NLO wishlist, NLO corrections and jet algorithms

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NLO cross sections

- Less sensitivity to unphysical input scales, i.e. renormalization and factorization scales
- First level of prediction where normalization (and sometimes shape) can be taken seriously
- More physics
  - parton merging gives structure in jets
  - initial state radiation
  - more species of incoming partons
- Suppose I have a cross section σ calculated to NLO ($O(\alpha_s^n)$)
- Any remaining scale dependence is of one order higher ($O(\alpha_s^{n+1})$)
  - in fact, we know the scale dependent part of the $O(\alpha_s^{n+1})$ cross section before we perform the complete calculation, since the scale-dependent terms are explicit at the previous order

$$\frac{d\sigma}{dE_T} = \alpha_s(\mu_R)^2 A + \alpha_s(\mu_R)^3 (B + 2b_0 L A) + \alpha_s(\mu_R)^4 (C + 3b_0 L B + (3b_0^2 L^2 + 2b_1 L) A)$$

Inclusive jet prod at NNLO

with $L = \log(\mu_R/E_T)$ and b_i the known beta function coefficients.

we know A and B, not C

LO has monotonic scale dependence

non-monotonic at NLO

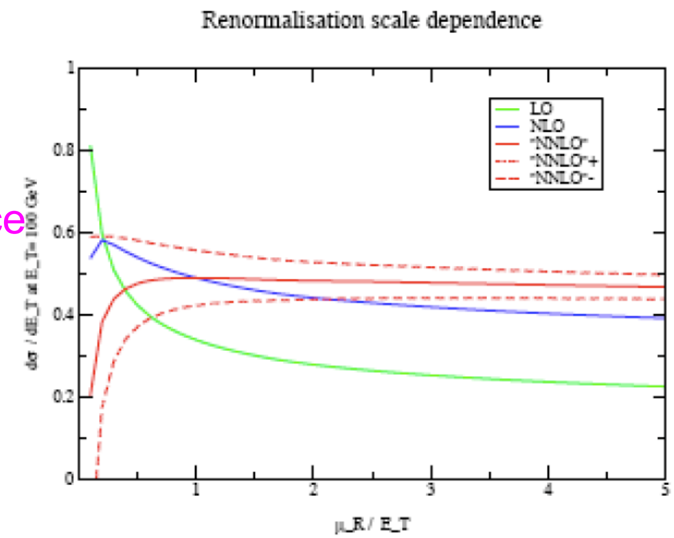


Figure 11: Single jet inclusive distribution at $E_T = 100$ GeV and $0.1 < |\eta| < 0.7$ at $\sqrt{s} = 1800$

The NNLO coefficient C is unknown. The curves show the guesses $C = 0$ (solid) and $C = \pm B^2/A$ (dashed).

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

- 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
- $\sigma_{W+3\ \text{iets}} > \sigma_{W+2\ \text{iets}}$

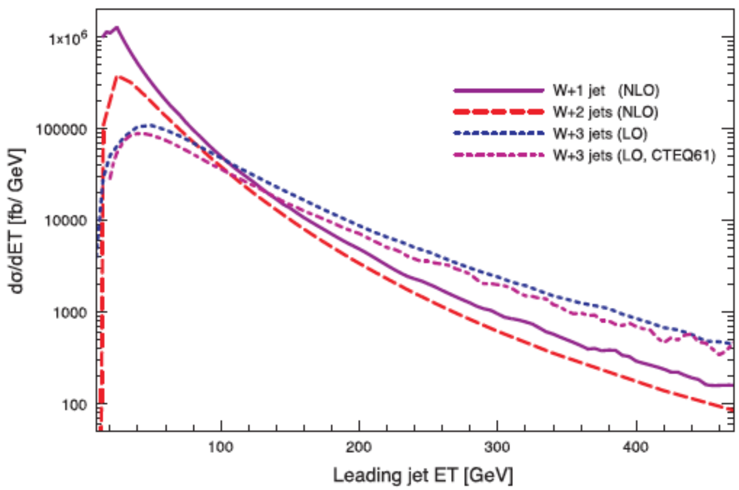


Figure 91. Predictions for the production of $W+ \geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

14 TeV

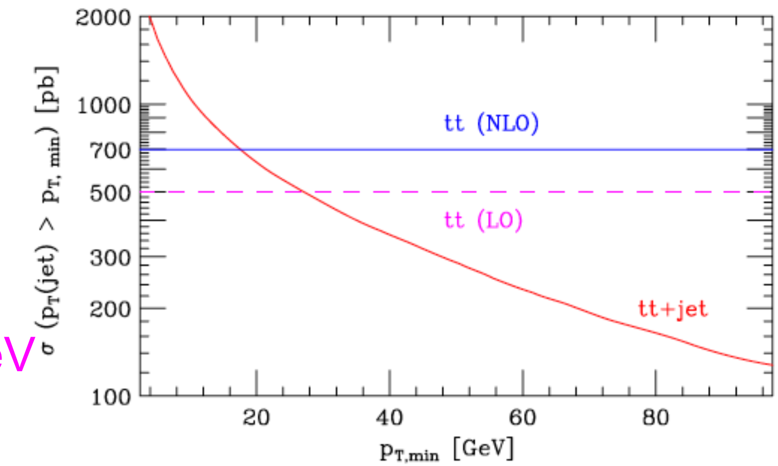


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

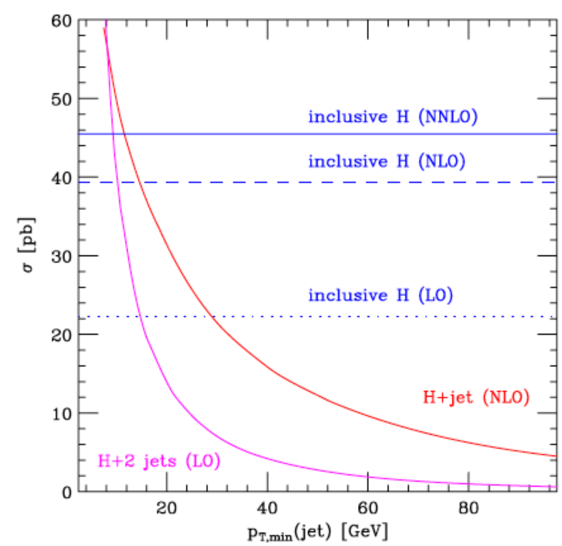


Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

- indication that can expect interesting events at LHC to be very *jetty* (especially from gg initial states)
- also can be understood from point-of-view of Sudakov form factors

State of the art

Relative order	**2->1**	**2->2**	**2->3**	**2->4**	**2-5**	**2->6**
1	LO					
α_s	NLO	LO				
α_s^2	NNLO	NLO	LO			
α_s^3		*NNLO*	NLO	LO		
α_s^4				NLO	LO	
α_s^5					*NLO*	LO

- LO: well under control, even for multiparticle final states
- NLO: well understood for 2->1, 2->2 and 2->3; first calculations of 2->4 (W +3 jets, ttbb) and 2->5 (W+4 jets (to leading color))
- NNLO: known for inclusive and exclusive 2->1 (i.e. Higgs, Drell-Yan); work on 2->2 (Higgs + 1 jet)

An experimenter's wishlist

Run II Monte Carlo Workshop

Single Boson	Diboson	Triboson	Heavy Flavour
$W+ \leq 5j$	$WW+ \leq 5j$	$WWW+ \leq 3j$	$t\bar{t}+ \leq 3j$
$W + b\bar{b} \leq 3j$	$W + b\bar{b}+ \leq 3j$	$WWW + b\bar{b}+ \leq 3j$	$t\bar{t} + \gamma+ \leq 2j$
$W + c\bar{c} \leq 3j$	$W + c\bar{c}+ \leq 3j$	$WWW + \gamma\gamma+ \leq 3j$	$t\bar{t} + W+ \leq 2j$
$Z+ \leq 5j$	$ZZ+ \leq 5j$	$Z\gamma\gamma+ \leq 3j$	$t\bar{t} + Z+ \leq 2j$
$Z + b\bar{b}+ \leq 3j$	$Z + b\bar{b}+ \leq 3j$	$ZZZ+ \leq 3j$	$t\bar{t} + H+ \leq 2j$
$Z + c\bar{c}+ \leq 3j$	$ZZ + c\bar{c}+ \leq 3j$	$WZZ+ \leq 3j$	$t\bar{b} \leq 2j$
$\gamma+ \leq 5j$	$\gamma\gamma+ \leq 5j$	$ZZZ+ \leq 3j$	$b\bar{b}+ \leq 3j$
$\gamma + b\bar{b} \leq 3j$	$\gamma\gamma + b\bar{b} \leq 3j$		single top
$\gamma + c\bar{c} \leq 3j$	$\gamma\gamma + c\bar{c} \leq 3j$		
	$WZ+ \leq 5j$		
	$WZ + b\bar{b} \leq 3j$		
	$WZ + c\bar{c} \leq 3j$		
	$W\gamma+ \leq 3j$		
	$Z\gamma+ \leq 3j$		

Realistic wishlist

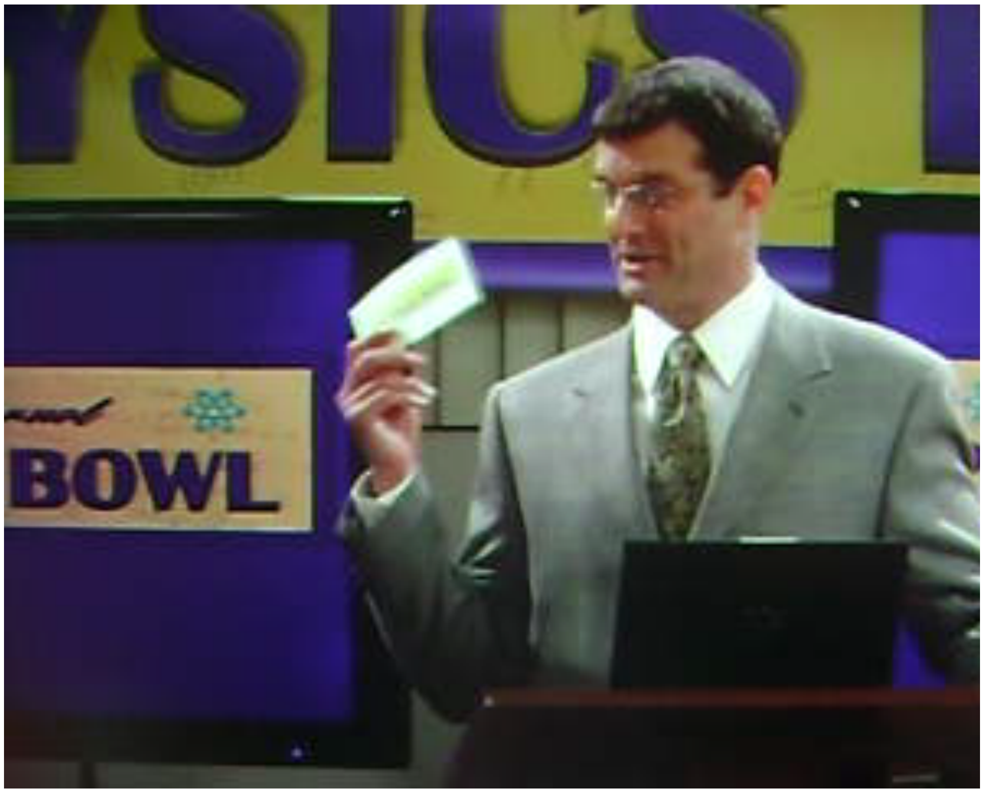
- Was developed at Les Houches in 2005, and expanded in 2007 and 2009
- Calculations that are important for the LHC AND do-able in finite time
- In 2009, we added tttt, Wbbj, Z+3j, W +4j plus an extra column for each process indicating the level of precision required by the experiments
  - to see for example if EW corrections may need to be calculated
- In order to be most useful, decays for final state particles (t,W,H) need to be provided in the codes as well

- Since the publication of Les Houches 2009 in March, processes 6 and 7 have been completed
- V + 4 jets (process 10) has been done to leading color

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

Table 1: The updated experimenter's wishlist for LHC processes

If all else fails…



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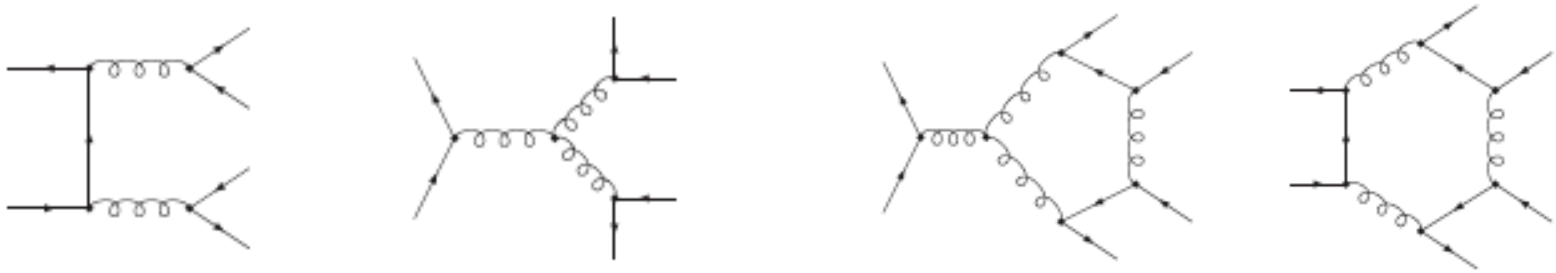
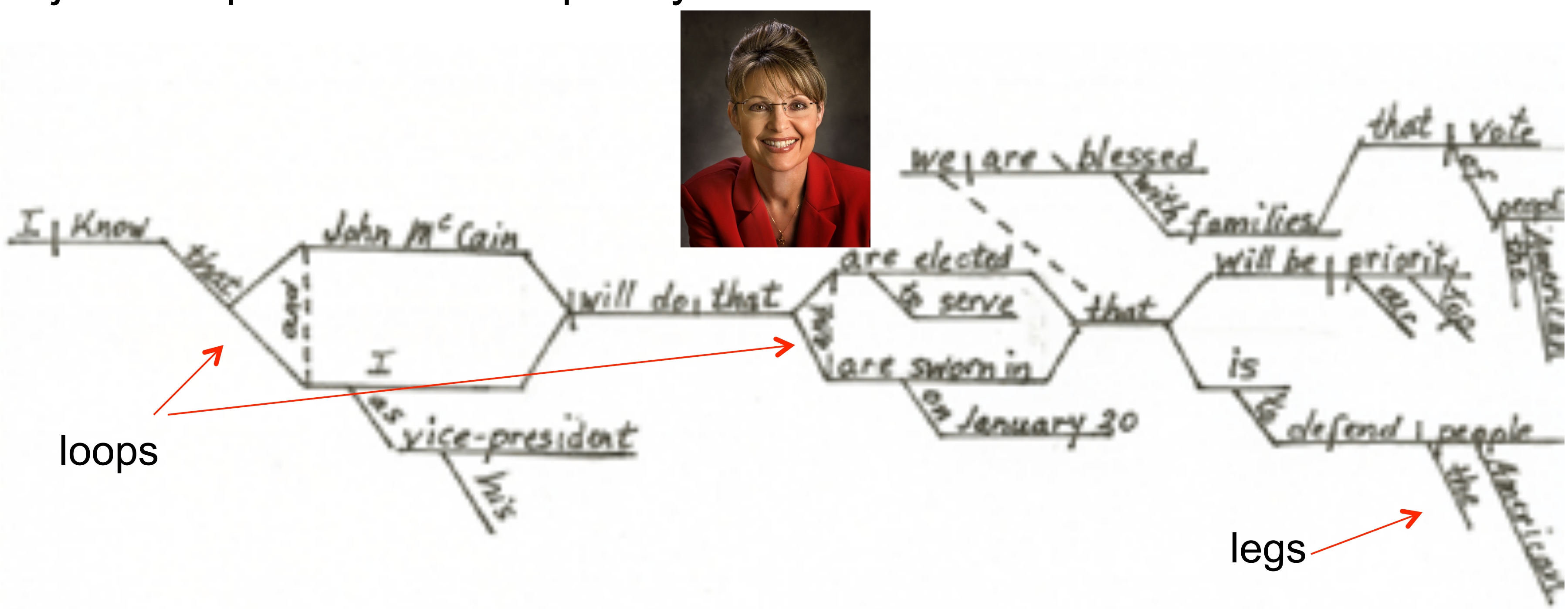
Loops and legs

2->4 is very impressive



but just compare to the complexity of the sentences that Sarah Palin uses

.



Some issues/questions

- Once we have the calculations, how do we (experimentalists) use them?

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- If a theoretical calculation is done, but it can not be used by any experimentalists, does it make a sound?

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- Once we have the calculations, how do we (experimentalists) use them?
- Best is to have NLO partonic level calculation interfaced to parton shower/hadronization
  - but that has been done only for relatively simple processes and is very (theorist) labor intensive
  - semi-automatic inclusion of new (complex) processes would be very welcome
- Even with partonic level calculations, need public code and/or ability to write out ROOT ntuples of parton level events
  - so that can generate once with loose cuts and distributions can be re-made without the need for the lengthy re-running of the predictions
  - what is done for example with MCFM for CTEQ4LHC
  - it's what Blackhat+Sherpa has provided me for W + 3 jets at NLO
    - but 10's of Gbytes for file sizes

ROOT ntuples with Blackhat/Sherpa

- 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 →
- No jet clustering has been performed; that's up to the user
- 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 and 0.7
  - but not 0.6

- bornLO (stands alone for pure LO comparisons; not to be added with other contributions below)
  - ~60 MB
- born
  - ~5 GB
- loop-lc (leading color loop corrections)
  - ~360 MB
- loop-fmlc (needed for full color loop corrections)
  - ~13 MB
- real (real emission terms)
  - ~27 GB
  - …and we're statistics limited because of this file
- vsub (subtraction terms)
  - ~5 GB

Jet Clustering

- For jet clustering, I use SpartyJet
  - which has some of its own jet algorithms, but also calls FastJet; useful user routines for analysis, especially in ATLAS
- and store the jet results in SJ ntuples
  - and they're very big since I store the results for multiple jet algorithms/sizes
- Then I 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

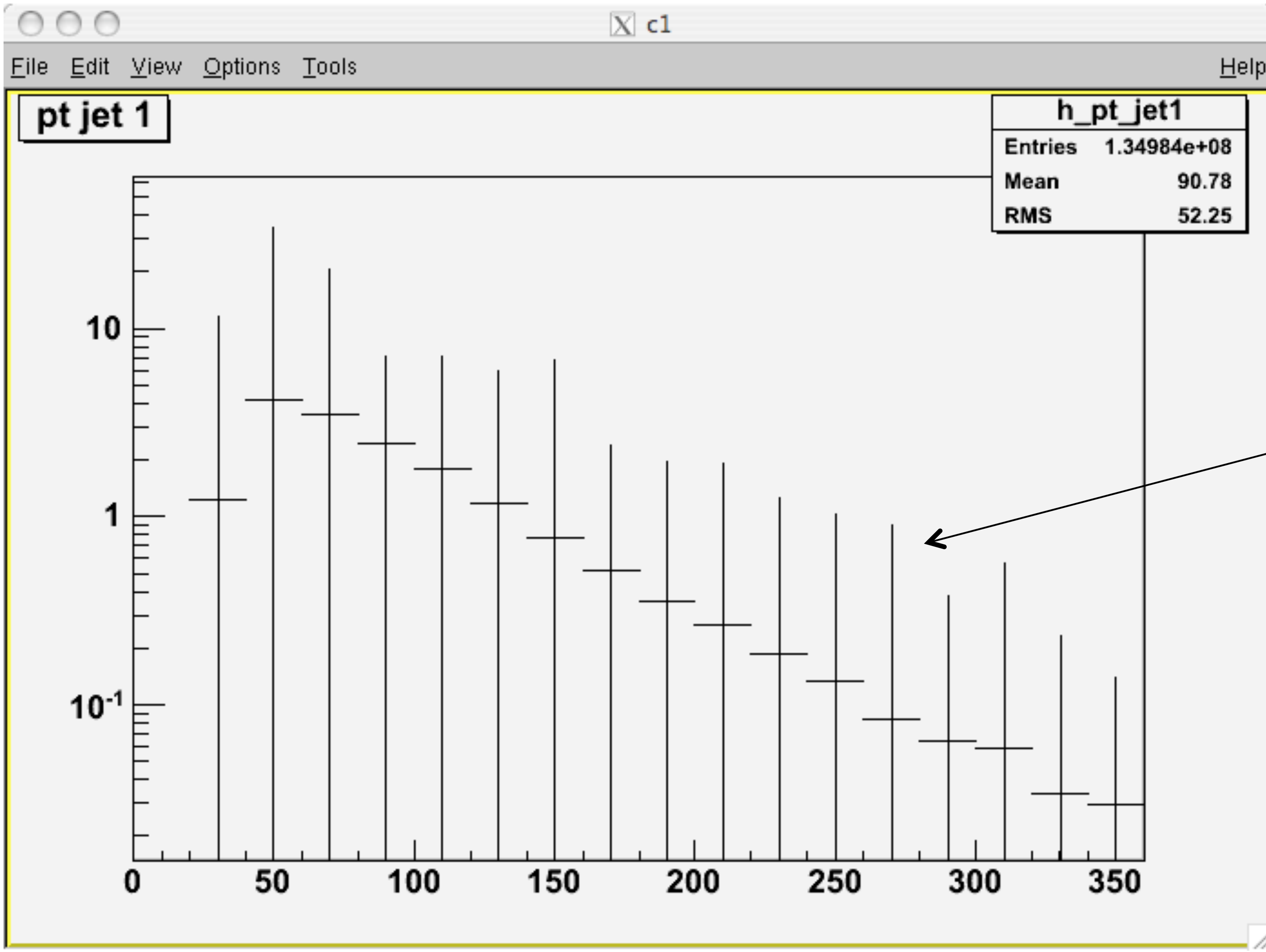
http://projects.hepforge.org/spartyjet/

…so for example

- $W^- + 3$ jets at 7 TeV for semi-standard cuts
  - $|y_e|<2.5$
  - $p_T^e>20$ GeV/c
  - $p_T^\nu> 20$ GeV/c
  - $P_T^{jet}>25$ GeV/c
  - $|y_{jet}|<3.0$
- New cuts or histograms means re-running through the ntuples: ~4 hours

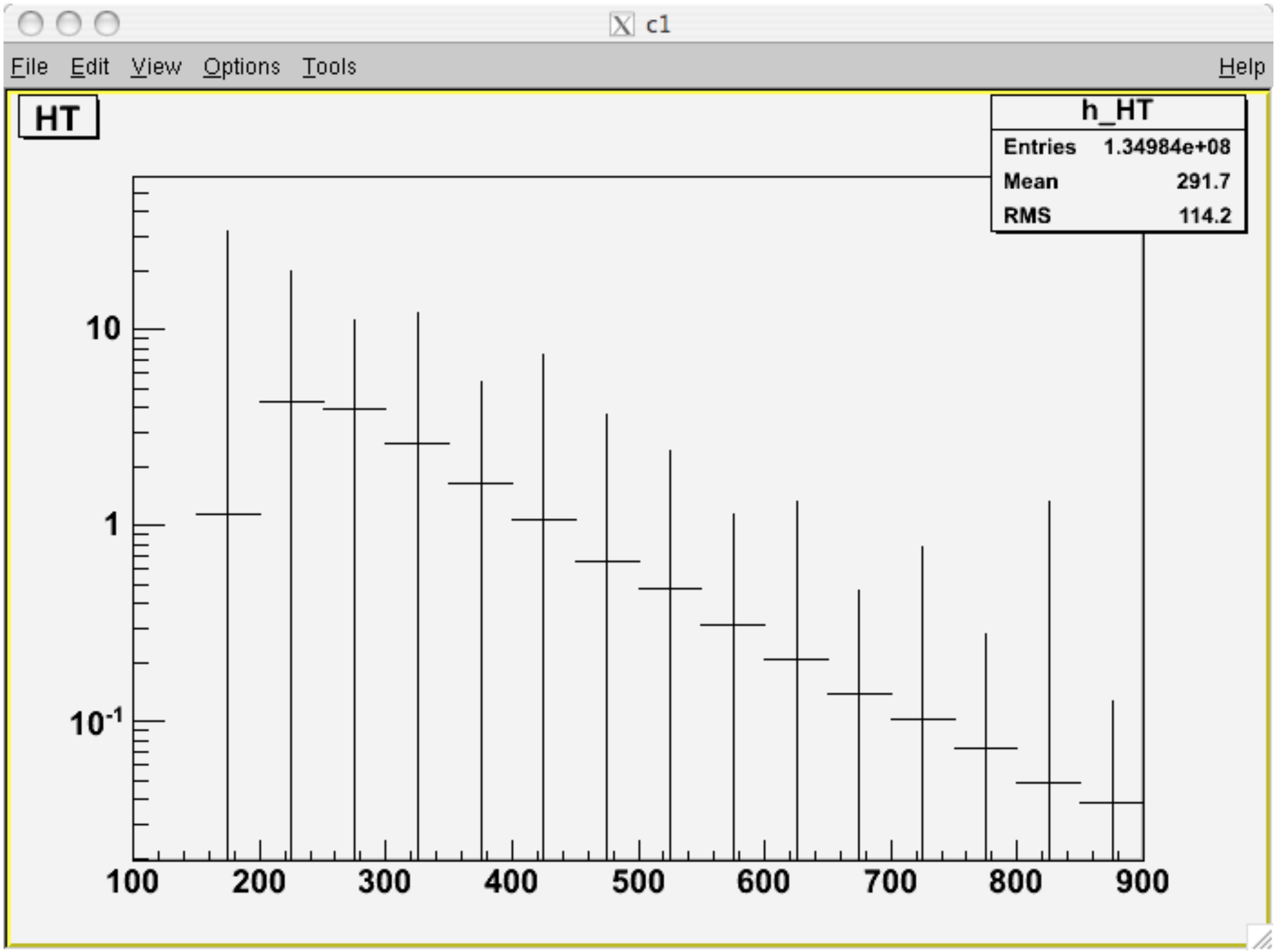
- For antikT4
  - bornLO: 18.4 nb
  - born: 15.6 nb
  - loop-lc: 4.9 nb
  - loop-fmlc: 0.5 nb
  - vsub: -16.3 nb
    - note large negative subtraction terms/ events; this is not something you can easily put into a parton shower
  - real: 12.4 nb
  - total: 17.1 nb

p_T for lead jet



ignore the size of the error bars; the smoothness of the data gives you an idea of the error

H_T



c1
File
Edit
View
Options
Tools
Help
HT
h_HT
Entries 1.34984e+08
Mean 291.7
RMS 114.2
10
1
10^{-1}
100
200
300
400
500
600
700
800
900

Proposed common ntuple output

- A generalization of the FROOT format used in MCFM
- Writeup in NLM proceedings

Table 4: Variables stored in the proposed common ROOT ntuple output.

ROOT Tree Branch	Description
Npart/I	number of partons (incoming and outgoing)
Px[Npart]/D	Px of partons
Py[Npart]/D	Py of partons
Pz[Npart]/D	Pz of partons
E[Npart]/D	E of partons
x1/D	Bjorken-x of incoming parton 1
x2/D	Bjorken-x of incoming parton 2
id1/I	PDG particle ID of incoming parton 1
id2/I	PDF particle ID of incoming parton 2
fac_scale/D	factorization scale
ren_scale/D	renormalization scale
weight/D	global event weight
Nuwgt/I	number of user weights
user_wgts[Nuwgt]/D	user event weights
evt_no/L	unique event number (identifier)
Nptr/I	number of event pointers
evt_pointers[Nptr]/L	event pointers (identifiers of related events)
Npdfs/I	number of PDF weights
pdf_wgts[Npdfs]/D	PDF weights

```
LhaNLOEvent* evt = new LhaNLOEvent();
evt->addParticle(px1,py1,pz1,E1);
evt->setProcInfo(x1,id1,x2,id2);
evt->setRenScale(scale);
...
```

Another class **LhaNLOTreeIO** is responsible for writing the events into the ROOT tree and outputting the tree to disk. In addition to the event-wise information global data such as comments, cross sections etc can be written as well. An example is shown below:

```
LhaNLOTreeIO* writer = new LhaNLOTreeIO(); // create tree writer
writer->initWrite(''test.root'');
...
writer->writeComment(''W+4 jets at NNLO''); // write global comments
writer->writeComment(''total cross section: XYZ+/-IJK fb'');
...
writer->writeEvent(*evt); // write event to tree (in event loop)
...
writer->writeTree(); // write tree to disk
```

Similarly, a tree can be read back from disk:

```
LhaNLOTreeIO* reader = new LhaNLOTreeIO(); // init reader
ierr=reader->initRead("test.root");
if (!ierr) {
  for (int i=0; i< reader->getNumberofEvents();i++) {
    event->reset();
    ierr=reader->readEvent(i,*event);
    ...
  }
}
```

K-factors

- Often we work at LO by necessity (parton shower Monte Carlos), but would like to know the impact of NLO corrections
- K-factors (NLO/LO) can be a useful short-hand for this information
- But caveat emptor; the value of the K-factor depends on a number of things
  - PDFs used at LO and NLO
  - scale(s) at which the cross sections are evaluated
- And often the NLO corrections result in a shape change, so that one K-factor is not sufficient to modify the LO cross sections

K-factor table from CHS paper

with mod LO PDFs; extra slides

K-factors for LHC slightly less K-factors at Tevatron

K-factors with NLO PDFs at LO are more often closer to unity

Process	Typical scales		Tevatron K-factor			LHC K-factor			
	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}''(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15	0.95
W+1jet	m_W	$p_T^{\rm jet}$	1.42	1.20	1.43	1.21	1.32	1.42	0.99
W+2jets	m_W	$p_T^{\rm jet}$	1.16	0.91	1.29	0.89	0.88	1.10	0.90
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42	1.10
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.19	1.09
$t\bar{t}$+1jet	m_t	$2m_t$	1.13	1.43	1.37	0.97	1.29	1.10	0.85
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51	–
Higgs	m_H	$p_T^{\rm jet}$	2.33	–	2.33	1.72	–	2.32	1.43
Higgs via VBF	m_H	$p_T^{\rm jet}$	1.07	0.97	1.07	1.23	1.34	0.85	0.78
Higgs+1jet	m_H	$p_T^{\rm jet}$	2.02	–	2.13	1.47	–	1.90	1.33
Higgs+2jets	m_H	$p_T^{\rm jet}$	–	–	–	1.15	–	–	1.13

Table 3: K-factors for various processes at the LHC calculated using a selection of input parameters. Have to fix this table. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO and $\mathcal{K}''$ uses the modified LO (2-loop) PDF set. For Higgs+1,2jets, a jet cut of 40 GeV/c and $|\eta| < 4.5$ has been applied. A cut of $p_T^{\rm jet} > 20\ GeV/c$ has been applied for the $t\bar{t}$+jet process, and a cut of $p_T^{\rm jet} > 50\ GeV/c$ for WW+jet. In the W(Higgs)+2jets process the jets are separated by $\Delta R > 0.52$, whilst the VBF calculations are performed for a Higgs boson of mass 120 GeV. In each case the value of the K-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.

Shapes of distributions may be different at NLO than at LO, but sometimes it is still useful to define a K-factor.

Note the value of the K-factor depends critically on its definition.

Go back to K-factor table

- Some rules-of-thumb
- NLO corrections are larger for processes in which there is a great deal of color annihilation
  - gg->Higgs
  - gg->γγ
  - *K*(gg->tT) > *K*(qQ -> tT)
  - these gg initial states want to radiate like crazy (see Sudakovs)
- NLO corrections decrease as more final-state legs are added
  - *K*(gg->Higgs + 2 jets) < *K*(gg->Higgs + 1 jet) < *K*(gg->Higgs)
  - unless can access new initial state gluon channel
- Can we generalize for uncalculated HO processes?
- What about effect of jet vetoes on K-factors? Signal processes compared to background. Of current interest.

Process	Typical scales μ_0	μ_1	Tevatron K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	LHC K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
W+1jet	m_W	p_T^{jet}	1.42	1.20	1.43	1.21	1.32	1.42
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$t\bar{t}$+1jet	m_t	$2m_t$	1.13	1.43	1.37	0.97	1.29	1.10
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs	m_H	p_T^{jet}	2.33	–	2.33	1.72	–	2.32
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Higgs+1jet	m_H	p_T^{jet}	2.02	–	2.13	1.47	–	1.90
Higgs+2jets	m_H	p_T^{jet}	–	–	–	1.15	–	–

Table 2: K-factors for various processes at the Tevatron and the LHC calculated using a selection of input parameters. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO. For most of the processes listed, jets satisfy the requirements $p_T > 15$ GeV/c and $|\eta| < 2.5$ (5.0) at the Tevatron (LHC). For Higgs+1,2jets, a jet cut of 40 GeV/c and $|\eta| < 4.5$ has been applied. A cut of $p_T^{\text{jet}} > 20\ GeV/c$ has been applied for the $t\bar{t}$+jet process, and a cut of $p_T^{\text{jet}} > 50\ GeV/c$ for WW+jet. In the W(Higgs)+2jets process the jets are separated by $\Delta R > 0.52$, whilst the VBF calculations are performed for a Higgs boson of mass 120 GeV. In each case the value of the K-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.

Casimir for biggest color representation final state can be in

Simplistic rule

$C_{i1} + C_{i2} - C_{f,max}$

L. Dixon

Casimir color factors for initial state

Shape dependence of a K-factor

- Inclusive jet production probes very wide x, Q^2 range along with varying mixture of gg,gq,and qq subprocesses
- PDF uncertainties are significant at high p_T
- Over limited range of p_T and y, can approximate effect of NLO corrections by K-factor but not in general
  - in particular note that for forward rapidities, K-factor <<1
  - LO predictions will be large overestimates
  - this is true for both the Tevatron and for the LHC
  - due to structure of scale dependence at NLO

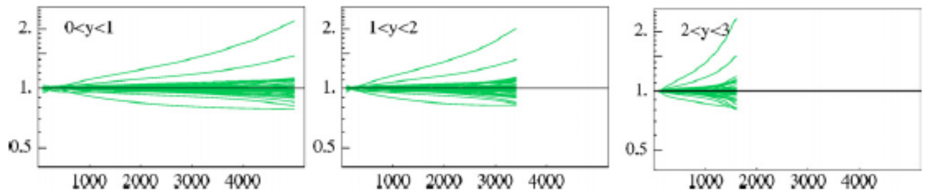


Figure 105. The ratios of the jet cross section predictions for the LHC using the CTEQ6.1 error pdfs to the prediction using the central pdf. The extremes are produced by eigenvector 15.

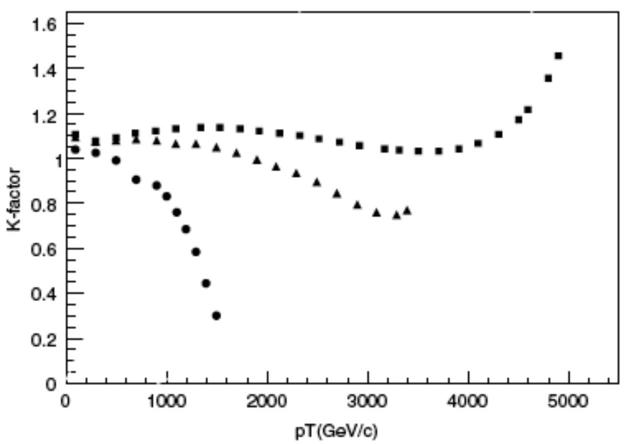


Figure 106. The ratios of the NLO to LO jet cross section predictions for the LHC using the CTEQ6.1 pdfs for the three different rapidity regions (0–1 (squares), 1–2 (triangles), 2–3 (circles)).

Consider the W + 3 jets process

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. $pp \to V\,V\,V$	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

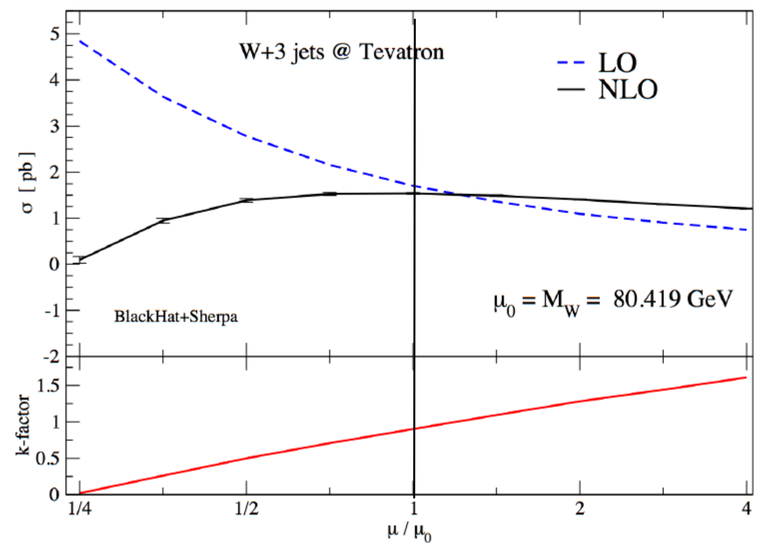
Table 1: The updated experimenter's wishlist for LHC processes

W + 3 jets

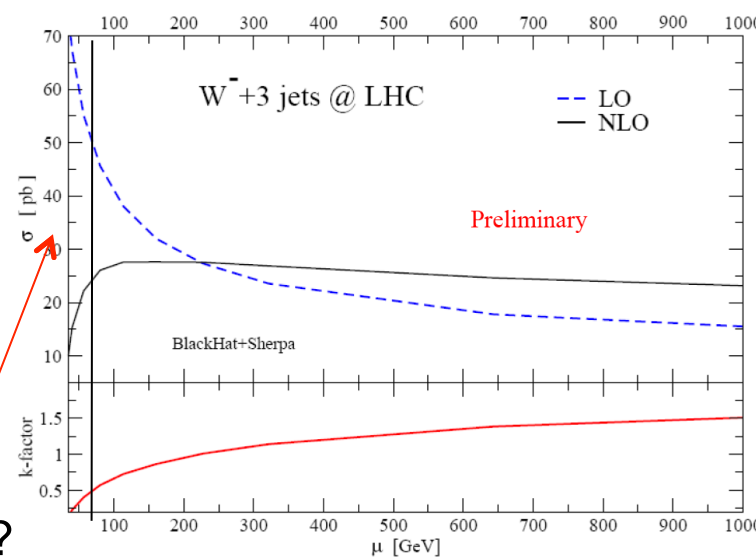
Consider a scale of m_W for W + 1,2,3 jets. We see the K-factors for W + 1,2 jets in the table below, and recently the NLO corrections for W + 3 jets have been calculated, allowing us to estimate the K-factors for that process. It is much smaller than one.

Process	Typical scales μ_0	μ_1	Tevatron K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	LHC K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}''(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15	0.95
W+1jet	m_W	$p_T^{\rm jet}$	1.42	1.20	1.43	1.21	1.32	1.42	0.99
W+2jets	m_W	$p_T^{\rm jet}$	1.16	0.91	1.29	0.89	0.88	1.10	0.90
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42	1.10
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.19	1.09
$t\bar{t}$+1jet	m_t	$2m_t$	1.13	1.43	1.37	0.97	1.29	1.10	0.85
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51	–
Higgs	m_H	$p_T^{\rm jet}$	2.33	–	2.33	1.72	–	2.32	1.43
Higgs via VBF	m_H	$p_T^{\rm jet}$	1.07	0.97	1.07	1.23	1.34	0.85	0.78
Higgs+1jet	m_H	$p_T^{\rm jet}$	2.02	–	2.13	1.47	–	1.90	1.33
Higgs+2jets	m_H	$p_T^{\rm jet}$	–	–	–	1.15	–	–	1.13

Table 3: K-factors for various processes at the LHC calculated using a selection of input parameters. Have to fix this table. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO and $\mathcal{K}''$ uses the modified LO (2-loop) PDF set. For Higgs+1,2jets, a jet cut of 40 GeV/c and $|\eta| < 4.5$ has been applied. A cut of $p_T^{\rm jet} > 20\ GeV/c$ has been applied for the $t\bar{t}$+jet process, and a cut of $p_T^{\rm jet} > 50\ GeV/c$ for WW+jet. In the W(Higgs)+2jets process the jets are separated by $\Delta R > 0.52$, whilst the VBF calculations are performed for a Higgs boson of mass 120 GeV. In each case the value of the K-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.



LHC total cross section



Is the K-factor (at m_W) at the LHC surprising?

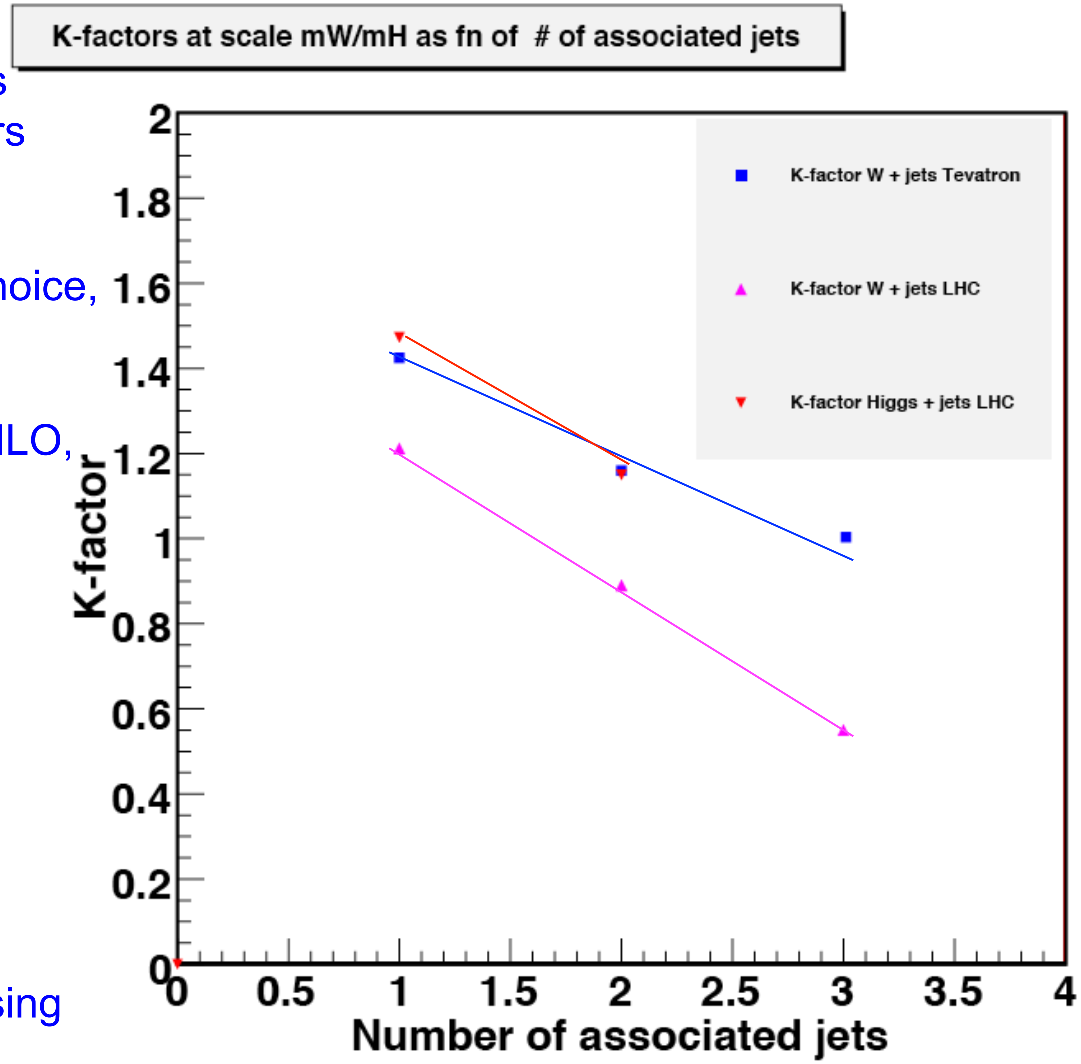
Is the K-factor (at m_W) at the LHC surprising?

The K-factors for W + jets (p_T>30 GeV/c) fall near a straight line, as do the K-factors for the Tevatron. By definition, the K-factors for Higgs + jets fall on a straight line.

Nothing special about m_W; just a typical choice, perhaps a low choice at the LHC.

The only way to know a cross section to NLO, say for W + 4 jets or Higgs + 3 jets, is to calculate it, but in lieu of the calculations, especially for observables that we have deemed important at Les Houches, can we understand the behavior with the associated number of jets?

Related to this is:
- understanding the reduced scale dependences/pdf uncertainties for cross section ratios we have been discussing
- scale choices at LO for cross sections uncalculated at NLO



Is the K-factor (at m_W) at the LHC surprising?

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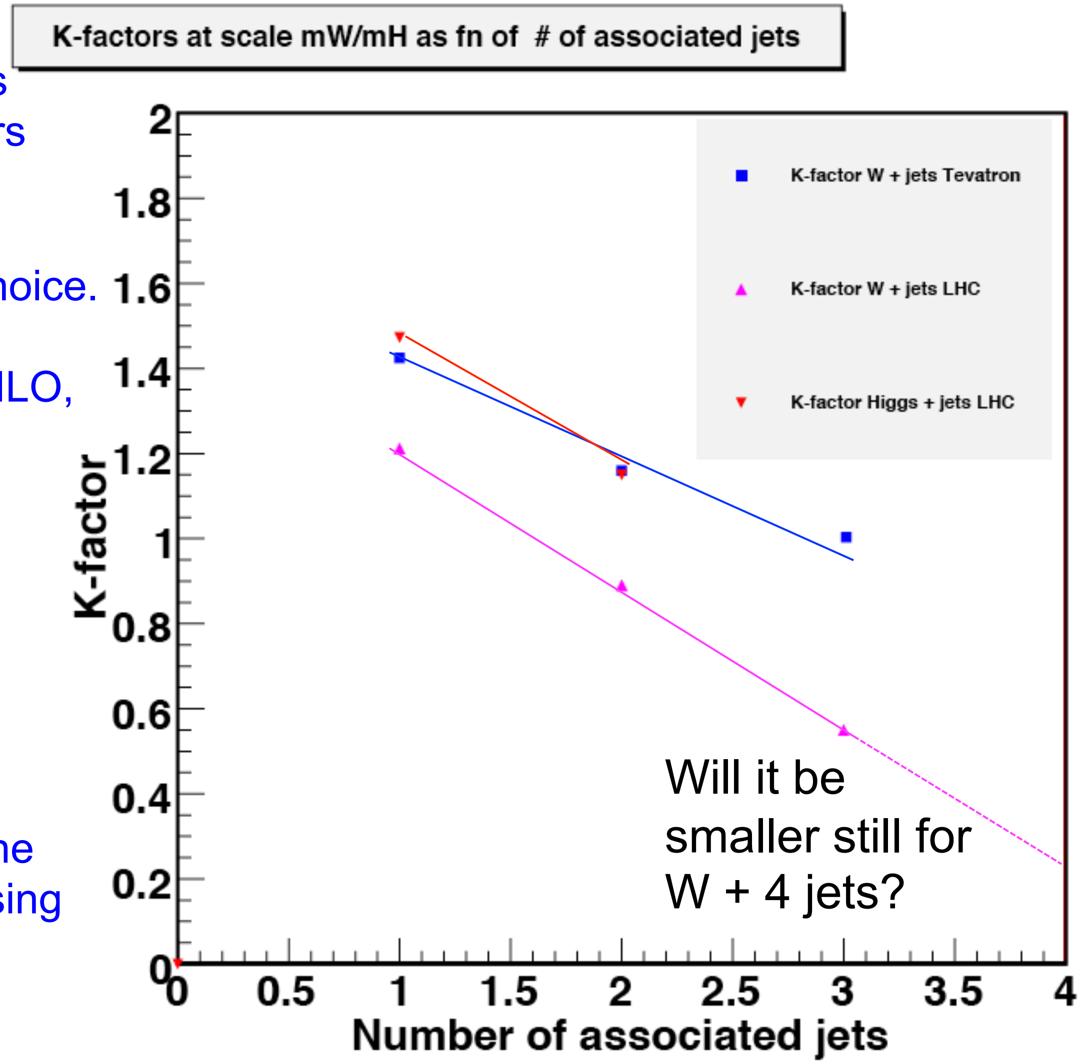
Nothing special about m_W; just a typical choice.

The only way to know a cross section to NLO, say for W + 4 jets or Higgs + 3 jets, is to calculate it, but in lieu of the calculations, especially for observables that we have deemed important at Les Houches, can we make rules of thumb?

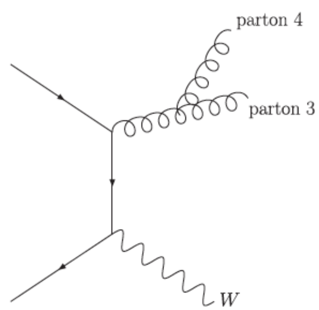
Related to this is:
- understanding the reduced scale dependences/pdf uncertainties for the cross section ratios we have been discussing
-scale choices at LO for cross sections calculated at NLO
-scale choices at LO for cross sections uncalculated at NLO



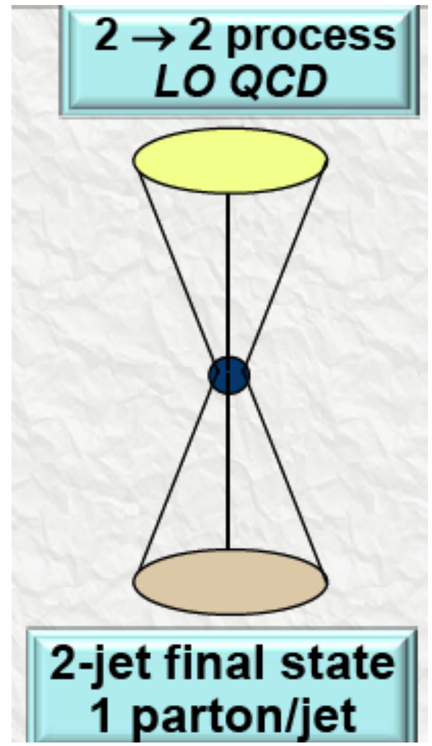
To understand this further, we have to discuss jet algorithms

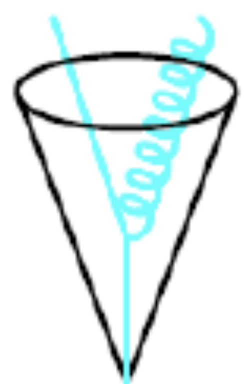
Jet algorithms at LO

- At (fixed) LO, 1 parton = 1 jet
  - why not more than 1? I have to put a ΔR cut on the separation between two partons; otherwise, there's a collinear divergence. LO parton shower programs effectively put in such a cutoff
  - Remember the collinear singularity



$$\log\left(\frac{1}{\Delta R_{34}}\right)$$





- But at NLO, I have to deal with more than 1 parton in a jet, and so now I have to talk about how to cluster those partons
  - i.e. jet algorithms

Jet algorithms at NLO

- At NLO, there can be two partons in a jet, life becomes more interesting and we have to start talking about jet algorithms to define jets
  - the addition of the real and virtual terms at NLO cancels the divergences in each

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

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

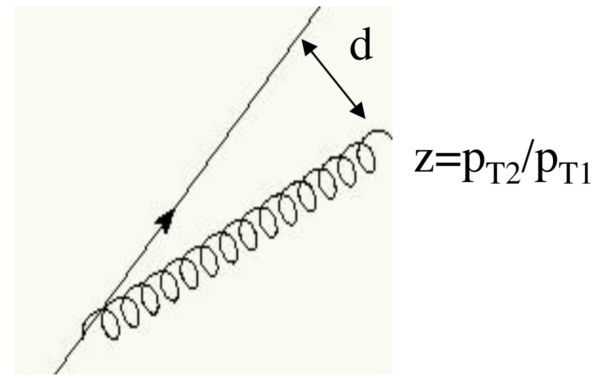
p=0; C-A
p=1: k_T
p=-1 anti-k_T

Pierre-Antoine Delsart's *reverse* k_T

- A jet algorithm is based on some measure of localization of the expected collinear spray of particles
- Start with an inclusive list of particles/partons/calorimeter towers/topoclusters
- End with lists of same for each jet
- …and a list of particles… not in any jet; for example, remnants of the initial hadrons
- Two broad classes of jet algorithms
  - cluster according to proximity in space: cone algorithms
  - ATLAS uses SISCone
  - cluster according to proximity in momenta: k_T algorithms
  - ATLAS uses k_T,antik_T

Jet algorithms at LO/NLO

- Remember at LO, 1 parton = 1 jet
- By choosing a jet algorithm with size parameter D, we are requiring any two partons to be > D apart
- The matrix elements have $1/\Delta R$ poles, so larger D means smaller cross sections
  - it's because of the poles that we have to make a ΔR cut
- At NLO, there can be two (or more) partons in a jet and jets for the first time can have some structure
  - we don't need a ΔR cut, since the virtual corrections cancel the collinear singularity from the gluon emission
  - **but there are residual logs that can become important if D is too small**
- Also, increasing the size parameter D increases the phase space for including an extra gluon in the jet, and thus increases the cross section at NLO (in most cases)



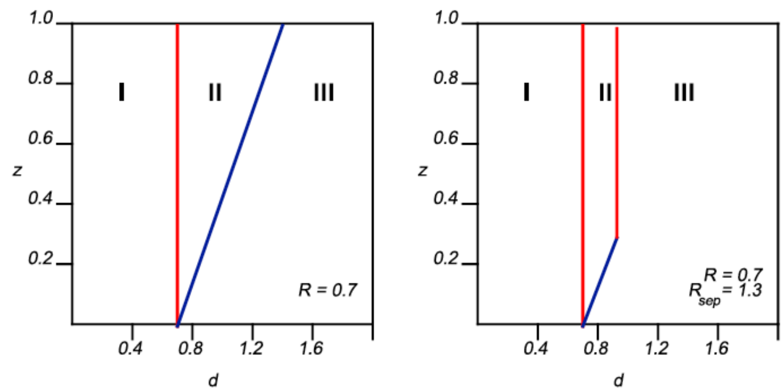


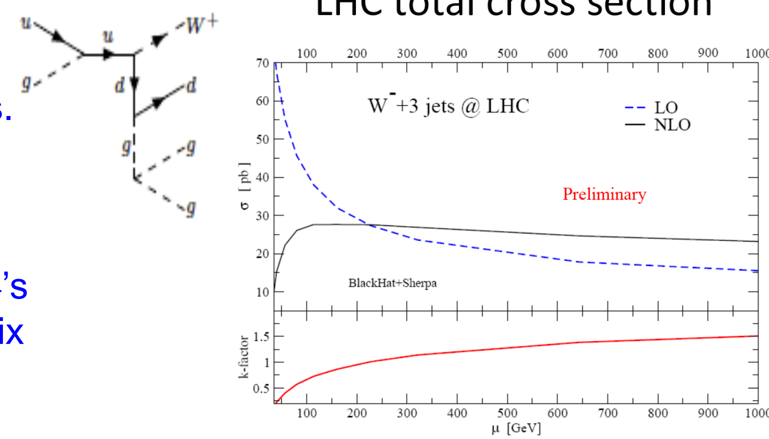
Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

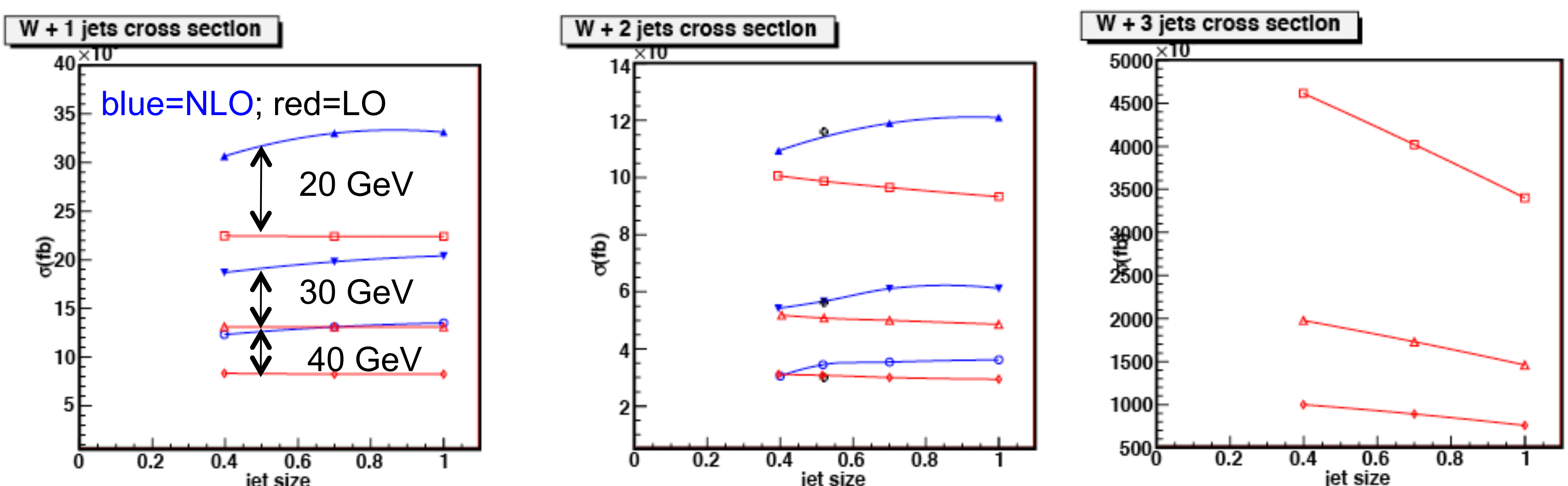
For $D=R_{cone}$, Region I = k_T jets, Region II (nominally) = cone jets; I say nominally because in data not all of Region II is included for cone jets

Is the K-factor (at m_W) at the LHC surprising?

The problem is not the NLO cross section; that is well-behaved.
The problem is that the LO cross section sits 'too-high'. The reason (one of them) for this is that we are 'too-close' to the collinear pole (R=0.4) leading to an enhancement of the LO cross section (double-enhancement if the gluon is soft (~20 GeV/c)). Note that at LO, the cross section increases with decreasing R; at NLO it decreases.
The collinear dependence gets stronger as n_{jet} increases.
The K-factors for W + 3 jets would be more *normal* (>1) if a larger cone size and/or a larger jet p_T cutoff were used. But that's a LO problem; the best approach is to use the appropriate jet sizes/jet p_T's for the analysis and understand the best scales to use at LO (matrix element + parton shower) to approximate the NLO calculation (as well as comparing directly to the NLO calculation).

LHC total cross section



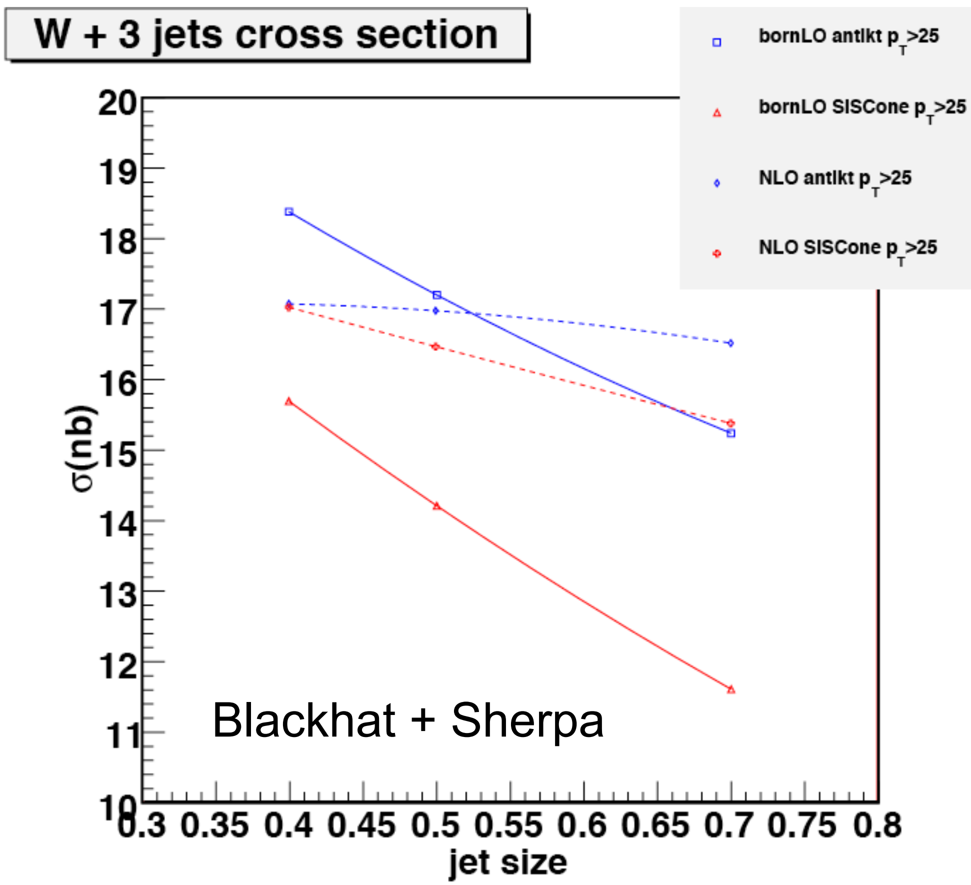


For 3 jets, the LO collinear singularity effects are even more pronounced.

NB: here I have used CTEQ6.6 for both LO and NLO; CTEQ6L1 would shift LO curves up

LO/NLO predictions for jet cross sections

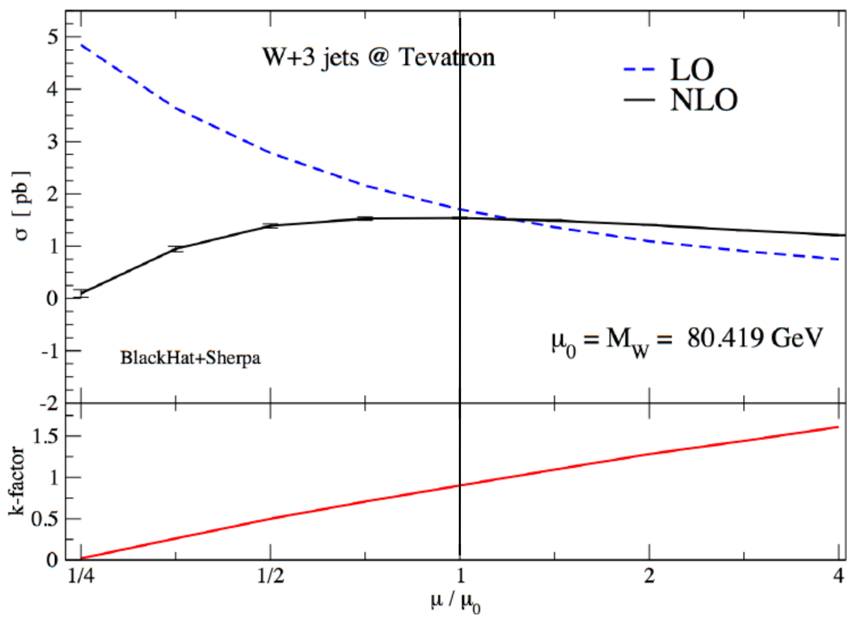
- Let's look at predictions for W + 3 jets for two different jet algorithms as a function of jet size at the LHC (7 TeV)
- At LO, both antikT and SISCone show a marked decrease in cross section as the jet size increases
  - because of the log(1/ΔR) effect
- But at NLO, the two cross sections show little dependence on the jet size, and are similar to each other
  - due to addition of extra gluon in jet possible at NLO
- You'll see the same thing in ATLAS Monte Carlo

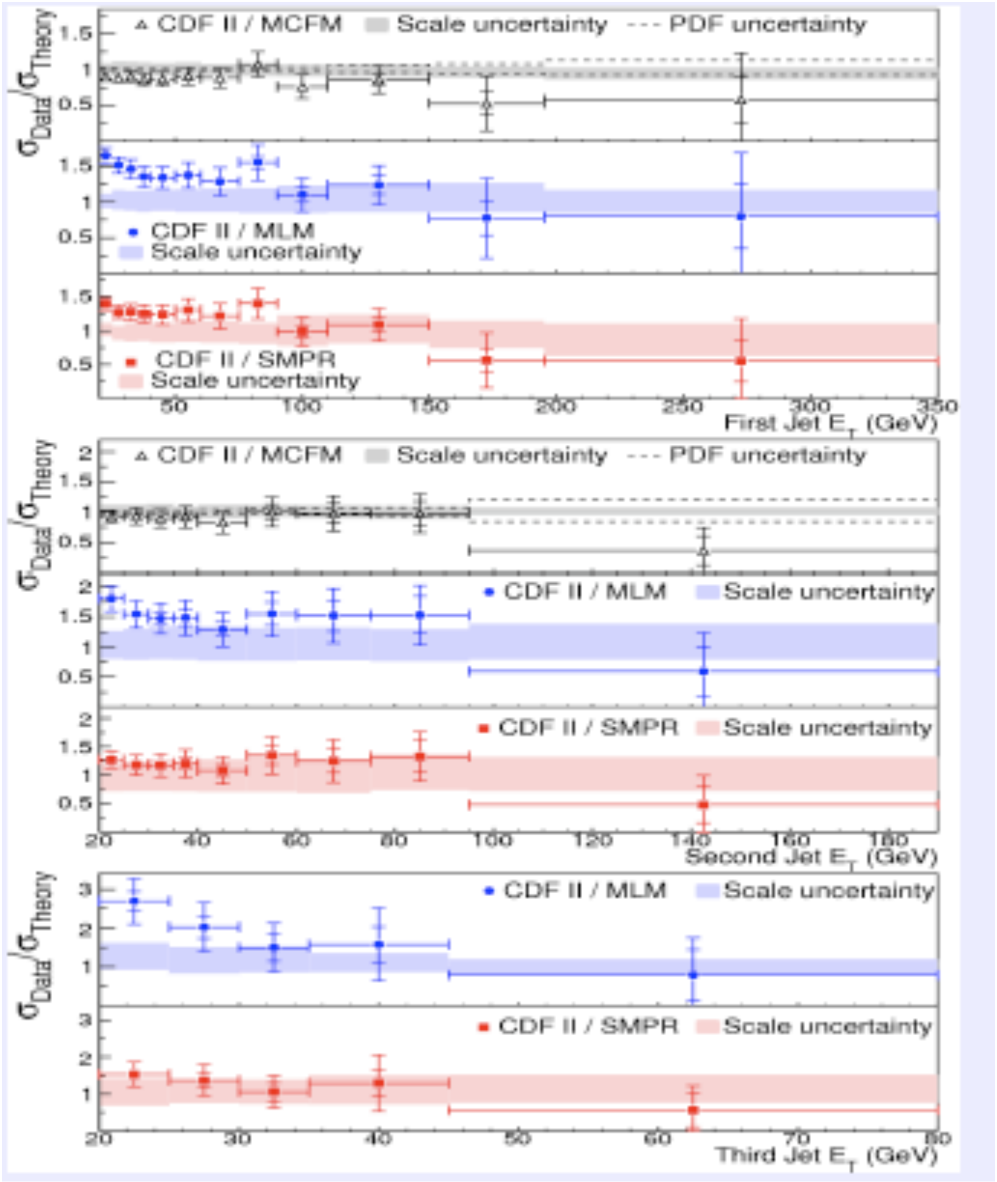


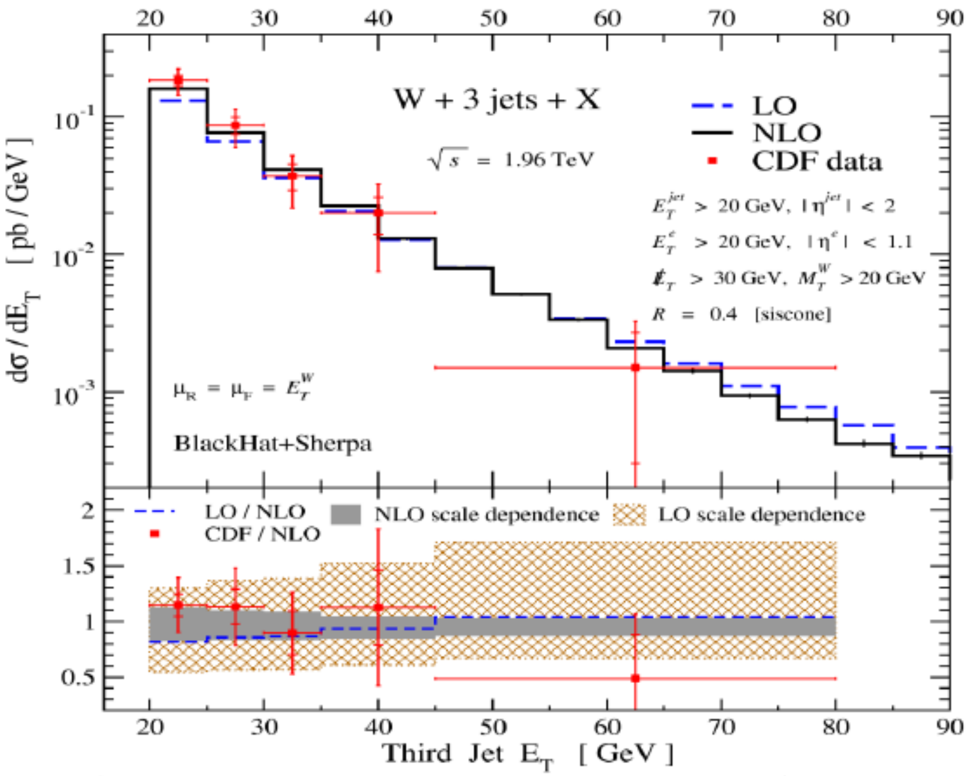
note NLO~LO because a scale of H_T has been used

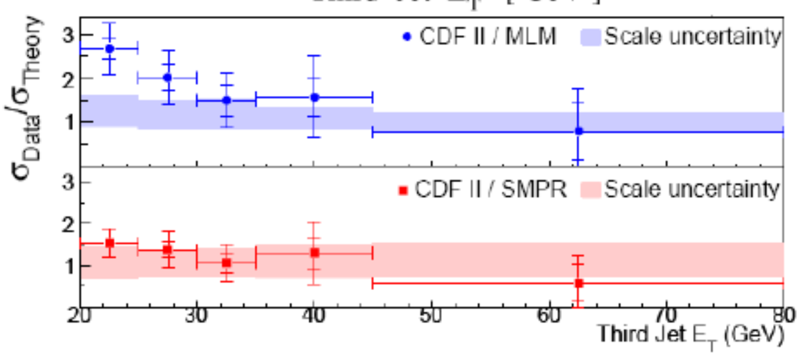
Scale choices at the Tevatron: W + jets

- At the Tevatron, m_W is a reasonable scale (in terms of K-factor~1)









Third jet in W+3 jets

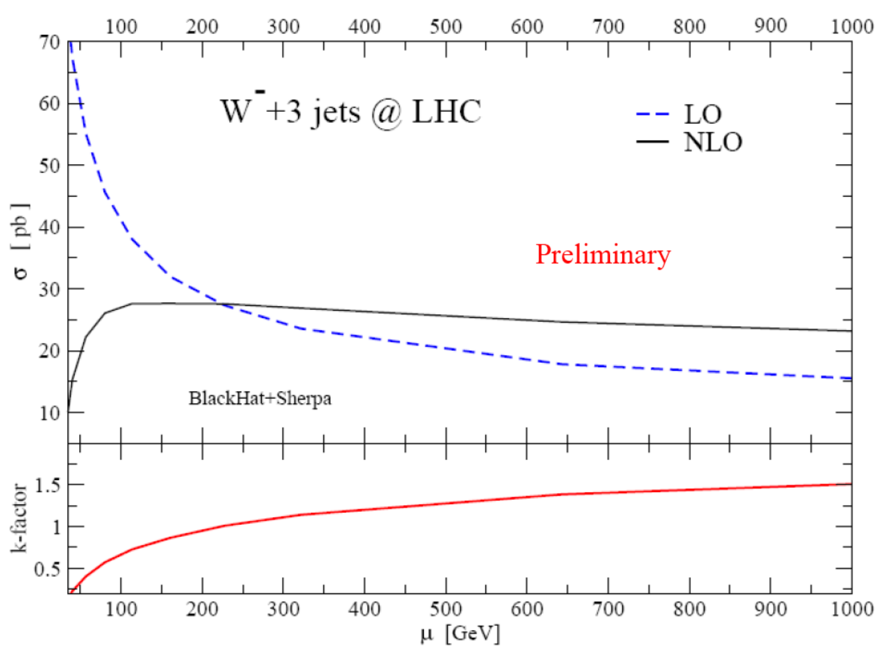
[BlackHat,0907.1984]

- Reduced scale dependence at NLO
- Shape change small compared to LO scale variation

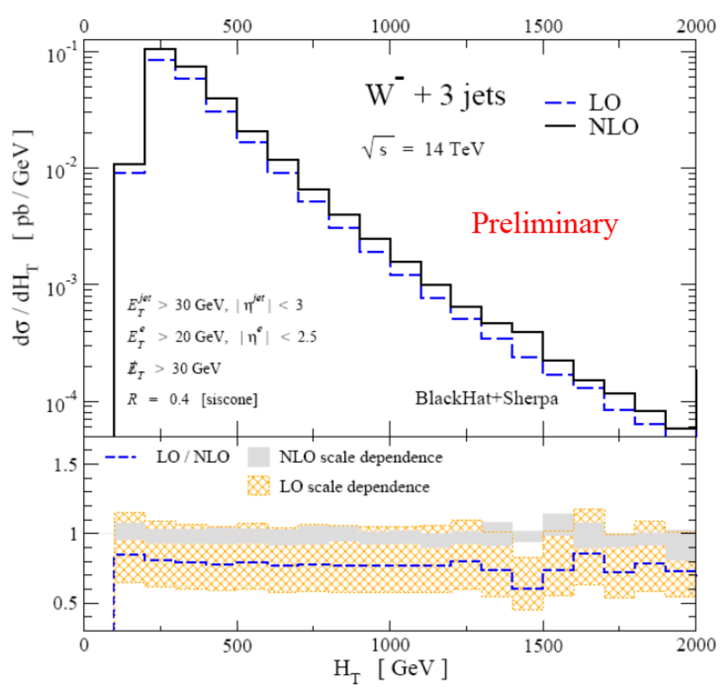
W + 3 jets at the LHC

A scale choice of m_W would be in a region where LO >> NLO. In addition, such a scale choice (or related scale choice), leads to sizeable shape differences in the kinematic distributions. The Blackhat+Sherpa people found that a scale choice of H_T worked best to get a constant K-factor for all distributions that they looked at.
Note that from the point-of-view of only NLO, all cross sections with scales above ~100 GeV seem reasonably stable

LHC total cross section



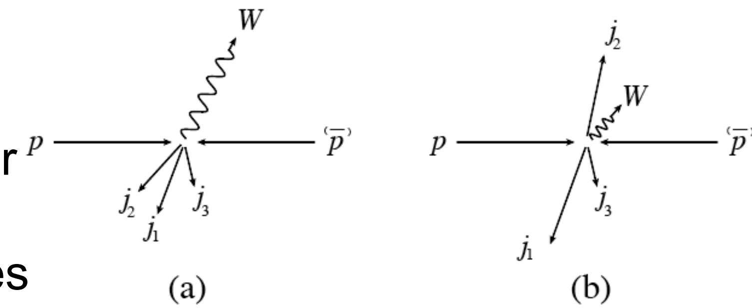
$$H_T = \sum_j E_{T,j}^{\rm jet} + E_T^e + \not{E}_T$$ distribution



mu = H_T

Scale choice: why is E_T^W a bad one at the LHC?

If configuration (a) dominated, then as jet E_T increased, E_T^W would increase along with it. But configuration (b) is kinematically favored for high jet E_T's (smaller partonic center-of-mass energy); E_T^W remains small, and that scale does not describe the process very well



Note that now split/merge can become important as the partonic jets can overlap and share partons

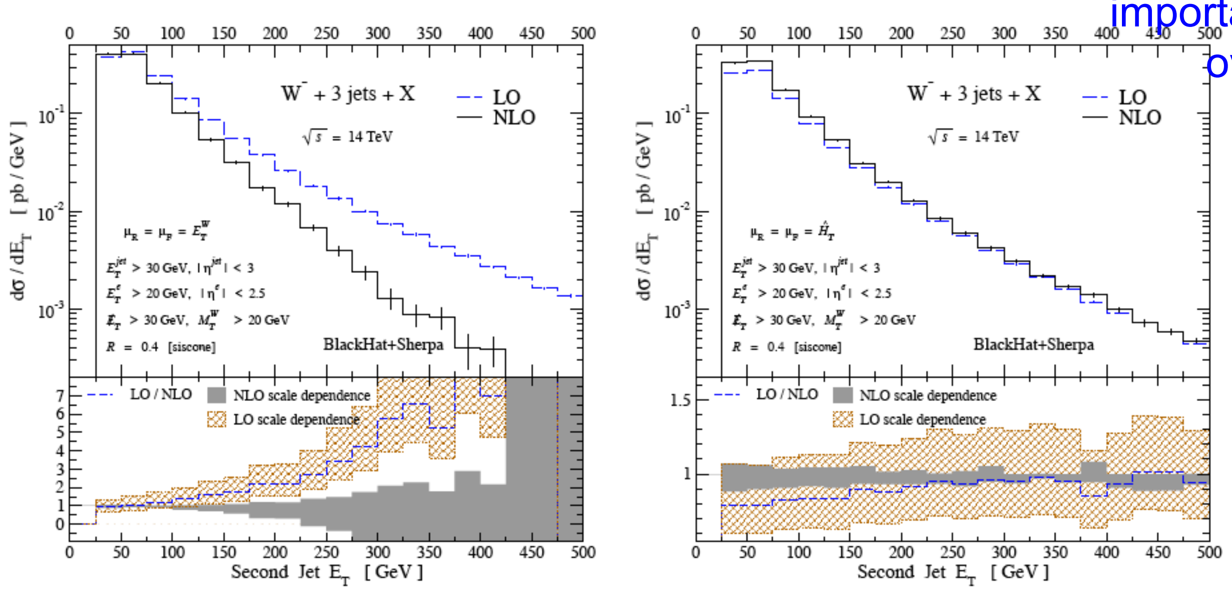


FIG. 9: The E_T distribution of the second jet at LO and NLO, for two dynamical scale choices, $\mu = E_T^W$ (left plot) and $\mu = \hat{H}_T$ (right plot). The histograms and bands have the same meaning as in previous figures. The NLO distribution for $\mu = E_T^W$ turns negative beyond $E_T = 475$ GeV.

Configuration b also tends to dominate in the tails of multi-jet distibutions (such as H_T or M_{ij}); for high jet E_T, W behaves like a massless boson, and so there's a kinematic enhancement when it's soft

arXiv:0907.1984

Scale choices

scales related to H_T work at both LO and NLO; CKKW also seems to agree well with NLO predictions in shape

Les Houches NLM proceedings

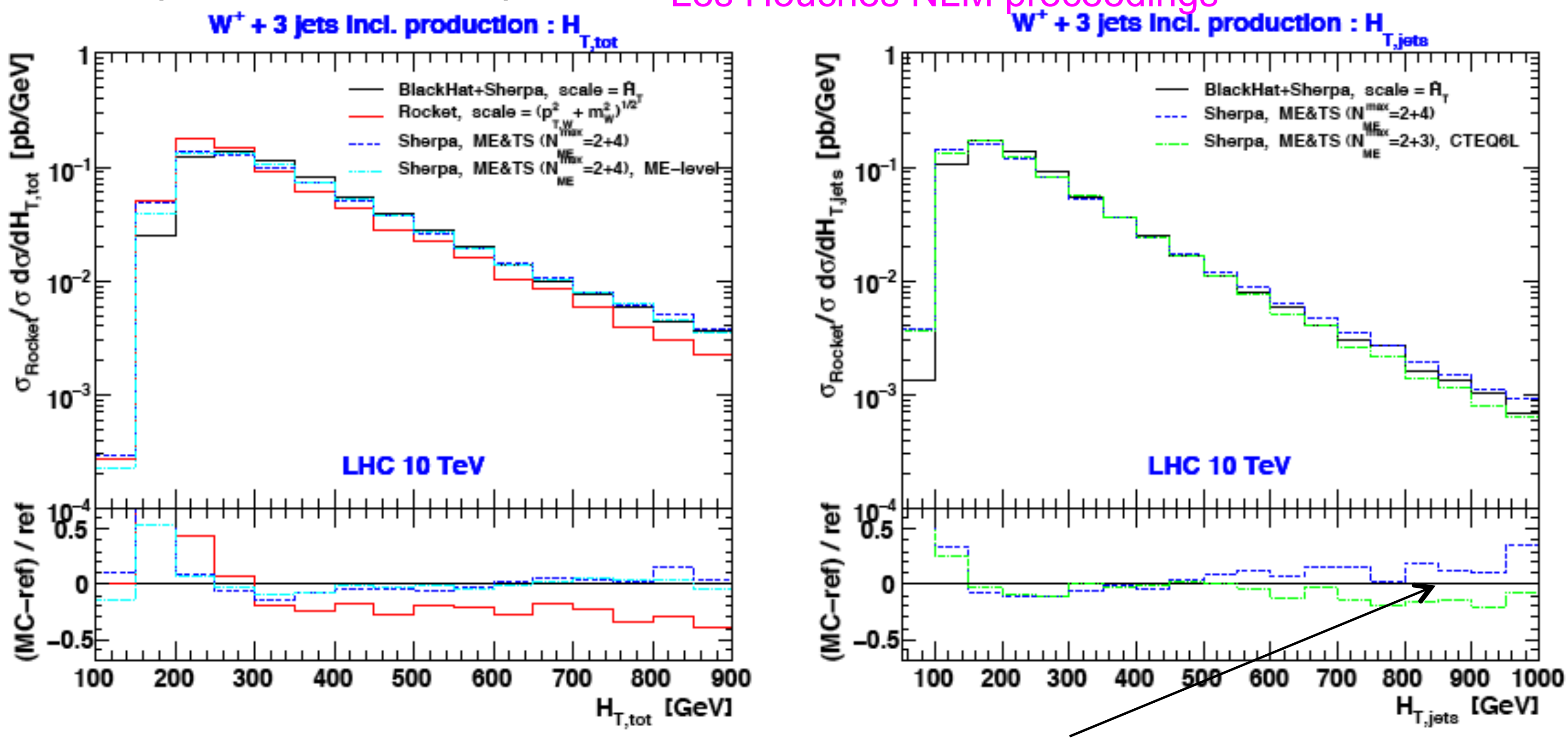


Fig. 19: H_T and $H_{T,\mathrm{jets}}$ distributions in inclusive $W^+ + 3$ jet production at the LHC. NLO predictions obtained from BLACKHAT+SHERPA (black line) and ROCKET (red line) are compared to LO results from SHERPA using the ME&TS merging. All curves have been rescaled to the ROCKET NLO cross section of Table 5; the BLACKHAT+SHERPA prediction is used as the reference; cuts and parameters are detailed in Section 12.2

Scale dependence

- Factorization and renormalization scale dependence for any cross section can be calculated (relatively easily) independent of the evaluation of the full matrix element, if you're careful to collect the relevant terms
- In new version of Blackhat+Sherpa ntuples, scale uncertainty (and pdf uncertainty) will be available

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

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

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

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

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

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

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

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,
  - …under investigation

Another motivation for the use of multiple jet algorithms/parameters (i.e. SpartyJet) in LHC analyses.

Jet sizes and scale uncertainties: the Goldilocks theorm

- Take inclusive jet production at the LHC for transverse momenta of the order of 50 GeV
- Look at the theory uncertainty due to scale dependence as a function of jet size
- It appears to be a minimum for cone sizes of the order of 0.7
  - i.e. if you use a cone size of 0.4, there are residual un-cancelled virtual effects
  - if you use a cone size of 1.0, you are adding too much tree level information with its intrinsically larger scale uncertainty
- This effect becomes smaller for jet p_T values on the order of 100 GeV/c
  - how does it translate for multi-parton final states?
  - currently under investigation

Scale dependence: jet algorithms

- Look at results for SISCone/antikT; antikT cross sections larger than SISCone, smaller scale dependence?

Multi-jet systematics: jet-algorithms Z+n jets.

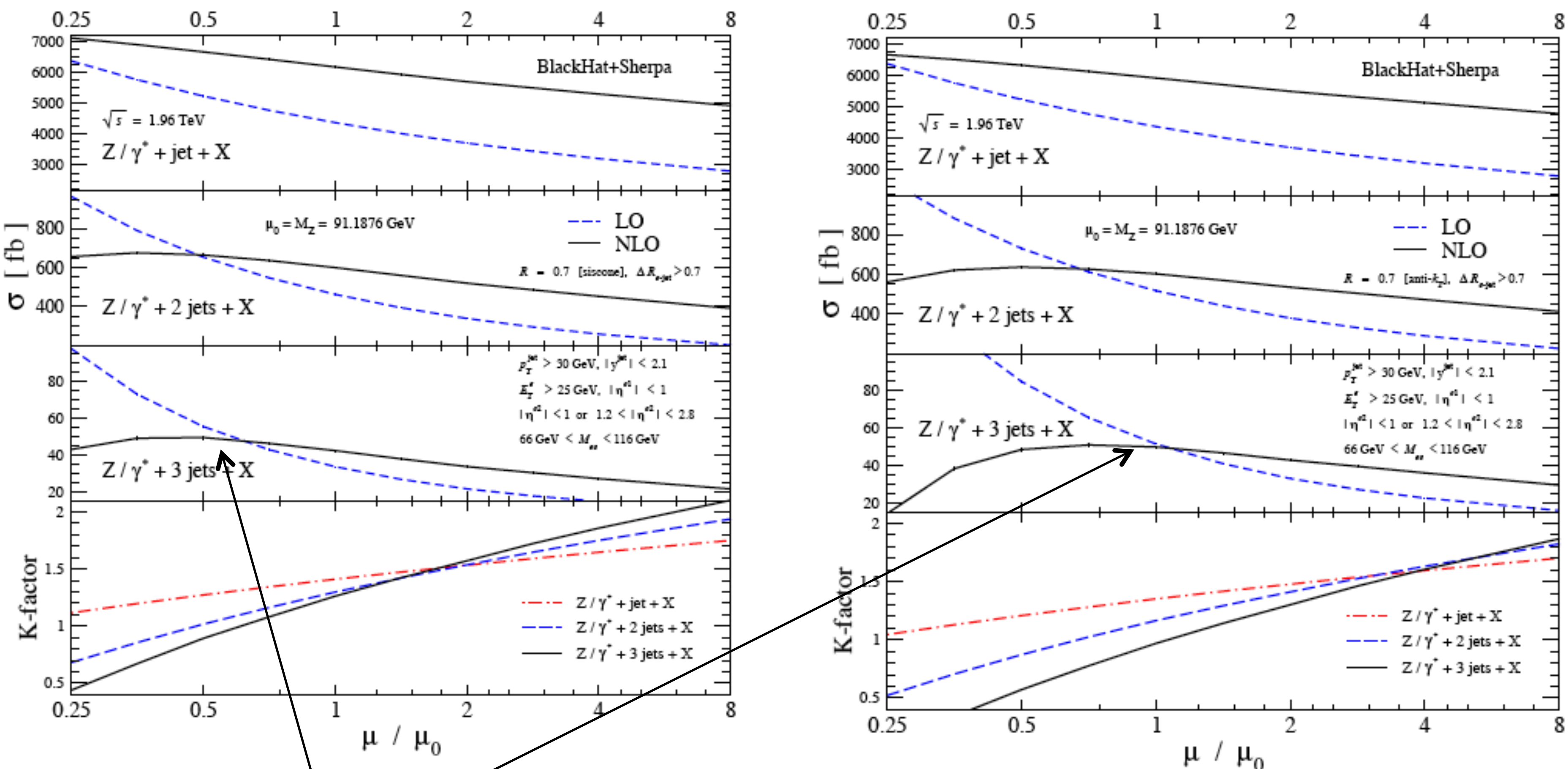
CDF: Phys. Rev. Lett. 100, 102001 (2008)
[BlackHat: 0912.4927, 1004.1659]
See also talk by J. Huston

σ in [fb]

# of jets	LO parton SISCone	NLO parton SISCone	LO parton anti-k_T	NLO parton anti-k_T	Non-pert correction
1	$4635(2)^{+928}_{-715}$	$6080(12)^{+354}_{-402}$	$4635(2)^{+928}_{-715}$	$5783(12)^{+257}_{-334}$	~1.1
2	$429.8(0.3)^{+171.7}_{-111.4}$	$564(2)^{+59}_{-70}$	$481.2(0.4)^{+191}_{-124}$	$567(2)^{+31}_{-57}$	~1.2
3	$24.6(0.03)^{+14.5}_{-8.2}$	$35.9(0.9)^{+7.8}_{-7.2}$	$37.88(0.04)^{+22.2}_{-12.6}$	$44.9(0.3)^{+4.7}_{-7.1}$	~1.4

H. Ita, SLAC Hadronic Final State Forum

Z + 3 jets: scale dependence



Note that peak cross sections are actually quite close; the cross sections just peak at different scales.

1004.1659

Jets at NLO: more complications

- Construct what is called a Snowmass potential

shown in Figure 50, where the towers unclustered into any jet are shaded black. A simple way of understanding these dark towers begins by defining a "Snowmass potential" in terms of the 2-dimensional vector $\vec{r} = (y, \phi)$ via

$$V(\vec{r}) = -\frac{1}{2}\sum_j p_{T,j}\left(R^2_{cone} - (\vec{r_j} - \vec{r})^2\right)\Theta\left(R^2_{cone} - (\vec{r_j} - \vec{r})^2\right) . \qquad (39)$$

The flow is then driven by the "force" $\vec{F}(\vec{r}) = -\vec{\nabla}V(\vec{r})$ which is thus given by,

$$\begin{aligned}\vec{F}(\vec{r}) &= \sum_j p_{T,j}(\vec{r_j} - \vec{r})\Theta\left(R^2_{cone} - (\vec{r_j} - \vec{r})^2\right)\\ &= \left(\vec{r}_{C(\vec{r})} - \vec{r}\right)\sum_{j\subset C(r)} p_{T,j}, \qquad (40)\end{aligned}$$

where $\vec{r}_{C(\vec{r})} = \left(\overline{y}_{C(\vec{r})}, \overline{\phi}_{C(\vec{r})}\right)$ and the sum runs over $j \subset C(\vec{r})$ such that $\sqrt{(y_j - y)^2 + (\phi_j - \phi)^2} \le R_{cone}$. As desired, this force pushes the cone to the stable cone position.

- The minima of the potential function indicates the positions of the stable cone solutions
  - the derivative of the potential function is the force that shows the direction of flow of the iterated cone
- The midpoint solution contains both partons

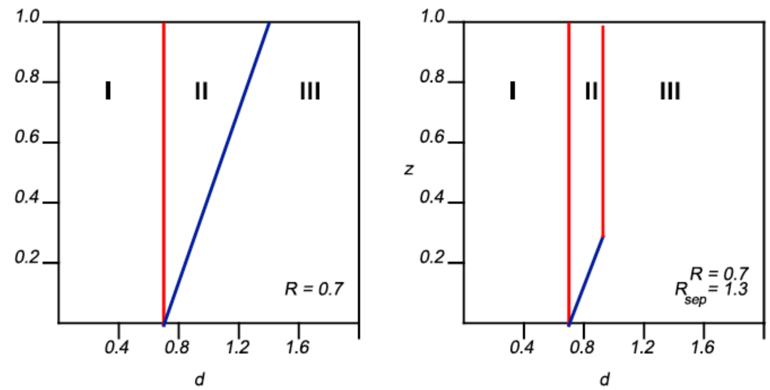


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

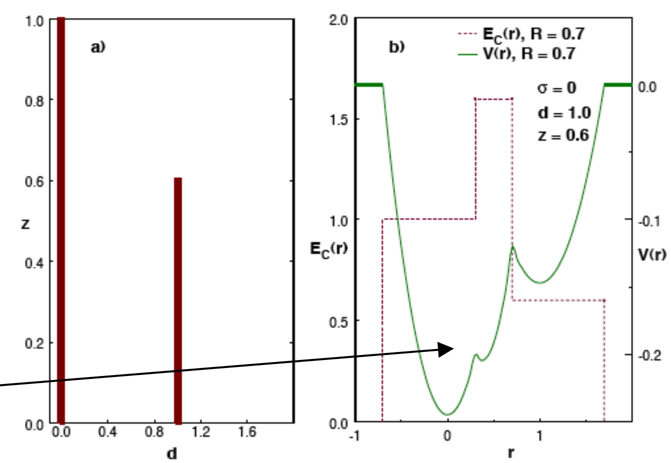


Figure 51. A schematic depiction of a specific parton configuration and the results of applying the midpoint cone jet clustering algorithm. The potential discussed in the text and the resulting energy in the jet are plotted.

Jets in real life

- Jets don't consist of 1 fermi partons but have a spatial distribution
- Can approximate jet shape as a Gaussian smearing of the spatial distribution of the parton energy
  - the effective sigma ranges between around 0.1 and 0.3 depending on the parton type (quark or gluon) and on the parton p_T
- Note that because of the effects of smearing that
  - the midpoint solution is (**almost always**) lost
    - thus region II is effectively truncated to the area shown on the right
  - the solution corresponding to the lower energy parton can also be lost
    - resulting in dark towers

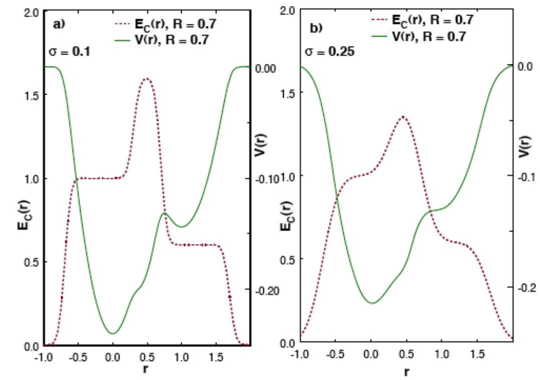


Figure 52. A schematic depiction of the effects of smearing on the midpoint cone jet clustering algorithm

remember the Snowmass potentials

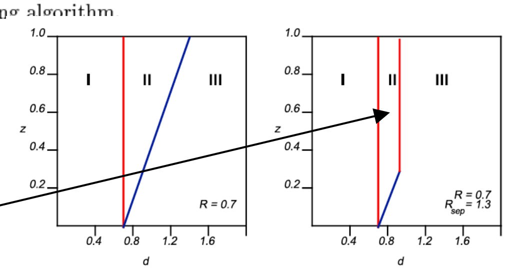


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

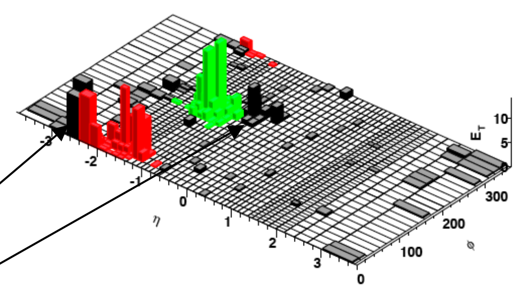


Figure 50. An example of a Monte Carlo inclusive jet event where the midpoint algorithm has left substantial energy unclustered.

Jets in real life

- In NLO theory, can mimic the impact of the truncation of Region II by including a parameter called R_{sep}
  - only merge two partons if they are within R_{sep}*R_{cone} of each other
    - R_{sep}~1.3
  - ~4-5% effect on the theory cross section; effect is smaller with the use of p_T rather than E_T
  - really upsets the theorists (but there are also disadvantages)
- Dark tower effect is also on order of few (<5)% effect on the (experimental) cross section
- Dark towers affect every cone algorithm

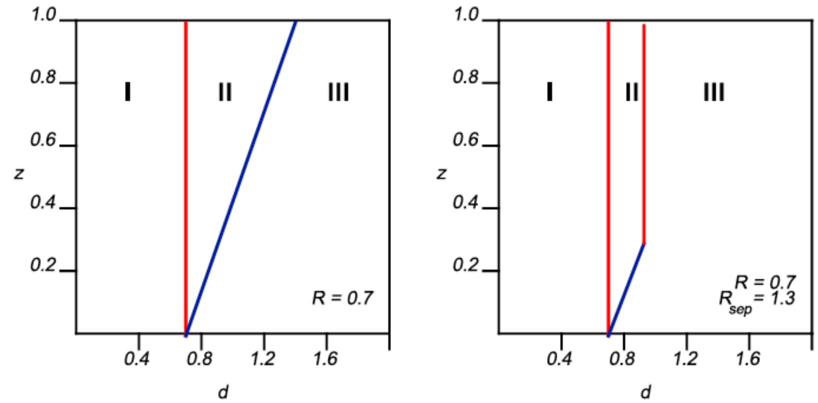
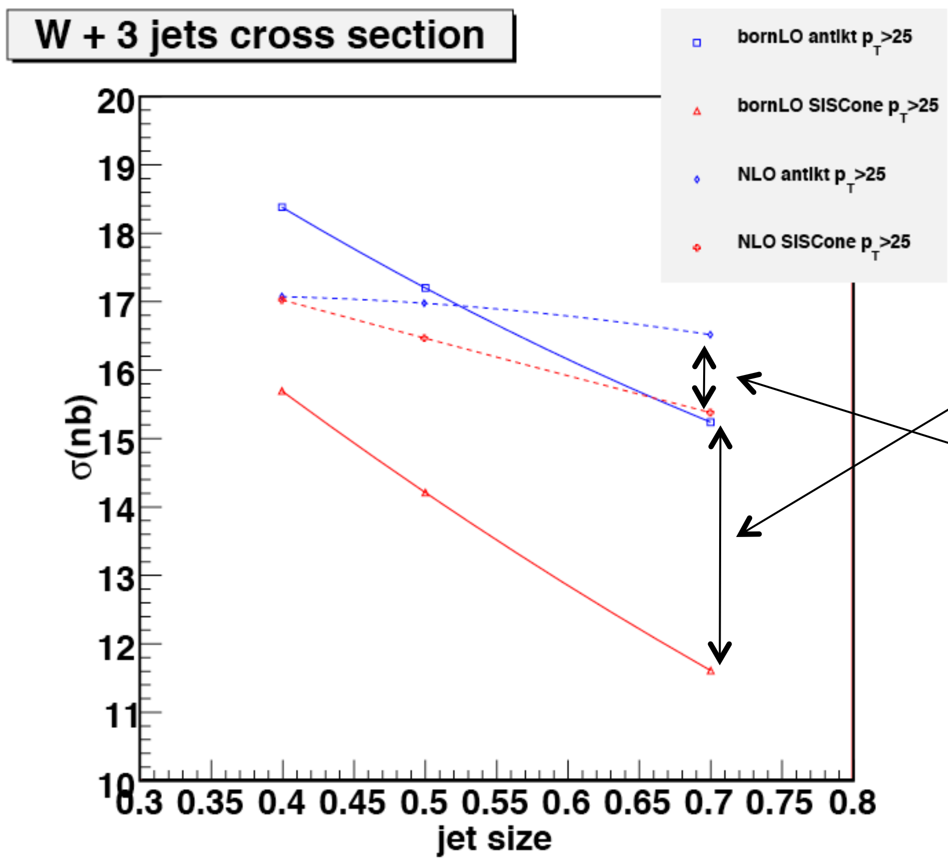


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

Don't believe (fixed) LO predictions for jet cross sections



Compare to ATLAS ALPGEN+ PYTHIA samples (ΔR=0.7 matching so we can only compare to last jet size)

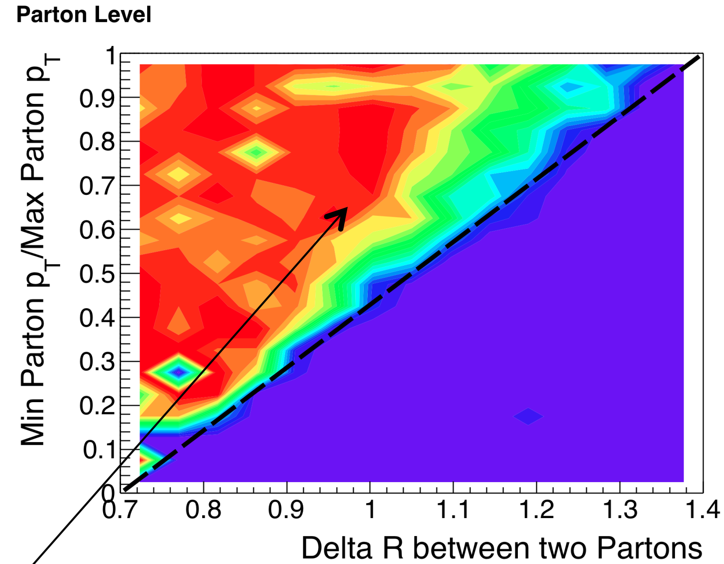
At parton level, antikT is ~25% higher than SISCone (same as we observe here at LO)

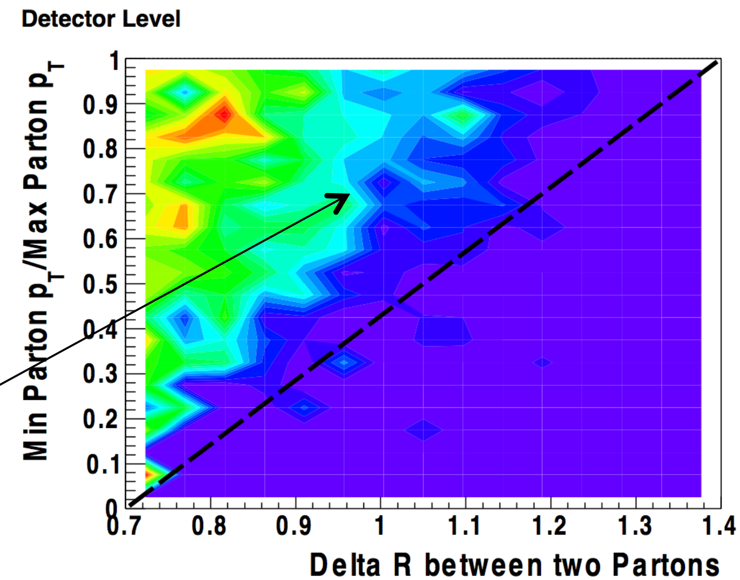
At topocluster level, antikT is ~2% higher than SISCone (not the 7% observed here)

Why 2%, not 7%?
Some of the W + 3 parton events reconstructed as 2 jets at the parton level for SISCone are reconstructed as 3 jets at the hadron. The cross section for 3 jets increases.

One of those LO/NLO differences

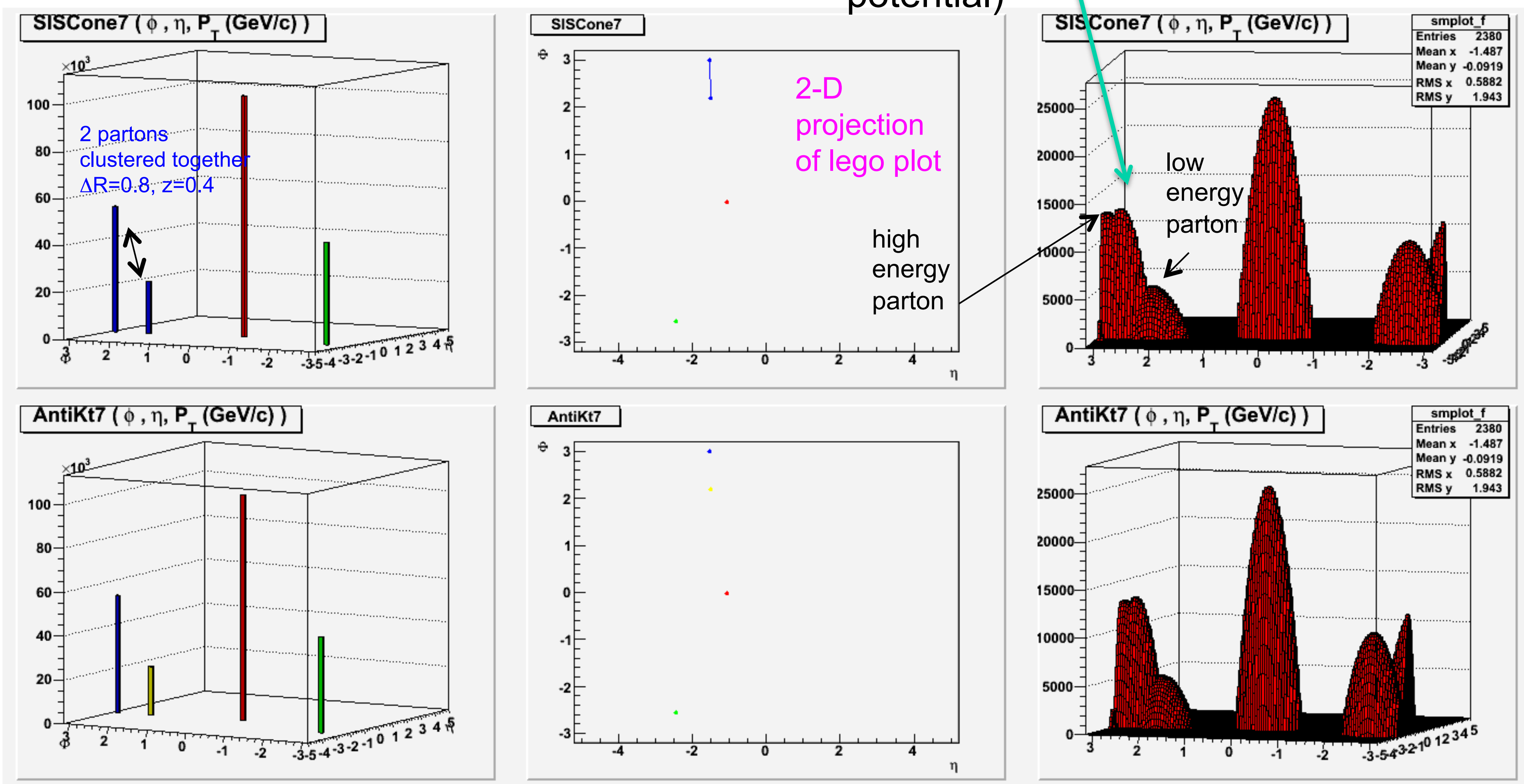
- Take W + 2 parton events (ALPGEN +PYTHIA), run SISCone 0.7 algorithm on parton level, hadron level (not shown) and topocluster level
- Plot the probability for the two sub-jets to merge as a function of the separation of the original two partons in ΔR
- Color code:
  - red: high probability for merging
  - blue: low probability for merging
  - everything for ΔR<0.7 is merged for SISCone (and antikT)
- Parton level reconstruction agrees with naïve expectation
  - everything above the diagonal should be reconstructed as one jet
- Topocluster level reconstruction shows that widely separated sub-jets will not be reconstructed into the same jet



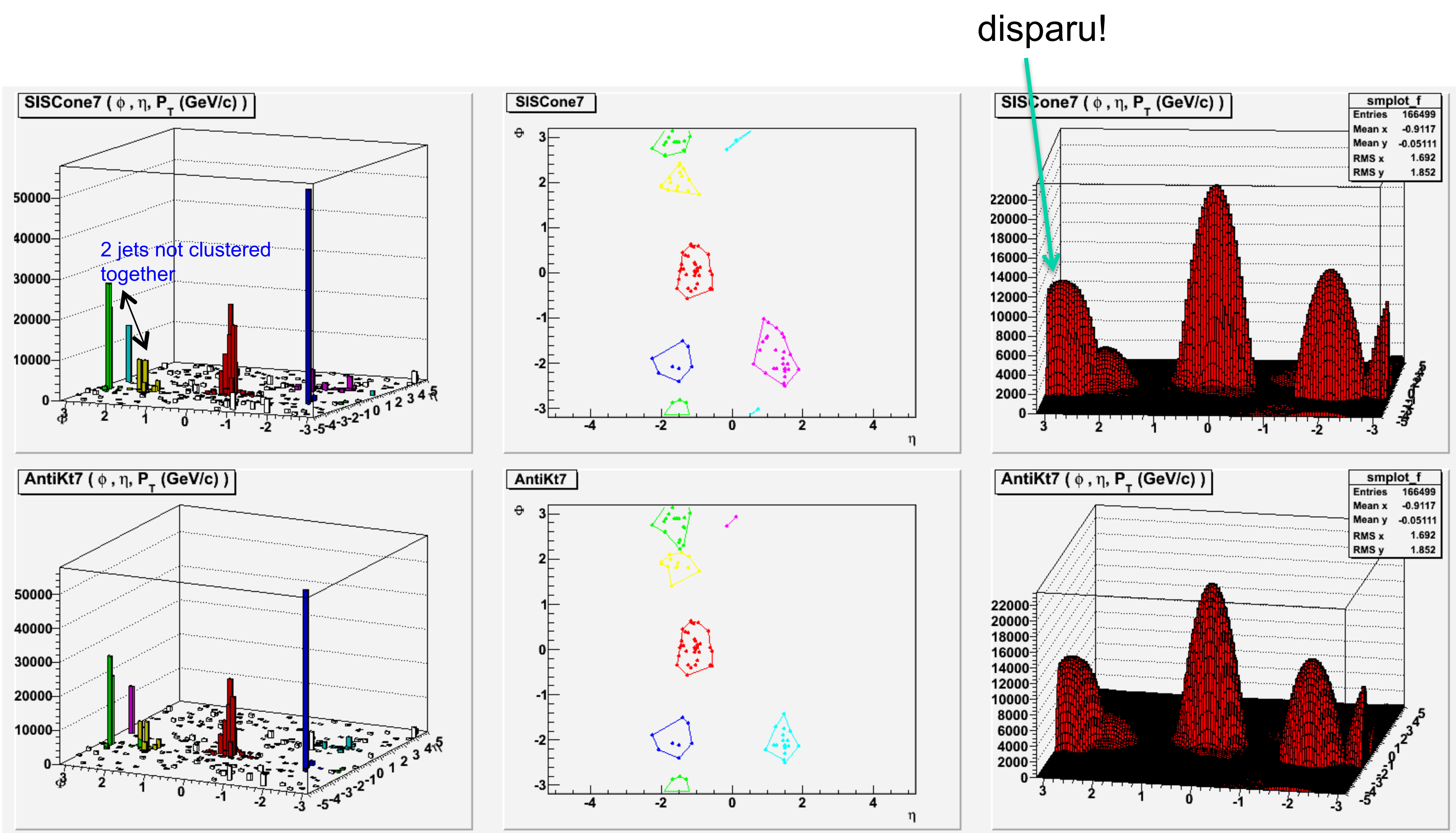


Now try ALPEN W + 3 parton event

SISCone solution including both partons (looking at inverted 2-D Snowmass potential)

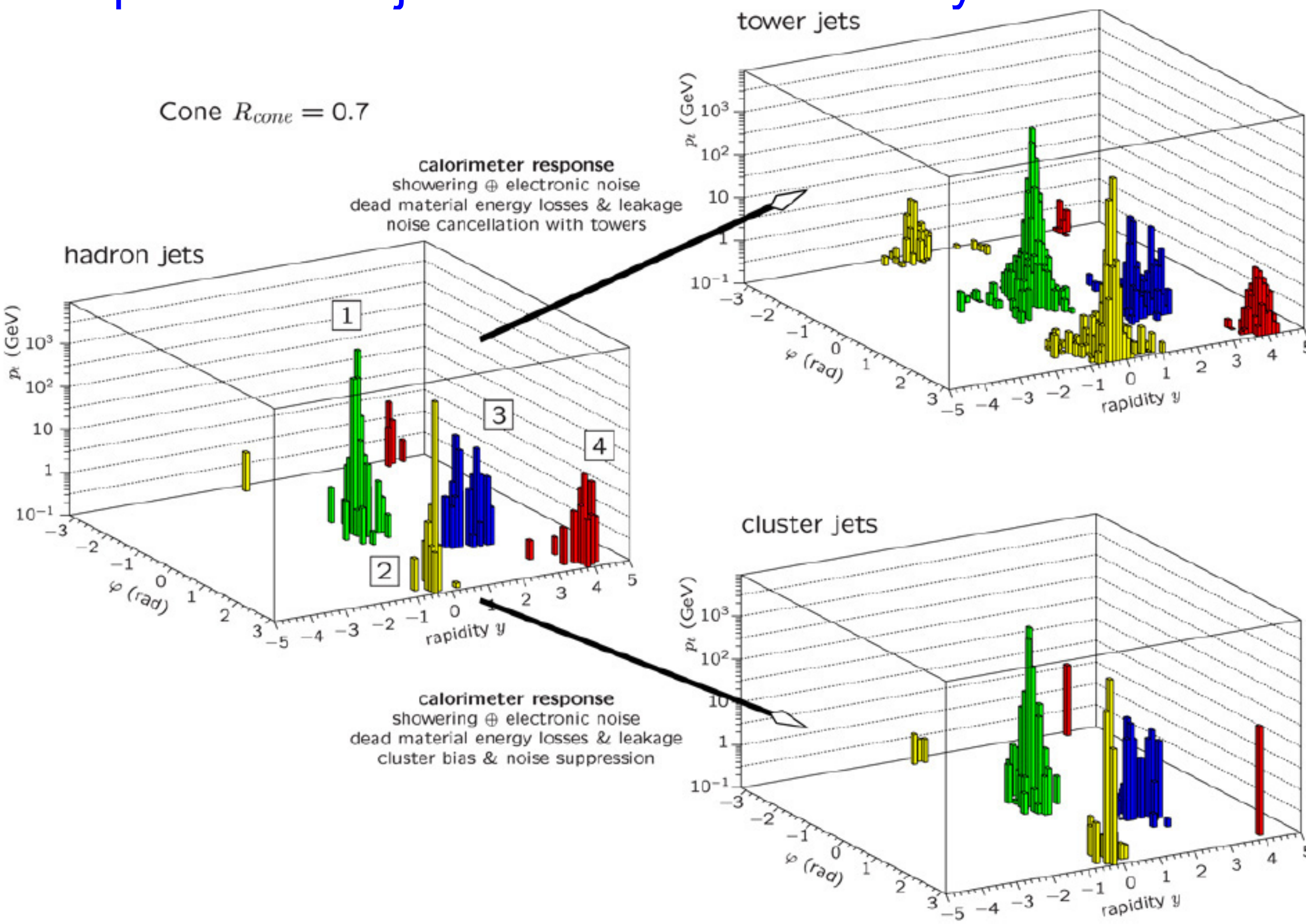


Same ALPGEN (+PYTHIA) event at topocluster level



ATLAS jet reconstruction

- Using calibrated topoclusters, ATLAS has a chance to use jets in a dynamic manner not possible in any previous hadron-hadron calorimeter, i.e. to examine the impact of multiple jet algorithms/ parameters/jet substructure on every event

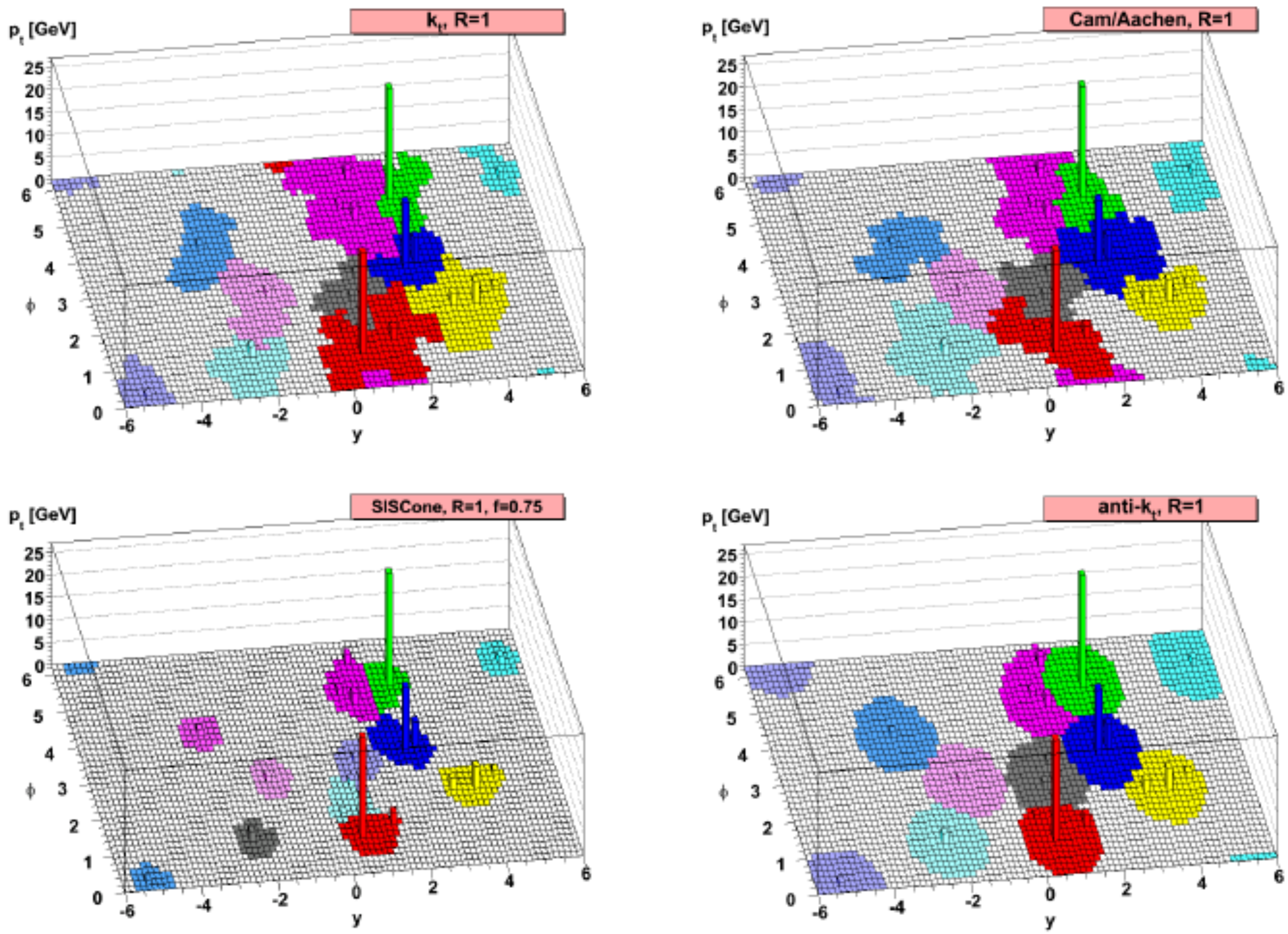


blobs of energy in the calorimeter correspond to 1/few particles (photons, electrons, hadrons); can be corrected back to hadron level

rather than jet itself being corrected

similar to running at hadron level in Monte Carlos

UE/pileup corrections: Jet areas



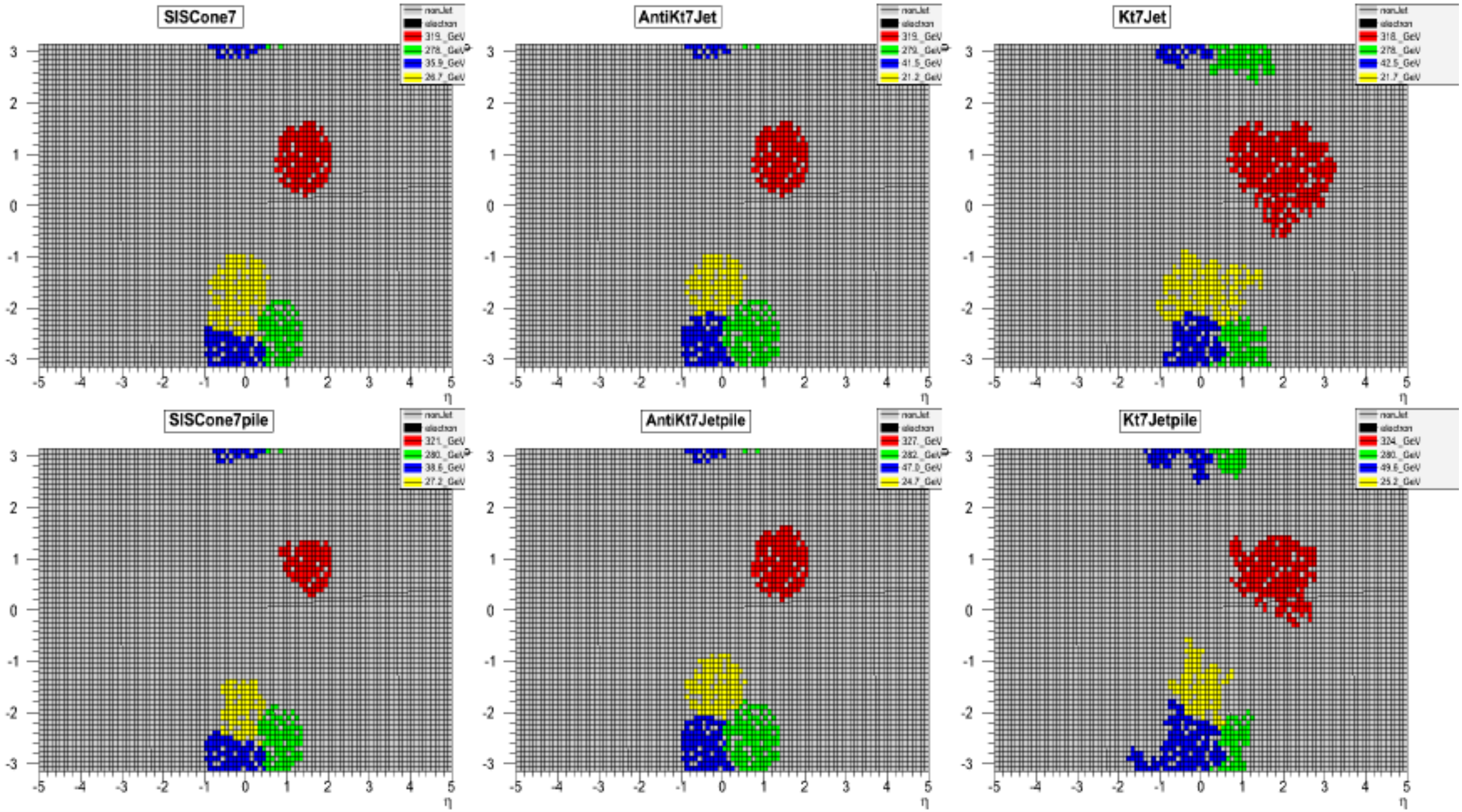
determined by clustering ghost particles of vanishing energy; see jet references

note that the k_T algorithm has the largest jet areas, SISCone the smallest and anti-k_T the most regular; one of the reasons we like the antikt

Jet areas in presence of pileup

- Single W+4jets event, all matched to partons.
- SISCone and kT show decreased area in presence of pileup

pileup nibbles away at perimeter of jet



Area-based correction: Cacciari/Salam/Soyez

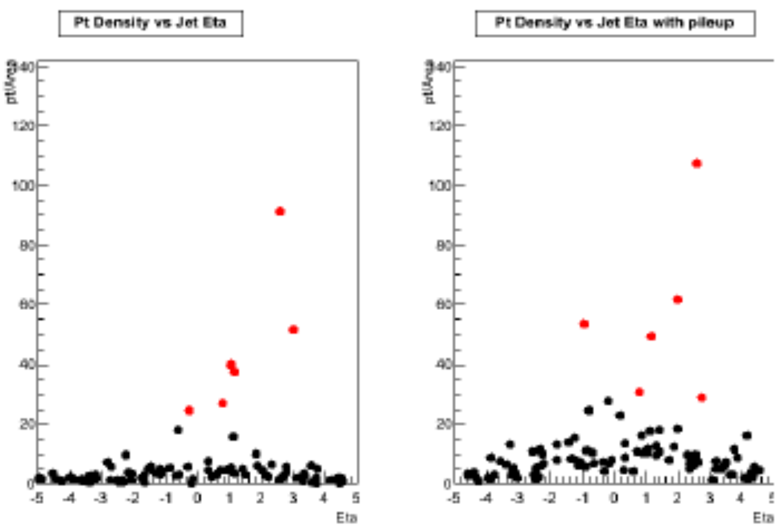
1) Find low p_T jets in event. (< 10GeV) We use kT5jet.
2) From these, find average/median pT density of event ρ
3) Determine area A of signal jets
4) Subtract "pileup/UE"estimate

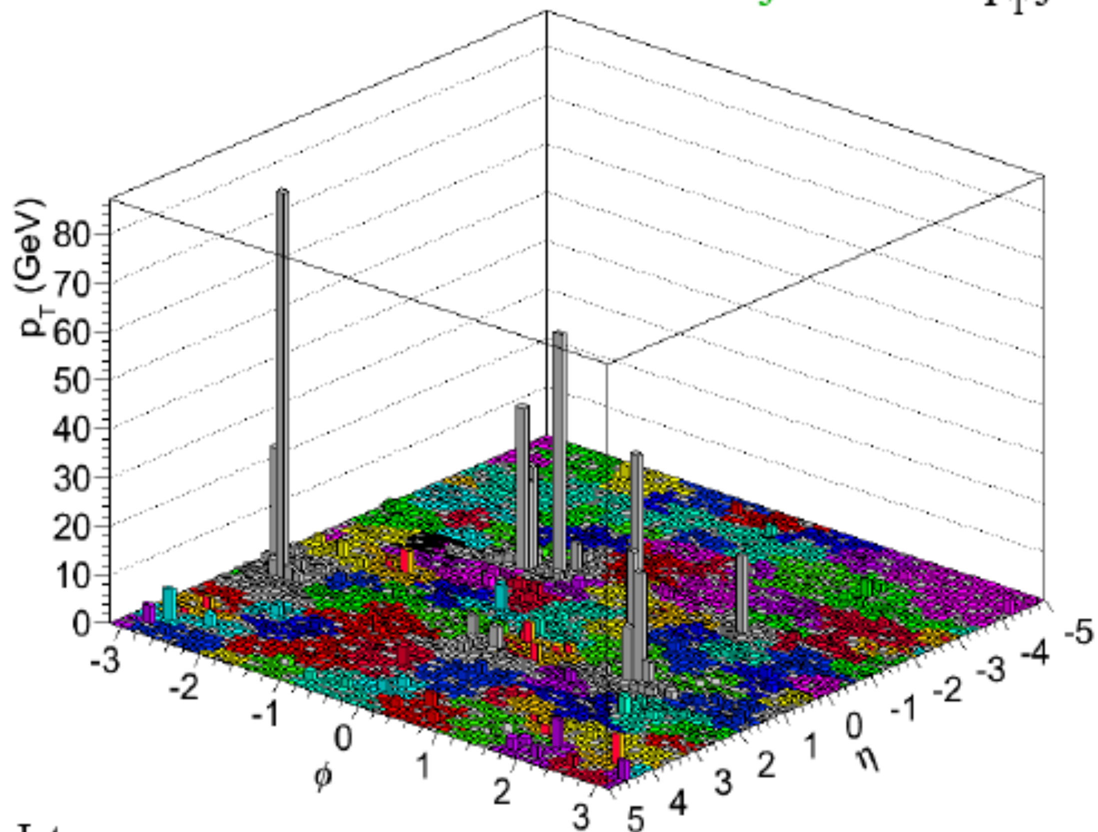
$$p_{Tcorr} = p_T - \rho A$$

<u>W+5j event with kT5Jets</u>

Gray jets = Signal Jets

Colored jets = Low p_T jets





- Black points used to find pT density
- Red points are then corrected according to Jet area

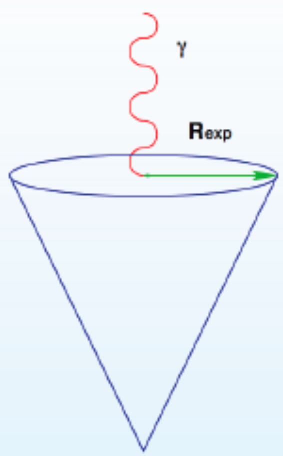
See presentations of Brian Martin in ATLAS jet meetings. Used in SpartyJet.

Aside: Photon isolation at the LHC

- From a theoretical perspective, it's best to apply a *Frixione-style* isolation criterion, in which the amount of energy allowed depends on the distance from the photon; this has the advantage of removing the fragmentation contribution for photon production, as well as discriminating against backgrounds from jet fragmentation
- But most of the energy in an isolation cone is from underlying event/pileup
- At Les Houches, we started to develop (being continued by Mike Hance, Brian,…in ATLAS):
  - (1) an implementation of the Frixione isolation appropriate for segmented calorimeters
  - (2) a hybrid technique that separates the UE/pileup energy from fragmentation (using SpartyJet)

Isolation criterion

courtesy J.P.Guillet



$E_T^{had} \leq E_{T\,max}$ inside $(y - y_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2_{exp}$

Large Log. when $R_{exp} \rightarrow 0$ and $E_{T\,max} \rightarrow 0$

Other isolation criterion (S. Frixione) where $E_{T\,max} = F(r)$

- **Action Items:**
  - Susan, Joey, Kajari, Jean-Philippe
- **Exp** :
  Look again in detail at the Frixione criterium, what is the impact at LHC of UE/PU, of fragmentation; see if some "hybrid" (simple cone vs Frixione) can be found, suitable for exp. application.
- **Theory**:
  use existing (and possibly upgraded) codes to study difference in x-sections obtained with Frixione-criterium and some "pedestal" allowed in the central cone
- Look also at **"democratic" approach**