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Jets In ATLAS

Peter Loch
University of Arizona
Tucson, Arizona
USA

ATLAS

This talk

- Focus on explanation of algorithms, methods, and measureable jet features
  - Including some pointers to underlying principles, motivations, and expectations
  - Some reference to physics
- Restricted to published or blessed material
  - Most performance expectations from "The ATLAS Experiment at the Large Hadron Collider" (G.Aad et al., 2008 JINST 3 S08003)
  - Most results shown >1 year old
- Everything is based on simulations
  - Experiments may tell a (very?) different story in some cases
- LHC beam conditions used for most studies are not appropriate for first data
  - Center of mass 14 TeV
    - Mostly a phase space limitation in the first data for basic jet performance studies
  - No pile-up effects included except where especially stated

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Roadmap

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1. **Jets at LHC**
   a. Where do they come from?
      - Selected hadronic final states
   b. Physics collision environment
      - Underlying event and pile-up
2. **Hadronic signals in ATLAS**
   a. The ATLAS detector
      - Focus on calorimeters
      - General response issues
   b. Signals for jet reconstruction
      - Unbiased and biased towers
      - Topological clusters
3. **Jet measurement**
   a. Jet input objects
      - Towers
      - Topological clusters
      - Particles
   b. Jet reconstruction and calibration
      - Reconstruction sequence
      - Calibration schemes
4. **Jet reconstruction performance**
   a. QCD di-jets
   b. Photon/z + jet(s)
   c. W mass spectroscopy
   d. Jet vertices and track jets
5. **Conclusions & Outlook**

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1. Jets at LHC

Where do Jets come from at LHC?

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Fragmentation of gluons and (light) quarks in QCD scattering

- Most often observed interaction at LHC

Decay of heavy Standard Model (SM) particles

- Prominent example:

$$t \Rightarrow bW \Rightarrow jjjj$$

$$t \Rightarrow bW \Rightarrow l\nu jjj$$

Associated with particle production in Vector Boson Fusion (VBF)

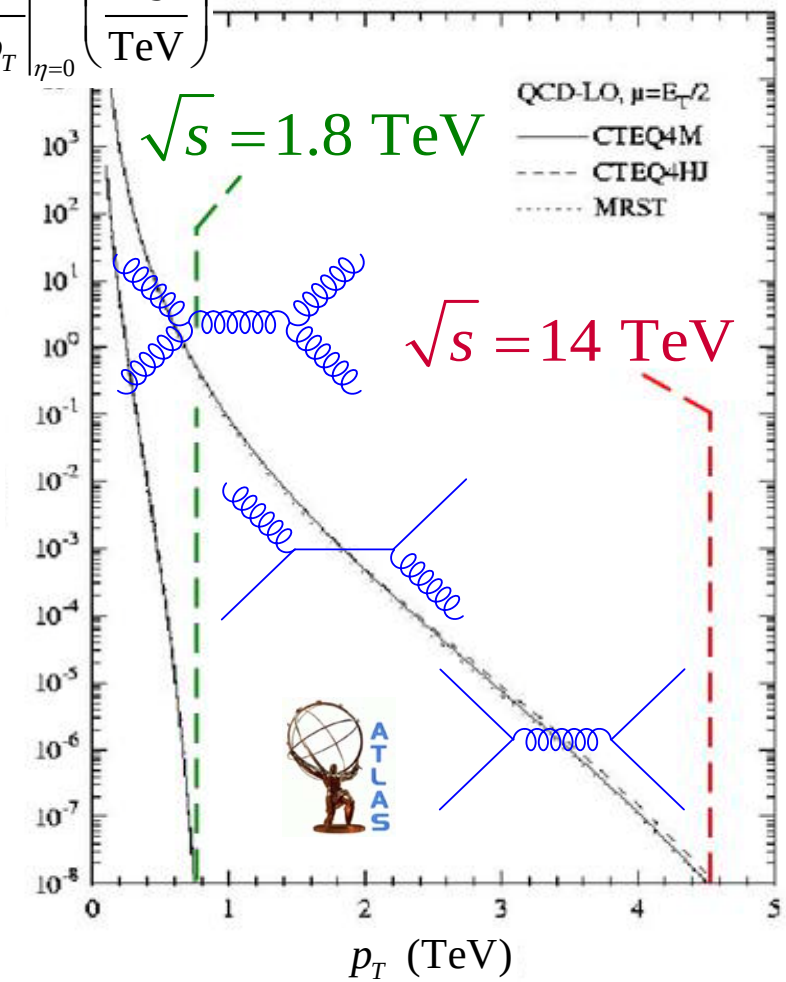
- E.g., Higgs

$$qq \Rightarrow qqWW \Rightarrow Hjj$$

Decay of Beyond Standard Model (BSM) particles

- E.g., SUSY

$$\left.\frac{d\sigma^2}{d\eta dp_T}\right|_{\eta=0} \left(\frac{\text{nb}}{\text{TeV}}\right)$$ inclusive jet cross-section



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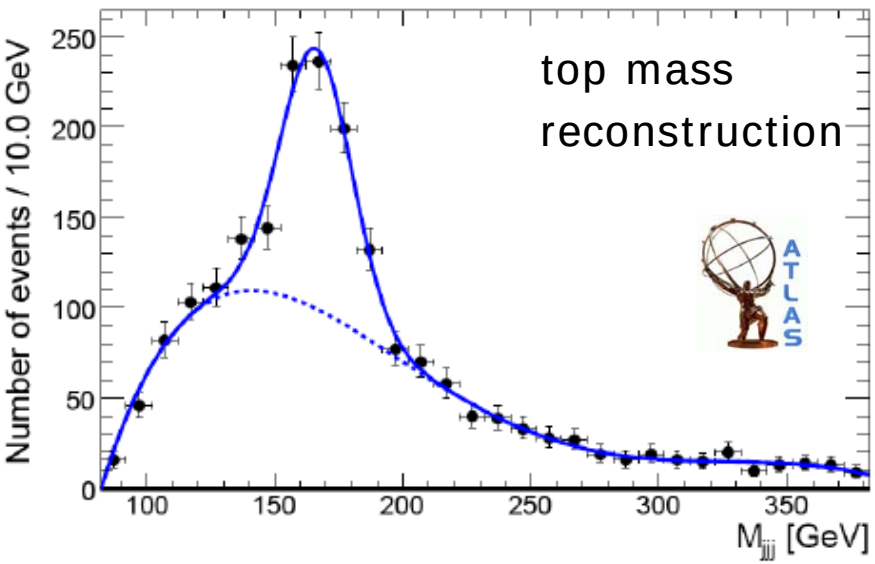

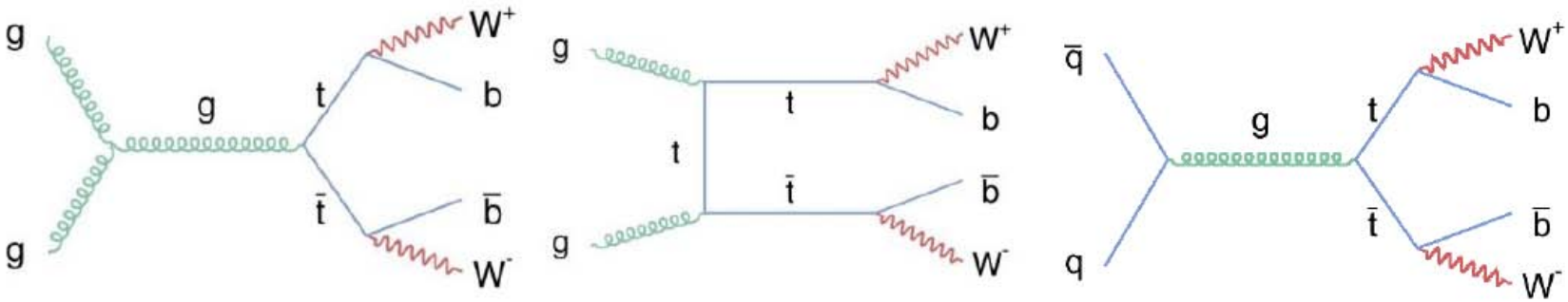

gg→tt 85%

qq→tt 15%

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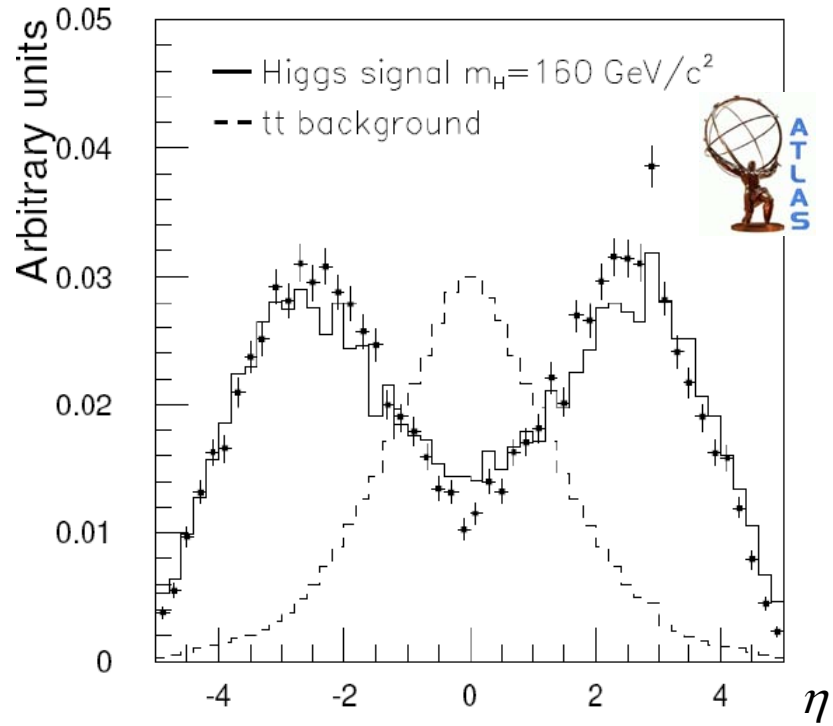

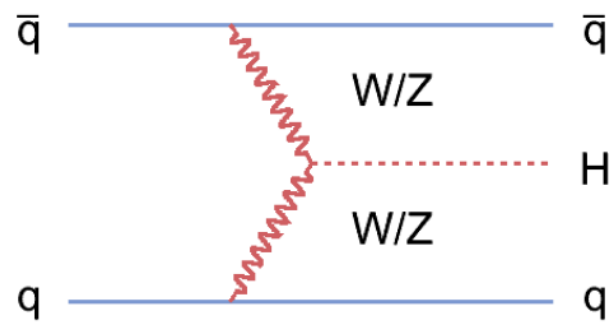

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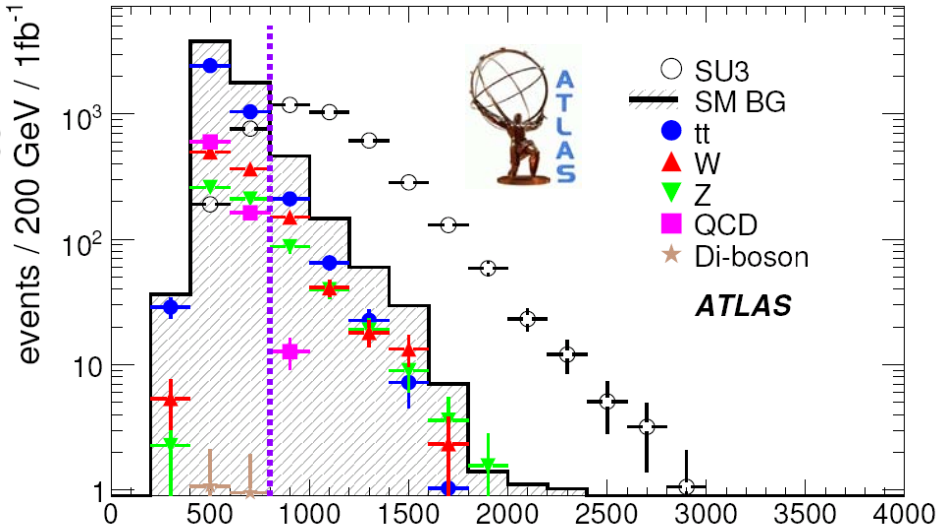
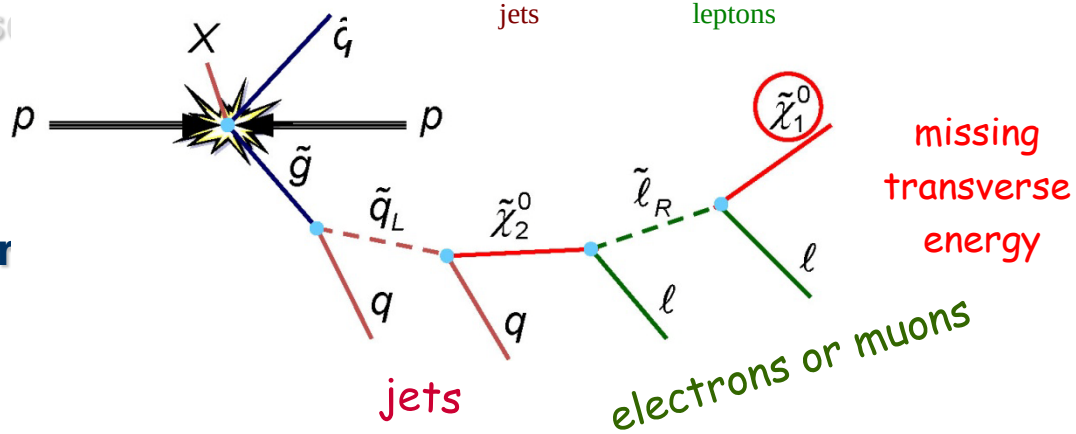


$$M_{eff} = \sum_{\text{jets}} |p_{T,j}| + \sum_{\text{leptons}} |p_{T,\ell}| + \not{p}_T$$



Underlying Event

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Collisions of other partons in the protons generating the signal interaction

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

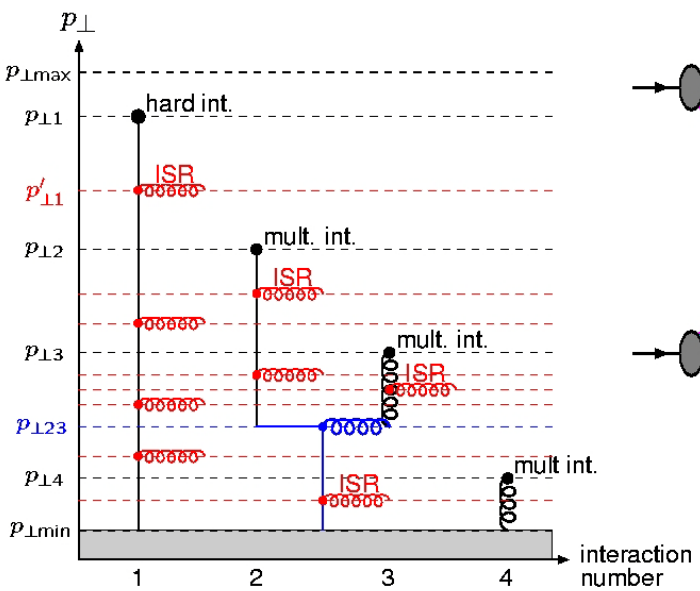
No real first principle calculations

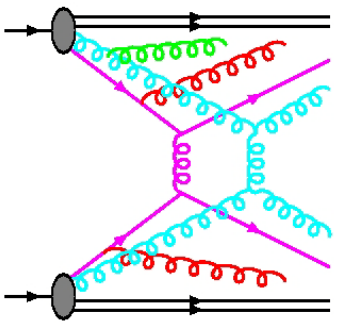
- Contains low pT (non-pertubative) QCD
  - Tuning rather than calculations
- Activity shows some correlation with hard scattering (radiation)
  - pTmin, pTmax differences
- Typically tuned from data in physics generators

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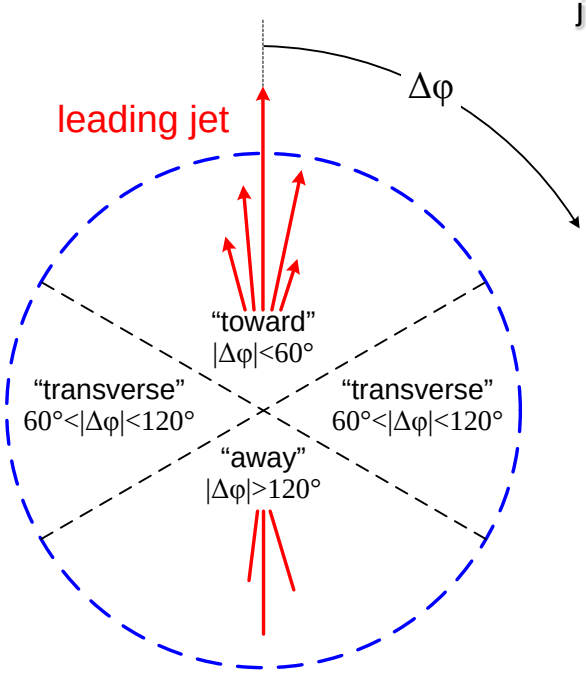
Rick Field's (CDF) view on di-jet events



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

Underlying Event

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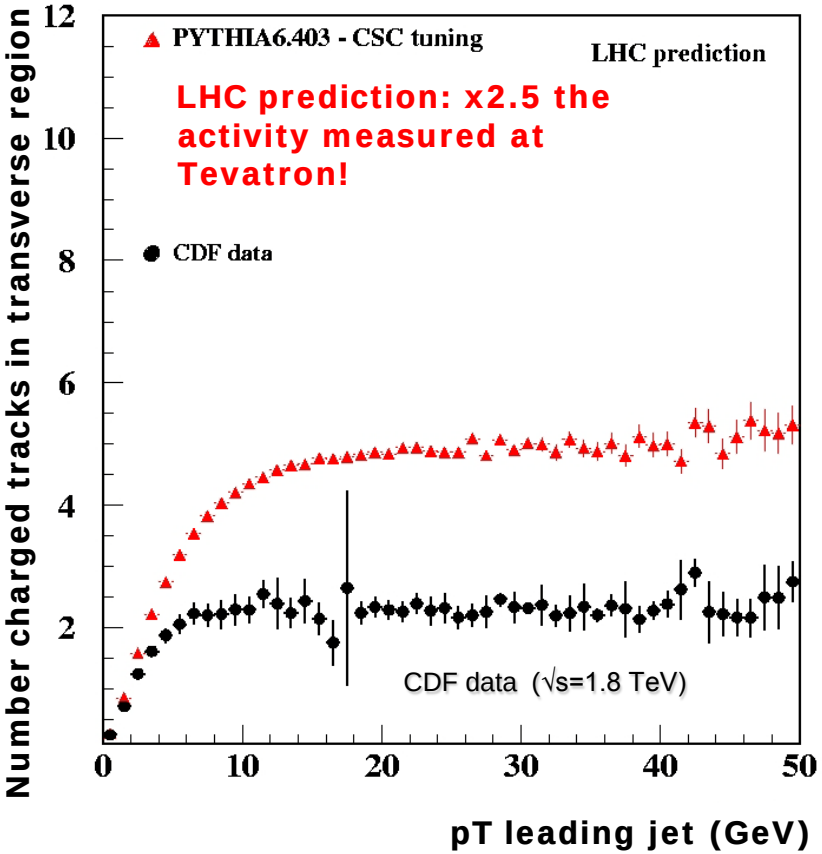
CDF data: Phys.Rev, D, **65** (2002)



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!

Multiple Proton Interactions

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Expect ~<20> additional proton collisions at each bunch crossing at LHC design luminosity

- Statistically independent
  - Actual number at given bunch crossing Poisson distributed
- Mostly soft to semi-hard collisions
  - Very similar dynamics as underlying event
- Generate 100's-1000's particles in addition to hard scatter
  - High occupancy in inner detector is experimentally challenging
- High ionization rate in calorimeters
  - Signal collection time versus bunch crossing an issue

Experimental handles

- Energy flow and track distributions in minimum bias events
  - Help to understand physics features of pile-up events
  - Feedback for modelers
- Multiple primary vertices
  - Explicit reconstruction of MPVs indicates event-by-event pile-up activity

Why Is That Important?

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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

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

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

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
- Control of underlying event and pile-up contributions

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2. Hadronic Signals in ATLAS

The ATLAS Detector

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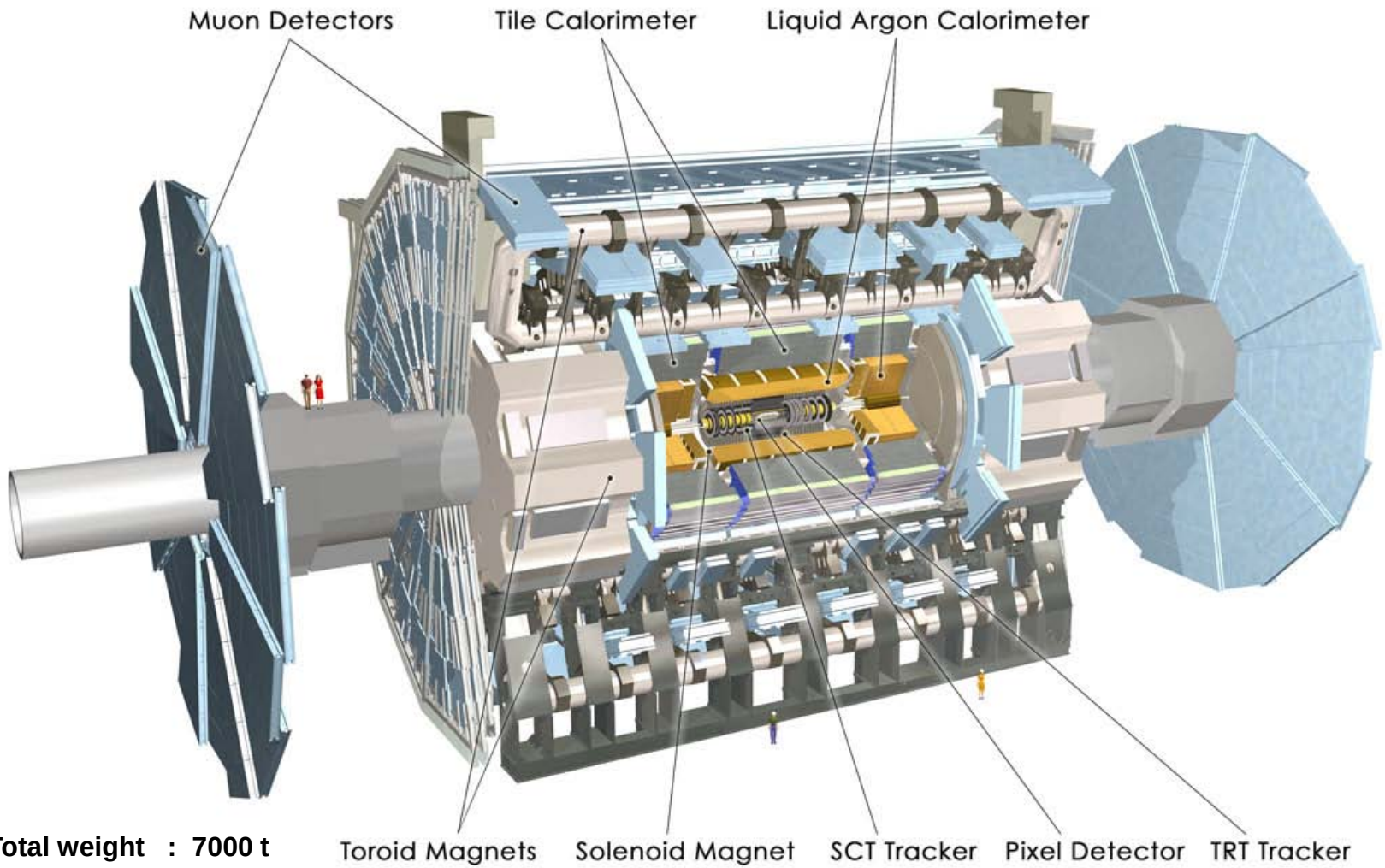

Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid
+ toroid

The ATLAS Calorimeters

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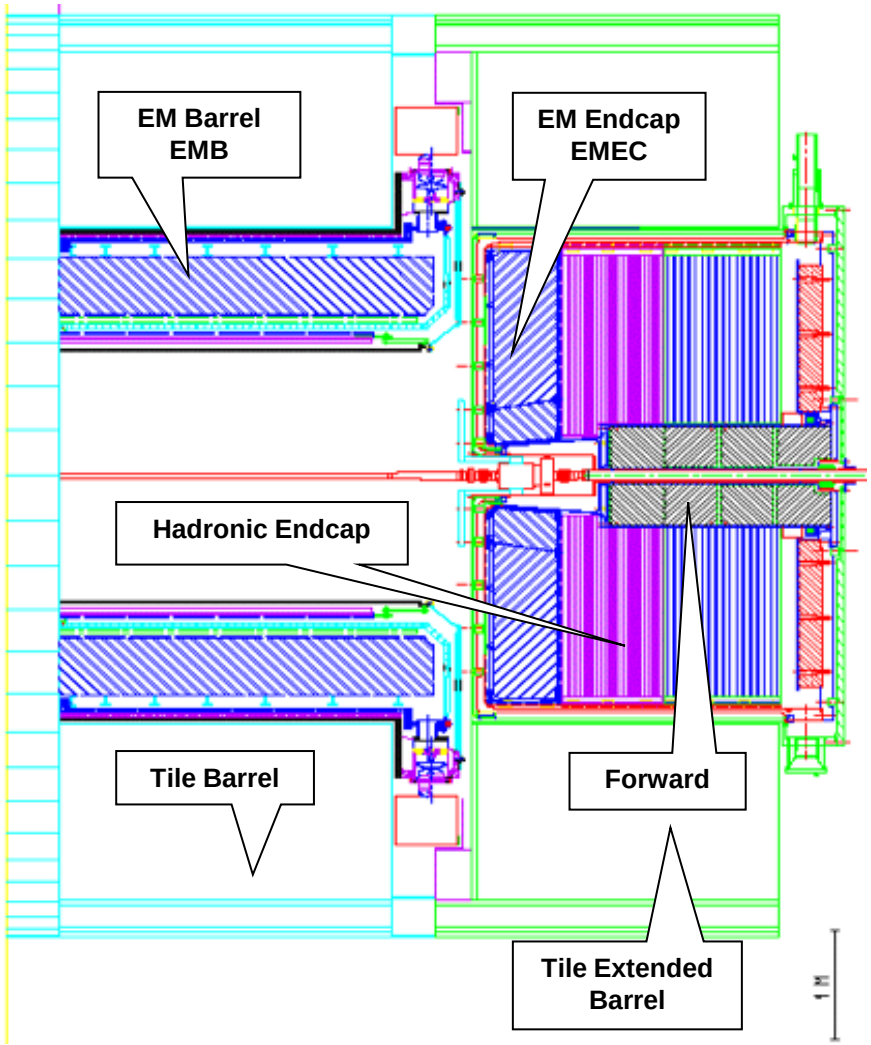

ATLAS Calorimeters

- 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,
  - $\Delta\eta \times \Delta\Phi = 0.75 \times 0.65 - 5.4 \times 4.7$

ATLAS Calorimeter Summary

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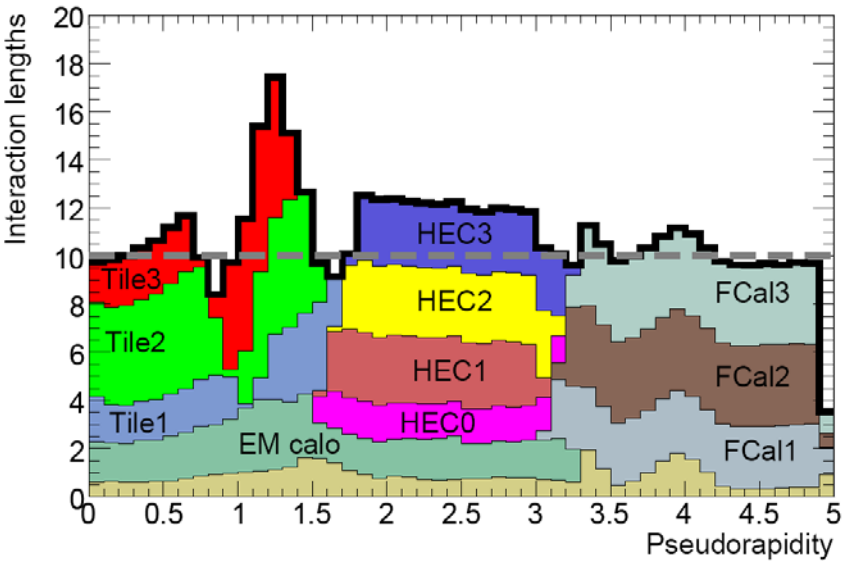
Non-compensating calorimeters

- Electrons generate larger signal than pions depositing the same energy
  - Typically $e/\pi \approx 1.3$

High particle stopping power over whole detector acceptance $|\eta|<4.9$

- ~26-35 X_0 electromagnetic calorimetry
- ~ 10 λ total for hadrons



Hermetic coverage

- No significant cracks in azimuth
- Non-pointing transition between barrel, endcap and forward
  - Small performance penalty for hadrons/jets

High granularity

- 6 (barrel)-7 (end-caps) longitudinal samplings
- ~200,000 independently read-out cells in total
- Pre-samplers in front of barrel and end-cap

Pile-Up in ATLAS (1)

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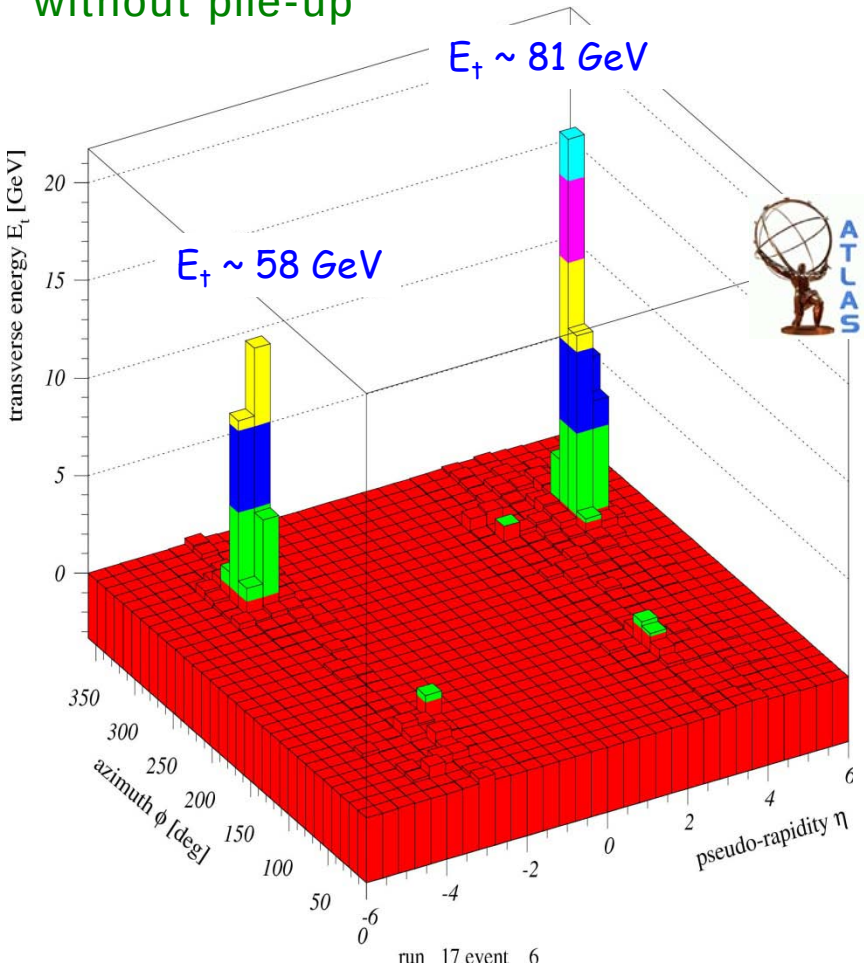
Signal history in calorimeter increases noise

- Signal collection in ATLAS 10-20 times slower than bunch crossing rate (25 ns)
  - Signal history effectively adds to noise
- Baseline suppressed by fast signal shaping
  - Bi-polar shape with net 0 integral

Noise has coherent character

- Cell signals linked through past shower developments

without pile-up



Prog.Part.Nucl.Phys. 60:484-551,2008

Pile-Up in ATLAS (2)

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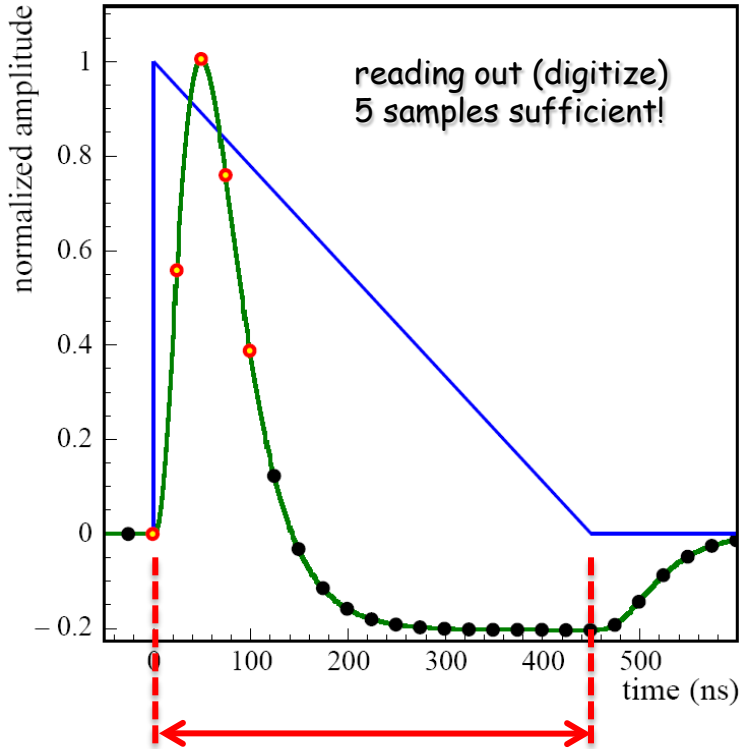
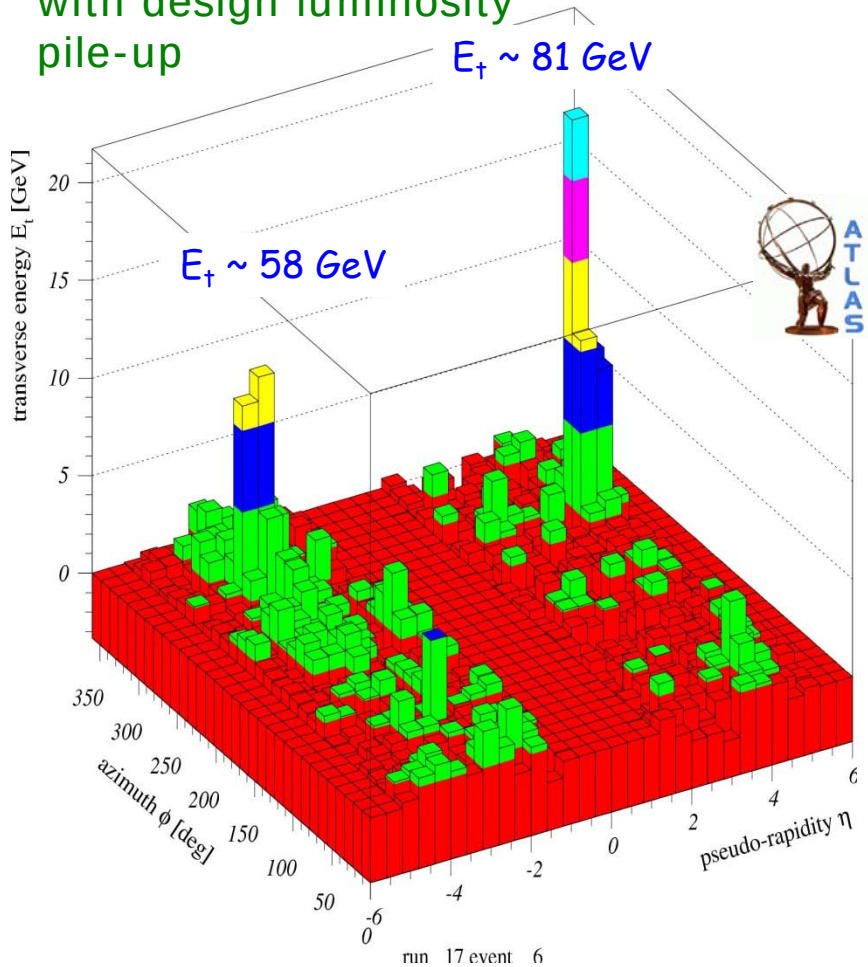
Cell signal shape in ATLAS LAr Calorimeter



~450 ns @ 2mm LAr, 1 kV/mm

with design luminosity pile-up



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Pile-Up in ATLAS (3)

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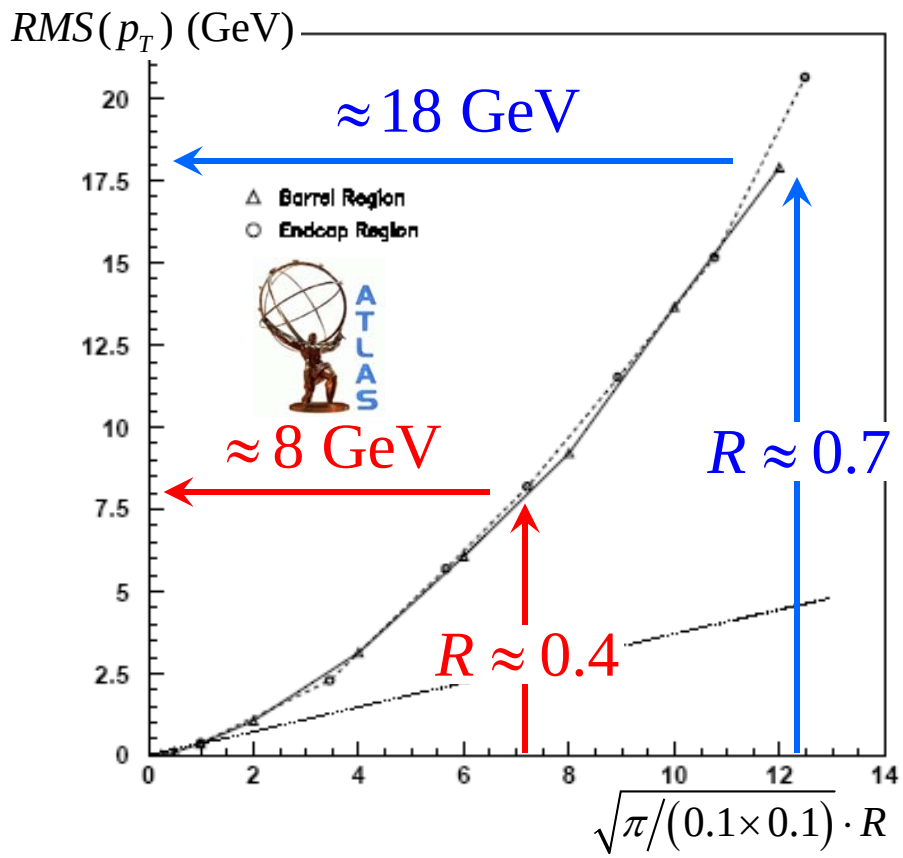
Online digital filtering

- Explicit knowledge of physics pulse shape allows precise reconstruction of amplitude
  - Needs linear filter coefficients and auto-correlation matrix
- Suppresses noise wrt single reading
  - $1/\sqrt{2}$ for 5 samples

First data issues

- Pulse-shape and filtering works best at high ionization rates
  - Most complete area cancellation
- Initial bunch crossing 50/75/450 ns introduce baseline
  - Magnitudes depend on actual bunch spacing
- Increased noise also possible for some configurations

$$L = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$



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Basic Signal Scales in ATLAS

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Cell signals

- Raw data for physics from online system is amplitude, time, filter quality, gain selection
  - Special readout configurations providing 5…32 samples possible
- Cell signals are energy, time, quality, and gain
  - Energy scale is "electromagnetic" – determined by electron testbeams and simulations
  - All electronic corrections are applied
  - Signal efficiency corrections are applied
    - Reduced signals due to HV problems etc.

Towers and clusters

- Individual cell signals hard to use
  - Can be <0 due to noise
  - Hard to determine source of signal without context/neighbourhood
    - e/h > 1 required specific corrections for hadronic signals
- Need to collect cell signals into larger objects
  - Towers and clusters

ATLAS Calorimeter Towers

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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

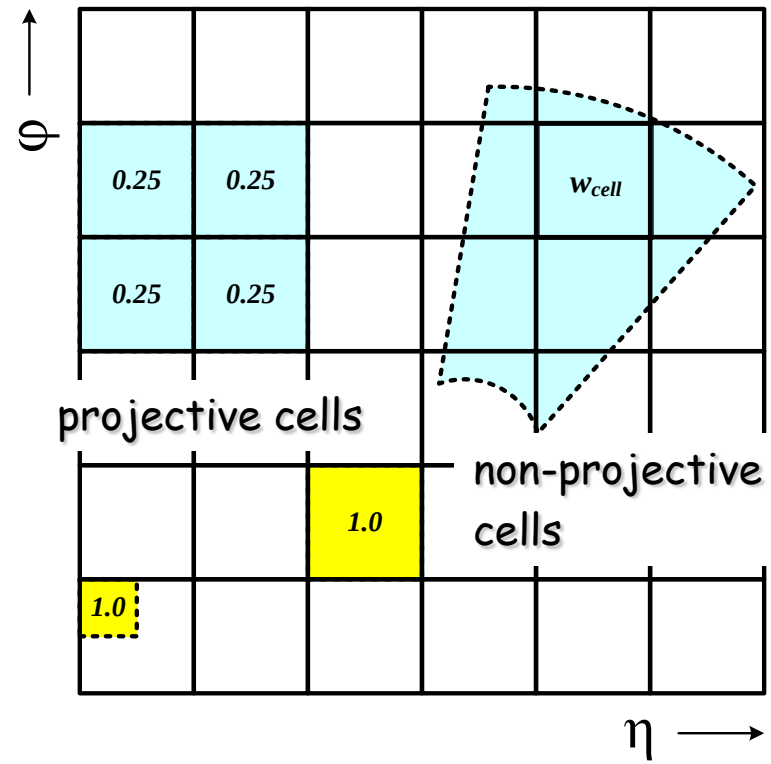
- Cells EM scale signals are summed with geometrical weights
  - Depend on cell area containment ratio
  - Weight = 1 for projective cells of equal or smaller than tower size
- Summing can be selective
  - See jet input signal discussion

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)

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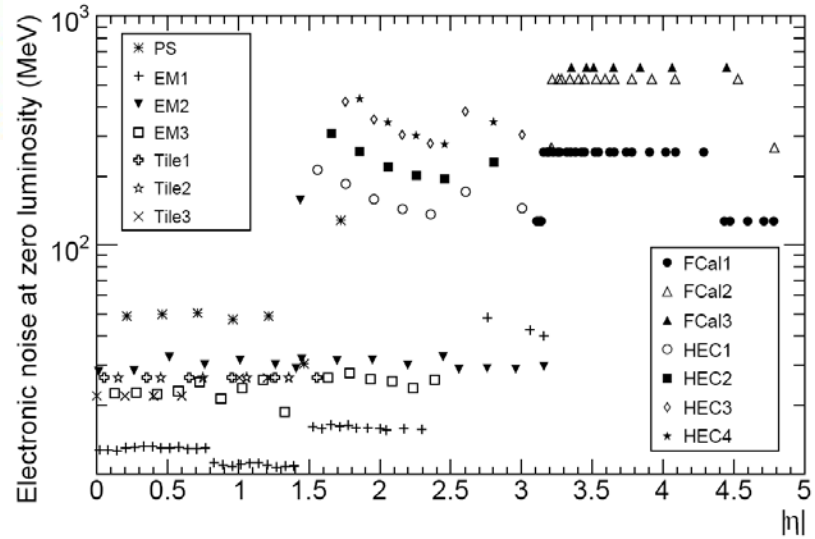
Signal extraction tool

- 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

ATLAS Topological Cell Clusters (2)

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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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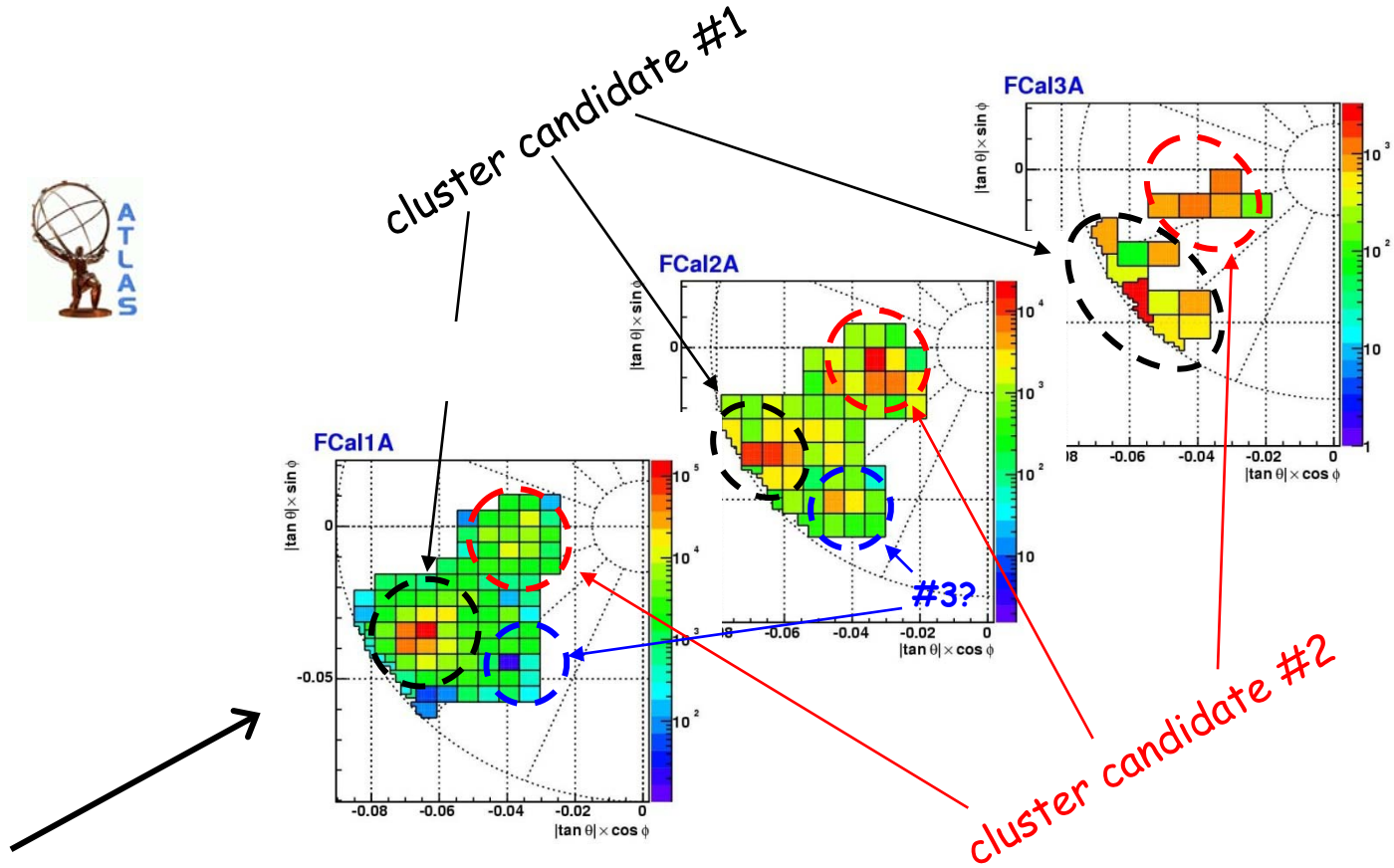

ATLAS Local Hadronic Calibration

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Local hadronic energy scale restoration 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 – missing curling tracks, dead material losses without correlated cluster signal,…

ATLAS Local Scale Sequence

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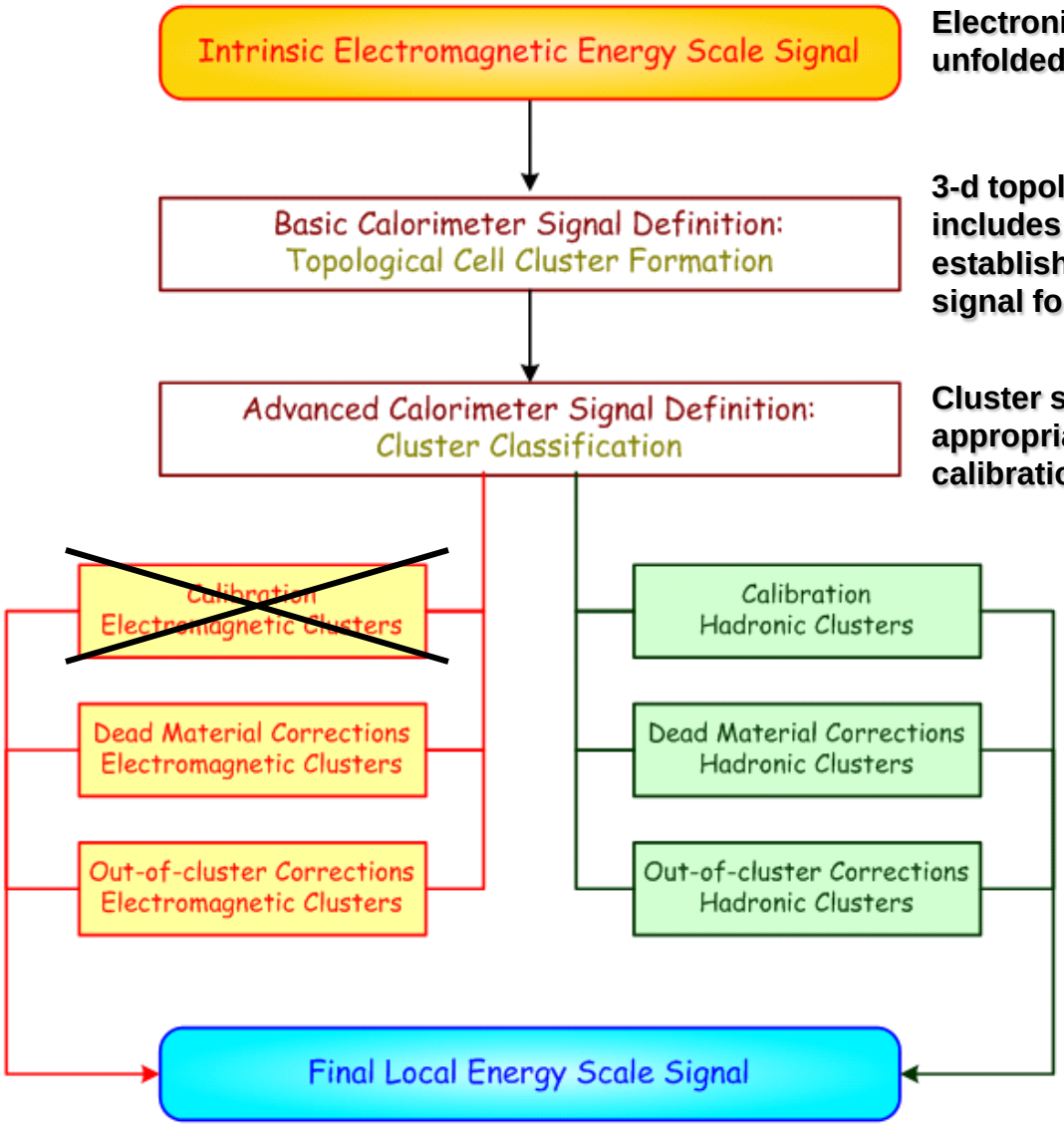
Quality of True Deposited Energy Estimate



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.

3. Jet Input Objects

Jet Input Objects (1)

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Calorimeter signal based

- Basic 0.1 x 0.1 calorimeter 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 calorimeter towers
  - Cells from topological clusters only
  - Electromagnetic energy scale signal
  - Noise suppression like for topological clusters
- Topological calorimeter cell clusters
  - Electromagnetic and local hadronic scale signals
  - Noise suppressed

From tracking detectors

- Reconstructed tracks
  - Charged particles only

From simulation

- Stable and interacting particles from generators reaching sensitive detectors
  - Lab lifetime > 10 ps
  - Excludes neutrinos and muons from hard interaction

Jet Input Objects (2)

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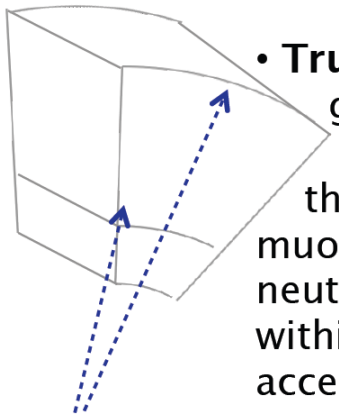
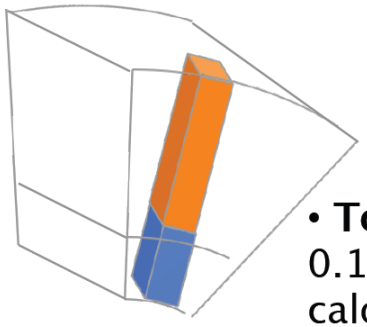
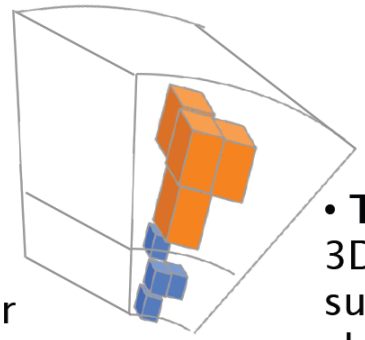


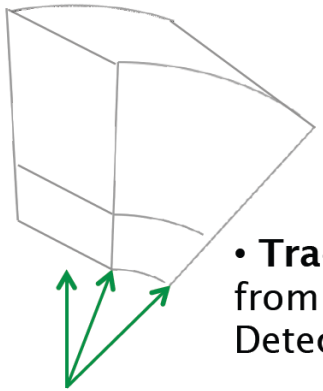
- **Truth**: generator particles that aren't muons or neutrinos, within η acceptance



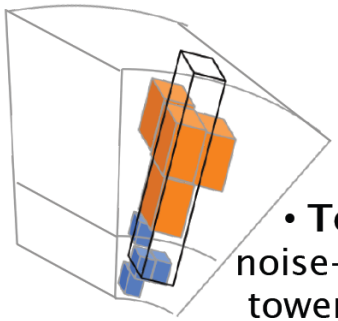
- **Towers**: 0.1x0.1 calorimeter towers



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



- **Tracks**: from Inner Detector

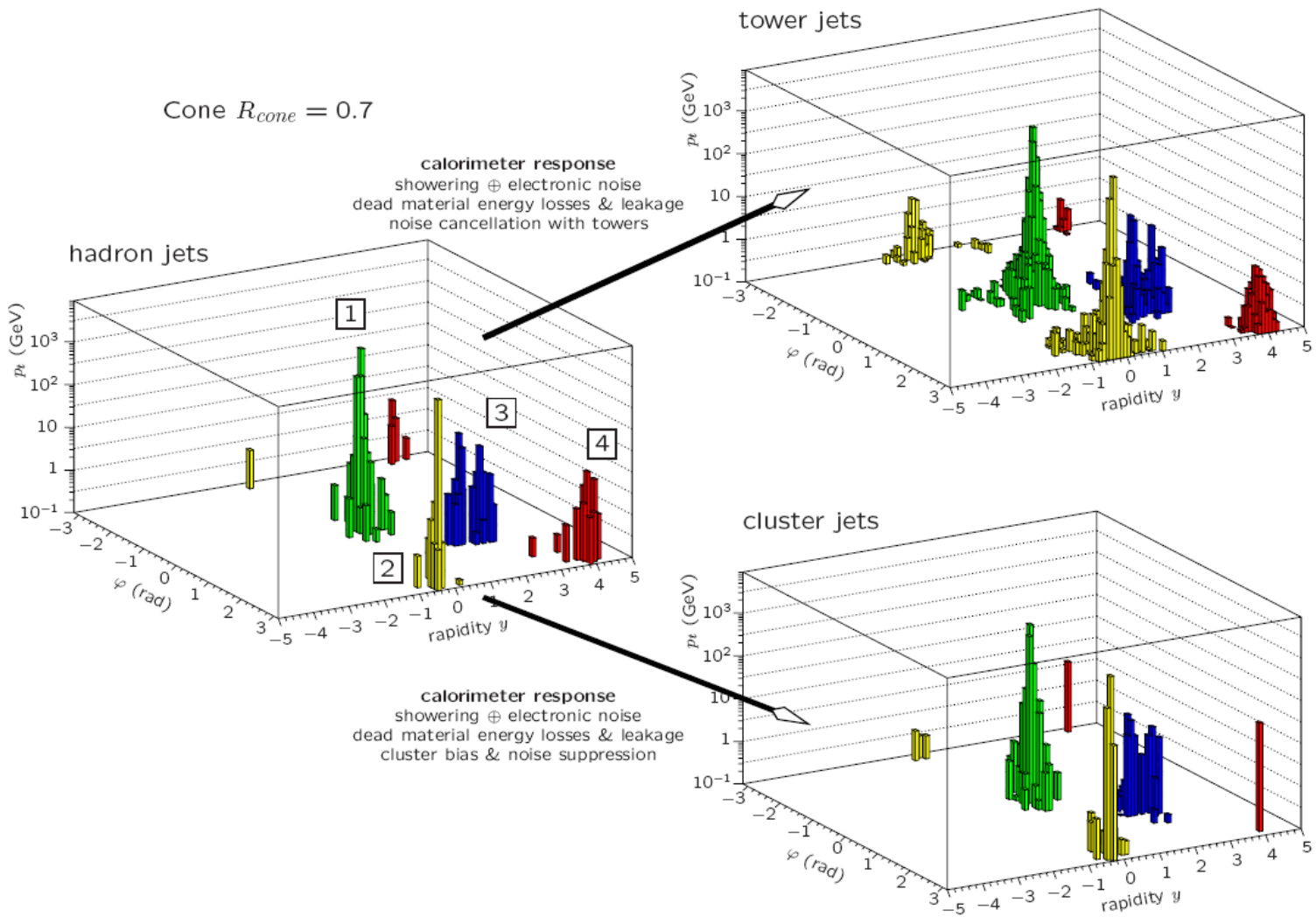


- **TopoTowers**: noise-suppressed towers built from topoclusters

from K. Perez, Columbia U.

Jets in the ATLAS Calorimeters

P. Loch
U of Arizona
Aug. 27, 2009



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

ATLAS Jet Reconstruction

P. Loch
U of Arizona
Aug. 27, 2009

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
    - All implementations from FastJet and SISCone available
  - Default is AntiKt4 with R = 0.4
    - Reference is legacy ATLAS seeded fixed cone
    - Narrow jets least affected by pile-up
- Jet calibration
  - Depending on detector input signal definition, jet finder choices, references...
  - Default calibration uses cell weights
- Jet selection
  - Apply cuts on kinematics etc. to select jets of interest or significance

Objective

- Reconstruct particle level features
  - Test models and extract physics

Monte Carlo Jet Calibration

P. Loch
U of Arizona
Aug. 27, 2009

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

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

ATLAS Jet Cell Weights

P. Loch
U of Arizona
Aug. 27, 2009

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 and location
  - 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

P. Loch
U of Arizona
Aug. 27, 2009

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
Aug. 27, 2009

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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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U of Arizona
Aug. 27, 2009

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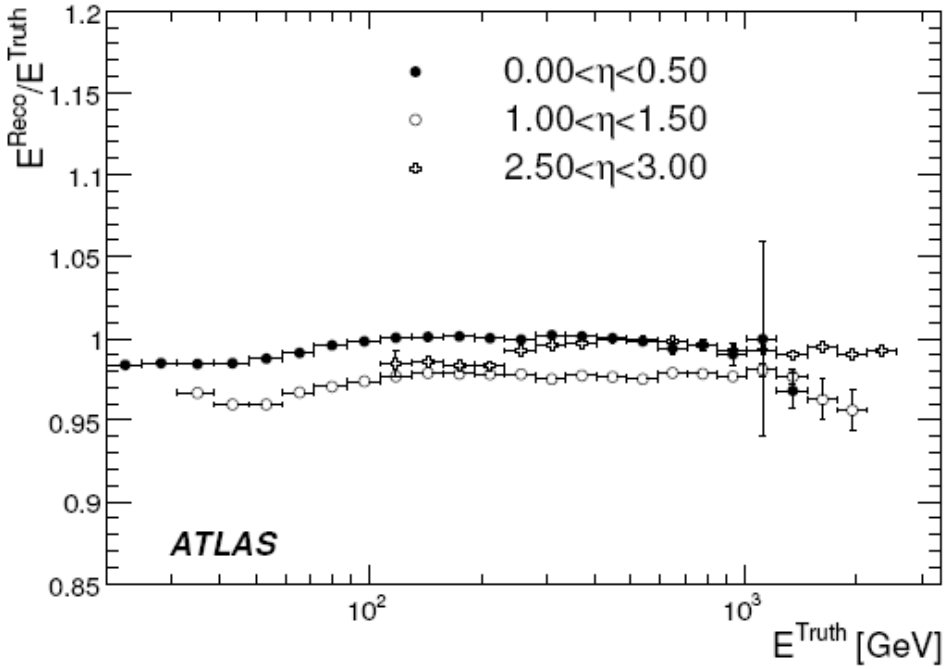

Response for jets in ttbar

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

Final Jet Energy Scale Calibration

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Aug. 27, 2009

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

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

ATLAS JES Correction Model for First Data

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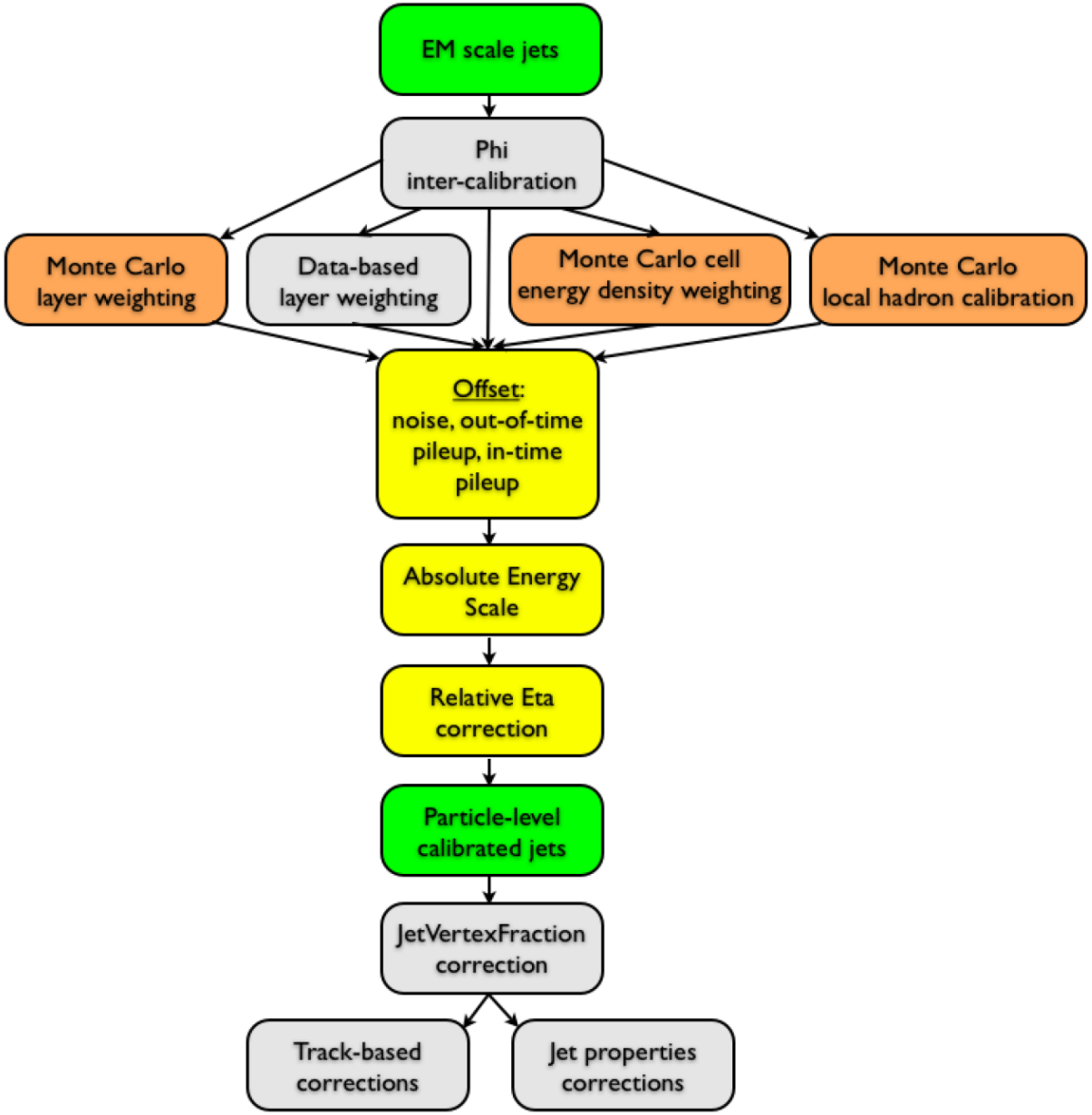
U of Arizona
Aug. 27, 2009

optional

data driven

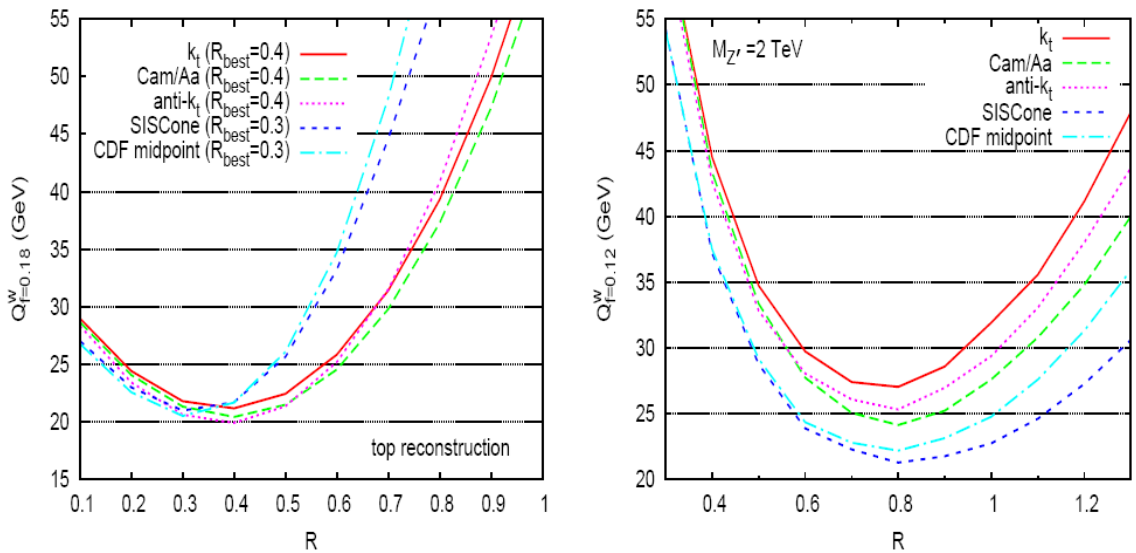
MC



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 Performance Evaluations (2)

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U of Arizona
Aug. 27, 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
    - E.g. towers vs clusters, calibration scheme

Jet Energy Scale (JES) stability

- Typically better than 2% with respect to signal linearity in closure tests
  - Calibration approaches are stable
- Signal uniformity within the same average deviations
- Resolution goal is achievable with studied calibration approaches
  - See next slide

Jet Energy Resolution

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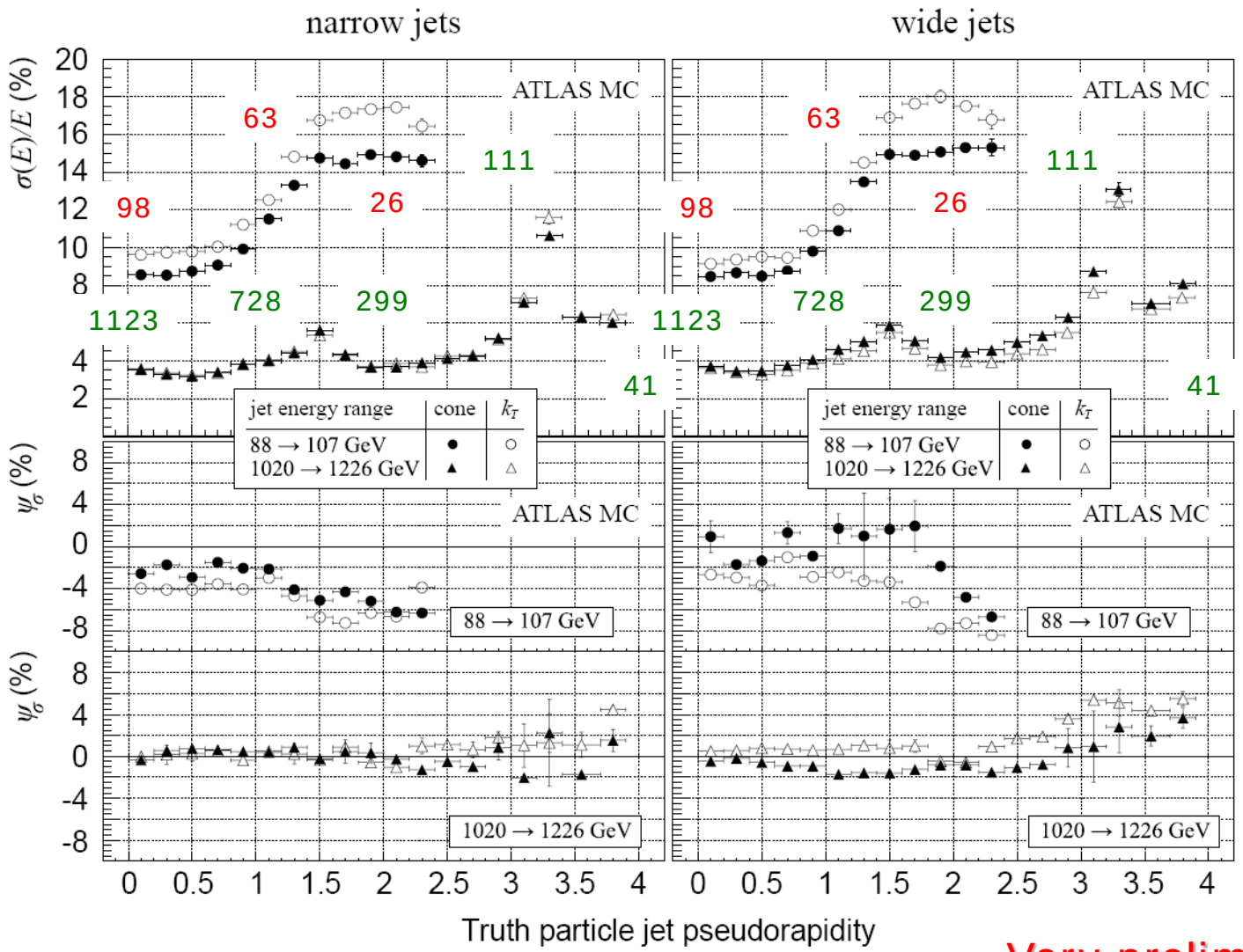


$\langle p_t \rangle$(GeV) for $88 < E_{jet} < 107$ GeV

$\langle p_t \rangle$(GeV) for $1020 < E_{jet} < 1226$ GeV

Very preliminary!
Older evaluation!

Data Driven Evaluation

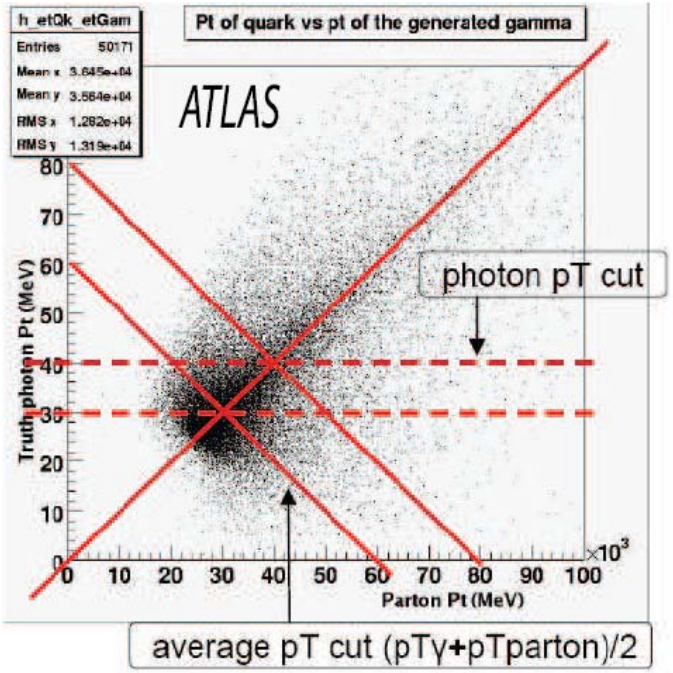
P. Loch
U of Arizona
Aug. 27, 2009

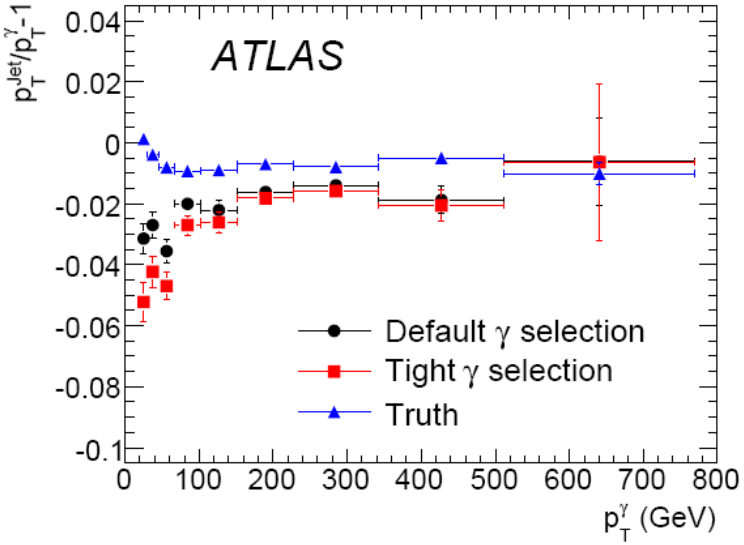
Photon+jet(s)

- 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





Data Driven Evaluation

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U of Arizona
Aug. 27, 2009

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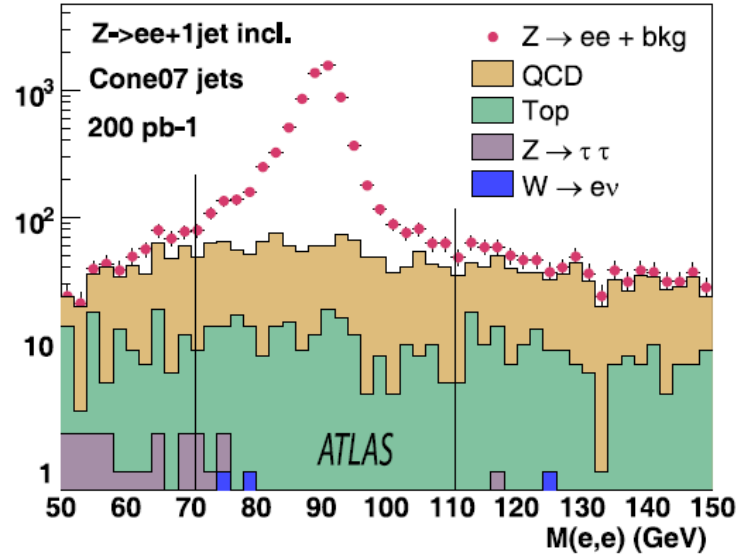

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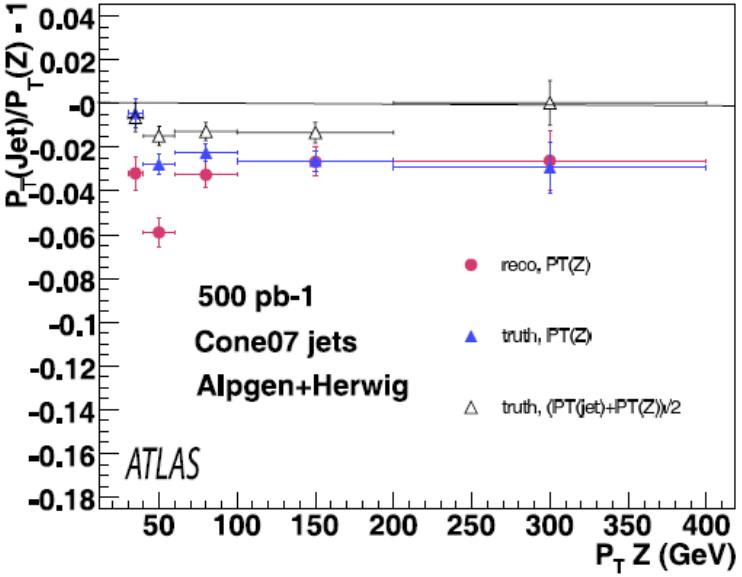
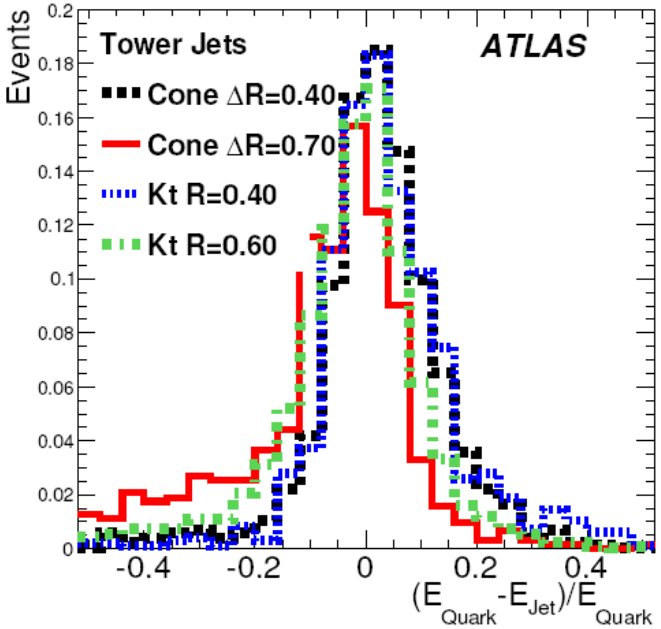


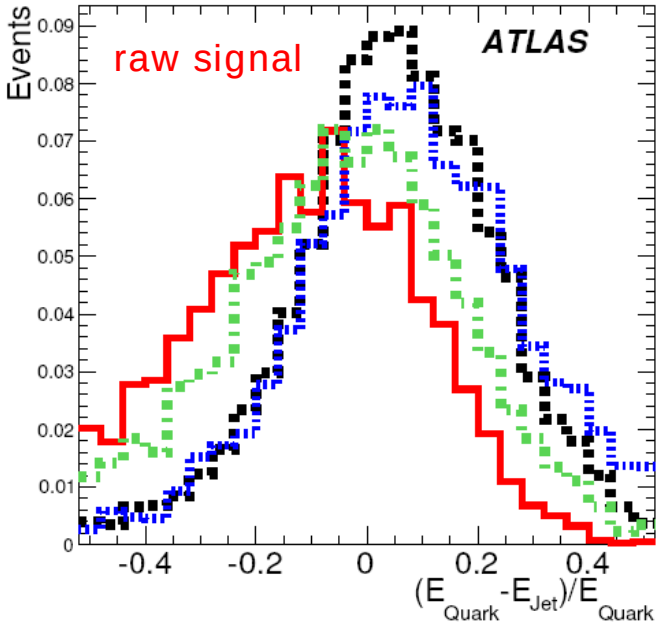
W Mass Spectroscopy

P. Loch
U of Arizona
Aug. 27, 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





Jets Not From Hard Scatter

P. Loch
U of Arizona
Aug. 27, 2009

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

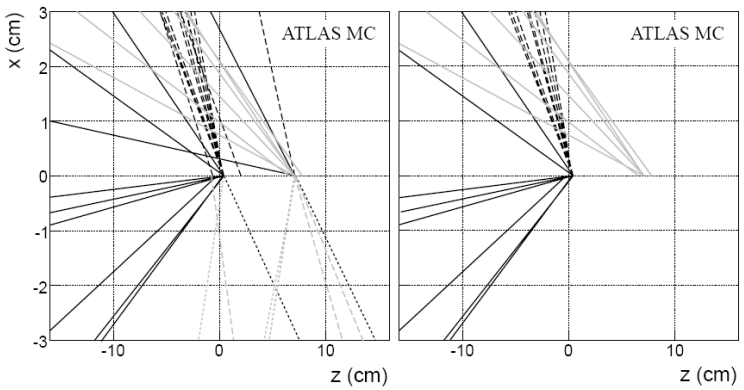
- No real experimental indication of jet source
  - Some correlation with hard scattering?
  - Jet area?
  - No separate vertex

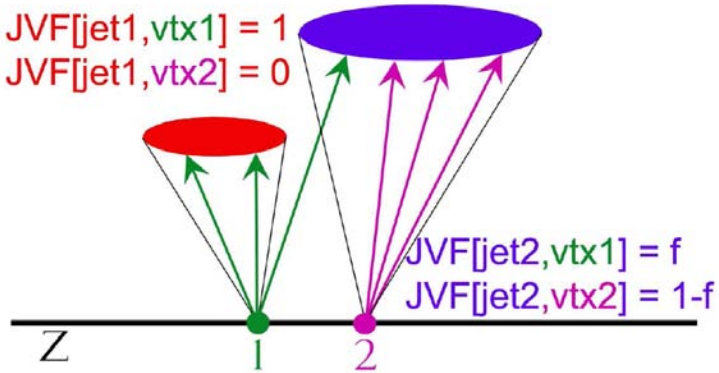
Jet-by-jet handle for multiple proton interactions

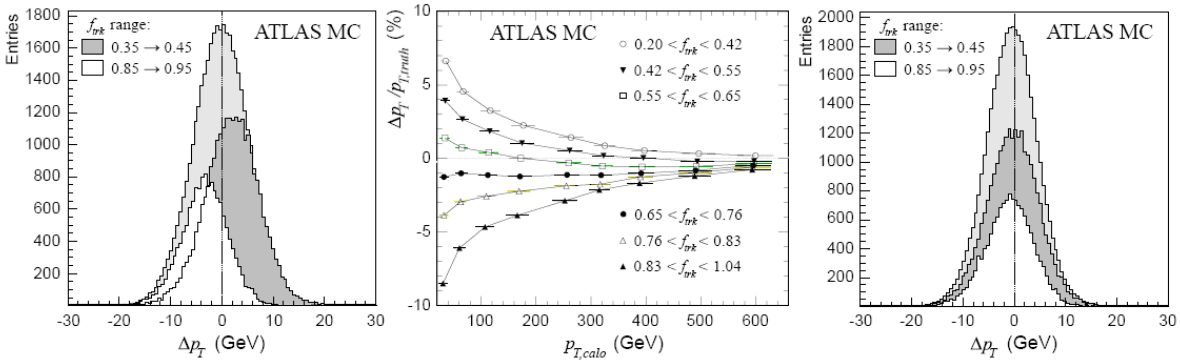
- Classic indicator for multiple interactions is number of reconstructed vertices in event
  - Tevatron with RMS(z_vertex) ~ 30 cm
  - LHC RMS(z_vertex) ~ 8 cm
- If we can attach vertices to reconstructed jets, we can in principle identify jets not from hard scattering
  - Limited to pseudorapidities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

Track jets

- Find jets in recon-structed 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!







6. Conclusions & Outlook

Conclusions

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U of Arizona
Aug. 27, 2009

This was a mere snapshot

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

First data jet reconstruction and calibration strategy in place

- Includes simulation and data input
  - Emphasis on "data driven"
  - Expect to establish flat jet response for first physics quickly
- Discussion on how to establish initial systematic uncertainties just started
  - Some ideas exist but procedures need to be ironed out better
  - Still on track for first useful collision data

We are looking beyond obvious jet performance variables

- Jet shapes are considered for refined JES calibration
  - Jet-by-jet corrections
- Experimental sensitivity to unfold jet substructure explored
  - Needs more studies with real data
  - Discovery tool for boosted heavy particles!

We are waiting for collision data!

Some Backup

Electromagnetic Calorimetry

P. Loch
U of Arizona
Aug. 27, 2009

Highly segmented lead/liquid argon accordion

- No azimuthal cracks
- 3 depth segments
  - + pre-sampler (limited coverage)

Strip cells in 1st layer

- Very high granularity in pseudo-rapidity

$$\Delta\eta \times \Delta\varphi \approx 0.003 \times 0.1$$

Deep cells in 2nd layer

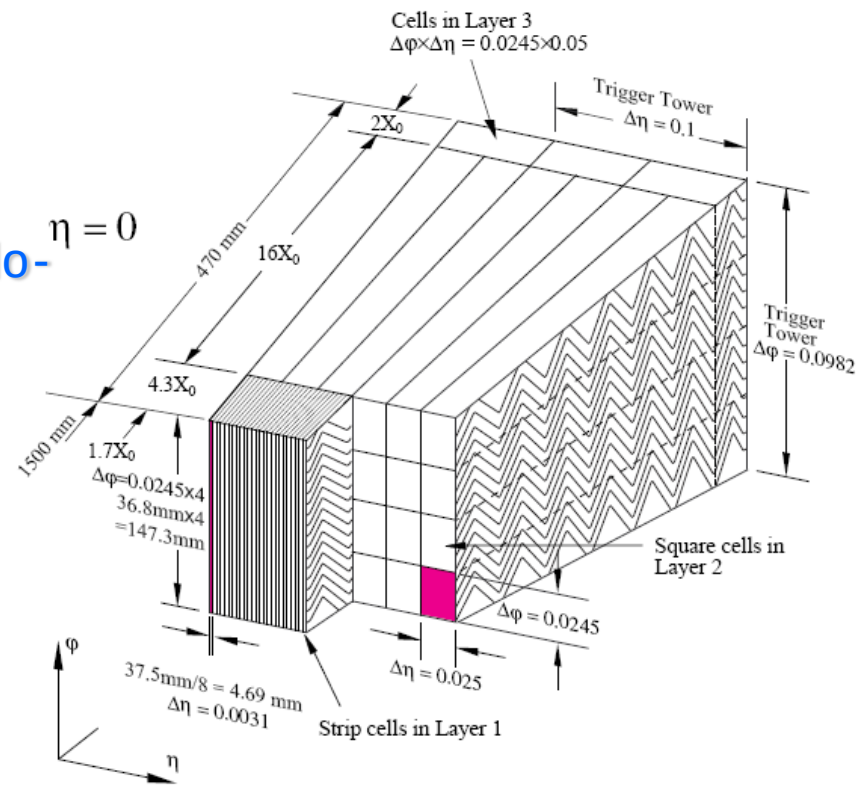
- High granularity in both directions

$$\Delta\eta \times \Delta\varphi \approx 0.025 \times 0.025$$

Shallow cells in 3rd layer

$$\Delta\eta \times \Delta\varphi \approx 0.05 \times 0.025$$

Electromagnetic Barrel



Hadronic Calorimetry

P. Loch
U of Arizona
Aug. 27, 2009

Tile calorimeter

- Iron/scintillator tiled readout
- 3 depth segments

Quasi-projective readout cells

- First two layers:

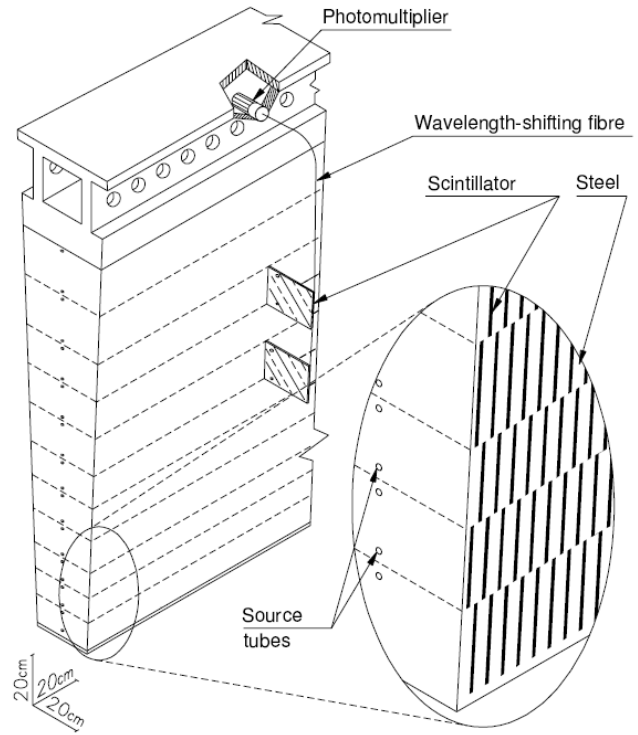
$$\Delta\eta \times \Delta\varphi \approx 0.1 \times 0.1$$

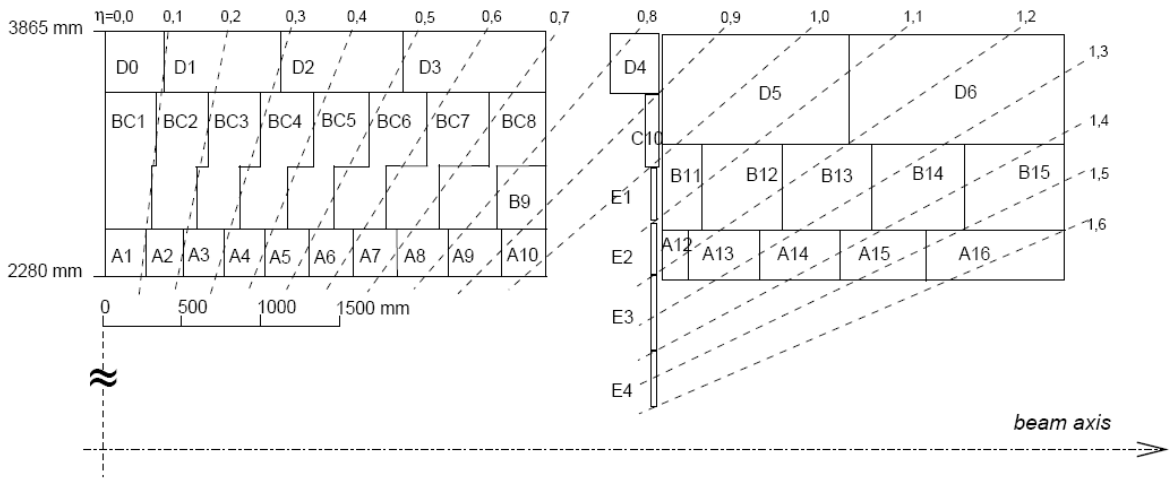
- Third layer

$$\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.1$$

Very fast light collection

- ~50 ns
- Dual fiber readout for each channel



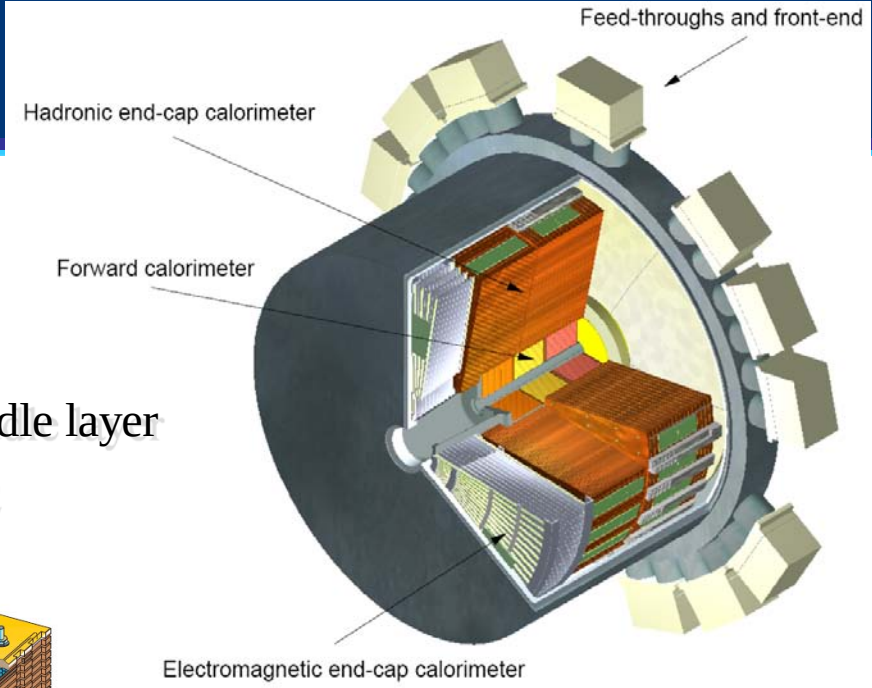


EndCap Calorimeters

Electromagnetic "Spanish Fan" accordion

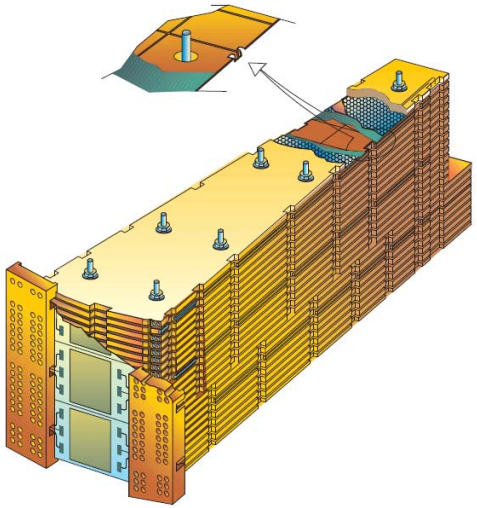
- Highly segmented with up to three longitudinal segments

$$\Delta\eta \times \Delta\varphi \approx \begin{cases} 0.025 \times 0.025 & |\eta| < 2.5, \text{ middle layer} \\ 0.1 \times 0.1 & 2.5 < |\eta| < 3.2 \end{cases}$$

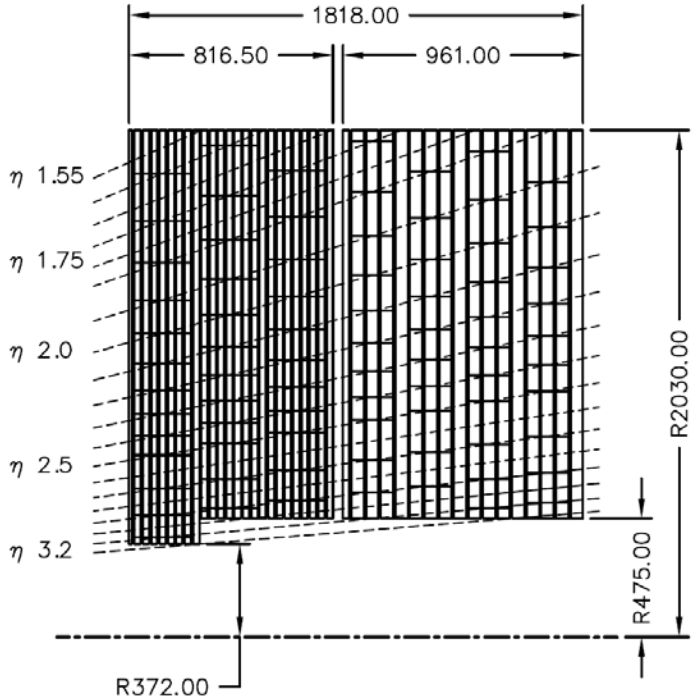


Hadronic liquid argon/copper calorimeter

- Parallel plate design
- Four longitudinal segments
- Quasi-projective cells



$$\Delta\eta \times \Delta\varphi \approx \begin{cases} 0.1 \times 0.1 & |\eta| < 2.5 \\ 0.2 \times 0.2 & 2.5 < |\eta| < 3.2 \end{cases}$$



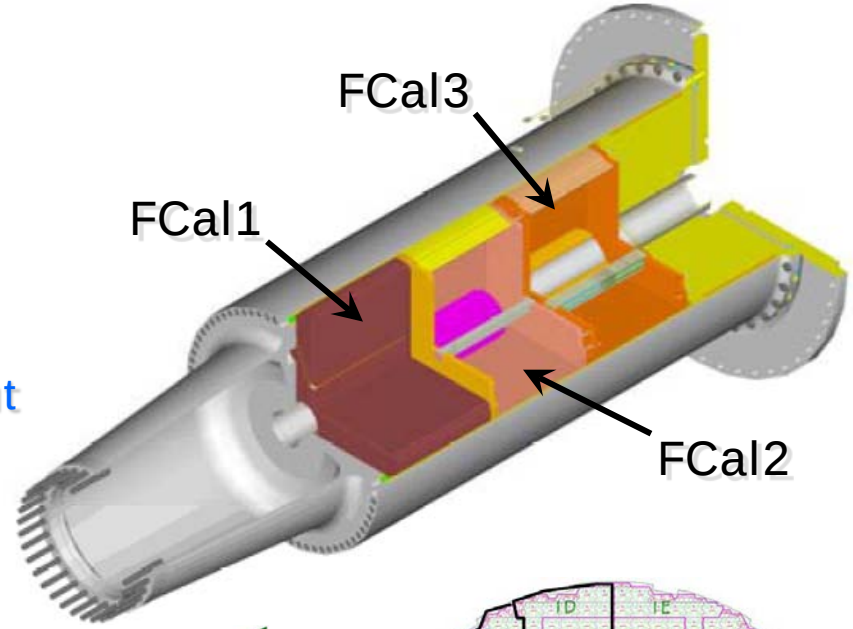
Forward Calorimeters

P. Loch
U of Arizona
Aug. 27, 2009

Design features

- Compact absorbers
  - Small showers
- Tubular thin gap electrodes
  - Suppress positive charge build-up (Ar+) in high ionization rate environment
  - Stable calibration
- Rectangular non-projective readout cells

$$\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.2$$



Electromagnetic FCal1

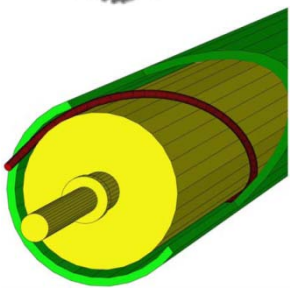
- Liquid argon/copper
  - Gap ~260 µm

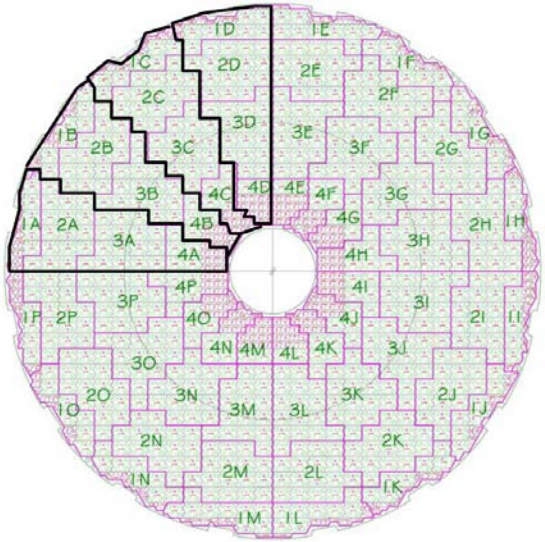
Hadronic FCal2

- Liquid argon/tungsten
  - Gap ~375 µm

Hadronic FCal3

- Liquid argon/tungsten
  - Gap ~500 µm





CaloTower Jets

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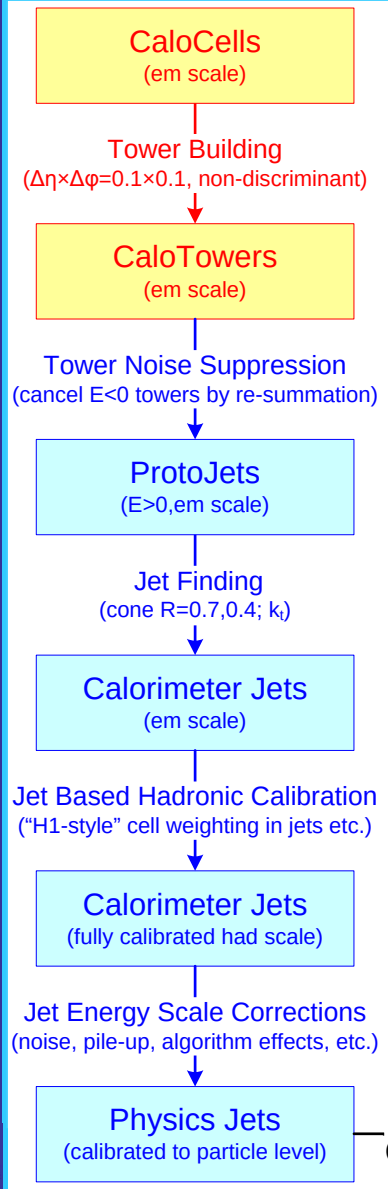
U of Arizona
Aug. 27, 2009



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

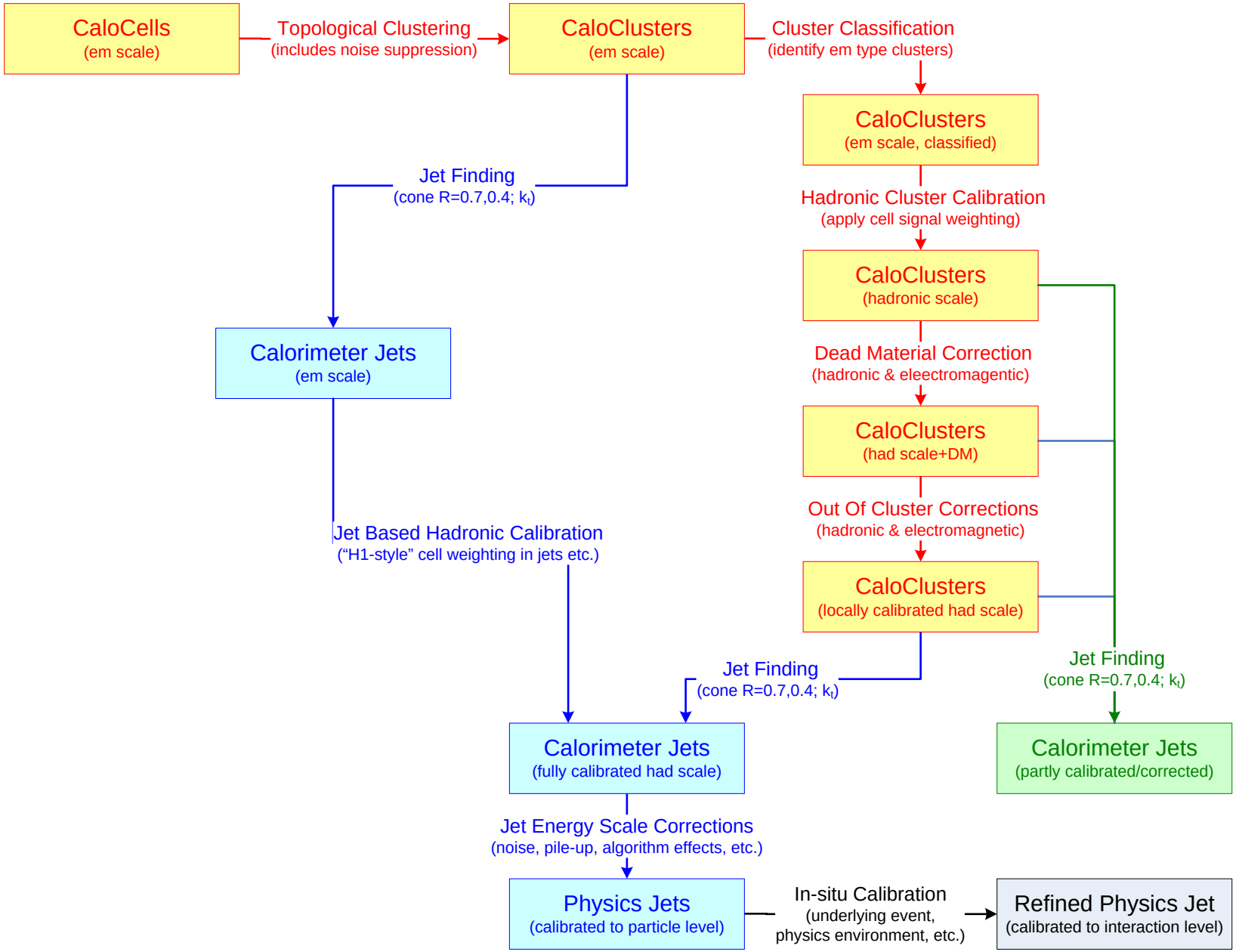
- Note: towers have signal on electromagnetic energy scale

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

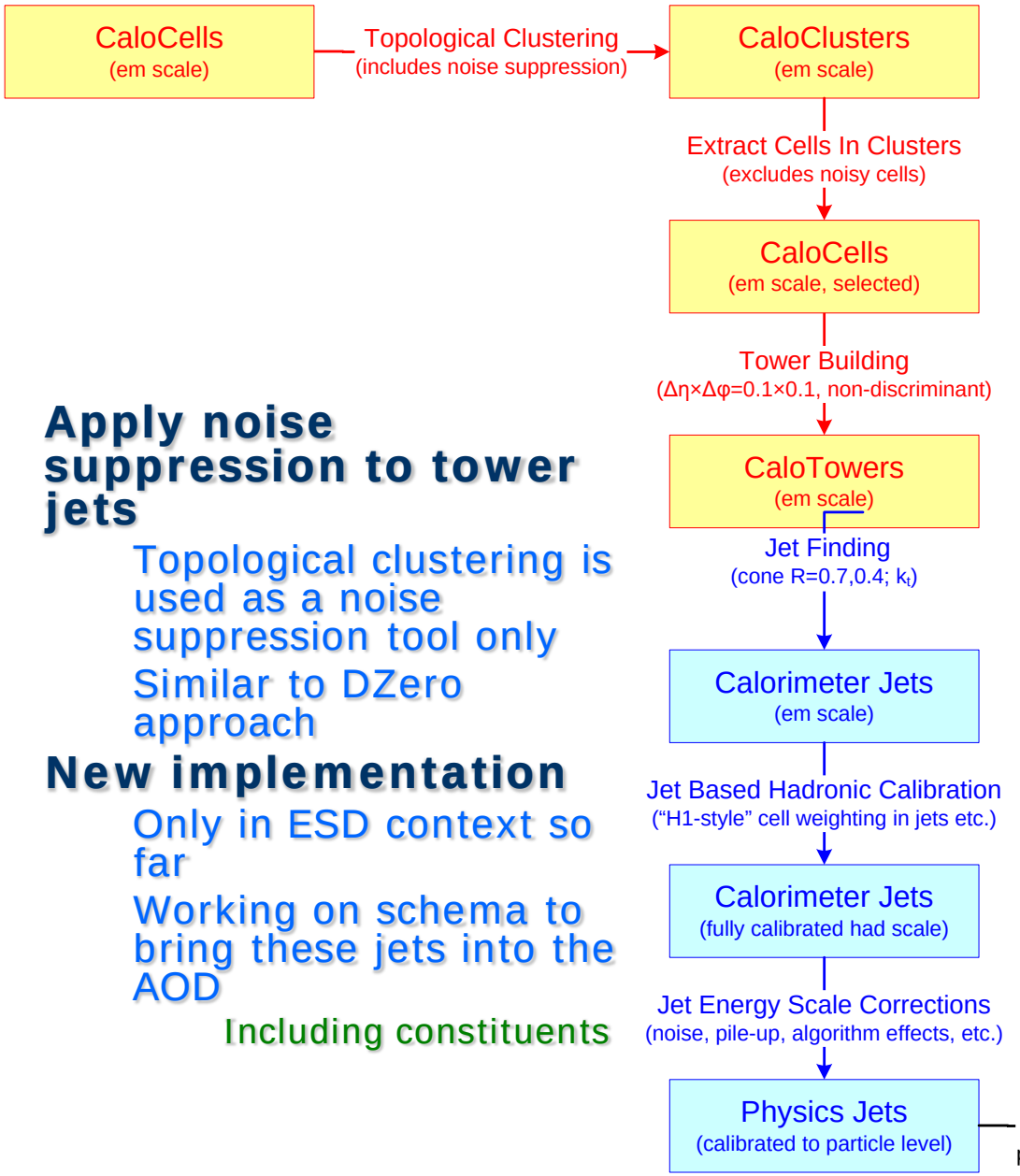
TopoCluster Jets

P. Loch
U of Arizona
Aug. 27, 2009



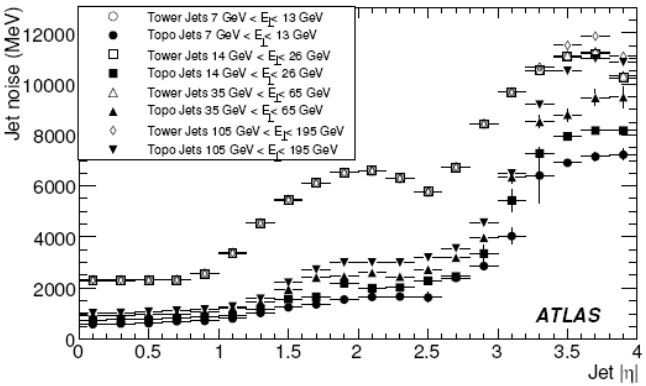
TopoTower Jets

P. Loch
U of Arizona
Aug. 27, 2009



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



CERN-OPEN-2008-020

Apply noise suppression to tower jets

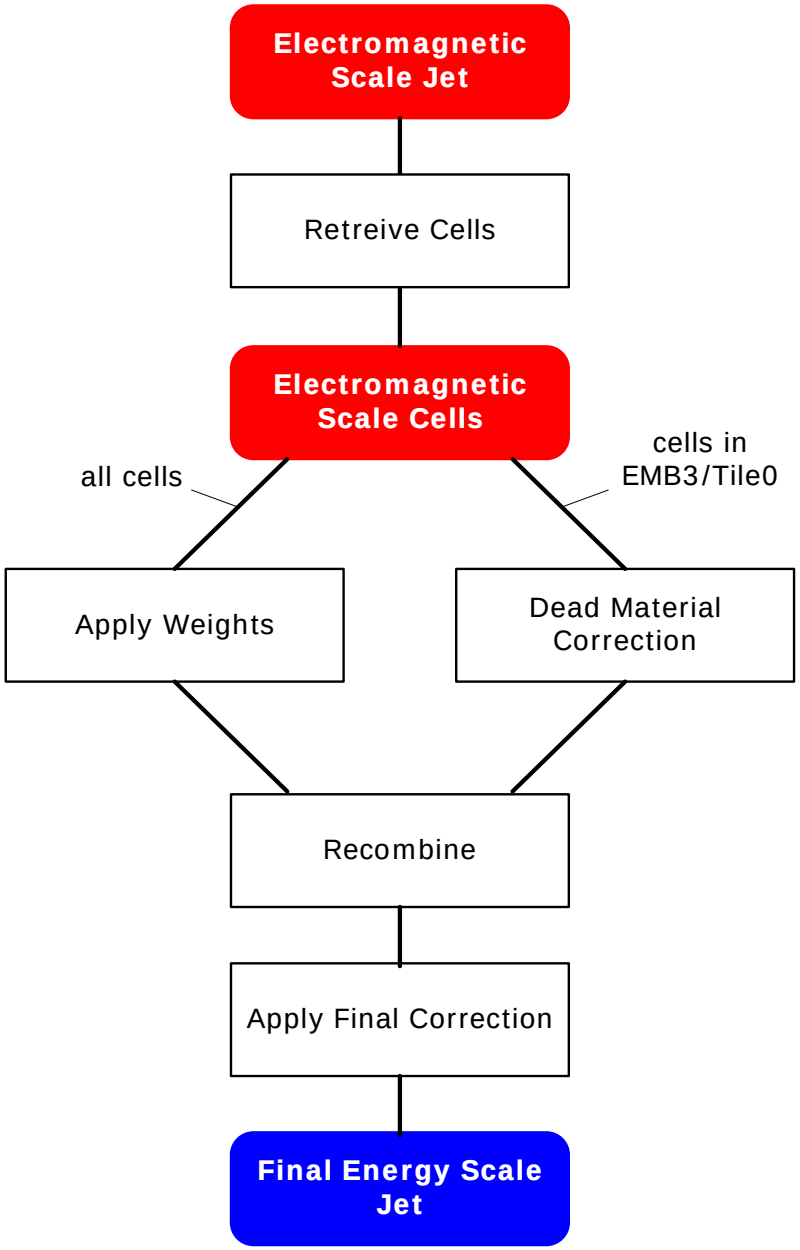
- Topological clustering is used as a noise suppression tool only
- Similar to DZero approach

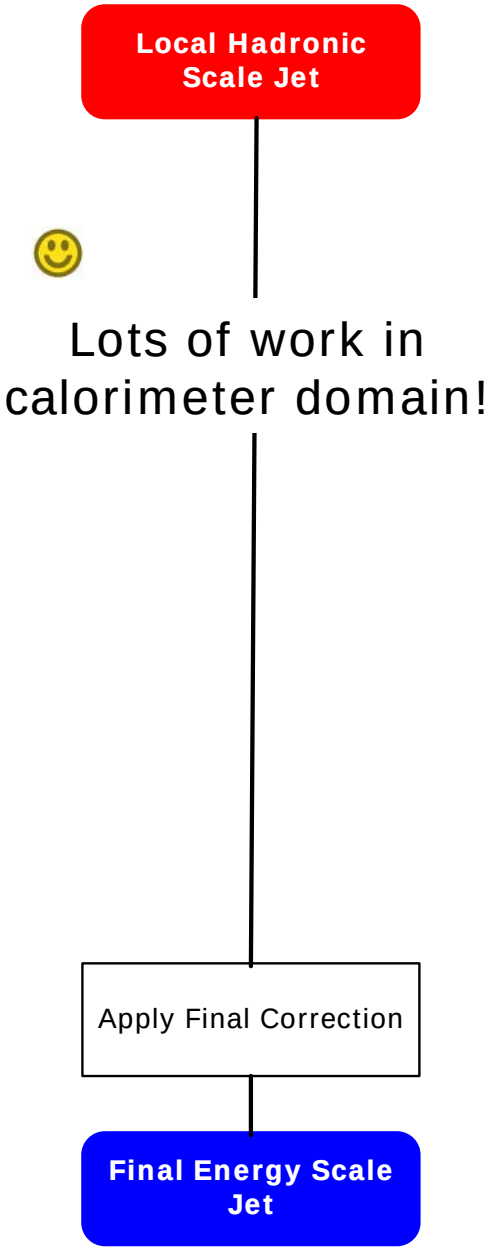
New implementation

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

Calibration Flow

P. Loch
U of Arizona
Aug. 27, 2009





Data Driven JES Corrections (1)

P. Loch
U of Arizona
Aug. 27, 2009

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:

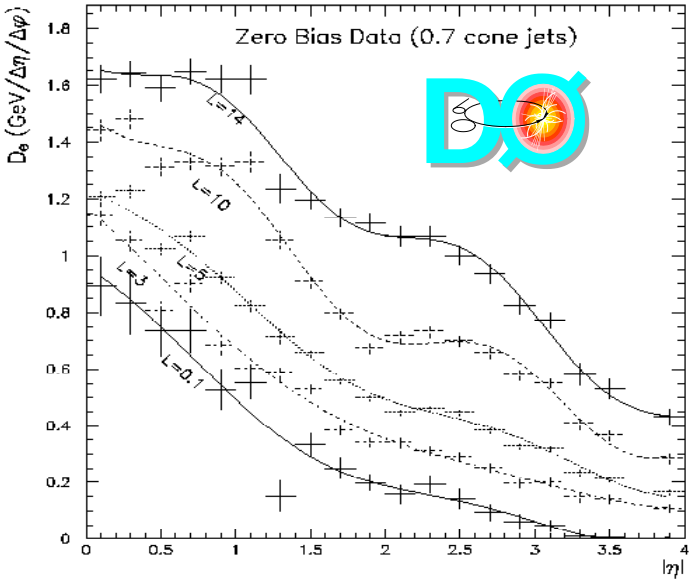
Uses expectations from the average Et flow for a given instantaneous luminosity

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)

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

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

Note that magnitude of correction depends on calorimeter signal processing!

Data Driven JES Corrections (2)

P. Loch
U of Arizona
Aug. 27, 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)

P. Loch
U of Arizona
Aug. 27, 2009

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

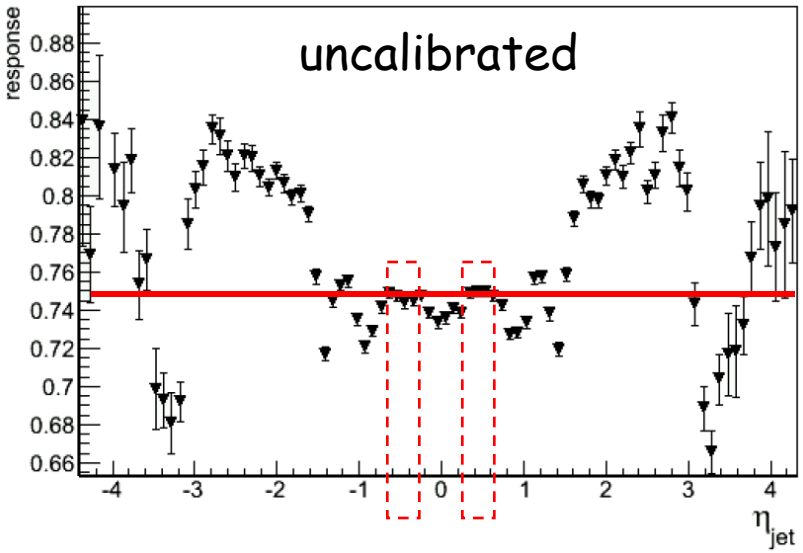
Remarks:

- 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

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



Jet Mass Sensitivity

P. Loch
U of Arizona
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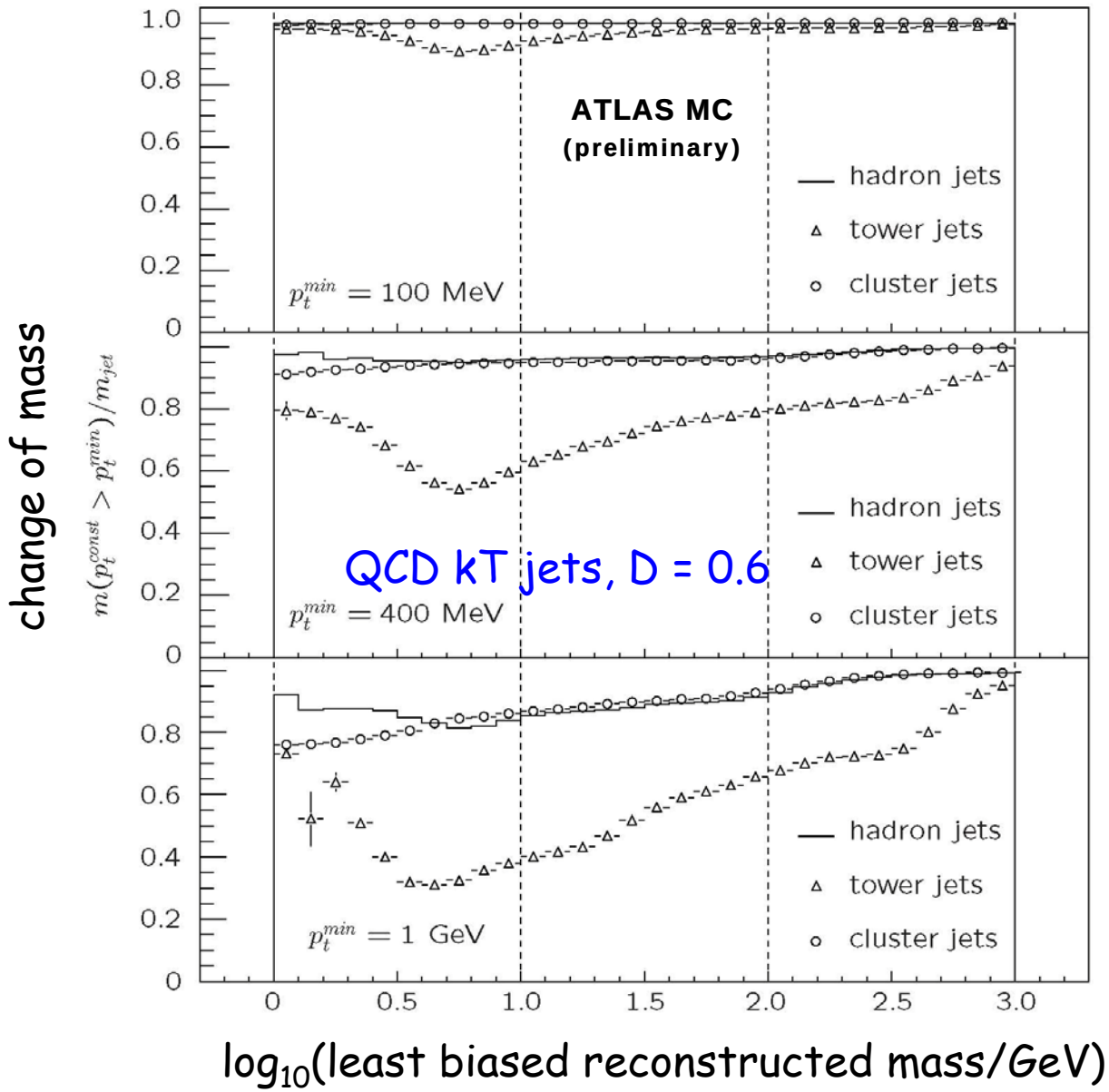

Jet Composition

P. Loch
U of Arizona
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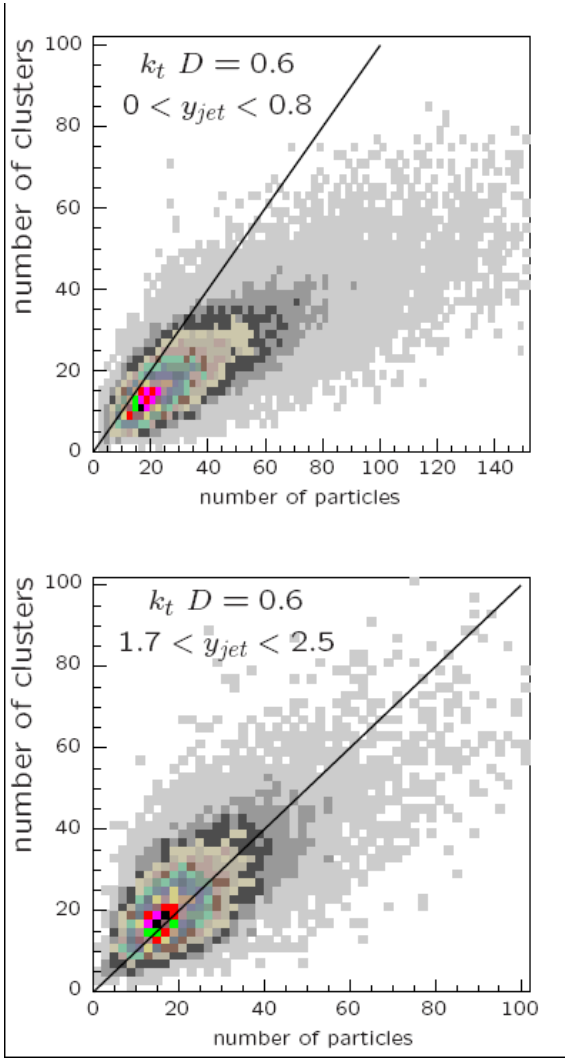
We expected clusters to represent individual particles

- 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

Jet Substructure

Mass too complex?

- Can be too sensitive to small signals in jets
  - UE, pile-up, other noise

Use YSplitter to detect substructure

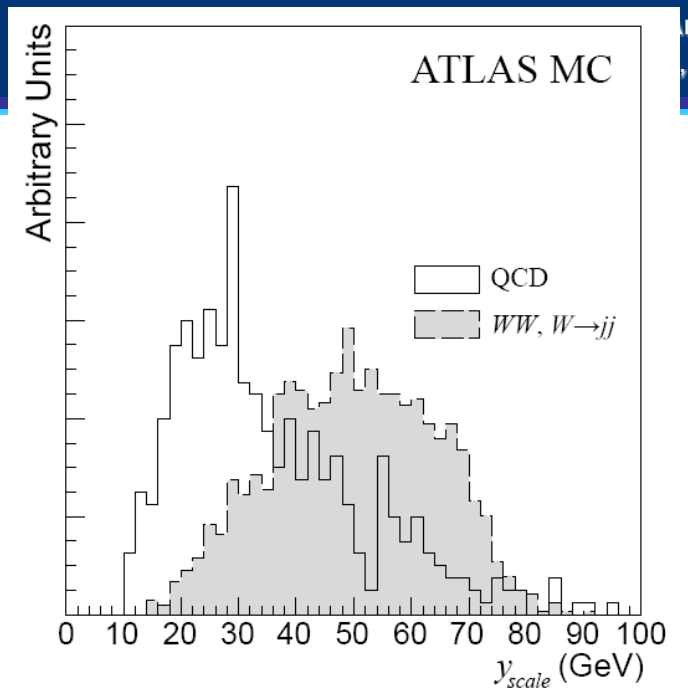
- Determines scale y for splitting a giving jet into 2,3,… subjects, as determined by y_{cut}, from

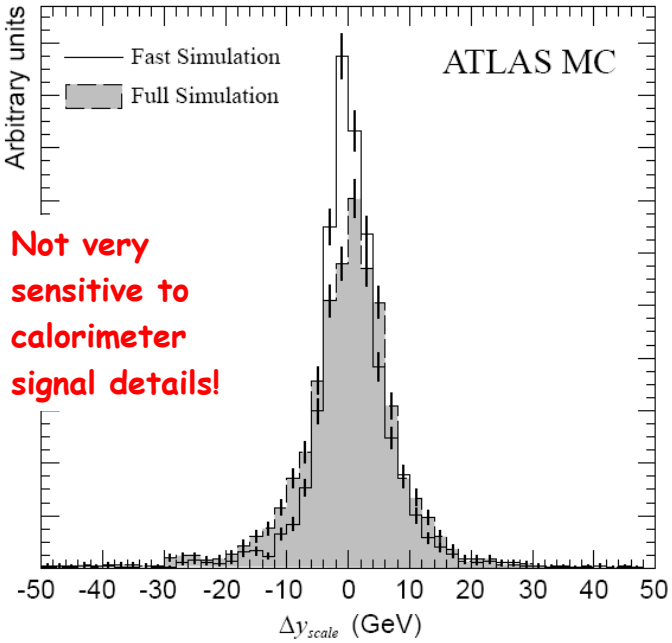
$$y = \sqrt{y_{cut}} \times p_T^{jet}$$

- More stable as only significant constituents are used ?
- At least additional information to mass

Other option:

- Look at mass of 2…n hardest constituents (Ben Lillie,ANL)





Not very sensitive to calorimeter signal details!