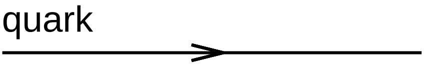
Jets in the standard model and beyond the standard model

Gavin Salam

CERN, Princeton & LPTHE/CNRS (Paris)

PANIC, MIT, 28 July 2011

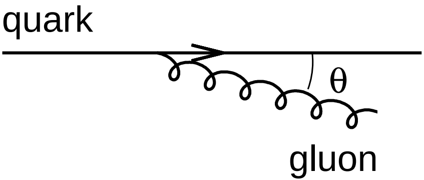


Gluon emission:

$$\int \alpha_s \frac{dE}{E} \frac{d\theta}{\theta} \gg 1$$

At low scales:

$$\alpha_s \to 1$$



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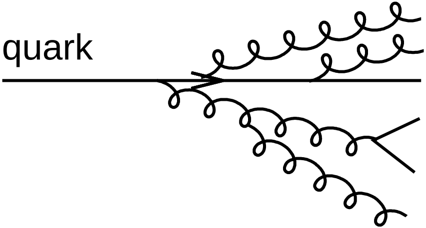

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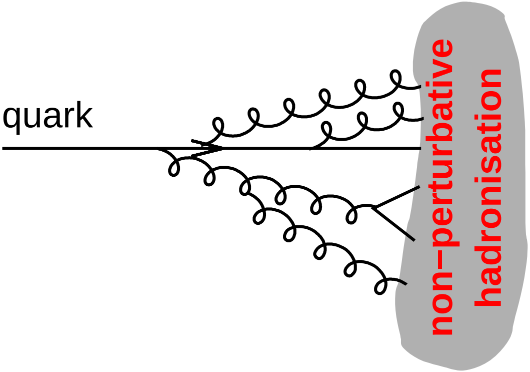

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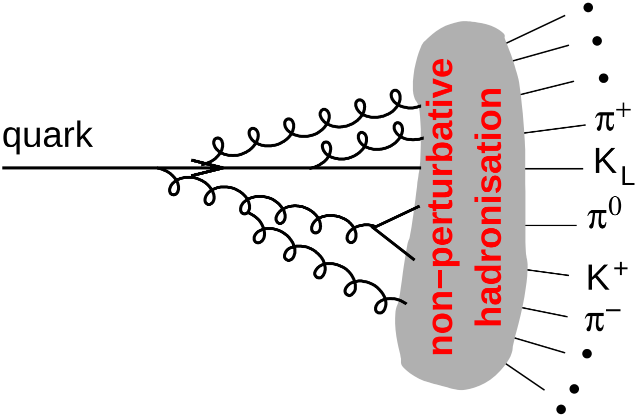

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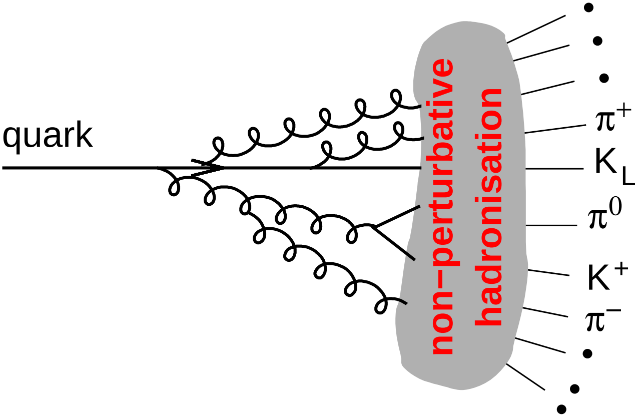

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This is a jet

Les Houches 2007 proceedings, arXiv:0803.0678

jet definition

$$\{p_i\} \xrightarrow{\text{jet algorithm}} \{j_k\}$$

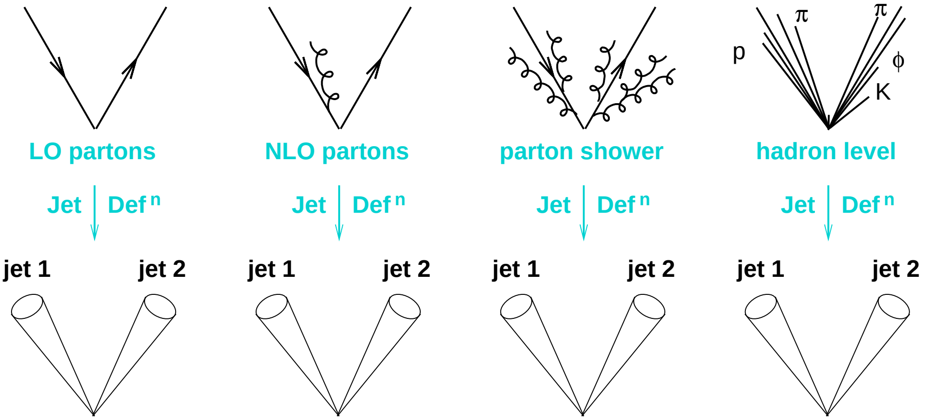
particles,
4-momenta,
calorimeter towers, ...

jets

+ parameters (usually at least the radius R)

+ recombination scheme

Reminder: running a jet definition gives a well defined physical observable, which we can measure and, hopefully, calculate



Projection to jets provides "common" view of different event levels

But projection is not unique: we must define what we mean by a jet

This talk

1. How are jets defined?
2. What pp physics is being done with jets?
3. What's the forefront of research into jet techniques?
4. How about jets in heavy-ion collisions?

1. How are jets defined?

The anti-k_t jet algorithm

Define "distance" between every pair of particles: [Cacciari, GPS & Soyez '08]

$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}$$

$$\left[\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j^2)\right]$$

Define a single-particle distance

$$d_{iB} = \frac{1}{p_{ti}^2}$$

1. Find the smallest of d_{ij} and d_{iB}
2. If it's a d_{ij}, merge i and j into a single particle
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4. Update all distances, go to step 1

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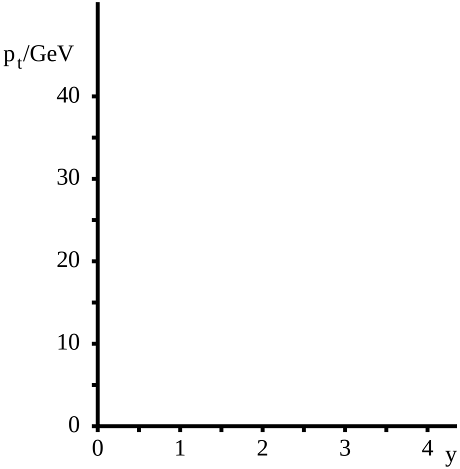

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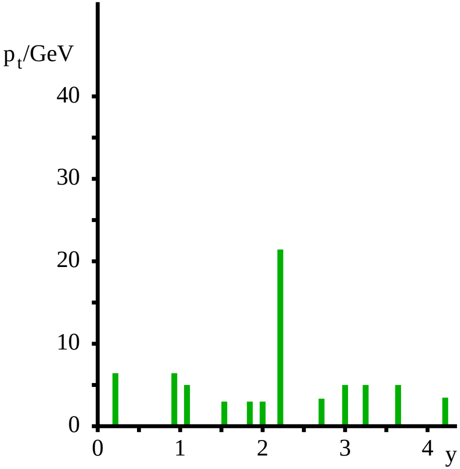

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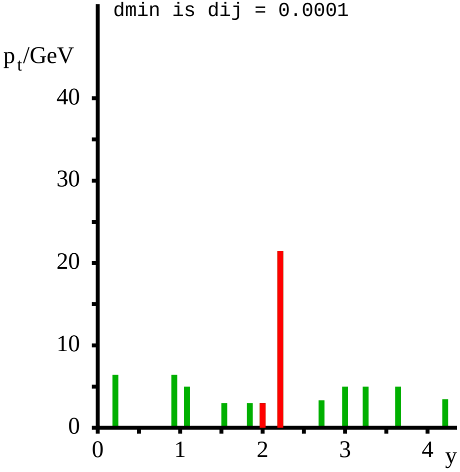

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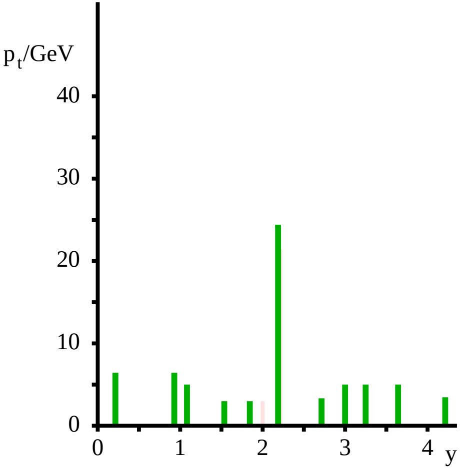

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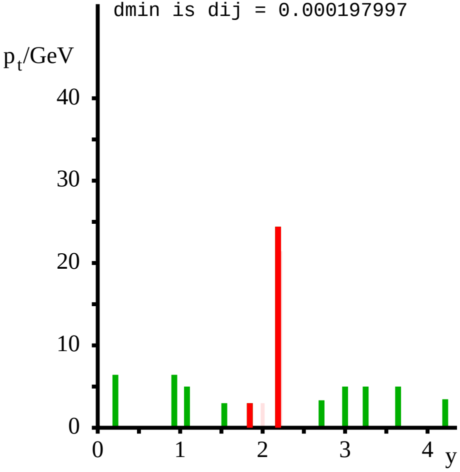

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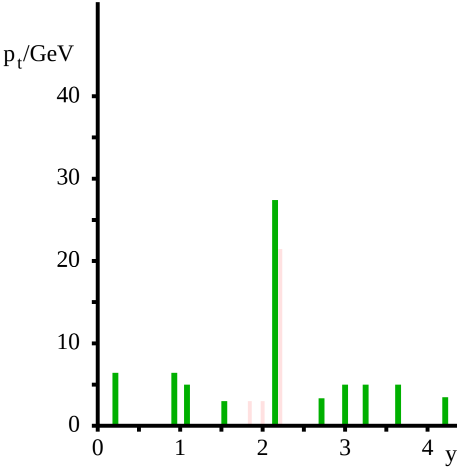

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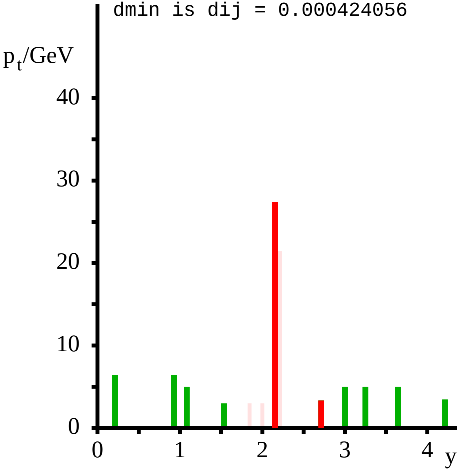

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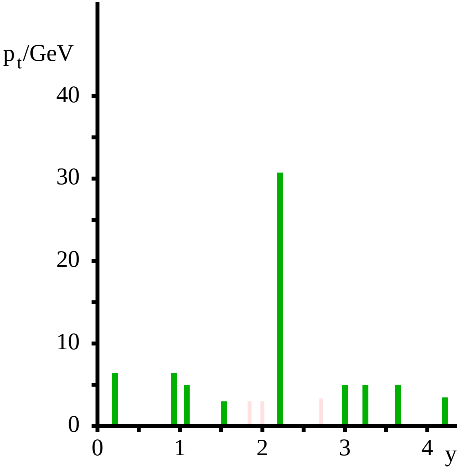

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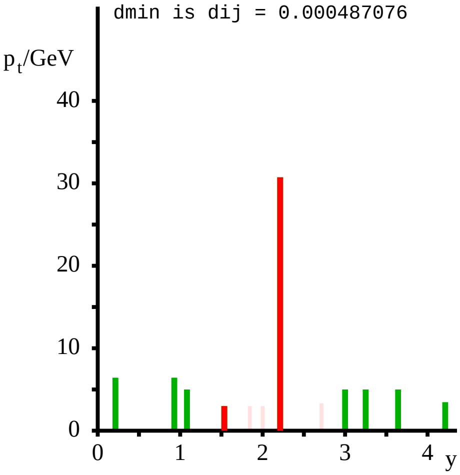

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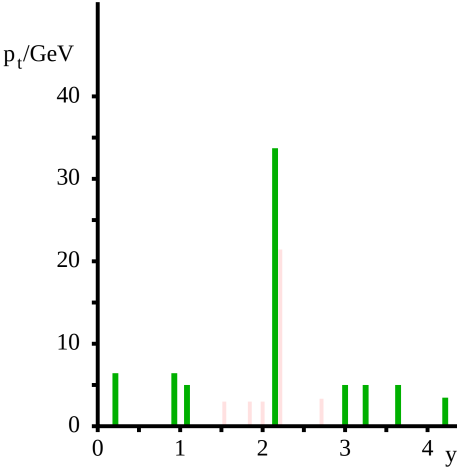

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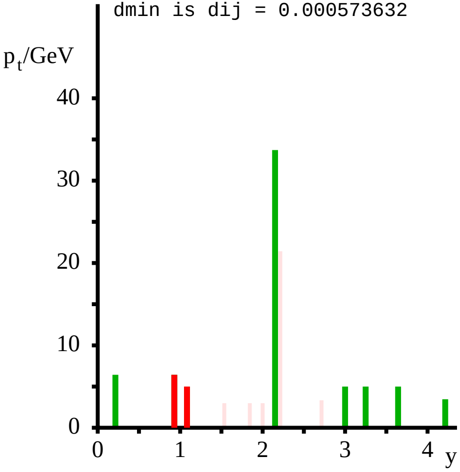

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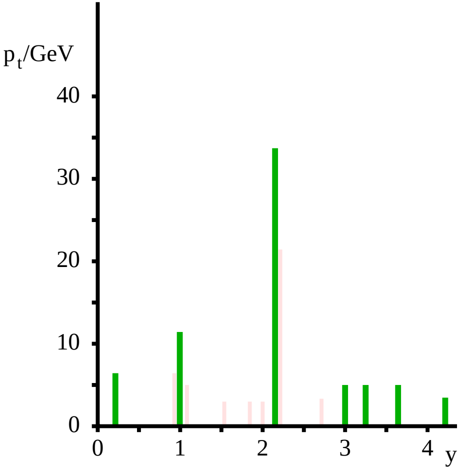

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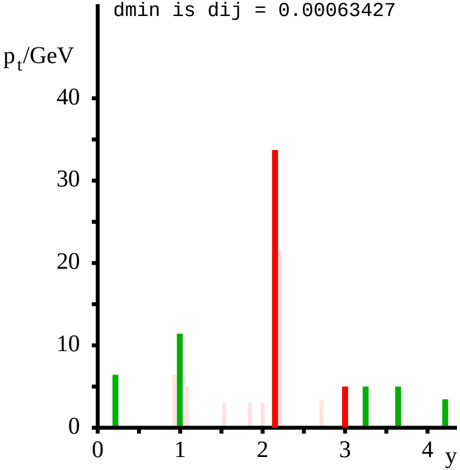

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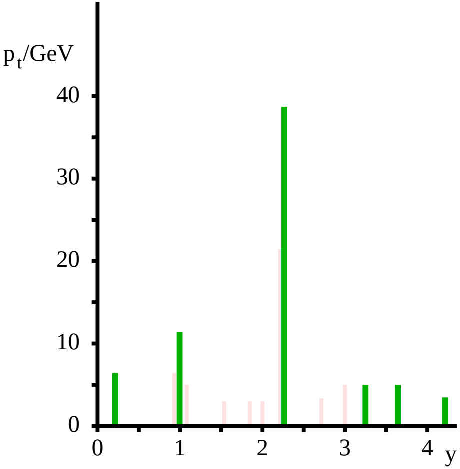

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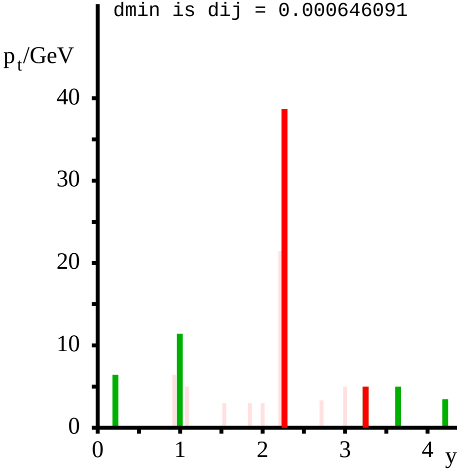

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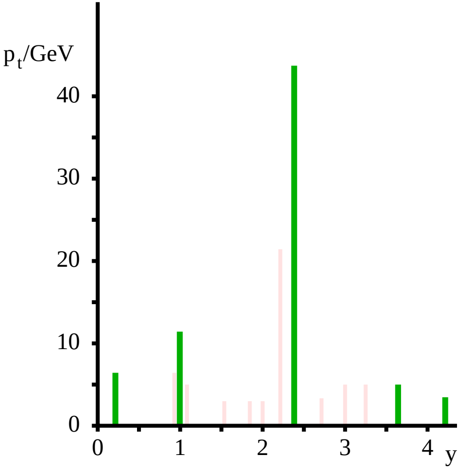

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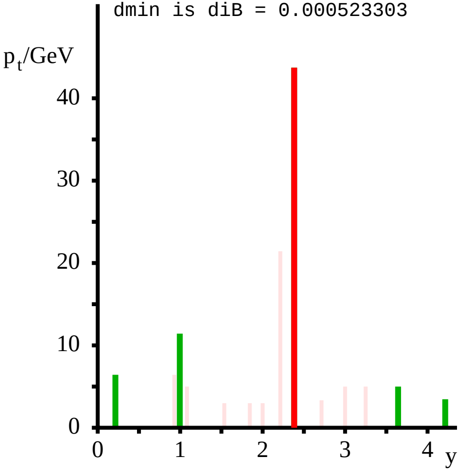

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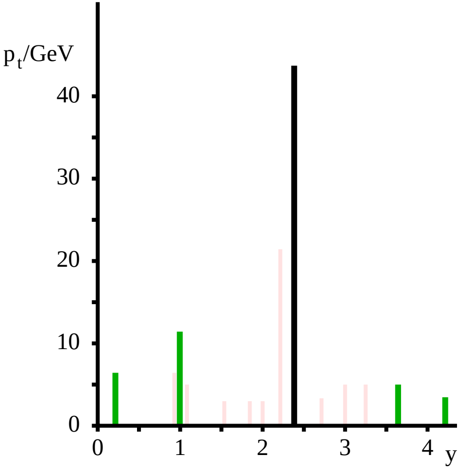

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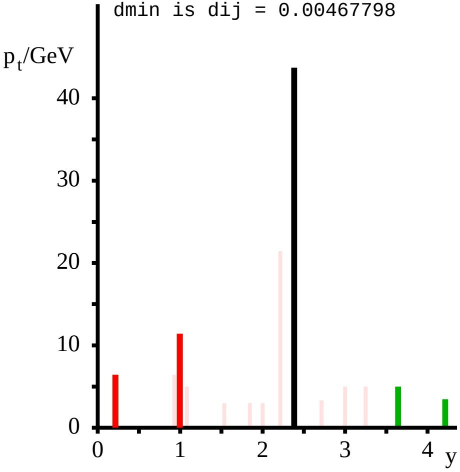

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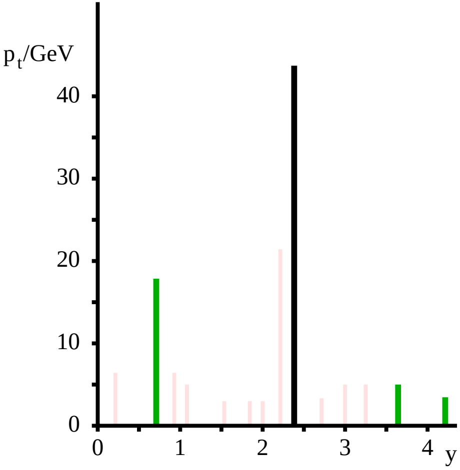

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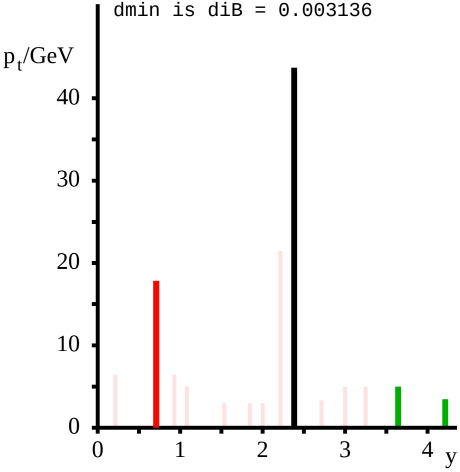

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Define "distance" between every pair of particles: [Cacciari, GPS & Soyez '08]

$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}$$

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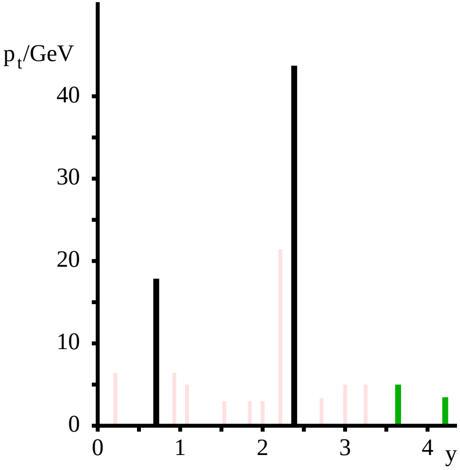

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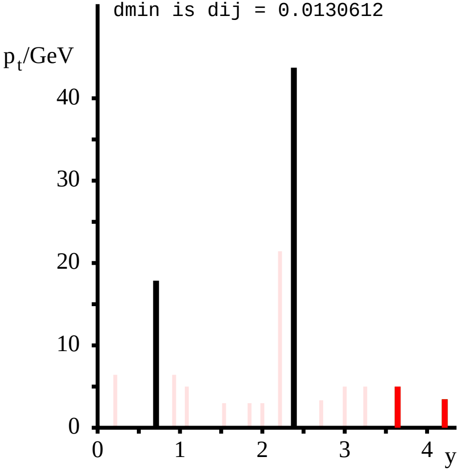

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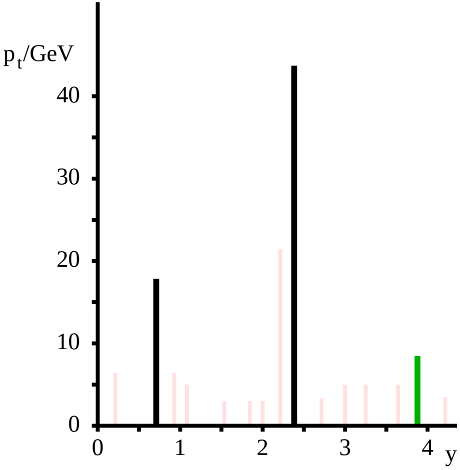

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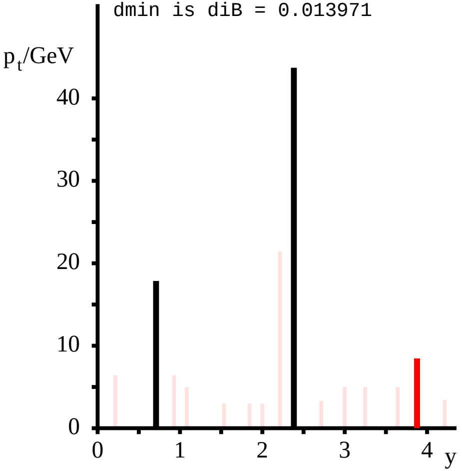

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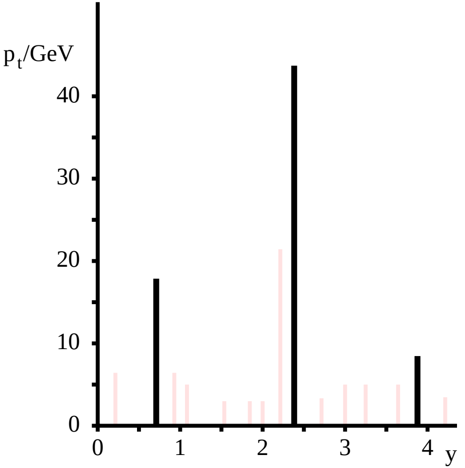

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Define a single-particle distance

The algorithm involves two parameters:

1. R, the angular reach for the jets
2. A p_t threshold for the final jets to be considered relevant

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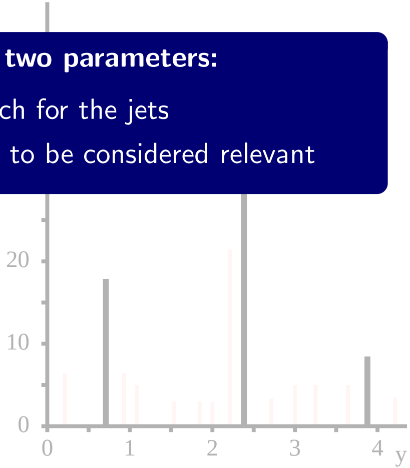
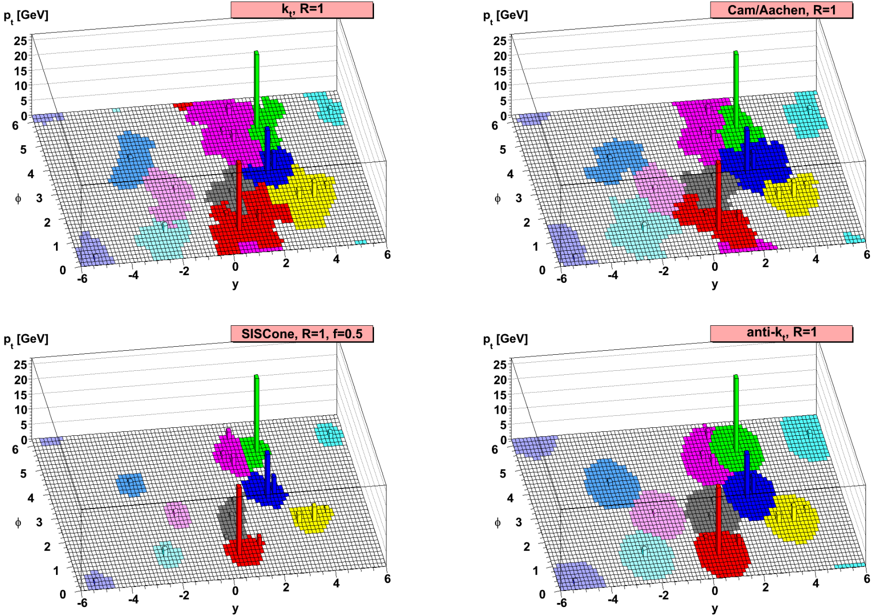


Jet contours – visualised



2. Standard use of jets in pp collisions?

As a stand-in for a final-state parton, where all you care about is the parton's energy and direction.

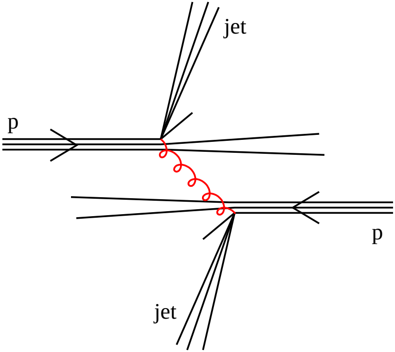
Partons ($\simeq$jets) are useful objects, e.g. to

a) find out how many partons you have in the proton to start with

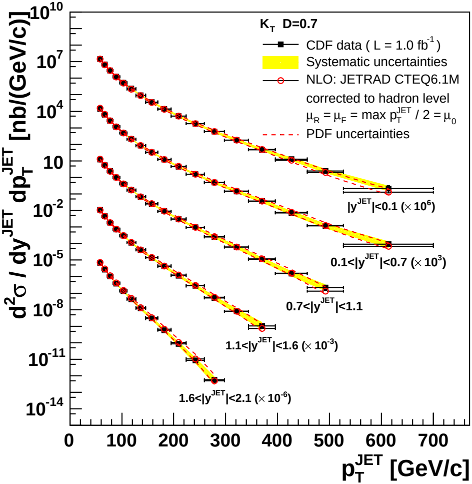
b) look for new physics that couples to partons (typically with large cross sections, allowing probes of highest scales)

Jets from scattering of partons

Largest source of jets is simply QCD scattering of incoming partons



Tevatron results



Jet cross section: data and theory agree over many orders of magnitude $\Leftrightarrow$ probe of underlying interaction

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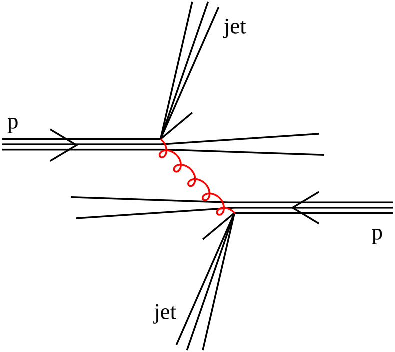
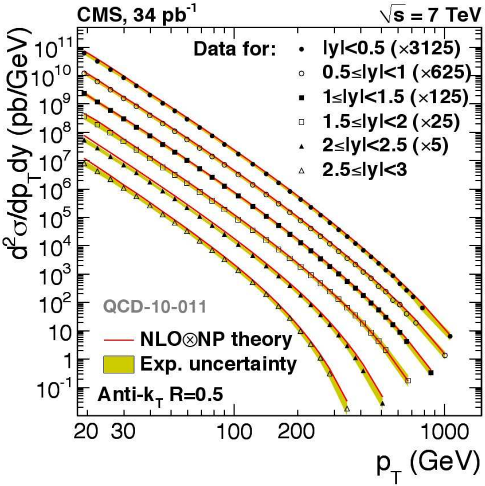


CMS results



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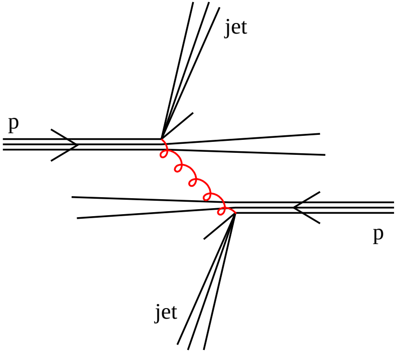
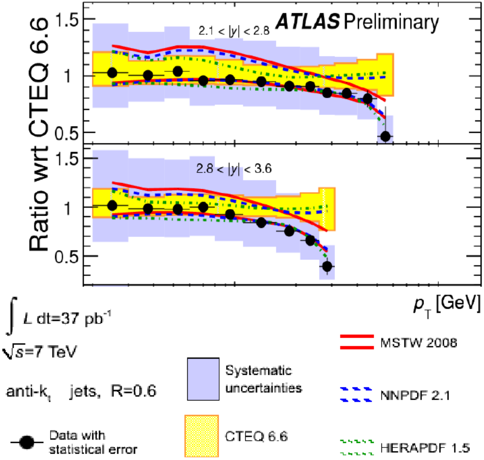


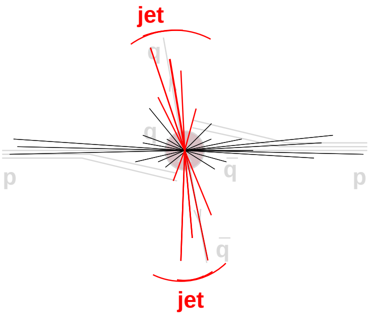
ATLAS results



Jet cross section: data and theory agree over many orders of magnitude ⇔ probe of underlying interaction **and also of proton structure**

Dijet resonance searches

Because of strong coupling of partons (and abundance in initial state), jets serve to probe the highest energy scales reachable at hadron colliders.



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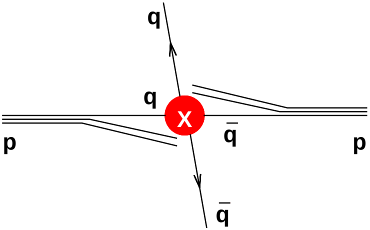

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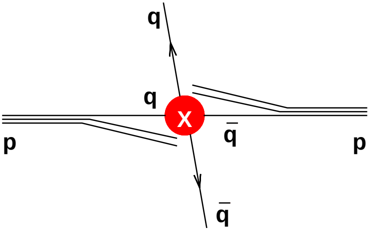

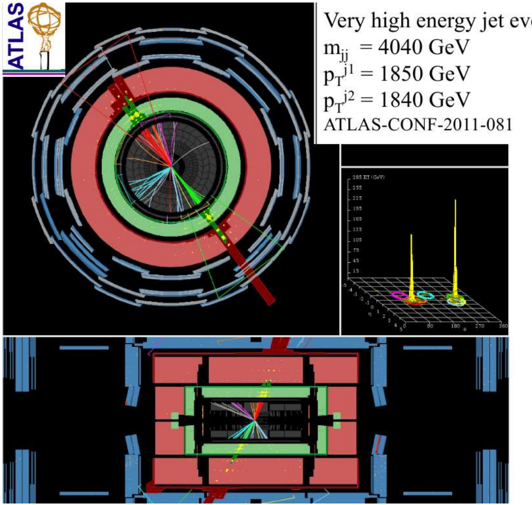

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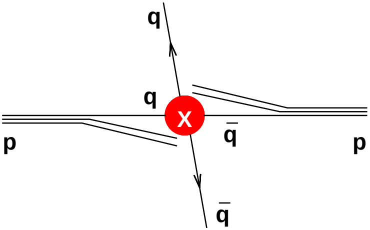
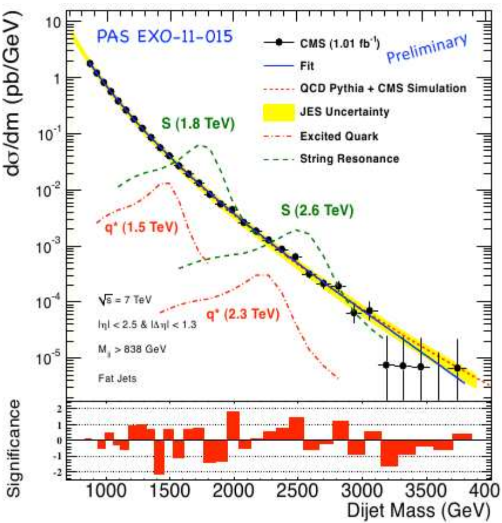


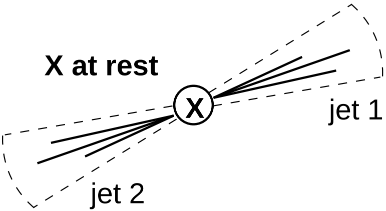


3. New Jet Techniques

When a jet contains more than one parton

Boosted massive particles, e.g.: EW bosons

Normal analyses: two quarks from $X \to q\bar{q}$ reconstructed as two jets



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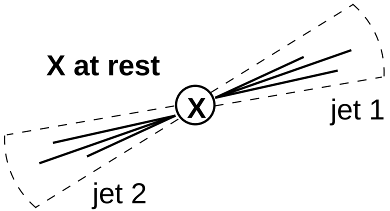
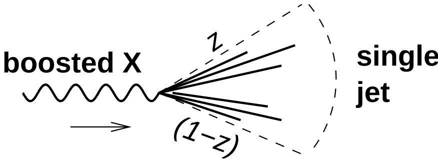


High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



Happens for $p_t \gtrsim 2m/R$

$p_t \gtrsim 320$ GeV for $m = m_W$, $R = 0.5$

As LHC starts to explore far above EW scale, such configurations become ubiquitous

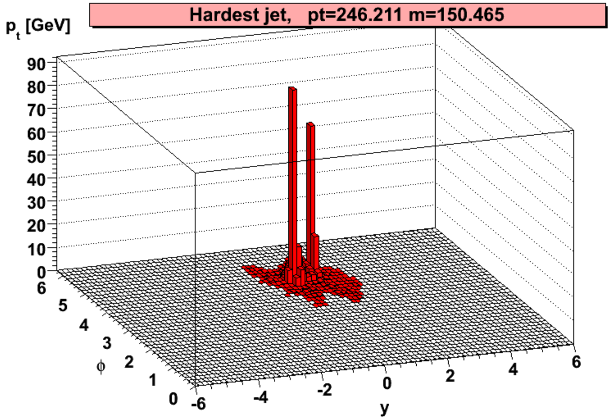
3 key ingredients

- Resolving the underlying $1 \to 2$ splitting and using its characteristic kinematics to help reject background [Leading-order Structure]
- Exploiting different colour structures of signal and background and resulting different energy flows [Higher-order structure]
- Protecting jet-mass resolution from the mess of underlying event and pileup [Non-perturbative structure]

There's no way I can do justice to this highly active field in just a few slides

See parallel sessions and recent Boost 2011 conference

Ingredient 1: undo jet clustering & cut on pieces



First proposed for W's by Seymour '93

Refined by Butterworth, Cox & Forshaw '02

Refined more + showed how to use it to find $H \to b\bar{b}$ at LHC, Butterworth, Davison, Rubin & GPS '08

Later in '08: extended to top quarks by ATLAS; Thaler & Wang; Kaplan, Rehermann, Schwartz & Tweedie.

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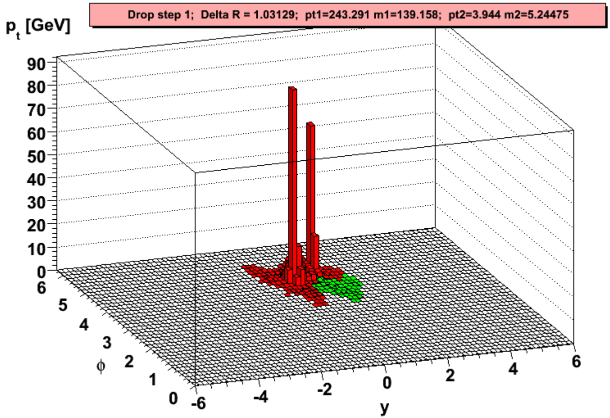

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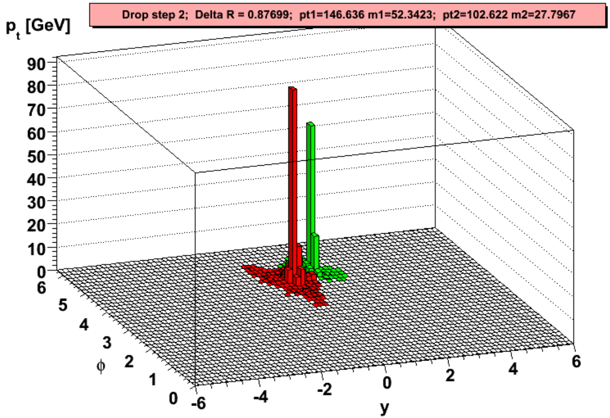

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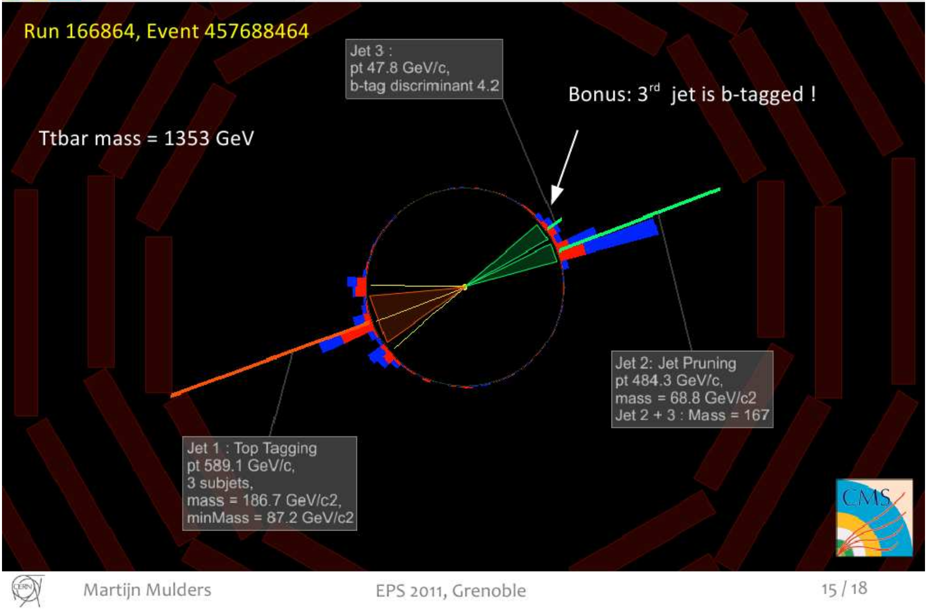
Beginning of a wave of intense activity — "fat" jets in SM, SUSY (standard & R-parity violating), Z' Extra Dimensions, etc. — motivating $\sim$ 6 dedicated workshops

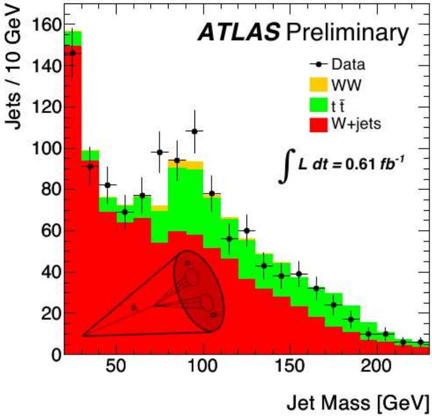
Golden (1+2) $t\bar{t}$ candidate event



ATLAS and CMS have both shown this working

and CDF have a related jet-mass based top study

ATLAS require lepton, missing E_T and 1 jet $R = 1.2$ with "mass-drop and filter" and plot mass of resulting jet — **clear W peak**



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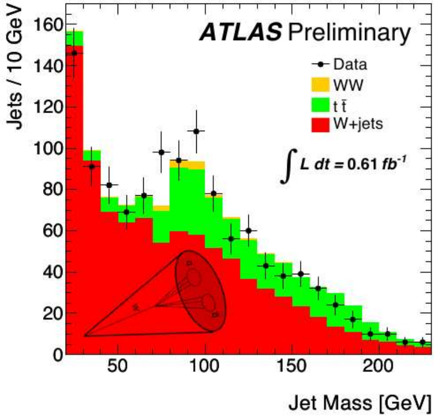

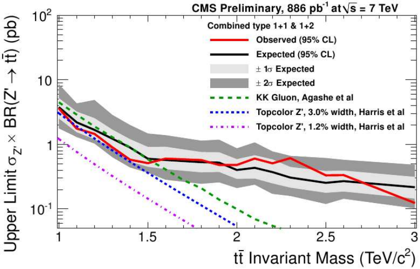

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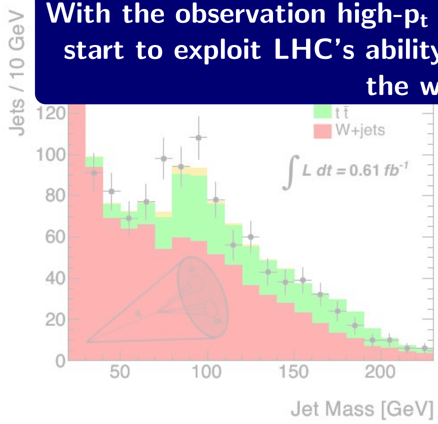
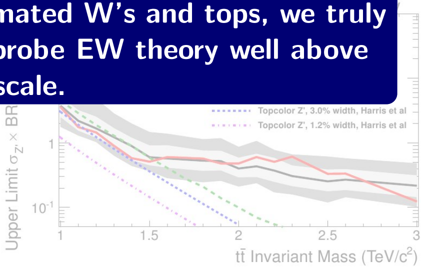
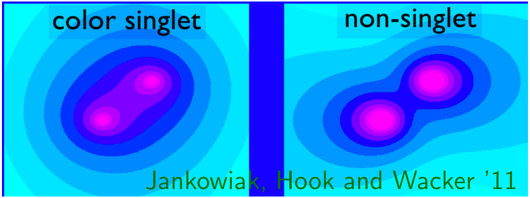
With the observation high-p_t collimated W's and tops, we truly start to exploit LHC's ability to probe EW theory well above the weak scale.





2. Exploiting energy-flow beyond LO structure



Background (e.g. $g \to gg$) and signal (e.g. $W \to q\bar{q}$) often have different colour structure $\to$ **different radiation patterns**.

- Pull (non-boosted context) — Gallicchio & Schwartz '10
- N-subjettiness — Jihun Kim '10; Thaler & Van Tilburg '10
- "Buried Higgs" light singlets — Falkowski et al '10; Chen et al '10
- Boosted decision trees — Cui & Schwartz '10
- Dipolarity, applied to HEPTopTagger — Jankowiak, Hook and Wacker '11
- Jet deconstruction — Soper & Spannowsky '11
- Template method beyond LO — Almeida et al '11
- ...

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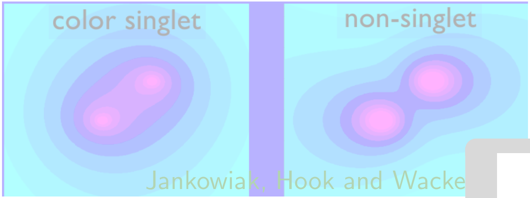

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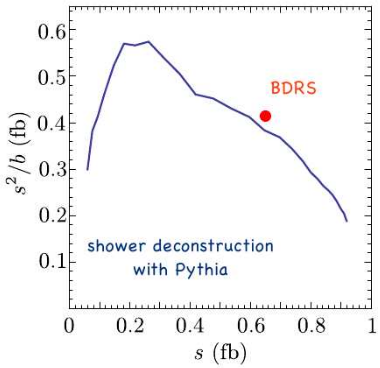
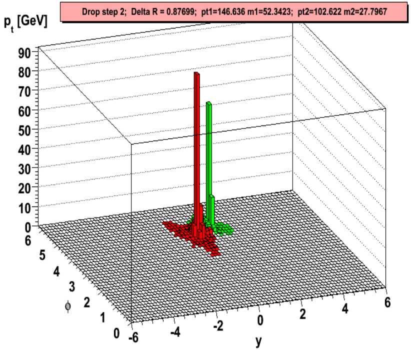


Jet-deconstruction $\simeq$ all-order analytic matrix-element method

3. Noise removal from jets



Key idea:

- Look at jet on smaller angular scale
- Discard its softer parts

- Filtering — Butterworth et al '08
- Pruning — Ellis, Vermillion and Walsh '09
- Trimming — Krohn, Thaler & Wang '09

[With earlier methods by Seymour '93 and Kodolova et al '07]

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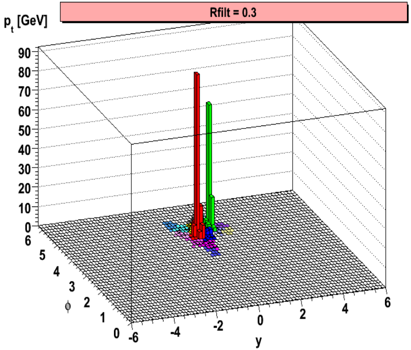

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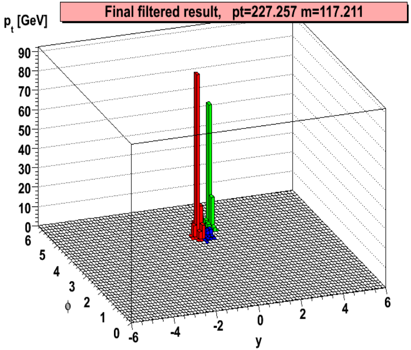

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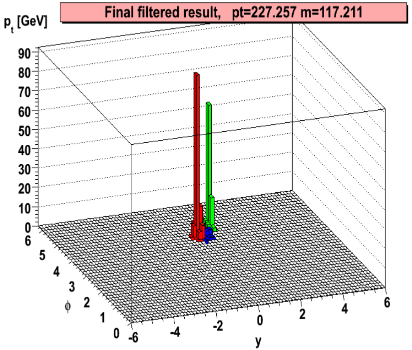

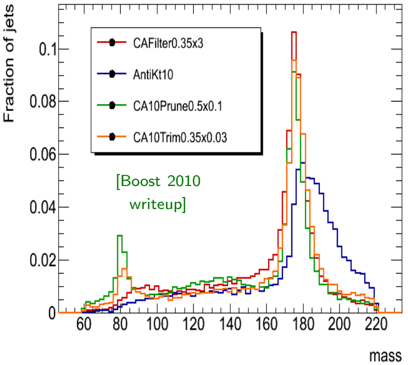

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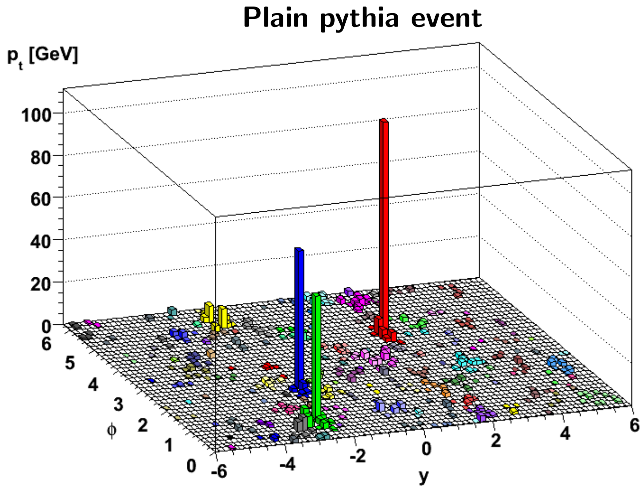
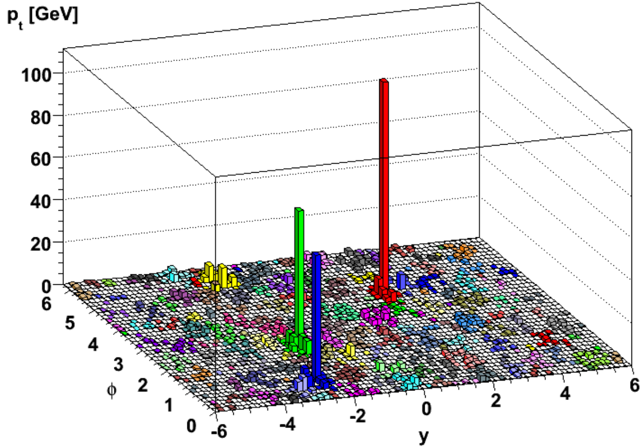
Noise & different kinds of event



The problem of noise and contamination is common to low-lumi pp running, high-lumi LHC pp running, and heavy-ion running

Noise & different kinds of event

Plain pythia event + today's pileup



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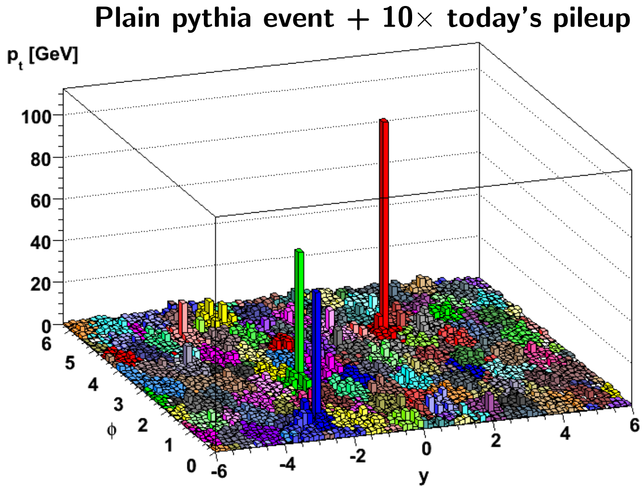

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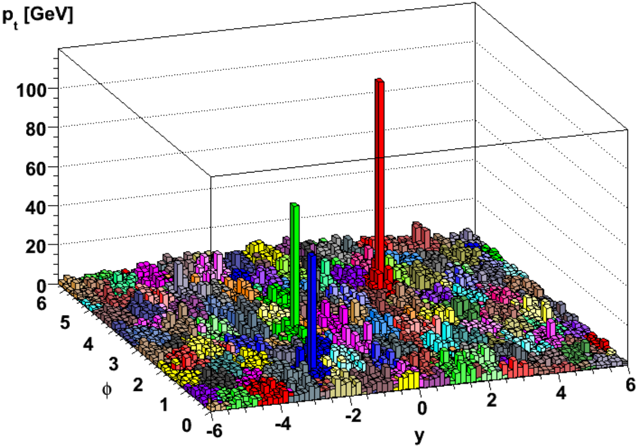
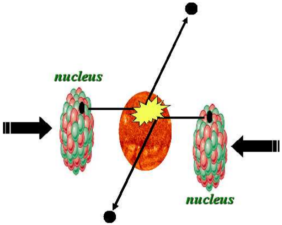
Noise & different kinds of event

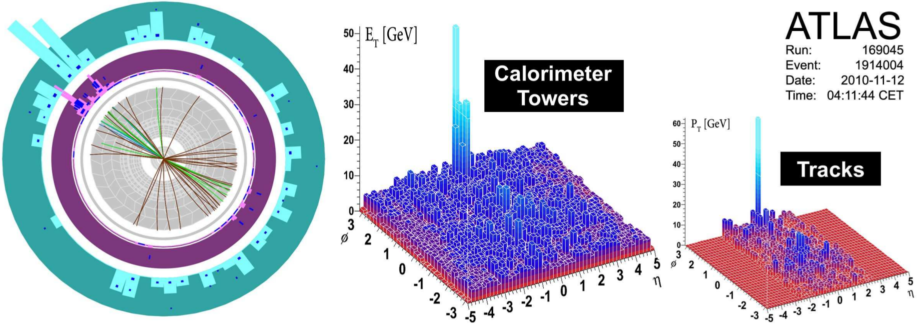
Plain pythia event + heavy-ion type bkgd



The problem of noise and contamination is common to low-lumi pp running, high-lumi LHC pp running, and heavy-ion running

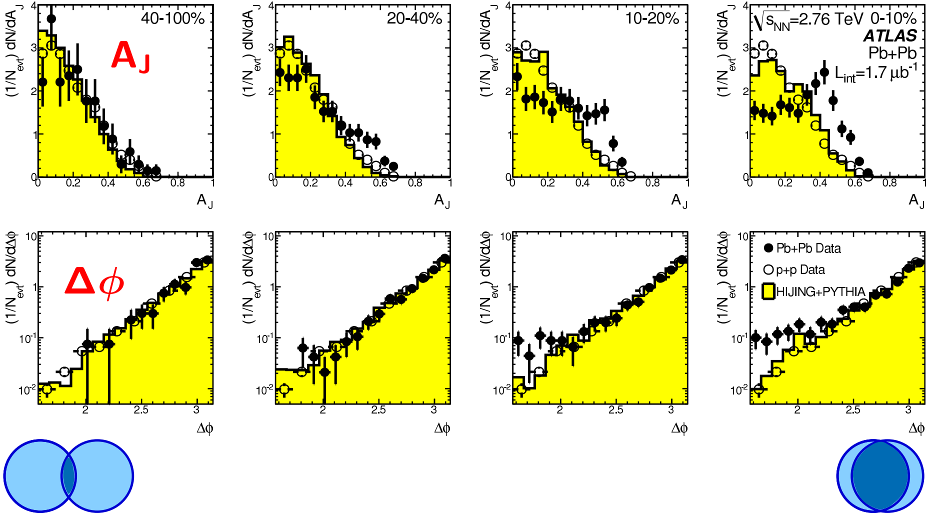
4. Full jet reconstruction in heavy-ion collisions



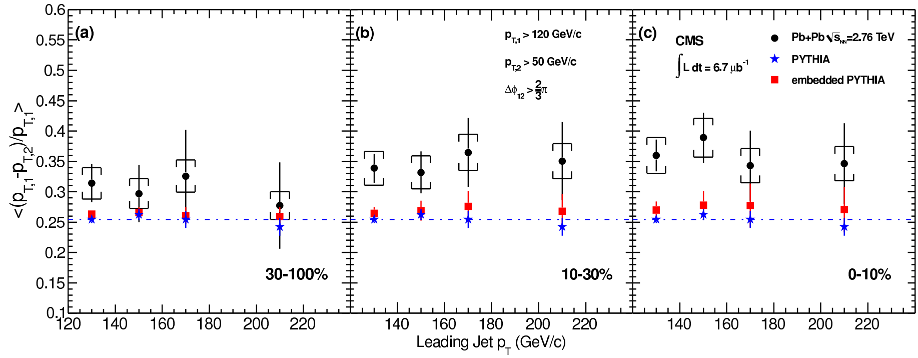


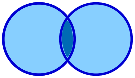
Quantitative measure: $A_J = \dfrac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$

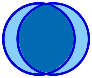
[with $\Delta\phi$ as a cross-check]



Average quantitative measure from CMS: $\left\langle \frac{p_{t1} - p_{t2}}{p_{t1}} \right\rangle$







Order of magnitude of medium effects: 10%

For quantitative HI studies at 10% level, *details of methods and their systematics become key:*

ATLAS (& ALICE, STAR, PHENIX): subtract off estimated background from jet, without noise suppression $\rightarrow$

- ✓ zero bias
- ✗ large fluctuations ($\sim$ 16 GeV; enhances asymmetries)

CMS: subtract more than estimated background, suppress "negative towers", i.e. powerful noise suppression $\rightarrow$

- ✓ lower fluctuations *[like filtering, pruning trimming]*
- ✗ but extra biases that cancel partially in a jet-structure dependent way (CMS sees 5% difference between quarks and gluons)

Tradeoff discussed e.g. in Cacciari, Rojo, GPS & Soyez '10
and Cacciari, GPS & Soyez '11

As LHC *pp* program $\rightarrow$ high lumi (high noise) and HI $\rightarrow$ precision, both stand to gain from deeper understanding of jet finding

Conclusions

We are at a turning point in jet finding

LHC is probing the highest scales ever through jets

LHC is starting to see W's, Z's, tops as *single* jets — as we reach above the electroweak scale they "become" light

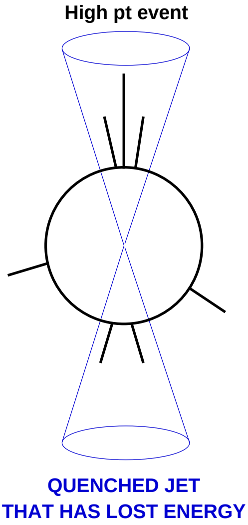
Fully reconstructed jets are a concrete and powerful reality in heavy-ion collisions and are starting to become quantitative probes

Theoretical understanding continues to accompany this progress

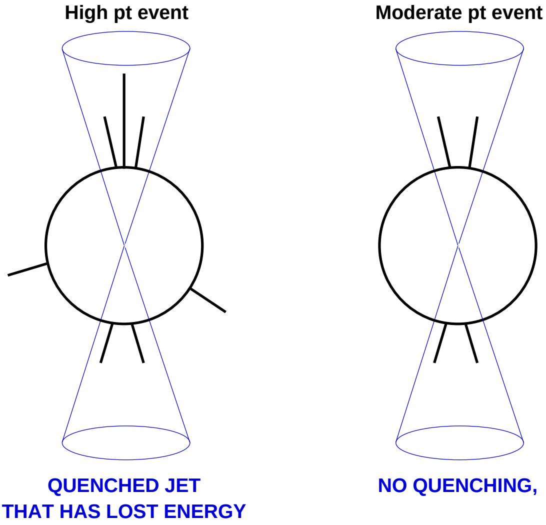
The time is here for advanced jet methods to be part of the search for the Higgs, BSM physics and probe the hot dense medium of HI collisions

EXTRAS

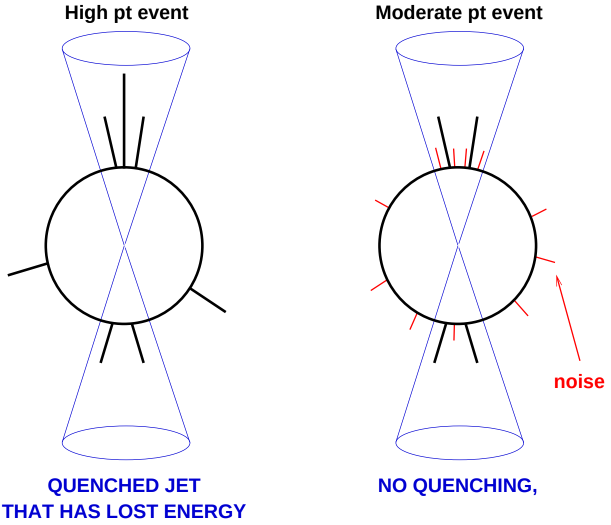
Quenching v. fluctuations



Quenching v. fluctuations

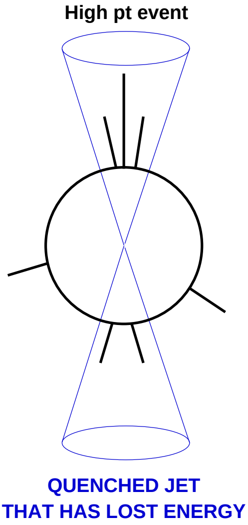


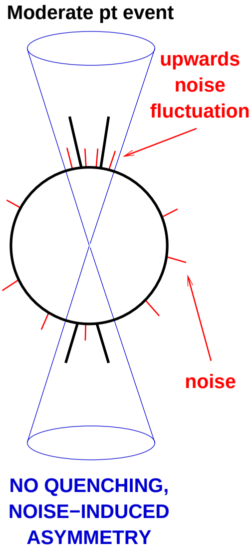
Quenching v. fluctuations



At LHC, each jet accompanied by $\mathcal{O}$ (100 GeV) of noise.

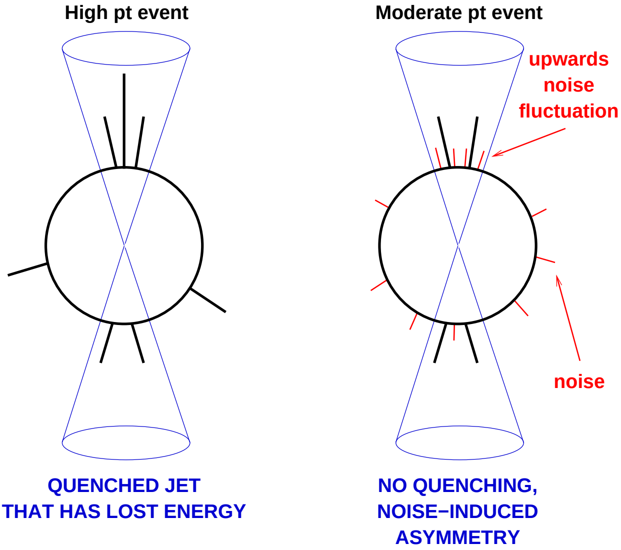
Quenching v. fluctuations





At LHC, each jet accompanied by $\mathcal{O}$ (100 GeV) of noise.

Quenching v. fluctuations



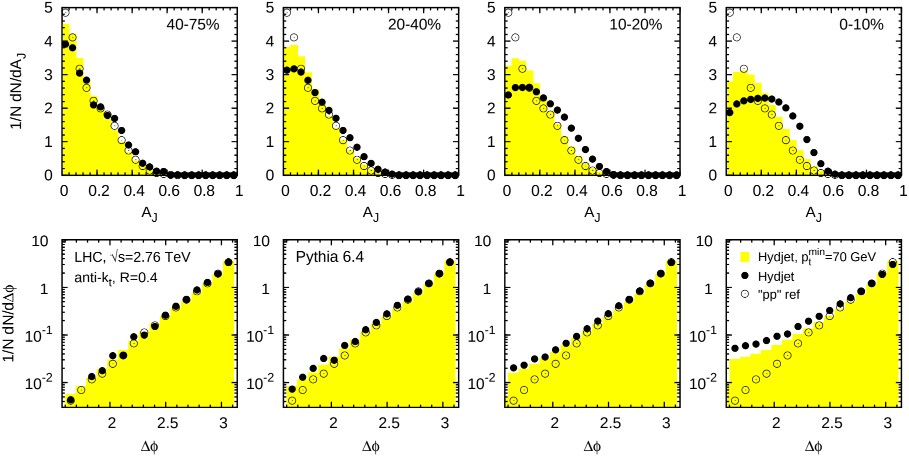
At LHC, each jet accompanied by $\mathcal{O}(100\text{ GeV})$ of noise.

Large, $\mathcal{O}(50\text{ GeV})$, fluctuations rare.

But moderate-p_t events much more common than high-p_t

Asym. may mix quenching & flucts; quantify latter to learn about former

Results from Hydjet embedding (ATLAS cuts)



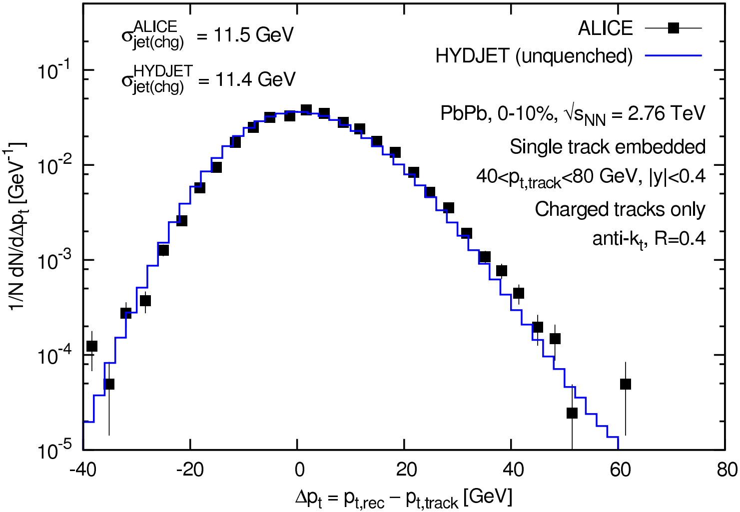
- Effect of fluctuations appears significant

Cacciari, GPS & Soyez '11

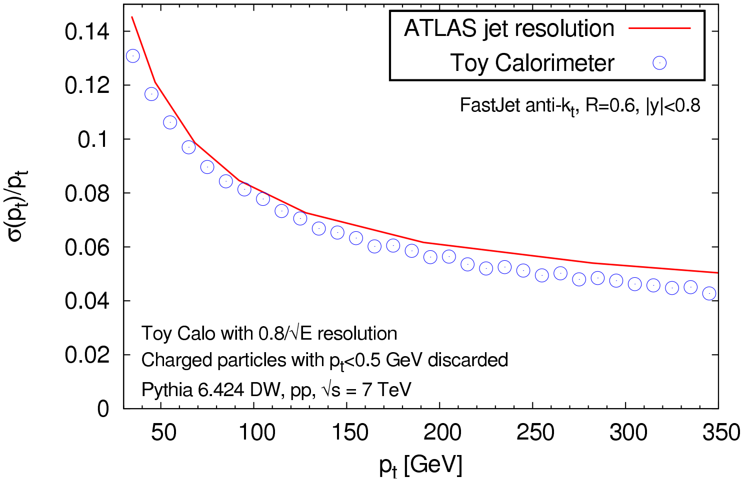
- It is crucial to include sufficiently low-p_t Pythia events

For the fluctuations present in Hydjet, original ATLAS choice of generation cut, 70 GeV, fails to reveal the true impact of fluctuations

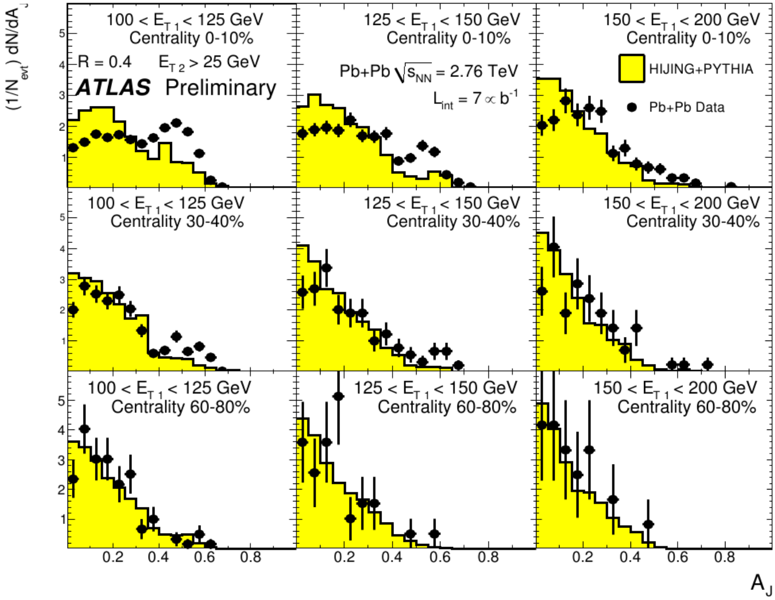
Crosscheck that HYDJET fluctuations are OK

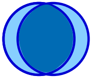


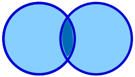
Crosscheck that our detector simulation is not crazy



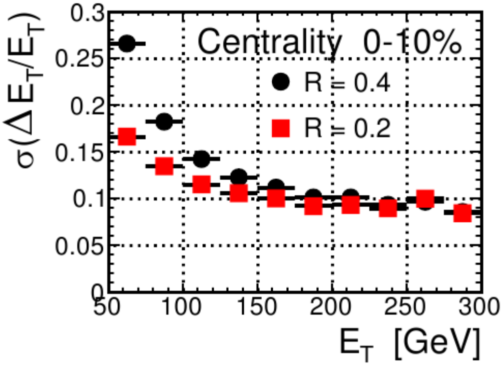
A_J v. p_t from ATLAS







ATLAS resolution from simulations



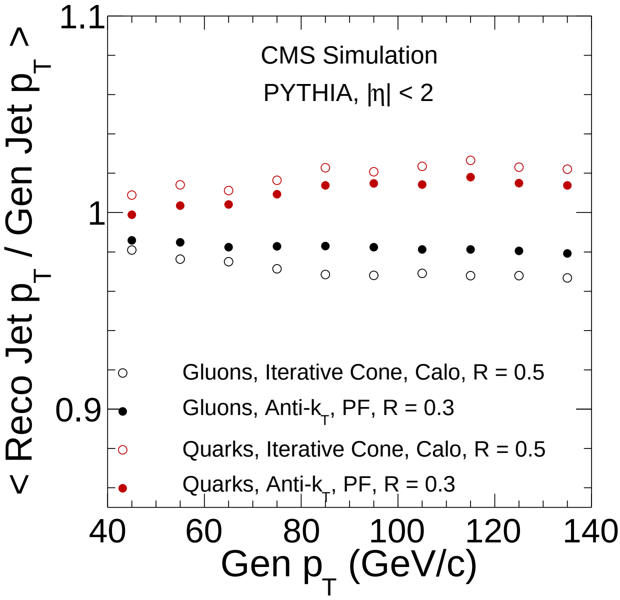
What is absolute resolution?

Take Lowest bin:

$26\% \times 60$ GeV $\simeq 16$ GeV

This is same ballpark as in our HYDJET simulations.

Jet-structure reconstruction dependence



quark and gluon jets have different internal structure

that induces 5% difference in reconstructed energy

caused by noise suppression?

how modified is quenched jet structure?

some data say not much