Les Houches wishlist\
use of NLO calculations\
extending NLO

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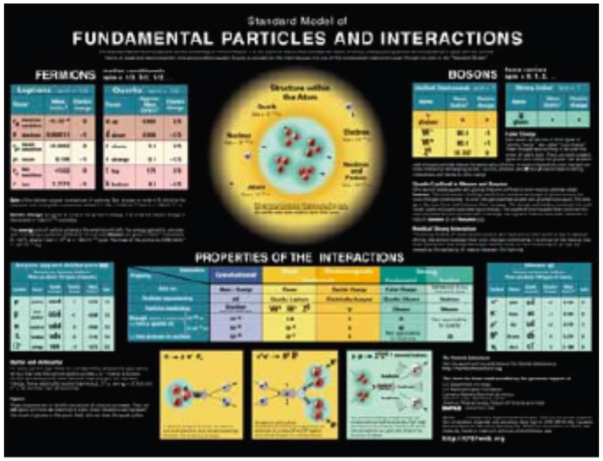
Pittsburgh and the Midwest

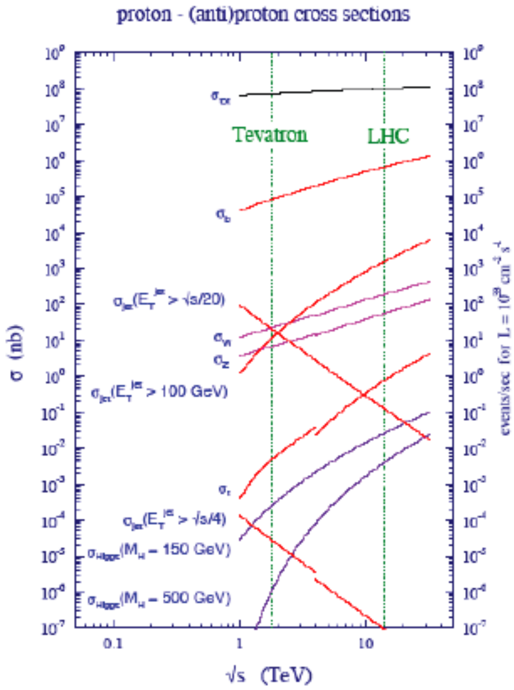
No matter what Sally may have told you, Pittsburgh is not in the Midwest

…but Pittsburgh has its own distinct accent, and given that I may be the only here with that accent, below is a website where you can get translations

Understanding cross sections at the LHC

- We' re all looking for BSM physics at the LHC
- Before we publish BSM discoveries from 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 and 2011 were largely spent 'Re-discovering the Standard Model' at the LHC
  - my phrase by the way, so reference me if you use it
- Much of what we found was expected, but the higher energy and expanded kinematics available has raised some interesting questions about the perturbative QCD framework



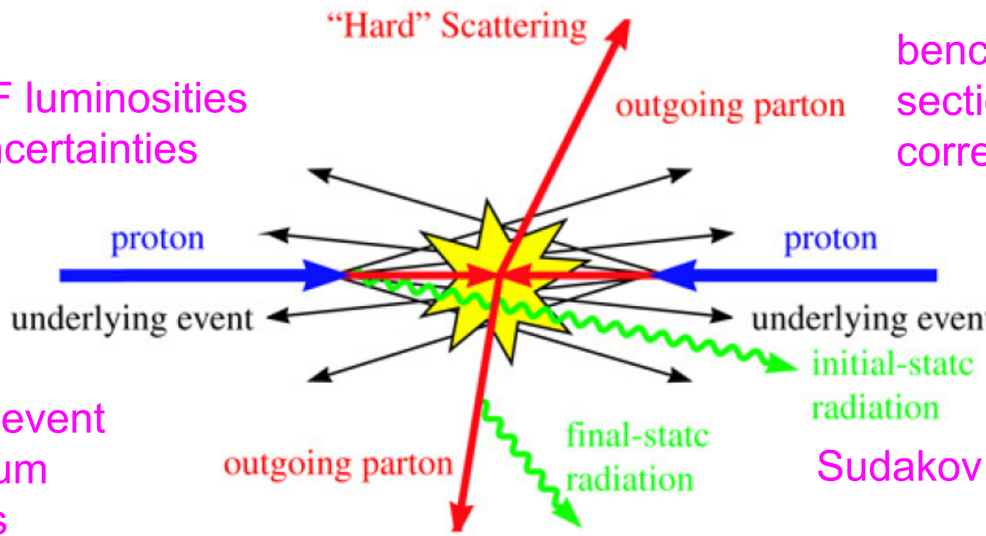


Understanding QCD at the LHC

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

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

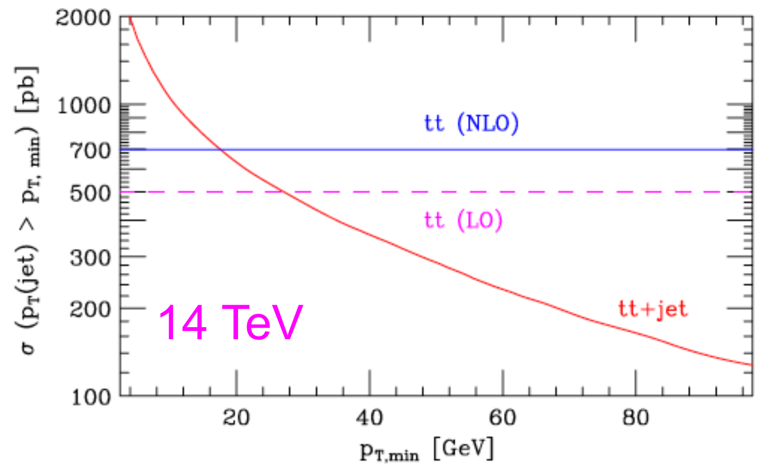


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\mathrm{min}}$, together with the top pair production cross sections at LO and NLO.

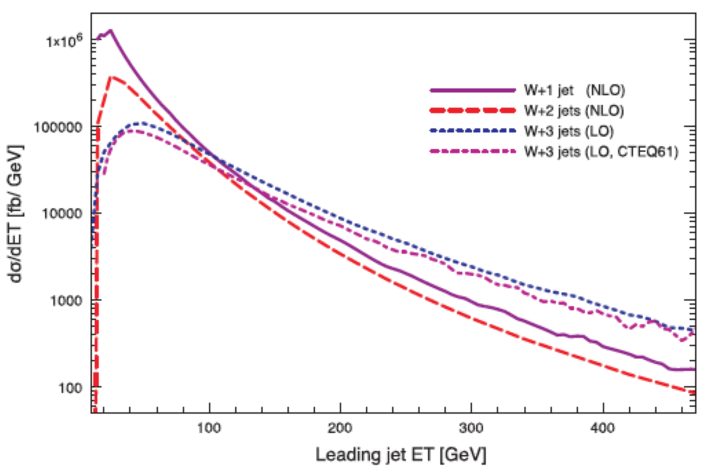


Figure 91. Predictions for the production of $W+\geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

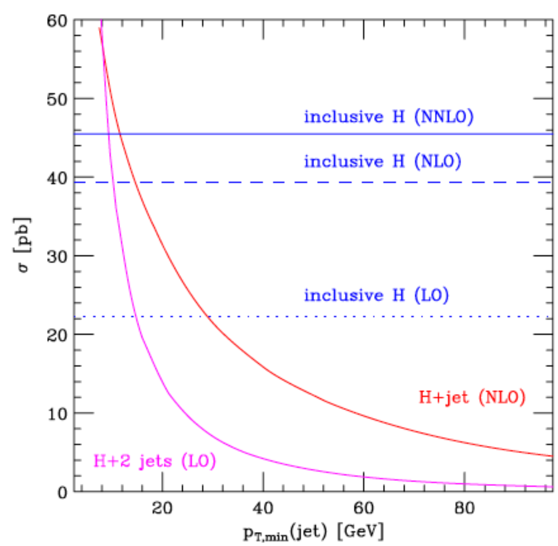


Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\mathrm{min}}$, together with the top pair production cross sections at LO and NLO.

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 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, C/A, k_T 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

Les Houches NLO wishlist

- Started in 2005 and added to in 2007 and 2009
- Idea was to collate those calculations that were needed for the LHC and were doable (although difficult) in a finite time
- Incredible advances in technology for carrying out multi-parton final state calculations…many by people in this room
- Basically every calculation on this wishlist (except tttt) has been completed

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer [27, 28]; Campbell/Ellis/Zanderighi [29]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [30]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [31]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [32, 33] Interference QCD-EW in VBF channel [34, 35]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [36] and WWZ by Hankele/Zeppenfeld [37], see also Binoth/Ossola/Papadopoulos/Pittau [38] VBFNLO [39, 40] meanwhile also contains $WWW, ZZW, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma, \gamma\gamma\gamma$ $WZj, W\gamma j, \gamma jj, W\gamma\gamma j$
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini [41, 42] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [43]
5. $pp \to V$+3jets	W+3jets calculated by the Blackhat/Sherpa [44] and Rocket [45] collaborations Z+3jets by Blackhat/Sherpa [46]
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 [47, 48]
7. $pp \to VV\, b\bar{b}$, 8. $pp \to VV$+2jets	Pozzorini et al.[25],Bevilacqua et al.[23] W^+W^++2jets [49], W^+W^-+2jets [50], VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [51, 52, 53]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al. [54, 55]
NLO calculations added to list in 2009	
10. $pp \to V+4$ jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets [22], Z+4jets [20] see also HEJ [56] for $W+n$jets
11. $pp \to Wb\bar{b}j$	top, new physics signatures, Reina/Schutzmeier [11]
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
also: $pp \to 4$ jets	Blackhat/Sherpa [19]

What's next for the Les Houches NLO wishlist?

- Nothing: I'm retiring the NLO wishlist
- It's being replaced by a NNLO wishlist (plus a wishlist for EW corrections for hard processes)

Below we construct a table of calculations needed at the LHC, and which are feasible within the next few years. Certainly, results for inclusive cross sections at NNLO will be easier to achieve than differential distributions, but most groups are working towards a partonic Monte Carlo program capable of producing fully differential distributions for measured observables.

- $t\bar{t}$ production: see talk by Mitov
  needed for accurate background estimates, top mass measurement, top quark asymmetry (which is zero at tree level, so NLO is the leading non-vanishing order for this observable, and a discrepancy of theory predictions with Tevatron data needs to be understood). Several groups are already well on the way to complete NNLO results for $t\bar{t}$ production [84, 85, 86, 87].
- W^+W^- production:
  importand background to Higgs search. At the LHC, $gg \to WW$ is the dominant subprocess, but $gg \to WW$ is a loop-induced process, such that two loops need to be calculated to get a reliable estimate of the cross section. Advances towards the full two-loop result are reported in [88, 89].
- inclusive jet/dijet production: see talk by Gehrmann-de Ridder
  NNLO parton distribution function (PDF) fits are starting to become the norm for predictions and comparisons at the LHC. Paramount in these global fits is the use of inclusive jet production to tie down the behavior of the gluon distribution, especially at high x. However, while the other essential processes used in the global fitting are known to NNLO, the inclusive jet production cross section is only known at NLO. Thus, it is crucial for precision predictions for the LHC for the NNLO corrections for this process to be calculated, and to be available for inclusion in the global PDF fits. First results for the real-virtual and double real corrections to gluon scattering can be found in [90, 91].

NNLO wishlist: continued

- V+1 jet production:
  $W/Z/\gamma$ + jet production form the signal channels (and backgrounds) for many key physics processes, for both SM and BSM. In addition, they also serve as calibration tools for the jet energy scale and for the crucial understanding of the missing transverse energy resolution. The two-loop amplitudes for this process are known [92, 93], therefore it can be calculated once the parts involving unresolved real radiation are available.
- V+γ production:
  important signal/background processes for Higgs and New Physics searches. The two-loop helicity amplitudes for $q\bar{q} \to W^{\pm}\gamma$ and $q\bar{q} \to Z^{0}\gamma$ recently have become available [94].
- Higgs+1 jet production: see talk by Stewart (NNLL)
  As mentioned previously, events in many of the experimental Higgs analyses are separated by the number of additional jets accompanying the Higgs boson. In many searches, the Higgs + 0 jet and Higgs + 1 jet bins contribute approximately equally to the sensitivity. It is thus necessary to have the same theoretical accuracy for the Higgs + 1 jet cross section as already exists for the inclusive Higgs cross section, i.e. NNLO. The two-Loop QCD Corrections to the Helicity Amplitudes for $H \to 3$ partons are already available [95].

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?
- Best perhaps is inclusion in parton shower Monte Carlos: but what is the learning curve to get new processes added
- Oftentimes, the fixed-order program is too complex (/non-public) to be run by non-authors
- In that case, ROOT ntuples may be the best solution
  - …or at least a useful stop-gap measure

My experiences with…

NLO with BlackHat+Sherpa

NLO cross section

Born loop: lc and fmlc real

$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n (\sigma_n^{virt} + \Sigma_n^{sub}) + \int_{n+1} (\sigma_{n+1}^{real} - \sigma_{n+1}^{sub})$$

vsub

BlackHat

so this is not Sherpa the parton shower, but Sherpa used as a (very efficient) fixed order matrix element generator

Sherpa

How it's put together

NLO with BlackHat+Sherpa

NLO cross section

Born loop: lc and fmlc real

$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n \left(\sigma_n^{virt} + \Sigma_n^{sub}\right) + \int_{n+1} \left(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub}\right)$$

vsub

for W+3 jets,
W+3 parton tree-level
matrix elements

the dipole subtraction terms evaluated in n-body phase space; to make matters more complex, vsub can be either + or -, compensated by other terms in the total cross section; note the sum over all quarks and antiquarks; makes matters more complex when coming to scale uncertainties

all of the real emission terms, (W+4 partons for W + 3 jets), modified by the dipole subtraction terms; divergences are gone

all of the virtual terms, both leading color and full-minus-leading color; the latter is typically a few % effect, but much of the complexity of the calculation

How it’s put together

NLO with BlackHat+Sherpa

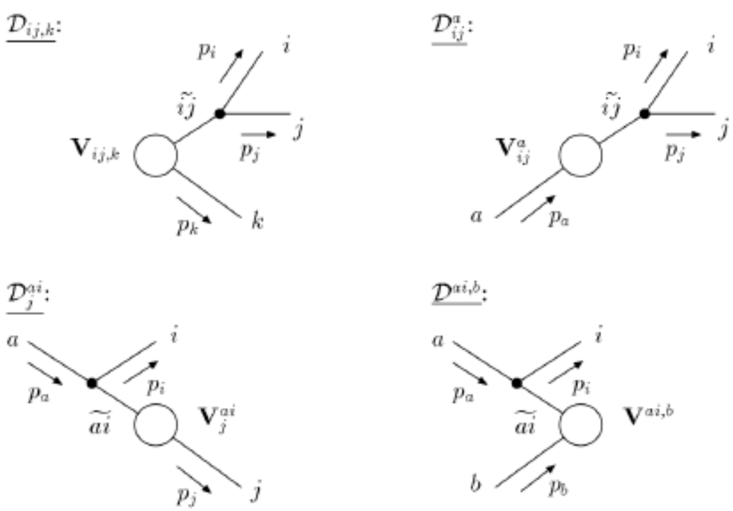
NLO cross section

Born loop: lc and fmlc real

$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n \left(\sigma_n^{virt} + \Sigma_n^{sub}\right) + \int_{n+1} \left(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub}\right)$$

vsub

possible Catani-Seymour dipoles, for FF, FI,IF and II situations



the dipole subtraction terms evaluated in n-body phase space; to make matters more complex, vsub can be either + or -, compensated by other terms in the total cross section; note the sum over all quarks and antiquarks

all of the real emission terms, (W+4 partons for W + 3 jets), modified by the dipole subtraction terms; divergences are gone

many counterevents due to C-S dipoles that are correlated; have to use special weights/procedures to get correct statistical error

note the need for a 3rd parton, the ‘spectator’; in the soft limit, it’s the color partner

ROOT ntuples

- More complex to use than MCFM
  - no manual for example
  - and you don't produce the events yourself
- ntuples produced separately by Blackhat + Sherpa for →
  - so TB's of disk space
- No jet clustering has been performed; that's up to the user
  - a difference from MCFM, where the program has to be re-run for each jet size/algorithm
- What algorithms/jet sizes that can be run depends on how the files were generated
  - i.e. whether the right counter-events are present
- For the files on the right at 7 TeV (for W^+ + 3 jets), one can use kT, antikT, siscone (f=0.75) for jet sizes of 0.4, 0.5, 0.6 and 0.7

- bornLO (stands alone for pure LO comparisons; not to be added with other contributions below)
  - 20 files, 5M events/file, 780 MB/file
- Born
  - 18 files, 5M events/file, 750 MB/file
- loop-lc (leading color loop corrections)
  - 398 files, 100K events/file, 19 MB/file
- loop-fmlc (needed for full color loop corrections)
  - 399 files, 15K events/file, 3 MB/file
- real (real emission terms)
  - 169 files, 2.5 M event/file, 5 GB/file
- vsub (subtraction terms)
  - 18 files, 10M events/file, 2.8 GB/file

Jet Clustering

- For jet clustering, we use SpartyJet, and store the jet results in SJ ntuples
  - and they tend to be big since we store the results for multiple jet algorithms/ sizes
- Then we friend the Blackhat +Sherpa ntuples with the SpartyJet ntuples producing analysis ntuples (histograms with cuts) for each of the event categories
- Add all event category histograms together to get the plots of relevant physical observables

http://projects.hepforge.org/spartyjet/

arXiv:1201.3617 (manual)

SpartyJet is a set of software tools for jet finding and analysis, built around the FastJet library of jet algorithms. SpartyJet provides four key extensions to FastJet: a simple Python interface to most FastJet features, a powerful framework for building up modular analyses, extensive input file handling capabilities, and a graphical browser for viewing analysis output and creating new on-the-fly analyses.

Branches in ntuple

branch name	type	Notes
id	I	id of the event. Real events and their associated counterterms share the same id. This allows for the correct treatment of statistical errors.
nparticle	I	number of particles in the final state
px	F[nparticle]	array of the x components of the final state particles
py	F[nparticle]	array of the y components of the final state particles
pz	F[nparticle]	array of the z components of the final state particles
E	F[nparticle]	array of the energy components of the final state particles
alphas	D	$alpha_s$ value used for this event
kf	I	PDG codes of the final state particles
weight	D	weight of the event
weight2	D	weight of the event to be used to treat the statistical errors correctly in the real part
me_wgt	D	matrix element weight, the same as weight but without pdf factors
me_wgt2	D	matrix element weight, the same as weight2 but without pdf factors
x1	D	fraction of the hadron momentum carried by the first incoming parton
x2	D	fraction of the hadron momentum carried by the second incoming parton
x1p	D	second momentum fraction used in the integrated real part
x2p	D	second momentum fraction used in the integrated real part
id1	I	PDG code of the firt incoming parton
id2	I	PDG code of the second incoming parton
fac_scale	D	factorization scale used
ren_scale	D	renormalization scale used
nuwgt	I	number of additional weights
usr_wgts	D[nuwgt]	additional weights needed to change the scale

Reweighting

can reweight each event to new

- -PDF
- -factorization scale
- -renormalization scale
- -α_s (tied to the relevant PDFs)

based on weights stored in ntuple (and linking with LHAPDF)

so, for example, the events were generated with CTEQ6, and were re-weighted to CTEQ6.6

2.1 Born and real contributions

The new weight is given by

$$w = \mathbf{me\_wgt2} \cdot f(\mathbf{id1}, \mathbf{x1}, \mu_F) F(\mathbf{id2}, \mathbf{x2}, \mu_F) \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n} \tag{1}$$

with μ_F the new factorization scale, μ_R the new factorization scale, f the new PDF, α_s the correponding running coupling and n the number of strong coupling (the number of jets n_j for the born contribution and $n_j + 1$ for the real contribution). If the factorization scale is not changed, one can simplify the computation (and save the pdf function call):

$$w = \mathbf{weight2} \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n} \tag{2}$$

2.2 Virtual contribution

The virtal contribution is treated like the real and born contribution, but the matrix element has a dependence on the renormalization scale parametrized using the additional weights **usr_wgts**.

$$\begin{aligned} w &= m \cdot f(\mathbf{id1}, \mathbf{x1}, \mu_F) F(\mathbf{id2}, \mathbf{x2}, \mu_F) \frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n} && (3) \\ m &= \mathbf{me\_wgt2} + l\,\mathbf{usr\_wgts}[0] + \frac{l^2}{2} \mathbf{usr\_wgts}[1] && (4) \\ l &= \log\left(\frac{\mu_R^2}{\mathbf{ren\_scale}^2}\right) && (5) \end{aligned}$$

Reweighting, cont.

2.3 Integrated subtraction

The computation of the new weight for the integrated subtraction is the most complicated. The ROOT file has 16 additional weights to make this possible.

$$
\begin{aligned}
w &= m\frac{\alpha_s(\mu_R)^n}{(\mathbf{alphas})^n} && (6)\\
m &= \mathbf{me\_wgt2}\cdot f(\mathbf{id1},\mathbf{x1},\mu_F)f(\mathbf{id2},\mathbf{x2},\mu_F) && (7)\\
&\quad + \left(f_a^1\omega_1 + f_a^2\omega_2 + f_a^3\omega_3 + f_a^4\omega_4\right)F_b(x_b) && (8)\\
&\quad + \left(F_b^1\omega_5 + F_b^2\omega_6 + F_b^3\omega_7 + F_b^4\omega_8\right)f_a(x_a) && (9)\\
\omega_i &= \mathbf{usr\_wgts}[i-1] + \mathbf{usr\_wgts}[i+9]\log\left(\frac{\mu_R^2}{\mathbf{ren\_scale}^2}\right) && (10)
\end{aligned}
$$

complex:
carry both
single and double
logs

where

$$
f_a^1 = \begin{cases} a = \text{quark} & : \quad f_a(x_a,\mu_F) \\ a = \text{gluon} & : \quad \sum_{\text{quarks}} f_q(x_a,\mu_F) \end{cases} \qquad (11)
$$

$$
f_a^2 = \begin{cases} a = \text{quark} & : \quad \frac{f_a(x_a/x'_a,\mu_F)}{x'_a} \\ a = \text{gluon} & : \quad \sum_{\text{quarks}} \frac{f_q(x_a/x'_a,\mu_F)}{x'_a} \end{cases} \qquad (12)
$$

$$
f_a^3 = f_g(x_a,\mu_F) \qquad (13)
$$

$$
f_a^4 = \frac{f_g(x_a/x'_a,\mu_F)}{x'_a} \qquad (14)
$$

we run into the
sum over quarks
and antiquarks
again

and $n = n_j + 1$.

PDF Errors

Better than what is done in MCFM (as far as disk space is concerned); PDF errors are generated on-the-fly through calls to LHAPDF. But then don't store information for individual eigenvectors.

```
void BlackhatAnalysis::GetPdfErrors(const std::vector<Double_t> x,
                                    const Double_t f_c,
                                    const std::vector<int> flav,
                                    Double_t Q,
                                    bool shiftUp,
                                    Double_t &delta)
{
    Double_t f_p,f_m;
    // Loop over all eigenvectors
    for(int e=1;e<=m_nEigen;e++)
    {
        LHAPDF::initPDF(2, 2*e-1); // init positive shift pdf
        LHAPDF::initPDF(3, 2*e); // init negative shift pdf
        //std::cout << "Eigenvector " << e << std::endl;
        f_p = LHAPDF::xfx(2,x[0],Q,flav[0])/x[0]*LHAPDF::xfx(2,x[1],Q,flav[1])/x[1];
        f_m = LHAPDF::xfx(3,x[0],Q,flav[0])/x[0]*LHAPDF::xfx(3,x[1],Q,flav[1])/x[1];
        if(shiftUp) // if positive pdf shift
            delta += pow(std::max(std::max(f_p-f_c,f_m-f_c),0.0),2);
        else // if negative pdf shift
            delta += pow(std::max(std::max(f_c-f_p,f_c-f_m),0.0),2);
    }
    delta = sqrt(delta);
    if(!shiftUp) delta *= -1.0;
    //std::cout << "Total delta: " << delta << std::endl;
}
```

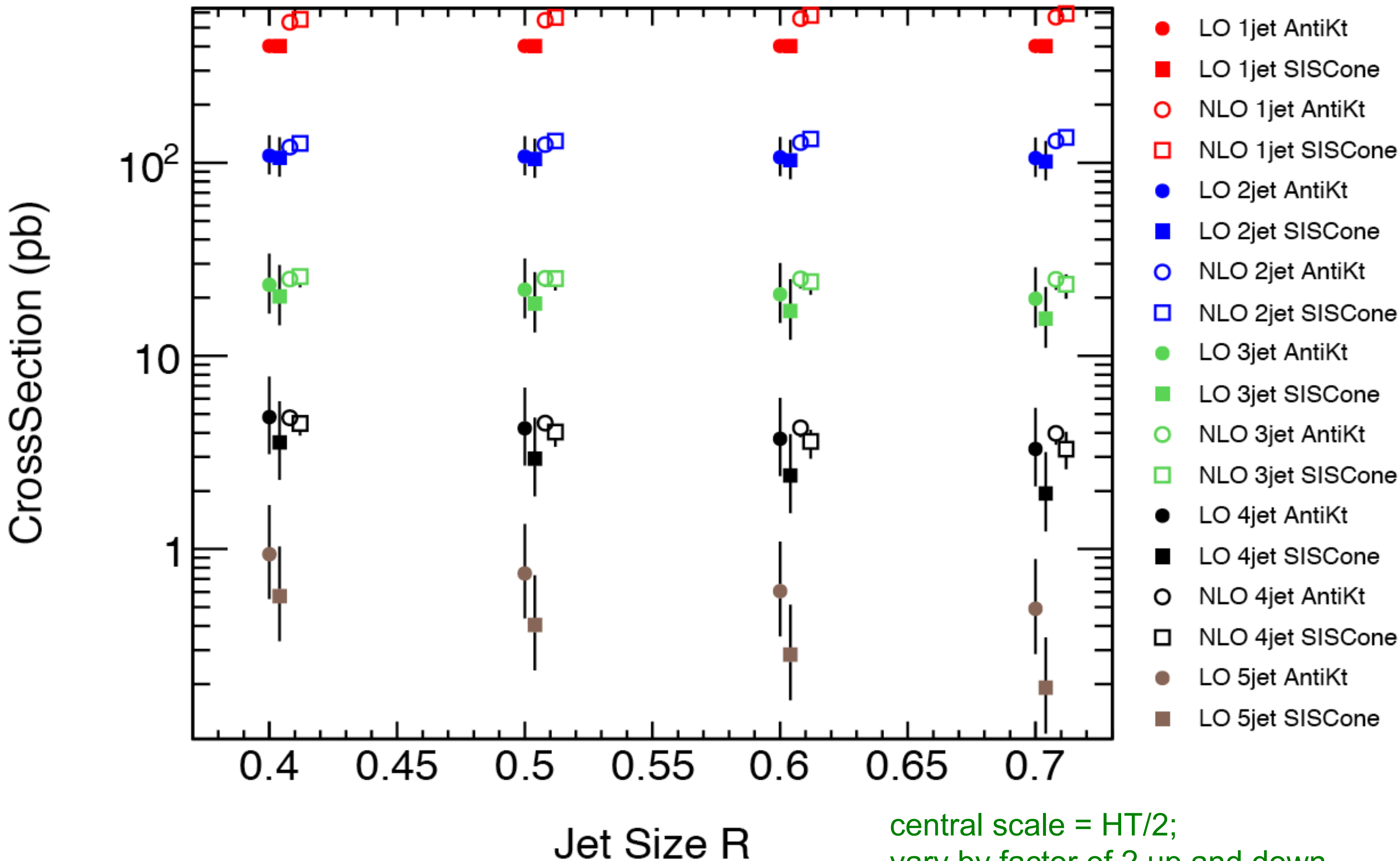
$$\Delta X^{+}_{\max} = \sqrt{\sum_{i=1}^{N} [\max(X_i^{+} - X_0, X_i^{-} - X_0, 0)]^2},$$

$$\Delta X^{-}_{\max} = \sqrt{\sum_{i=1}^{N} [\max(X_0 - X_i^{+}, X_0 - X_i^{-}, 0)]^2}.$$

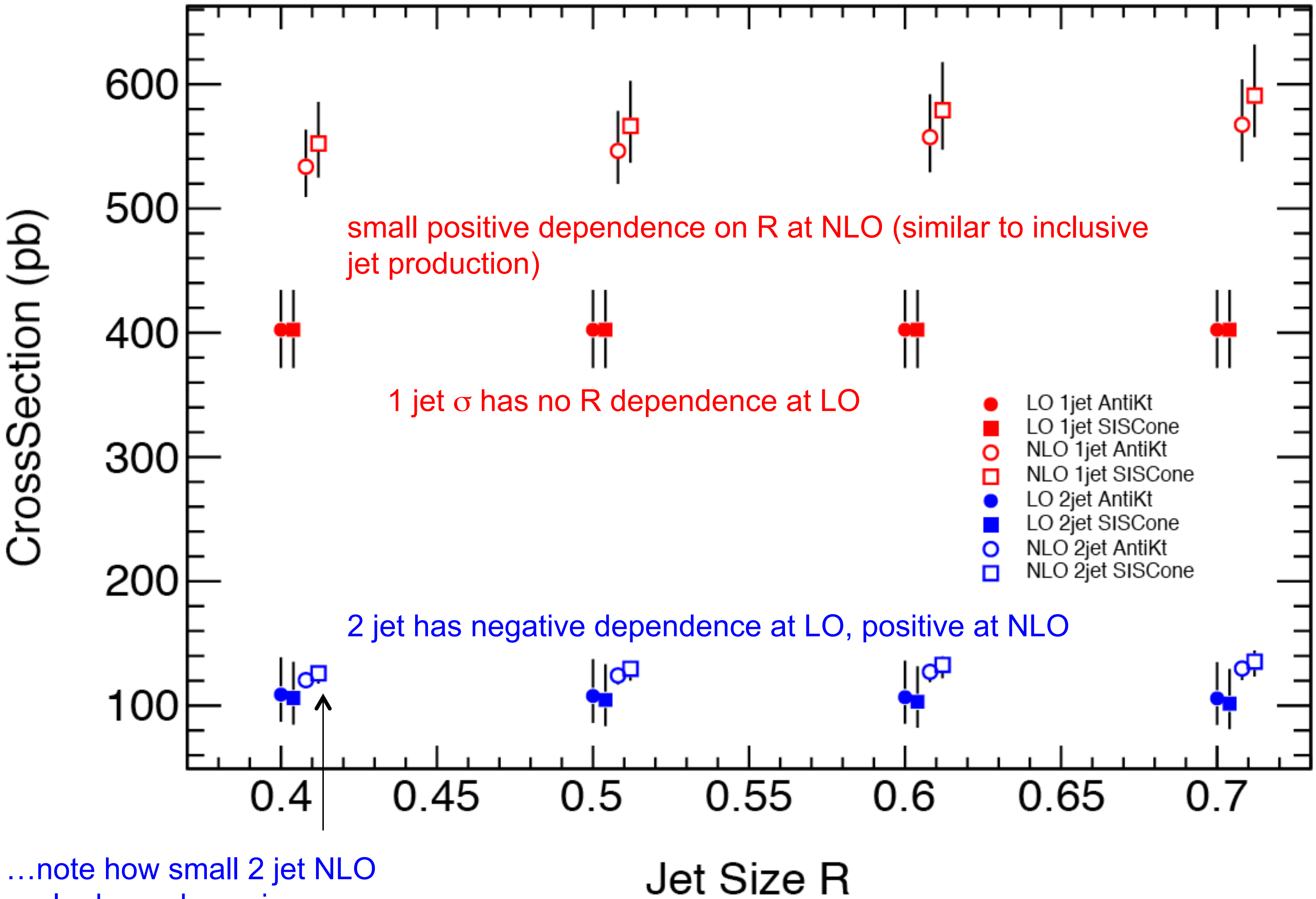
Logistics

- So total file disk space is quite large, multi-TB (and there are many events to be processed)
  - I bought several 20TB disks specifically for this purpose
- But they're divided into few GB files (Blackhat+SJ)
- So we can make our analysis parallel using 200-250 nodes at MSU
  - we've agreed not to take up more than 50% of the nodes at any one time
- With all of the jet algorithms, scale choices, histograms that I've been using ~3 weeks running time
- A slimmer set can finish within a week

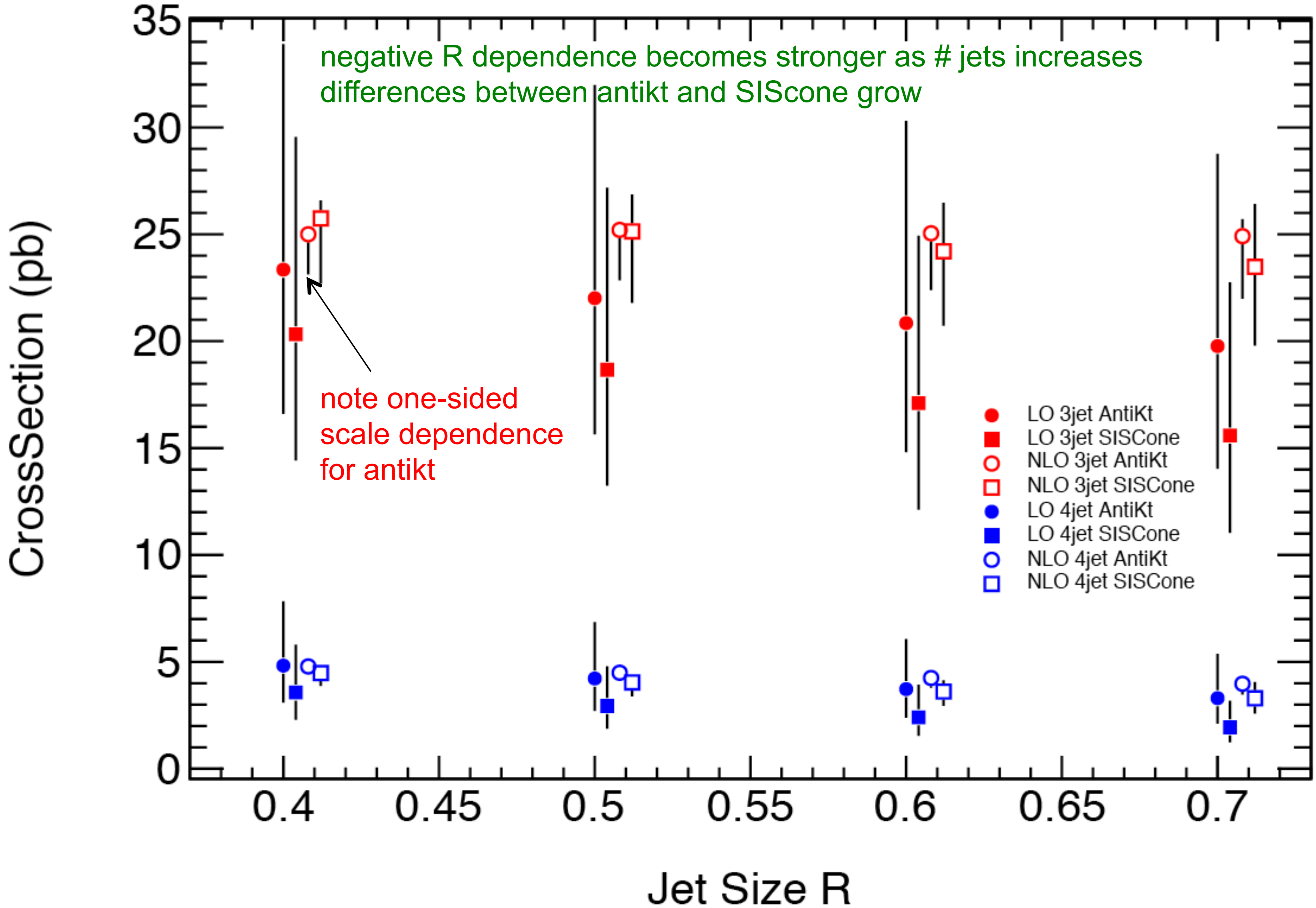
Look at jet size, algorithm dependences; scale uncertainty



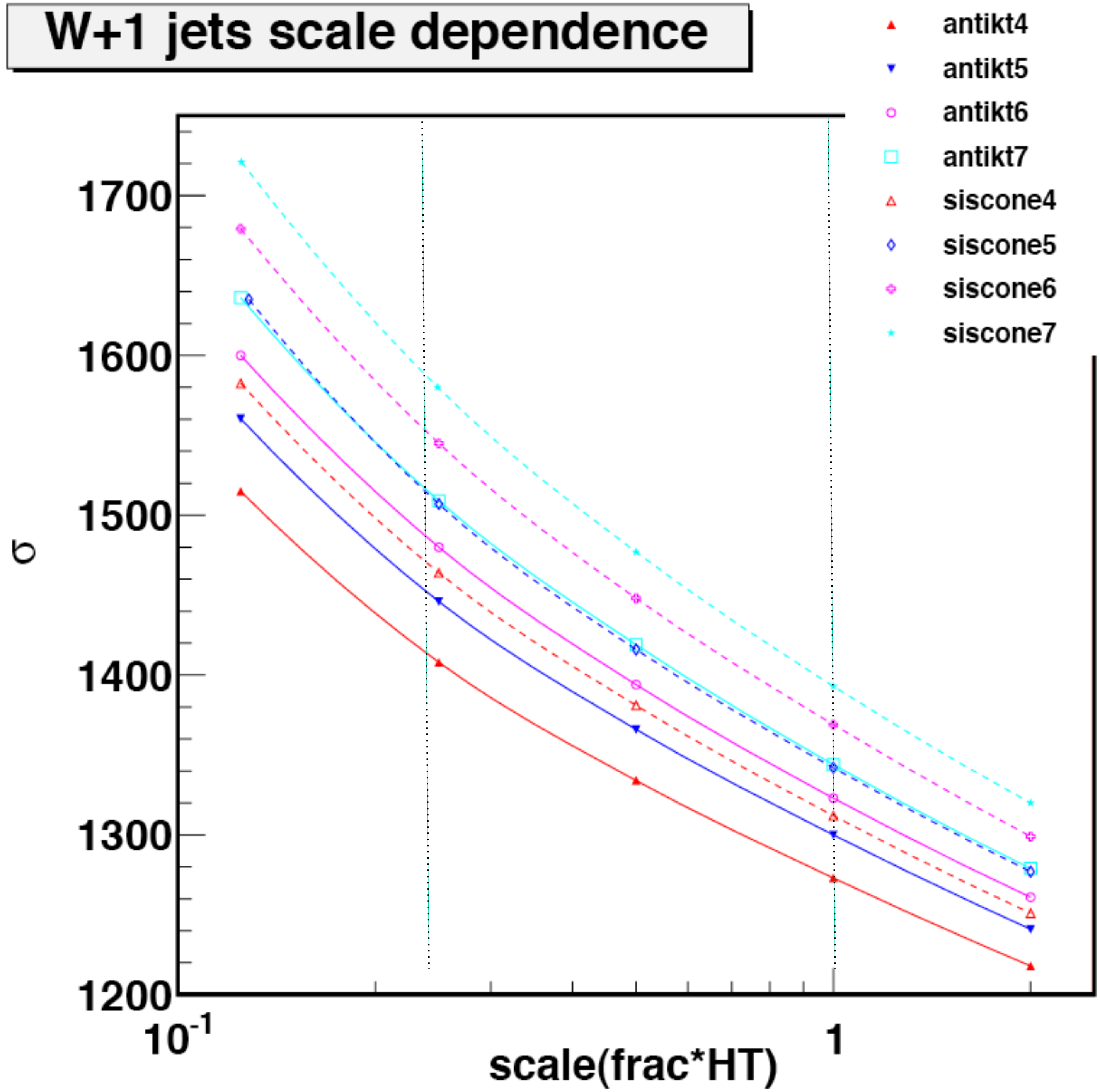
central scale = HT/2;
vary by factor of 2 up and down



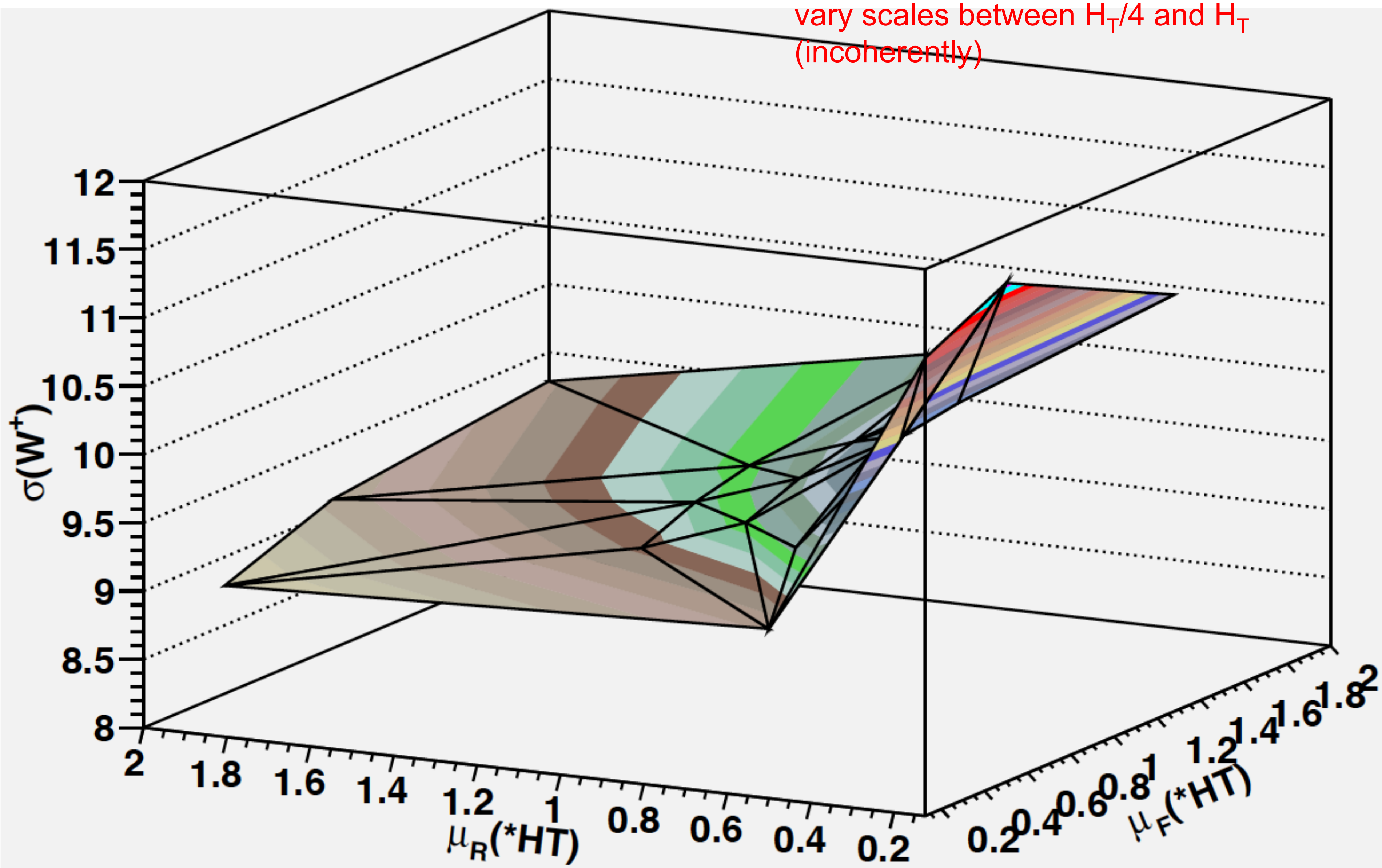
…note how small 2 jet NLO scale dependence is


negative R dependence becomes stronger as # jets increases
differences between antikt and SIScone grow
note one-sided
scale dependence
for antikt
LO 3jet AntiKt
LO 3jet SISCone
NLO 3jet AntiKt
NLO 3jet SISCone
LO 4jet AntiKt
LO 4jet SISCone
NLO 4jet AntiKt
NLO 4jet SISCone
CrossSection (pb)
Jet Size R
0
5
10
15
20
25
30
35
0.4
0.45
0.5
0.55
0.6
0.65
0.7

note monotonic scale dependence at NLO, similar to what is seen in a typical LO calculation



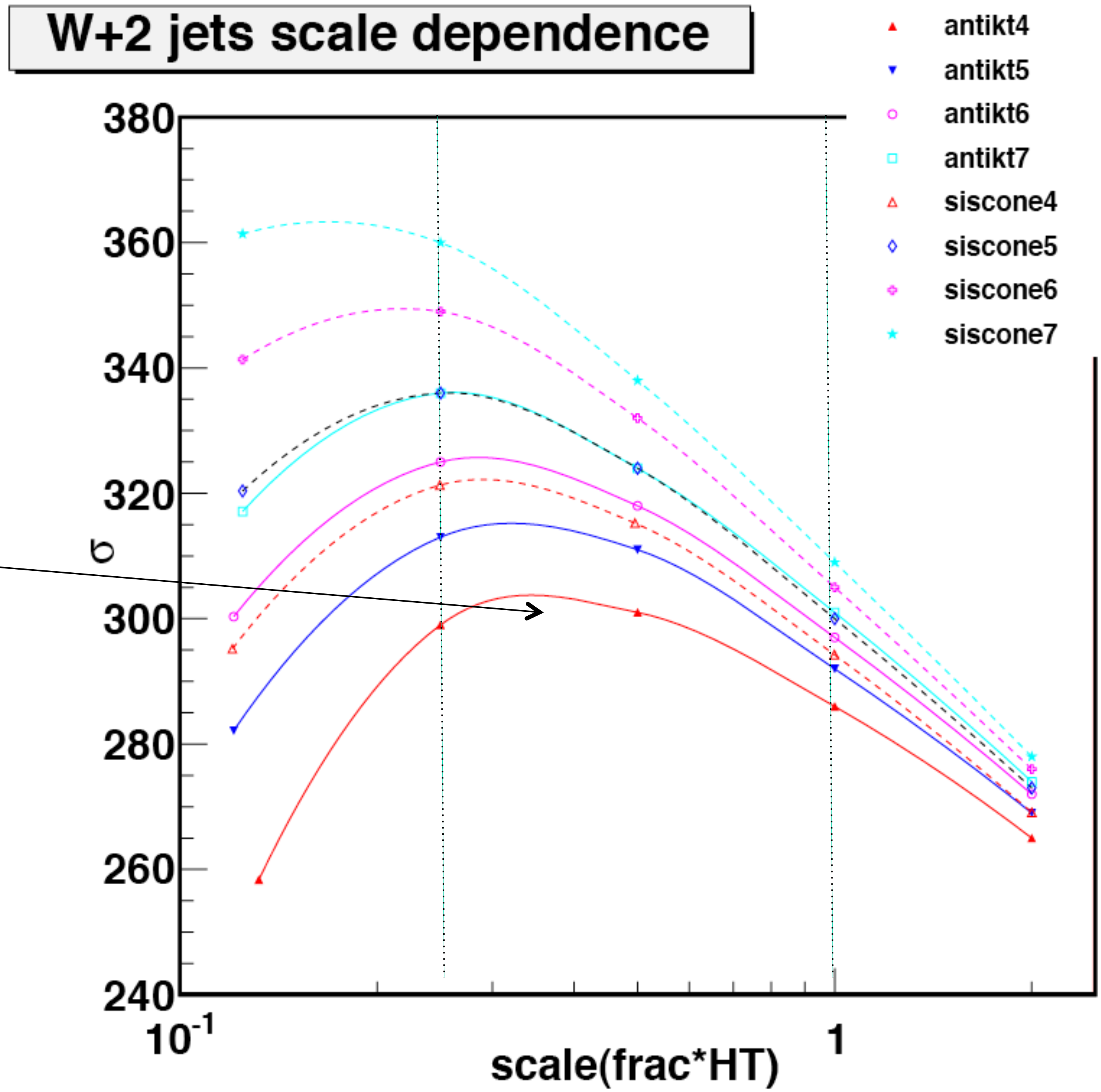
Look at 2D scale dependence

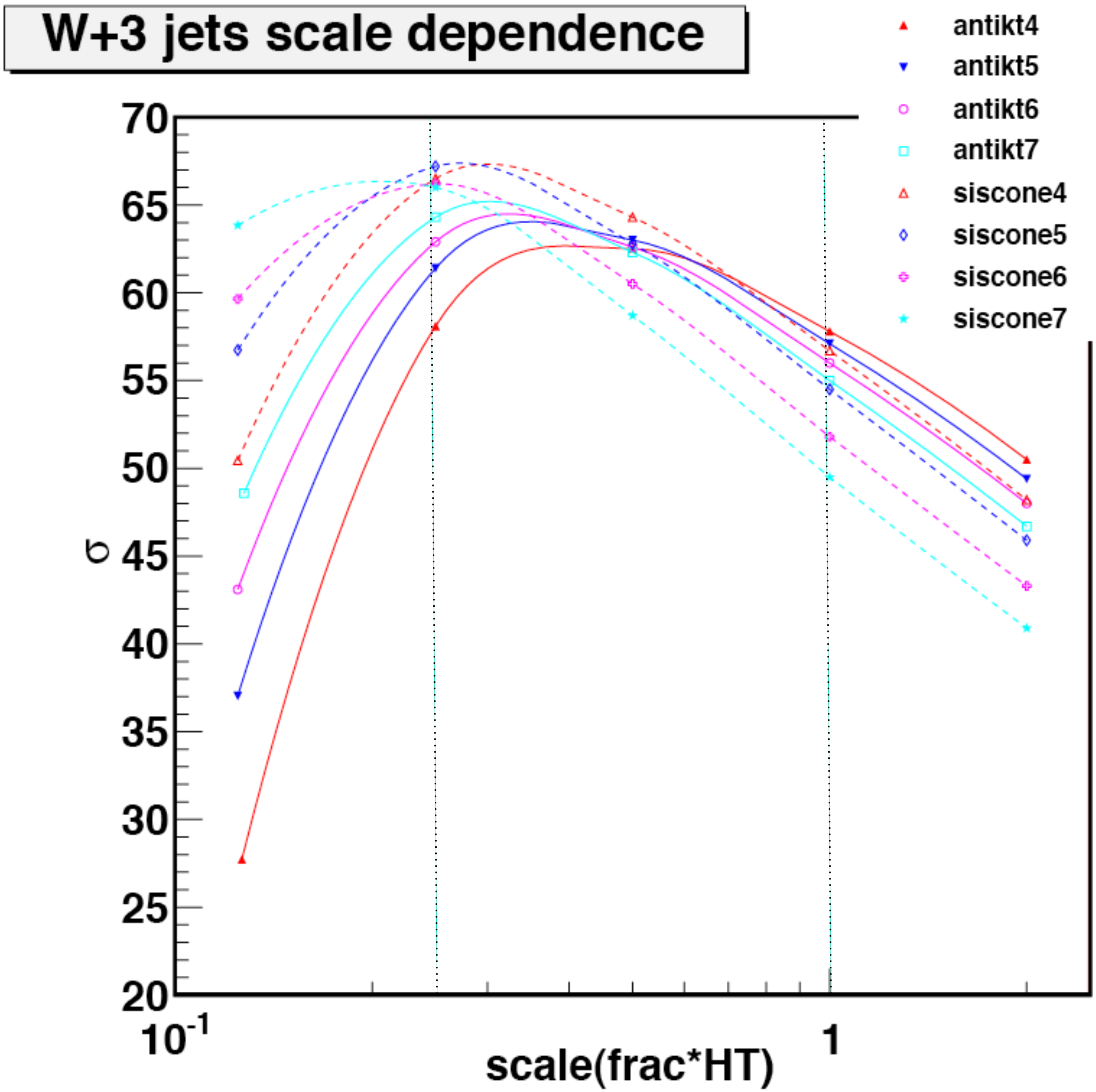


See parabolic shape for W+2 jets

Note that for antikT4, the scale $H_T/2$ is at the same point as $H_T/4$; scale dependence will appear smaller

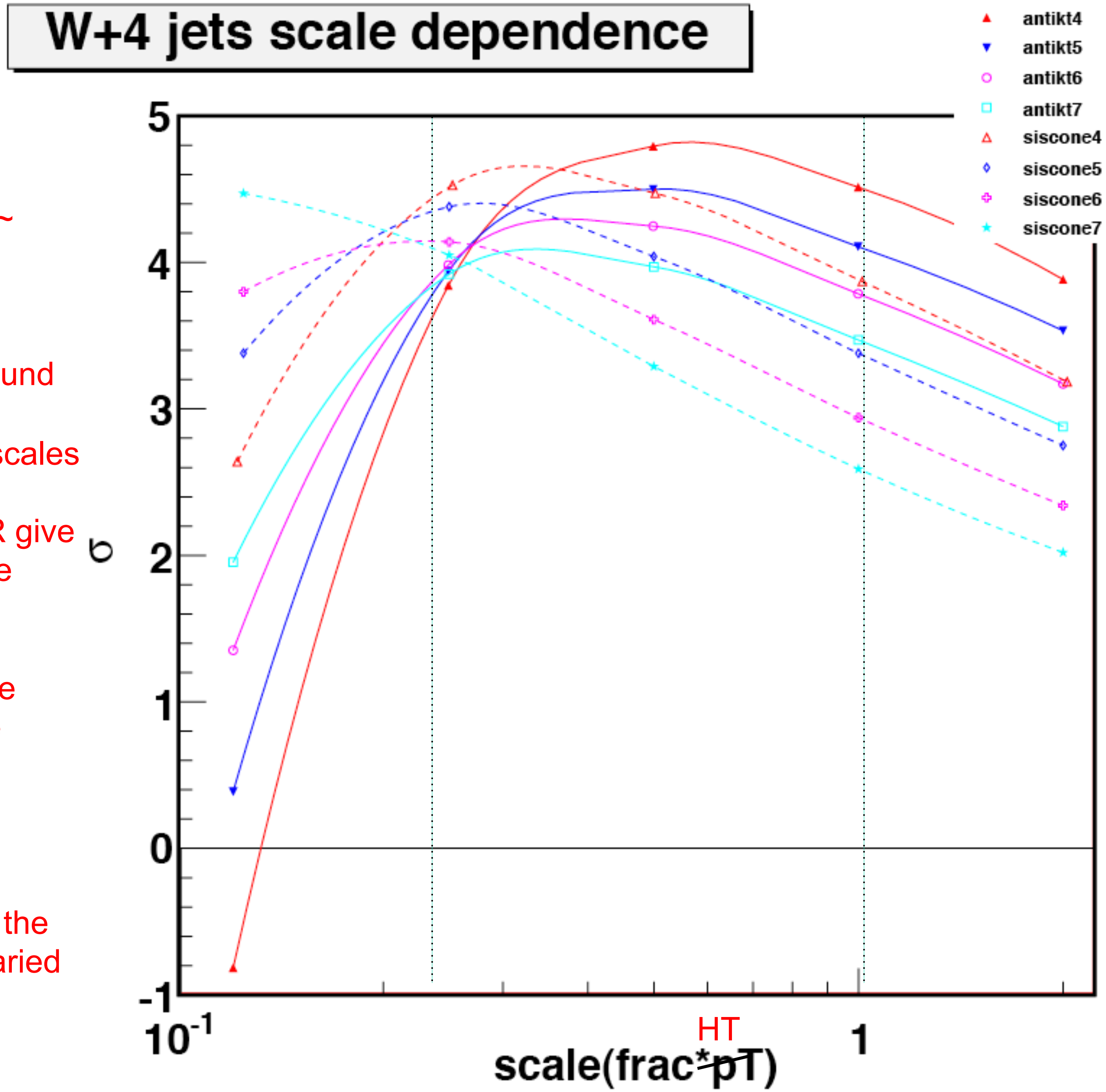
may be better to look for max/min over scale range (in 2D)





W+3 jets scale dependence
antikt4
antikt5
antikt6
antikt7
siscone4
siscone5
siscone6
siscone7
σ
70
65
60
55
50
45
40
35
30
25
20
10^{-1}
1
scale(frac*HT)

- A scale of HT/2 is ~ the peak for antikt4; so all deviations are negative
- Siscone peaks around HT/3
- Moves to smaller scales for larger R
- @HT/4, all antikt R give same result; that scale seems to be around HT/5 for siscone
- it is difficult to make conclusions about the uncertainty of any particular W + n jet cross section without understanding the scale dependence as the jet size/algorithm is varied



2010 ATLAS W+jets data

…testing LHC environment with 36 pb^{-1} and antikT4 jet algorithm

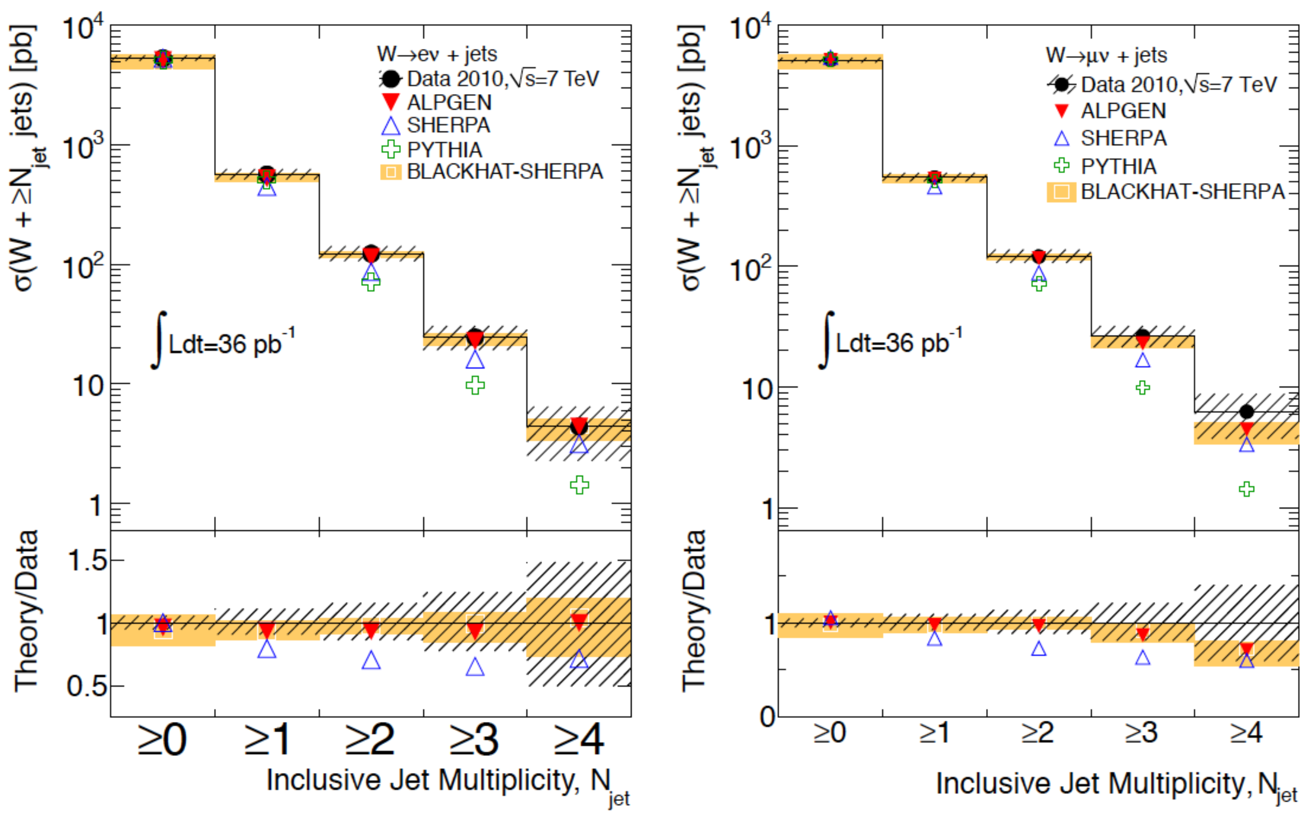
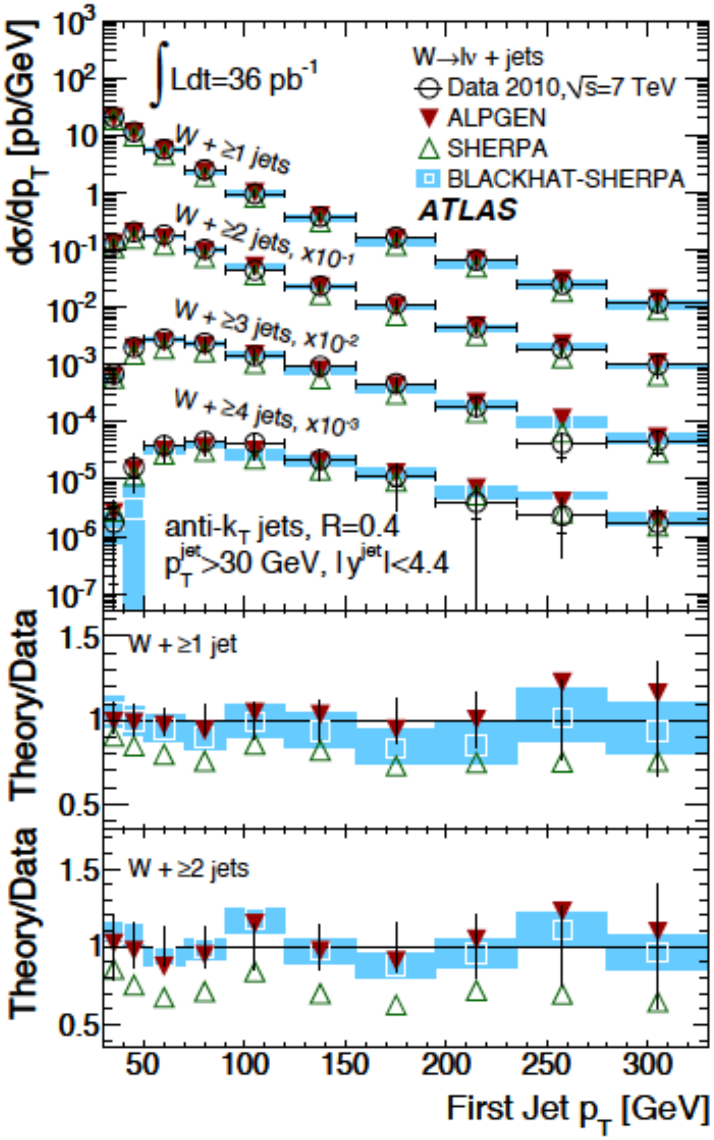
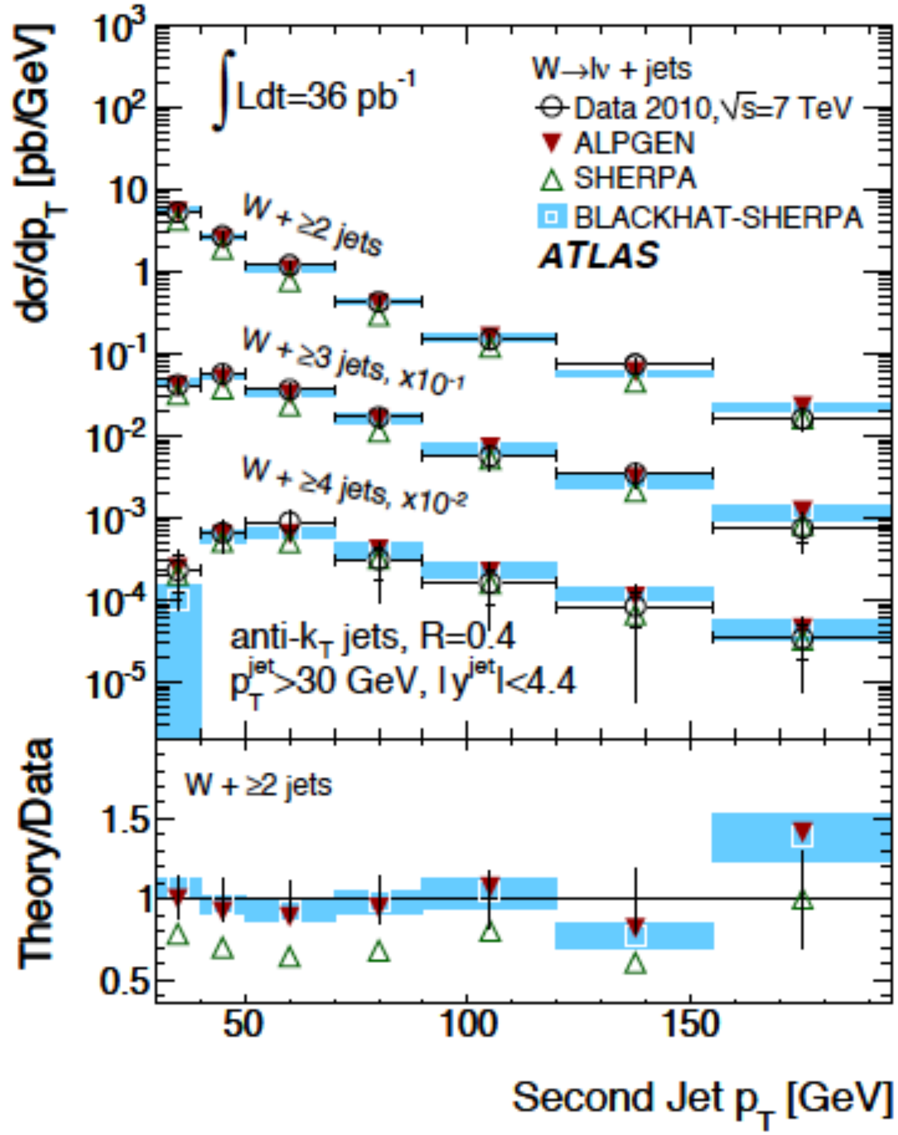


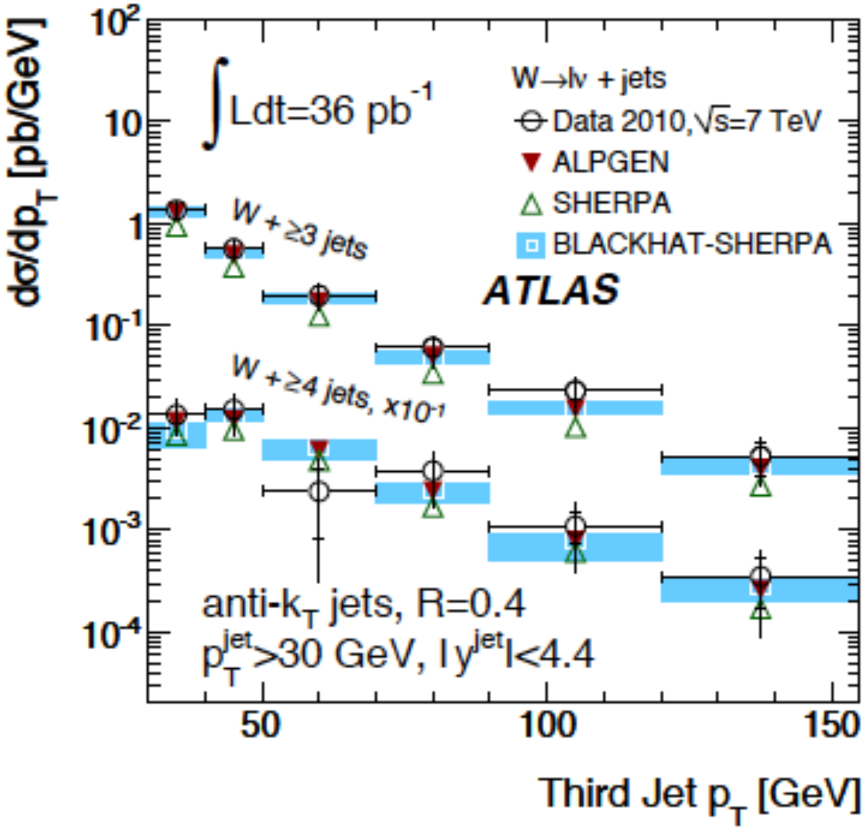
Figure 67: Inclusive jet multiplicity cross section results for the electron channel (left) and muon channel (right). For the data the statistical and systematic uncertainties are combined. Also shown are ALPGEN, SHERPA, PYTHIA, and NLO BLACKHAT-SHERPA calculations corrected for non-pQCD effects.

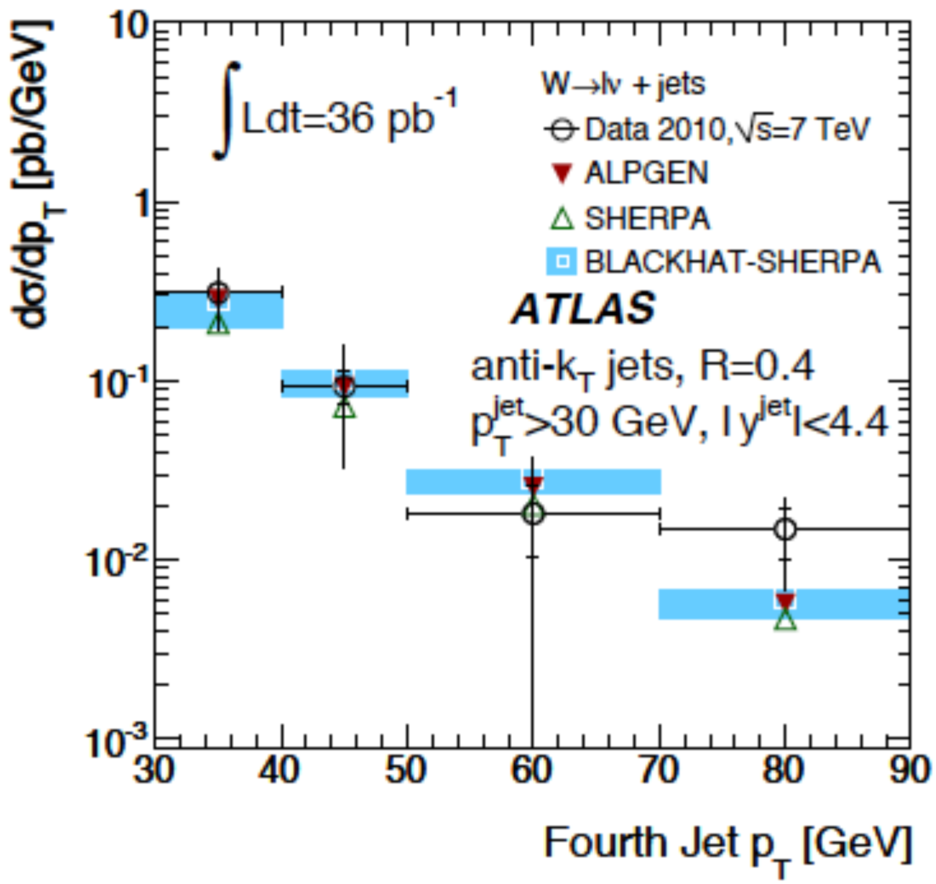
ATLAS: first and second jet p_T distributions



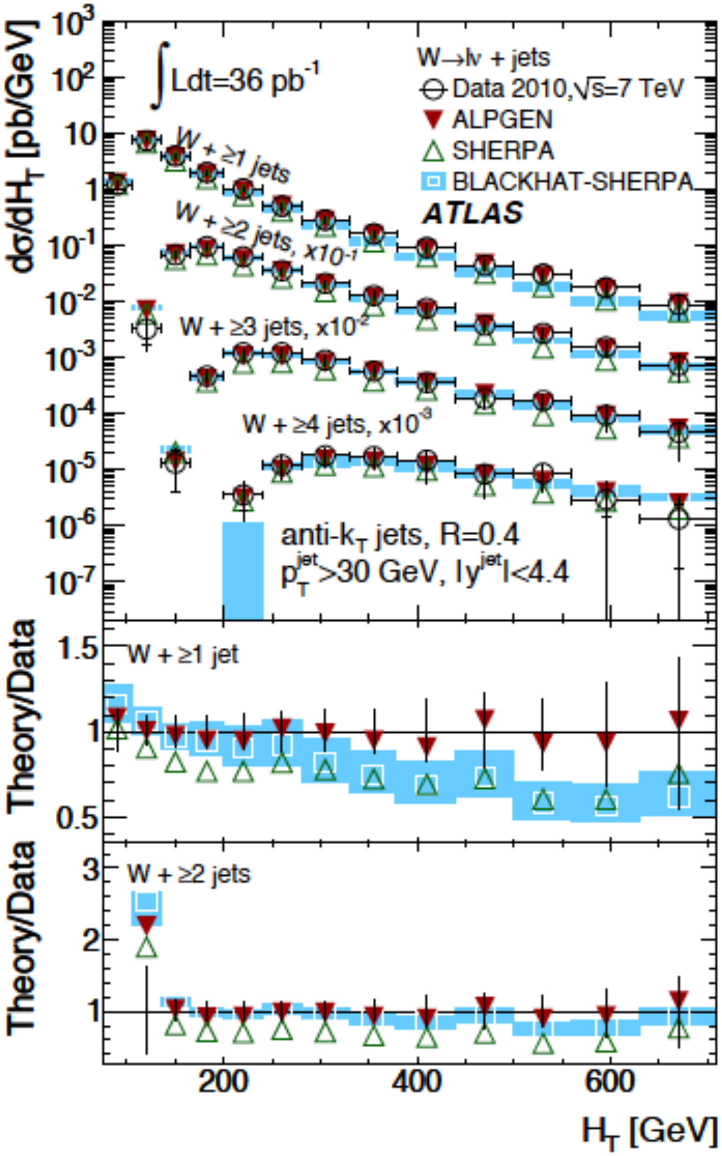


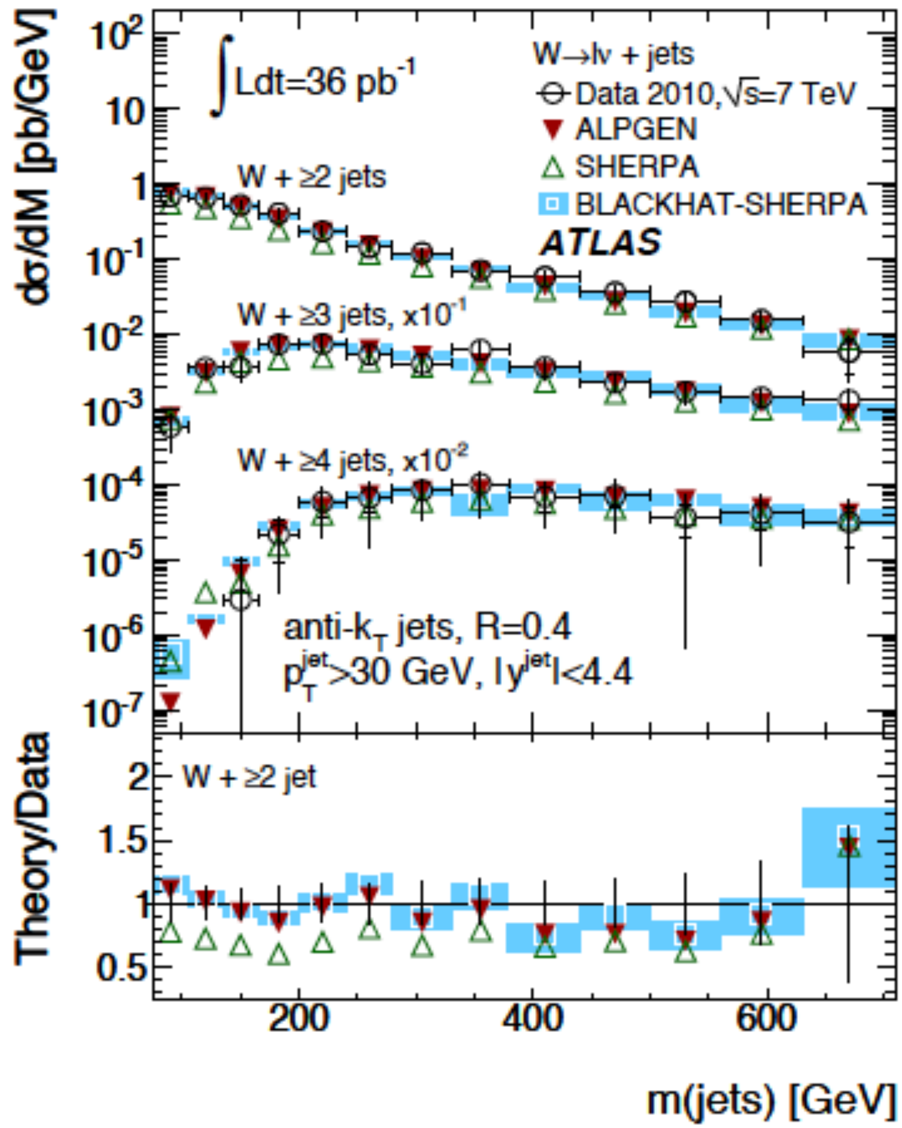
Third and fourth jet p_T distributions





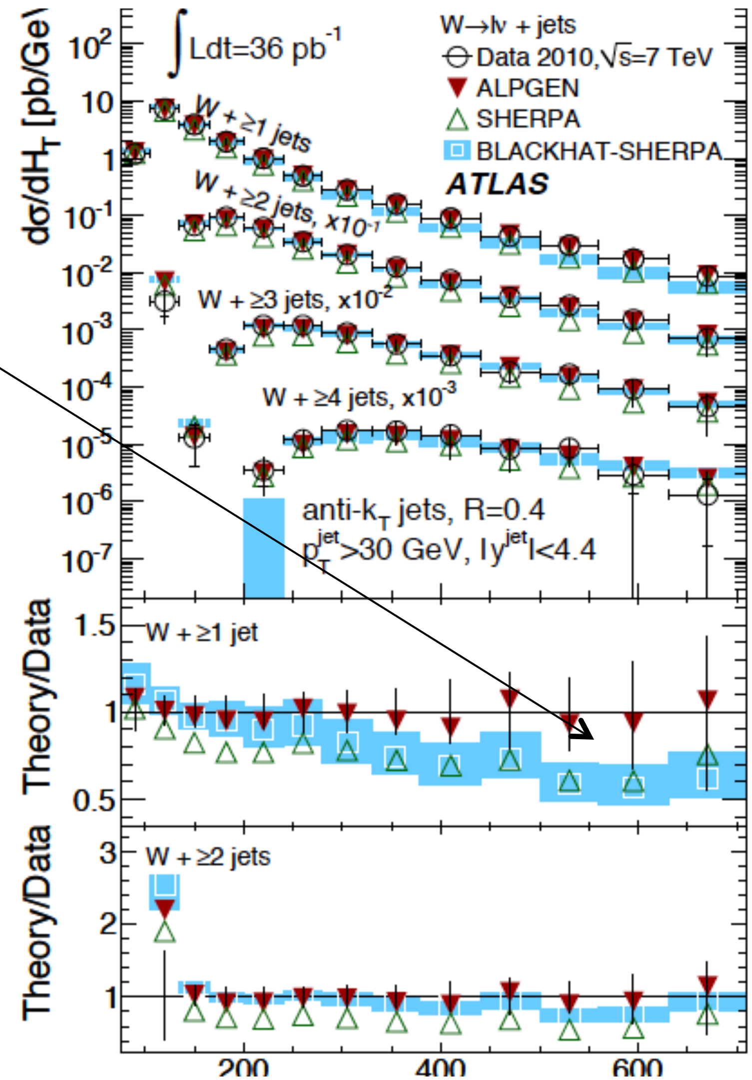
Look at very exclusive variables: H_T and m_{jets}





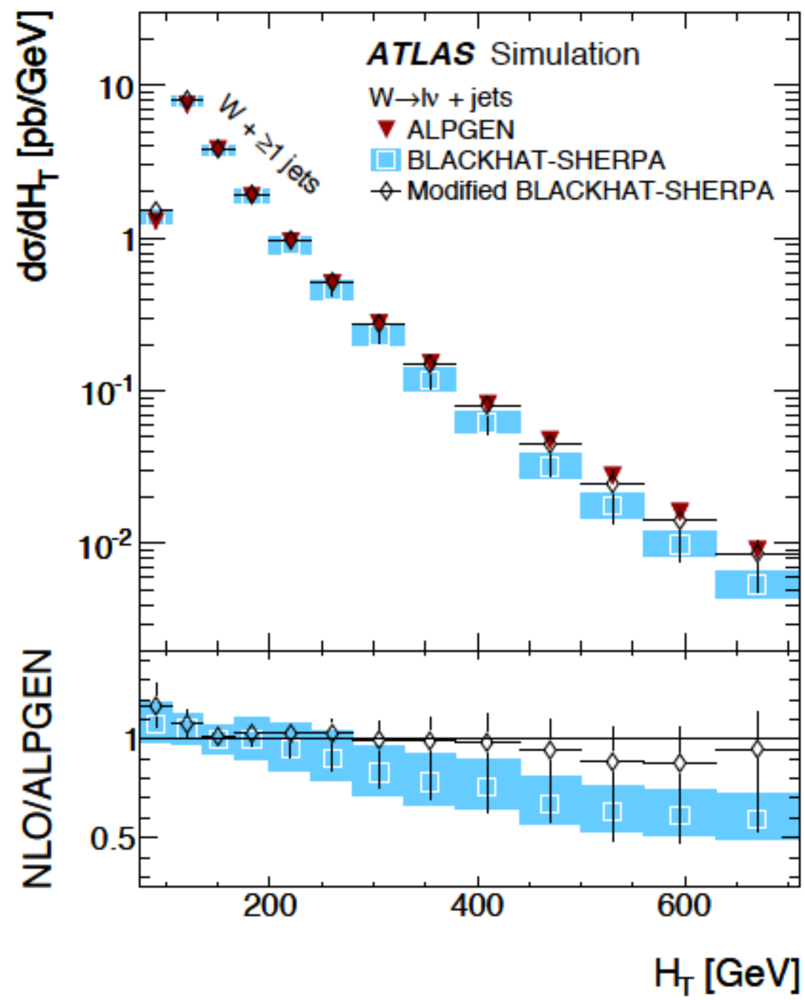
Going beyond NLO inclusive

- In the previous slide, we saw that the H_T distribution for W+>=1 jet was not well-described by the NLO W+1 jet prediction



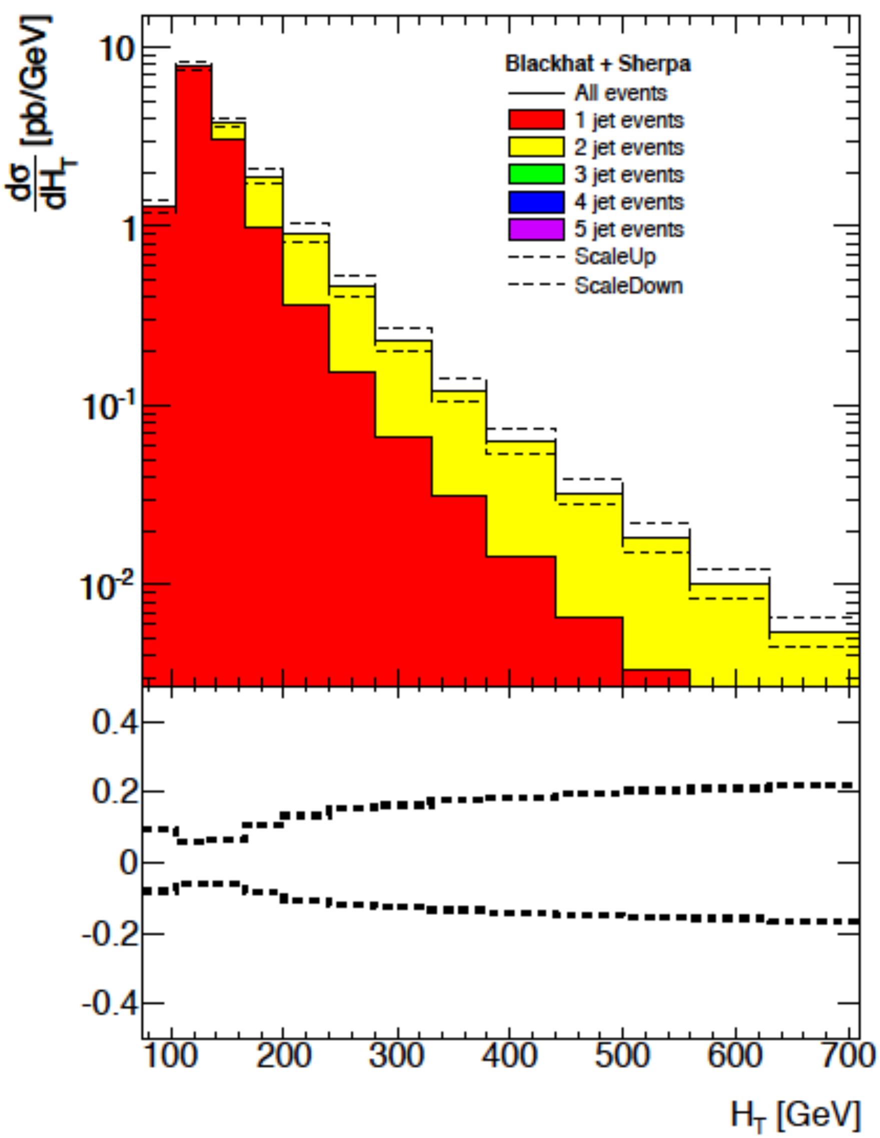
Going beyond NLO inclusive

- In the 2010 data, we saw that the H_T distribution for W+>=1 jet was not well-described by the NLO W +1 jet prediction
- However, it was better described when additional information was included from W+2,3,4 jets at NLO
- This is very tricky to do many of you may be offended
  - by definition the inclusive W+1 jet NLO calculation includes explicit W+2 jet information (at LO) and implicitly, through DGLAP evolution, information from 3,4,5, …. additional jets (in the collinear limit)
  - …and the real correction for W+1 jet is the same as the born term for W+2 jets…so double-counting is a problem



…but first, consider scale dependence for inclusive W+>=1 jet

- Why does the scale dependence get worse as H_T increases?
- Large H_T->more perturbative, so you might naively expect it to get better
- As H_T increases, most of cross section comes from W +2 jets, which is present only at LO in the calculation



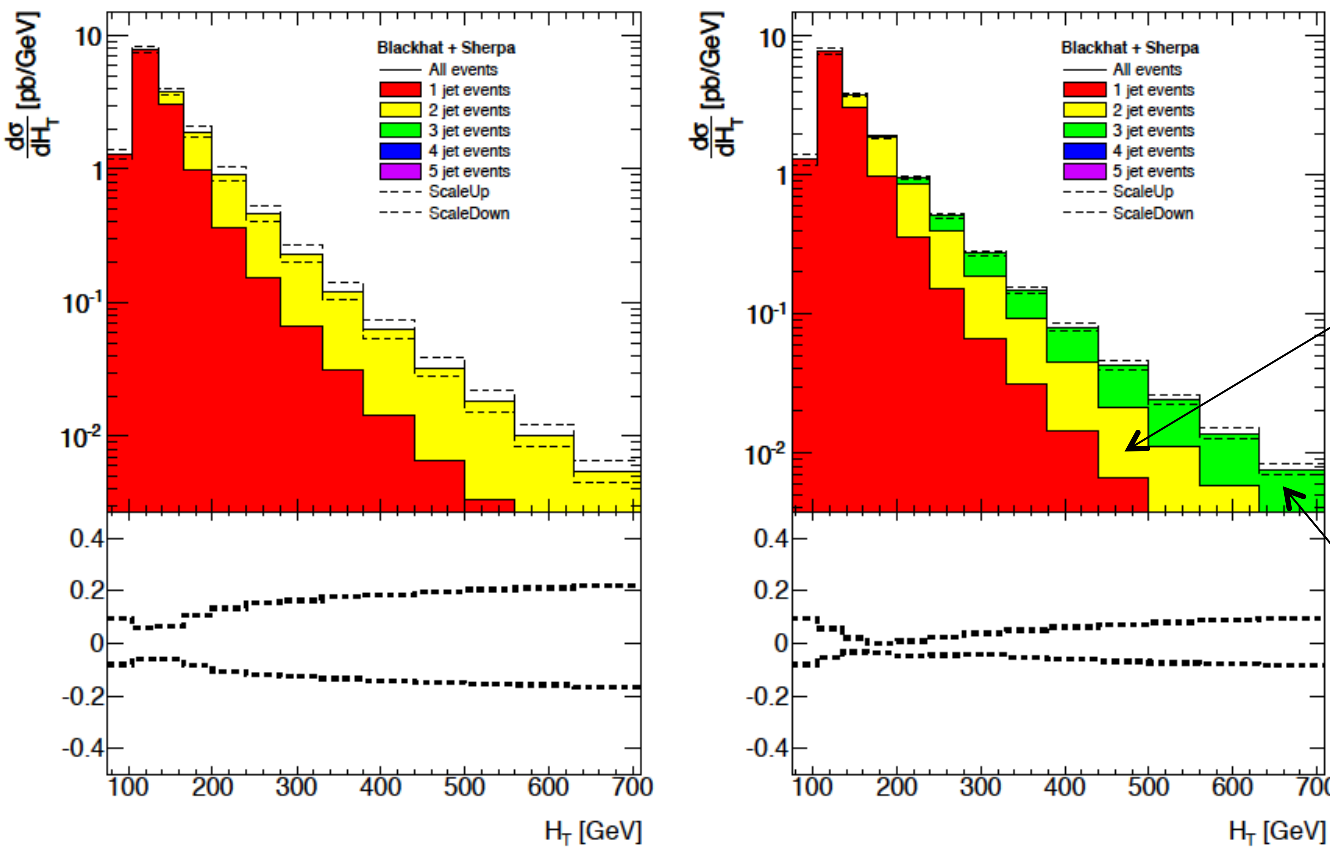
Exclusive sums

- The NLO Blackhat+Sherpa calculations consist of separate ntuples for born, virtual, subtraction and real
- Suppose we define exclusive sums such that for W+n jets, we remove any events in the W+n jet sample where there is an n+1 jet with p_T>some cutoff (30 GeV/c in the case of the 2010 data)
  - or we actually do the equivalent, where we keep all of the n+1 jets from the W+n jet real contribution, but remove the W+n+1 born events
- So we have explicit contributions for the exclusive sum W+1 jet cross section from 2 jets, 3 jets, 4 jets and 5 jets (LO)

$$\sigma^{\text{tot}} \equiv \sigma_m^{\text{inc}} = \sum_{n=m}^{M-1} \sigma_n^{\text{exc}} + \sigma_M^{\text{inc}}$$

- This is similar to the data where if we form the H_T cross section for >=1 jet, we have contributions from all of those higher multiplicity final states
- So how does it work

Pretty well when adding W+2 jets

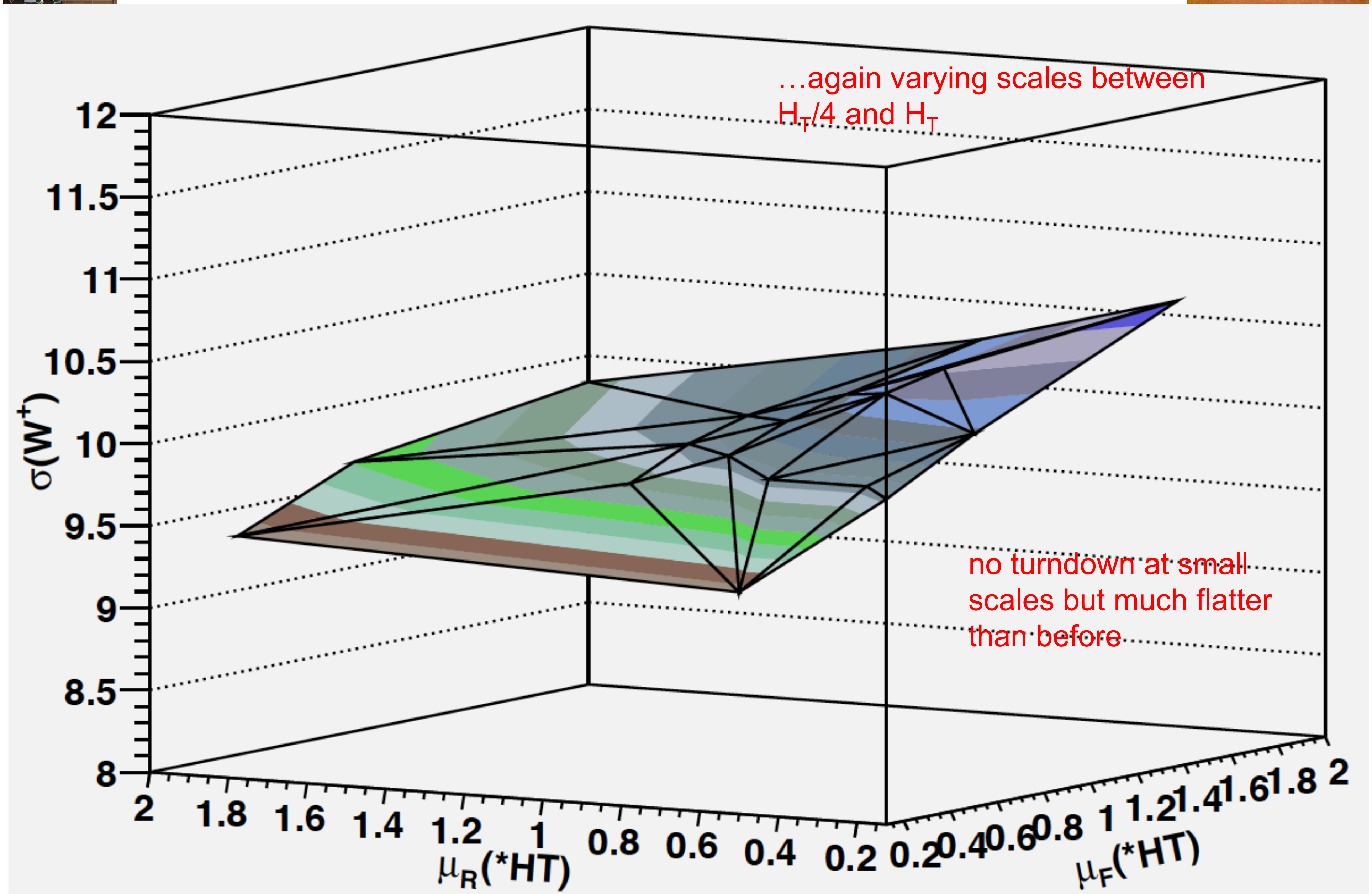


…note that the 2-jet information now comes in at NLO

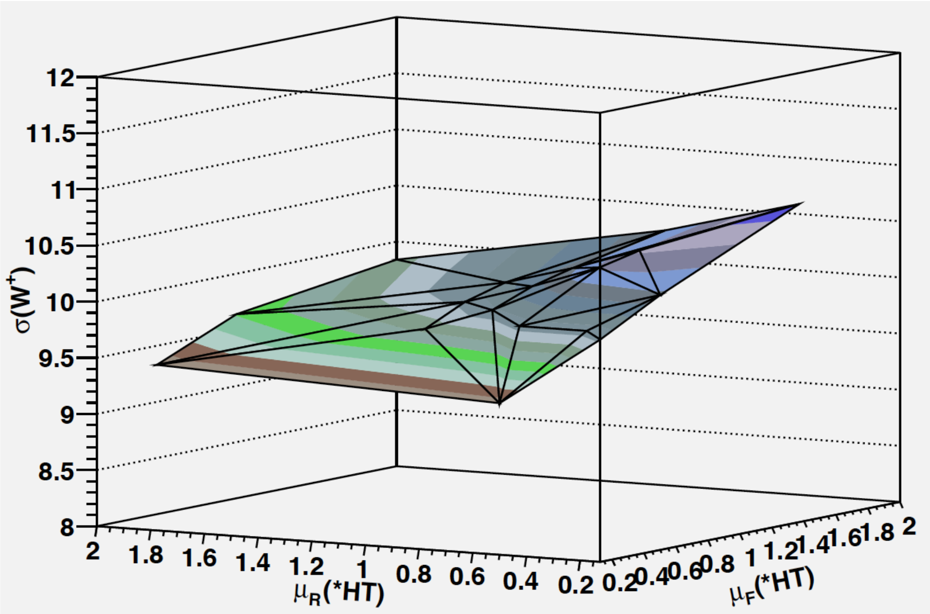
the 3-jet contribution is now at LO

Fig. 1: The W + jets cross section, as a function of H_T, for the NLO inclusive $W+ \geq 1$ jet prediction (left) and for the exclusive sums approach, adding in W + 2 jet production at NLO (right). The cross sections have been evaluated at a central scale of $H_T/2$ and the uncertainty is given by varying the renormalization and factorization scales independently up and down by a factor of 2, while ensuring that the ratio of the two scales is never larger than a factor of 2.

Look at 2D scale dependence for exclusive sum (W+1+2 jets at NLO)

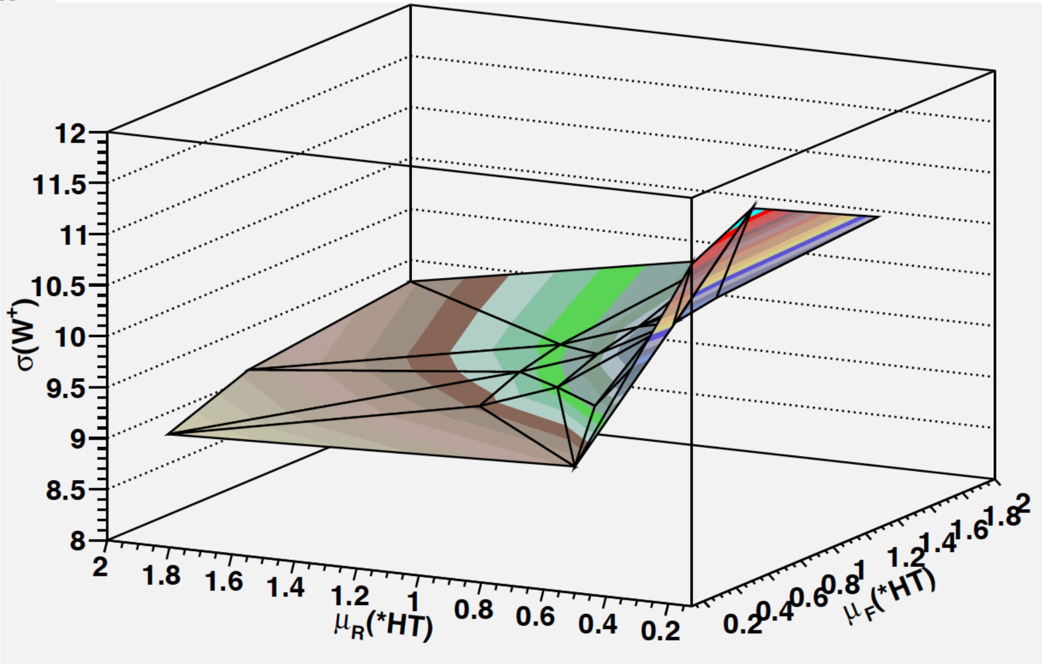


Comparison with inclusive case



exclusive NLO sum

inclusive NLO



Not quite as well for adding 3 and 4 jets

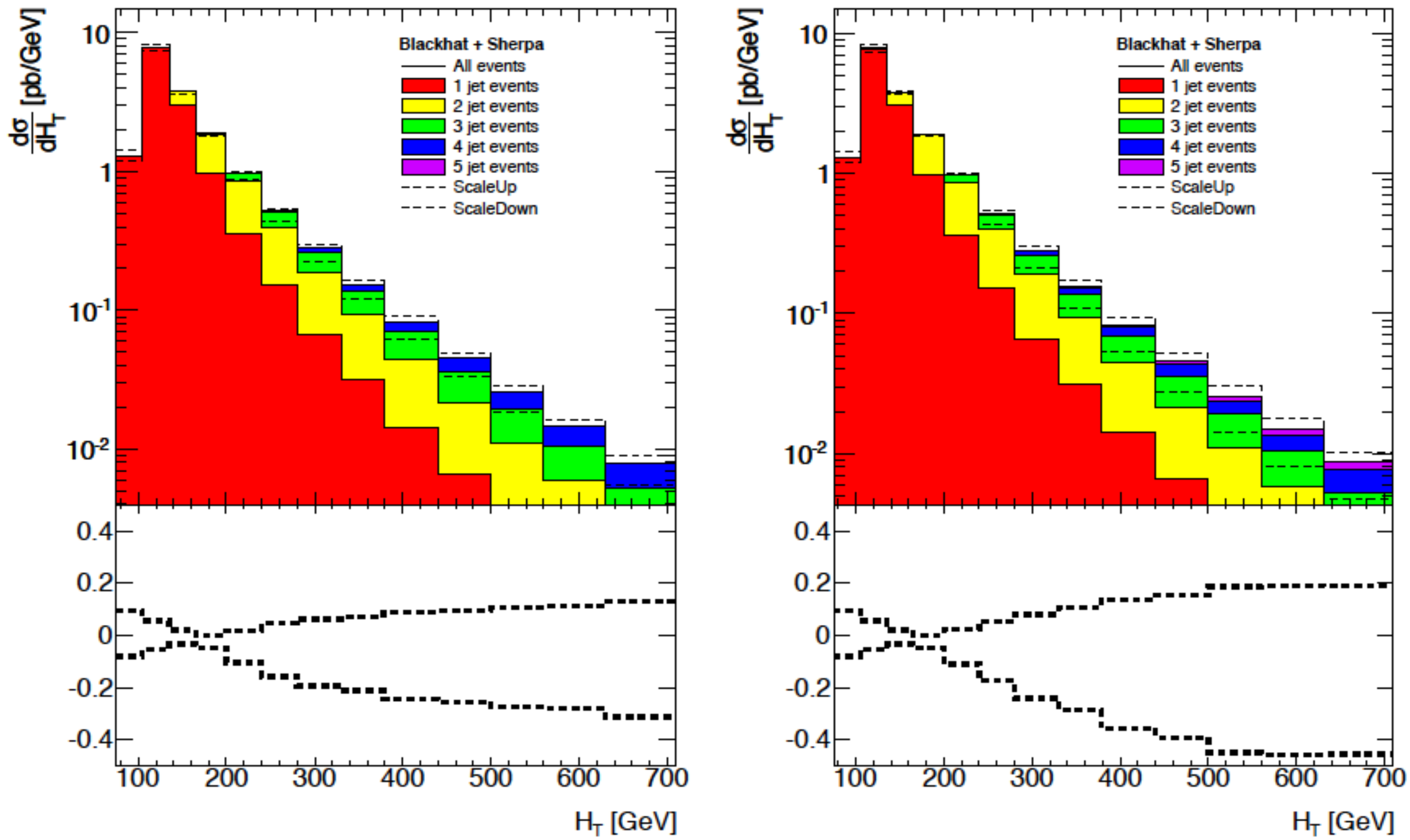


Fig. 2: The W + jets cross section, as a function of H_T, for $W+\geq 1$ jet production using the exclusive sums approach, and adding up to 3 jets at NLO (left) and 4 jets at NLO (right). The cross sections have been evaluated at a central scale of $H_T/2$ and the uncertainty is given by varying the renormalization and factorization scales independently up and down by a factor of 2, while ensuring that the ratio of the two scales is never larger than a factor of 2.

So what went wrong…with the scale dependence

NLO predictions into fixed multiplicities sets[3] and test the stability of the prediction. For the exclusive sums approach outlined here for $W+\geq 1$ jets, contributions are added proportional to α_s^2 (W+1 jet at NLO), α_s^3 (W+2 jets at NLO), α_s^4 (W+3 jets at NLO) and α_s^5 (W+4 jets at NLO). So this procedure mixes powers of α_s and thus is missing essential Sudakov form factors that effectively bring each term to the same power of α_s. One could imagine accomplishing this by embedding the NLO matrix elements in a parton shower Monte Carlo framework, however the technology for merging different multiplicities of NLO calculations with a parton shower is still under development. Alternatively the LoopSim method can be used to provide approximations to the higher-loop terms missing in the exclusive sums approach. As we have seen here, prospects for using it together with Blackhat+Sherpa ntuples seem promising.

…need something else to obtain necessary logarithmic accuracy …we're currently working with LoopSim

Performing the sum over n, which corresponds to summing an infinite tower of NLO exclusive jet calculations, leads to

$$\sigma(p_{t,W})^{\mathrm{DLA}} = \sum_{n=1}^{\infty} \sigma_{n,excl}^{\mathrm{NLO(DLA)}}(p_{t,W}) \tag{5a}$$

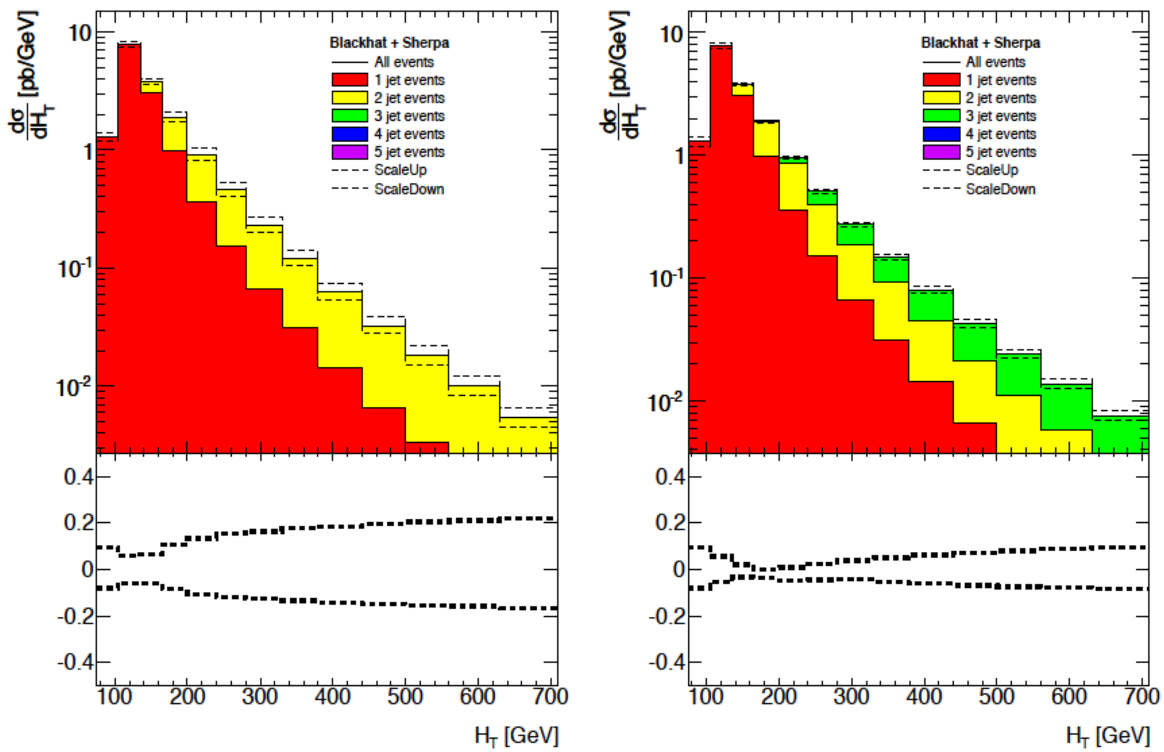
$$= \sigma_1^{\mathrm{LO}}(p_{t,W}) \exp\left(\frac{2C\alpha_s}{\pi}L^2\right)\left(1 - \frac{2C\alpha_s}{\pi}L^2\right) \tag{5b}$$

$$= \sigma_1^{\mathrm{LO}}(p_{t,W}) \left(1 - \frac{1}{2}\left(\frac{2C\alpha_s}{\pi}L^2\right)^2 + \mathcal{O}(\alpha_s^3 L^6)\right). \tag{5c}$$

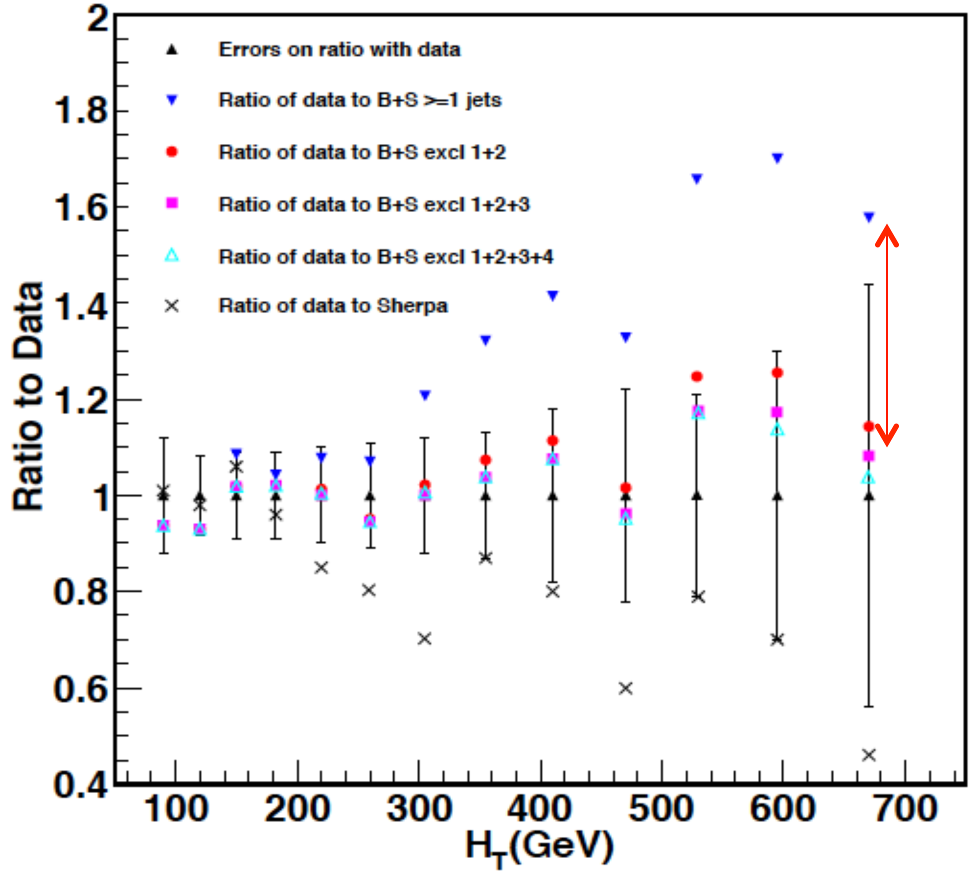
As long as L^2 is not large, the difference between this and the correct answer of Eq. (3) is a straightforward NNLO correction, i.e. small. However in when $p_{t,W} \gg p_{t,\mathrm{min}}$ the logarithms become large, the $\alpha_s^2 L^4$ term can be of order 1 and the exclusive sums method may then no longer be a good approximation. A similar analysis can be performed for an exclusive sum truncated at some finite order, as used below.

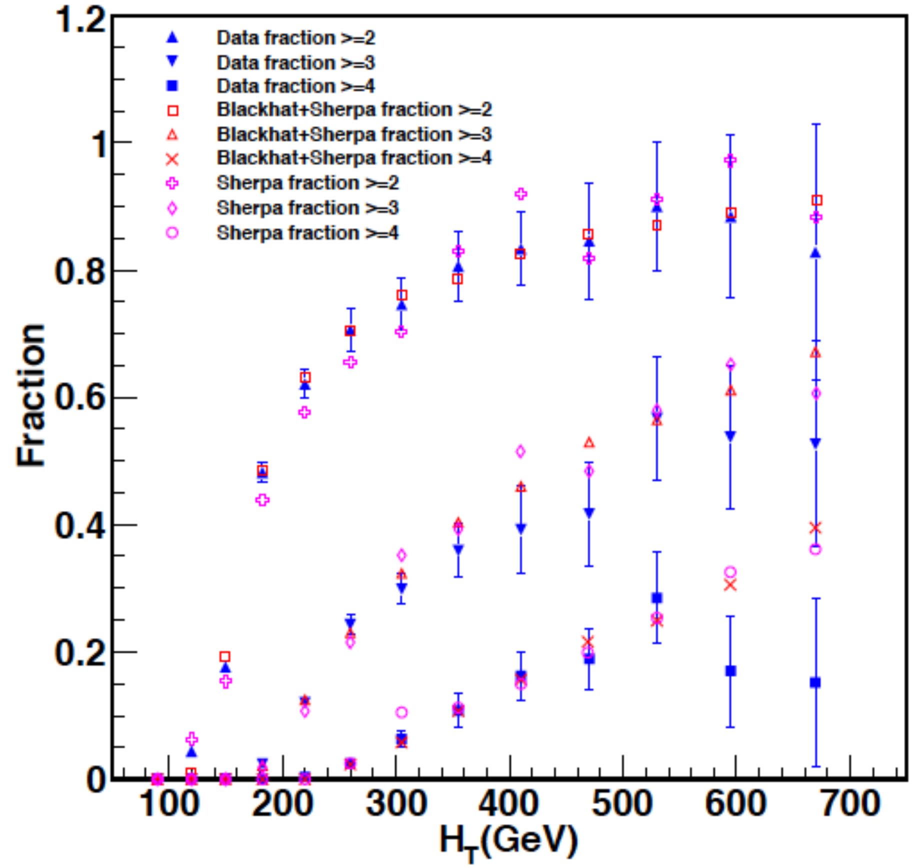
What went right with W+2?

- There are substantial qq->q'qW contributions that enter at LO for W+2 jet (so in the real terms for W+1 jet at NLO) that are stabilized by the addition of the W+2 jet full NLO terms
- So (I think) adding the W+1 and W+2 NLO using the exclusive sums approach gives a superior prediction compared to W+1 jet alone
- Higher multiplicities may need more work a la LoopSim to reduce the scale dependence
- But I think there must be a simpler way as well to take into account the proper Sudakovs



Some comparisons

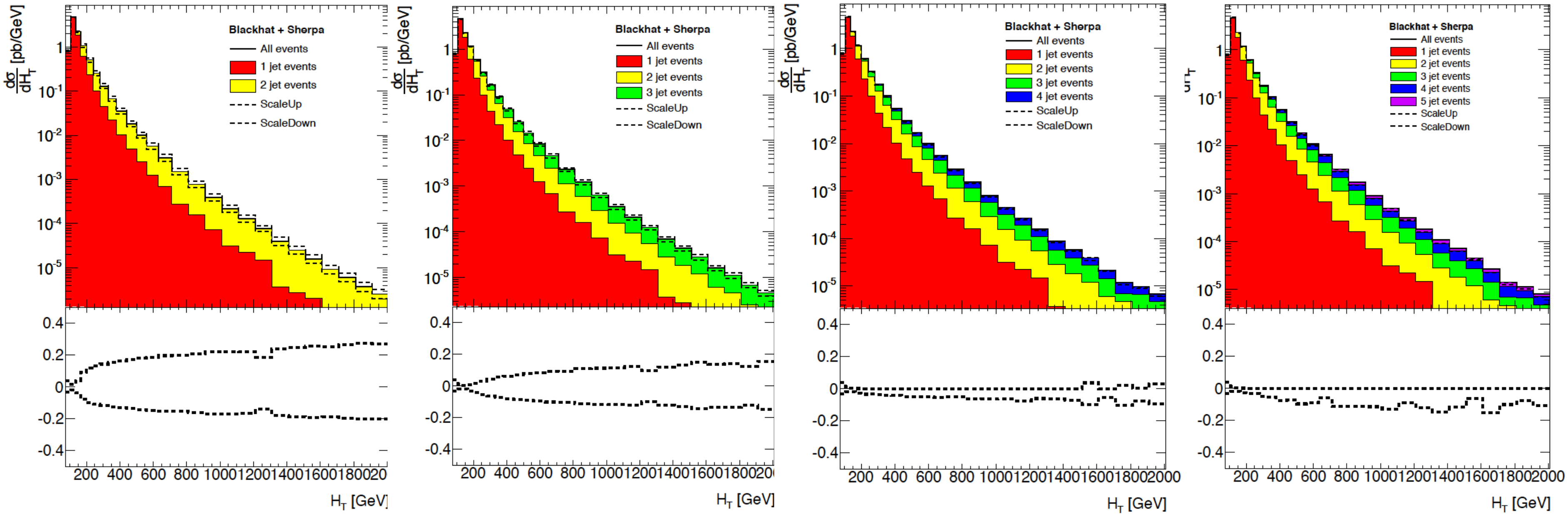




…most of the increase in the H_T cross section comes from adding W+2 jets

exclusive sums does get the contributions from each jet multiplicity right

H_T



Most of problems with exclusive sums results from going down to scale of $H_T/4$.
What if we use H_T as a central scale and vary up and down by a factor of 2 from that?

…so you can see that the scale uncertainty in this case isn't ruined by adding in the higher jet multiplicities; the same is true if you stick to lower scales but user larger jet sizes

Of course, doing this would require a justification for why the higher scale is more appropriate, i.e. a better understanding of the exclusive sum approach.

Also, it would be of interest to understand why using a larger jet size seems to work better, even with the lower scale choices

For more details, see the following contribution to Les Houches

arXiv: 1203.6803

W+jets production at the LHC: a comparison of perturbative tools

J. Andersen[1], *J. Huston*[2], *D. Maître*[3,4], *S. Sapeta*[5], *G.P. Salam*[3,5,6], *J. Smillie*[7], *J. Winter*[3]
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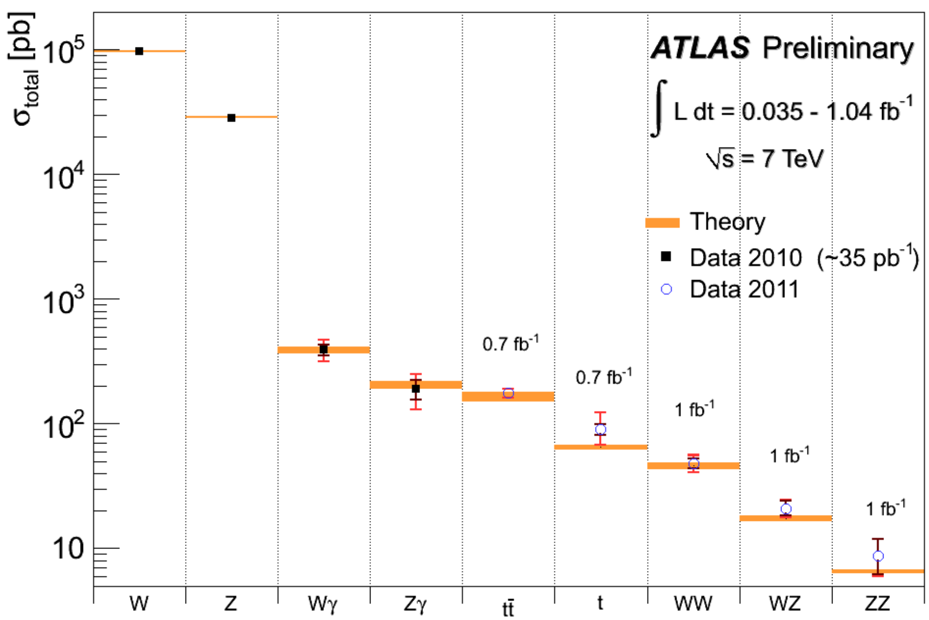
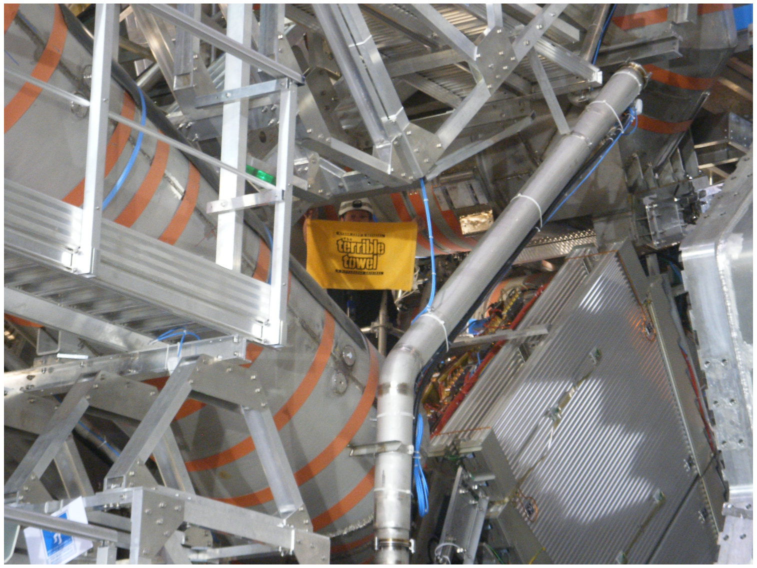
Abstract
In this contribution, we discuss several theoretical predictions for W plus jets production at the LHC, compare the predictions to recent data from the ATLAS collaboration, and examine possible improvements to the theoretical framework.

…plus I'm working on some followup studies with Gavin Salam, Sebastian Sapeta, Daniel Maitre, Jan Winter et al on LoopSim treatment

Summary

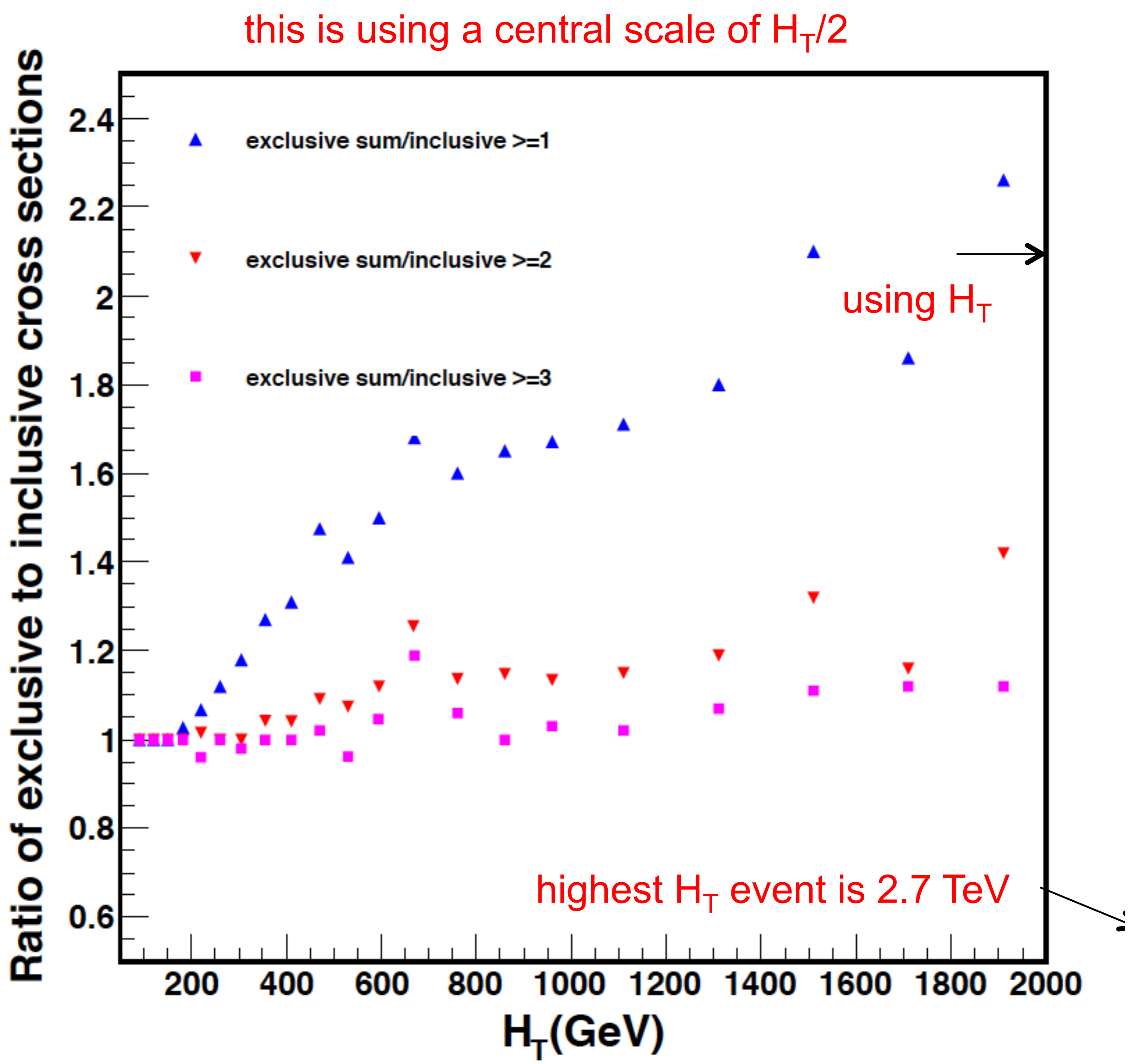
- The LHC data will continue to pour in, allowing for detailed comparisons to and understanding of perturbative QCD at the energy frontier
  - >4.5 fb-1 in 2011
  - ~15-20 fb-1 in 2012 (at 8 TeV)
- The data is in broad good agreement with the perturbative predictions, but there are enough questions to make both experimentalists and theorists work
- 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, amd more sophisticated scale choices
  - ATLAS will have calibrated jet corrections for kT, C/A and antikT for jet sizes of 0.3-1.2
- This will be an interesting decade





The future

- If we extrapolate up to the kinematic reach of 2011 (2012), then we might expect there to be a significant deficit in the conventional NLO predictions not only for W+1 jet but for W+2 jets as well
- Caveat: I don't know how the addition of the Sudakov form factors that would be part of a complete treatment of the exclusive sums would affect the size of the large H_T cross section
- But we have ~4.7 fb^{-1} from the 2011 data and will have the ability to measure cross sections for jet sizes of 0.3-1.2 for several jet algorithms
- I don't have that amount of energy, but would like to check 0.4-0.7



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

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

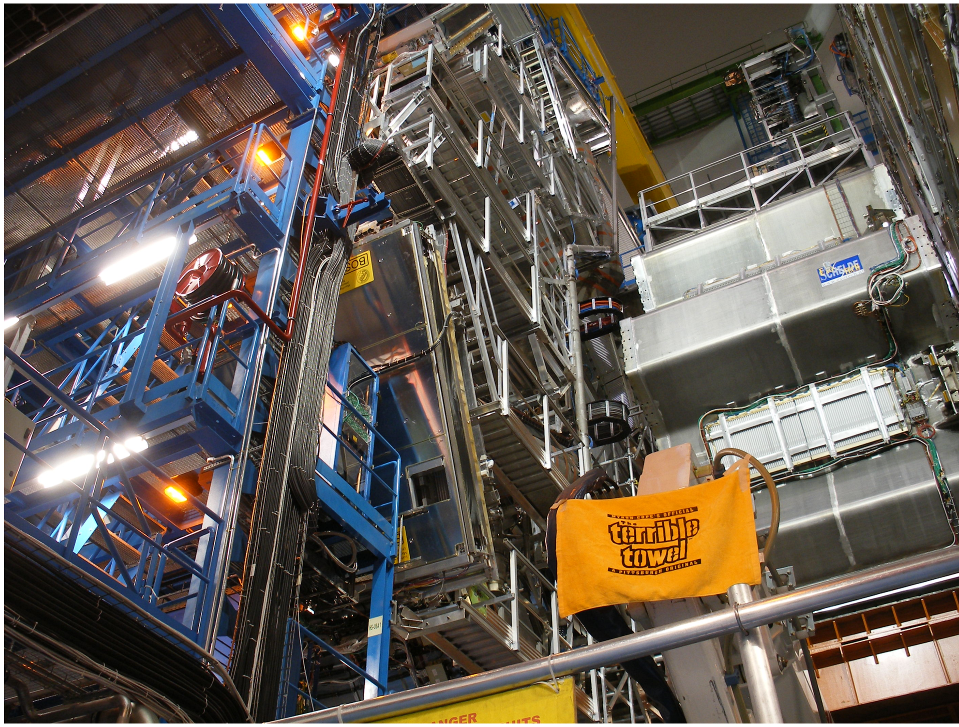
QCD @ LHC 2012

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.

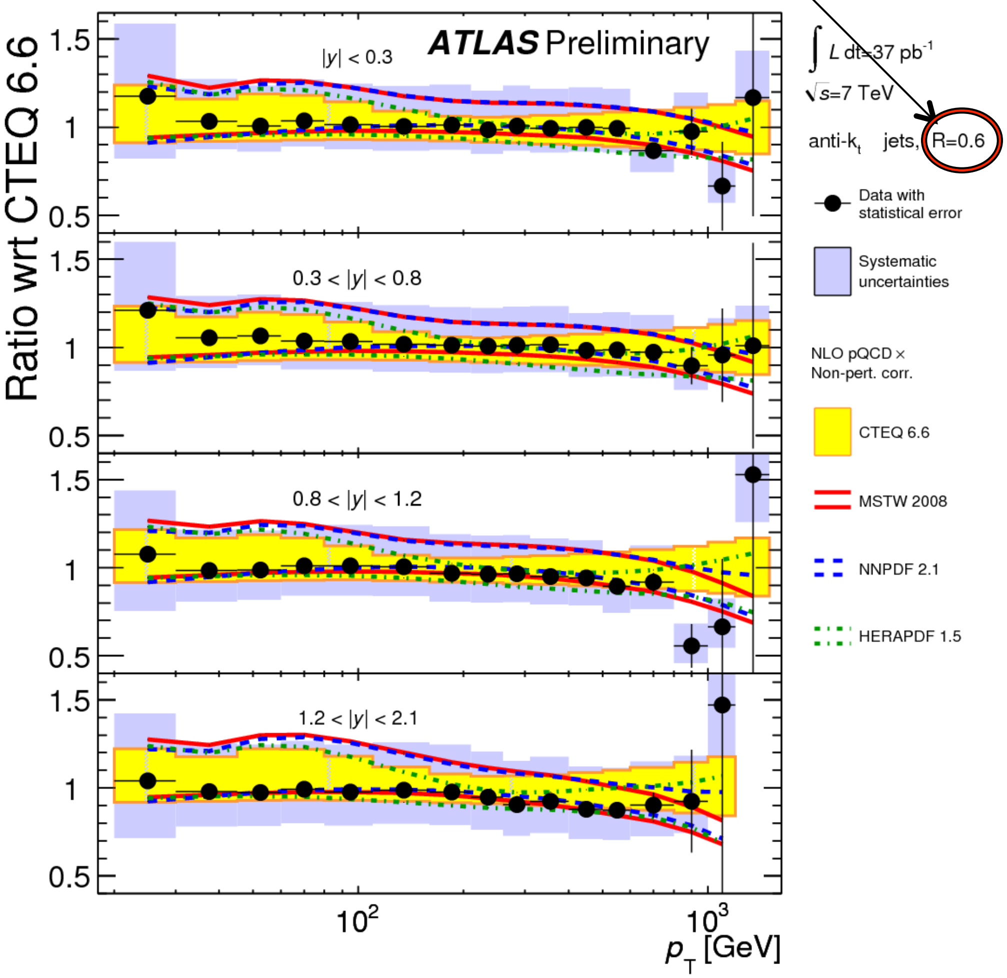
…a continuation of the series that started in Trento (2010) and St. Andrews (2011)

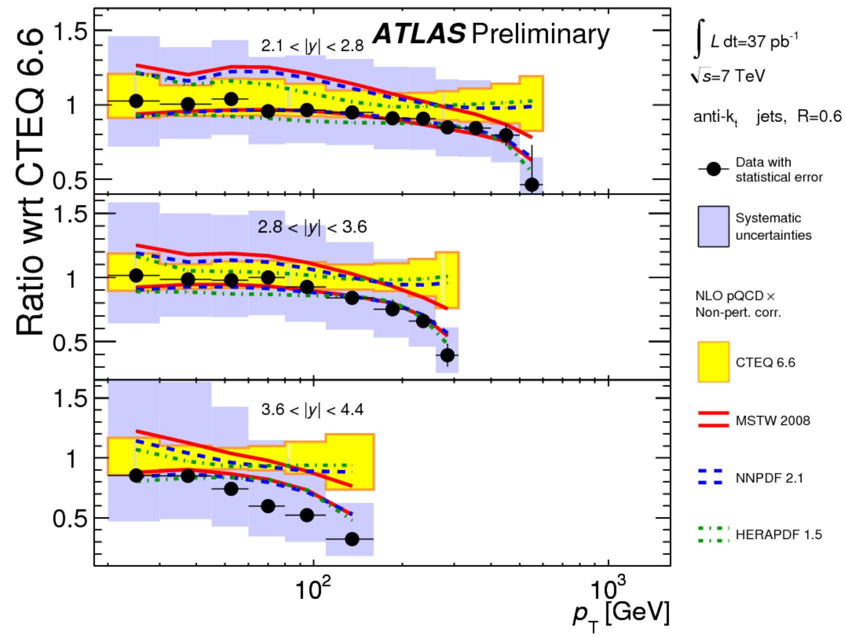
Terrible Towel visits ATLAS



ATLAS: inclusive jets

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

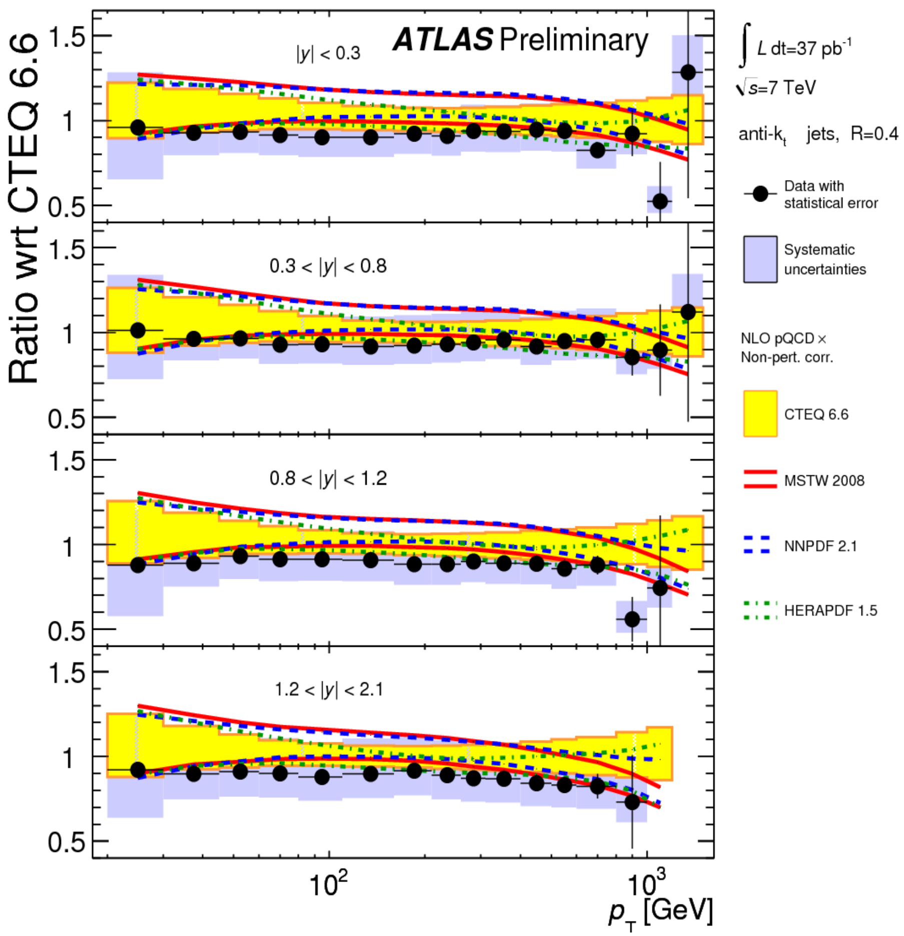


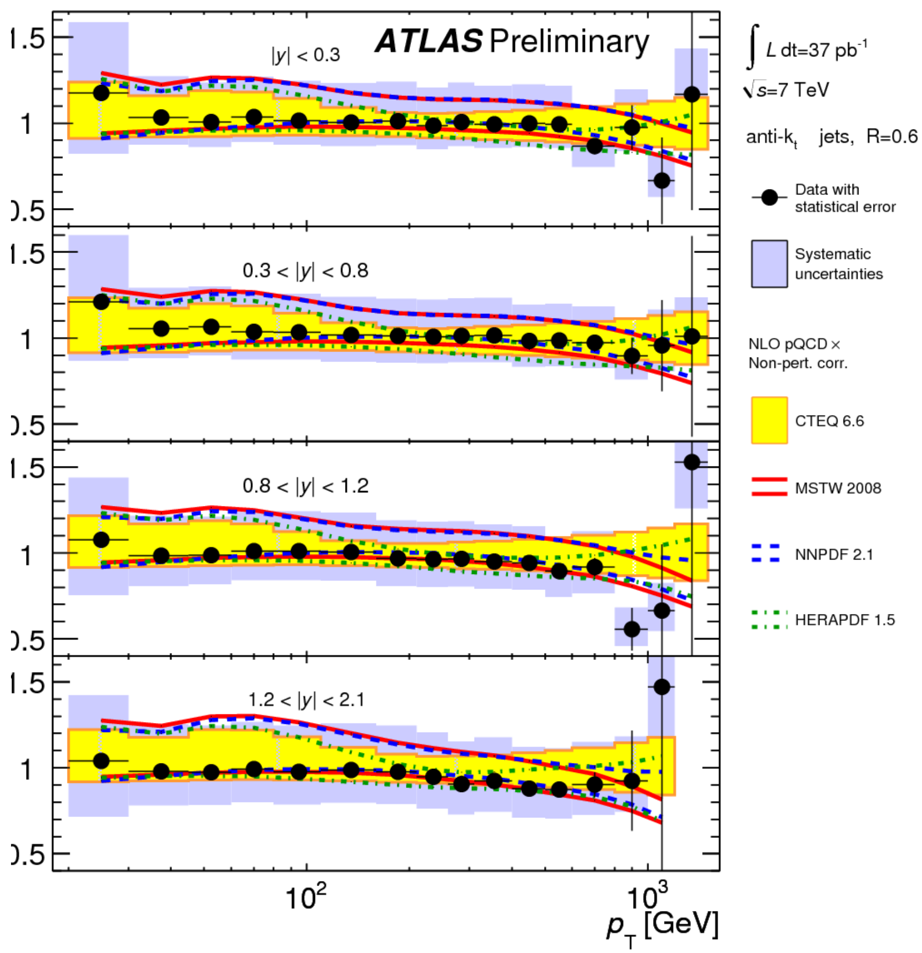


The data tend to fall off faster at high p_T/high y. Is this due just to PDFs or is there other physics also involved?

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

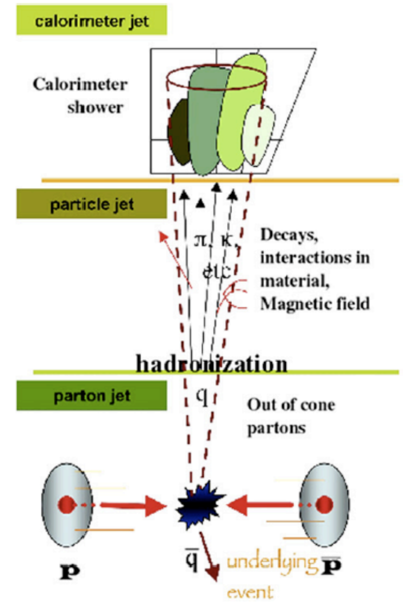




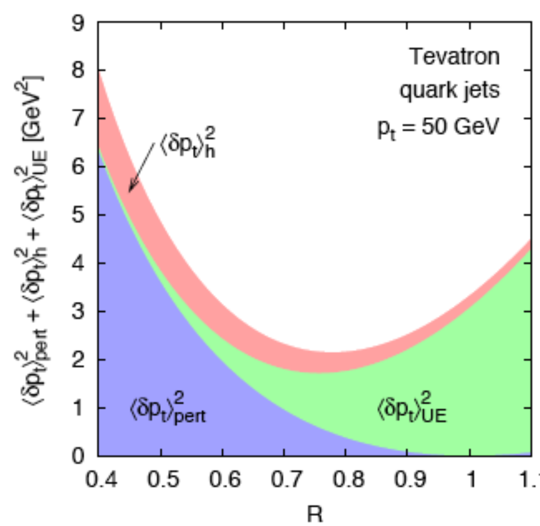
Choosing jet size

- 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,

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

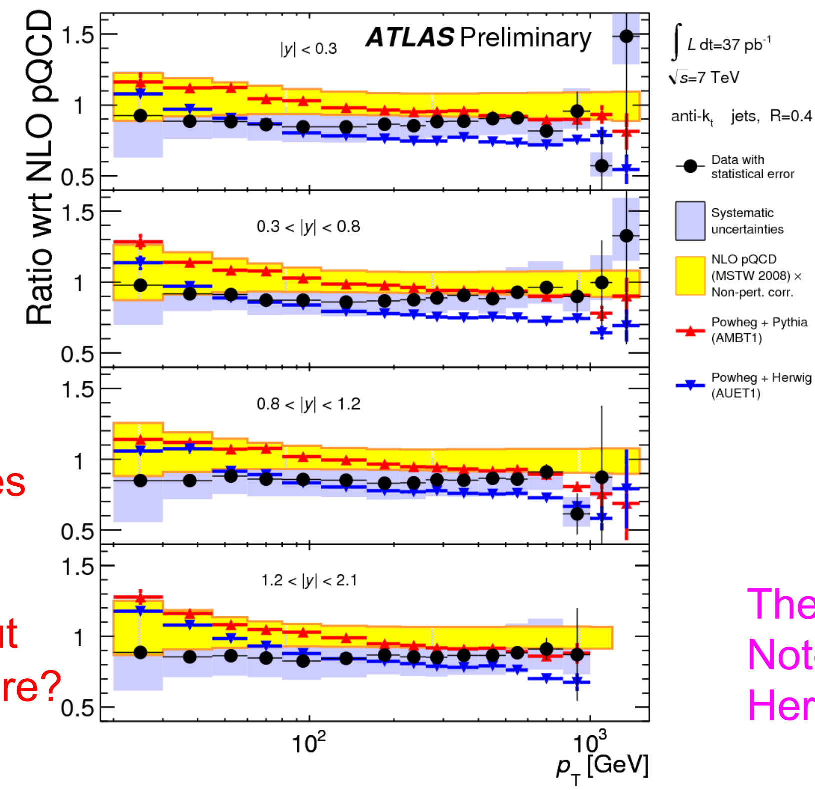


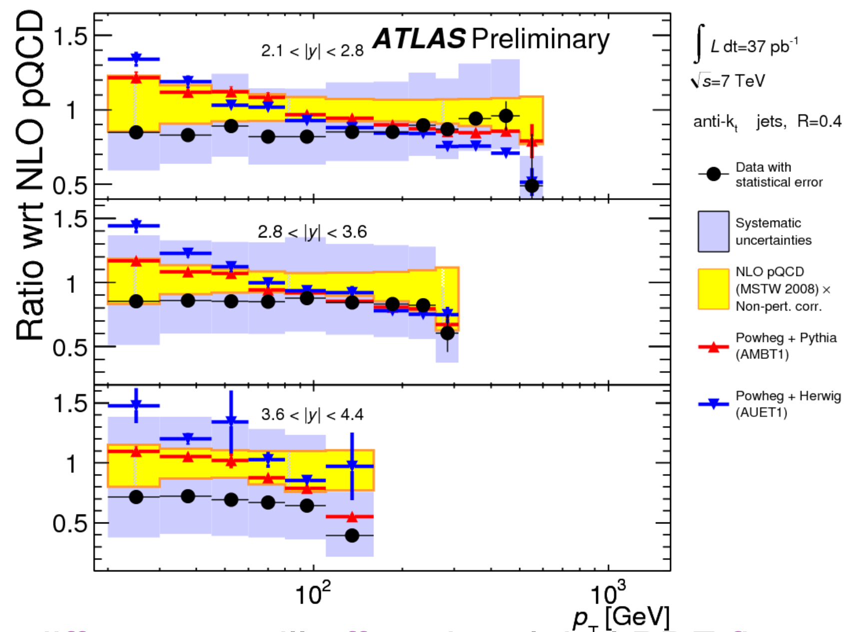
Dasgupta, Magnea, Salam arXiv0712.3014



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 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

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

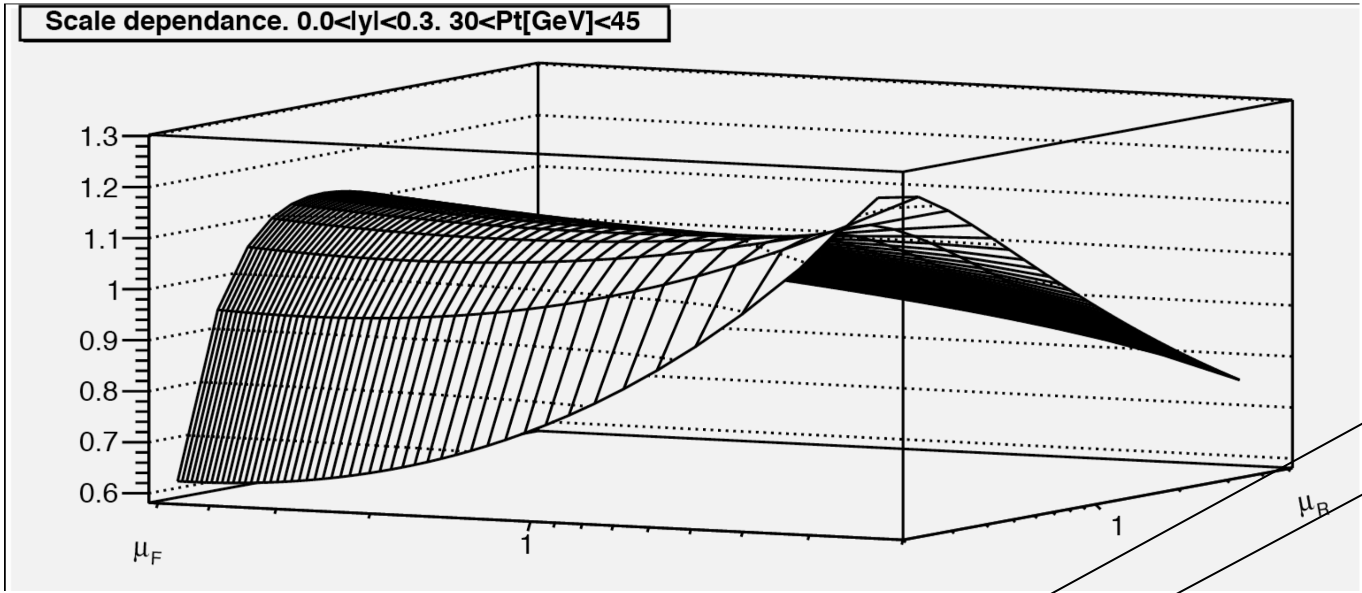
When one calculates the $\mathcal{O}(\alpha_s^3)$ contributions to the inclusive cross section, the result can be written as

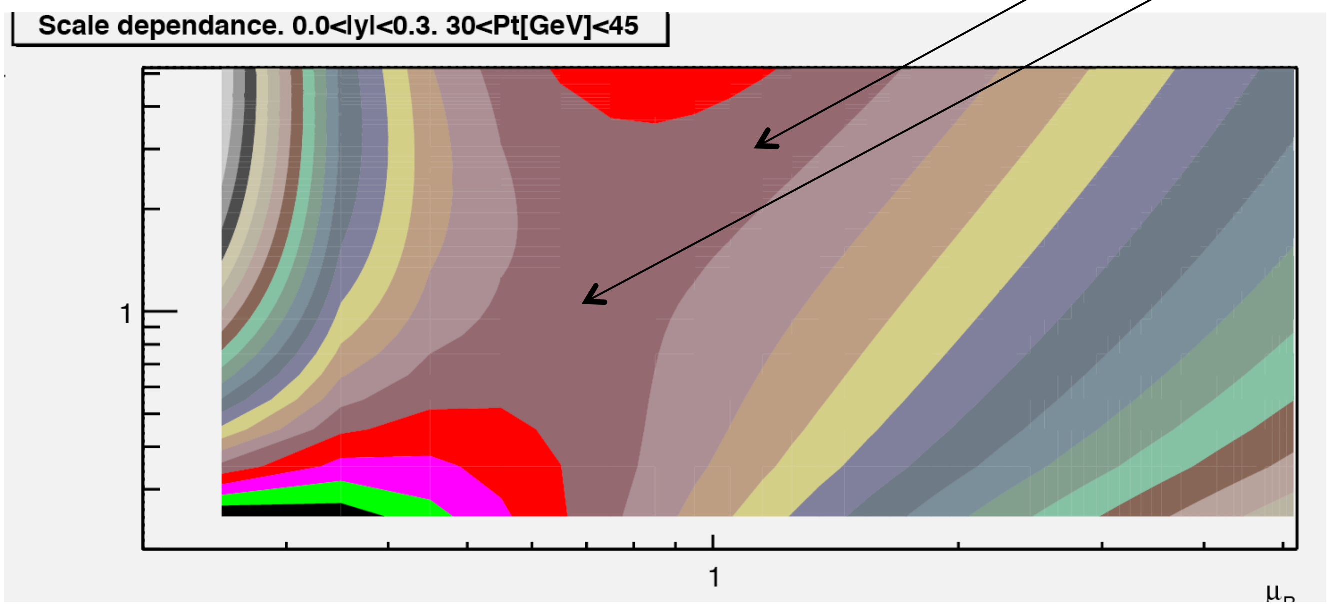
$$\begin{aligned}
&(1) \quad \sigma = a^2(\mu)\,\hat{\sigma}_B \otimes q(M) \otimes q(M) \\
&(2) \quad + 2a^3(\mu)\, b \ln(\mu/p_T)\hat{\sigma}_B \otimes q(M) \otimes q(M) \\
&(3) \quad + 2a^3(\mu)\, \ln(p_T/M) P_{qq} \otimes \hat{\sigma}_B \otimes q(M) \otimes q(M) \\
&(4) \quad + a^3(\mu)\, K \otimes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

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



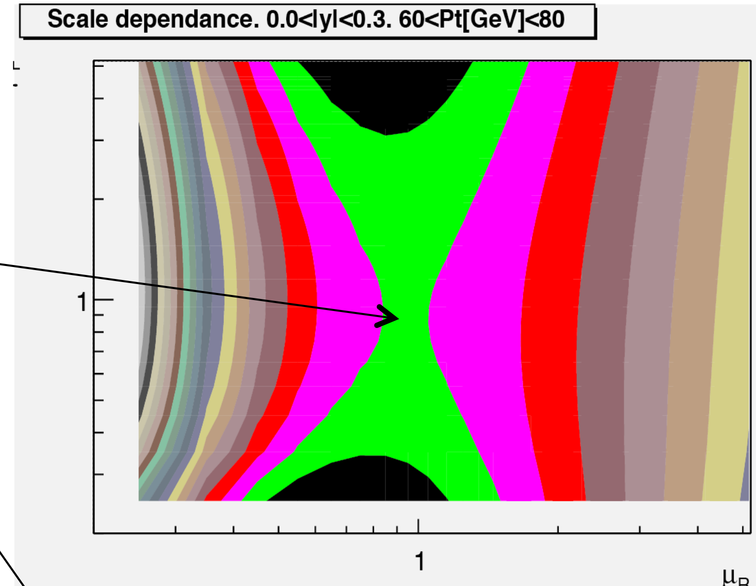


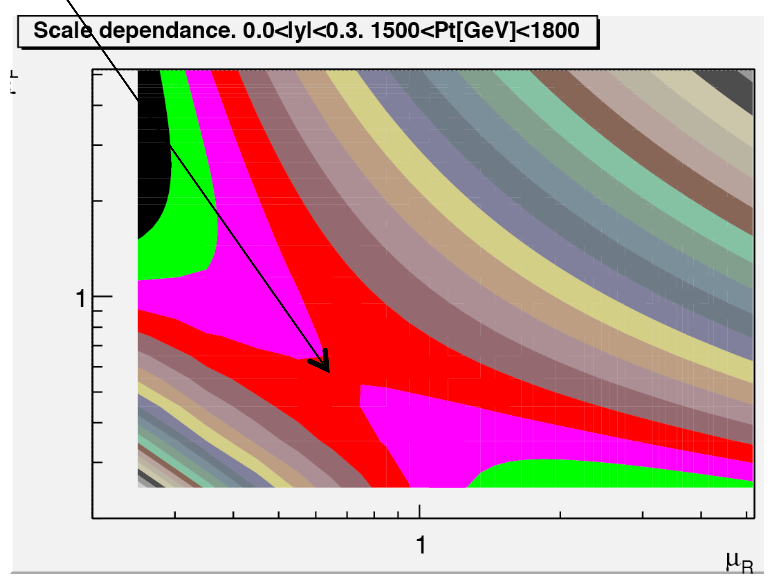
- …since perturbative QCD is logarithmic
- Note that there’s a saddle region, and a saddle point, where locally there is no slope for the cross section with respect to the two scales
- This is kind of the ‘golden point’ and typically around the expected scale (p_T^{jet} in this case)

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

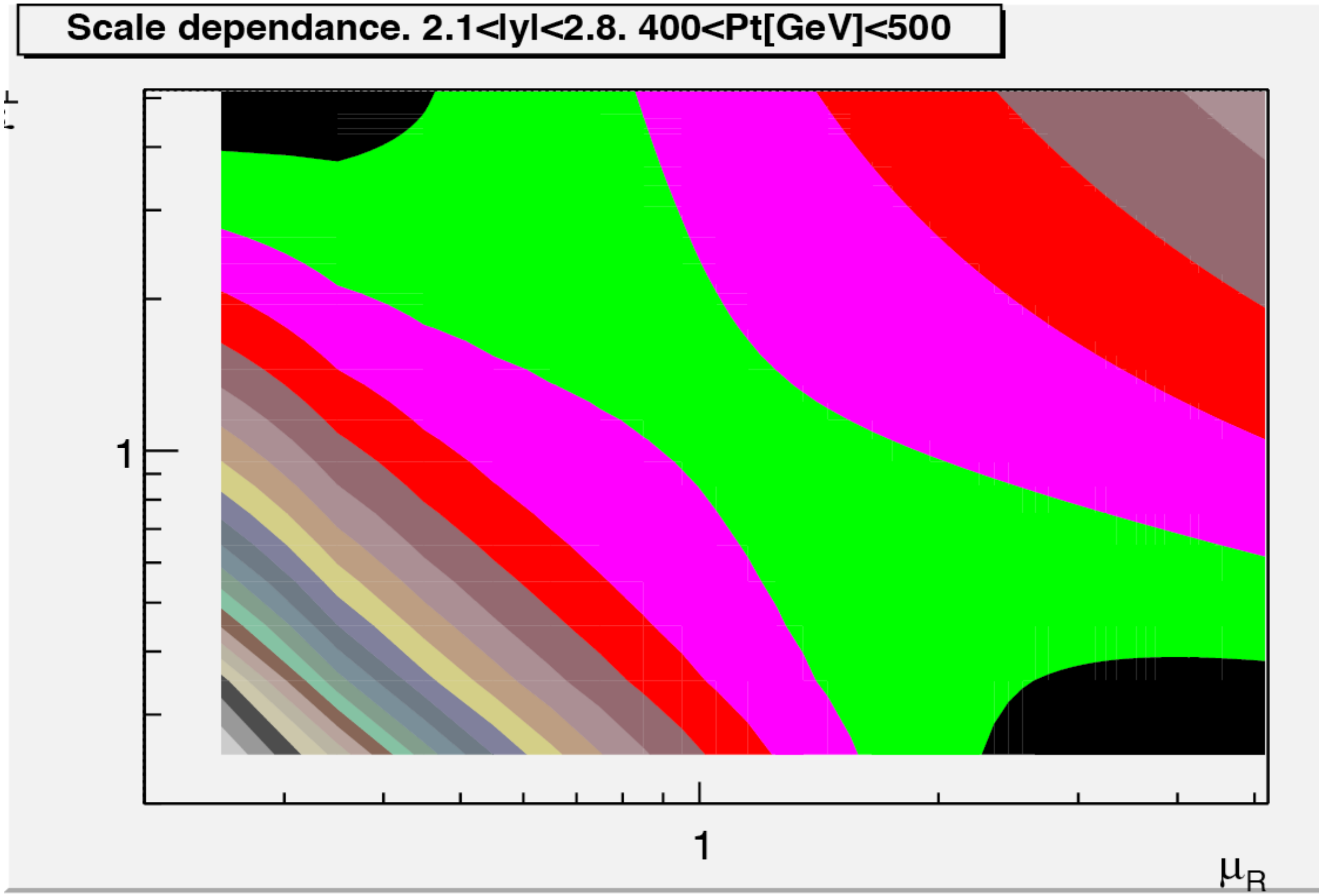
R=0.4
antikT





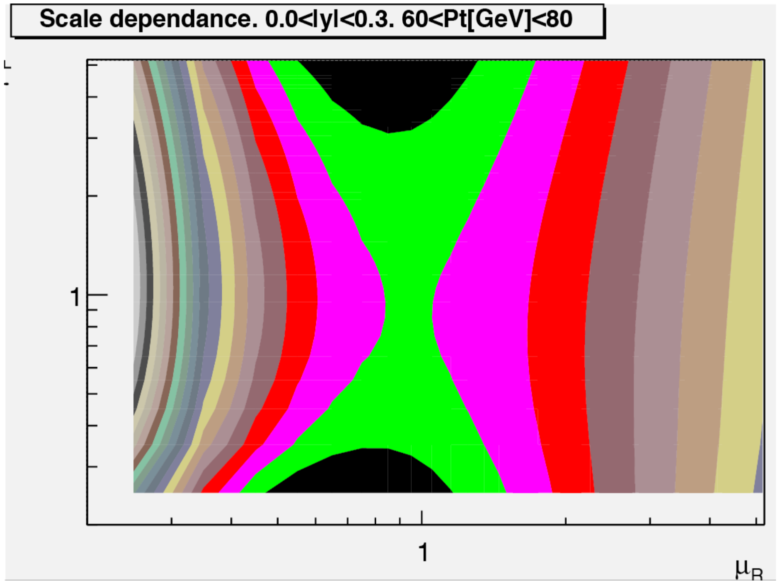
Scale dependence depends on rapidity

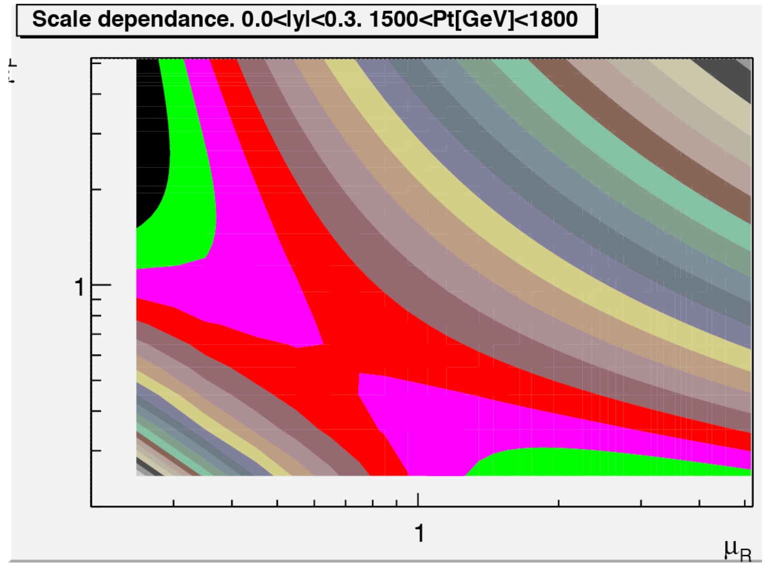
- The saddle point tends to move upwards in scale as the rapidity increases
- Is the physics changing; no, just the kinematics



Scale dependence also depends on jet size; again see equation on previous slide

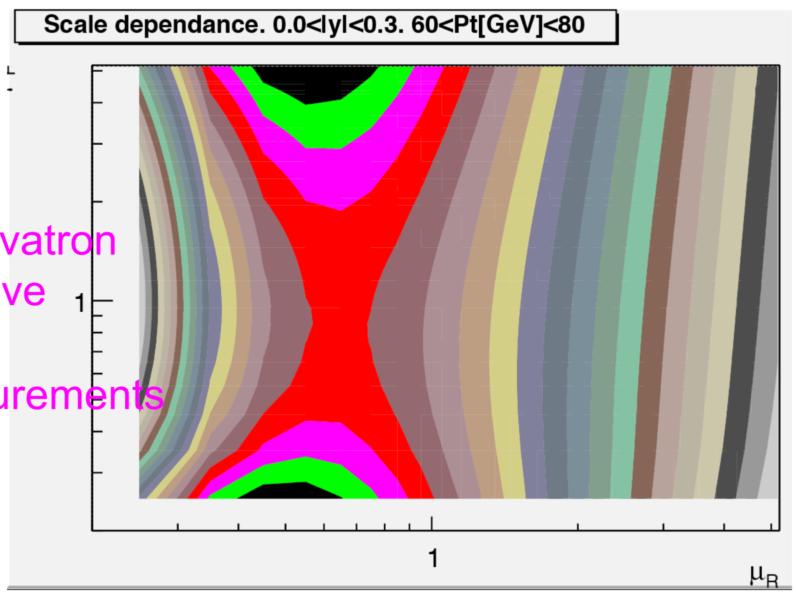
R=0.4
antikT

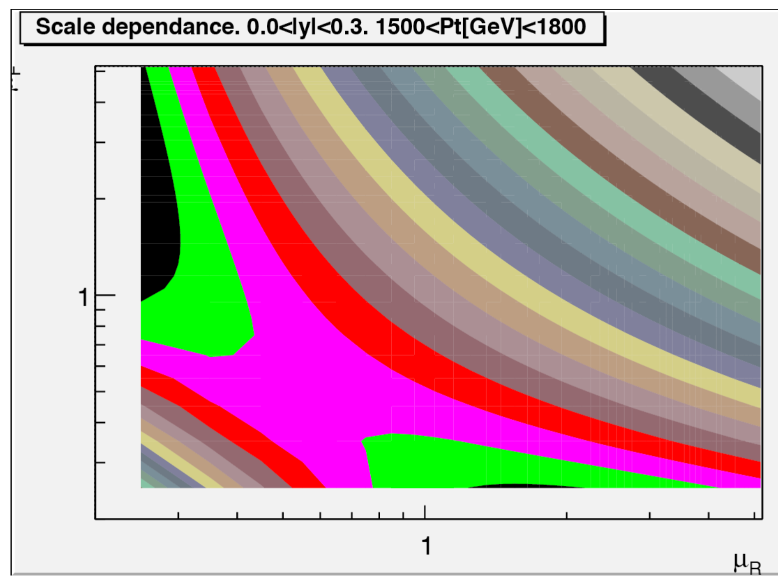




R=0.6
antikT

NB:Tevatron inclusive jet measurements with R=0.7

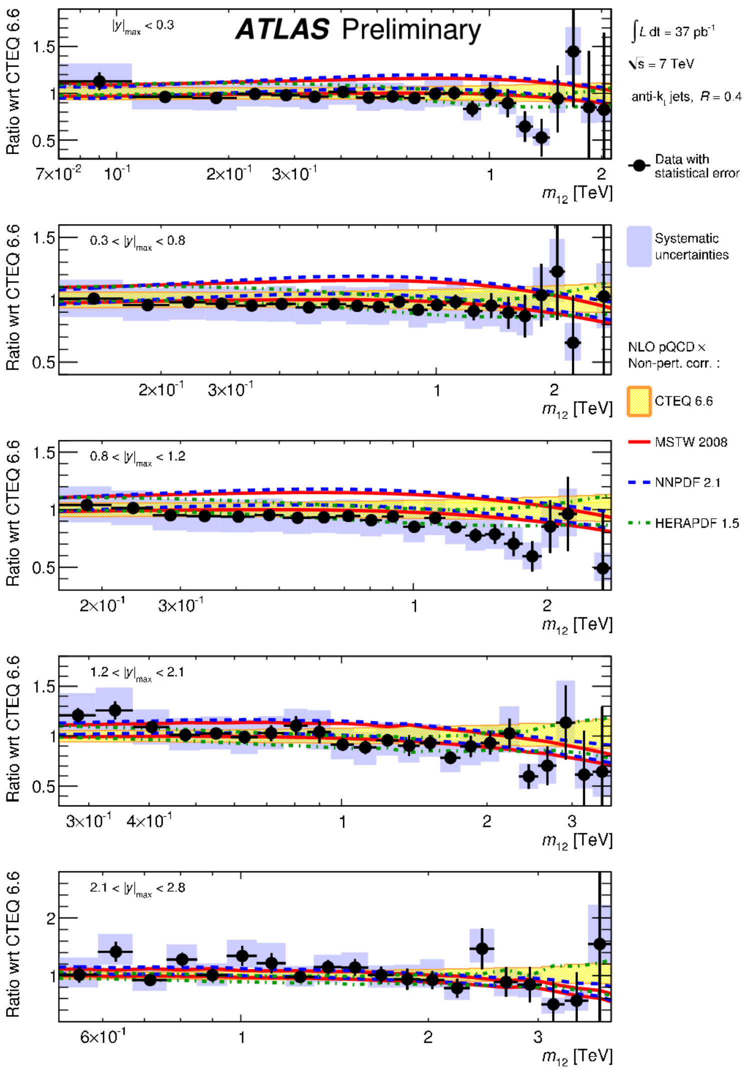




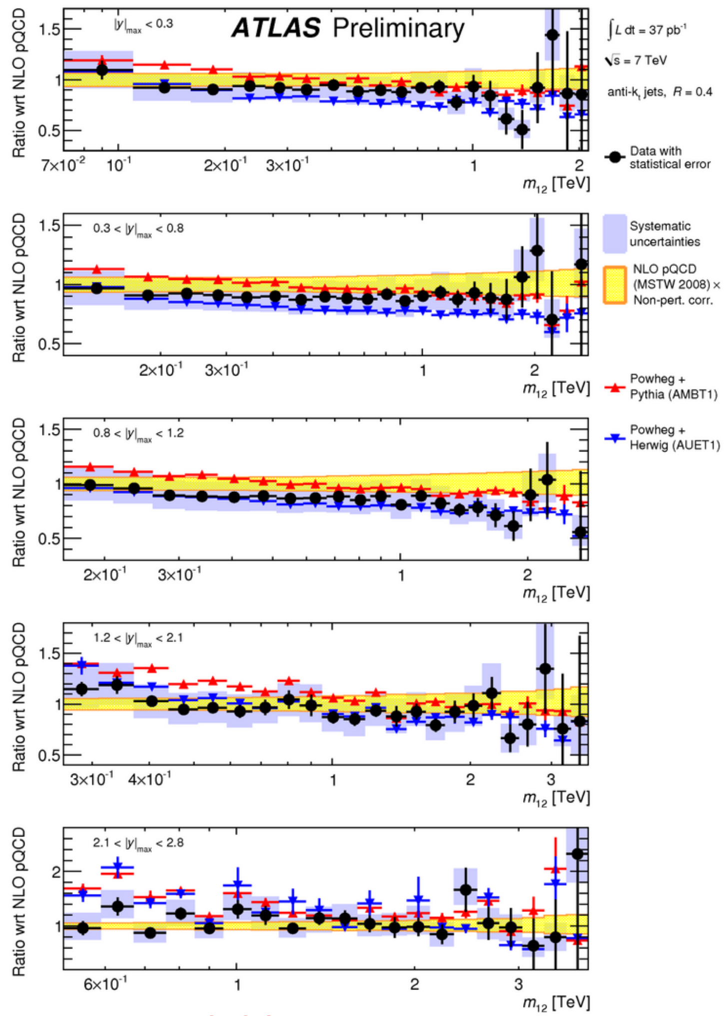
ATLAS: dijets

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

NLOJET++



Powheg

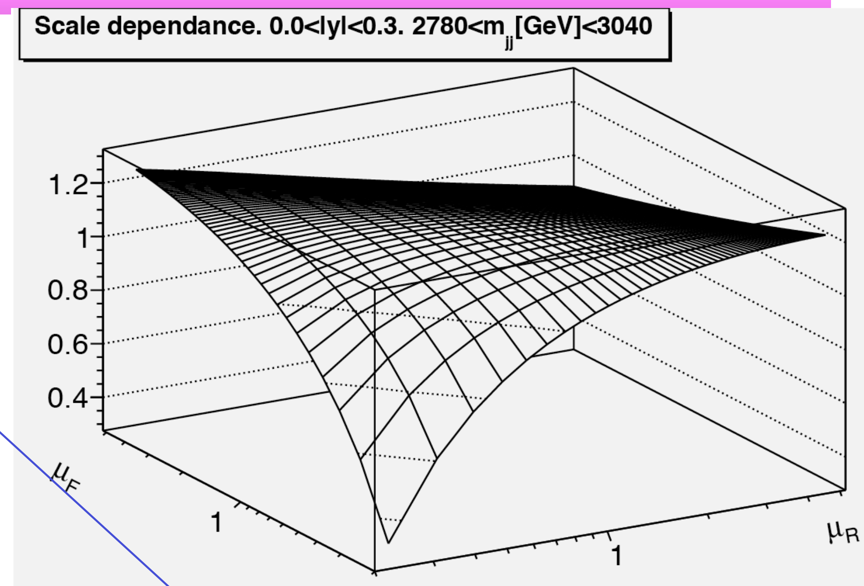


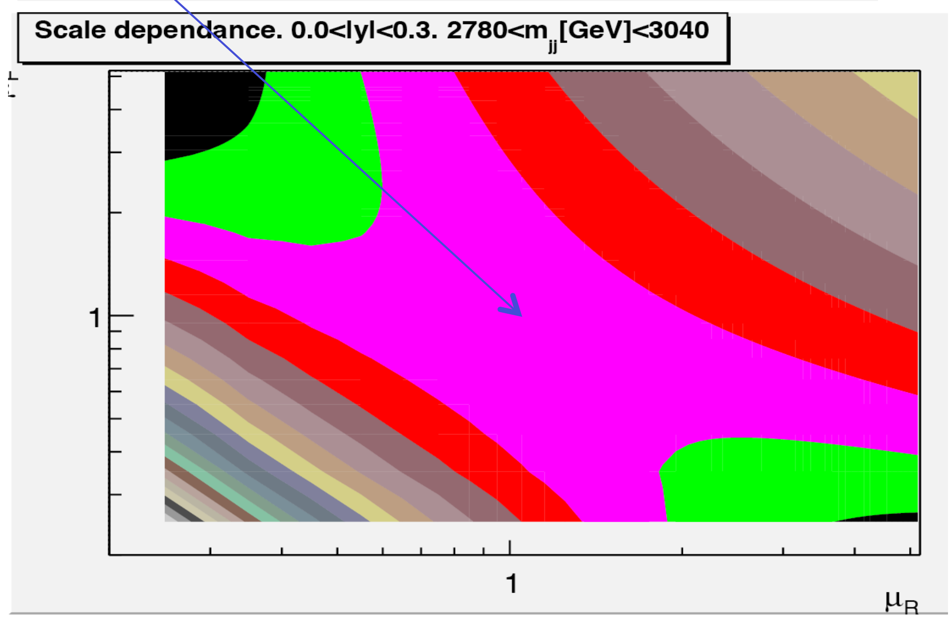
ATLAS-CONF-2011-047

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.

Now look at the dijet mass cross section

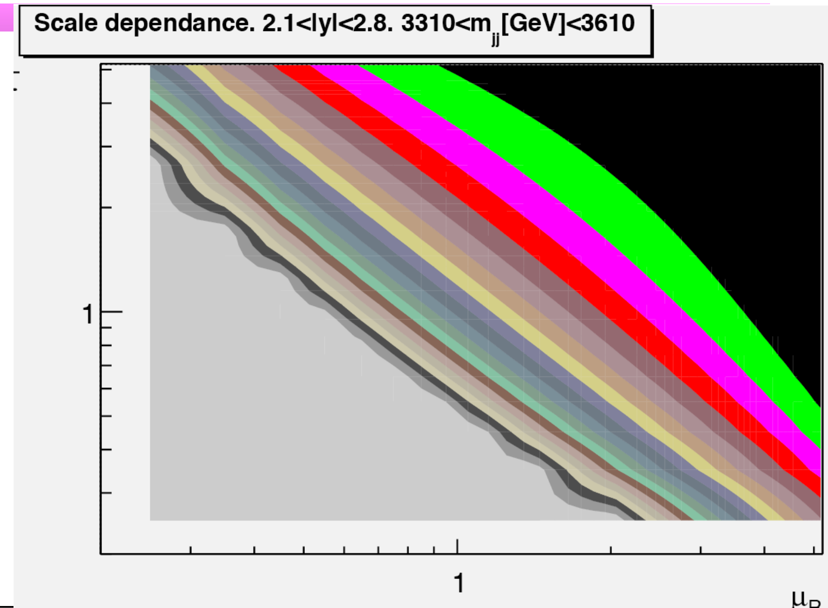
- In most cases, get a nice saddle region around p_T^{jet}

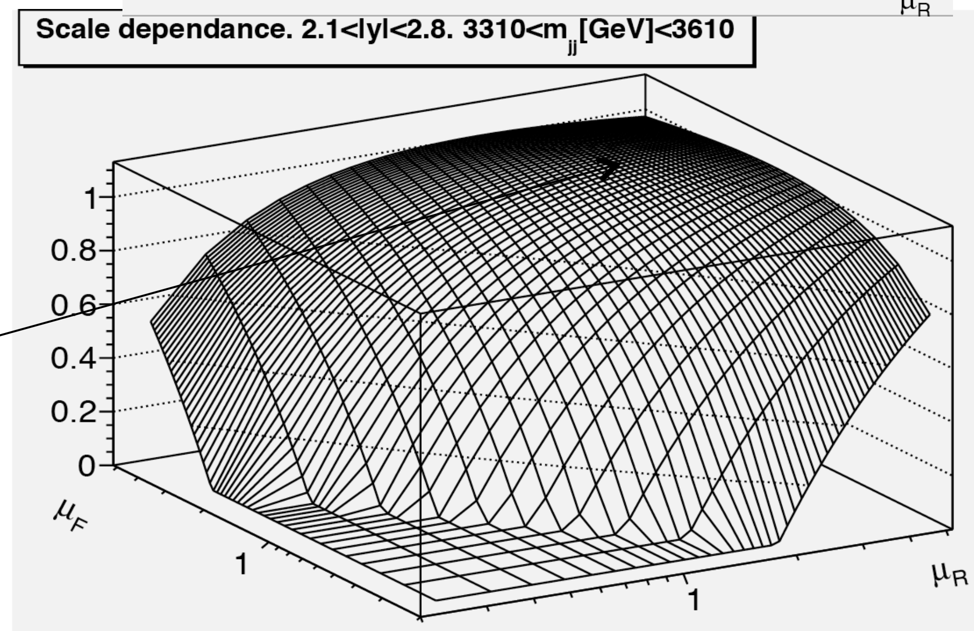




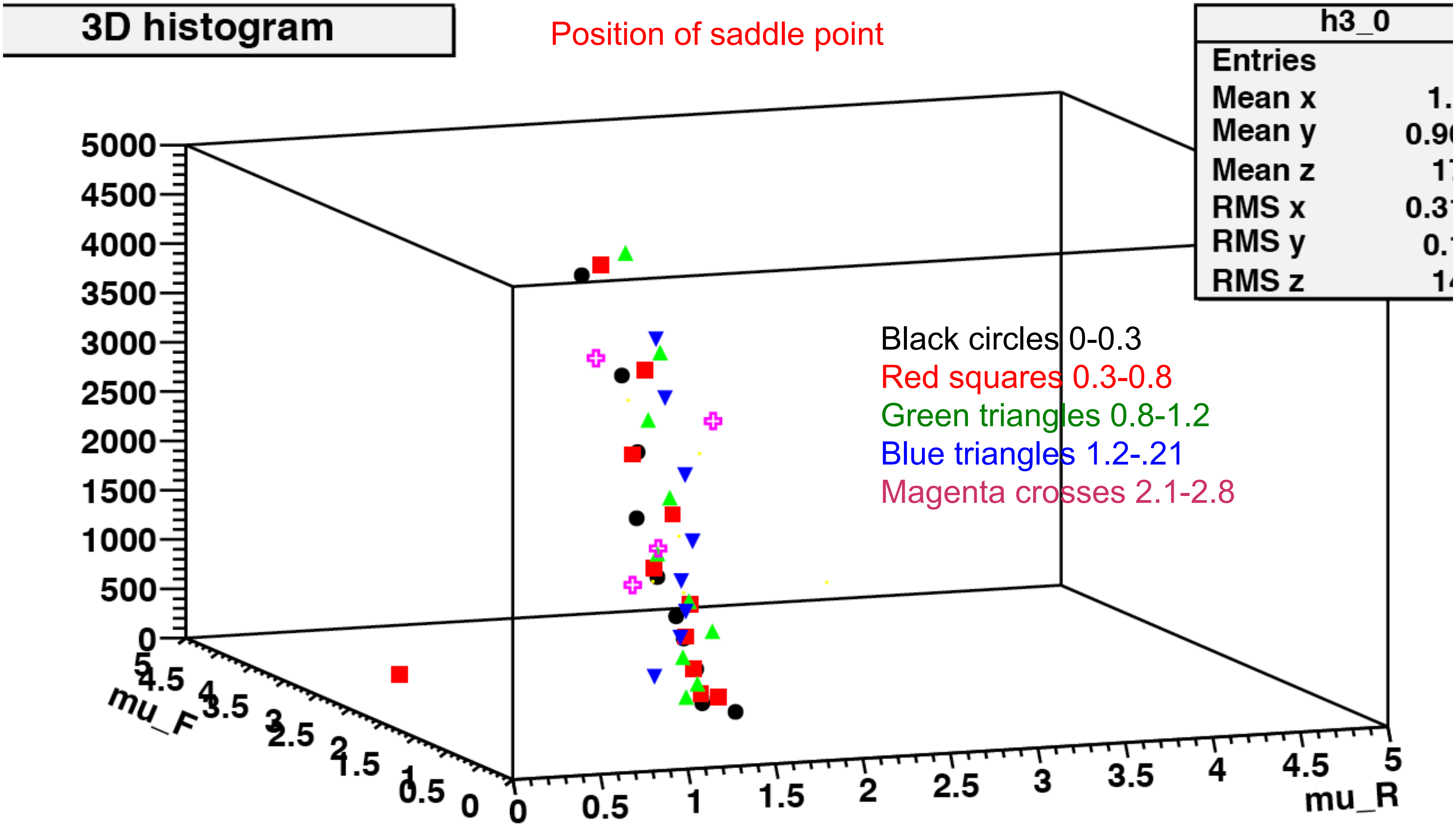
…but not for forward rapidities

- 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?)





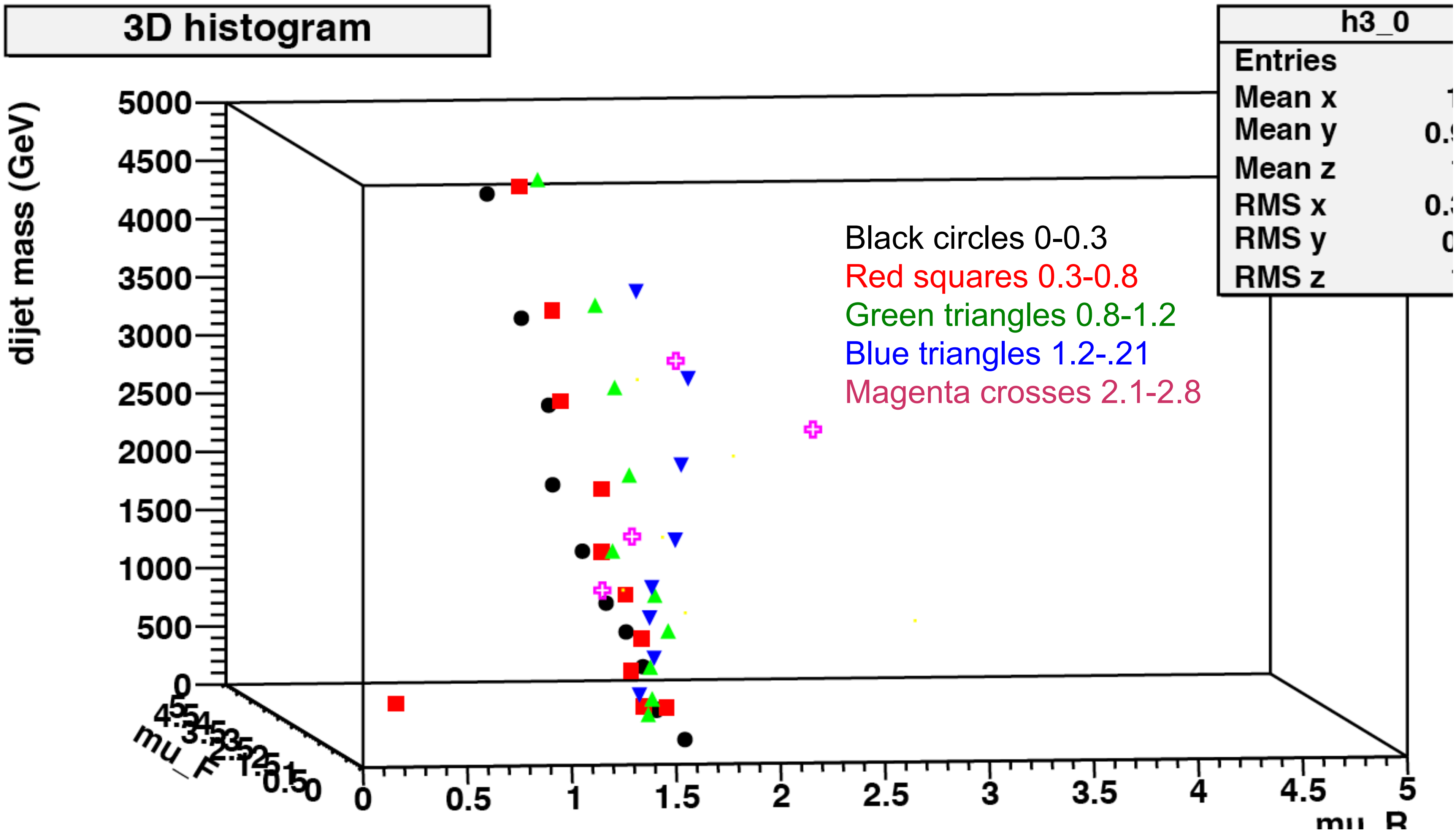
Look for saddle point position



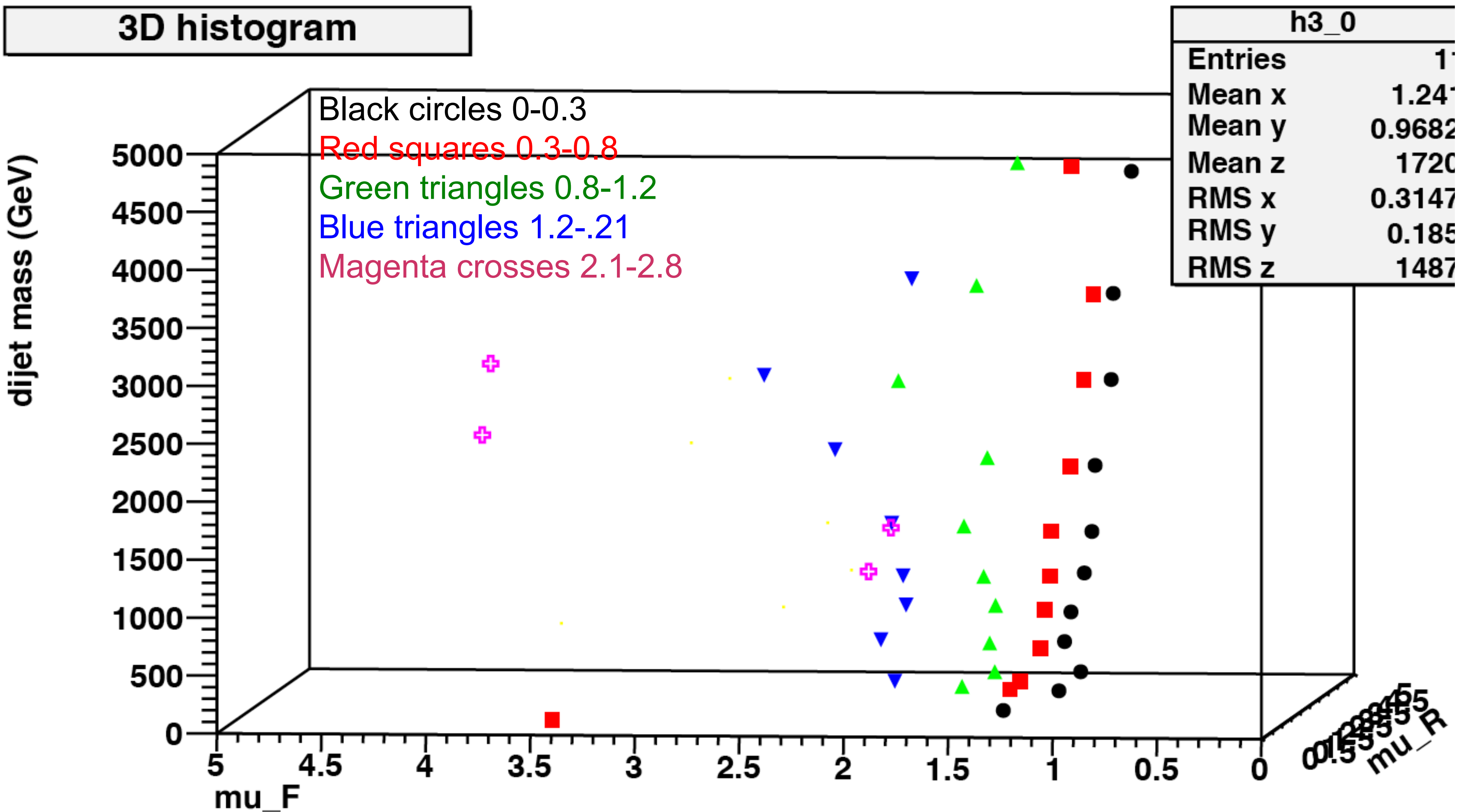
…using a Python script written by Jessie Muir, (now) a Cambridge (Part 3) student

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

…and now for something completely different

electroweak effects may be important at the LHC

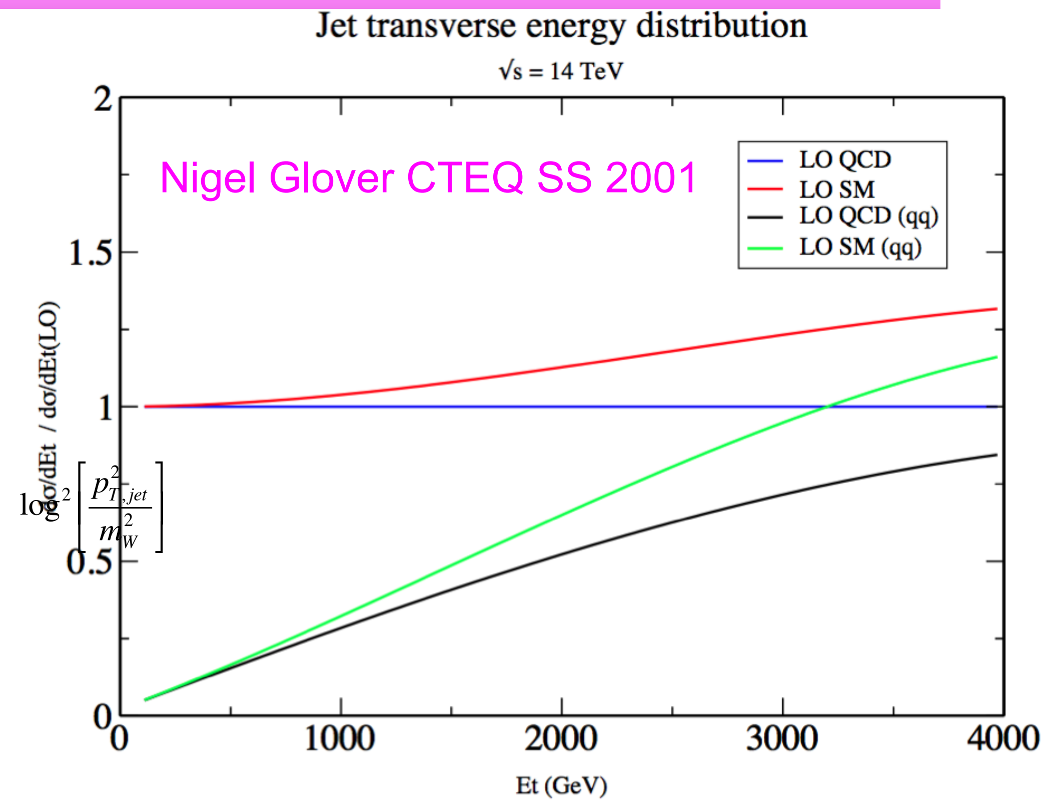
$\alpha_s > \alpha_W$ but α_W runs more slowly than does α_s

…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



$$\log^2\left[\frac{p_{T,jet}^2}{m_W^2}\right]$$

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

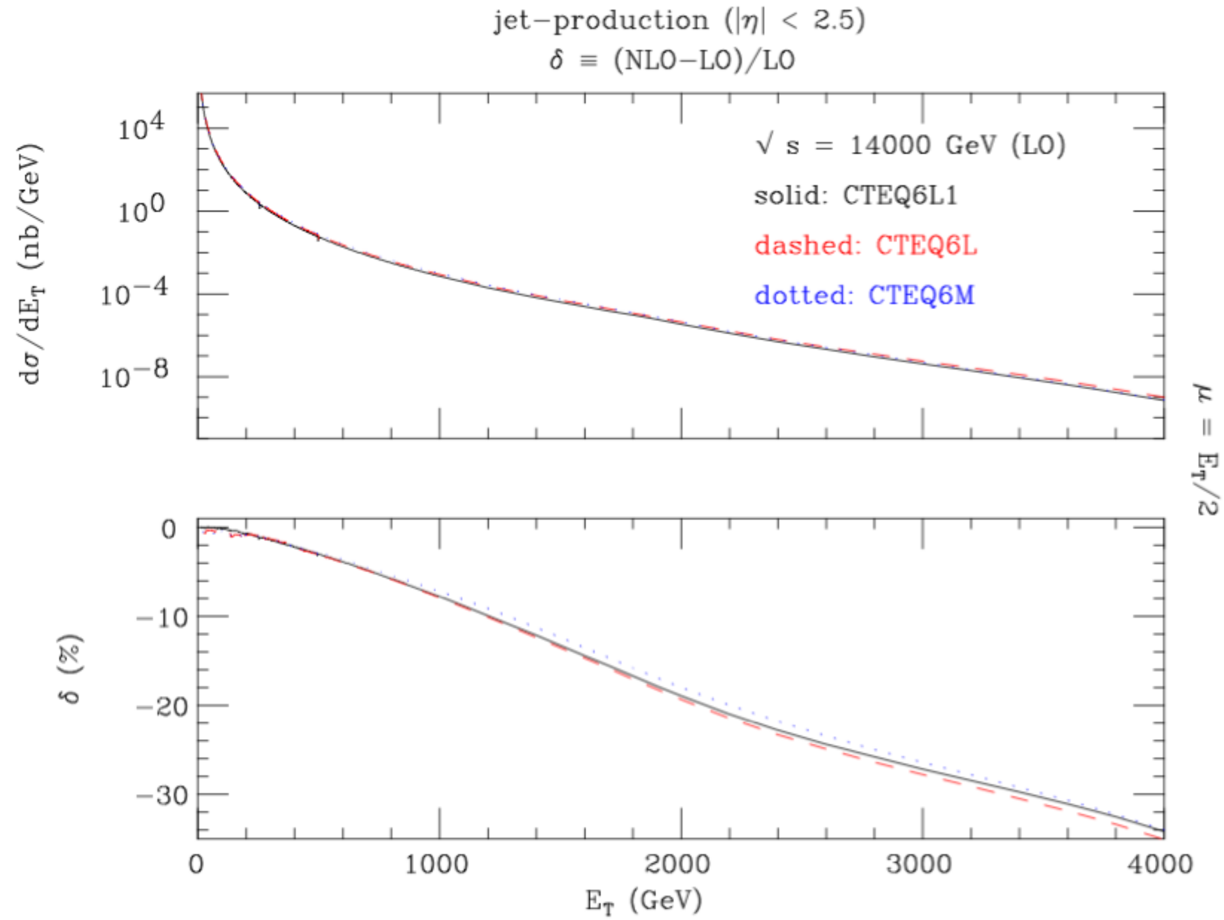
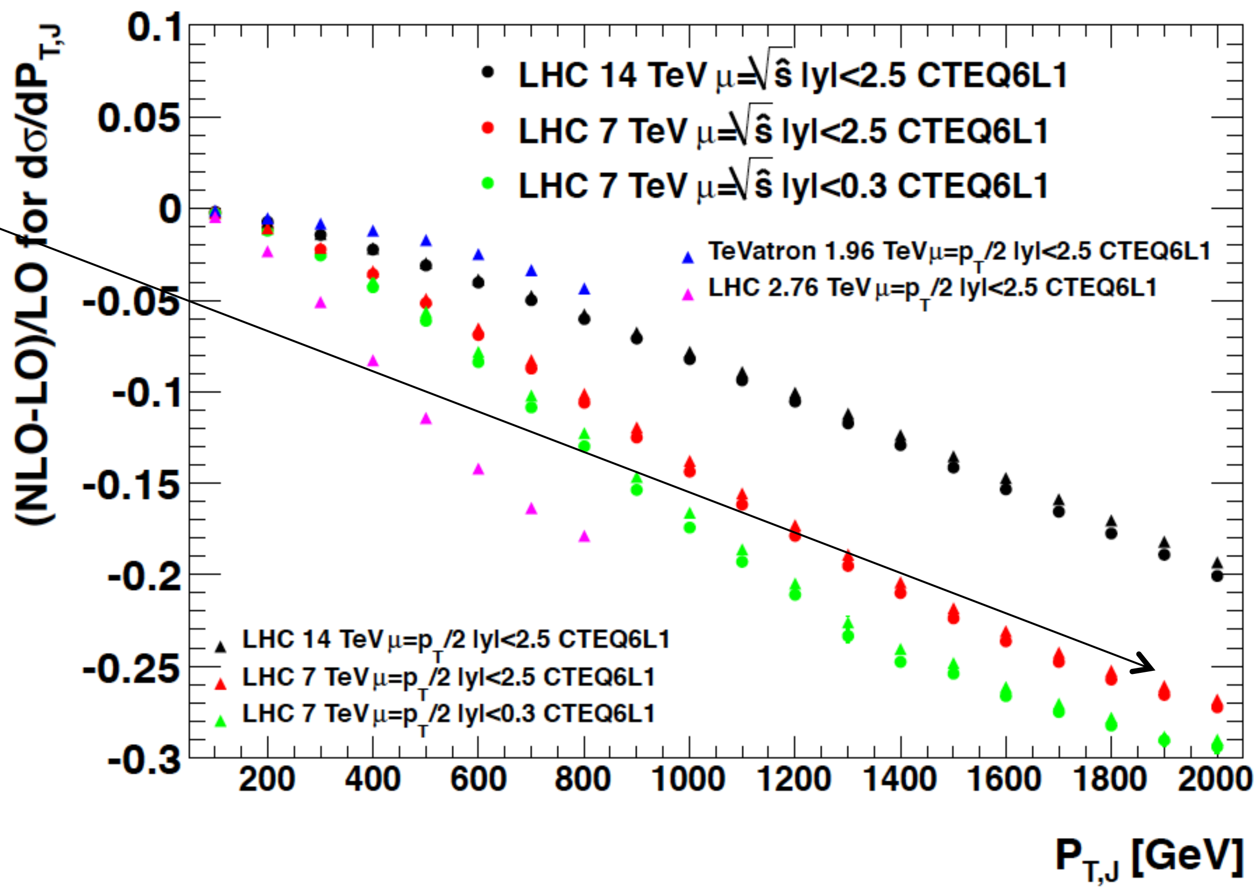


Figure 19: The effects of the $\mathcal{O}(\alpha_S^2\alpha_W)$ corrections [bottom] relative to the full LO results (i.e., through $\mathcal{O}(\alpha_S^2 + \alpha_S\alpha_{EW} + \alpha_{EW}^2)$) [top] for the case of LHC for three choices of PDFs. They are plotted as function of the jet transverse 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

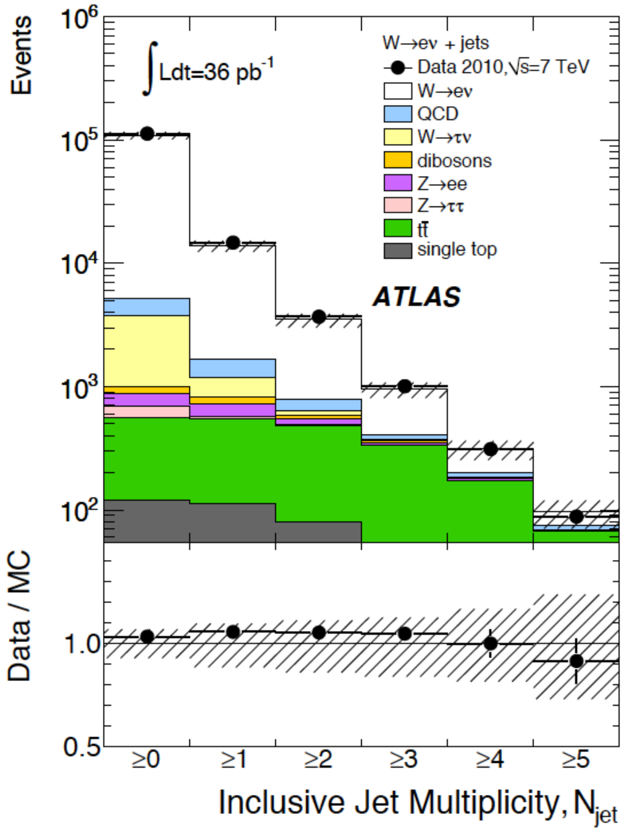
- I'm working on a followup paper with Stefano Moretti, Doug Ross, Mario Campanelli and Juan Terron
- Stefano, Doug and I are also organizing a workshop on electroweak corrections at the LHC to be held in Durham September 24-26

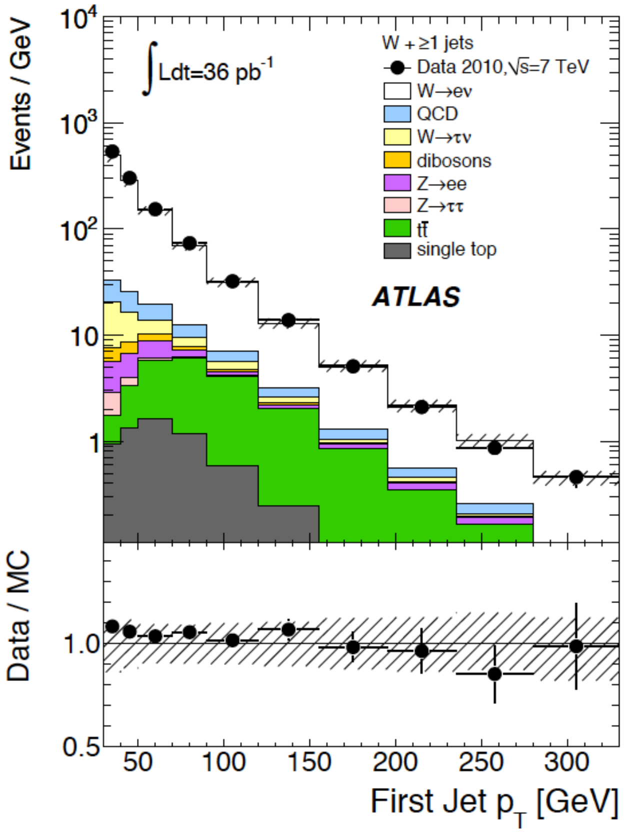
20-25% effect at high p_T



ATLAS: W+jets

- One of the key benchmark processes at both the Tevatron and the LHC
- 2010 data was enough to probe up to 5 jets with statistics
- Out to >300 GeV/c for lead jet transverse momentum





ATLAS: W+jets

- Measurements were conducted with the kinematic cuts listed to the right
- Theory is capable of forming predictions for same cuts, so no need for any corrections back to ‘full cross section’
- Resulting measurements were unfolded to hadron level; may seem obvious but CDF measurement was the first to do so
- Underlying event and fragmentation corrections determined to allow for partonic level theory to be compared to data at hadron level
- Two corrections are in opposite directions and of roughly equal size, so net correction tends to be small

- $p_T^{\text{lepton}} > 20$ GeV ,
- $|\eta^{\text{lepton}}| < 2.4$,
- $E_T^{\text{miss}} > 25$ GeV ,
- $m_{T,W} > 40$ GeV ,
- $p_T^{\text{jet}} > 30$ GeV ,
- $|y^{\text{jet}}| < 4.4$,
- $\Delta R^{\text{lepton-jet}} > 0.5$.

Table 3: Non-perturbative corrections: first jet p_T ($N_{jet} \geq 1$)

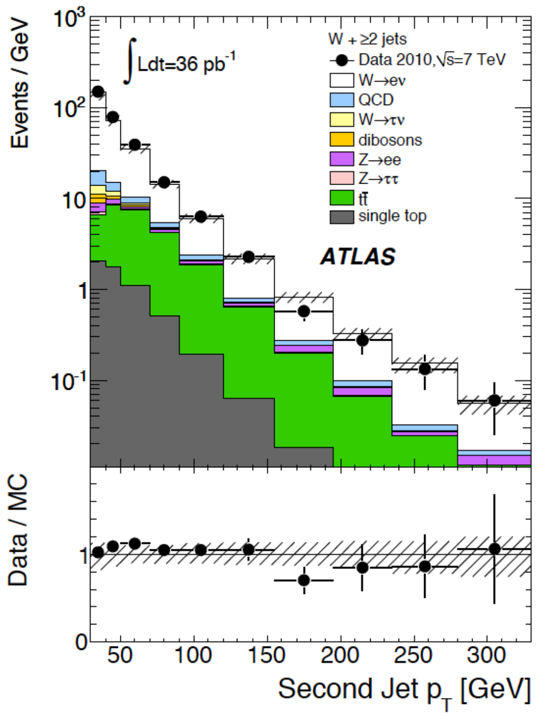
Bin	C_{UE}	C_{Had}
30-40	1.107 ± 0.001 (stat) ± 0.043 (sys)	0.926 ± 0.001 (stat) ± 0.009 (sy
40-50	1.065 ± 0.001 (stat) ± 0.031 (sys)	0.939 ± 0.001 (stat) ± 0.006 (sy
50-70	1.044 ± 0.001 (stat) ± 0.022 (sys)	0.948 ± 0.001 (stat) ± 0.006 (sy
70-90	1.027 ± 0.001 (stat) ± 0.017 (sys)	0.957 ± 0.001 (stat) ± 0.002 (sy
90-120	1.017 ± 0.000 (stat) ± 0.015 (sys)	0.965 ± 0.001 (stat) ± 0.004 (sy
120-155	1.015 ± 0.001 (stat) ± 0.013 (sys)	0.969 ± 0.001 (stat) ± 0.005 (sy
155-195	1.010 ± 0.002 (stat) ± 0.019 (sys)	0.971 ± 0.002 (stat) ± 0.001 (sy
195-235	0.998 ± 0.003 (stat) ± 0.016 (sys)	0.978 ± 0.002 (stat) ± 0.001 (sy
235-280	1.000 ± 0.004 (stat) ± 0.002 (sys)	0.980 ± 0.003 (stat) ± 0.001 (sy
280-330	1.018 ± 0.003 (stat) ± 0.002 (sys)	0.979 ± 0.004 (stat) ± 0.000 (sy

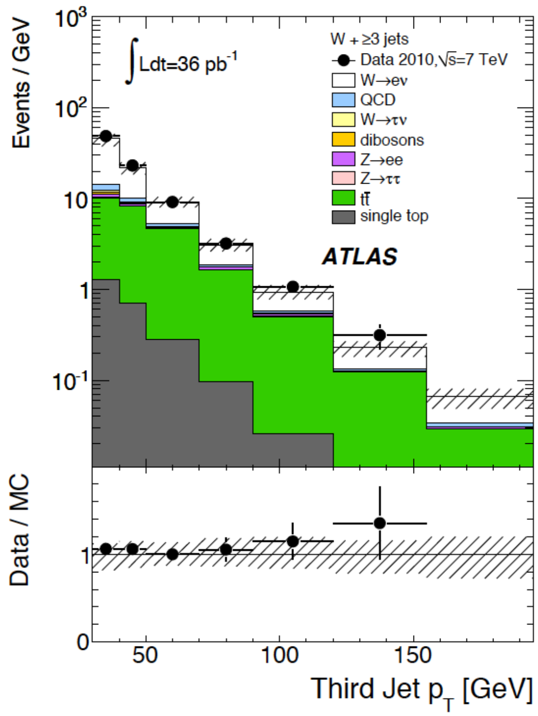
Table 6: Non-perturbative corrections: first jet p_T ($N_{jet} \geq 4$)

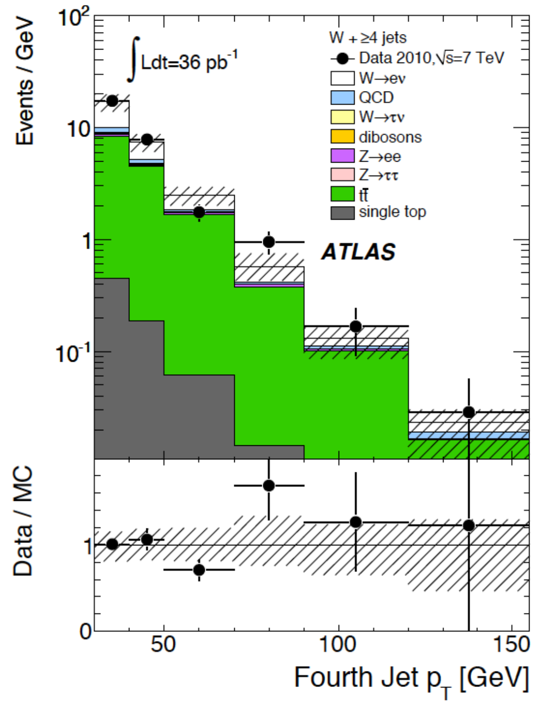
Bin	C_{UE}	C_{Had}
30-40	1.546 ± 0.162 (stat) ± 0.091 (sys)	0.734 ± 0.041 (stat) ± 0.073 (sys)
40-50	1.351 ± 0.066 (stat) ± 0.064 (sys)	0.775 ± 0.016 (stat) ± 0.032 (sys)
50-70	1.252 ± 0.023 (stat) ± 0.086 (sys)	0.807 ± 0.007 (stat) ± 0.010 (sys)
70-90	1.176 ± 0.020 (stat) ± 0.047 (sys)	0.825 ± 0.007 (stat) ± 0.008 (sys)
90-120	1.122 ± 0.010 (stat) ± 0.041 (sys)	0.852 ± 0.005 (stat) ± 0.000 (sys)
120-155	1.101 ± 0.013 (stat) ± 0.063 (sys)	0.869 ± 0.006 (stat) ± 0.006 (sys)
155-195	1.089 ± 0.014 (stat) ± 0.013 (sys)	0.886 ± 0.007 (stat) ± 0.005 (sys)
195-235	1.043 ± 0.012 (stat) ± 0.019 (sys)	0.885 ± 0.009 (stat) ± 0.012 (sys)
235-280	1.086 ± 0.025 (stat) ± 0.019 (sys)	0.891 ± 0.011 (stat) ± 0.015 (sys)
280-330	1.093 ± 0.024 (stat) ± 0.033 (sys)	0.900 ± 0.013 (stat) ± 0.017 (sys)

W+jets continued…

- All cross sections and corrections have been posted on the Durham website, so every theorist has direct access
- See later

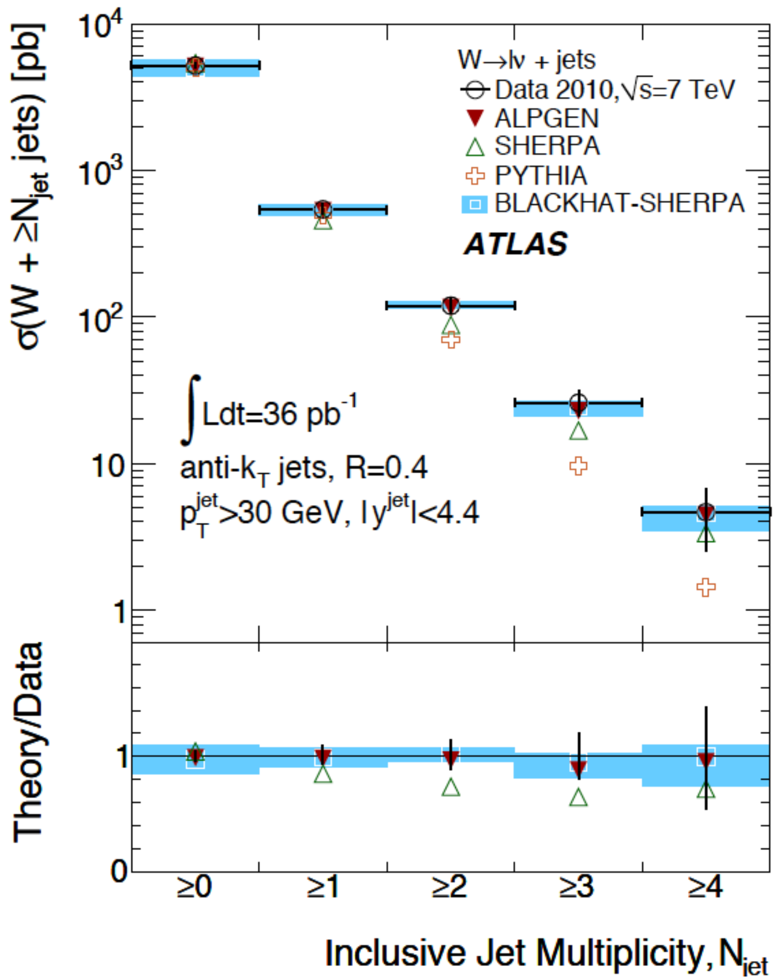






Comparisons to theory

- All Blackhat+Sherpa predictions for the 2010 W+jets paper generated by ATLAS experimentalists (my student and myself) using ROOT ntuples generated by B+S



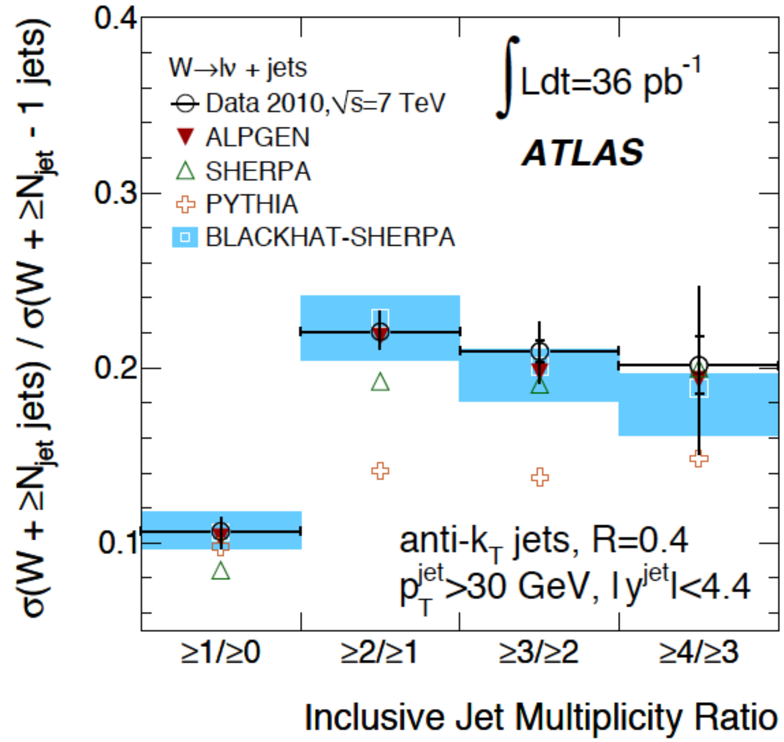
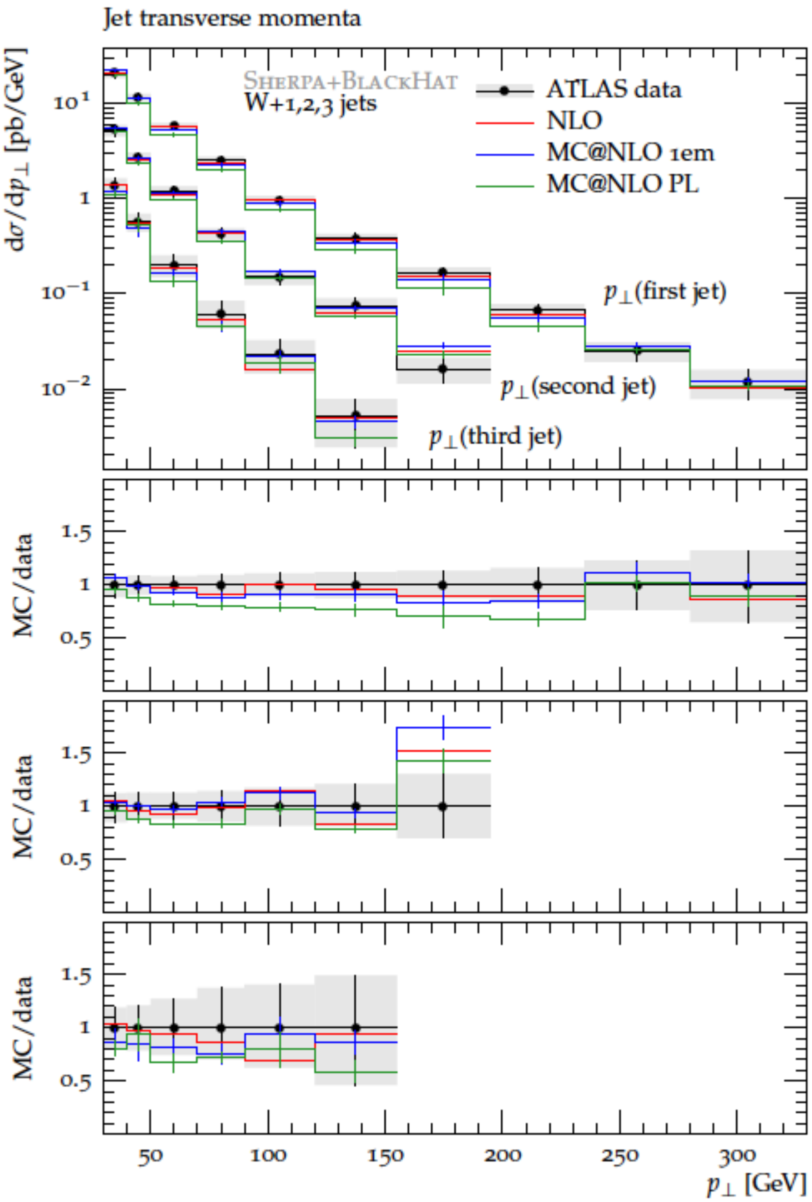


FIG. 19. W+jets cross section ratio results as a function o corrected jet multiplicity.

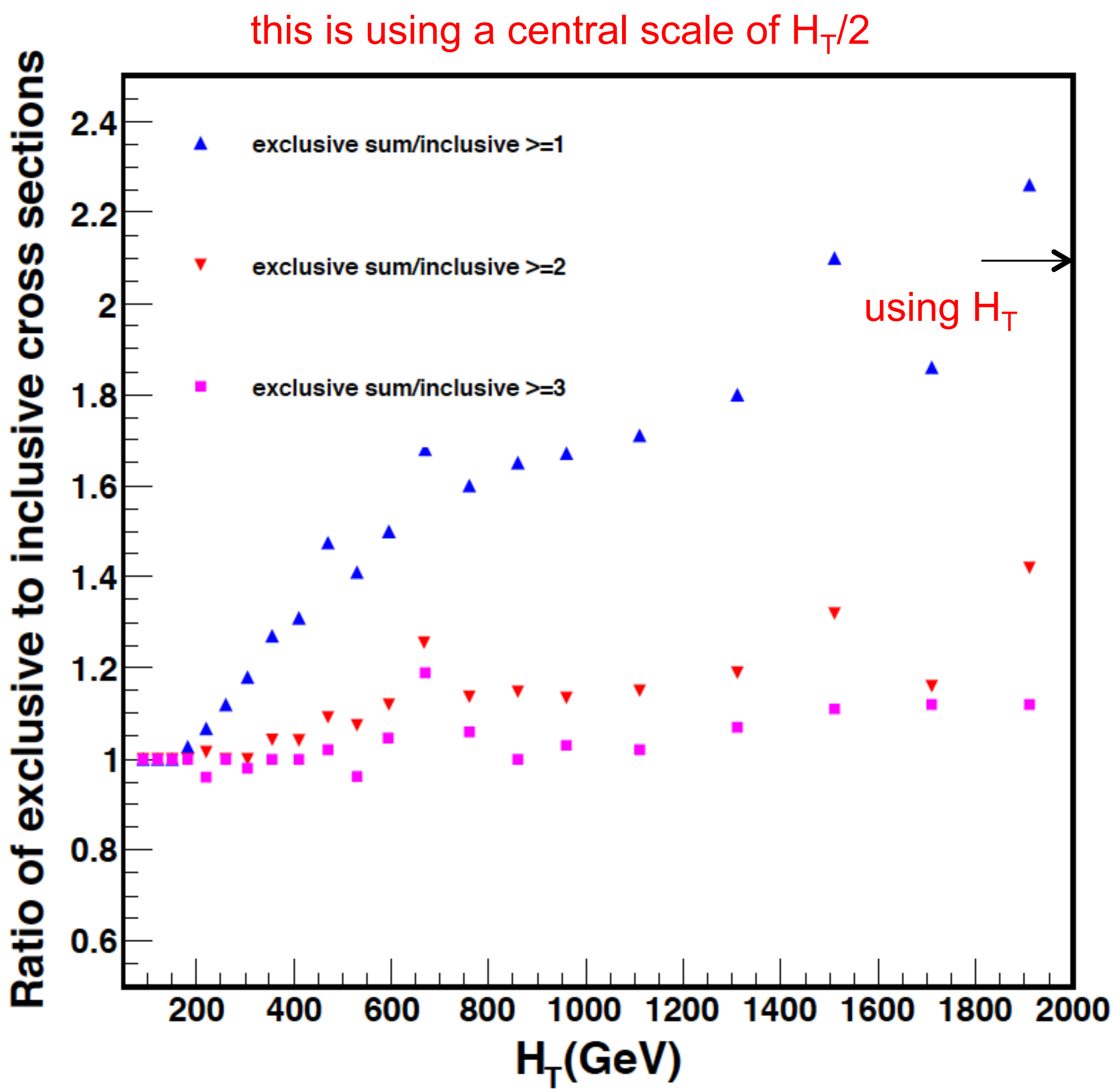
Sherpa+Blackhat

- Just to add to the confusion, here, the NLO virtual matrix elements of Blackhat have been used with Sherpa parton showering using the MC@NLO framework
- Comparing to the ATLAS data recorded at the Durham site
- W+1,2 and 3 jets at NLO
  - the last is a world record for the complexity of a final state in a NLO parton shower Monte Carlo (as far as I know)
  - aMC@NLO previously did W+2 jets at NLO
- What we would really like is CKKW@NLO
  - I know that Leif Lonnblad gave a talk on ongoing work at the CERN NLO PS workshop



The future

- If we extrapolate up to the kinematic reach of 2011 (2012), then we might expect there to be a significant deficit in the conventional NLO predictions not only for W+1 jet but for W+2 jets as well
- Caveat: I don't know how the addition of the Sudakov form factors that would be part of a complete treatment of the exclusive sums would affect the size of the large H_T cross section
- But we have ~4.7 fb^{-1} from the 2011 data and will have the ability to measure cross sections for jet sizes of 0.3-1.2 for several jet algorithms
- I don't have that amount of energy, but would like to check 0.4-0.7



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