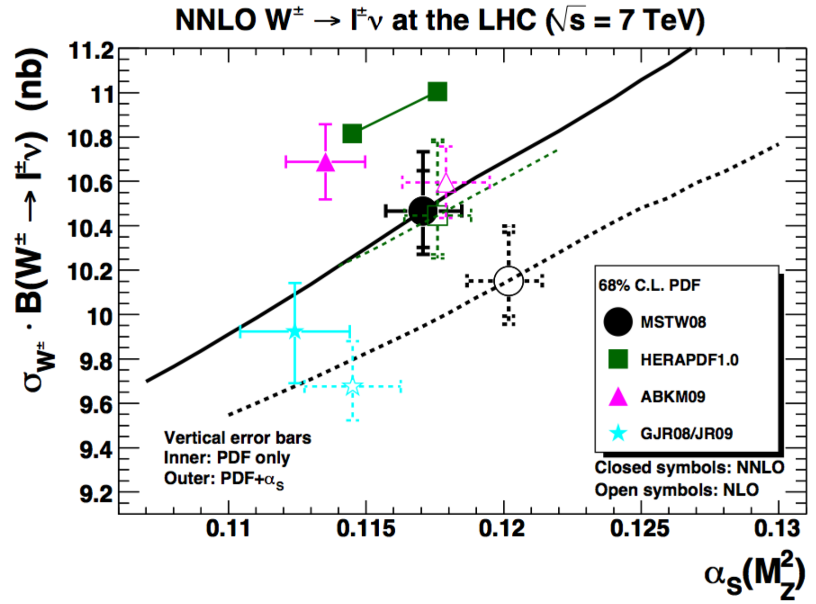
Comparison of NNLO PDF luminosity functions

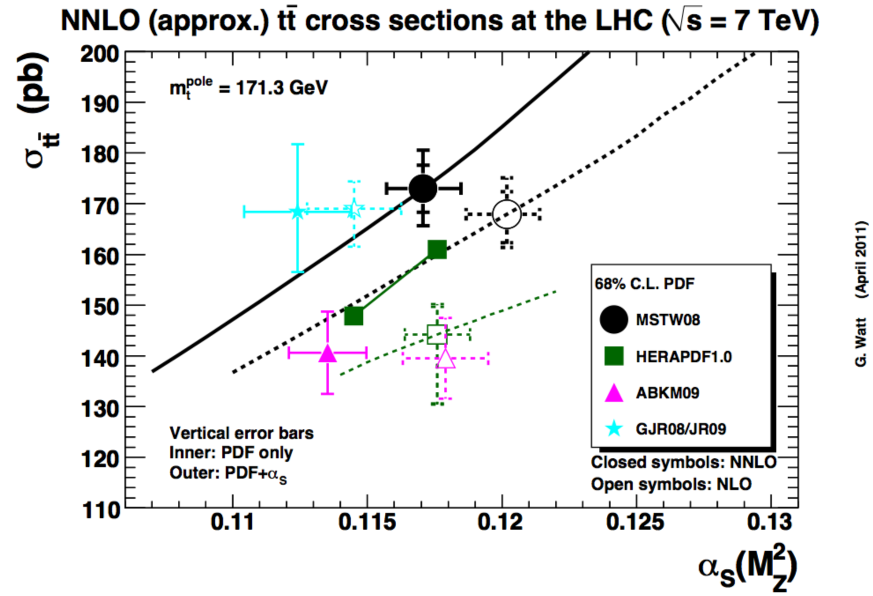
- NNLO trends are similar to those observed at NLO

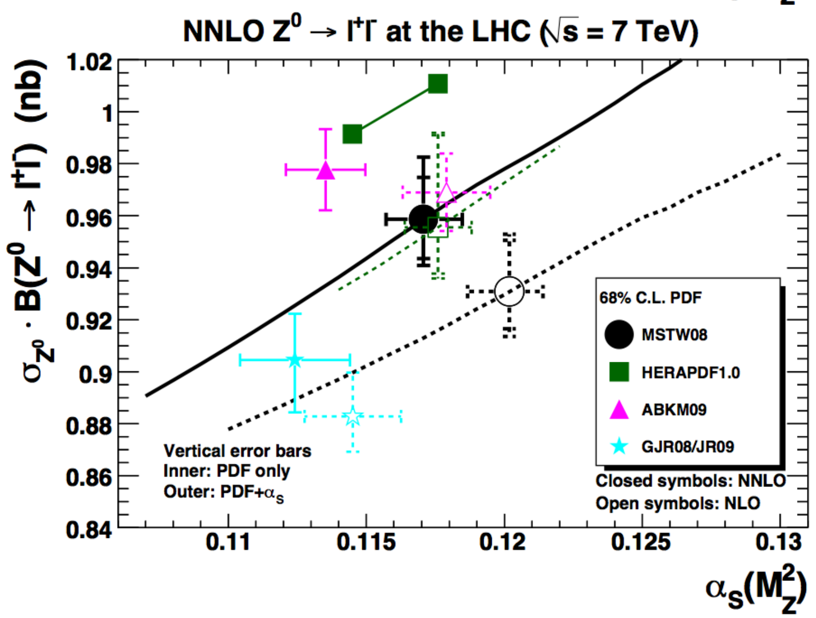


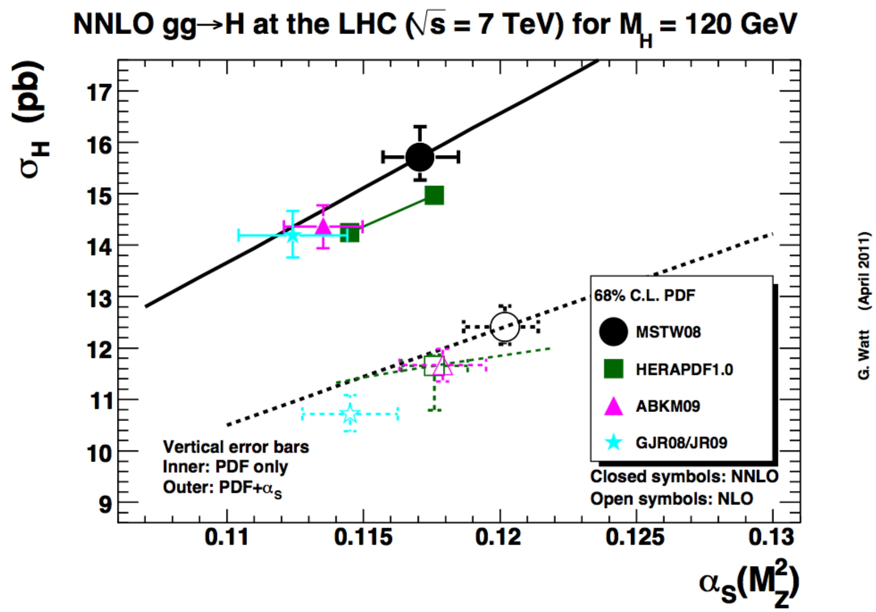


Comparison of NNLO predictions









PDF4LHC recommendations

2. The PDF4LHC recommendation

Before the recommendation is presented, it is useful to highlight the differences between two use cases: (1) cross sections which have not yet been measured (such as, for example, Higgs production) and (2) comparisons to existing cross sections. For the latter, the most useful comparisons should be to the predictions using individual PDFs (and their uncertainty bands). Such cross sections have the potential, for example, to provide information useful for modification of those PDFs. For the former, in particular the cross section predictions in this report, we would like to provide a reliable estimate of the true uncertainty, taking into account possible differences between the central values of predictions using different PDFs [1]. From the results seen it is clear that this uncertainty will be larger than that from any single PDF set, but we feel it should not lose all connection to the individual PDF uncertainties (which would happen for many processes if the full spread of all PDFs were used), so some compromise is proposed.

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:

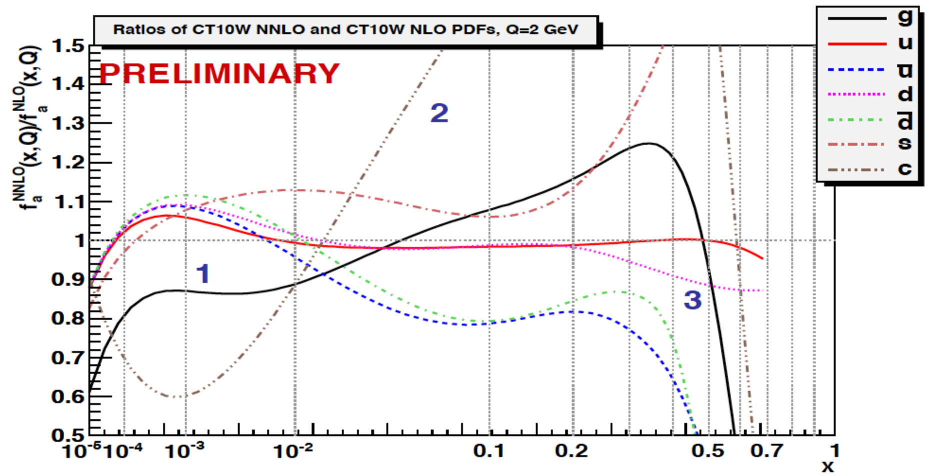
- As a central value, use the MSTW08 prediction. As an uncertainty, take the same percentage uncertainty on this NNLO prediction as found using the NLO uncertainty prescription given above.

Of course, there is the freedom/encouragement to use any individual PDF desired for comparison to measured cross sections. This has been the norm for the 2010 LHC results.

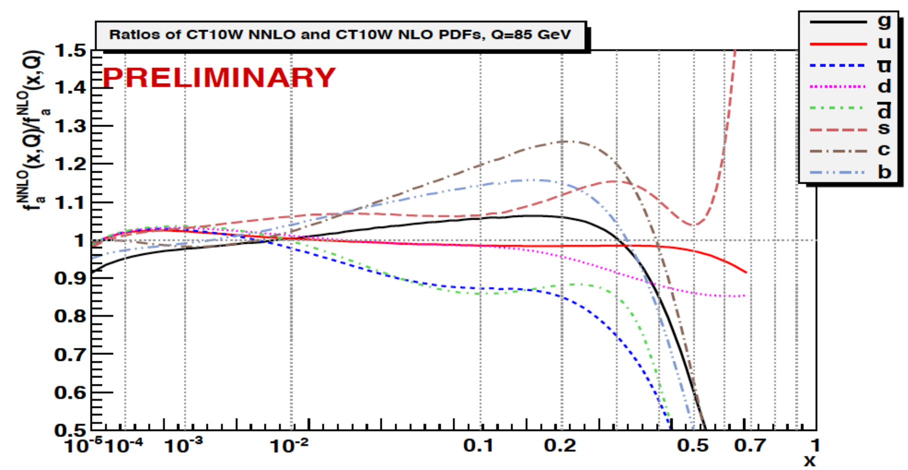
Update: CT10 and CT12

- CT10 NNLO
  - complements CT10 NLO PDF set
  - only pre-LHC CT10 data
  - same input parameters and parametrization forms as in CT10 NLO PDFs
  - NLO and NNLO PDFs produce about same χ^2
  - shapes of CT10 NNLO PDFs have evolved compared to CT10 NLO as a result of order α_s^2 contributions, updated EWK contributions and revised statistical procedures
- CT12 NLO and NNLO
  - include LHC W and Z rapidity data
  - include ATLAS and CMS jet data
  - include HERA 2011 F_L data
- $\alpha_s(mZ)$ fixed at 0.118 for both NLO and NNLO fits in accordance with world average

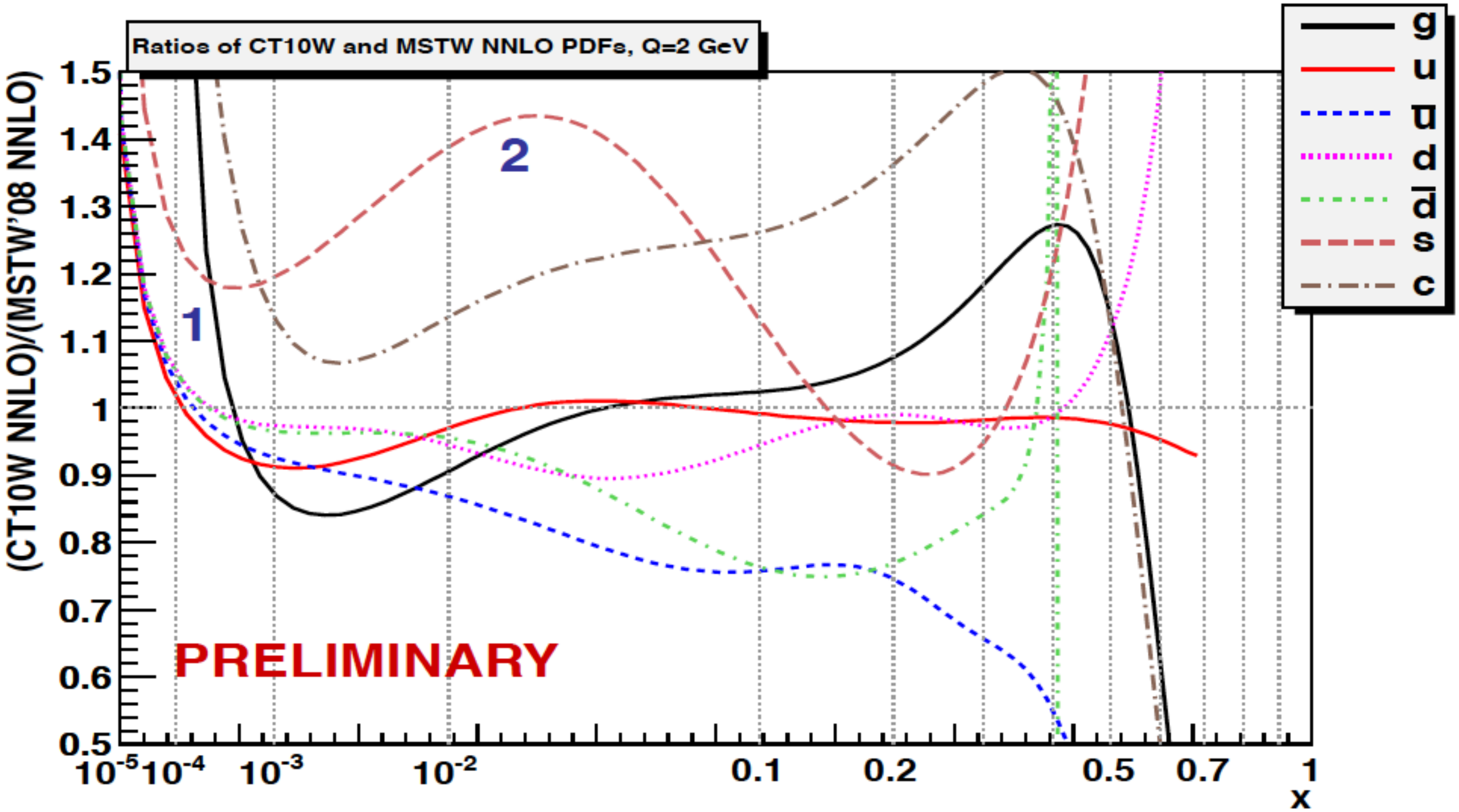
CT10W NNLO central PDFs, as ratios to NLO, Q=2 GeV



1. At $x < 10^{-2}$, $\mathcal{O}(\alpha_s^2)$ evolution suppresses $g(x,Q)$, increases $q(x,Q)$
2. $c(x,Q)$ and $b(x,Q)$ change as a result of the $\mathcal{O}(\alpha_s^2)$ GM VFN scheme
3. At $x > 0.1$, $g(x,Q)$ and $d(x,Q)$ are reduced by revised EW couplings, alternative treatment of correlated systematic errors, scale choices



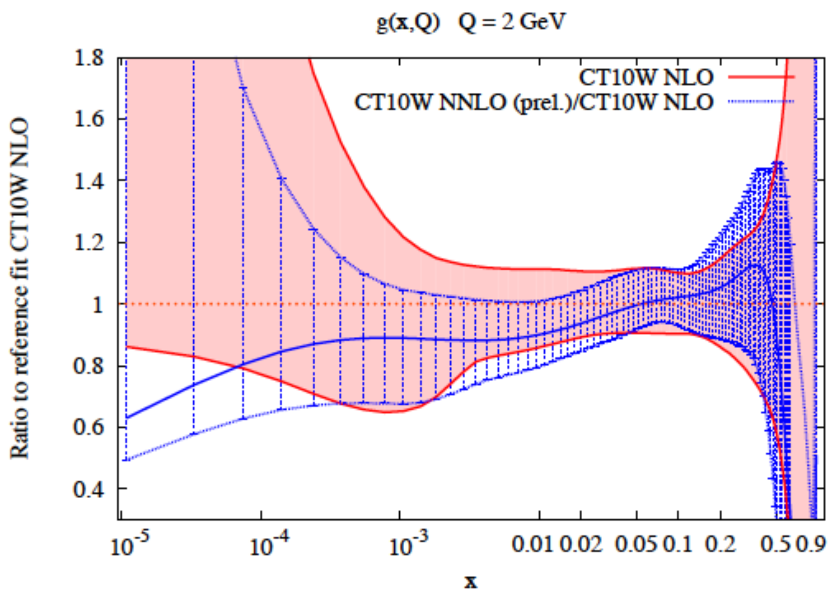
CT10W NNLO compared to MSTW08 NNLO

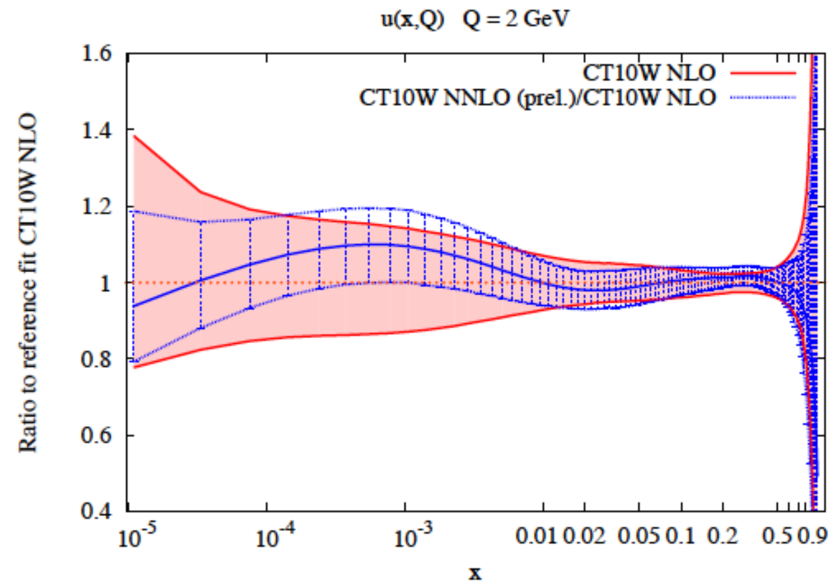


1. CT10 gluon and quarks are harder at $x \to 0$;
$g(x, Q_0) > 0$ at $10^{-5} \leq x \leq 1$

2. The CT10 strange PDF is larger at $x \sim 10^{-3}$

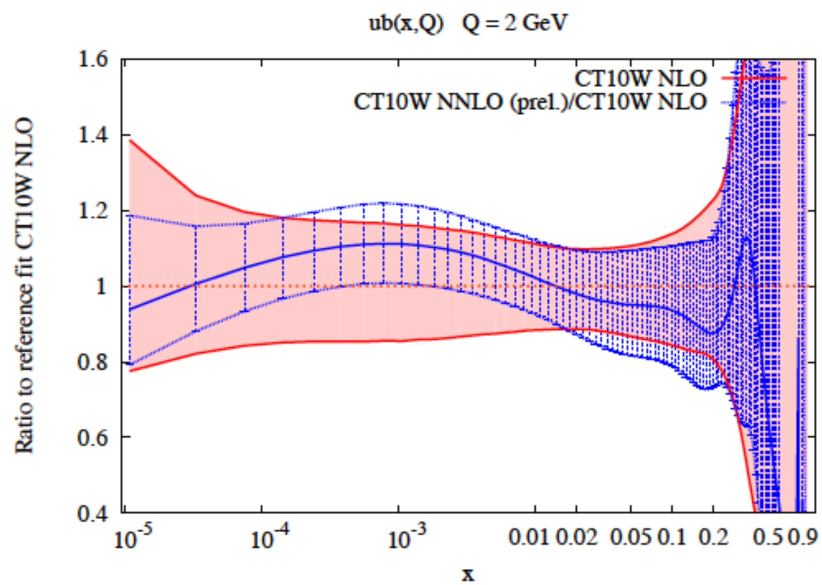
CT10W NNLO vs CT10W NLO (preliminary)





NNLO typically within NLO error bands

NNLO error bands are of similar size (determined primarily by experimental errors)

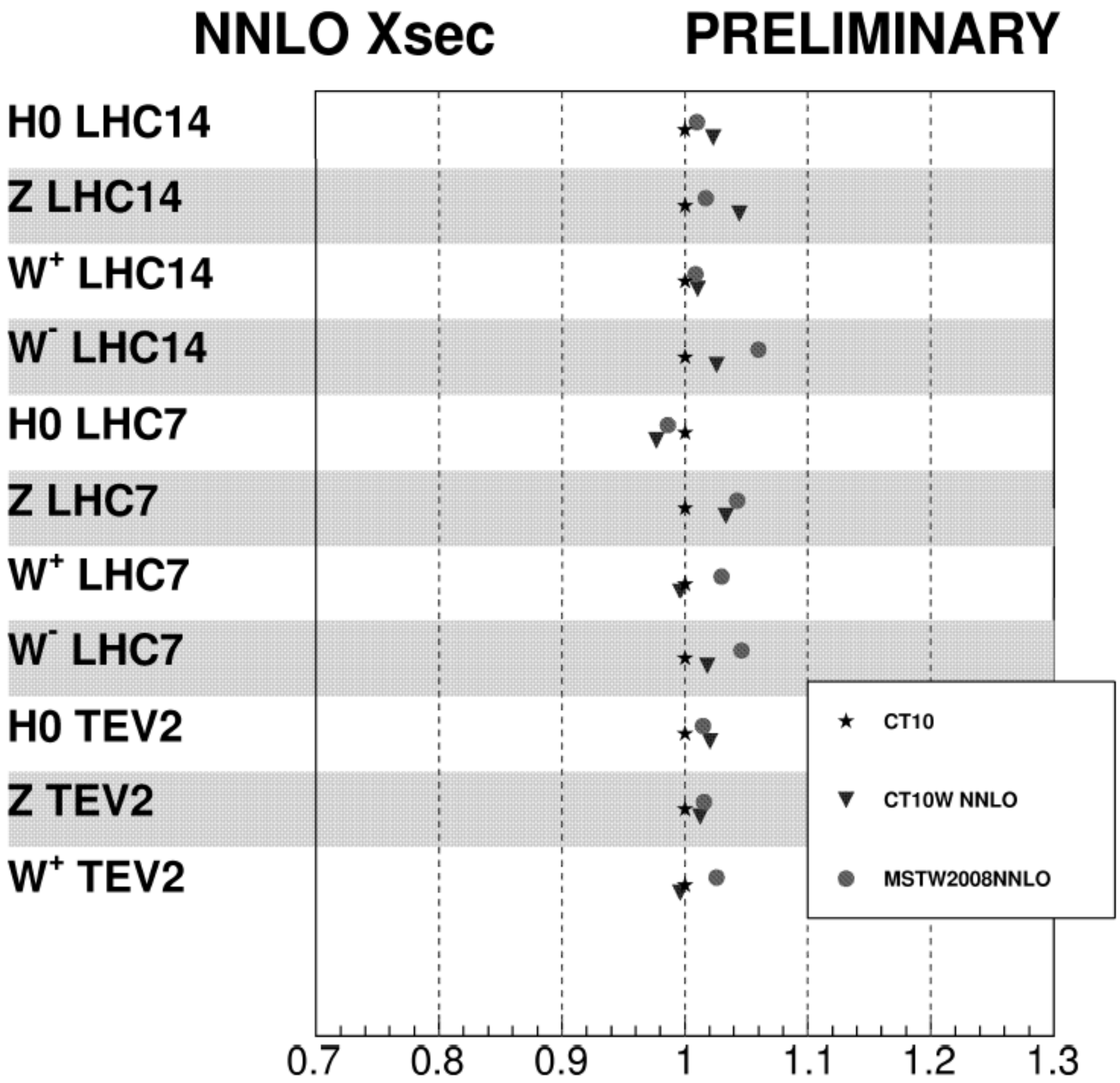


…figures from Marco Guzzi

Some NNLO comparisons

CT10 NLO used
as reference

…figure from Zhao Li



LHC: W, Z cross sections

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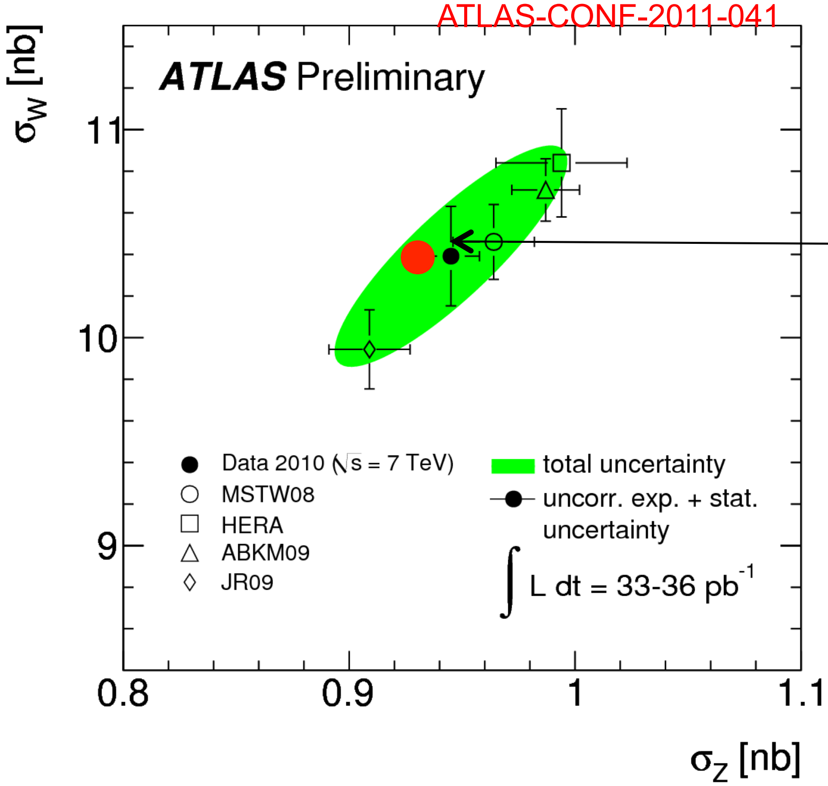
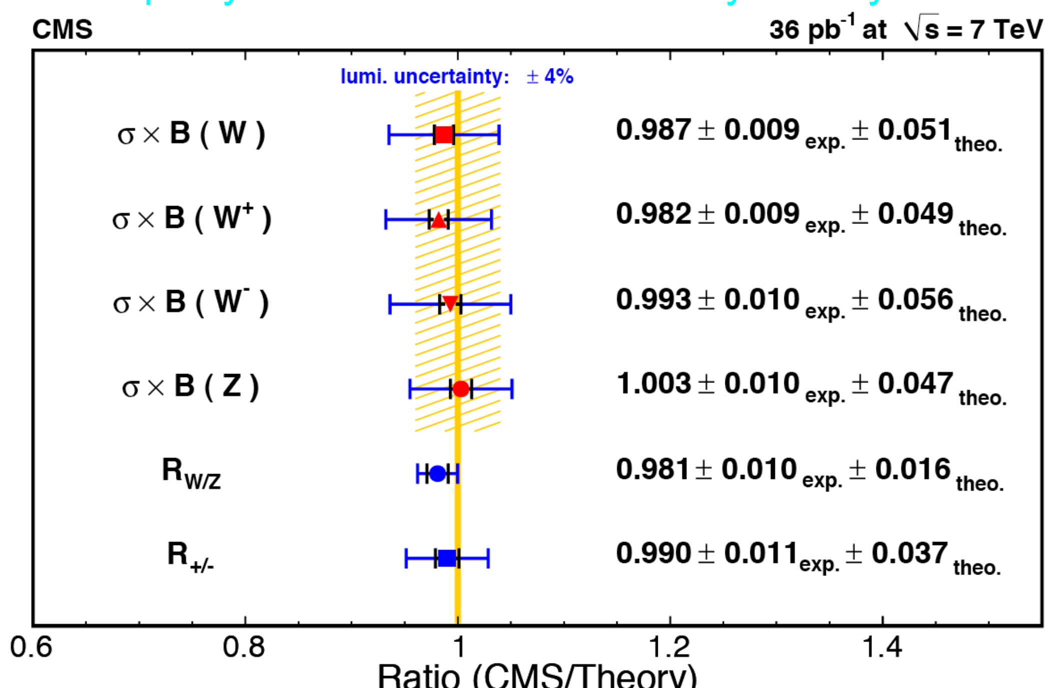


Many of the experimental/theory errors cancel with the ratio

CT10 NNLO prediction

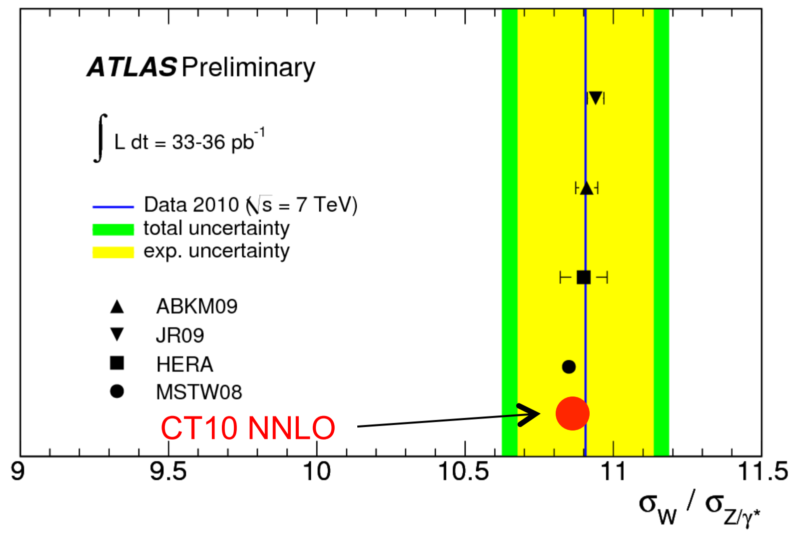
Of course, there is much additional information that will be used in PDF fits, such as the Z rapidity distribution and the W asymmetry.

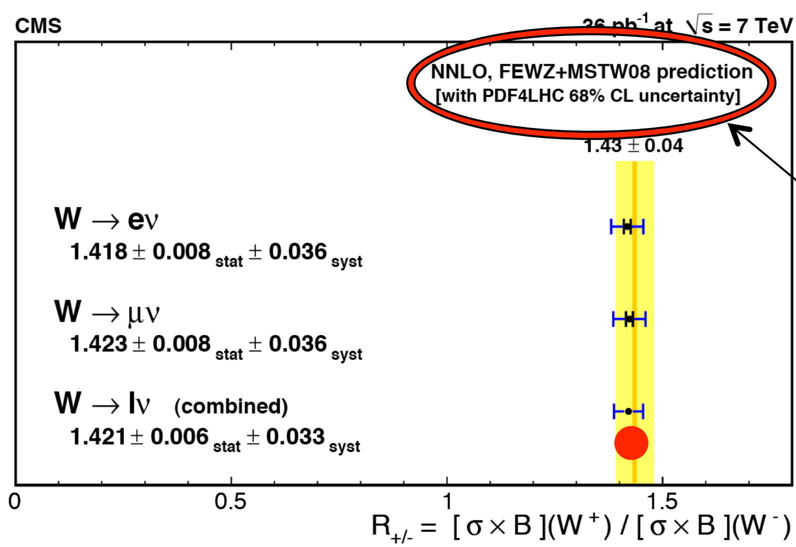
ATLAS W/Z cross section ratio in good agreement with NNLO predictions from the PDF groups shown



PDF4LHC CMS PAS EWK-10-005

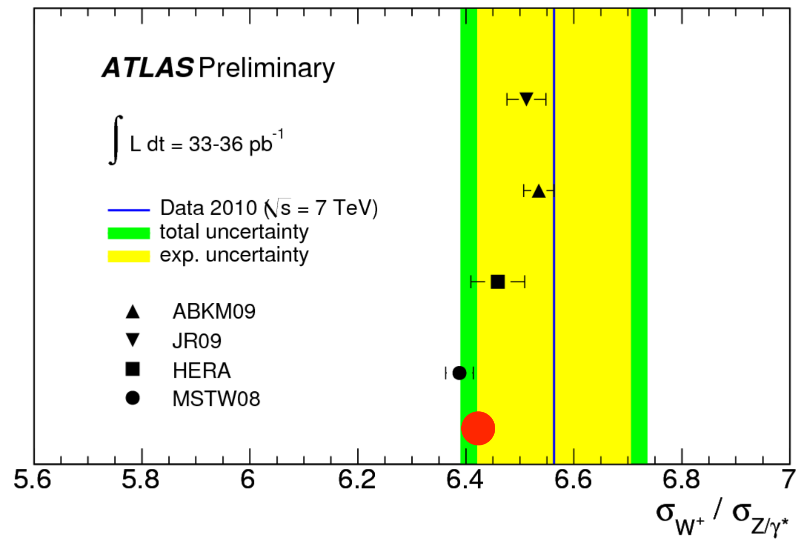
LHC: W/Z ratios

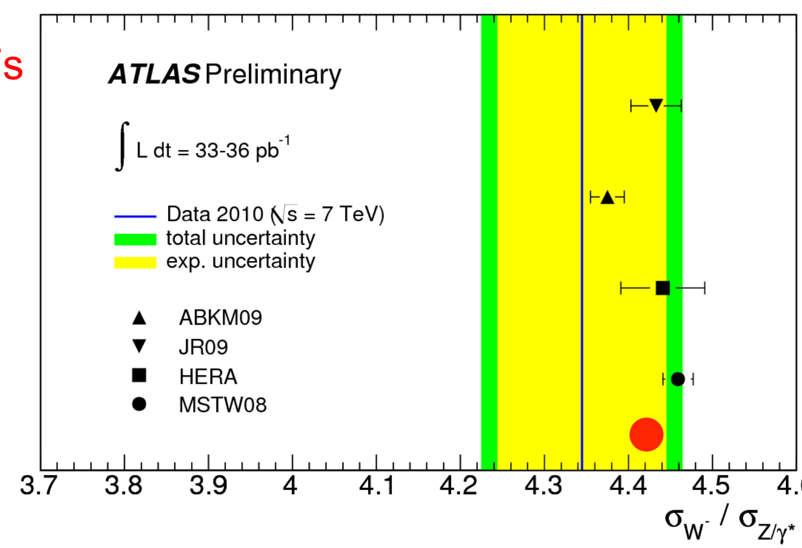




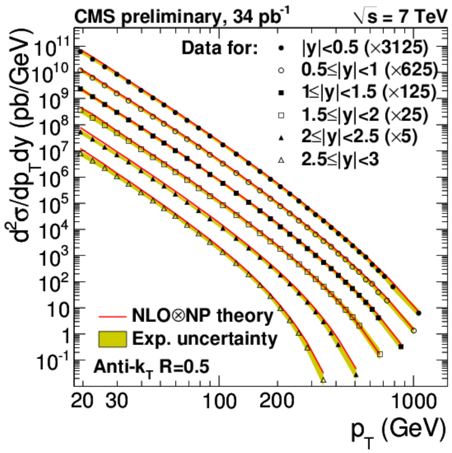
Total W/Z ratio from ATLAS in good agreement with theory, but separate W^+/Z and W^-/Z ratios show some differences (at 1 sigma level) for some of PDFs

CMS results for W,Z use PDF4LHC recipe for NNLO; good agreement with theory





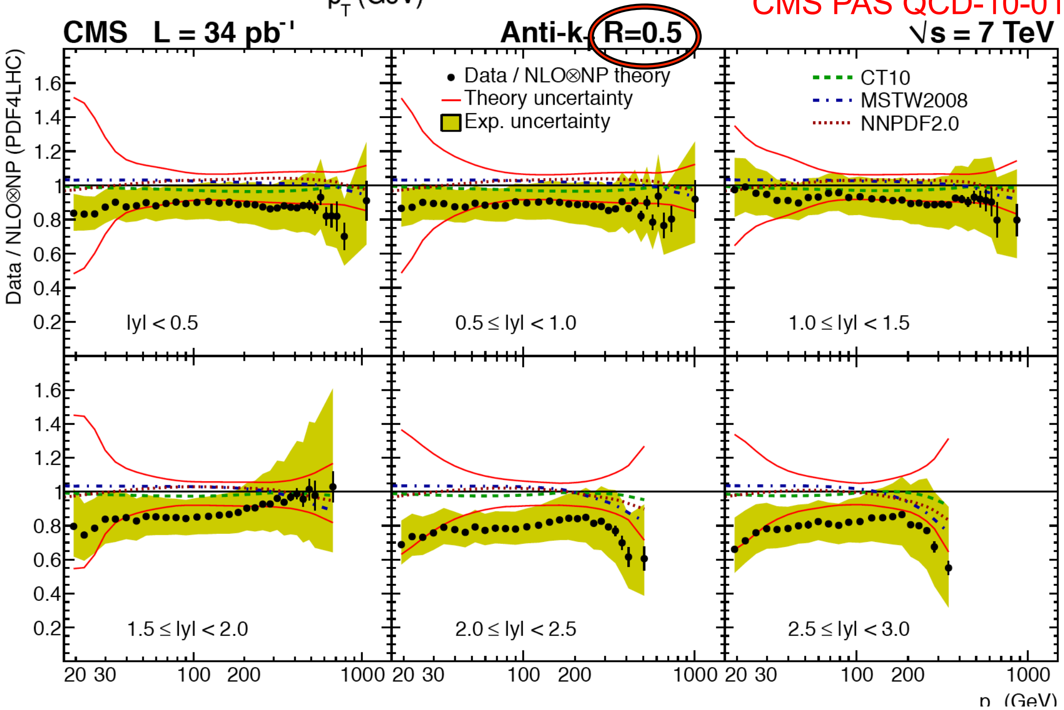
CMS: inclusive jets

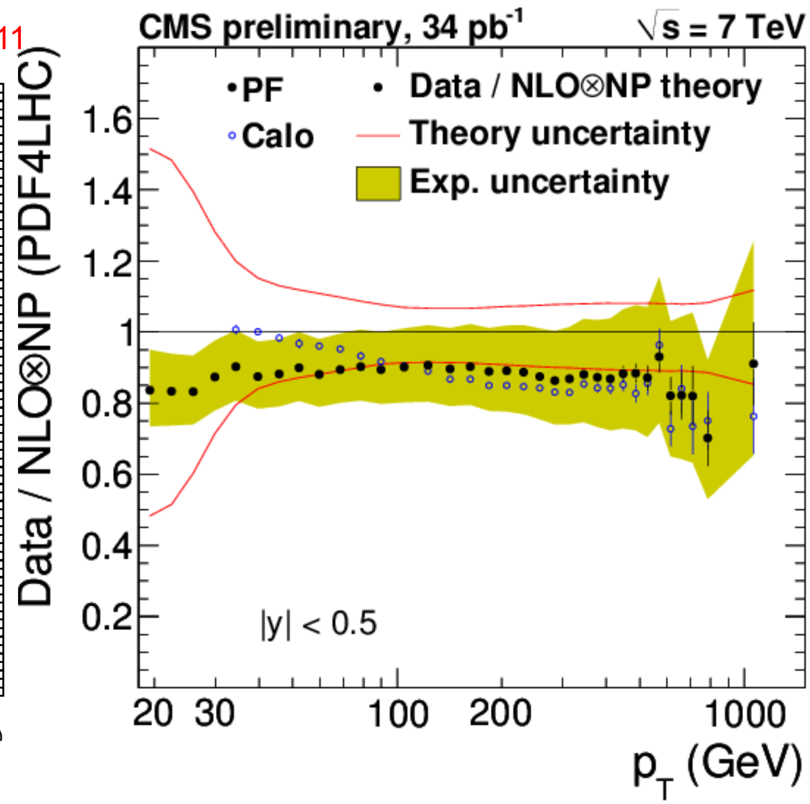


Here the comparison is to predictions using the midpoint of CT10, MSTW2008 and NNPDF2.0, with the error band given by the envelope (i.e. the PDF4LHC prescription). The theory error also includes the scale choice and NP uncertainties.

The physics results are more robust if they can be carried out with two (or more) measurement techniques, in this case a calorimeteric meaurement and one using the Particle Flow method.

CMS PAS QCD-10-011





…agreement but data a bit low compared to theory

ATLAS inclusive jets

- Important to carry predictions out over wide rapidity range. New physics tends to be central. Old physics (PDFs) has an impact on all rapidity regions. This data (or higher statistics version can be fed back into global PDF fits and can/will have impact, especially on high x gluon.

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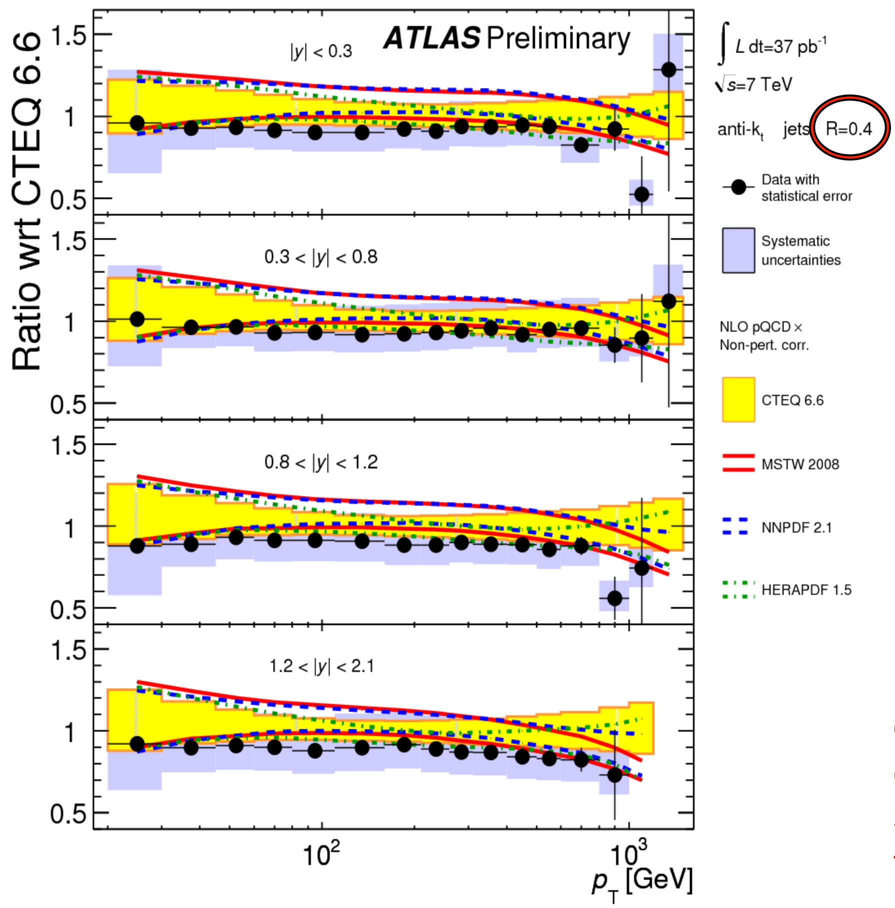
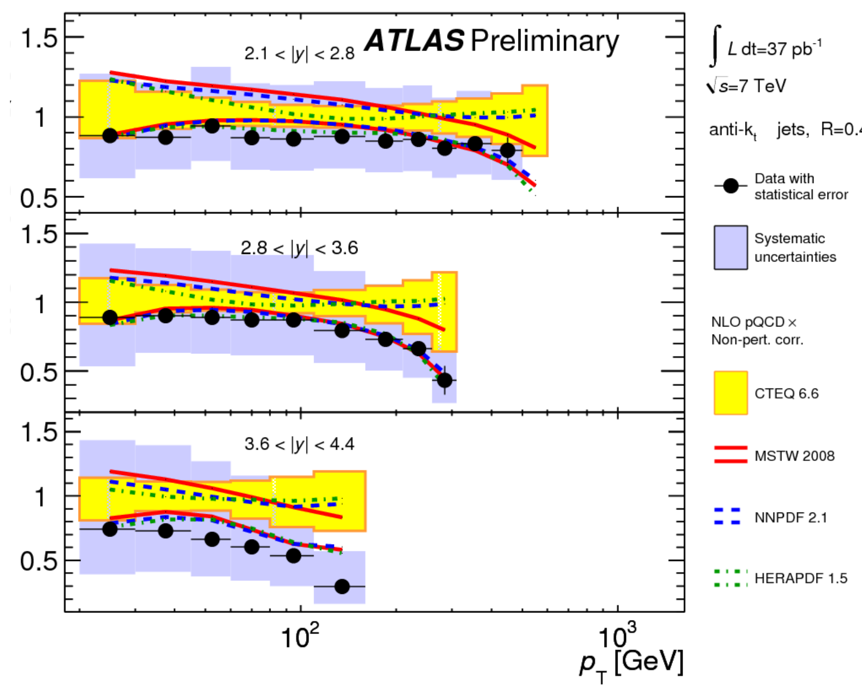
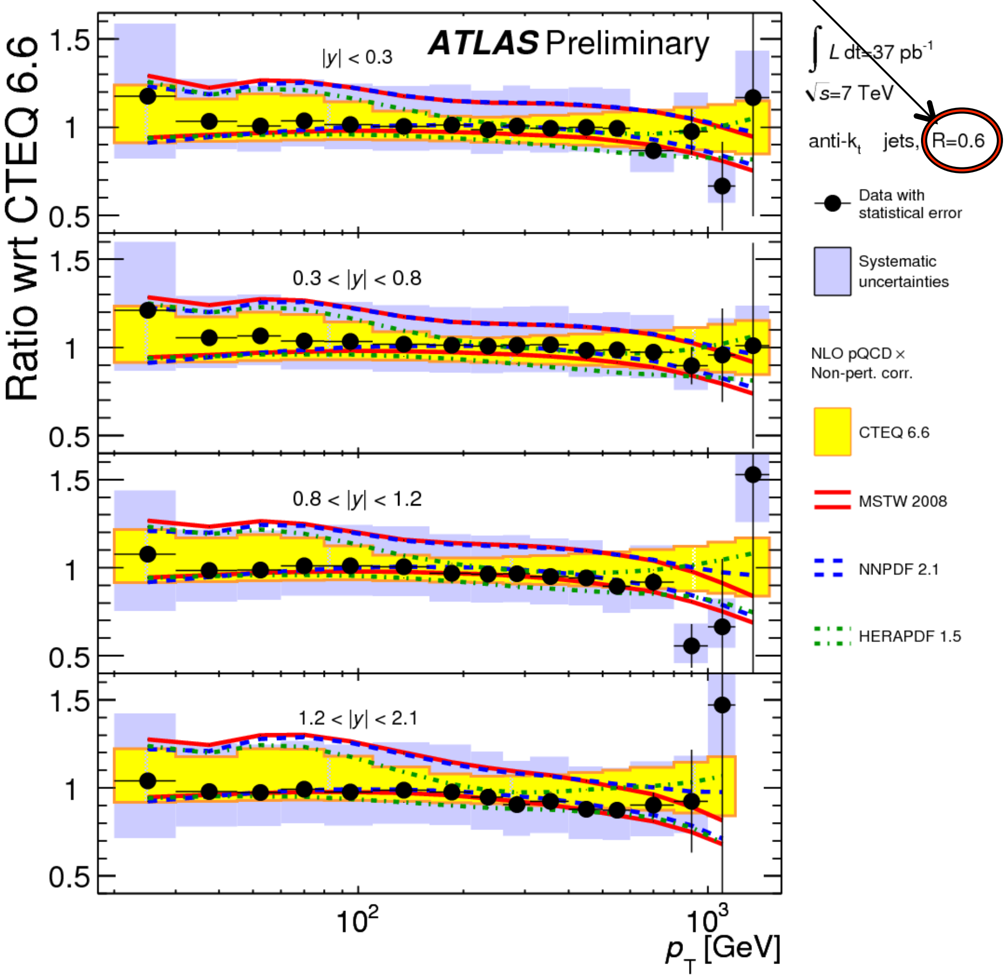


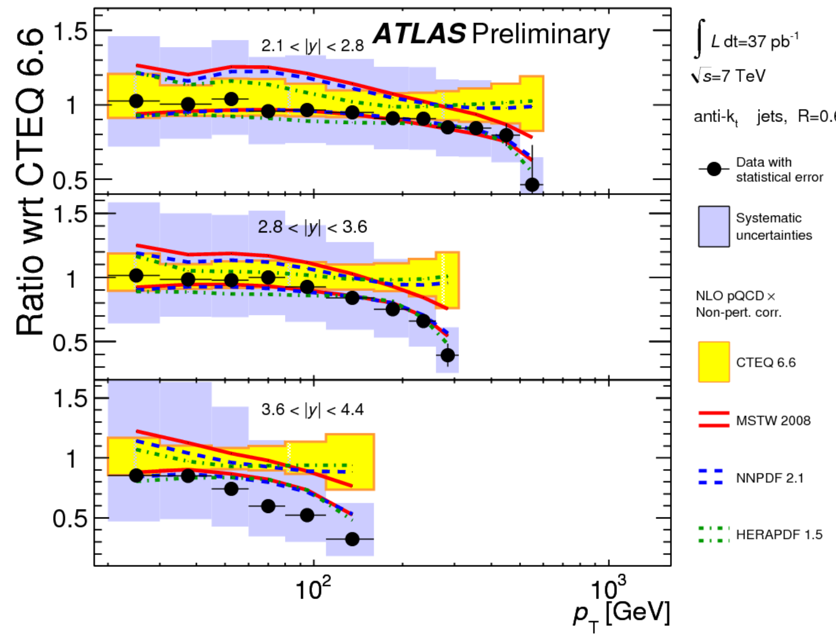


but the use in global PDF fits is possible only once detailed correlated systematic error information is made available. For jets, systematic errors are much more important than statistical errors. This has been done for the ATLAS (but not CMS) 2010 data.

ATLAS: inclusive jets

Important to use more than one jet size. Different dependence on underlying event, fragmentation and also on perturbative prediction.

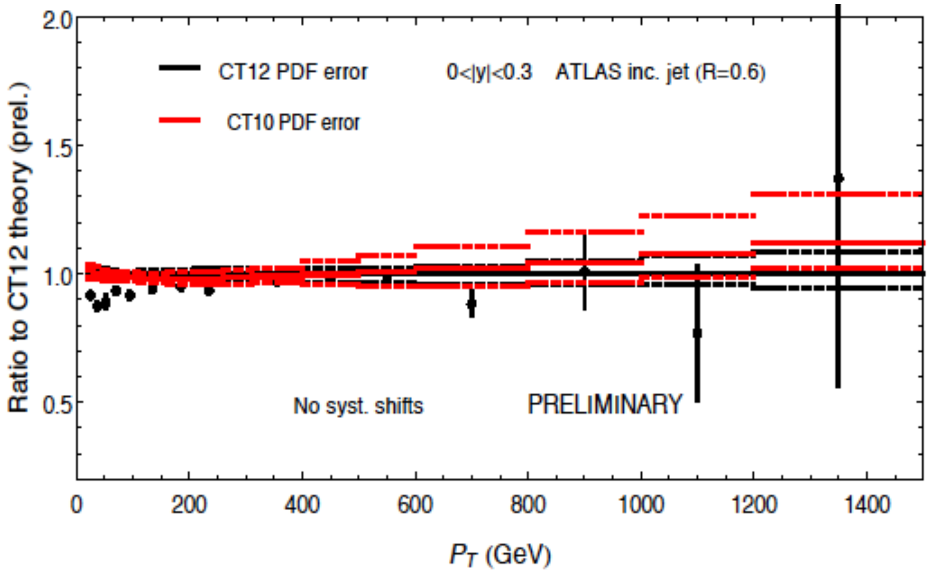


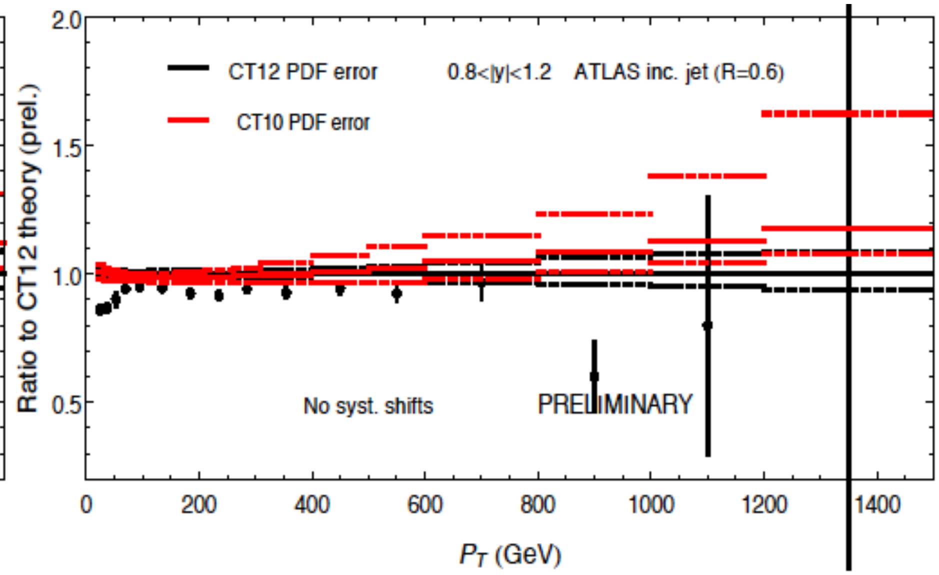


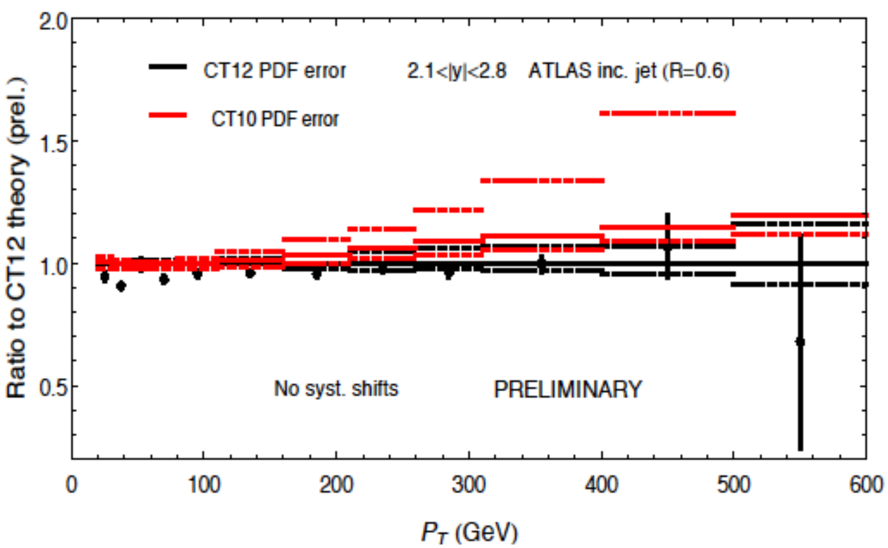
The data tend to fall off faster at high p_T/high y. Is this due just to PDFs or is there other physics also involved?

CT12 NLO predictions for ATLAS jet production (preliminary)

- CT12 NLO PDFs predict smaller jet cross sections at large p_T than CT10





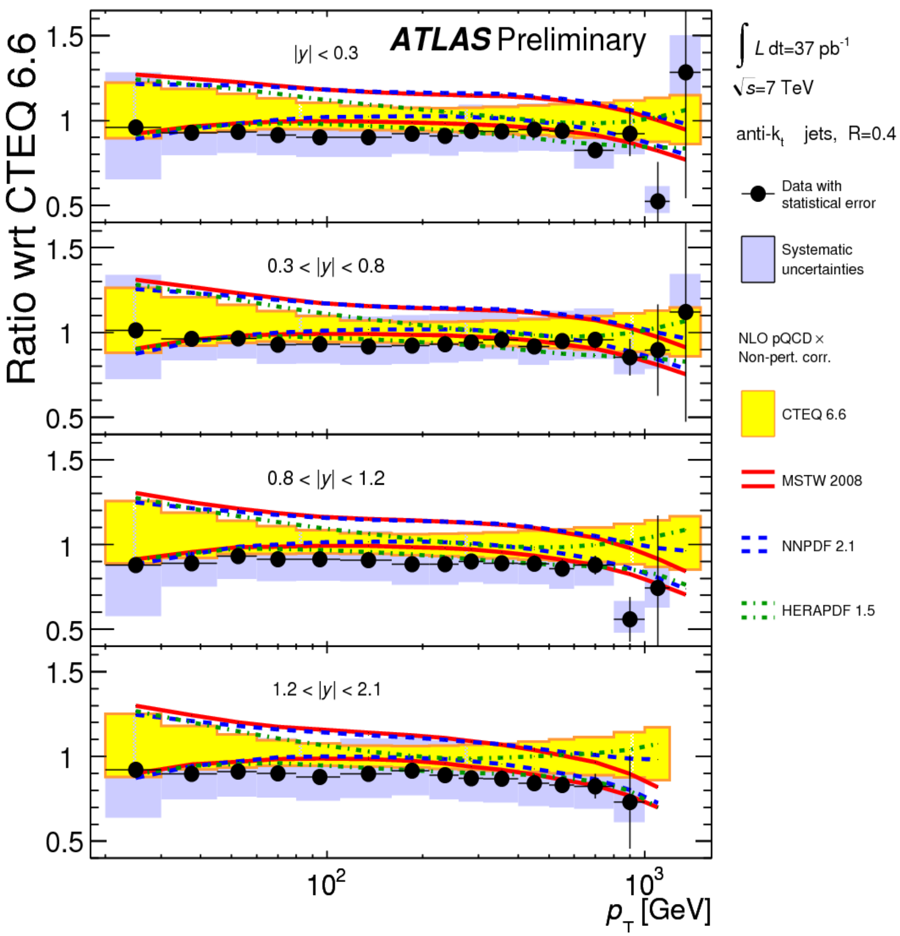


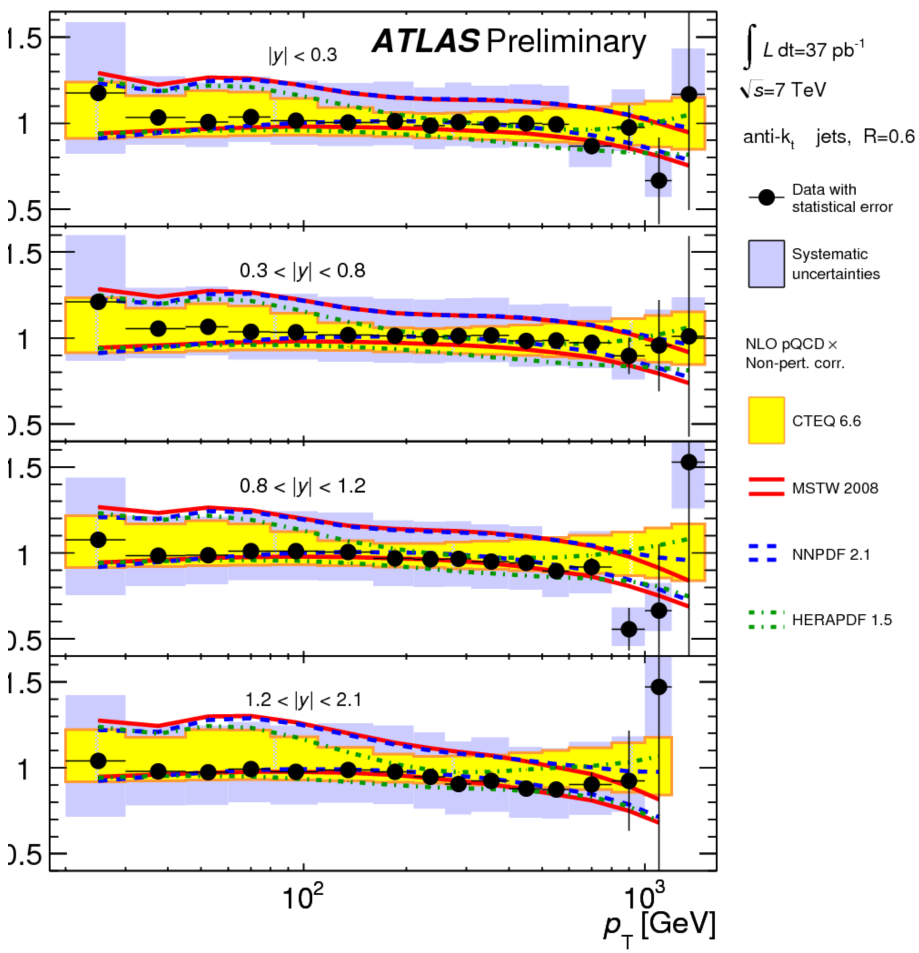
χ^2/dof=0.72 (0.98) for CT12 NLO (CT10 NLO)

…figures from Jun Gao

ATLAS: inclusive jets

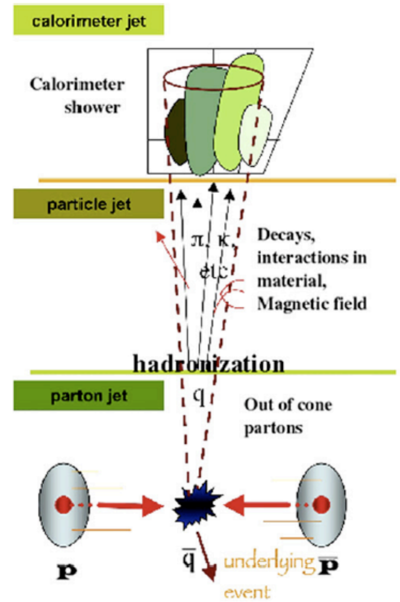
Relative agreement between the data and theory for the two jet sizes reasonable, but not perfect. Do we understand the R-dependence of jet cross sections? Note that correction for UE/hadronization implicitly assumes that NLO=parton shower as far as jet shape properties are concerned. Is that correct to the level we need it? NLO parton shower MC's should be able to tell us



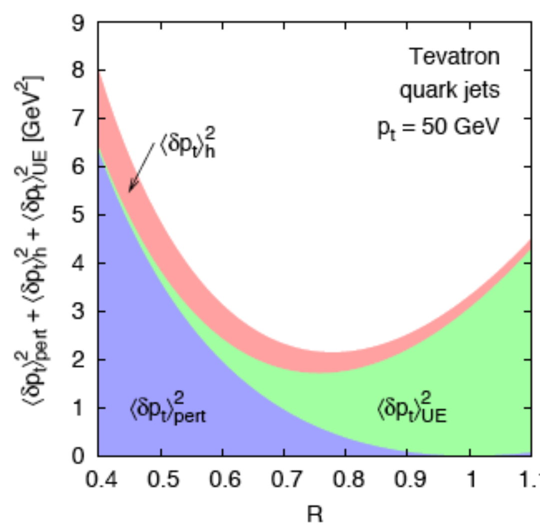


Choosing jet size

- Experimentally
  - in complex final states, such as W + n jets, it is useful to have jet sizes smaller so as to be able to resolve the n jet structure
  - this can also reduce the impact of pileup/underlying event
- Theoretically
  - hadronization effects become larger as R decreases
  - for small R, the ln R perturbative terms can become noticeable
  - this restriction in the gluon phase space can affect the scale dependence, i.e. the scale uncertainty for an n-jet final state can depend on the jet size,



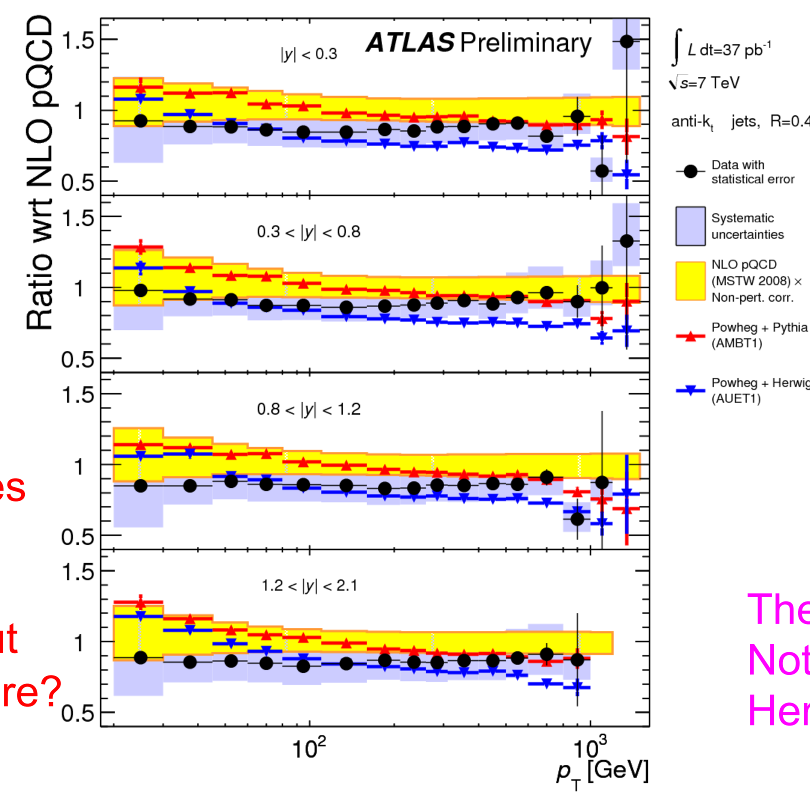
Dasgupta, Magnea, Salam arXiv0712.3014



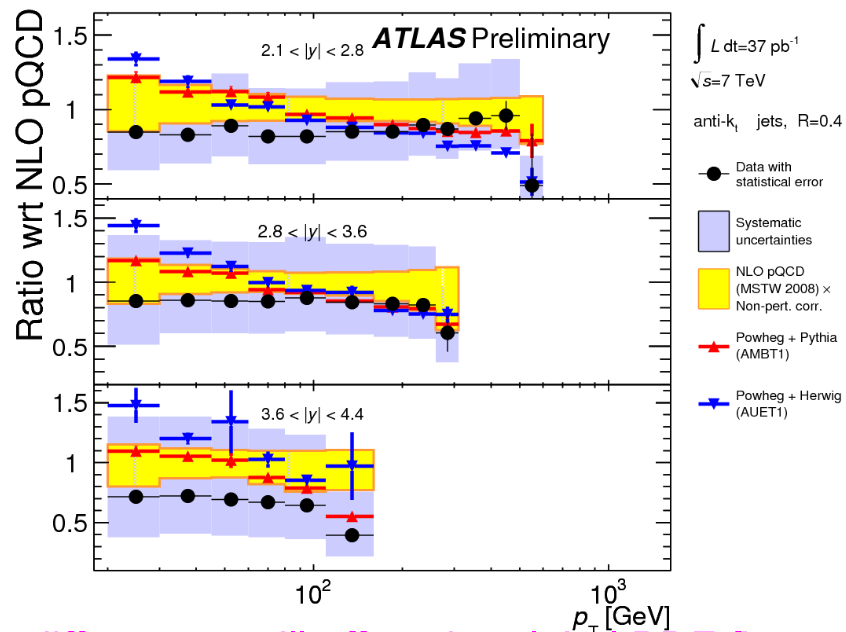
Another motivation for the use of multiple jet algorithms/parameters in LHC analyses.

Inclusive jets: Powheg

- Powheg is a method for the inclusion of NLO matrix element corrections into parton shower Monte Carlos
- Experimentalists were ecstatic when inclusive jet production was added
- Note that Powheg predictions have a different shape than fixed order perturbative predictions (NLOJET++). This is something that must be understood, and investigation is currently underway by Powheg authors.
- Also: dijets in aMC@NLO->S. Frixione



expect differences at low p_T, kinematic edges, but everywhere?



These differences will affect the global PDF fits. Note also differences between Pythia and Herwig showering.

Now to scale dependence

- Write cross section indicating explicit scale-dependent terms
- First term (lowest order) in (3) leads to monotonically decreasing behavior as scale increases (the LO piece)
- Second term is negative for $\mu<p_T$, positive for $\mu>p_T$
- Third term is negative for factorization scale $M < p_T$
- Fourth term has same dependence as lowest order term
- Thus, lines one and four give contributions which decrease monotonically with increasing scale while lines two and three start out negative, reach zero when the scales are equal to p_T, and are positive for larger scales
- At NLO, result is a roughly parabolic behavior (if you're lucky)
- Note that each of these terms depends on the kinematics of the cross section under investigation

Consider a large transverse momentum process such as the single jet inclusive cross section involving only massless partons. Furthermore, in order to simplify the notation, suppose that the transverse momentum is sufficiently large that only the quark distributions need be considered. In the following, a sum over quark flavors is implied. Schematically, one can write the lowest order cross section as

$$E\frac{d^3\sigma}{dp^3} \equiv \sigma = a^2(\mu)\,\hat{\sigma}_B \otimes q(M) \otimes q(M) \tag{1}$$

where $a(\mu) = \alpha_s(\mu)/2\pi$ and the lowest order parton-parton scattering cross section is denoted by $\hat{\sigma}_B$. The renormalization and factorization scales are denoted by μ *and* M, respectively. In addition, various overall factors have been absorbed into the definition of $\hat{\sigma}_B$. The symbol $\otimes$ denotes a convolution defined as

$$f \otimes g = \int_x^1 \frac{dy}{y}\, f(\frac{x}{y})\, g(y). \tag{2}$$

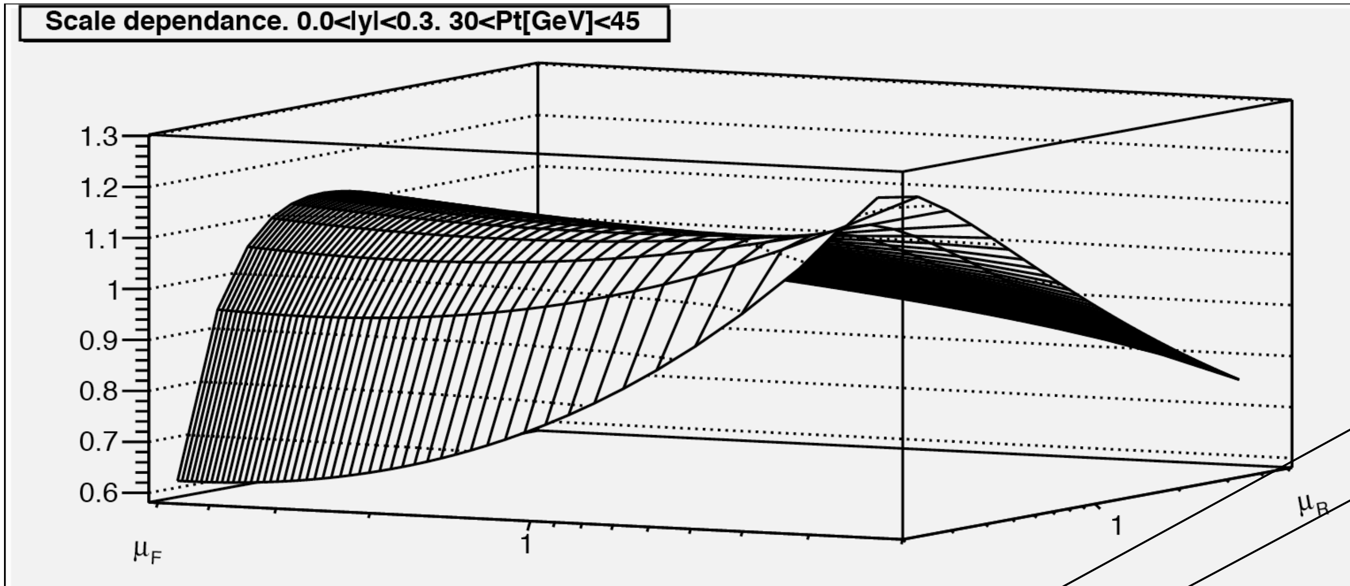
When one calculates the $\mathcal{O}(\alpha_s^3)$ contributions to the inclusive cross section, the result can be written as

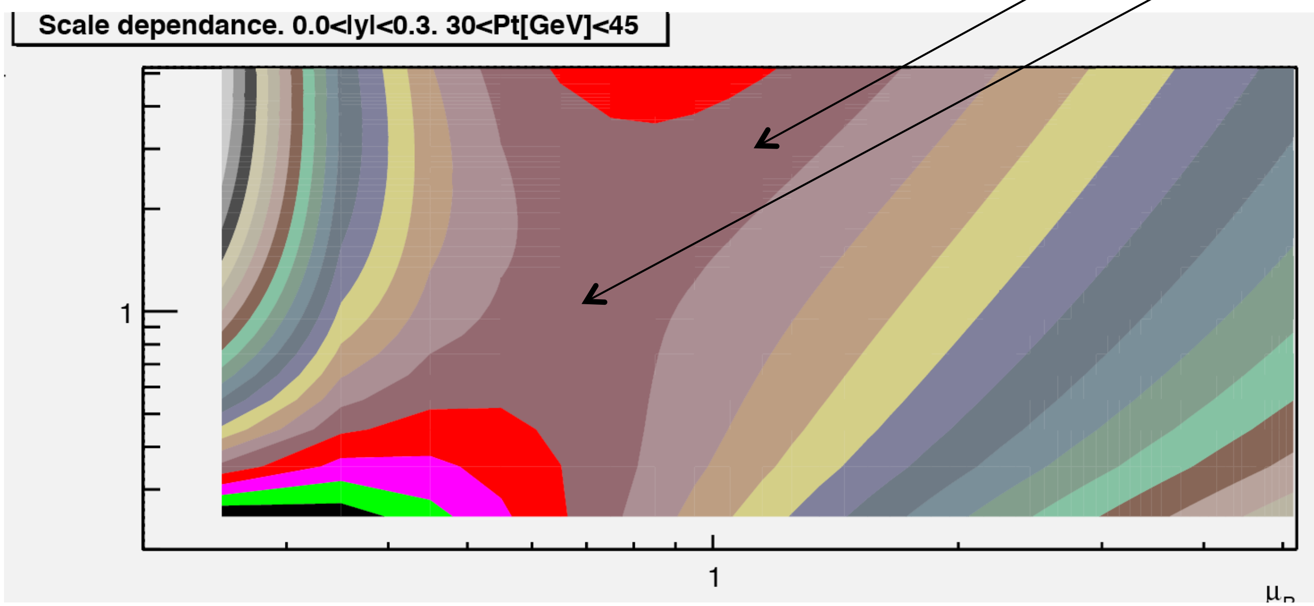
$$\begin{aligned}
&(1) \quad \sigma = a^2(\mu)\,\hat{\sigma}_B \otimes q(M) \otimes q(M)\\
&(2) \quad + 2a^3(\mu)\, b \ln(\mu/p_T)\hat{\sigma}_B \otimes q(M) \otimes q(M)\\
&(3) \quad + 2a^3(\mu)\, \ln(p_T/M) P_{qq} \otimes \hat{\sigma}_B \otimes q(M) \otimes q(M)\\
&(4) \quad + a^3(\mu)\, K \otimes q(M) \otimes q(M).
\end{aligned} \tag{3}$$

In writing Eq. (3), specific logarithms associated with the running coupling and the scale dependence of the parton distributions have been explicitly displayed; the remaining higher order corrections have been collected in the function K in the last line of Eq. (3). The μ

from CHS

It’s useful to use a log-log scale



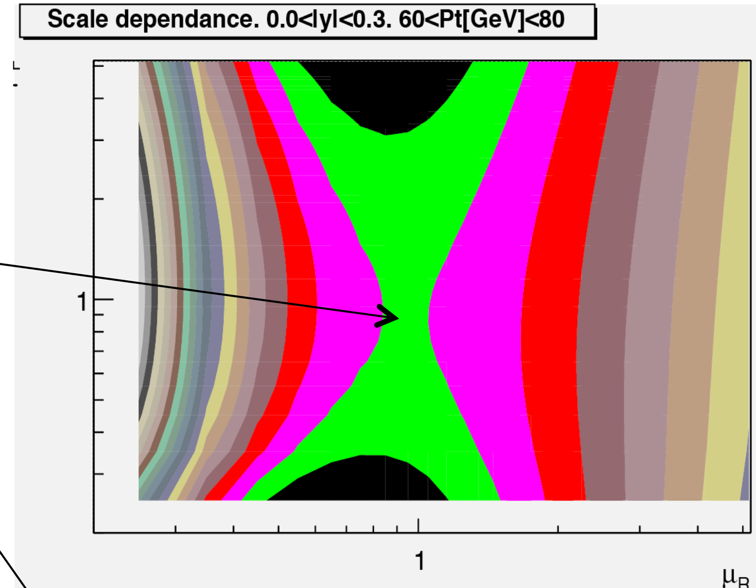


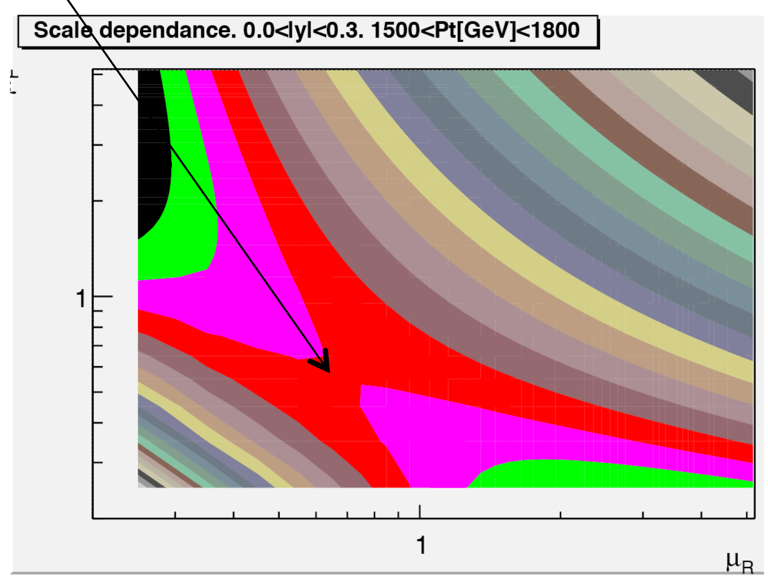
- …since perturbative QCD is logarithmic
- Note that there’s a saddle region, and a saddle point, where locally there is no slope for the cross section with respect to the two scales
- This is kind of the ‘golden point’ and typically around the expected scale (p_T^{jet} in this case)

Scale choices

- Take inclusive jet production at the LHC
- Canonical scale choice at the LHC is $\mu_r=\mu_f=1.0*p_T$
  - CDF used $0.5p_T$
  - CTEQ6.6/CT10 used this scale for determination of PDFs
  - new CT PDFs use p_T
- Close to saddle point for low p_T
- But saddle point moves down for higher p_T (and the saddle region rotates)
- Our typical scale choices don't work for all LHC kinematics; more extreme movements for some of measured cross sections
- Rather than look for some magic formula, we should try to understand what is going on the kinematic/scale point-of-view

R=0.4
antikT





Scale dependence also depends on jet size

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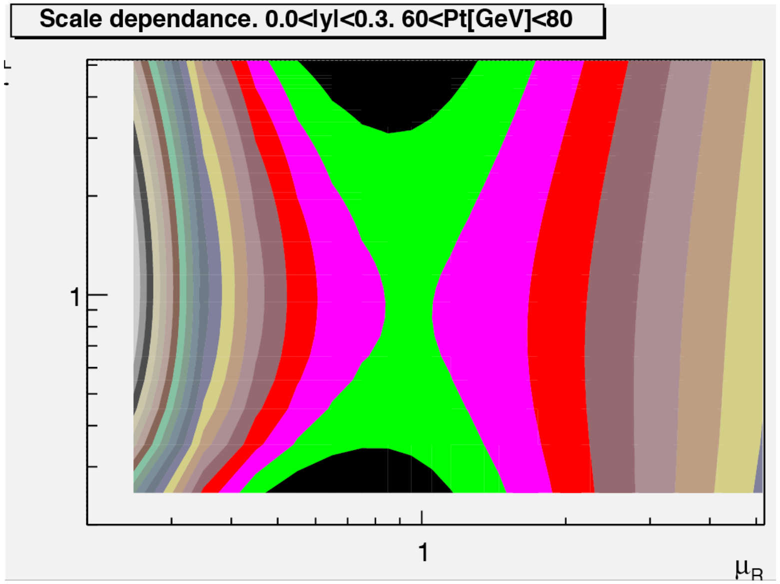
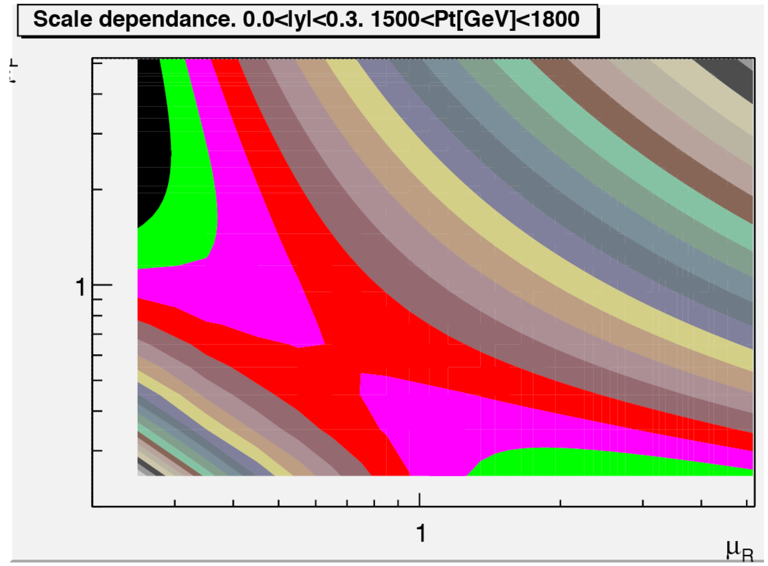
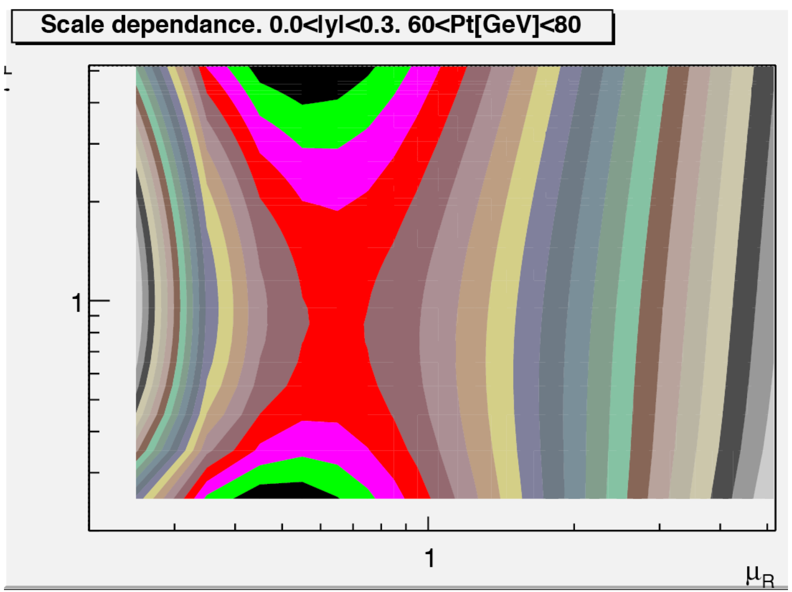
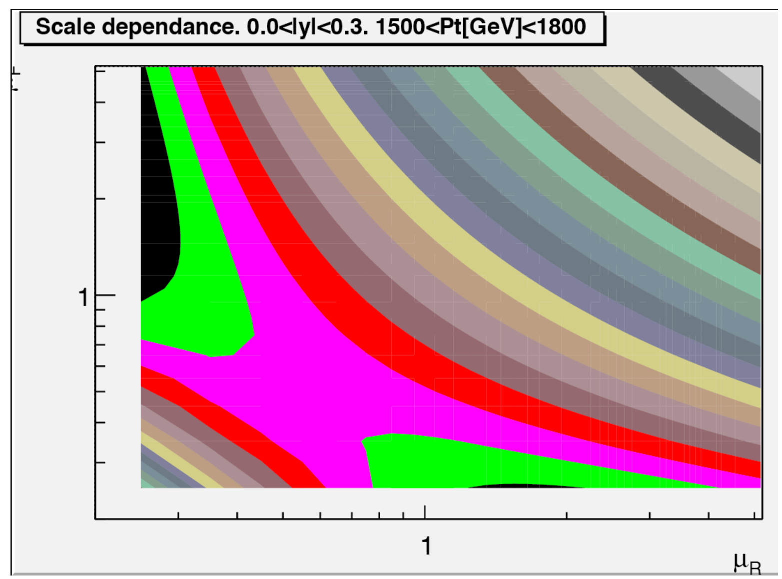
antikT





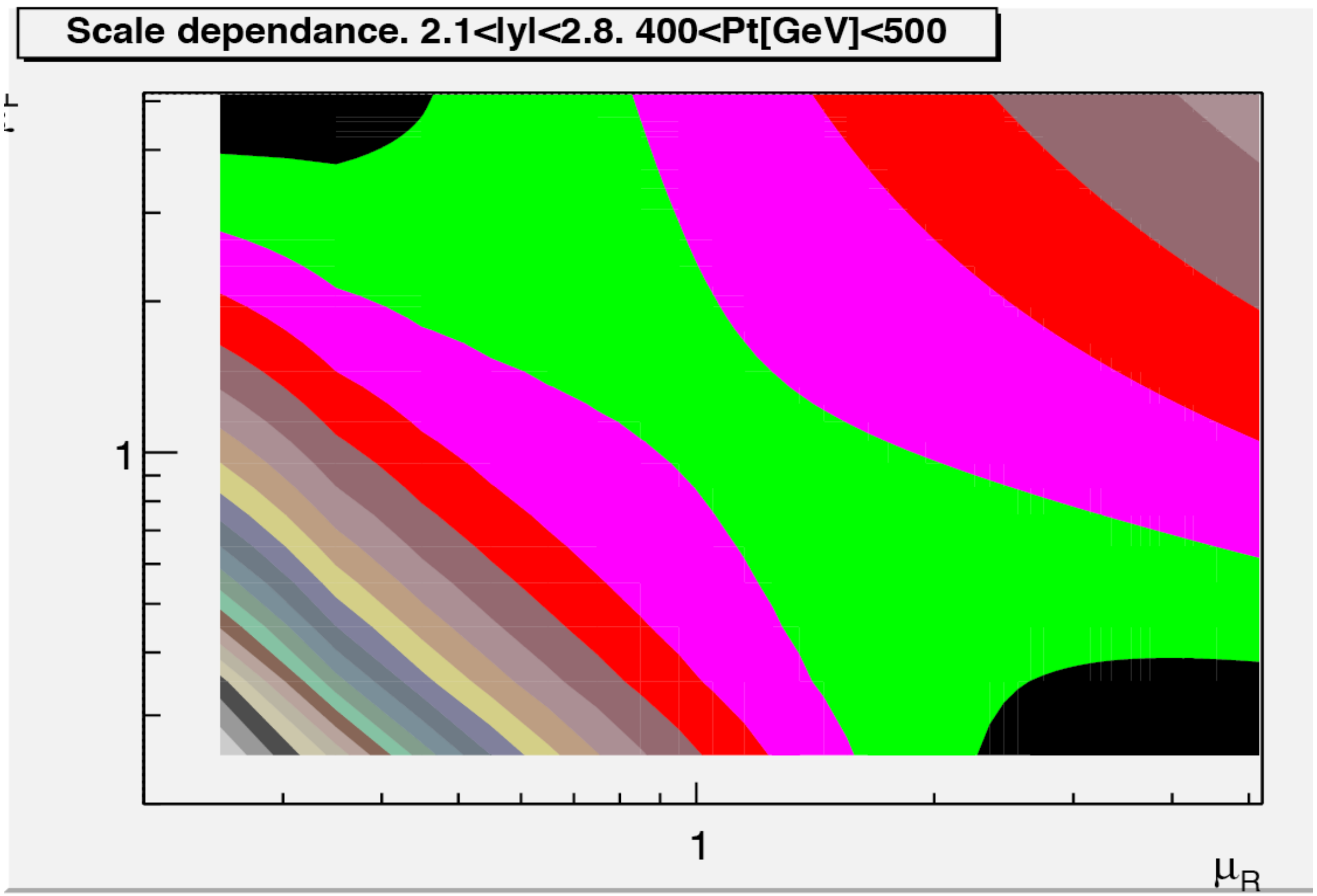
R=0.6
antikT





Scale dependence depends on rapidity

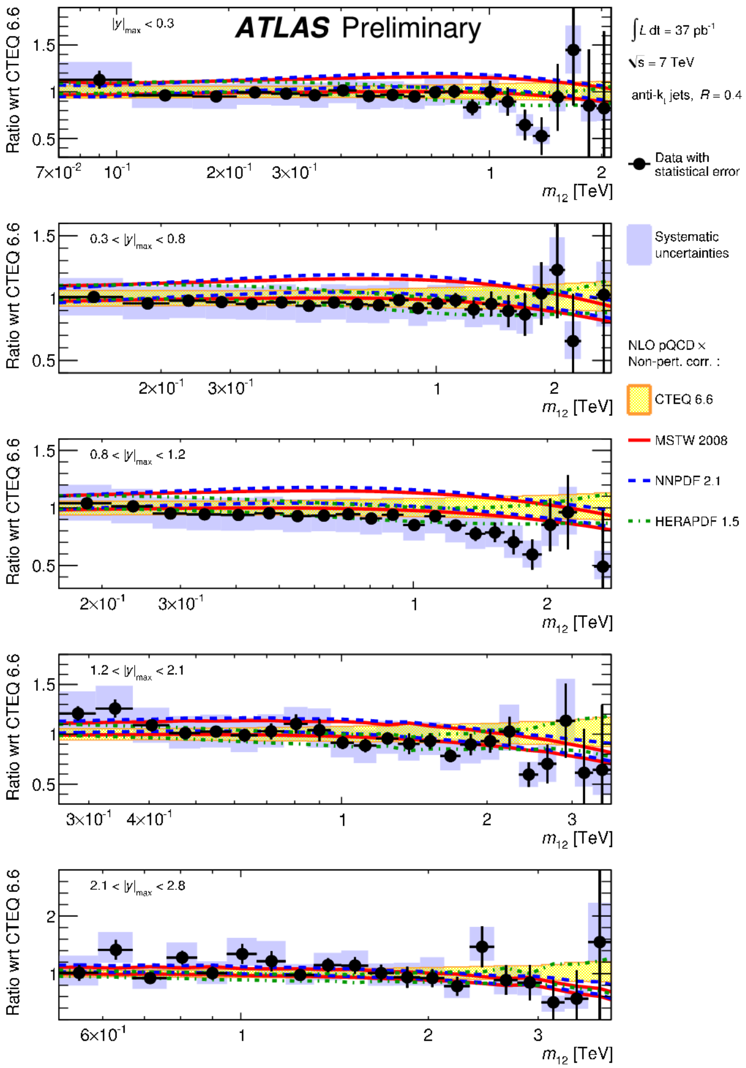
- The saddle point tends to move upwards in scale as the rapidity increases
- Is the physics changing; no, just the kinematics



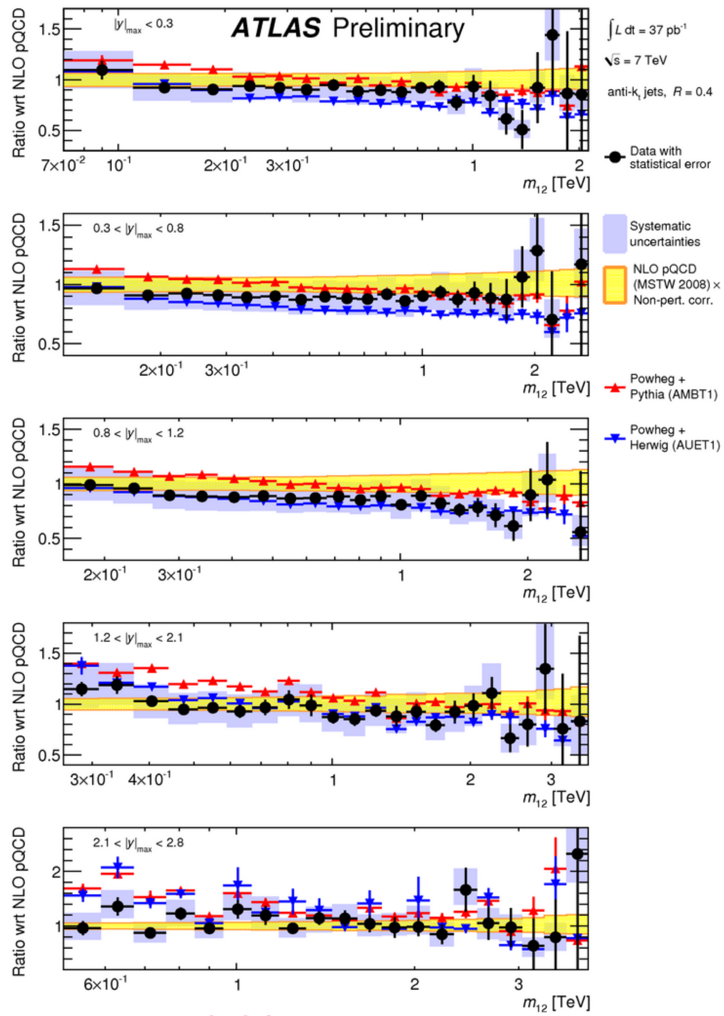
ATLAS: dijets

Plot the dijet cross section as a function of $|y_{max}|$.

NLOJET++



Powheg

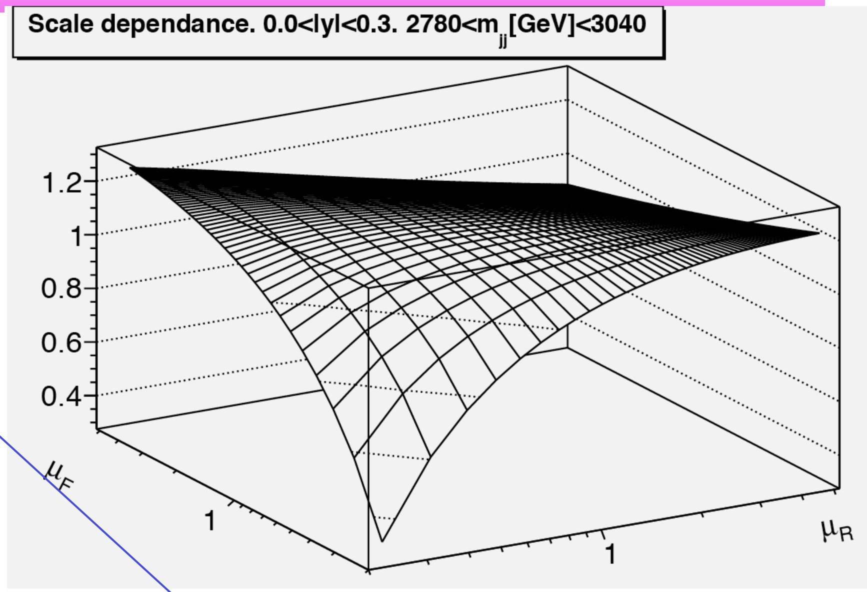


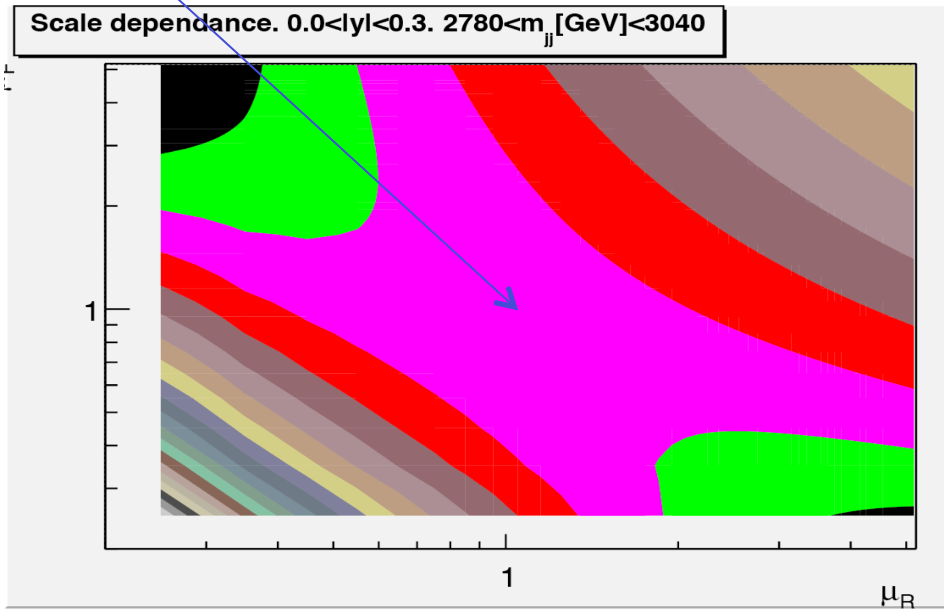
ATLAS-CONF-2011-047

Again, as for inclusive jet production, we see that there are some shape differences between fixed order and Powheg that need to be understood, especially in the forward region. If Powheg is right, our PDFs are wrong.

Now look at the dijet mass cross section

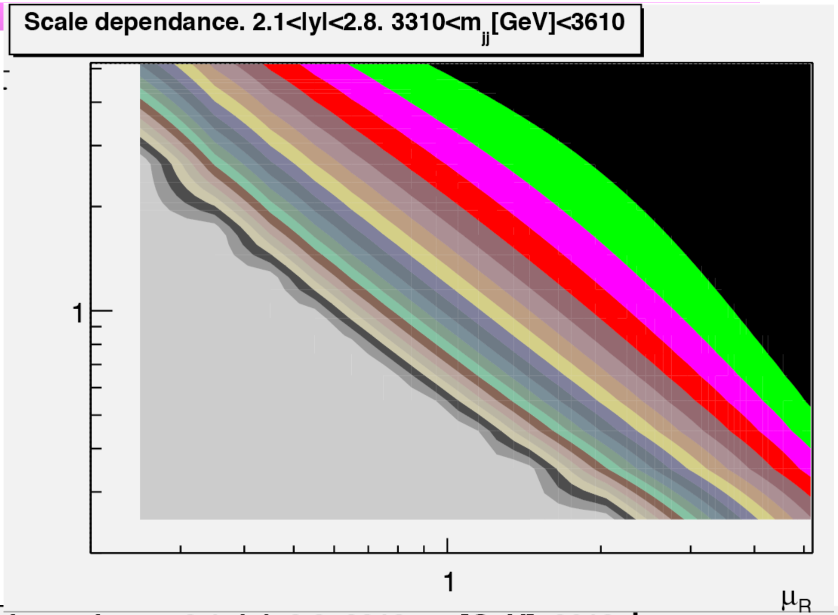
- In most cases, get a nice saddle region around p_T^{jet}

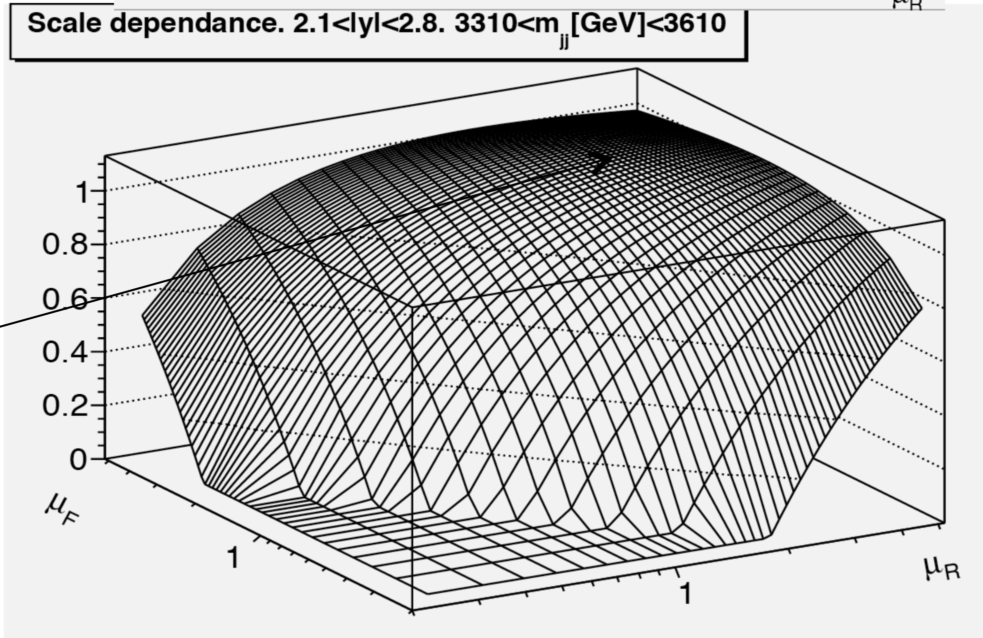




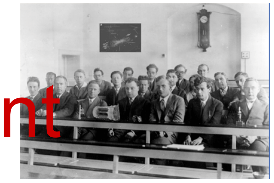
…but not for forward rapidities

- Is perturbation theory not valid here?
- It's ok as long as *reasonable scales* are chosen
- It's a continuation of the effect that we've been looking at
- To be on the plateau requires scales of the order of 3-4*p_T
- Our 'motivated' scale, though, is p_T
  - in this case, I would argue that kinematics forces us to change
  - ok, here's the bizarre thing; this plateau cross section agrees with the data (great!) and with the Powheg cross section generated with a scale of p_T^{jet} (huh?)





…and now for something completely different



electroweak effects may be important at the LHC

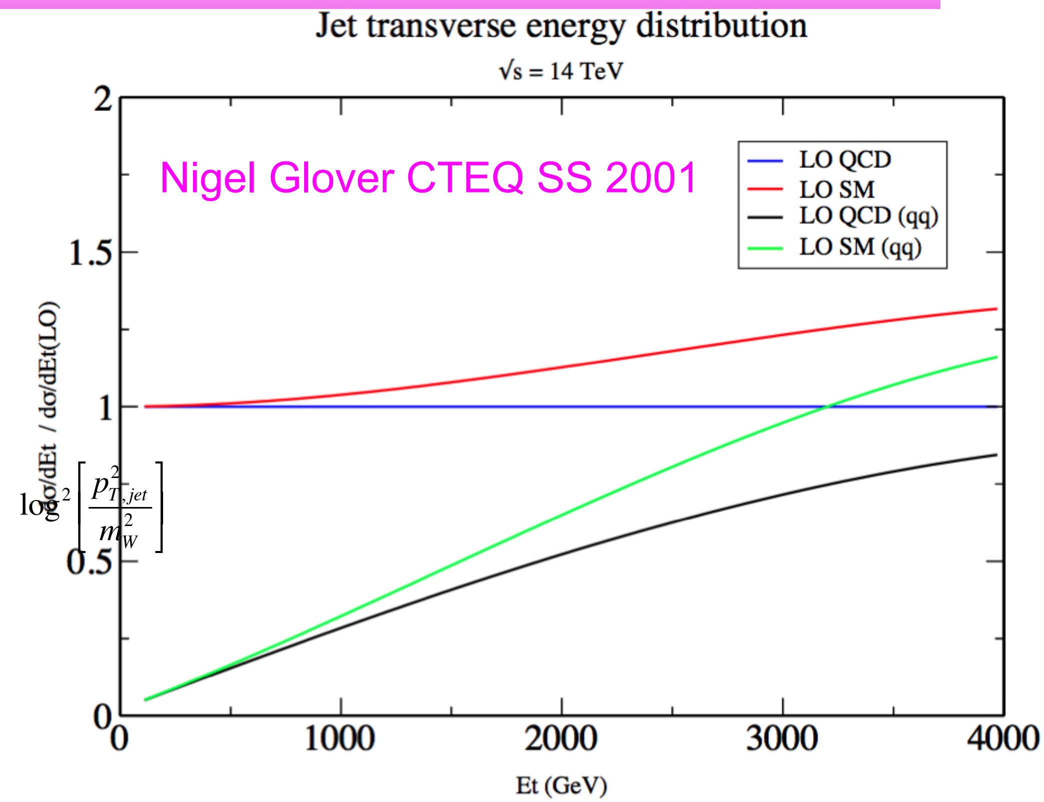
$\alpha_s > \alpha_W$ but α_W runs more slowly than does α_s

…in addition, and more importantly, there are EWK Sudakov logs that become important in the TeV range (that Nigel didn't take into account)

$$\log^2\left[\frac{\mu^2}{m_W^2}\right]$$

where μ is scale typical of the process

due to a lack of cancellation between virtual and real W emission



Will see same sort of rise over QCD as jet energy increases.

Due to new physics? or old physics?

In fact it is Standard Model $\mathcal{O}(\alpha_s \alpha_w)$ contributions to qq scattering processes - interference of t-channel Z exchange with u-channel gluon exchange.

Moretti, Nolten and Ross: hep/ph/0606201

- These Sudakov logs are important
  - negative contribution to cross section
  - real radiation (of W/Z's) gives a positive contribution
- Typically, real radiation terms contribute (positively) much less than NLO weak virtual terms (Sudakov FFs) contribute, so there's a very incomplete cancellation
- For 2 TeV/c jets, total effect on inclusive jet cross section is more like 20%
- This size of effect can't be ignored for precision comparisons and for inclusion of high p_T jet data in global PDF fits
- and in searches for new physics

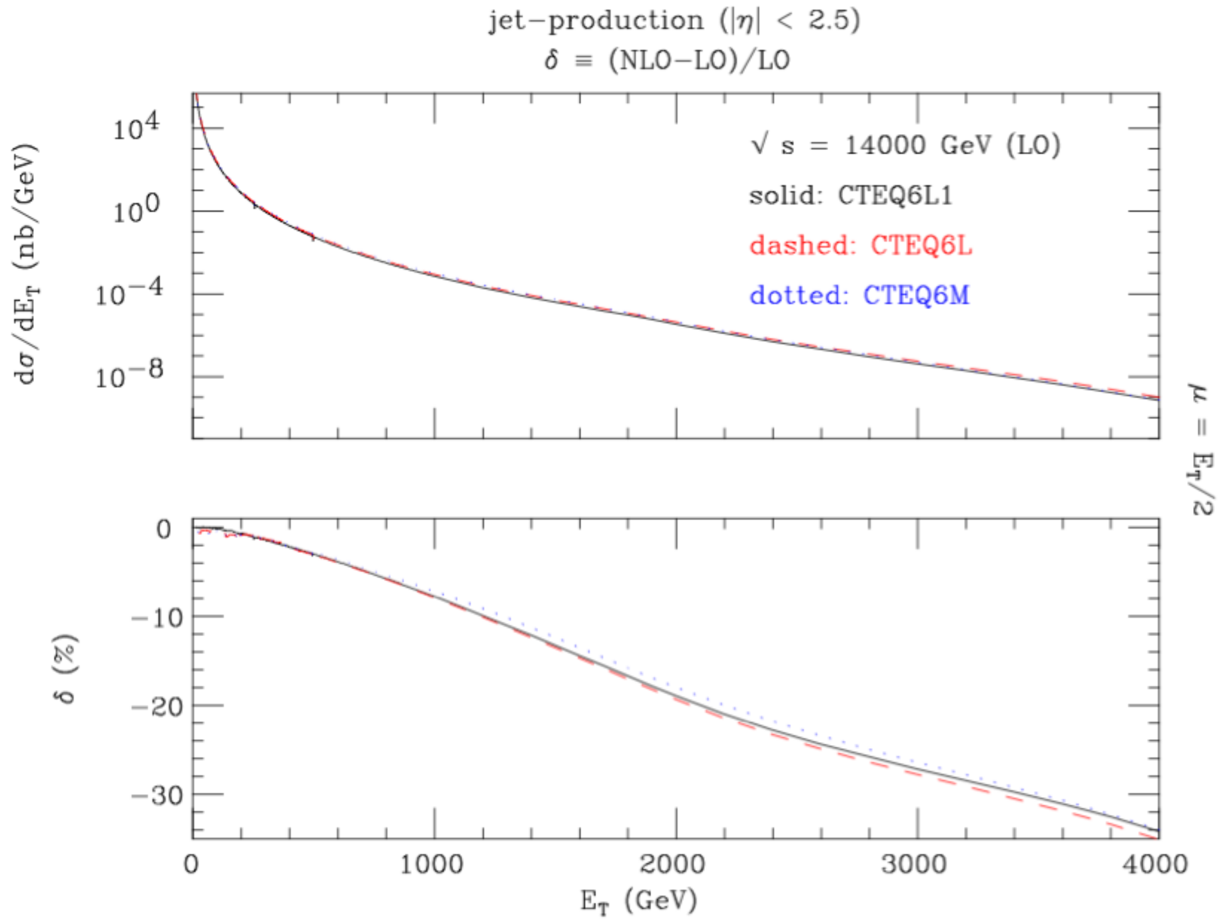
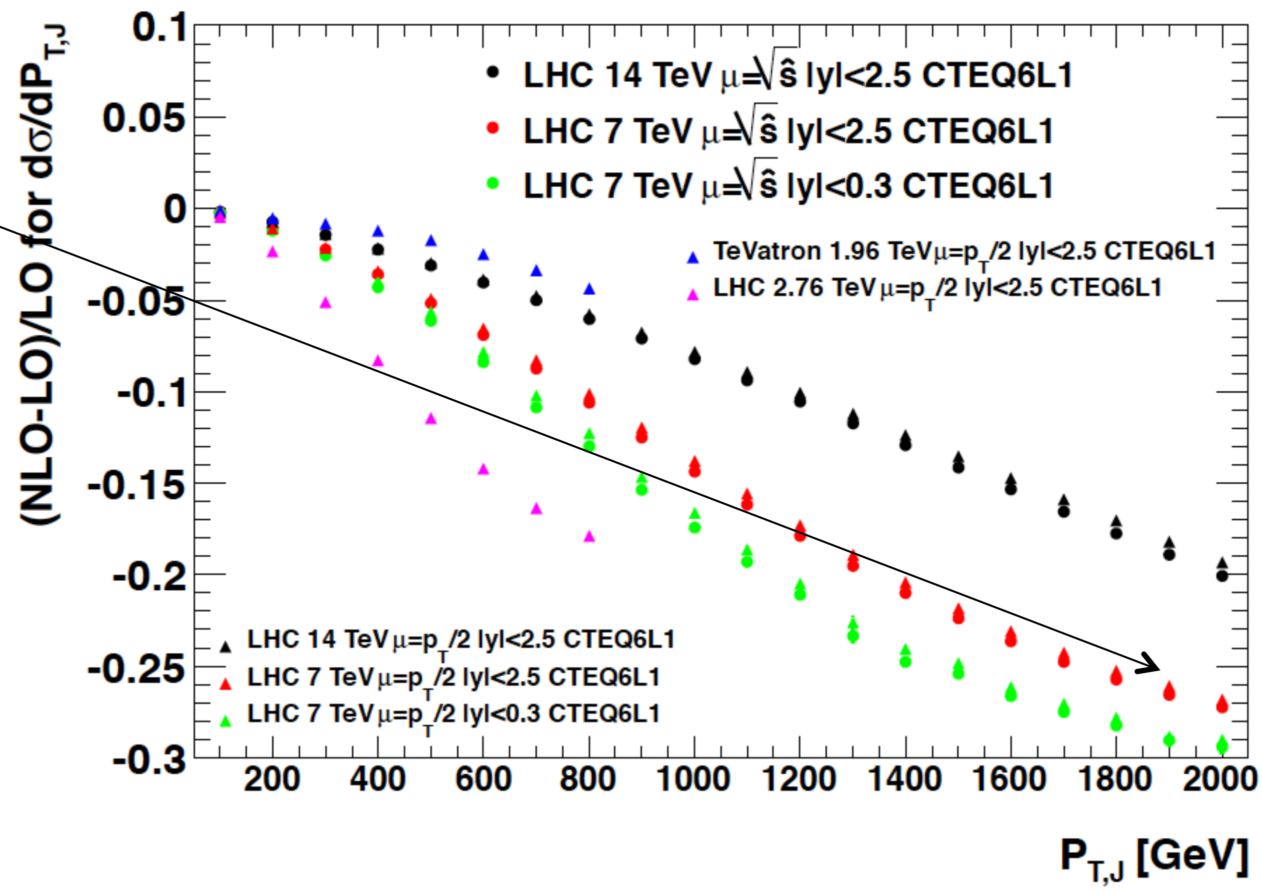


Figure 19: The effects of the $\mathcal{O}(\alpha_S^2\alpha_W)$ corrections [bottom] relative to the full LO results (i.e., through $\mathcal{O}(\alpha_S^2 + \alpha_S\alpha_{EW} + \alpha_{EW}^2)$) [top] for the case of LHC for three choices of PDFs. They are plotted as function of the jet transverse energy E_T. The cut $|\eta| < 2.5$ has been enforced, alongside the standard jet cone requirement $\Delta R > 0.7$. The factorisation/renormalisation scale adopted was $\mu = \mu_F \equiv \mu_R = E_T/2$.

Electroweak corrections for hard processes at the LHC

- I'm working on a followup paper with Stefano Moretti, Doug Ross, Mario Campanelli and Juan Terron
- Stefano, Doug and I are also organizing a workshop on electroweak corrections at the LHC to be held in Durham September 24-26

20-25% effect at high p_T



PDF correlations

- Consider a cross section X(a), a function of the Hessian eigenvectors
- i^{th} component of gradient of X is

$$\frac{\partial X}{\partial a_i} \equiv \partial_i X = \frac{1}{2}(X_i^{(+)} - X_i^{(-)})$$

- Now take 2 cross sections X and Y
  - or one or both can be pdf's
- Consider the projection of gradients of X and Y onto a circle of radius 1 in the plane of the gradients in the parton parameter space
- The circle maps onto an ellipse in the XY plane
- The angle ϕ between the gradients of X and Y is given by

$$\cos\varphi = \frac{\vec{\nabla} X \cdot \vec{\nabla} Y}{\Delta X \Delta Y} = \frac{1}{4 \Delta X \, \Delta Y} \sum_{i=1}^{N} \left(X_i^{(+)} - X_i^{(-)}\right)\left(Y_i^{(+)} - Y_i^{(-)}\right)$$

- The ellipse itself is given by

$$\left(\frac{\delta X}{\Delta X}\right)^2 + \left(\frac{\delta Y}{\Delta Y}\right)^2 - 2\left(\frac{\delta X}{\Delta X}\right)\left(\frac{\delta Y}{\Delta Y}\right)\cos\varphi = \sin^2\varphi$$

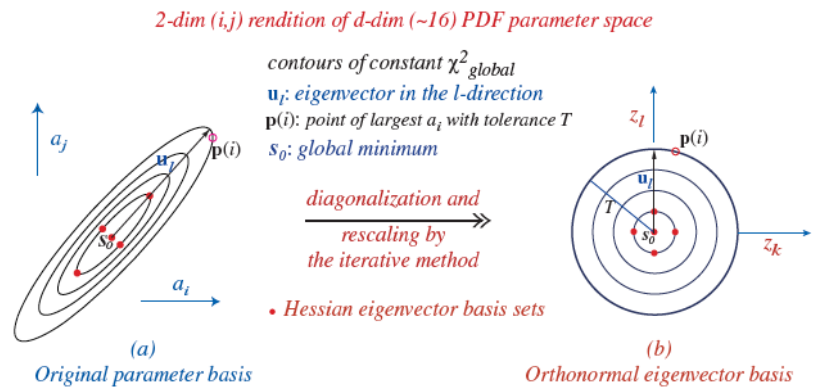


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

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

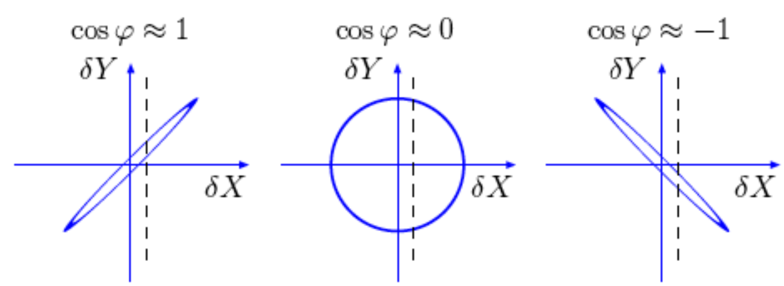


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

…from PDF4LHC report (CTEQ6.6)

Process	σ	PDF (asym)	PDF (sym)	$\alpha_s(m_Z)$ error	combined	orrelation
$\sigma_{W^+} * BR(W^+ \to l^+\nu)[nb]$	6.057	+0.123/-0.119	0.116	0.045	0.132	0.87
$\sigma_{W^-} * BR(W^- \to l^-\nu)[nb]$	4.106	+0.088/-0.091	0.088	0.029	0.092	0.92
$\sigma_{Z^o} * BR(Z^o \to l^+l^-)[nb]$	0.9469	+0.018/-0.018	0.018	0.006	0.0187	1.00
$\sigma_{t\bar{t}}[pb]$	156.2	+7.0/-6.7	6.63	4.59	8.06	-0.74
$\sigma_{gg\to Higgs}(120\ GeV)[pb]$	11.59	+0.19/-0.23	0.21	0.20	0.29	0.01
$\sigma_{gg\to Higgs}(180\ GeV)[pb]$	4.840	+0.077/-0.091	0.084	0.091	0.124	-0.47
$\sigma_{gg\to Higgs}(240\ GeV)[pb]$	2.610	+0.054/-0.058	0.056	0.055	0.078	-0.73

Table 5: Benchmark cross section predictions and uncertainties for CTEQ6.6 for $W^\pm, Z, t\bar{t}$ and Higgs production (120, 180, 240 GeV) at 7 TeV. The central prediction is given in column 2. Errors are quoted at the 68% c.l.. Both the symmetric and asymmetric forms for the PDF errors are given. In the next-to-last column, the (symmetric) form of the PDF and $\alpha_s(m_Z)$ errors are added in quadrature. In the last column, the correlation cosine with respect to Z production is given.

The values of ΔX, ΔY, and $\cos\varphi$ are also sufficient to estimate the PDF uncertainty of any function $f(X,Y)$ of X and Y by relating the gradient of $f(X,Y)$ to $\partial_X f \equiv \partial f/\partial X$ and $\partial_Y f \equiv \partial f/\partial Y$ via the chain rule:

$$\Delta f = \left|\vec{\nabla} f\right| = \sqrt{(\Delta X\ \partial_X f\ )^2 + 2\Delta X\ \Delta Y\ \cos\varphi\ \partial_X f\ \partial_Y f + (\Delta Y\ \partial_Y f)^2}. \quad (9)$$

Used for LHC Higgs searches

Procedure for the LHC Higgs boson search combination in summer 2011

(LHC Higgs Combination Group Report)

A. Armbruster[1], K. A. Assamagan[2], S. Banerjee[3], G. Gomez-Ceballos[4], M. Chen[5], G. Cowan[6], K. Cranmer[7], S. Ferrag[8], E. Gross[9], J. Huston[10], A. Korytov[5], C. Mariotti[11], L. Moneta[12], W. J. Murray[13], G. Petrucciani[14], J. Qian[2], G. Schott[15], V. Sharma[14], G. E. Steele[8], R. Tanaka[16], F. Tarrade[17], O. Vitells[9], and H. Wang[4]

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[7] *New York University, New York, NY, USA*
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[10] *Michigan State University, East Lansing, MI, USA*
[11] *INFN, Torino, Italy*
[12] *CERN, Geneva, Switzerland*
[13] *Rutherford Appleton Laboratory, Didcot, UK*
[14] *University of California, San Diego, CA, USA*
[15] *IEKP, Karlsruhe Institute of Technology, Karlsruhe, Germany*
[16] *LAL, Orsay, France*
[17] *Carleton University, Ottawa, ON, Canada*

June 30, 2011

…in YR2 report

Table 10: The up-to-date PDF4LHC average for the correlations between all signal processes with other signal and background processes for Higgs production considered here. The processes have been classified in correlation classes, as discussed in the text.

$M_H = 120$ GeV	ggH	VBF	WH	$t\bar{t}H$
ggH	1	−0.6	−0.2	−0.2
VBF	−0.6	1	0.6	−0.4
WH	−0.2	0.6	1	−0.2
$t\bar{t}H$	−0.2	−0.4	−0.2	1
W	−0.2	0.6	0.8	−0.6
WW	−0.4	0.8	1	−0.2
WZ	−0.2	0.4	0.8	−0.4
$W\gamma$	0	0.6	0.8	−0.6
$Wb\bar{b}$	−0.2	0.6	1	−0.2
$t\bar{t}$	0.2	−0.4	−0.4	1
$t\bar{b}$	−0.4	0.6	1	−0.2
$t(\rightarrow \bar{b})q$	0.4	0	0	0

$M_H = 160$ GeV	ggH	VBF	WH	$t\bar{t}H$
ggH	1	−0.6	−0.4	0.2
VBF	−0.6	1	0.6	−0.2
WH	−0.4	0.6	1	0
$t\bar{t}H$	0.2	−0.2	0	1
W	−0.4	0.4	0.6	−0.4
WW	−0.4	0.6	0.8	−0.2
WZ	−0.4	0.4	0.8	−0.2
$W\gamma$	−0.4	0.6	0.6	−0.6
$Wb\bar{b}$	−0.2	0.6	0.8	−0.2
$t\bar{t}$	0.4	−0.4	−0.2	0.8
$t\bar{b}$	−0.4	0.6	1	0
$t(\rightarrow \bar{b})q$	0.6	0	0	0

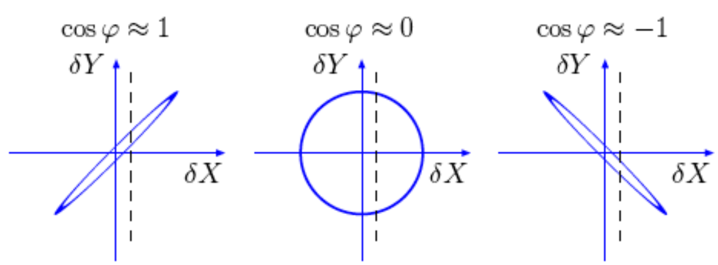
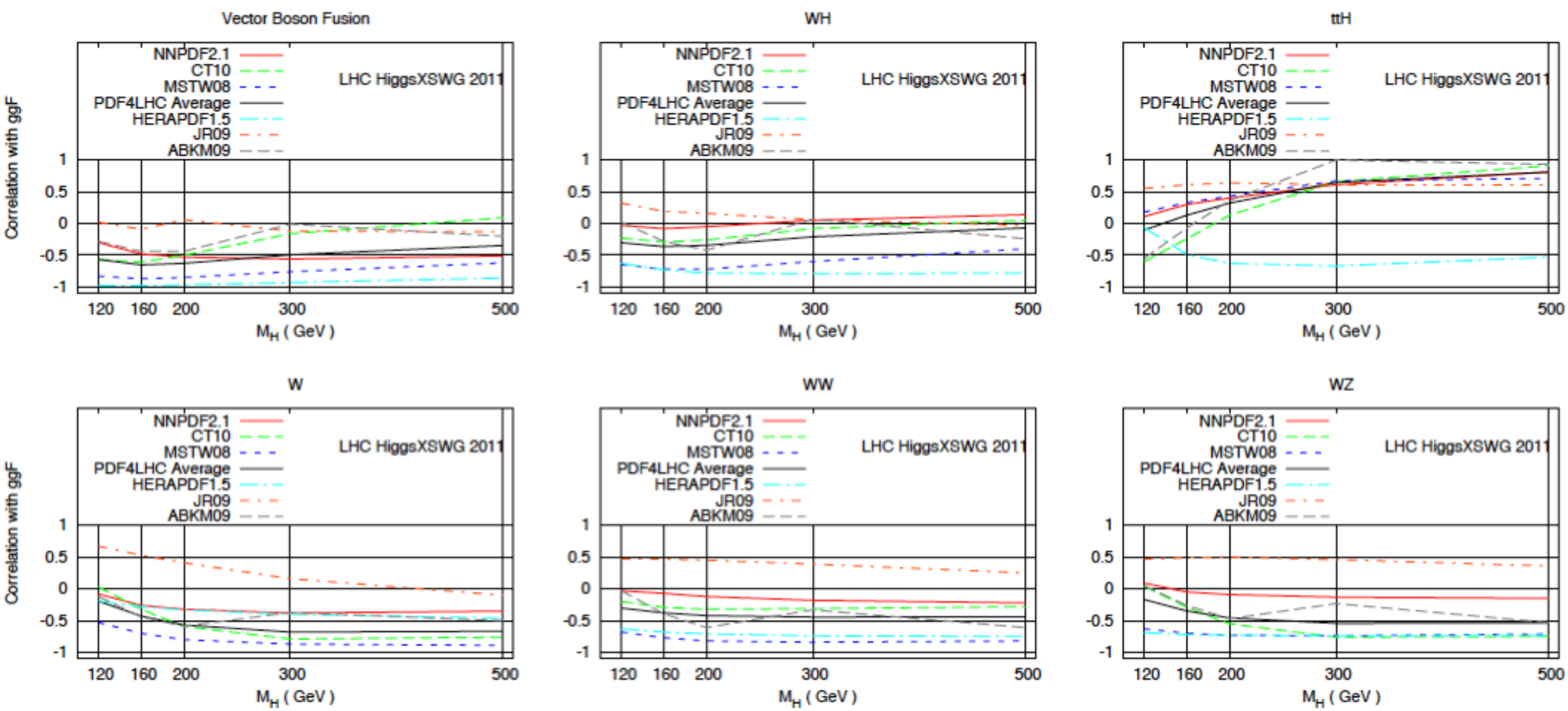


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

Correlations…

- For the 2nd Higgs Yellow Report, we expanded the correlation information to include all PDF groups
- Note that the CTEQ, MSTW, NNPDF correlations tend to be very similar; correlations for other PDFs can vary



Background correlations

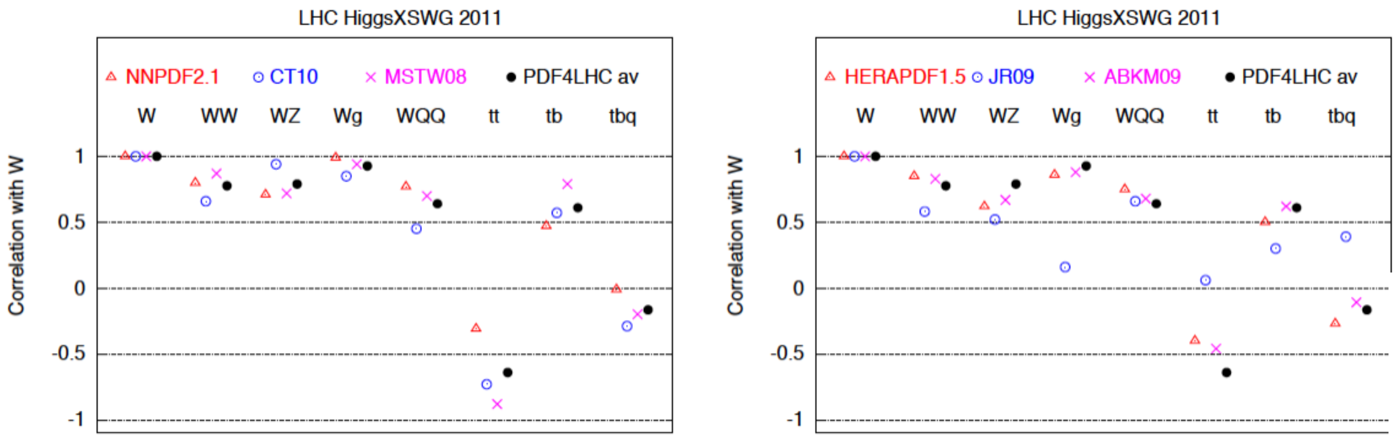


Table 11: The same as Table 10 for the correlations between background processes.

	W	WW	WZ	Wγ	$Wb\bar{b}$	$t\bar{t}$	$t\bar{b}$	$t(\to \bar{b})q$
W	1	0.8	0.8	1	0.6	−0.6	0.6	−0.2
WW	0.8	1	0.8	0.8	0.8	−0.4	0.8	0
WZ	0.8	0.8	1	0.8	0.8	−0.4	0.8	0
Wγ	1	0.8	0.8	1	0.6	−0.6	0.8	0
$Wb\bar{b}$	0.6	0.8	0.8	0.6	1	−0.2	0.6	0
$t\bar{t}$	−0.6	−0.4	−0.4	−0.6	−0.2	1	−0.4	0.2
$t\bar{b}$	0.6	0.8	0.8	0.8	0.6	−0.4	1	0.2
$t(\to \bar{b})q$	−0.2	0	0	0	0	0.2	0.2	1

Figure 5: Correlation between background processes for Higgs production: the correlation between W production and the eight other background processes considered.

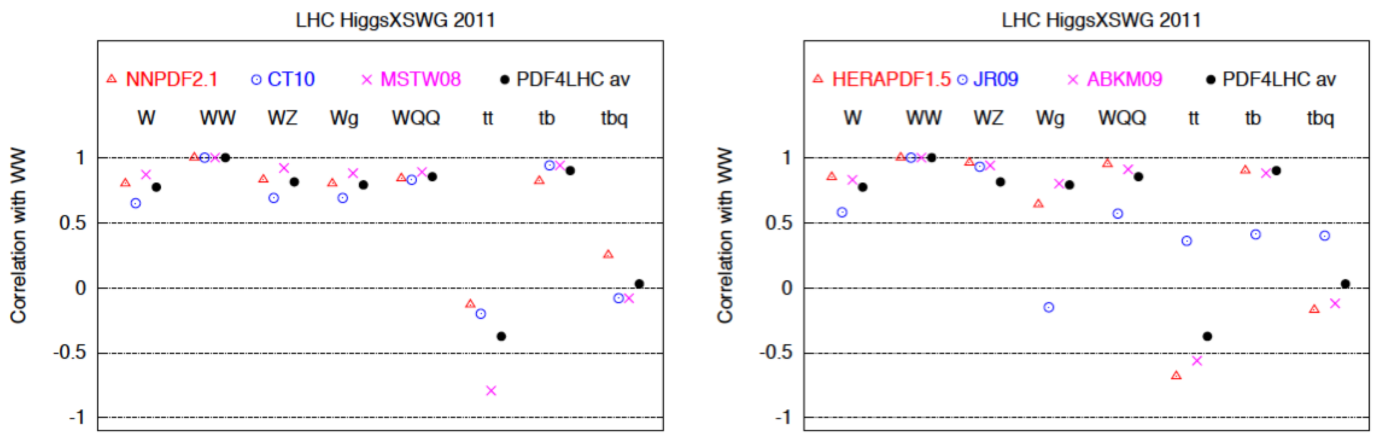


Figure 6: Correlation between background processes for Higgs production: the correlation between WW production and the eight other background processes considered.

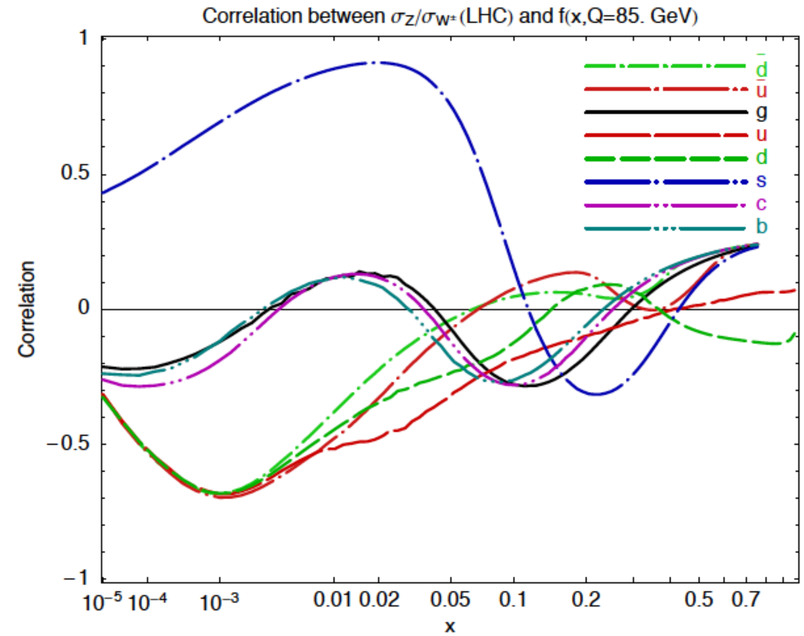
Correlations, strangeness and ATLAS W/Z cross sections

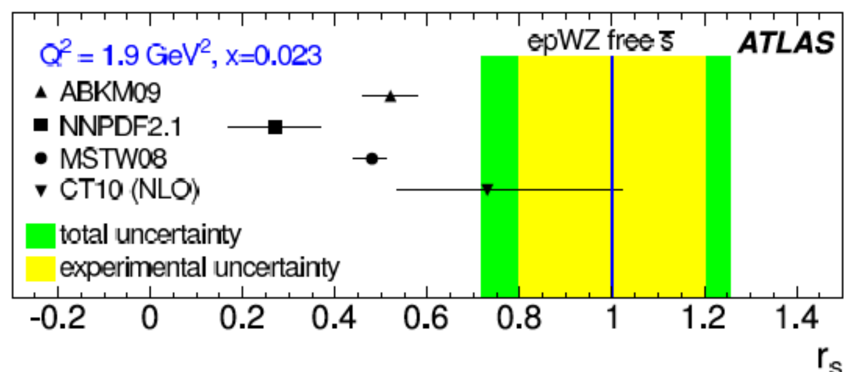
- There's a strong correlation for the ratio of the W to Z cross section at the LHC to the strange quark distribution
  - Nadolsky et al, PRD78 (2008) 013004
- ATLAS analysis of W and Z production (taking correlated errors into account) suggests that

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

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

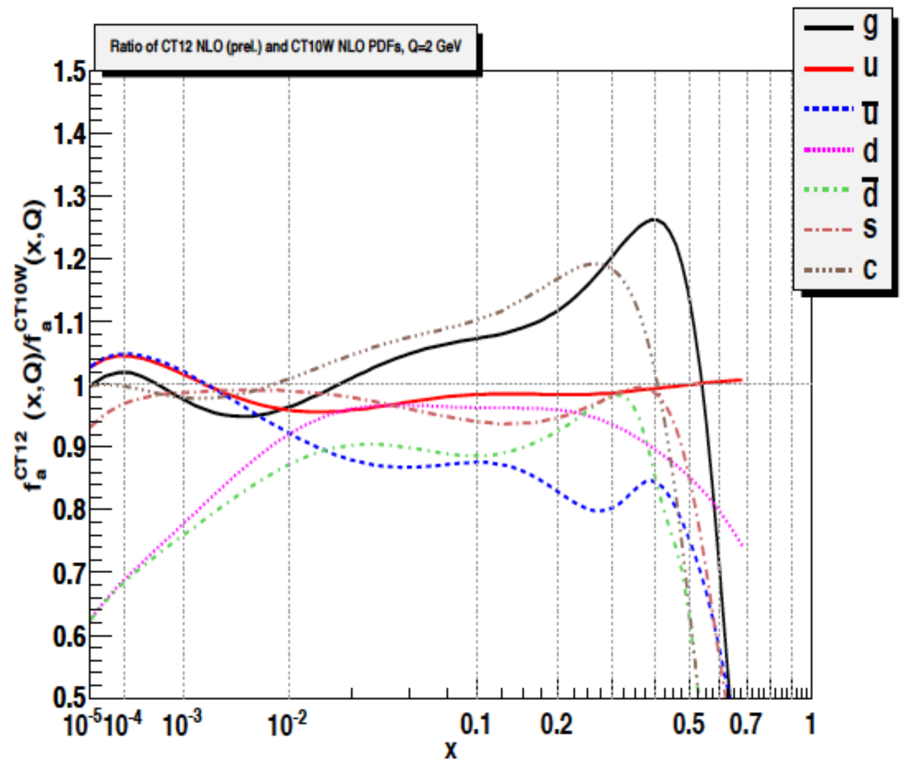
- Consistent within errors of CT10
  - more exploration of strange uncertainty in CT12

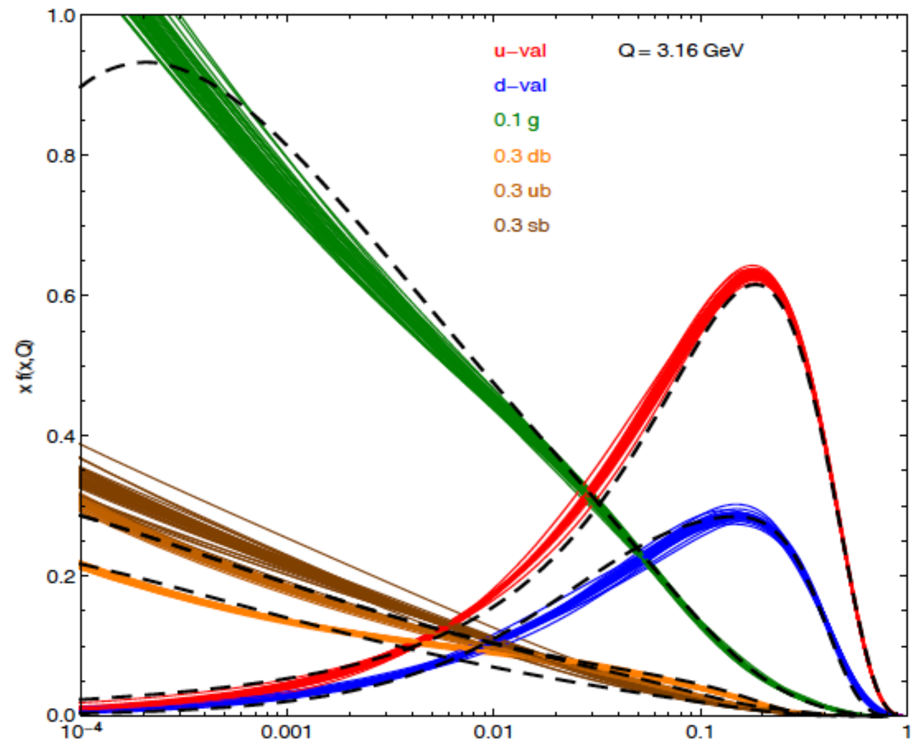




Small x limits

- CT12 analysis explores possibility of dbar/ubar≠1 as x->0
- Some CT12 candidates have sbar(x,Q)/ubar(x,Q)>1 at $x<10^{-3}$; is this acceptable?
- More investigation is underway





More benchmarking

2 studies in 2011 Les Houches proceedings(1203.6803)

- Benchmarking for inclusive DIS cross sections
  - with S. Alekhin, A. Glazov, A. Guffanti, P. Nadolsky, and J. Rojo
  - excellent agreement observed between CTEQ code with alternative DIS calculation provided by A. Guffanti
- Benchmark comparison of NLO jet cross sections
  - J. Gao, Z. Liang, H.-L. Lai, P. Nadolsky, D. Soper, C.-P. Yuan
  - compare EKS results with FastNLO (NLOJET++)
  - excellent agreement between the two if care is taken on settings for jet algorithm, recombination scheme, QCD scale choices

Followup for PDF4LHC

- Study of NNLO PDFs from all 6 PDF groups
  - drawing from what Graeme has done, but now including CT10/12 NNLO
  - detailed comparisons to LHC data which have provided detailed correlated systematic error information, keeping track of required systematic error shifts, normalizations, etc
    - ATLAS W/Z rapidity distributions
    - ATLAS inclusive jet cross section data

From 7 to 8 TeV

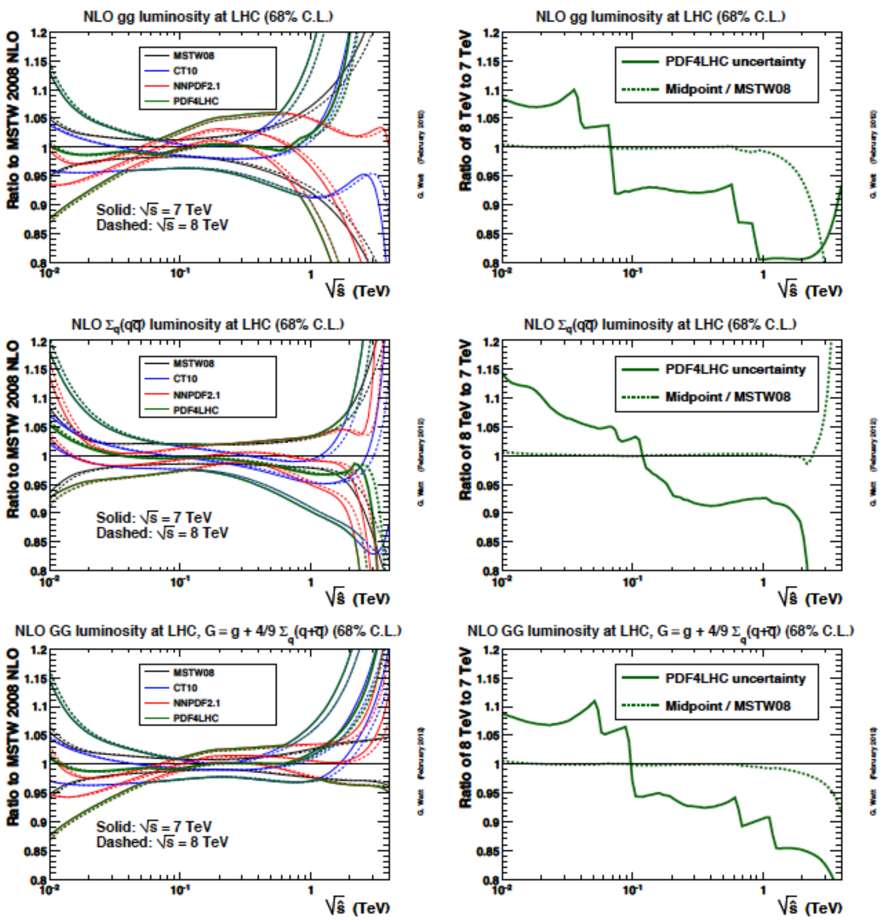


Figure 1: *Left*: NLO partonic luminosities versus $\sqrt{\hat{s}}$ at the LHC ($\sqrt{s}$ = 7 or 8 TeV) for MSTW08, CT10 and NNPDF2.1 with the default α_S values, together with the midpoint and uncertainty of the PDF4LHC envelope, all normalised to the central MSTW08 predictions with the same $\sqrt{s}$ value. *Right*: The 8 TeV to 7 TeV ratios of the relative PDF4LHC uncertainty and midpoint (normalised to the MSTW08 central value). [G. Watt, 24th February 2012]

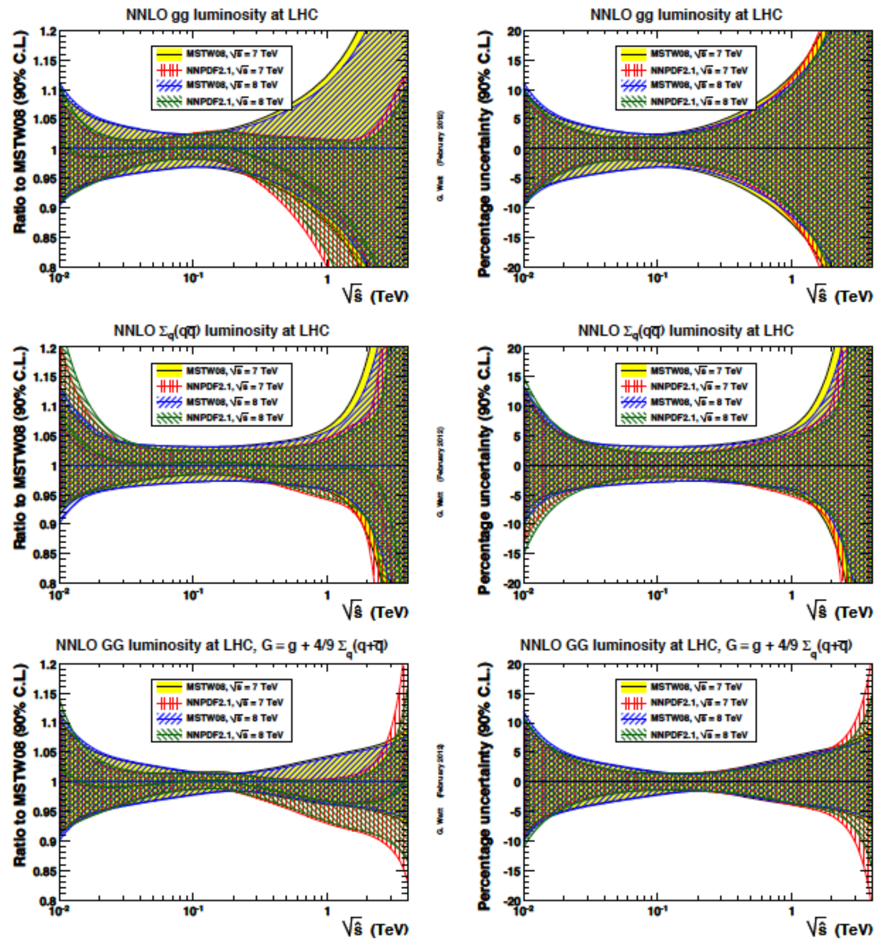
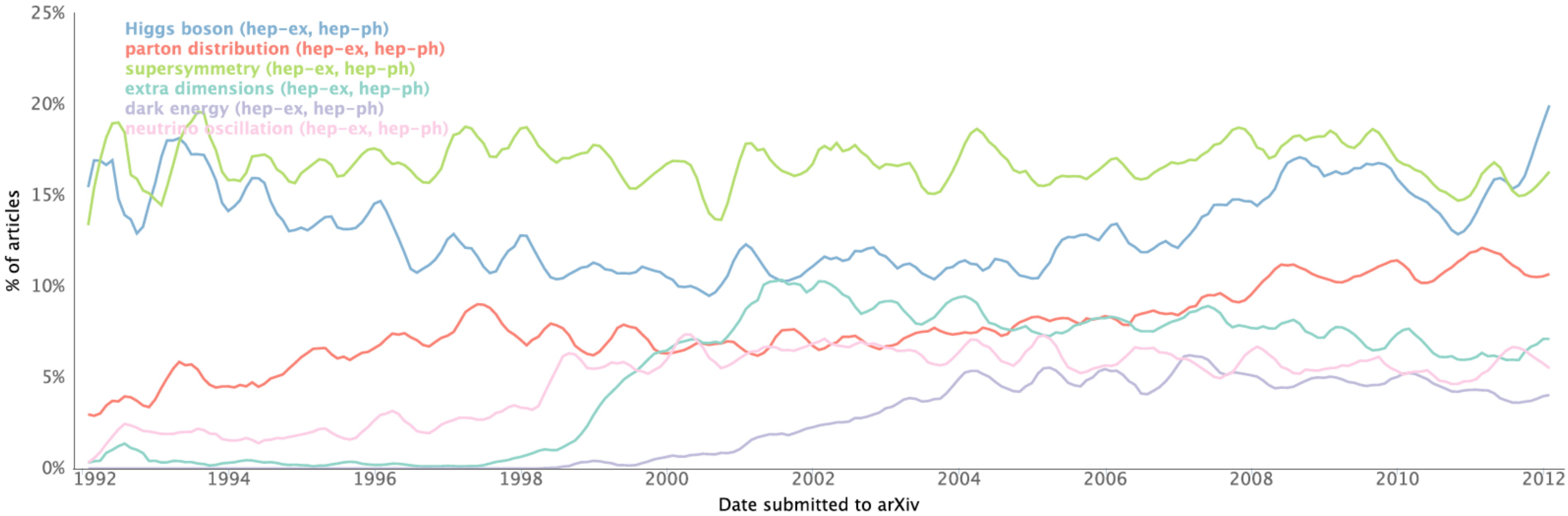


Figure 1: NNLO partonic luminosities versus $\sqrt{\hat{s}}$ at the LHC ($\sqrt{s}$ = 7 or 8 TeV) for MSTW08 and NNPDF2.1 with the default α_S values. The left plots are normalised to the MSTW08 predictions with the same $\sqrt{s}$ value, while the right plots show only the percentage PDF uncertainties. Both the fractional PDF uncertainties and the trend between groups (MSTW/NNPDF) is almost independent of the LHC energy of 7 TeV or 8 TeV. [G. Watt, 21st February 2012]

…and finally

percentage of articles to the archive that mention the following phrases



…so if we're willing to wait a few years, we'll beat out supersymmetry

Higgs may be having a growth spurt

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

HOME | PROGRAM | REGISTRATION | CONFERENCE FEE | LOCATION | TRAVEL | LODGING

QCD @ LHC 2012

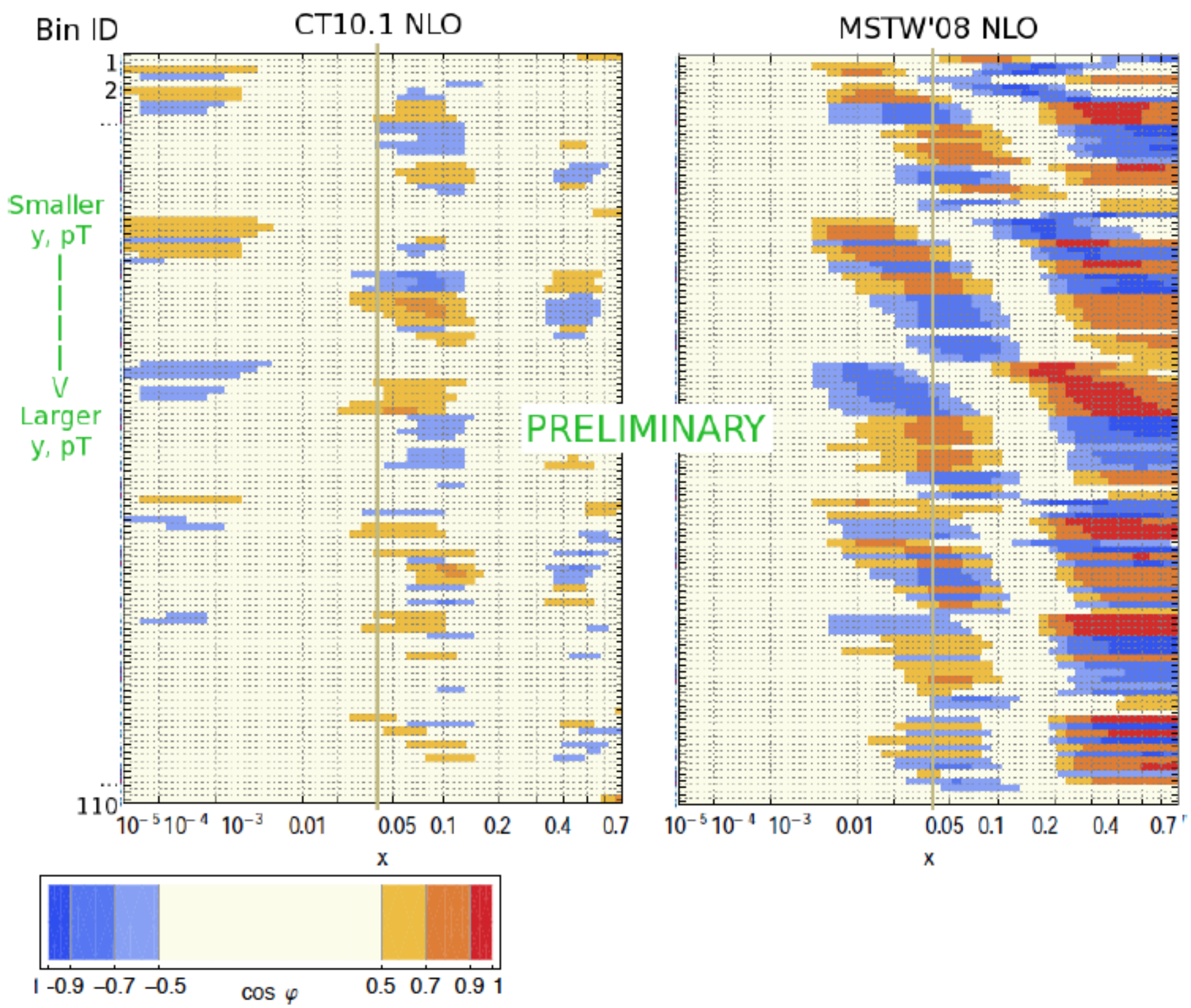
20th-24th August 2012 at Michigan State University

This workshop aims at instigating discussions and future work between experimenters and theorists, working on strong interactions at the LHC.

…a continuation of the series that started in Trento (2010) and St. Andrews (2011)

Correlations between D0 Run-2 inc. jet data and gluon PDF

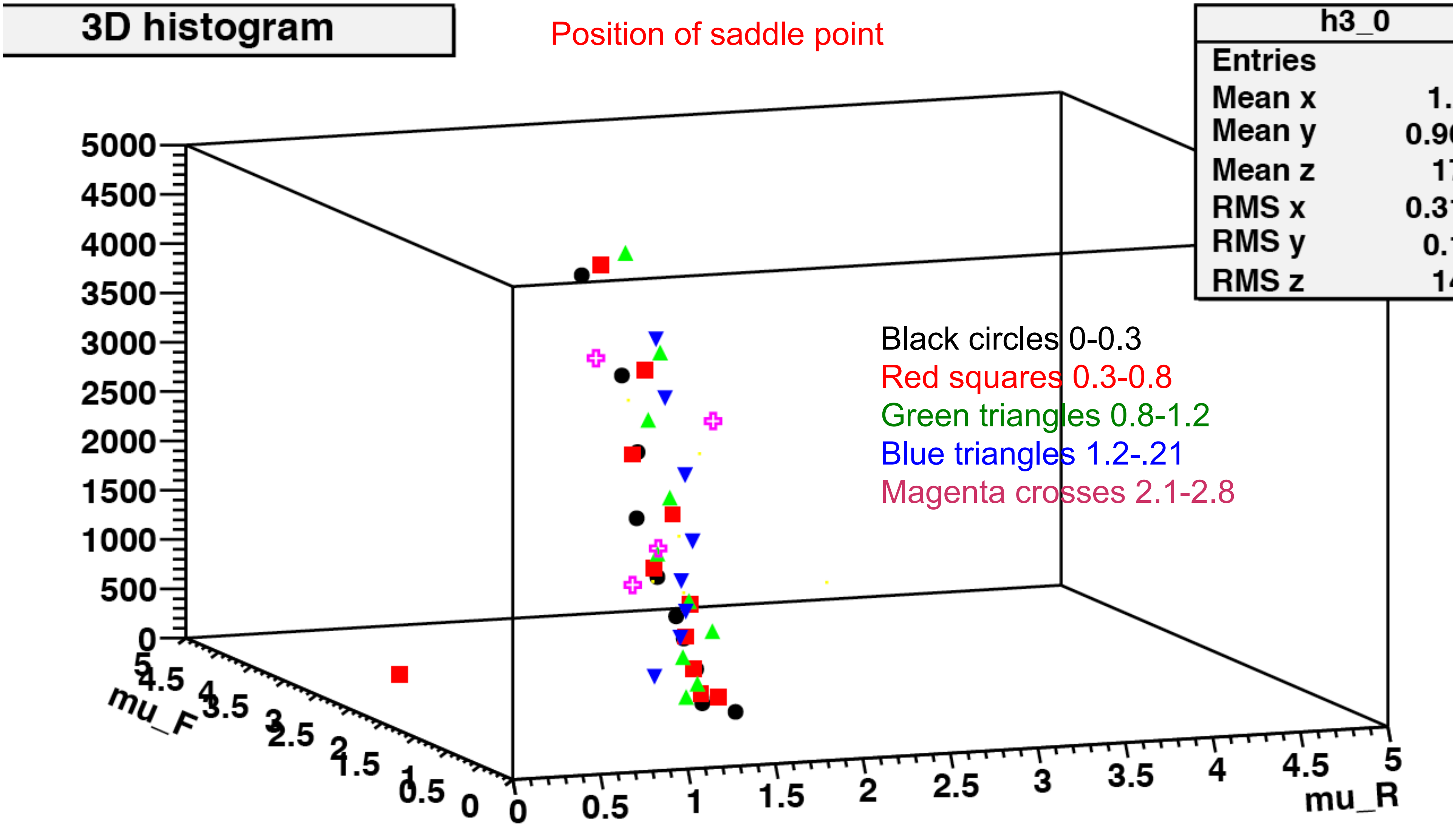
Z. Liang, P. Nadolsky, in progress



Correlation between $g(x, Q = 3.163\text{ GeV})$ and χ_i^2 in jet p_T bins (with syst. shifts)...

...is more pronounced for the MSTW'08 sets (right) than for many CT10(.1) candidate sets (left)

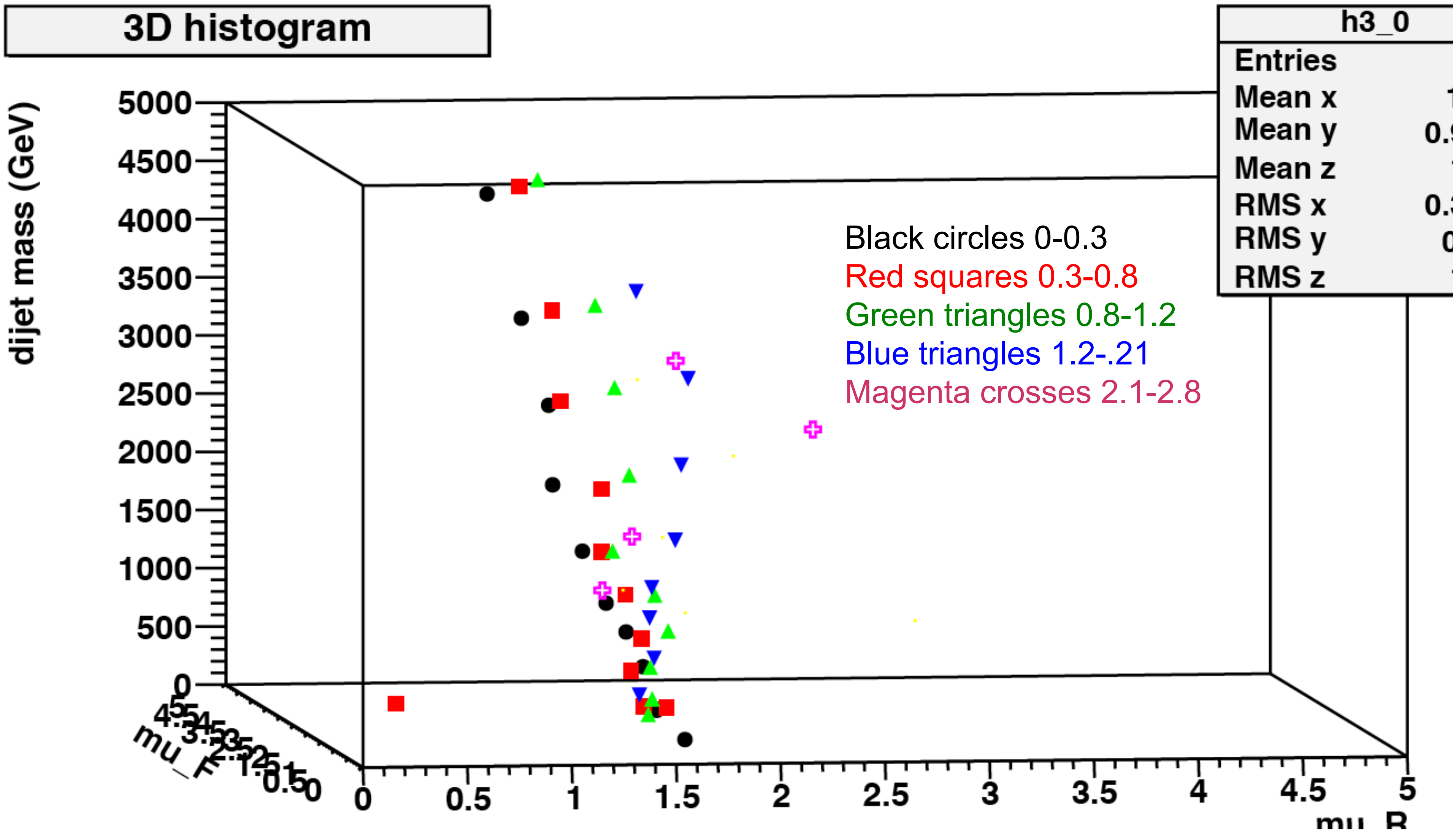
Look for saddle point position



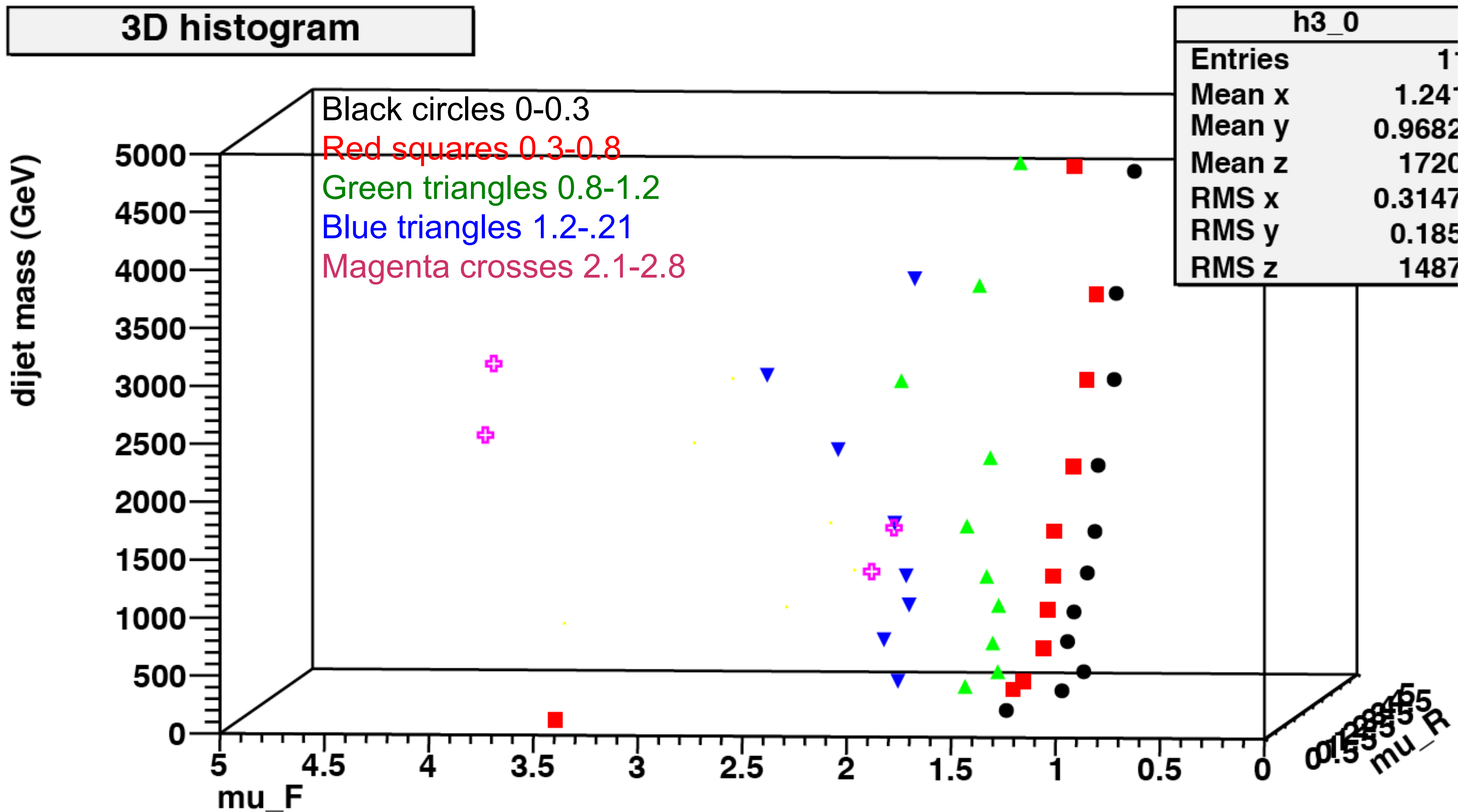
…using a Python script written by Jessie Muir, (now) a Cambridge (Part 3) student

μ_R increases with y^*/y_{max}

$y^*=(y_{j1}-y_{j2})/2$



μ_F increases with y^*/y_{max}



Note: maybe no true saddle points at high y* and high mass, so script has trouble finding them; there are still flat places