QCD experimental review

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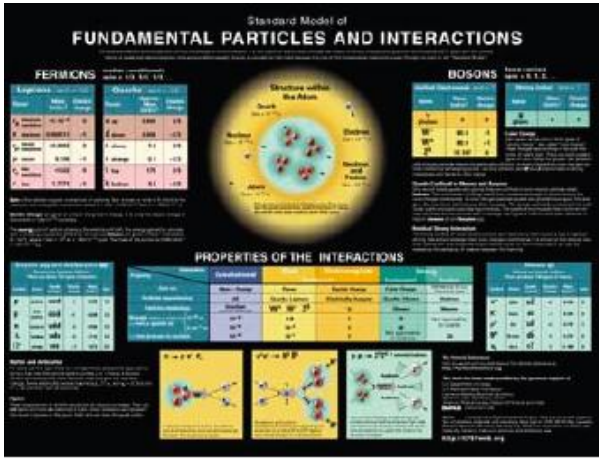
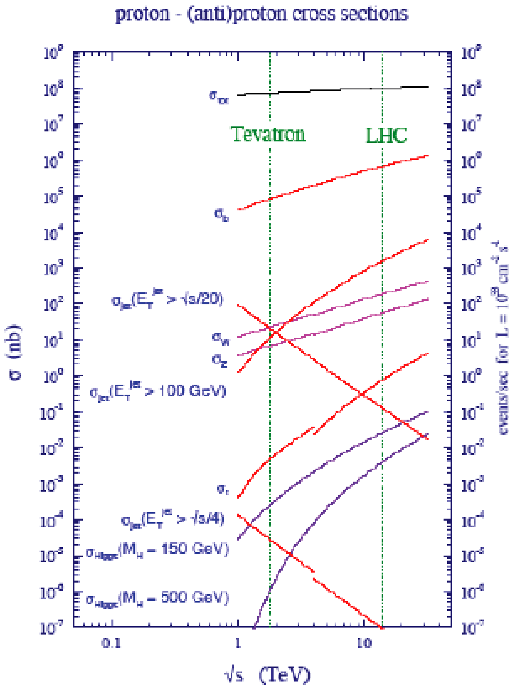
Understanding cross sections at the LHC

- We' re all looking for BSM physics at the LHC
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM 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
- So most (but not all) of my talk will deal with QCD measurements/issues at the LHC
    - apologies in advance



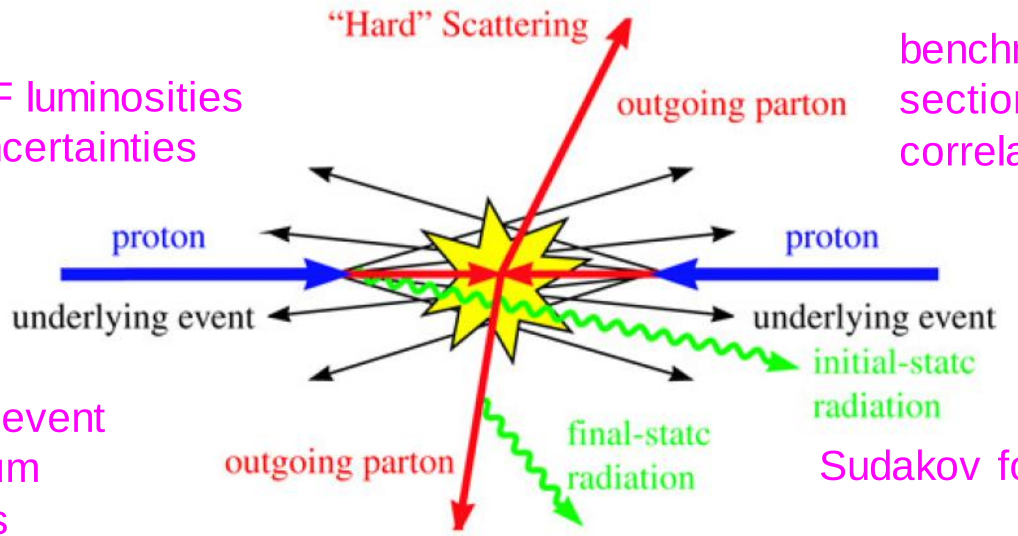


Understanding QCD at the LHC

final states involving bosons, jets, photons and heavy quarks in a new energy regime over a wider kinematic range than at the Tevatron

PDF’s, PDF luminosities and PDF uncertainties

benchmark cross sections and pdf correlations



underlying event and minimum bias events

Sudakov form factors

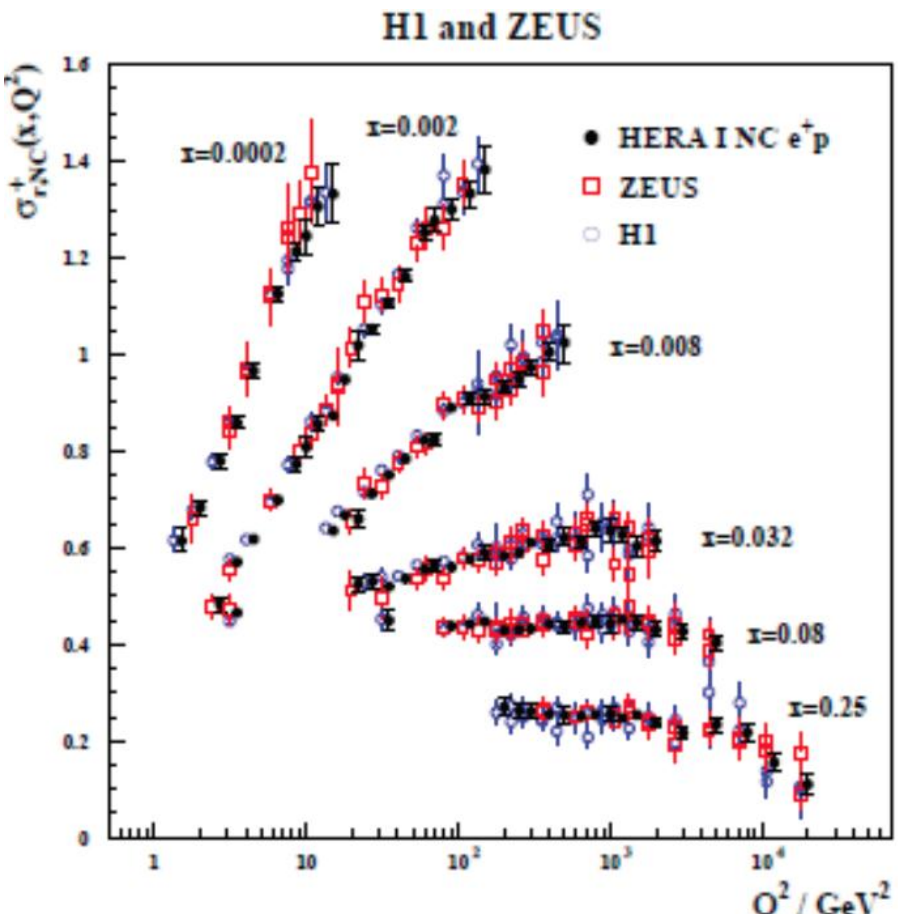
jet algorithms and jet reconstruction

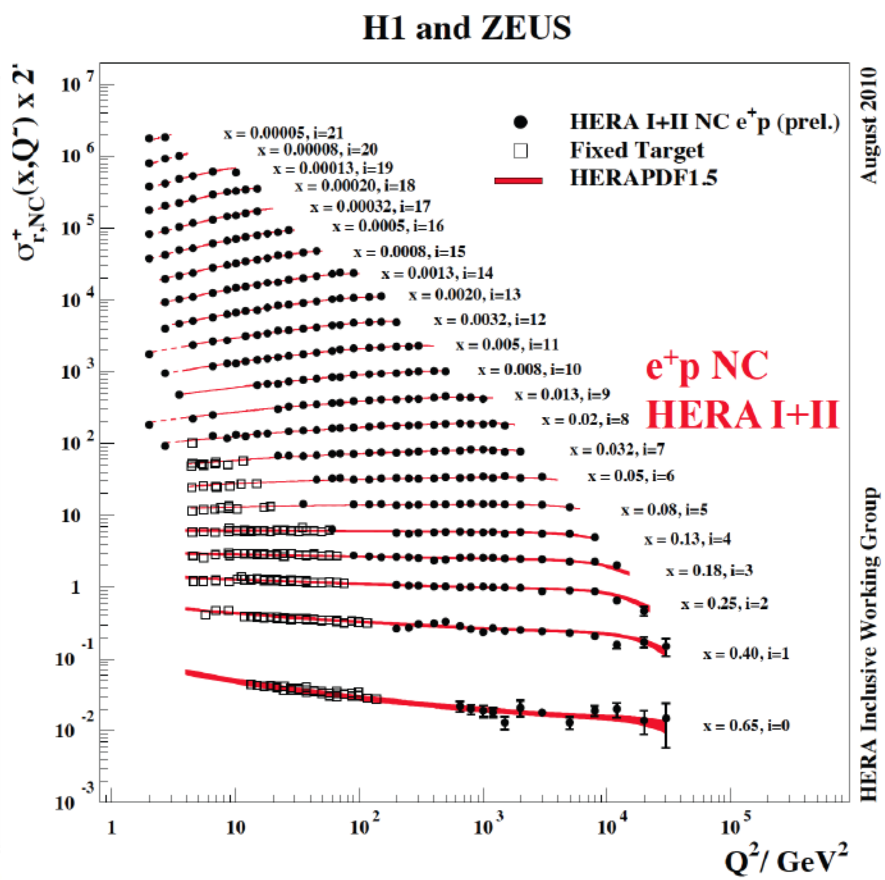
with comparisons to LO, NLO and NNLO predictions
(more detail provided in Christian’s talk)

I’ll only have time to touch on some of these aspects, concentrating on the data from 2010, which we are now publishing. More apologies in advance.

HERA: Runs I+II combined

- Combination of HERA data from H1 and ZEUS provides a well-understood data set with systematic errors that are smaller than the statistical errors across most of the kinematic region (total errors < 1% for Q^2 between 20-100 GeV^2 and less than 2% for most of the rest of the data.
- Of crucial importance for PDF fits.

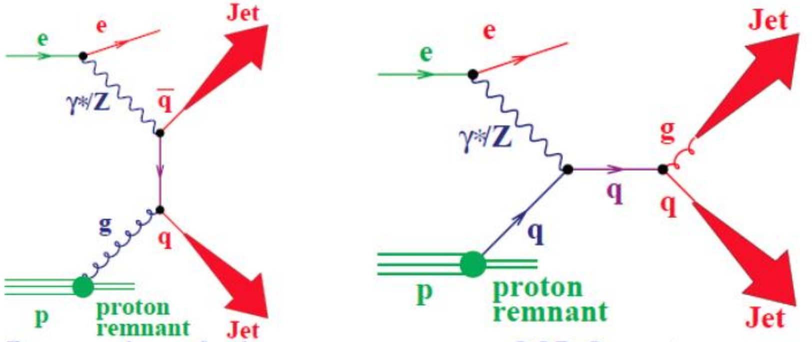




JHEP 1001:109 (2010)

HERA: jet production and α_s

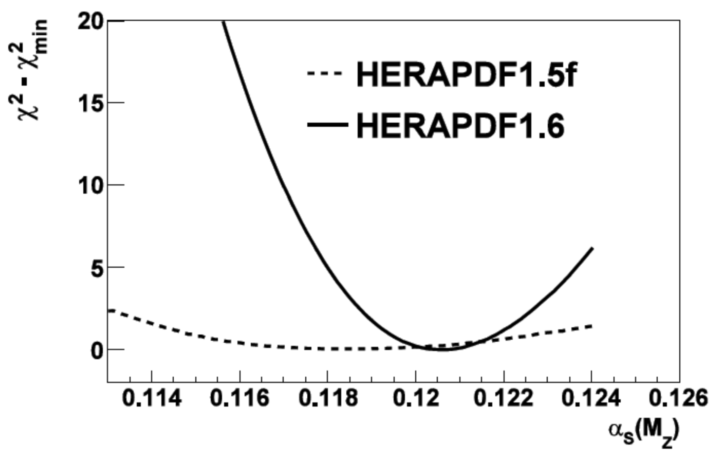
- Measurements of jet production at HERA provide an additional handle on the gluon distribution and a reasonable measurement of α_s, in combination with the HERA DIS data
- Do have to be careful about correlations between α_s and the gluon distribution if gluon distribution is not flexible enough

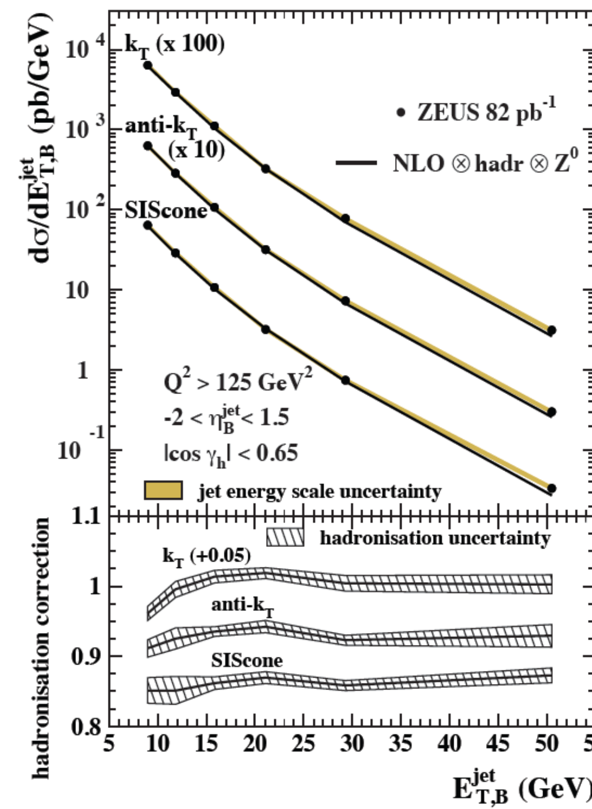


Boson-gluon fusion

QCD Compton

α_s scan





$\alpha_s(M_Z)$ =0.1202 ± 0.0013 (exp) ± 0.0007(model/param) ± 0.0012(hadronisation)

+0.0045/-0.0036 (scale)

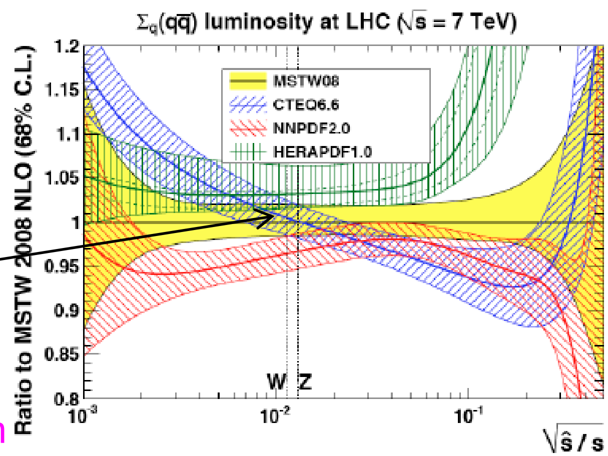
$\alpha_s(M_Z)$ = 0.1202 ± 0.0019 ± scale error

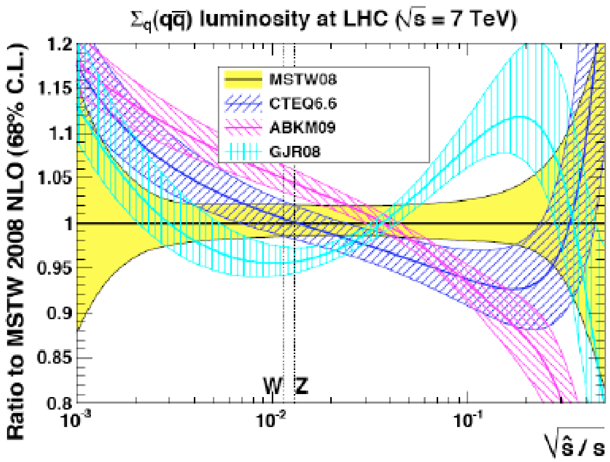
PDFs

- We've learned a lot from the PDF4LHC exercises (arXiv:1101.0536)
- In particular, we've seen where the PDFs agree and where they don't
- The exercise was at NLO; now we are updating to NNLO for the next round

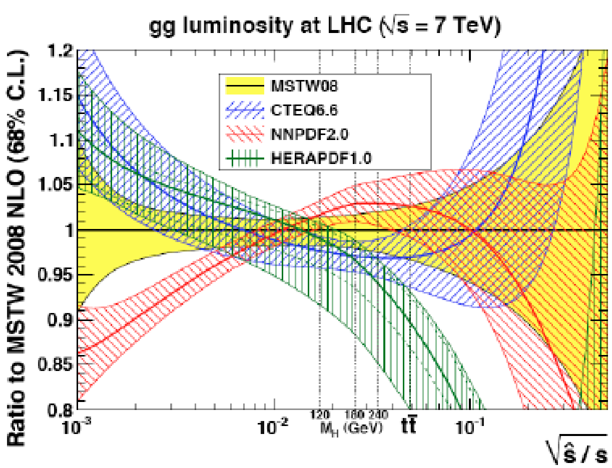
Plots by G. Watt arXiv: 1106.5788

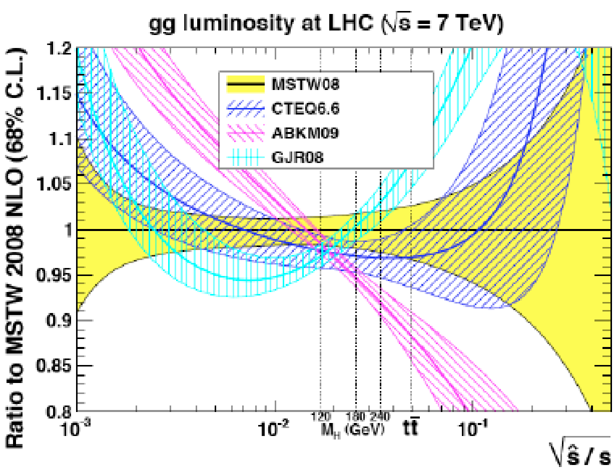
note that qQ luminosities are similar in W/Z region





all 6 PDF groups listed now have PDFs at NNLO

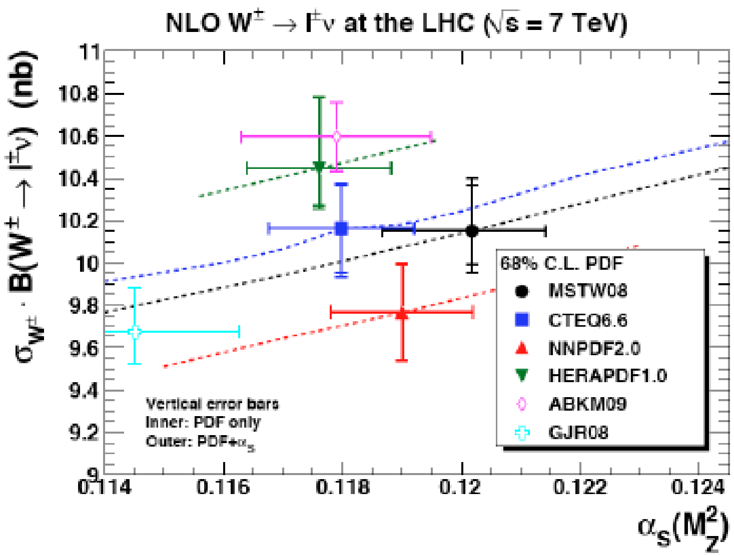


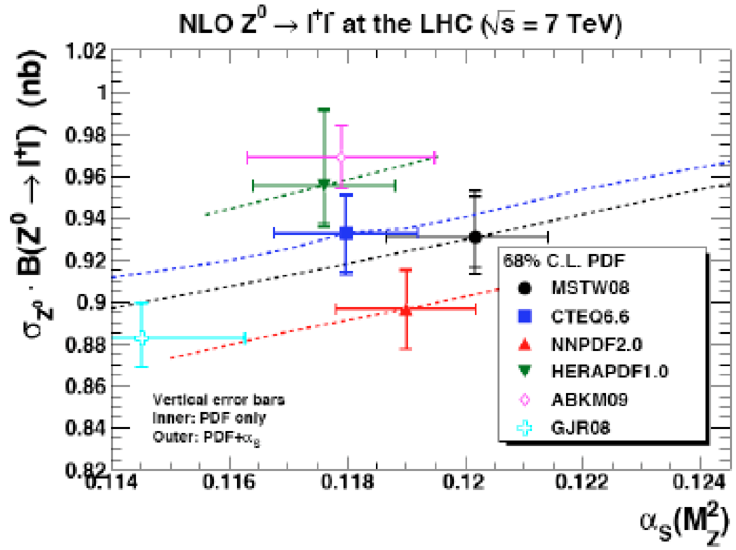


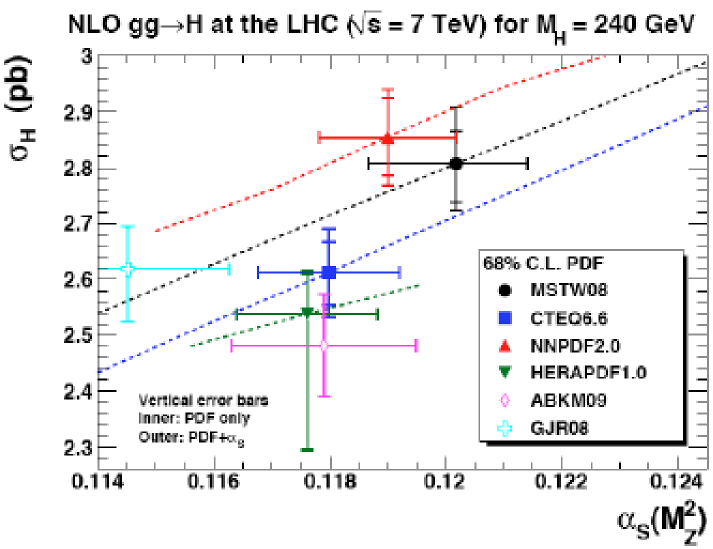
more differences for gg luminosities, especially at high mass

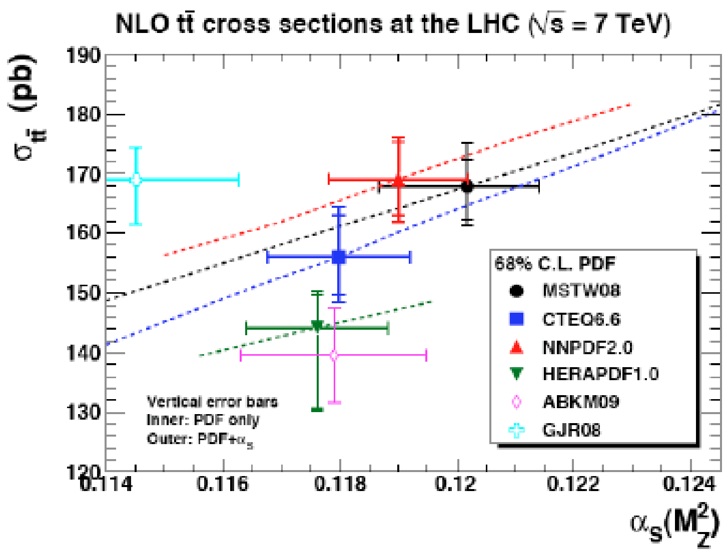
Cross section comparisons

CTEQ and MSTW predictions for W/Z cross sections very close; little dependence on α_s









larger gg differences and greater dependence on α_s lead to larger differences in Higgs/tT cross sections

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.

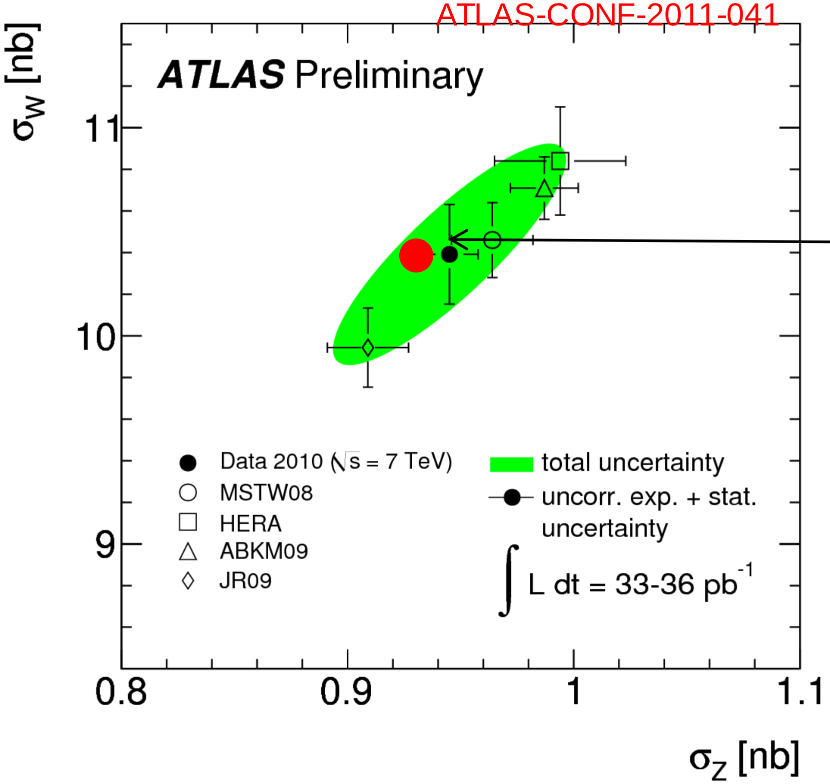
So the prescription at NNLO is:

- 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.

LHC: W, Z cross sections

ATLAS-CONF-2011-041

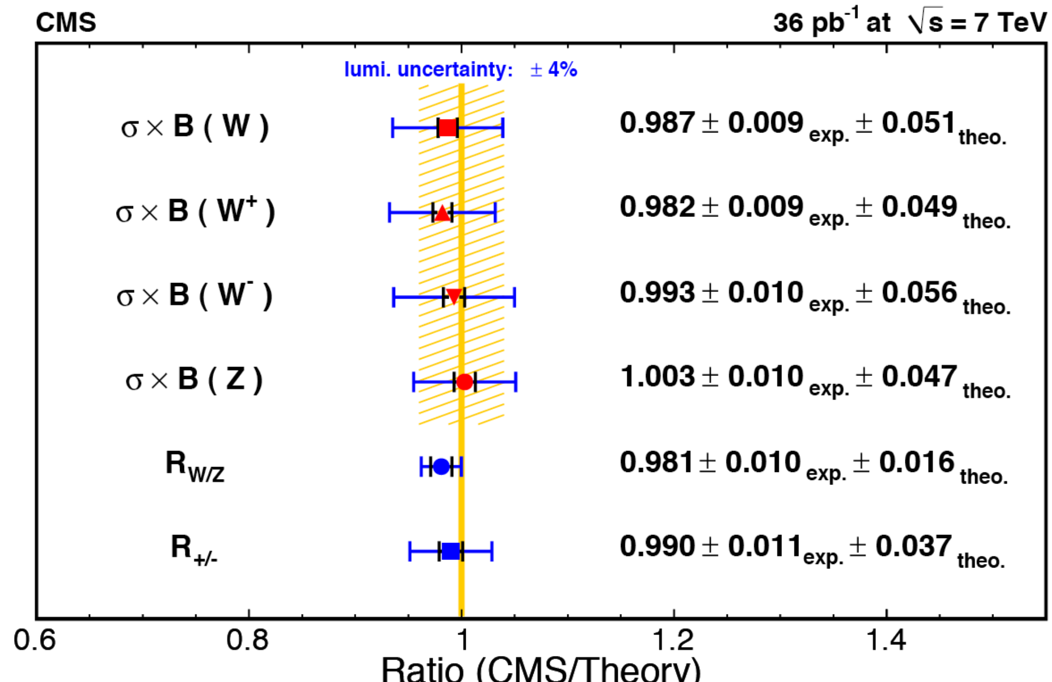


Many of the experimental/theory errors cancel with the ratio

CT10.2 NNLO prediction

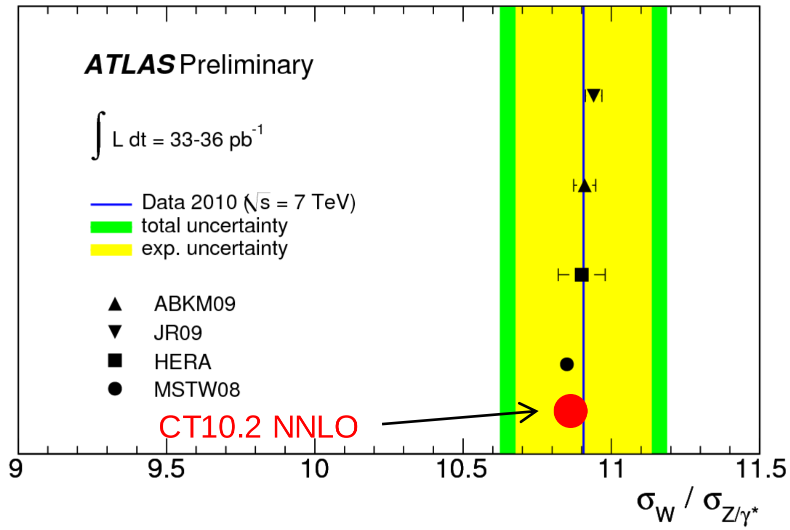
ATLAS W/Z cross section ratio in good agreement with NNLO predictions from the PDF groups shown

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

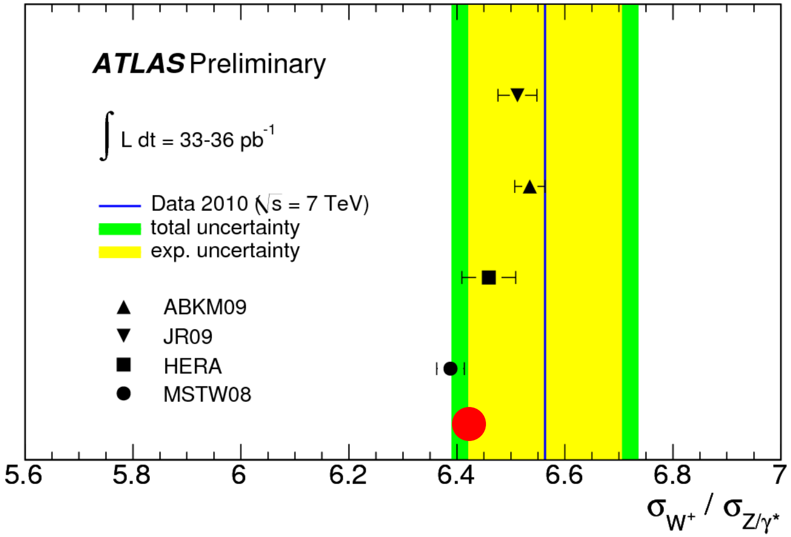


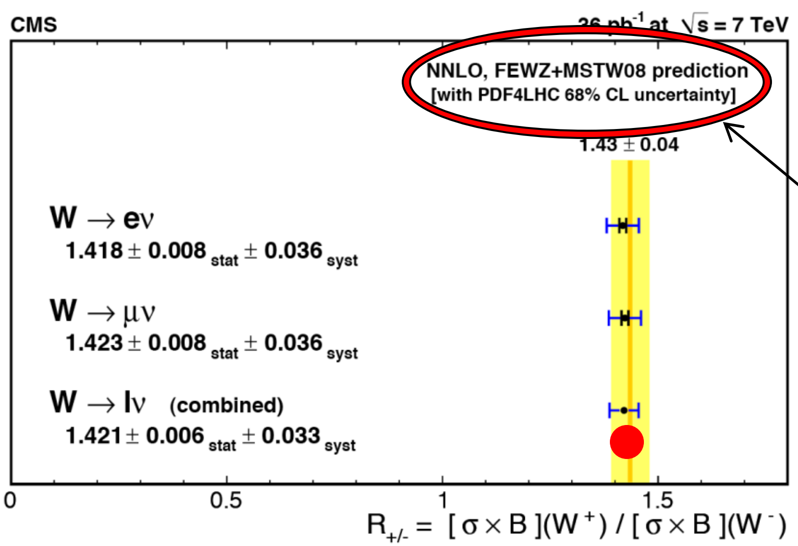
CMS PAS EWK-10-005

LHC: W/Z ratios

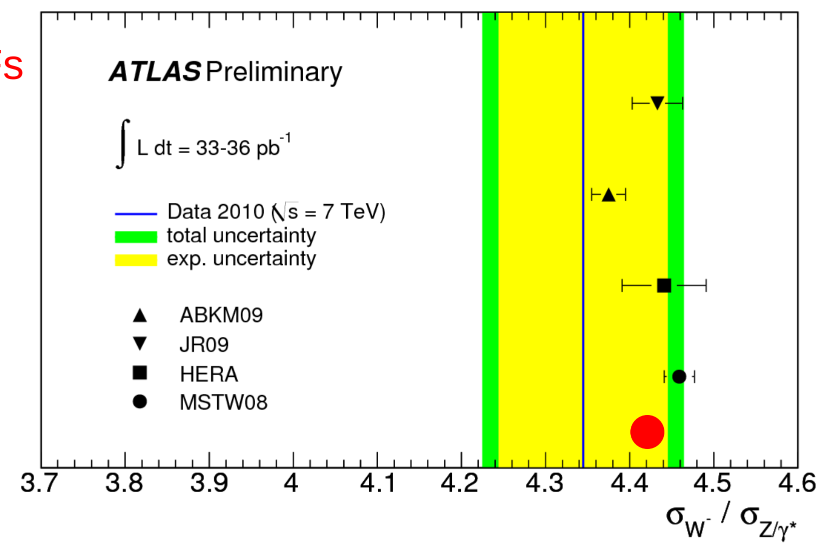


Total W/Z ratio from ATLAS in good agreement with theory, but separate W^+/Z and W^-/Z ratios show some differences (at 1 sigma level) for some of PDFs





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



The LHC ~~will be~~ is a very *jetty* place

- Relatively small x values (large phase space for gluon emission) and dominance of the gluon distribution leads to copious jet production
- Total cross sections for tT and Higgs production saturated by tT (Higgs) + jet production for jet p_T values of order 10-20 GeV/c

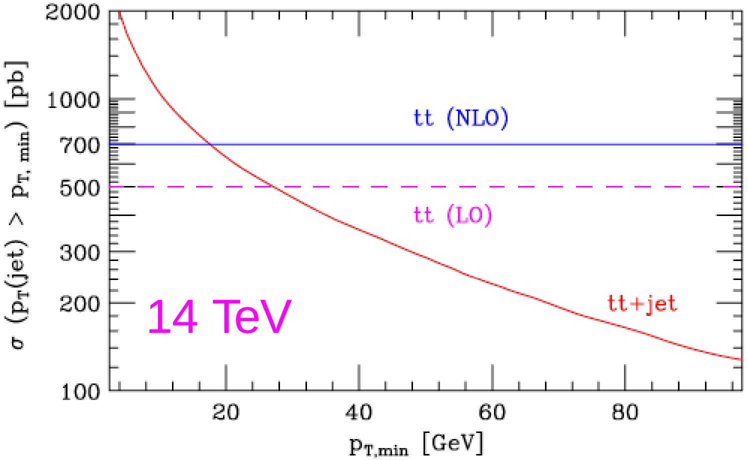


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\mathrm{min}}$, together with the top pair production cross sections at LO and NLO.

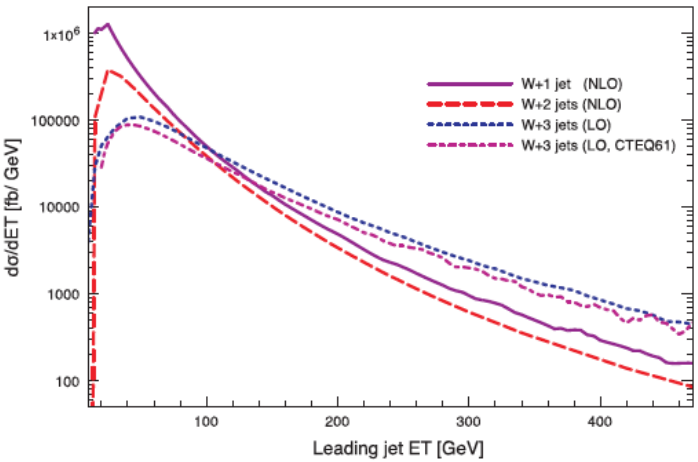


Figure 91. Predictions for the production of $W+\geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

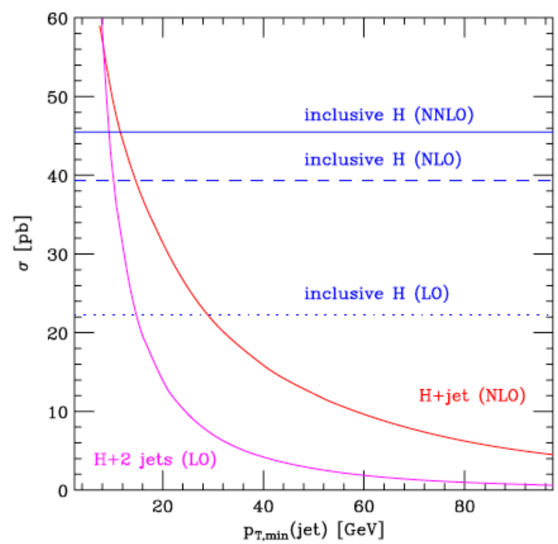


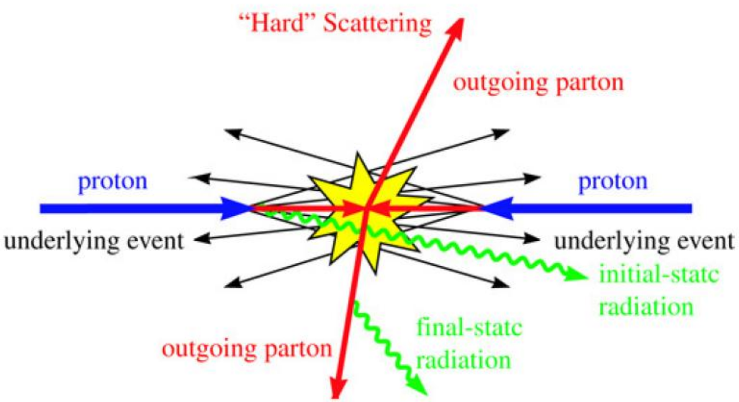
Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\mathrm{min}}$, together with the top pair production cross sections at LO and NLO.

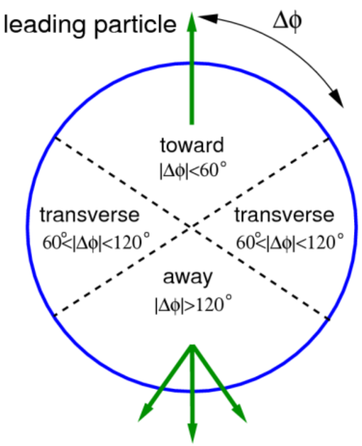
CHS review article Rep. Prog. Phys.70: 89, 2007

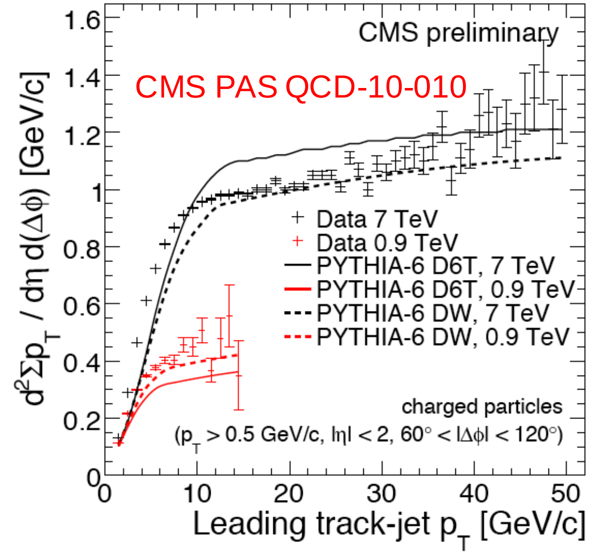
- indication that can expect interesting events at LHC to be very *jetty* (especially from gg initial states)

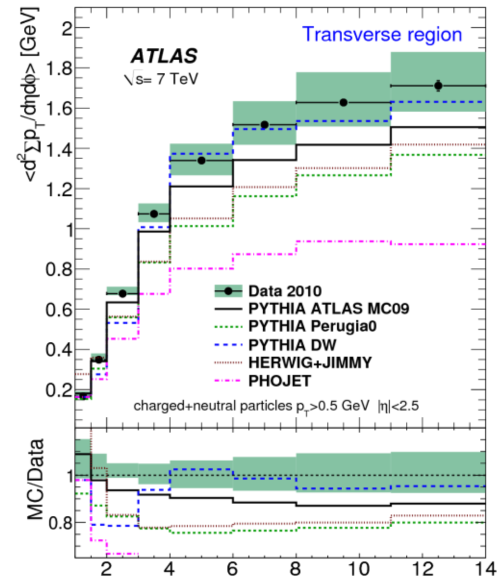
LHC: underlying event

- Have to deal with effects of underlying event in any measurements involving jets
- Level of activity is higher at 7 TeV, as expected, but also higher than any pre-LHC tunes predicted
- Data can be well-described by tunes incorporating the LHC data



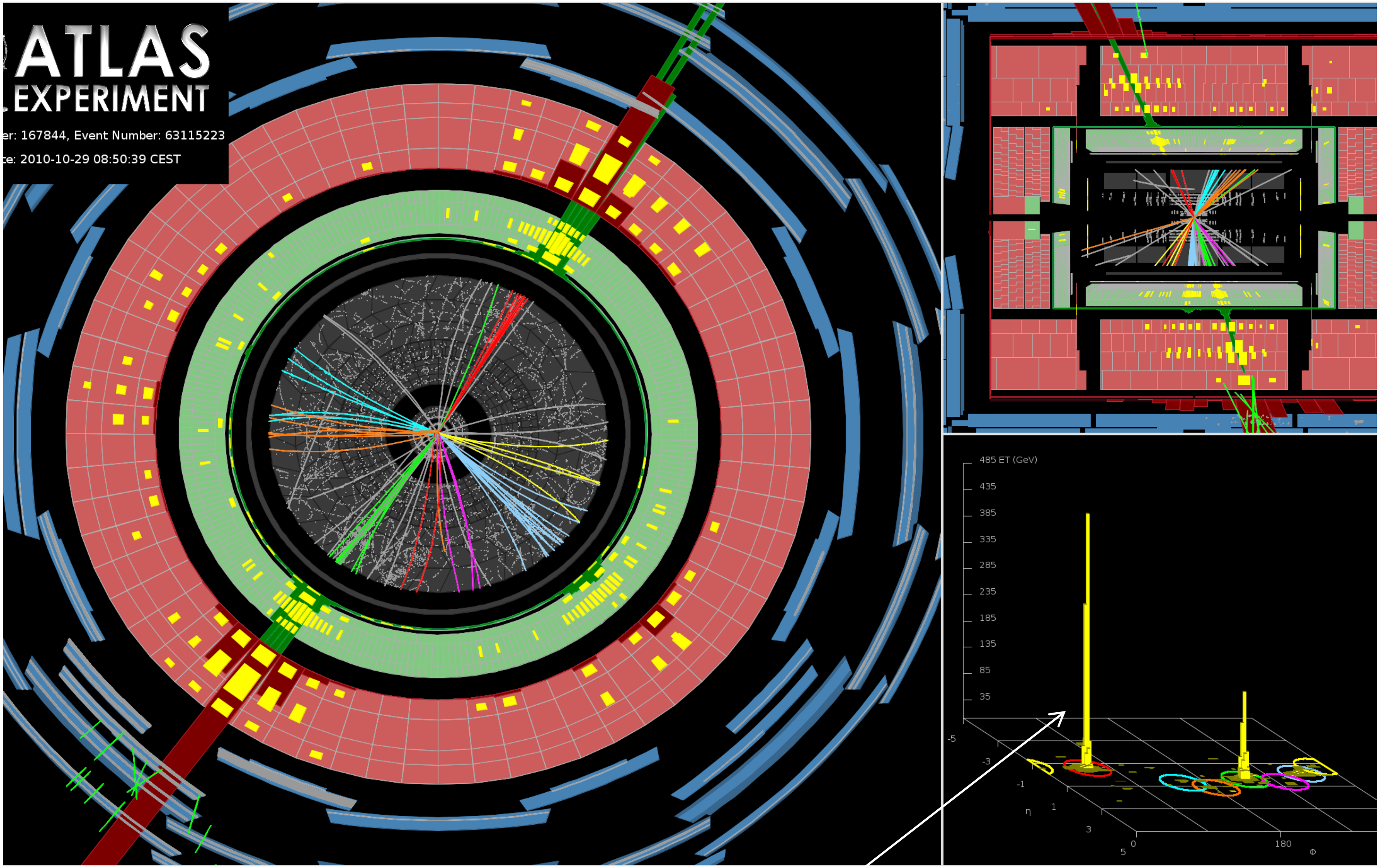






arXiv:1103.1816

LHC: inclusive jets



1.5 TeV jet

LHC jets

- ATLAS and CMS are both using an IR-safe jet algorithm (anti-kT)
  - the theorists are ~~happy~~ ecstatic (according to Lance Dixon
- Unfortunately no common sizes

  $$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

  - 0.4 and 0.6 for ATLAS
  - 0.5 and 0.7 for CMS
- It would be nice to
  - have at least one common jet size
  - exploit any capability to perform analyses with multiple jet sizes/algorithms
  - e.g. SISCone in addition to anti-kT

$$d_{ij} = \min\left(p_{T,i}^{2p}, p_{T,j}^{2p}\right)\frac{\Delta R_{ij}^2}{D^2}$$

$$d_{ii} = p_{T,i}^{2p}$$

- p=1: regular kT algorithm
- p=0: Cambridge-Aachen
- p=-1: antikT algorithm

Cacciari, Salam, Soyez '08

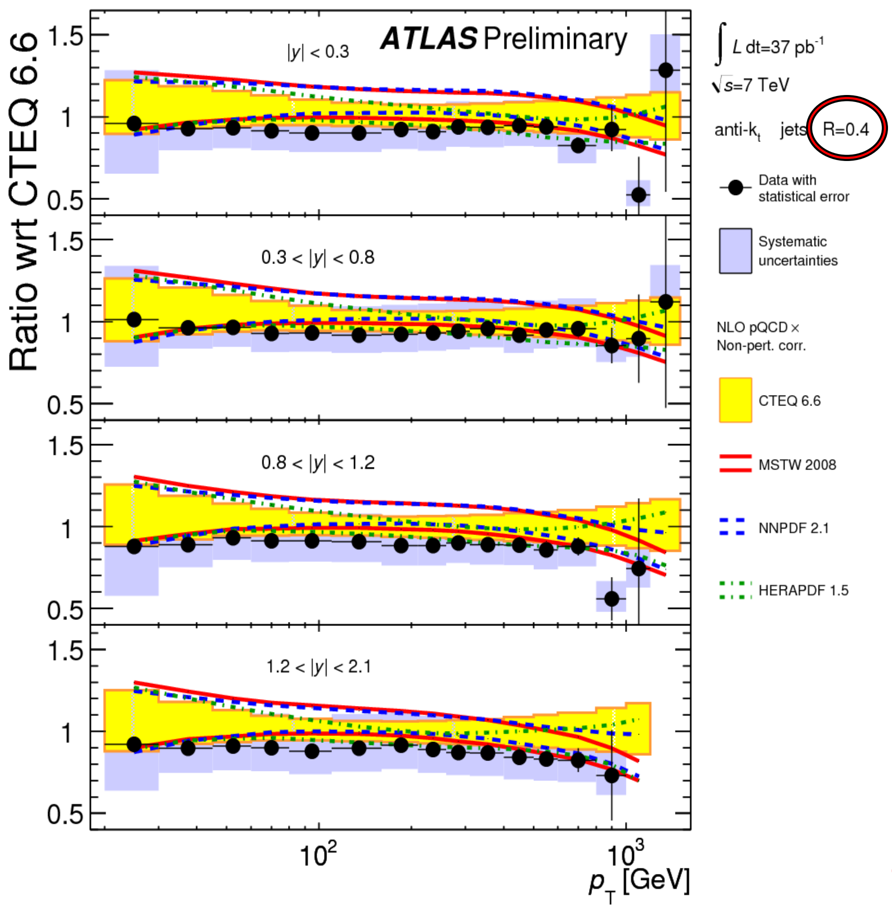
P-A. Delsart, reverse kT '08

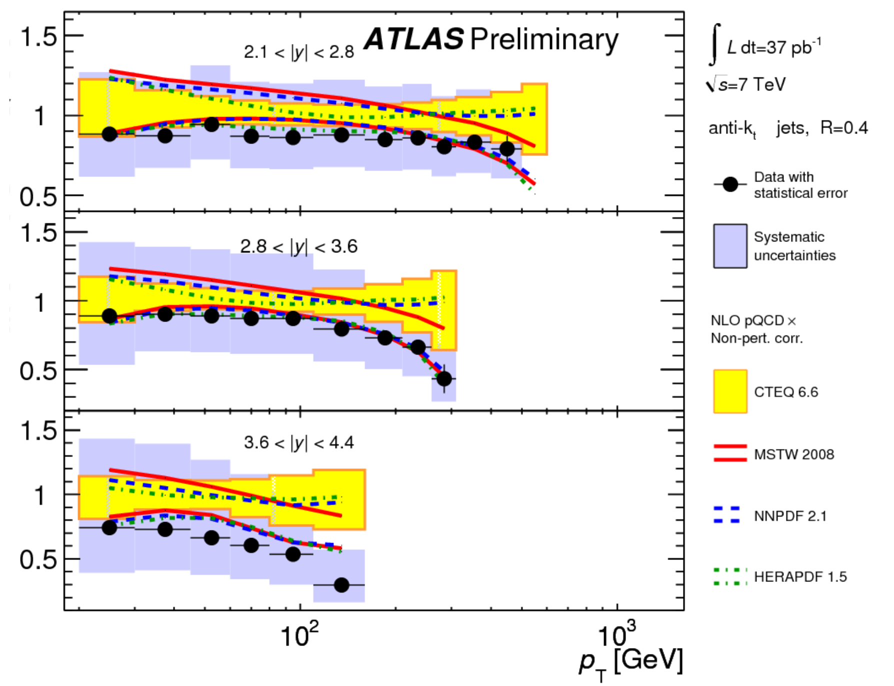
- Both ATLAS and CMS have the potential to allow for more flexibility in jet analyses, something which should be encouraged

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.

ATLAS-CONF-2011-047

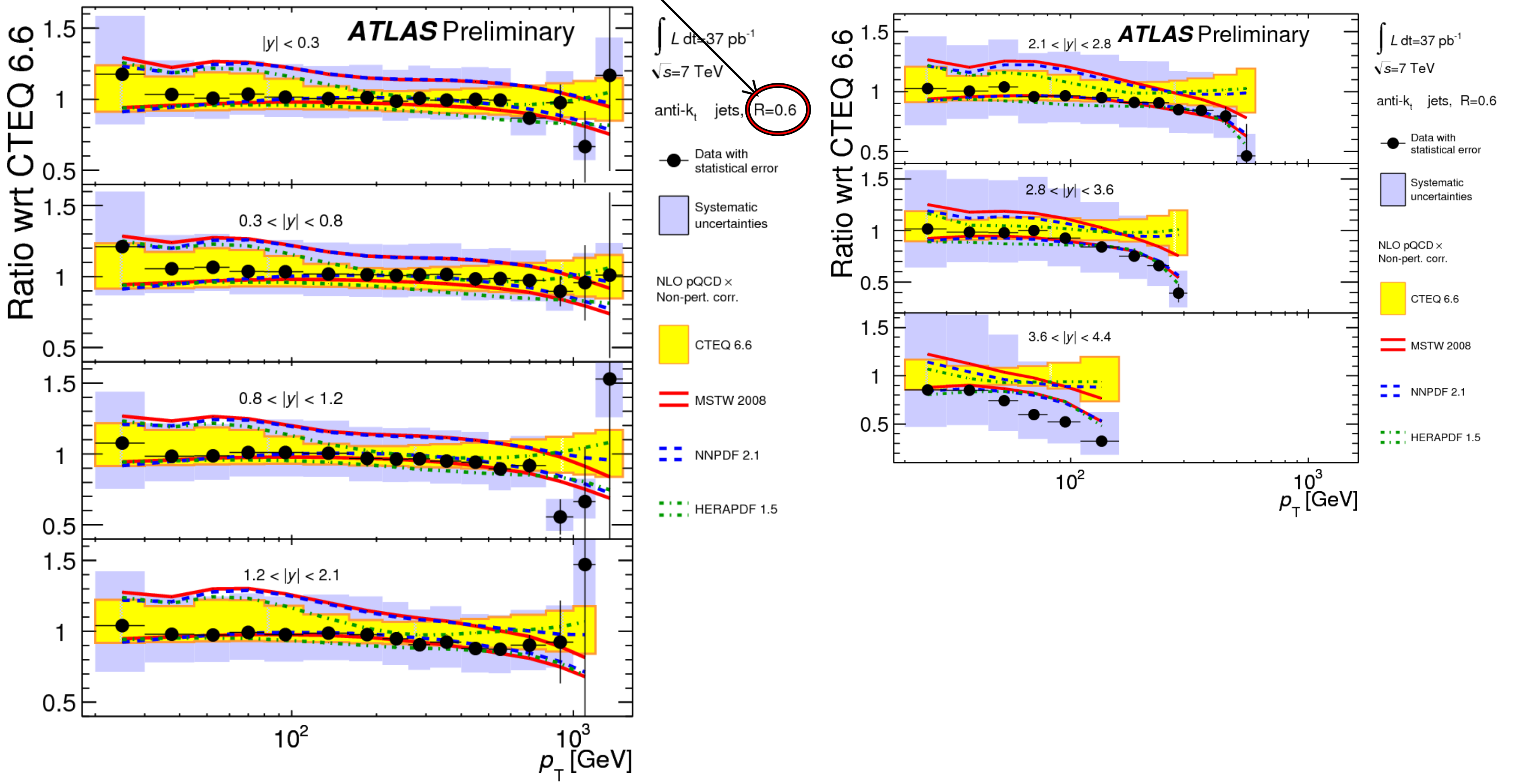




but the use in global PDF fits is possible only once detailed correlated systematic error information is made available. For jets, systematic errors are much more important than statistical errors.

ATLAS: inclusive jets

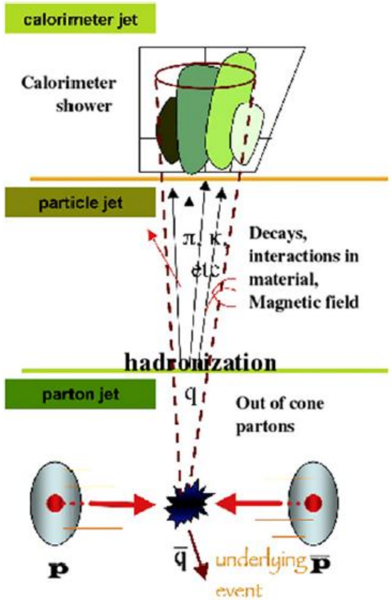
Important to use more than one jet size. Different dependence on underlying event, fragmentation and also on perturbative prediction.



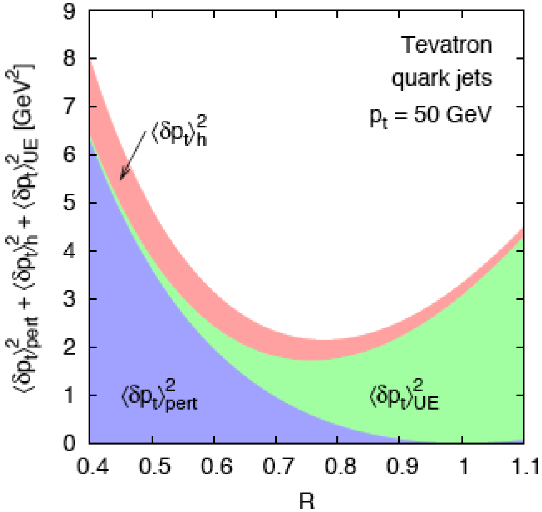
Choosing jet size

- 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 referred to previously 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,

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

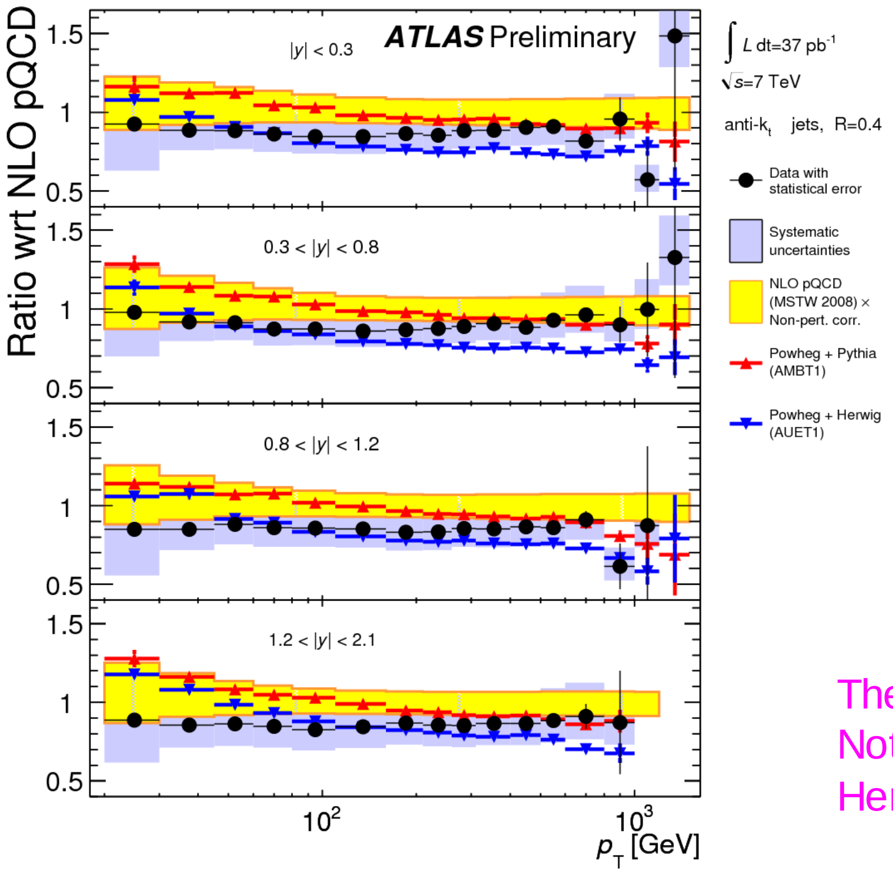


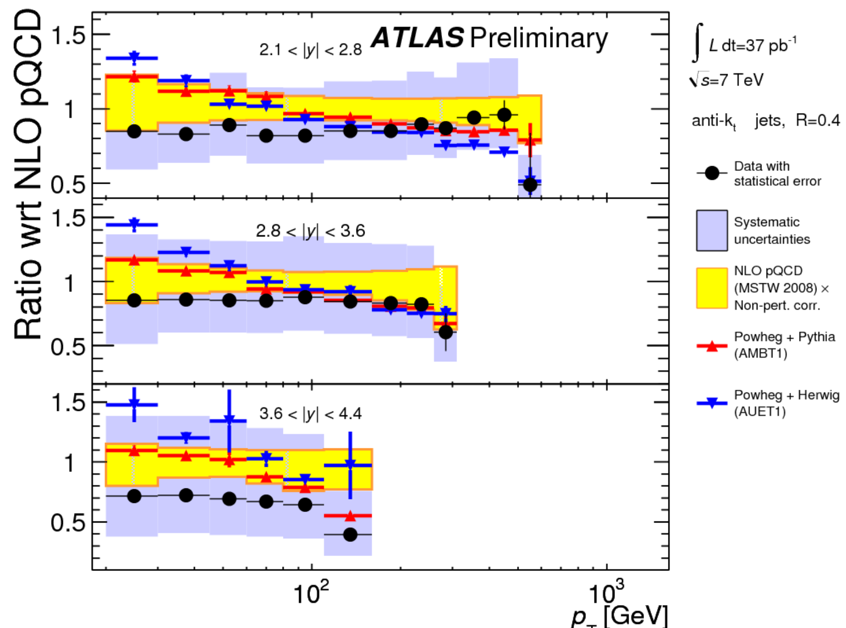
Dasgupta, Magnea, Salam arXiv0712.3014



Inclusive jets: Powheg

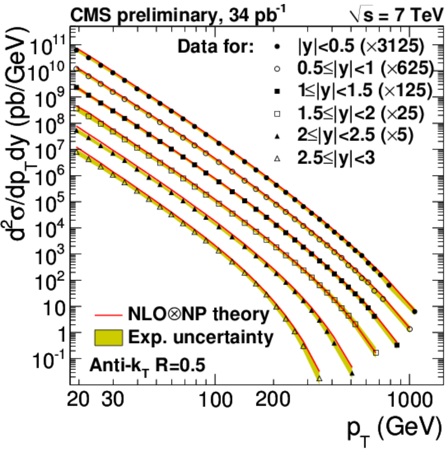
- Powheg is a method for the inclusion of NLO matrix element corrections into parton shower Monte Carlos
- Experimentalists were ecstatic when inclusive jet production was added
- Note that Powheg predictions have a somewhat different shape than fixed order perturbative predictions (NLOJET++). This is something that must be understood,





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

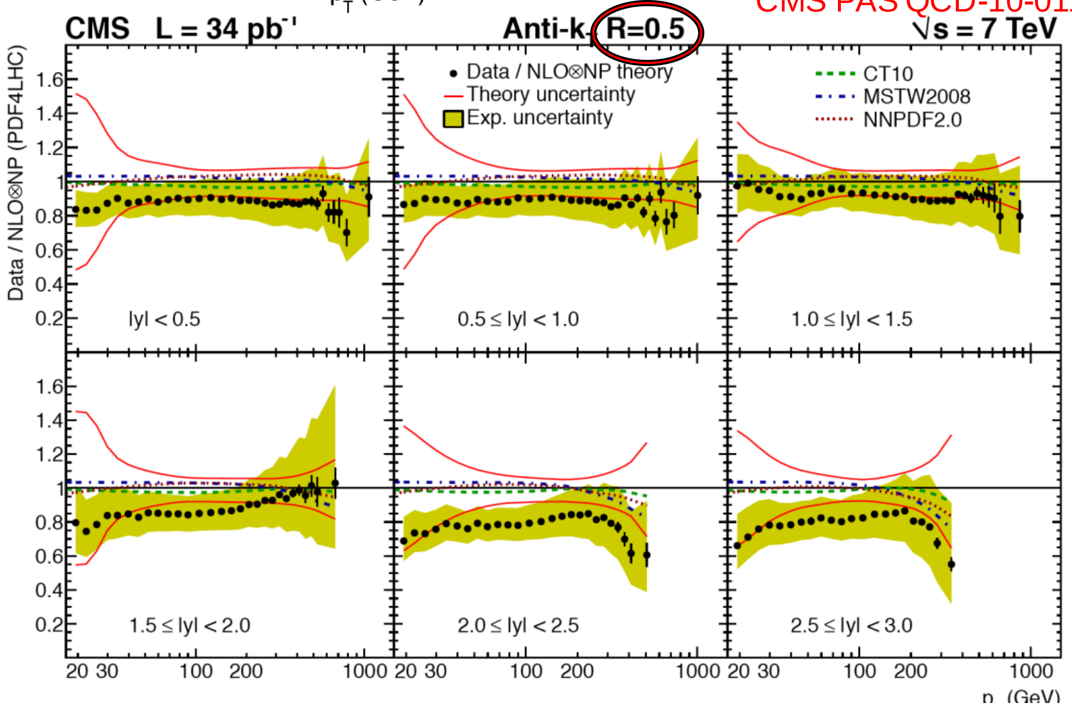
CMS: inclusive jets

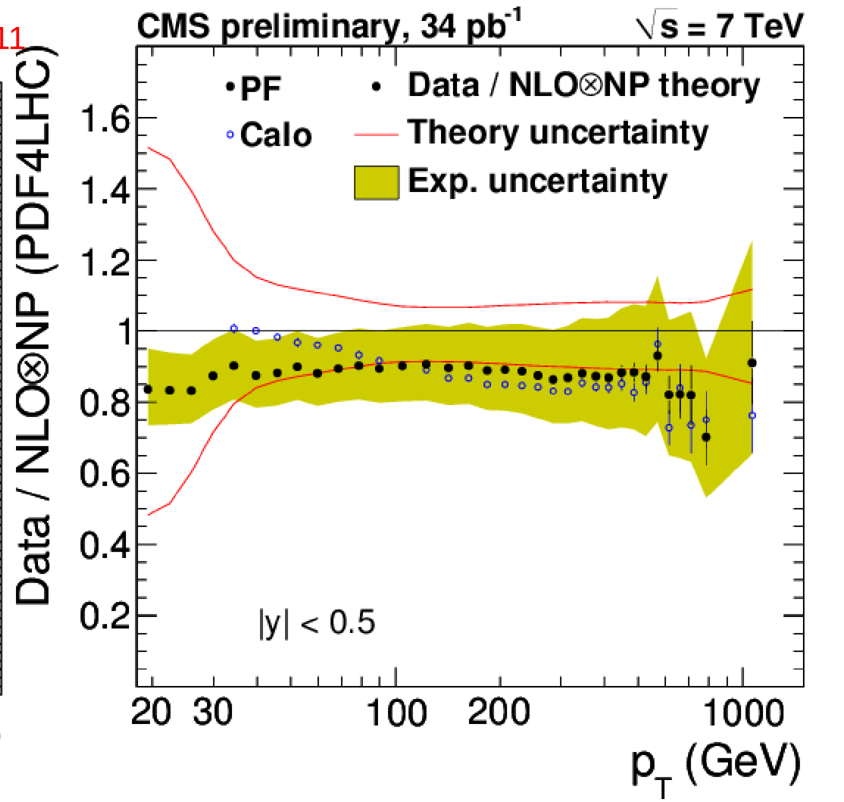


Here the comparison is to predictions using the midpoint of CT10, MSTW2008 and NNPDF2.0, with the error band given by the envelope (i.e. the PDF4LHC prescription). The theory error also includes the scale choice and NP uncertainties.

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.

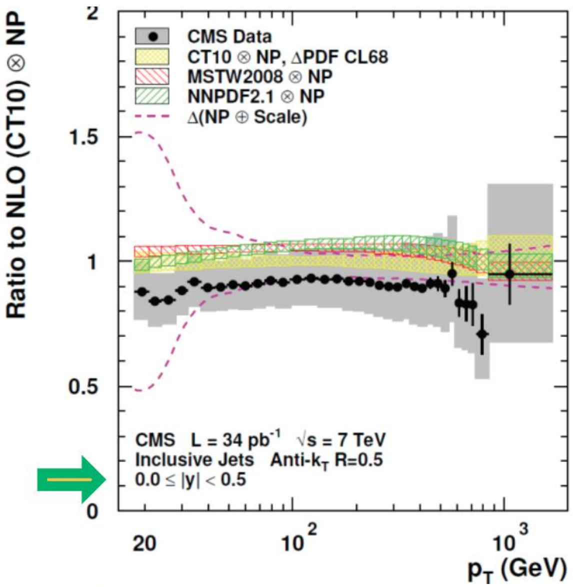
CMS PAS QCD-10-011

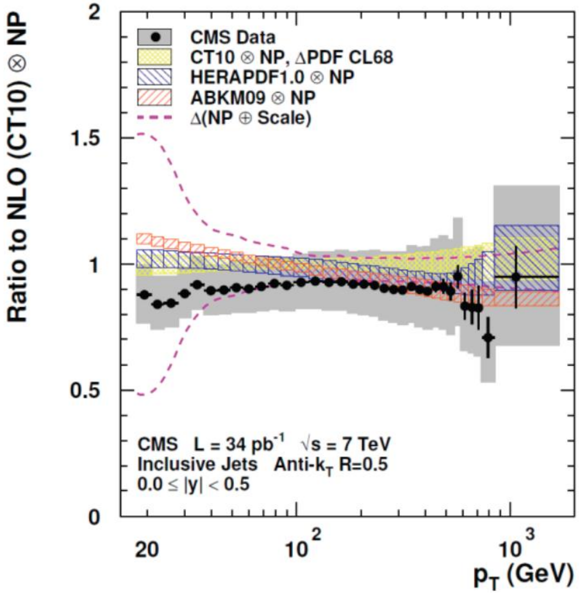




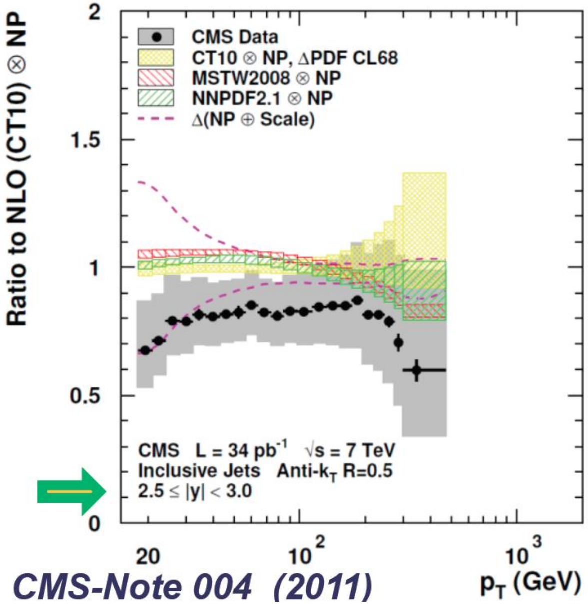
…agreement but data a bit low compared to theory

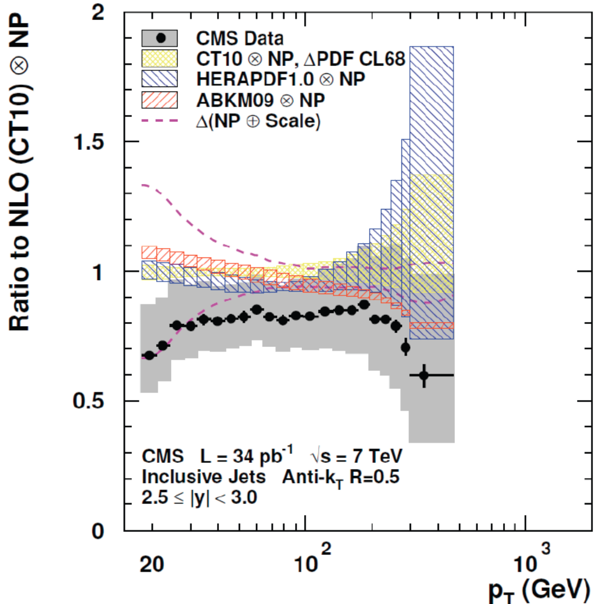
Comparisons to additional PDFs





The data tends to fall off more rapidly at high p_T and y than the predictions using current PDFs.





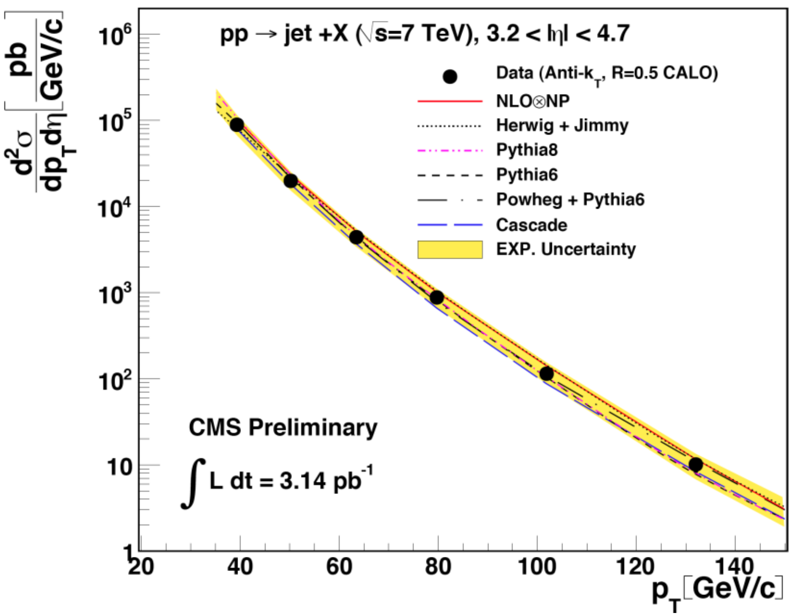
There are some current phenomenological issues regarding the best scale to use in fixed order theory for very forward kinematics.

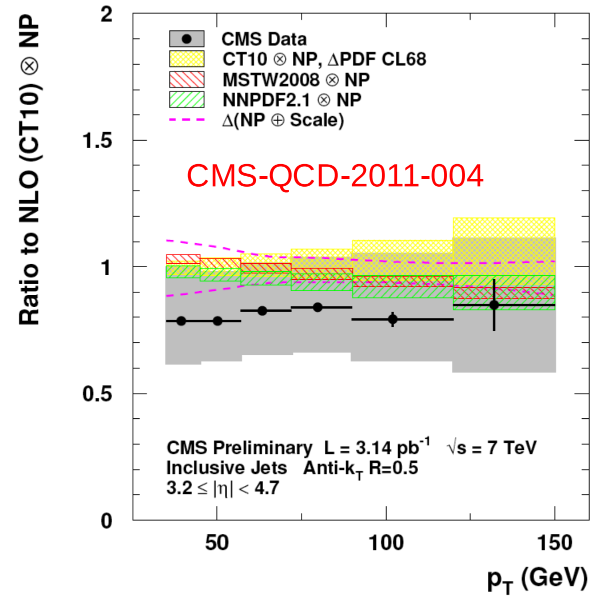
Some *traditional* scales can lead to negative cross sections.

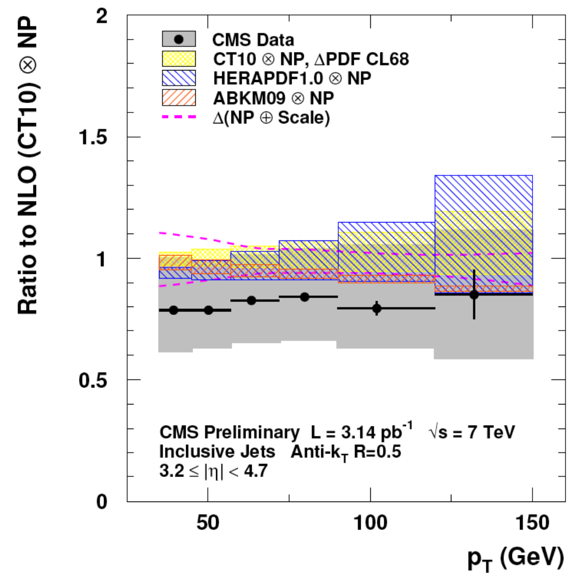
CMS-Note 004 (2011)

CMS: forward jets

- CMS has measured forward jet production (up to an $|\eta|$ of 4.7 with a reduced luminosity sample (3.14 pb^{-1})







- NLO predictions from the various PDFs are fairly similar with each other, and agree, within systematic errors, with the data

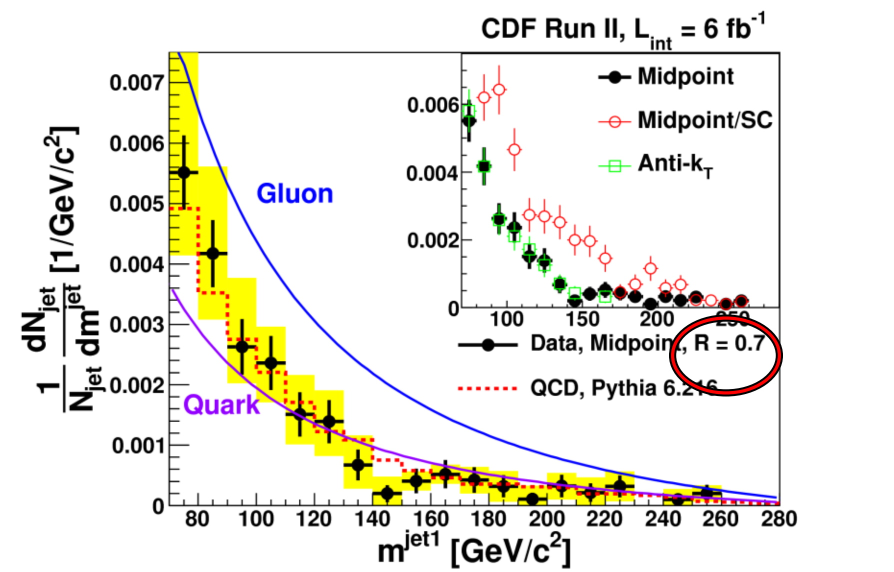
Jets->CDF: jet structure

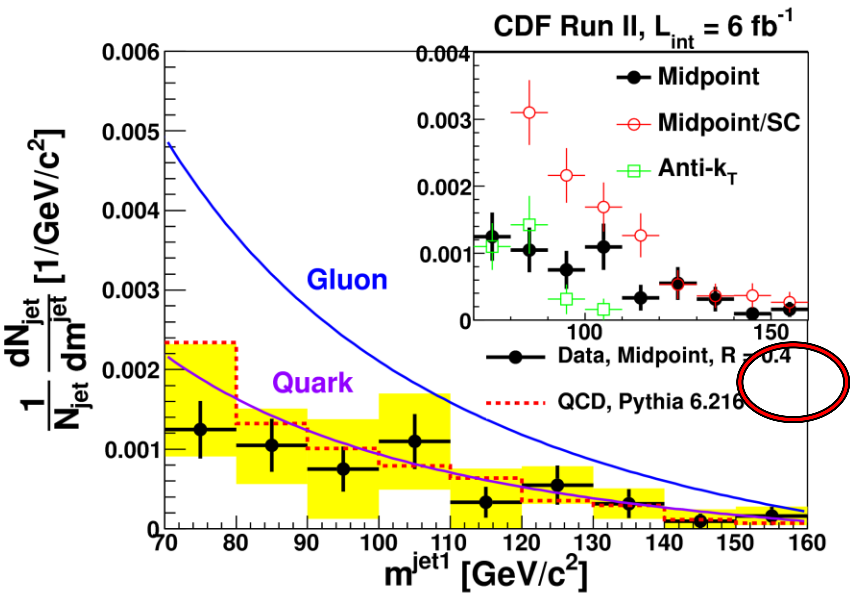
Look at jet mass for jets with p_T>400 GeV/c, 0.1<|η|<0.7, R_{cone}=0.4,0.7 and 1.0, corrected for multiple interactions, and with top rejection cuts

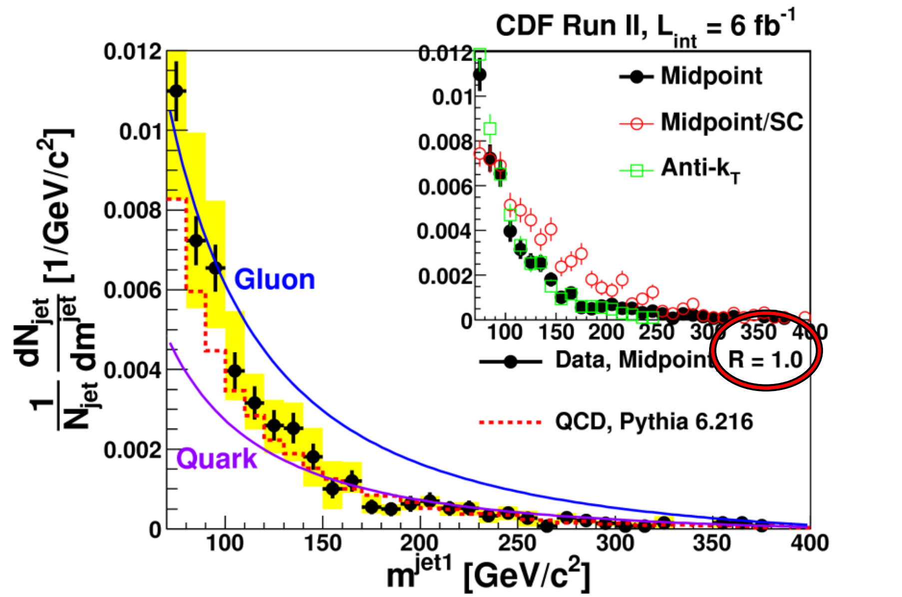
Above the mass peak, the jet mass distribution should be described by the expression

$$J(m_J, p_T, R) \approx \alpha_s(pT)\frac{4C_{q,g}}{\pi m_J}\log\left(\frac{Rp_T}{m_J}\right)$$

where C is the appropriate color factor for quarks (4/3) or gluons (3)

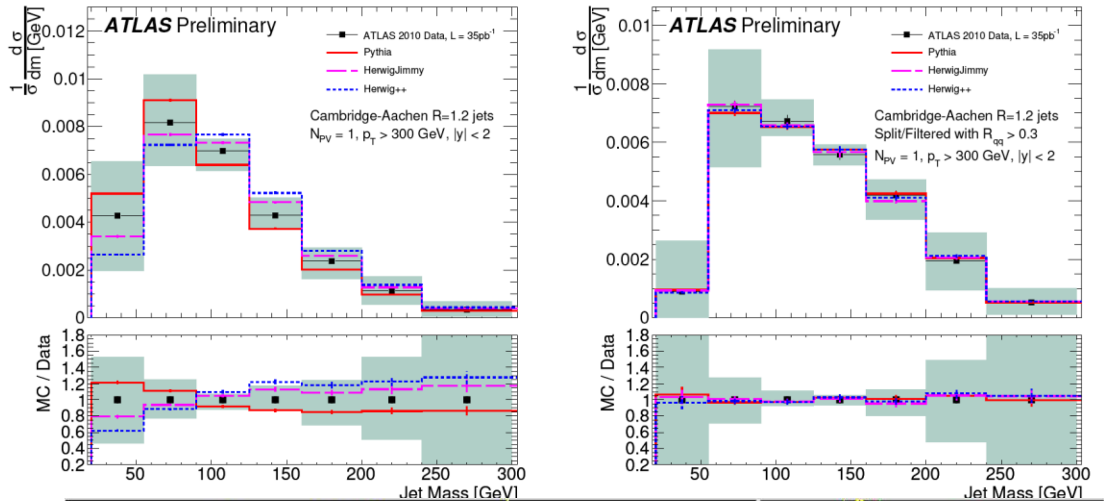


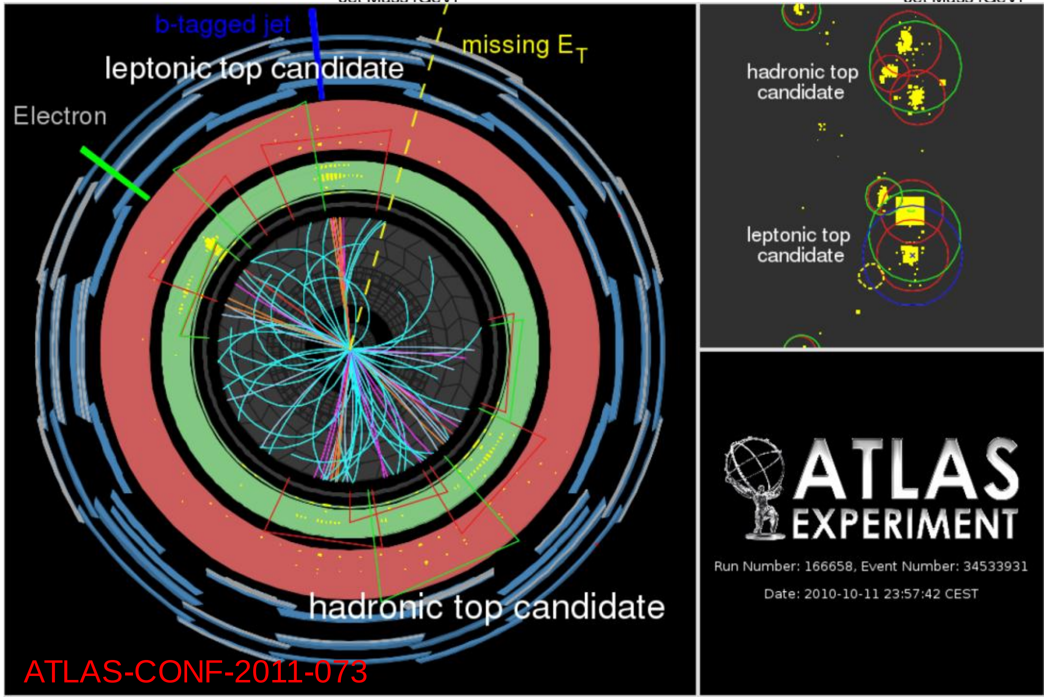




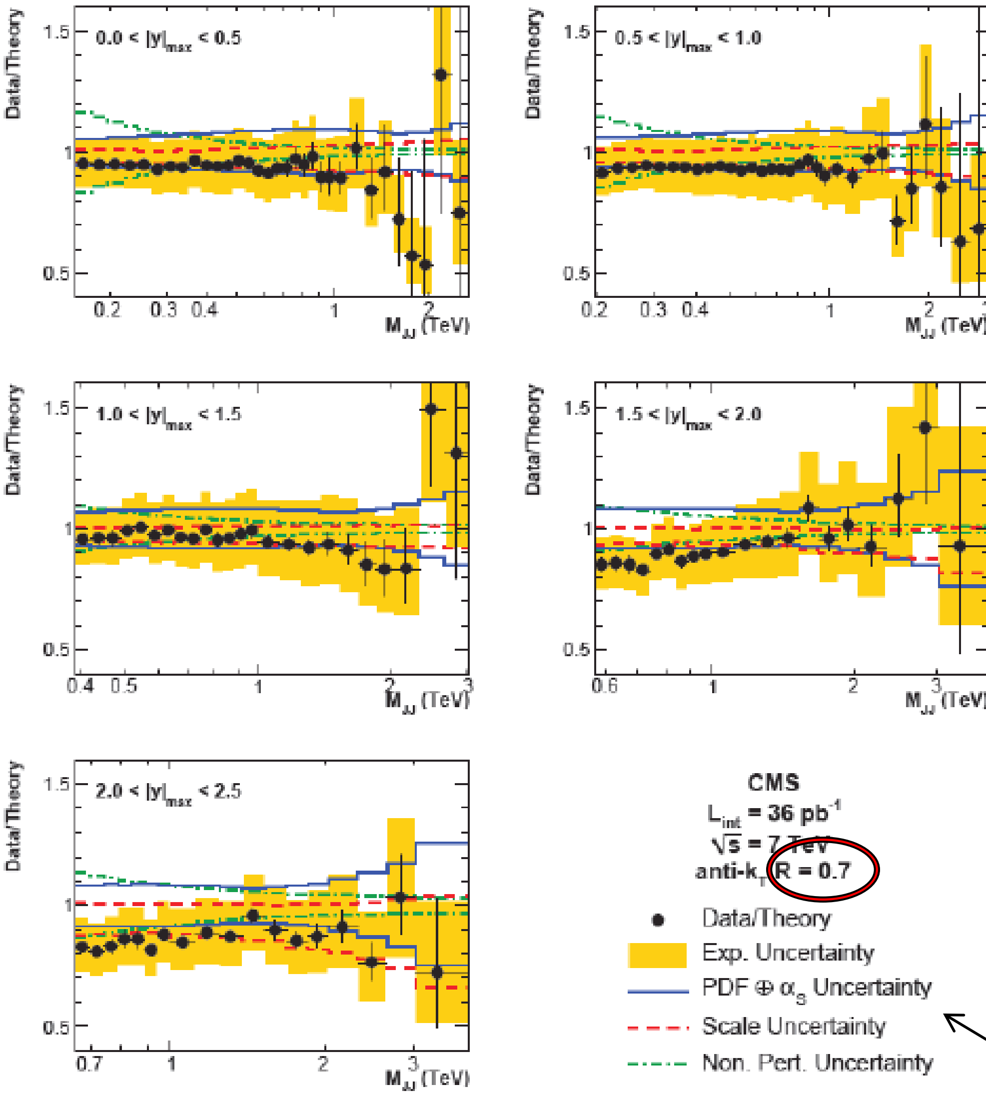
ATLAS: jet masses

- Quite an extensive technology has arisen in the last few years regarding trimming, filtering, pruning jets to reveal the underlying hard scatter/massive decay products, especially on boosted jets
- The top right plot shows the mass distribution for jets (p_T>300 GeV, |y|<2) reconstructed with the Cambridge-Aachen algorithm with R=1.2, before (left) and after (right) a splitting and filtering algorithm has been applied
- The bottom right plot shows a boosted top candidate (p_T=356 GeV), clustered with the anti-kT algorithm with

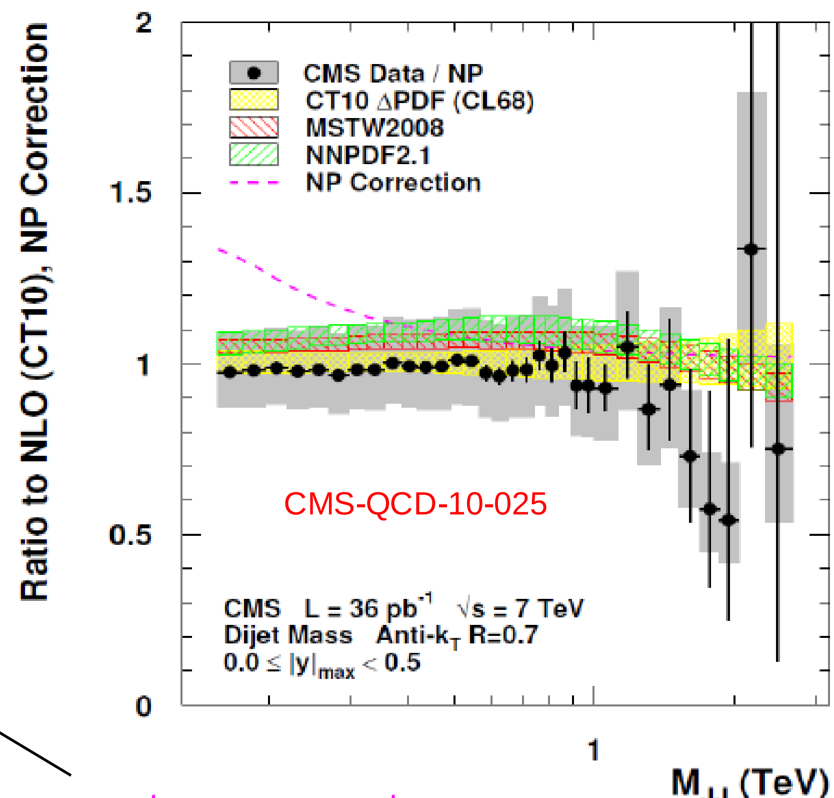




CMS: dijets



Here, the results (plotted vs y_{max}, the maximum rapidity of the two leading jets, are in reasonable agreement with the NLO predictions (using CT10) over the full kinematic range.

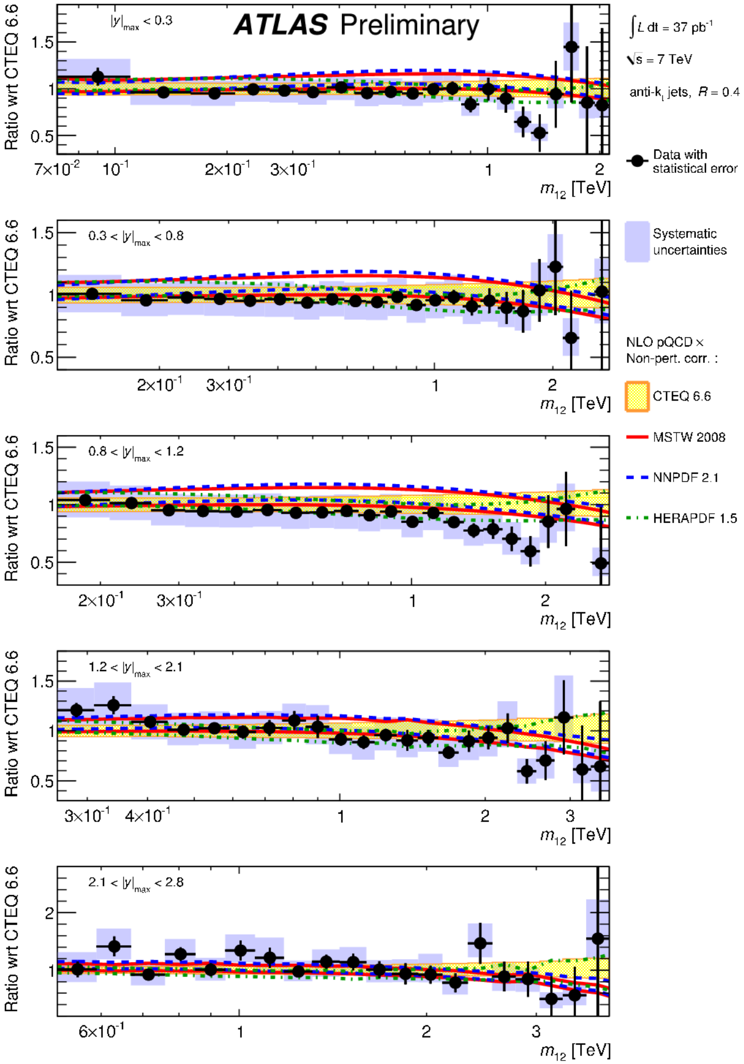


Theory error broken down into separate components.

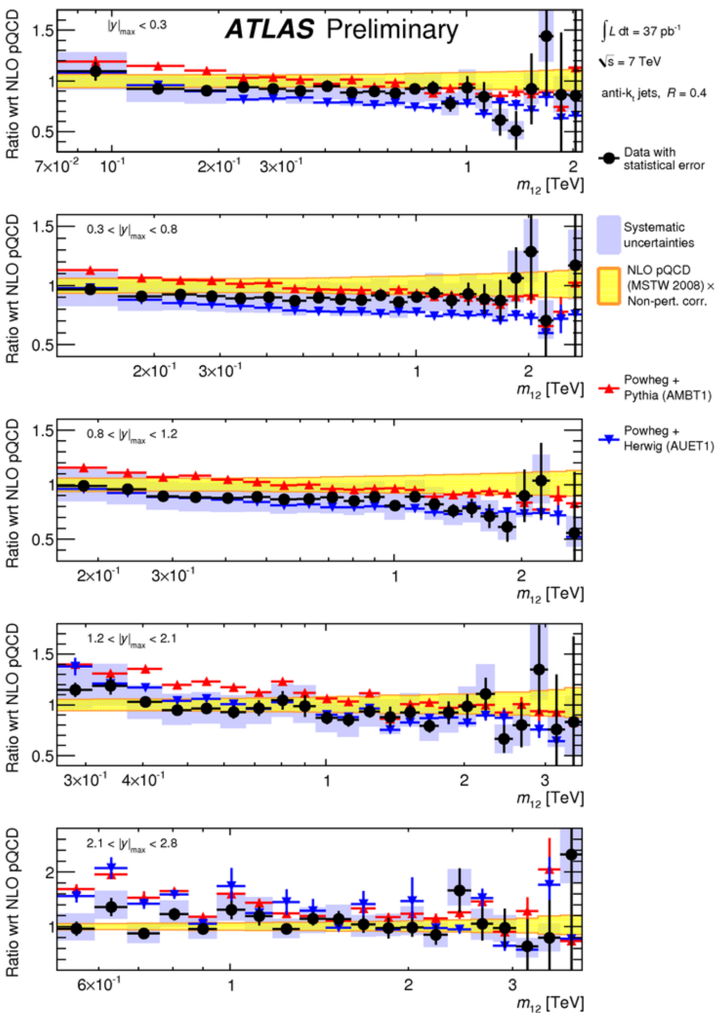
ATLAS: dijets

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

NLOJET++



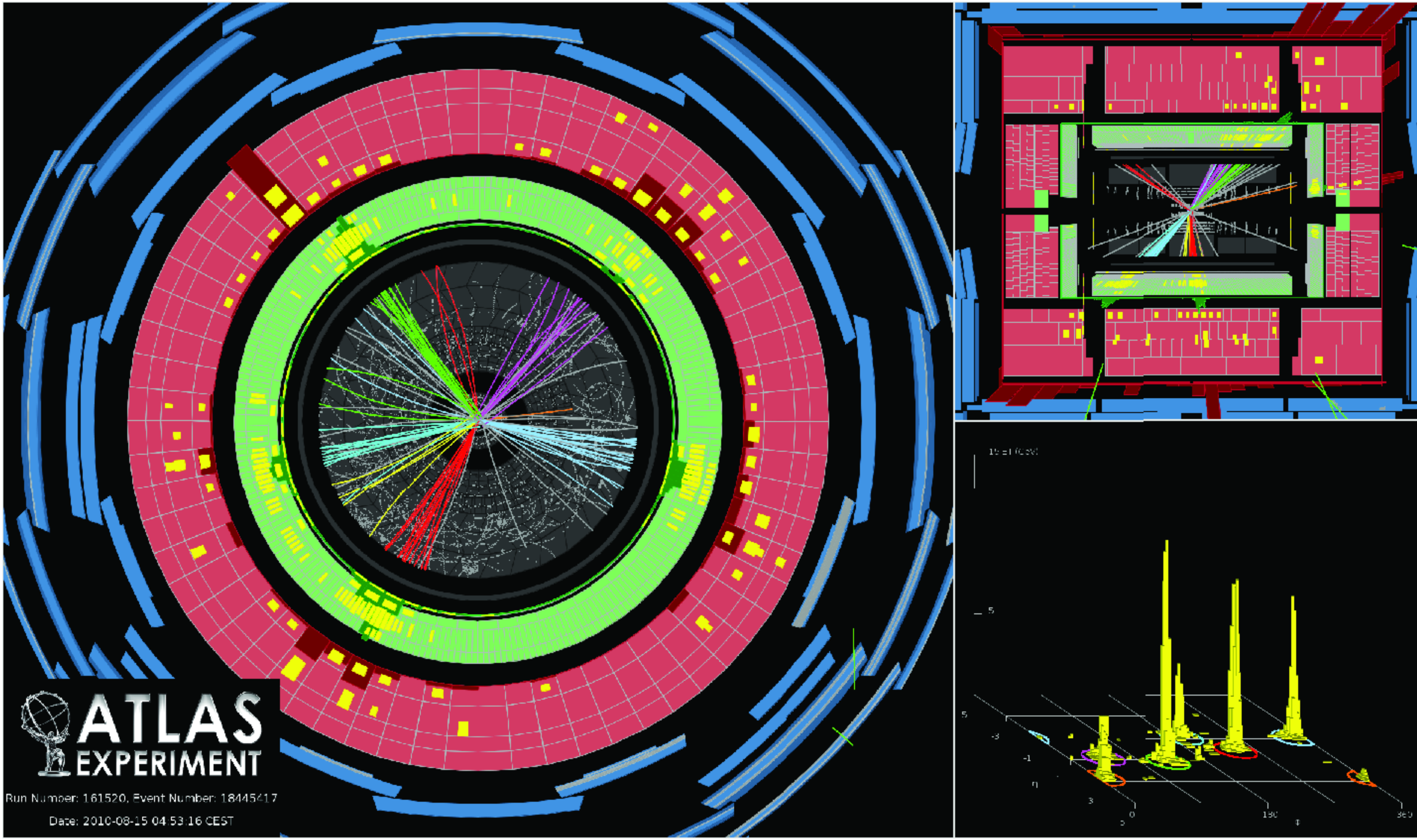
Powheg



ATLAS-CONF-2011-047

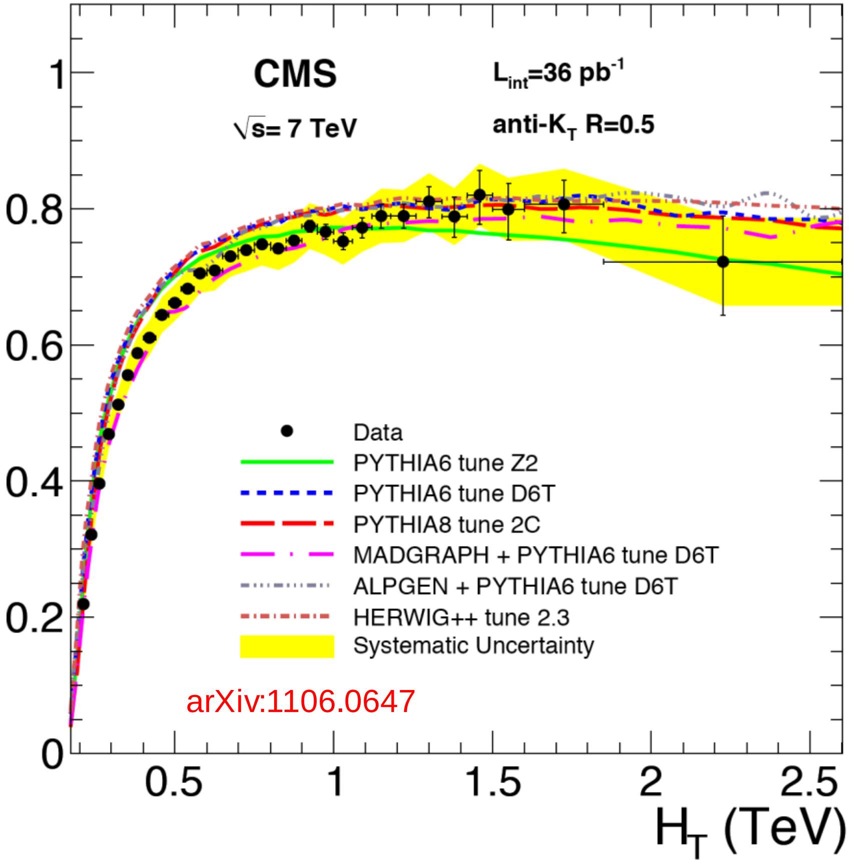
Again, as for inclusive jet production, we see that there are some shape differences between fixed order and Powheg that need to be understood, especially in the forward region.

LHC: multijet production



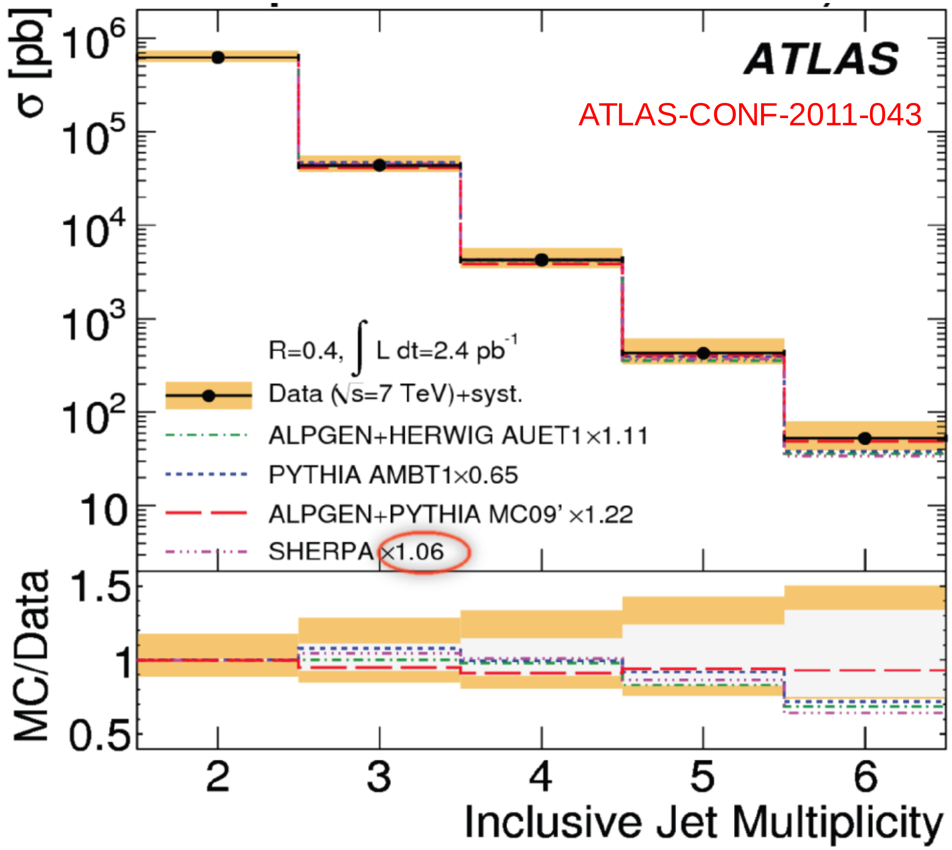
LHC: Multijet Production

CMS: 3 jet to 2 jet ratio vs H_T (sum of p_T's)



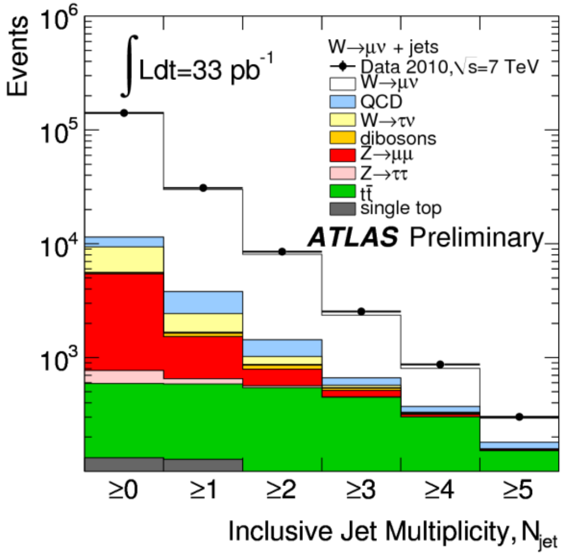
Potential for a measurement of α_s.

ATLAS: inclusive jet multiplicity



Good agreement with matrix element + parton shower predictions, if normalizations are allowed to float. Sherpa requires lowest normalization.

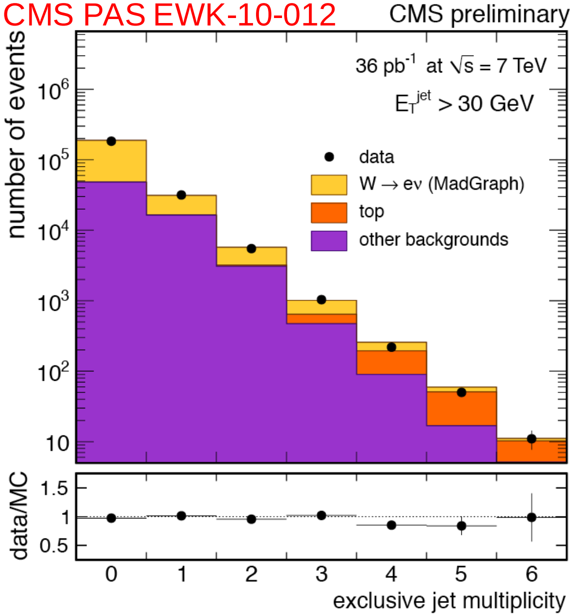
LHC: W/Z+jets

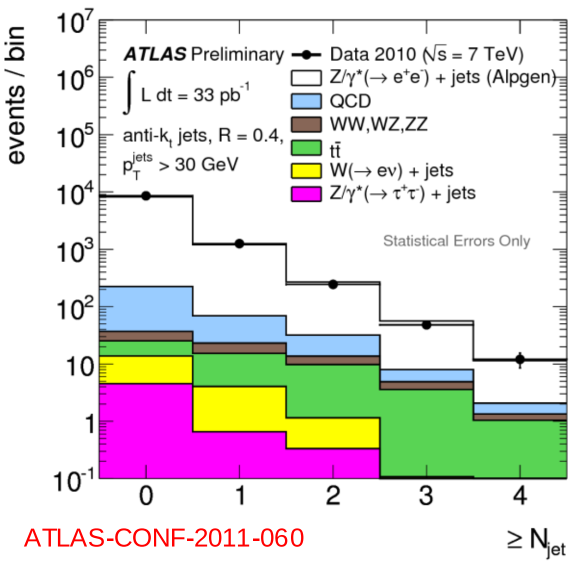


Even with only 33 pb^{-1}, can access higher jet multiplicities and test the new theoretical predictions that have become available in the last few years.

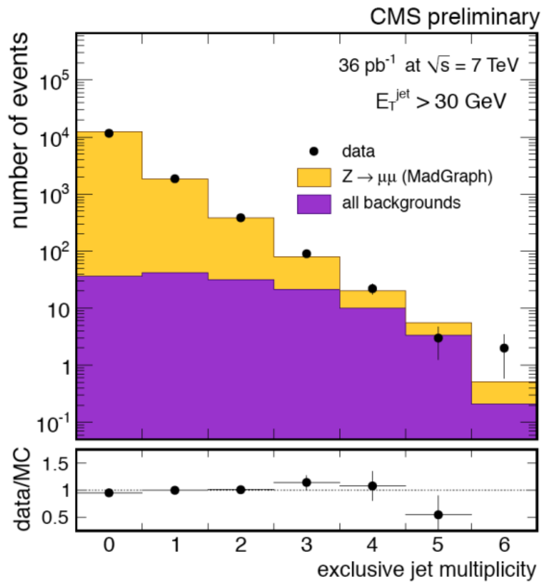
Such high jet multiplicity final states will serve as signal channel (and background) for new physics searches at the LHC.

CMS PAS EWK-10-012



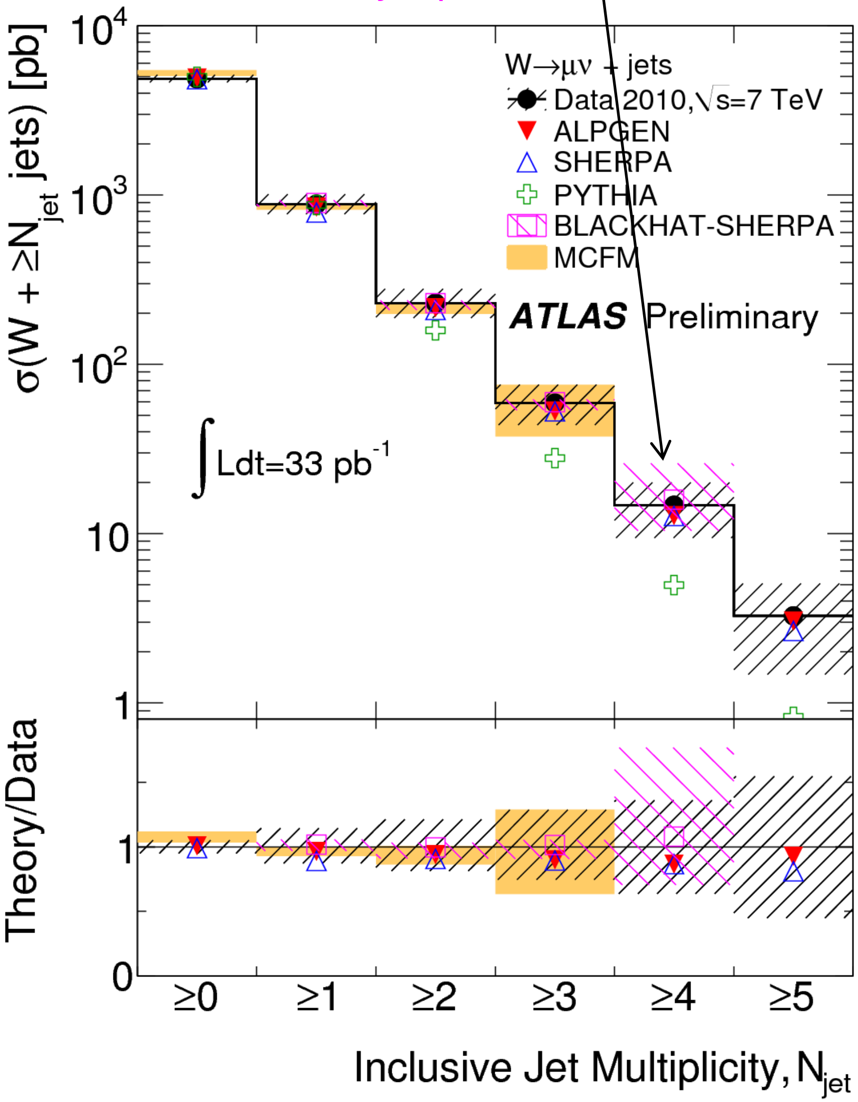


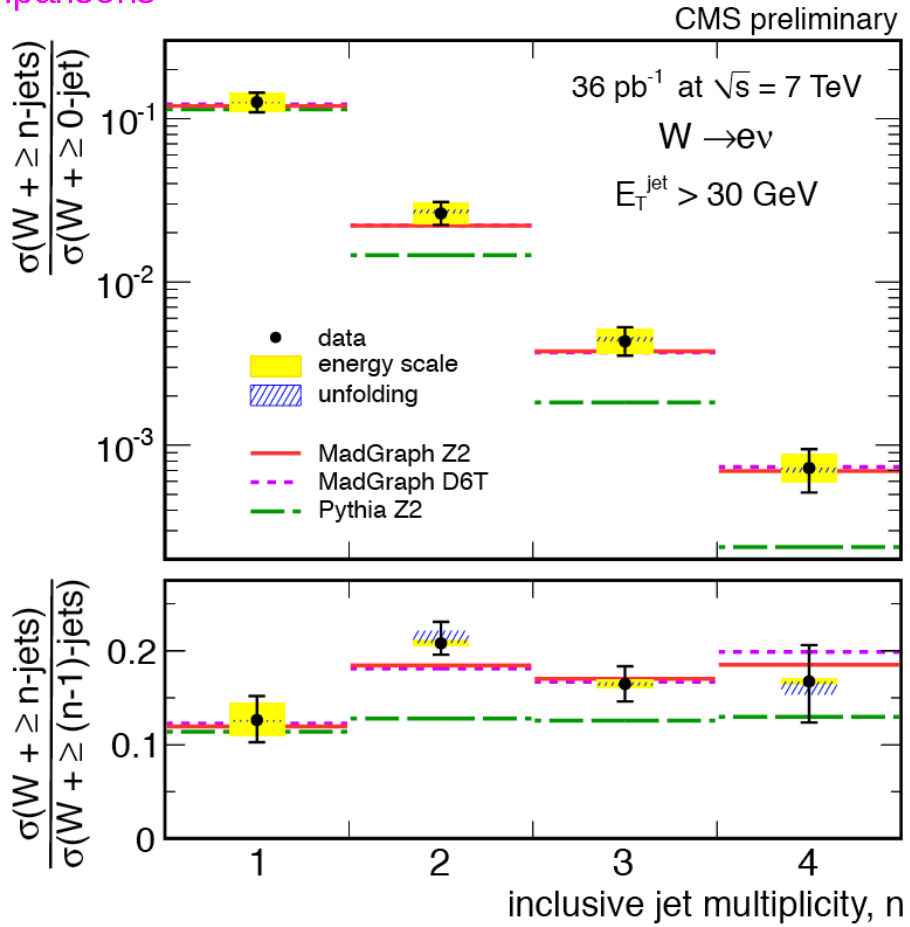
ATLAS-CONF-2011-060



LHC: W/Z+jets

BH+S is LO only for 4th jet; NLO comparisons not yet public

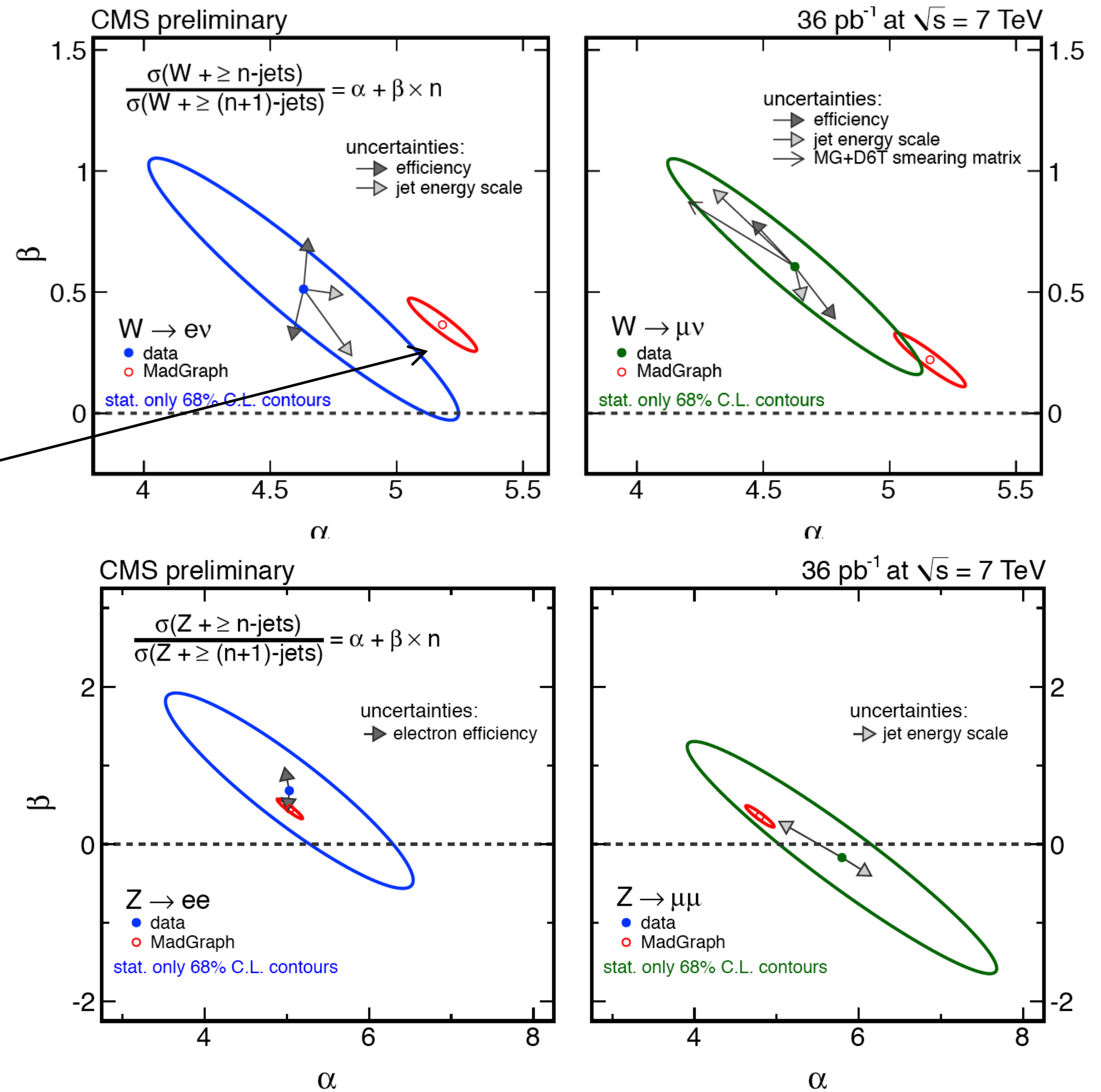


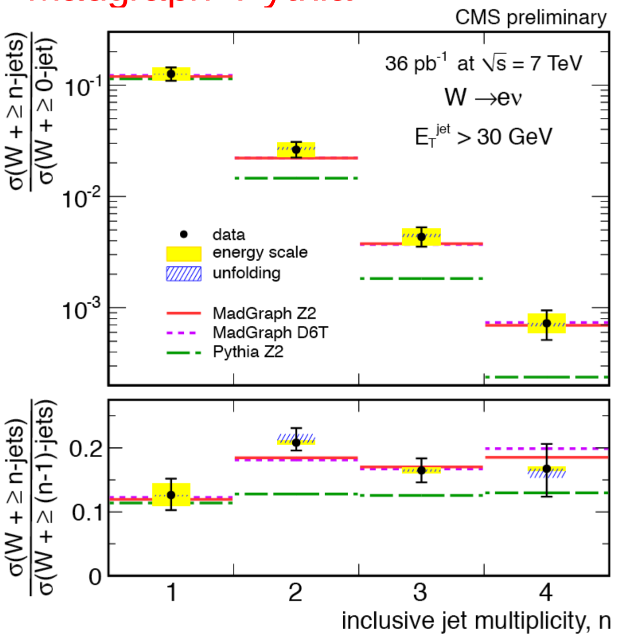


Note the use of Blackhat+Sherpa for predictions for 3 and 4 jet final states. First use of B+S by experimentalists (more later).

CMS: Berends scaling

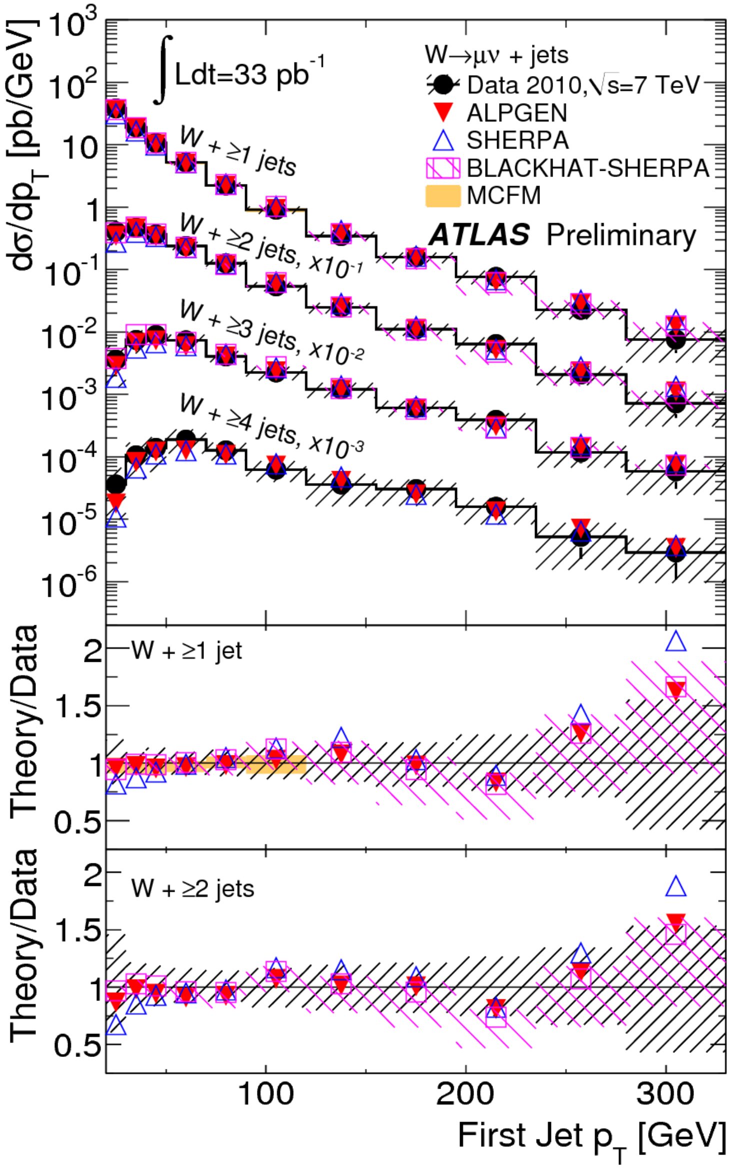
- Test of the empirical scaling observed in W/Z+jets events
- Berends-Giele scaling states that ratio of n jets to n+1 jets is approximately constant for n>=1
- Fit the data with the constraint $C(n)=\alpha+\beta X n$, and compare to theory predicton from Madgraph+Pythia





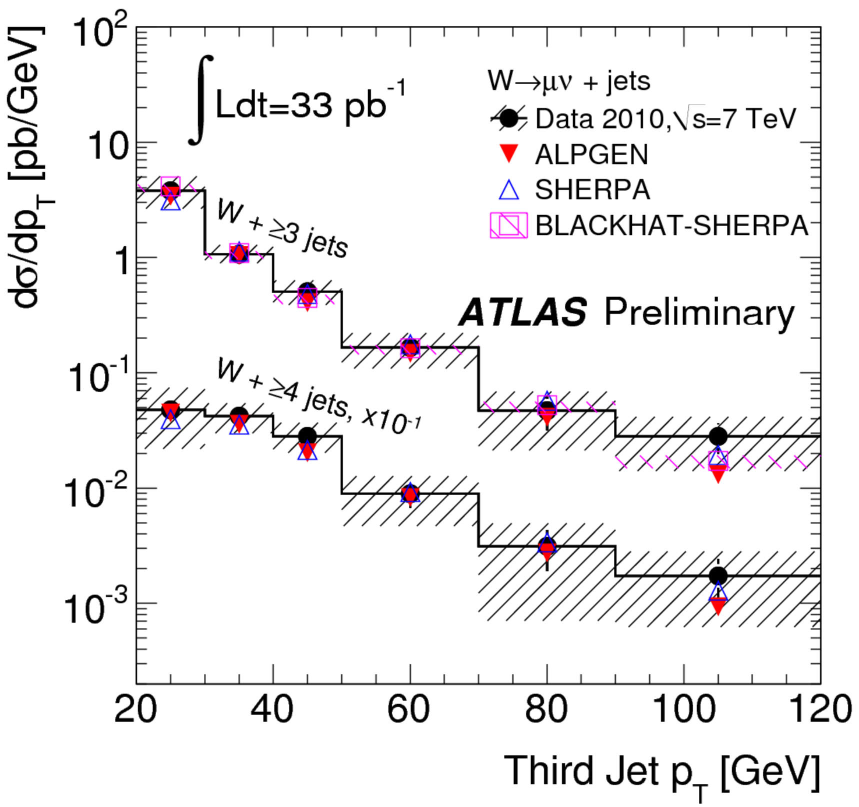
ellipses represent 68% contours (stat only)

ATLAS: W+jets



Good agreement observed between the predictions and the data over full kinematic range. Again, NLO BH+S comparisons to W+4 jets soon to be public.

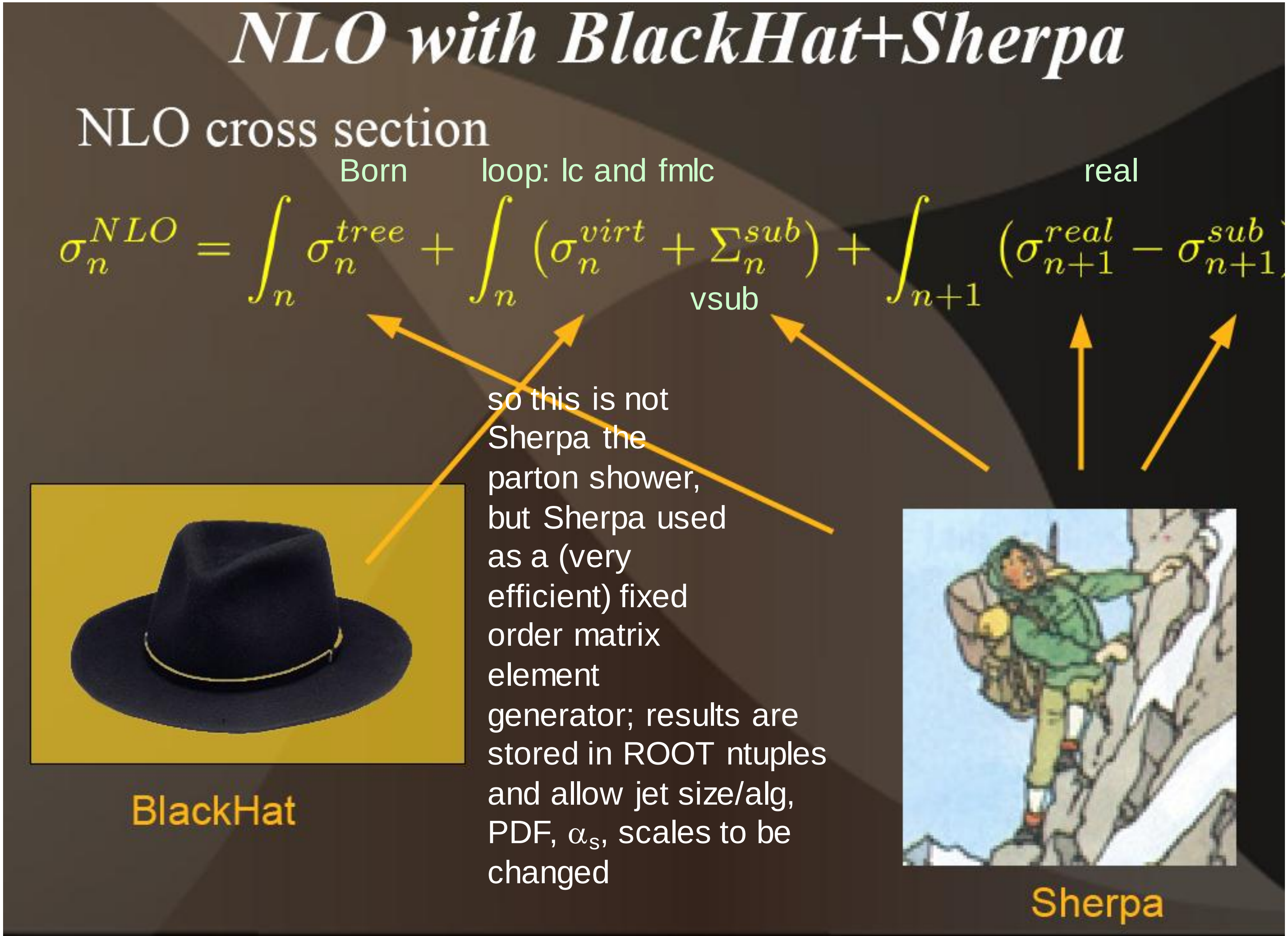
Note that UE/hadronization corrections not trivial, i.e. they don't fall as $1/p_T$, due to to steepness of n jet cross section and multiplicative factor of n jets.



Editorial Comment

- Once we have the calculations, how do we (experimentalists) use them?
- If a theoretical calculation is done, but it can not be used by any experimentalists, does it make a sound?
- We need public programs and/or public ntuples
- Oftentimes, the program is too complex to be run by non-authors
- In that case, ROOT ntuples may be the best solution

For example: Blackhat+Sherpa ntuples



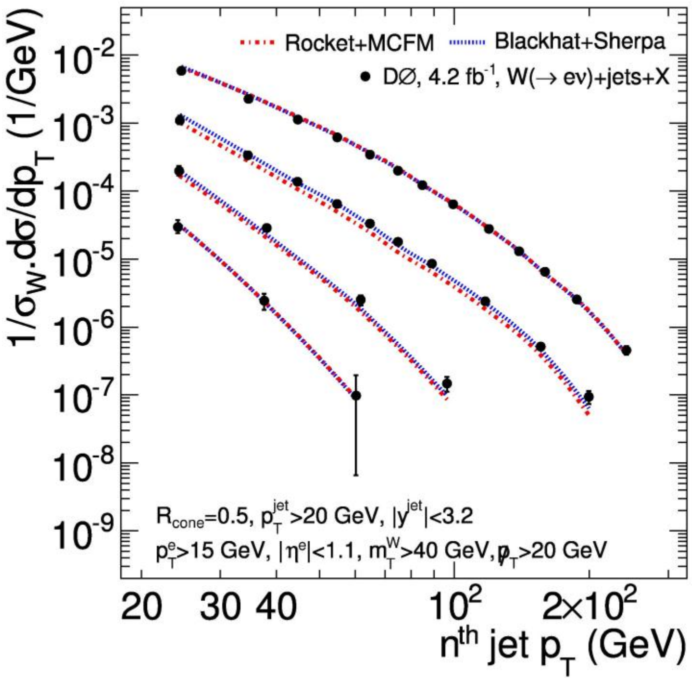
Many calculations have now been done at NLO: Les Houches NLO Wishlist

- Began in 2005, added to in 2007 and 2009
  - only process 12 left among NLO
- Are there other motivated needs for NLO multi-parton final states?
  - from dedicated calculation or automatic calculation?
- Should we move on to expanding the NNLO list?
- There's also the issue of how experimentalists can use these calculations
  - aMC@NLO: but what is the learning curve to get to say W + 3,4 jets at NLO
  - ntuples more practical for immediate future?

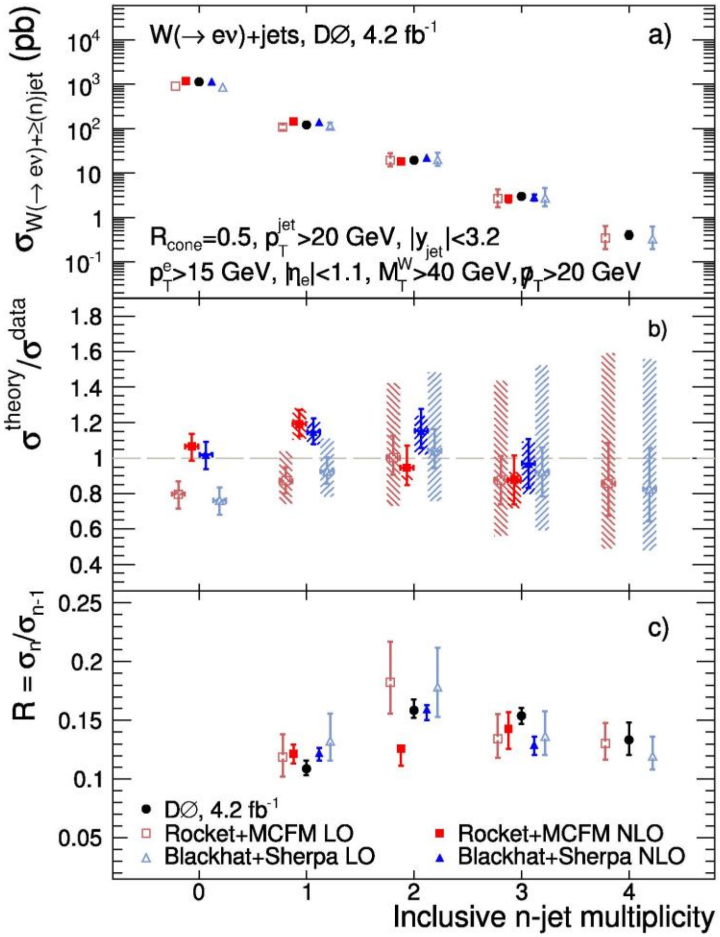
Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [4, 5]; Campbell/Ellis/Zanderighi [6]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9, 10]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14, 15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \to VV b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [20–22]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

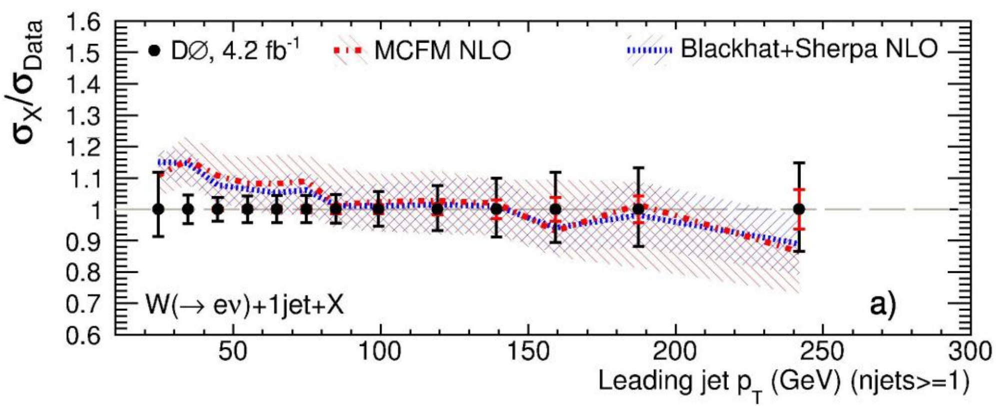
D0:W+jets

arXiv:1106,1457

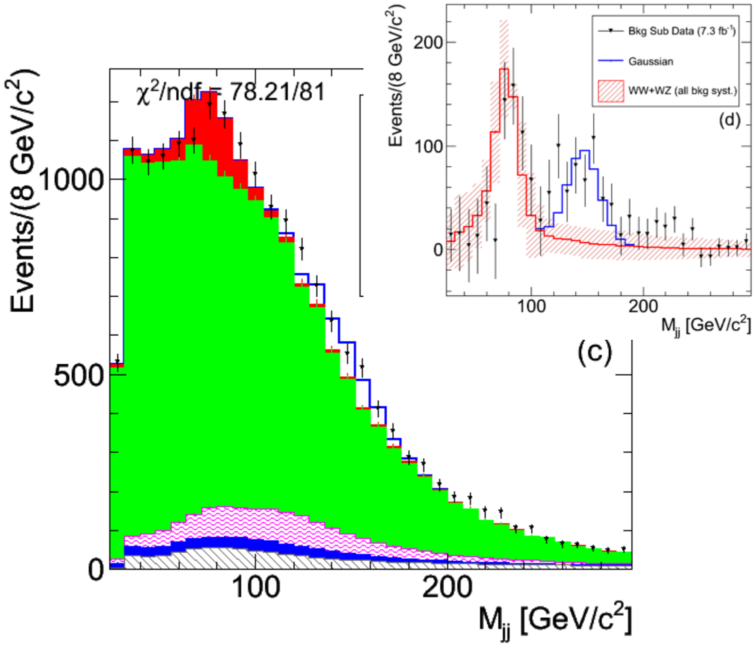


good agreement with NLO predictions from B+S and Rocket

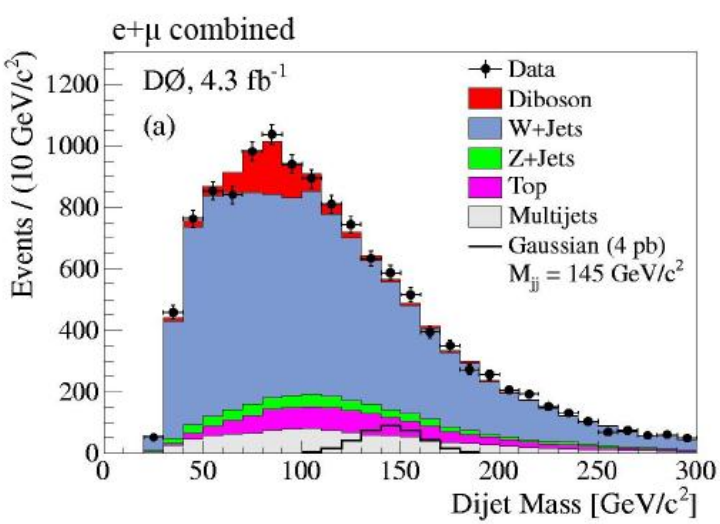


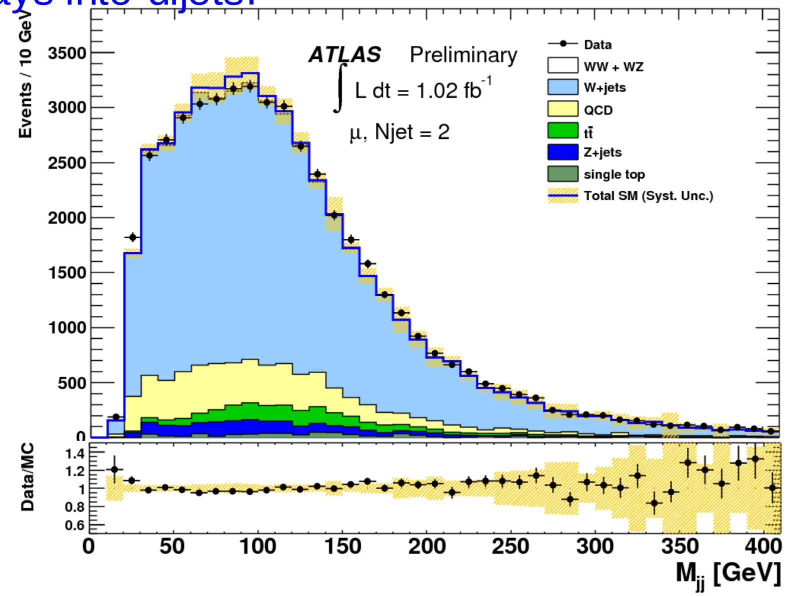


Tevatron+LHC: W + dijets



- CDF observed an excess of events at a dijet mass around 150 GeV. D0 finds a distribution consistent with the standard model.
- Currently, CDF/D0/theorists are working to try to understand the differences in their results; perhaps the most stringest test of modelling of W+jets final state
- Of course, both ATLAS and CMS are looking as well. ATLAS has observed no excess with 1 fb^{-1}. This is expected, as the sensitivity is not present for even observing WW(WZ) where the second W(Z) decays into dijets.

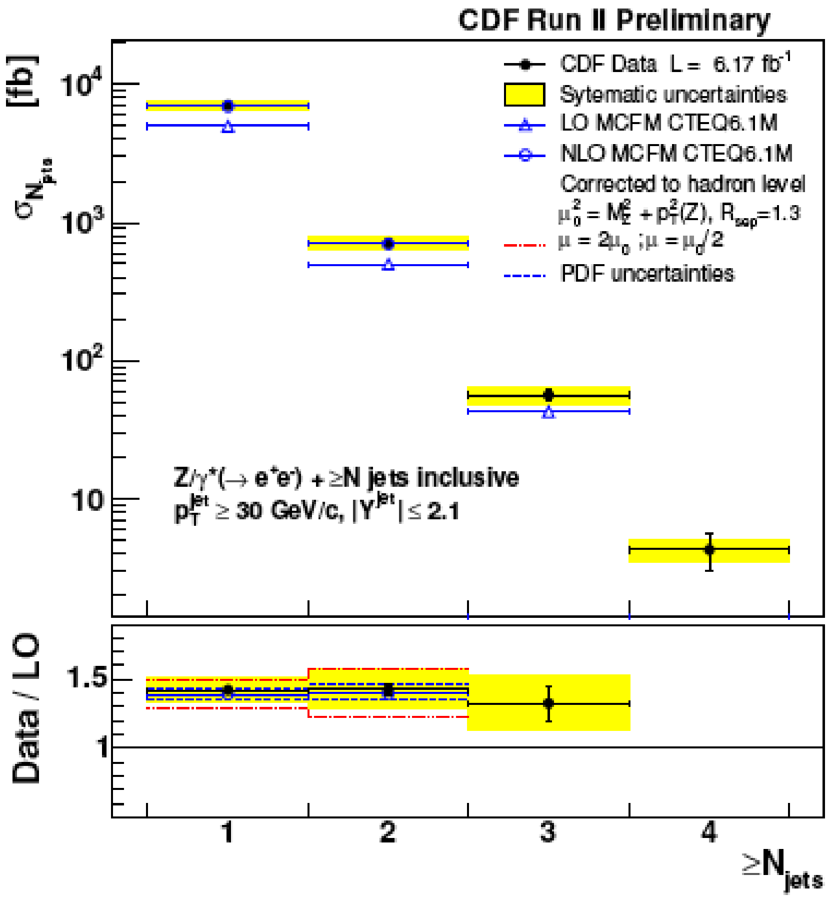




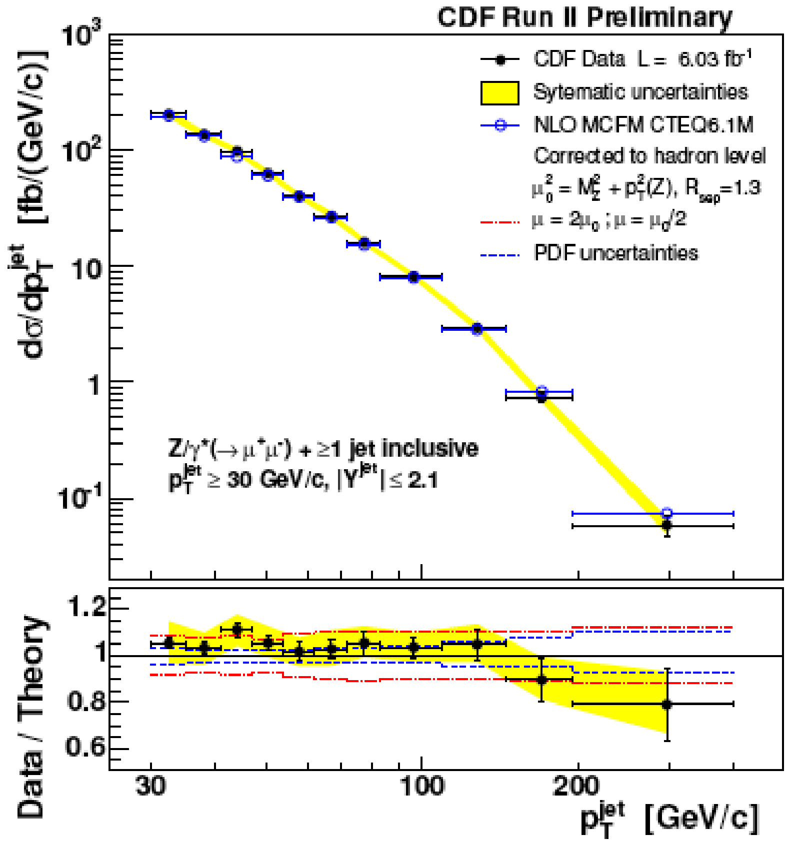
CDF:Z + jets

Measurement with over 6 fb^{-1} allows first access to 4 jet bin at Tevatron

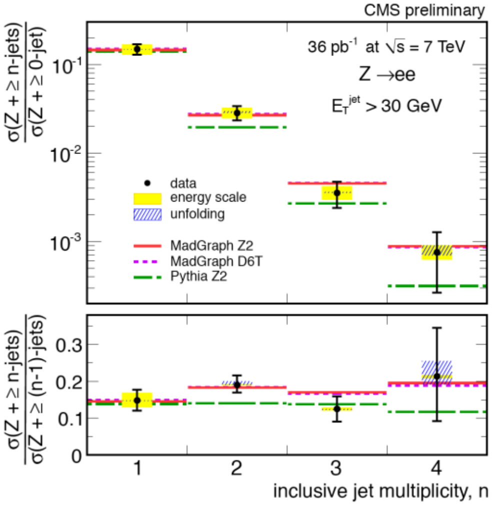
Inclusive jet Multiplicity



Inclusive jet p_T

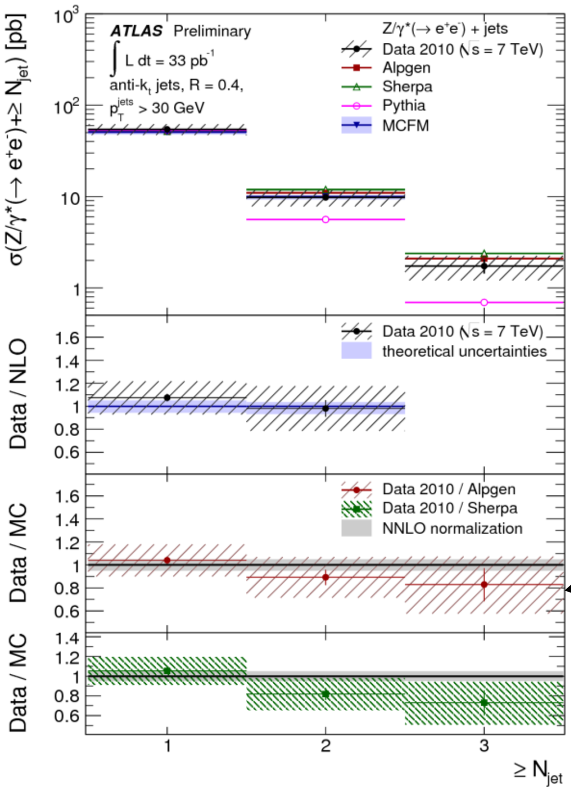


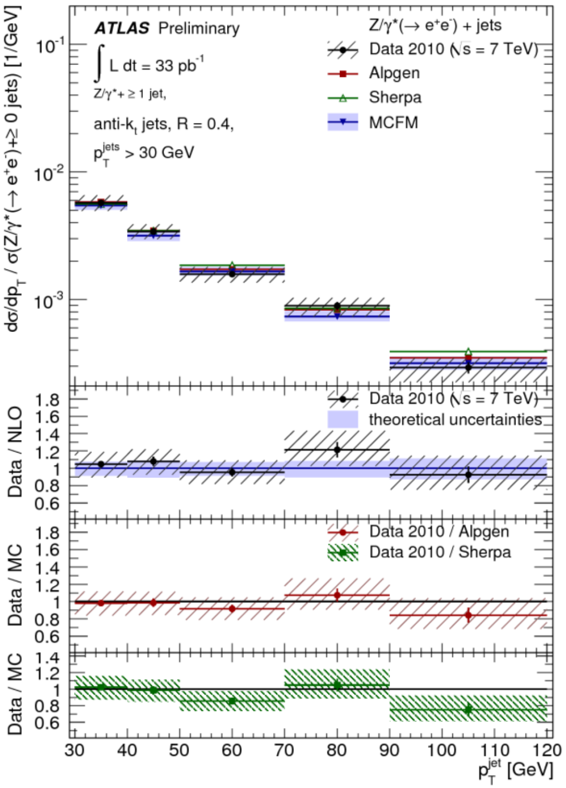
LHC: Z+jets



Good agreement with MCFM for up to 2 jets in the final state. Comparisons for up to 4 jets with B+S forthcoming.

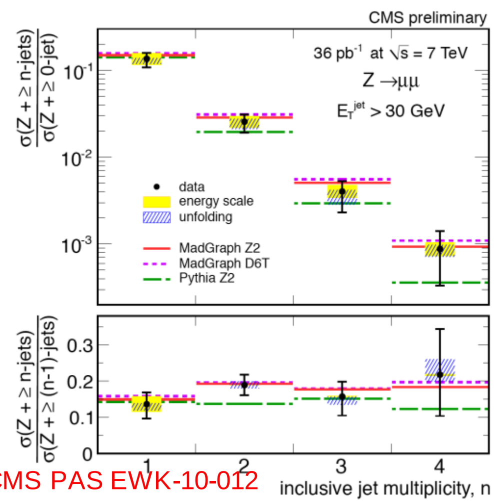
Statistics are running out in the >=4 jet bin in 2010 sample, but many more events in 2011.





ATLAS-CONF-2011-042

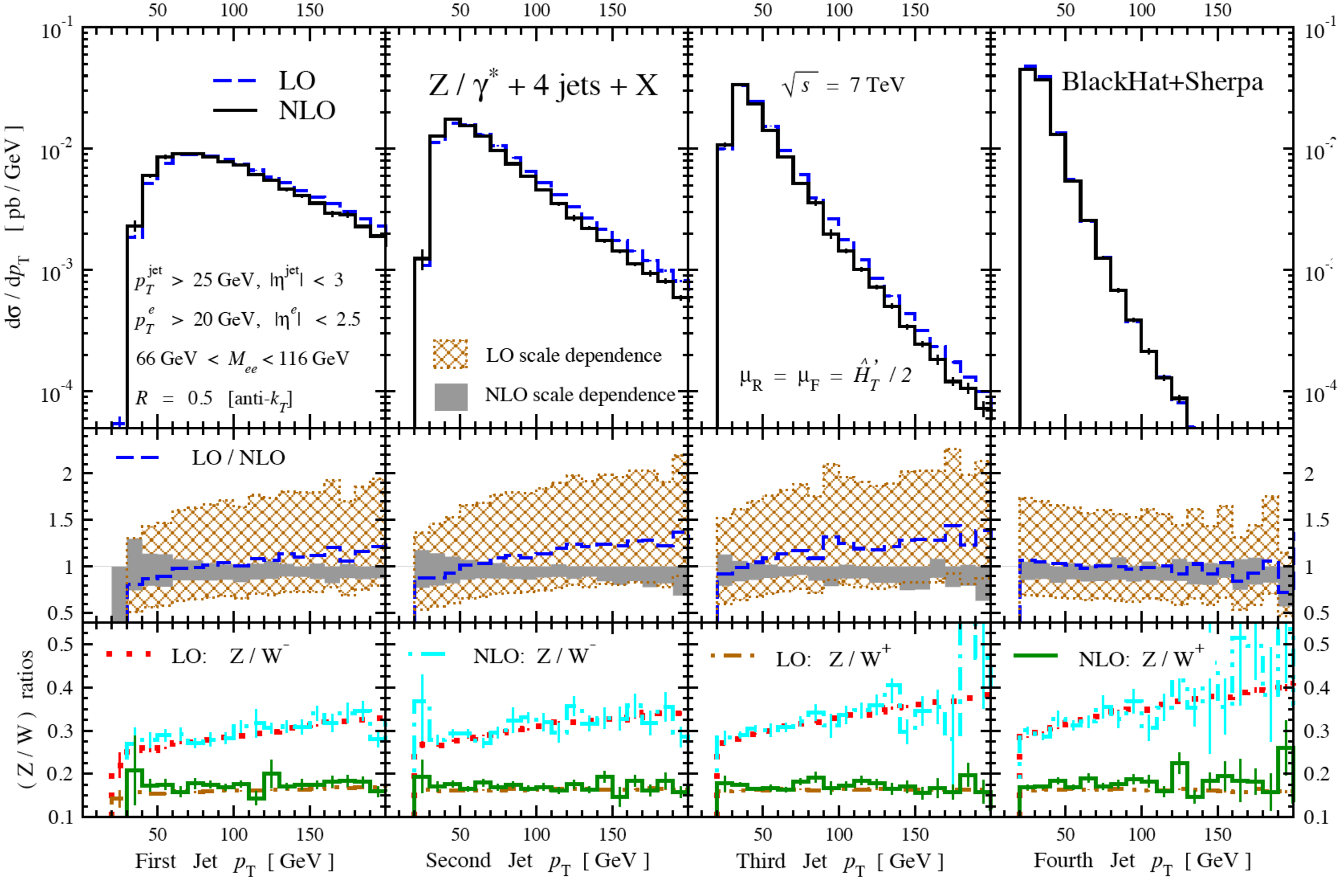
Alpgen and Sherpa predictions tend to be low for 3rd jet.



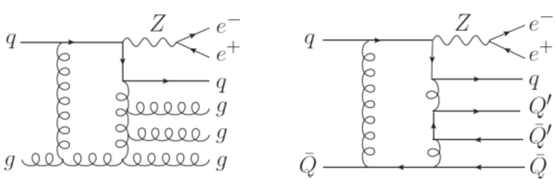
CMS PAS EWK-10-012

NLO:Z+4 jets

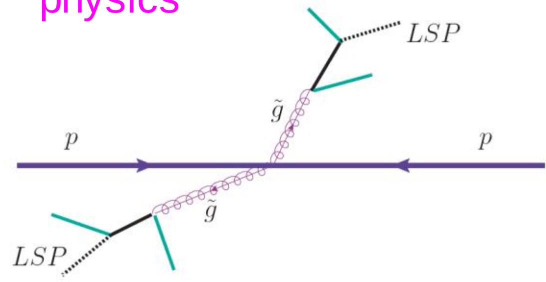
- First time this prediction has been shown in public (thanks BH+S collaboration)
- Great reduction in the scale dependence in going from LO to NLO ($H_T/2$ used as central scale; factor of 2 variations around to get scale uncertainty)
- Notice that Z/W(+n jets) change very little from LO to NLO



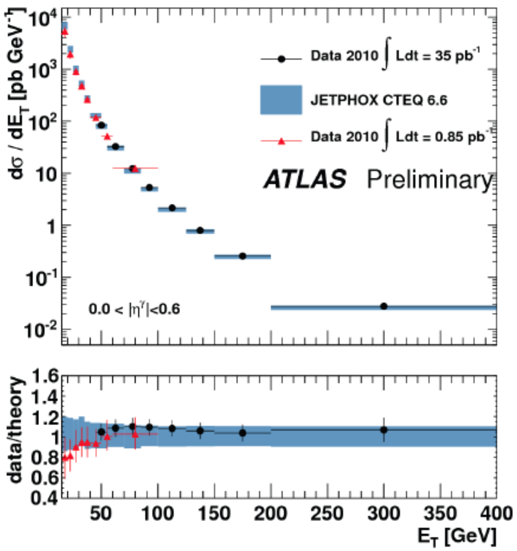
amazing that the technology allows for *routine* calculation of 2->5 processes

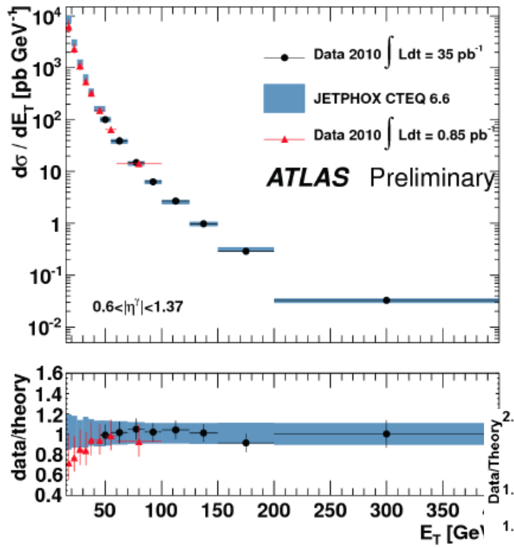


when the Z decays to neutrino pairs, serious background to new physics



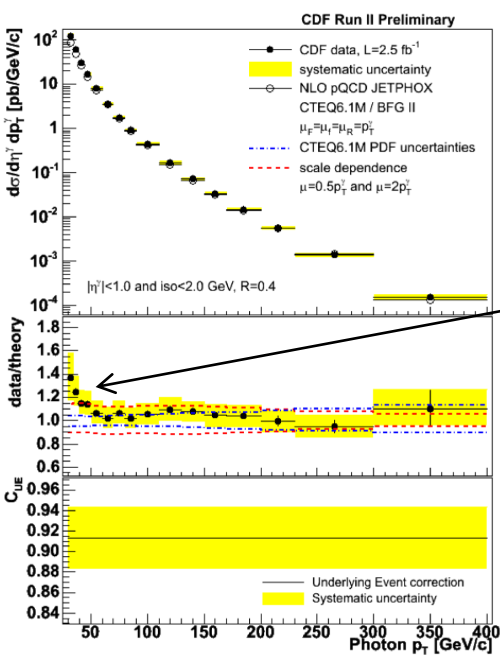
LHC: inclusive photon production





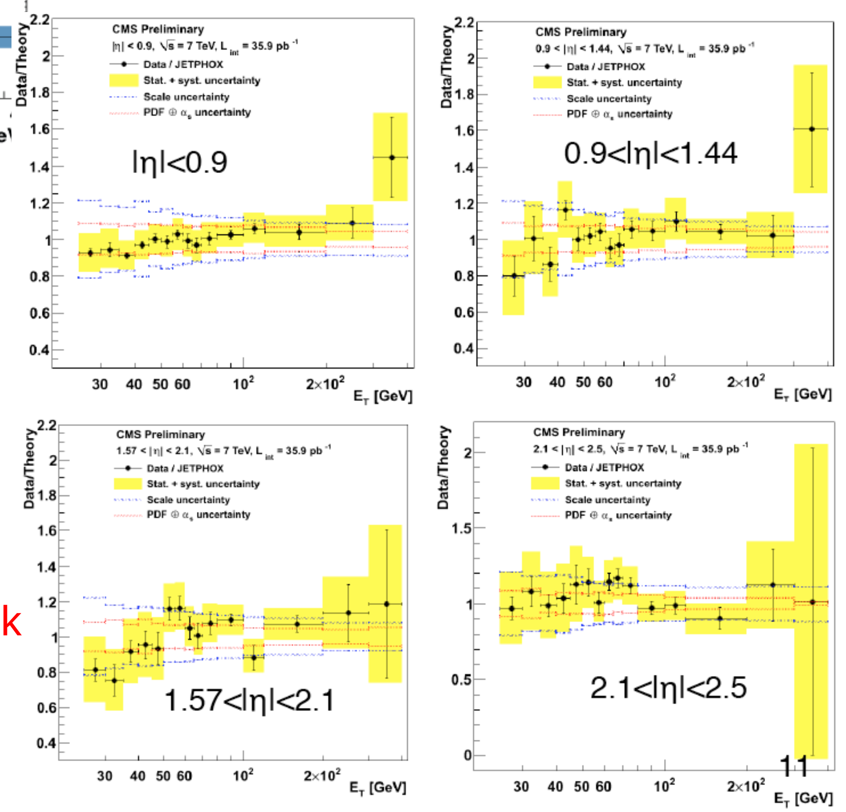
PRD83, 052005(2011)
ATLAS-CONF-2011-058

PRL106, 082001 (2011)
CMS-QCD 10-037



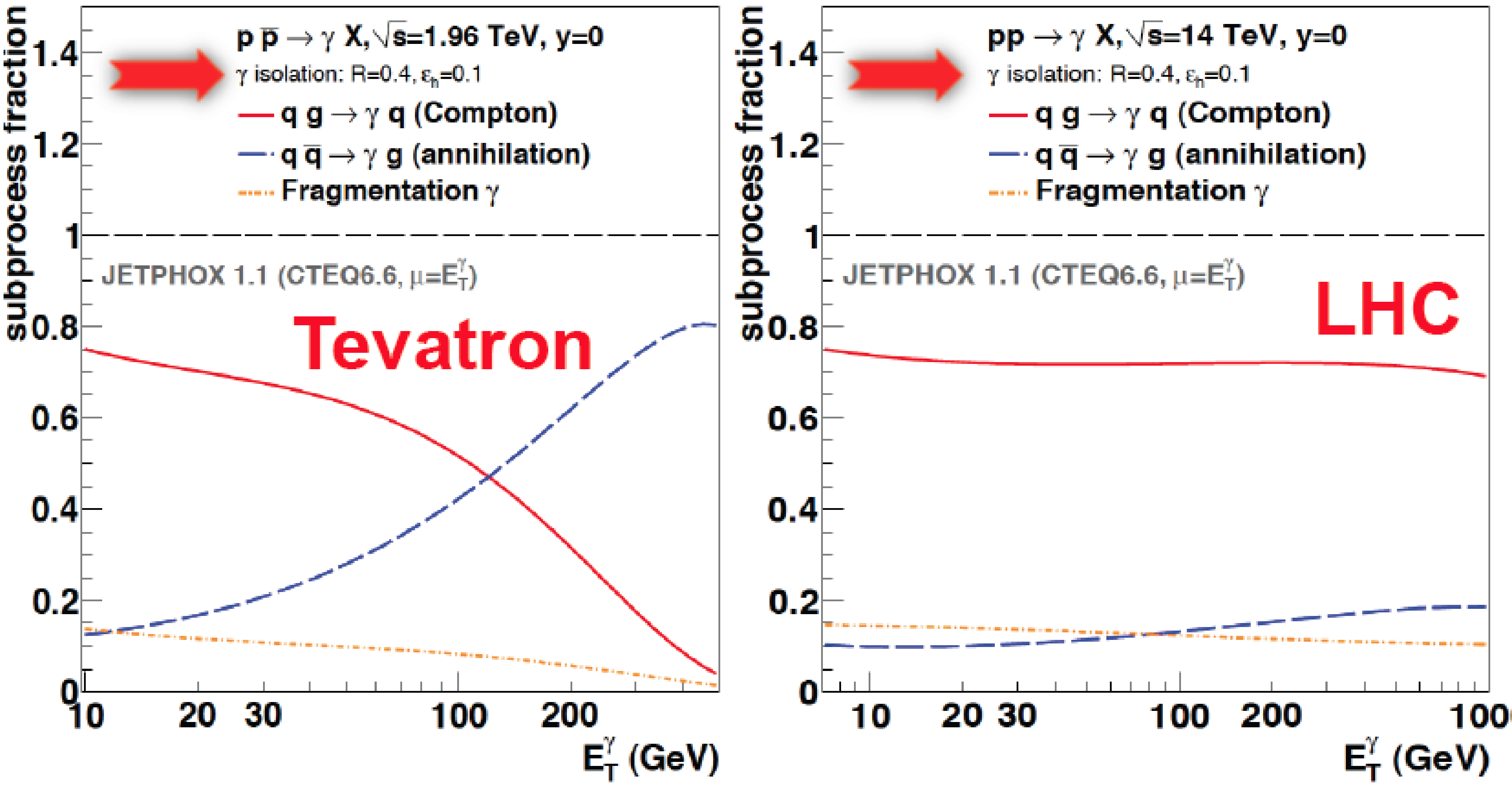
some (negative) deviations observed at low E_T, in contrast to positive deviations observed at Tevatron

still might be unresolved issues regarding fragmentation (quark->quark +γ) and isolation, in theory vs experiment (my humble opinion)

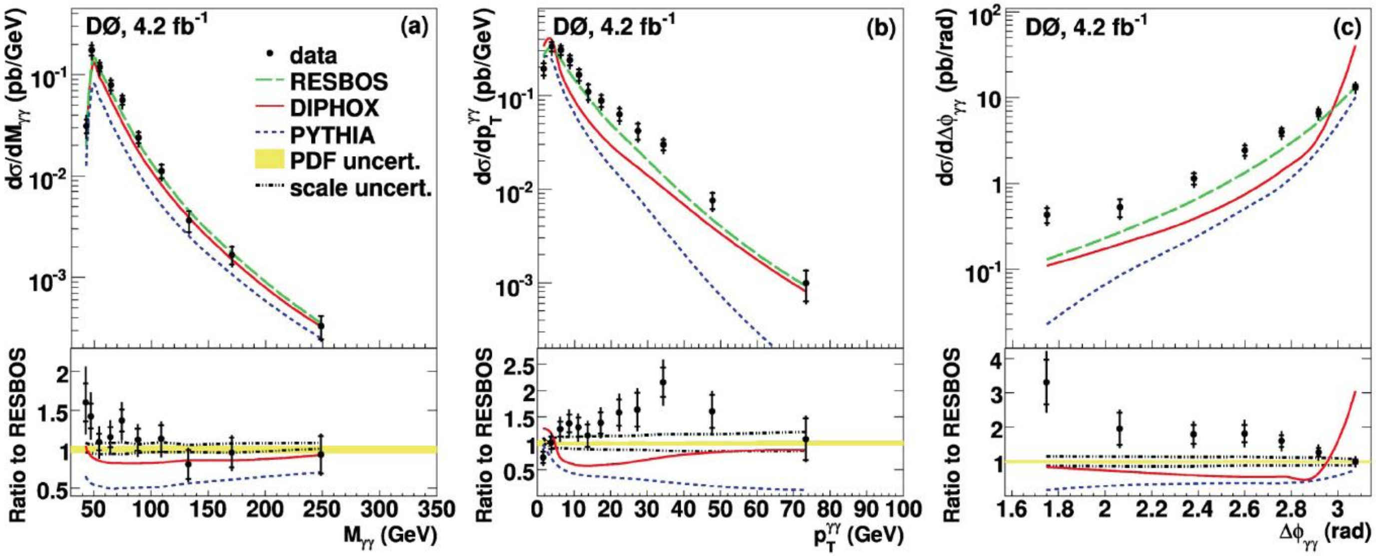


Tevatron vs LHC

- High p_T direct photon production at the Tevatron is dominated by qq scattering
  - and so does not contribute much information about the gluon distribution at high x
- We have a much broader reach at the LHC, and a domination by the gq scattering process->another handle on the gluon distribution in PDF fits

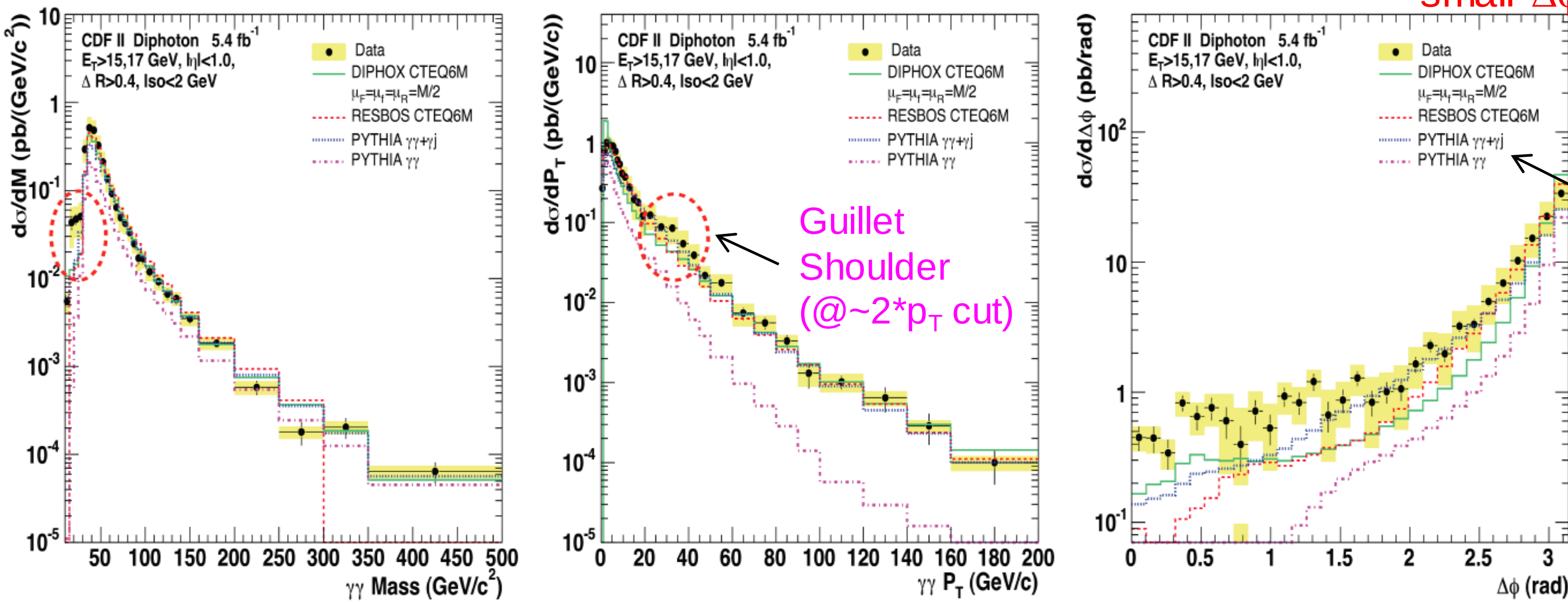


Diphotons:Tevatron



PLB690, 108 (2010)

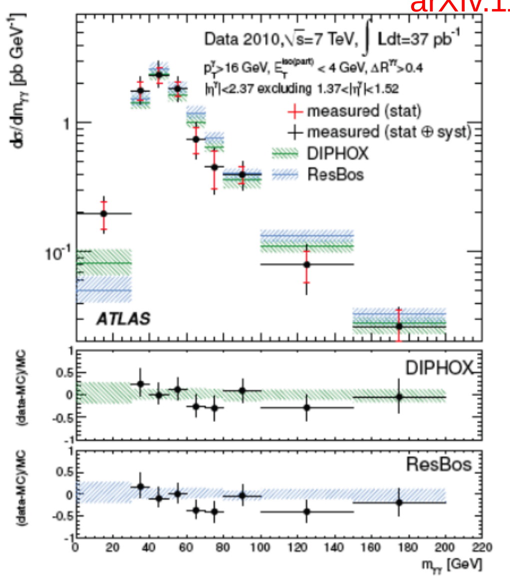
Data indicate need for:
-resummation at low to moderate diphoton p_T (ResBos)
-large fragmentation contributions at low mass/intermediate p_T/ small $\Delta\phi$ (DIPHOX)

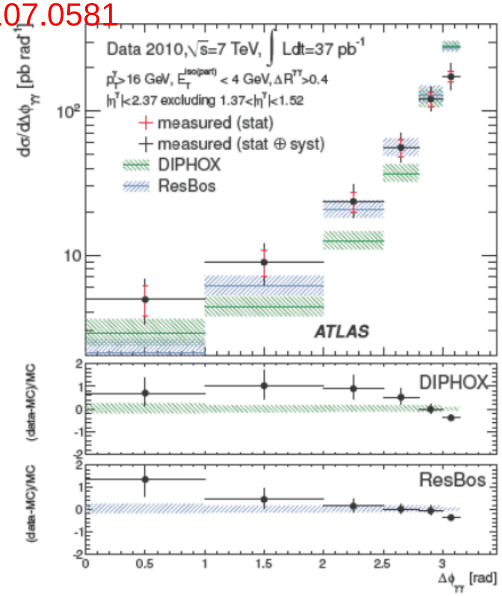


Pythia (including fragmentation) is able to provide better-than-expected agreement.

LHC: diphotons

arXiv:1107.0581



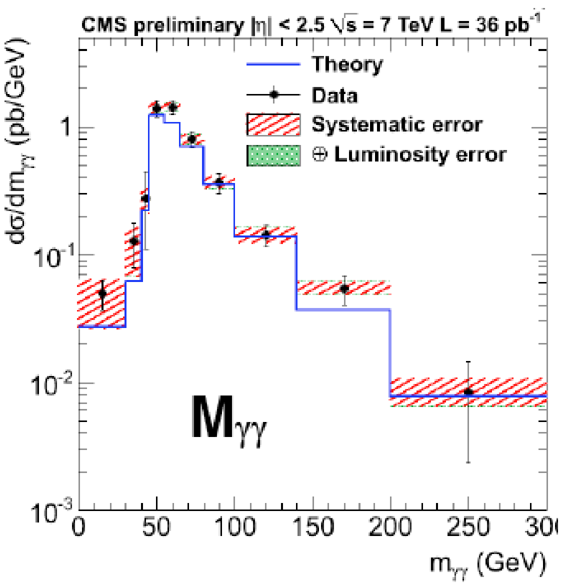


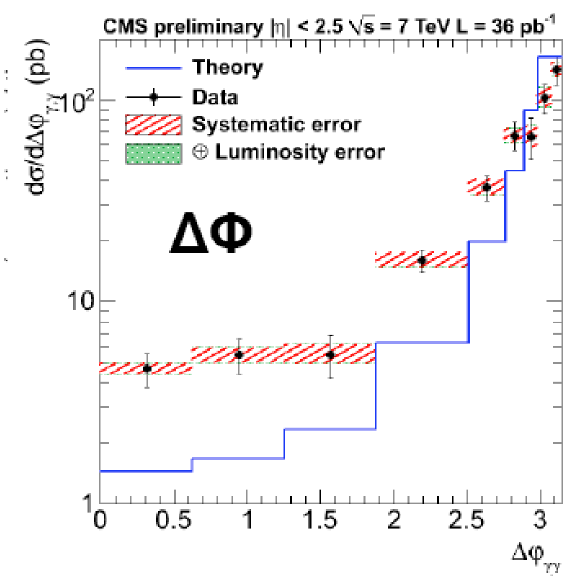
crucial channel for Higgs discovery/ measurement, potential new physics

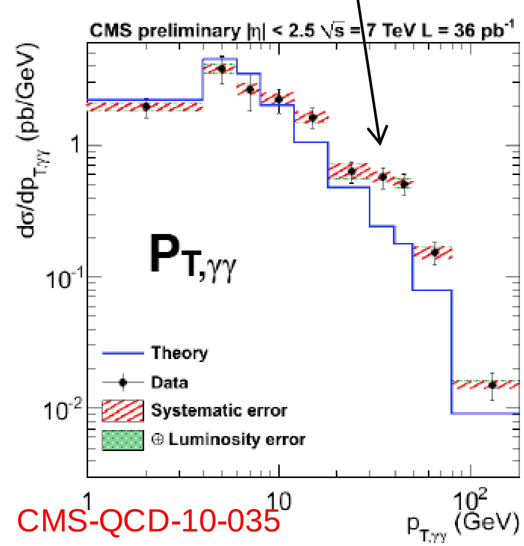
…again evidence for substantial fragmentation contributions not accounted for in perturbative predictions

…luckily, fragmentation effects mostly at low mass

Guillet shoulder



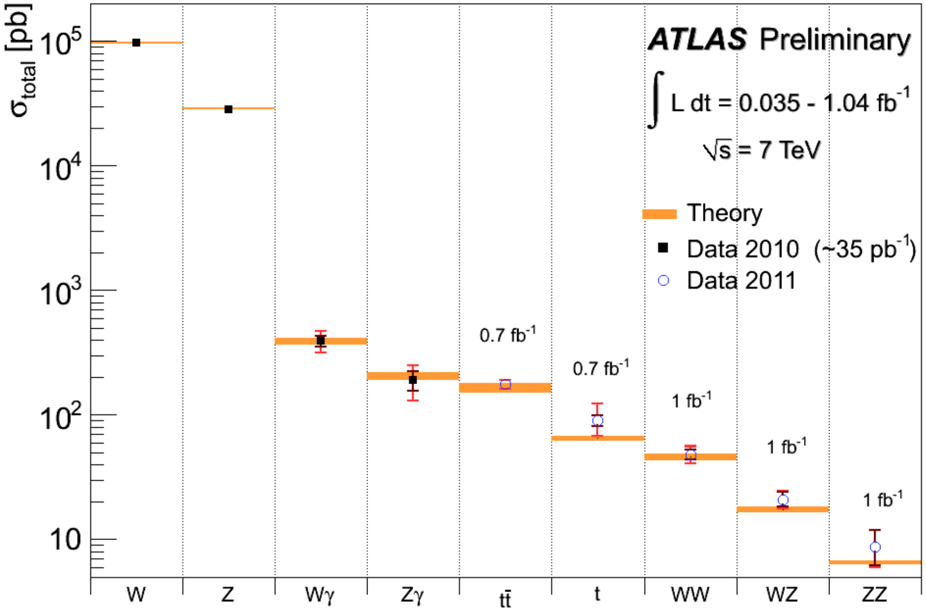




CMS-QCD-10-035

Summary

- The LHC data continues to pour in, allowing for detailed comparisons to and understanding of perturbative QCD at the energy frontier
- The data is in broad good agreement with the perturbative predictions, but there are enough questions
- We need to make full use of the capabilities of our detectors/analysis strategies, and of the theory that is available for comparison, by making use of multiple jet algorithms/sizes
- This will be an interesting decade



Thanks

- To Albert de Roeck, Nikos Varelas, Daniel Maitre, Zvi Bern, Lance Dixon, Brian Martin…