Srážky těžkých iontů v detektoru ATLAS

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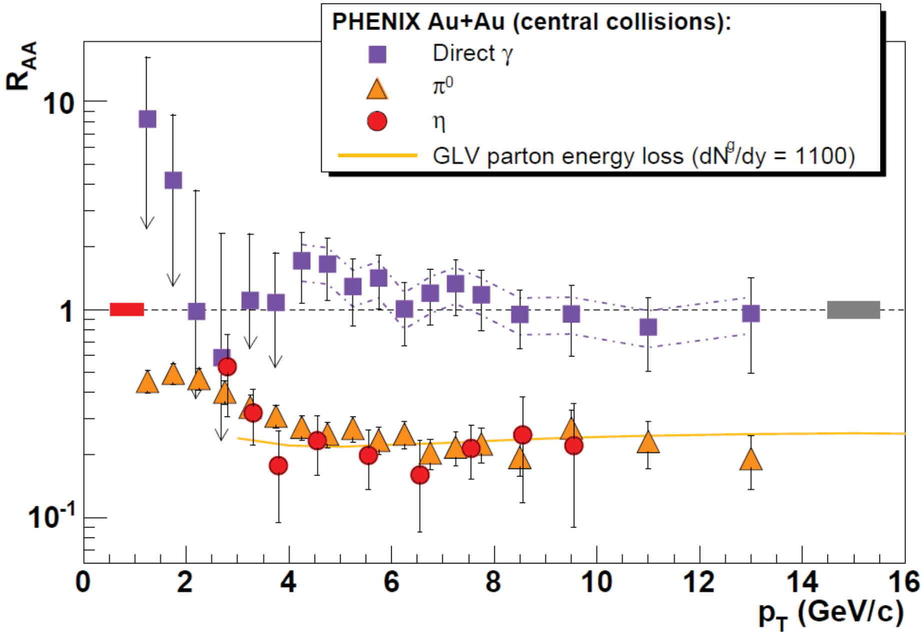
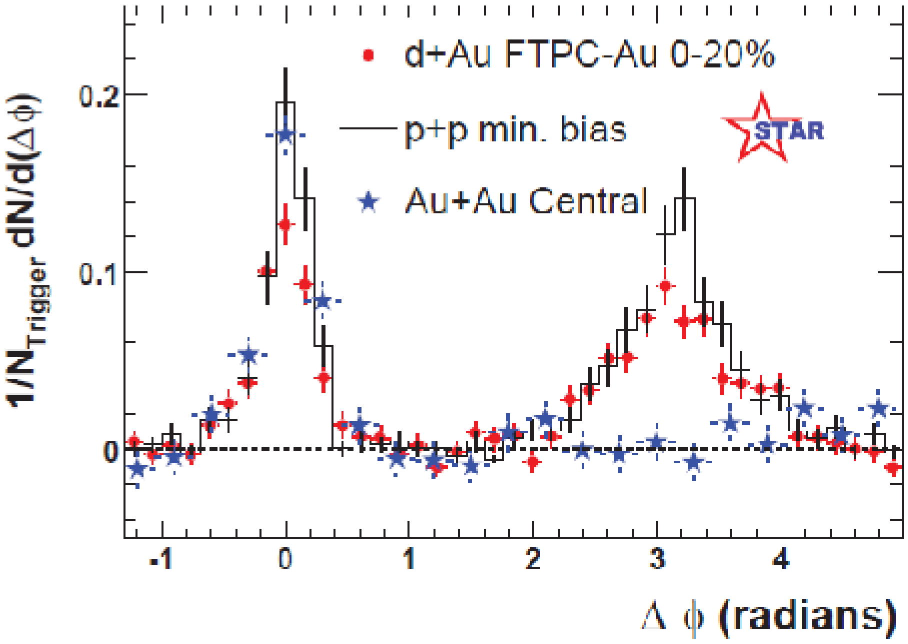
Motivation

- Main task is to better understand QCD at high temperature where quarks and gluons are deconfined.
- In this limit strong interactions can possibly exhibit unexpected characteristics that do not follow from perturbative considerations.
- One of useful tools are jets - jet quenching predicted in early 90's and observed at RHIC experiments.





Motivation

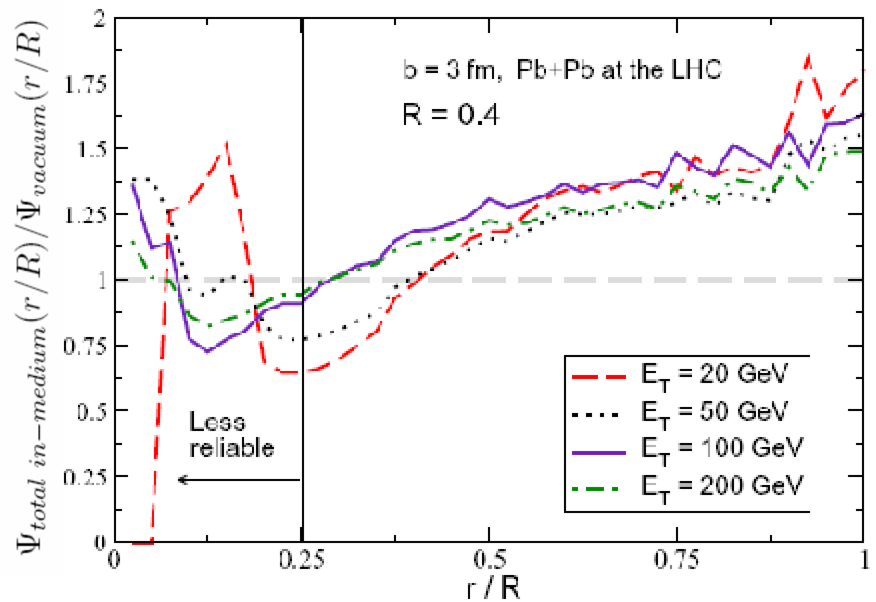
The **main results** concerning high-p_T probes from RHIC experiments:

- High p_T hadrons are suppressed by a factor of ~5 compared to binary scaled p+p.
- Away side peak is completely absent in di-jet correlation measurements.
- Measured spectra obey power-law behavior characteristic for pQCD processes.
- ...

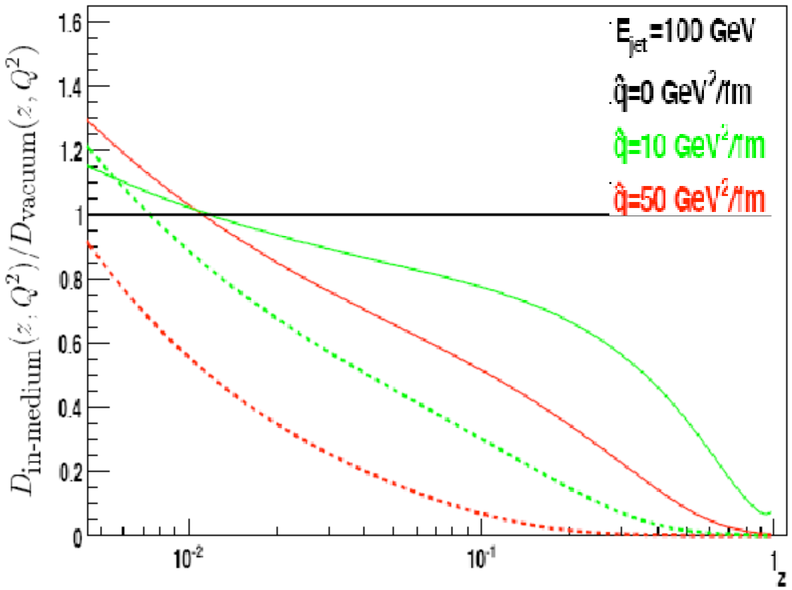
- Energy loss is a final state effect, not an initial state effect.
- Energy loss is at the parton level, not at the hadron level.
- Partons lose their energy dominantly by the radiative energy loss, collisional energy loss may be important only for heavy quarks.
- Partons lose 1-10 GeV/fm^3 in the created medium. This energy loss seems to depend linearly on the path-length traveled through the expanding medium.

Motivation

- Jets copiously produced at LHC energies → possibility to study details of energy loss mechanism in QGP medium
- Models and predictions for LHC energies exist but the details of QCD energy loss mechanisms in medium not well understood



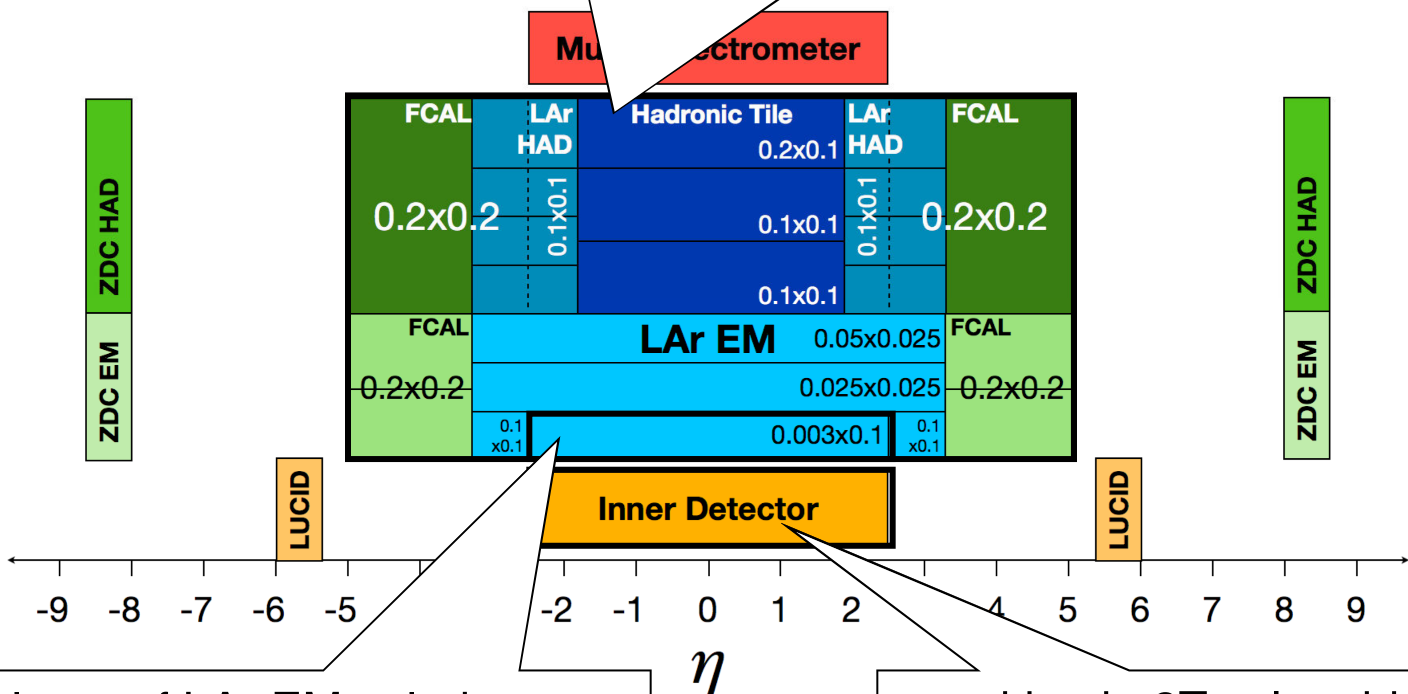
I.Vitev, *et al.* – modification of jet shapes



N.Armesto, *et al.* – modification of fragmentation functions

Why ATLAS?

jet reconstruction using calorimeter, full azimuth, 10 units of pseudorapidity

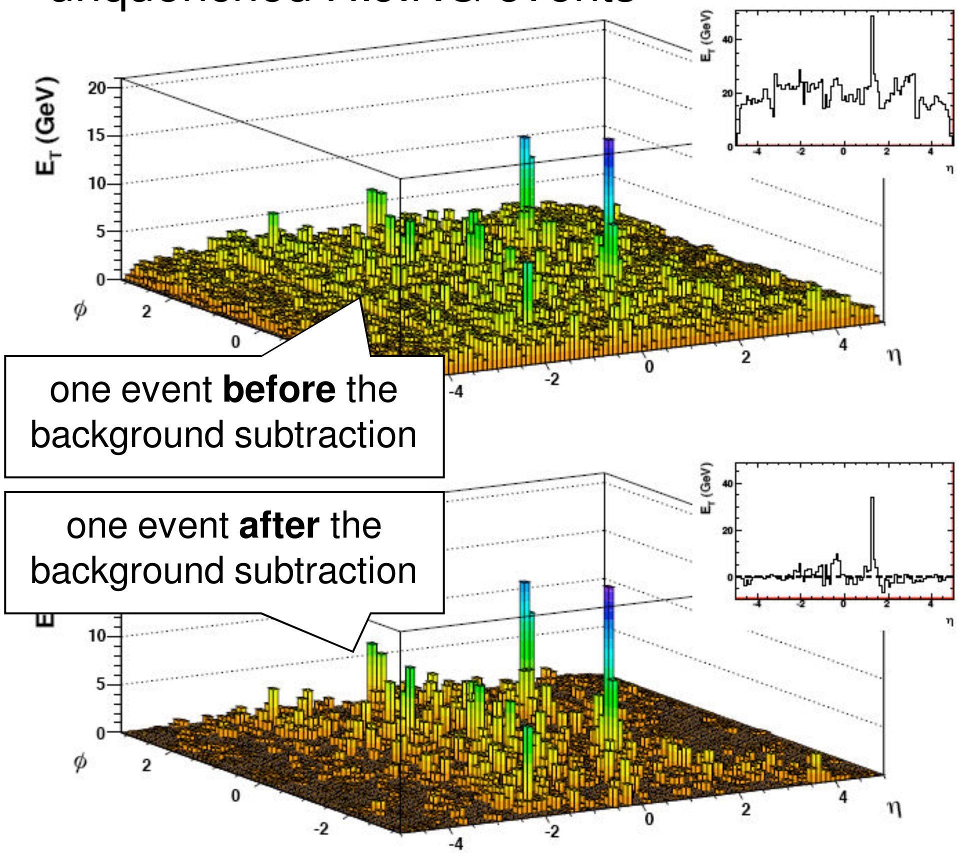


first layer of LAr EM calorimeter excellent for photon isolation, other layers also well segmented

tracking in 2T solenoid – fragmentation studies

Jet reconstruction strategy

PYTHIA dijets embedded to the unquenched HIJING events



Cone jet reconstruction:

- regions of interest found (seed regions) – fast sliding window algorithm used
- background computed
  - excluding the seed-regions
  - vs. η, vs. *layer*
- background subtracted
- standard p+p jet finding algorithm used (seeded iterative R=0.4 cone algorithm)

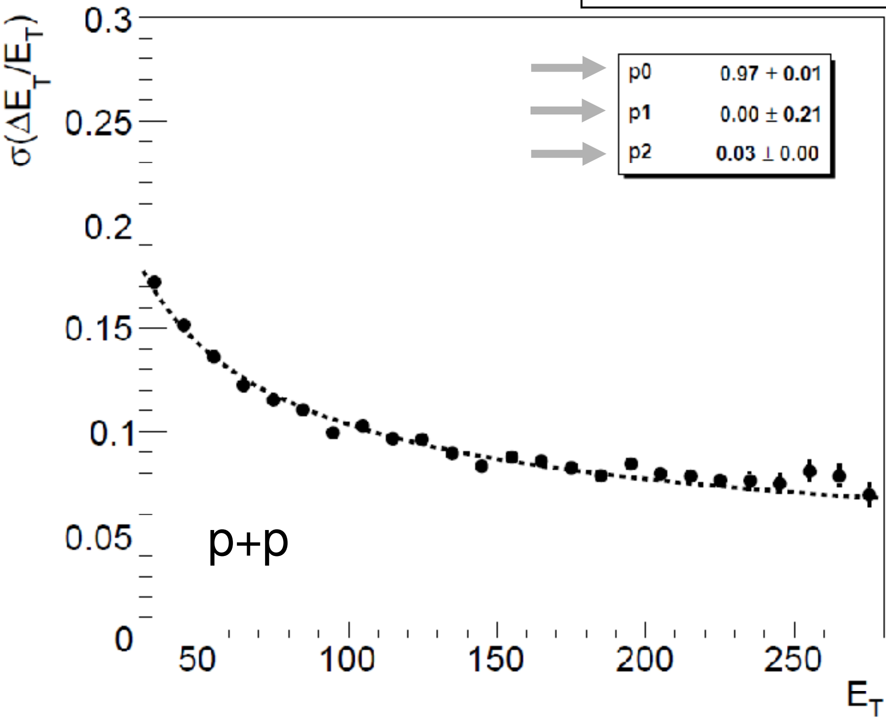
$$R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

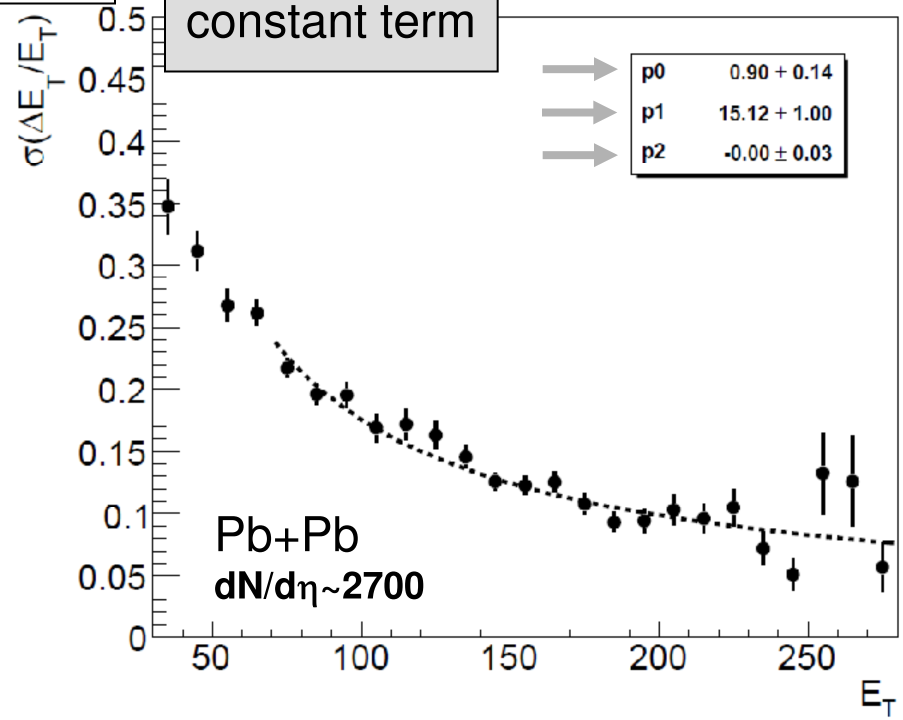
An alternative: **k_T-algorithm** based reconstruction strategy – also studied

Jet energy resolution

Fitting well known formula: $$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$ to p+p and Pb+Pb energy resolution

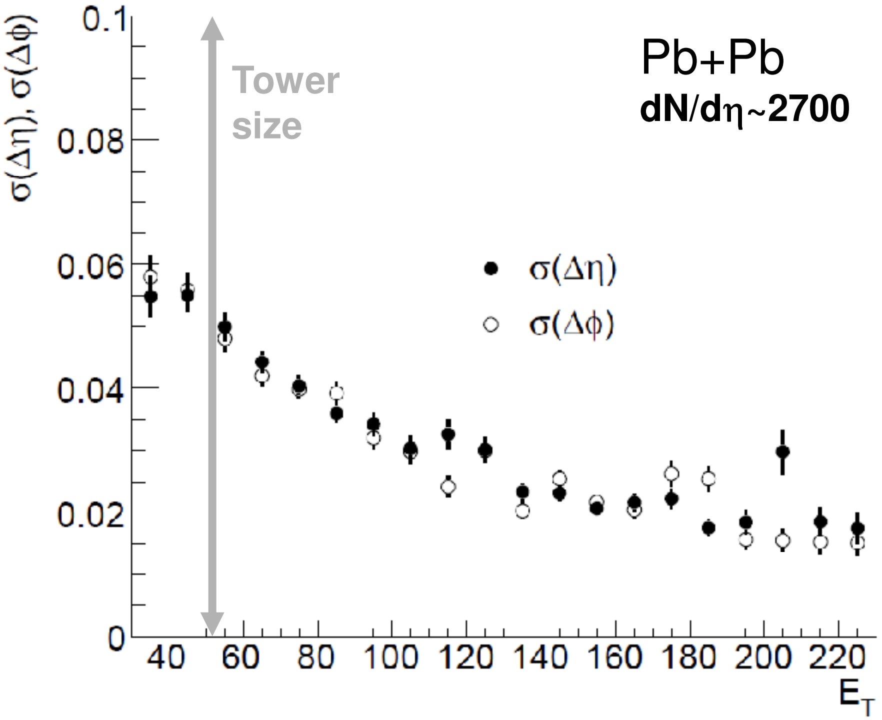
stochastic term (a) — noise term (b) — constant term (c)

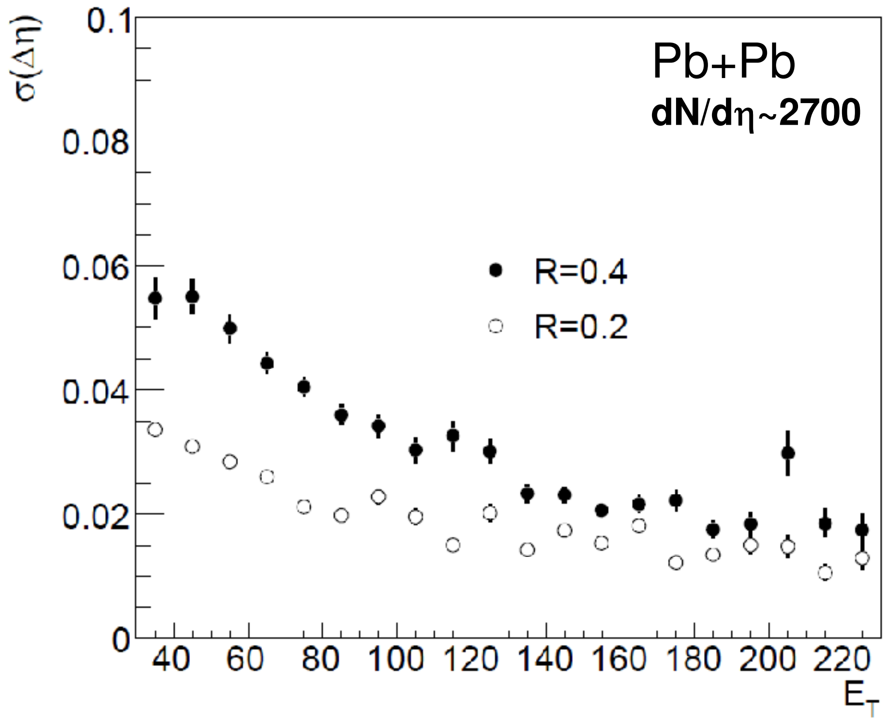




- Jet energy resolution bellow 25% for 70 GeV jets in the most central collisions (dN/dη~2700 ⇔ b=2 fm, unquenched HIJING)
- Irreducible background fluctuations: ~ 15 GeV / jet

Jet position resolution

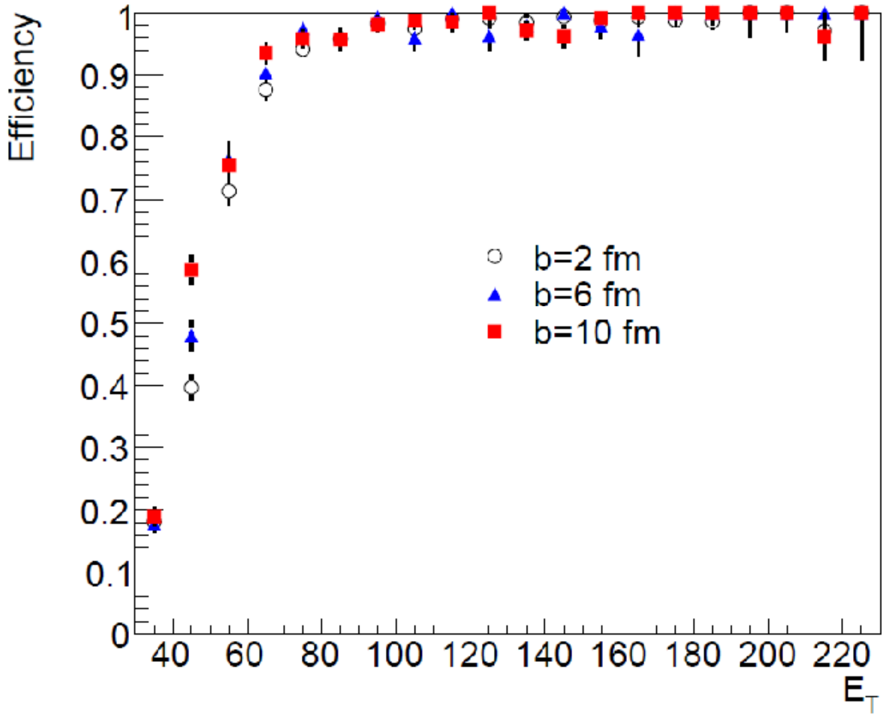


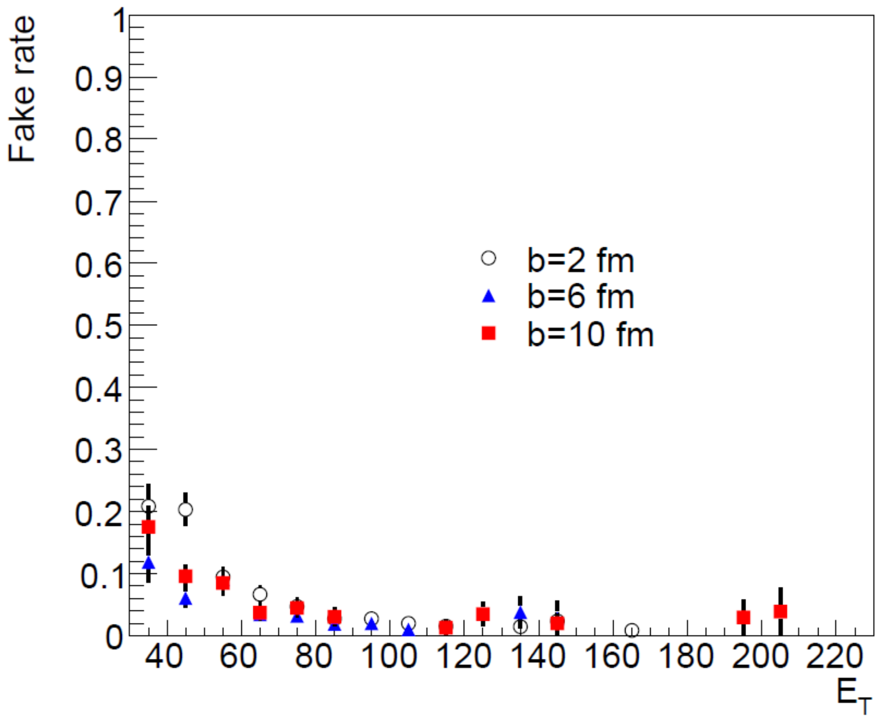


- Jet position resolution in ϕ similar to that in η (full field simulated)
- It proves with increasing jet energy, in the whole energy range jet position resolution is within a half of a tower

- Jet position resolution can be improved using a method of smaller cones: jet axis of a reconstructed jet is substituted by the jet axis from jet reconstructed with $R<R_{orig}$

Efficiency and fake-rate

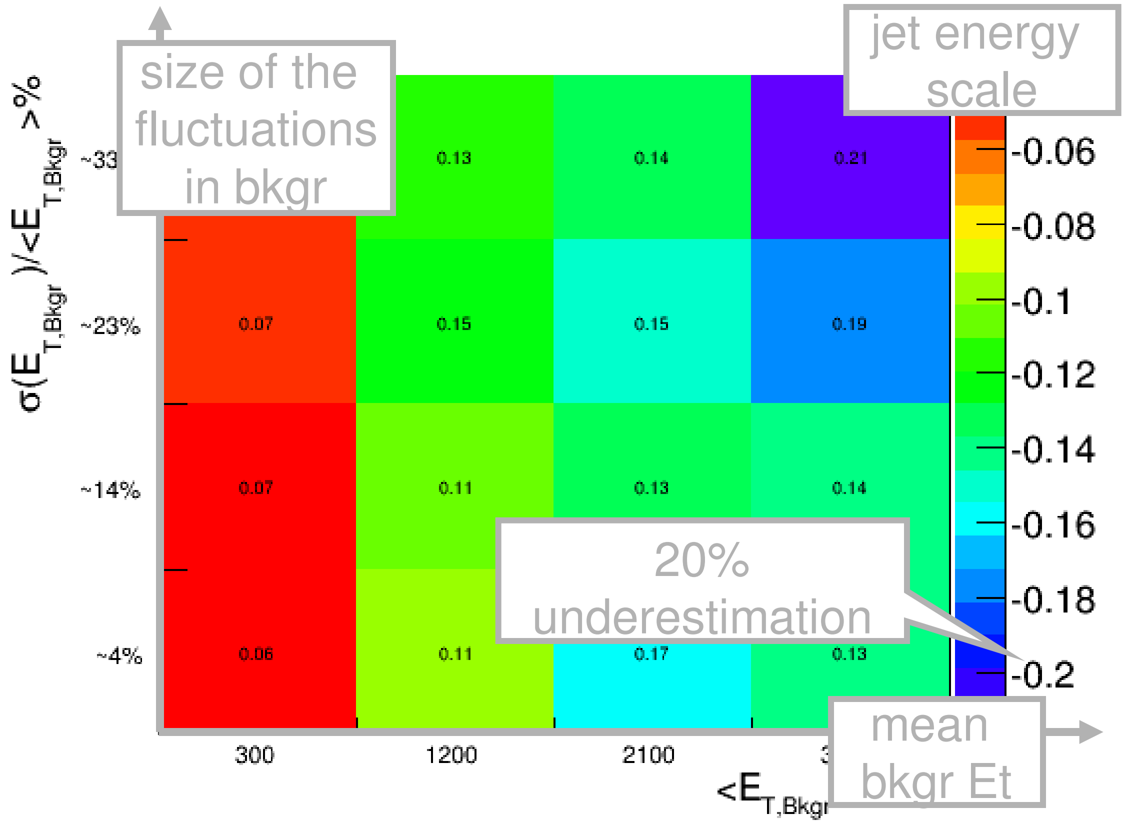




- Efficiency is almost centrality independent – easier interpretation of jet properties vs. centrality
- Above 70 GeV the efficiency is above 90%
- Above 70 GeV very low fake rate < 5% (without any fake rejection)

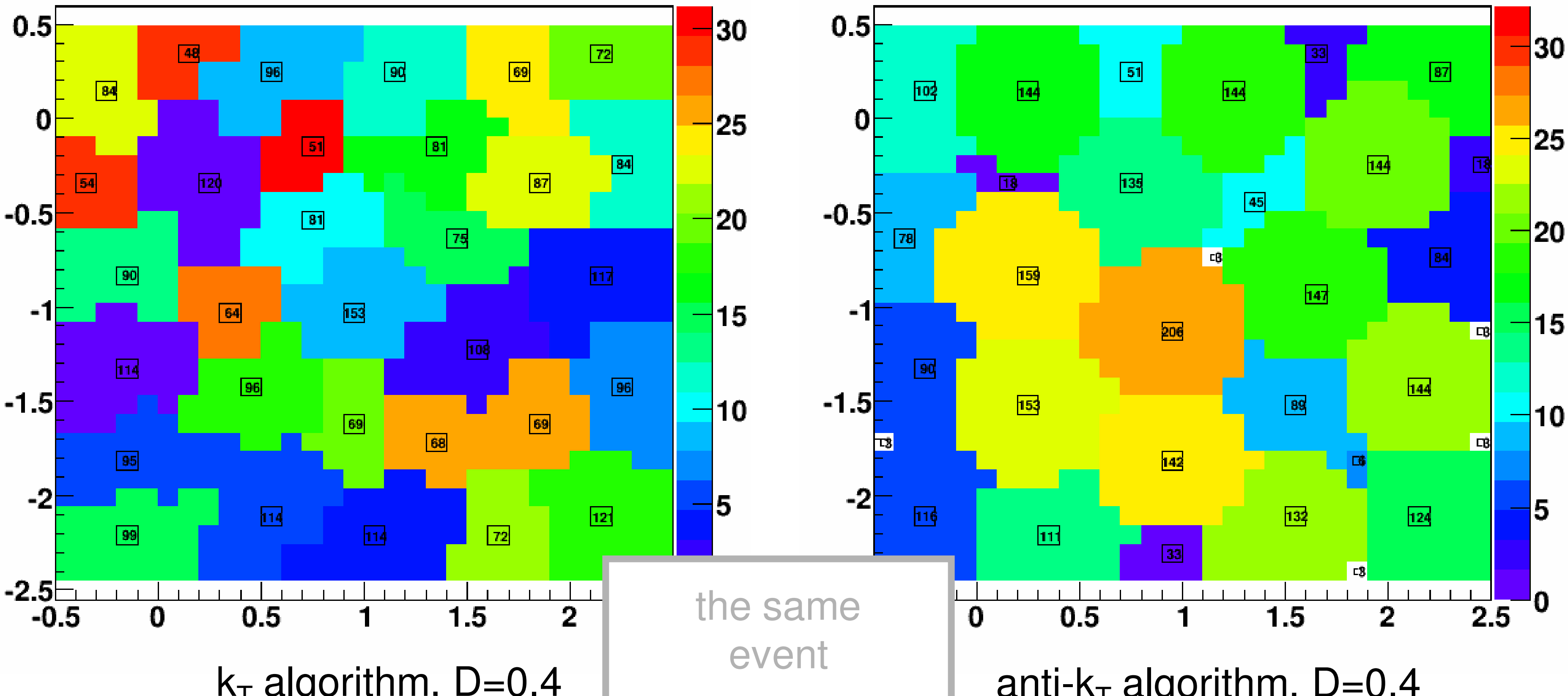
Comparison among jet finding algorithms

- k_T algorithm exhibits serious problems with the jet energy scale: for more severe background, k_T underestimates the jet energy. This is due to the fact that k_T preferably clusters the softer part of a jet with the background k_T
- Problematic algorithms:
  - k_T algorithm,
  - Cambridge/Aachen
- Non-problematic:
  - anti-k_T algorithm,
  - (ATLAS) cone algorithm
- Difference among algorithms should be studied with real data (real jets & real noise) **x** favoured strategy of ATLAS is to rely on one (max. two) jet algorithms!



Comparison among jet finding algorithms

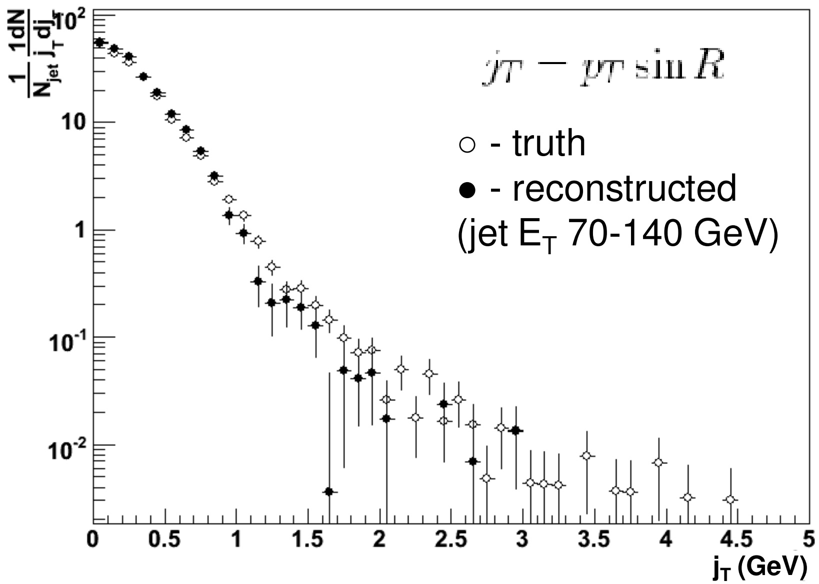
Area of jets delivered by different algorithms is very different in the noisy environment

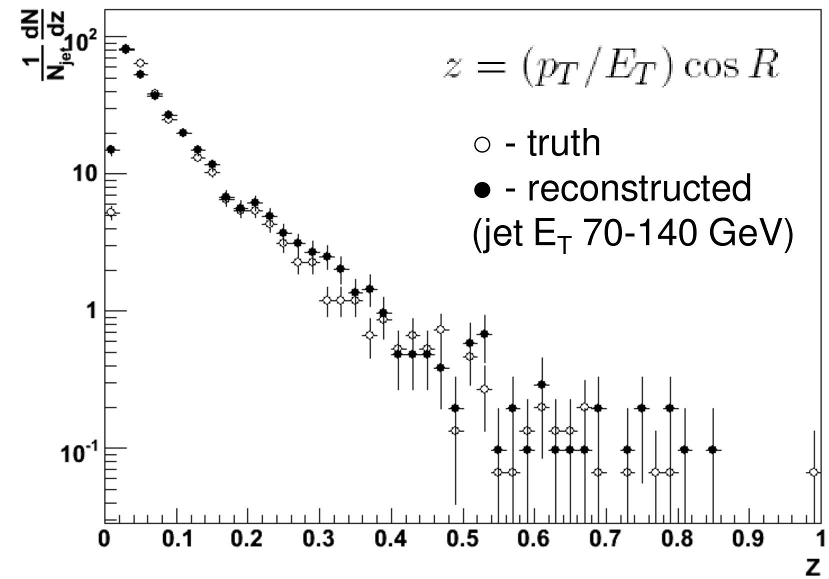


k_T algorithm, D=0.4

anti-k_T algorithm, D=0.4

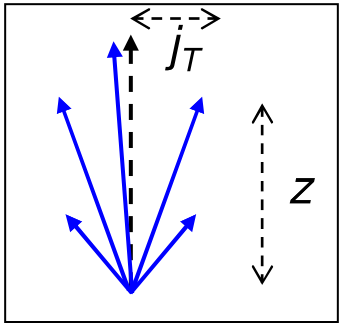
Fragmentation function and j_T





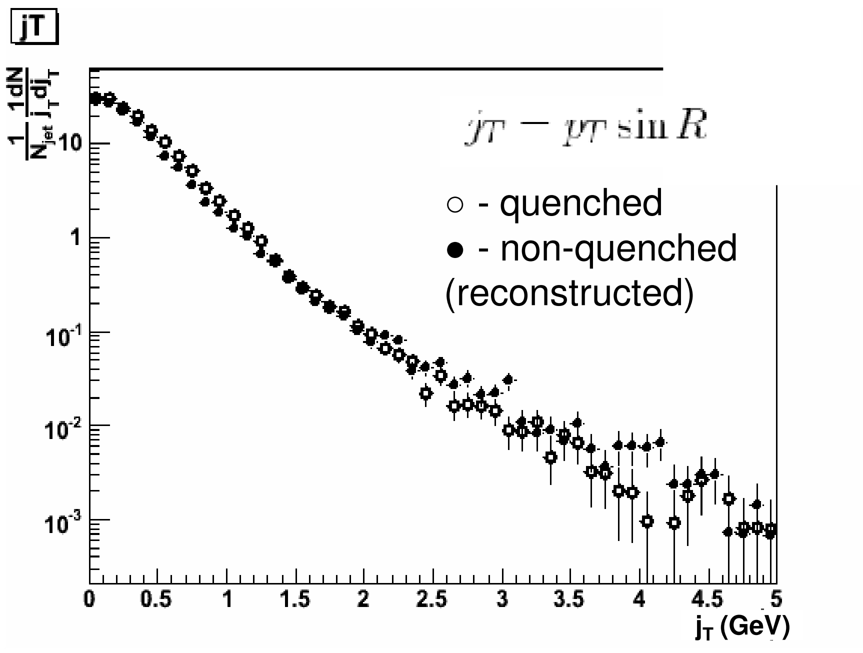
Reconstruction procedure:

- tracks are matched to calorimeter towers of a jet
- j_T and z for tracks above 2 GeV is computed
- background distributions of j_T and z are computed using tracks that match with HIJING particles, these distributions are subtracted, correction for the jet position resolution is applied

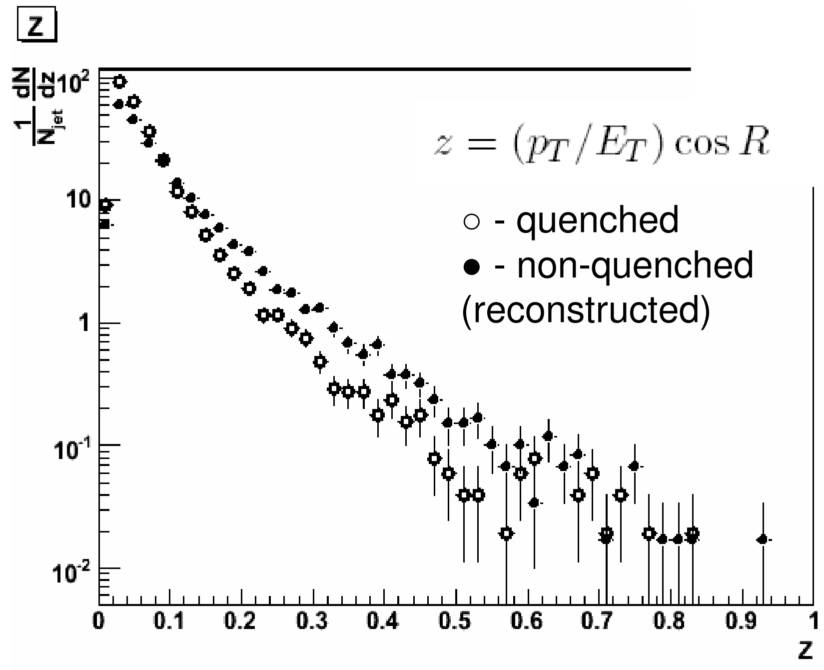


… we can well reproduce j_T distribution and fragmentation function

Fragmentation function and j_T from PYQUEN – reconstructed



Large j_T suppressed ⇔ gluons radiated from large angles

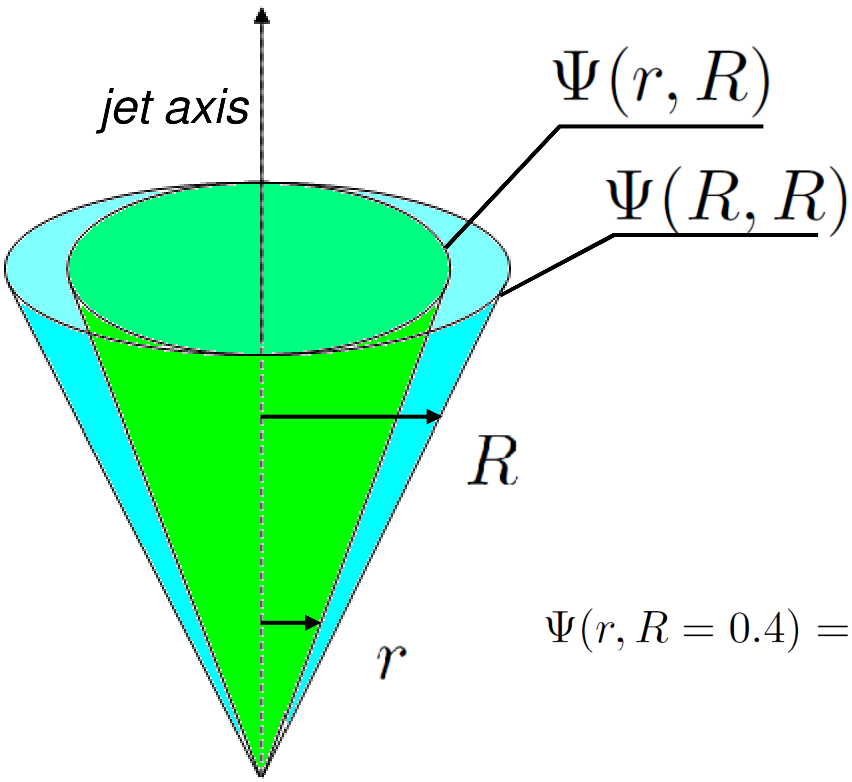


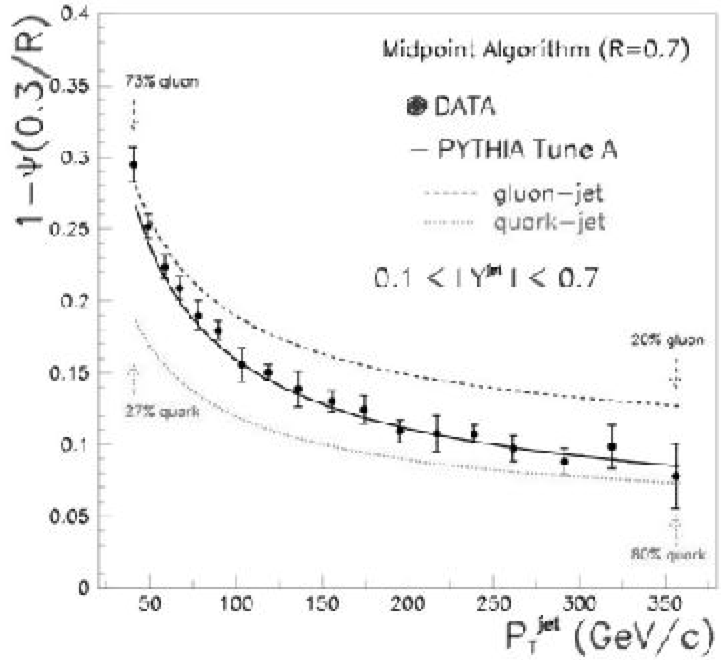
Low z enhanced, higher z suppressed ⇔ leading particle suppressed, redistribution of energy out of a jet core

… if the quenching is of that order we should be able to measure it

Jet shapes

- Measure the energy flow inside the jet at the calorimeter level
- Well defined in QCD, measured at Tevatron





$$\Psi(r, R = 0.4) = \frac{\int_0^r E_T(\rho)\mathrm{d}\rho}{\int_0^R E_T(\rho)\mathrm{d}\rho}$$

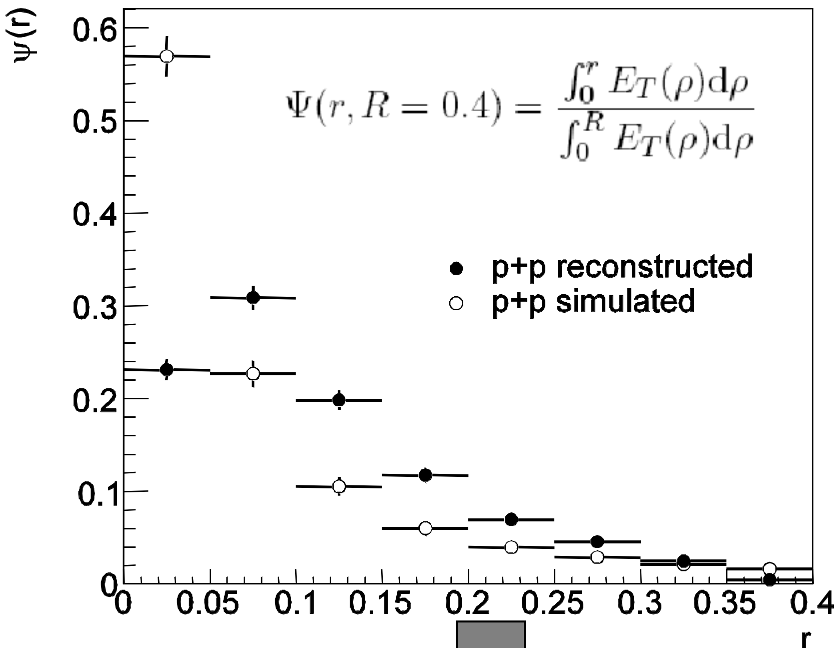
... integral jet shape

$$\psi(r, R = 0.4) = \frac{\mathrm{d}\Psi(r, R)}{\mathrm{d}r}$$

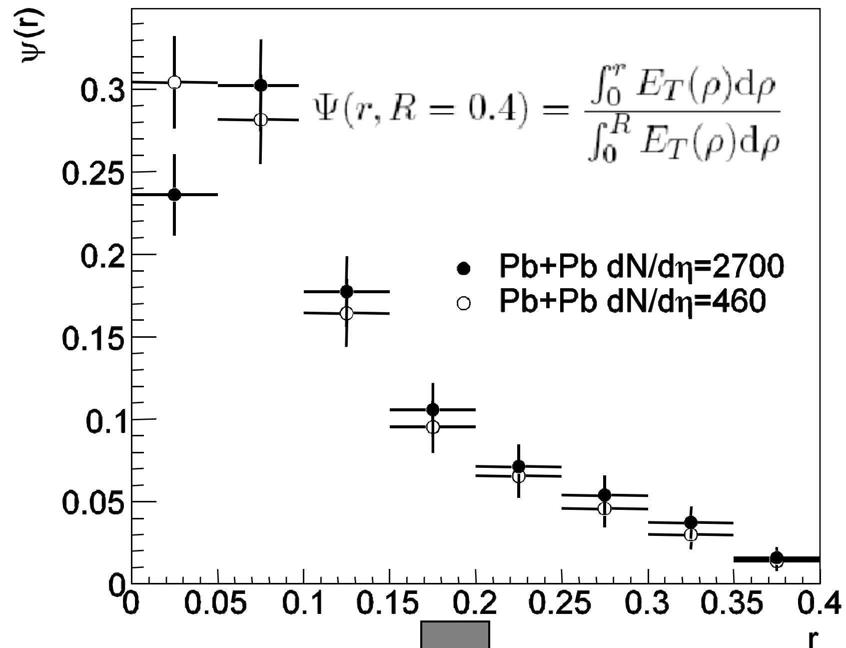
... differential jet shape

Problems of jet shapes

1. Effect of the calorimeter



2. Effect of the background (only applying subtraction is not enough)



How to match “closed” to “open”?

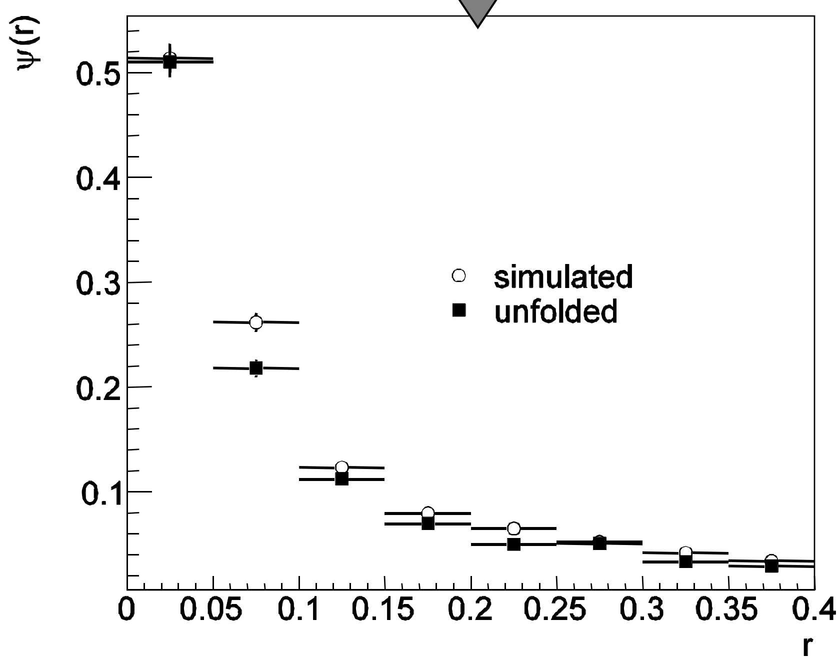
Deconvolution

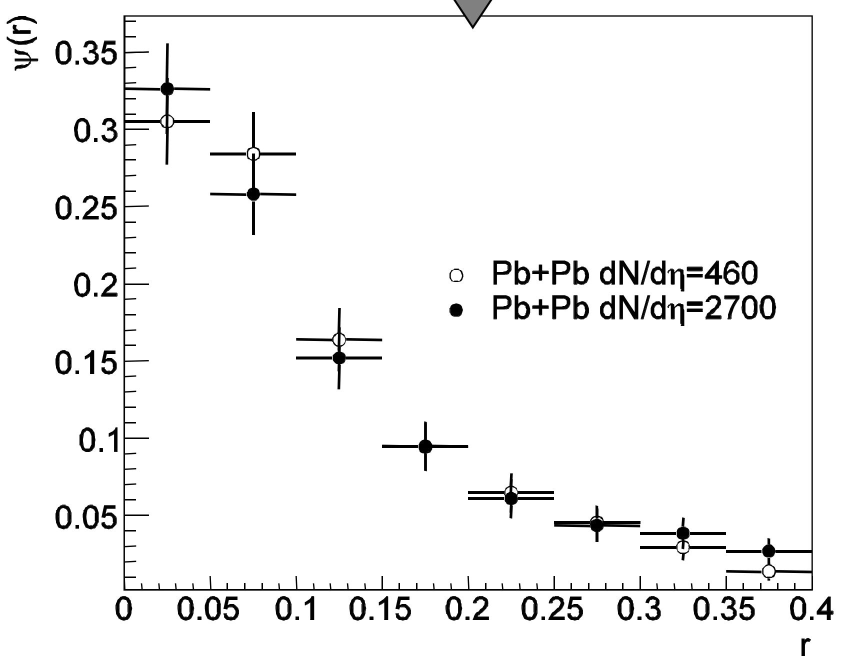
Better estimation of the jet position

Problems of jet shapes

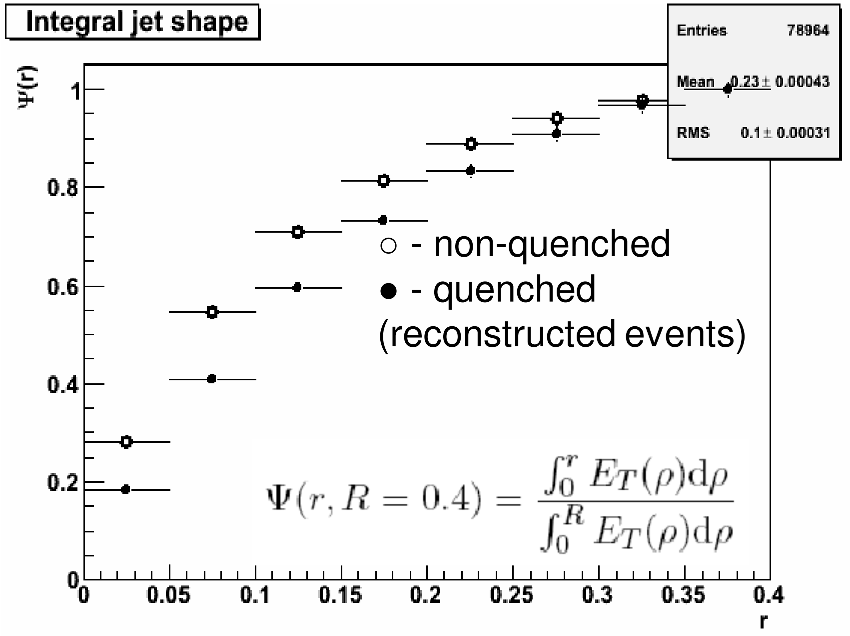
Deconvolution: Bayesian unfolding

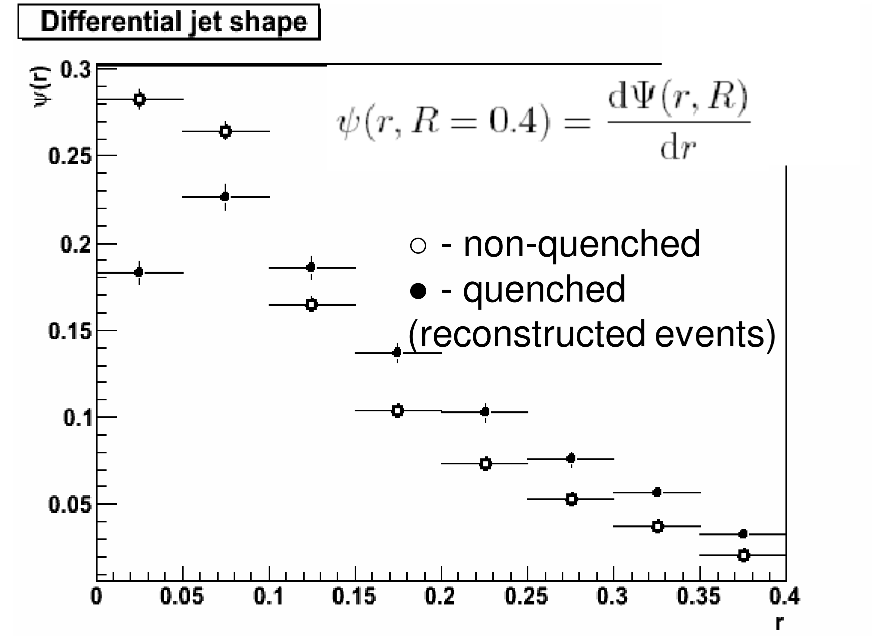
Better estimation of the jet position: using the method of smaller cones





Jet shapes from PYQUEN – reconstructed



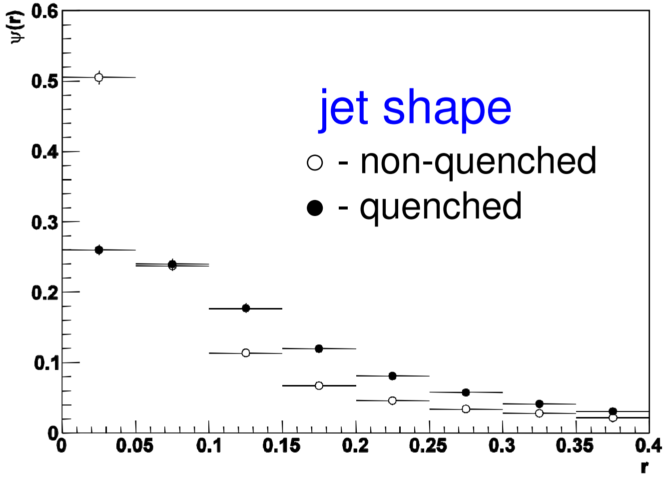


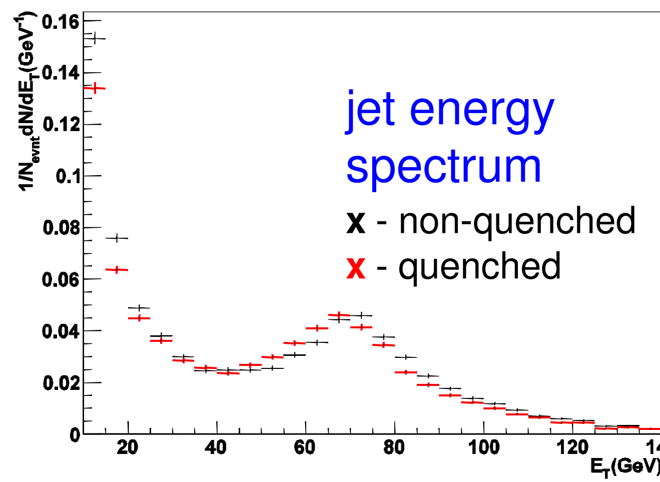
- Result at the **after the reconstruction**
- Jet quenching effect still well visible

… if the quenching is of that order we should be able to measure it

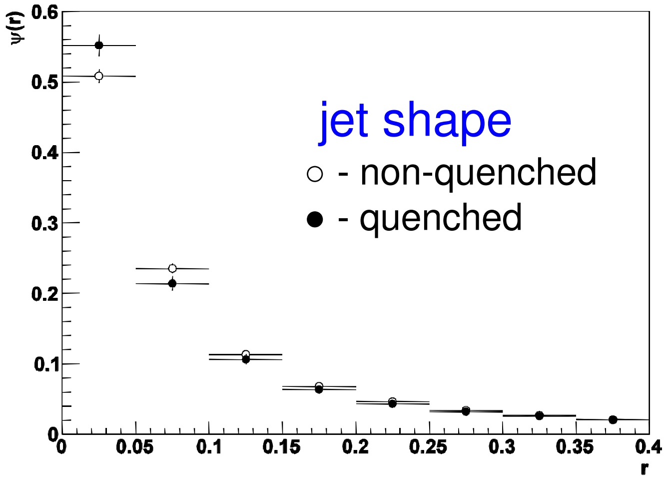
Complementary quantities to measure different energy loss mechanisms

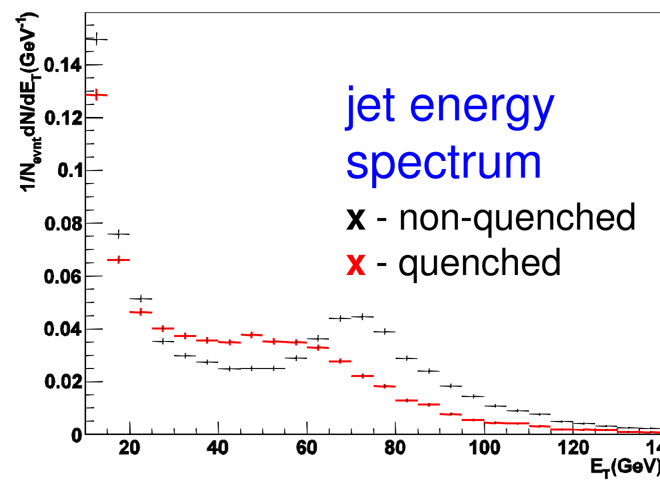
PYQUEN with only radiative energy loss





PYQUEN with only collisional energy loss





Summary

- We didn't talk about:
  - di-jet azimuthal correlations
  - γ-jet correlations
  - p_{OUT}, radial moments, ...

    ... all these quantities can be used to distinguish different energy loss scenarios.
- ATLAS is very good detector for the jet heavy ion physics (it is also good detector for soft heavy ion physics, quarkonia, and other important measurements).
- We have in our hands tools for reconstruction and analysis of heavy ion data.
- Bearing in mind that p+p with full luminosity is expected to be similar to peripheral Pb+Pb collisions, we can say that these tools could be useful also for p+p measurements.

Backup slides

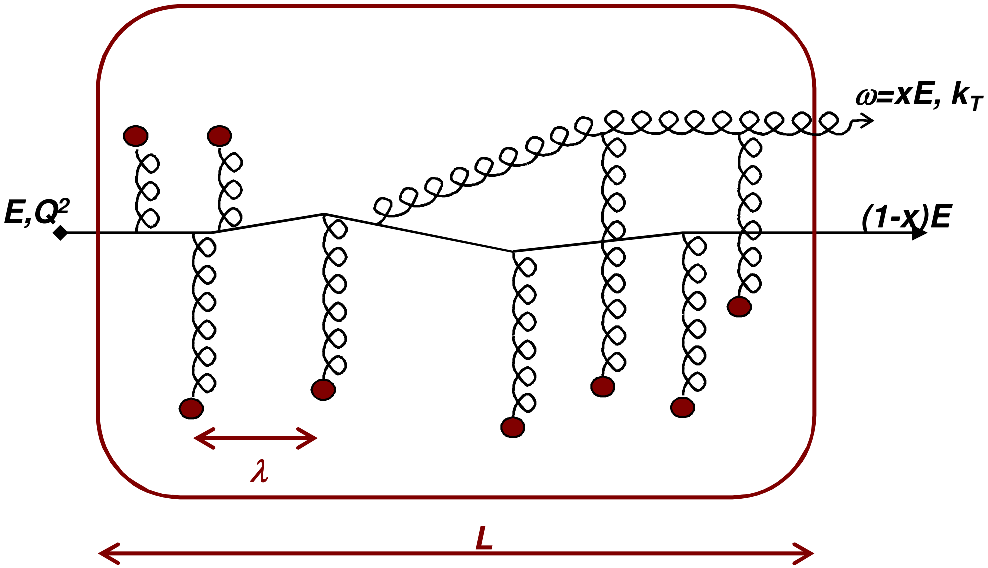
Backup slides

Path integral in opacity (ASW)

$$\omega \frac{dI_{\text{med}}}{d\omega\, d\mathbf{k}} = \frac{\alpha_s C_F}{(2\pi)^2 \omega^2} 2\text{Re} \int_0^\infty dy_l \int_{y_l}^\infty d\bar{y}_l \int d^2\mathbf{u}$$
$$\times e^{-i\mathbf{k}_\perp \cdot \mathbf{u}}\, e^{-\frac{1}{2}\int_{\bar{y}_l}^\infty d\xi\, n(\xi)\,\sigma(\mathbf{u})} \frac{\partial}{\partial \mathbf{y}} \cdot \frac{\partial}{\partial \mathbf{u}}$$
$$\times \int_{\mathbf{y}=\mathbf{r}(y_l)}^{\mathbf{u}-\mathbf{r}(\bar{y}_l)} \mathcal{D}\mathbf{r} \exp\left[i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2} \left(\dot{\mathbf{r}}^2 - \frac{n(\xi)\,\sigma(\mathbf{r})}{i\,2\omega} \right) \right]$$

$$\epsilon = \frac{1}{E_q} \int_0^\infty \omega \frac{\mathrm{d}I_{med}}{\mathrm{d}\omega} \mathrm{d}\omega$$

$$D_{q\to h}^{med}(x, Q^2) = \int_0^1 \mathrm{d}\epsilon P(\epsilon) \frac{1}{1-\epsilon} D_{q\to h}\left(\frac{x}{1-\epsilon}, Q^2\right)$$

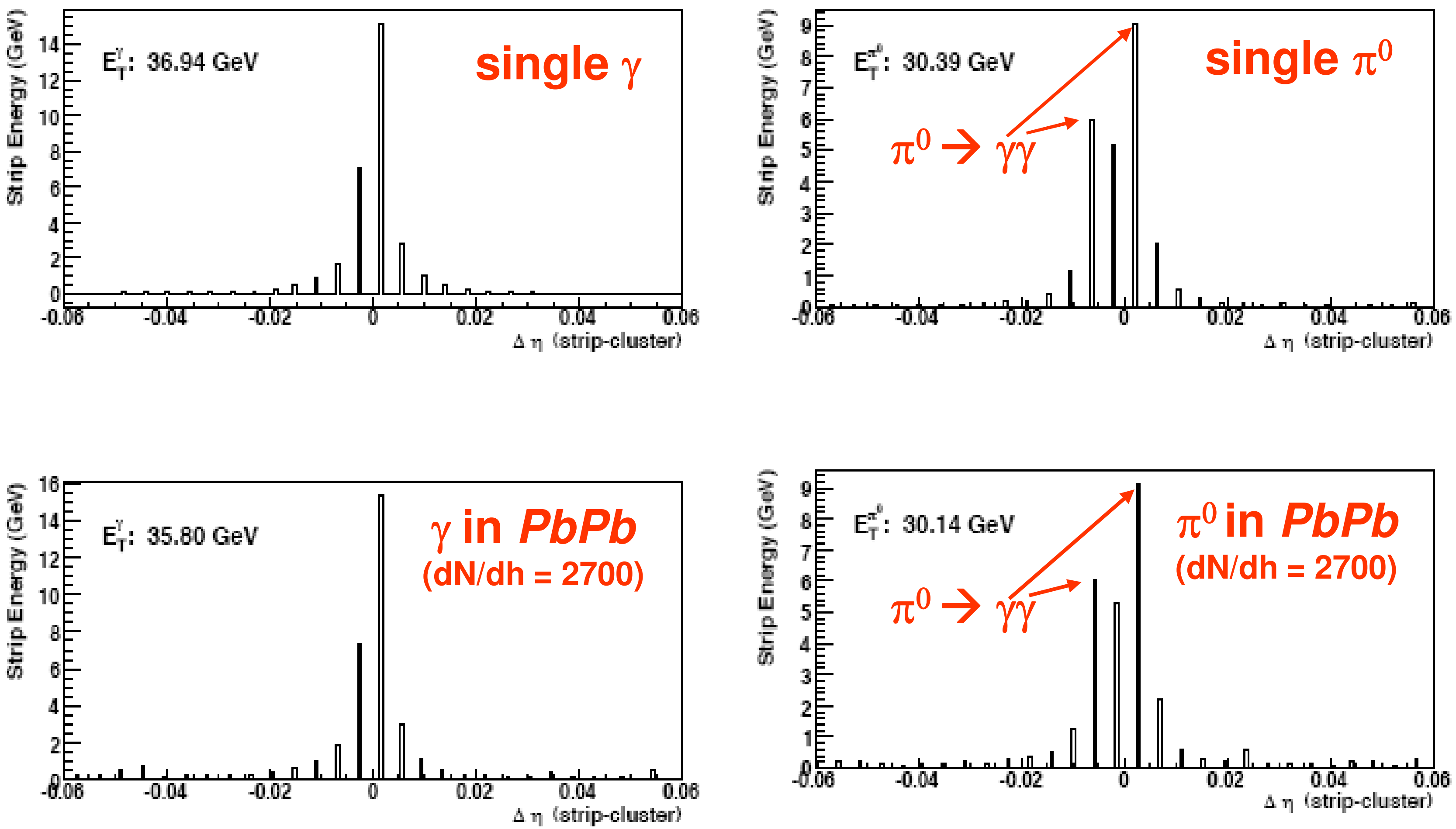


Gluon energy spectrum can be computed in 2 limits:

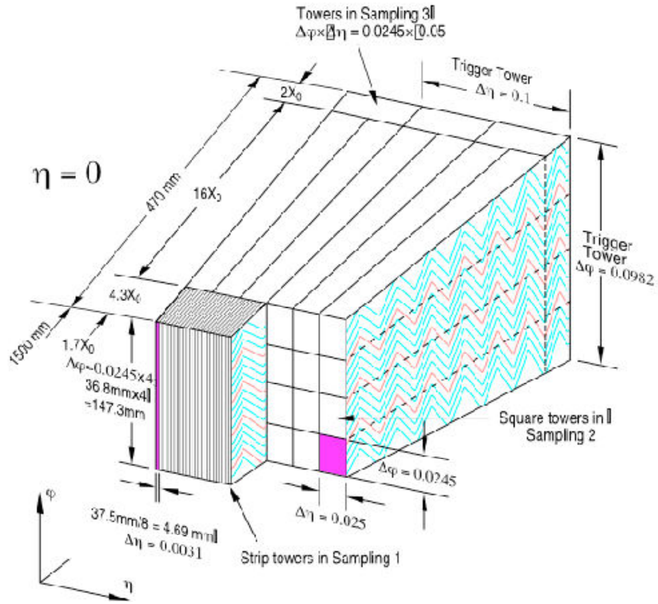
- **few hard scatterings (GLV)**
- **many soft scatterings (BDMPS)**

Other approaches: Higher Twists (direct computation of fragmentation function – formally similar to DGLAP), Finite Temperature approach (AMY), techniques which use AdS/CFT correspondence

Backup slides: γ-isolation

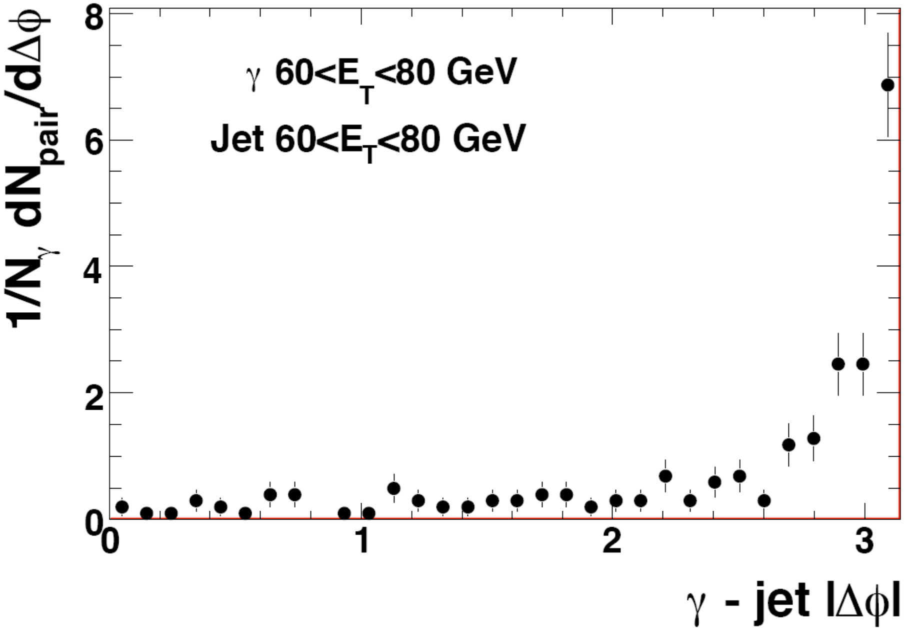


Backup slides: γ-isolation



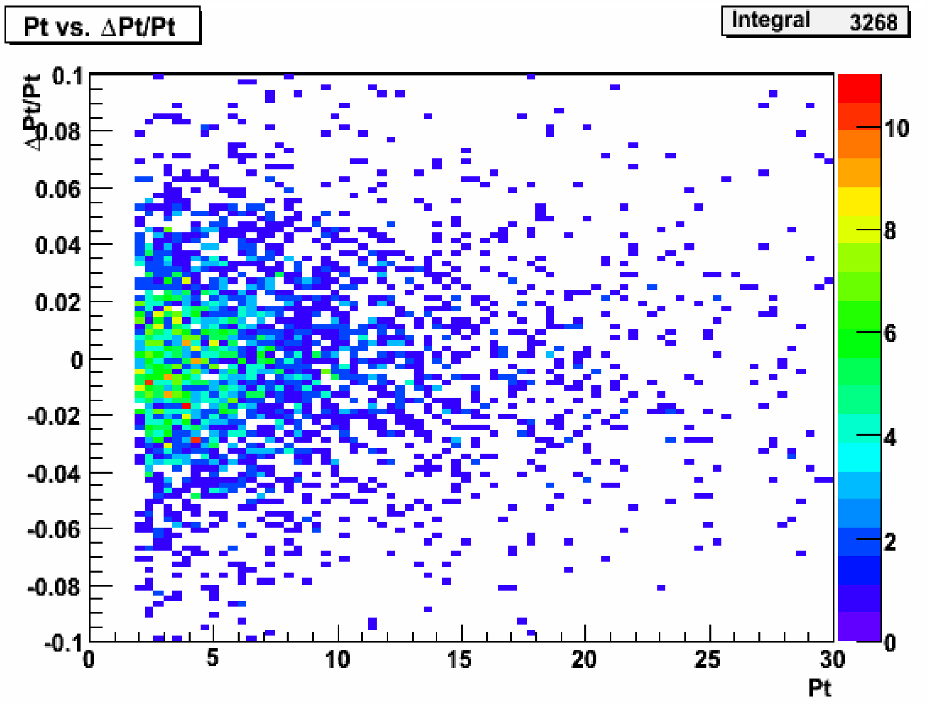
- can benefit from excellent longitudinal segmentation (0.003 for the first sampling of EMCAL)
- a set of cuts to distinguish a direct photons from neutral hadrons – based on the shower shape
- double peaked or wide showers rejected
- the most important cuts:
  - the fraction of energy in 8 strips around the core of 6 strips
  - energy of second peak minus the minimum energy between the two peaks

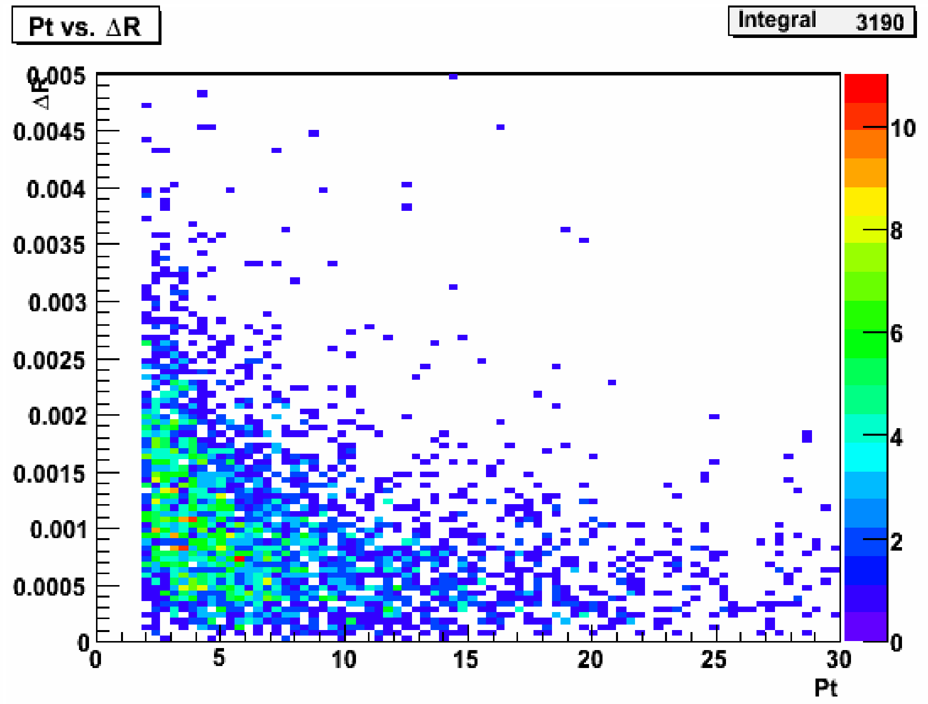
Backup slides: γ-jet correlations



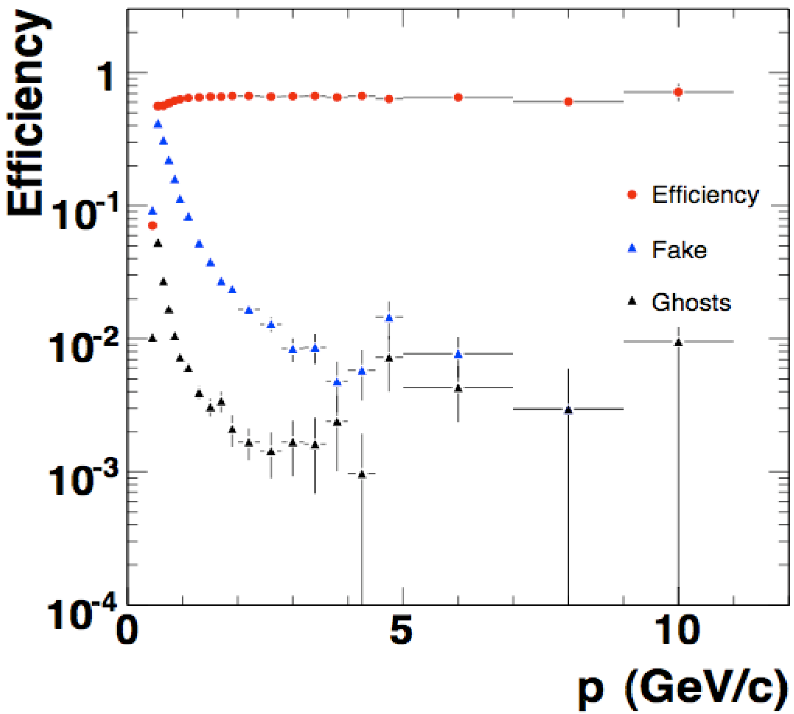
- γ-jet correlation measurements can help jet analysis at low E_T, can be used for the fake rejection
- important for in-medium fragmentation studies

Backup slides: tracking performance



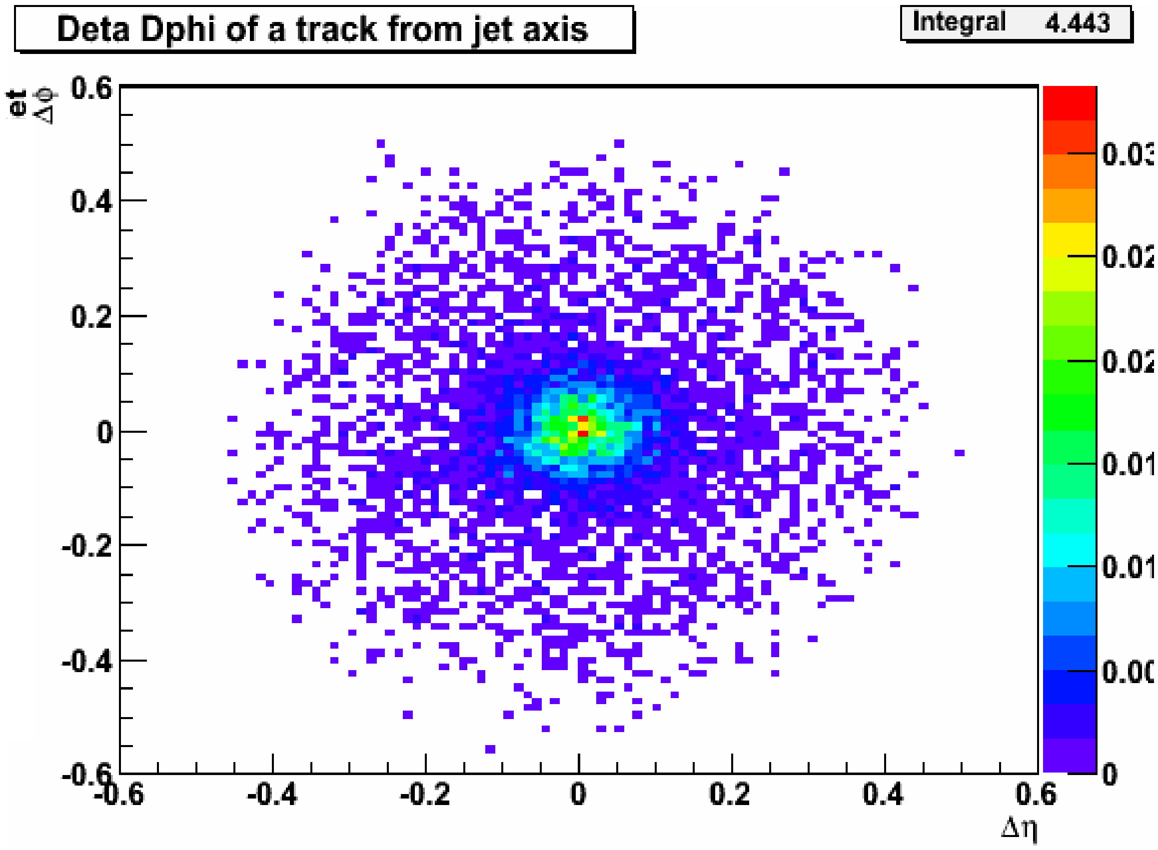


Backup slides: tracking efficiency



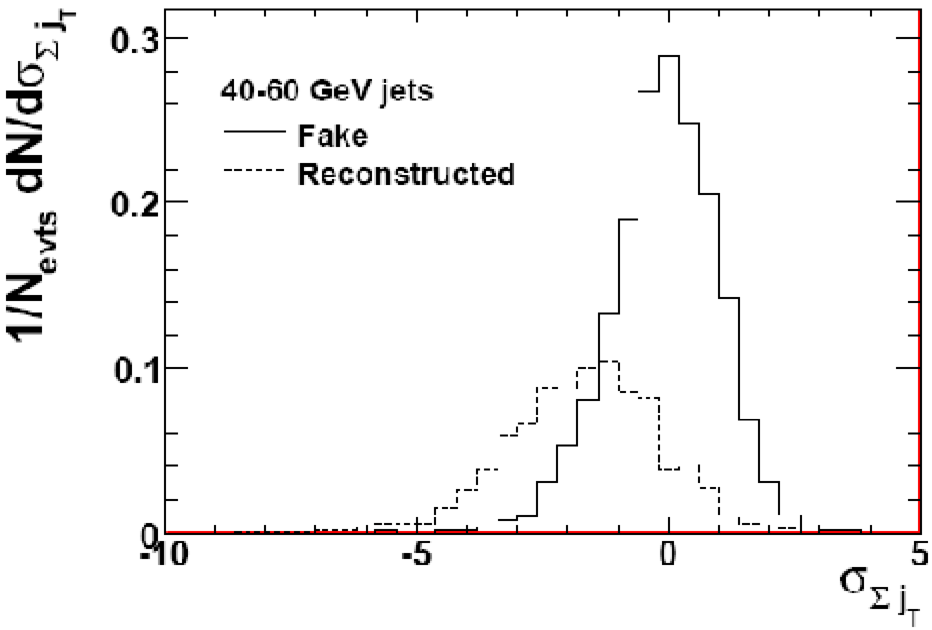
Tracking efficiency ~ 70% for the most central collisions

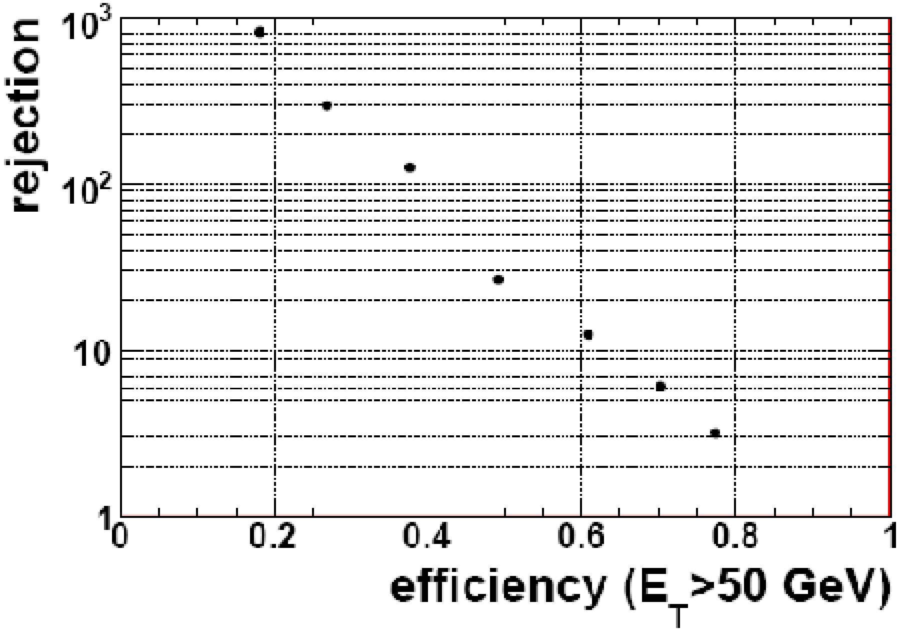
Backup slides: jet's tracks



Shape of the jet from tracking

Backup slides: fake jet rejection

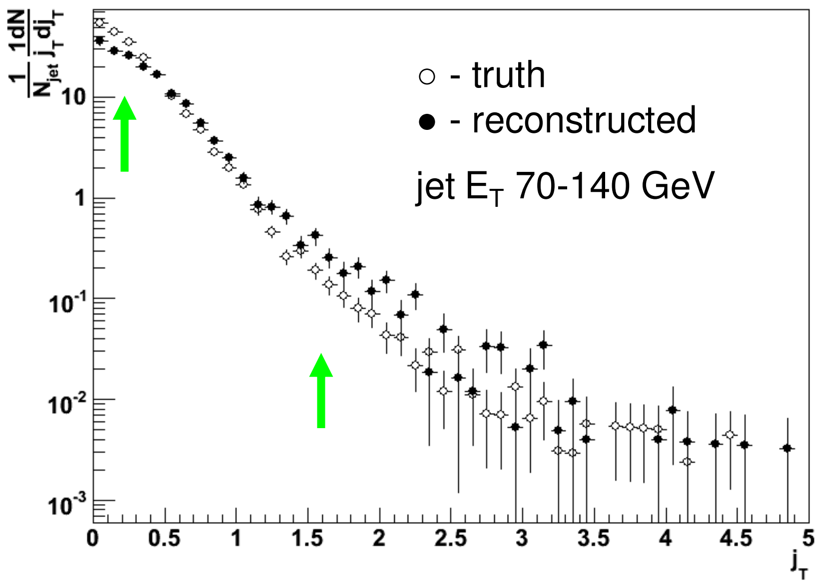


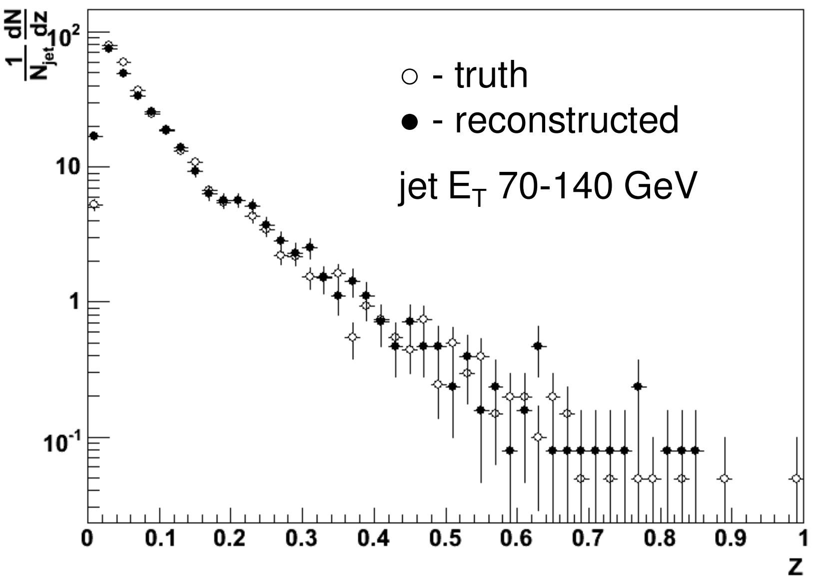


$$\Sigma j_T = \sum_{\text{cell}\in\text{jet}} E_{T,\text{cell}} \sin R_{\text{cell}}$$

$$\sigma_{\Sigma j_T} = \frac{\Sigma j_T - \langle \Sigma j_T \rangle (E_T)}{\sigma(E_T)}$$

Backup slides: Sensitivity to the jet position

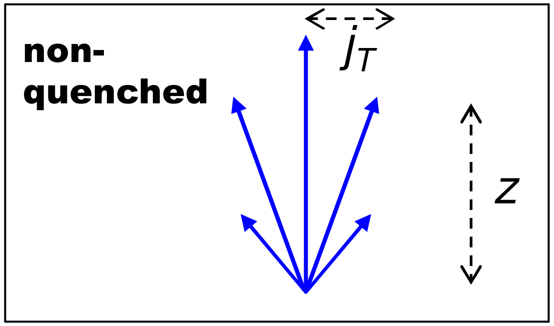


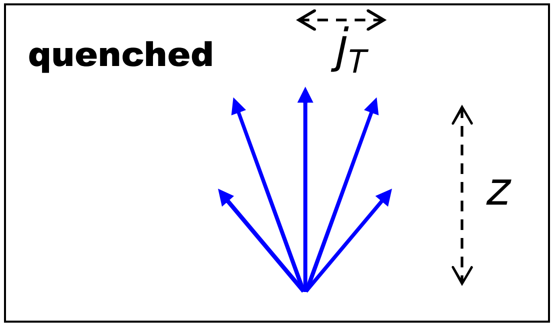


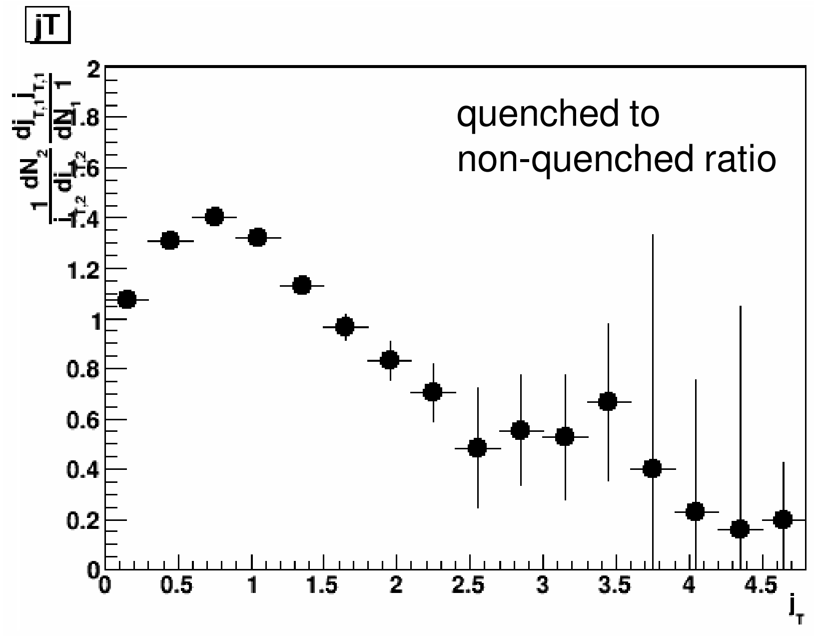
Background distributions subtracted but the correction on the jet position resolution not applied => visible underestimation at small j_T (z is not affected much by the jet position resolution). Discrepancy can be removed using jet position determined by the cone reconstruction with smaller R.

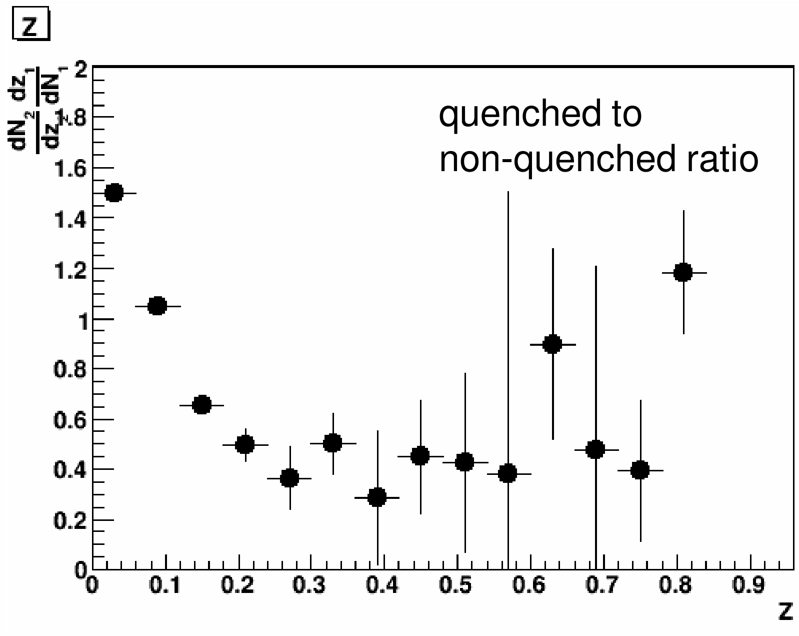
Backup slides: PYQUEN simulations - ratios

illustration …

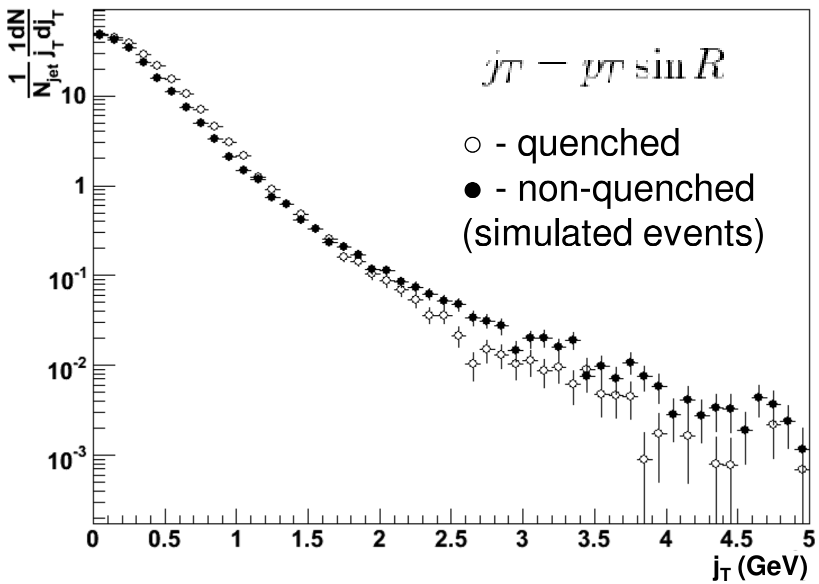




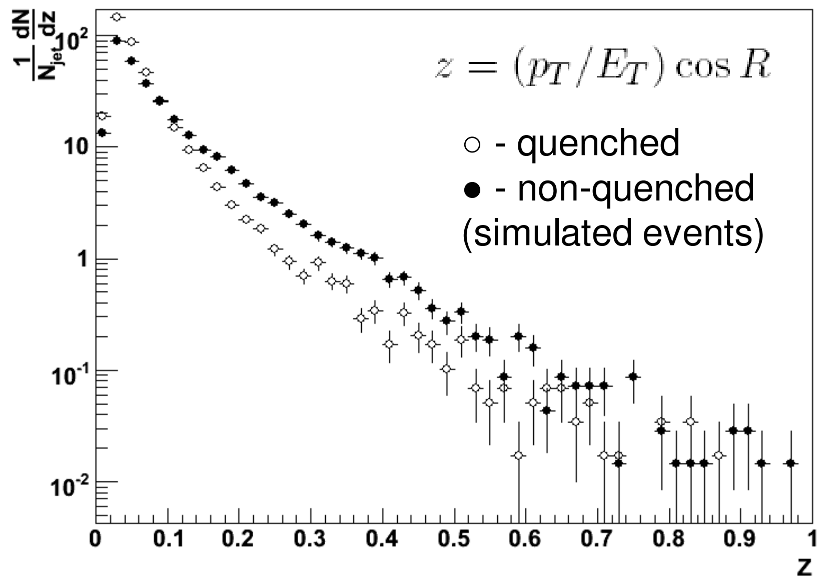




Fragmentation function and j_T from PYQUEN – generator level



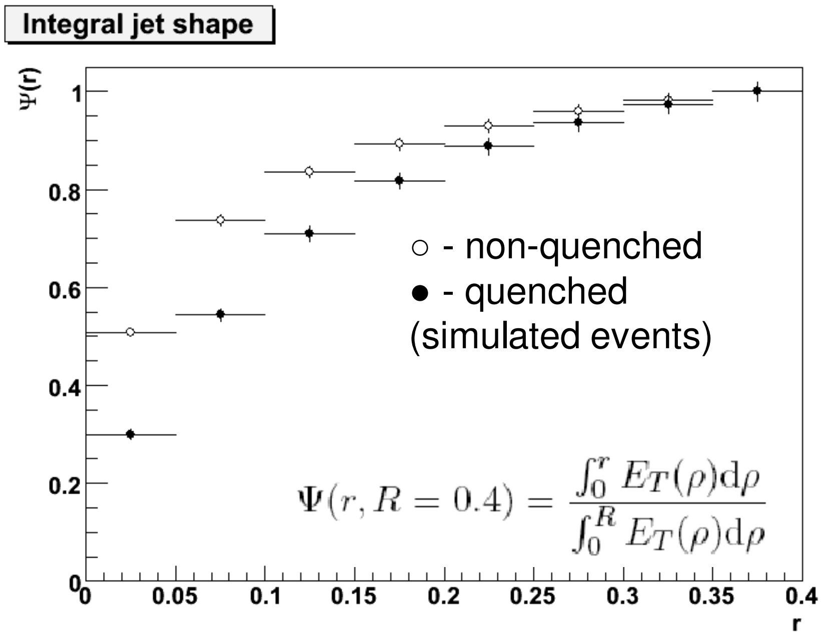
Large j_T suppressed ⇔ gluons radiated from large angles

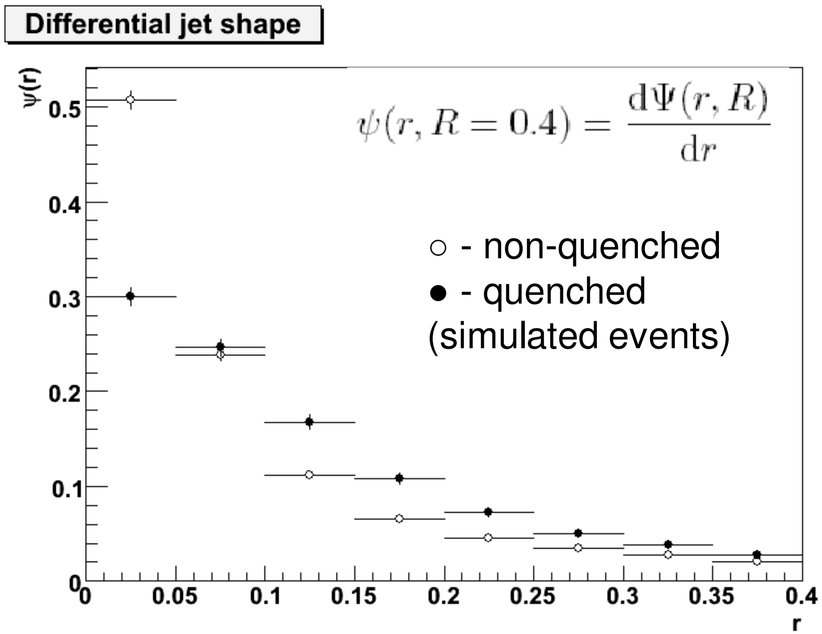


Low *z* enhanced, higher *z* suppressed ⇔ leading particle suppressed, redistribution of energy out of a jet core

- Result at the **generator level**
- PYQUEN settings: default setting for quenching, b=0, $p_{T,min}$=70 GeV, *PbPb*, LHC energy

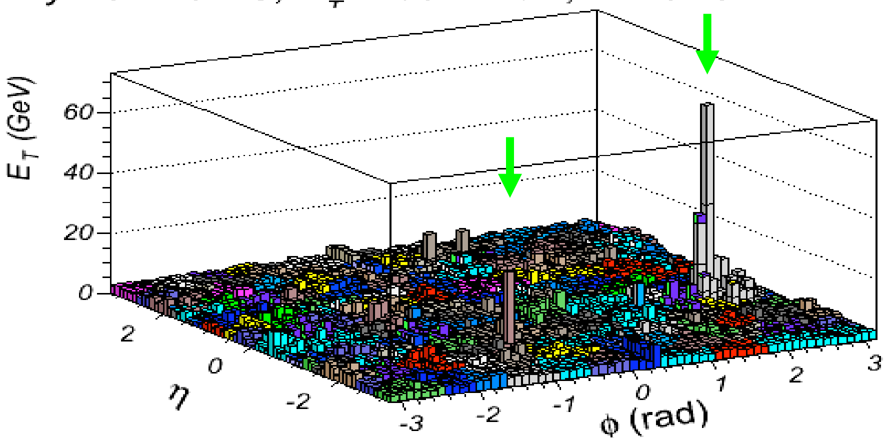
Jet shapes from PYQUEN – generator level

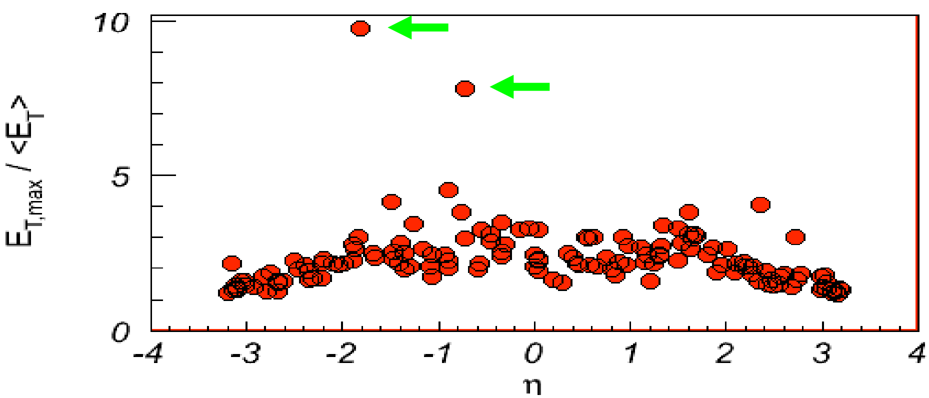




- Result at the **generator level**
- Almost factor of two in the jet core
- Differential jet shape can show better the flow of the energy – energy is redistributed out of center of the jet

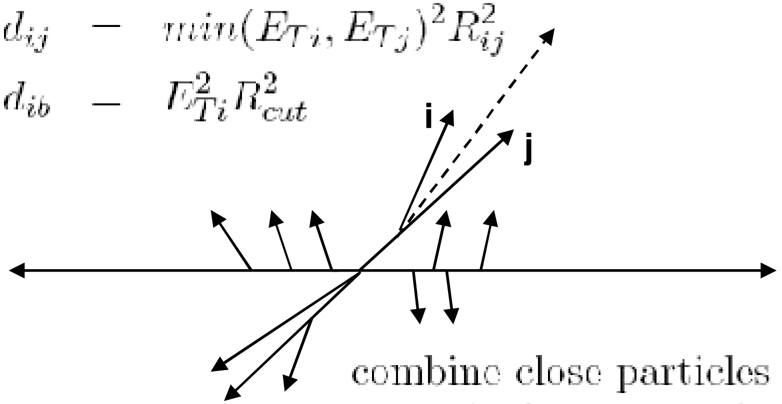
Fast k_T jet reconstruction strategy





k_T algorithm

$$d_{ij} = min(E_{Ti}, E_{Tj})^2 R_{ij}^2$$
$$d_{ib} = E_{Ti}^2 R_{cut}^2$$



… reconstructs jets backwards along fragmentation chain

k_T jet reconstruction:

- run fast k_T algorithm
- separate jet from the background
- subtract background from jets
- calibrate jet energy

Backup slides