Revealing the Details of QCD Energy Loss with Jets:

Prospects of ATLAS Heavy-Ion Jet Measurements

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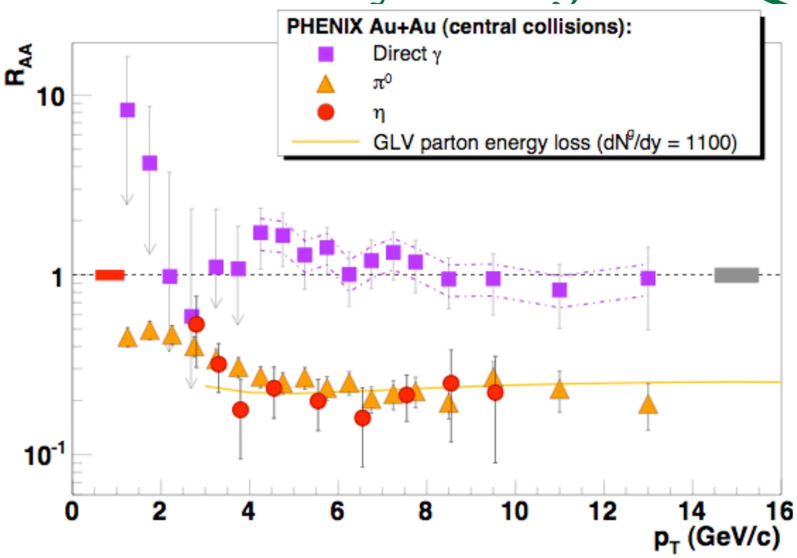
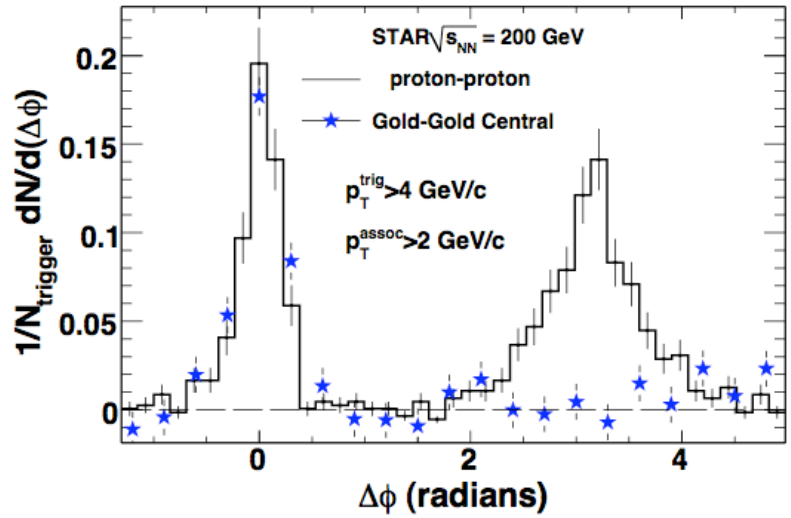
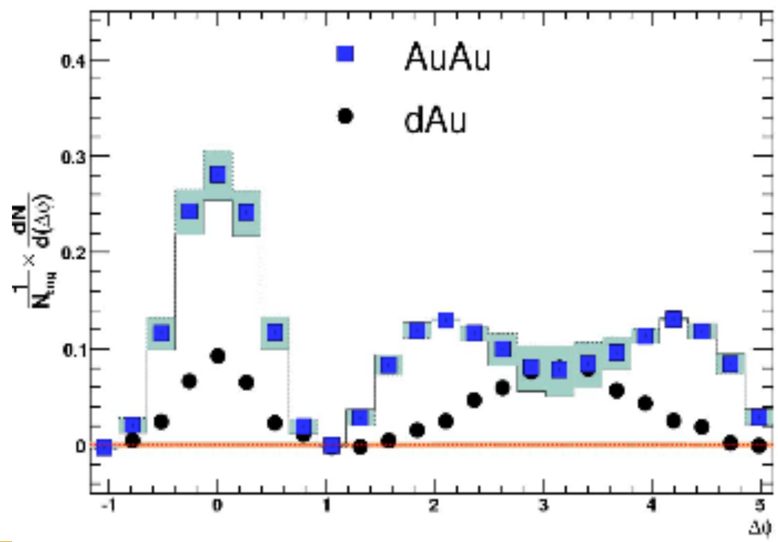
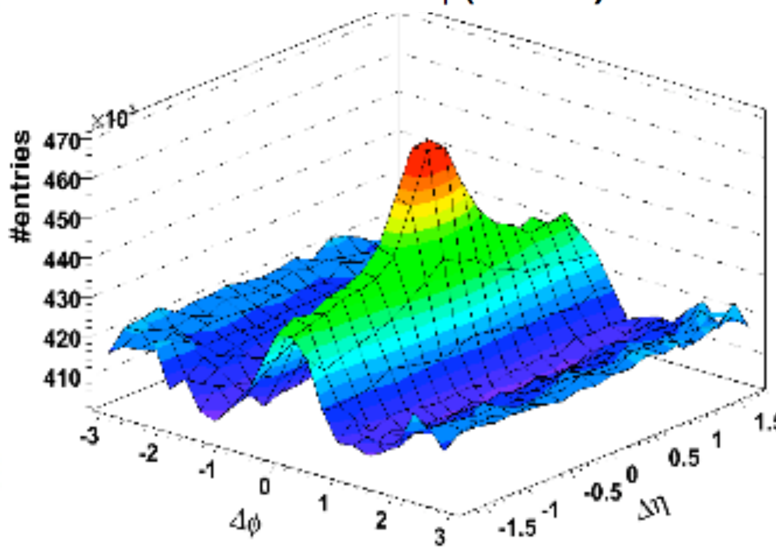
Discovery of Jet Quenching at RHIC



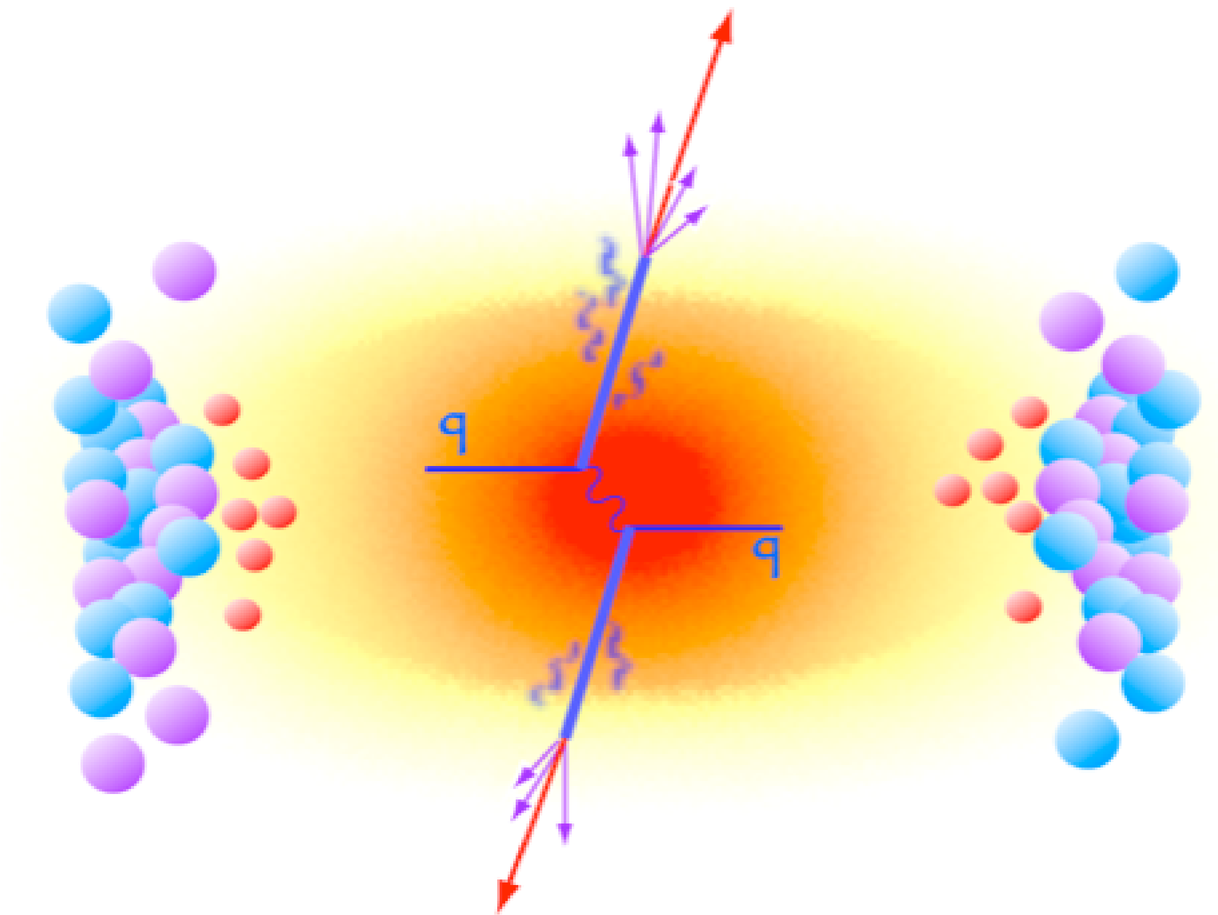






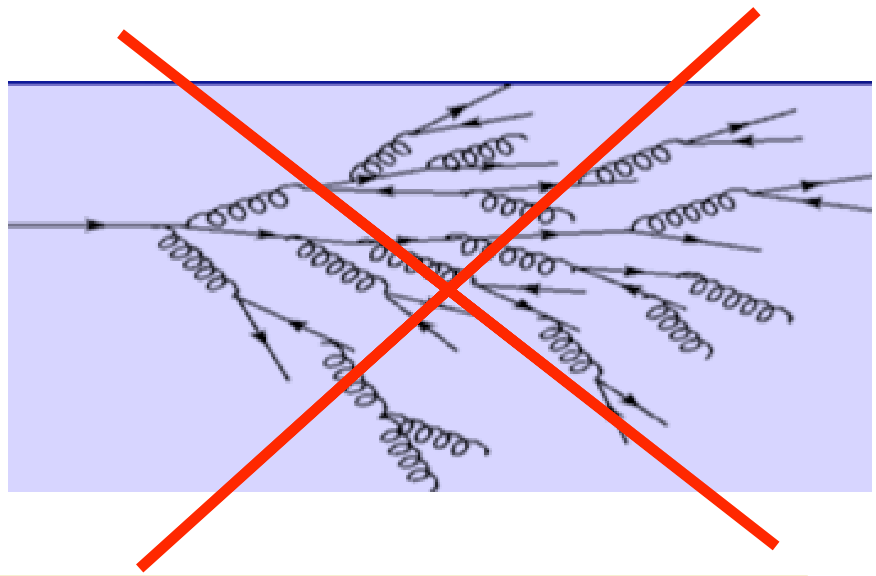
Fundamental Question of Energy Loss

- Is energy loss dominated by perturbative effects?
  - Is it dominated by radiative energy loss?
  - What is dE/dx (L,E)
  - What is the medium's response?

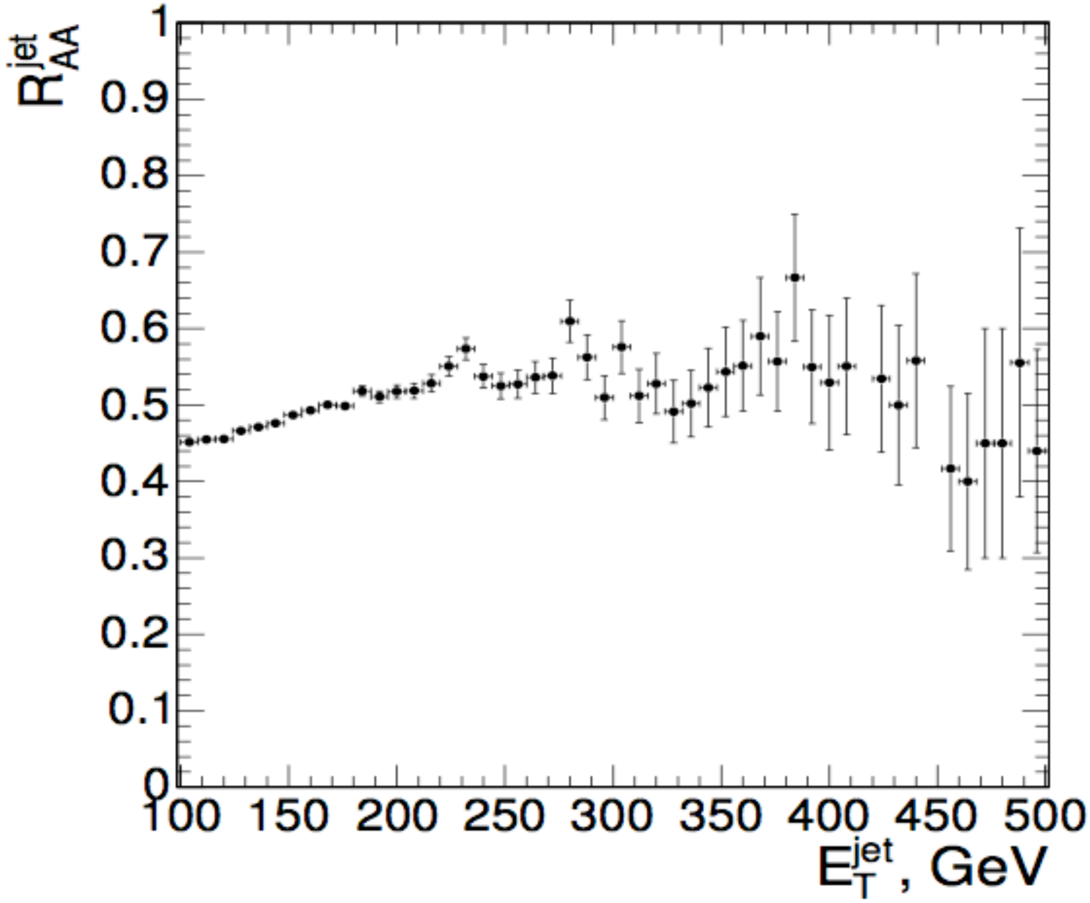


Fundamental Question of Energy Loss

- What is the mechanism if not perturbative?
  - Insights from AdS/CFT $E_{max}(m,L)$ [Kharzeev]
  - Chromo-magnetic effects [Shuryak]
  - Do jets fragment outside of the medium?
  - Strongly coupled liquid so scattering from a field?



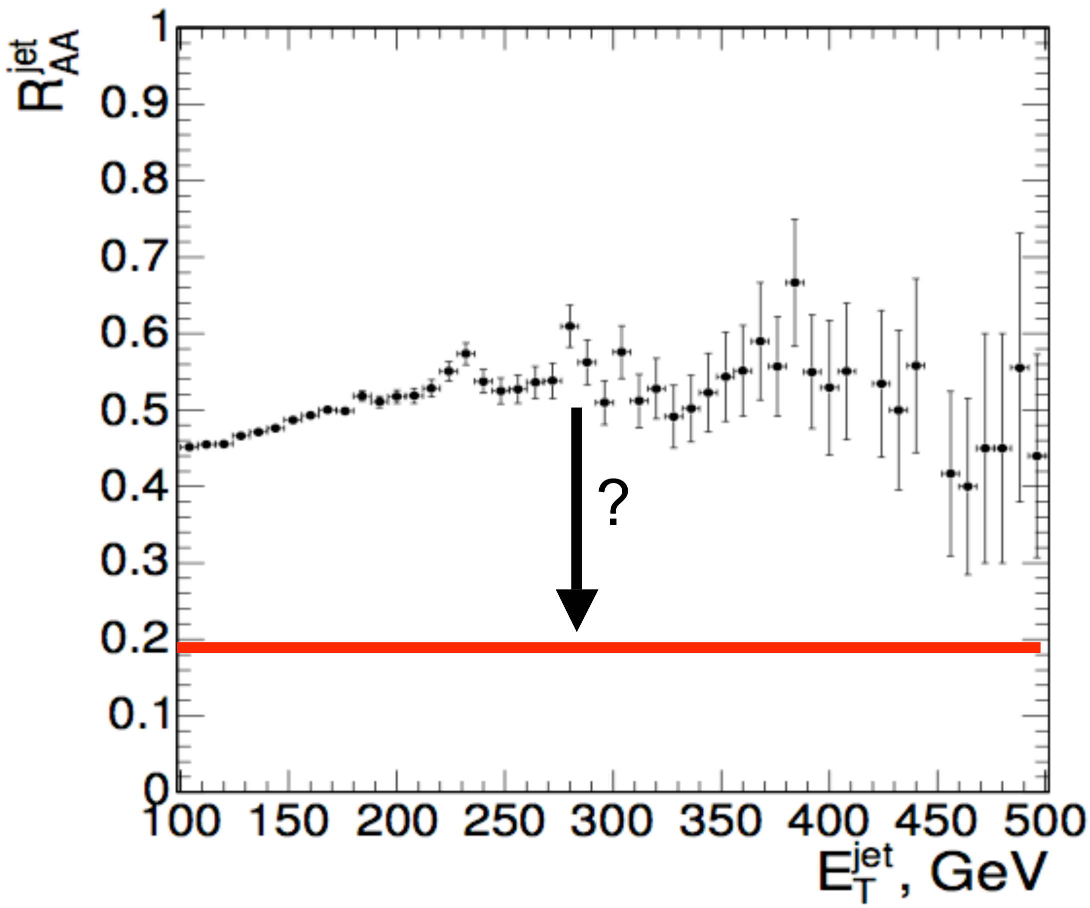
First Experimental Test



Lohktin, PYQUEN

- Measure Jet R_{AA} using standard algorithms
- Sensitive to
  - Perturbative effects
    - Collisional energy loss
    - Energy radiated outside the cone

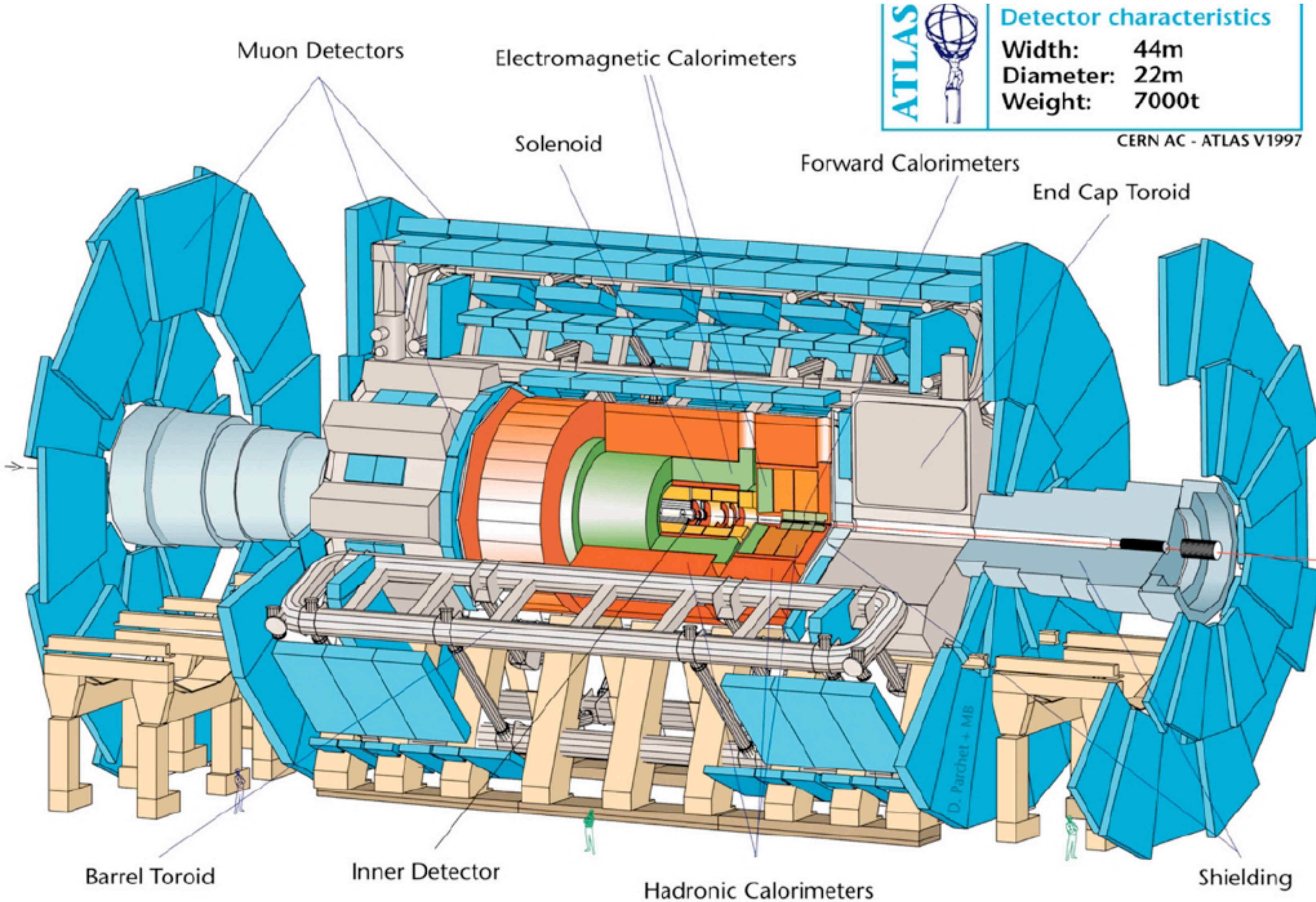
First Experimental Test



Lohktin, PYQUEN

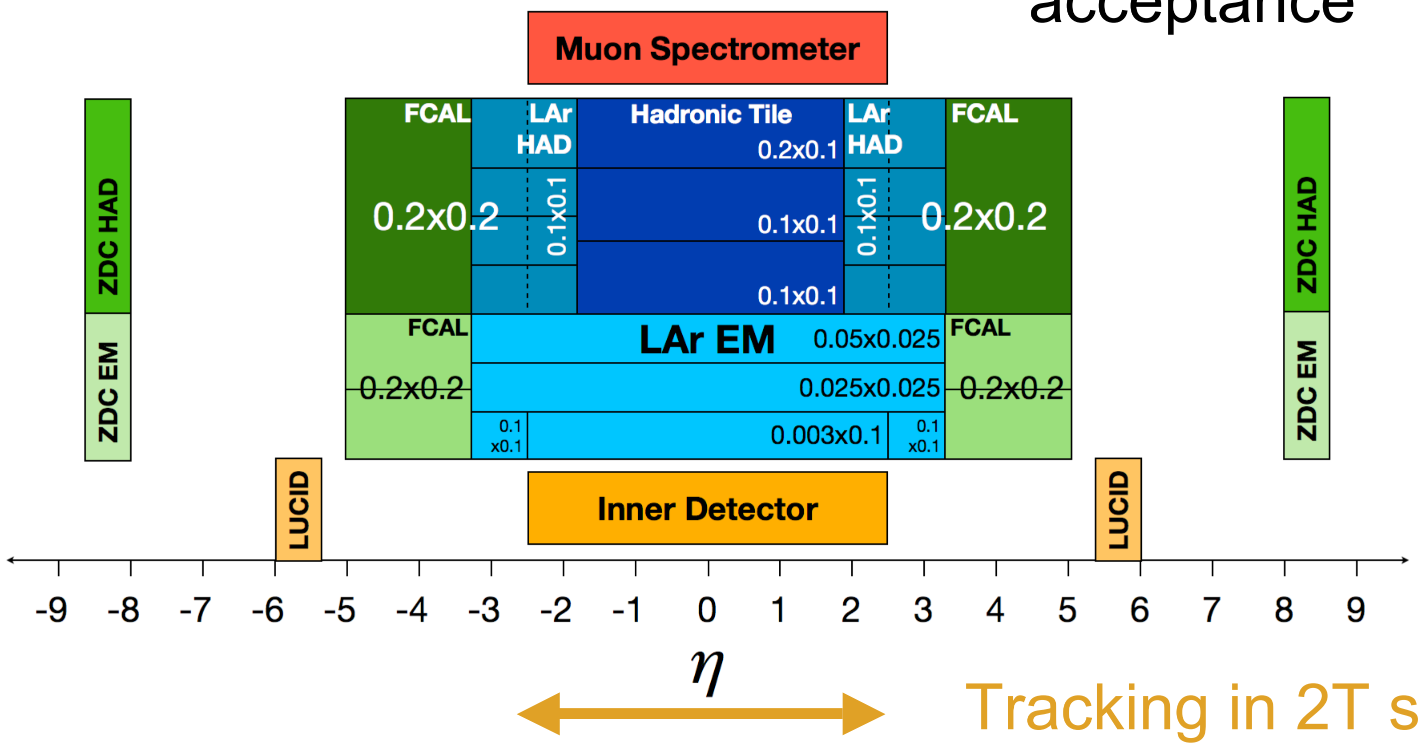
- Measure Jet R_{AA} using standard algorithms
- Sensitive to
  - Perturbative effects
    - Collisional energy loss
    - Energy radiated outside the cone
  - Non-perturbative effects
    - Loss of jets because not reconstructed as a jet

The ATLAS Detector



The ATLAS Detector

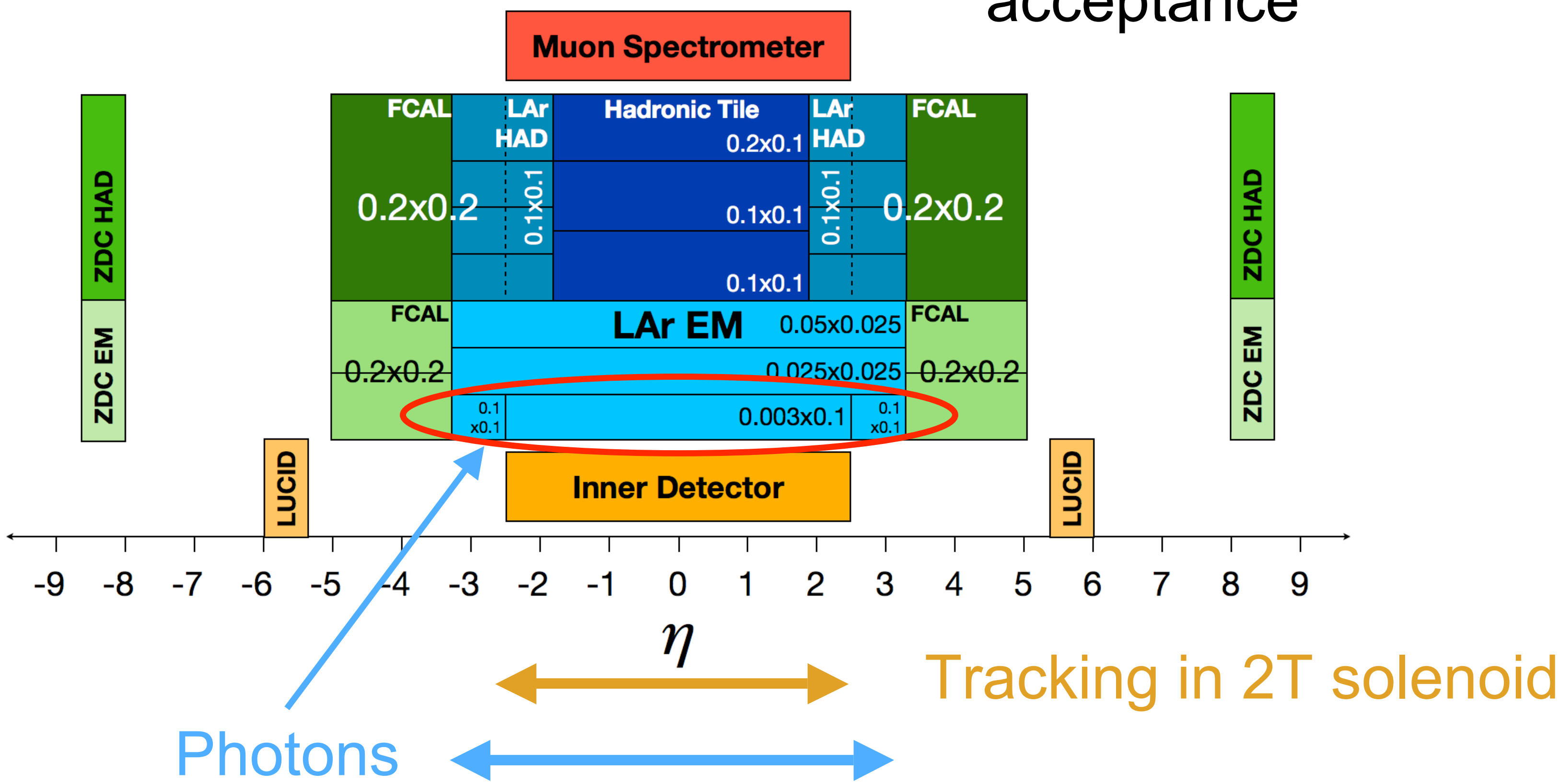
Full azimuthal acceptance



Tracking in 2T solenoid

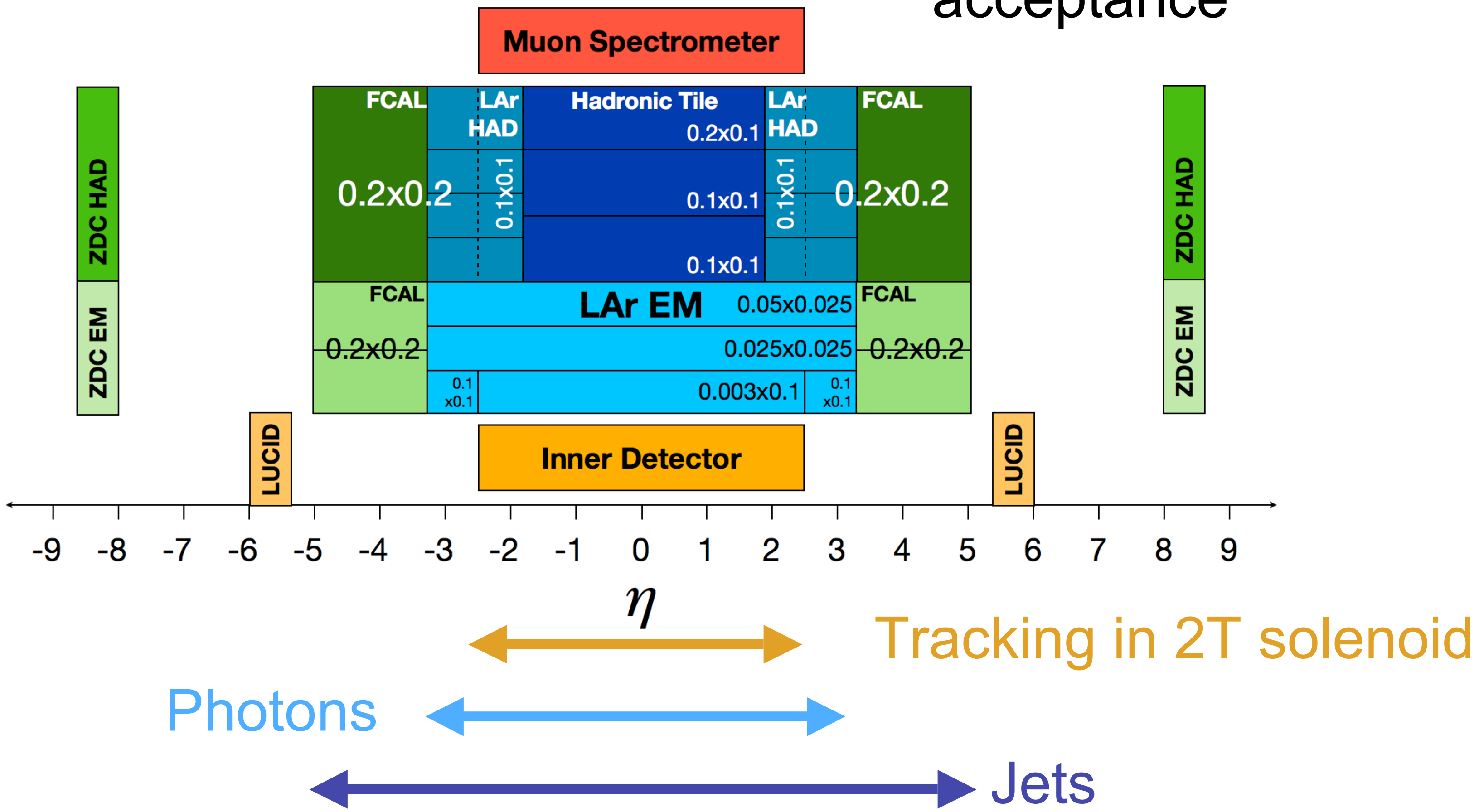
The ATLAS Detector

Full azimuthal acceptance

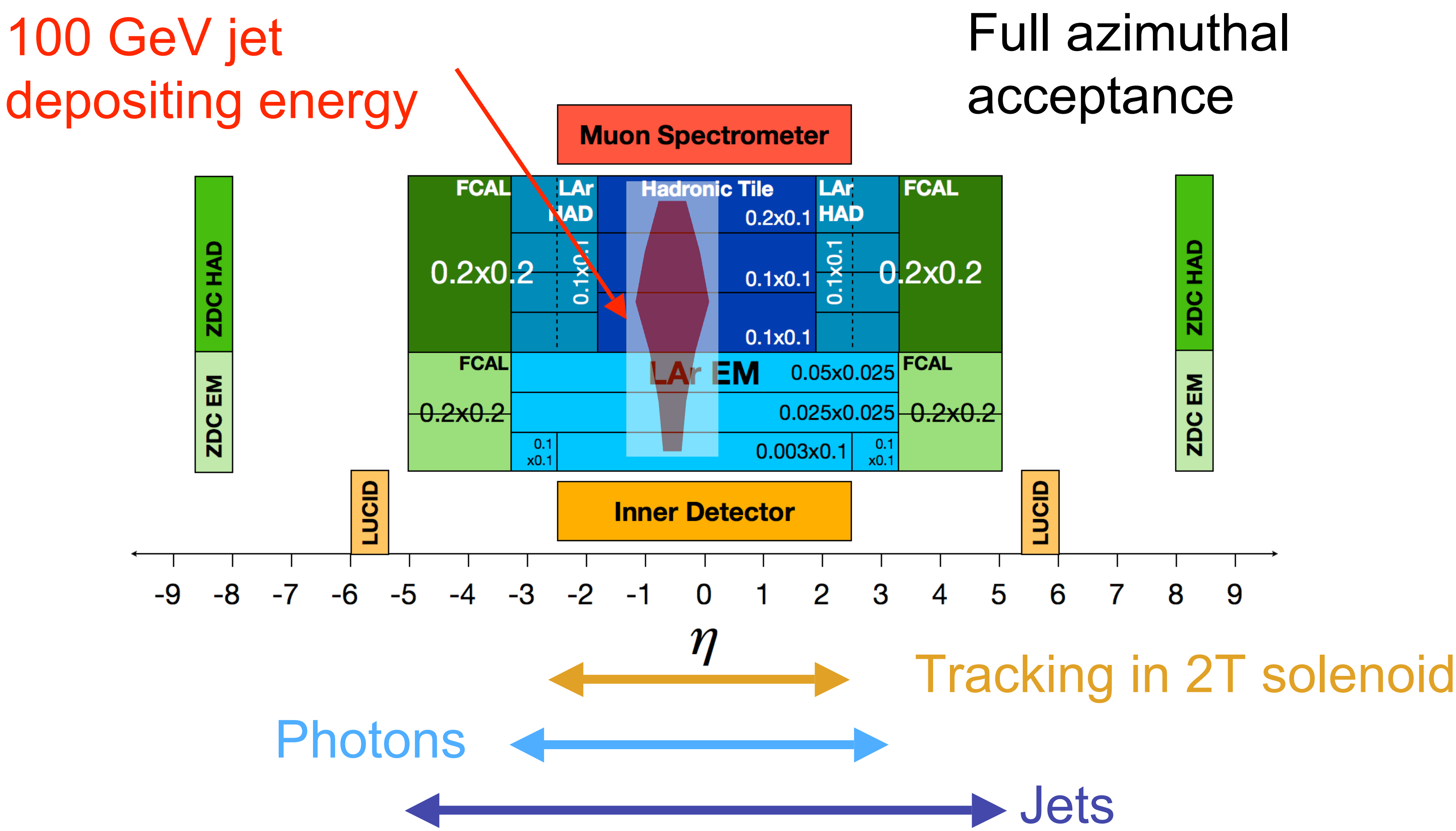


The ATLAS Detector

Full azimuthal acceptance

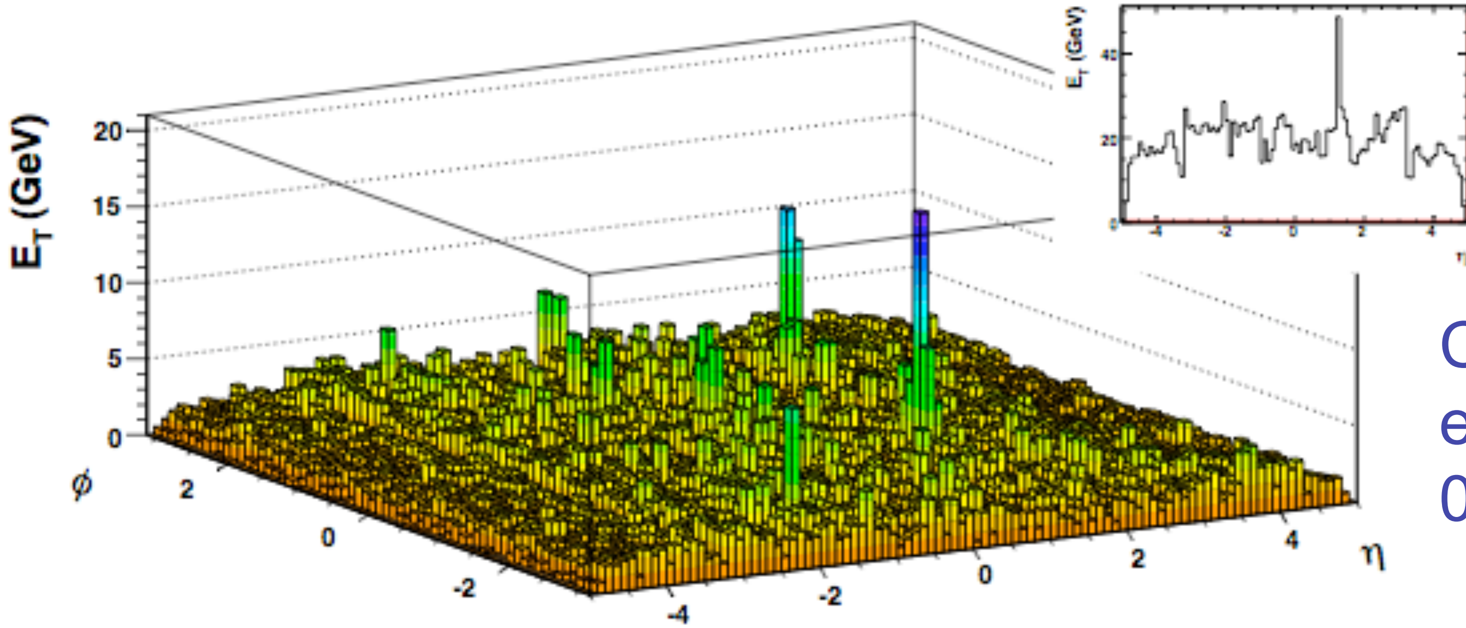


The ATLAS Detector



Cone Jet Reconstruction: Embedding

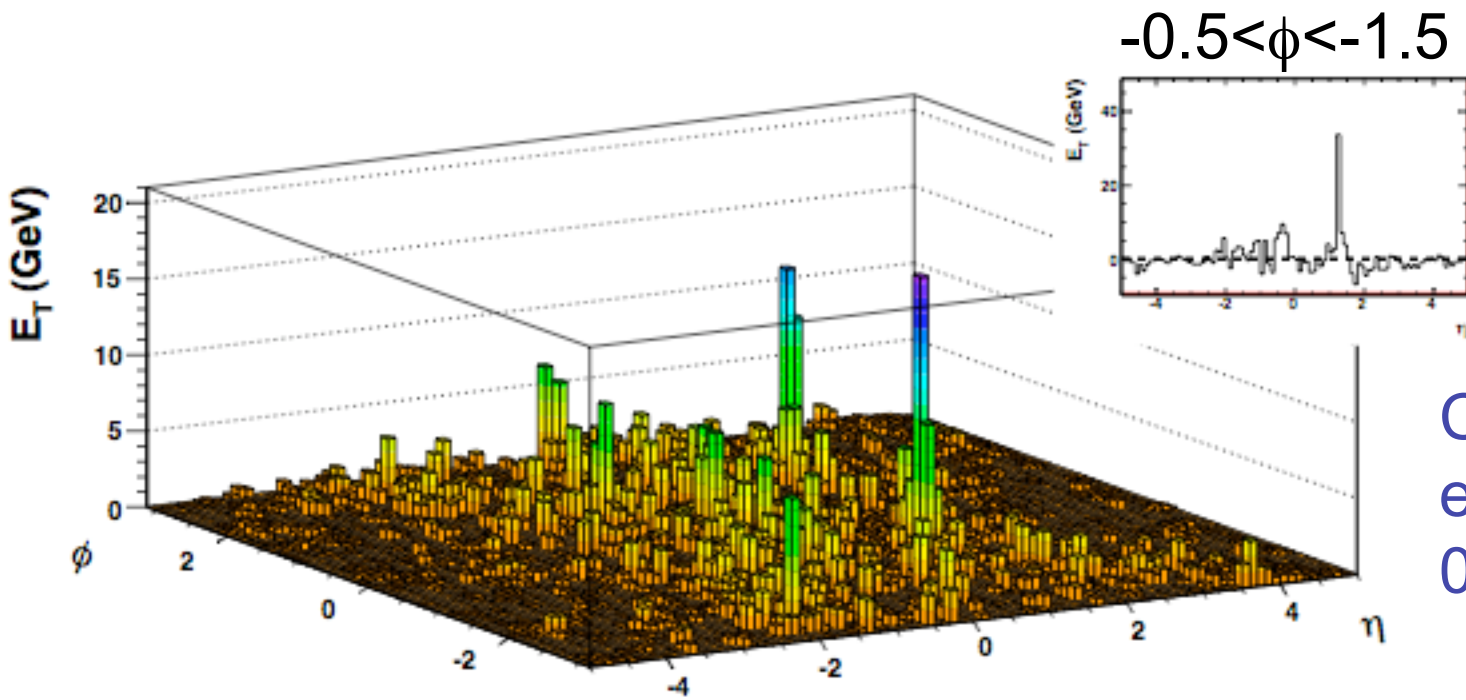
-0.5<φ<-1.5



Calorimeter energy in 0.1x0.1 towers

- Pythia di-jets embedded in unquenched HIJING
  - Lots of correlations: Mini-jets, c-cbar, b-bbar, longitudinal strings, etc.

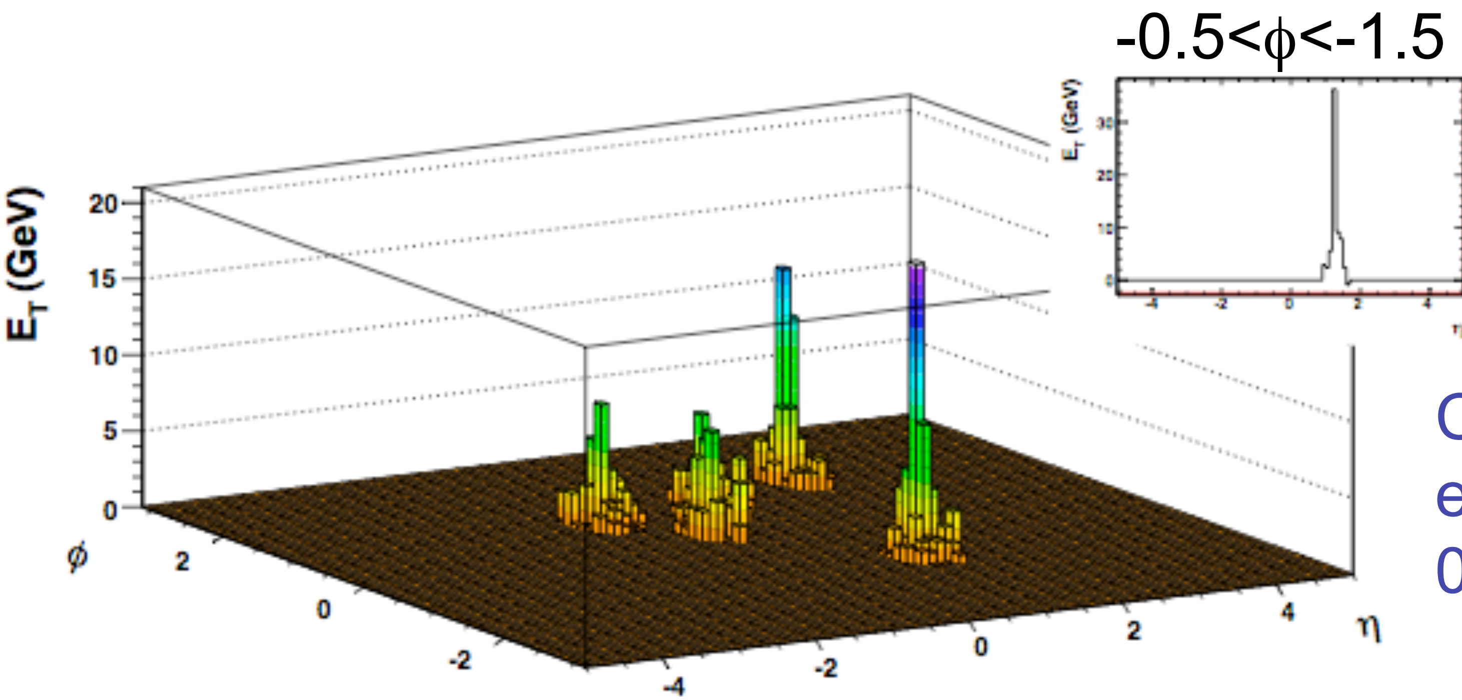
Cone Jet Reconstruction: Subtraction



Calorimeter energy in 0.1x0.1 towers

- Remove <E_T> layer-by-layer and vs. η

Cone Jet Reconstruction: Jets



Calorimeter energy in 0.1x0.1 towers

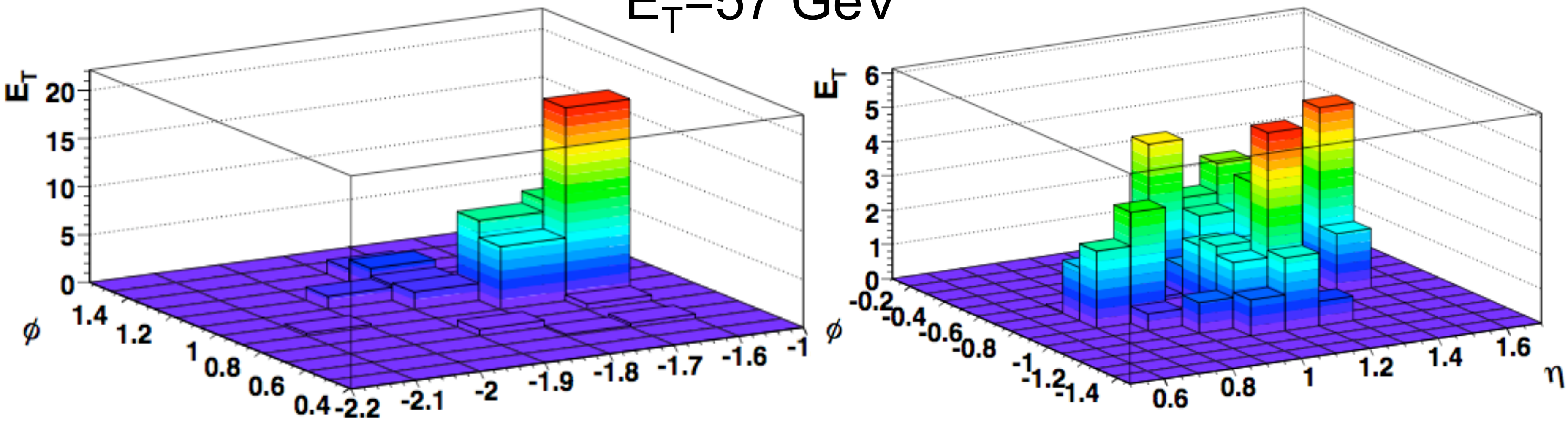
- Reliably reconstruct the input jets
- And some fake jets

Evaluating Fake Jets

- Run HIJING with a hard cut of 10 GeV
  - No direct hard scattering above this scale
- Still could have jets above 10 GeV because
  - initial and final state radiation
  - longitudinal string fragmentation
- Remove from reconstructed jets matching to parton with E_T cut
- No embedded PYTHIA jets

Distinguishing Real and Fake Jets

E_T=57 GeV



- Left: Reconstructed jet from embedded PYTHIA
  - Asymmetric fragmentation
- Right: Reconstructed jet from a HIJING sample without jets > 10 GeV and nothing embedded
  - Large angle fragments and no core
- Need a distinguishing variable.

Fake Jet Rejection: SumJt

- Need a variable which enhances the large angle towers/cells in the jet
- Define

$$SumJt = \sum_{cells \in jet} E_T^{cell} \sin R$$

with $R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ the angle from the jet

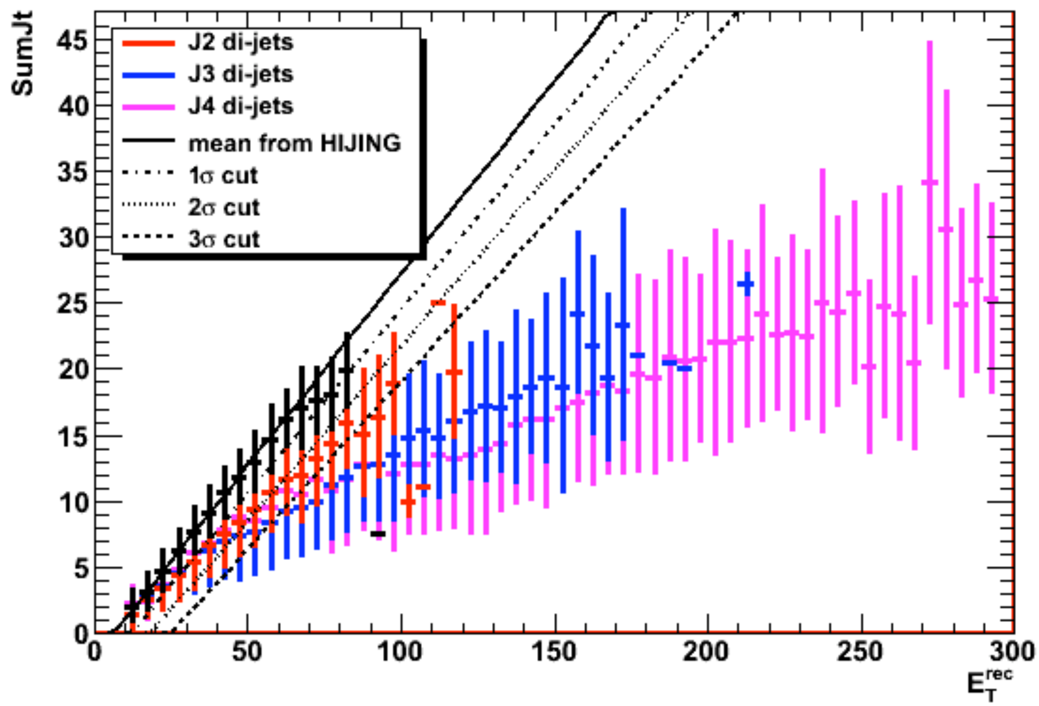
Fake Jet Rejection: SumJt

$$SumJt = \sum_{cells \in jet} E_T^{cell} \sin R$$

$$= \frac{\sum_{cells \in jet} E_T^{cell} \sin R}{E_T^{jet}} E_T^{jet}$$

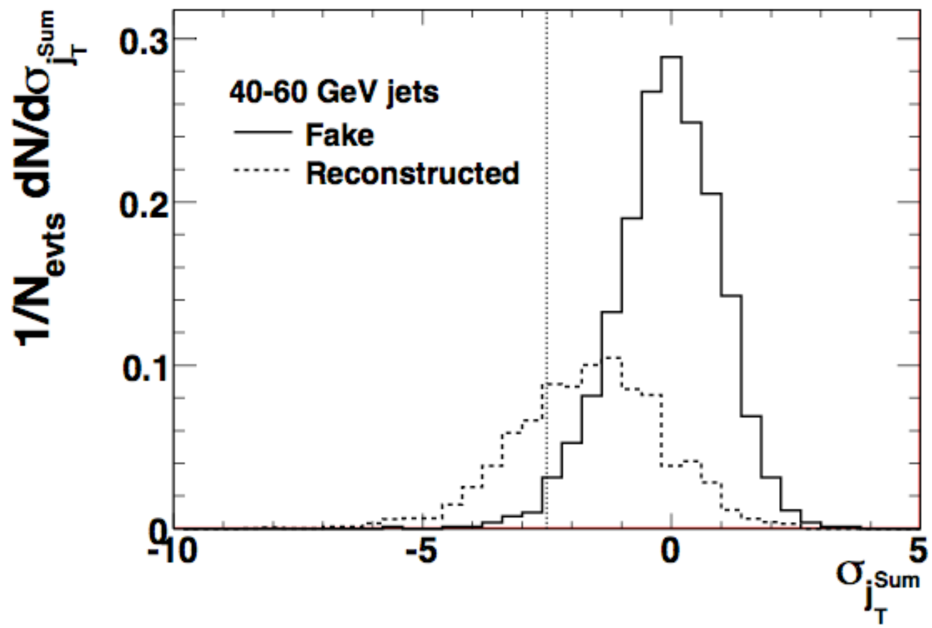
$$= \frac{\sum_{cells \in jet} E_T^{cell} \sin R}{\sum_{cells \in jet} E_T^{cell}} E_T^{jet}$$

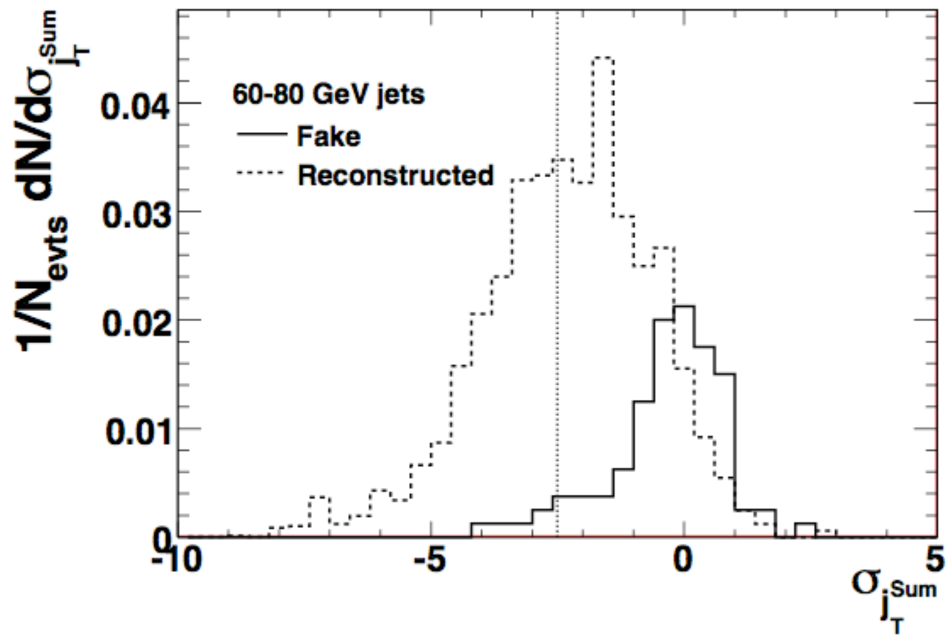
$$= \langle \sin R \rangle E_T^{jet} \approx \langle R \rangle E_T^{jet}$$



- Fake jets SumJt>Pythia jets
- <R> for Pythia jets decreases with increasing jet energy

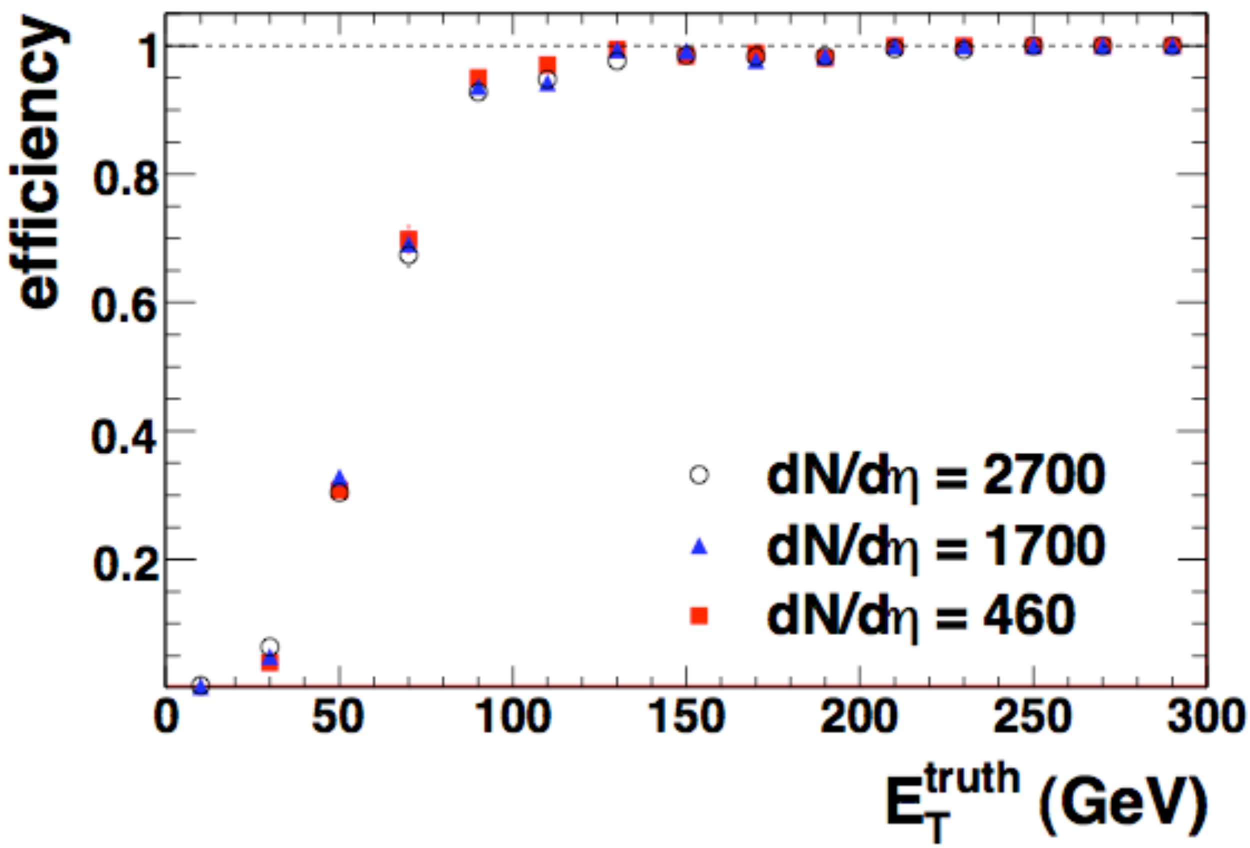
Fake Jet Rejection: SumJt





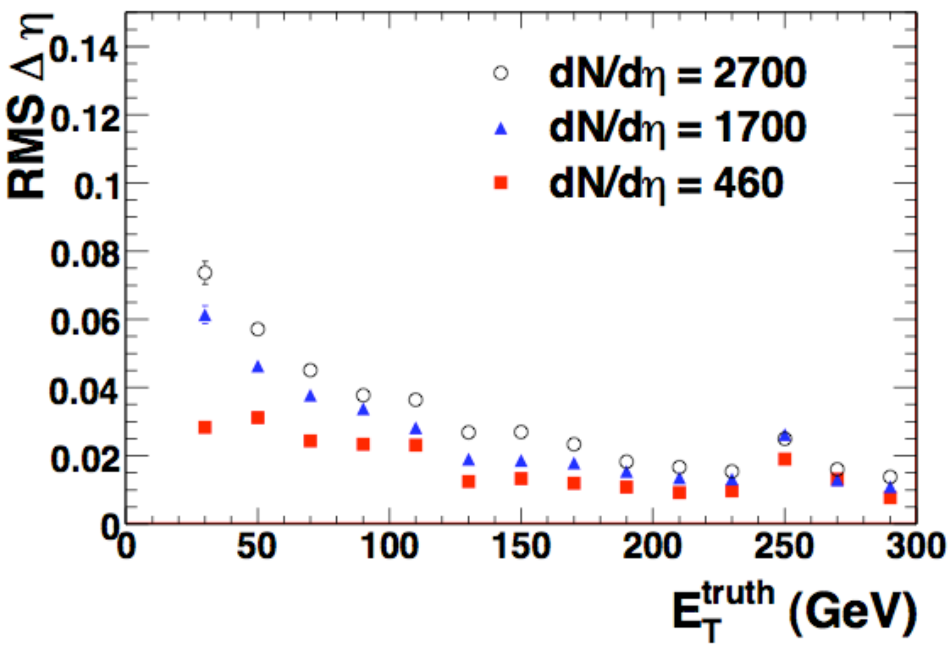
- Fit the fake jet data from HIJING without jets to remove trivial E_T dependence (by definition centered at 0 with width of 1)
- Real jets will have a much smaller SumJt and a cut to reject fake jets is made.

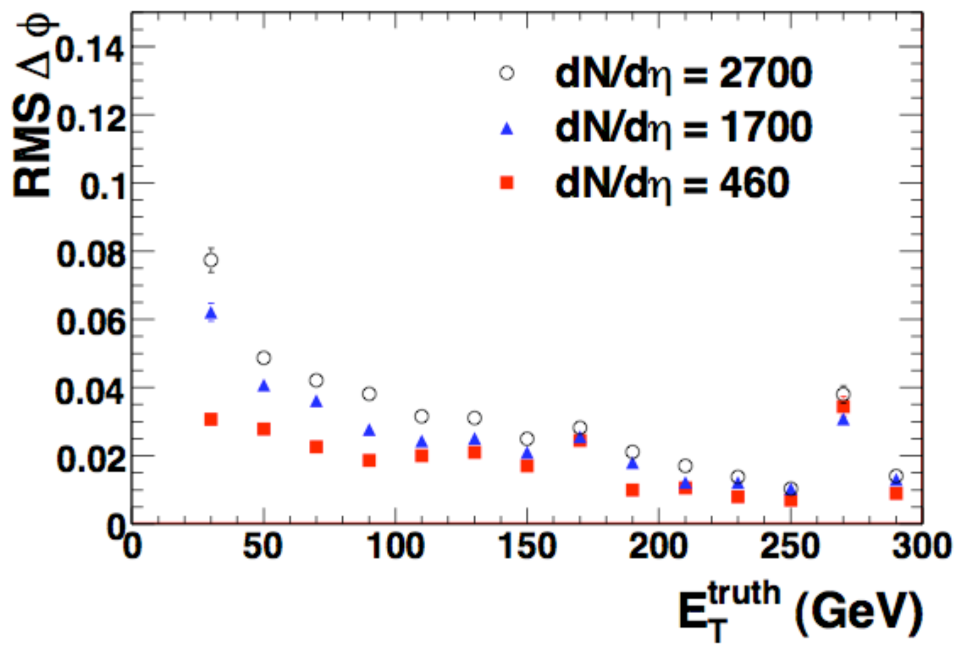
Cone Jet Results: Efficiency



- Efficiency is independent of centrality
  - Important for jet R_{CP}, centrality-dependent effects
- Affected by
  - 5 GeV seed selection
  - Fake rejection

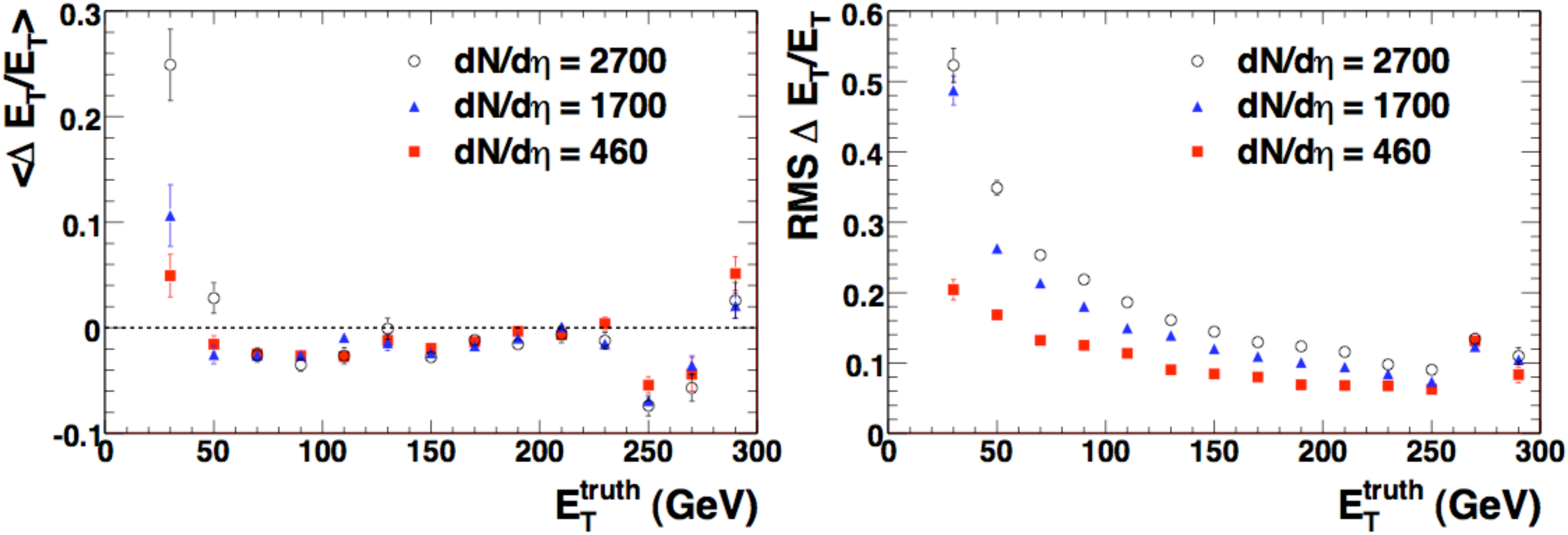
Cone Jet Results: Position Resolution





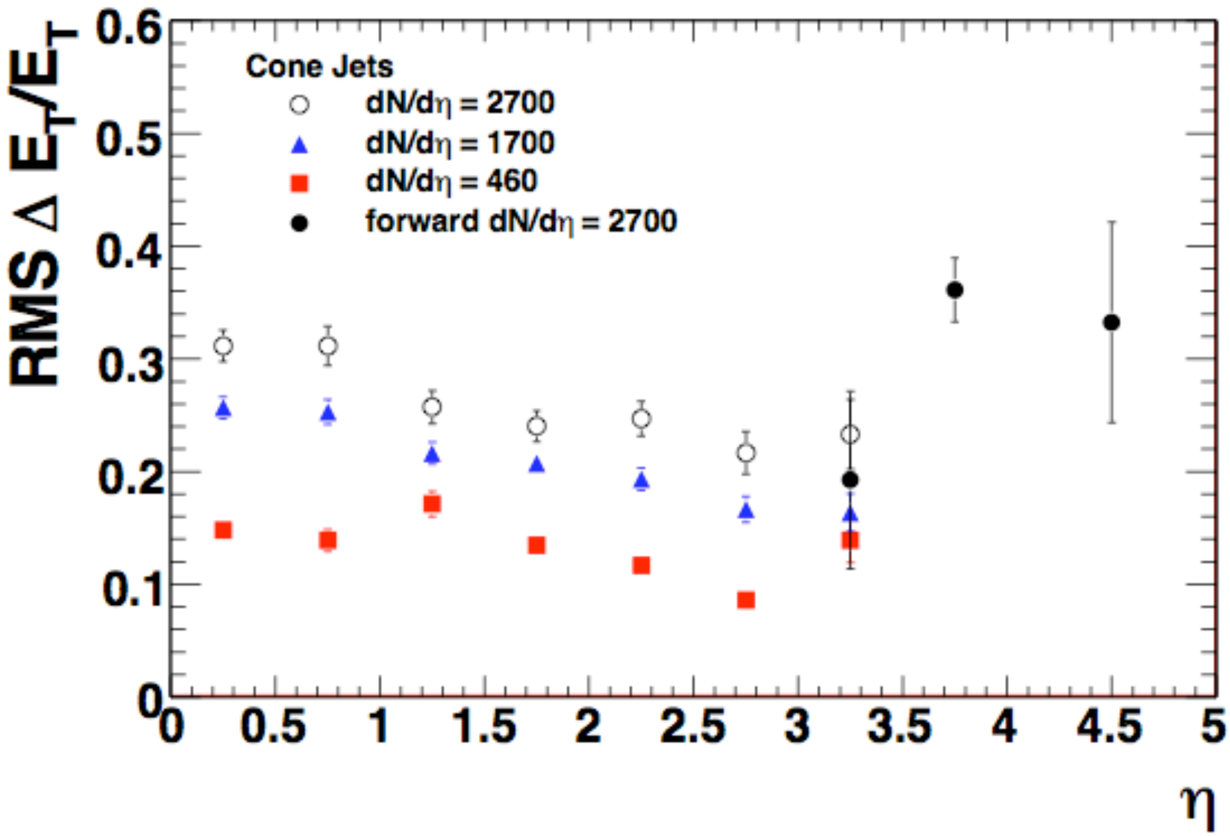
- Position resolution in η and φ is very good

Cone Jet Results: Energy Resolution



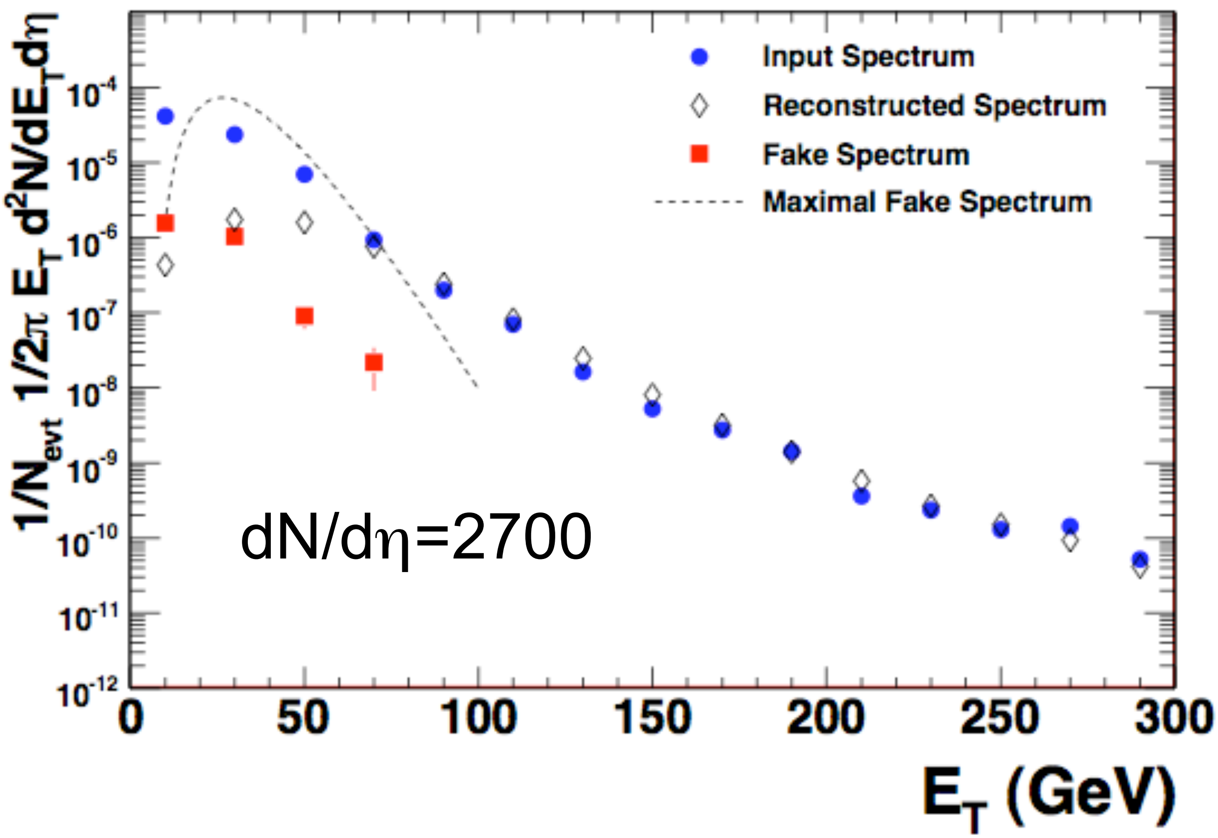
- Jet scale good to 2% for E_T>50 GeV using p+p calibrations
- Energy resolution < 25% for E_T>70 GeV for extreme conditions of unquenched HIJING and dN/dη = 2700

Cone Jet Results: Energy Resolution



- Energy resolution
  - decrease to |η|~3
  - FCAL(|η|>3.2) same as |η|~0

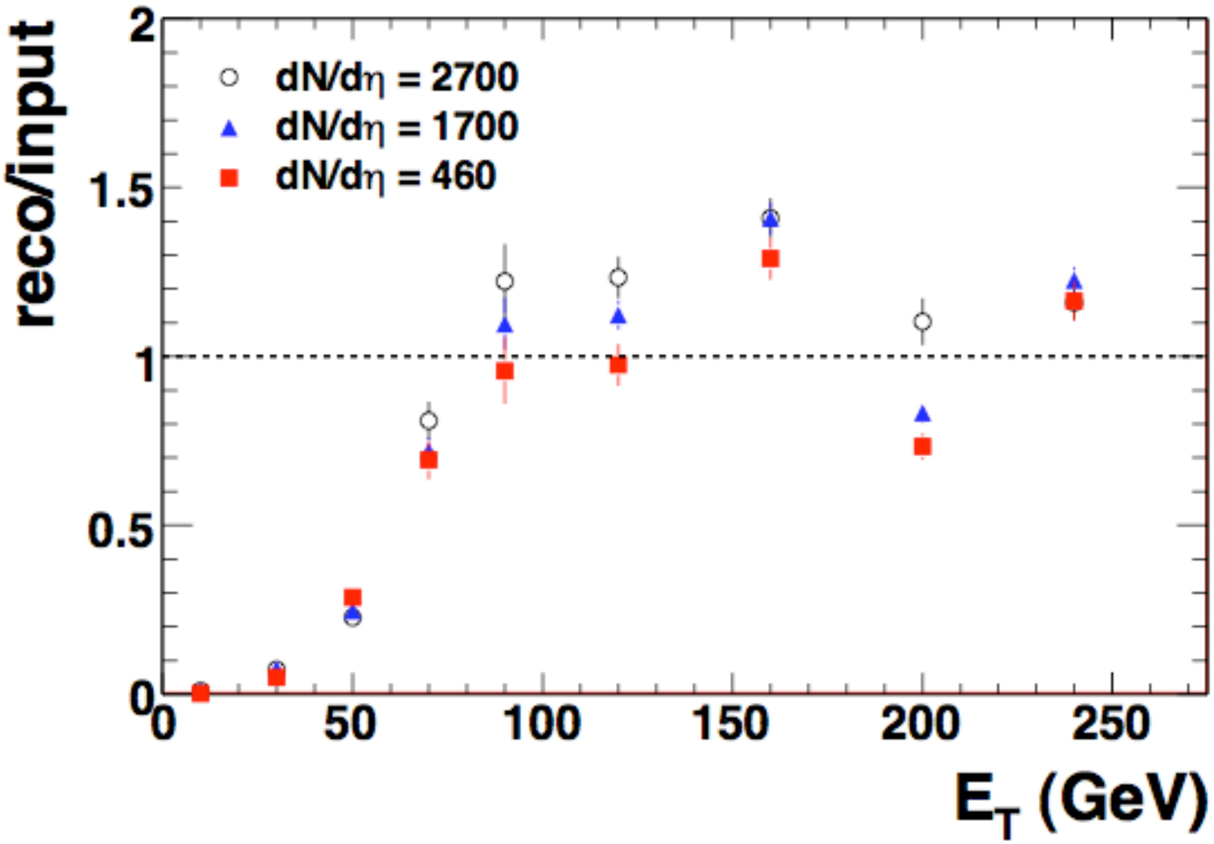
Cone Jet Results: Spectrum



Reco spectrum uncorrected for efficiency and energy resolution

- Reconstructed spectrum uncorrected for E_T res. and efficiency
- Fake spectrum (red squares) after rejection from dashed line.

Cone Jet Results: Spectrum



Reco spectrum uncorrected for efficiency and energy resolution

- Ratio ~20%
- Will be sensitive to this level of effects from perturbative and non-perturbative effects.

Physics Conclusion

- Only after we establish that jets we measure lose energy in some perturbative way can we go to measure D(z), j_T distributions, etc. to understand the details of the perturbative energy loss.
- Until then we must, at both RHIC and the LHC, to find measurements which are sensitive to perturbative and non-perturbative energy loss.

A Further Outlook

- Whole set of results not shown which will be necessary experimental tools for understanding jet energy loss:
  - k_T algorithm, γ-jets, heavy flavor tagging
- Background subtraction will be complicated by the medium response to jets
- Fake jet rejection will be complicated by the energy loss mechanism
- What other new physics is waiting to be discovered?

The ATLAS Heavy Ion Working Group

Brookhaven National Laboratory, Upton, USA
Charles University, Prague, Czech Republic
Columbia University, New York, USA
University of Geneva, Geneva, Switzerland
IHEP, Moscow, Russia
IFJ PAN, Krakow, Poland
Iowa State University, Ames, USA
JINR, Dubna, Russia
MePHI, Moscow, Russia
Universidad Catolica de Chile, Santiago, Chile
Santa Maria University, Valparaiso, Chile
Stony Brook University (Chemistry) Stony Brook, USA
Weizmann Institute, Rehovot, Israel

Backup Slides

COLUMBIA UNIVERSITY
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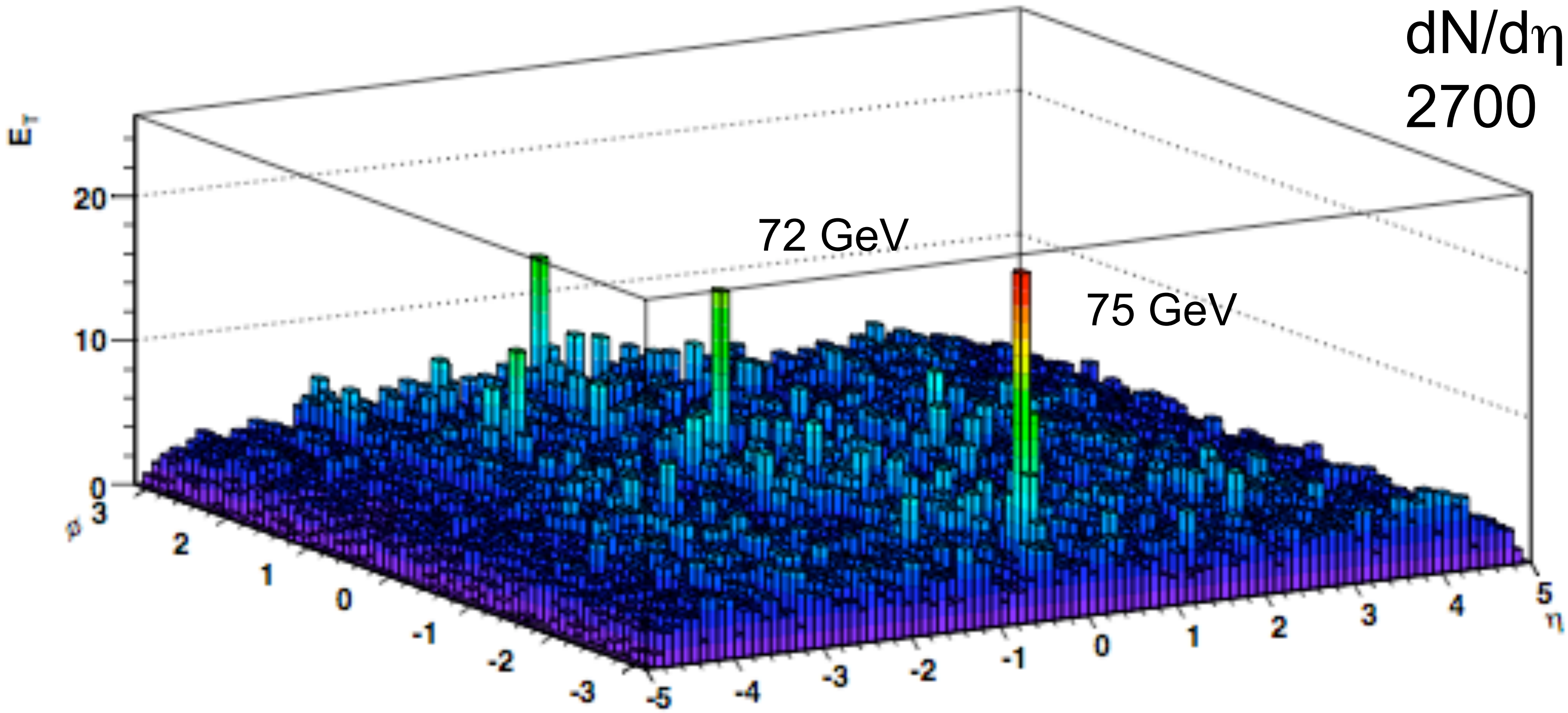
Life at the LHC



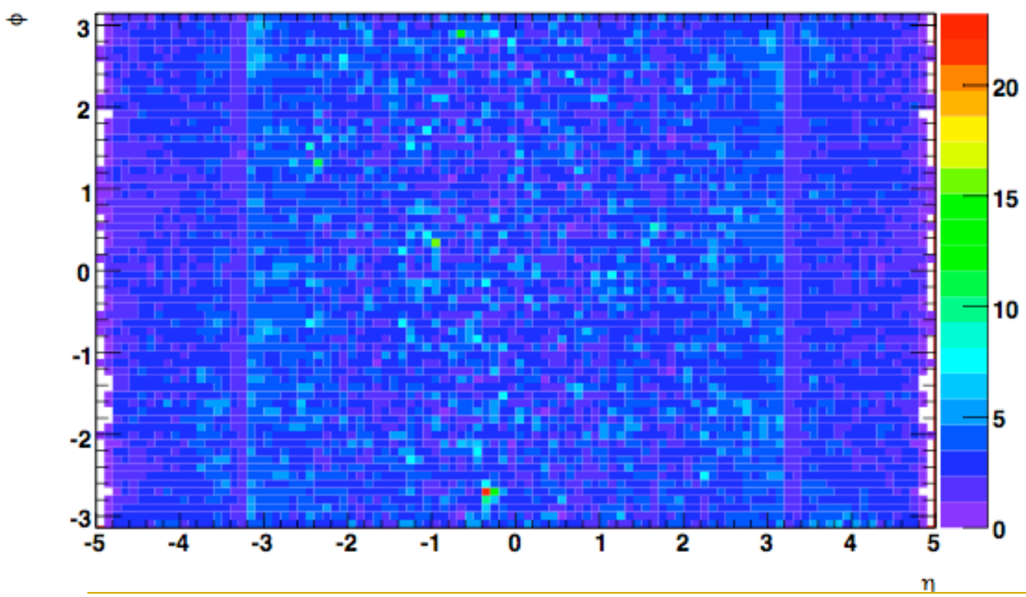
- Plenty of high-E_T jets visible above the background
- Use standard jet reconstruction algorithms to measure full jets instead of di-hadrons
- But there are two important issues: the underlying event and fake jets.

Subtraction of the Background

- Overall scheme: subtract the average background calorimetric E_T ($<E_T>$)
  - Done for each layer of the calorimeter since background contribution (and noise) is different in each layer
  - Done as a function of η because of physics and because of cracks, inner detector material differences as a function of η.
  - Do not include *jets* in the $<E_T>$ calculation of the *background*

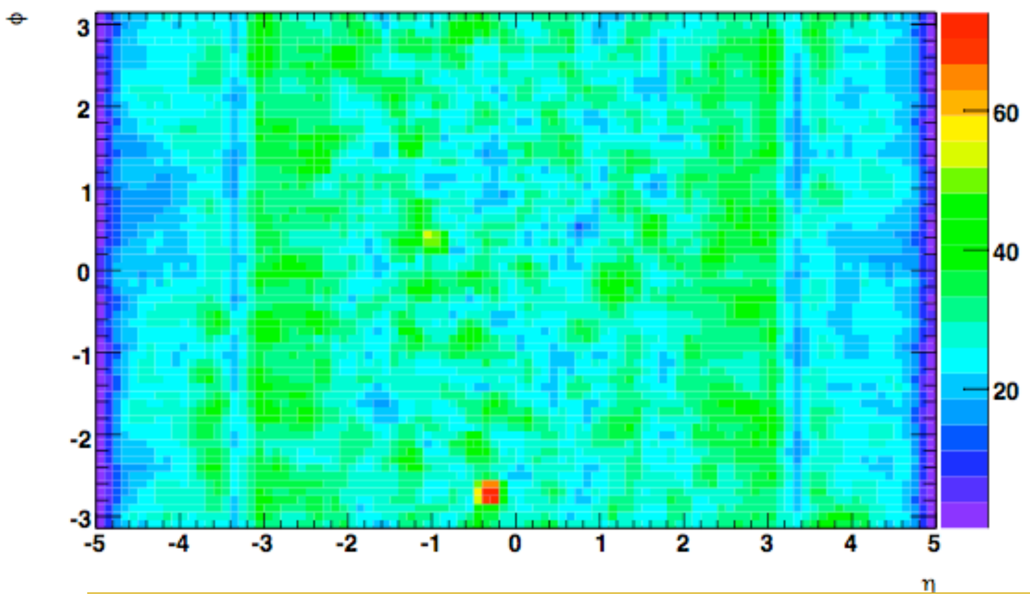
Finding High Towers

- Use a 0.3x0.3 size sliding window



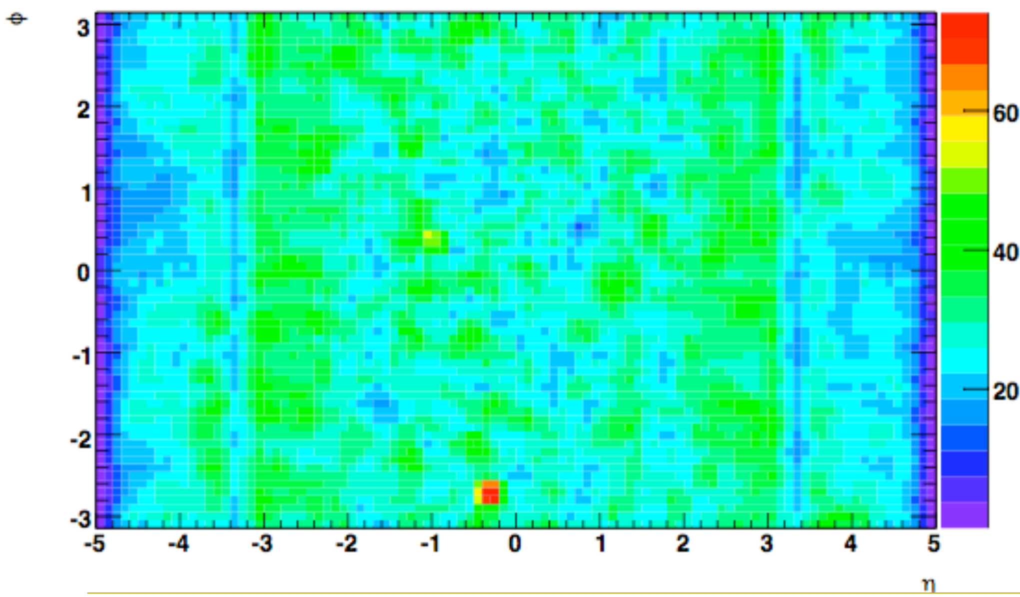
Finding High Towers

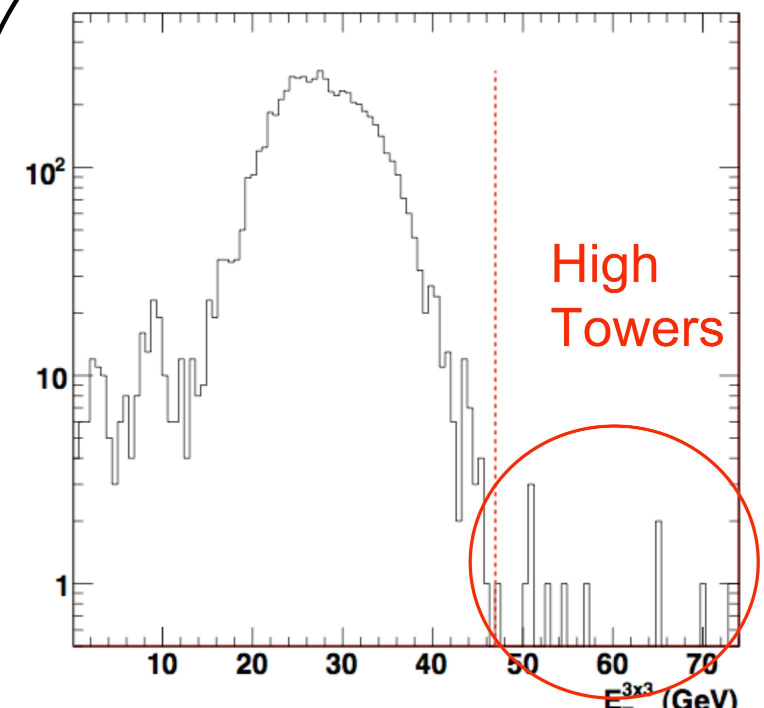
- Use a 0.3x0.3 size sliding window



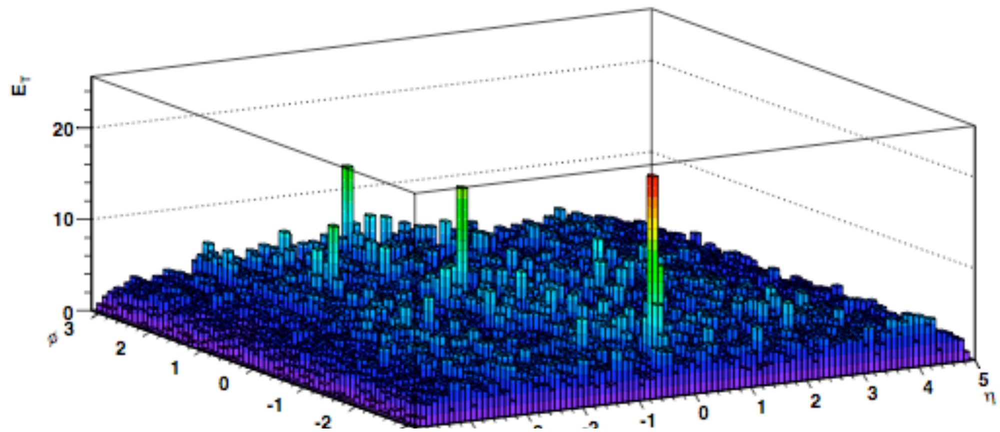
Finding High Towers

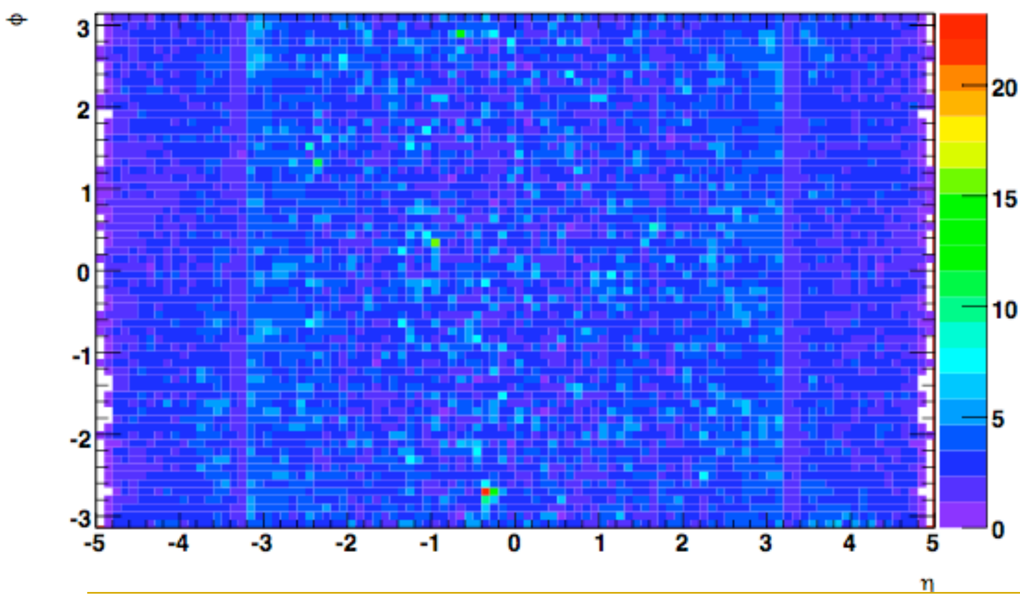
- Use a 0.3x0.3 size sliding window
- Find <E_T> and RMS of summed towers
- Select high tail





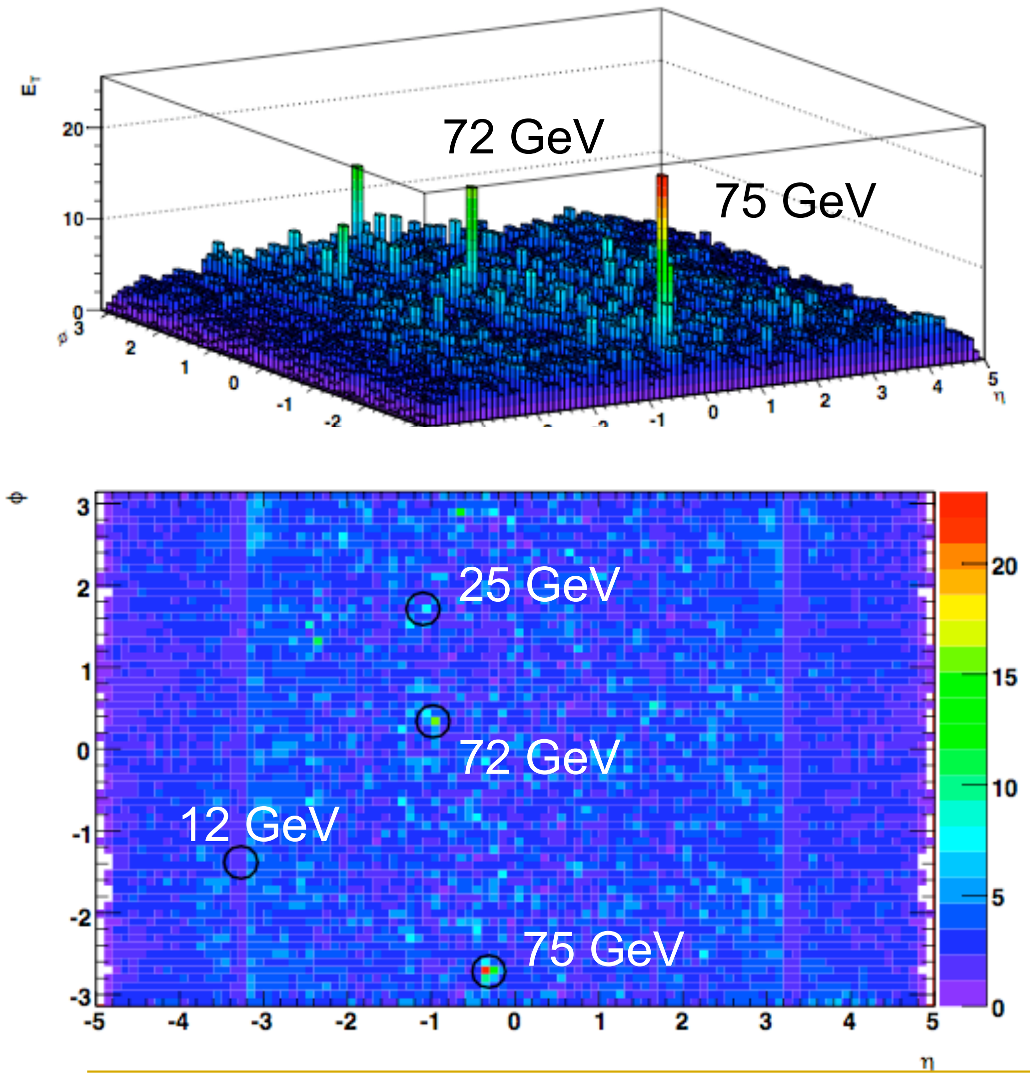
An Example Event : Towers





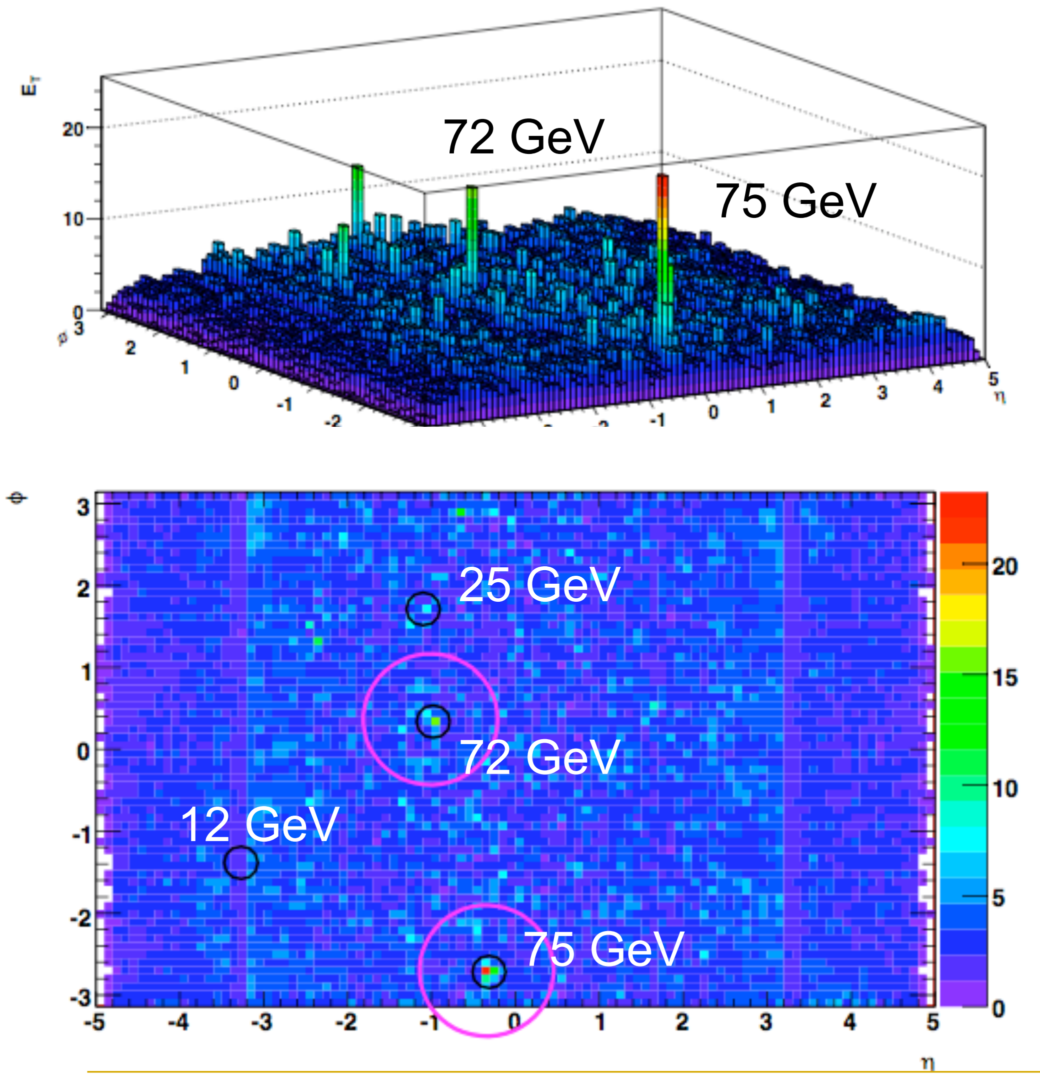
- PYTHIA event in $dN/d\eta=2700$ unquenched HIJING
- 0.1x0.1 Towers

An Example Event : Truth Jets



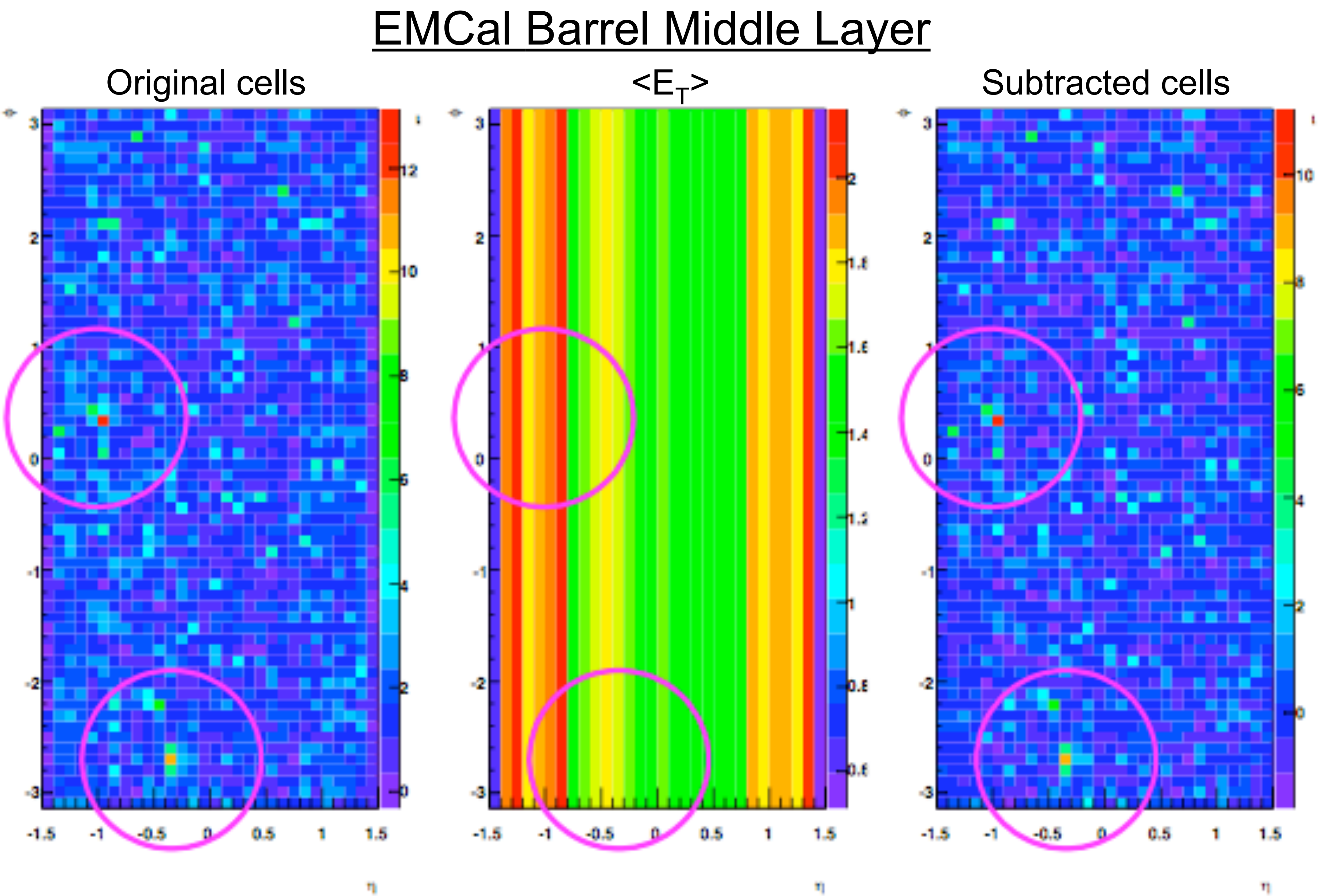
- PYTHIA event in $dN/d\eta$=2700 unquenched HIJING
- 0.1x0.1 Towers
- Truth jets from PYTHIA

An Example Event : High Towers

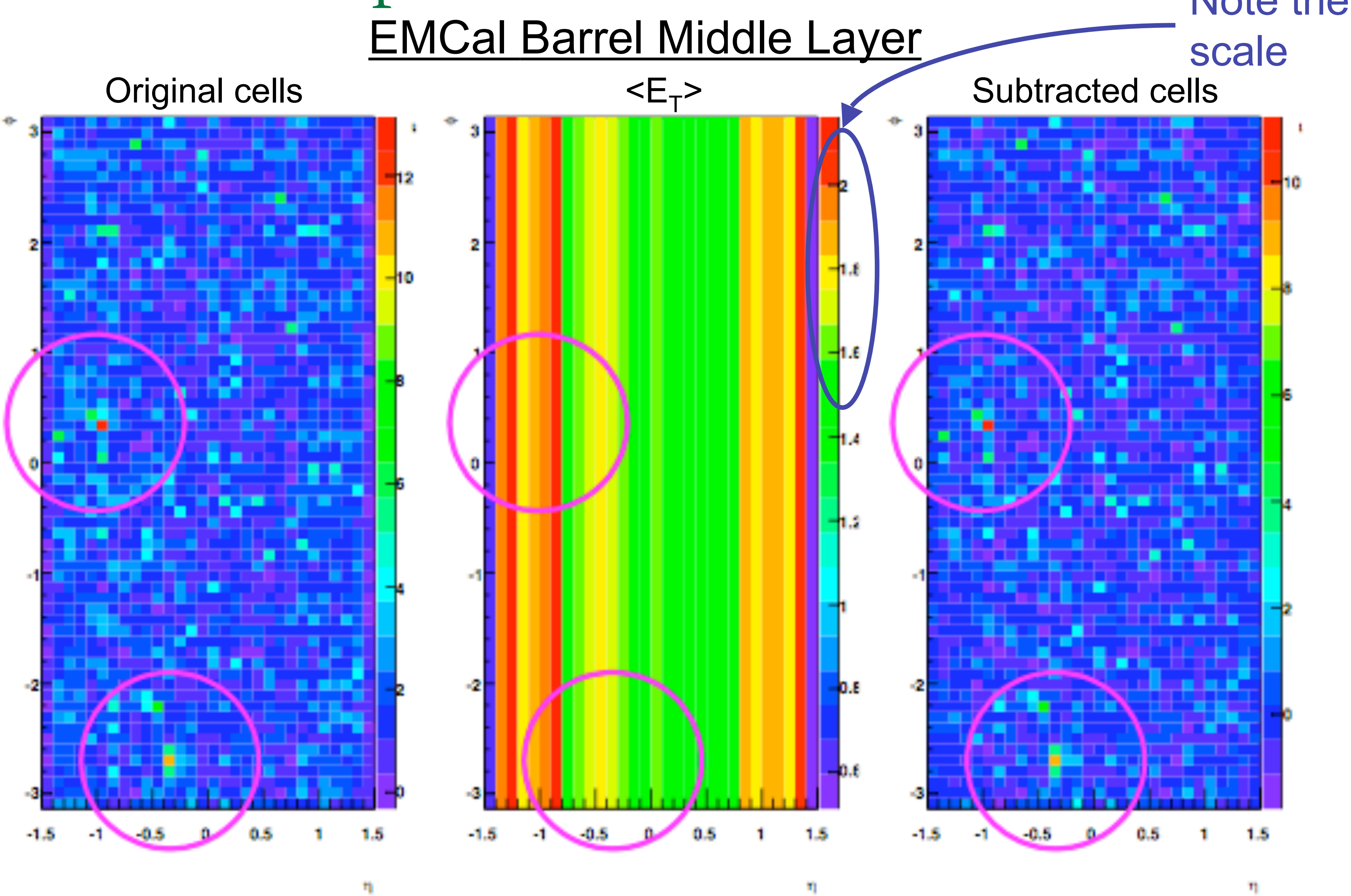


- PYTHIA event in $dN/d\eta=2700$ unquenched HIJING
- 0.1x0.1 Towers
- Truth jets from PYTHIA
- High towers regions exclude jets from $<E_T>$

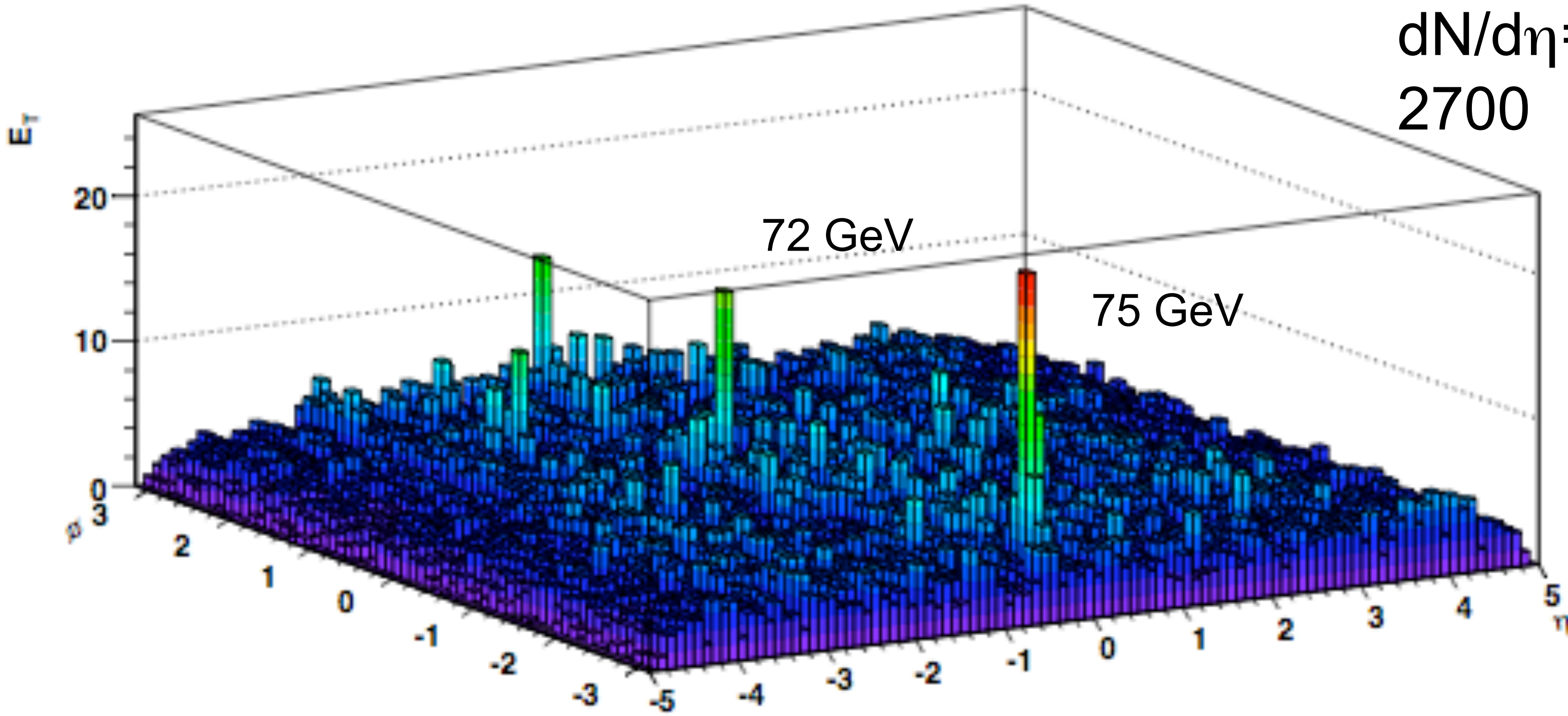
An Example Event: Subtraction



An Example Event: Subtraction

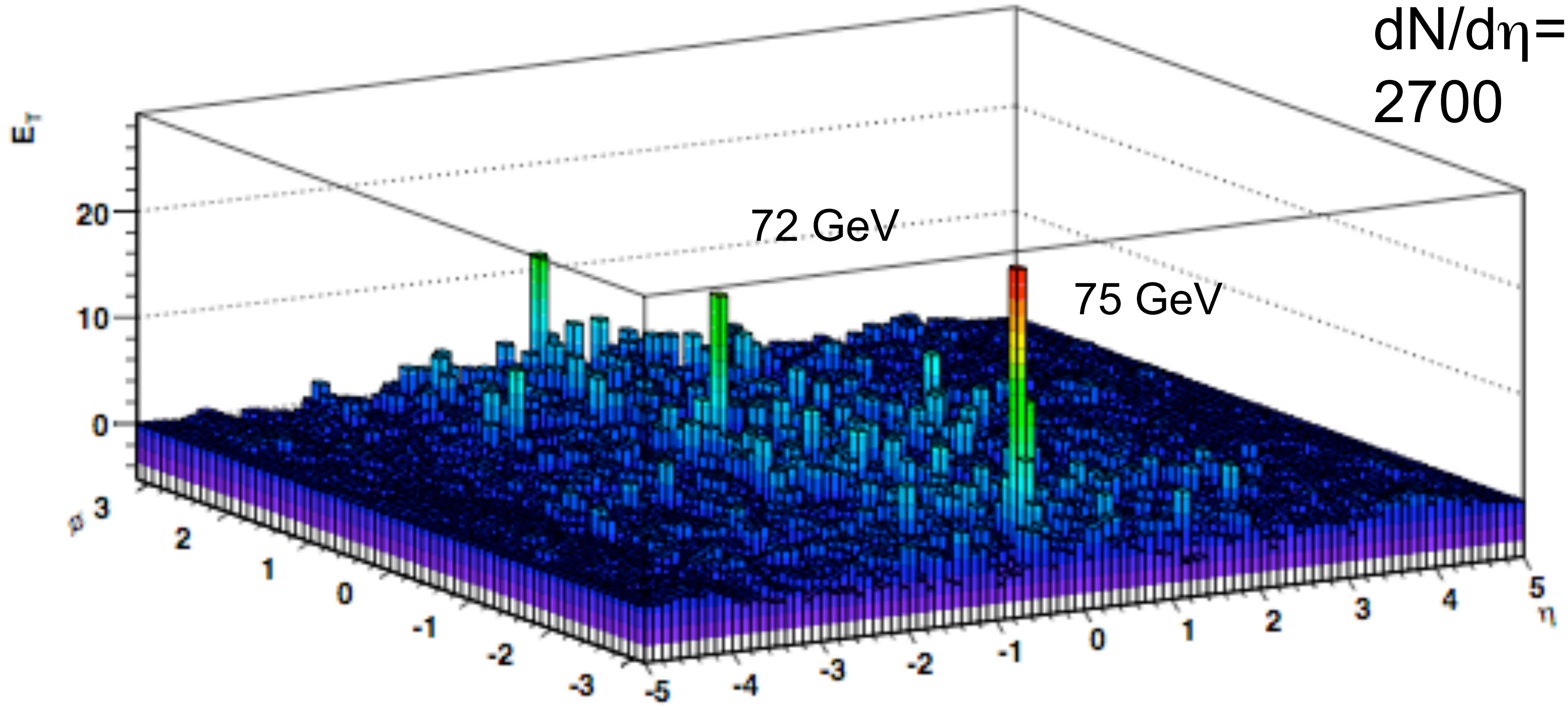


An Example Event: Before



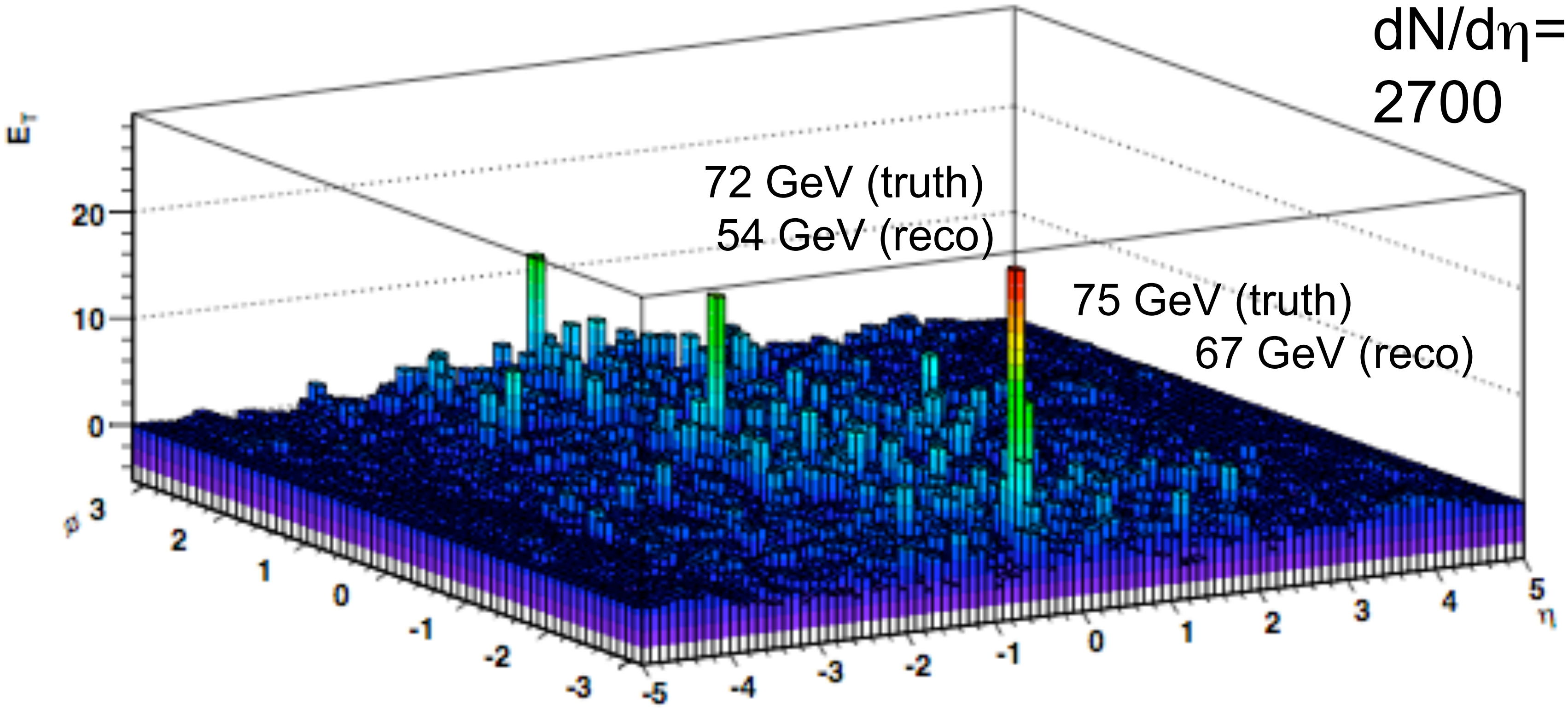
dN/dη= 2700

An Example Event: After



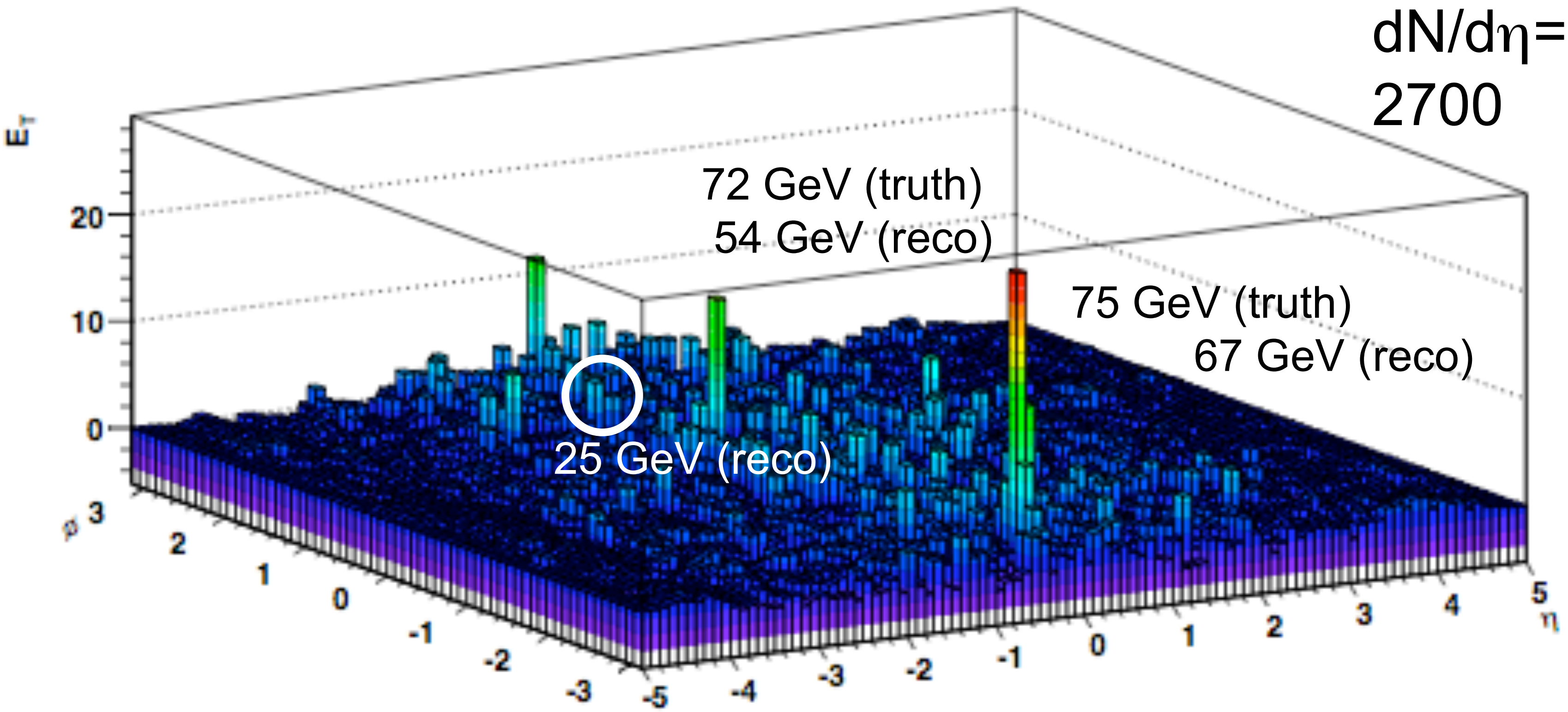
dN/dη= 2700

An Example Event: Reconstructed Jets



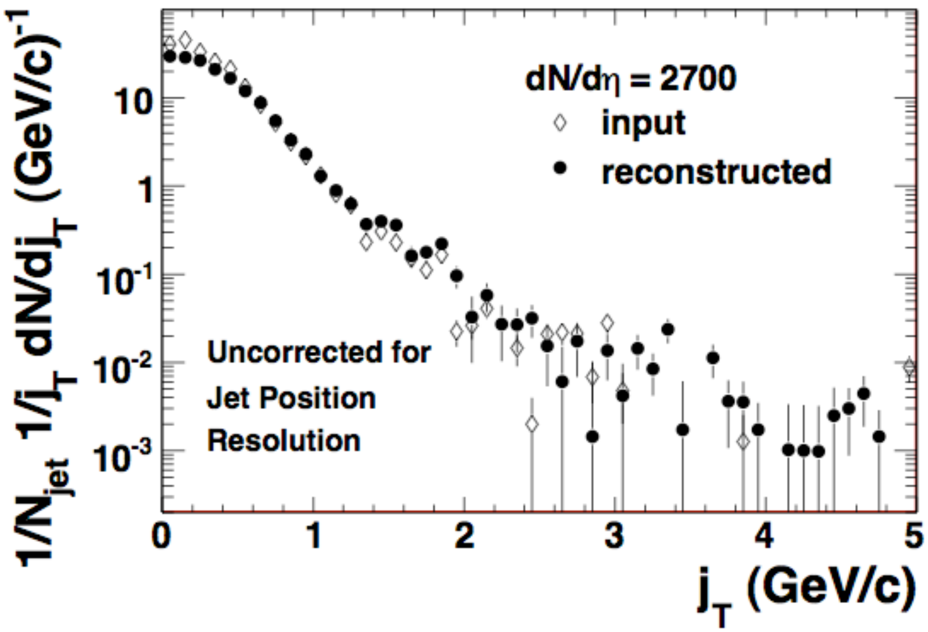
- Applying an R=0.4 iterative cone algorithm with seed > 5 GeV tower we find jets

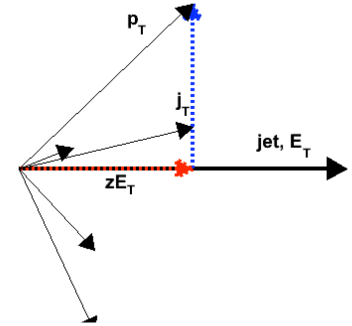
An Example Event: Fake Jets



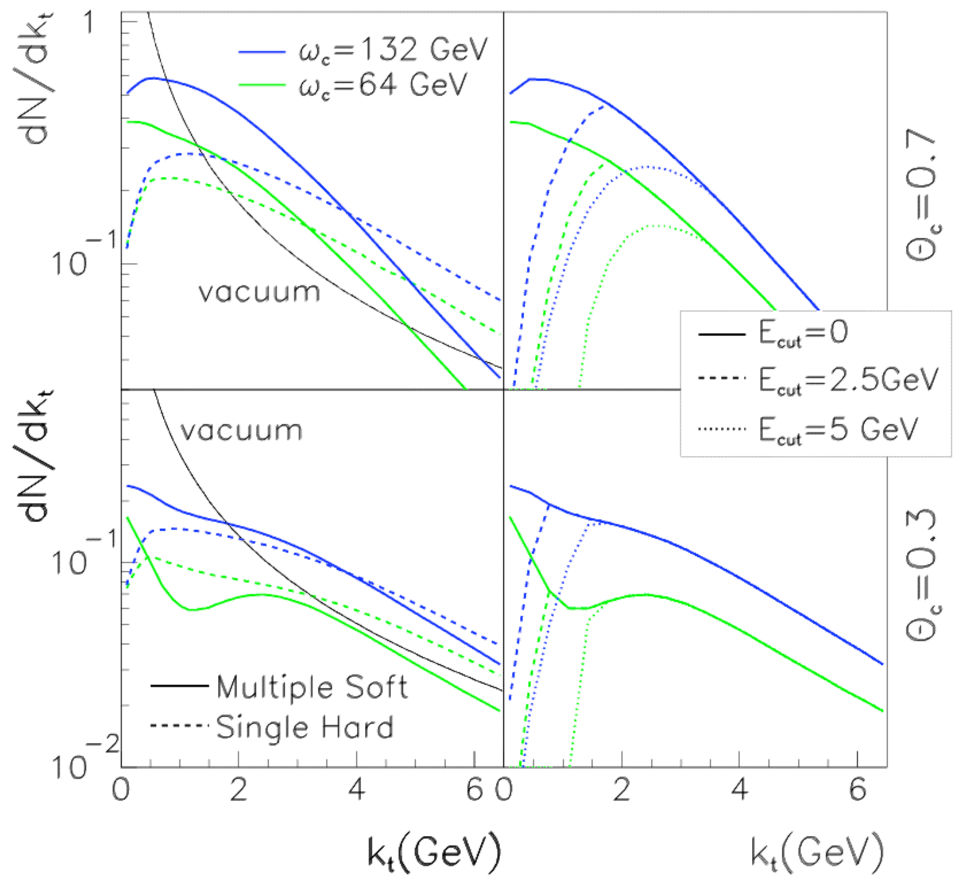
- Algorithm also finds a stable cone for fluctuations in the background
- Need to reject fake jets

Some Physics: j_T



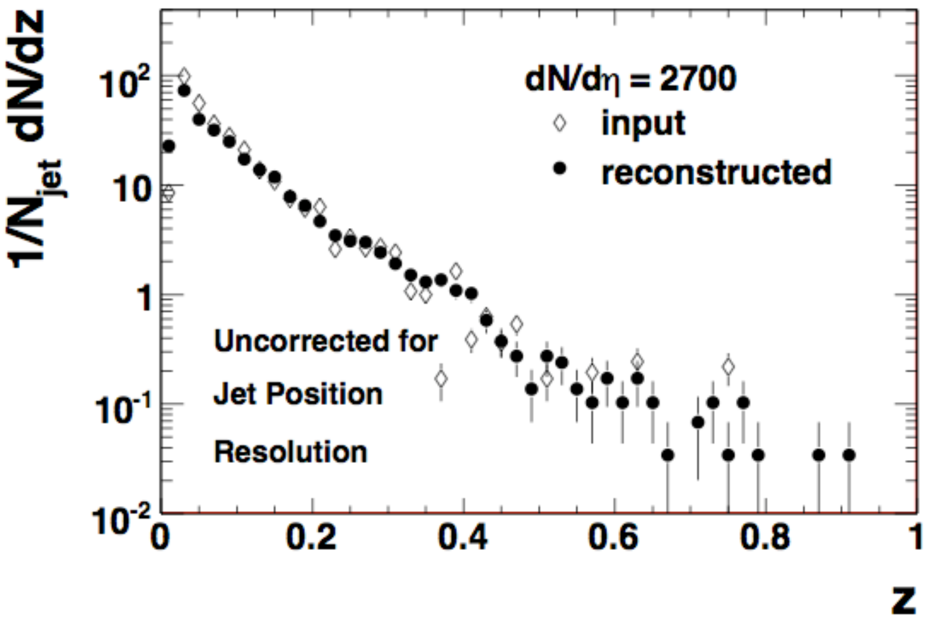


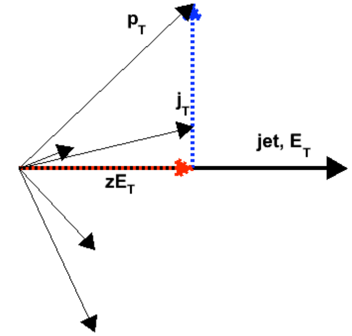
Salgado, Wiedemann
Phys. Rev. Lett. 93
042301 (2004)



- Match charged tracks to jets
- Reproduce input j_T before jet corrections

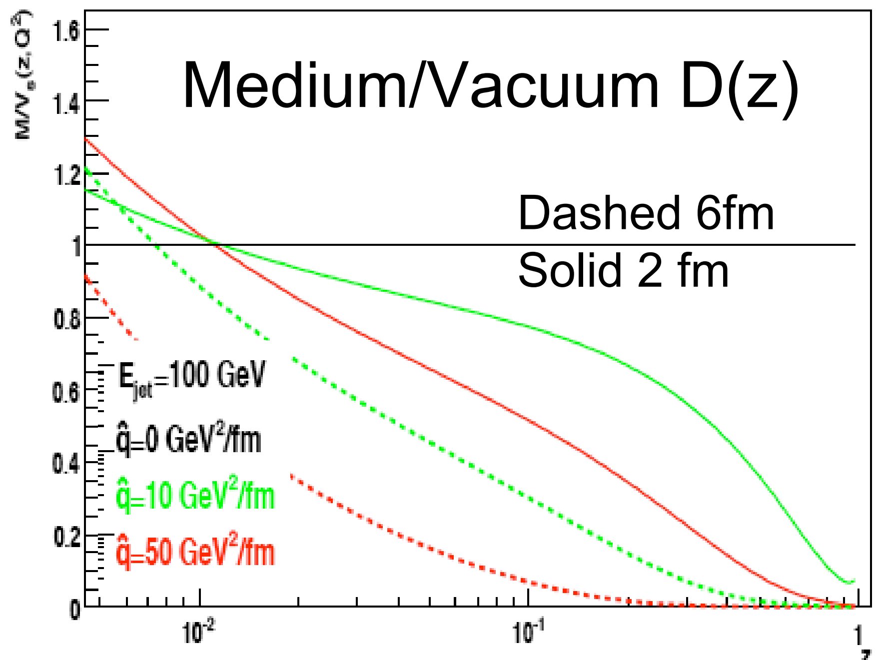
Some Physics: D(z)





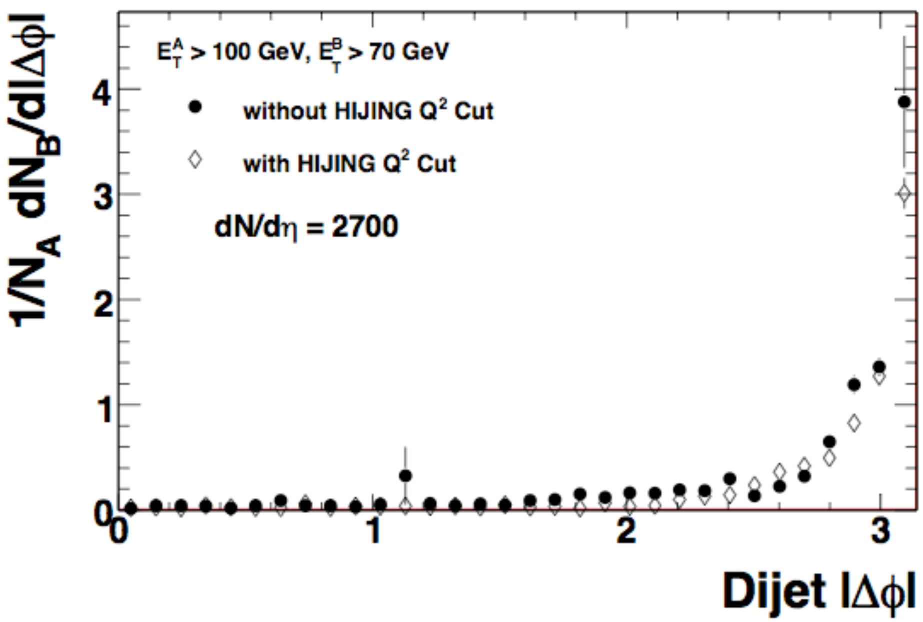
Armesto et al. JHEP02(2008) 048

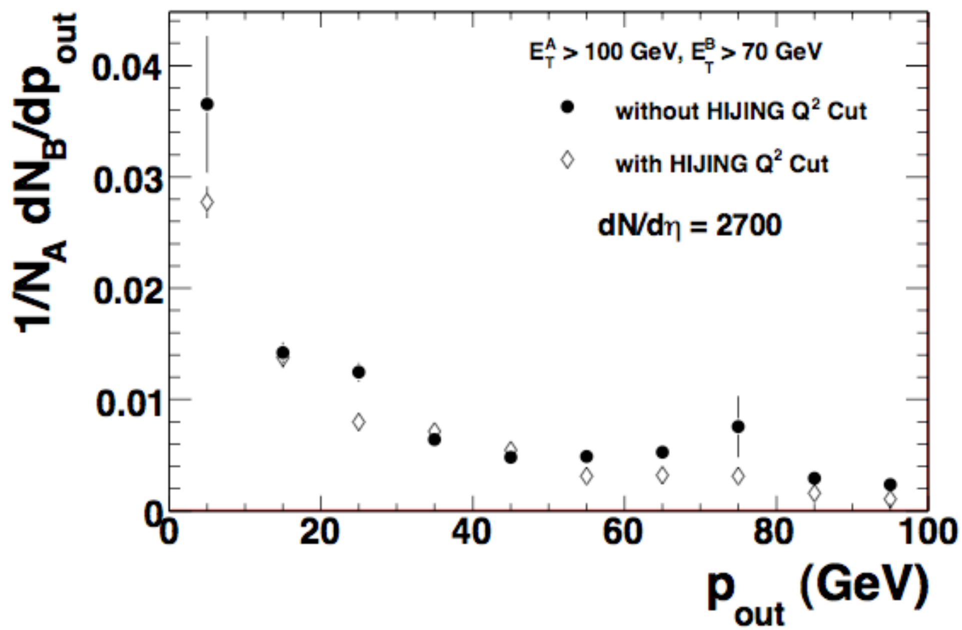
Gluon to Pion D(z)



- Reliable reproduction of D(z) before jet energy resolution correction.

Some Physics: Di-jet Correlations





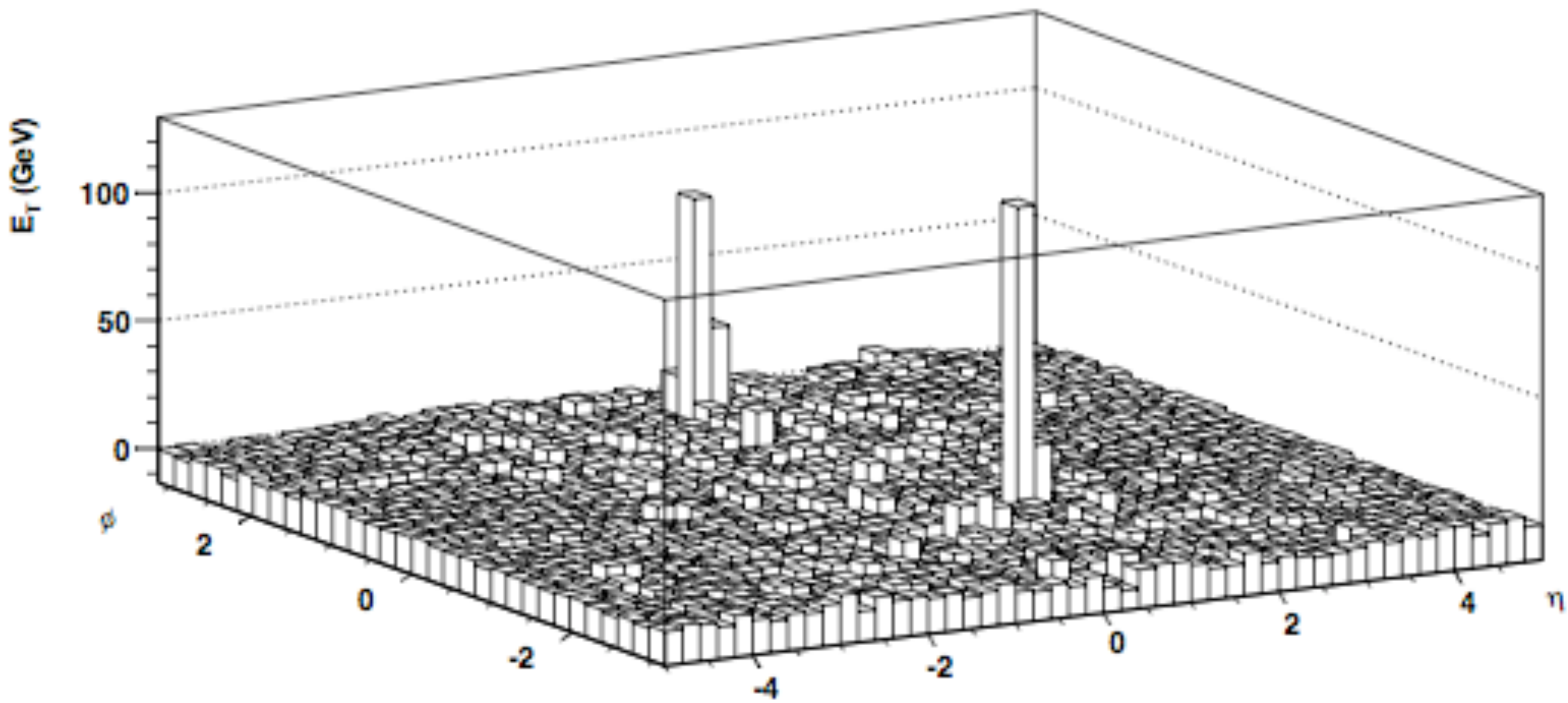
- Correlations of reconstructed jets as a function of $\Delta\phi$ and $p_{out} = E_{TB}\sin\Delta\phi$
- Clear peak at $\Delta\phi=\pi$ indicative of hard back-to-back jets.

Further Avenue: k_T Algorithm

- Using the k_T algorithm
  - Clusters based on relative energy between nearby towers/cells/particles but not in a fixed cone
  - Infrared and collinearly safe
- Because the k_T algorithm is O(N log N) [FastJet by Cacciari, Gavin, and Salam] run directly on HI events before background subtraction

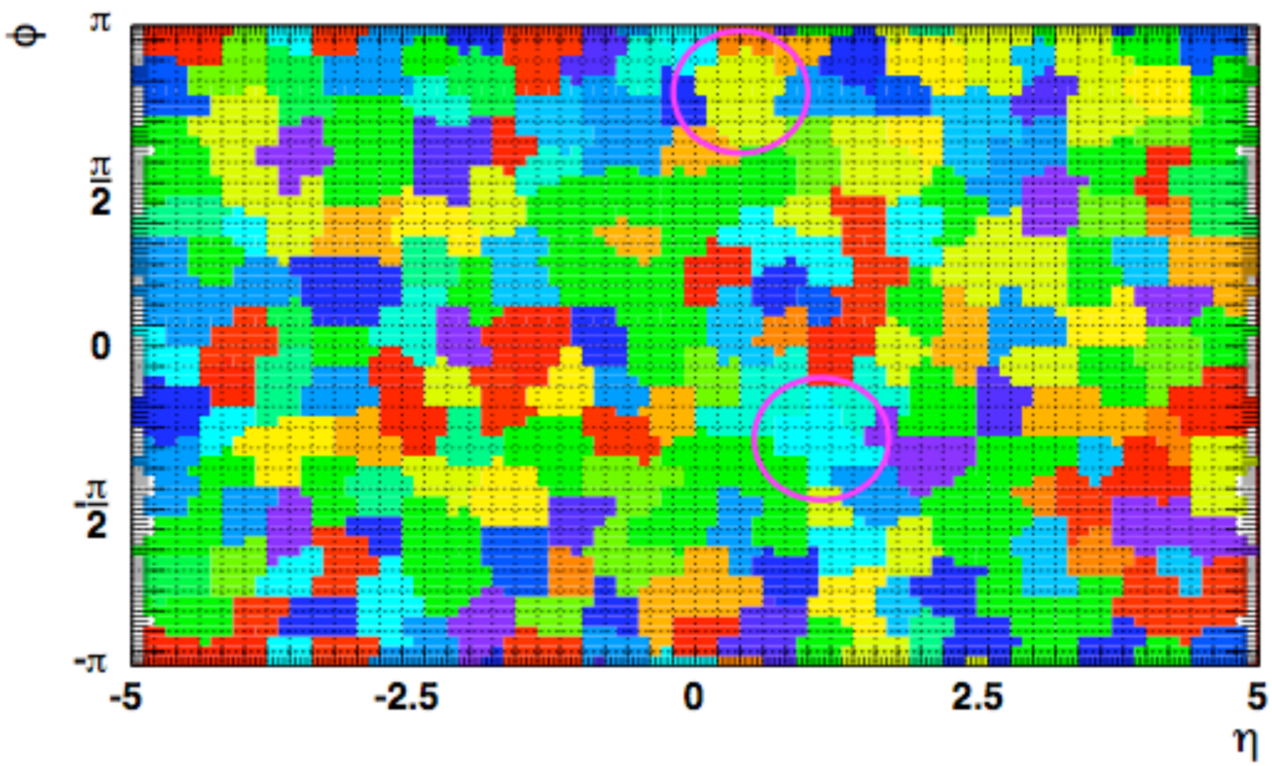
Example k_T Event

- Example event with Pythia di-jet embedded in unquenched HIJING



Example k_T Event

- Applying the k_T algorithm directly on the HI event clusters all towers into a jet

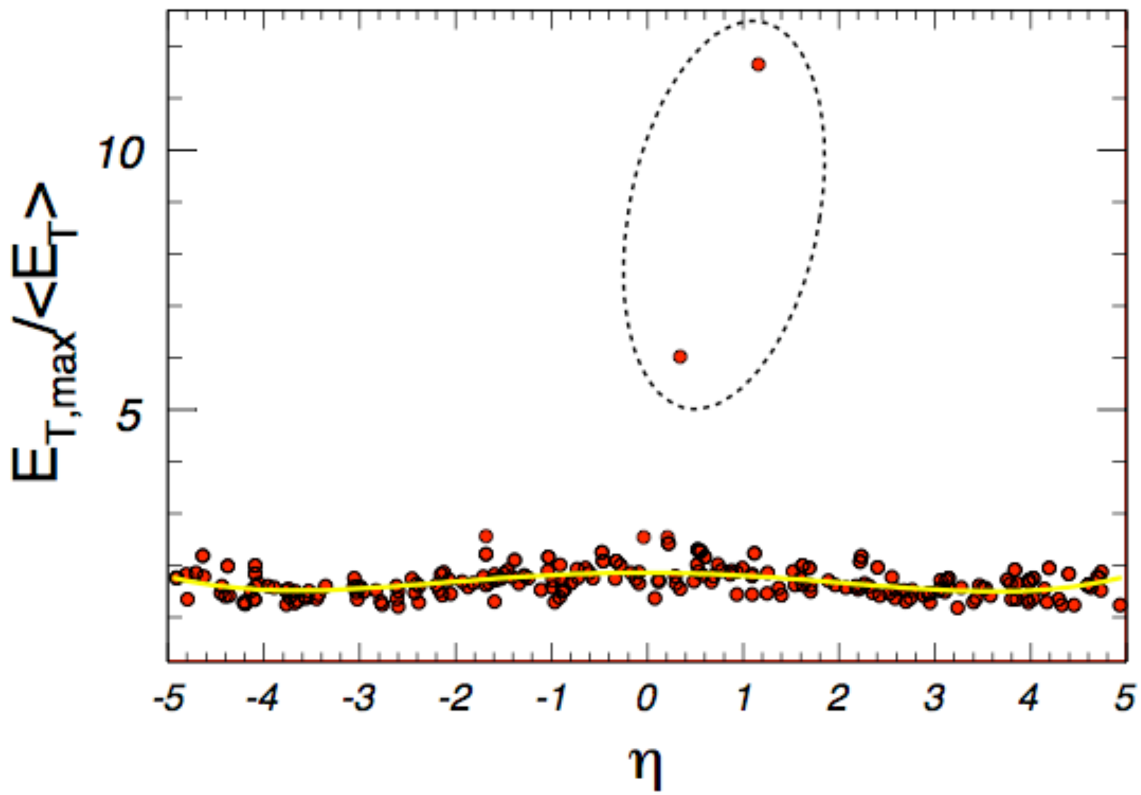


Pink circles indicate pythia di-jets

All other jets are composed primarily of background

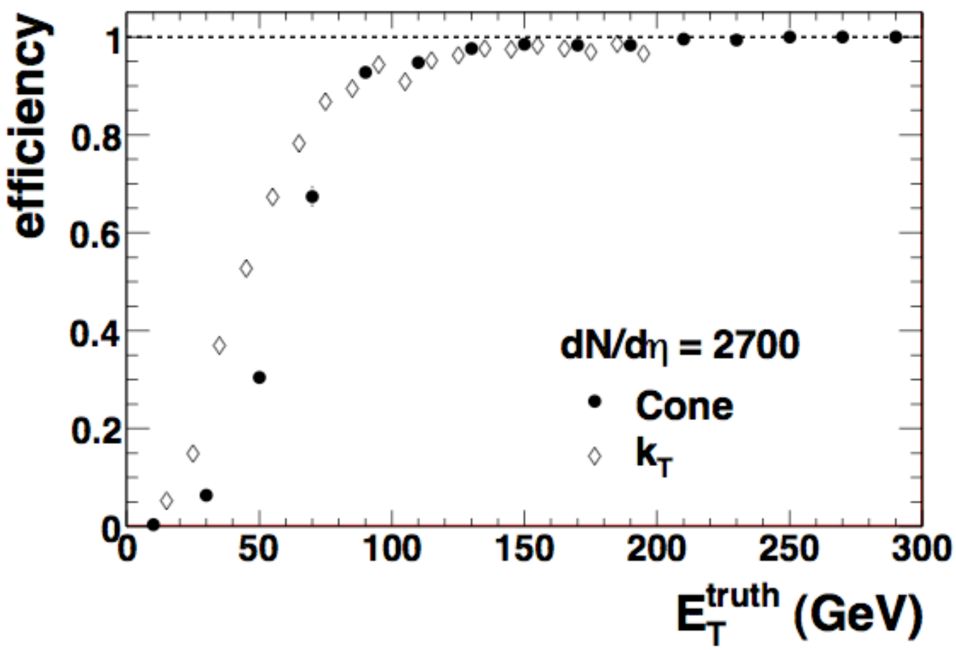
Example k_T Event: Discrimination

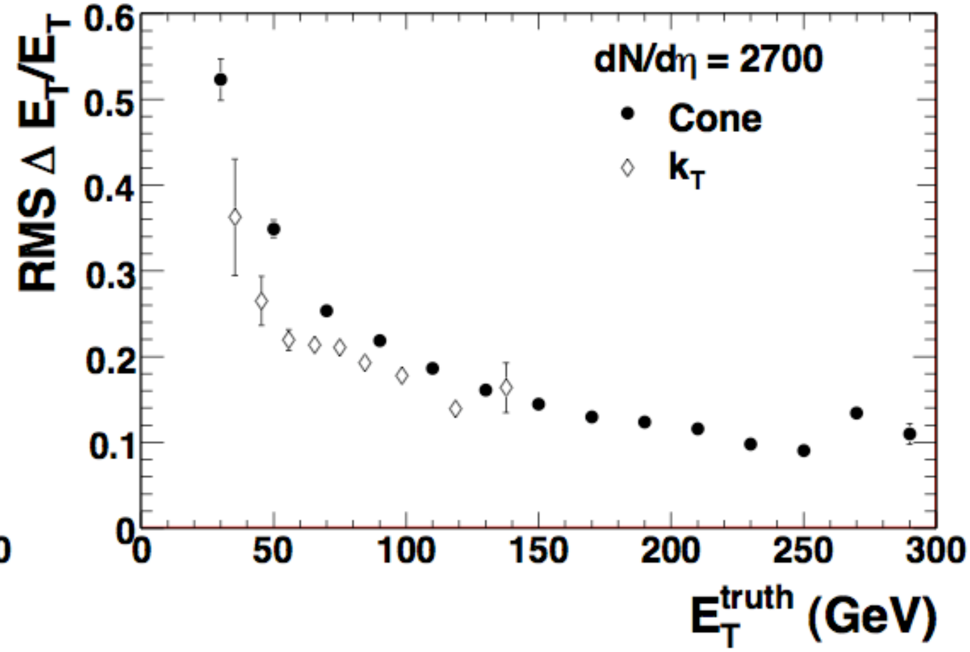
- Define a (several) discriminating variable(s) to distinguish between real and fake jets



- Example is max/avg tower E_T jet-by-jet.
- Pythia dijets are clearly visible.
- Use fake jets to subtract background

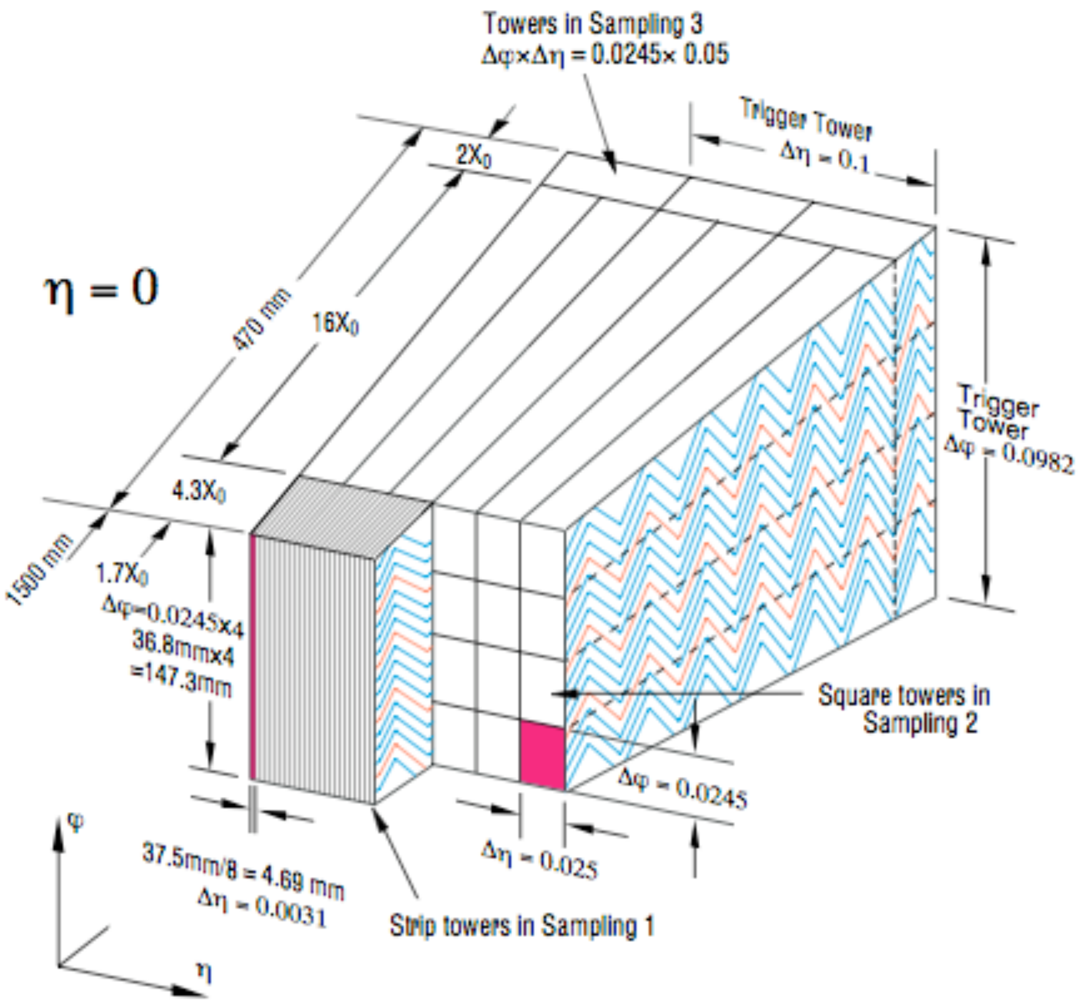
Cone and k_T Performance Comparison





- Performance differences due to differences
  - Intrinsic to the jet algorithms
  - In handling the background
  - In rejection fake jets
- Multiple methods allow control of systematics

Photon ID: The Strip Layer

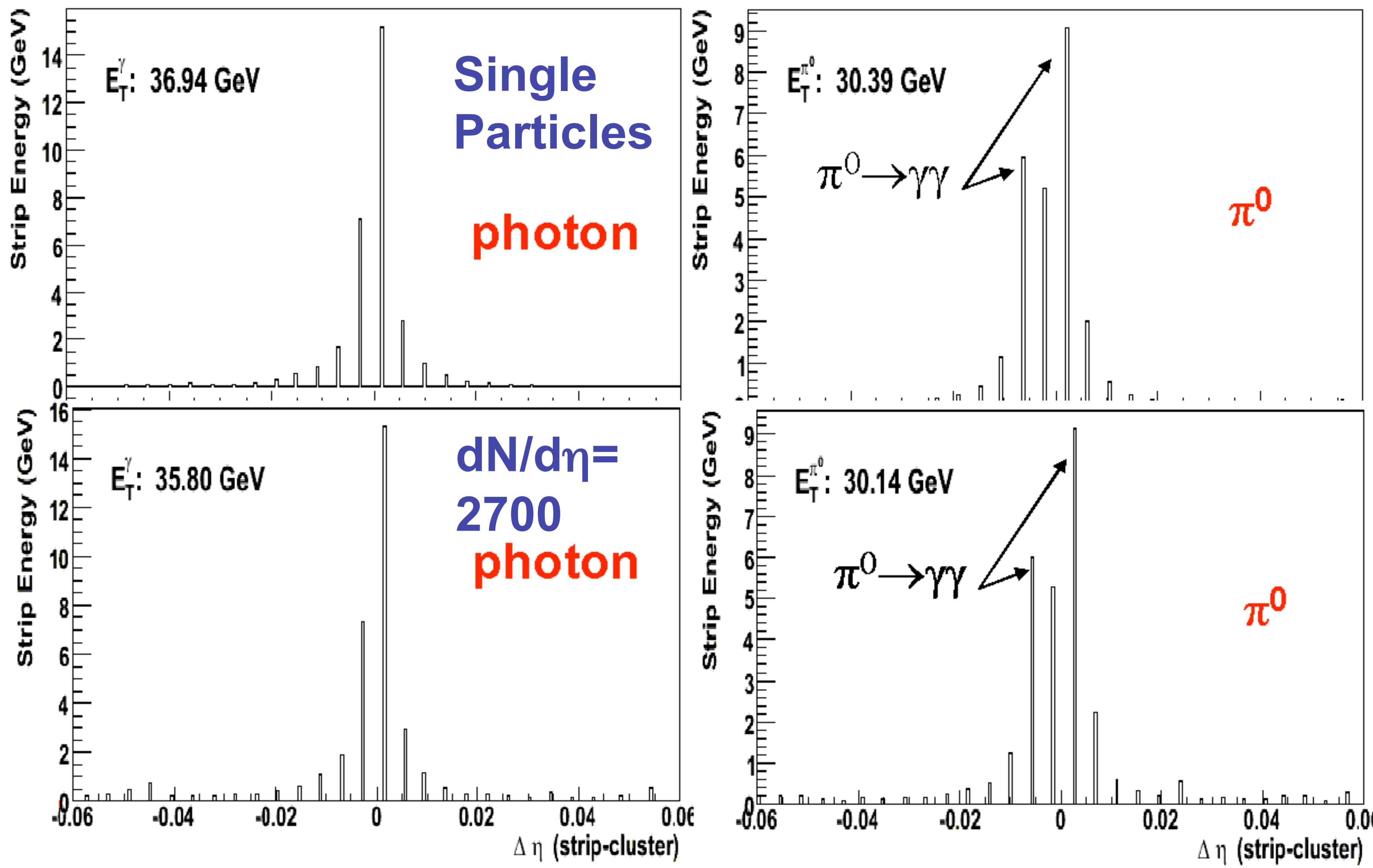


- Designed to measure

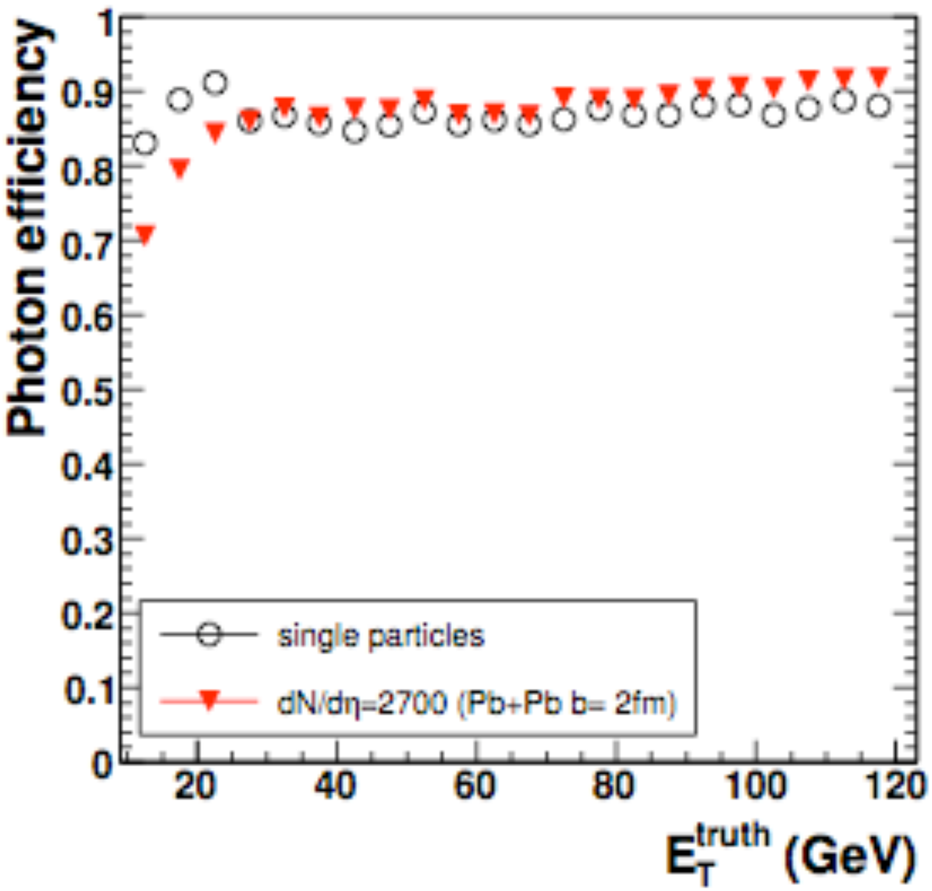
  $H \to \gamma\gamma$

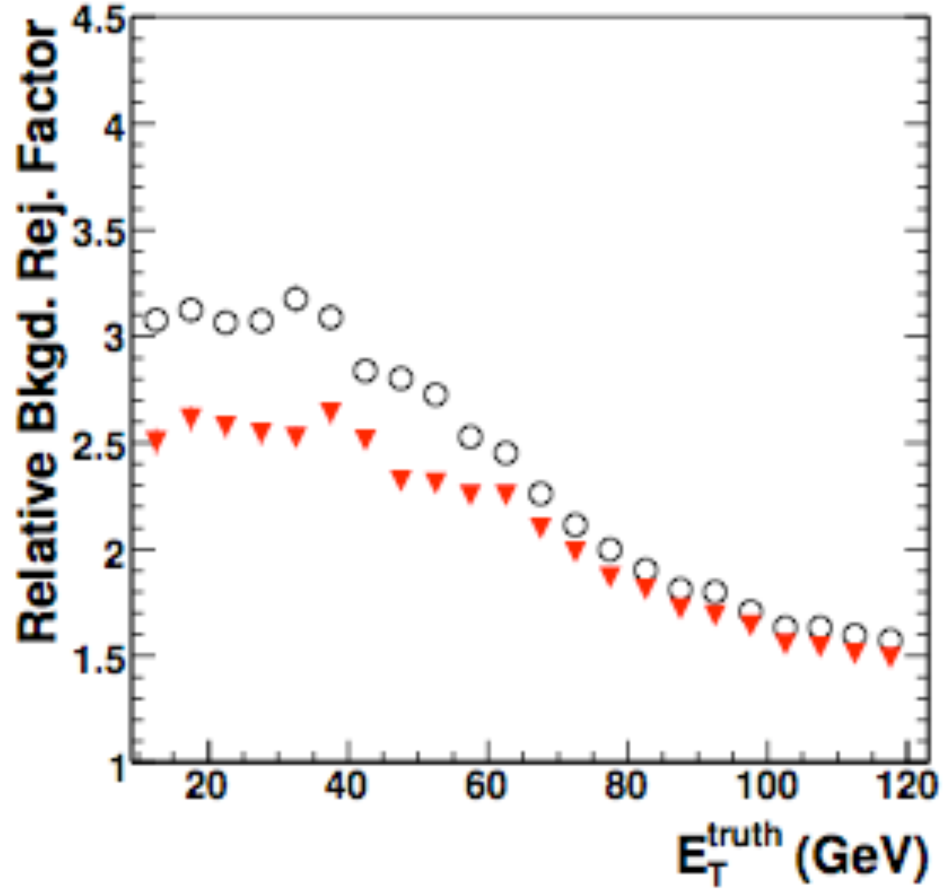
  and rejecting di-jets
- γ and π^0 separation for wide range of E_T
- Front layer: strips
  - Typically 0.003x0.1 in $\Delta\eta$x$\Delta\phi$
  - Over $|\eta|$<2.5

Photon ID: The Strip Layer



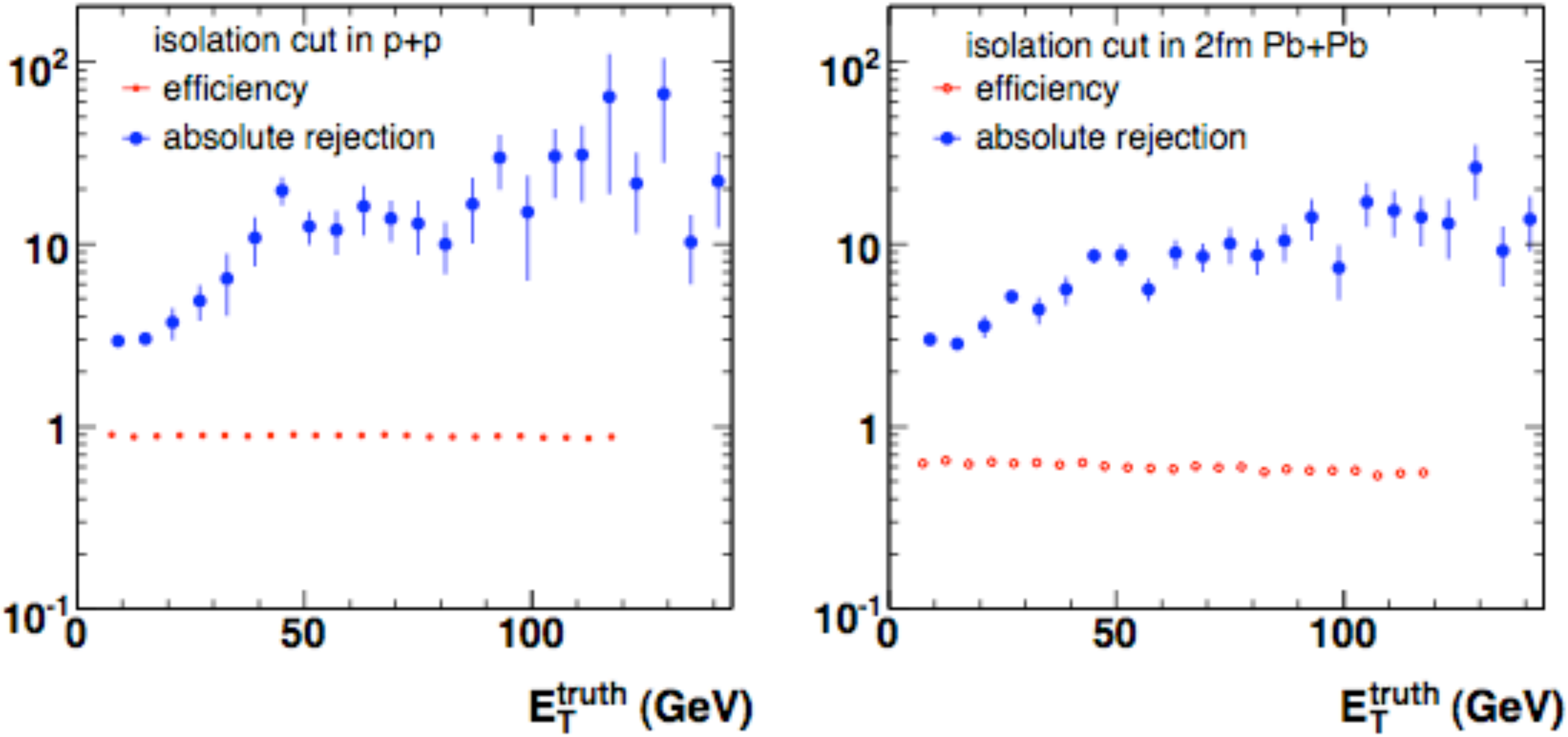
Photon ID: Strip Layer Rejection





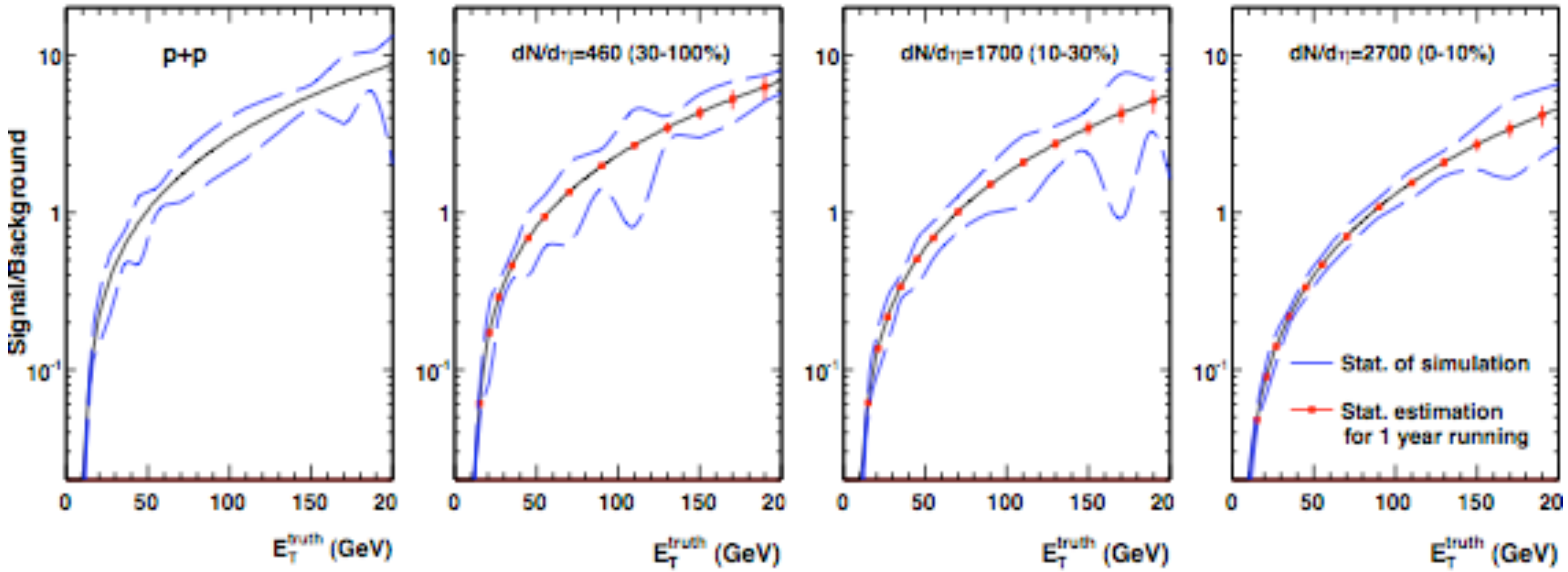
- Rejection of background from strip layer
  - Before isolation means measurement of fragmentation photons!

Photon ID: Isolation



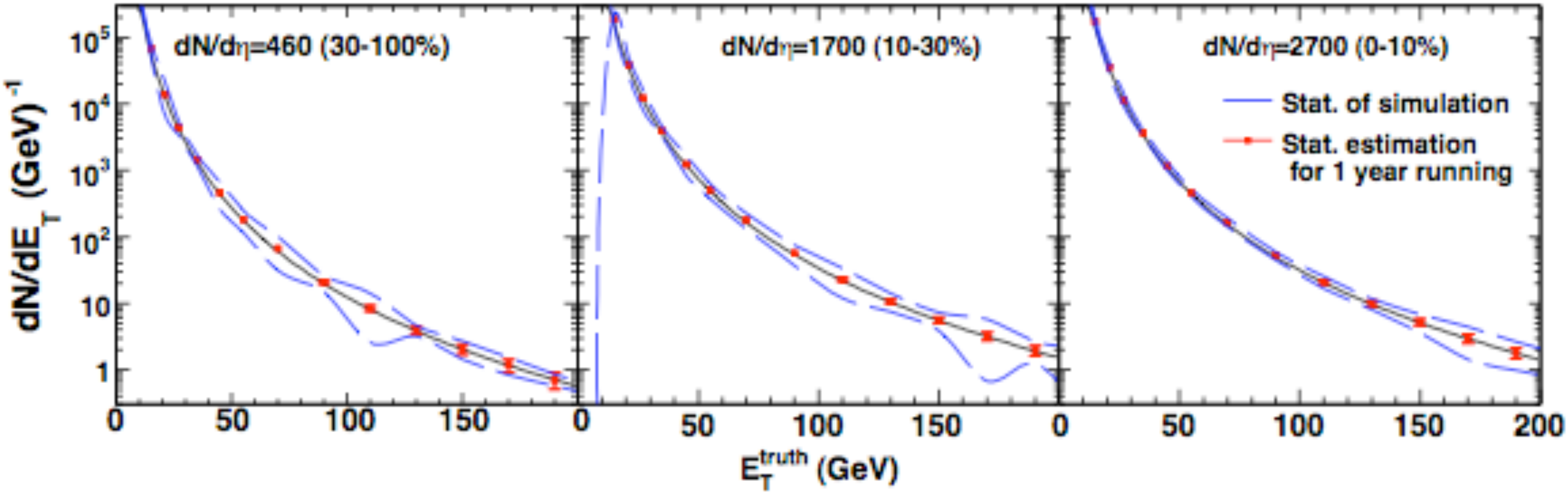
- Require ΣE_T^{EMC}<f(cent,E_T) and no p_T>g(cent,E_T)

Combined Strip/Isolation Rejection



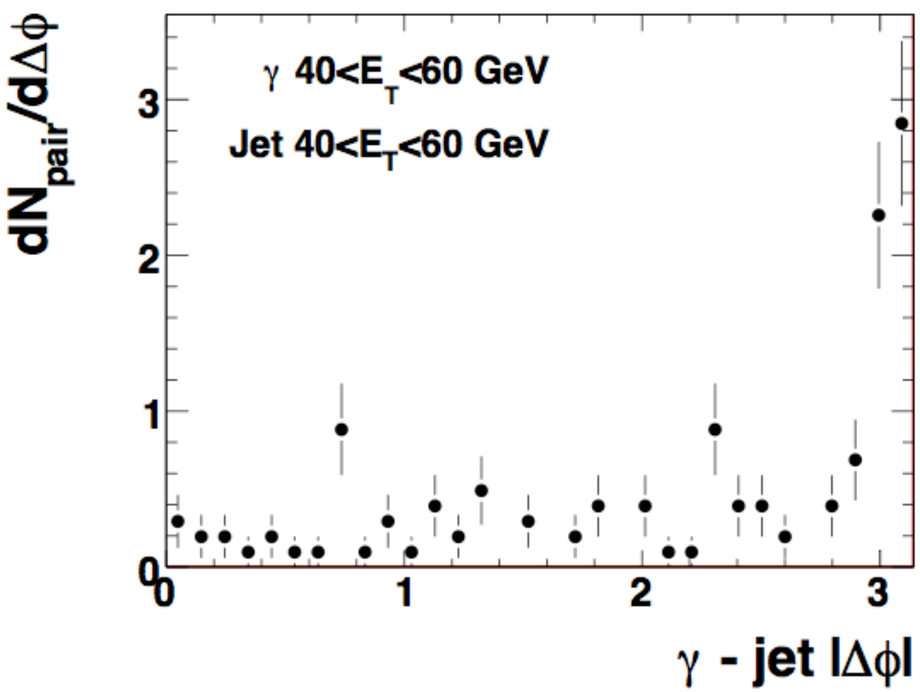
- Worst case scenario: $R_{AA}{}^{h}=1$
- If $R_{AA}{}^{h}=0.2$, S/B=1 at 30 GeV for dN/dη=2700
- Expect 200k direct photons for $E_T>30$ GeV

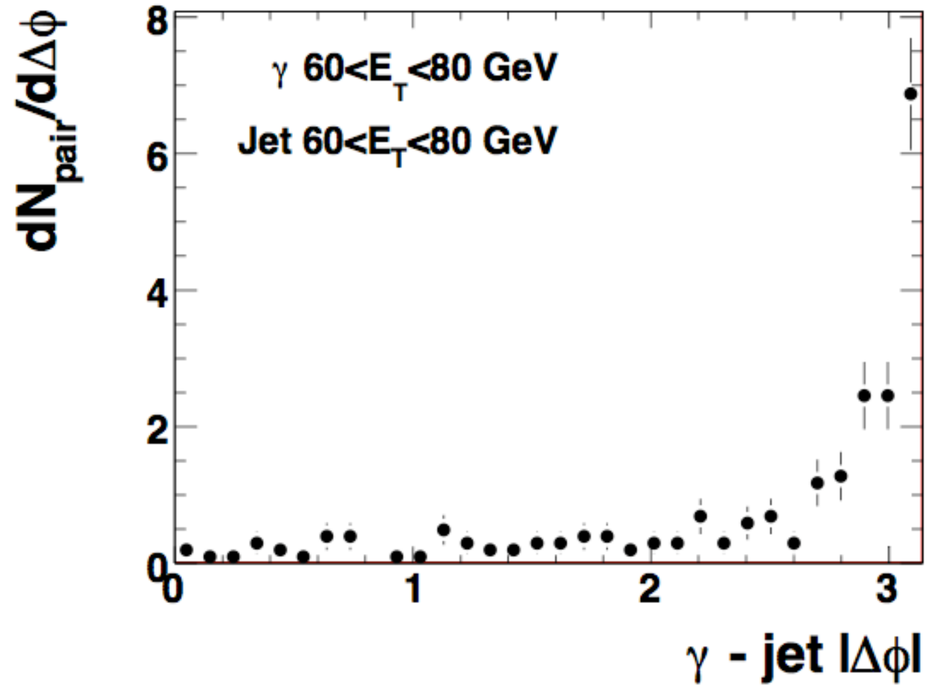
Photon Spectra



- Estimated spectra for different centrality from 1 LHC year (1 month, 0.5 nb^{-1})

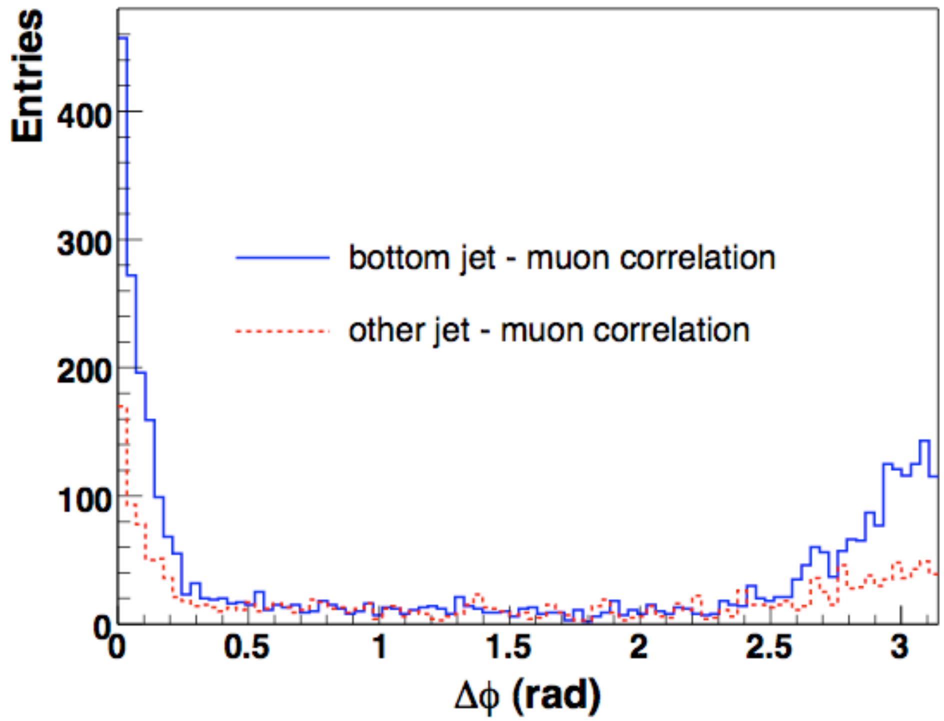
γ-Jet Correlations

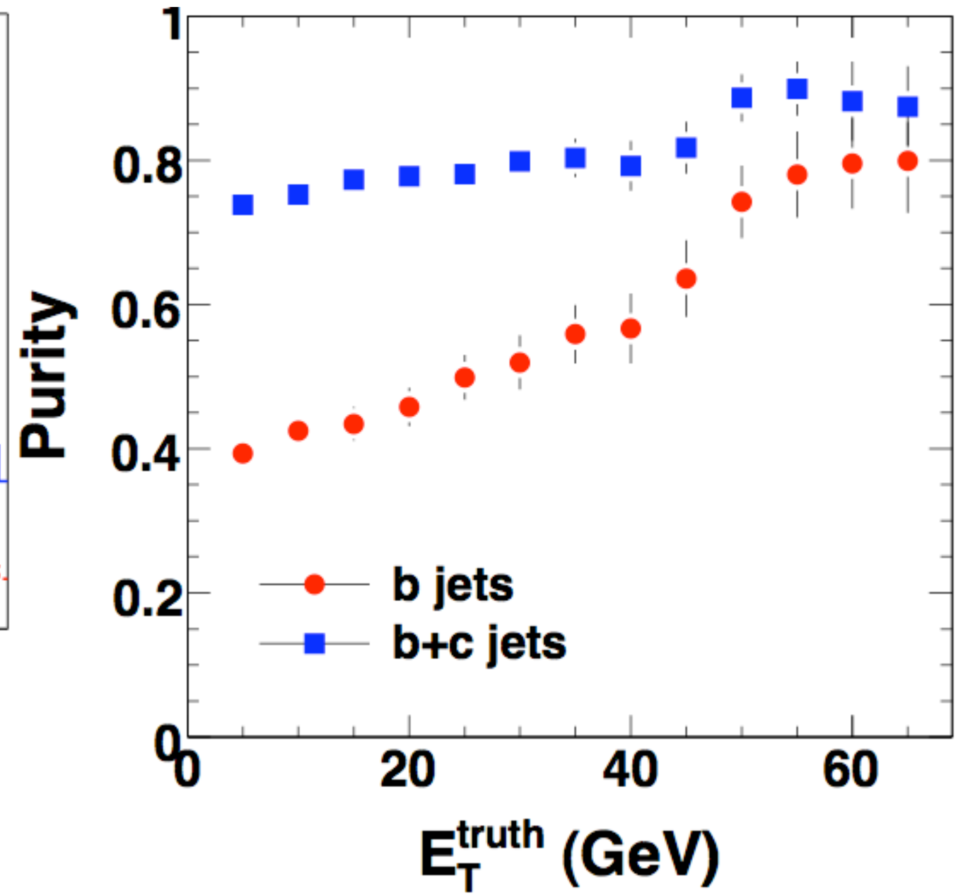




- Clear back-to-back correlations down to 40 GeV!
- Small Δφ dominated by fake reconstructed jets
  - Use correlations to study background rejection of jets

Muon Tagging: Heavy Quark E-loss





- Require muon in jet o in recoil jet
- Cut on muon p_T