XIII MEXICAN SCHOOL OF PARTICLES AND FIELDS
UNIVERSITY OF SONORA & SAN CARLOS, SONORA, MEXICO.
OCTOBER 2-11 2008

The Mexican School of Particles and Fields is a biennial conference organized by the Division of Particles and Fields of the Mexican Physical Society, designed to gather specialists in different areas of high energy physics to discuss the latest developments in the field. The format of the conference will consist of morning sessions devoted to theoretical and experimental reviews and afternoon thematic sessions.

Jet Reconstruction at the LHC
(Lecture 2)

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ATLAS

THE UNIVERSITY OF ARIZONA.
Arizona's First University.

UAPhysics
THE UNIVERSITY OF ARIZONA
College of Science

Remember?

- **Jets are bundles of particles with correlated kinematics**
  - ~25% photons, rest charged and neutral hadrons
- **Calorimeters are detectors of choice for jets**
  - Generate signals from neutral and charged particles
- **Calorimeter response to particles depends on particle type**
  - More signal from electrons/photons than from pions of the same energy (non-compensation)
  - Larger intrinsic fluctuations for hadrons
  - Direct proportionality of electron signal to incoming energy
  - Hadron response is energy dependent
  - Hadronic showers are less compact and larger
- **Jet response is a convolution of the jet particle content with particle response**
  - Typically higher than hadron response
- **Calorimeter signal definition affects image of jet in detector**
  - Towers and clusters

How To Deal With Non-Compensation

- **Can we get the hadronic shower branch signals up to a signal corresponding to the electromagnetic signal?**
  - Lower fluctuations
  - Direct proportionality of energy and signal
- **One approach: cell signal weighting in highly granular calorimeter**
  - Small signal densities in a calorimeter cell indicate hadronic deposit and should receive an additional correction (weight)
    - Pioneered by CDHS (1977) and developed by H1 (1992)
  - High signal densities indicate electromagnetic signals and don’t need additional corrections
    - Dense, compact showers from electrons/photons
- **But how can we determine these weights?**
  - It’s mostly a matter of context: are we trying to determine them for single particles (clusters) or jets
  - ATLAS works with both approaches

Jet Calibration With Cell Weights

Statistical approach

- Weights are determined by resolution minimalization fits with calorimeter jets

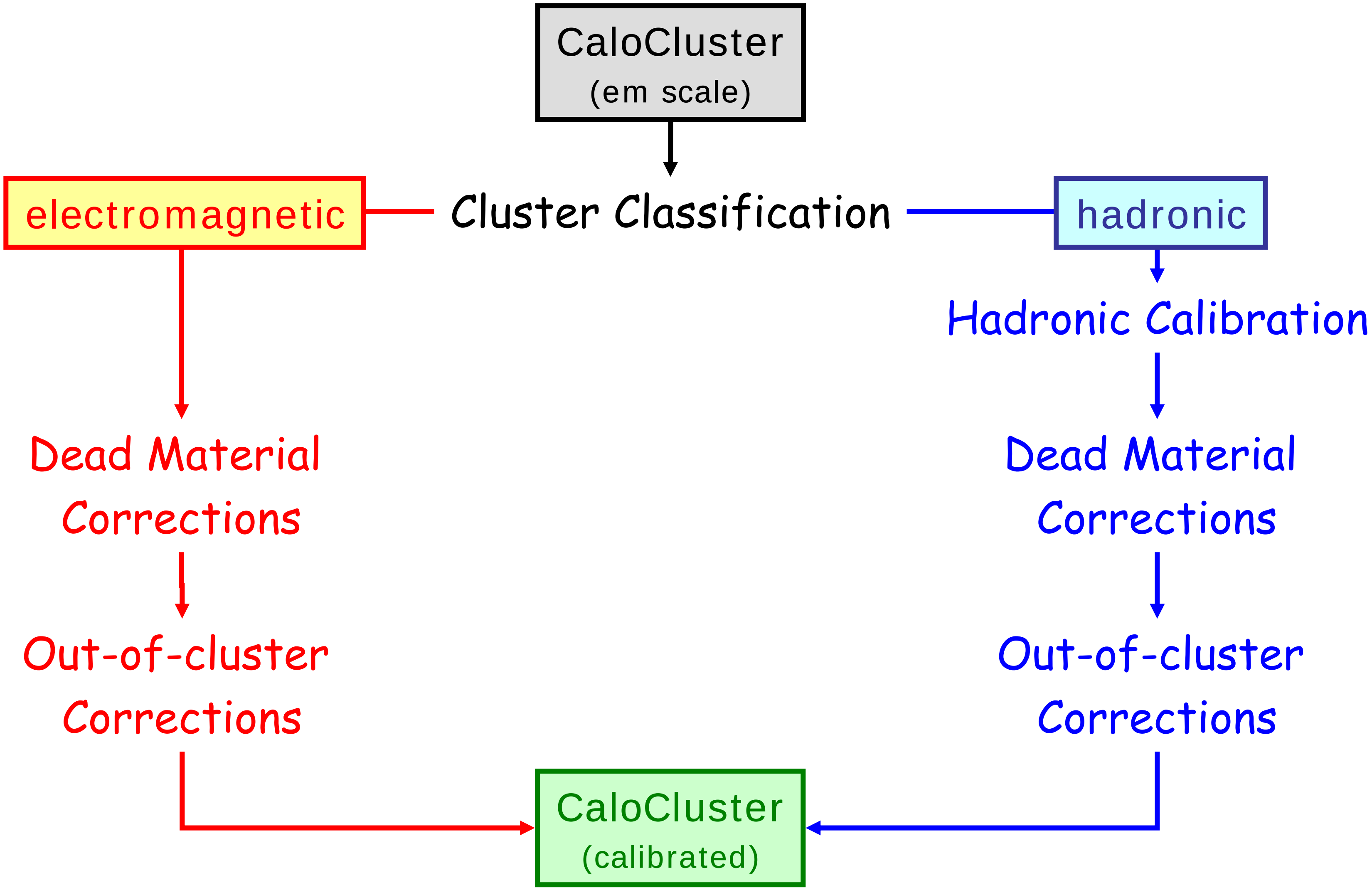
$$\left\langle E_{calo}^{jet} \right\rangle = \left\langle \sum_{cells} w(\rho_{cell}, \vec{X}_{cell}) \cdot E_{cells} \right\rangle = \left\langle E_{true}^{jet} \right\rangle$$

- Truth reference typically corresponding simulated particle jet
- Weights will include primary electromagnetic component of jet
  - Do we really want this? They should only correct hadronic signals!
- Weights compensate all signal inefficiencies, not only e/h
  - Dead material corrections, leakage
  - Low level of factorization!
- Weights need to be determined for all jet finders and jet finder configurations
  - Need to find the jet first in uncalibrated signals
  - Then apply correct weight for given jet finder and configuration
  - Huge task!

Hadronic Calibration

- **Why not calibrating calorimeter signals first?**
  - No jet context
  - But need other context for cell signal weighting normalization → topological cell cluster
    - Energy blobs follow shower shape somewhat
- **Cluster based hadronic calibration**
  - Advantages to jet context: can use cluster shape to parametrzie cell weights
    - Measure compactness of signal cluster by cluster
    - Shape and size variables are easily reconstructed for each cluster
      - E.g. 2nd geometrical moments
- **Allows factorization**
  - Deal with e/h at detector level (not jet level)
  - Correct for local dead material at cluster level already
  - But need to apply further jet context corrections for particles lost in magnetic field and dead material losses not correlated with cluster signals

Local Hadronic Calibration



CaloCluster
(em scale)

Cluster Classification

electromagnetic

Dead Material Corrections

Out-of-cluster Corrections

hadronic

Hadronic Calibration

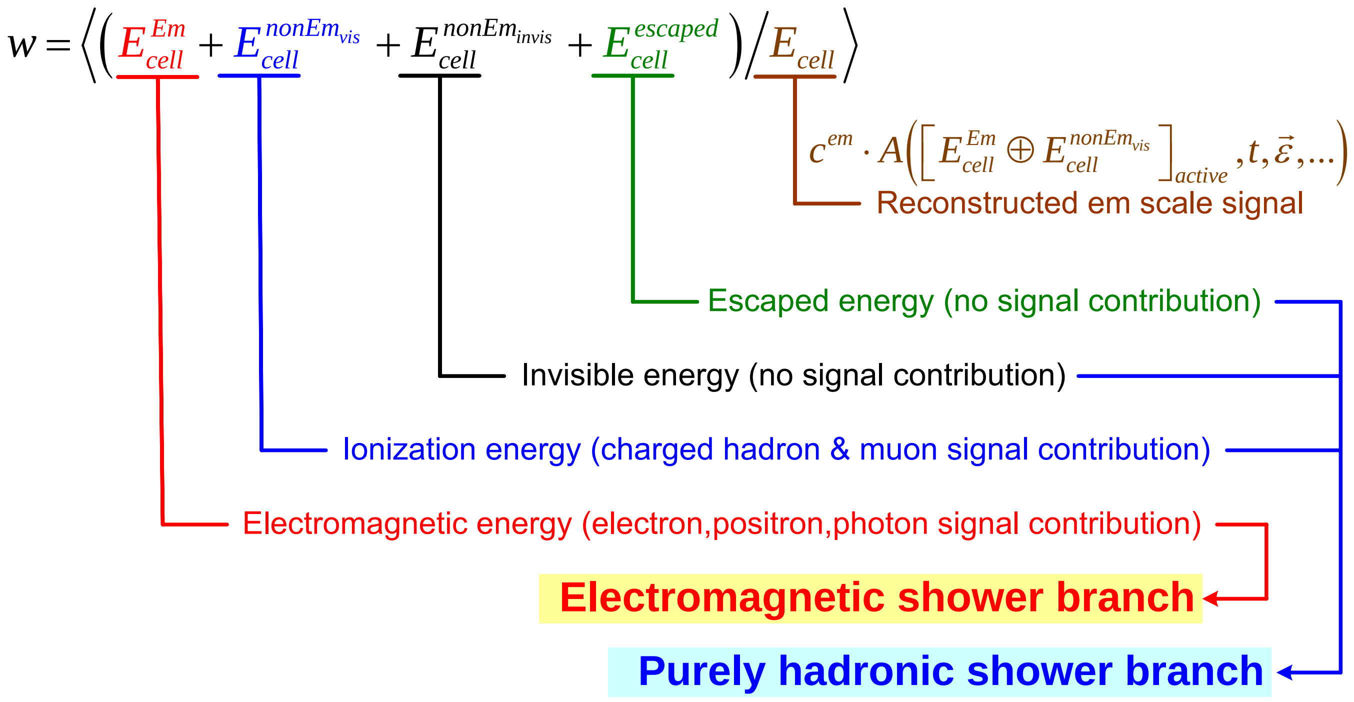
Dead Material Corrections

Out-of-cluster Corrections

CaloCluster
(calibrated)

Cell Signal Weighting In ATLAS

- **Weights are extracted from simulations**
  - Signals and deposited energies from single charged pion MC



$$w = \left\langle \left(E_{cell}^{Em} + E_{cell}^{nonEm_{vis}} + E_{cell}^{nonEm_{invis}} + E_{cell}^{escaped} \right) \Big/ E_{cell} \right\rangle$$

$$c^{em} \cdot A\left(\left[E_{cell}^{Em} \oplus E_{cell}^{nonEm_{vis}} \right]_{active}, t, \vec{\varepsilon}, \ldots \right)$$

Reconstructed em scale signal

Escaped energy (no signal contribution)

Invisible energy (no signal contribution)

Ionization energy (charged hadron & muon signal contribution)

Electromagnetic energy (electron,positron,photon signal contribution)

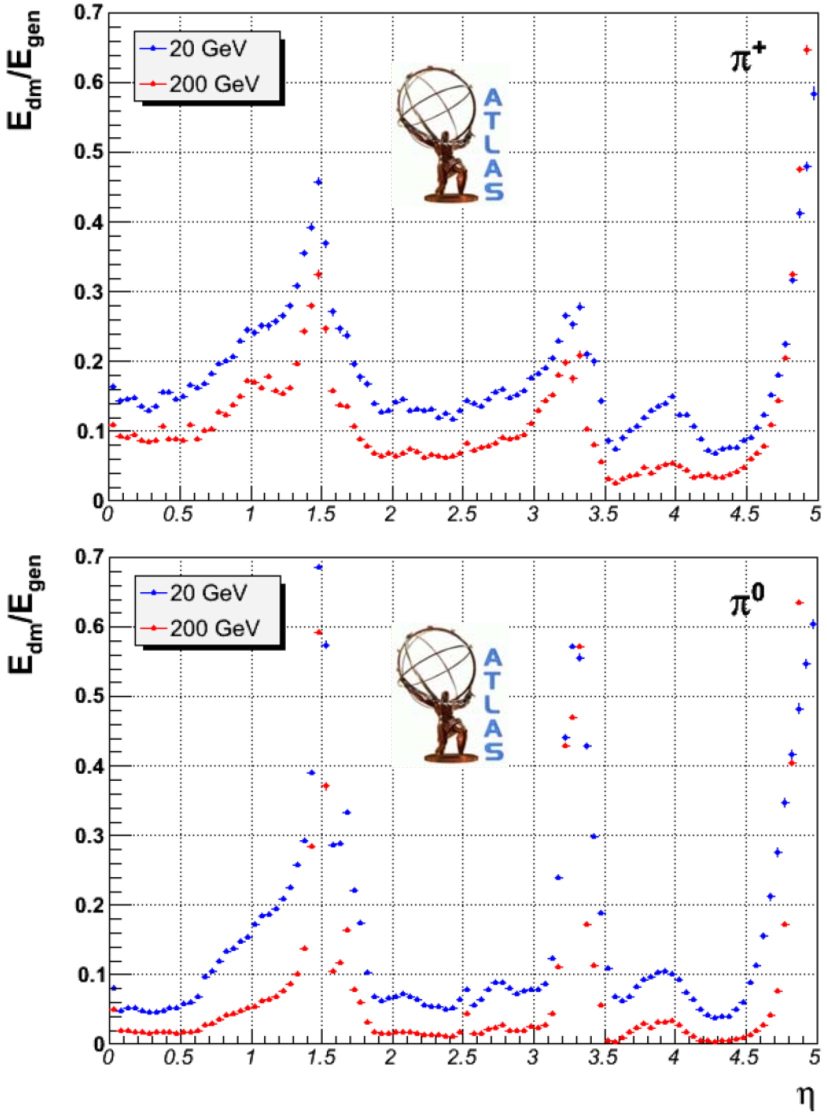
Electromagnetic shower branch

Purely hadronic shower branch

- **Weights are calculated as function of cluster & cell variables**
  - Signal environment used as additional indicator of hadronic character

Dead Material Energy Losses

- **Tracking device in front of a calorimeter**
  - And maybe even a cryostat wall
- **Try to use the cluster signal to correct for the losses**
  - In front
  - Inbetween
    - Central ATLAS!
  - Between
    - Endcap and forward cracks
- **Approach:**
  - Correlate cluster signal with nearby dead material energy loss in simulations
  - Do this for each dead material region separately



Local Hadronic Calibration Summary

- **Attempt to calibrate hadronic calorimeter signals in smallest possible signal context**
  - Topological clustering implements noise suppression with least bias signal feature extraction
  - No bias towards a certain physics analysis
  - Good common signal base for all hadronic final state objects
    - Jets, missing Et, taus
- **Factorization of cluster calibration**
  - Cluster classification largely avoids application of hadronic calibration to electromagnetic signal objects
    - Low energy regime challenging
  - Signal weights for hadronic calibration are functions of cluster and cell parameters and variables
    - Cluster energy and direction
    - Cell signal density and location (sampling layer)
  - Dead material and out of cluster corrections are independently applied

Overview

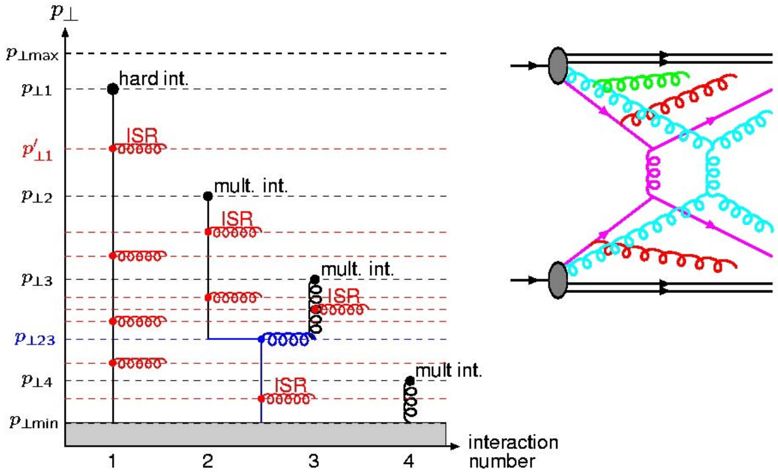
- Lecture 1 (Saturday, October 4th, 2008, 12:30-13:30): Signals from particle jets
  - Experimentalist view on jets
  - Brief review of the basics of calorimetric energy measurement
  - Jet response of a non-compensating calorimeter
  - Calorimeter signal reconstruction: cells, towers, clusters
- **Lecture 2 (Sunday, October 5th, 2008, 12:30-13:30): Jet algorithms and reconstruction**
  - Physics environment for jet reconstruction at LHC
  - Jet algorithms and reconstruction guidelines
  - Jet calibration strategies
  - Jet Reconstruction Performance
- Lecture 3 (Sunday, October 5th, 2008, 17:00-18:00): Refinement of jet reconstruction at LHC
  - Refined calibration using other detectors
  - Tagging jets from pile-up
  - The origin of jets: masses and shapes
  - AOB

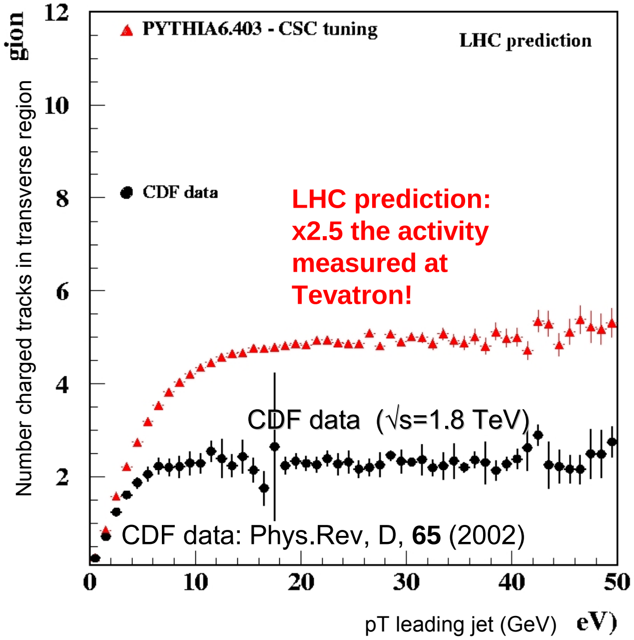
Jet Reconstruction Environment At LHC

Physics Environments @ LHC

- **Physics environment different from Tevatron**
  - Increased underlying event activity (more phase space)
    - Already at lowest (initial) luminosities ~10^{31}-10^{32} cm^{-2} s^{-1}
  - Additional activity from pile-up
    - Proportional to instantaneous luminosity

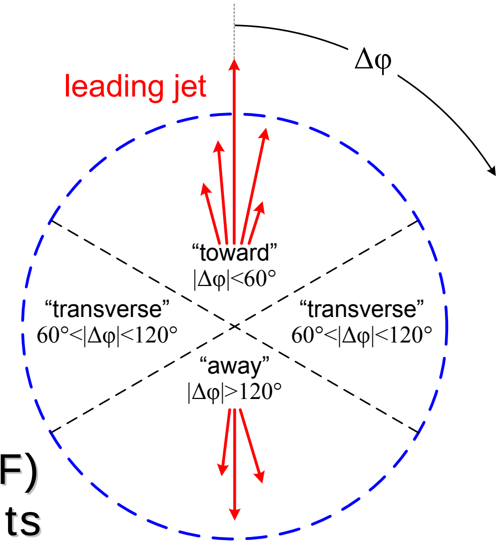
Interleaved Multiple Interactions





LHC prediction: x2.5 the activity measured at Tevatron!

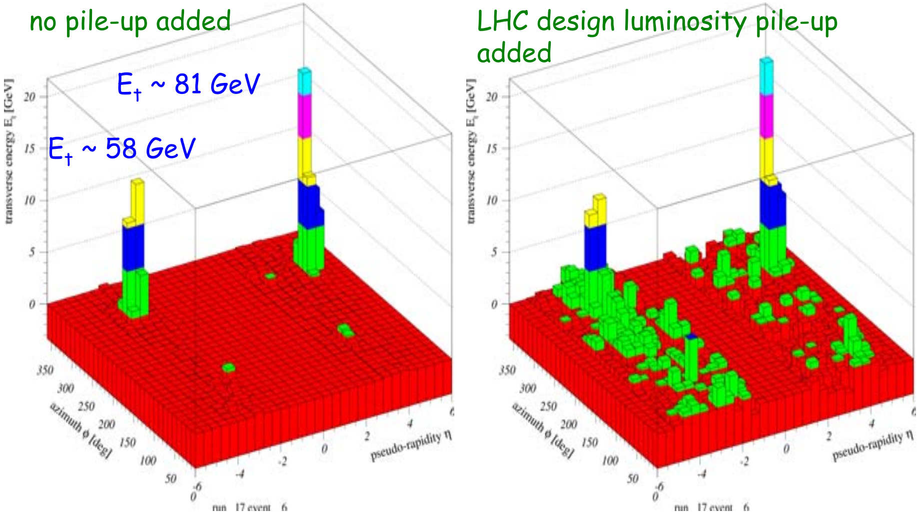
CDF data: Phys.Rev, D, **65** (2002)



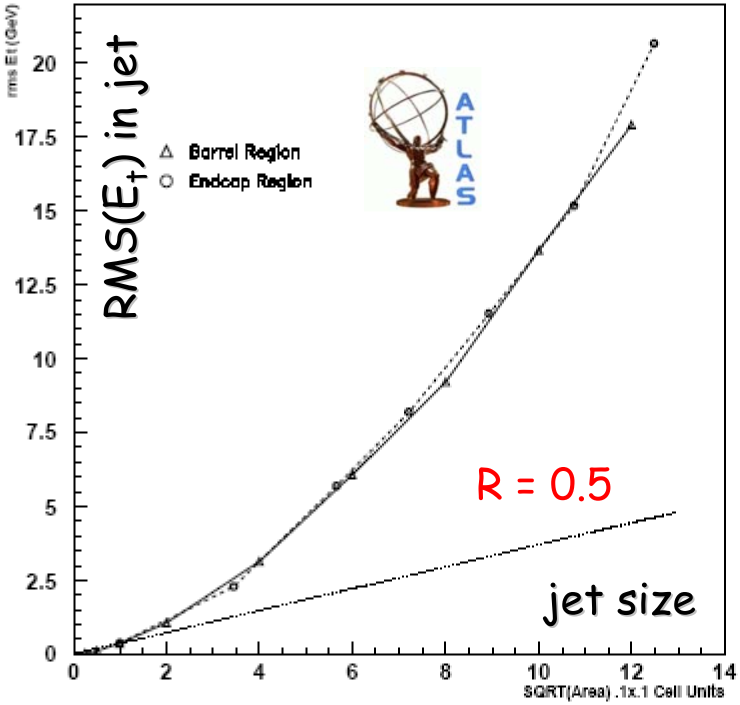
Rick Field's (CDF) view on di-jet events

Pile-Up Events

- **Multiple collisions of other protons in bunch crossings**
  - Effect of high luminosity at LHC
  - Independent of (triggered) hard scattering process
  - Generates additional particles and particle jets
- **Generates additional noise in detectors**
  - High bunch crossing rate creates signal history from pile-up in detectors
    - Sensitivity up to 25 bunch crossings for "slow" detectors (calorimeters)
  - Average contribution cancels due to chosen signal shaping
- **Pile-up noise is not gaussian**
  - Coherent effects due to physics source


no pile-up added

LHC design luminosity pile-up added



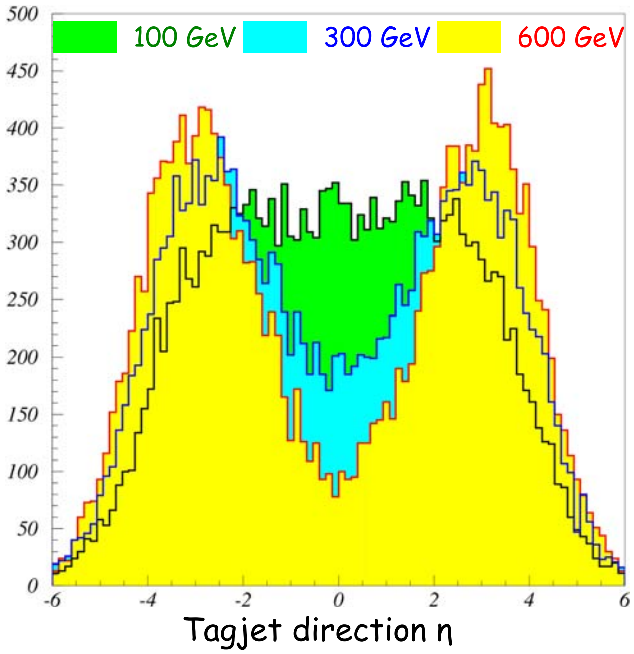
Final State At LHC

- **Final state can make jet reconstruction more challenging**
  - "Low activity" signatures like QCD di-jets (2->2 process + radiation)
    - Mostly gluons, more quarks at high pT
  - Busy final states in SUSY
    - Many leptons
    - Many (quark) jets
    - Higher likelihood of signal overlap
- **Source of jet**
  - Hadronic W decays in ttbar production
    - W color-disconnected to rest of collision
    - Quark jets
  - Prompt photon + jet(s)
    - Mostly quark jet

Physics Environments @ LHC

Discovery physics at LHC

- Expect extreme busy final states
  - Lots of leptons, missing Et and jets O(10) in SUSY
  - Many x 10 jets in black hole production
  - Good spatial resolution power to find the jets
  - Good energy resolution for reliable missing Et calculation
- Need large rapidity coverage
  - Tag vector boson fusion production of Higgs and exotics
    - WW, WZ, ZZ with associated quark jets
  - These “tag jets” often go forward
  - Jets are uncorrelated with each other, but balance the central system (Higgs)



Direction of tag jets in Higgs VBF production for m_H = 100, 300, 600 GeV

this is a very old plot!

Finding Jets

Jet Definition

- **Jet finding algorithm and its configuration**
  - Seeded or seedless cone and its parameters
    - Cone size, seed threshold
    - Recombination algorithm
  - Recursive recombination algorithms
    - Distance parameter
    - Recombination algorithm
- **Signal or constituent definition**
  - Calorimeter towers or clusters
  - Reconstructed tracks
  - Generated particles
  - Generated partons

"Snowmass"

$$E_T^{jet} = \sum E_{T,i}$$

$$\eta_{jet} = \frac{1}{E_T^{jet}} \sum E_{T,i} \cdot \eta_i$$

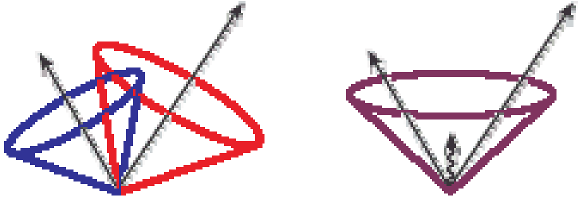
$$\varphi_{jet} = \frac{1}{E_T^{jet}} \sum E_{T,i} \cdot \varphi_i$$

4-momentum

$$\left(E_{jet}, \vec{p}_{jet}\right) = \left(\sum E_i, \sum \vec{p}_i\right)$$

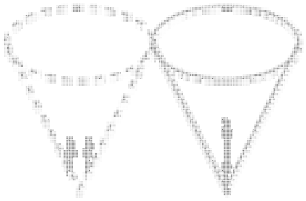
Theoretical Requirements

- **Infrared safety**
  - Additional soft particles should not affect jet reconstruction
  - See extra slides from Gavin Salam
- **Collinear safety**
  - Split energies (one instead of two particles) should not change the jet
  - See extra slides from Gavin Salam



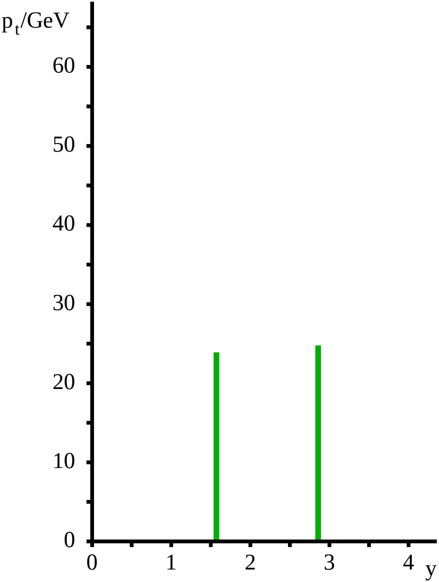
infrared sensitivity
(soft gluon radiation merges jets)

collinear sensitivity (1)
(sensitive to E_t ordering of seeds)



collinear sensitivity (2)
(signal split into two towers below threshold)

(Animation courtesy of Gavin Salam)



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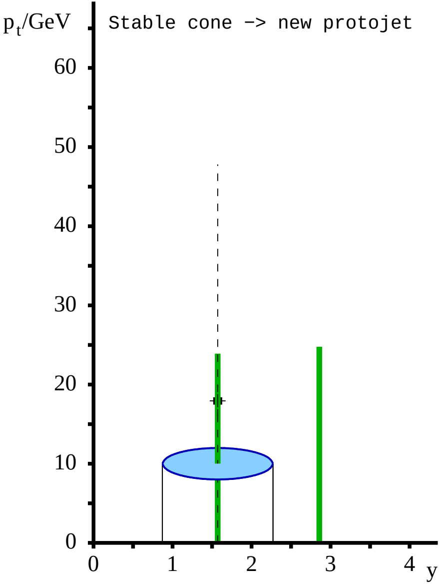

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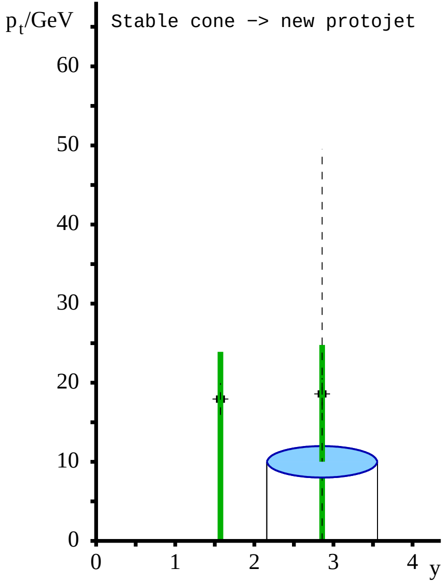

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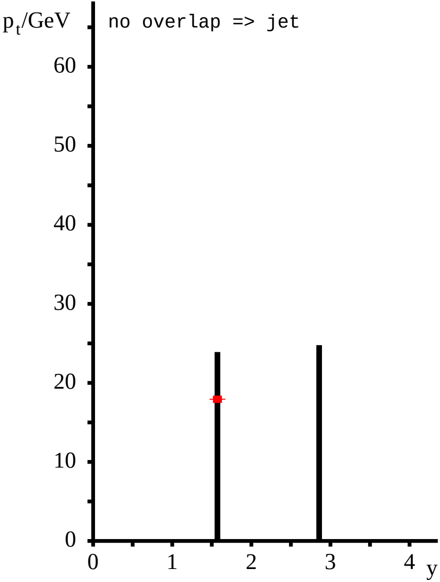

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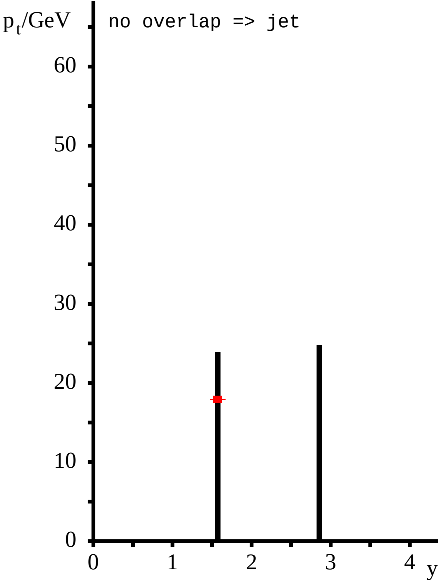

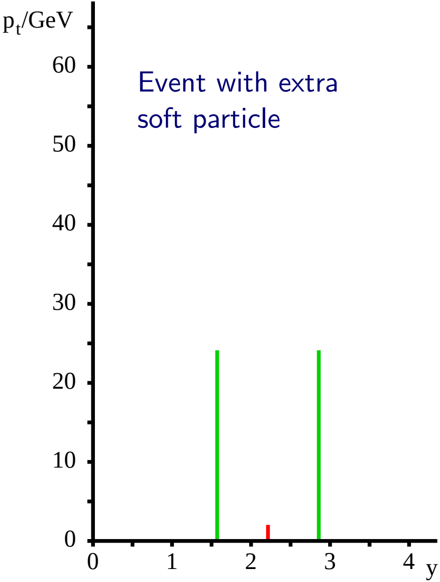

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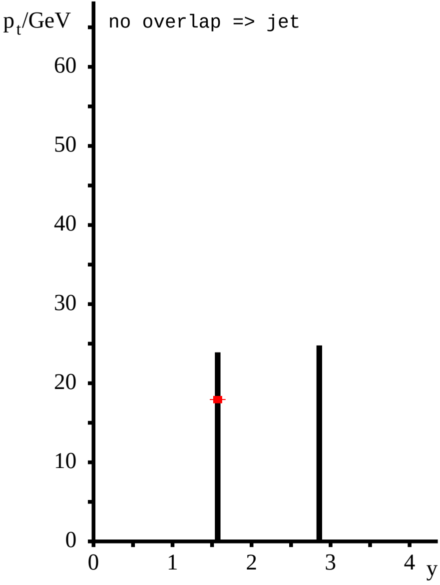
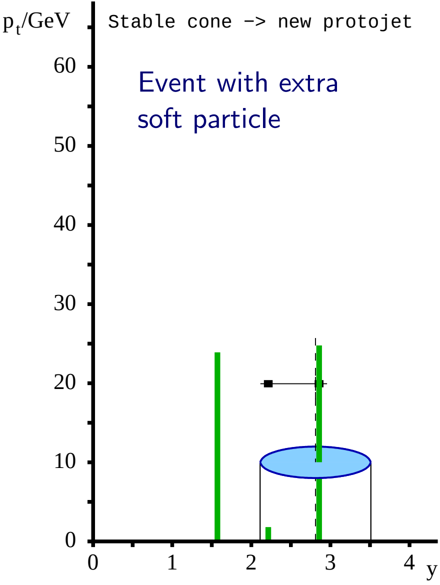
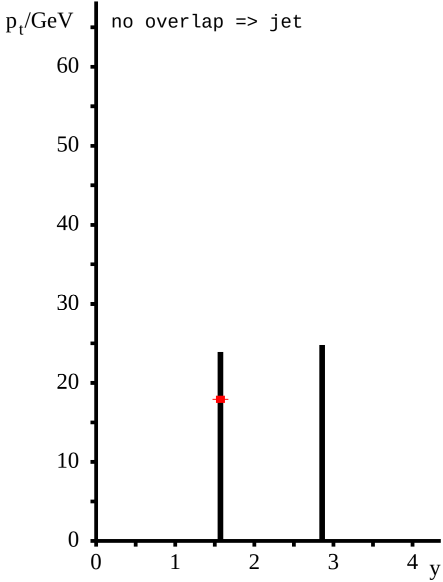
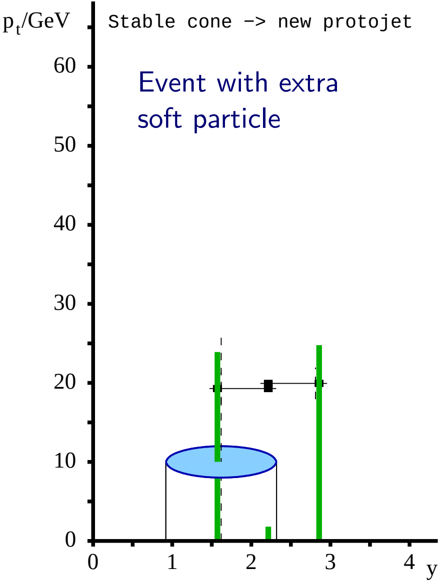



Event with extra soft particle

(Animation courtesy of Gavin Salam)





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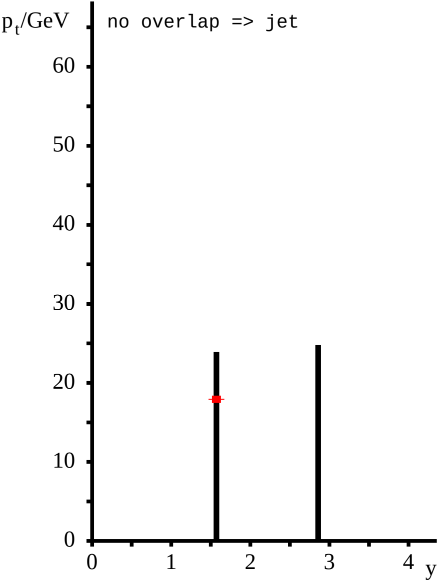

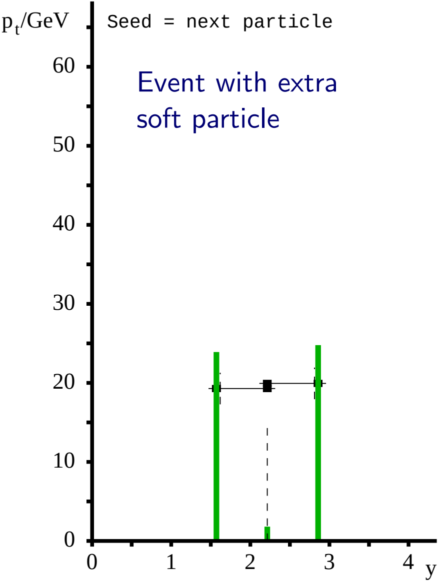

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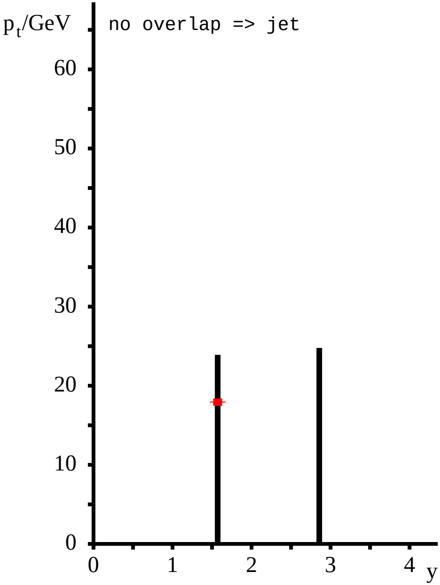

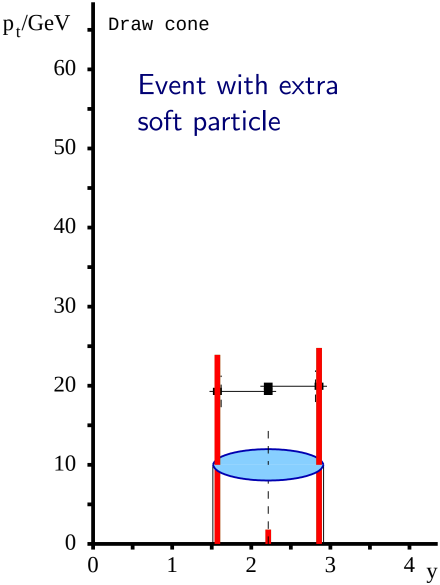
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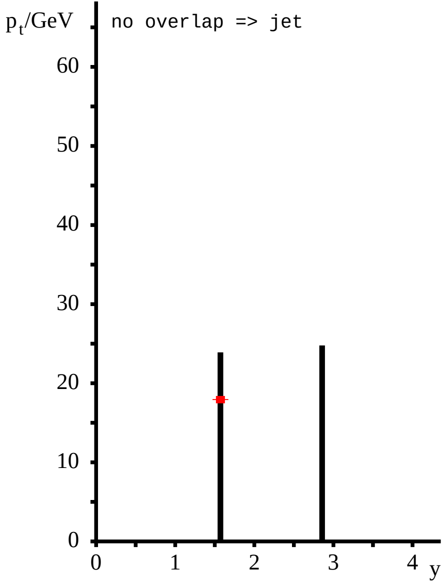

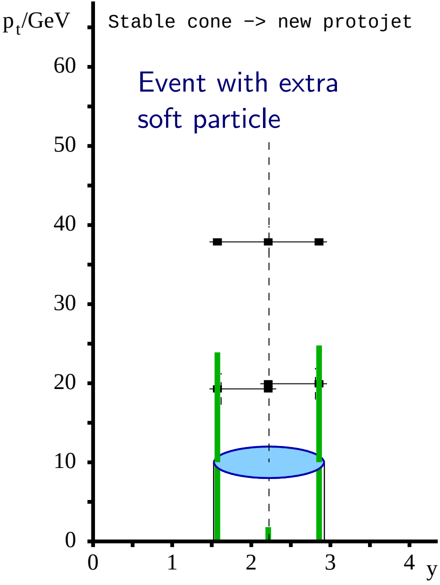
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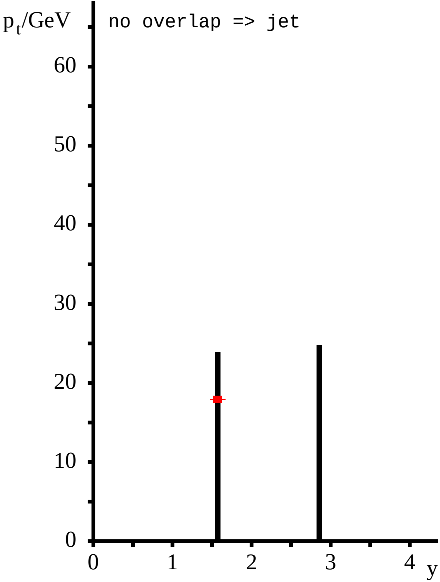

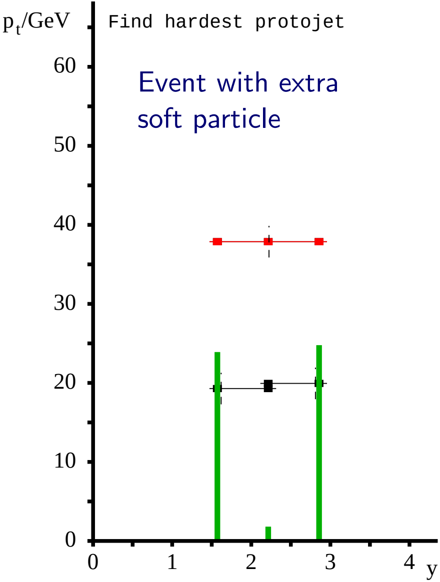

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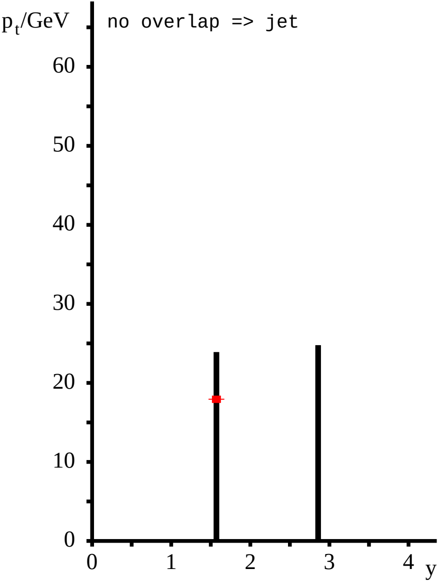

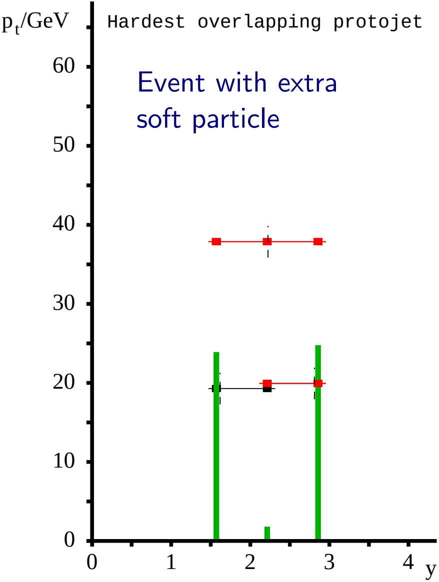
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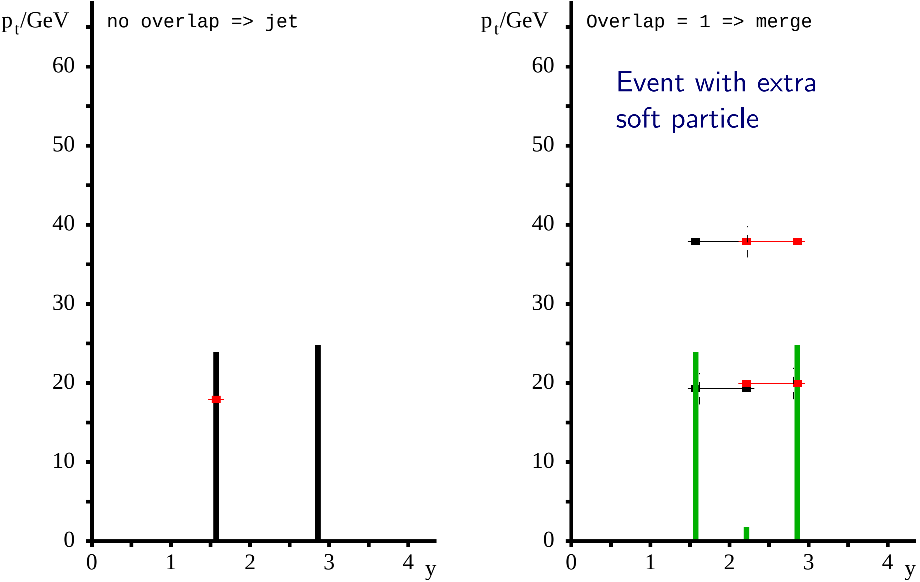
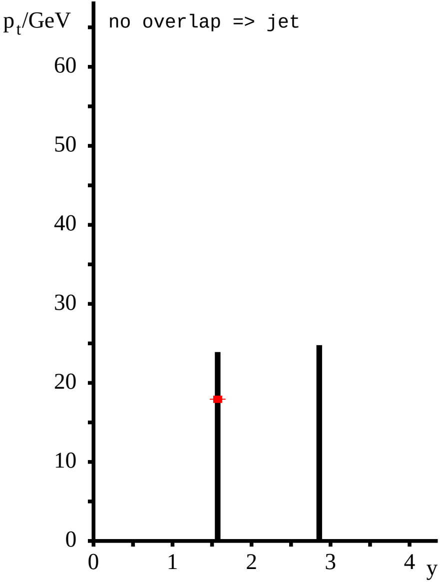


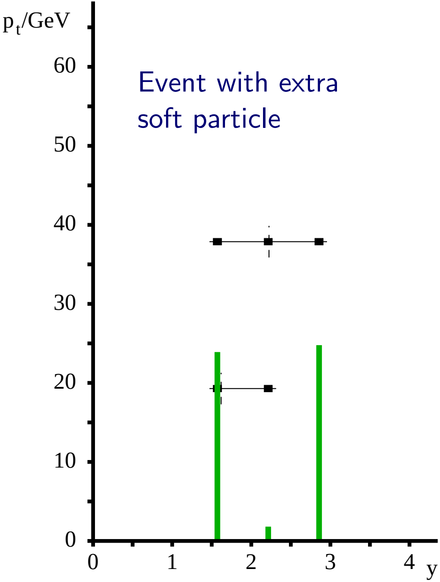
no overlap => jet

Overlap = 1 => merge

Event with extra soft particle

(Animation courtesy of Gavin Salam)





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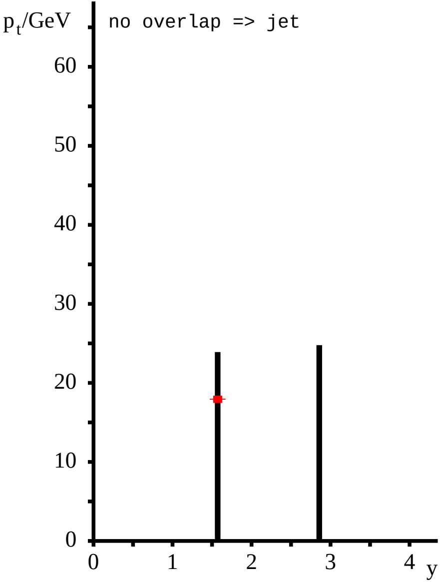

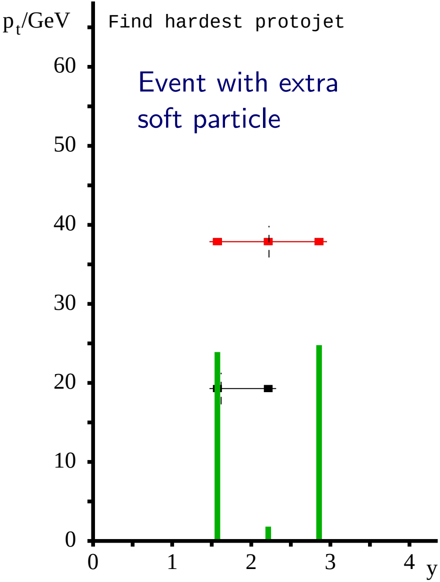
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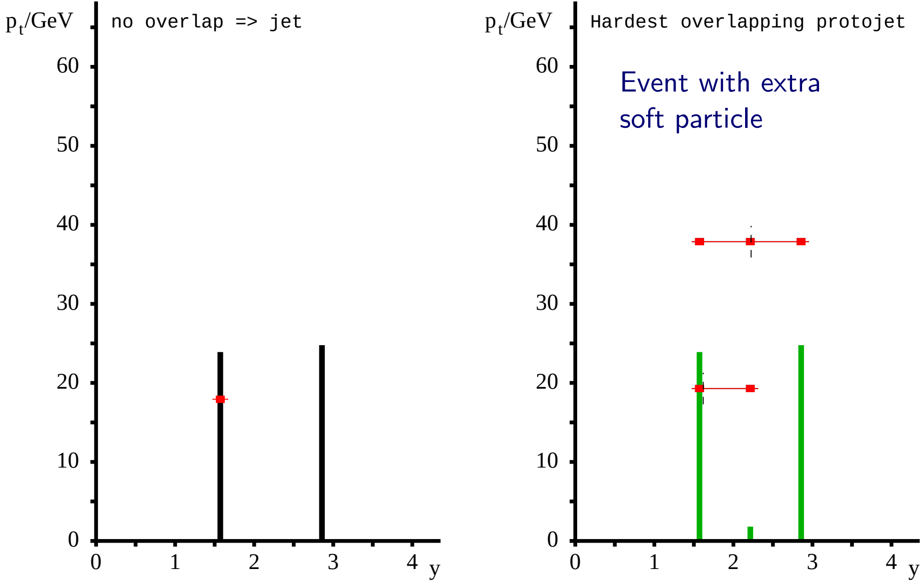

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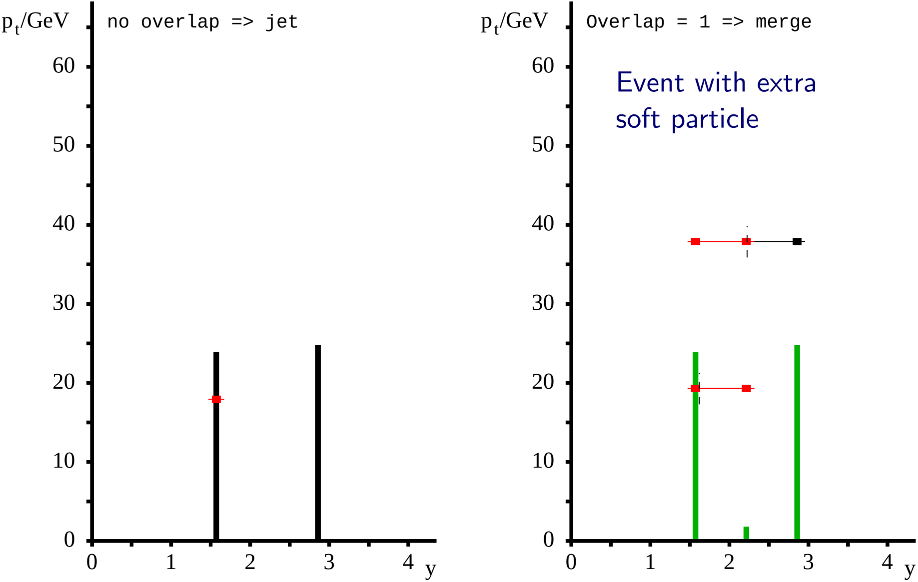

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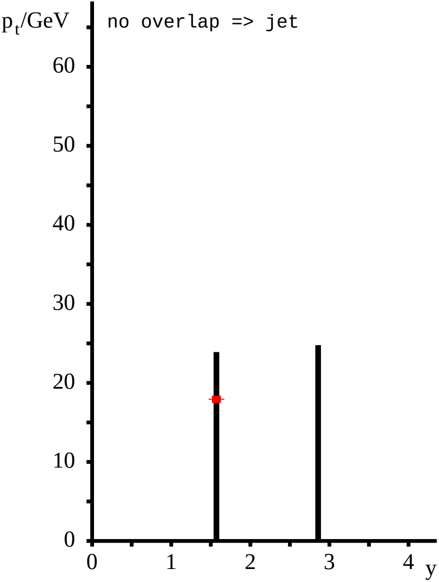

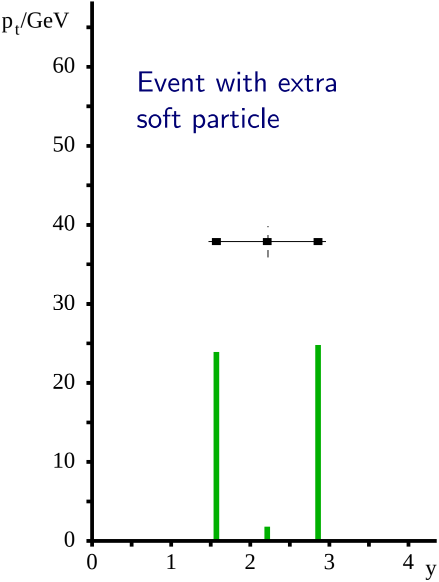

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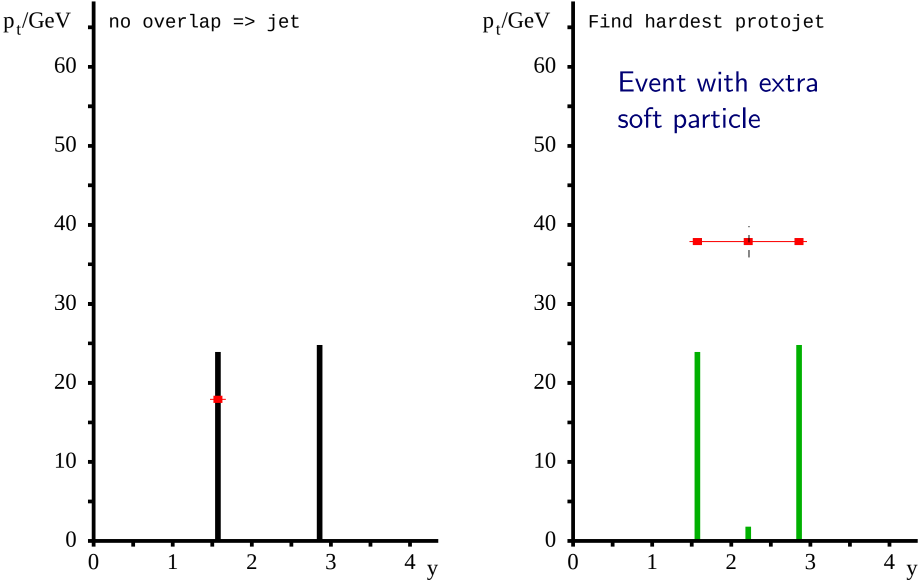

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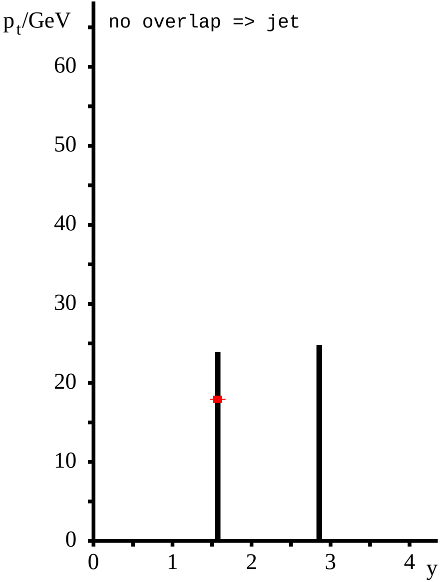
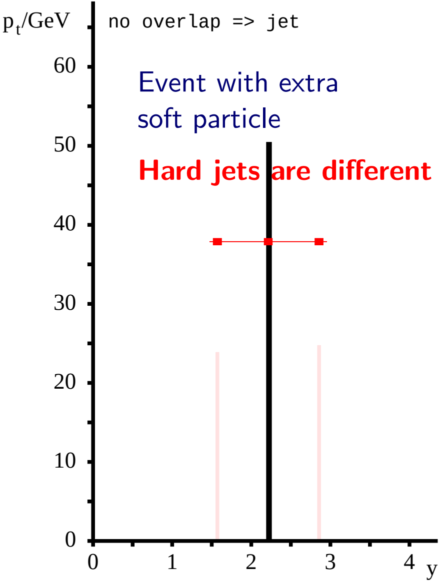




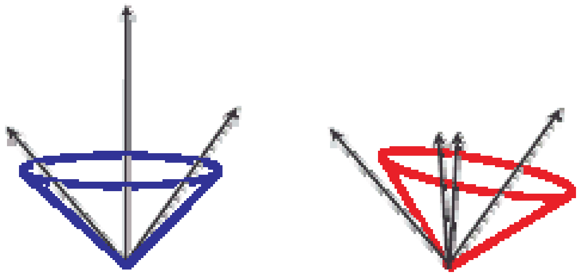
Event with extra soft particle

Hard jets are different

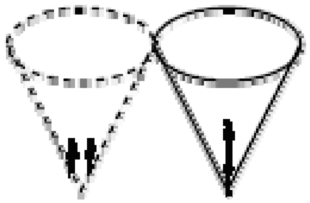
Theoretical Requirements

- **Infrared safety**
  - Additional soft particles should not affect jet reconstruction
  - See extra slides from Gavin Salam
- **Collinear safety**
  - Split energies (one instead of two particles) should not change the jet
  - See extra slides from Gavin Salam

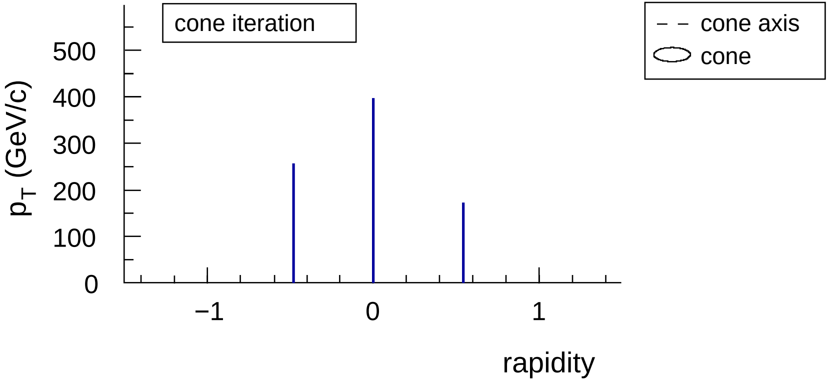
infrared sensitivity
(soft gluon radiation merges jets)



collinear sensitivity (1)
(sensitive to E_t ordering of seeds)

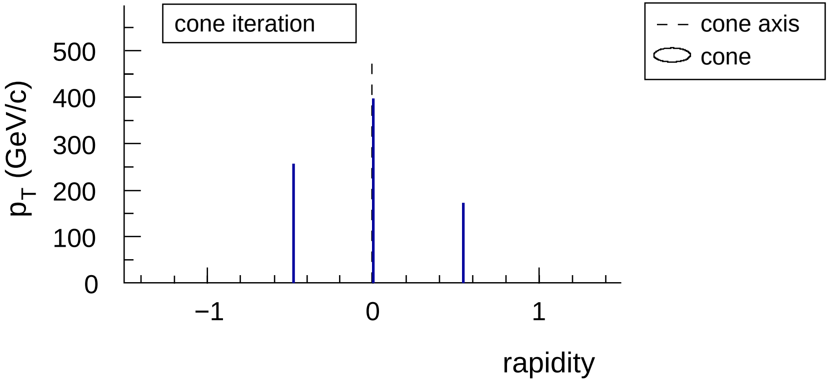


collinear sensitivity (2)
(signal split into two towers below threshold)



Collinear splitting can modify the hard jets: ICPR algorithms are collinear unsafe $\Longrightarrow$ perturbative calculations give ∞

(Animation courtesy of Gavin Salam)



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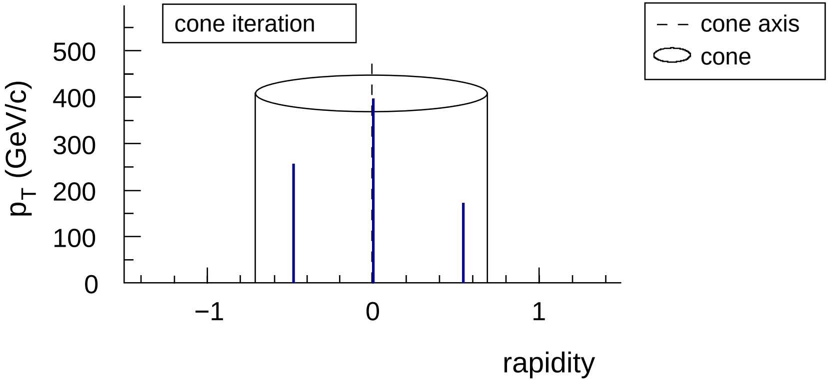

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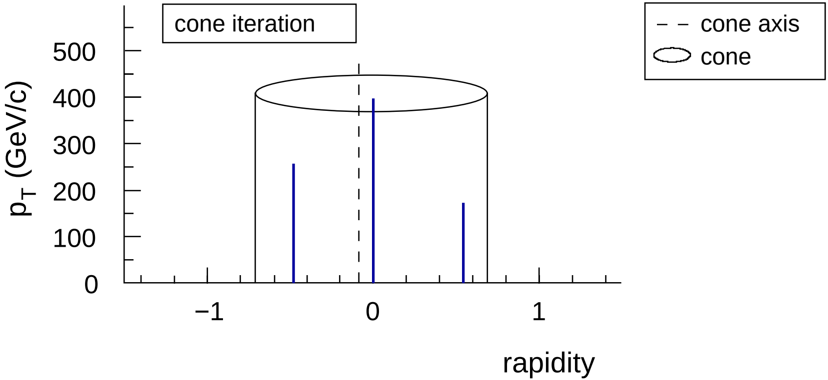

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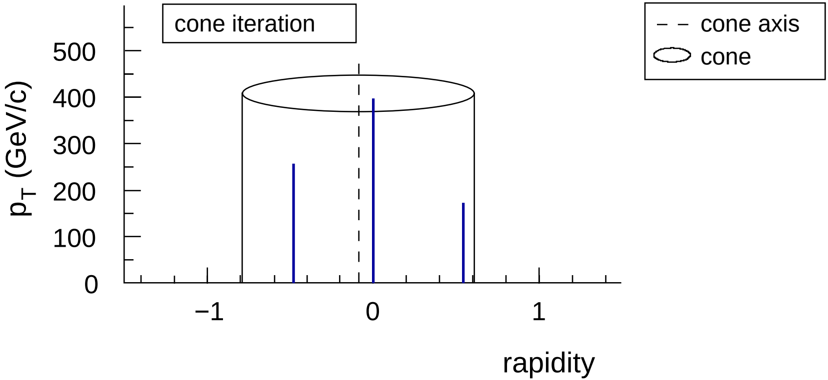

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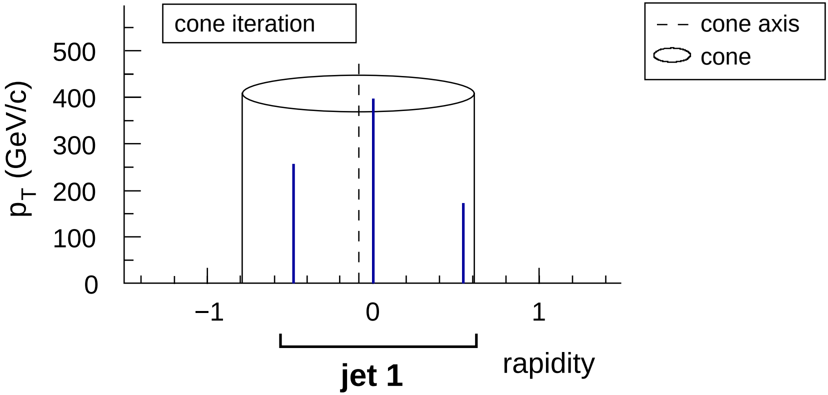

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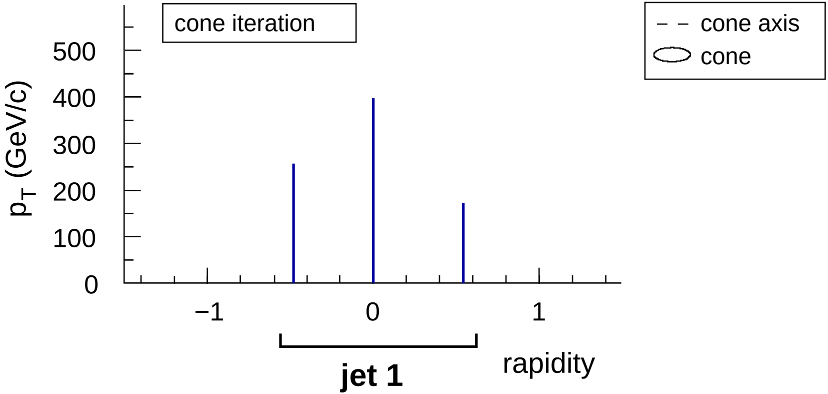

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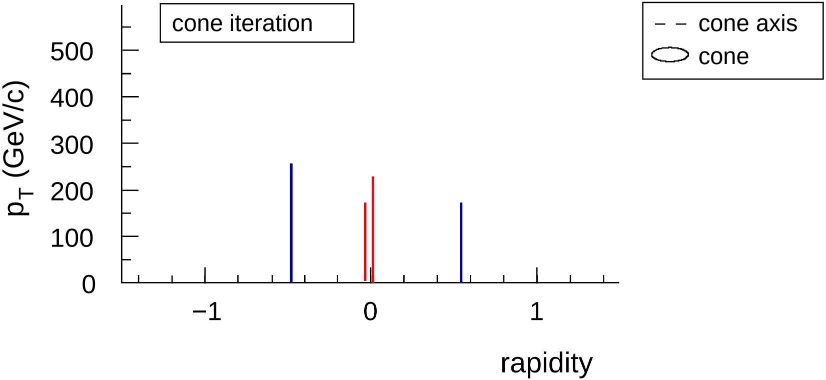

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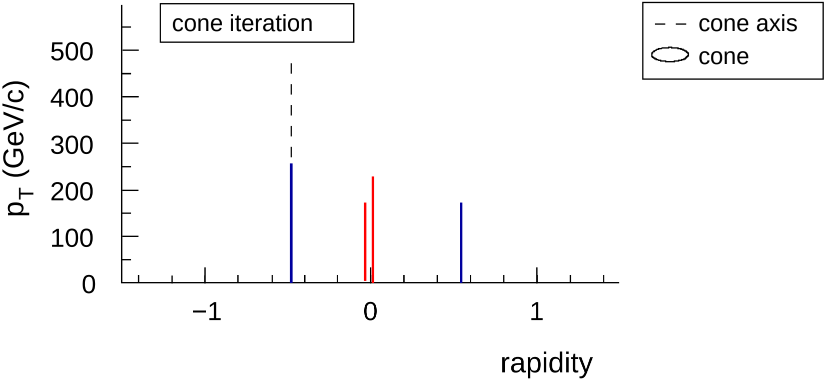

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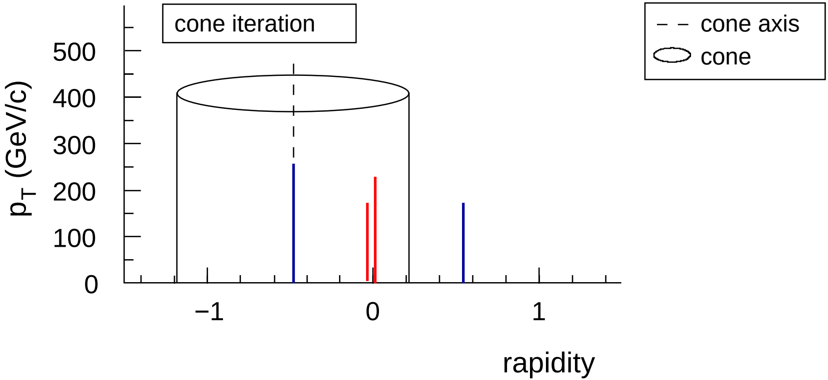

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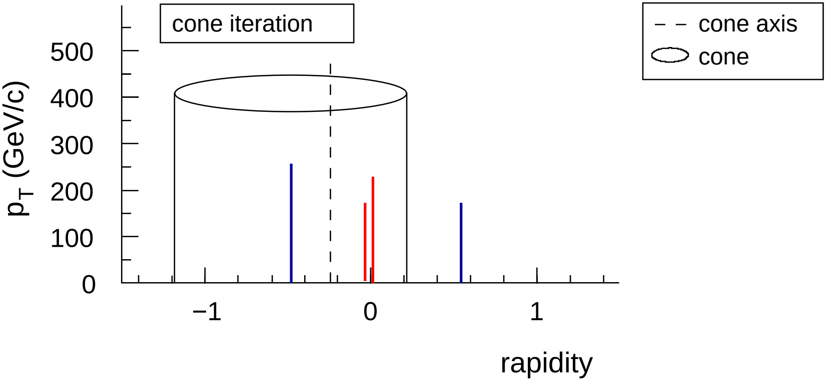

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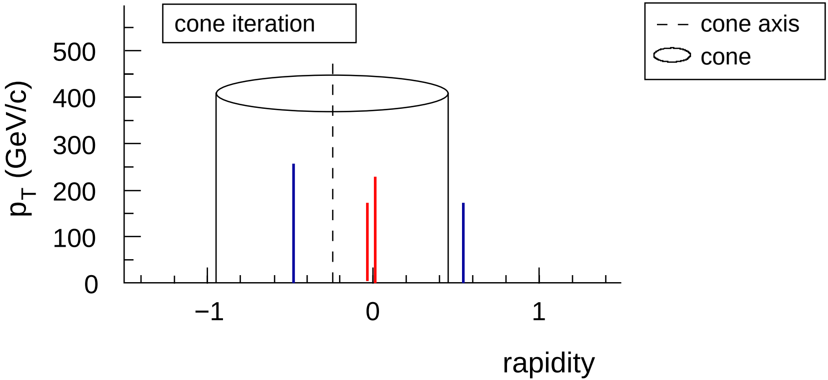

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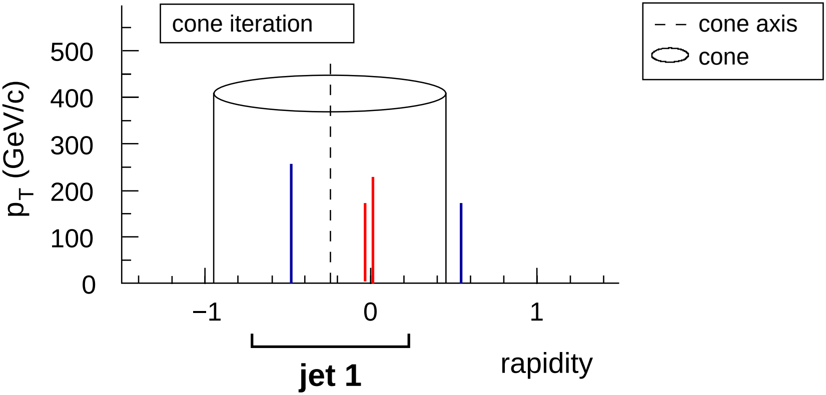

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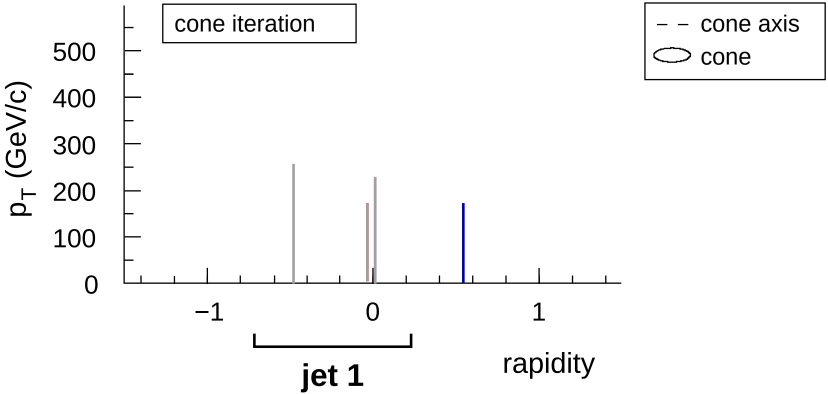

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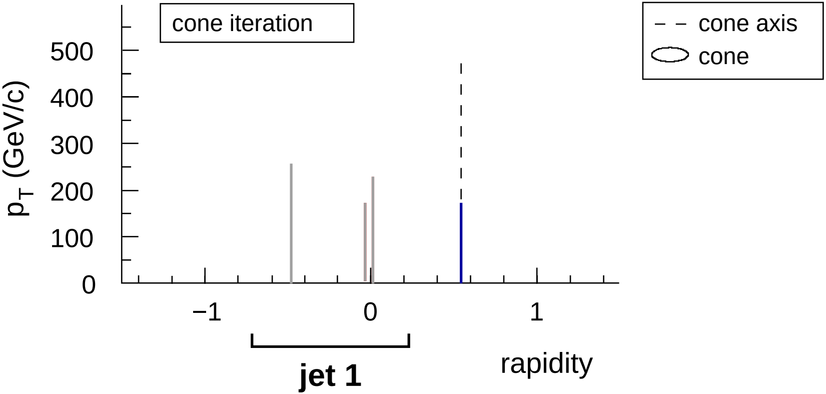

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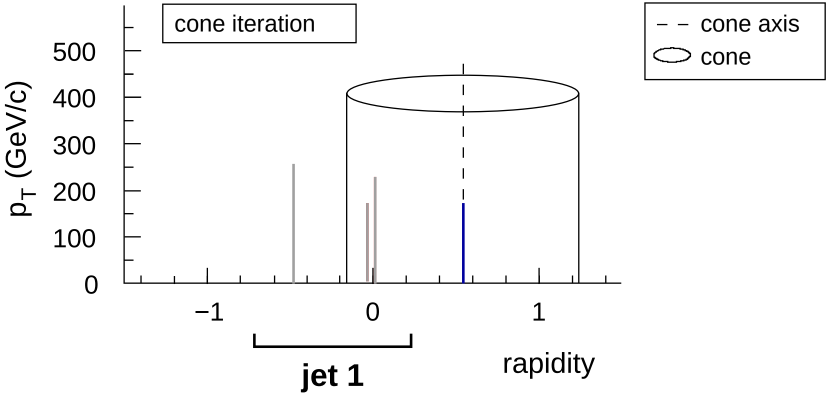

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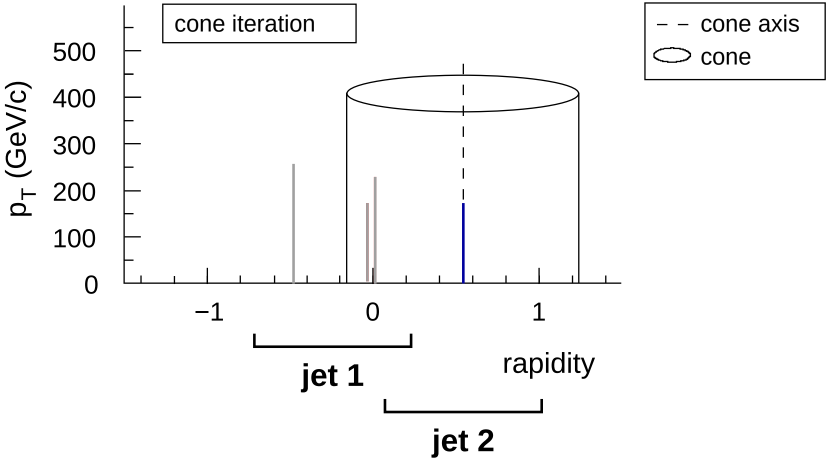

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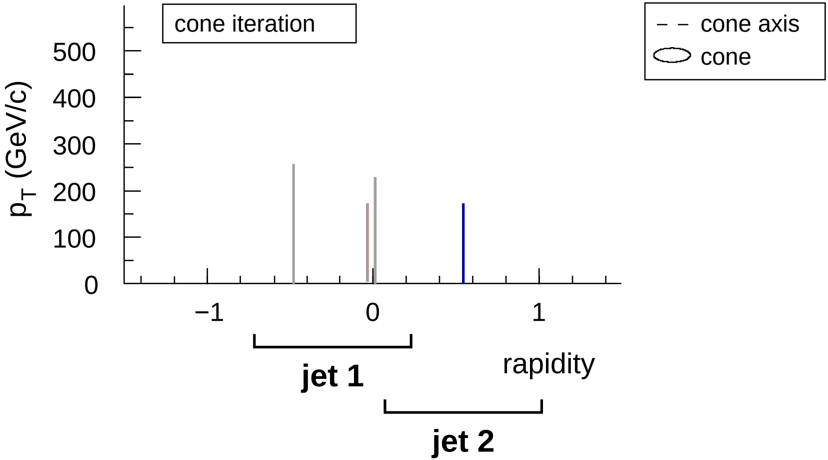

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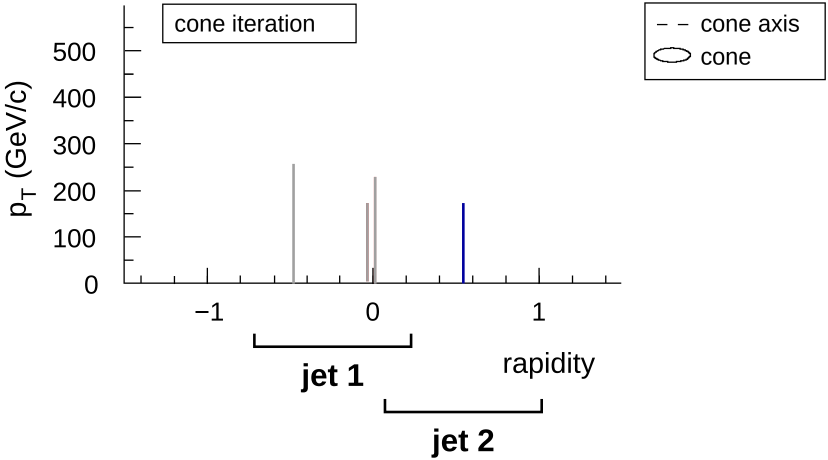

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(Animation courtesy of Gavin Salam)

Experimental Requirements for Jet Finders

- **Detector technology independence**
  - Minimal contributions to spatial and energy resolution
  - Insignificant effects of detector environment
    - Noise
    - Dead material
    - Cracks
  - Easy to calibrate
    - Well…
- **Environment independence**
  - Stability with changing luminosity
  - Identify all physically interesting jets from energetic partons in pertubative QCD (pQCD)
  - High reconstruction efficiency
- **Implementation**
  - Fully specified
    - All selections and other configurations known
  - Efficient use of computing sources

Popular Jet Algorithms in ATLAS

Seeded cone

- Place cone with radius R around seed
  - pT > 1 GeV
- Collect all particles in cone
- Re-calculate energy and direction of cone
  - 4-momentum recombination
- Find more particle in new cone
- Stop until no more particles to be found
  - Stable solution
  - Particles can be shared between jets
- Is not infrared safe
  - Needs split & merge (50% threshold)
- May miss signficant energy
  - Dark jets

Recursive recombination (kT)

- Calculate for all particles *i* and pairs *ij* :

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

$$= \min(p_{t,i}^2, p_{t,j}^2)\frac{\Delta y_{ij}^2 + \Delta\varphi_{ij}^2}{D^2}$$

$$d_i = p_{t,i}^2$$

- Find minimum d_{min} from all d_i, d_{ij}
- If d_{min} is a d_i, call i a jet and remove it from the list
- Else combine i and j into a jet
  - 4-momentum recombination
- Calculate new combinations
  - Stop when all particles declared jets
  - Each particle is part of one jet only (exclusive assignment)
- Infrared safe

kT Clustering Visualization (Gavin Salam)

$\mathbf{k_t}$ alg.: Find smallest of

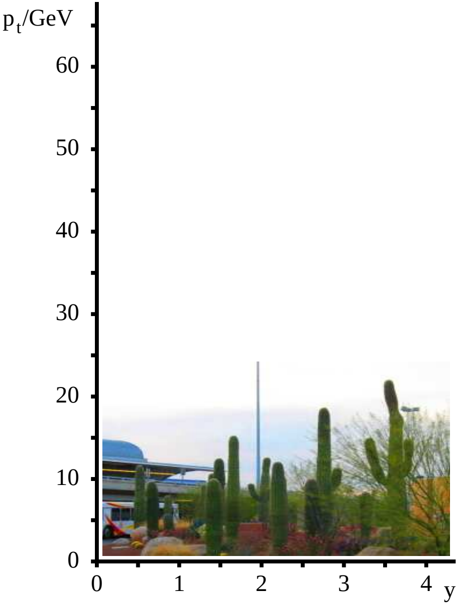
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

If d_{ij} recombine; if d_{iB}, i is a jet

Example clustering with k_t algorithm, $R = 0.7$

ϕ assumed 0 for all towers

(Animation courtesy of Gavin Salam)



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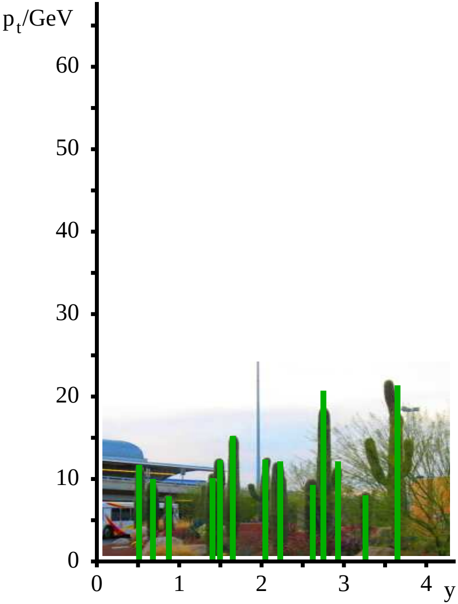

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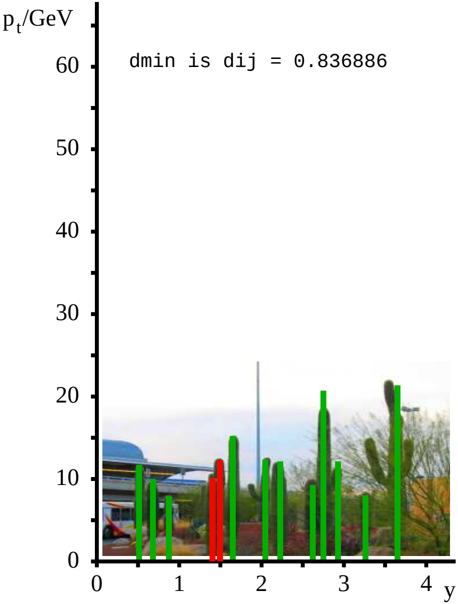

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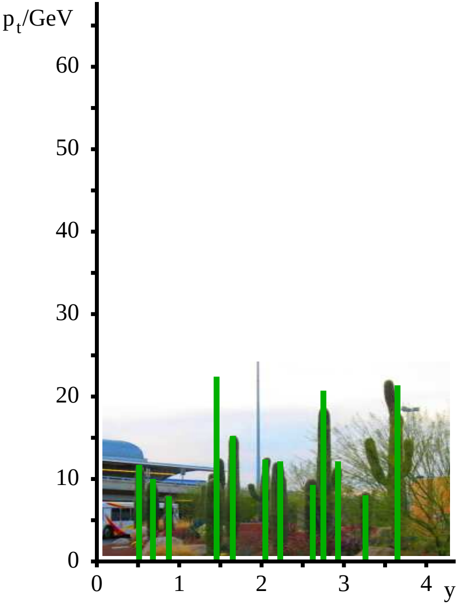

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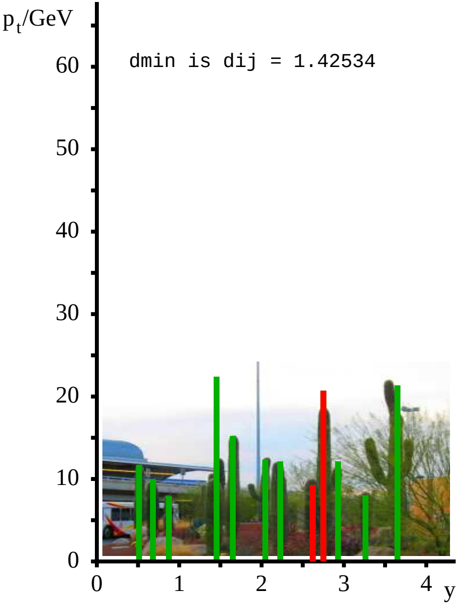

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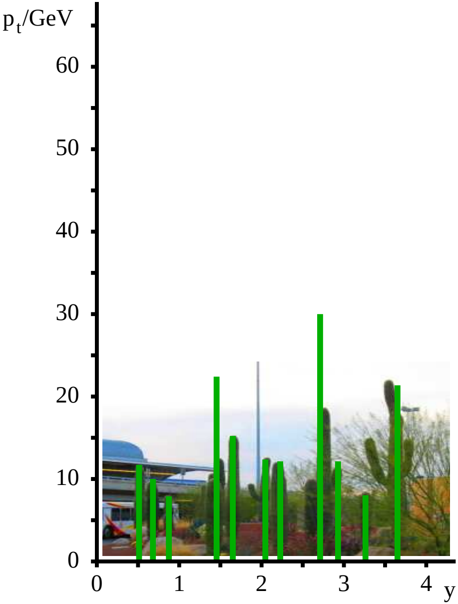

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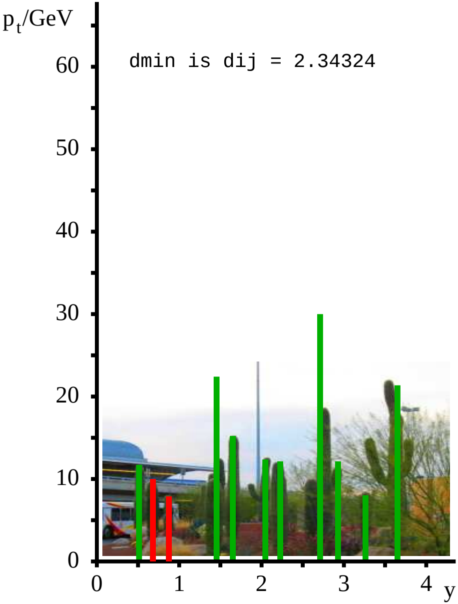

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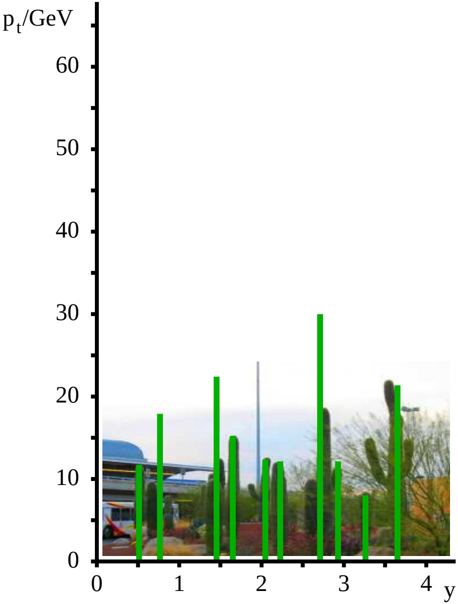

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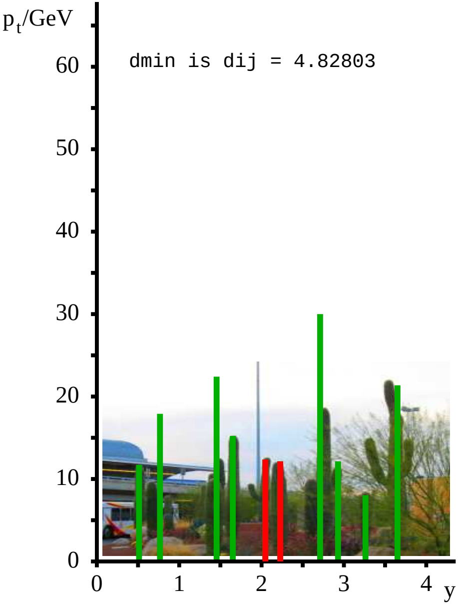

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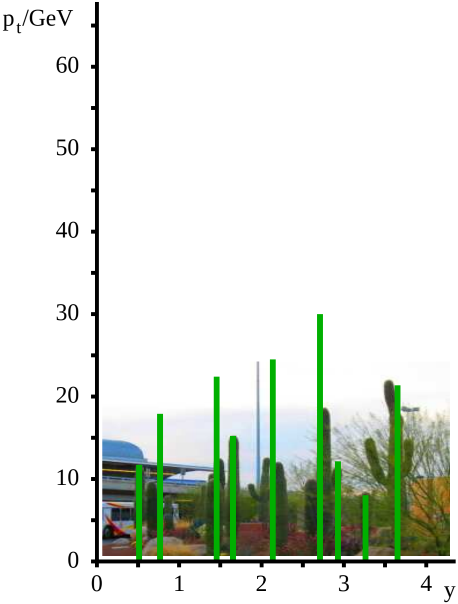

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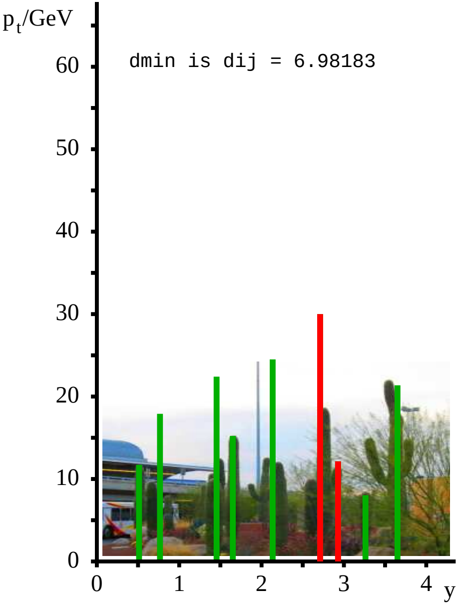

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dmin is dij = 6.98183
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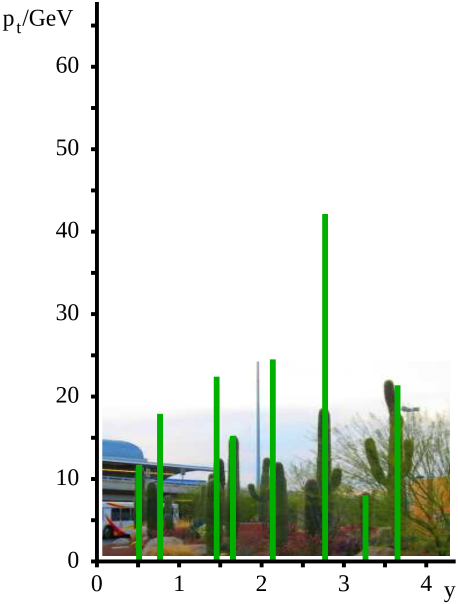
(Animation courtesy of Gavin Salam)



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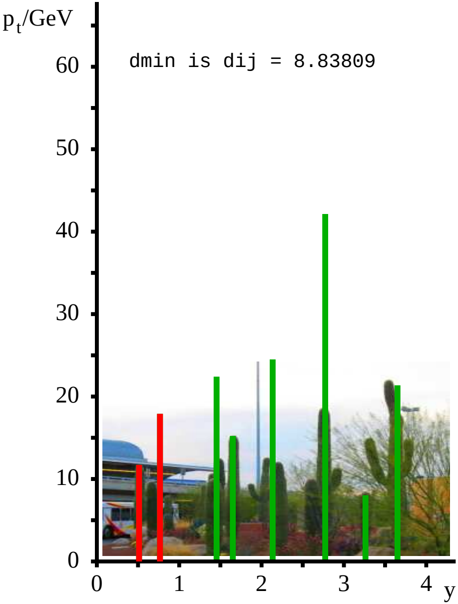

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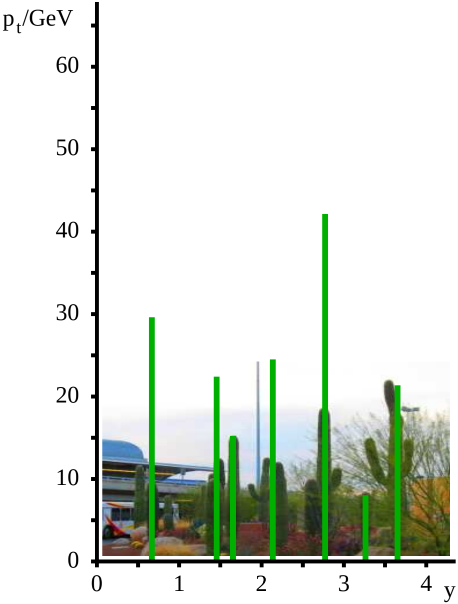

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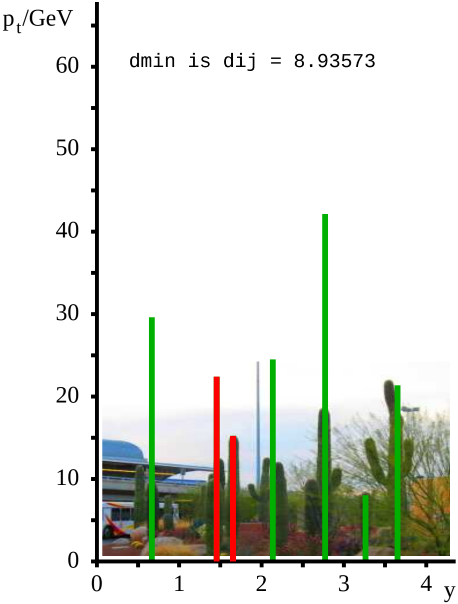

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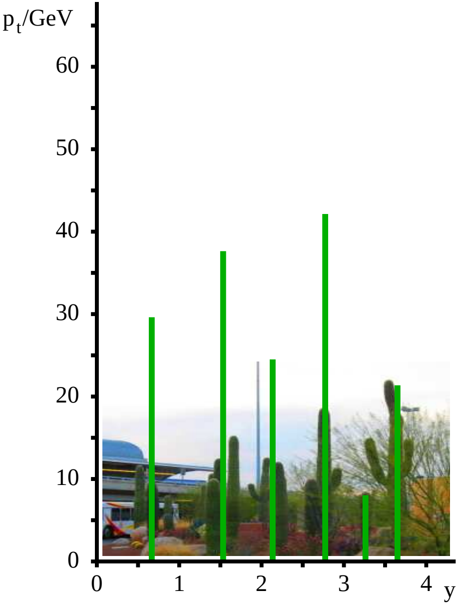

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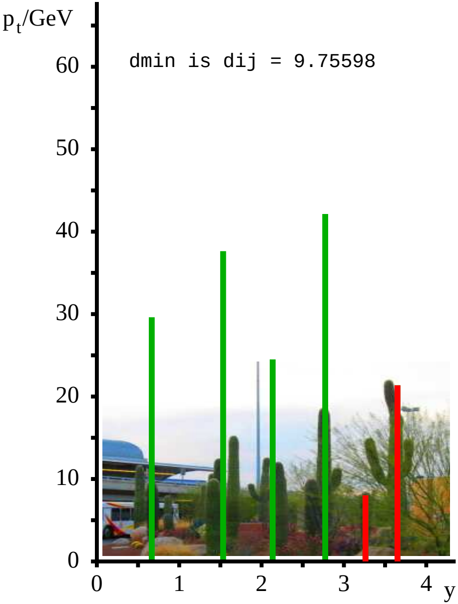

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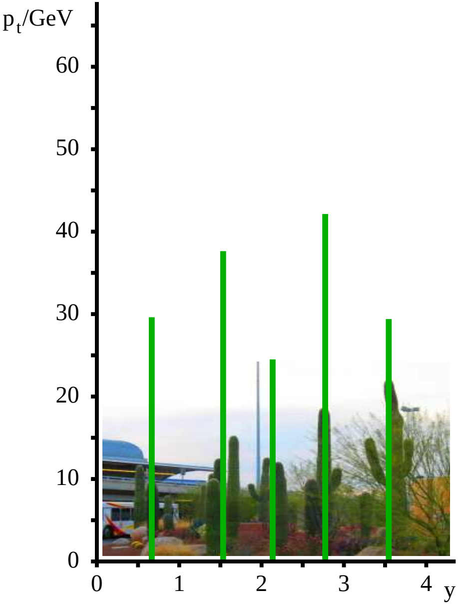

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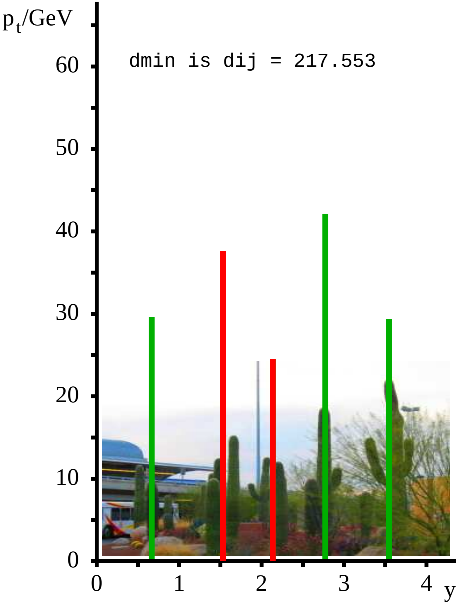

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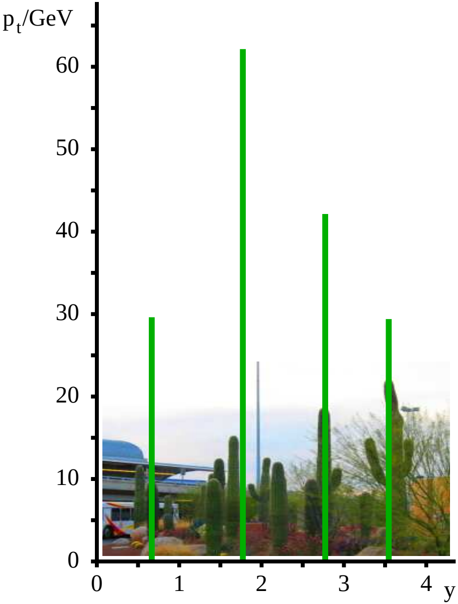

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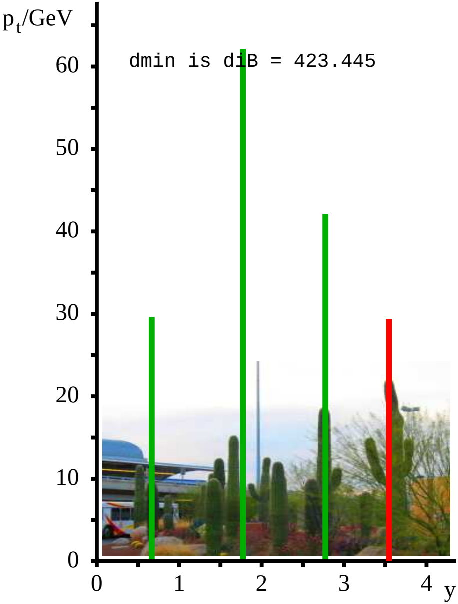

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Example clustering with k_t algorithm, $R = 0.7$

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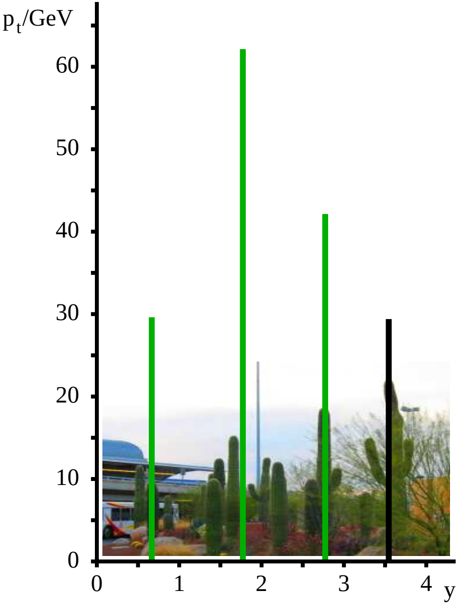
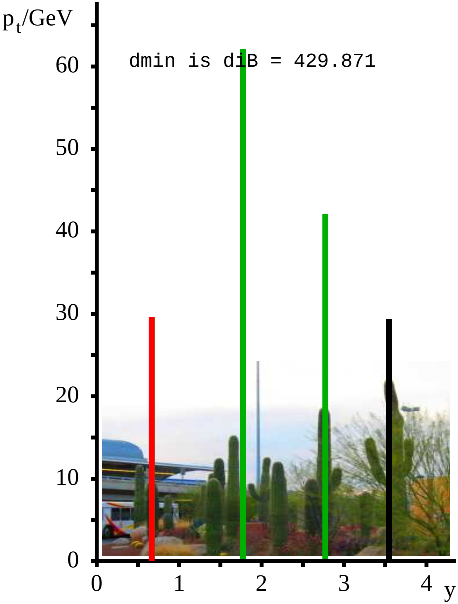


(Animation courtesy of Gavin Salam)



$\mathbf{k_t}$ alg.: Find smallest of

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2, \quad d_{iB} = k_{ti}^2$$

If d_{ij} recombine; if d_{iB}, i is a jet
Example clustering with k_t algorithm, $R = 0.7$

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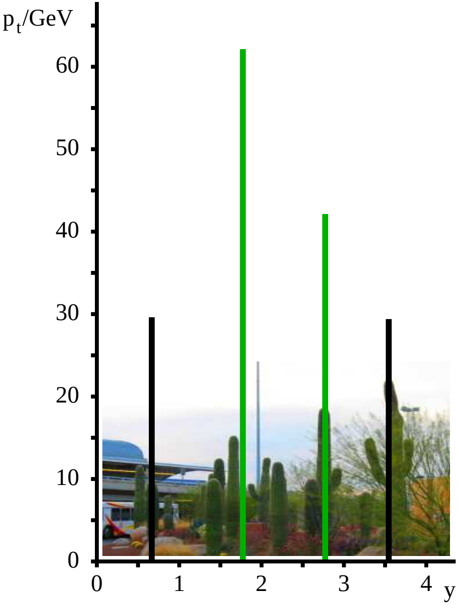
(Animation courtesy of Gavin Salam)



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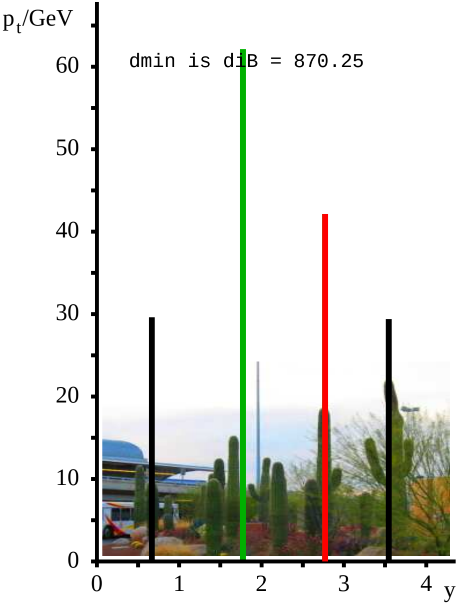

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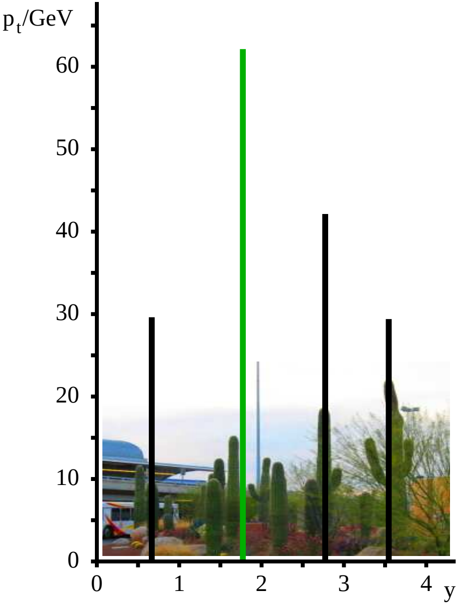

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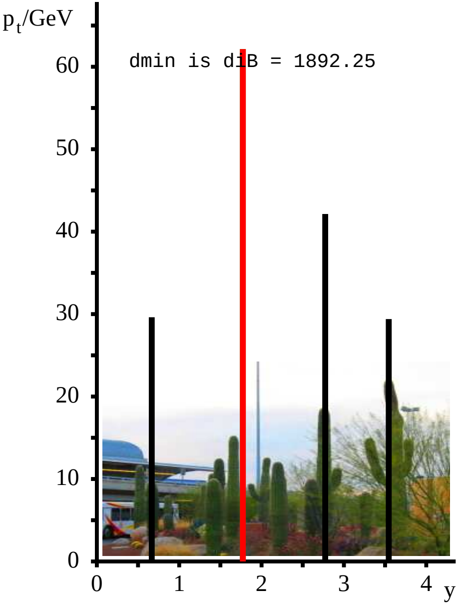

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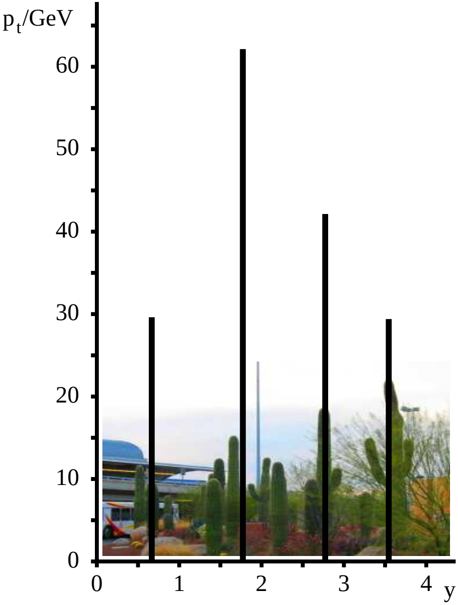

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ϕ assumed 0 for all towers

(Animation courtesy of Gavin Salam)

Jet Calibration

Jet Response

Jets are bundles of particles

- ~25% initial photons
- Hadronic particles include mostly pions, kaons, protons and their anti-particles
  - Different response!

Jet response in non-compensating calorimeters

- Jet signal depends on fragmentation/particle content
  - Significant jet-to-jet response variations due to more or less photons

$$E^{jet}_{true} = E^{calo}_{dep} + E^{loss}_{mag} + E^{loss}_{low} + E^{loss}_{leak} + E^{loss}_{out} - E^{gain}_{UE\otimes PU} - E^{gain}_{env}$$

E^{calo}_{dep}	energy deposited in the calorimeter within signal definition
E^{loss}_{mag}	charged particle energy lost in solenoid field
E^{loss}_{low}	particle energy lost in dead material
E^{loss}_{leak}	energy lost due to longitudinal leakage
E^{loss}_{out}	energy lost due to jet algorithm/calorimeter signal definition
$E^{gain}_{UE\otimes PU}$	energy added by underlying event and/or pile-up
E^{gain}_{env}	energy added by response from other nearby particles/jets

only source of signal!

Jet Calibration Strategies

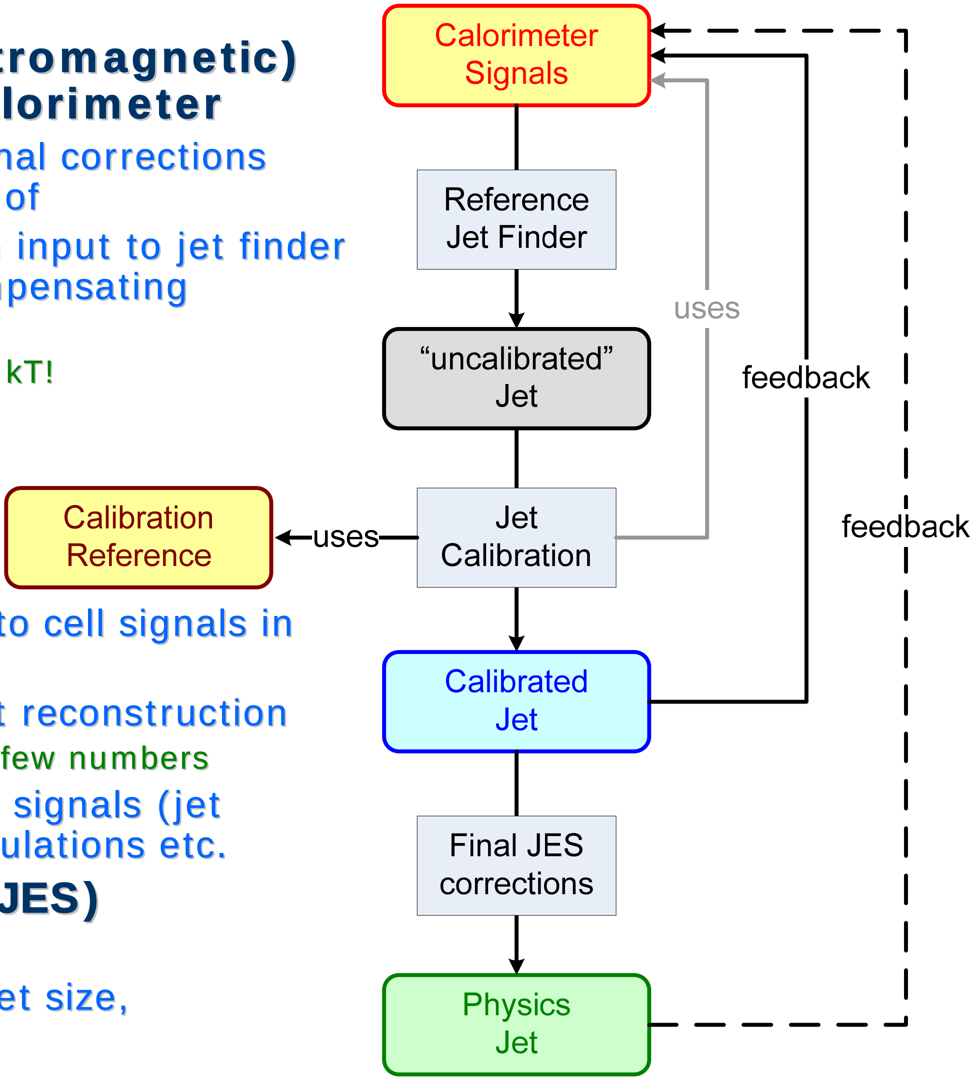
- **Preliminaries**
  - There is no universal model for jet calibration
    - Immediate consequence from the fact that there is no universal jet finder (or jet finder configuration) appropriate for all physics reconstruction/analysis
    - Calibration approach depends on much more than detector signal characteristics and signal definitions
    - But there two general strategies
  - Publications often refer to jets corrected to parton level
    - Ill-defined concept in pp (c.f. Gavin Salam)
    - Maybe more useful in e^+e^- or deep inelastic scattering (?)
  - At LHC jets are foremost calibrated to the particle (hadron) level
    - First aim to reconstruct the energy carried by particles into the detector (calorimeter, of course)
      - Needs detailed and most accurate detector signal simulations for testbeams and physics processes
    - Link to interaction physics needs full modeling of collision processes
      - Need all particles, not only hard scatter fragments (don't really know which those are anyway)
  - Factorize jet calibration as much as possible
    - Better control of systematics
      - Can even use hadron testbeams to a point (see later)
- **Most of all: every experiment needs its own model in the end!**

Jet Calibration Strategies Overview

- **Two models:**
  - Model I: Calibration in jet context
    - First find jet, then calibrate, then correct if needed
  - Model II: Calibration in cluster context
    - Calibrate calorimeter signals, then find jet, then correct (likely needed)
      - Local hadronic calibration plugs in here!
- **Best calibration likely a combination of both models**
  - Need to keep track of systematics!

Full Calibration in Jet Context

- **Find the jet using basic (electromagnetic) energy scale signals in the calorimeter**
  - Assumes that all elementary signal corrections (electronics etc.) are taken care of
  - Relative mis-calibration between input to jet finder can O(30%) or more in non-compensating calorimeters
    - Can be a problem especially for kT!
  - Best for compensating calorimeters, as basic energy scale is ~hadronic scale
- **Then calibrate it**
  - Complex signal weights applied to cell signals in jet (default)
  - Lower level of factorization of jet reconstruction
    - Many corrections absorbed in a few numbers
  - Feedback of calibrations to basic signals (jet constituents) for missing ET calculations etc.
- **Apply final Jet Energy Scale (JES) corrections**
  - Correct for different algorithm, jet size, calorimeter signal definition


Calorimeter Signals

Reference Jet Finder

“uncalibrated” Jet

Jet Calibration

Calibration Reference

uses

uses

feedback

feedback

Calibrated Jet

Final JES corrections

Physics Jet

Cell Calibration Functions From Jets

- **Sample of fully simulated QCD di-jet events from pT>17 GeV/c to ~4000 TeV/c**
  - Match reconstructed calorimeter jet with close-by particle jet
  - Both jets reconstructed with Seeded Cone R=0.7
  - Match only successful if only one jet close by
  - Calorimeter jets are based on tower signals in a grid of $\Delta\eta x \Delta\eta = 0.1x0.1$
- **Determine cell signal weights (H1-style)**
  - De-compose matched calorimeter jet into individual cell signals
  - Determine cell signal weights in resolution optimization fit using truth particle jet energy as normalization
    - Weights are function of cell location and cell signal density
      - Dense signals – em, less dense signals hadronic
  - Re-calculate jet four-momentum using cell weights
    - Jet energy and direction change
- **Determine additional correction functions**
  - Different jet size, cluster jets, different jet algorithm (kT)

"H1" Style Cell Signal Weighting in ATLAS

Fit constraint for weights:

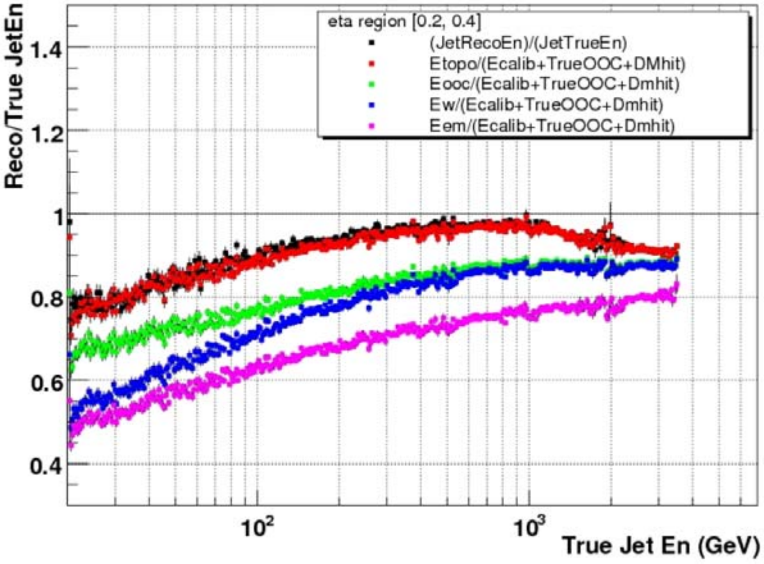
$$\frac{\partial}{\partial w}\sum_{j=1}^{N_{evts}}\left(\left(\sum_{i=1}^{N_{cells}} w(\rho_i,\vec{X}_i)E_i\right)-E_{truth}^{jet}\right)^2=0$$

Jet four-momentum calculation after fit

$$\left(E_{reco}^{jet},\vec{p}_{reco}^{\,jet}\right)=\left(\sum_{i=1}^{N_{cells}} w(\rho_i,\vec{X}_i)\left(E_i,\vec{p}_i\right)\right)\times\underbrace{f\left(\eta_{jet},p_t^{jet}\right)}_{=1\ \text{for reference jets}},\ \text{with}\ E_i=\left|\vec{p}_i\right|$$

Cluster Context Jet Calibration

- **Calibrate calorimeter signals first as much as possible, then find jets**
  - Detector motivated (use measured signal shapes)
    - Applies calibration in the context of a specific calorimeter signal definition (topological clusters)
      - No jet context needed
    - Provides calibrated input to jet finding
      - Better for kT
  - Needs final jet energy scale corrections
    - Calibration derived from single particles
    - Feedback of final corrections for missing ET calculations etc.
  - High level of factorization, better control of systematics (?)
    - To be investigated
- **Provides hadronic calibration outside of jet context**
  - Previous discussion of local hadronic calibration



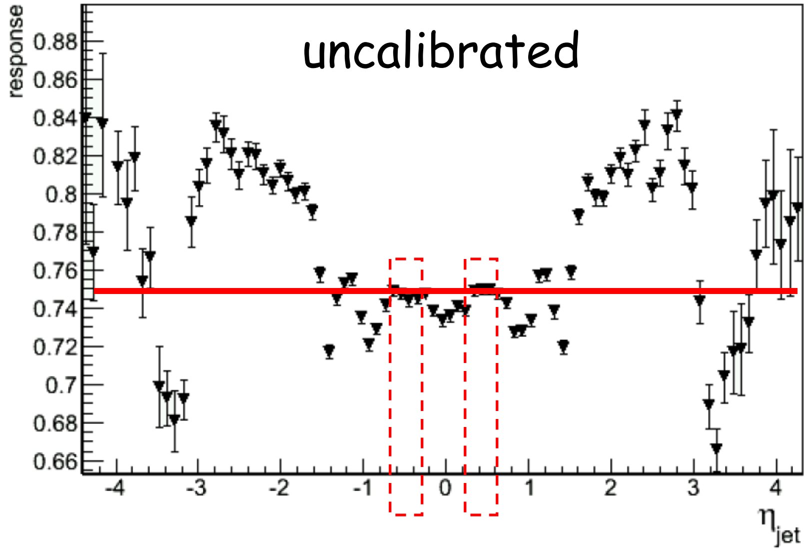
“Data Only” Jet Calibration

	Task	JES	Tool
1	PileUp Subtraction	$E_{bc}^{jet}(\eta_{jet},\varphi_{jet}) = E_{0}^{jet}(\eta_{jet},\varphi_{jet}) - \overline{\rho}_{0}^{mb}(N_{vtx},\eta_{jet},\varphi_{jet})\cdot A_{\eta\varphi}^{jet}$	minbias events (determine E/Et density in pile-up as function of # vertices, next slide)
2	Relative response corrections (η,φ)	$E_{rel}^{jet} = \overline{f}(\eta_{jet},\varphi_{jet})\cdot E_{bc}^{jet}(\eta_{jet},\varphi_{jet})$	di-jet pT balance (equalize jet response of calorimeter system with respect to central region in slices of φ, next slide)
3	Absolute energy scale corrections	$E_{rec}^{jet} = \overline{C}(p_{t,rel}^{jet},\ldots)\otimes E_{rel}^{jet}$	photon/jet pT balance in direct photon production (correct JES from pT balance with photon, as function of jet pT etc.)

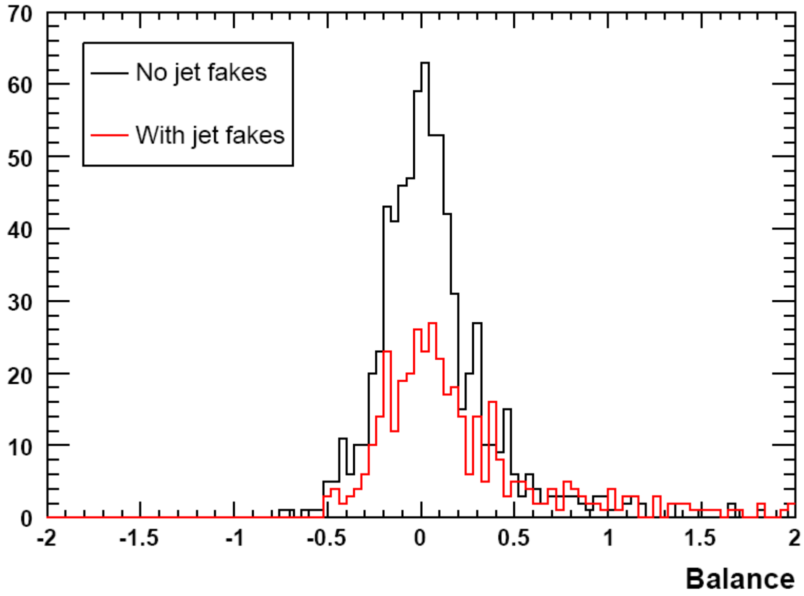
Conceptional Features & Limitations

- **Data only approach from three different events**
  - MB for PileUp corrections
    - Underlying event is folded in
  - Di-jets for response equalization in pseudorapidity and azimuth
    - Use central jet as reference
    - Back-to-back topologies needed
  - Prompt photons for absolute JES corrections
    - Precision limit by photon reconstruction quality and di-jet background
    - Also theoretical uncertainties (ISR,FSR) important for very high precision
  - Control of systematics seems to be possible
    - “independent” calibration and correction sources
- **More is needed care is needed…**
  - E.g., mostly gluon jets di-jets versus mostly quark jets in prompt photon production
  - Absolute correction is to interaction (parton) level, not particle level!

D.Schouten, M. Vetterli, *ATL-PHYS-INT-2007-011*

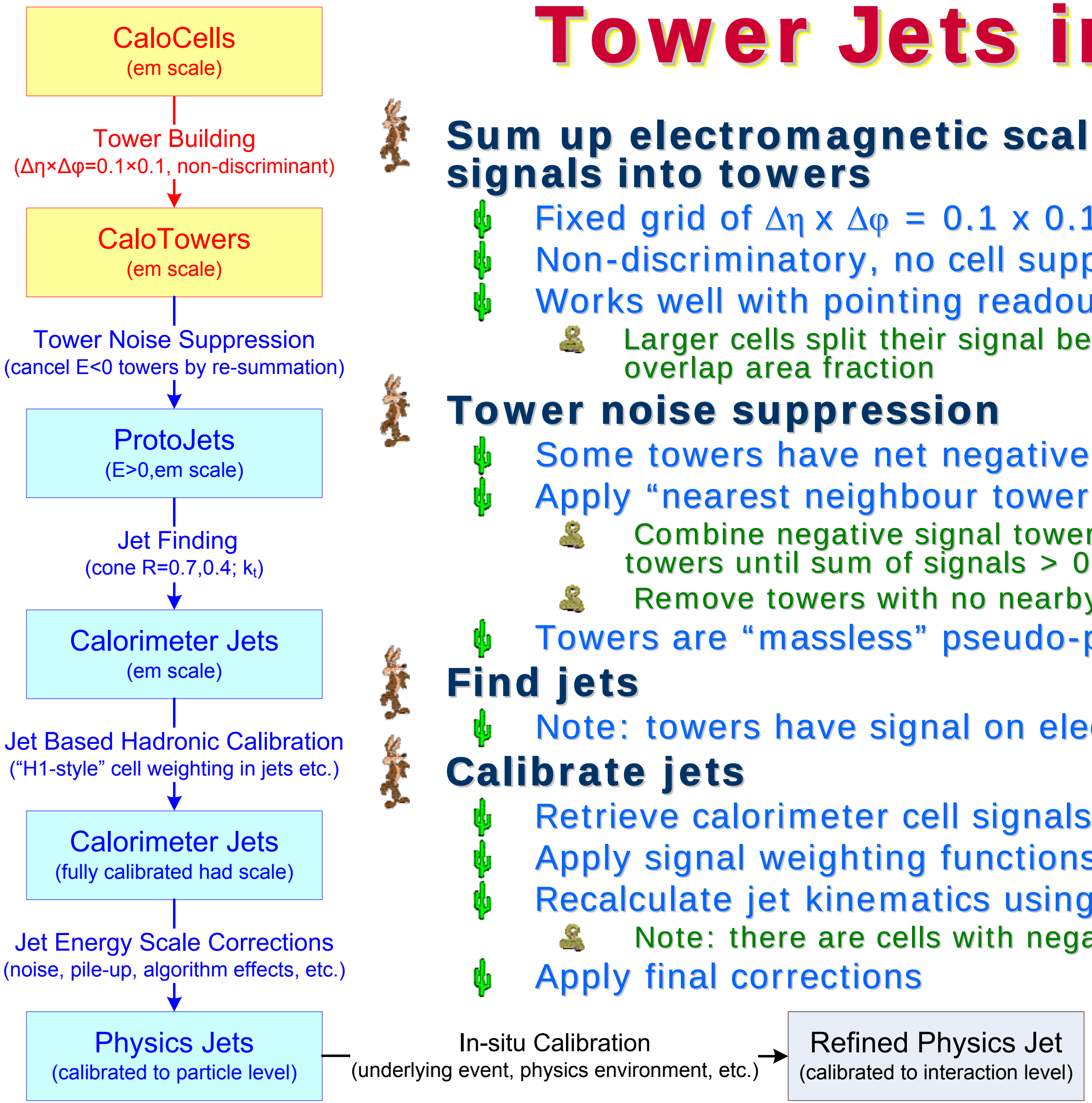


M. Hurwitz, FDR-1 User *Meeting April 1, 2008*



Jet Reconstruction

Tower Jets in ATLAS



CaloCells
(em scale)

Tower Building
($\Delta\eta\times\Delta\varphi=0.1\times0.1$, non-discriminant)

CaloTowers
(em scale)

Tower Noise Suppression
(cancel E<0 towers by re-summation)

ProtoJets
(E>0,em scale)

Jet Finding
(cone R=0.7,0.4; k_t)

Calorimeter Jets
(em scale)

Jet Based Hadronic Calibration
("H1-style" cell weighting in jets etc.)

Calorimeter Jets
(fully calibrated had scale)

Jet Energy Scale Corrections
(noise, pile-up, algorithm effects, etc.)

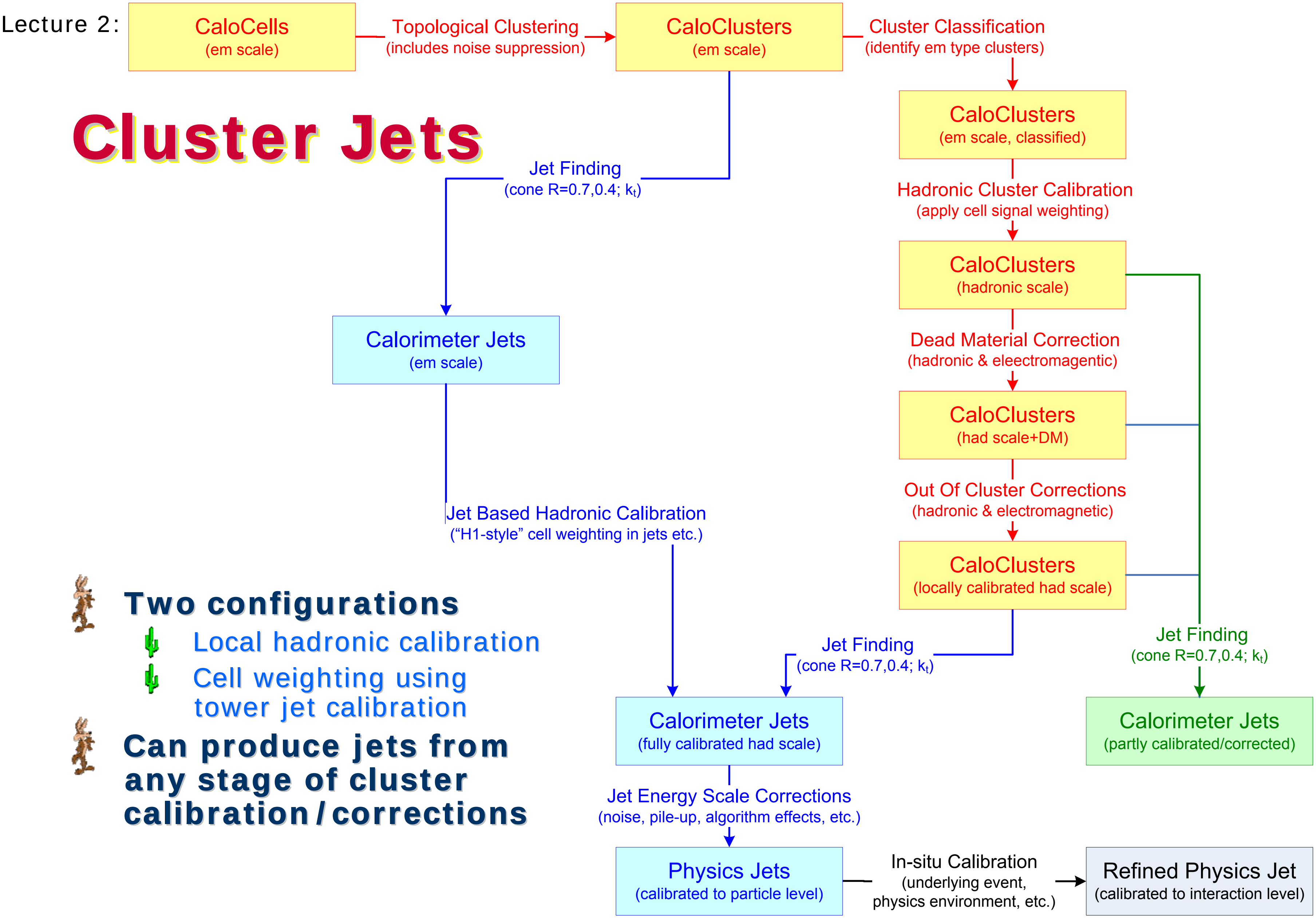
Physics Jets
(calibrated to particle level)

In-situ Calibration
(underlying event, physics environment, etc.)

Refined Physics Jet
(calibrated to interaction level)

- **Sum up electromagnetic scale calorimeter cell signals into towers**
  - Fixed grid of $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
  - Non-discriminatory, no cell suppression
  - Works well with pointing readout geometries
    - Larger cells split their signal between towers according to the overlap area fraction
- **Tower noise suppression**
  - Some towers have net negative signals
  - Apply "nearest neighbour tower recombination"
    - Combine negative signal tower(s) with nearby positive signal towers until sum of signals > 0
    - Remove towers with no nearby neighbours
  - Towers are "massless" pseudo-particles
- **Find jets**
  - Note: towers have signal on electromagnetic energy scale
- **Calibrate jets**
  - Retrieve calorimeter cell signals in jet
  - Apply signal weighting functions to these signals
  - Recalculate jet kinematics using these cell signals
    - Note: there are cells with negative signals!
  - Apply final corrections

Cluster Jets



Lecture 2:

CaloCells (em scale) → Topological Clustering (includes noise suppression) → CaloClusters (em scale)

CaloClusters (em scale) → Cluster Classification (identify em type clusters) → CaloClusters (em scale, classified)

CaloClusters (em scale, classified) → Hadronic Cluster Calibration (apply cell signal weighting) → CaloClusters (hadronic scale)

CaloClusters (hadronic scale) → Dead Material Correction (hadronic & eleectromagentic) → CaloClusters (had scale+DM)

CaloClusters (had scale+DM) → Out Of Cluster Corrections (hadronic & electromagnetic) → CaloClusters (locally calibrated had scale)

CaloClusters (em scale) → Jet Finding (cone R=0.7,0.4; k_t) → Calorimeter Jets (em scale)

Calorimeter Jets (em scale) → Jet Based Hadronic Calibration (“H1-style” cell weighting in jets etc.) → Calorimeter Jets (fully calibrated had scale)

CaloClusters (locally calibrated had scale) → Jet Finding (cone R=0.7,0.4; k_t) → Calorimeter Jets (fully calibrated had scale)

CaloClusters (hadronic scale), CaloClusters (had scale+DM), CaloClusters (locally calibrated had scale) → Jet Finding (cone R=0.7,0.4; k_t) → Calorimeter Jets (partly calibrated/corrected)

Calorimeter Jets (fully calibrated had scale) → Jet Energy Scale Corrections (noise, pile-up, algorithm effects, etc.) → Physics Jets (calibrated to particle level)

Physics Jets (calibrated to particle level) → In-situ Calibration (underlying event, physics environment, etc.) → Refined Physics Jet (calibrated to interaction level)

- **Two configurations**
  - Local hadronic calibration
  - Cell weighting using tower jet calibration
- **Can produce jets from any stage of cluster calibration / corrections**

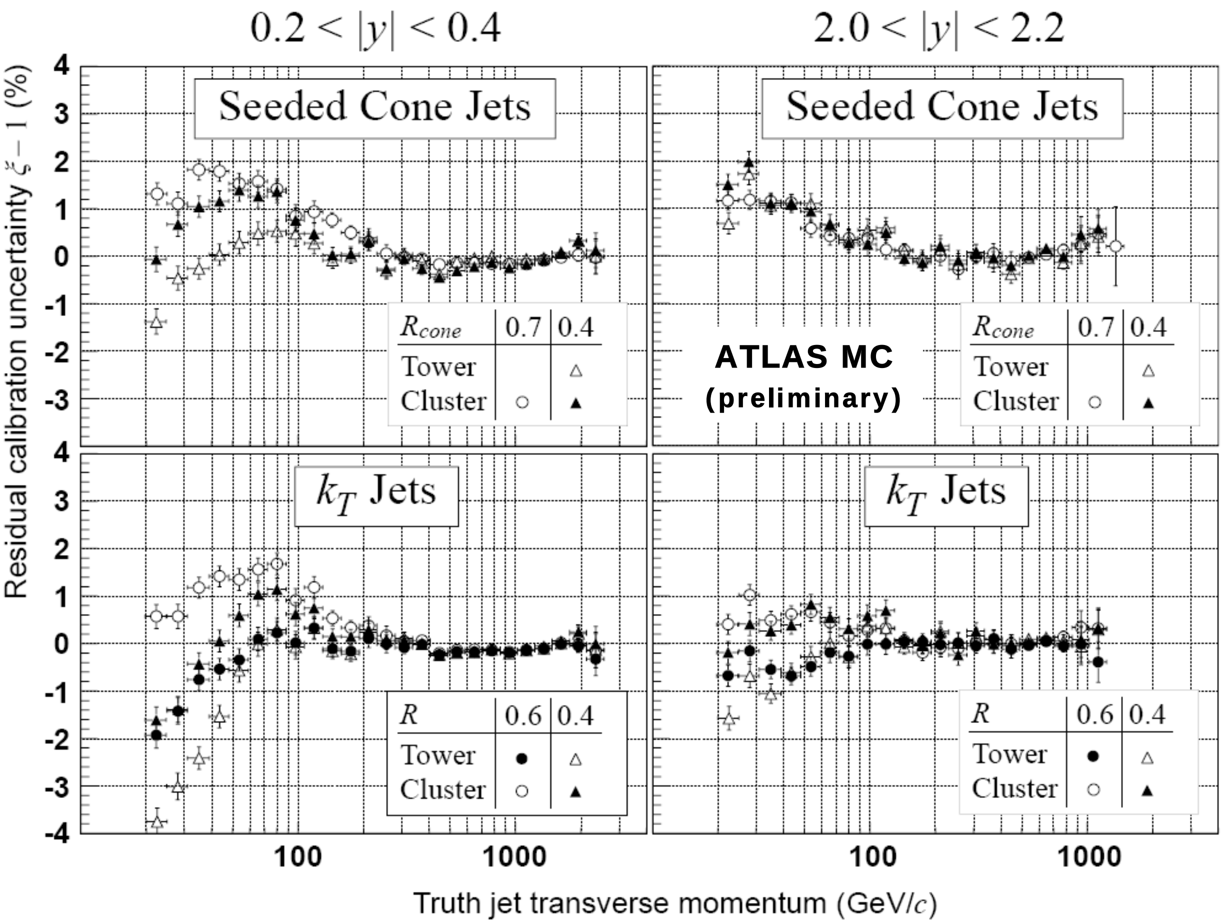
Deviations Signal Linearity

Estimated effect of a distorted detector

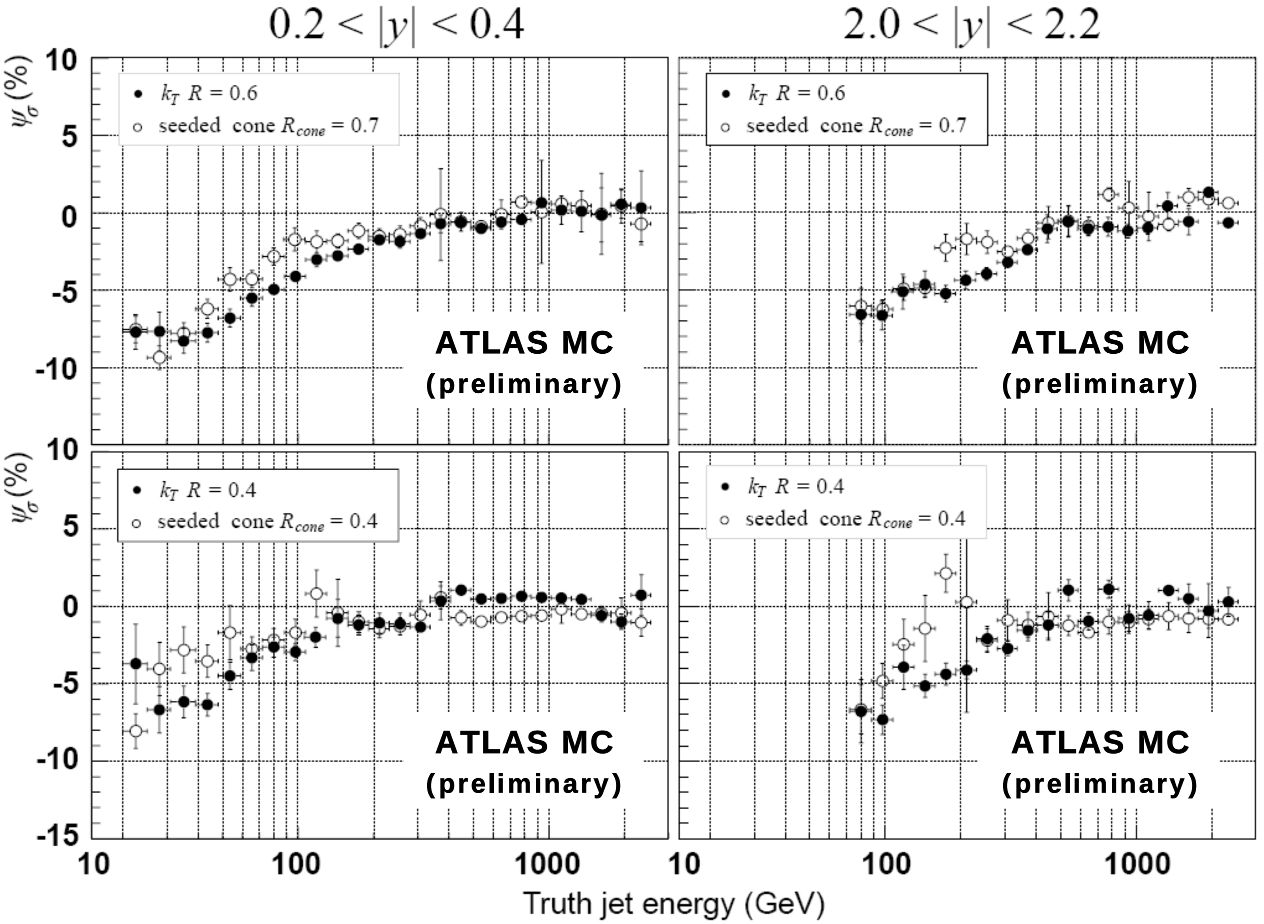
$$\xi = \frac{\left(E_{jet}^{calo} / E_{jet}^{truth}\right)_{alt}}{\left(E_{jet}^{calo} / E_{jet}^{truth}\right)_{ref}}$$

Effect of detector distortion depends on jet size, calo signal choice, and kinematic domain:

~ 2% for cone jets, up to ~4% for central (narrow) kT jets!



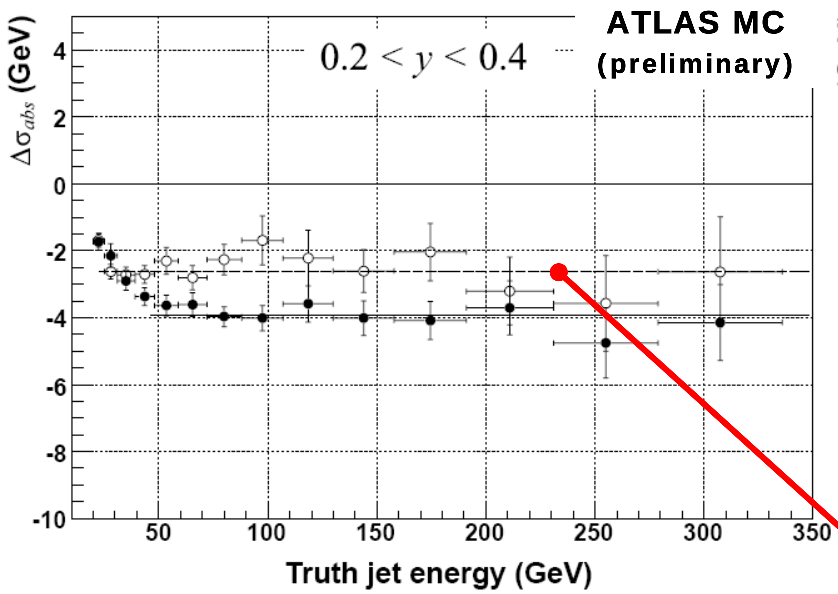
Effect of calorimeter signal choice on jet energy resolution

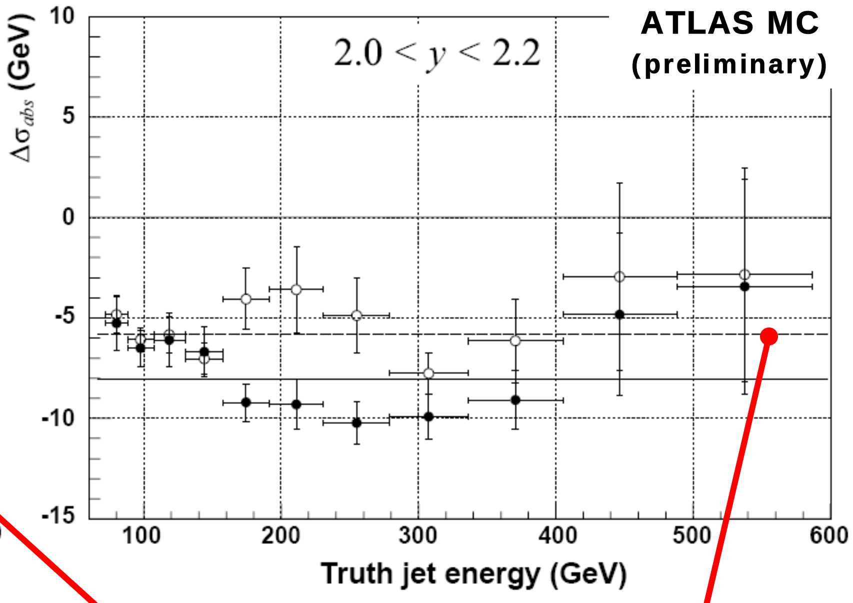


Cluster jets have better resolution at low energies even for non-optimal cell weights! ->noise?

$$\psi_\sigma = \begin{cases} \sqrt{\Delta\sigma_{rel}} & \Delta\sigma_{rel} > 0 \\ -\sqrt{-\Delta\sigma_{rel}} & \Delta\sigma_{rel} < 0 \end{cases}, \Delta\sigma_{rel} = \left(\frac{\sigma(E_{cluster})}{E_{cluster}}\right)^2 - \left(\frac{\sigma(E_{tower})}{E_{tower}}\right)^2$$

Energy Resolution Differences





open symbols: cone, filled symbols: kT

$$\Delta\sigma_{abs} = \psi_{\sigma} \cdot E_{jet}$$

Clear indication of noise suppression by TopoClusters!