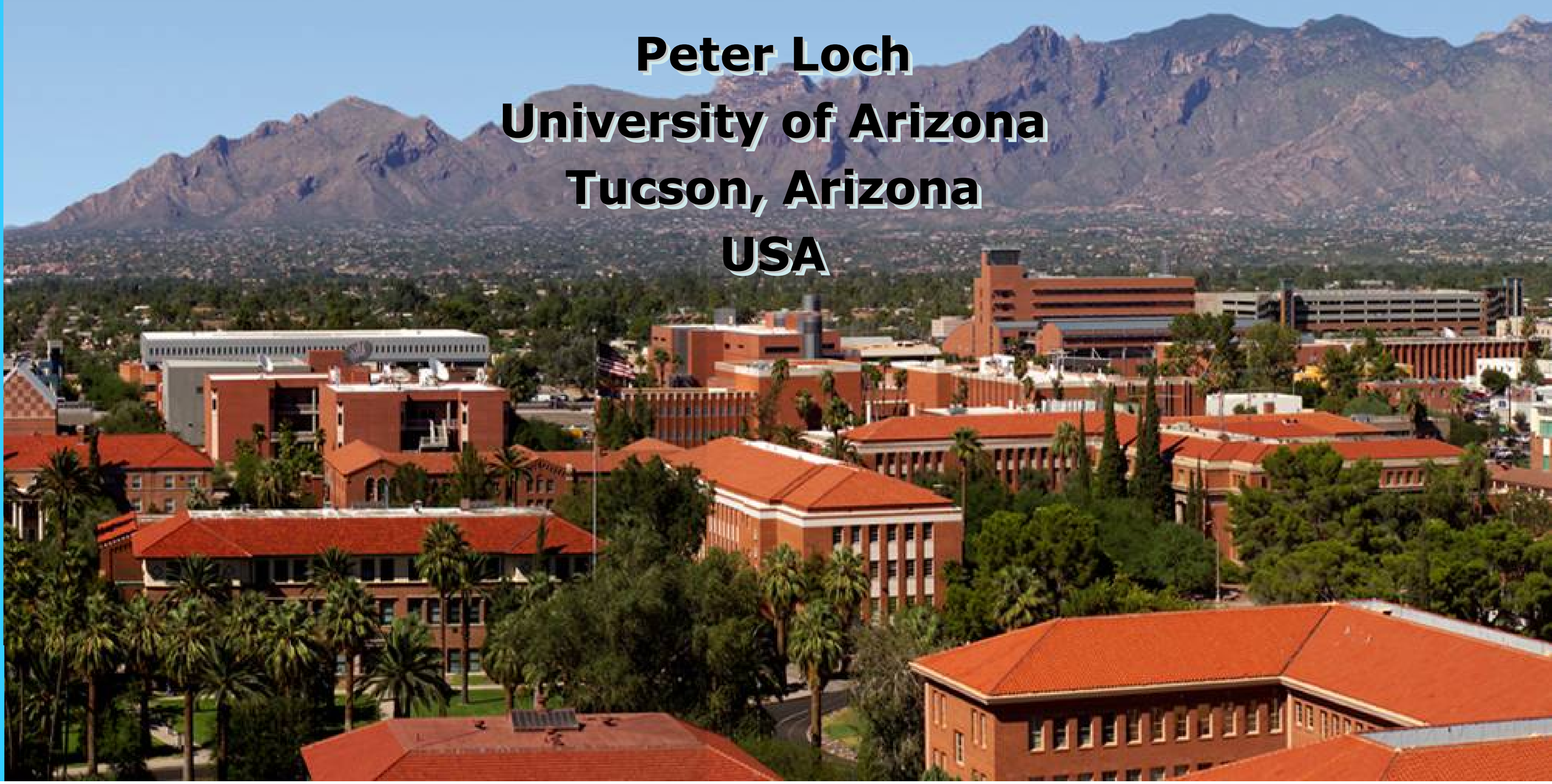
THE UNIVERSITY OF ARIZONA

Detector Understanding with First LHC Data
DESY, Hamburg, 29 June – 3 July 2009

Introduction To Jet & Missing Transverse Energy Reconstruction at LHC

Peter Loch
University of Arizona
Tucson, Arizona
USA



Preliminaries

Scope

- Focus on explanation of features, algorithms and methods
  - Including some pointers to underlying principles, motivations, and expectations
  - Some reference to physics
- Everything is based on simulations
  - Experiments may tell a (very?) different story in some cases
  - Restricted to published material (mixed CMS/ATLAS audience)
    - i.e., we think we know more!!

To the audience

- Clearly introductory character
  - Please – ask questions!
  - And please, do not try to compare ATLAS and CMS performances in detail from the plots shown here!
- Hopefully useful even for people already working on the topics
  - If you are bored – that's what you get when you ask a research scientist to do this!

Roadmap

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1. **Jets and Missing Et at LHC**
   a. Where do they come from?
      Selected hadronic final states
   b. Physics collision environment
      Underlying event and pile-up
2. **Jet reconstruction in general**
   a. Jet algorithms at LHC
      Guidelines
      Fixed cone
      Recursive recombination
      Jet definition
   b. Experimentalist's view on jets
      Understanding of the object
      Jet reconstruction task overview
3. **Jet measurement**
   a. General signal features
      Response issues in non-compensating calorimeters
   b. Detector signals
      Towers (ATLAS & CMS)
      Energy flow (CMS)
      Topological clusters (ATLAS)
   c. Jet calibration
      Simulation based approach
      Data driven
4. **Jet reconstruction performance**
   a. QCD di-jets
      Performance evaluation
   b. Photon/z + jet(s)
   c. W mass spectroscopy
5. **Missing transverse energy**
   a. Event variables composition
      Understanding the variable
      CMS & ATLAS approach
   b. Scale and resolution
      Instrumental effects
      Validation or calibration?
   c. Performance evaluation
      Simulation based
      Data driven
6. **Conclusions**

1. Jets & Missing Et at LHC

Where do Jets come from at LHC?

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

Fragmentation of gluons and (light) quarks in QCD scattering

- Most often observed interaction at LHC

Decay of heavy Standard Model (SM) particles

- Prominent example:

$$t \rightarrow bW \rightarrow jjj$$

$$t \rightarrow bW \rightarrow l\nu jj$$

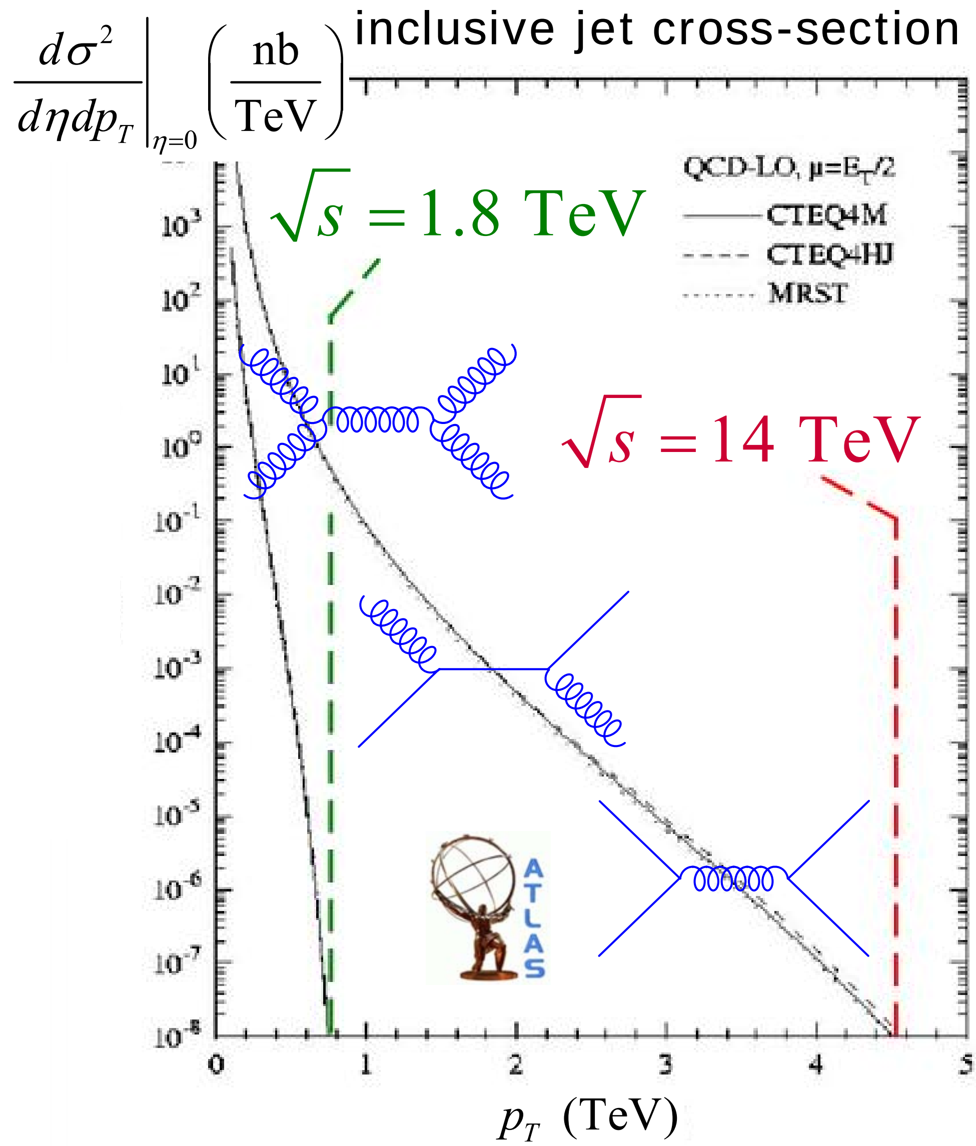
Associated with particle production in Vector Boson Fusion (VBF)

- E.g., Higgs

$$q\tilde{q} \rightarrow q'\tilde{q}'WW \rightarrow Hjj$$

Decay of Beyond Standard Model (BSM) particles

- E.g., SUSY



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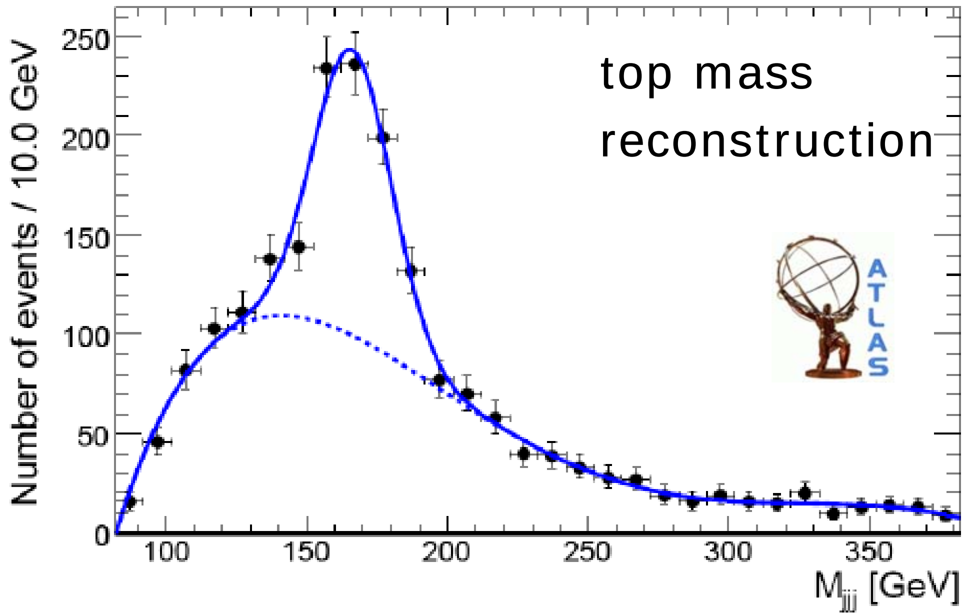

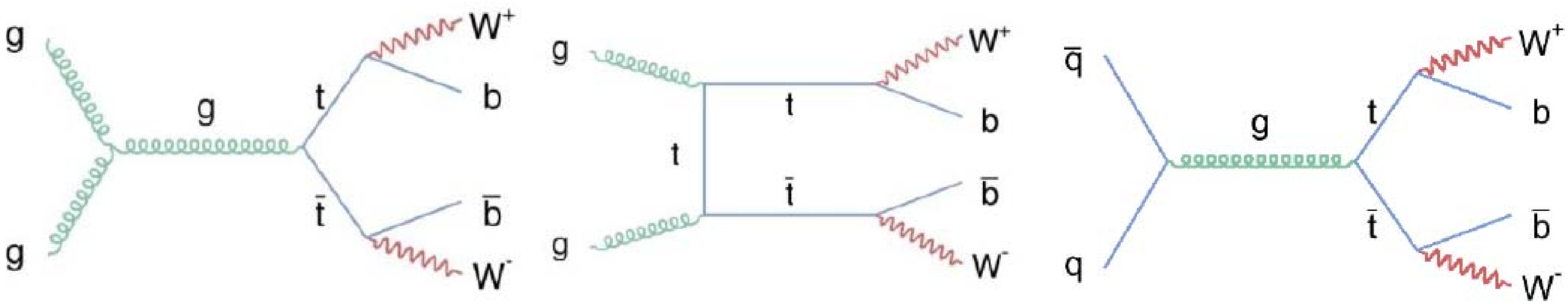

$gg \rightarrow tt$ 85%

$qq \rightarrow tt$ 15%

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1.a
1.b
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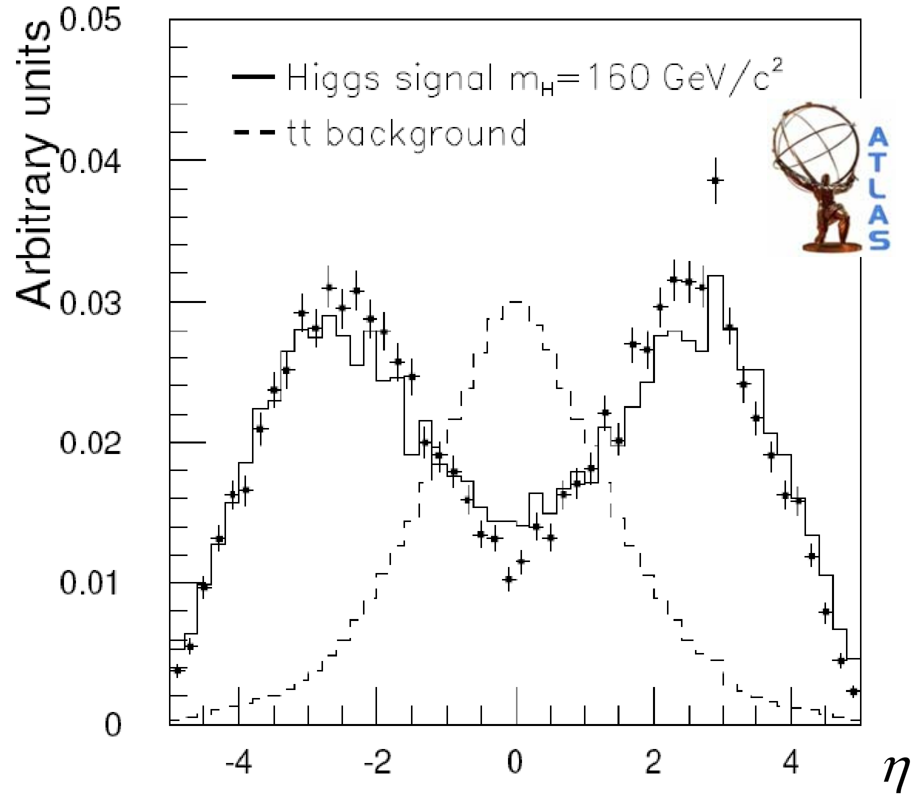

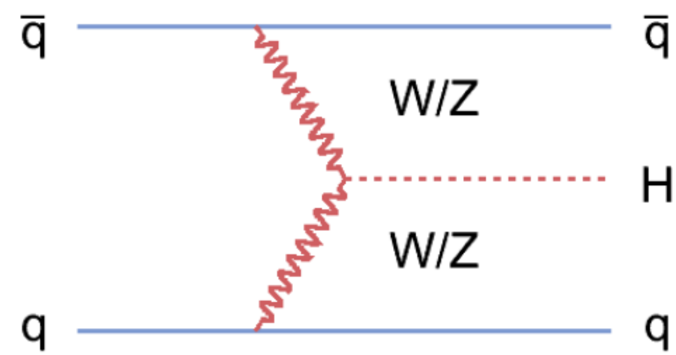

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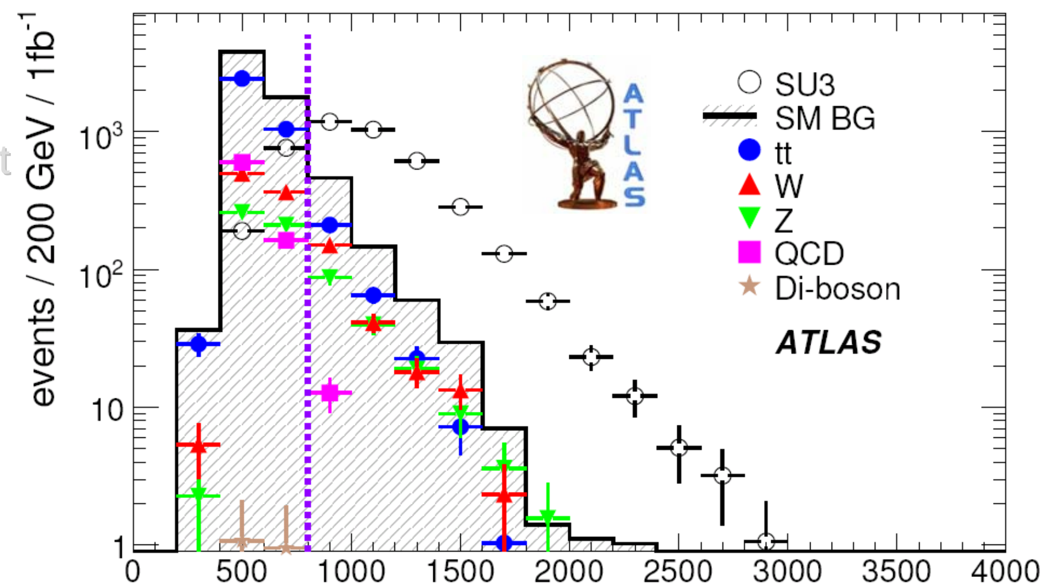
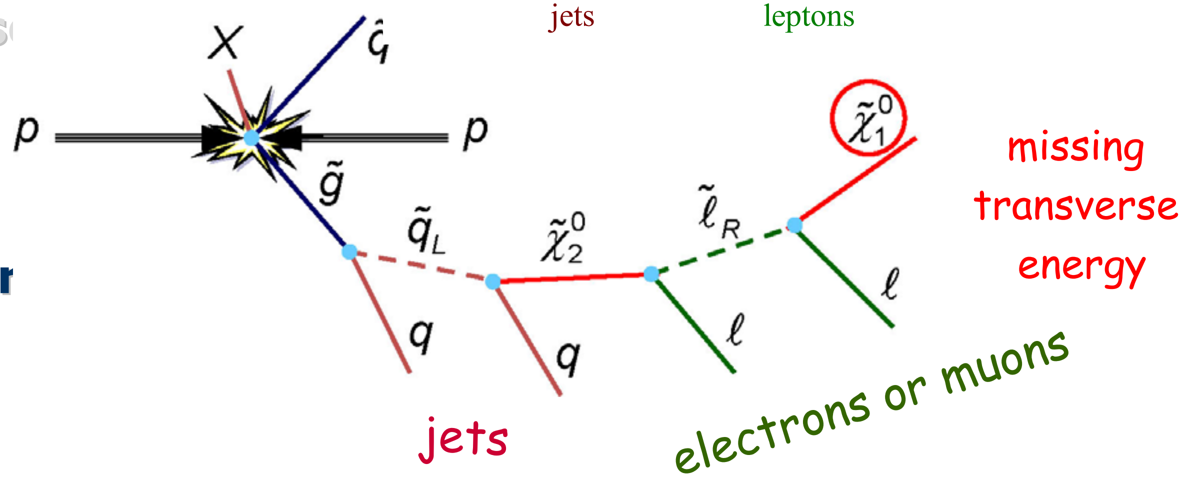


$$M_{eff} = \sum_{\text{jets}} \left| p_{T,j} \right| + \sum_{\text{leptons}} \left| p_{T,\ell} \right| + \not{p}_T$$



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Final States with Missing E_T

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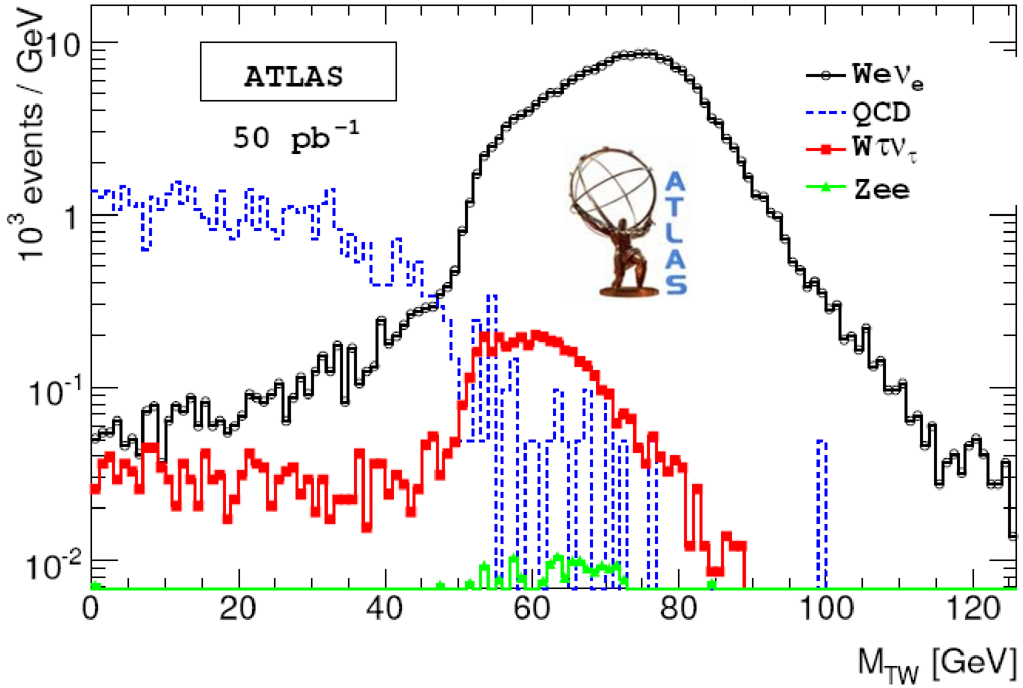
Important signature for many standard model channels

- Neutrino carry missing transverse energy
  - W mass measurement in leptonic final state
  - Z decays to tau pairs
  - Higgs decays to tau or W pairs

New physics signatures

- Final states with neutrinos
  - MSSM Higgs (A) decays into tau pairs
  - Associated with W or invisible Z decays
- New non-interacting particles
  - Neutralinos, gluinos
- Long lived particles
  - Decay outside detector trigger window



$$m_T = \sqrt{2 p_T \not{E}_T (1 - \cos \Delta\varphi_{\ell\nu})}$$

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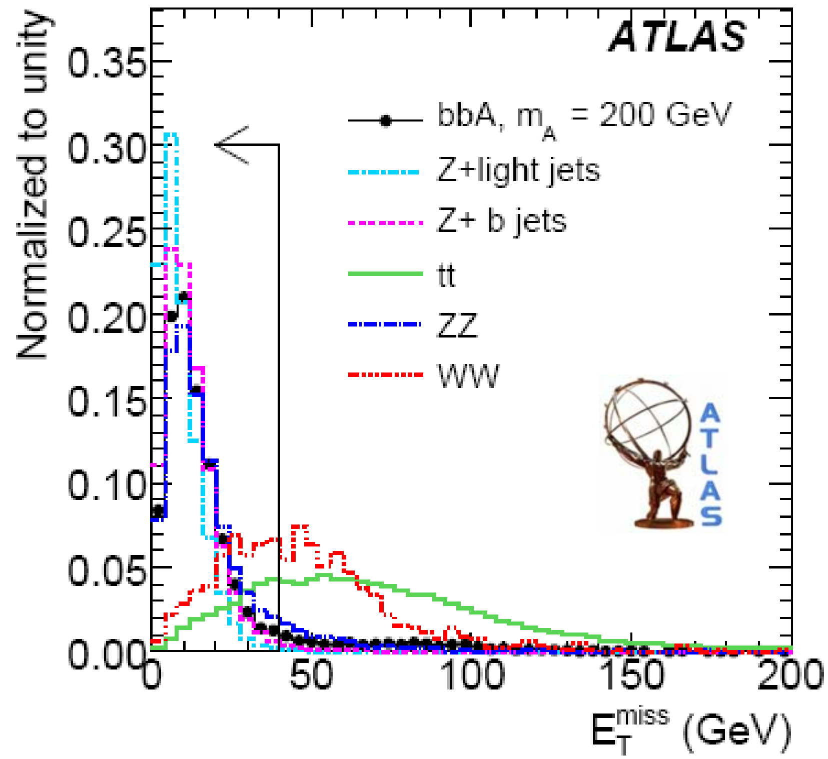

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Underlying Event

Collisions of other partons in the protons generating the signal interaction

- Unavoidable in hadron-hadron collisions
- Independent soft to hard multi-parton interactions

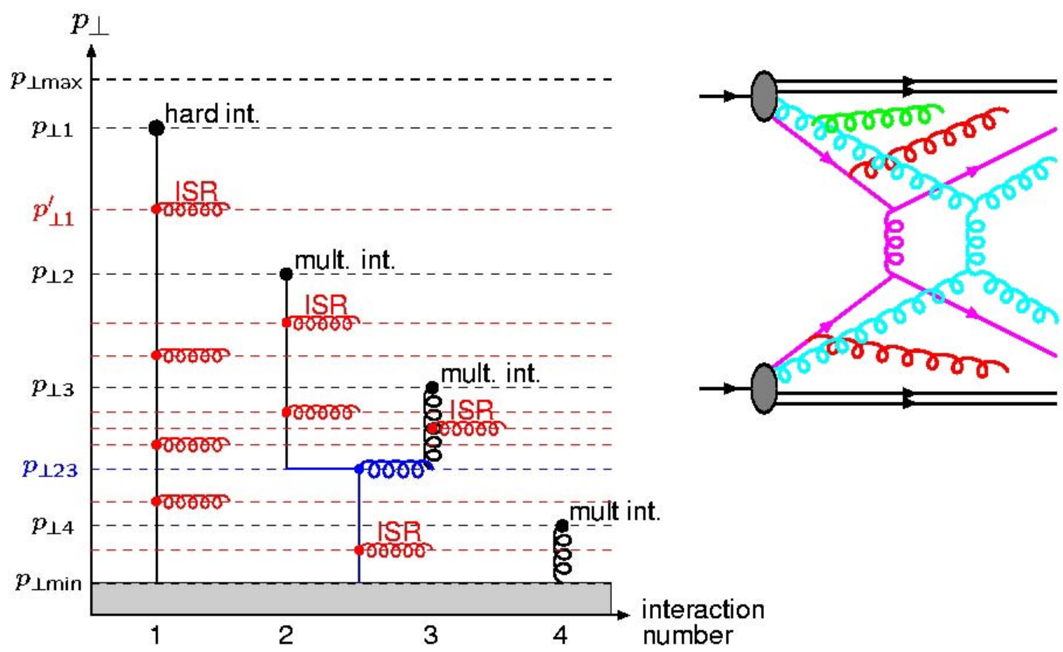
No real first principle calculations

- Contains low pT (non-pertubative) QCD
  - Tuning rather than calculations
- Activity shows some correlation with hard scattering (radiation)
  - pTmin, pTmax differences
- Typically tuned from data in physics generators

Carefully measured at Tevatron

- Phase space factor applied to LHC tune in absence of data
- One of the first things to be measured at LHC

Interleaved Multiple Interactions



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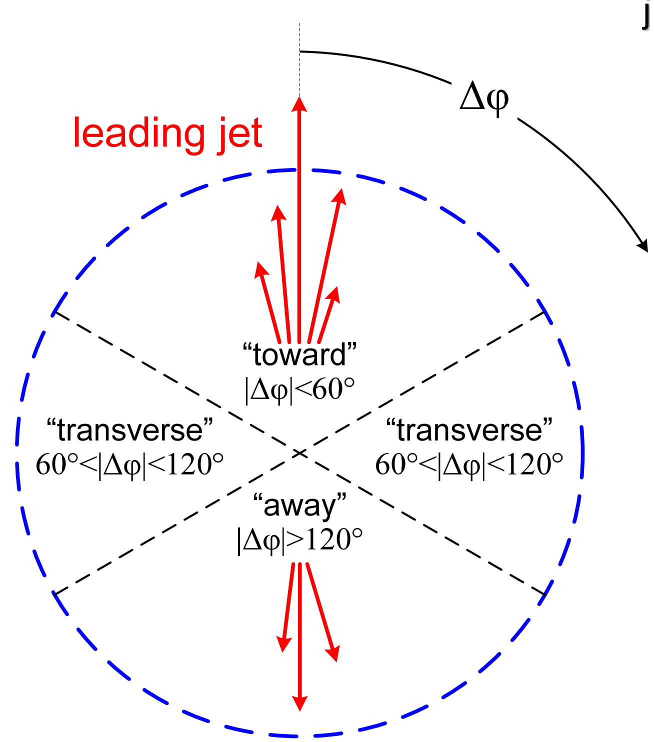
Rick Field's (CDF) view on di-jet events



Look at activity (pT, # charged tracks) as function of leading jet pT in transverse region

Underlying Event

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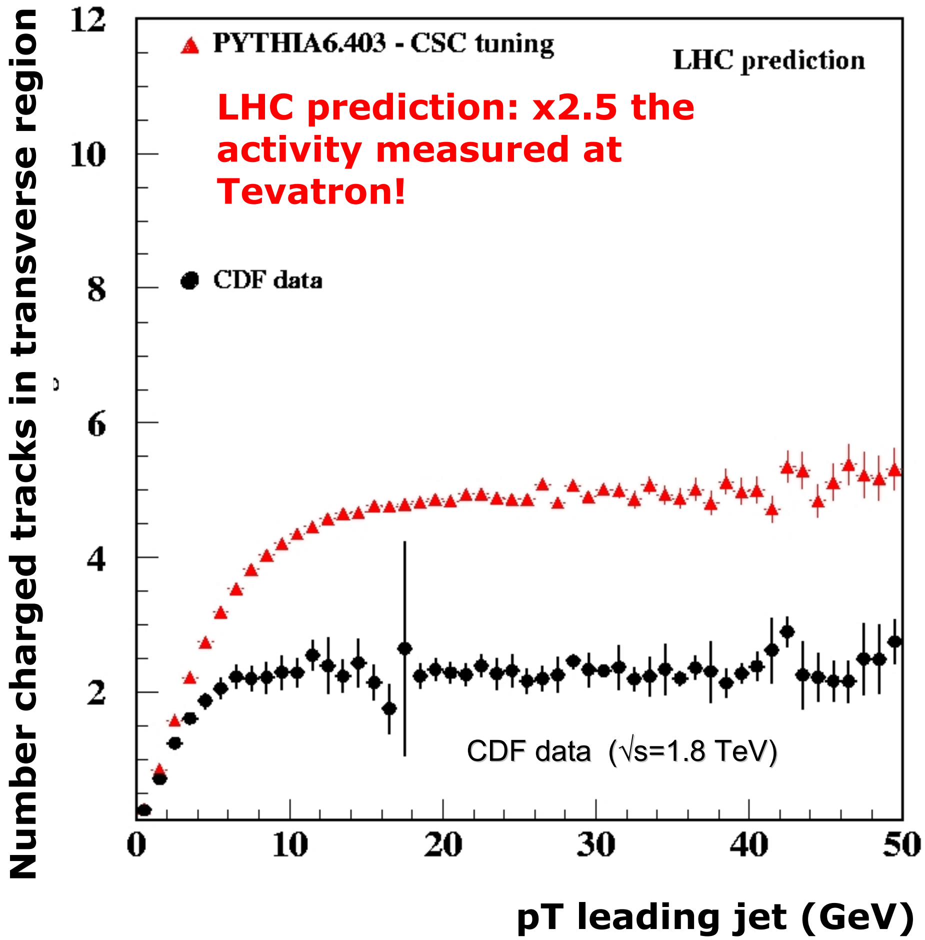
CDF data: Phys.Rev, D, **65** (2002)



Model depending extrapolation to LHC:

$\sim \ln^2 \sqrt{s}$ for PYTHIA

$\sim \ln \sqrt{s}$ for PHOJET

but both agree Tevatron/Sp$\bar{p}$S data!

Pile-Up

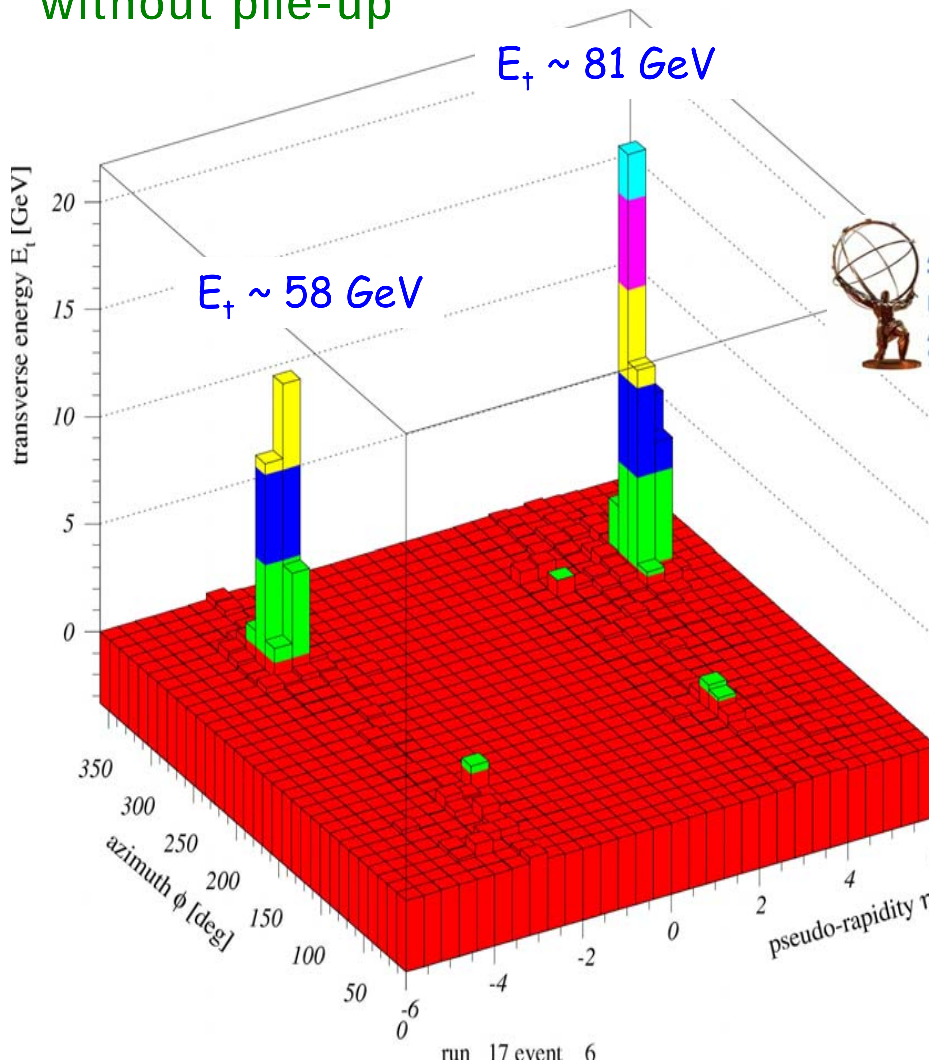
Multiple interactions between partons in other protons in the same bunch crossing
- Consequence of high rate (luminosity) and high proton-proton total cross-section (~75 mb)

Statistically independent of hard scattering
- Similar models used for soft physics as in underlying event

Signal history in calorimeter increases noise
- Signal 10-20 times slower (ATLAS) than bunch crossing rate (25 ns)

Noise has coherent character
- Cell signals linked through past shower developments

without pile-up



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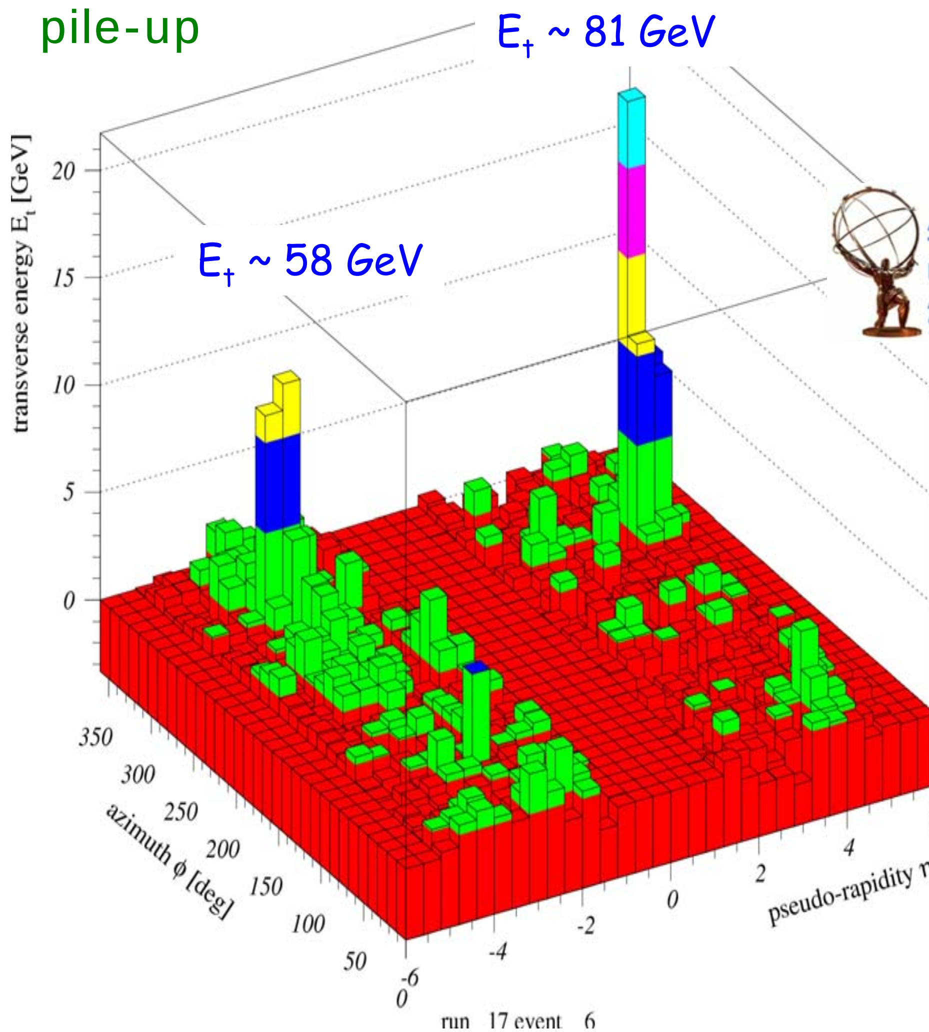

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Pile-Up

1.a
1.b
2.a
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3.b
3.c
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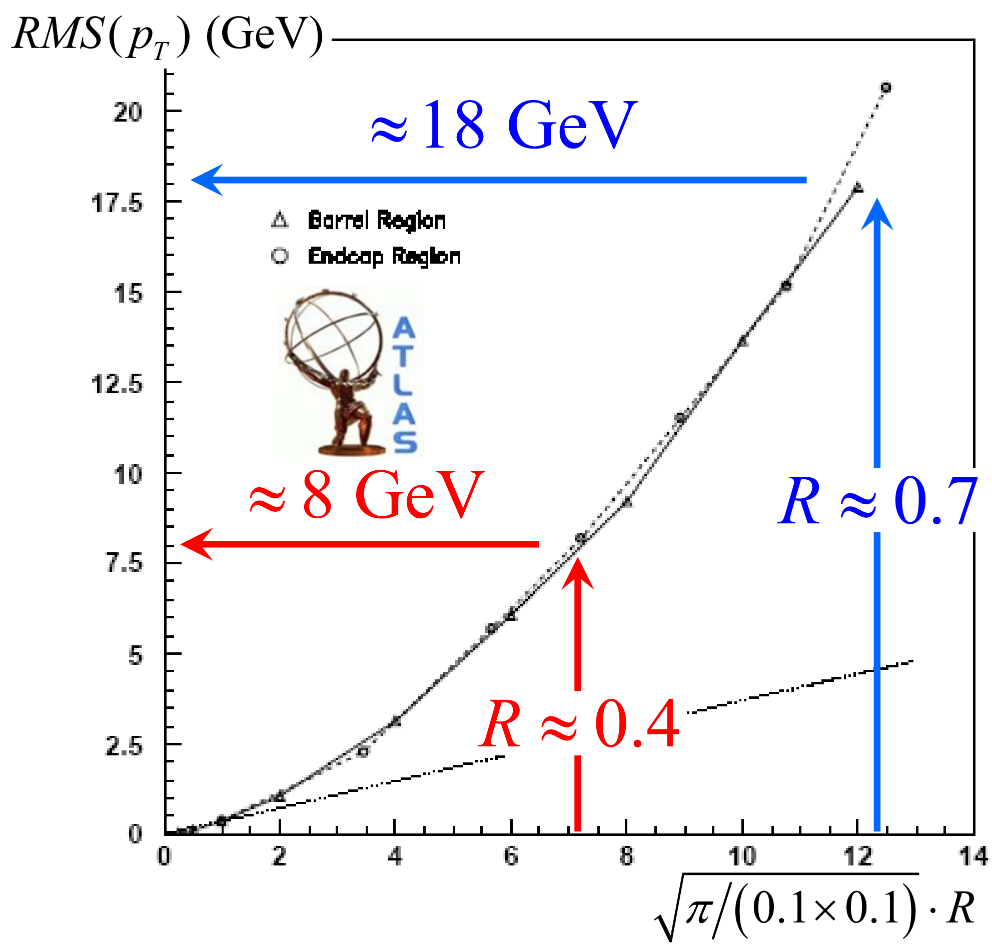
$$L = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$



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Why Is That Important?

Jet calibration requirements very stringent

- Systematic jet energy scale uncertainties to be extremely well controlled
  - Top mass reconstruction
- Relative jet energy resolution requirement
  - Inclusive jet cross-section
  - Di-quark mass spectra cut-off in SUSY

$$\frac{\Delta m_T}{m_T} < 1\text{ GeV} \Rightarrow \frac{\Delta E_{jet}}{E_{jet}} < 1\%$$

$$\frac{\sigma}{E} = \begin{cases} \frac{50\%}{\sqrt{E(\text{GeV})}} \oplus 3\% & |\eta| < 3 \\ \frac{100\%}{\sqrt{E(\text{GeV})}} \oplus 5\% & |\eta| > 3 \end{cases}$$

Event topology plays a role at 1% level of precision

- Extra particle production due to event color flow
  - Color singlet (e.g., *W*) vs color octet (e.g., gluon/quark) jet source
- Small and large angle gluon radiation
  - Quark/gluon jet differences

2. Jet Reconstruction in General

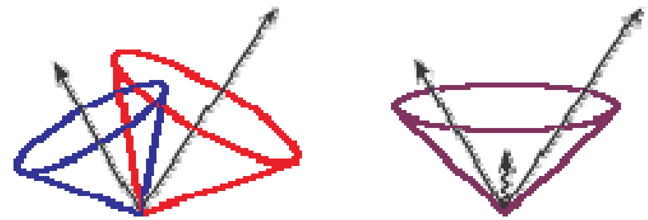
Jet Algorithm Guidelines (1)

Very important at LHC

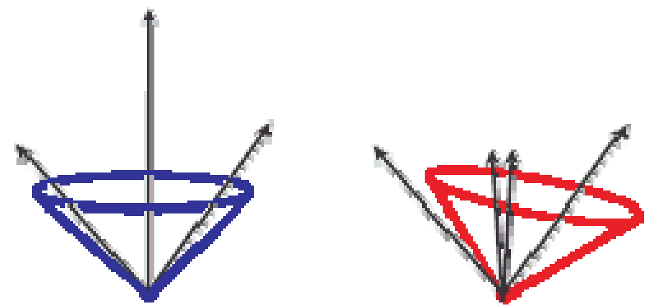
- Often LO (or even NLO) not sufficient to understand final states
  - Potentially significant K-factors can only be applied to jet driven spectra if jet finding follows theoretical rules
    - E.g., jet cross-section shapes
- Need to be able to compare experiments and theory
  - Comparison at the level of distributions
    - ATLAS and CMS will unfold experimental effects and limitations independently – different detector systems

Theoretical guidelines

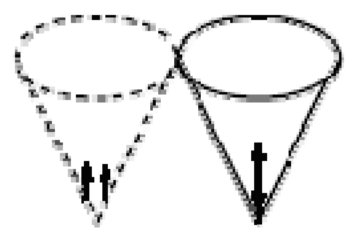
- Infrared safety
  - Adding or removing soft particles should not change the result of jet clustering
- Collinear safety
  - Splitting of large pT particle into two collinear particles should not affect the jet finding



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)

Jet Algorithm Guidelines

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Detector technology independence

- Jet efficiency should not depend on detector technology
  - Final jet calibration and corrections ideally unfolds all detector effects

Minimal contribution from spatial and energy resolution to reconstructed jet kinematics

- Unavoidable intrinsic detector limitations set limits

Stability within environment

- (Electronic) detector noise should not affect jet reconstruction within reasonable limits
  - Energy resolution limitation
  - Avoid energy scale shift due to noise
- Stability with changing (instantaneous) luminosity at LHC
  - Control of underlying event and pile-up signal contribution

"Easy" to calibrate

- Small algorithm bias for jet signal
  - Probably means high signal stability

High reconstruction efficiency

- Identify all physically interesting jets from energetic partons in perturbative QCD
- Jet reconstruction in resonance decays
  - High efficiency to separate close-by jets from same particle decay
  - Least sensitivity to boost of particle

Iterative Cone Algorithms

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1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

Seeded fixed cones

- Geometrically motivated jet finders
  - Collect particles or detector signals into fixed sized cone of chosen radius R

$$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

  - Basic parameters are seed pT threshold and cone size
- Theoretical concerns
  - Seed introduces collinear instability
    - One particle above seed splits into two collinear particles below seed
  - Infrared safety
    - Cone formation sensitive to low energetic particles
    - Can ignore large signal due to change of direction at each iteration (e.g., "dark towers" @ CDF)
  - Addressed by split and merge
    - One more parameter – see later

Seedless fixed cones

- No seeds
  - Collect particles around any other particle into a fixed cone of chosen radius
  - Otherwise similar to seeded cone
- Theoretical issues
  - Collinear stability – no issue
  - Infrared safety
    - Higher stabilty but still needs split and merge

Often considered "simple"

- Implementation obvious
  - Especially seeded cone
  - Computational limitations on seedless cone
    - LHC O(1000) particles possible
- Provide an area
  - Careful – split and merge makes shape less regular

Attempt to undo parton fragmentation

- QCD branching happens all the time

$$\left[dk_j\right]\left|M^2_{g\to g_i g_j}(k_j)\right| \simeq \frac{2\alpha_s C_A}{\pi}\frac{dE_j}{\min(E_i,E_j)}\frac{d\theta_{ij}}{\theta_{ij}}, \quad (E_j \ll E_i, \theta_{ij} \ll 1)$$

- Pair with strongest divergency between them likely belongs together
  - kT/Durham first used in e^+e^-
- Longitudinal invariant version for hadron colliders
  - Catani, Dokshitzer, Seymour & Webber '93
  - S.D. Ellis & D. Soper '93
- Modern implementations
  - kT with clustering sequence using pT and distance parameter
    - Ordered in kT, sequence follows jet structure
  - Durham/Aachen clustering sequence using angular distance
    - Ordered in angular distance, sequence follows jet structure
  - Anti-kT using pT and distance parameter with inverted sequence
    - No particular ordering, sequence not meaning full

Valid at all orders!

arXiv:0802.1189v1 [hep-ph] 8 Feb 2008

Clustering Algorithms

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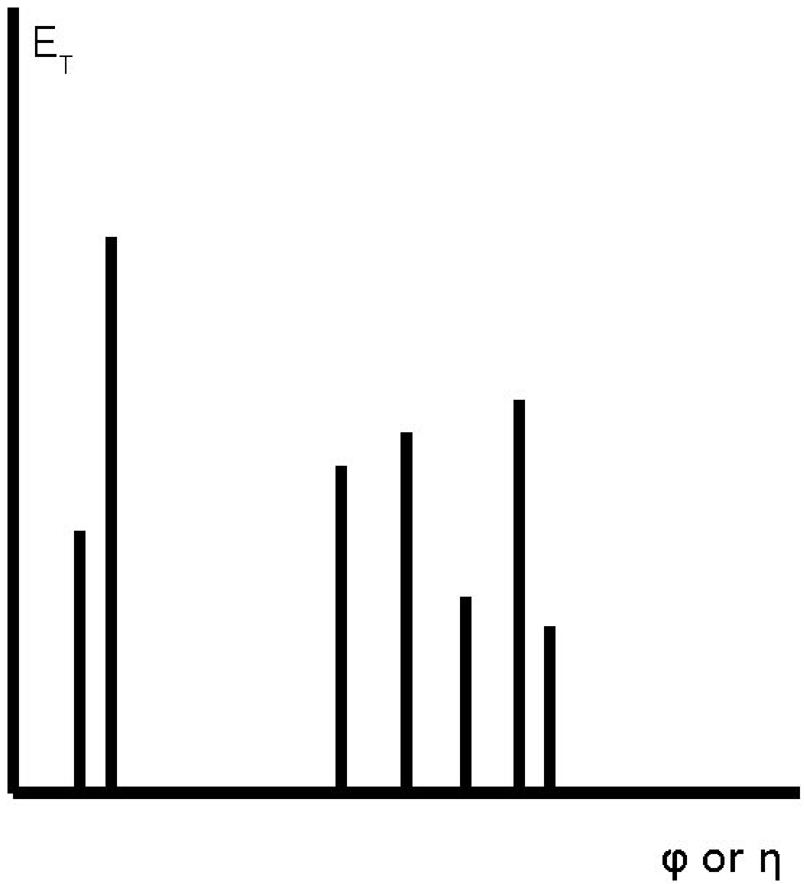
Gavin Salam Lectures on Jets



Clustering Algorithms:

- Define a distance d_{ij} between two objects i, j:

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$
$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2 / R^2$$

and a distance d_{iB} between one object i and the beam direction B:

$$d_{iB} = k_{ti}^2$$

- Find the smallest of d_{ij}, d_{iB} .

  If d_{ij} recombine i, j;

  If d_{iB} , i is a jet.

Clustering Algorithms

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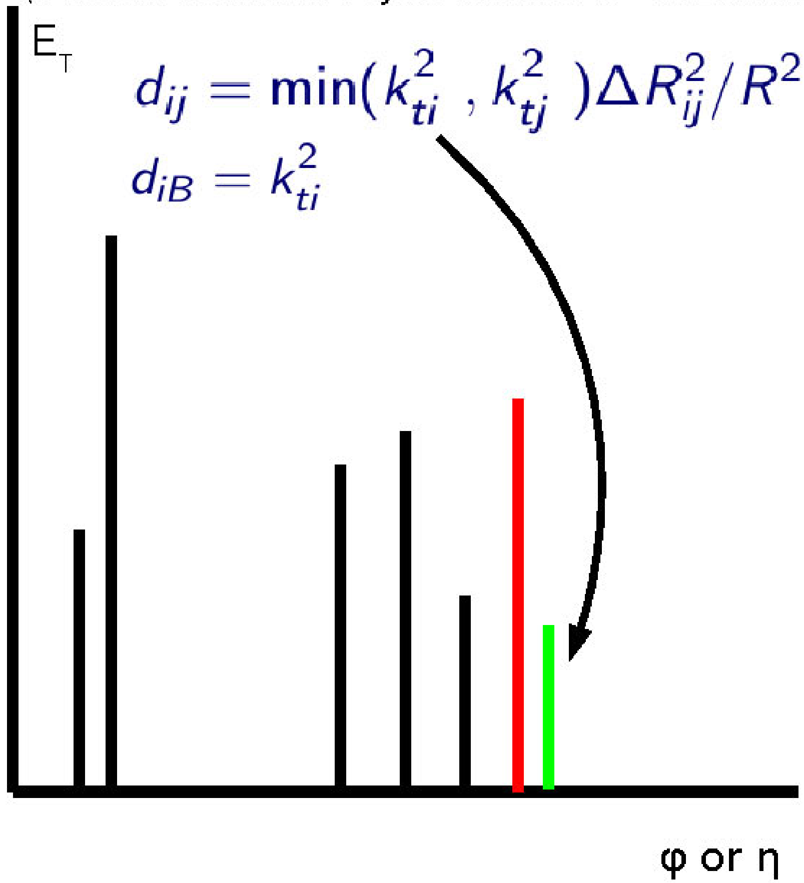
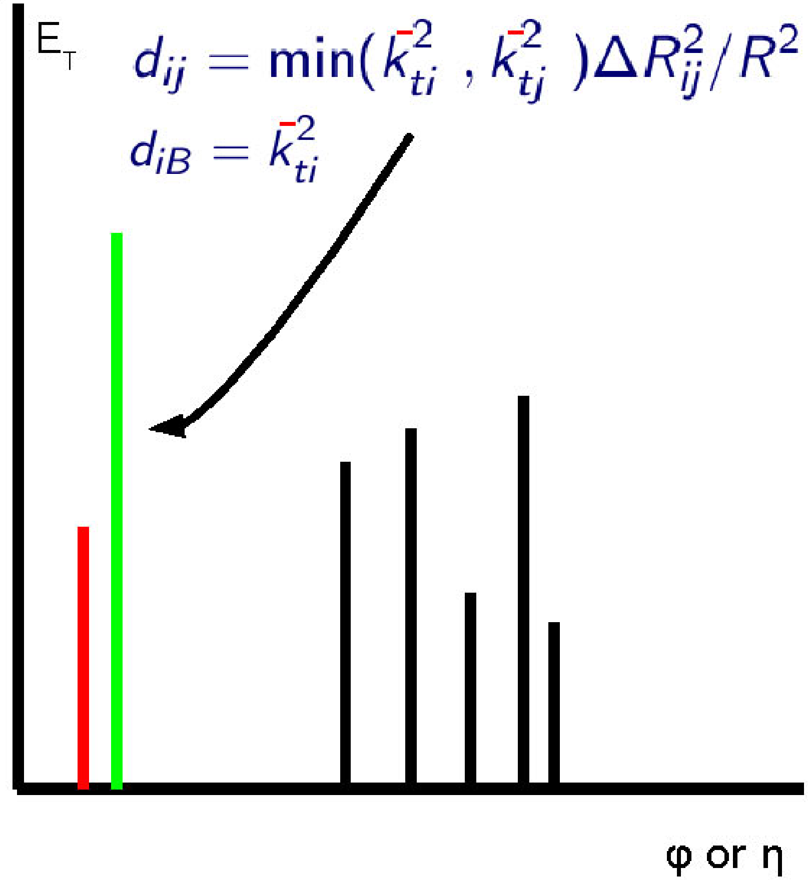
Kt

(Catani/Dokshitzer/Seymour/Webber - S.Ellis/Soper)



AntiKt

(Cacciari/Salam/Sovez)



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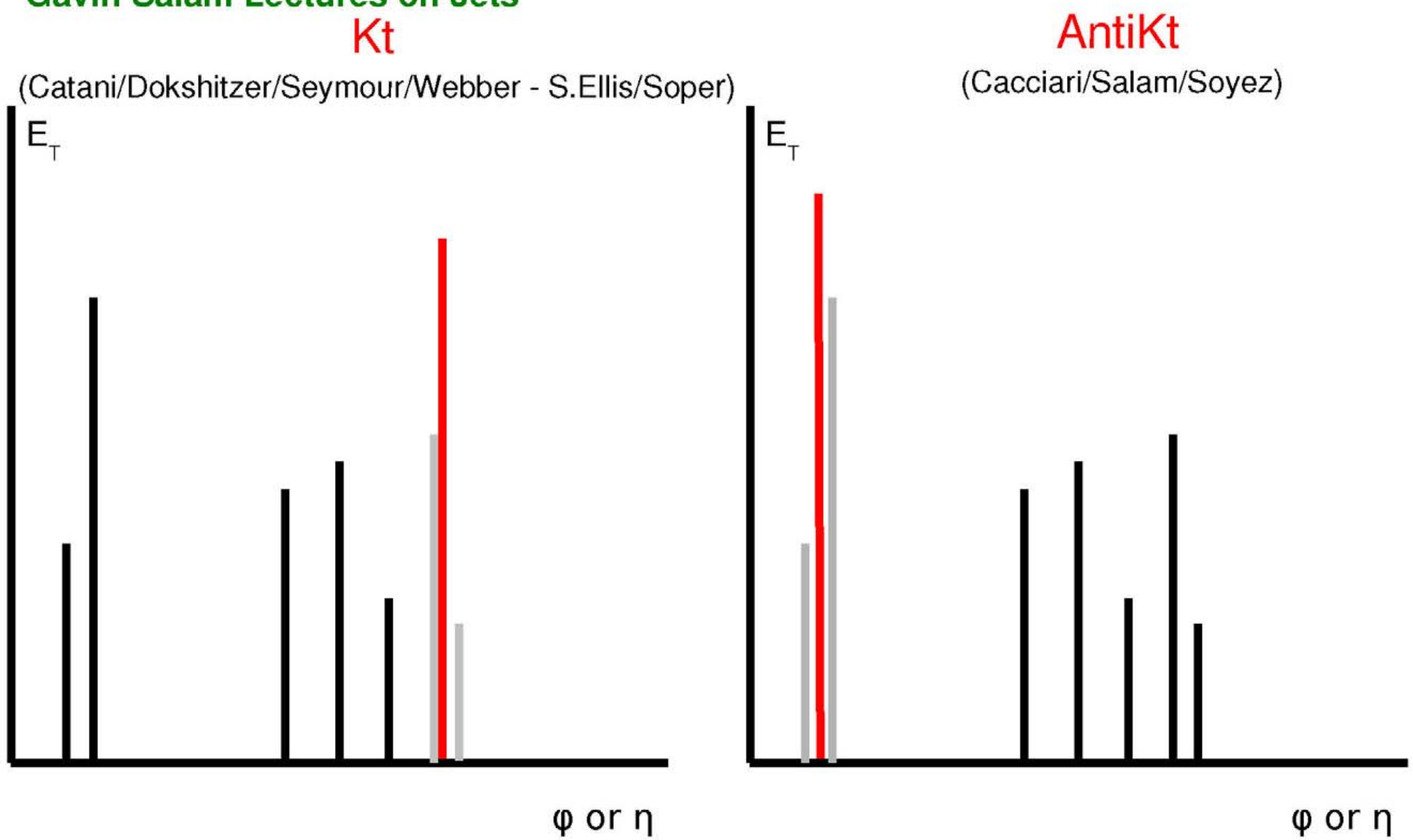

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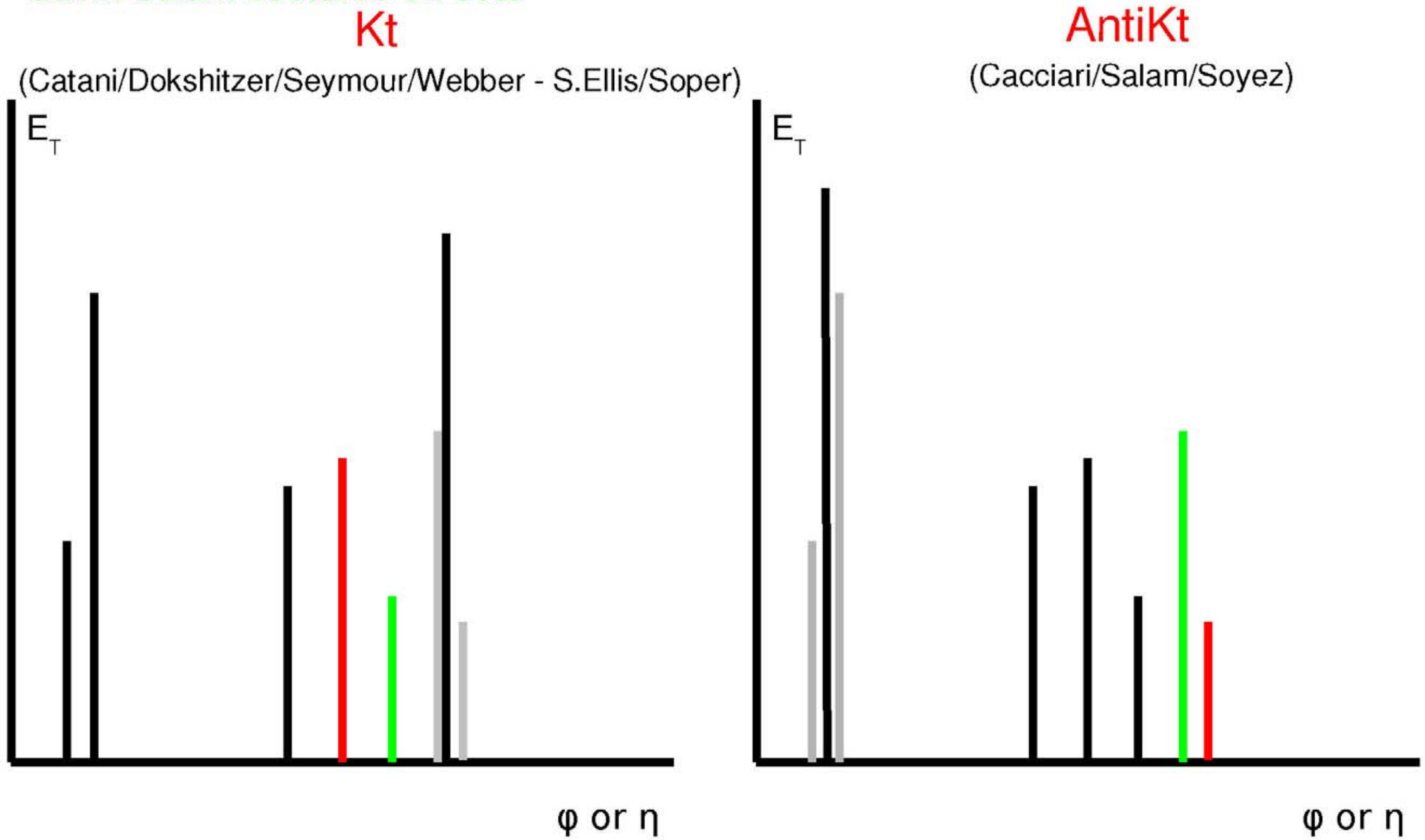

Recursive Recombination Algorithms

Clustering Algorithms

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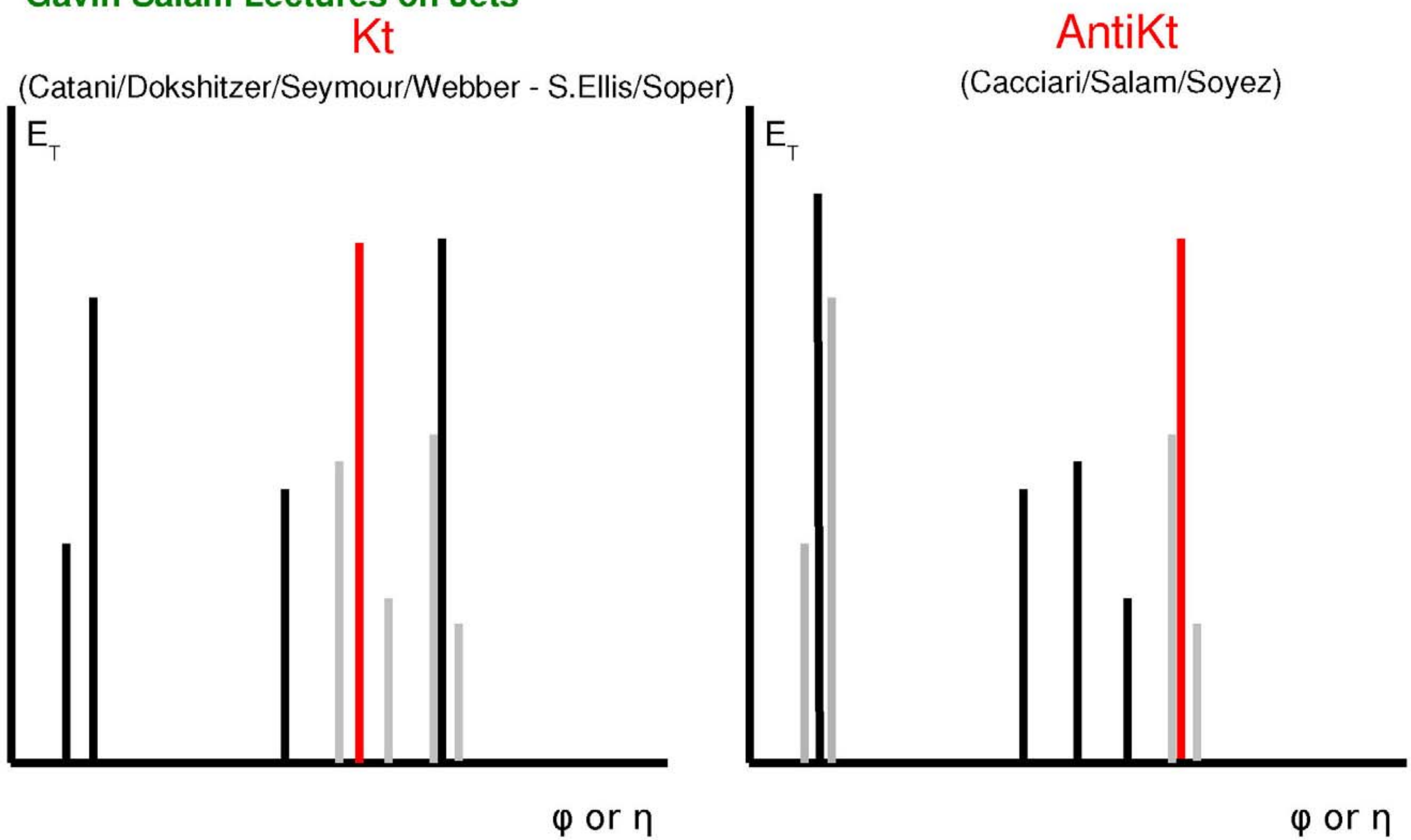

Paolo Francavilla Jet Algorithms 8

1.a
1.b
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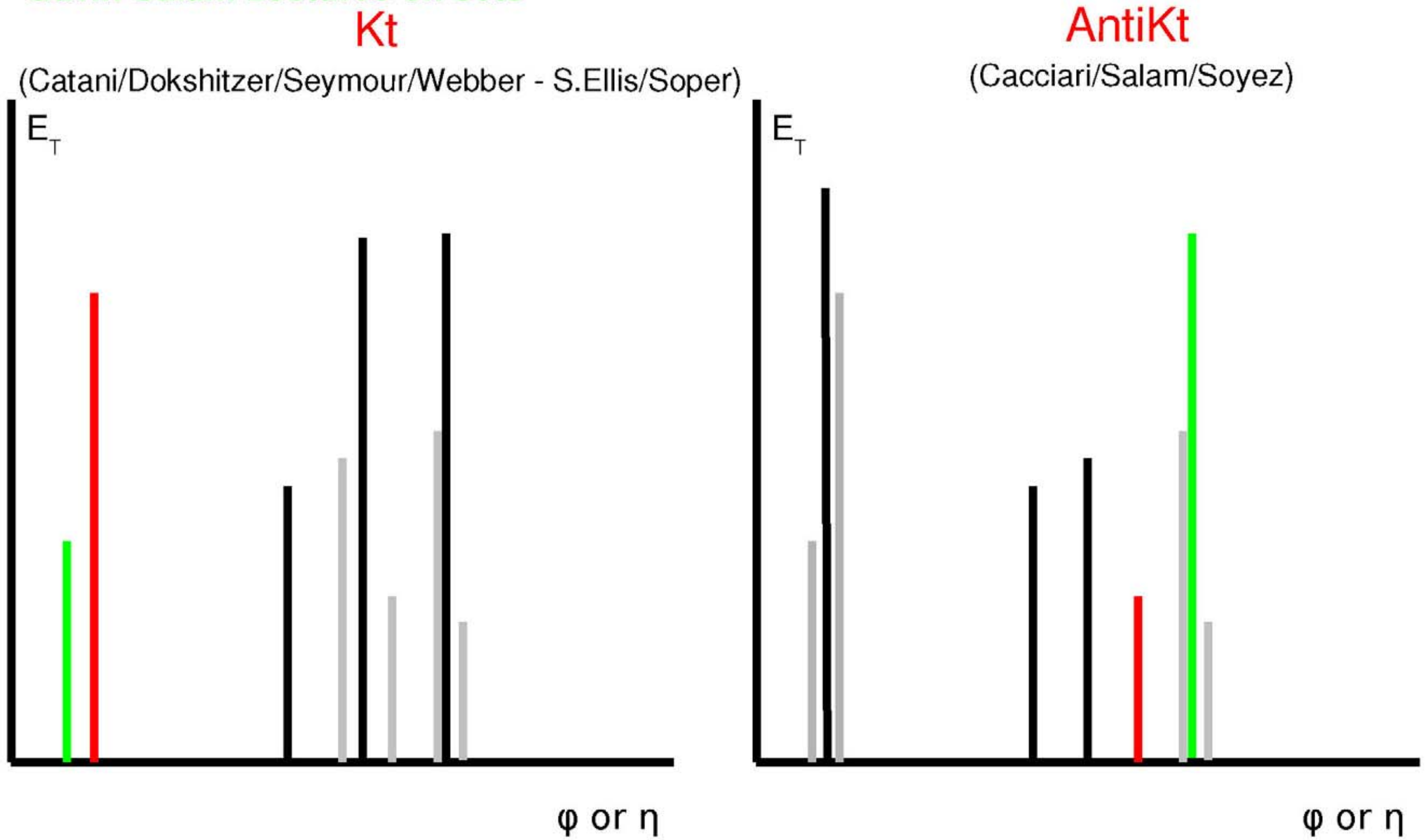

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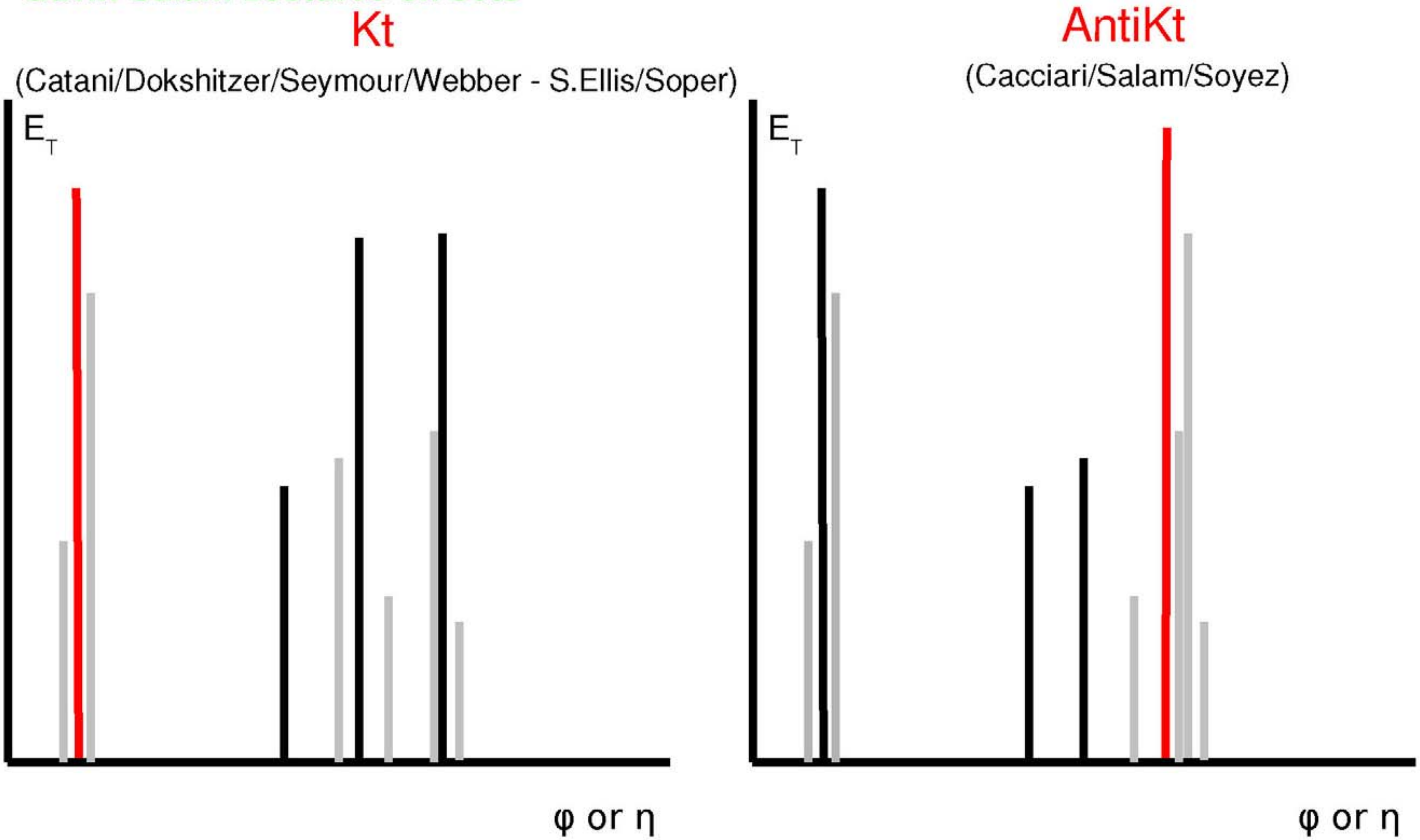

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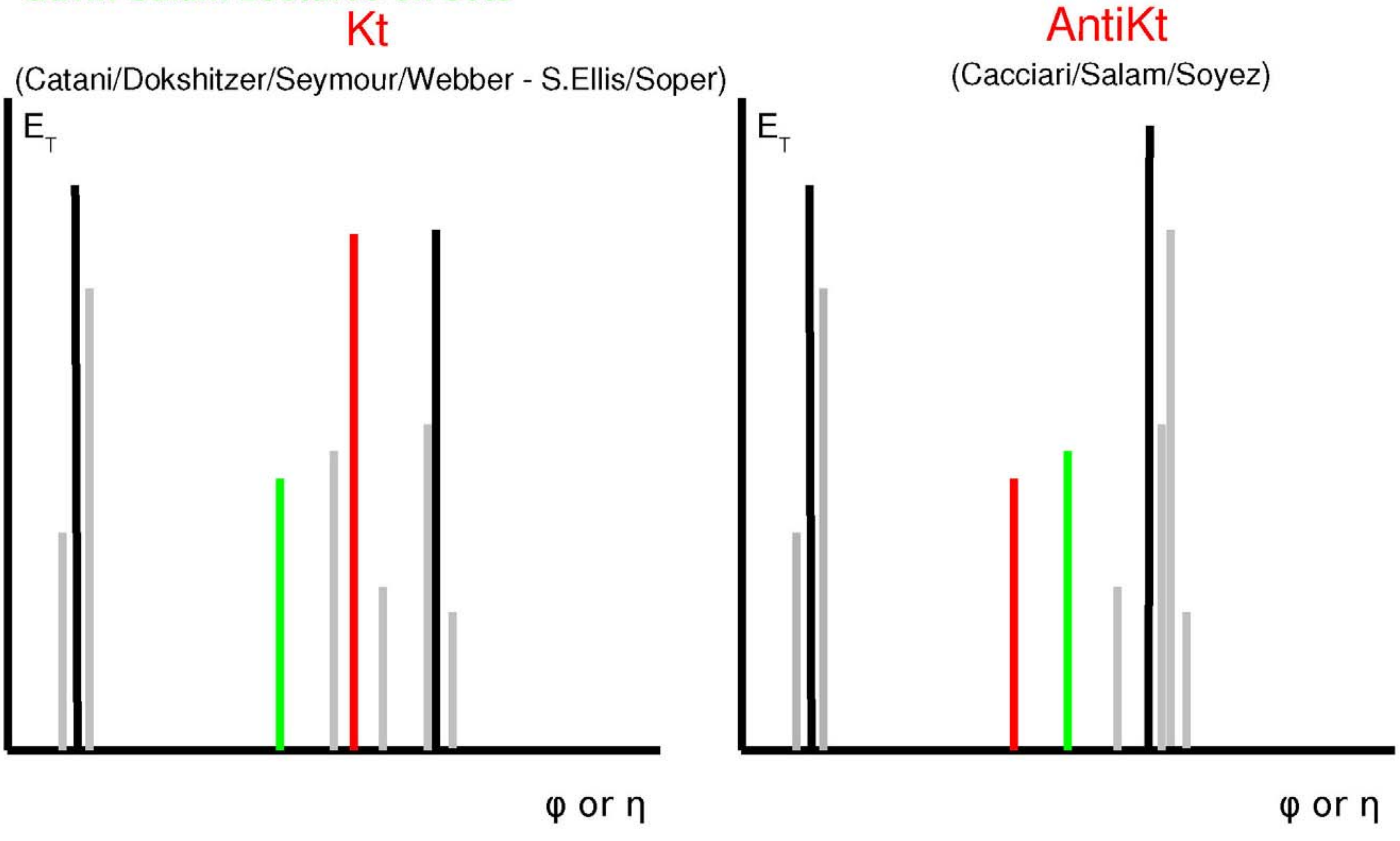

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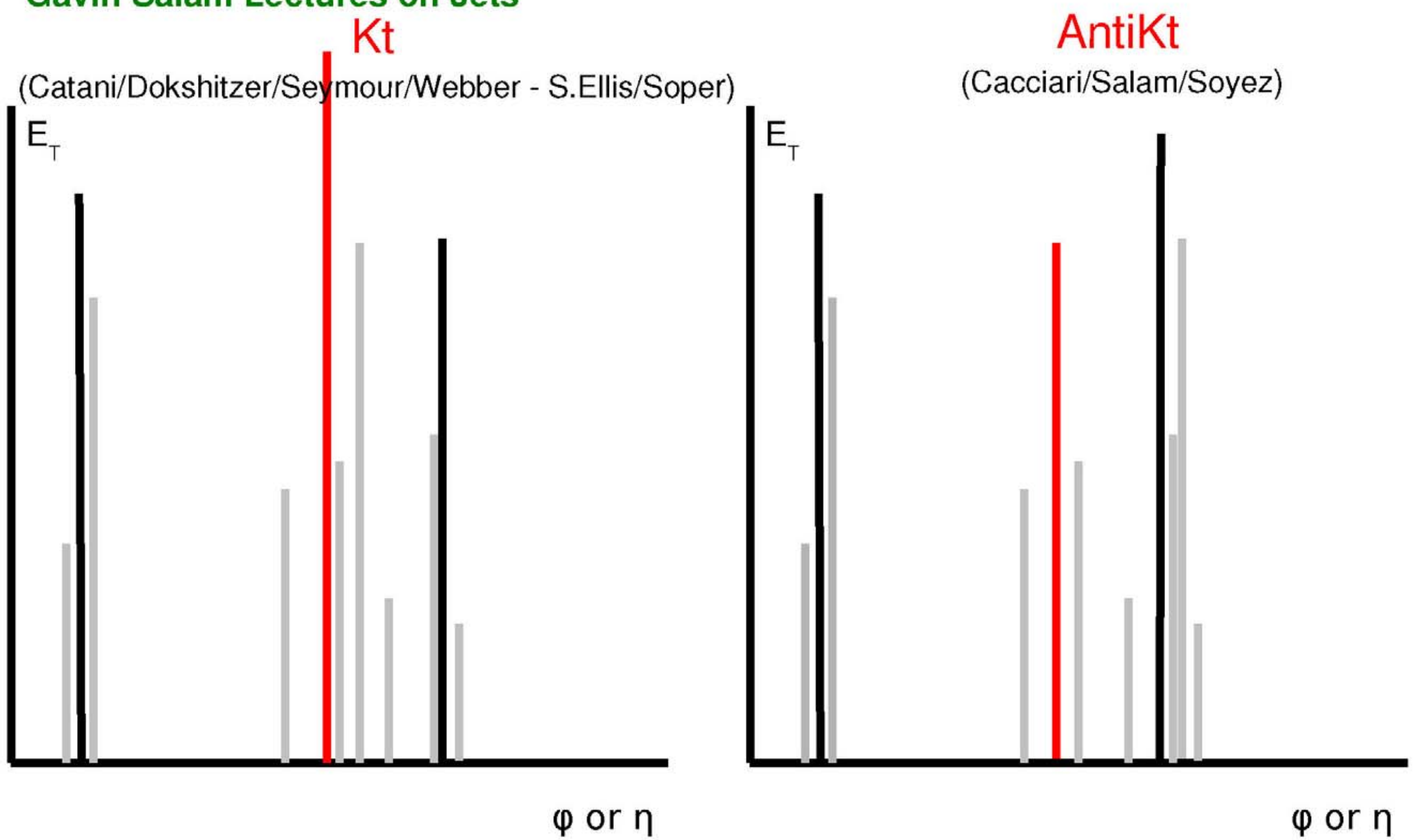

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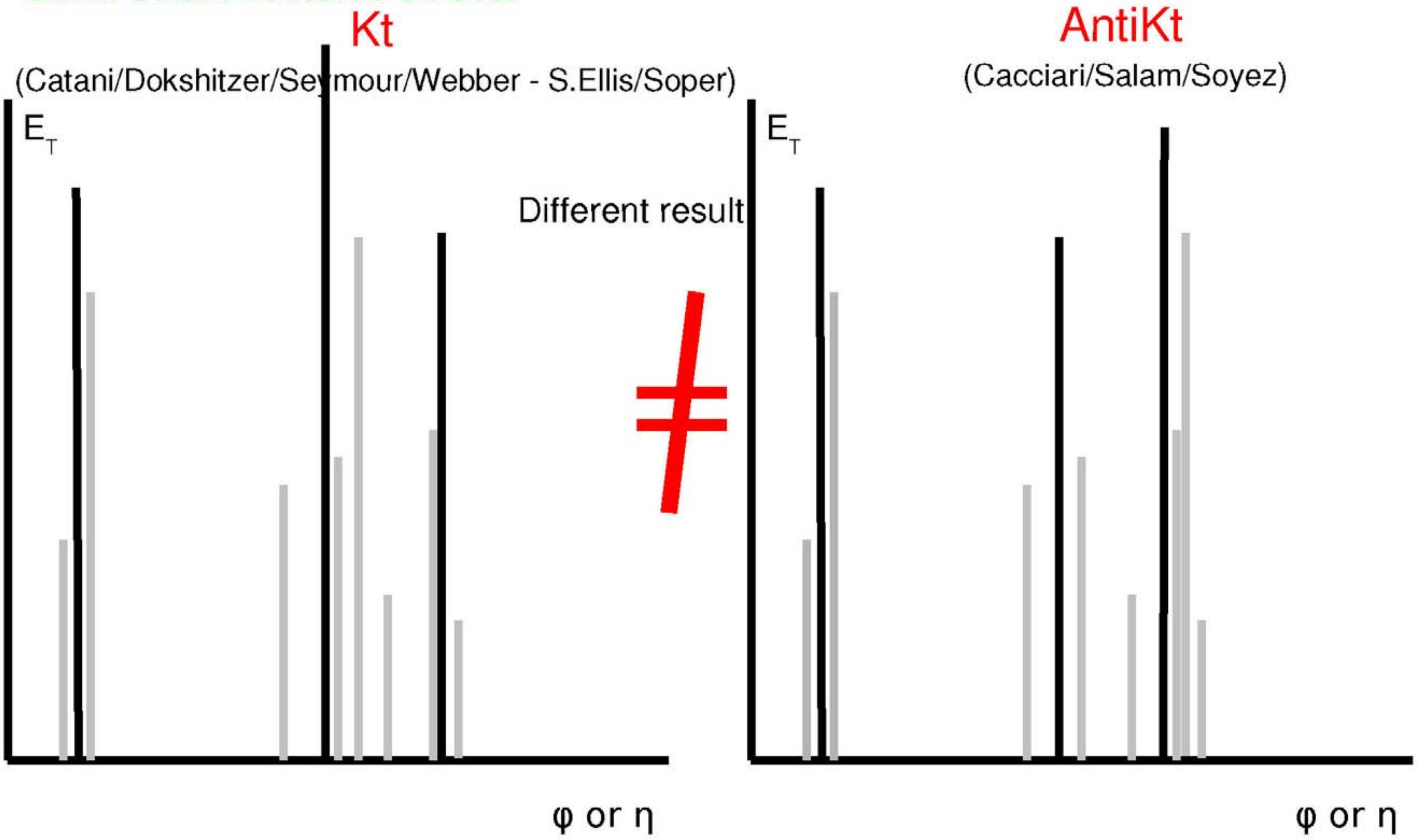
CTEQ-MCnet school 2008
Gavin Salam Lectures on Jets



Seeded Cone Algorithm

P. Loch
U of Arizona
June 30, 2009

Algorithm flow

- Find seed with Et > Etmin
- Collect all particles within R of seed
  - Typical R = 0.4, R = 0.7
- Recalculate new cone direction
- Collect particles in new cone and find new direction
- Stop if cone is stable
  - There may not be a stable solution!
- Interative cone with removal (CMS)
  - Remove particles assigned to the cone from list and find next seed
  - Find next surviving seed and new cone
  - Stop if no more seeds or stable cones
- Overlapping cones (ATLAS)
  - Find next seed and new cone until all seeds are exhausted
  - Apply split and merge procedure

Split and merge

- Merge jets
  - Use pT of overlapping constituents above fraction f of pT of lower pT jet
    - f = 50% in ATLAS
- Otherwise split lower pT jet
  - Assign split constituents to higher pT jet

Theoretical concerns

- Collinear safety
  - "Tower signal" can split seeds
- Infrared safety
  - Additional soft particles affect cone formation and stabilitiy
  - Stable solution may leave significant energy unclustered
- Addressed by variations
  - E.g., Mid-point cone at Tevatron places seeds between particles

Limitations for physics final state calculations

	Last meaningful order		
	ATLAS cone [IC-SM]	MidPoint [IC_{mp}-SM]	CMS it. cone [IC-PR]
Inclusive jets	LO	NLO	NLO
$W/Z + 1$ jet	LO	NLO	NLO
3 jets	**none**	LO	LO
$W/Z + 2$ jets	**none**	LO	LO
$m_{\rm jet}$ in $2j + X$	**none**	**none**	**none**

G. Salam, 2008

Infrared safe seedless cone

- SISCone (Salam, Soyez 2007)
  - No collinear issue in the absence of seed thresholds
  - Available for use in ATLAS & CMS
- Finds *all* stable cones in all particles
  - Avoid infrared safety issues
- Apply split and merge to those
  - Recommended high split & merge fraction f = 75% suppresses merging
- Uses geometry principles for faster execution
  - Time ~$N^2 \log N$ not as fast as latest kT but at least manageable

Jet Definition

We need to be able to talk to each other

- CMS ↔ ATLAS, Tevatron ↔ LHC experiments, experiments ↔ theory
  - Need to agree on a jet definition
- Simple proposal out since Les Houches 2007
  - Specify algorithm, all parameters, signal choice, cuts, and recombination strategy
  - Obvious but rarely done at required level of completeness and precision
- Requires common software implementations
  - Cannot allow misunderstandings in private implementations – no way to compare!!

ATLAS & CMS use same code for most algorithms

- FastJet libraries (Salam et al.)
  - Provides kT flavours, SISCone and legacy cones
  - Includes CMS and ATLAS specific implementations of cone algorithms

"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

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

Interesting recent papers on jet issues at LHC

Towards Jetography

G.P. Salam, **arXiv-0906.1833v1** [hep-ph] 10 June 2009

Quantifying the Performance of Jet Definitions for Kinematic Reconstruction at LHC

M. Cacciari, J. Rojo, G.P. Salam, G. Soyez, **JHEP 0812:032,2008**

Standard Model Handles and Candles Working Group: Tools and Jets Summary Report

C. Buttar *et al.*, **arXiv:0803.0678** [hep-ph] March 2008

The Anti-k(t) Jet Clustering Algorithm

M. Cacciari, G.P. Salam, G. Soyez, **JHEP 0804:063,2008**
(original idea by P.A. Delsart, ATLAS)

Non-perturbative QCD effects in jets at hadron colliders

M. Dasgupta, L. Magnea, G.P. Salam, **JHEP 0802:055,2008**

Pileup subtraction using jet areas

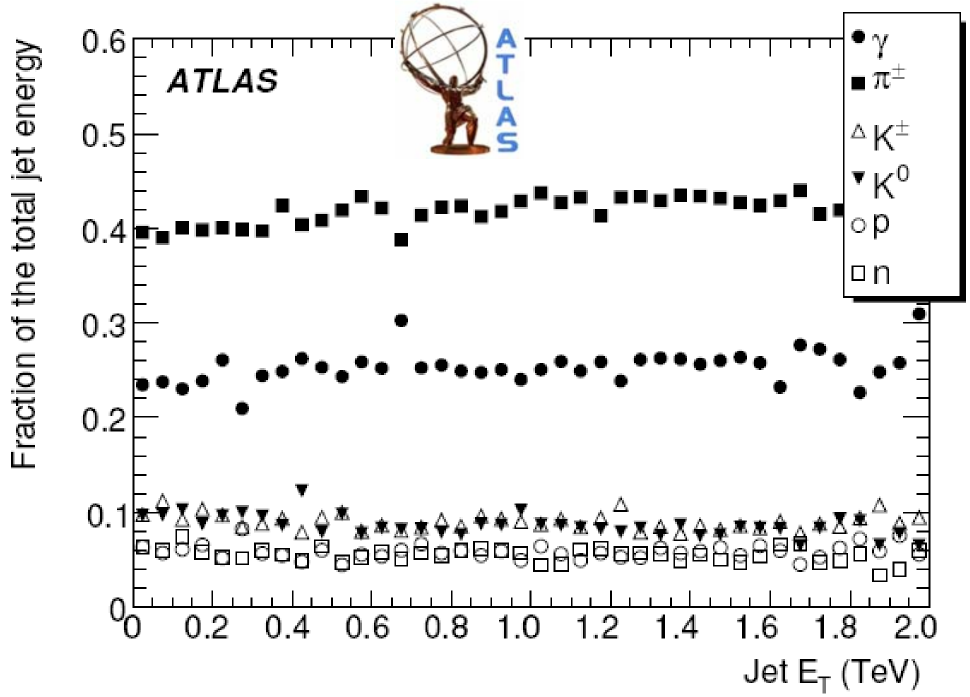
M. Cacciari, G.P. Salam, **Phys.Lett.B659:119-126,2008**

A Practical Seedless Infrared-Safe Cone jet algorithm

G.P. Salam, G. Soyez, **JHEP 0705:086,2007**.

What are jets for experimentalists?

- A bunch of particles generated by hadronization of a common source
  - Quark, gluon fragmentation
- As a consequence, the particles in this bunch have correlated kinematic properties
  - Reflecting the source by sum rules/conservations
- The **interacting** particles in this bunch generated an observable signal in a detector
  - Protons, neutrons, pions, photons, electrons, muons, other particles with laboratory lifetimes >~10ps, and the corresponding anti-particles
- The **non-interacting** particles do not generate a directly observable signal
  - Neutrinos, mostly

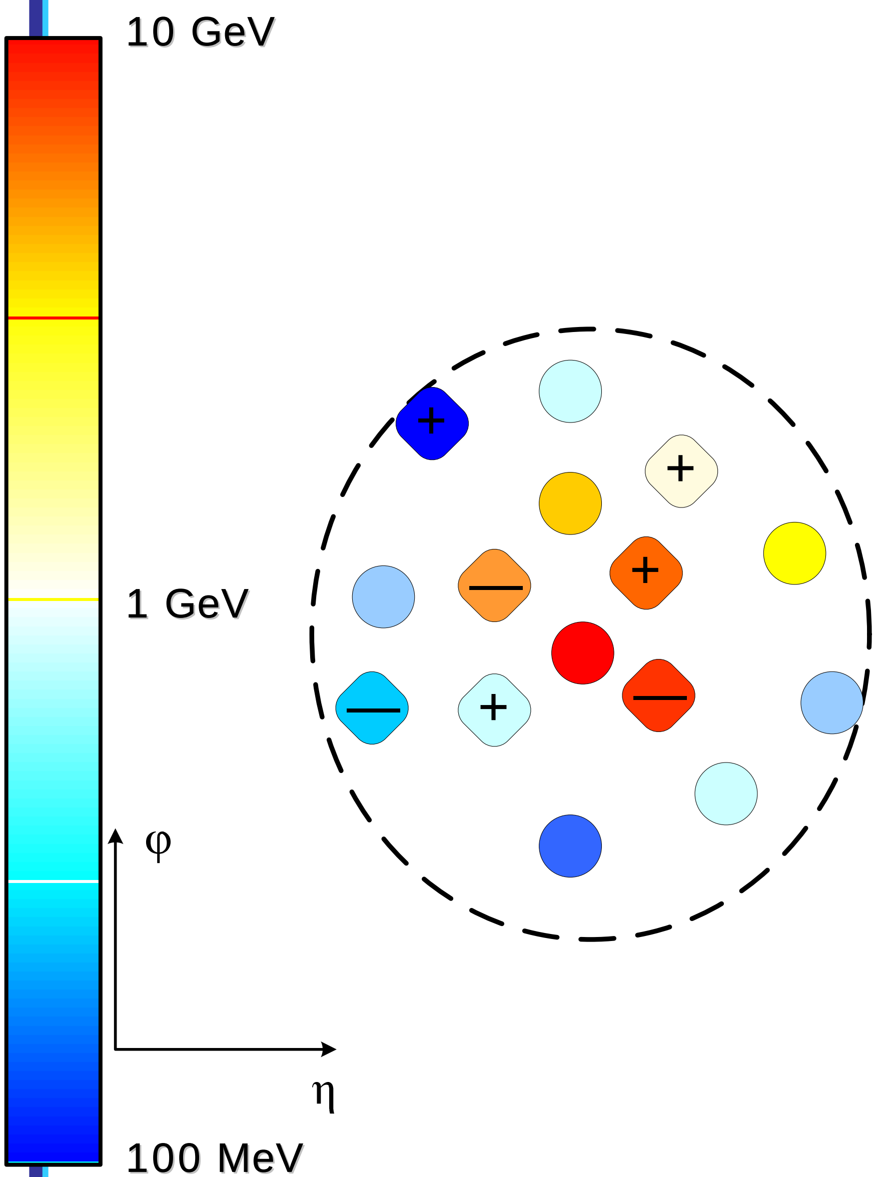


What is jet reconstruction, then?

- Model/simulation: particle jet
  - Attempt to collect the final state particles described above into objects (jets) representing the original parton kinematic
  - Re-establishing the correlations
- Experiment: detector jet
  - Attempt to collect the detector signals from these particles to measure their original kinematics
  - Usually not the parton!

CERN-OPEN-2008-020

Image of Jet in the Detector



Change of composition

- Radiation and decay inside detector volume
- "Randomization" of original particle content

Defocusing changes shape in lab frame

- Charged particles bend in solenoid field

Attenuation changes energy

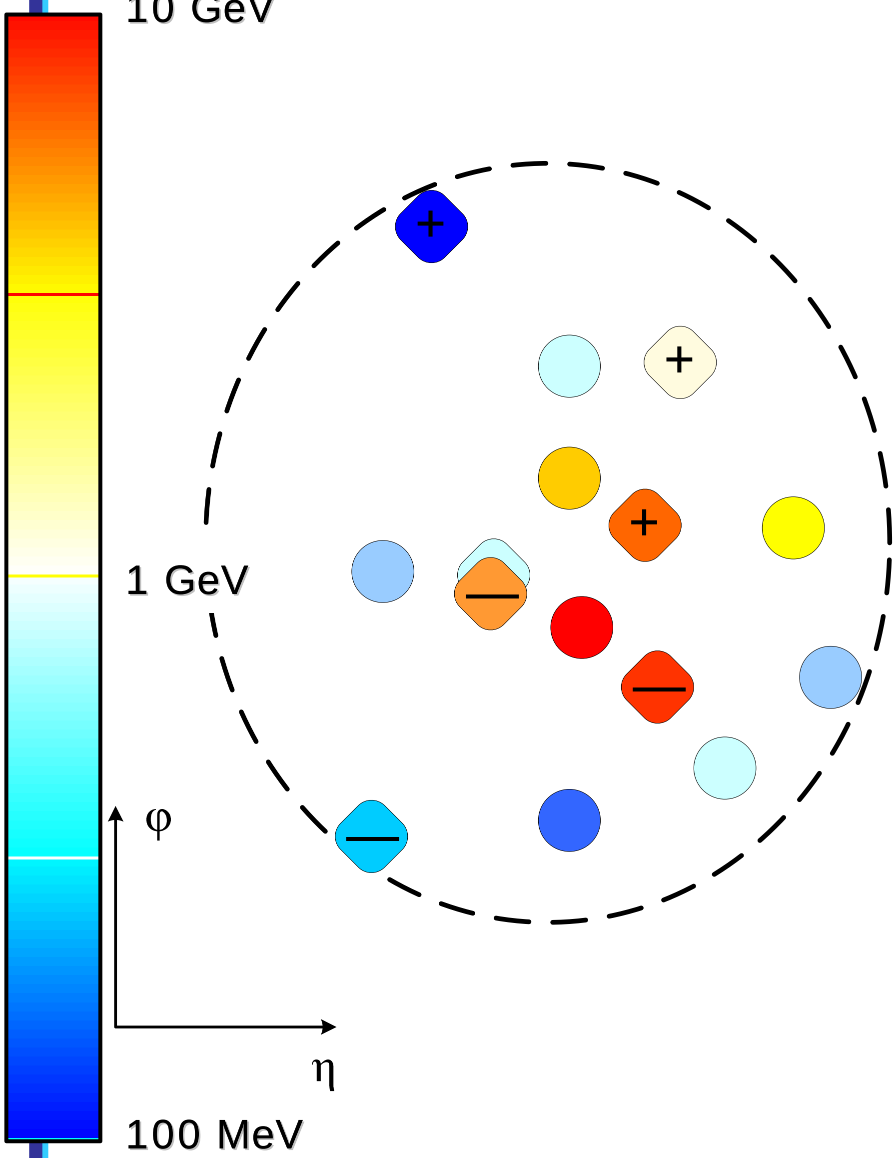
- Total loss of soft charged particles in magnetic field
- Partial and total energy loss of charged and neutral particles in inactive upstream material

Hadronic and electromagnetic cacades in calorimeters

- Distribute energy spatially
- Lateral particle shower overlap

Image of Jet in the Detector

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c



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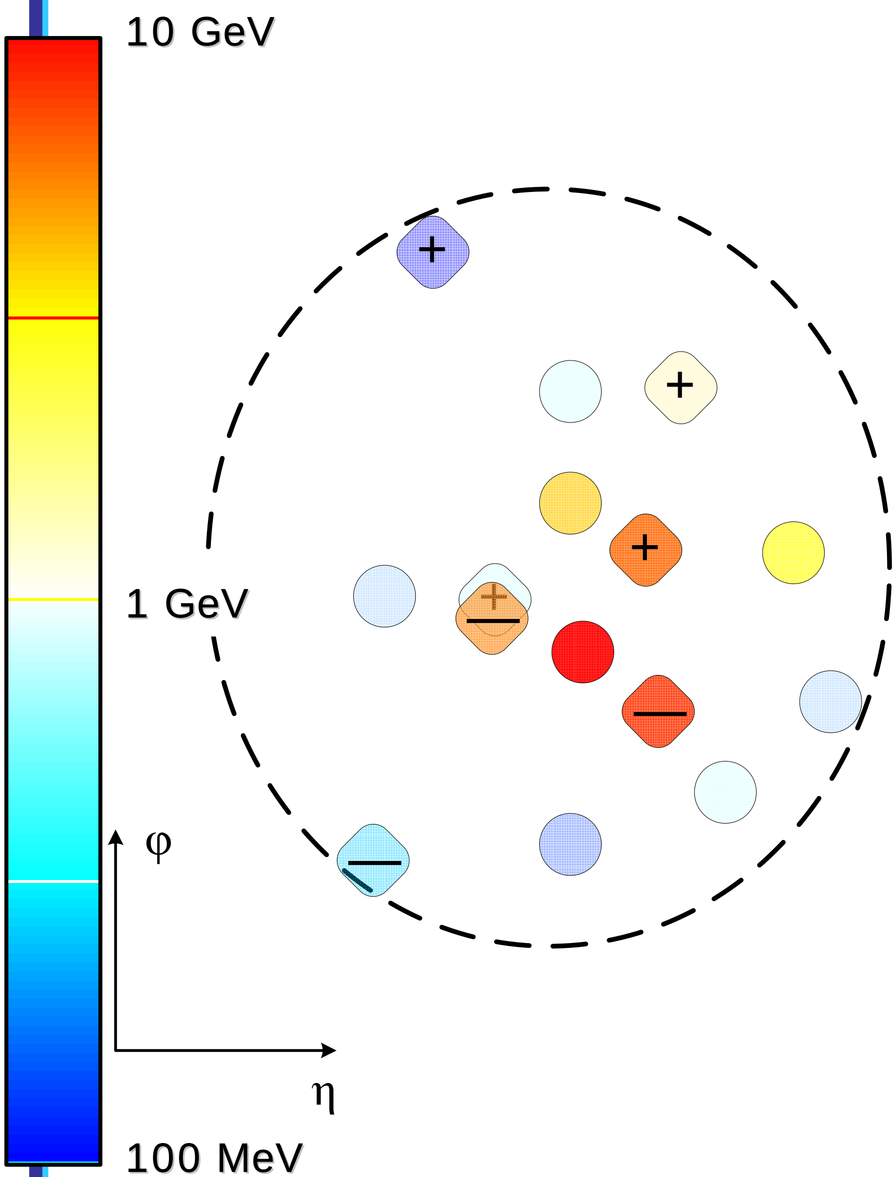

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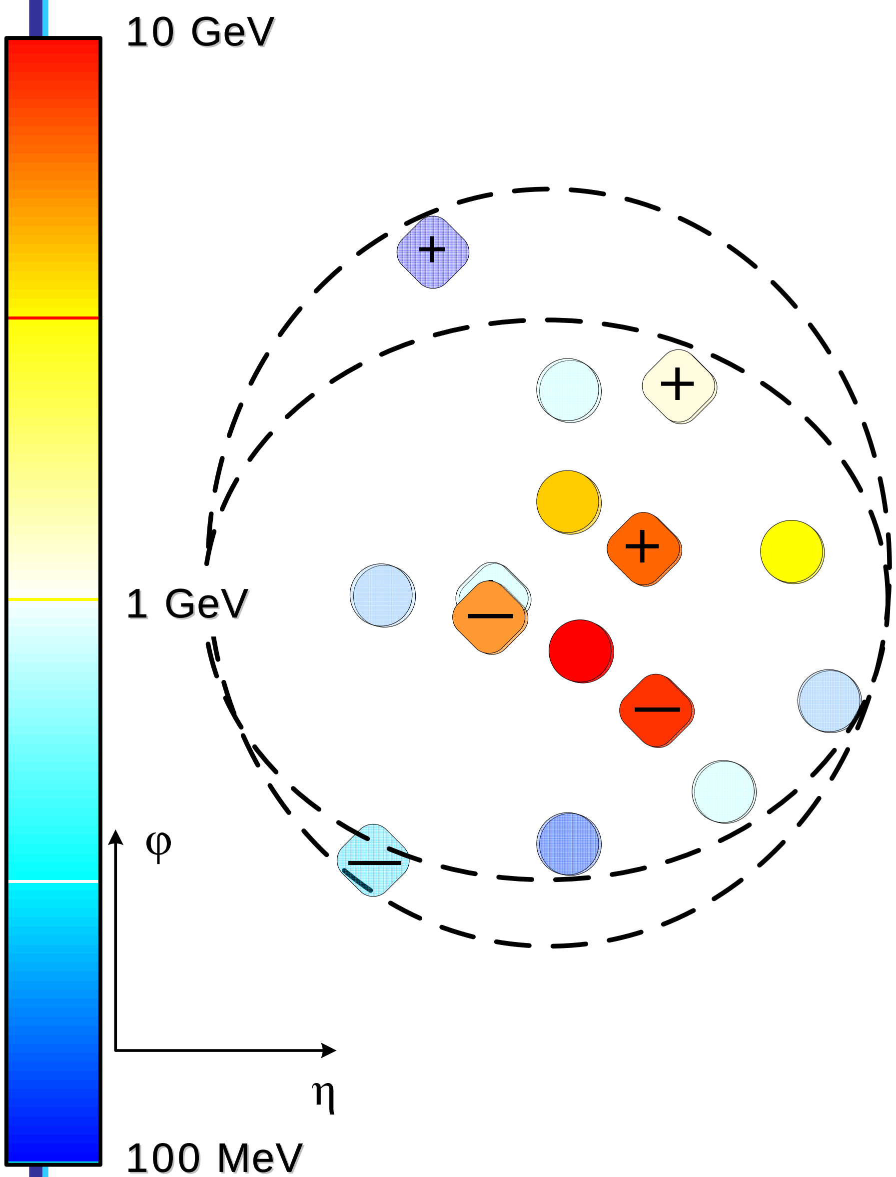

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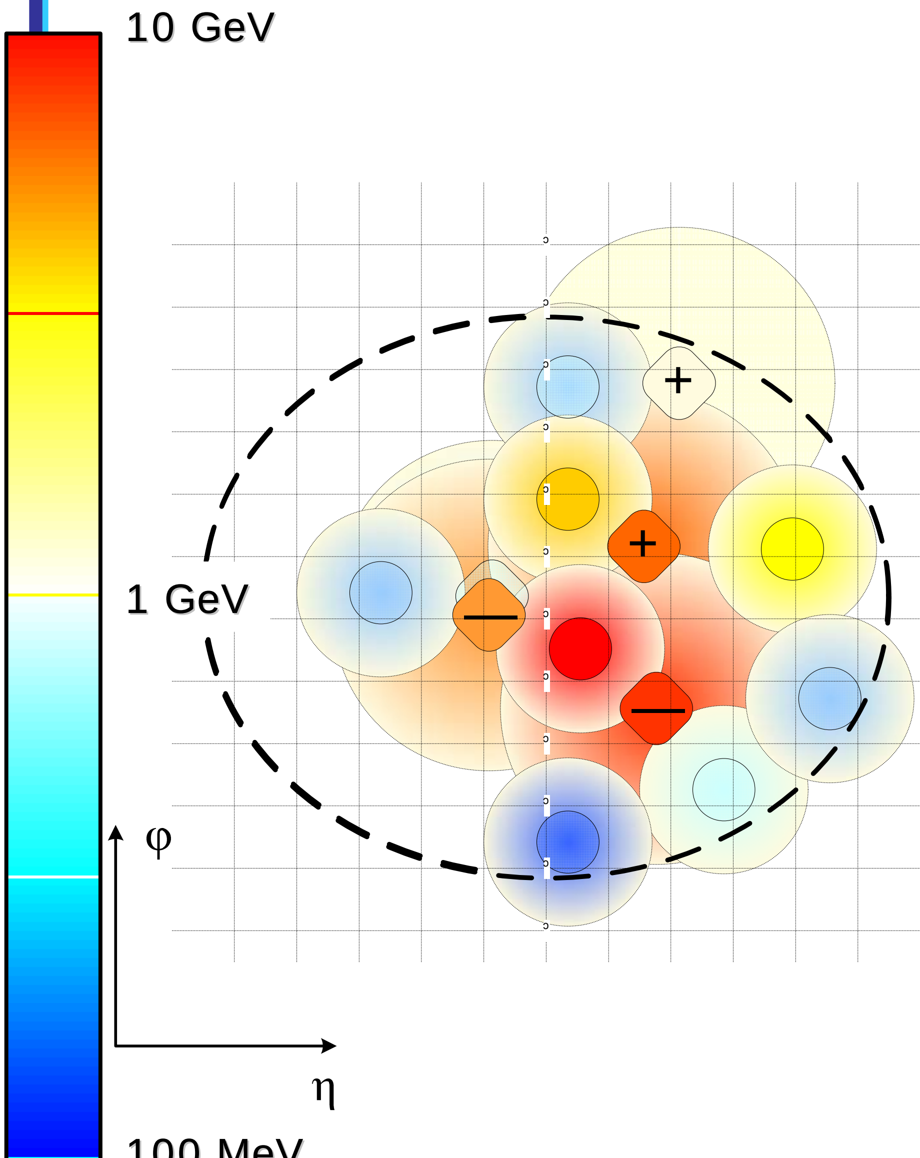

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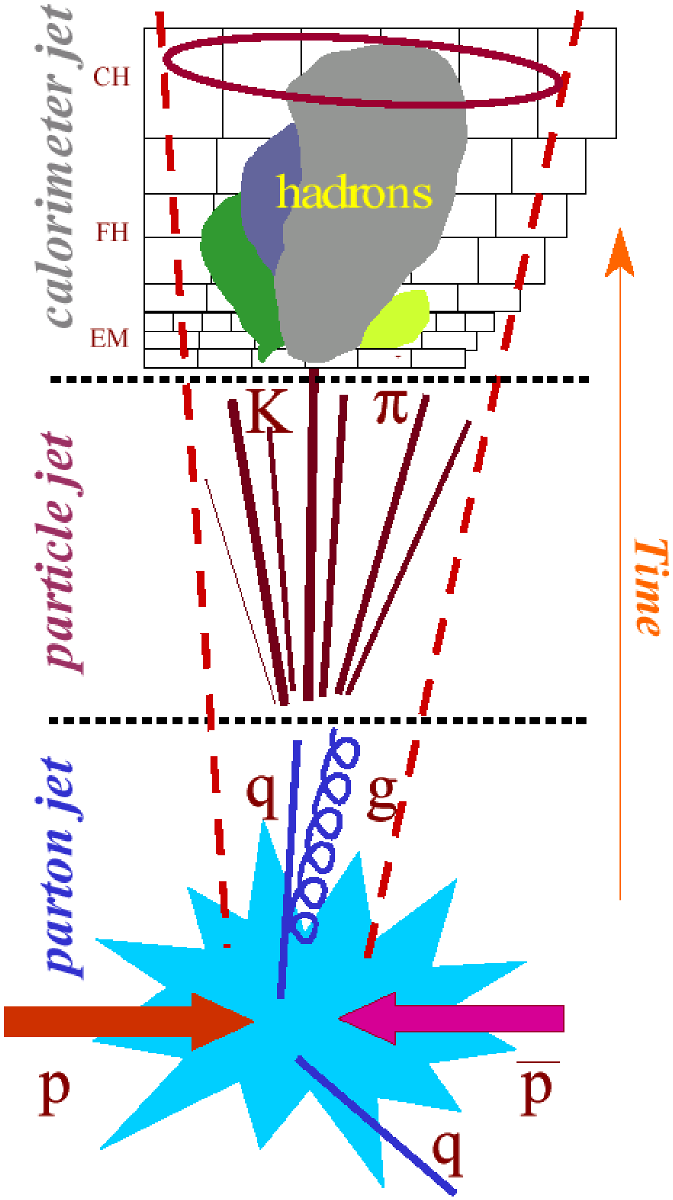
Jet Reconstruction Tasks

P. Loch
U of Arizona

Experiment ("Nature")



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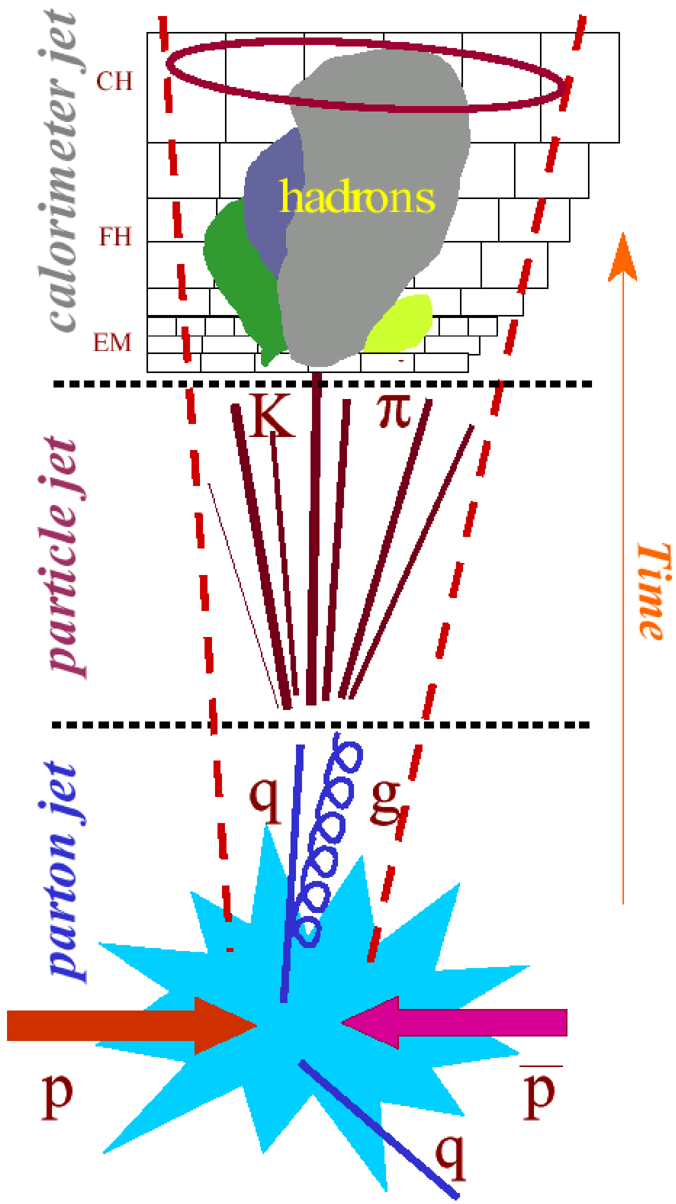
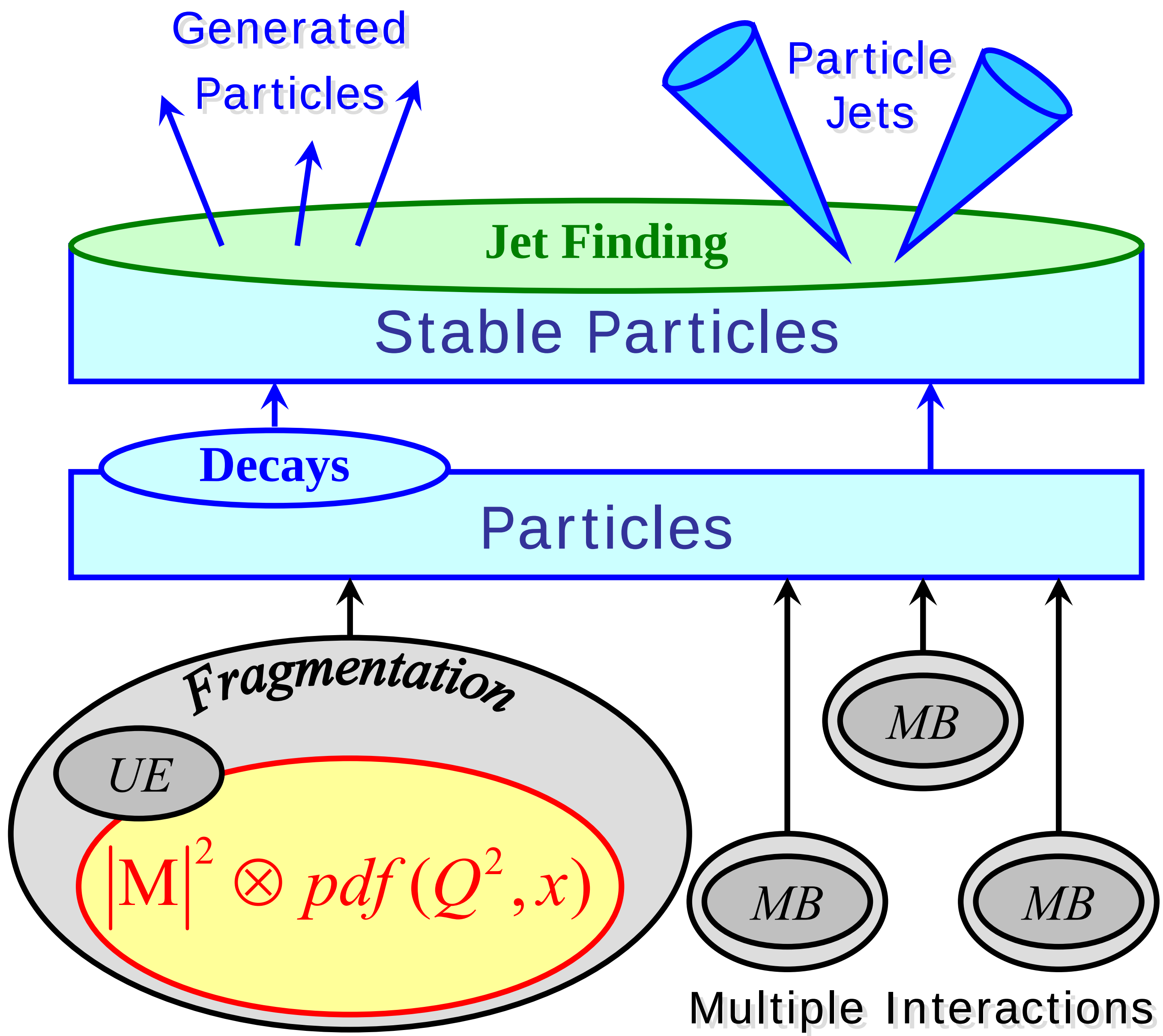


Modeling Particle Jets



Jet Reconstruction Task Overview

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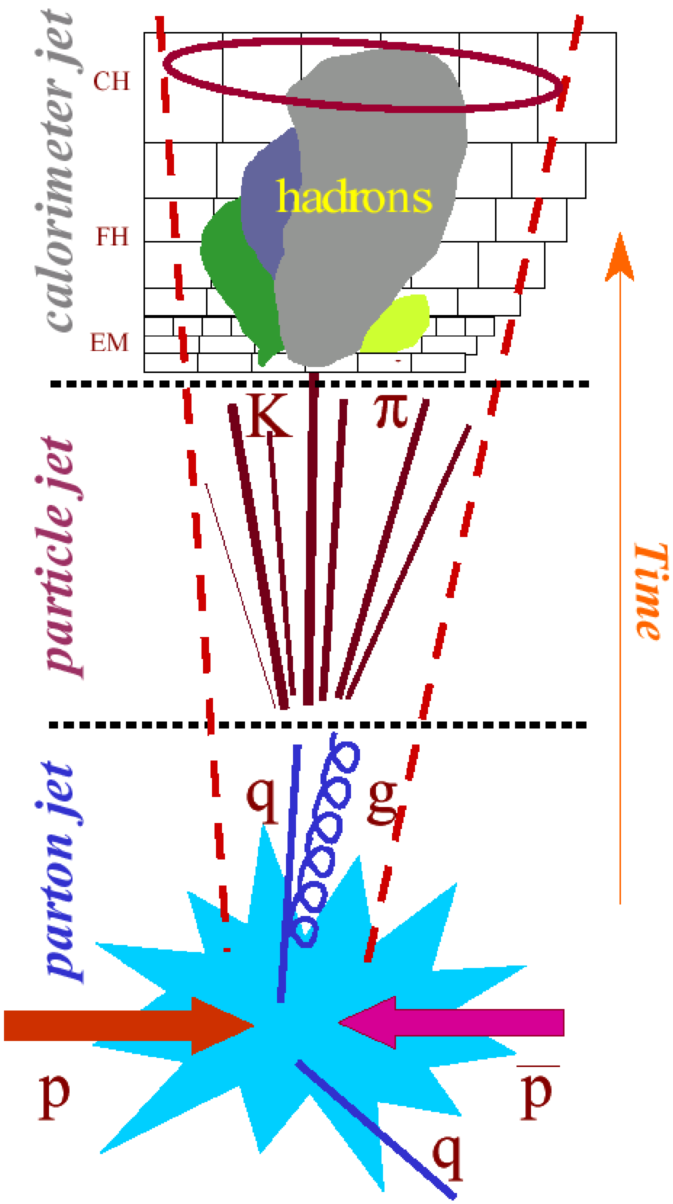
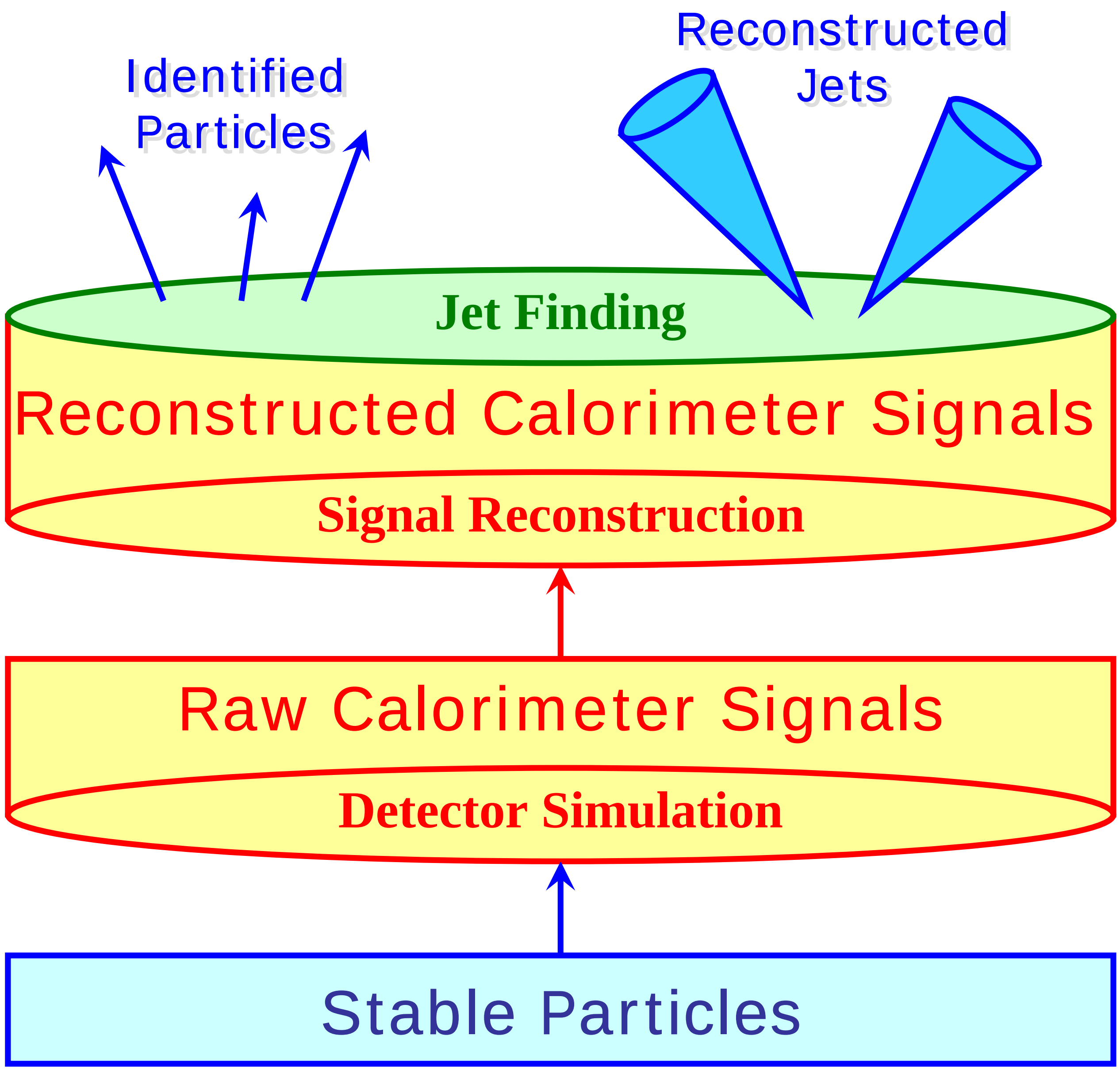
U of Arizona
June 30, 2009

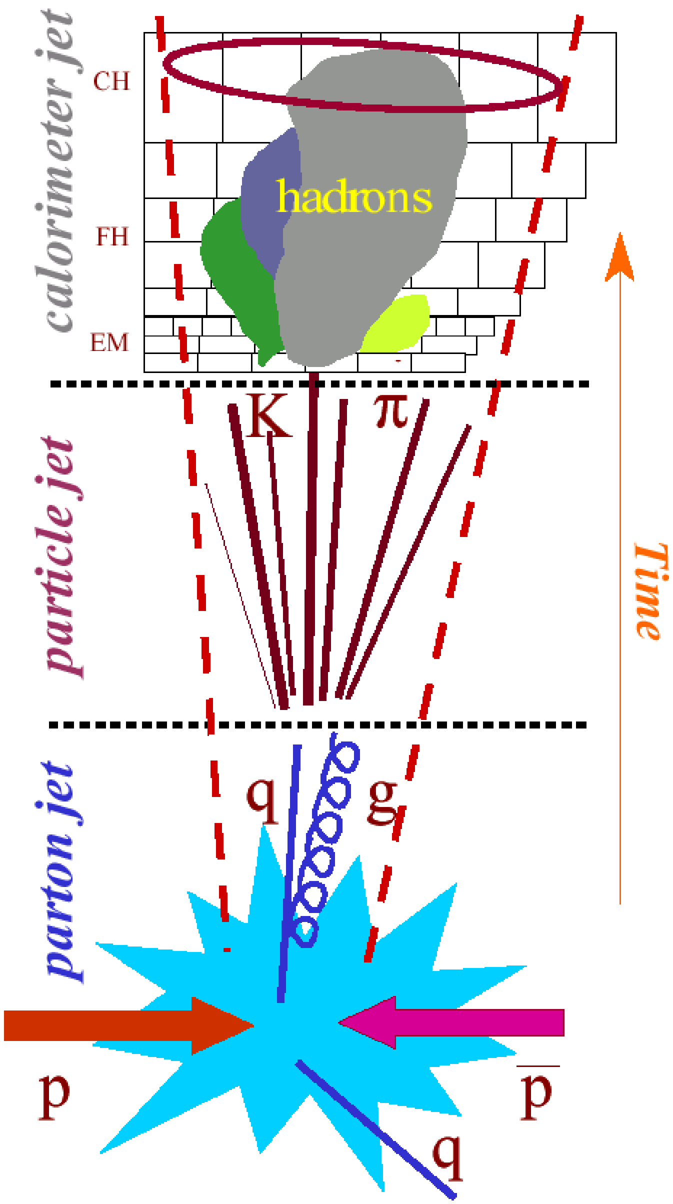
Experiment ("Nature")



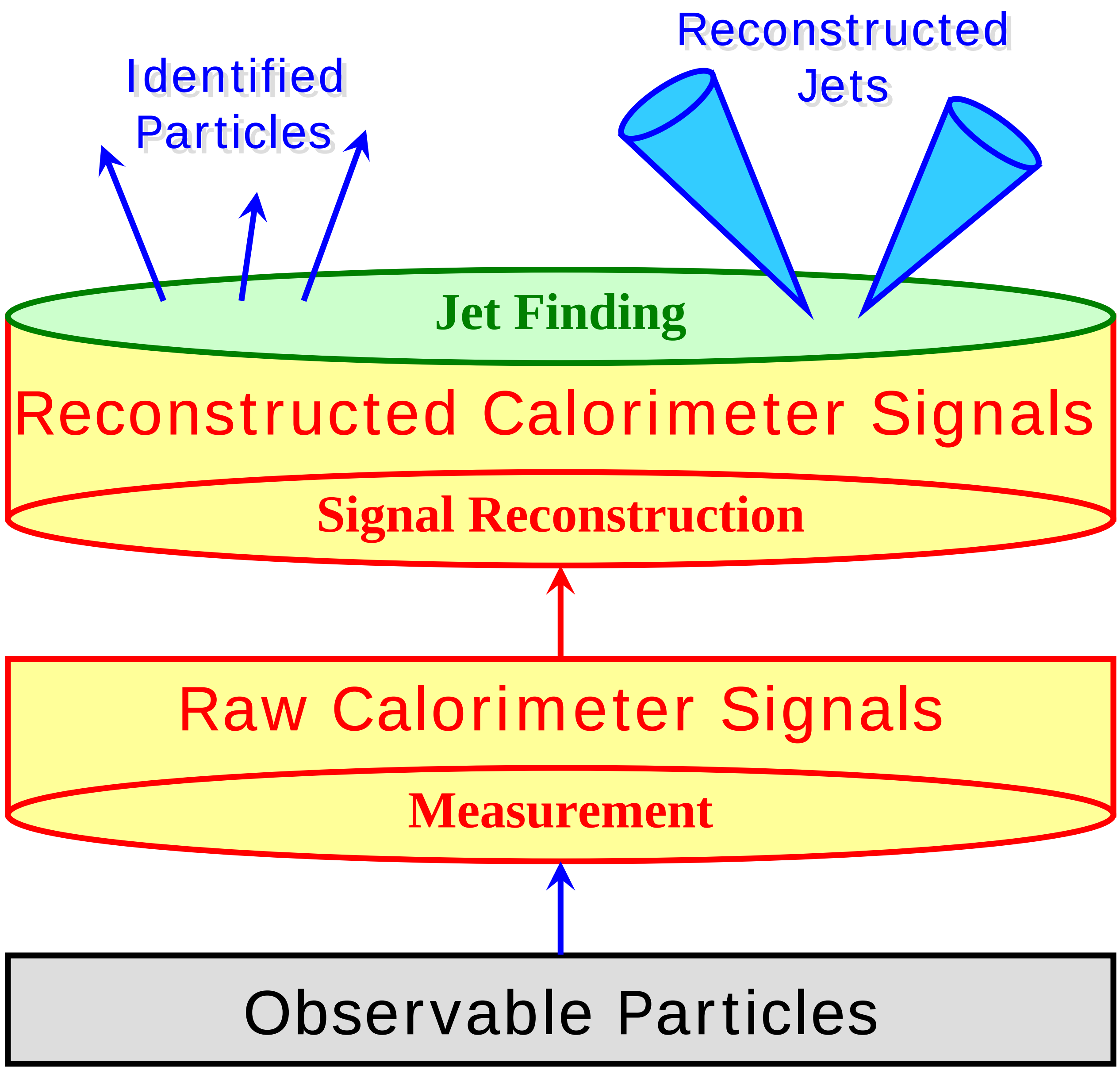
Modeling Calorimeter Jets



Experiment (“Nature”)



Measuring Calorimeter Jets



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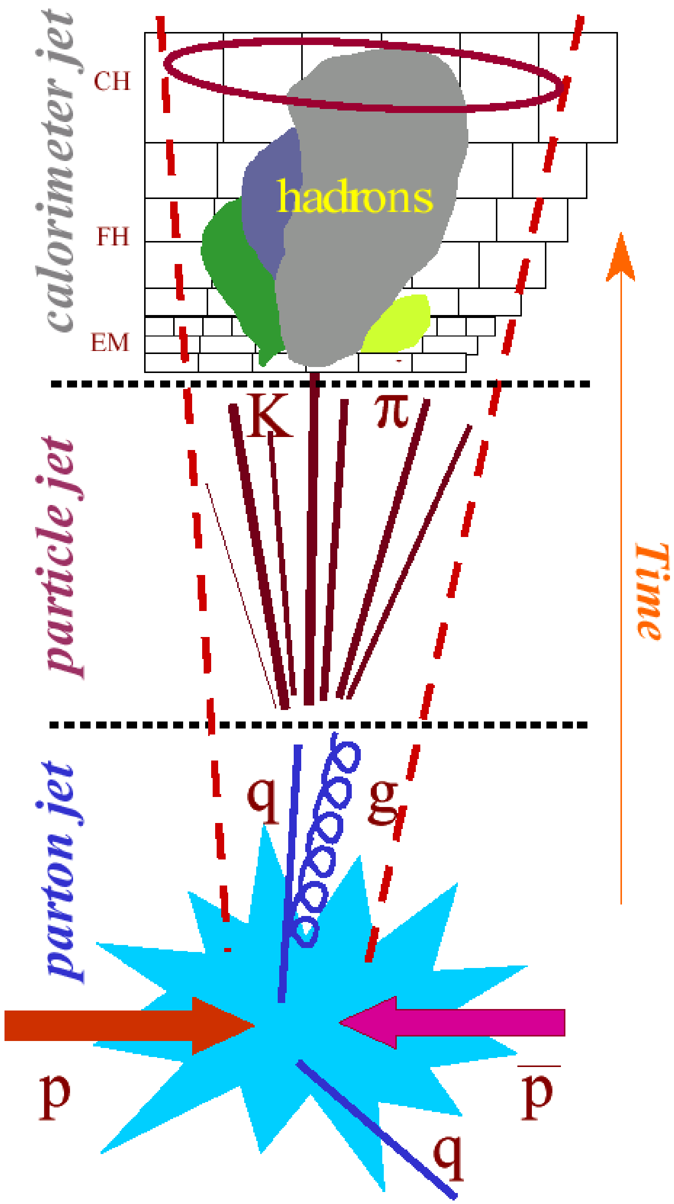

Jet Reconstruction Challenges

longitudinal energy leakage
detector signal inefficiencies (dead channels, HV…)
pile-up noise from (off- and in-time) bunch crossings
electronic noise
calo signal definition (clustering, noise suppression…)
dead material losses (front, cracks, transitions…)
detector response characteristics (e/h ≠ 1)
jet reconstruction algorithm efficiency
lost soft tracks due to magnetic field

added tracks from underlying event
added tracks from in-time (same trigger) pile-up event
jet reconstruction algorithm efficiency

physics reaction of interest (interaction or parton level)

3. Jet Measurements

The ATLAS Detector

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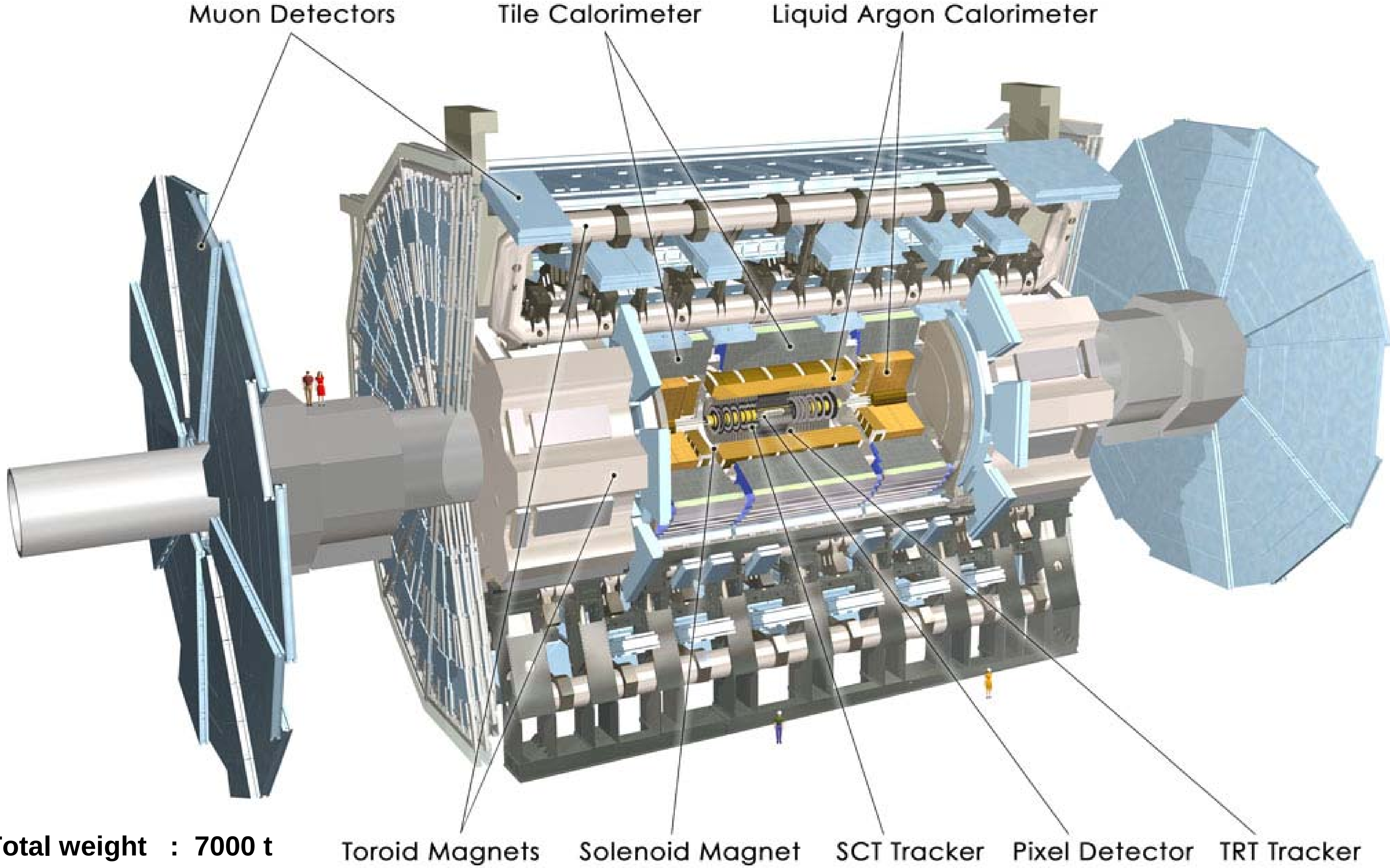
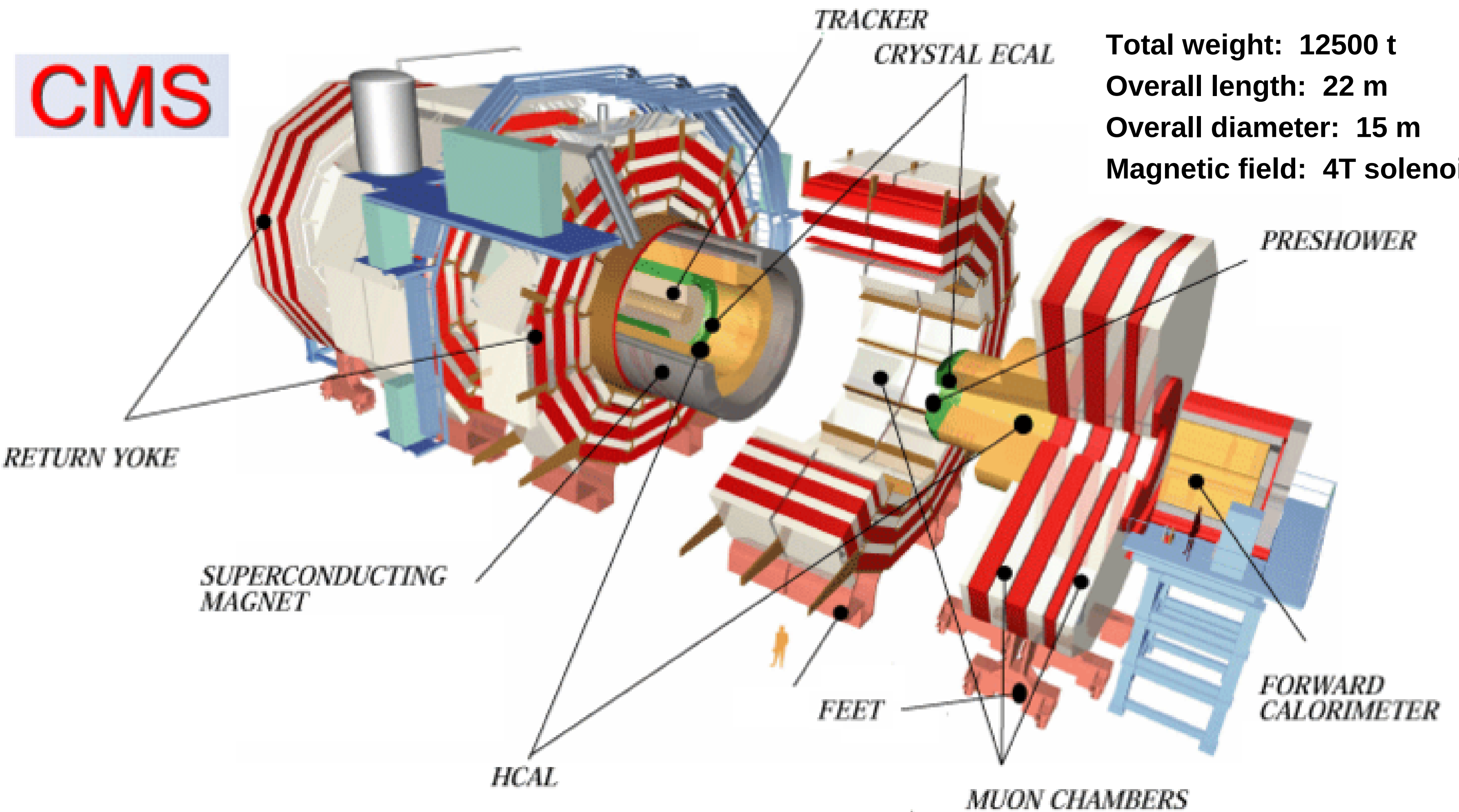
June 30, 2009



Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid
+ toroid

The CMS Detector

Total weight: 12500 t
Overall length: 22 m
Overall diameter: 15 m
Magnetic field: 4T solenoid



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Calorimeters Side-by-Side

P. Loch
U of Arizona
June 30, 2009

ATLAS Calorimeters

- EM: $|\eta| < 3.2$,
  - Pb/LAr calorimeter,
  - 22-26 X_0, 1.2 λ,
  - 3 longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.025 \times 0.025 - 0.1 \times 0.1$
  - $\sigma/E \simeq 10\%/\sqrt{E}$.
- Central Hadronic: $|\eta| < 1.7$,
  - Fe/Scintillator sampling calorimeter
  - 7.4 λ,
  - 3 longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1 - 0.2 \times 0.1$,
  - $\sigma/E \simeq 50\%/\sqrt{E} \oplus 0.03$.
- EndCap Hadronic: $1.7 < |\eta| < 3.2$,
  - Cu/LAr sampling calorimeter,
  - 4 longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1 - 0.2 \times 0.2$
- FCAL: $3 < |\eta| < 4.9$,
  - EM: Cu/LAr, HAD: W/LAr calorimeter,
  - 10 λ,
  - 1 EM + 2 HAD longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.75 \times 0.65 - 5.4 \times 4.7$

CMS calorimeters

- EM : $|\eta| < 3$,
  - $PbWO_4$ cristals,
  - 24.7-25.8 X_0, 1.1 λ,
  - 1 longitudinal section + preshower ($3X_0$),
  - $\Delta\eta \times \Delta\Phi = 0.0175 \times 0.0175$,
  - $\sigma/E \simeq 2 - 5\%/\sqrt{E}$.
- HCAL : $|\eta| < 3$,
  - Brass/Scintillator sampling calorimeter,
  - 6-10 λ
  - 2 longitudinal sections + Outer HCAL (3λ for $|\eta| < 1.4$)
  - $\Delta\eta \times \Delta\Phi \geq 0.0875 \times 0.0875$,
  - $\sigma/E \simeq 100\%/\sqrt{E} \oplus 0.05$.
- HF : $3 < |\eta| < 5$,
  - Fe/Quartz fibers, Cerenlov light
  - EM 90 X_0, HAD 9.5 λ
  - 1 EM + 1 HAD longitudinal sections

from “Jets & Heavy Flavour at LHC”, A.-M. Magnan, Photon09, May 2009

Quick Look at Hadronic Showers

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U of Arizona
June 30, 2009

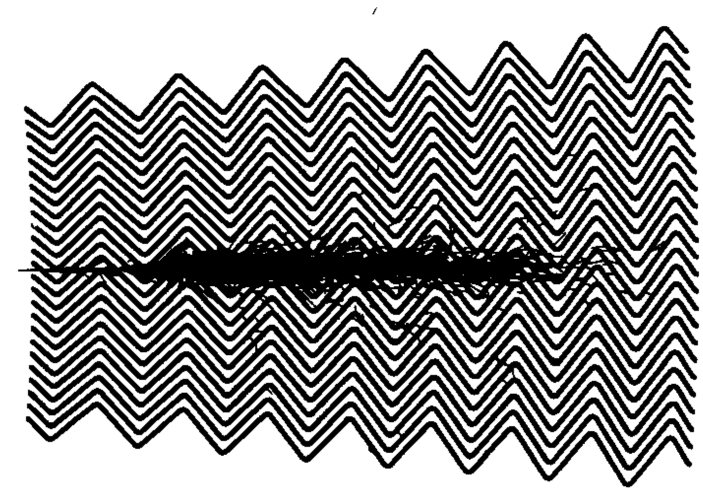
More complex than EM showers

- Visible EM O(50%)
  - $e^{\pm}$, γ, $\pi^{o} \rightarrow \gamma\gamma$
- Visible non-EM O(25%)
  - Ionization of $\pi^{\pm}$, p, $\mu^{\pm}$
- Invisible O(25%)
  - Nuclear break-up
  - Nuclear excitation
- Escaped O(2%)
  - Neutrinos produced in shower

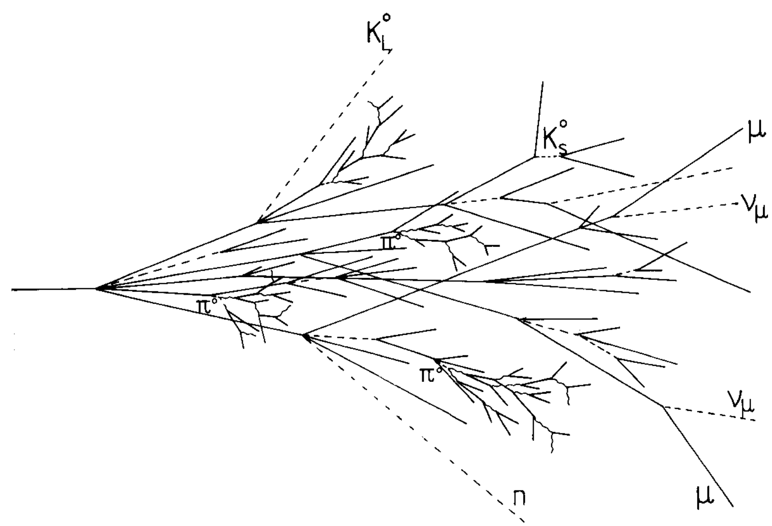
Only part of the visible energy is sampled into the signal

- No intrinsic compensation for losses in ATLAS or CMS
  - Both are non-compensating calorimeters
  - Electron signal on average larger than pion signal at same deposited energy (e/h > 1)
- Introduces complex jet response
  - Mixture of electromgnetic and hadronic signals in a priori unknown fluctuations

EM shower



RD3 note 41, 28 Jan 1993



Grupen, Particle Detectors

Showers Side-by-Side

Electromagnetic

- Compact
  - Growths in depth ~log(E)
- Longitudinal extension scale is radiation length X_0
  - Distance in matter in which ~50% of electron energy is radiated off
  - Photons 9/7 X_0
- Strong correlation between lateral and longitudinal shower development
- Small intrinsic shower-to-shower fluctuations
  - Very regular development
- Can be simulated with high precision
  - 1% or better, depending on features

Hadronic

- Scattered, significantly bigger
  - Growths in depth ~log(E)
- Longitudinal extension scale is interaction length λ
  - Average distance between two inelastic interactions in matter
  - Varies significantly for pions, protons, neutrons
- Weak correlation between longitudinal and lateral shower development
- Large intrinsic shower-to-shower fluctuations
  - Very irregular development
- Can be simulated with reasonable precision
  - ~2-5% depending on feature

Signals from Hadronic Showers

Signal components

- Hadronic signal contributions change with energy
  - Visible non-EM fraction decreases with *E*
  - Shower look more electromagnetic at high energies
- Hadron response not linear with *E*
  - Invisible energy is the main source of e/h > 1
  - Different signals from intrinsic em showers and ionizations by charged hadrons
- Large fluctuations of each component fraction lead to large signal fluctuations
  - Intrinsic fluctuations bigger than sampling fluctuations

Electromagnetic energy scale calibration does not recover loss

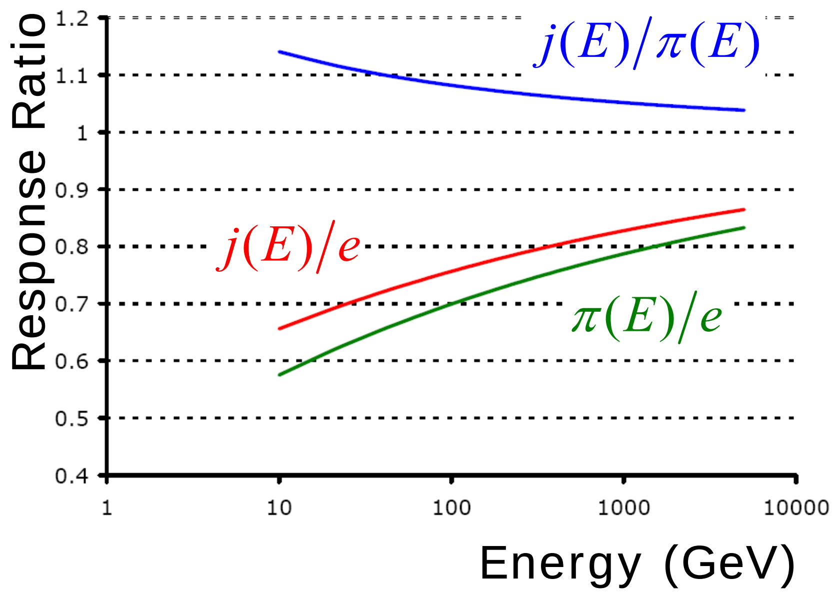
- Basic signal scale in calorimeters is defined by electron response
  - Linear response to whole shower
  - All processes leave observable signal – in principle
- Need additional corrections to measure hadron or jet energy
  - Typically non-linear response corrections to restore scale
  - Additional attempt to reduce fluctuations
- Increased complexity due to

$$\frac{e}{\pi} = \frac{1}{1-(1-h/e)(E/E_0)^{m-1}}$$

$$0.80 \le m \le 0.85$$

$$E_0 = \begin{cases} 1\ \text{GeV} & \pi^{\pm} \\ 2.6\ \text{GeV} & p \end{cases}$$

T.A. Gabriel, D.E. Groom,
Nucl. Instr. Meth. **A338** (1994) 336



Smallest signal collection volume

- Defines resolution of spatial structures
  - Finest granularity depends on direction and sampling layer in ATLAS
- Each is read out independently
  - Can generate more than one signal (e.g., ATLAS Tile cells feature two readouts)

Individual cell signals

- Sensitive to noise (different for CMS and ATLAS)
  - Fluctuations in electronics gain and shaping
  - Time jitters
  - Physics sources like multiple proton interaction history in pile-up
- Hard to calibrate for hadrons
  - No measure to determine if electromagnetic or hadronic in cell signal alone, i.e. no handle to estimate e/h
  - Need signal neighbourhood and/or other detectors to calibrate
- Basic energy scale
  - Use electron calibration to establish basic energy scale for cell signals

Cell geometry

- Quasi-projective by pointing to the nominal collision vertex in ATLAS and CMS
  - Lateral sizes scale with pseudo-rapidity and azimuthal angular opening
  - Non-projective in ATLAS Forward Calorimeter

ATLAS Calorimeter Towers

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June 30, 2009

Impose a regular grid view on event

- $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ grid
- Motivated by particle Et flow in hadron-hadron collisions
- Well suited for trigger purposes

Collect cells into tower grid

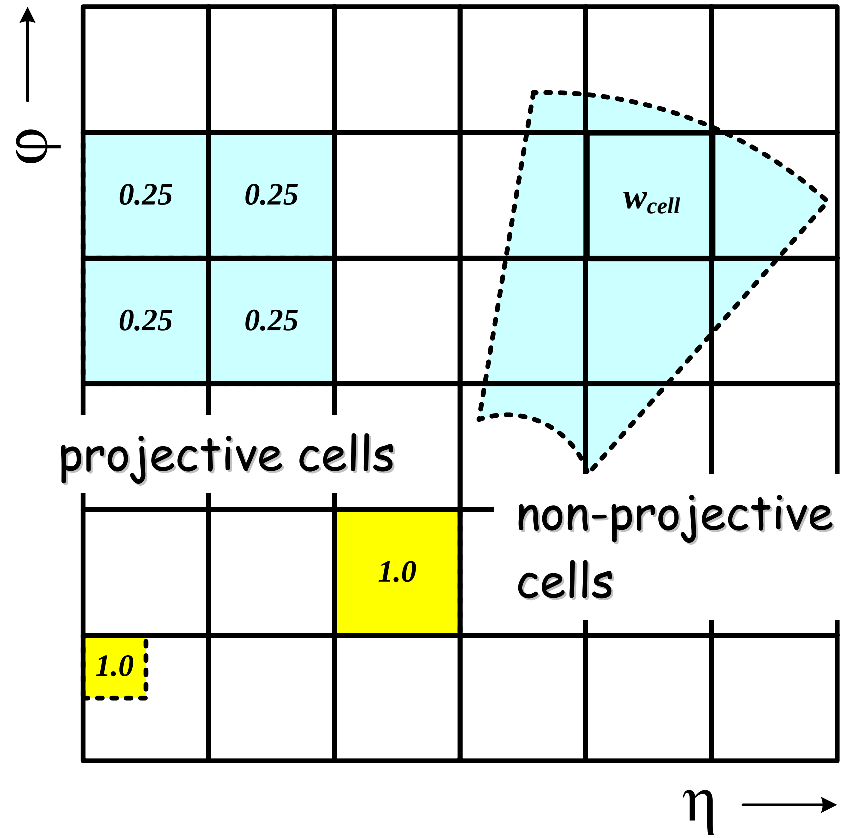
- Cells EM scale signals are summed with geometrical weights
  - Depend on cell area containment ratio
  - Weight = 1 for projective cells of equal or smaller than tower size
- Summing can be selective
  - See jet input signal discussion

Towers have massless four-momentum representation

- Fixed direction given by geometrical grid center

$$\left(E_{\eta\varphi},\eta,\varphi\right) \mapsto \left(E = p, p_x, p_y, p_z\right)$$

$$p = \sqrt{p_x^2 + p_y^2 + p_z^2}$$



$$E_{\eta\varphi} = \sum_{\left(A_{cell}^{\eta\varphi} \cap A_{\eta\varphi}\right) \neq 0} w_{cell} E_{0,cell}$$

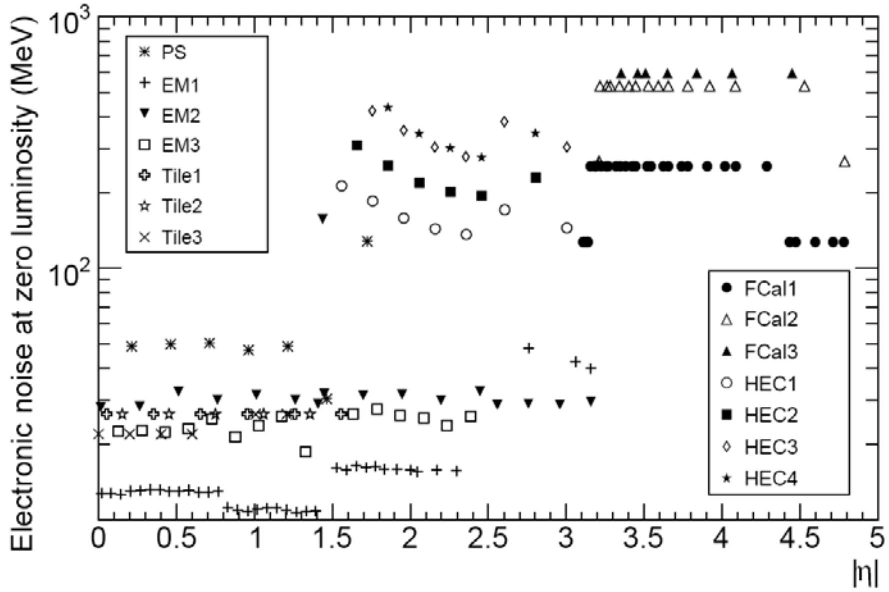
$$w_{cell} = \begin{cases} 1 & \text{if } A_{cell}^{\eta\varphi} \leq \Delta\eta \times \Delta\varphi \\ <1 & \text{if } A_{cell}^{\eta\varphi} > \Delta\eta \times \Delta\varphi \end{cases}$$

ATLAS Topological Cell Clusters (1)

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

Signal extraction tool

- Attempt reconstruction of individual particle showers
  - Reconstruct 3-dim clusters of cells with correlated signals
- Use shape of these clusters to locally calibrate them
  - Explore differences between electromagnetic and hadronic shower development and select best suited calibration
- Supress noise with least bias on physics signals
  - Often less than 50% of all cells in an event with "real" signal



Some implications of jet environment

- Shower overlap cannot always be resolved
  - Clusters represent merged particle showers in dense jets
- Clusters have varying sizes
  - No simple jet area as in case of towers
- Clusters are mass-less 4-vectors (as towers)
  - No "artificial" mass contribution due to showering
- Issues with IR safety at very small scale insignificant
  - Pile-Up environment triggers split as well as merge
  - Note that calorimeters themselves are not completely IR safe

JINST 3:S08003, 2008

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

Cluster seeding

- Cluster seed is cell with significant signal above a primary threshold

Cluster growth: direct neighbours

- Neighbouring cells (in 3-d) with cell signal significance above some basic threshold are collected

Cluster growth: control of expansion

- Collect neighbours of neighbours for cells above secondary signal significance threshold
  - Secondary threshold lower than primary (seed) threshold

Cluster splitting

- Analyze clusters for local signal maxima and split if more than one found
  - Signal hill & valley analysis in 3-d

Final "energy blob" can contain low signal cells

- Cells survive due to significant neighbouring signal
- Cells inside blob can have negative signals

ATLAS also studies "TopoTowers"

- Use topological clustering as noise suppression tool only
- Distribute only energy of clustered cells onto tower grid
- Motivated by DZero approach

ATLAS Topological Cell Clusters (3)

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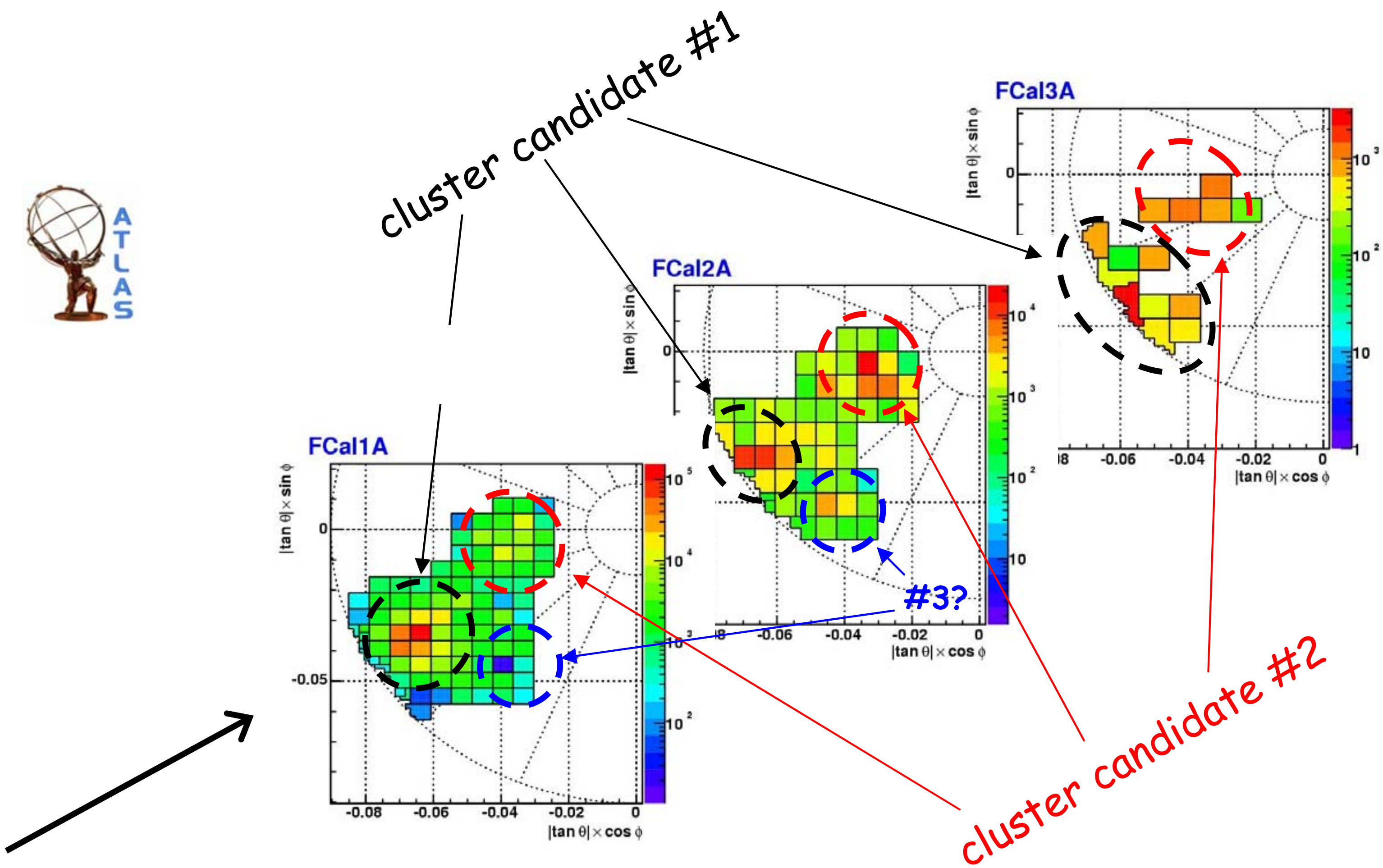

Local hadronic energy scale restauraion depends on origin of calorimeter signal

- Attempt to classify energy deposit as electromagnetic or hadronic from the cluster signal and shape
  - Allows to apply specific corrections and calibrations

Local calibration approach

- Use topological cell clusters as signal base for a hadronic energy scale
  - Recall cell signals need context for hadronic calibration
- Basic concept is to reconstruct the locally deposited energy from the cluster signal first
  - This is not the particle energy
- Additional corrections for energy losses with some correlation to the cluster signals and shapes extend the local scope
  - True signal loss due to the noise suppression in the cluster algorithm (still local)
  - Dead material losses in front of, or between sensitive calorimeter volumes (larger scope than local deposit)

After all corrections, the reconstructed energy is on average the isolated particle energy

- E.g., in a testbeam
  - But not the jet energy (see later)

ATLAS Local Scale Sequence

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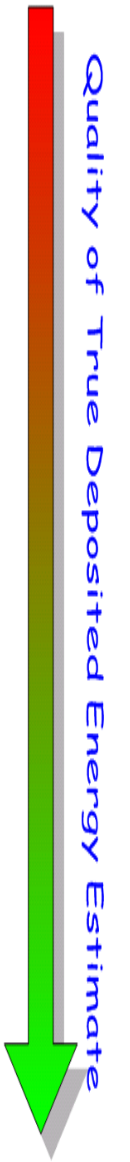
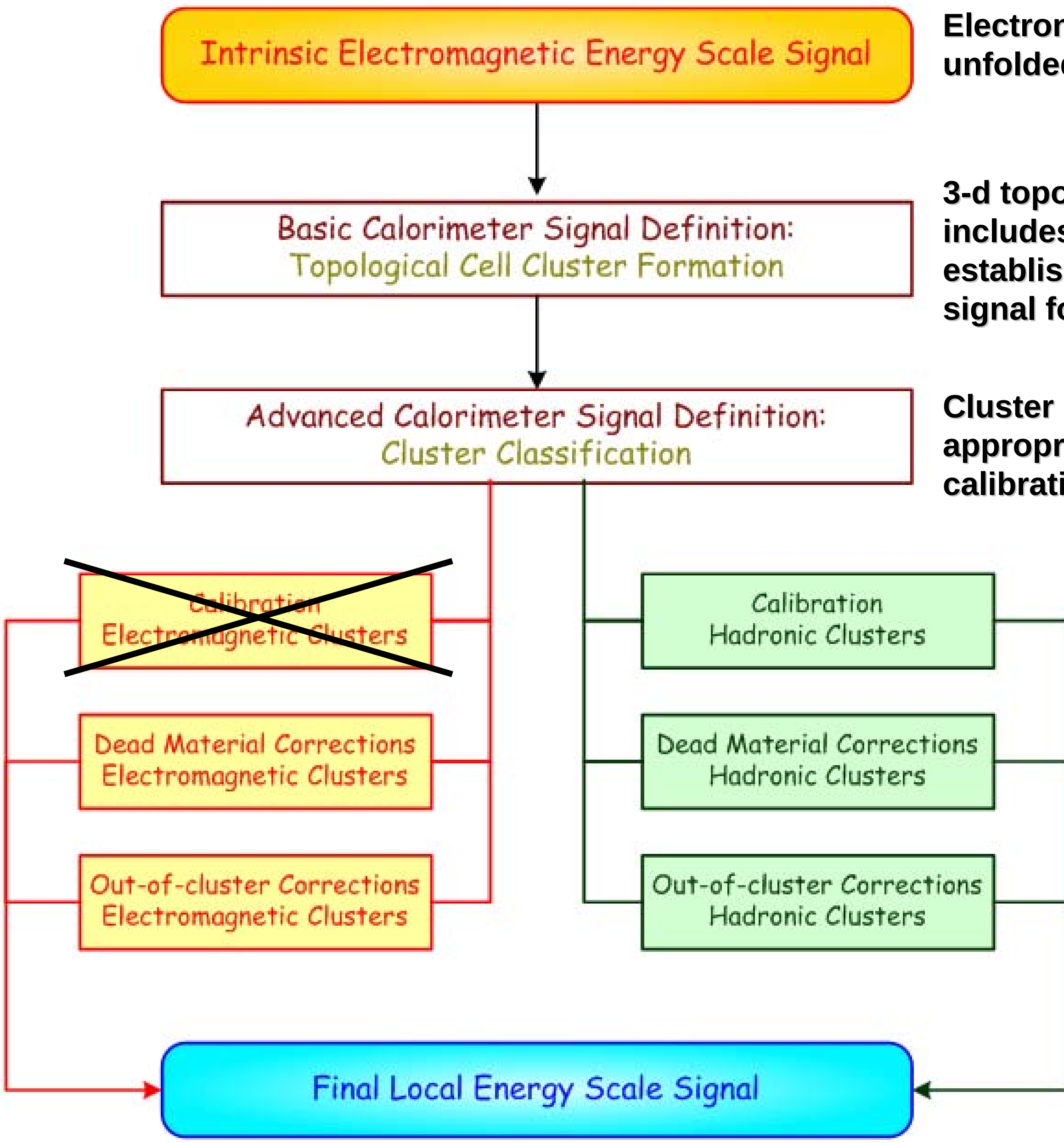
June 30, 2009





Electronic and readout effects unfolded (nA->GeV calibration)

3-d topological cell clustering includes noise suppression and establishes basic calorimeter signal for further processing

Cluster shape analysis provides appropriate classification for calibration and corrections

Cluster character depending calibration (cell signal weighting for HAD, to be developed for EM?)

Apply dead material corrections specific for hadronic and electromagnetic clusters, resp.

Apply specific out-of-cluster corrections for hadronic and electromagnetic clusters, resp.

CMS Energy Flow Signal

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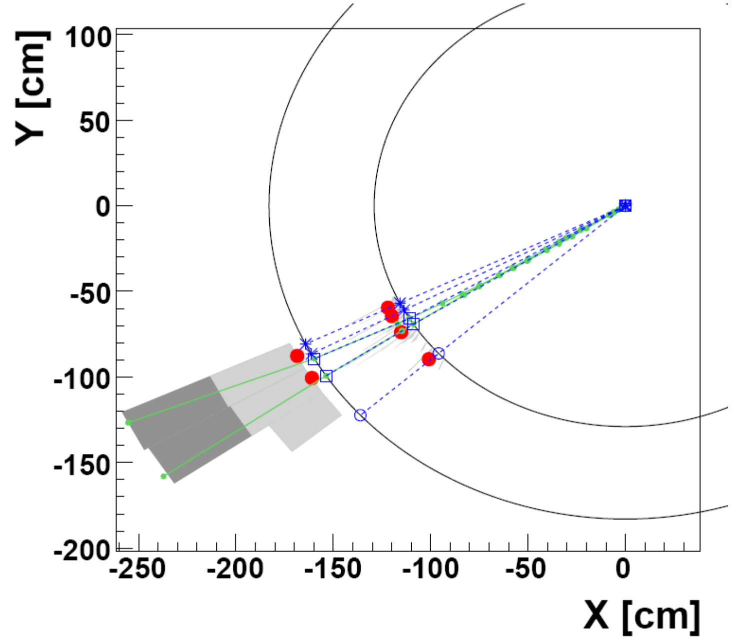
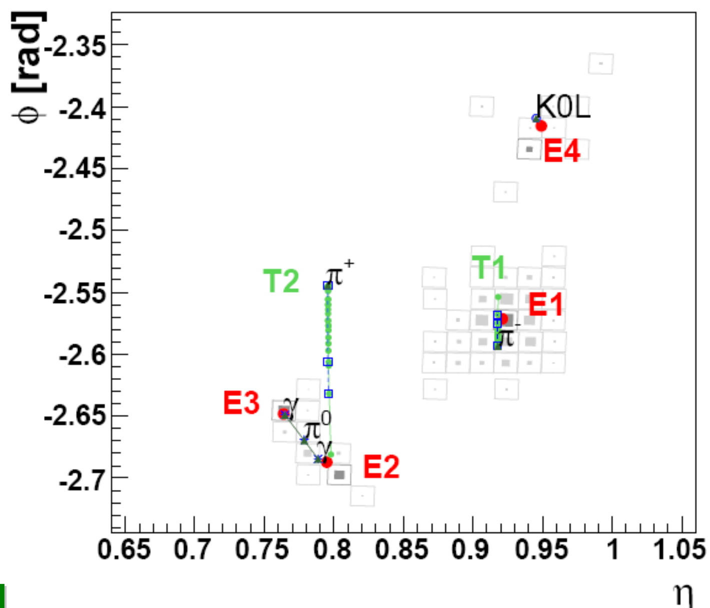
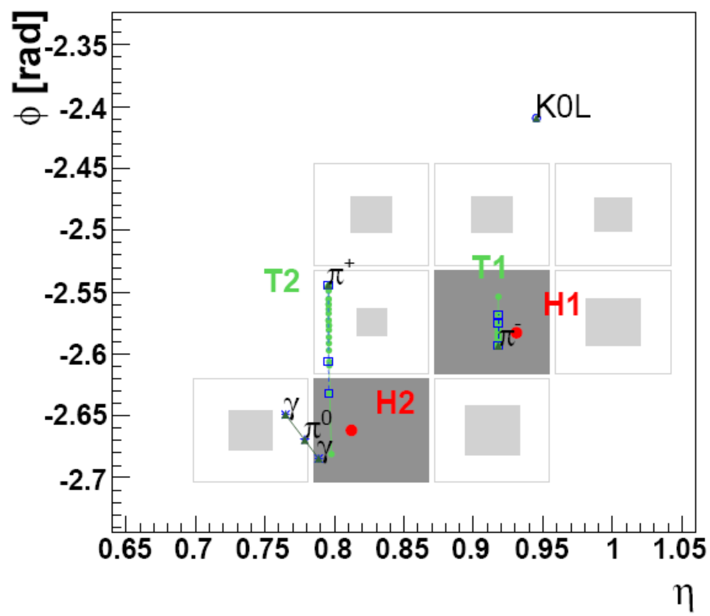
Attempt to reconstruct each particle separately

- Start with topological calorimeter signal clusters
  - Clusters formed in similar way as in ATLAS
  - Hadronic cluster calibration depends on energy sharing between sections



- Use energy flow approach
  - Replace cluster signal with better measured tracks for charged hadrons and identified muons





CMS PAS PFT-09/001

CMS Link Algorithm

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U of Arizona
June 30, 2009

Links between detector signals

- Based on pseudo-rapidity and azimuth difference between clusters and tracks
  - Between clusters and tracks
  - Between clusters in ECAL and in HCAL
- Establish all links
  - Direction overlap criteria apply

Particle-flow charged hadrons

- Cluster(s) linked to tracks have less signal than track pT suggests
  - Charged hadron hypothesis: momentum and energy from track
    - Pion mass assumption
- Cluster(s) and tracks have comparable signal
  - Total charged hadron energy from error-weighted mean of track and calorimeter signals

Particle flow photons and neutral hadrons

- Cluster(s) have significant energy excess with respect to closests track
  - If excess larger than ECAL energy, photon is created from ECAL energy and neutral hadron is created from HCAL

CMS PAS PFT-09/001

Jet Input Signals (1)

Electromagnetic energy scale signals in calorimeters

ATLAS basic towers

- No noise suppression, all cells (~190,000) used
- Noise cancellation by re-summation of negative tower signals with near-by positive signals
- Et(tower) > 0 threshold

ATLAS topological clusters & towers

- Noise suppressed by topological cell cluster formation
- Different signal geometry
- Et(tower) > 0 threshold

CMS towers

- No cell noise suppression
- Et(tower) > 500 MeV(1 GeV?) threshold

Particle or hadronic scale signals

CMS particle flow

- Fully reconstructed particle flow with charged and neutral hadrons, electrons and photons (isolated/non-isolated), photons, muons
- Follow event particle flow as much as possible

ATLAS local hadronic scale

- Locally calibrated topological cell clusters
- Correlated with event particle flow but no explicite particle reconstruction

Jet Input Signals (2)

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ATLAS

- Basic 0.1 x 0.1 towers
  - All cells (~190,000) projected into towers
  - Electromagnetic energy scale signal
  - No noise suppression but noise cancellation attempt
- Topological 0.1 x 0.1 towers
  - Cells from topological clusters only
  - Electromagnetic energy scale signal
  - Noise suppression like for topological clusters
- Topological cell clusters
  - Electromagnetic and local hadronic scale signals
  - Noise suppressed
- Tower and clusters create different jets
  - Cluster sequences different
  - Shapes different

CMS

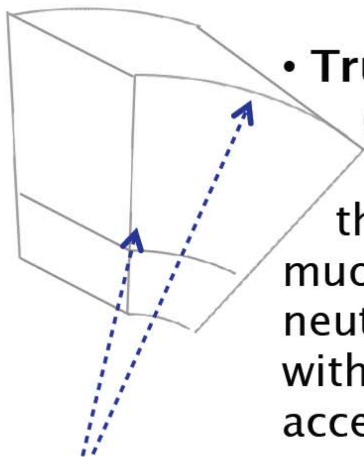
- Basic towers 0.1 x 0.1
  - Electromagnetic scale signal
  - Et > 1 GeV (500 MeV) noise suppression for each tower
- Energy flow objects provide particle level signal representation
  - Charged hadrons
  - Neutral hadrons
  - Muons
  - Electrons (isolated and non-isolated)
  - Photons

Both:

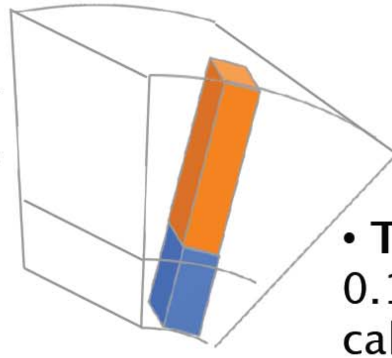
- Reconstructed tracks
  - Track jets
- Stable truth particles in simulations
  - Truth jets
- Fast simulation pseudo-cells, -towers, -clusters

Jet Input Signals (3)

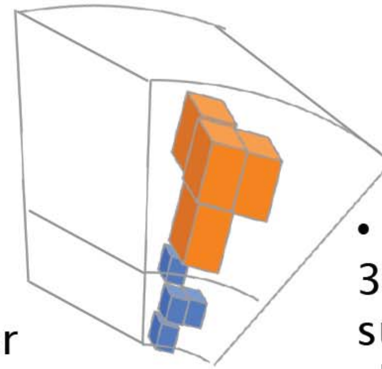
1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c



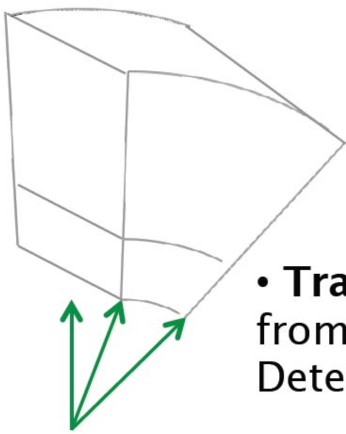
- **Truth**: generator particles that aren't muons or neutrinos, within η acceptance



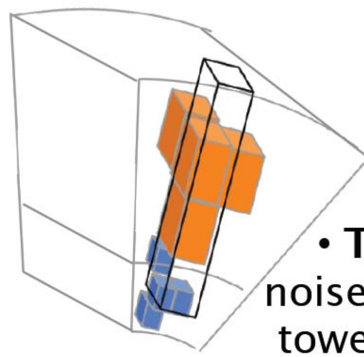
- **Towers**: 0.1x0.1 calorimeter towers



- **TopoClusters**: 3D noise-suppressed clusters of cells



- **Tracks**: from Inner Detector

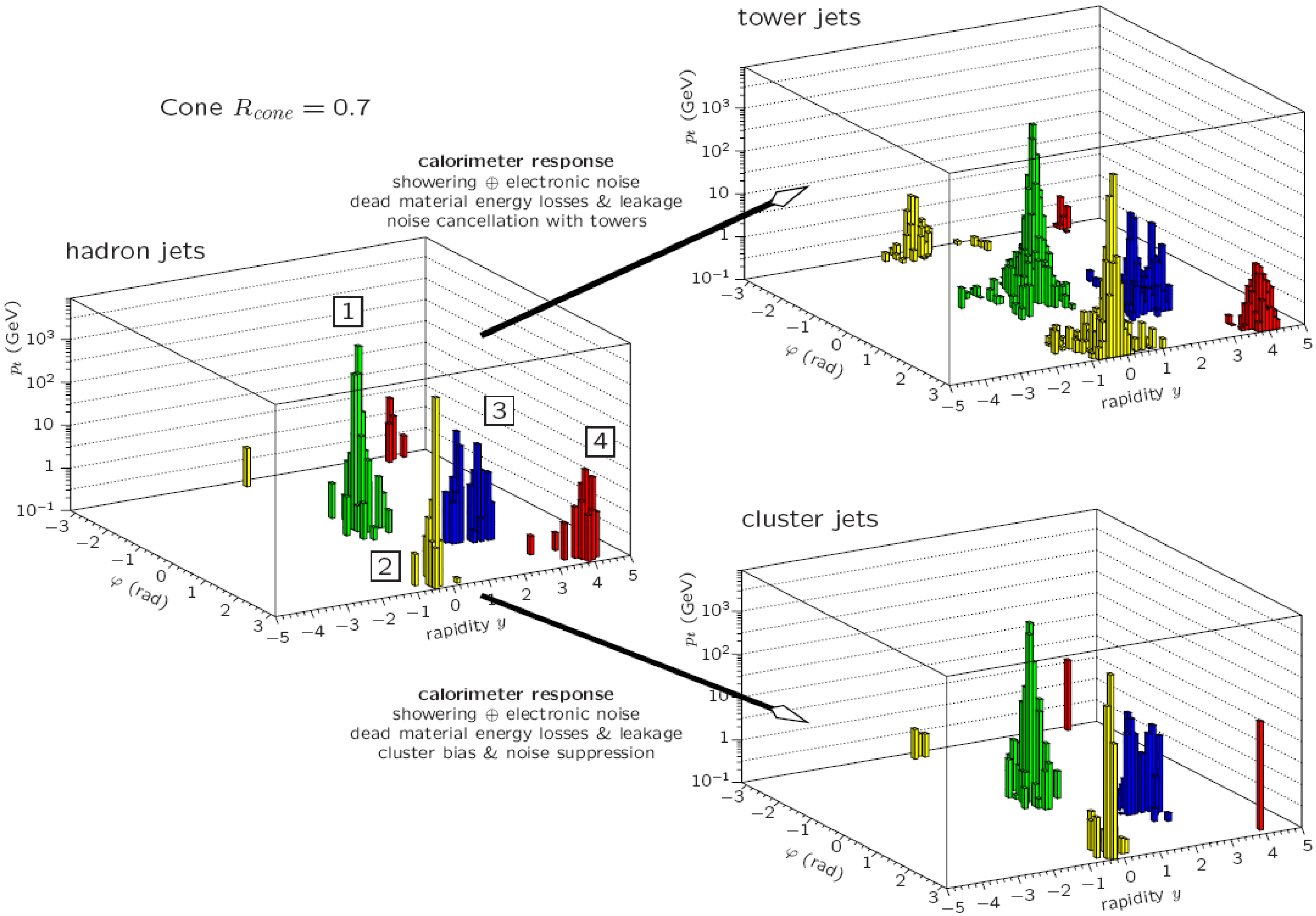


- **TopoTowers**: noise-suppressed towers built from topoclusters

from K. Perez, Columbia U.

Jets in the ATLAS Calorimeters

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c



S.D. Ellis, J. Huston, K. Hatakeyama, P. Loch, M. Toennesmann, **Prog.Part.Nucl.Phys.60:484-551,2008**

Sequential process

- Input signal selection
  - Get the best signals out of your detector on a given signal scale
- Preparation for jet finding
  - Suppression/cancellation of "unphysical" signal objects with E<0 (due to noise)
  - Possibly event ambiguity resolution (remove reconstructed electrons, photons, taus,… from detector signal)
    - Not done in ATLAS before jet reconstruction!
  - Pre-clustering to speed up reconstruction (not needed anymore)
- Jet finding
  - Apply your jet finder of choice
- Jet calibration
  - Depending on detector input signal definition, jet finder choices, references…
- Jet selection
  - Apply cuts on kinematics etc. to select jets of interest or significance

Objective

- Reconstruct particle level features
  - Test models and extract physics

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

Typical Monte Carlo based normalization

- Match particle level jets with detector jets in simple topologies (fully simulated QCD di-jets)
  - Use same specific jet definition for both
  - Match defined by maximum angular distance
    - Can include isolation requirements
- Determine calibration function parameters using truth particle jet energy constraint
  - Fit calibration parameters such that relative energy resolution is best
    - Include whole phase space into fit (flat in energy)
- Correct residual non-linearities by jet energy scale correction function
  - Numerical inversion technique applied here
- Little factorization here

Magnitudes of calibrations and corrections depend on signal choices

- Electromagnetic energy scale signals require large corrections while particle level or local hadronic signal have much less corrections
  - Effect on systematic errors

Numerical Inversion

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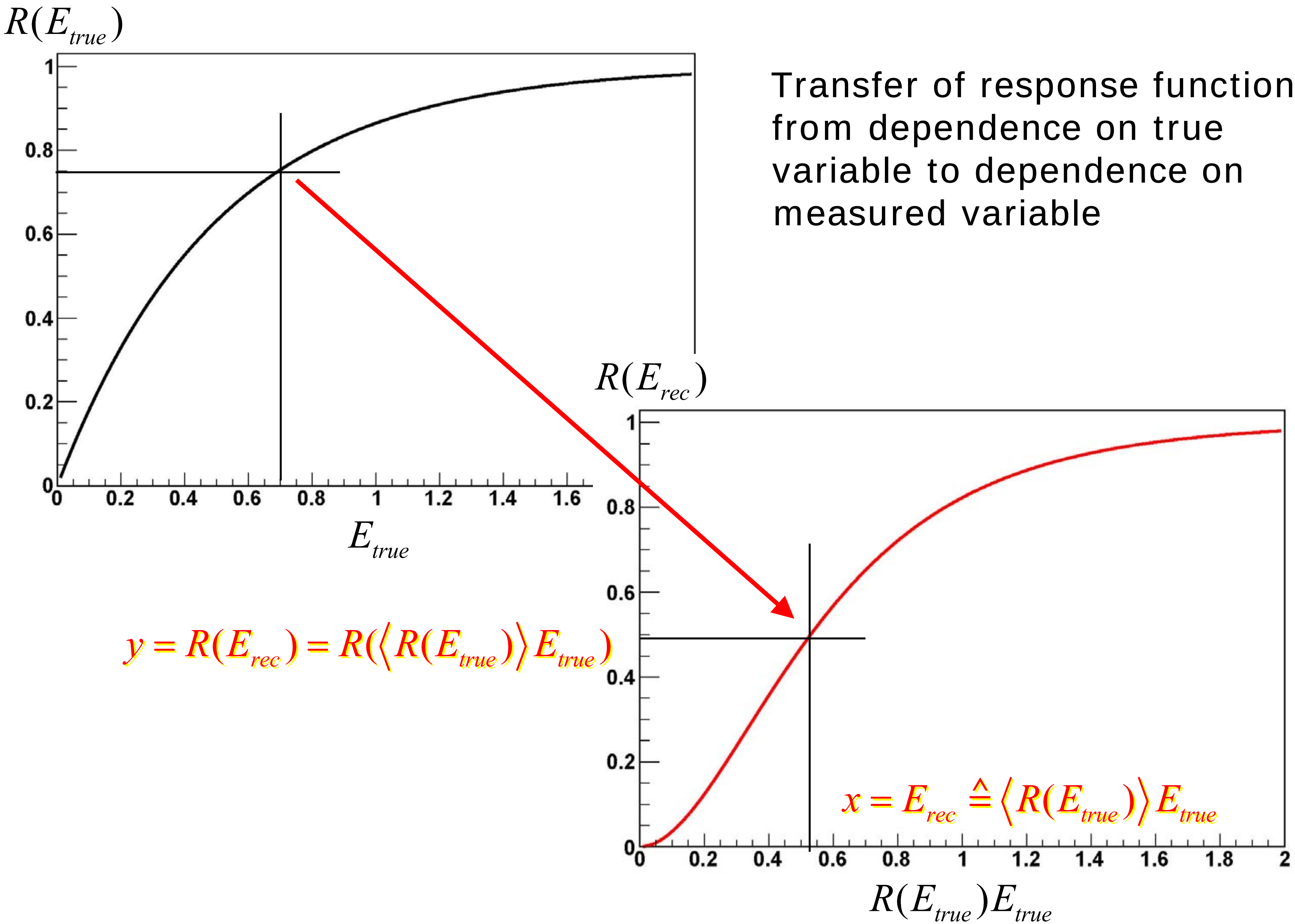

Transfer of response function from dependence on true variable to dependence on measured variable

$$y = R(E_{rec}) = R(\langle R(E_{true})\rangle E_{true})$$

$$x = E_{rec} \triangleq \langle R(E_{true})\rangle E_{true}$$

ATLAS Cell Weights

Cell signal weighting

- Statistically determined cell signal weights try to compensate for e/h>1 in jet context
  - Motivated by H1 cell weighting
  - High cell signal density indicates on average electromagnetic signal origin
    - Ideally weight = 1
  - Low cell signal indicates hadronic deposit
    - Weight > 1

$$\chi^2 = \sum_{jets} \left(\frac{E_{rec} - E_{true}}{E_{true}} \right)^2$$

$$E_{rec} = \sum_{i=1}^{N_{cells}} w_i(\rho_i = E_i / V_i, \vec{X}_i) E_i$$

- Cell weights are determined as function of cell signal density
  - Use truth jet matching in fully simulated QCD di-jet events
  - Crack regions not included in fit

Residual jet energy scale corrections – see next slides

Cell Weight Calibration For Jets

Cell signal weighting functions do not restore jet energy scale for all jets

- Crack regions not included in fits
- Only on jet context used for fitting weights
  - Cone jets with R=0.7
- Only one calorimeter signal definition used for weight fits
  - CaloTowers

Additional response corrections applied to restore linearity

- Non-optimal resolution for other than reference jet samples can be expected

Changing physics environment not explicitly corrected

- Absolute precision limitation

$$\left(E^{calo}, p_x^{calo}, p_y^{calo}, p_z^{calo}\right)$$

$$=$$

$$\sum_{cells} w(\rho_{cell}, \vec{X}_{cell}) \cdot \left(E^{cell}, p_x^{cell}, p_y^{cell}, p_z^{cell}\right)$$

$$+$$

$$\alpha_{DM} \sqrt{E_{t,EMB3}^{calo} \cdot E_{t,Tile0}^{calo}}$$

$$\times$$

$$\left(p^{calo}/p_T^{calo}, p_x^{calo}/p_T^{calo}, p_y^{calo}/p_T^{calo}, p_z^{calo}/p^{calo}\right)$$

ATLAS Cell Weight Calibration For Jets

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U of Arizona

Cell signal weighting functions do not restore jet energy scale for all jets

- Crack regions not included in fits
- Only on jet context used for fitting weights
  - Cone jets with R=0.7
- Only one calorimeter signal definition used for weight fits
  - CaloTowers

Additional response corrections applied to restore linearity

- Non-optimal resolution for other than reference jet samples can be expected

Changing physics environment not explicitly corrected

- Absolute precision limitation

$$\left(E^{final}, p_x^{final}, p_y^{final}, p_z^{final}\right)$$

$$=$$

$$f(p_T^{calo}, \eta^{calo}) \cdot \left(E^{calo}, p_x^{calo}, p_y^{calo}, p_z^{calo}\right)$$

ATLAS Cell Weight Calibration For Jets

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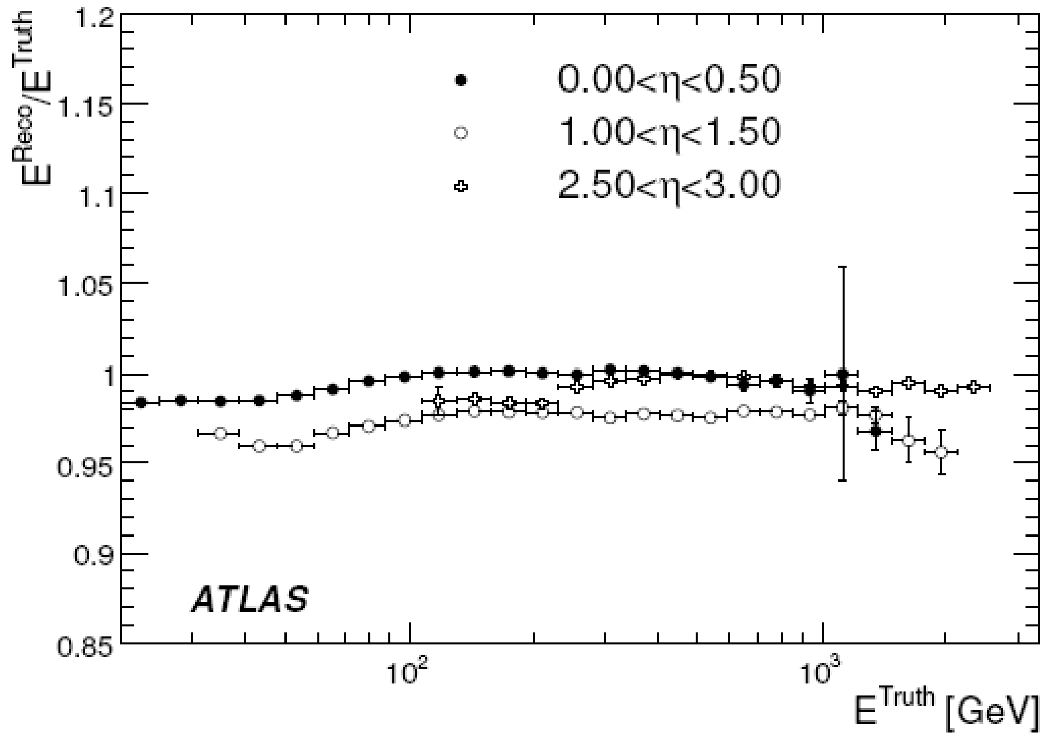
- **Cell signal weighting functions do not restore jet energy scale for all jets**
  - Crack regions not included in fits
  - Only one jet context used for fitting weights
    - Cone jets with R=0.7
  - Only one calorimeter signal definition used for weight fits
    - CaloTowers
- **Additional response corrections applied to restore linearity**
  - Non-optimal resolution for other than reference jet samples can be expected
- **Changing physics environment not explicitly corrected**
  - Absolute precision limitation



Response for jets in ttbar

(same jet finder as used for determination of calibration functions with QCD events)

Jet energy scale (JES) for first data

- Fully Monte Carlo based calibrations hard to validate quickly with initial data
  - Too many things have to be right, including underlying event tunes, pile-up activity, etc.
  - Mostly a generator issue in the beginning
- Need flat response and decent energy resolution for jets as soon as possible
  - Data driven scenario a la DZero implemented both for ATLAS and CMS

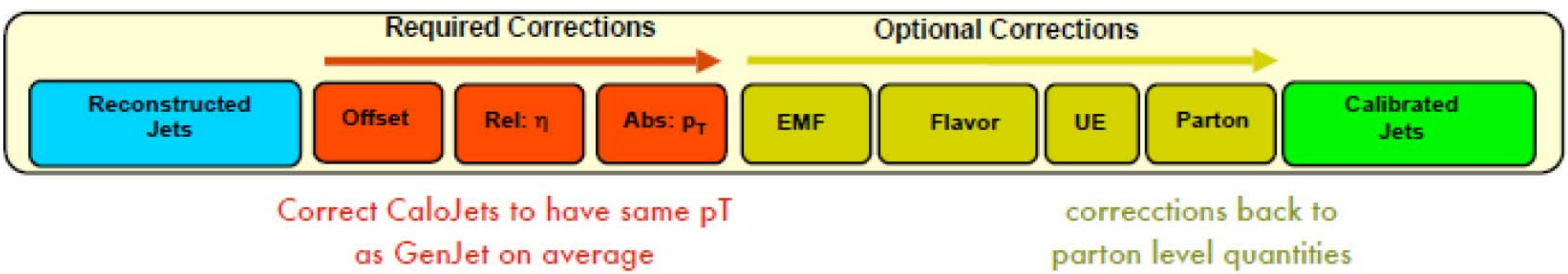
Additional jet by jet corrections

- Interesting ideas to use all observable signal features for jets to calibrate
  - Geometrical moments
  - Energy sharing in calorimeters
- Concerns about stability and MC dependence to be understood
  - Can consider e.g. truncated moments using only prominent constituents for stable signal

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

Factorized calibration allows use of collision data

- CMS sequence applies factorized scheme with required and optional corrections
- Required corrections can initially be extracted from collision data
  - Average signal offset from pile-up and UE can be extracted from minimum bias triggers
  - Relative direction dependence of response can be corrected from di-jet pT balance
  - The absolute pT scale correction can be derived from prompt photon production
- Optional corrections refine jet calibration
  - Use jet by jet calorimeter or track observables to reduce fluctuations
  - Includes energy fractions in EMC, track pT fractions, underlying event corrections using jet areas, flavor dependencies and others…
  - May need very good simulations!



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ATLAS JES Correction Model for First Data

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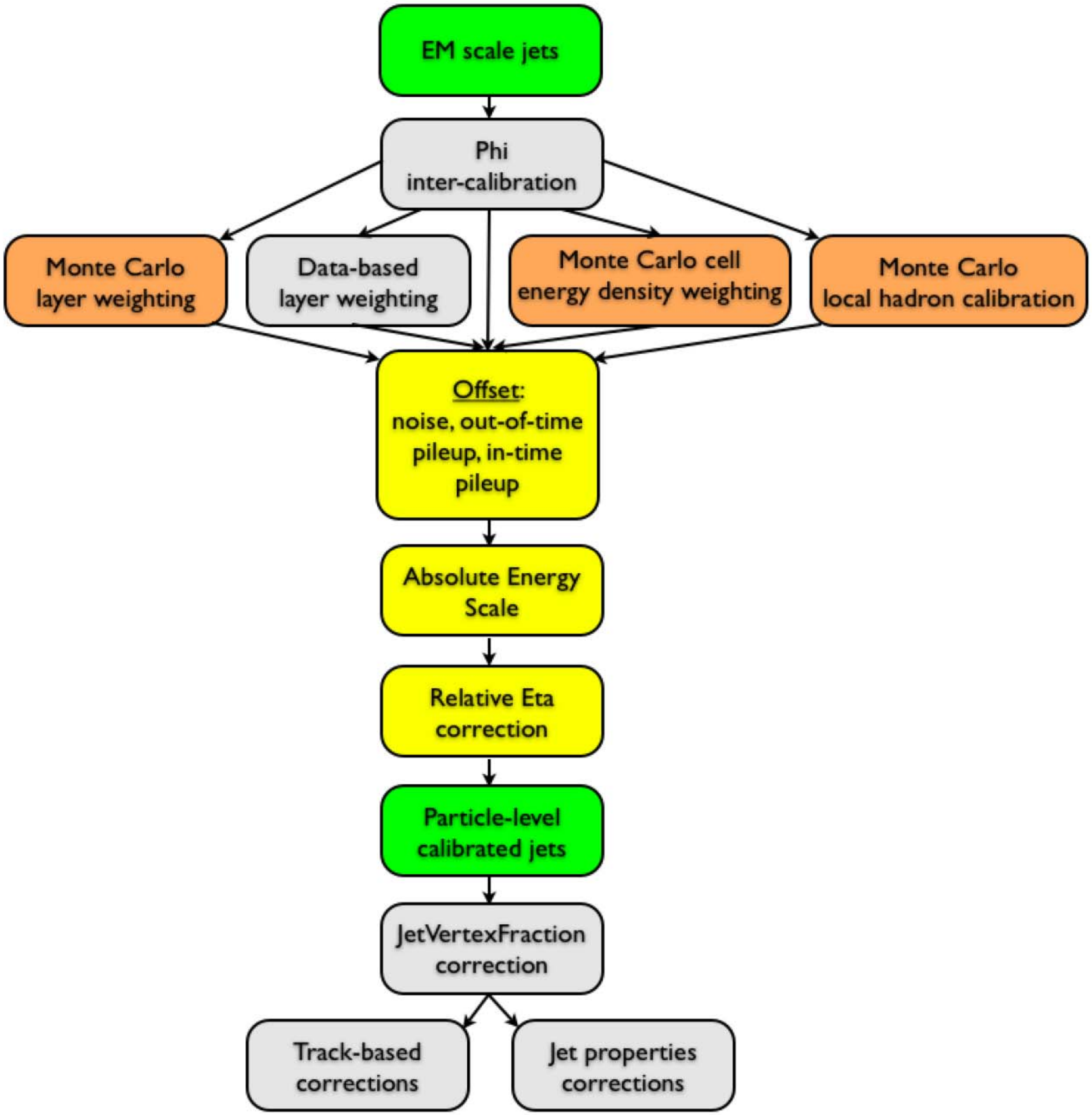
optional

data driven

MC



Data Driven JES Corrections (1)

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U of Arizona
June 30, 2009

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

PileUp subtraction

Goal:

Correct in-time and residual out-of-time pile-up contribution to a jet on average

Tools:

Zero bias (random) events, minimum bias events

Measurement:

Et density in $\Delta\eta\times\Delta\varphi$ bins as function of # vertices

TopoCluster feature (size, average energy as function of depth) changes as function of # vertices

Remarks:

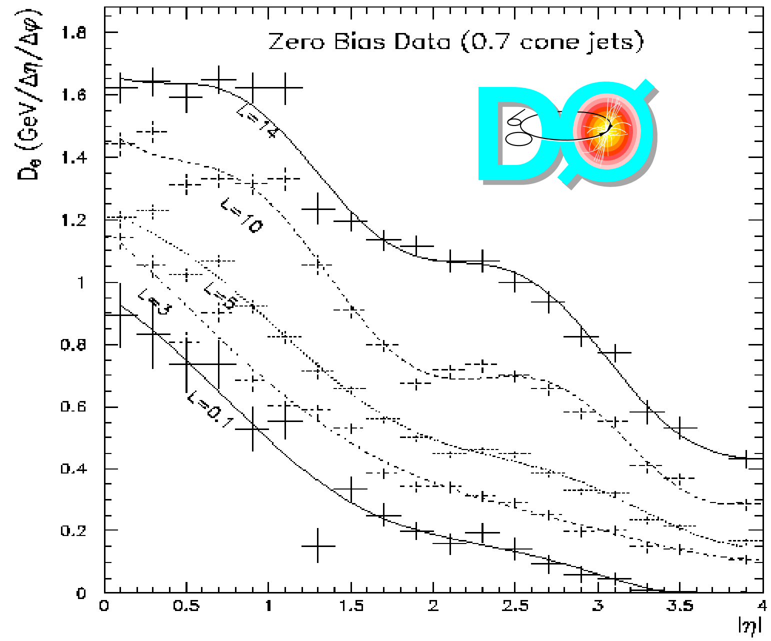
Uses expectations from the average Et flow for a given instantaneous luminosity

Instantaneous luminosity is measured by the # vertices in the event

Requires measure of jet size (AntiKt advantage)

Concerns:

Stable and safe determination of average



Determination of the Absolute Jet Energy Scale in the D0 Calorimeters. NIM A424, 352 (1999)

$$\rho_{UE} = E_T^{UE} \Big/ \left(\Delta\eta \times \Delta\varphi\right)$$

$$E_{offset}^{UE} = \left(\rho_{UE} A_{jet}\right)\cosh\eta_{jet}$$

Note that magnitude of correction depends on calorimeter signal processing!

Data Driven JES Corrections (2)

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June 30, 2009

Absolute response

Goal:

- Correct for energy (pT) dependent jet response

Tools:

- Direct photons, Z+jet(s),…

Measurement:

- pT balance of well calibrated system (photon, Z) against jet in central region

$$f_{p_t} = \frac{p_t^{jet} - p_t^{\gamma}}{p_t^{\gamma}}$$

Remarks:

- Usually uses central reference and central jets (region of flat reponse)

Concerns:

- Limit in precision and estimates for systematics w/o well understood simulations not clear

Data Driven JES Corrections (3)

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Direction response corrections

Goal:

- Equalize response as function of jet (pseudo)rapidity

Tools:

- QCD di-jets
- Direct photons

Measurement:

- Di-jet pT balance uses reference jet in well calibrated (central) region to correct second jet further away
- Measure hadronic response variations as function of the jet direction with the missing Et projection fraction (MPF) method

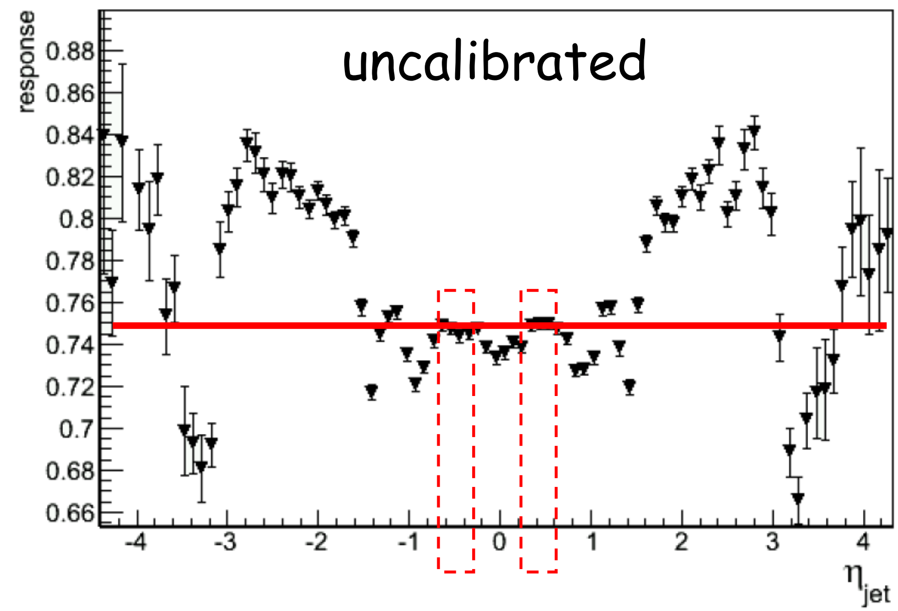
Remarks:

- MPF only needs jet for direction reference
- Bi-sector in di-jet balance explores different sensitivities

Concerns:

- MC quality for systematic uncertaunty evaluation
- Very different (jet) energy scales between reference and probed jet

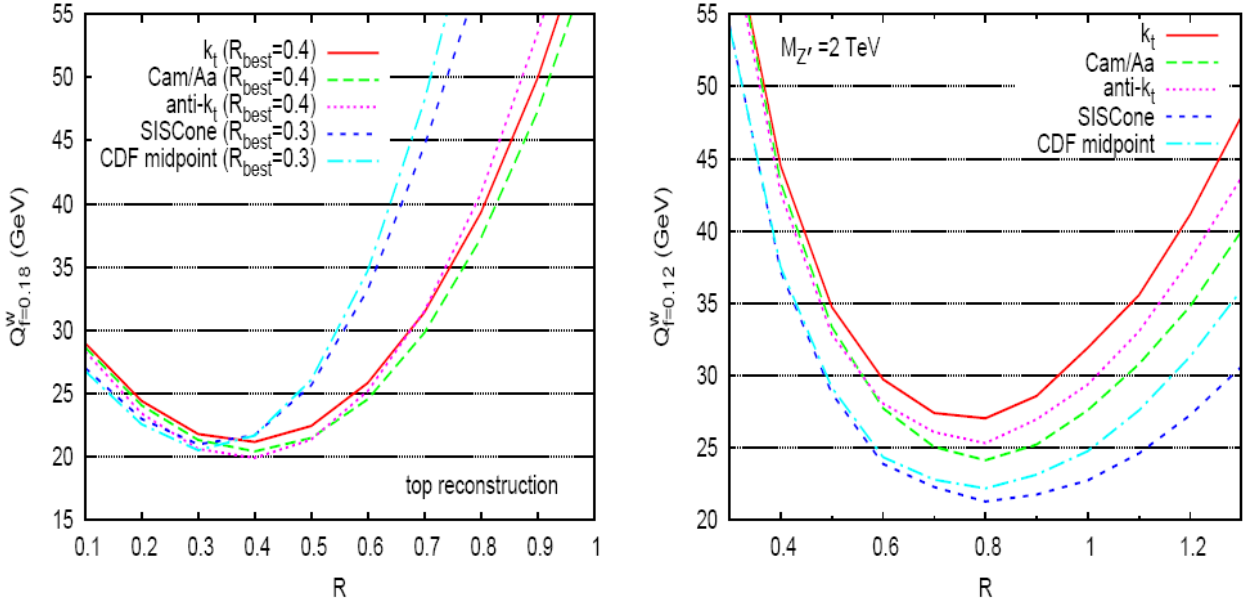
$$R_{calo}^{jet} = -\frac{\sum\limits_{\text{calo signals}} \frac{\vec{p}_t^{\,calo} \cdot \vec{p}_t^{\,\gamma}}{\left|\vec{p}_t^{\,\gamma}\right|}}{\left|\vec{p}_t^{\,\gamma}\right|}$$



4. Jet Reconstruction Performance

Jet performance evaluation

- Proof of success for each method
  - Closure tests applied to calibration data source
- Strong indications that one jet reconstruction approach is not sufficient
  - Evaluation needs to be extended to different final states
  - Systematic errors and corrections for alternative jet finders and configurations need to be evaluated



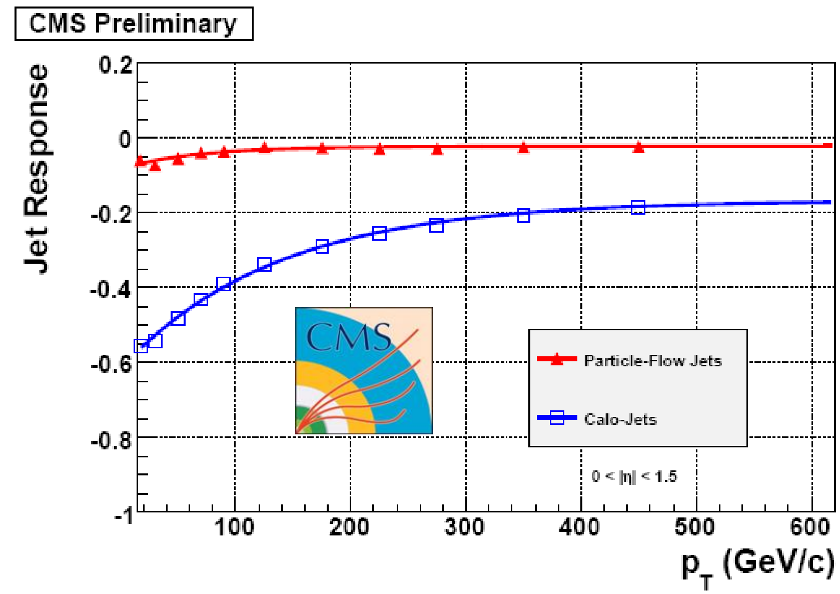
G. Salam, talk at ATLAS Hadronic Calibration Workshop, Tucson, Arizona, USA, March 2009

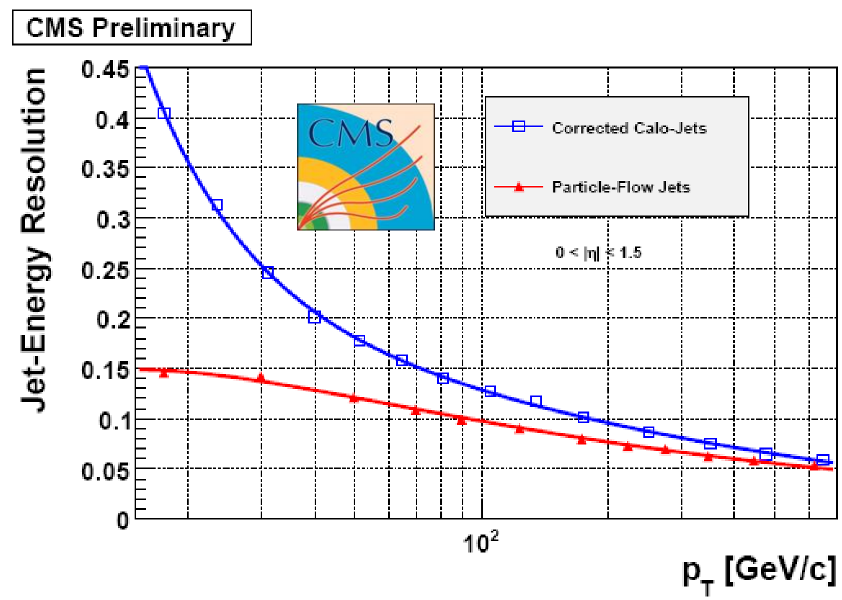
Jet signal linearity and resolution

- Closure tests for calibration determination
  - Ultimate precision and resolution for given method applied to calibration sample
- Response comparisons for different signal definitions
  - Need to reduce exploration phase space
  - Real data needed for final decision

Effect of calibration on inclusive jet cross-section

- One the first physics results expected from ATLAS & CMS





CMS PAS PFT-09-001

Jet Performance Evaluations (3)

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June 30, 2009

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

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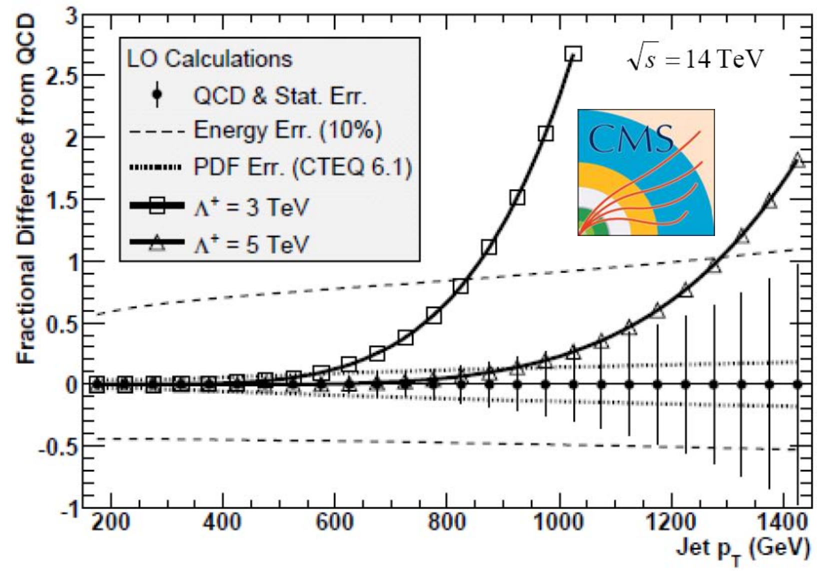

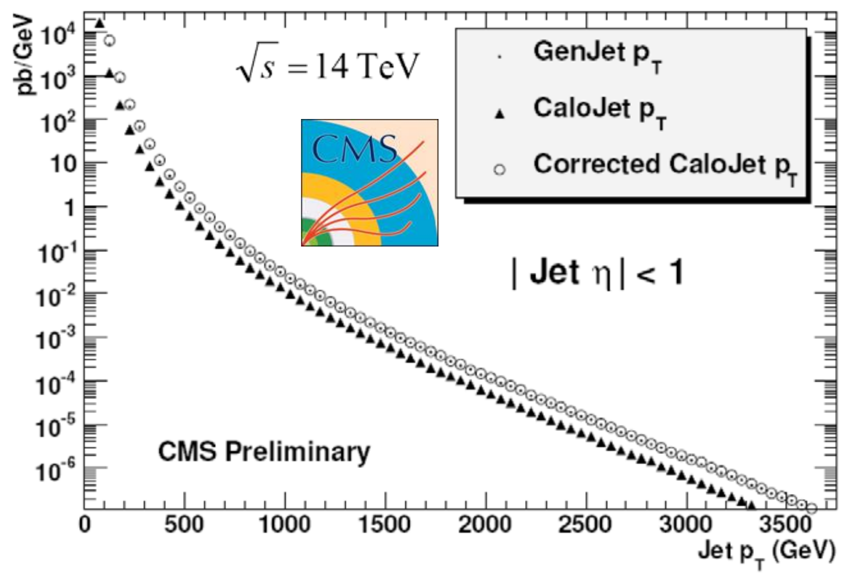

CMS PAS SBM-07-001

Data Driven Evaluation

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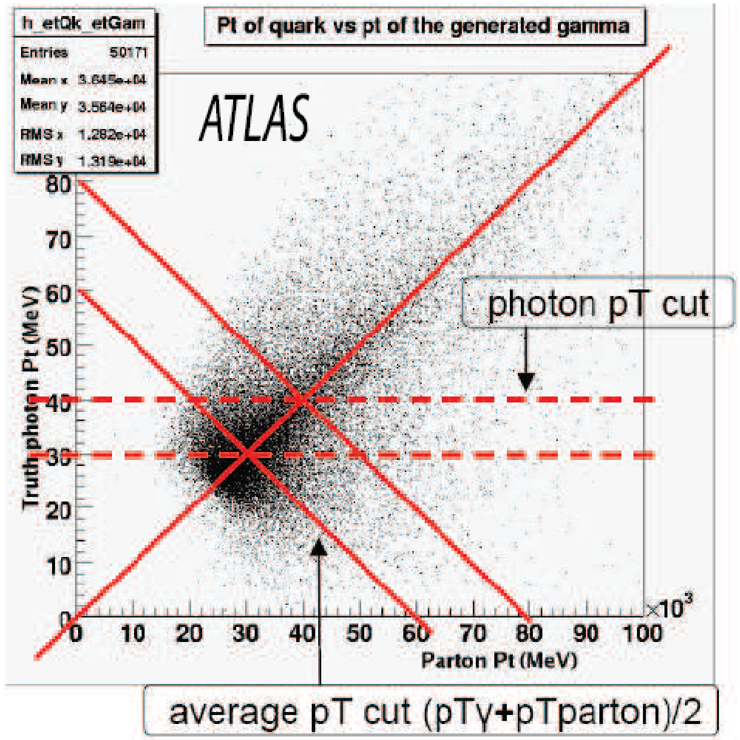
June 30, 2009

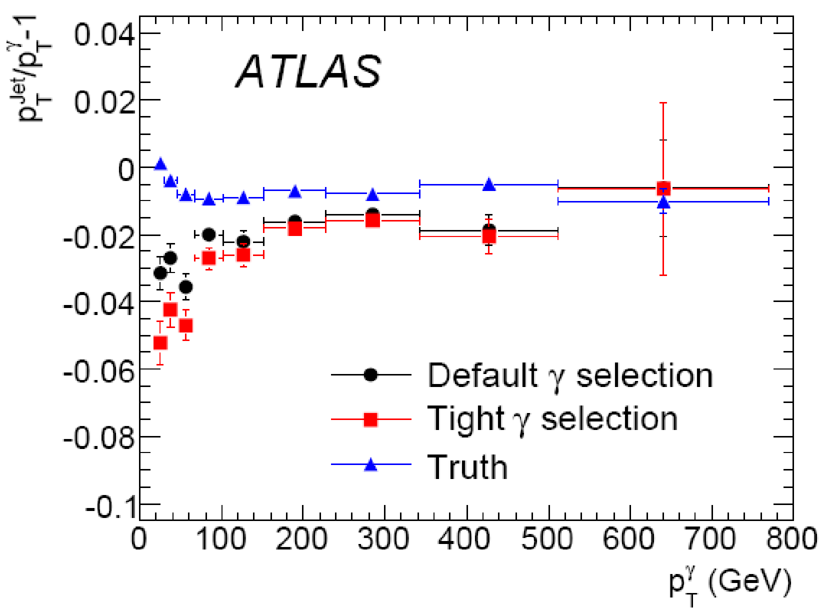
Photon+jet(s)

- Well measured electromagnetic system balances jet response
  - Central value theoretical uncertainty ~2% limits precision
    - Due to photon isolation requirements
  - But very good final state for evaluating calibrations
- Can test different correction levels in factorized calibrations
  - E.g., local hadronic calibration in ATLAS
- Limited pT reach for 1-2% precision
  - 25->300 GeV within 100 pb^{-1}

Z+jet(s)

- Similar idea, but less initial statistics
  - Smaller reach but less background





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Data Driven Evaluation

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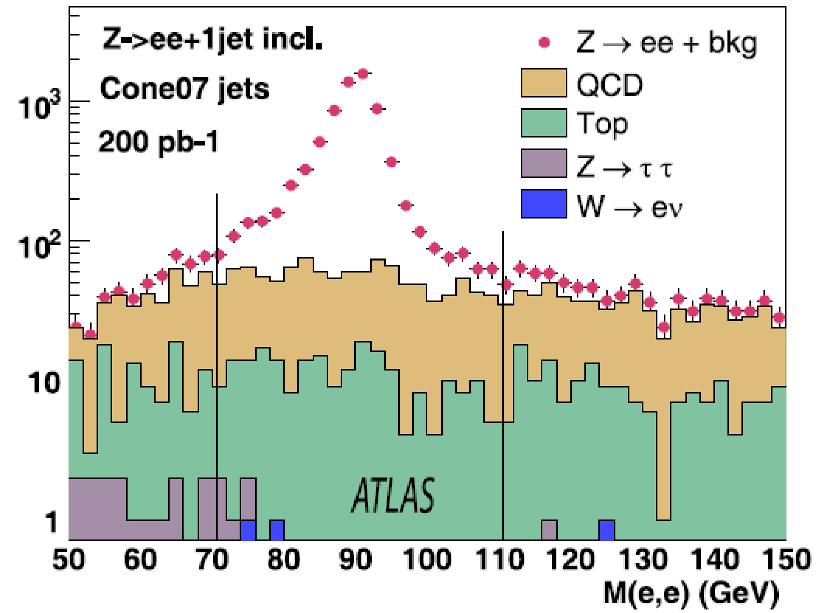

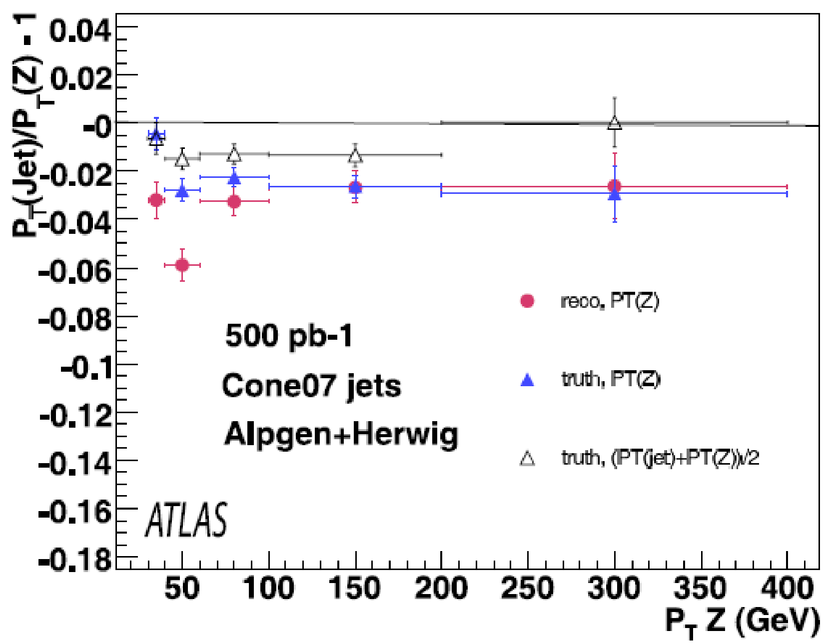

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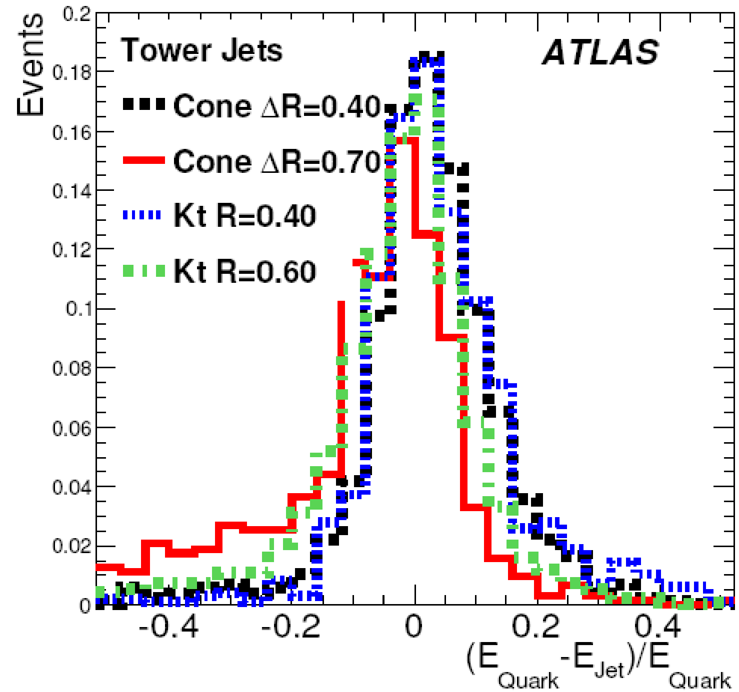
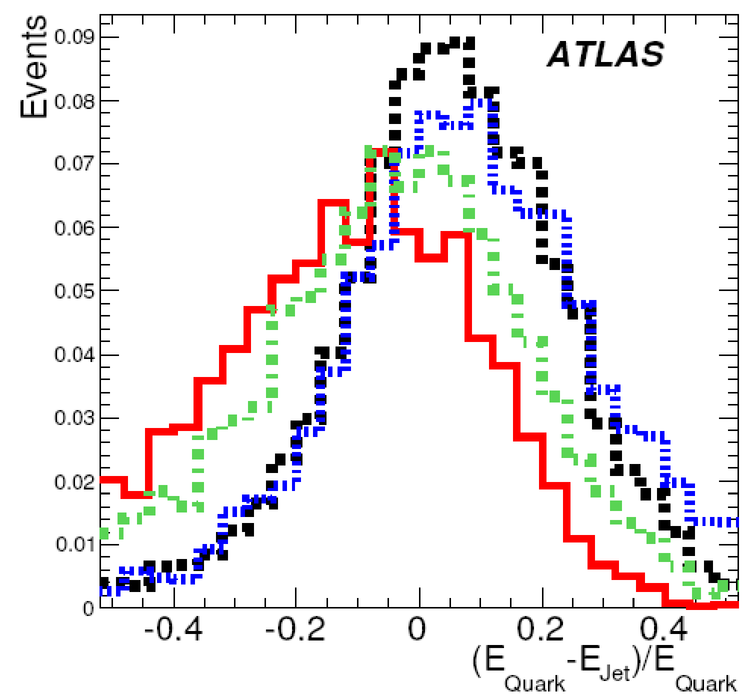
W Mass Spectroscopy

P. Loch
U of Arizona
June 30, 2009

In-situ calibration validation handle

- Precise reference in ttbar events
  - Hadronically decaying W-bosons
- Jet calibrations should reproduce W-mass
  - Note color singlet source
  - No color connection to rest of collision – different underlying event as QCD
  - Also only light quark jet reference
- Expected to be sensitive to jet algorithms
  - Narrow jets perform better – as expected





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Dangerous background for W+n jets cross-sections etc.

- Lowest pT jet of final state can be faked or misinterpreted as coming from underlying event or multiple interactions

Extra jets from UE are hard to handle

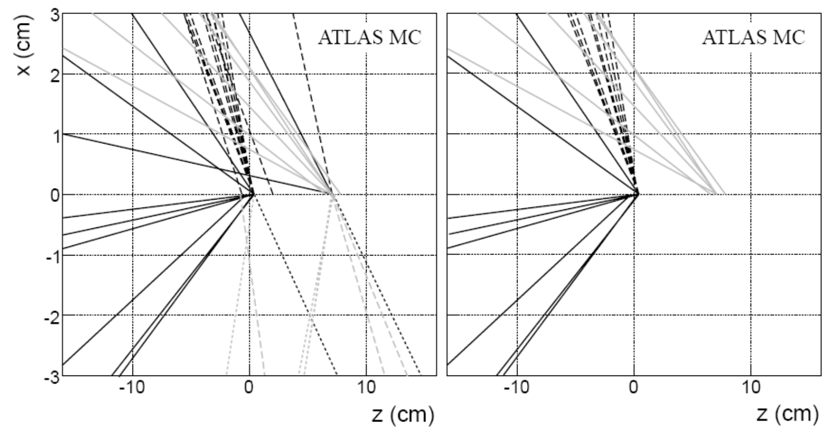
- No real experimental indication of jet source
  - Some correlation with hard scattering?
  - Jet area?
  - No separate vertex

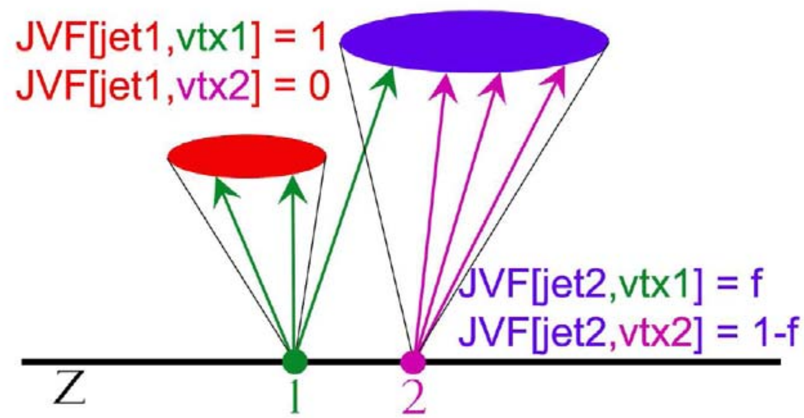
Jet-by-jet handle for multiple proton interactions

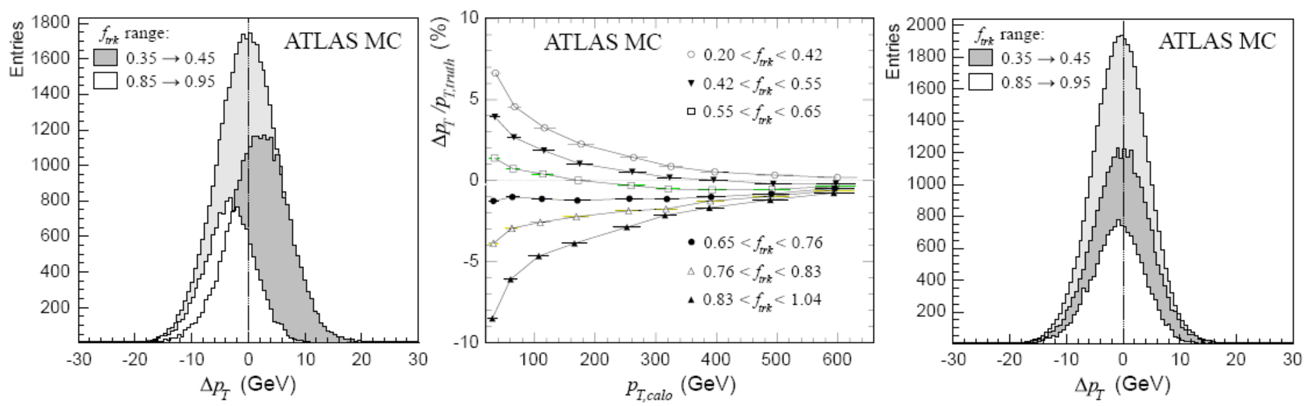
- Classic indicator for multiple interactions is number of reconstructed vertices in event
  - Tevatron with RMS(z_vertex) ~ 30 cm
  - LHC RMS(z_vertex) ~ 8 cm
- If we can attach vertices to reconstructed jets, we can in principle identify jets not from hard scattering
  - Limited to pseudorapidities within 2.5!

Track jets

- Find jets in reconstructed tracks
  - ~60% of jet pT, with RMS ~0.3 – not a good kinematic estimator
- Dedicated algorithm
  - Cluster track jets in pseudo-rapidity, azimuth, and delta(Z_{Vertex})
- Match track and calorimeter jet
  - Also helps response!







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5. Missing Transverse Energy

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

Hard signal in calorimeters

- Fully reconstructed & calibrated particles and jets
  - Not always from hard interaction!

Hard signal in muon spectrometer

- Fully reconstructed & calibrated muons
  - May generate isolated or embedded soft calorimeter signals
  - Care needed to avoid double counting

Soft signals in calorimeters

- Signals not used in reconstructed physics objects
  - I.e., below reconstruction threshold(s)
- Needs to be included in MET to reduce scale biases and improve resolution

Need to avoid double counting

- Common object use strategy in ATLAS
  - Find smallest available calorimeter signal base for physics objects (cells or cell clusters)
- Check for exclusive bases
  - Same signal can only be used in one physics object
- Veto MET contribution from already used signals
  - Track with selected base
- Priority of association is defined by reconstruction uncertainties
  - Electrons (highest quality) → photons → muons* → taus → jets (lowest quality)

Remarks to MET Calibration

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U of Arizona
June 30, 2009

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

MET is determined by hard signals in event

- Reconstructed particles and jets above threshold
  - All objects on well defined energy scale, e.g. best reconstruction for individual object type
- Really no freedom to change scales for any of these objects
  - Little calibration to be done for MET
  - Note that detector inefficiencies are corrected for physics objects

Some freedom for soft MET contribution…

- Signals not used in physics objects often lack corresponding context to constrain calibration
  - ATLAS has developed a low bias "local" calibration for the calorimeters based on signal shapes inside calorimeters
- Some degree of freedom here
  - But contribution is small and mostly balanced in Et anyway
    - Source here often UE/pile-up!

…and overall acceptance limitations

- Detector "loses" particles in non-instrumented areas or due to magnetic field in inner cavity
  - Same remarks as above, very small and likely balanced signals
- Event topology dependent adjustments to MET are imaginable to recover these losses

I prefer "validation" rather than "calibration"

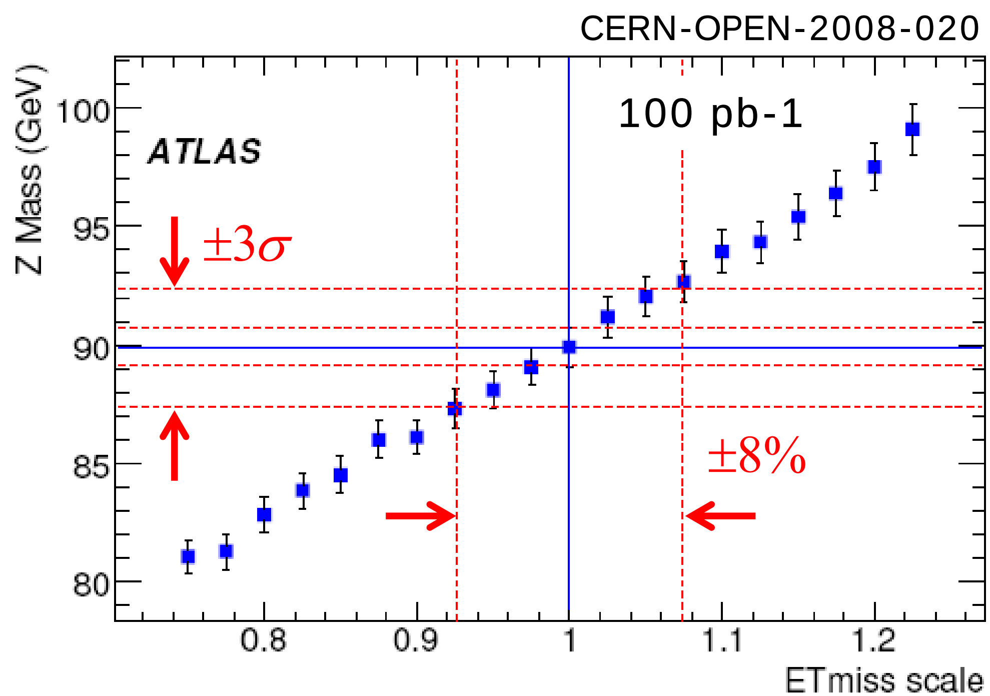
- Discrepancies in MET need to be isolated for systematic control

MET scale can be checked with physics

- Look for one hadronic and one leptonic tau from Z decays
  - Can be triggered nicely with lepton + MET requirement
- Use collinear approximation to reconstruct invariant mass
  - Massless taus
  - Neutrinos assumed to be collinear to observable tau decay products

Check dependence of invariant mass on MET scale variations

- Expect correlation!



$$m_{\tau\tau} = \sqrt{2(E_{had} + E_{\nu_1})(E_{\ell} + E_{\nu_2})(1 - \cos\theta)}$$

Determined from two reconstructed MET components and directions of detectable decay products

Fake Missing Et

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What is that?

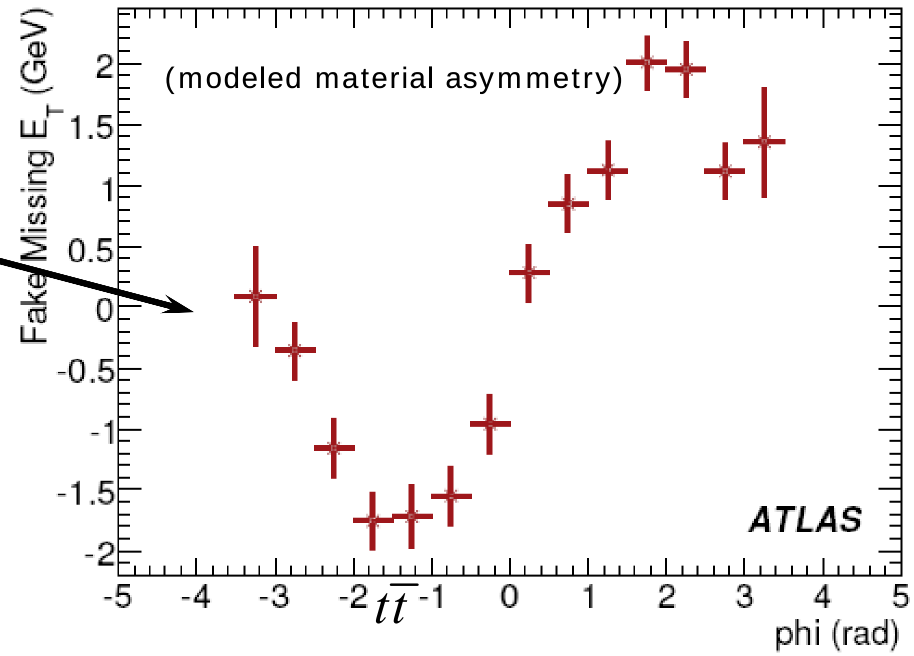
- MET contribution from response variations
  - Cracks, azimuthal response variations…
  - Never/slowly changing
  - Particle dependent
- MET contribution from mis-calibration
  - E.g., QCD di-jet with one jet under-calibrated
  - Relative effect generates MET pointing to this jet

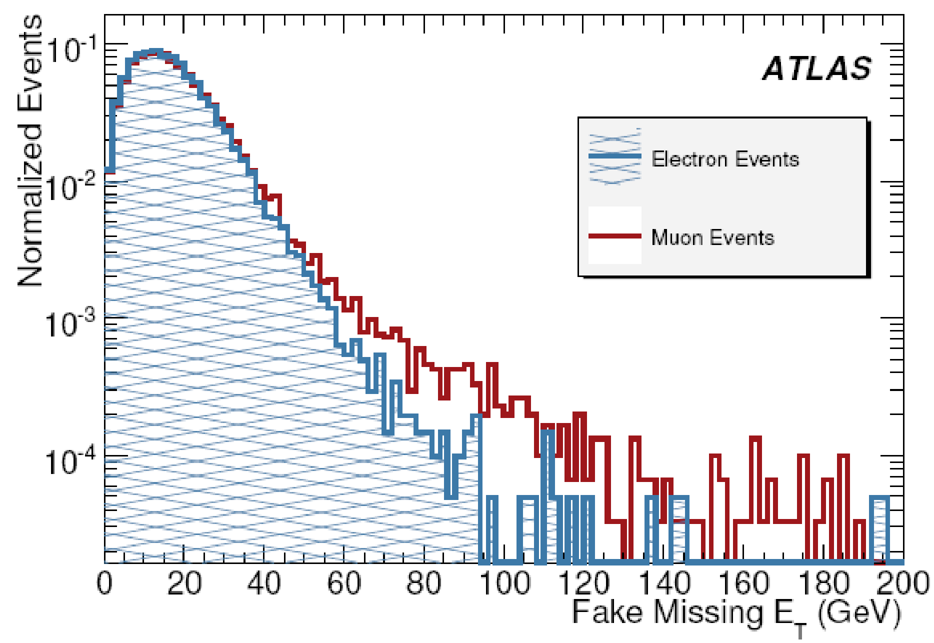
Dangerous source of MET

- Disturbs many final states in a different way
- Can fake new physics

Suppression strategies

- Track jets
- Energy sharing between calorimeters
- Event topology analysis





MET Resolution From MC

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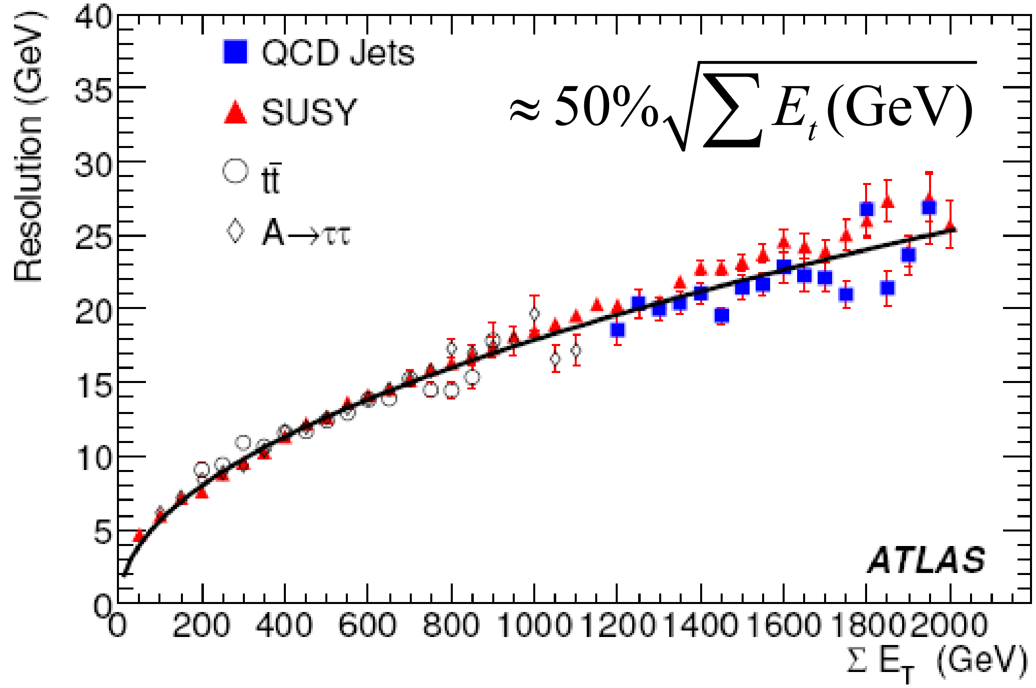
MET resolution

- Driven by calorimeter
  - Expect sqrt(E) dependence
- Studied as function of scalar Et
  - Systematically evaluated with MC
- No direct experimental access
  - Minimum bias with limited reach/precision?
  - Concern is pile-up effect on scalar Et



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Will discuss experimental access on next slide(s)

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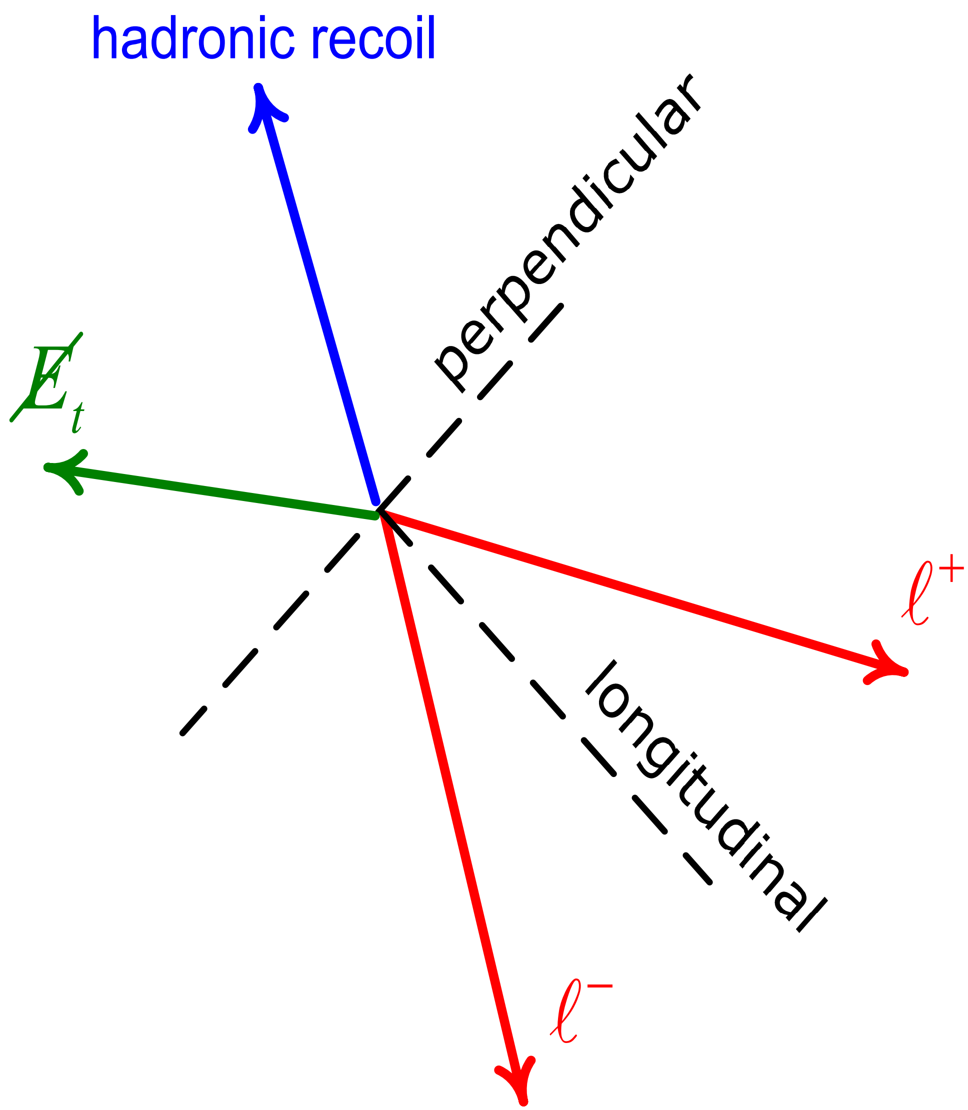
1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

Experimental access

- Use bi-sector signal projections in Z decays
- Longitudinal projection sensitive to scale
  - Calibration of hadronic recoil
- Perpendicular projection sensitive to angular resolution

Neutrinofication

- Assumed to be very similar in Z and W
  - One lepton in Z decay can be "neutrinofied"
- Access to MET resolution and scale
  - Hadronic recoil contribution



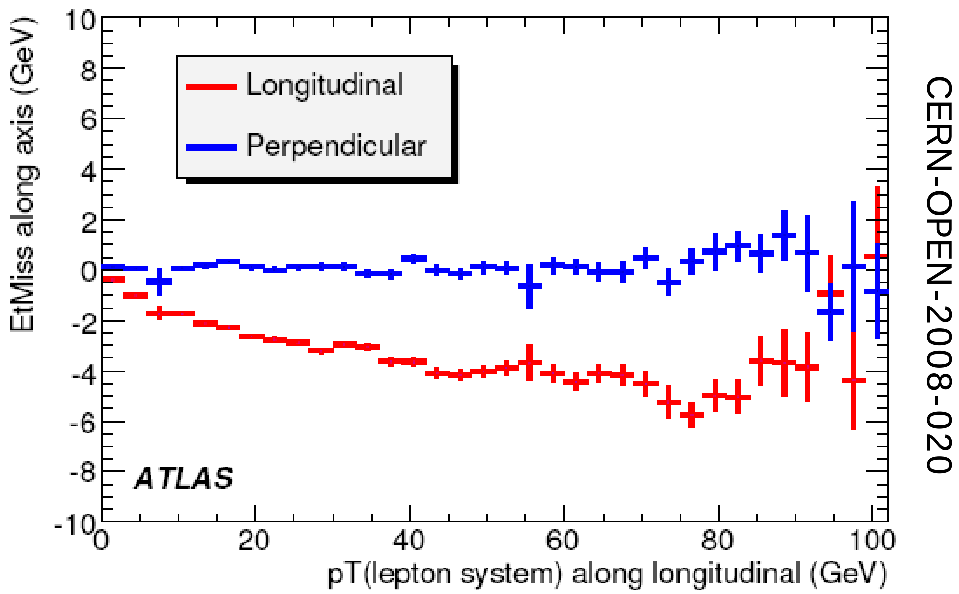
Data Driven MET Scale & Resolution (2)

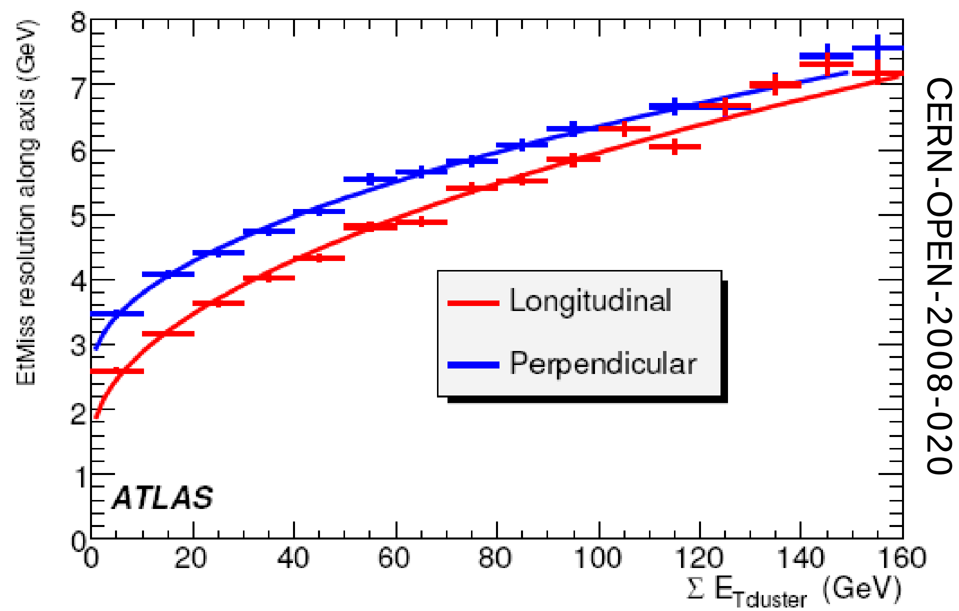
MET scale

- Folds hadronic scale with acceptance
  - Note: no jets needed!
- Experimental tool to validate calibration of "unused" calorimeter signal
  - Hard objects can be removed from recoil
  - One possible degree of freedom in MET "calibration"
- Relevance for other final states to be evaluated
  - Otherwise purely experimental handle!

MET resolution

- Can be measured along perpendicular and longitudinal axis
  - Resolution scale is scalar Et sum of hadronic calorimeter signal
  - Biased by UE and pile-up (MC needed here)
- Qualitatively follows calorimeter energy resolution





Final Remarks on MET

1.a
1.b
2.a
2.b
3.a
3.b
3.c
4.a
4.b
4.c
5.a
5.b
5.c

Missing ET is a complex experimental quantity

- Sensitive to precision and resolution of hard object reconstruction
  - MET is calibrated by everything
- Easily affected by detector problems and inefficiencies
  - Careful analysis of full event topology
  - Signal shapes in physics and detector

Known unknown (1): effect of underlying event

- Some correlation with hard scattering
- Insignificant contribution??
  - To be confirmed early with di-jets

Known unknown (2): effect of pile-up

- Level of activity not so clear
  - Minimum bias first and urgent experimental task
- Expectation is cancellation on average (at least)
  - Detector signal thresholds/acceptance potentially introduce asymmetries
  - Need to know the "real" detector
- Considerable contribution to MET fluctuations
  - Severe limitation in sensitivity for discovery

6. Conclusions

Conclusions

This was a mere snapshot

- Jet reconstruction at LHC deserves a book
  - Complex environment, complex signals, lots of information content both in ATLAS and CMS events

Both experiments are on their way

- Expected performance could be confirmed or exceeded with full simulations in large LHC phase space
  - No real problems expected, but data can always bring a few surprises

Missing Et performance expectations well developed

- Complex quantity likely needs most time to be understood
  - Collects all systematics from all other physics object reconstruction!

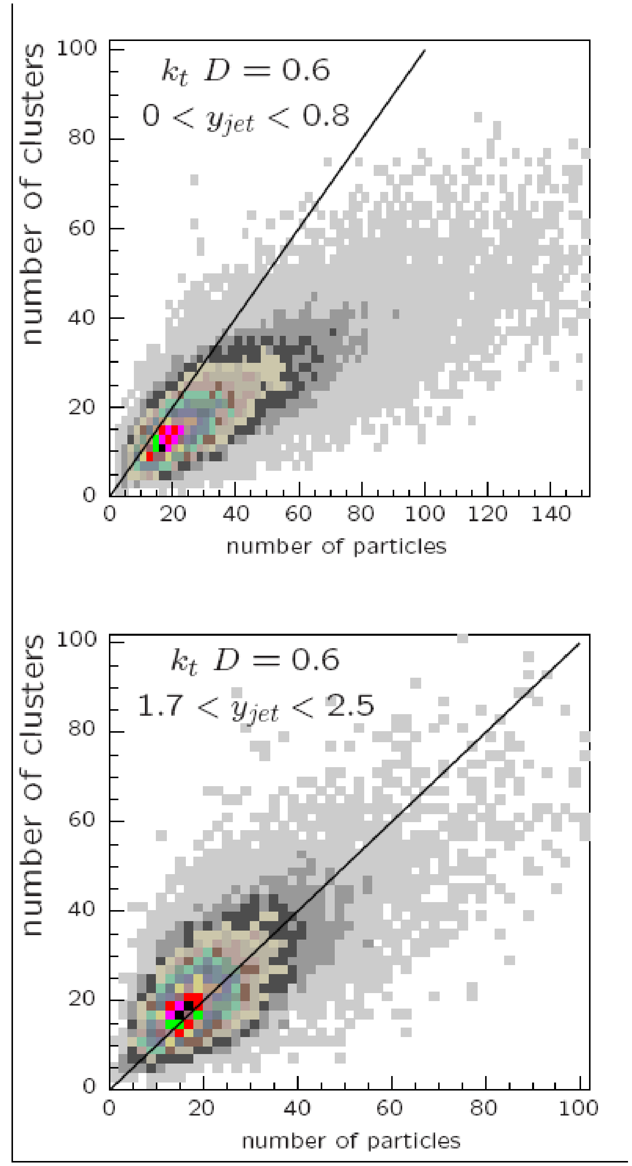
We are waiting for data!

The Other Stuff

Jet Composition

We expected clusters to represent individual particles

- Cannot be perfect in busy jet environment!
  - Shower overlap in finite calorimeter granularity
- Some resolution power, though
  - Much better than for tower jets!
- ~1.6:1 particles:clusters in central region
  - This is an average estimator subject to large fluctuations
- ~1:1 in endcap region
  - Best match of readout granularity, shower size and jet particle energy flow
  - Happy coincidence, not a design feature of the ATLAS calorimeter!



S.D. Ellis et al., Prog.Part.Nucl.Phys.60:484-551,2008

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Jet Shapes

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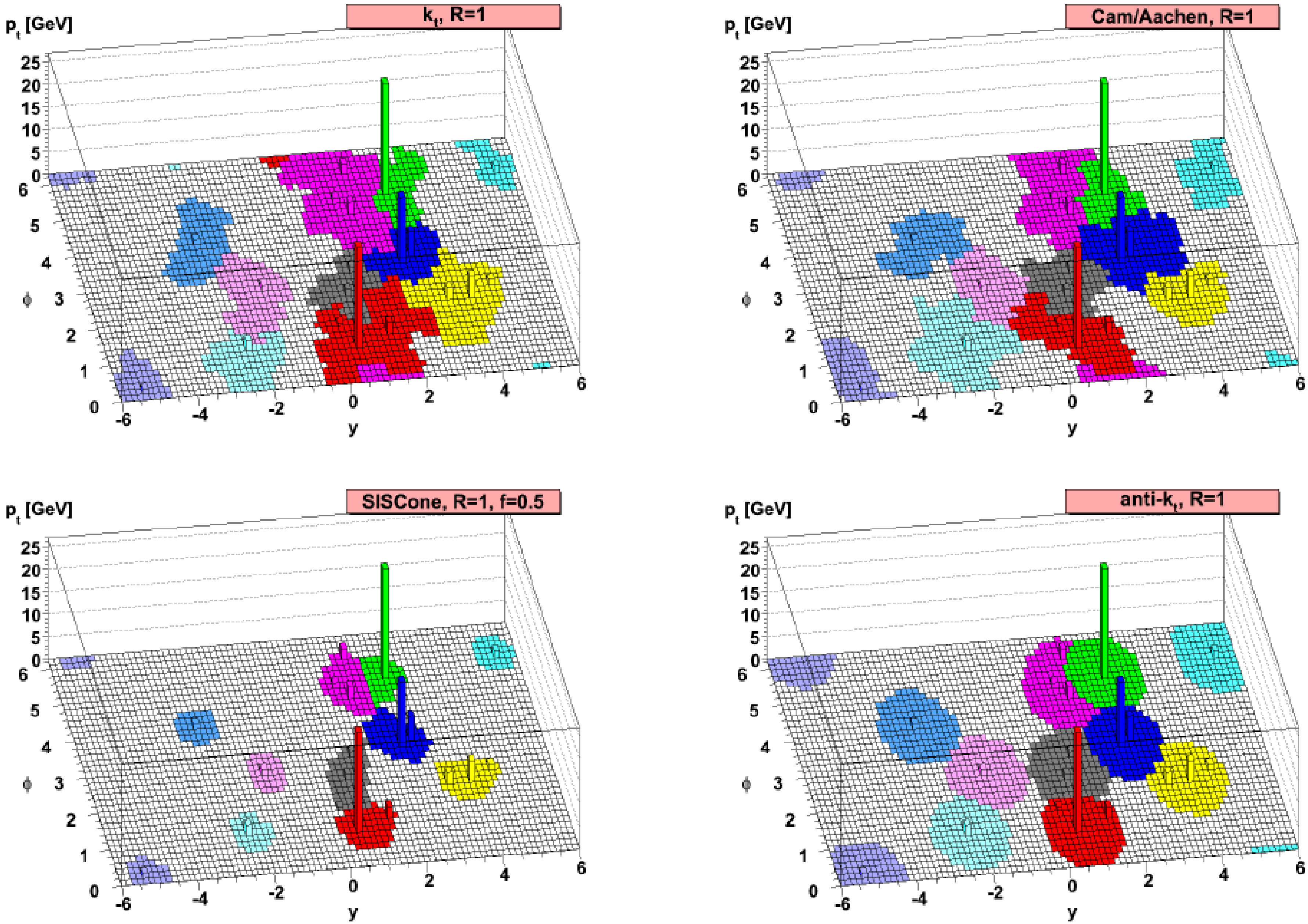

(from G. Salam's talk at the ATLAS Hadronic Calibration Workshop Tucson 2008)

Calibration Flow

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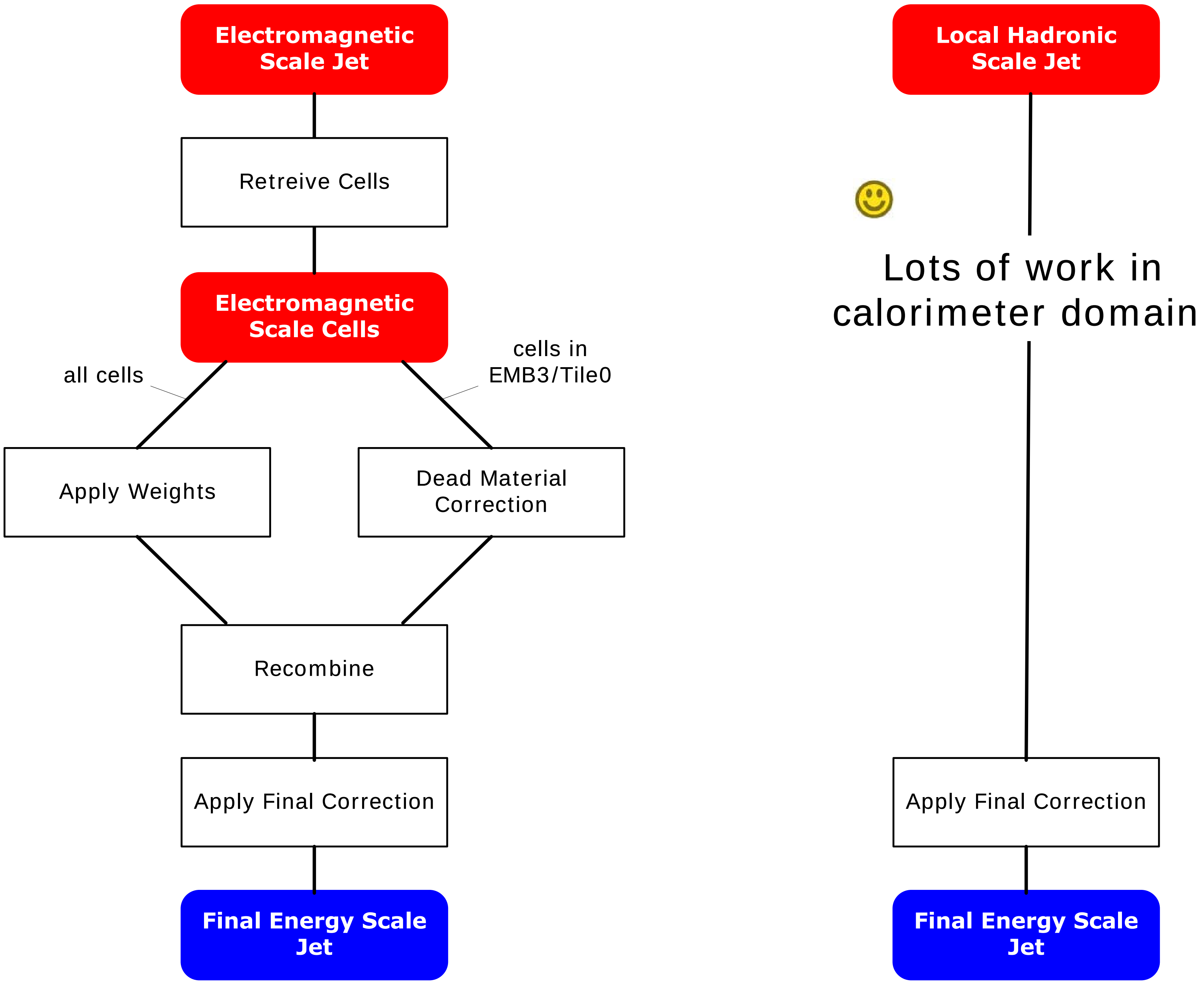

CaloTower Jets

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CaloCells (em scale)
↓ Tower Building ($\Delta\eta\times\Delta\varphi$=0.1×0.1, 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 $\Delta\eta$ x $\Delta\varphi$ = 0.1 x 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

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TopoCluster Jets

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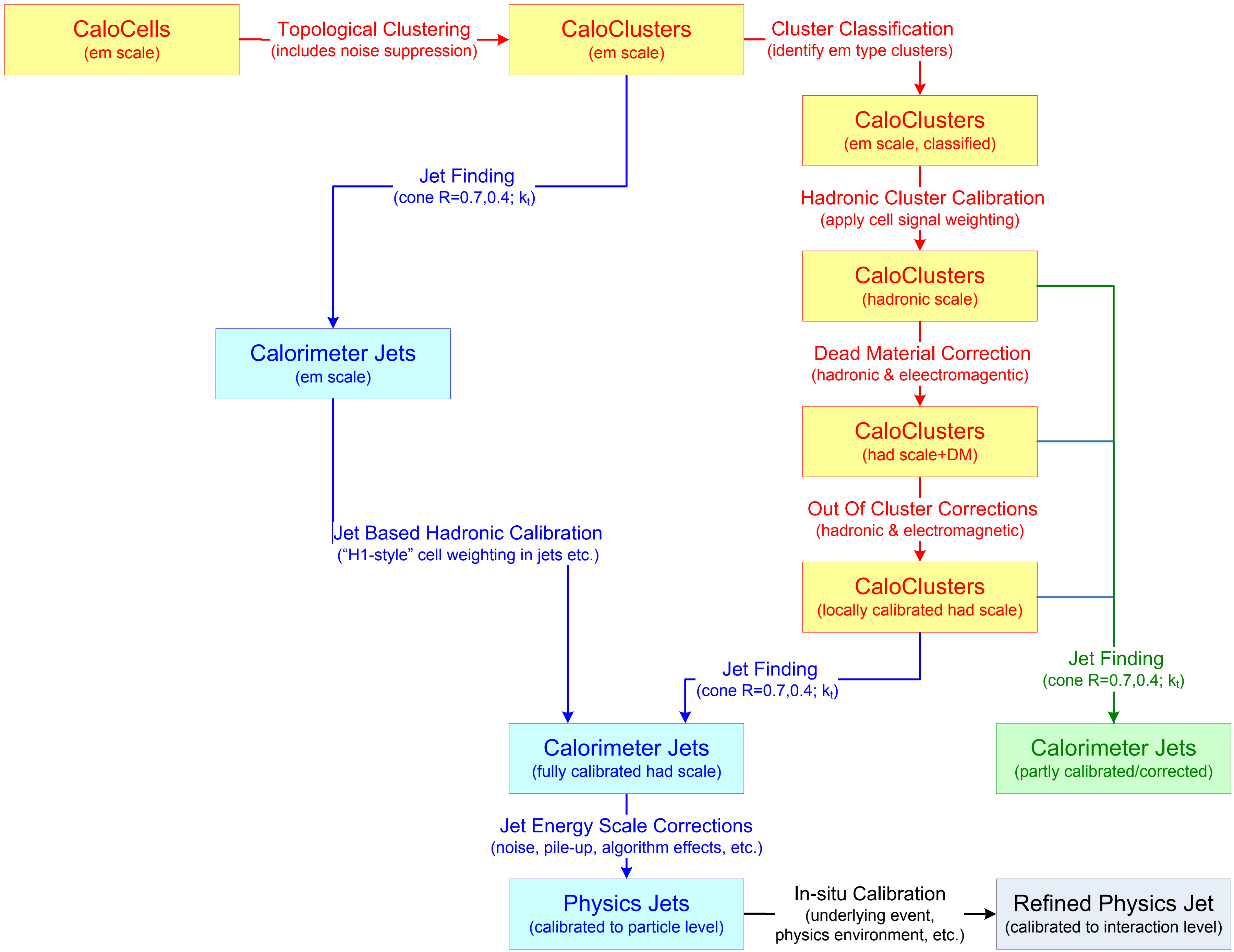

ATLAS

TopoTower Jets

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CaloCells (em scale)
→ Topological Clustering (includes noise suppression) →
CaloClusters (em scale)
→ Extract Cells In Clusters (excludes noisy cells) →
CaloCells (em scale, selected)
→ Tower Building ($\Delta\eta\times\Delta\varphi$=0.1×0.1, non-discriminant) →
CaloTowers (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)

Apply noise suppression to tower jets

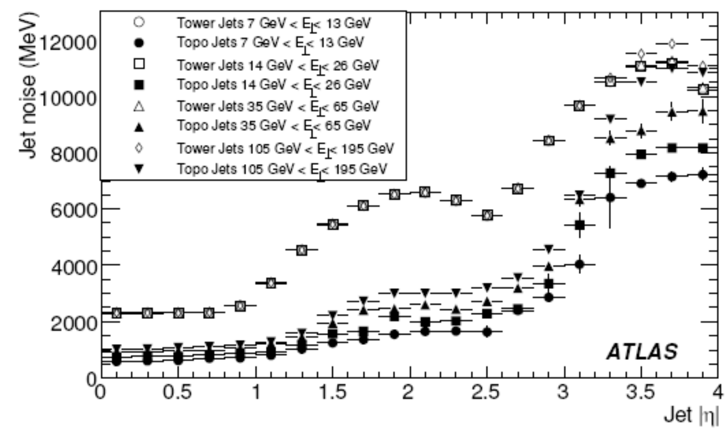
- Topological clustering is used as a noise suppression tool only
- Similar to DZero approach

New implementation

- Only in ESD context so far
- Working on schema to bring these jets into the AOD
  - Including constituents

Allows comparisons for tower and cluster jets with similar noise contribution

- Should produce rather similar jets than tower jets at better resolution
- Less towers per jet



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MET Calorimeter Issues

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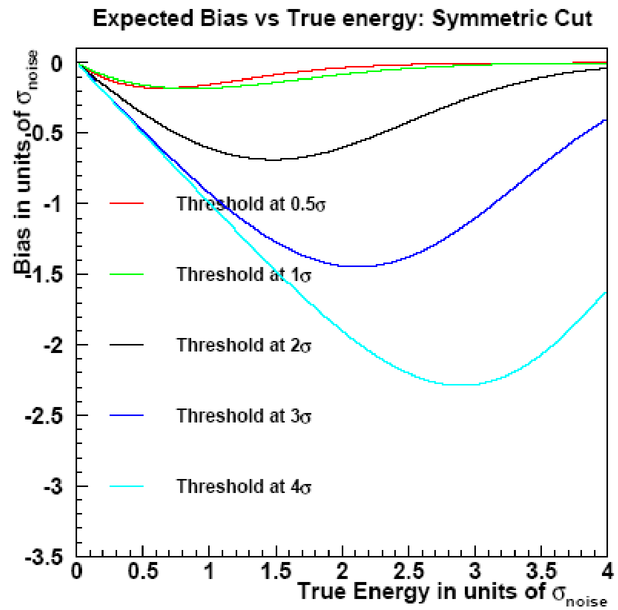
Calorimeter issues

- About 70-90% of all cells have no true or significant signal
  - Depending on final state, of course
- Applying symmetric or asymmetric noise cuts to cell signals
  - Reduces fluctuations significantly
  - But introduces a bias (shift in average missing Et)



K. Cranmer, in talk by S. Menke, ATLAS Physics Workshop 07/2005

- Topological clustering applies more reasonable noise cut
  - Cells with very small signals can survive based on the signals in neighboring cells
  - Still small bias possible but close-to-ideal suppression of noise

Cluster Overlap

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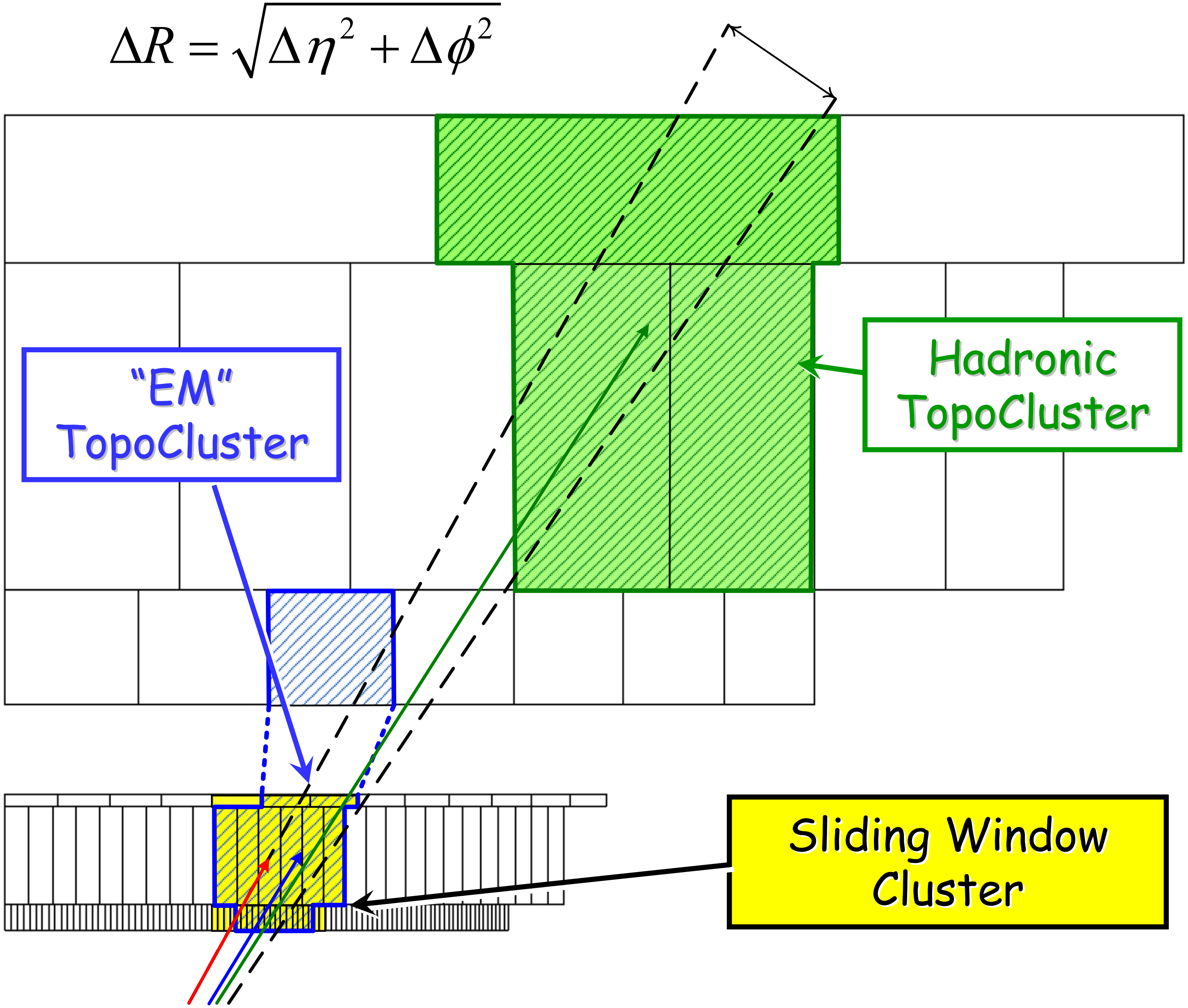
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



Variables For Cluster Overlap Resolution

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TopoClusters and Sliding Window clusters representing the same em shower are different

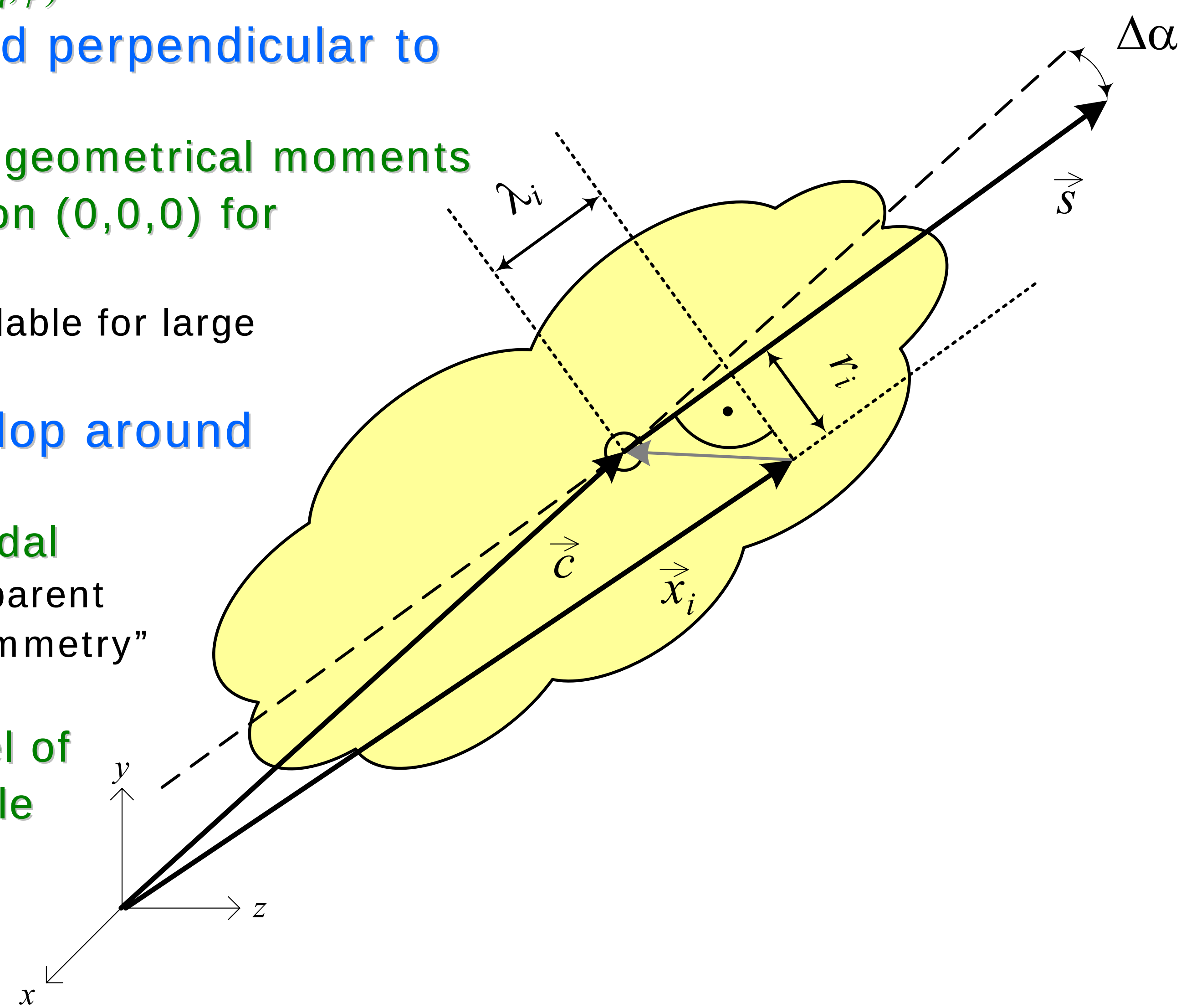
- Different shapes
  - TopoCluster size determined by cell signal topology
  - SW cluster size fixed by client
  - Both clusters will have different cell content!
- Different signal fluctuations
  - No noise suppression in SW clusters
    - But less direct contributions from small signal “marginal” cells
  - Noise suppression in TopoClusters
    - Potentially more small signal cells with relatively large fluctuations

Possible variables to measure overlap (under study)

- Total raw signal
  - Affected by different noise characteristics
- Relative signal distribution in sampling layers
  - Could be better as some noise is unfolded in the ratios
- Geometrical distance (barycenter-to-barycenter in 3-d)
  - Not available for SW (could easily be implemented!)
  - Subject to detector granularity changes (?)
- **Measure common cell content**
  - Similar motivation as for ESD
  - Adds several other (more stable) measures to overlap resolution, see next slides

TopoClusters have 3-d geometry

- Barycenter (x,y,z)
  - In AOD, from (R,η,φ)
- Extension along and perpendicular to "direction of flight"
  - Measured by 2nd geometrical moments
  - Vertex assumption (0,0,0) for right now
    - Principal axis available for large enough clusters
- Can calculate envelop around barycenter
  - Presently ellipsoidal
    - Could include apparent "longitudinal asymmetry" of em showers
  - Use simple model of longitudinal profile



Associating Cells With TopoClusters

AOD TopoClusters have no cells

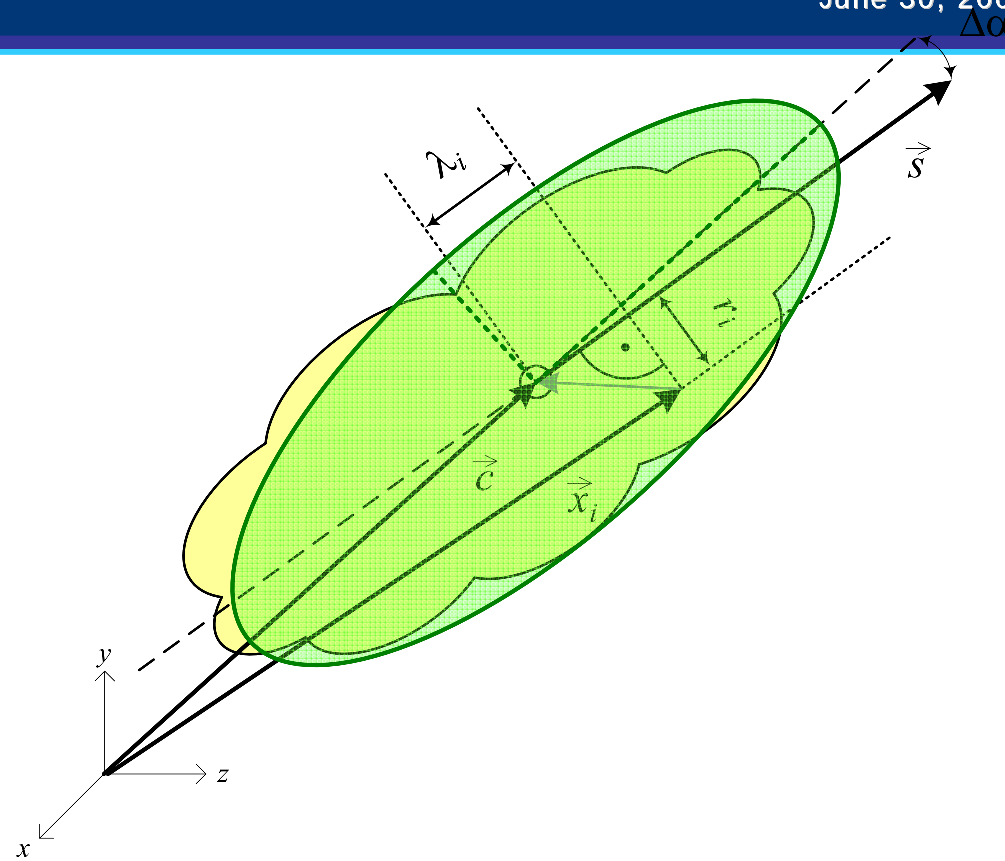
- Need to come up with some geometrical measure
  - Use the envelop!

Can calculate likelihood that cell is within envelop

- Introduces two parameters with typical values:

$$p_r = 3, \;\; p_\lambda = 3$$

  - May need some tuning!
- Define cell i is inside topo cluster c when…



$$i \in c \rightarrow \begin{cases} \dfrac{r_i}{\sqrt{\langle R_c^2 \rangle - \langle R_c \rangle^2}} < p_r \\ \dfrac{|\lambda_i|}{\sqrt{\langle \lambda_c^2 \rangle - \langle \lambda_c \rangle^2}} < p_\lambda \end{cases}$$

Shared cells between SW and TopoCluster provide:

- Fractional number of cells shared
  - Can be calculated for both clusters
    - Likely more useful for TopoCluster
- Energy density measure
  - Fraction of cluster signal in shared cells
    - Raw signal reference
- Relative profiles
  - Re-summation of raw sampling energies allows to calculate fractions by sampling for both types of clusters
- …

When used with muons:

- Fraction of cells associated with a muon inside a TopoCluster
  - Discard TopoCluster signal in MET calculation if muon corrected for calo energy loss