The challenges of high luminosity and jets

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C T E Q

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My take on Snowmass "Top algorithms and detectors" summary
(arXiv:1307.6908)

Outline

1. **Theory and jets**
   - Jet definitions
   - What do we want to see?
2. **Experimental predictions for high luminosity**
   - "Low" energy jets ($p_{Tj} < 100$ GeV)
   - Boosted jets (focus on top)
3. **Conclusions**

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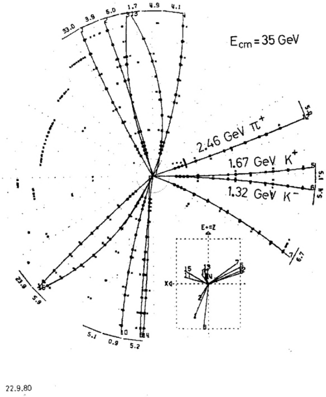
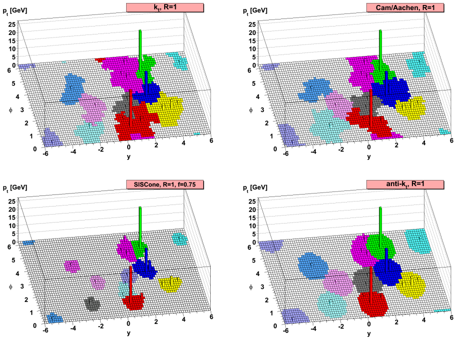
QCD becomes convincing in low multiplicity

1979 PETRA finds three isolated jets: from q, $\bar{q}$, g



This picture has dominated our thinking about QCD radiation as nice isolated jets ever since.

Jet definitions



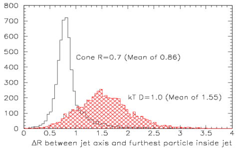
Modern jet algorithms cluster energy with successive recombination into various arbitrary objects.

General iterative jet algorithm:

$$d_{ij} = \min\left(k_{Ti}^{2p}, k_{Tj}^{2p}\right) \frac{\Delta R_{ij}}{R_{\rm cut}}$$

Combine pair with smallest distance, remove smallest object, repeat.

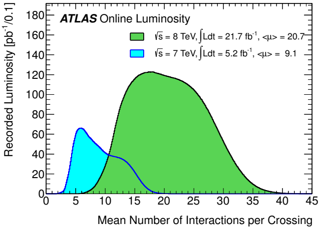
- $p = -1$: Anti-k_T
  Choice for jets at LHC
  Will it hold up at 14 TeV?
- $p = 0$: Cambridge/Aachen
  Form of adaptive cone
  Popular for "boosted jets"
- $p = 1$: k_T
  Theorists' choice until 2001
  After DØ measurement, not



DØ, Grinstein W&C talk 2001

14 TeV LHC will have no isolated jets

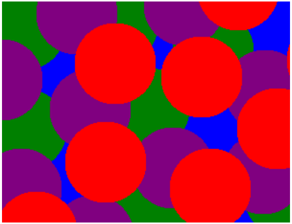
Pileup at 7/8 TeV



Snowmass studies considered:

$<\mu>= 50$ (baseline)
$<\mu>= 140$ (high lumi. upgrade)

Artist's rendition of anti-K_T at 14 TeV LHC



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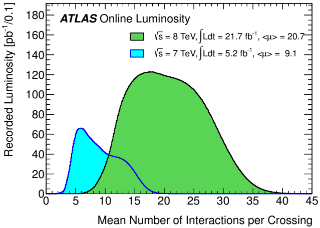

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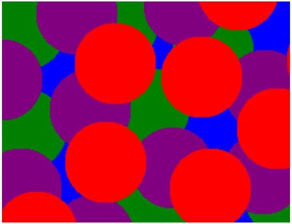

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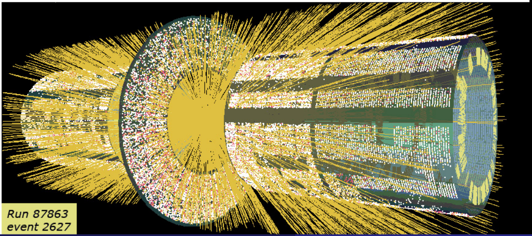
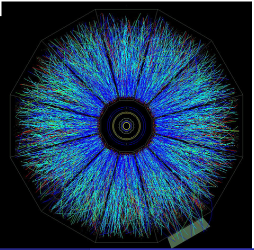
LHC events will look a lot like RHIC events





What do we want to measure?

- The first goal will be to reproduce the known Standard Model.
  - Vector bosons: $W \to jj$, $Z \to jj$
  - Top quarks: $t \to Wb \to jjb/\ell\nu b$
  - Various SM cross sections: $t\bar{t}$, $Z + \text{jets}$, $W + \text{jets}$, $\gamma + \text{jets}$, etc.
- The second goal will be to measure new physics.
  - Higgs: $H \to b\bar{b}$, $H \to WW \to \ell\nu jj$, etc.
  - SUSY: $\tilde{g} \to q\tilde{\bar{q}} \to q\bar{q}\chi_1^0$, etc.
  - Any cascade decay with nearly degenerate states.
  - Z', W', $T \to tj$

Most of these signals produce low energy jets ($p_T < 100$ GeV).
Heavy resonance searches will produce hard jets ($p_T > 700$ GeV).
Can we see any of this in a high luminosity environment?

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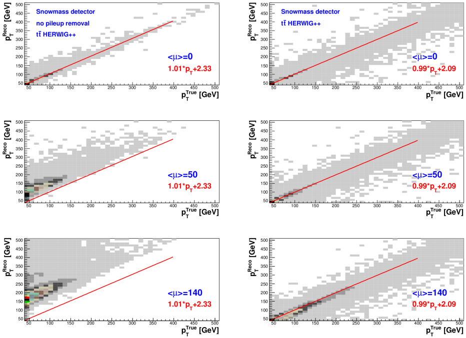


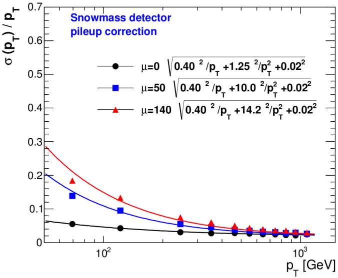
Best case for 30 GeV jet (n=140):

— 60 GeV in charged particles (15 GeV tracked to vertex)

— 60 GeV in neutral particles

$p_{Tj} \approx 30 \pm 12$ GeV

Particle flow, after pileup removal



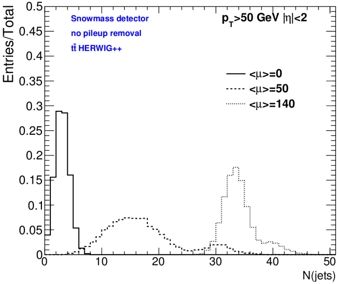
Jets in $t\bar{t}$ events before/after pileup removal

$\overline{k_T}$ jets will begin with additional ~ 1 GeV per pileup event!

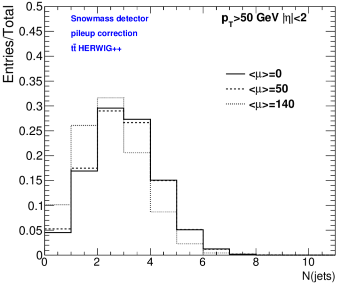
Low energy jets (< 100 GeV) will have poor energy resolution.

Pileup jets/pileup subtraction

50 GeV "jets" from pileup



Pileup (over-)subtracted jets



You have to ignore 80–90% of the 50 GeV jets you reconstruct.

What will this do to triggers?

— Jet triggers only for 400 GeV jets?

— No traditionally isolated e.

— Can you track μ through this?

Pileup removal: $-\frac{\text{jet area}}{\text{detector area}} \times E_{\text{det}}^{\text{tot}}$

This does not work at higher lumi.

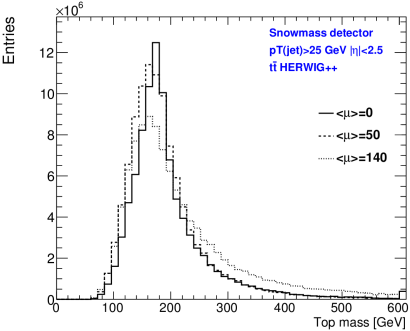
Need to use local information:

$\Rightarrow$ sensitivity to local fluctuations

This is THE key problem to solve

Can we see the Standard Model in low-energy jets?

We can see top quarks



Jet Energy Scale (JES) $\sim 2.5\times$ worse

Conclusion:

Improved measurements of
m_t, single-top, $t\bar{t}$-assym., etc.
not possible w/o new ideas

arXiv:1307.6908

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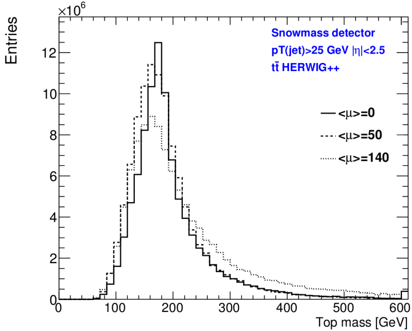

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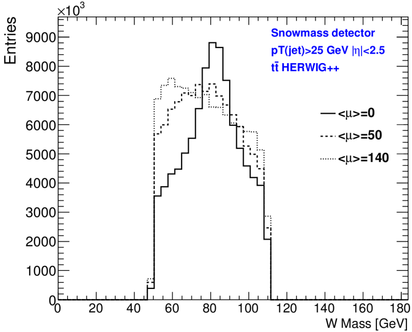
W dijet mass peak



W/Z not resolvable in jets

$H \to b\bar{b}$ challenging

Conclusion:

Need new jet definitions for low P_T jets with less sensitivity to pileup

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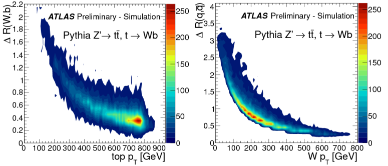
High P_T using jet substructure: boosted top jets

Early motivation: High mass resonances ($Z'/W' > 1.5$ TeV) the top quark is highly boosted

It becomes difficult to reconstruct isolated jets from $t \to bW \to bjj$

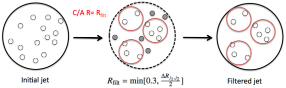


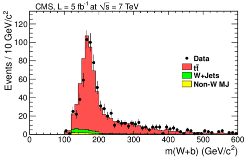
ATLAS-CONF-2012-065

Many "boosted top" algorithms have been developed: (Hot topic!)

Filtering	Butterworth et al. PRL 100 (2008)
Pruning	Ellis et al. PRD 80 (2009)
Trimming	Krohn et al. JHEP 1002 (2010)
Mass-drop	Butterworth et al. PRL 100 (2008)
JHU tagger	Kaplan et al. PRL 101 (2008)
HEP tagger	Plehn et al. JHEP 1010
tree-less	Jankowiak et al. JHEP 1106
y-splitter	Butterworth et al. PRD 55 (2002)
energy flow	Thaler, Wang JHEP 0807
N-subjettiness	Kim PRD 83 (2011), Thaler et al. JHEP 1103
Shower decon.	Soper et al. 1102.3480
Multivariate	Gallicchio et al. JHEP 1104
Template	Almeida et al. PRD 82 (2010)

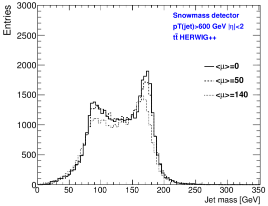
The basic idea is to create a fat (large ΔR) jet, and find identifiable clustered substructure we can associate with hadronic top decays.

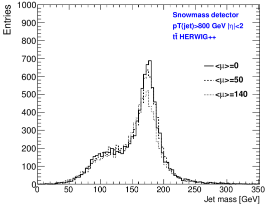




Boosted top jets at 14 TeV: Particle flow+anti-k_T

Combining particle flow (PF) and anti-k_T: not sensitive to pileup





Very sensitive to p_T

Need $p_{Tt} \gtrsim$ 800 GeV

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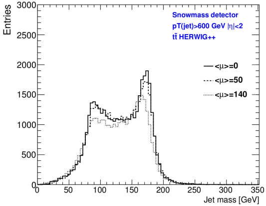

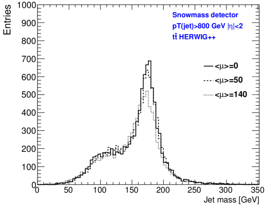

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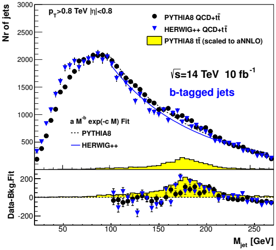
If you can b-tag inside a top jet *and* you have 10% JES resolution *then* PF-$\overline{k_T}$ top-jets are golden



arXiv:1301.5810

The problem w/ PF-$\overline{k_T}$:

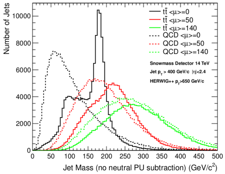
If $p_{Tt} > 1.6$ TeV, M_t resolution is a factor 2 worse.

Fortunately, there are many other boosted algorithms

Other boosted algos: local vs. global pileup removal

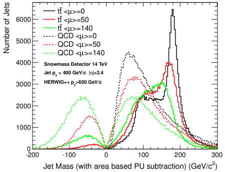
All boosted algorithms must deal with pileup: Begin w/ 650 GeV C/A jets

Charged Hadron pileup sub.



Cannot tell top jets from light jets

Add area based sub.



Negative mass jets, poor resolution

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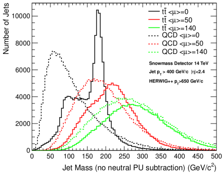

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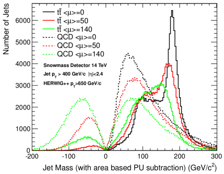
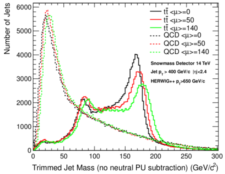


Negative mass jets, poor resolution

Add jet trimming instead



Trimming uses substructure.

—Very stable light jets

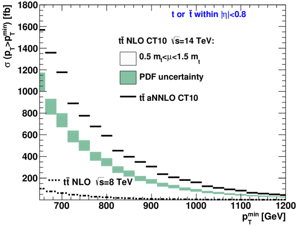
—Correctable top jets

Conclusions: Local measures of pileup are important.

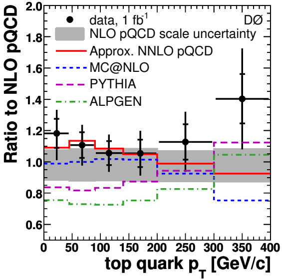
Experimental reconstruction will not be a limiting factor.

Tails and accidentals: theoretical issues dominate

- Tails: Theory is poor at predicting tails of distributions.



arXiv:1301.5810



DØ, PLB 693, 515 (10)

Large corrections to high-p_T $t\bar{t}$ dijet spectrum are predicted.

—Explains part of anomaly in LHC $t\bar{t}$ data never shown publicly.

LO n-jet matching sort-of fakes it.

NLO n-jet matching needed.

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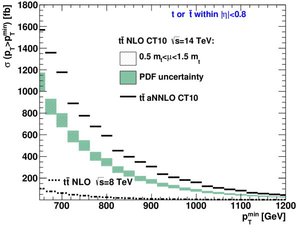

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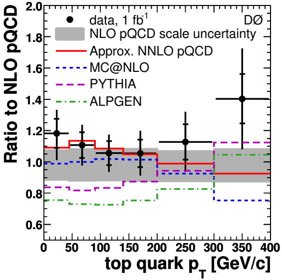

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- Accidentals: For the most part, extreme phase space configurations are not considered in current measurements.

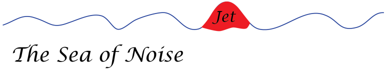
  E.g., In $W' \to tb$ searches, Wjj/Wbj can fake the tj final state.
  $p_{Tj} > 750$ GeV: $Wjj/Wbj \sim 4 \times t\bar{t}$ w/ 1 boosted tag arXiv:1307.1820

Tails and accidentals are examples of extreme corners of phase space, and will require significant theoretical work to improve.

Conclusions

Theorists have a lot of work to do to prepare for 14 TeV.

- High-p_T jets: Continued improvement in higher-order calculations and resummation will enable full use of boosted objects.
  Jet algorithms that use substructure will be fully vetted by the experiments.
- Low-p_T jets: Are what we want to reproduce the Standard Model. We will be in an intrinsically high multiplicity (noisy) environment.



This qualitatively different regime will require a new approach for precision jet measurements.

We look forward to the challenge.

THANK YOU