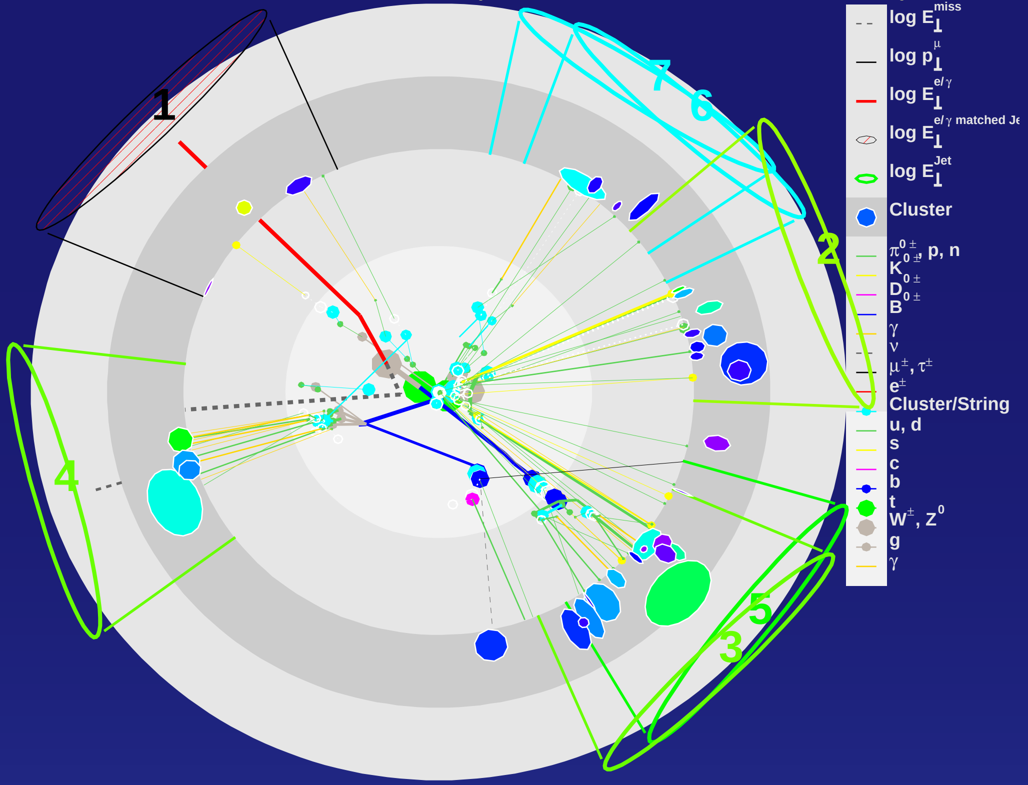
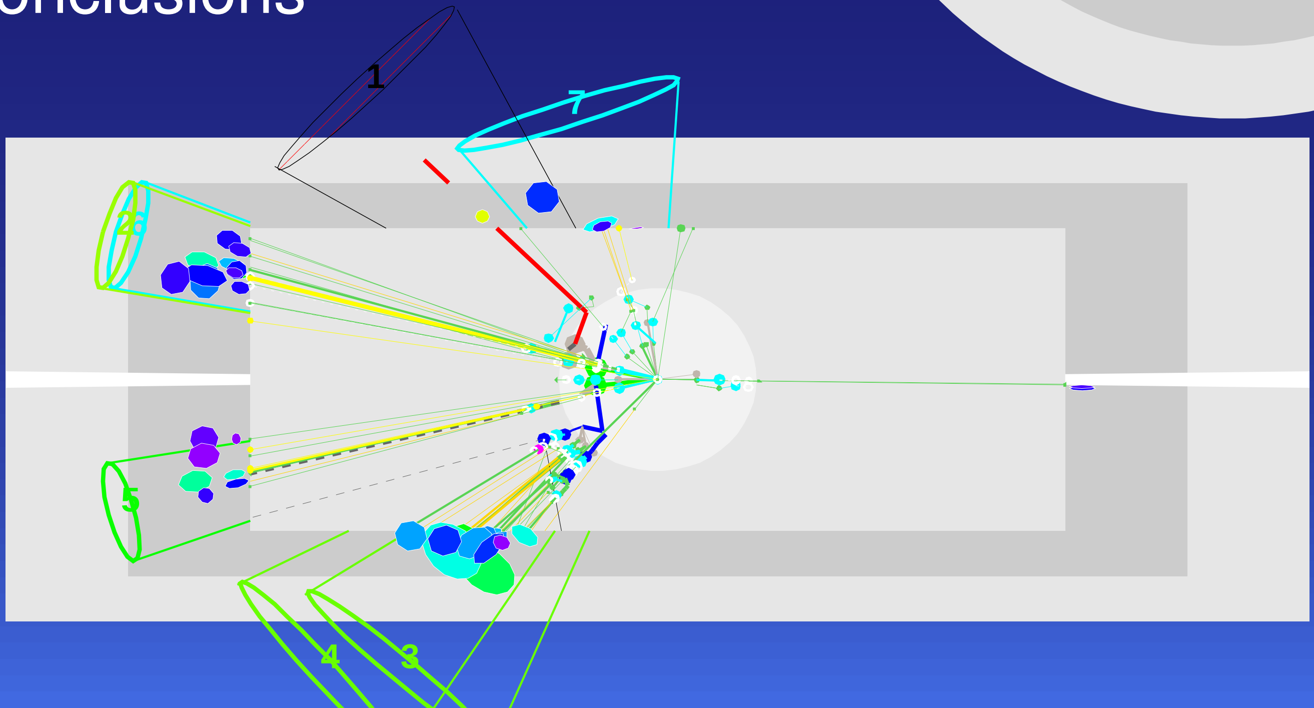
Determination of the Jet Energy Scale

Hadron Collider Physics Symposium   Sven Menke, MPI München   24. May 2007, Isola d'Elba, Italy

- ► Introduction
- ► Jets
- ► Calibration Approaches
- ► Calibration to Particle Level
- ► Calibration to Parton Level
- ► Uncertainties
- ► Conclusions



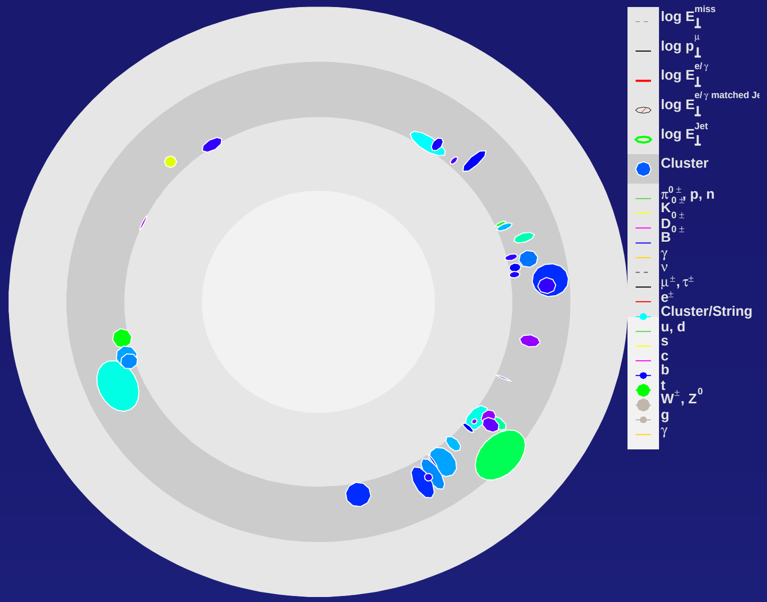


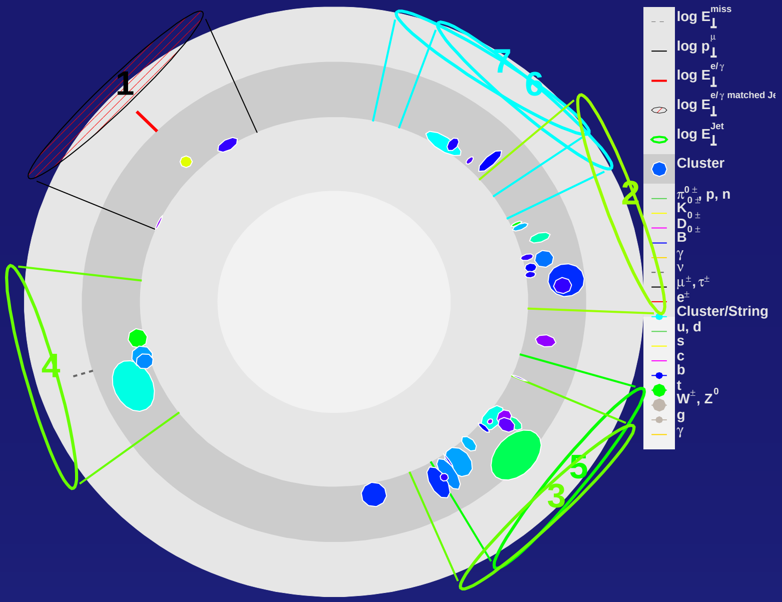
►

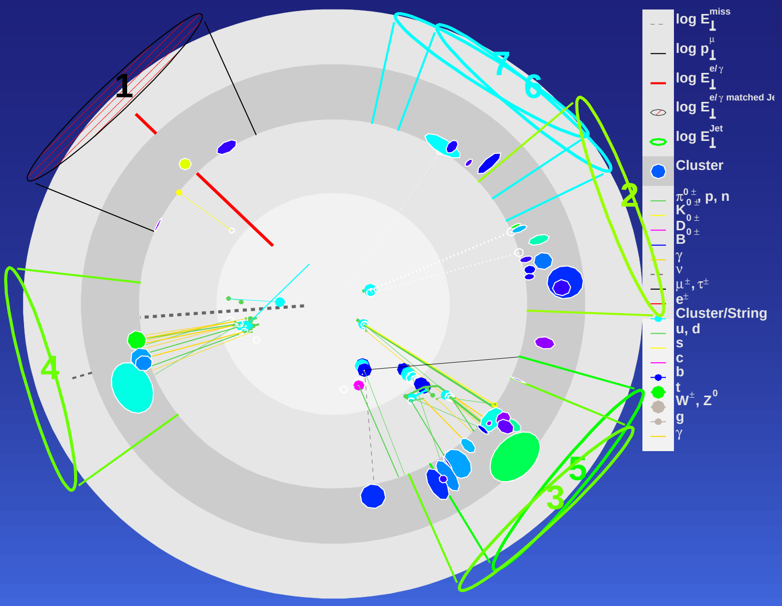
Introduction

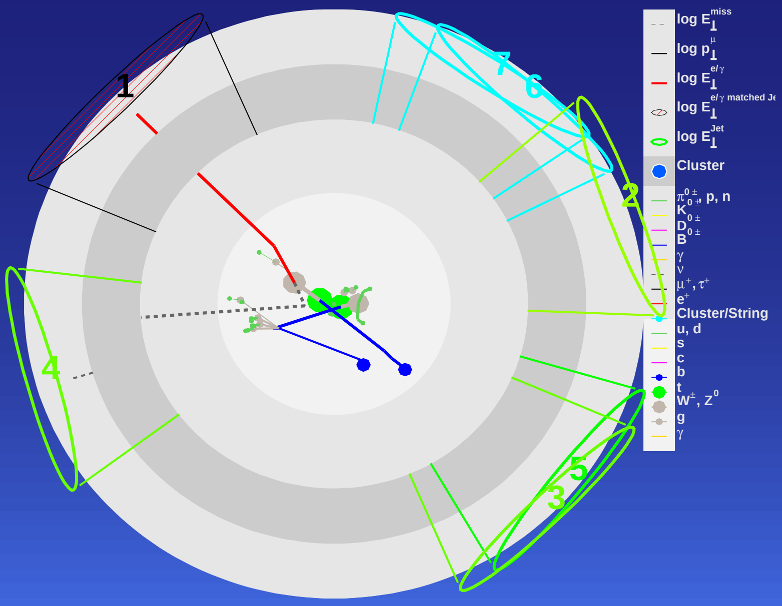
- Jet energy calibration can be divided in 4 steps

1. calorimeter tower/cluster reconstruction
2. jet making
3. jet calibration from calorimeter to particle scale
4. jet calibration from particle scale to the parton scale



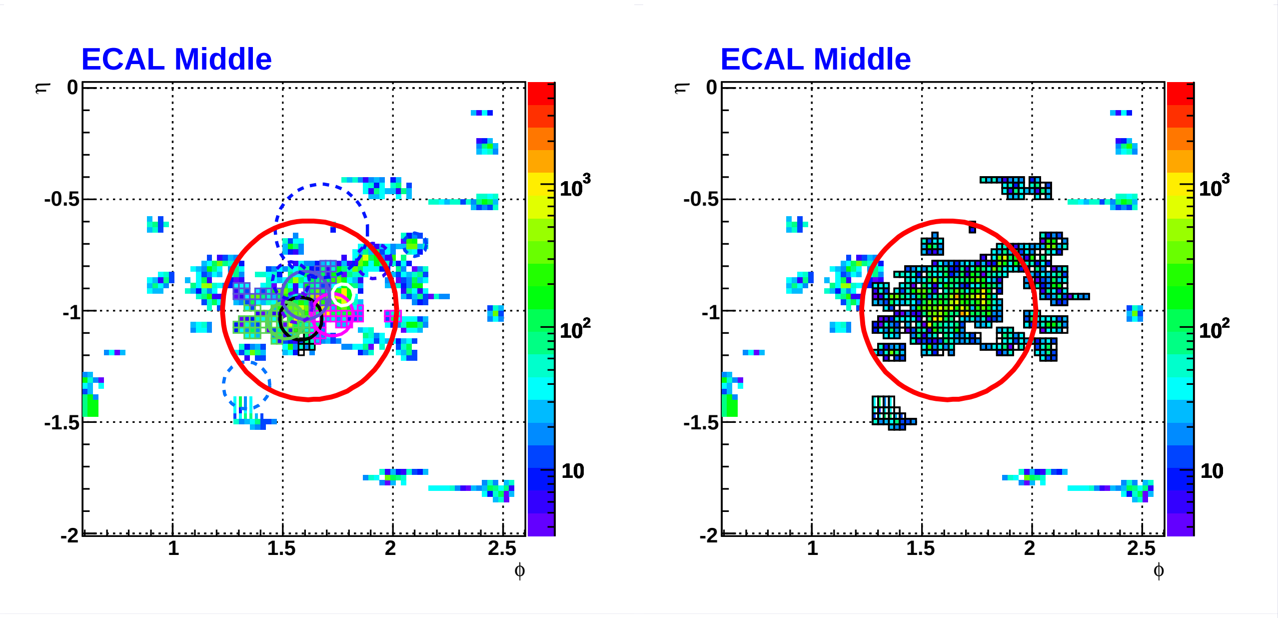


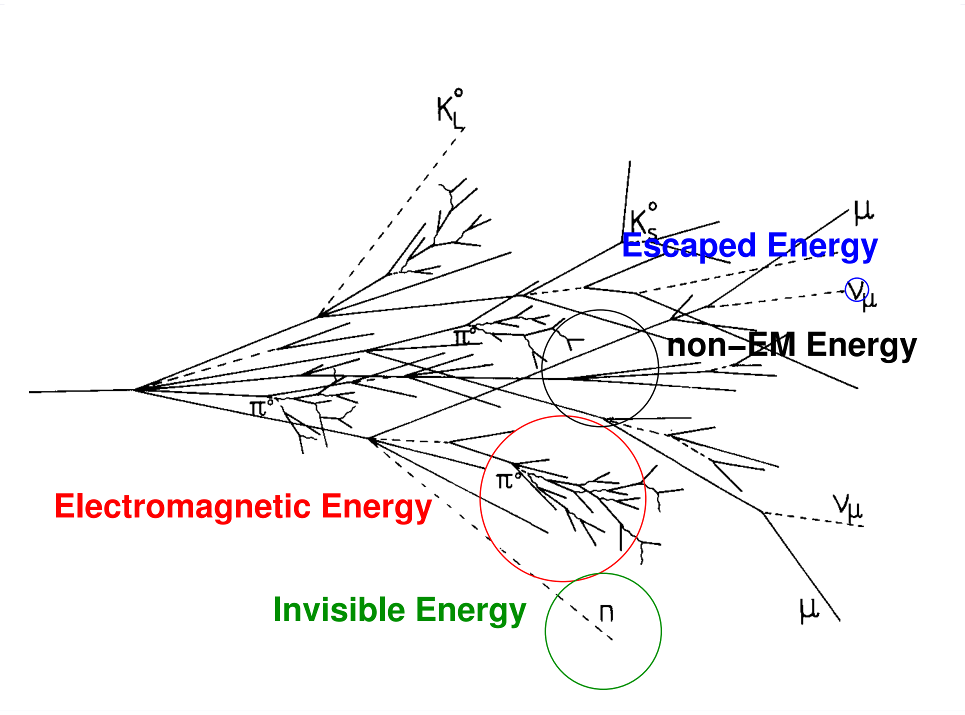




Experimental Challenges

- Calorimeter Cluster Reconstruction
  - shower containment
  - particle separation and identification
  - electronics noise
  - pile-up
- Jet Making
  - choice of input (cells, towers, clusters, proto-jets, . . .)
  - choice of algorithm (cone, $K_\perp$, . . .)
  - jet size
  - overlap with electrons
- Jet Calibration to Particle Level
  - e/h compensation
  - dead material corrections
  - out-of-cluster corrections
  - out-of-jet corrections
- Jet Calibration to Parton Level
  - match to parton jet
  - differences for light-quark, b-quark, gluon-jets
  - MC dependencies

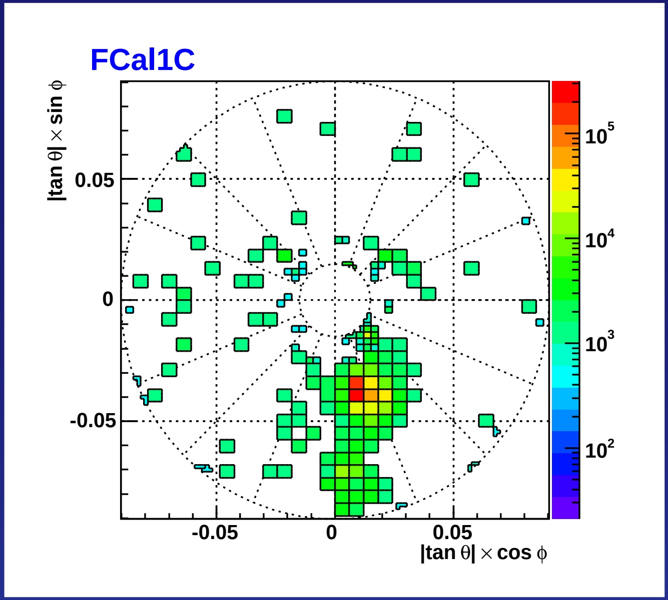




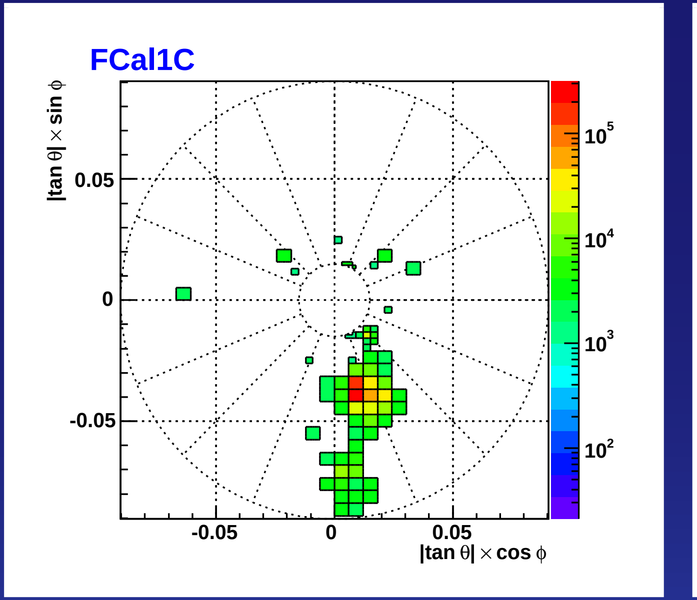
Topological Clusters (ATLAS) ► Example

- look at di-jet MC sample including electronics noise with activity in the forward region
- plots show $|E_{\mathrm{cell}}|$ on a color coded log-scale in MeV in the first (EM) FCal sampling for one event

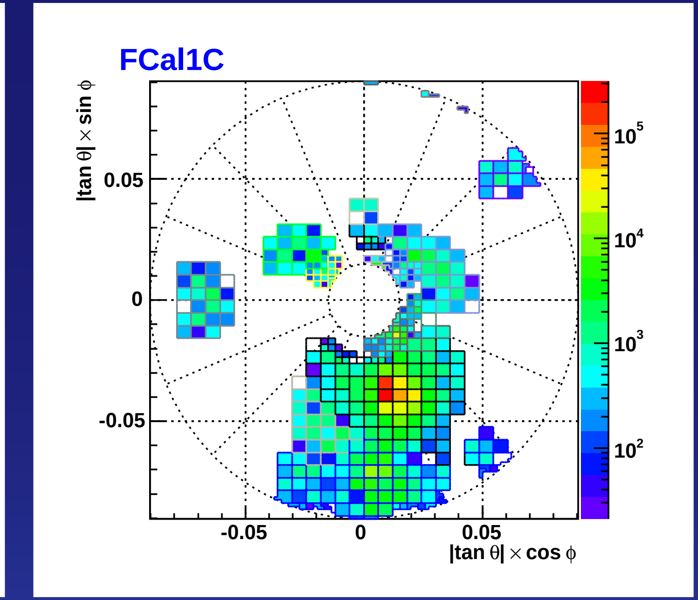
$|E| > 2\,\sigma_{\mathrm{noise}}$



$|E| > 4\,\sigma_{\mathrm{noise}}$



4/2/0 topological clusters



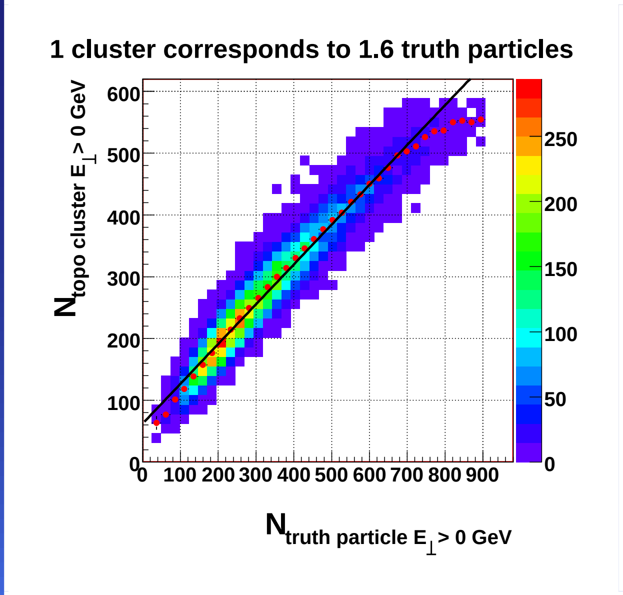
- $2\,\sigma$ cut is removing cells from the signal region
- $4\,\sigma$ cut shows seeds for the cluster maker
- after clustering all cells in the signal regions are kept
- cluster splitter finds hot spots

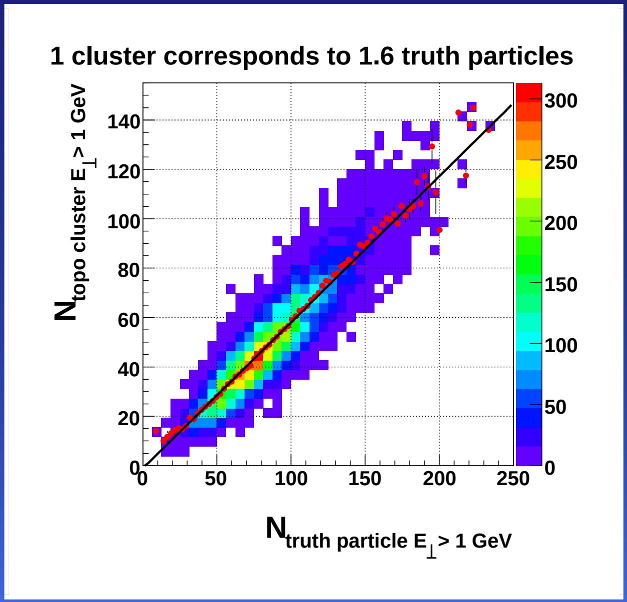
Jets

- Jets are
  - a collection of 4-vectors based on tracks and/or calorimeter objects (cells or towers or clusters)
  - defined by a metric on 4-vector level
  - the easiest reference level to base particle level calibration or monitoring of calibration on although in some cases the constituents are the objects being calibrated
  - receiving the final parton level calibration
  - used for physics studies
- in use are:
  - seeded/seedless cone algorithms with split and merge and cells, towers, or clusters as input for $R = 0.4 – 1.0$ with seed cuts of typically 1 or $2\,\mathrm{GeV}$ in $E_\perp$
  - the $\mathrm{K}_\perp$ algorithm (FastKt) with towers or clusters as input (no pre-clustering) for $R = 0.4 – 1.0$
  - typically an $E_\perp$ cut of $5 – 10\,\mathrm{GeV}$ on the final jets

Jet Input

- Pro’s & Con’s of towers and clusters as jet input
- Towers
  - + have always the same fixed size $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
  - + have no seed – all cells end up in towers
  - − do not provide noise or pile-up suppression
  - − do not contain showers
- Clusters
  - + provide efficient noise and pile-up suppression
  - + optimized to contain showers of individual hadrons
  - − typically have detector region dependent size $r \sim 0.1 - 0.2$


1 cluster corresponds to 1.6 truth particles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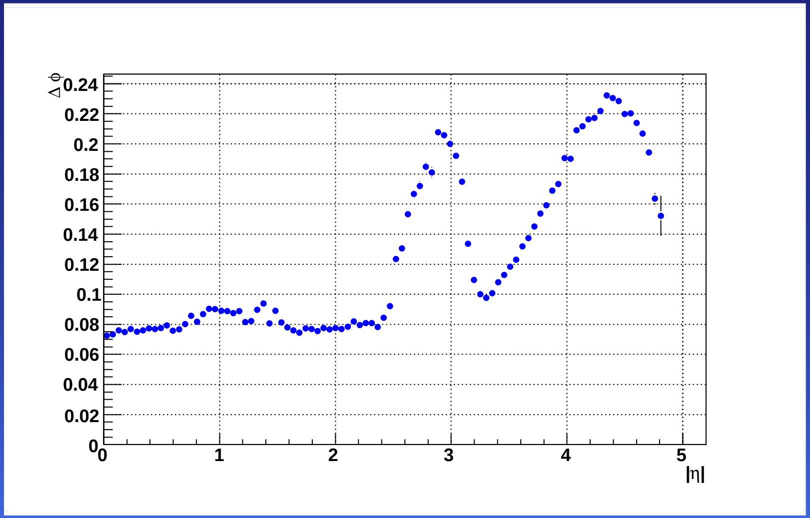


Calibration Approaches

- Global Jet Calibration
  - use towers or clusters on EM-scale as input to jets
  - match a truth particle jet with each reco jet
  - fit a calibration function in η, E to all matched jet pairs
- Local Hadron Calibration
  - calibrate clusters independent of any jet algorithm to individual particle scale
  - make jets out of calibrated clusters
- Hadronic Scale
  - from single isolated hadrons in test-beam, minimum bias events and τ decays (E/p-ratio)
  - tune simulation to describe reco jet level and map to corresponding truth particle jet
- Non Uniformity in η
  - from di-jet events
- Final In-situ Calibration
  - with W-mass in $\mathrm{t\bar{t}} \to \mathrm{Wb\,Wb} \to \mathrm{l}\nu j_{\mathrm{b}}\, jjj_{\mathrm{b}}$
  - with $p_\perp$ balance in $\mathrm{Z}/\gamma + \mathrm{jet}$

Calibration Approaches ► Tevatron

CDF Jet Calibration

- seeded iterative cone jets with split/merge made of towers
- Midpoint and $K_\perp$ also used and corrected in similar manner
- $p_\perp = (p_\perp^{\mathrm{raw}} \times C_\eta - C_{\mathrm{MI}}) \times C_{\mathrm{Abs}}$
- correct with C_η for non-uniformity in η
- remove offset C_{MI} due to pile-up of multiple interactions
- absolute correction C_{Abs} from simulation corrects to particle level
- $p_\perp^{\mathrm{parton}} = p_\perp - C_{\mathrm{UE}} + C_{\mathrm{OOC}}$
- remove offset C_{UE} from the underlying event
- correction for particles radiated out of the jet cone C_{OOC}
- mainly simulation (GFlash for detector response) driven with tuned Monte Carlo to describe data (lots of validation samples)

D0 Jet Calibration

- seeded iterative tower cone jets with midpoints and split/merge
- $E = (E^{\mathrm{raw}} - O) \times F_\eta^{-1} \times R^{-1} \times S^{-1}$
- remove offset O due to noise and pile-up
- correct with F_η for non-uniformity in η
- absolute response correction R from $\gamma + \mathrm{jet}$
- showering correction S corrects for out-of-cone effects
- no parton-scale calibration
- mainly in-situ driven with different corrections for data and simulation

Calibration Approaches ► LHC

CMS Jet Calibration

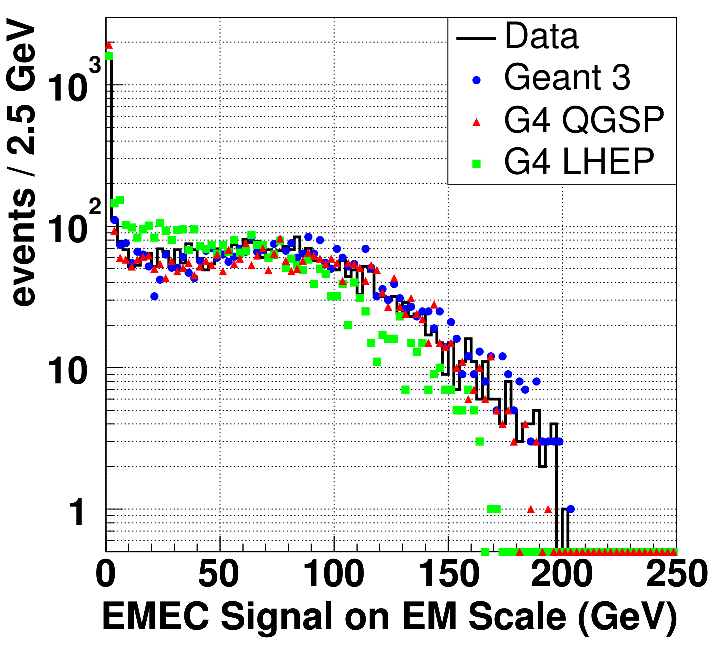
- iterative cone jets without split/merge made of towers
- cone with midpoints and split/merge and Fast$K_\perp$ also in use
- wants to adopt factorization approach like Tevatron and abandon ”monolithic” correction functions
- remove offset O due to pile-up and residual noise
- flatten response in η with di-jet events
- find absolute scale from test-beam tuned simulations, later from data (isolated charged pions, $\mathrm{Z}/\gamma + \mathrm{jet}$, t-mass, W-mass)
- optional corrections to parton level:
- flavor dependency
- underlying event
- out-of-cone

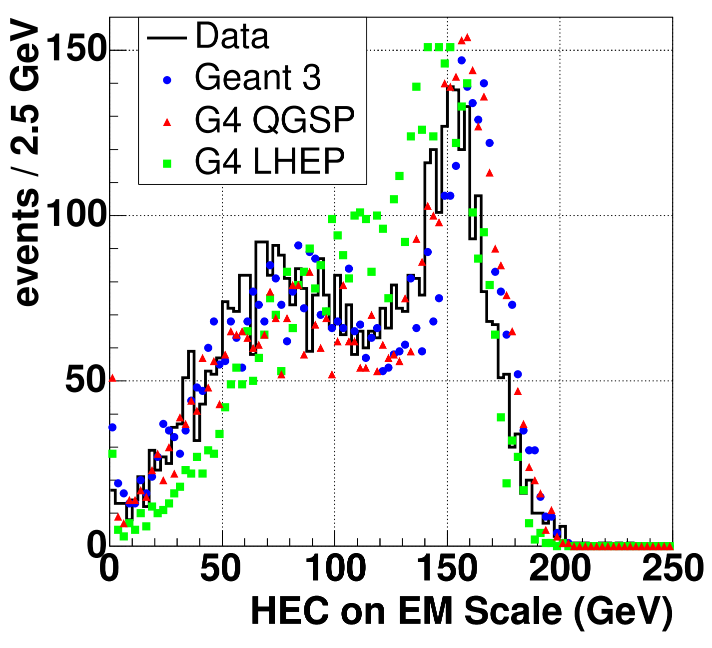
ATLAS Jet Calibration

- seeded iterative cone jets with split/merge made of towers/clusters
- or inclusive $K_\perp$-jets made of towers/clusters
- global truth-match based jet correction function from di-jets on cell or sampling level
- or factorized local hadron calibration of clusters to individual particle level plus jet-based correction to particle level
- final parton-level corrections from in-situ calibration

Calibration to Particle Level ► Response to Single Particles

- Response to single particles (pions, electrons) in test beam
  - important ingredient for all experiments
  - essential to establish confidence in Simulation
  - for LHC tuning of Geant4 hadronic simulation (physics lists) is a major task
- Plots show response to 200 GeV pions in ATLAS Endcap test beam (2002)
  - upper plot shows EM Endcap Calorimeter
  - lower plot shows Hadronic Endcap Calorimeter
  - Geant3 and Geant4 QGSP describe data reasonably well
  - Geant4 LHEP deviates substantially
  - validation need for every new Geant4 release
  - improvements in modified QGSP physics lists (Bertini, Birk's law) possible





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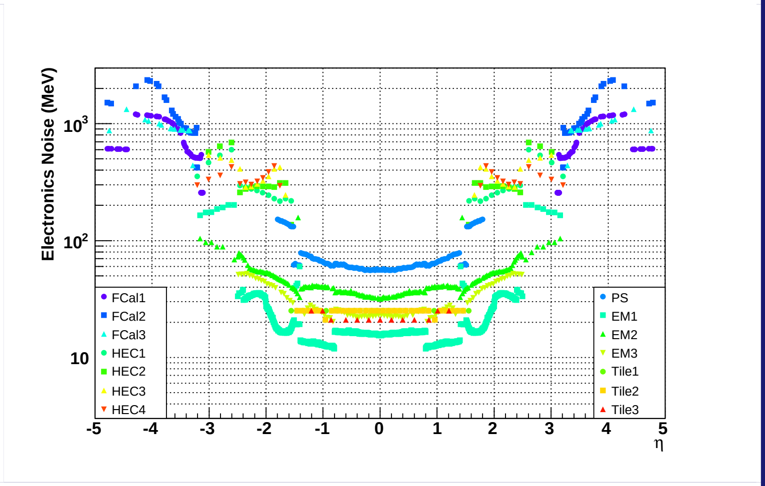
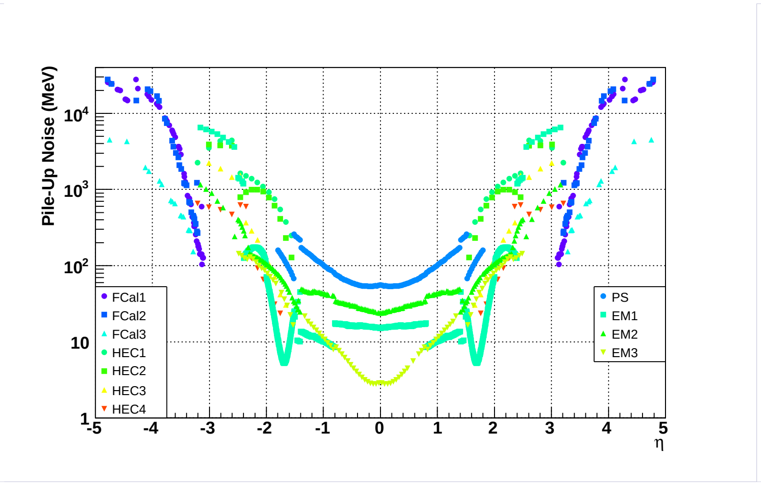
Calibration to Particle Level ► Noise and Pile-Up Offset

ATLAS Electronics Noise per Cell

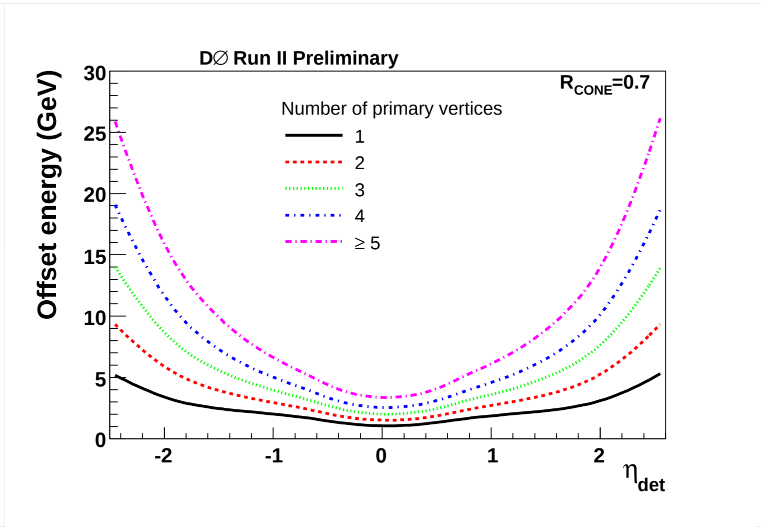


ATLAS Pile-Up Noise per Cell ($N_{\mathrm{MB}} = 23$)



- ► Effects from Zero suppression
  - Noise RMS is larger inside than outside jets
  - Noise Mean is biased even for cuts on $|E|$ in the presence of small signals
- ► Pile-Up Effects
  - Multiple Interactions and in-time Pile-Up look just like signal ► not suppressed
  - Pile-Up from other bunch crossings can lead to negative signals
- ► Corrections
  - Measure η, jet-size and #-Vertices dependent offset from minimum bias events without Zero suppression
  - Uncertainty typically $10 - 15\,\%$ (CDF,D0) from residual luminosity dependency

D0 Run II Offset for Cone-Jet ($R = 0.7$)

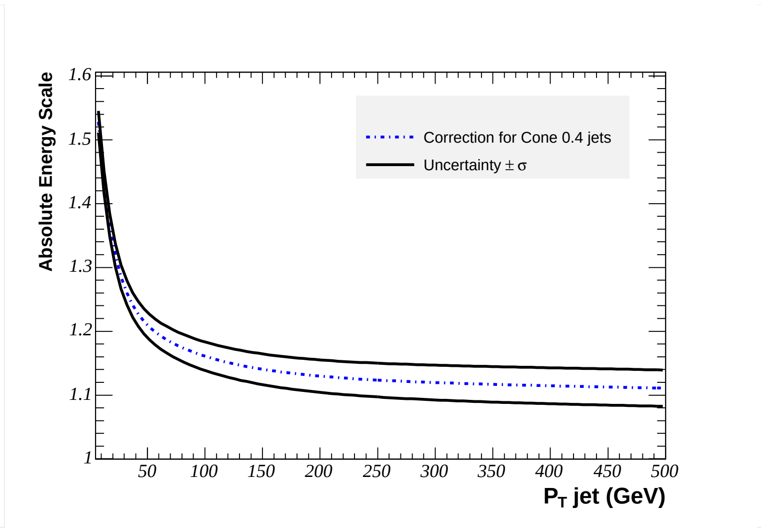


www-d0.fnal.gov/phys.id/jes/public/plots_v7.1

Calibration to Particle Level ► Compensation

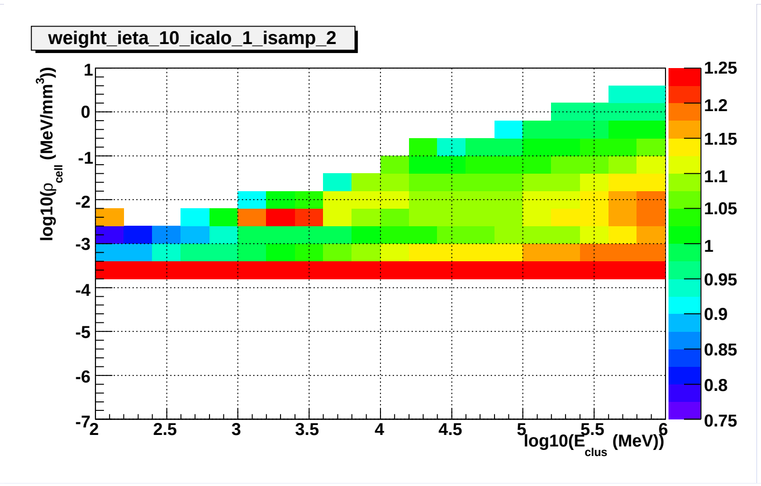
- Absolute Scale correction with truth match (CDF, CMS, ATLAS)
  - tune di-jet simulation such that fragmentation, particle densities and particle spectra describe data for all $p_\perp$ in well understood η-areas
  - match truth particle and reco jets and fit calibration function(s) on cell-level (in $E_\text{cell} / V_\text{cell}$), and jet-level (in E, η) (ATLAS) or jet-level only (in $p_\perp$) (CDF, CMS)
- Local Hadron Calibration (ATLAS)
  - simulate single pions with detailed info about lost and invisible energy in active and in-active material
  - compute cell weights as averaged ratio: $w_\text{cell} = \langle (E_\text{active} + E_\text{in-active}) / E_\text{cell} \rangle$ in $E_\text{cluster}, E_\text{cell} / V_\text{cell}, \eta$
  - classify (small) $3D$-energy blobs (clusters) as em or hadronic and apply weights to hadronic clusters
- Hadronic Recoil (MPF-method) in $\gamma +$ jet-events (D0)
  - assume $p_\perp$ balance in selected $\gamma +$ jet-events
  - measure Missing $E_\perp$ Projection Fraction in $\gamma +$ jet: $R = 1 + \frac{\vec{\not{E}}_\perp \vec{p}_\perp^{\,\gamma}}{|p_\perp^\gamma|^2}$
  - back to back topology: $R_\text{had} \simeq R_\text{jet}$

CDF Absolute Energy Scale for Cone-Jet ($R = 0.4$)



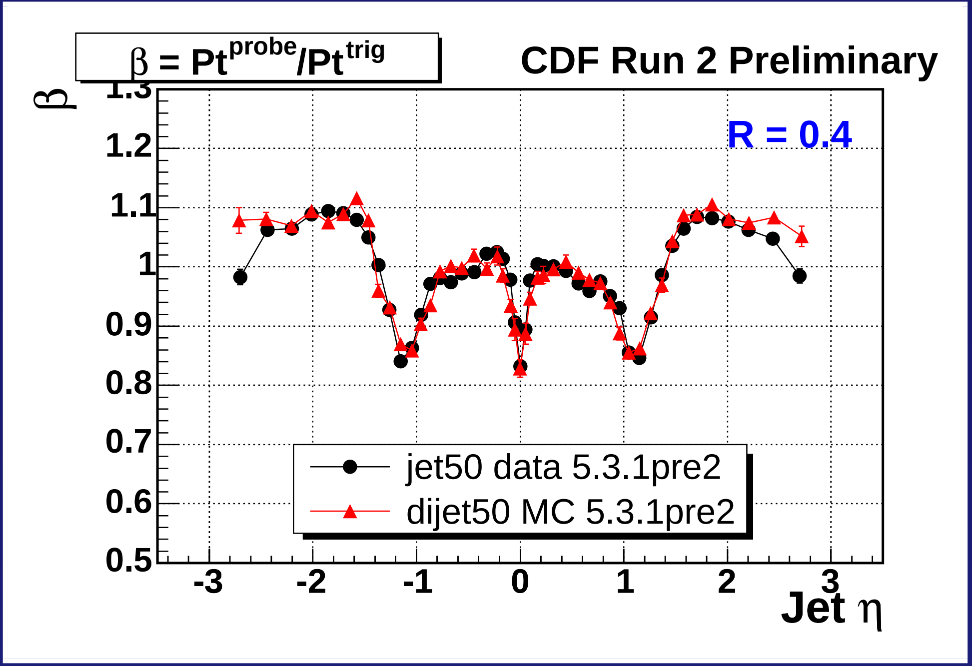
www-cdf.fnal.gov/physics/new/top/2004/jets/cdfpublic.html

ATLAS Local Hadron Calibration Weights (EM Endcap)



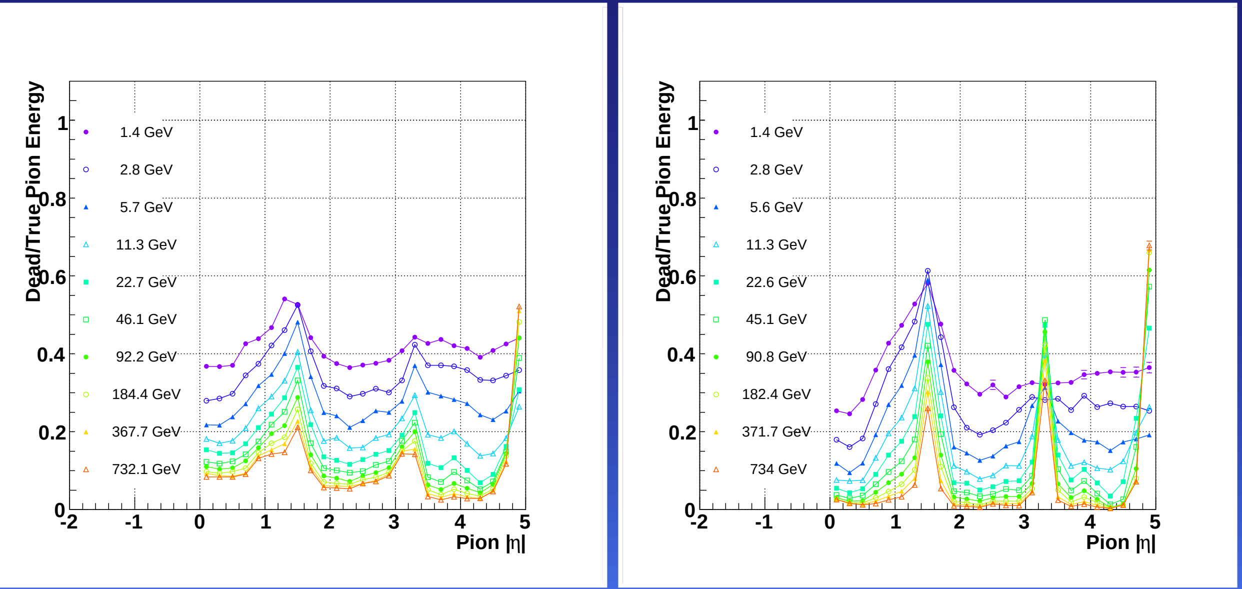
Calibration to Particle Level ► Dead Material Corrections

CDF Di-Jet Balance for Cone-Jet ($R = 0.4$)



www-cdf.fnal.gov/physics/new/top/2004/jets/cdfpublic.html

ATLAS Dead Material Fraction for $\pi^{\pm}$ (left), (π^{0}) (right)



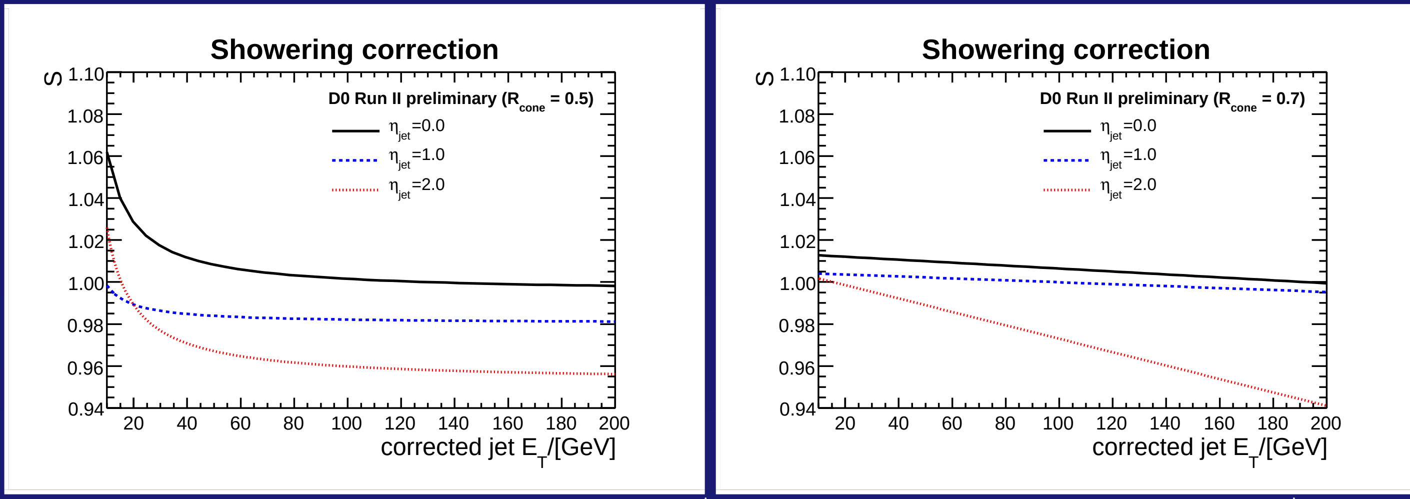
G. Pospelov et al.

- Relative η Correction on Jet Level with di-jet events:
  - implicit in fitted weights and special dead-material terms ($E_{\mathrm{cryo}} \sim \sqrt{E_{\mathrm{EM3}} E_{\mathrm{Tile1}}}$) from simulation (ATLAS)
  - or explicit from $p_{\perp}^{\mathrm{probe}} / p_{\perp}^{\mathrm{trig}}$ in simulation and data (CDF, CMS)
  - or from MPF-method separately for data and MC (D0, CMS)
- Local Hadron Calibration (ATLAS)
  - different corrections for clusters classified as em and hadronic from single $\pi^{\pm}$, π^{0} simulations again with geometrical mean of surrounding energy

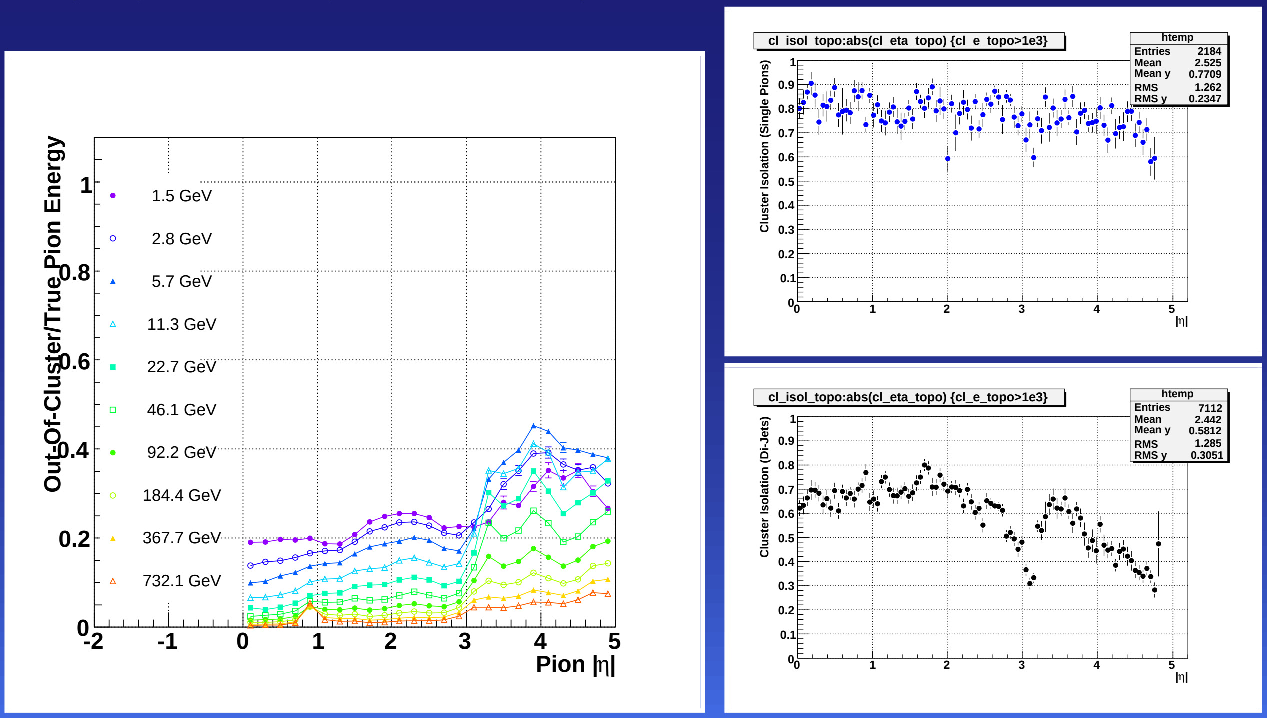
Calibration to Particle Level ► Shower Corrections

- Jet Level Corrections
  - implicit in Particle-level Corrections (CDF, ATLAS) see slide 12
  - explicit to separate detector effects from physics from ratio of out-of-jet energy in reco jets over out-of-jet energy in simulated truth particle jets in $\gamma + 1$jet (D0)
- Local Hadron Calibration (ATLAS)
  - calculate cluster isolation on cell level
  - correct clusters by fraction of isolation times predicted out-of-cluster energy from simulated single pions

D0 Showering Correction from $\gamma + 1$jet for Cone-Jet $R = 0.5$ (left), $R = 0.7$ (right) www-d0.fnal.gov/phys_id/jes/public/plots_v7.1

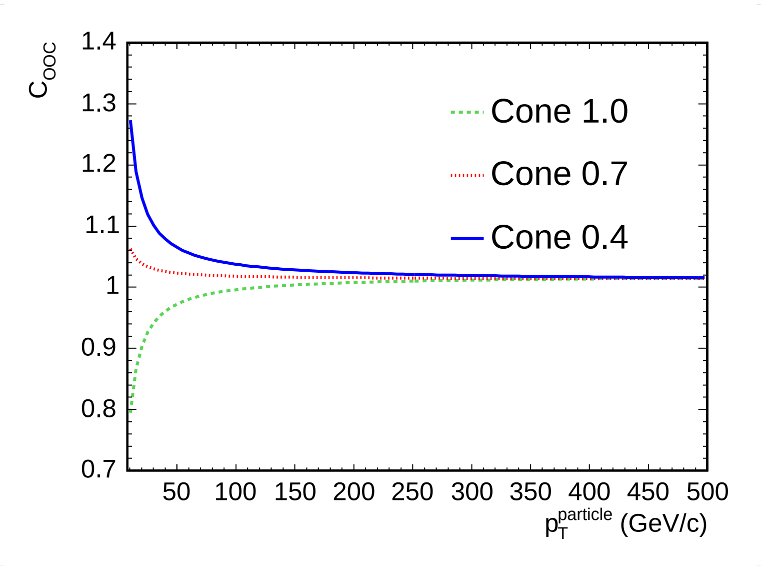


ATLAS Out-Of-Cluster Fraction for $\pi^\pm$ (left), Isolation of clusters for $\pi^\pm$ (top-right) and di-jets (bottom-right)



Calibration to Parton Level ► Out-Of-Cone

CDF Out-Of-Cone Correction for Cone-Jet ($R = 0.4, 0.7, 1.0$)



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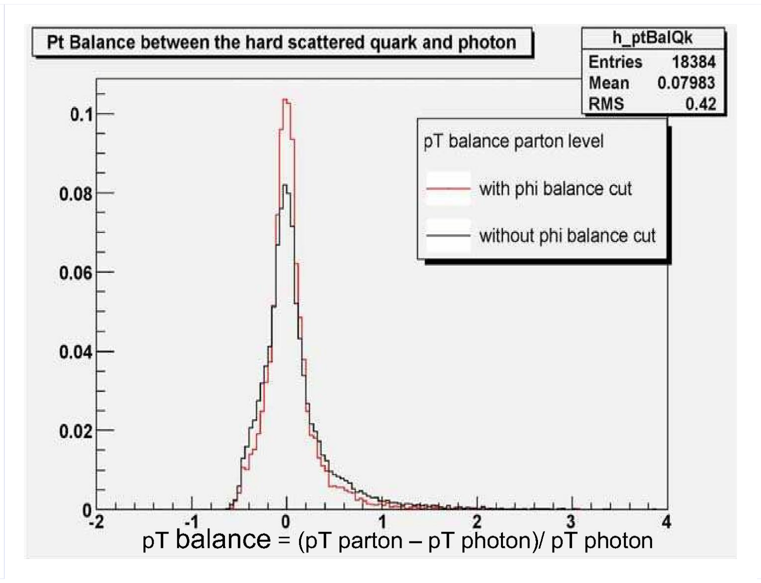
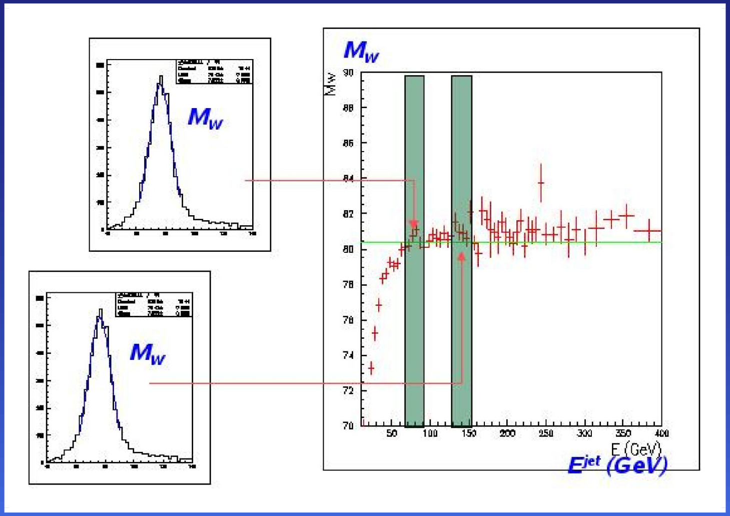
ATLAS $p_\perp$-balance in $\gamma + $ jet



S. Jorgensen et al.

- ► Global Out-Of-Cone Correction to Parton-Level
  - match hard parton to particle jet in di-jet events (simulation) including effects of gluon radiation, fragmentation, hadronization, and cone size (CDF)
  - $p_\perp^{\rm jet}/p_\perp^{\gamma}$ ratio in $\gamma + $ jet events with hard back-to-back and 2nd jet energy cuts (CMS, ATLAS)
- ► In-situ methods from top-mass or W-mass and more
  - template methods with smeared parton distributions to describe data
  - rescaling methods with mass constraints on corrected jets
  - validation of all previous corrections with data

ATLAS m_W-rescaling method

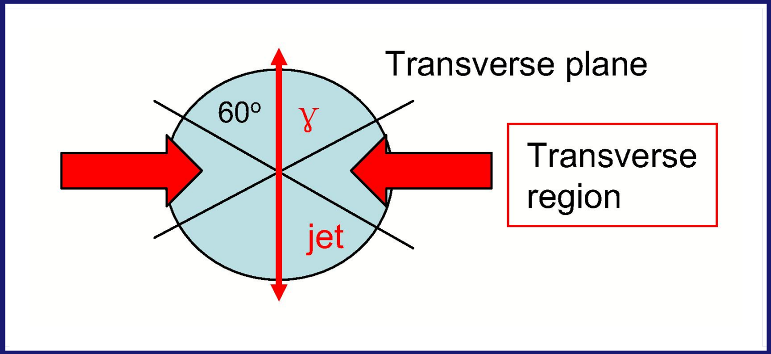


D. Pallin et al.

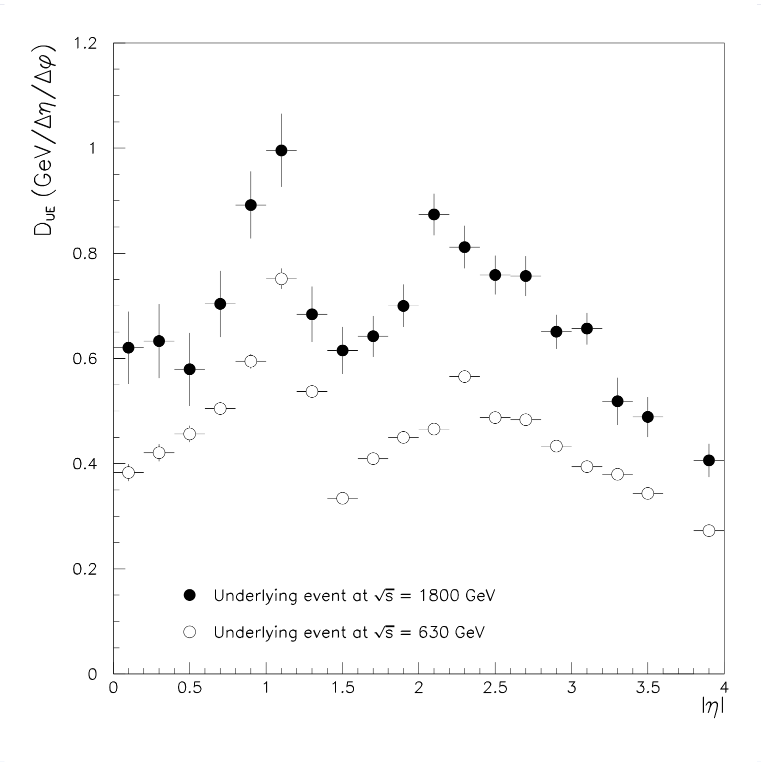
Calibration to Parton Level ► Underlying Event

- In-Situ Measurement of Underlying Event
  - Measure activity in "transverse region" $60^\circ < \Delta\phi < 120^\circ$
  - data-MonteCarlo differences o.k. for `Pythia`, 30% for `Herwig` (CDF)
- Average correction of Underlying Event
  - $\langle E_\perp \rangle$-content in Random Cone for min-bias events - zero-bias events

Transverse region



D0 $E_\perp$-density (per $\Delta\eta \times \Delta\phi$)



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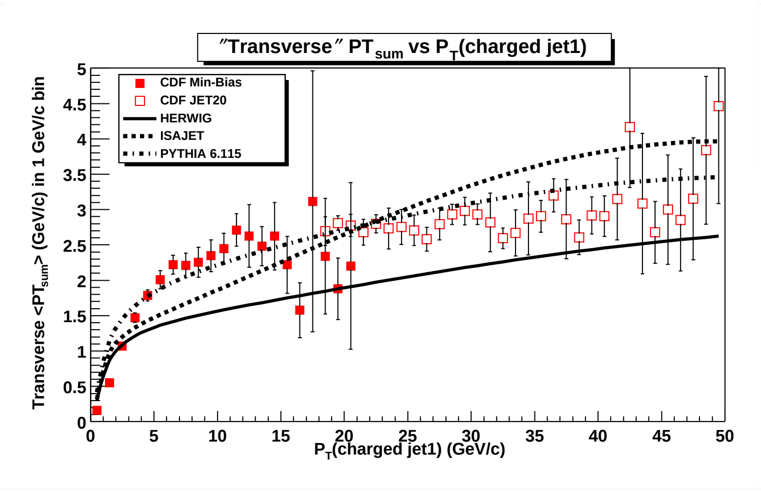
CDF Transverse $p_\perp$-sum



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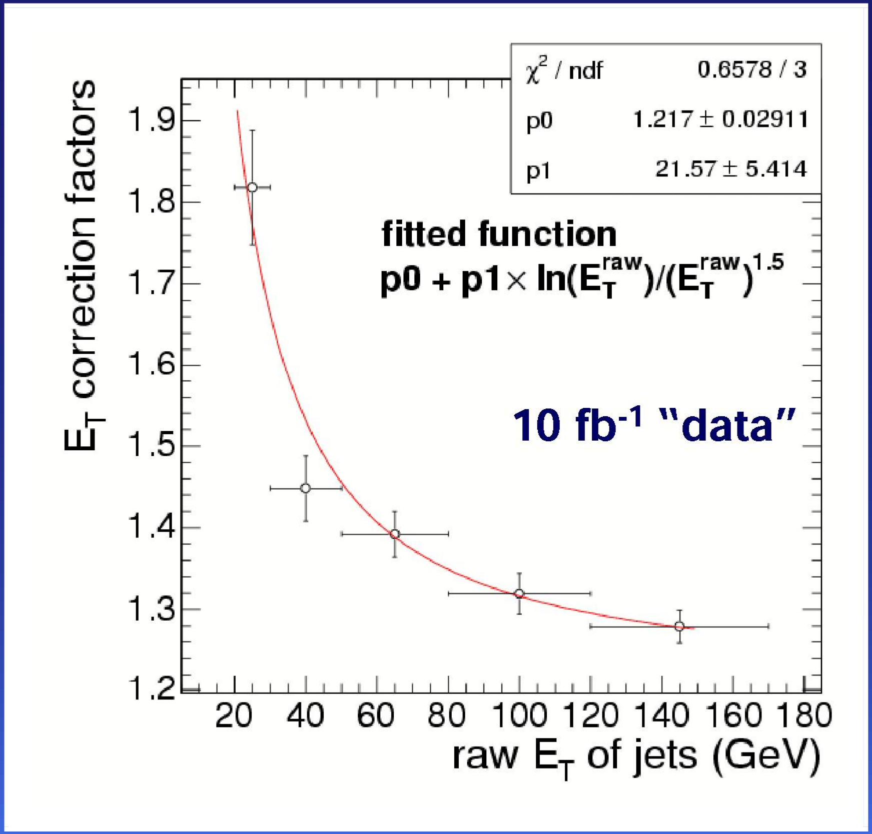
Calibration to Parton Level ► Flavor

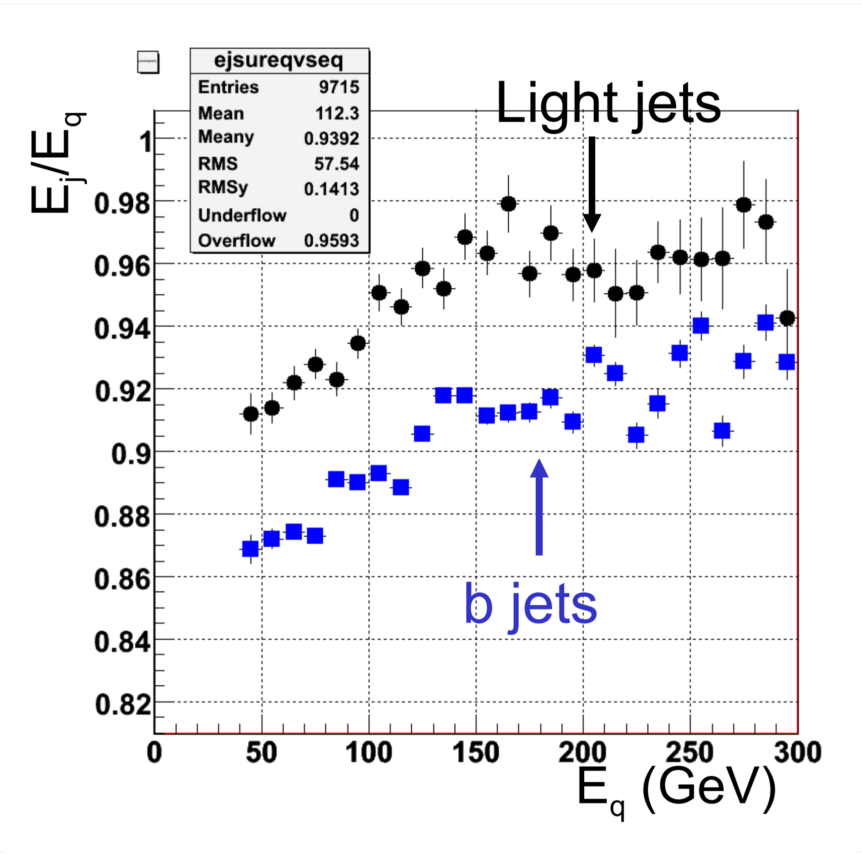
- b-jet energy corrections from bbZ, Z $\rightarrow \ell\ell$ (CMS)
  - separate correction function for b-jets (CMS)
- additional correction on top of light jet corrections
  - taken directly from simulation (e.g. top events)
  - or from top-mass (rescaling or templates)
  - or $p_\perp$ balance in Z $+$ b-jet

CMS b-jet correction from bbZ



A. Nikitenko et al.

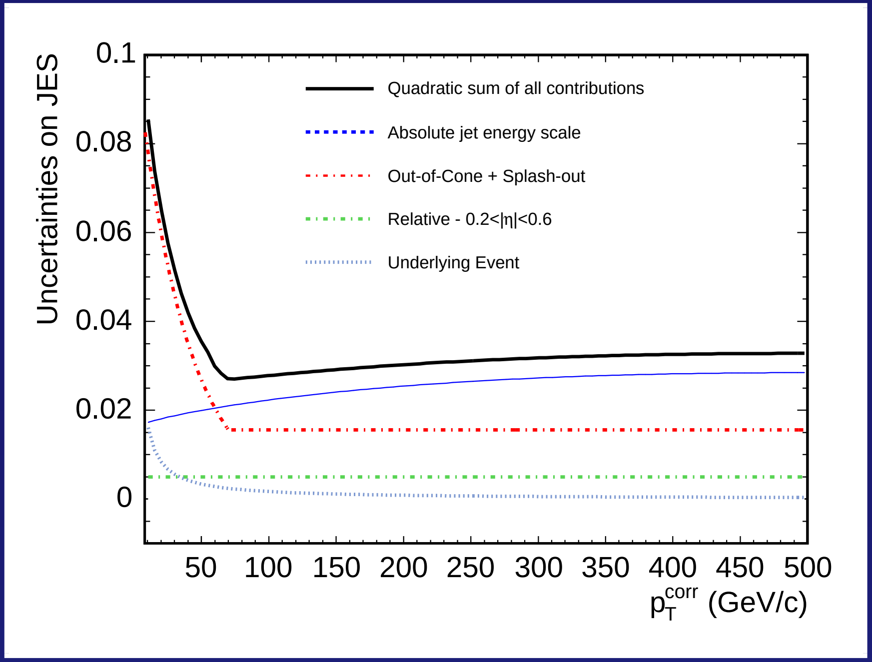
ATLAS b-jet scale on-top of light-jet-scale in top-events



J. Schwindling et al.

Uncertainties

CDF Uncertainty on JES up to parton-level ($R = 0.4$)



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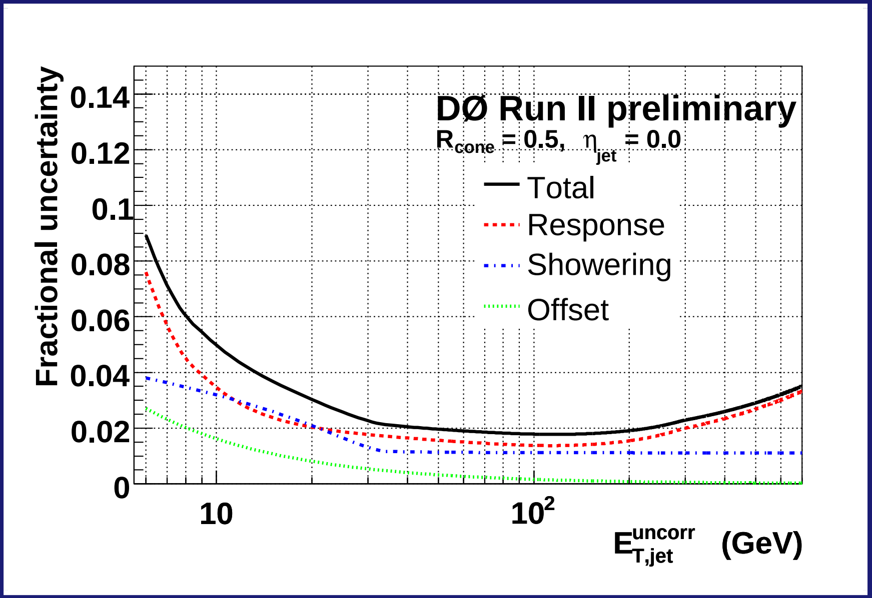
D0 Uncertainty on JES up to particle-level ($R = 0.5$)

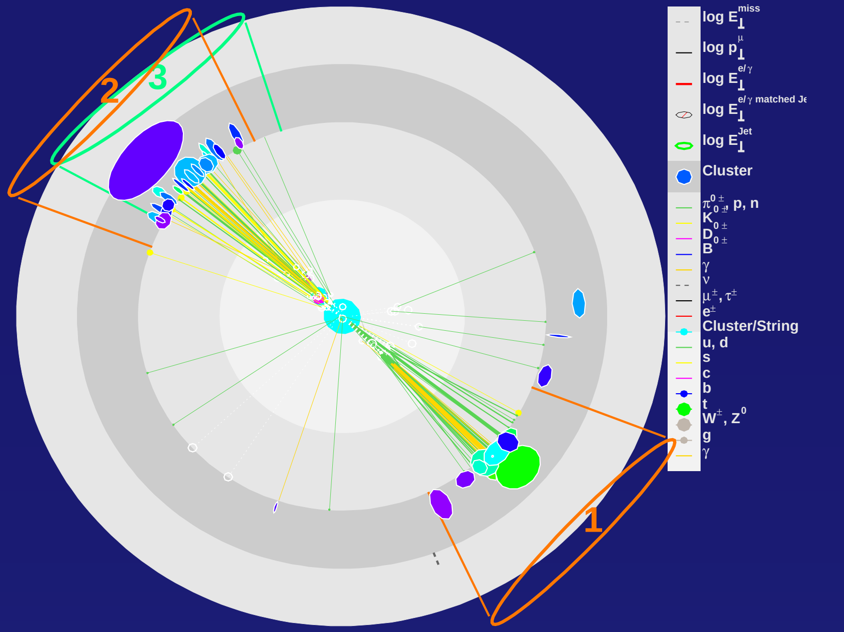


www-d0.fnal.gov/phys-id/jes/public/plots.v7.1

- CDF: Absolute jet scale; D0: Response
  - dominates at high $p_\perp$ (statistics limited; high $p_\perp$ single particles (CDF); γ + jet (D0))
- CDF: Out-Of-Cone; D0: Showering
  - dominates at low $p_\perp$ (understanding simulation, getting low energetic single particles)
- CDF: Underlying-Event; D0: Offset
  - small contribution mainly at low $p_\perp$ (luminosity dependence)

Conclusions

- Jet Energy Calibration is a complex task
- Choice of Constituents
    - towers or clusters?
- Choice of Jet Algorithm and Size
    - cone or $K_\perp$?
    - $R = 0.4, 0.6, 0.7, 1$?
- Choice of Calibration Method/Process
    - jet-level or cluster-level?
    - modular and factorizable or monolithic?
    - data (di-jet, top-pairs, $Z/\gamma+$ jet(s)) or simulation driven?
- Impact of Noise, Underlying Event, and Pile-Up
    - treat already on cluster level or subtract later from jets?
- Will keep all options open for the start of LHC since only data can tell which way is best



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M. Bosmann, C. Roda, P. Loch,
N. Varelas