Jet reconstruction performance in p+p and Pb+Pb collisions in ALICE experiment from full detector simulation

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for the ALICE Collaboration

ECT* Workshop – Trento

Parton fragmentation processes: in the vacuum and in the medium

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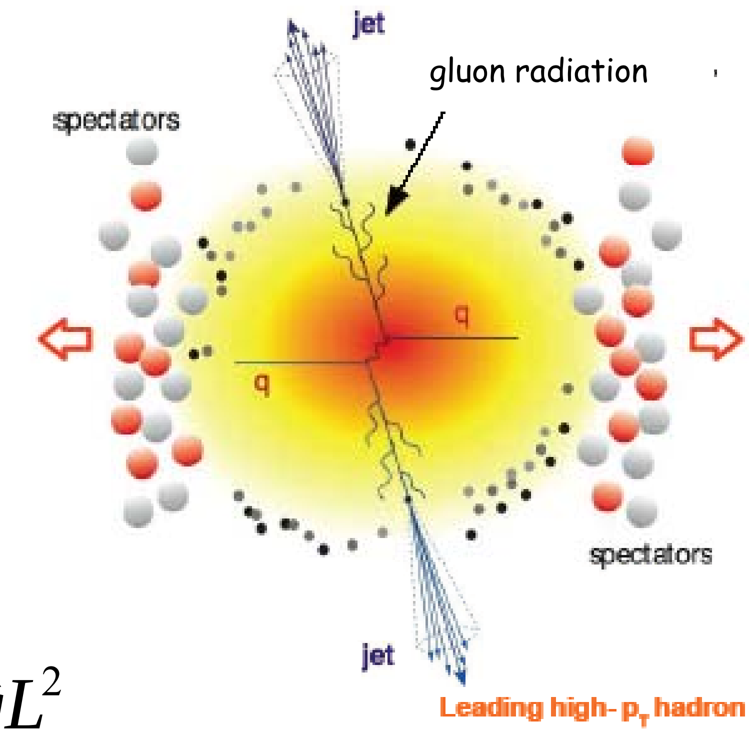
First ALICE motivation

- Following an initial hard scattering in e+ e-, e- p, hadron collisions, high energetic partons will create a high energy cluster of particles moving in a same collimated direction → jets
- In HIC, the scene of parton fragmentation is changed from vacuum to a QCD medium.
- These partons will first travel through a dense color medium. They are expected to lose energy through collisional energy loss and medium induced gluon radiation, "jet quenching".
- The magnitude of the energy loss depends on the gluon density of the medium and on the path length



$$\Delta E \propto \alpha_s C_R \hat{q} L^2$$

Consequences…

- Total jet energy is conserved, but "quenching" should change the jet shape and the fragmentation function
- Measurement of the parton fragmentation products reveals information about the QCD medium

Outline

…but also…

At the LHC, many physicists will work on quantum chromodynamics in vacuum or in medium.
Many points still need to be understood in QCD in both cases
ALICE is dedicated to the studies in medium however we have started some very preliminary discussions to try to estimate to which extent the phenomenology à la « e+ e- », « e p » or « p pbar » will be accessible to ALICE.

One more motivation to join this worshop !

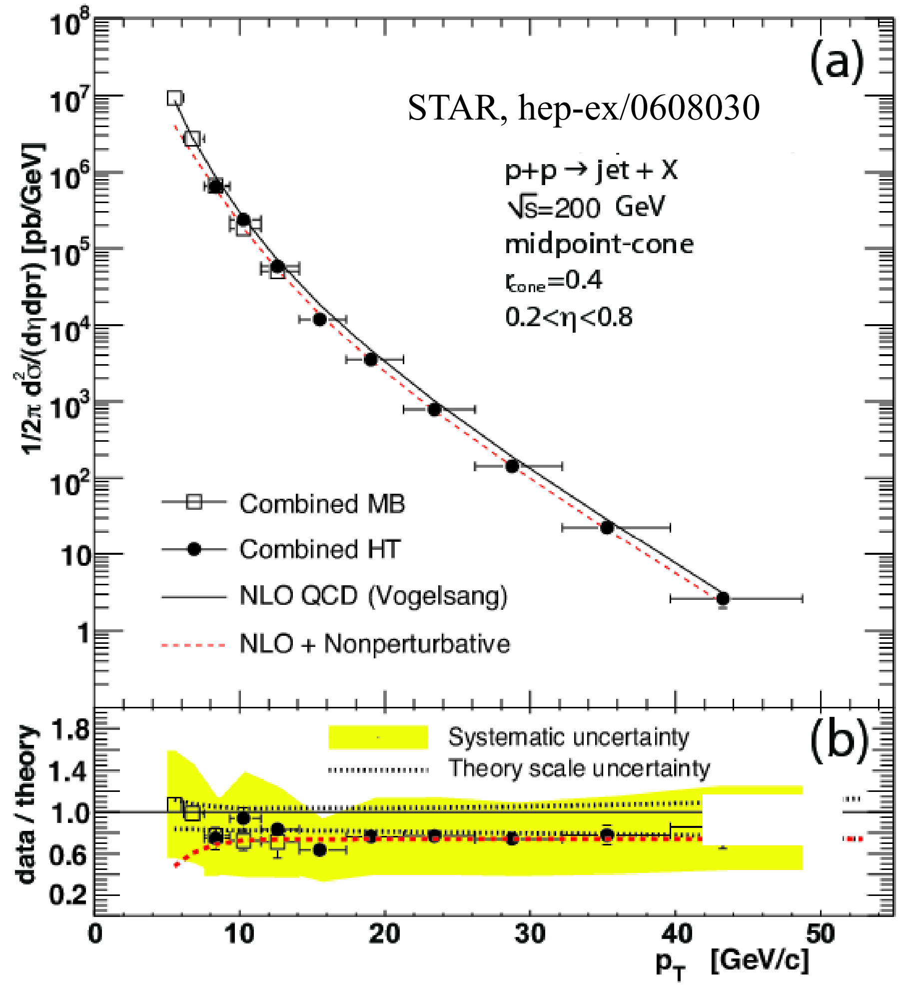
- **Jet physics motivations and requirements**
- **Jet reconstruction in the ALICE experiment (full detector simulation)**
- **Background effect in Heavy Ion Collisions**

Jet Physics motivations and requirements

First jet measurement at RHIC

- First measurement of reconstructed jets at RHIC in p+p polarized collisions at $\sqrt{s_{NN}}$ = 200 GeV
  - Charged particles: TPC - all ϕ, $|\eta|<1.3$
  - Neutral particles: BEMC – all ϕ, $0 < \eta < 1$
  Lead-scintillator sampling calorimeter
- Reconstruction using a mid-point jet cone algorithm with R = 0.4
- Still dominant incertainty on jet energy scale

Measured spectrum agrees with NLO pQCD



Note: Statistics out to p_T=**50 GeV/c** !!!

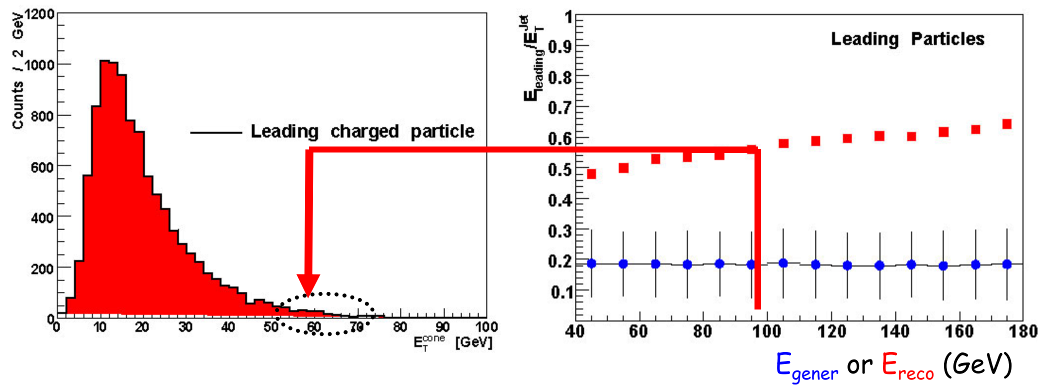
… more being collected

STAR has demonstrated that the study of jet using a combination of momentum measurement of charged particles and energy measurement of neutral particles is possible

Motivations for jet studies in heavy ion collisions

RHIC uses leading particle as a probe. There are limitations at LHC...

Energy fraction carried by the leading charged particle in jets:

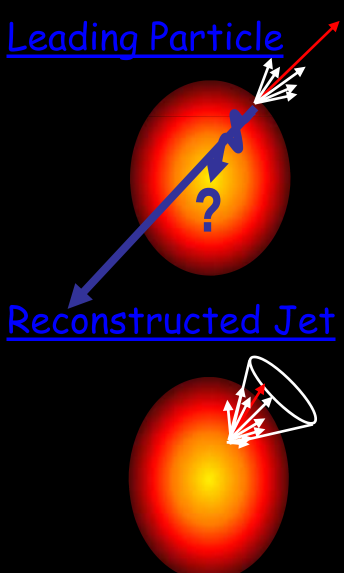


- Even if the leading particle has approximately the direction of the original parton, it carries (on average) only a small fraction (18%) of its energy.
- Due to the **bias induced by the steeply falling parton production spectrum the fraction increases to ~ 50%** **[trigger bias]**

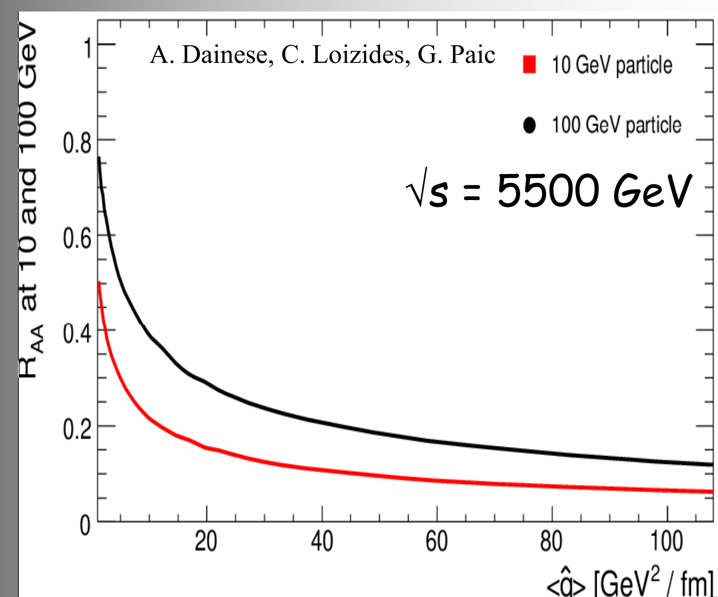
<u>2 consequences</u>:

=> **strong bias** to evaluate the FF

=> High-p_T parton identified with very **poor efficiency** !



- The study of R_{AA} at RHIC and LHC (will) only give a **lower bound** on transport parameter **[surface bias]**.
- Ideally, the analysis of reconstructed jets should increase the sensitivity to medium parameters by **reducing surface bias**.



In Pb+Pb collisions: jet structure modification

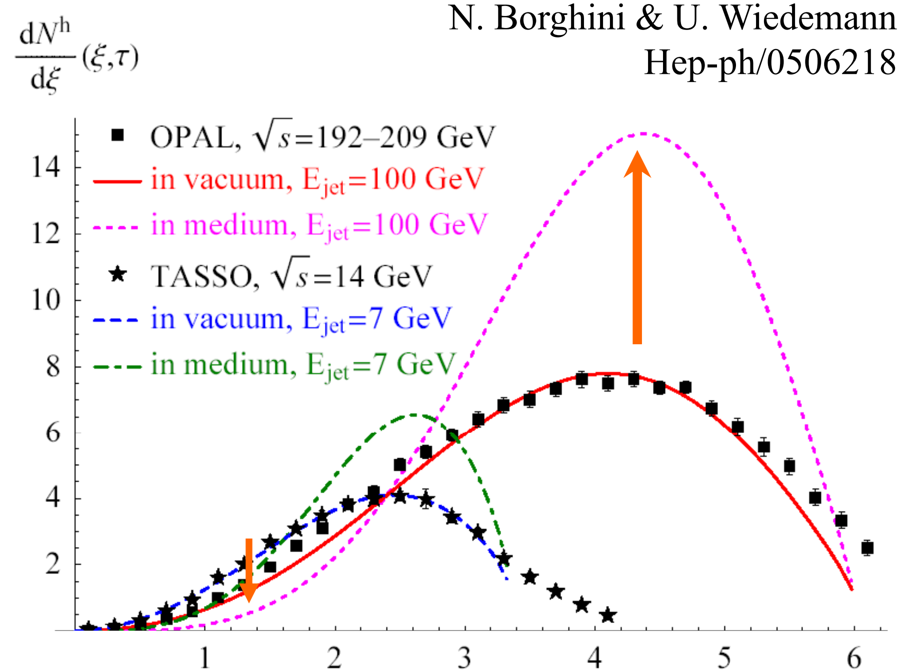
Medium effects introduced at parton splitting

Simple scheme: Jet(E) →Jet(E-ΔE) + soft gluons (ΔE)

Hump-backed plateau

- Decrease of the particles at high z (low ξ) [energy loss]
- Increase of the particles at low z (high ξ) [radiated energy]
- Jet broadening & out of cone radiations increase => reduction of jet rate
- Increase of di-jet energy inbalance and acoplanarity
- Fragmentation strongly modified at p_{hadron}~1-5 GeV/c even for the highest energy jets

N. Borghini & U. Wiedemann
Hep-ph/0506218



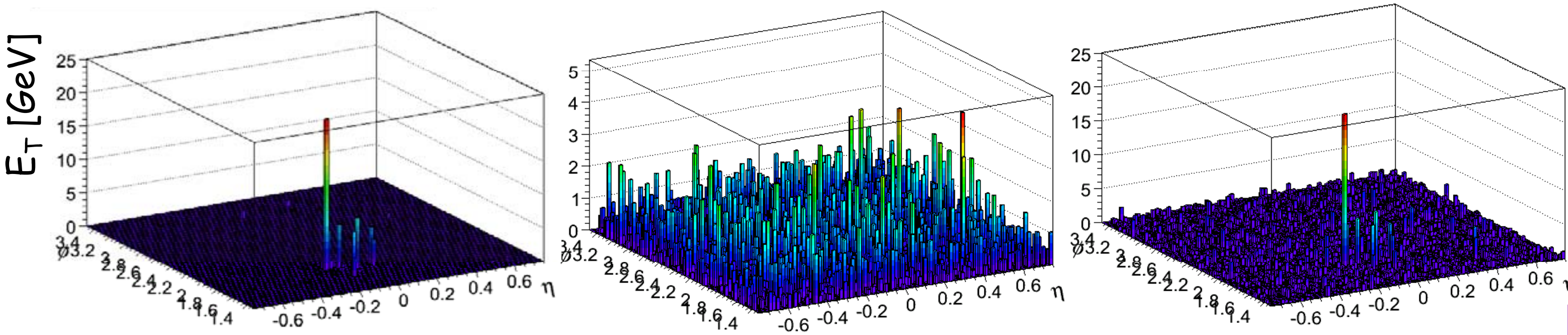
$\xi = \ln(E_{Jet}/p_{hadron})$

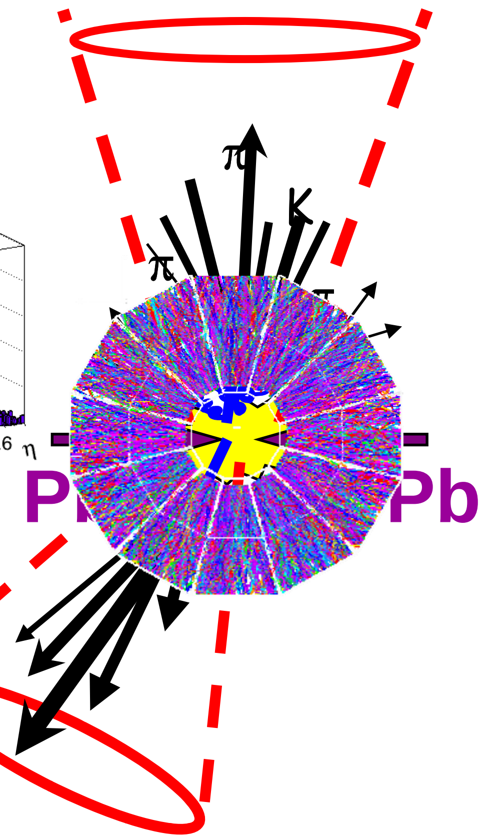
- ALICE should be well dedicated to test this ξ range thanks to tracking down to 100 MeV/c and excellent PID !!!
- Question: to which extent E_{jet} can be measured ?

Other contribution: background from the UE

The picture is a bit more complicated:

Jet(E) →Jet(E-ΔE) + soft gluons (ΔE) + soft hadrons from UE





- The UE and its fluctuations in Pb+Pb induce important bias on:
  - Jet identification / reconstruction
  - Jet energy resolution
  - Low-p_T information for jet structure studies

- At LHC, assuming dN/dη ~ 5000 and <p_T> ~ 0.5 GeV/c:
  - In R=1, E_{UE} ~ 1.5-2 TeV (O(10) > highest jet energy)
  - Fluctuations ~ 40 GeV
  - BUT => High jet rates expected
    => Jets strongly collimated

<u>Question</u>: to which extent the collimated nature of jets persists in HIC ?

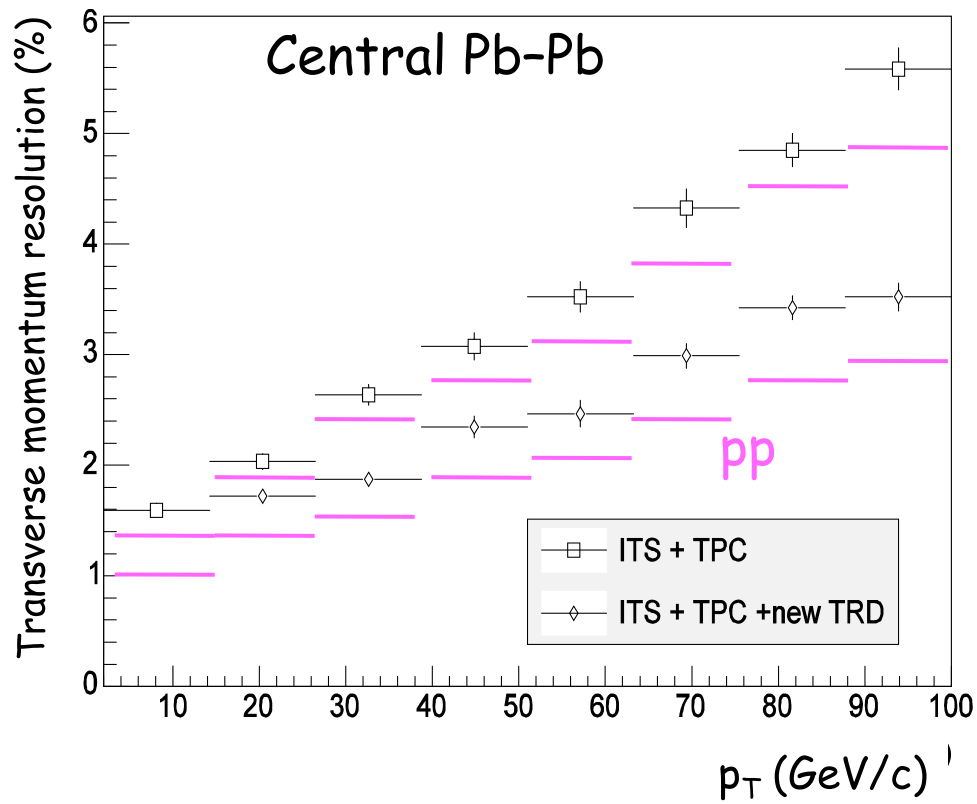
Jet reconstruction in the ALICE experiment

(full detector simulation)

ALICE central barrel

Excellent tracking in a high density environment !

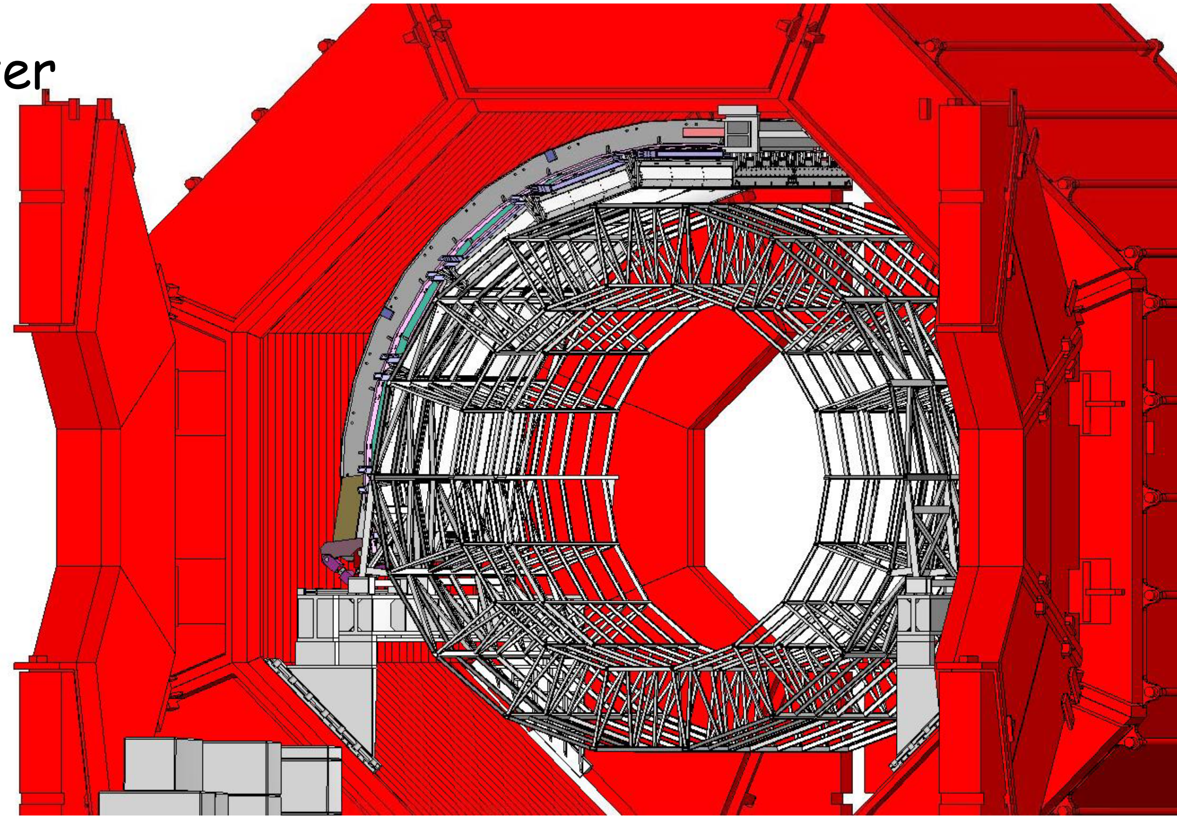
- Central barrel: $|\eta| < 0.9$
- Optimized for high multiplicity (8000 particles)
- Tracking down to 100 MeV/c, $O(\Lambda_{QCD})$
- Excellent particle ID
- High p_T charged hadrons identification up to 100 GeV/c
- Momentum resolution better than 10% up to 100 GeV/c



✓ Minimize out-of-cone radiation and unmeasured low-p_t particles
✓ Improve the measurement of particles radiated from soft gluons
✓ Reduce systematic of background subtraction

ALICE EMCal

- Pb scintillator sampling calorimeter
  - $r_M \sim$ 2cm
  - 22.1 X_0
  - Acc: $80 < \phi < 190°$, $|\eta| < 0.7$
- Shashlik geometry – 11 SM
  - ~13000 towers
  ($\Delta\eta \times \Delta\phi = 0.014 \times 0.014$)
- $\sigma_E/E \sim 15\%/\sqrt{E(GeV)}$
- Energy from neutral particles: π^0/γ discrimination to ~ 30 GeV/c
- Trigger capabilities



✓ Essential for the reference collisions and for p+p studies !
✓ Extend jet energy range
✓ Improve the jet energy reconstruction and resolution

System	jet trigger?	N_{jets} (125 GeV)	N_{jets} (175 GeV)
Pb+Pb cent	y	1.1×10^4	1700
	n	2100	320
Pb+Pb periph	y	410	62
	n	8	1
p+Pb 8.8 TeV	y	2.7×10^4	4200
	n	250	40
p+p 14 TeV	y	6.9×10^5	1.0×10^5
	n	1200	190

Jet production in ALICE

- Whole spectrum of jet production from mini-jets $E_T > 2$ GeV to high-E_T jets of several hundred GeV studied:

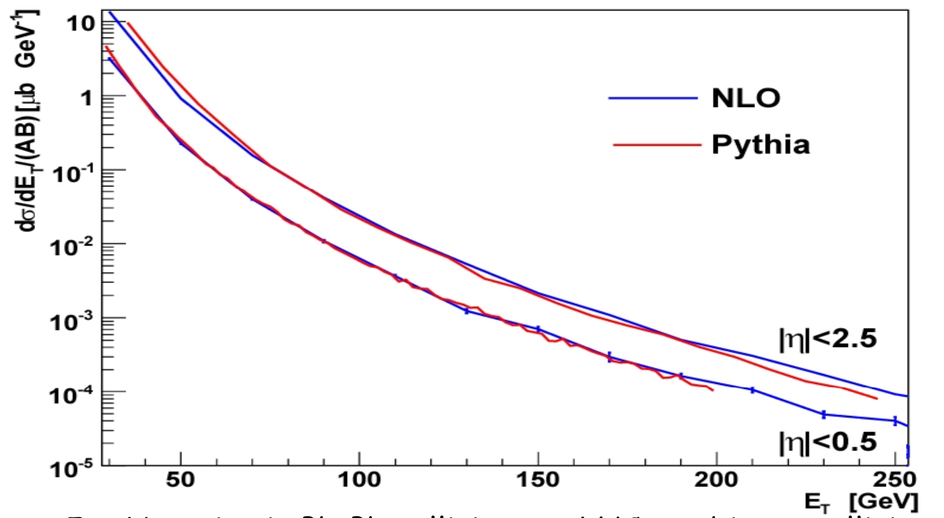
(L(Pb+Pb) = 5.10^{26}cm^{-2}s^{-1} – 10^{6}s)

- **E_T < 20 GeV**: domain of **mini-jets** (>> E_{RHIC}) => several jet overlap in 1 event in ALICE acceptance

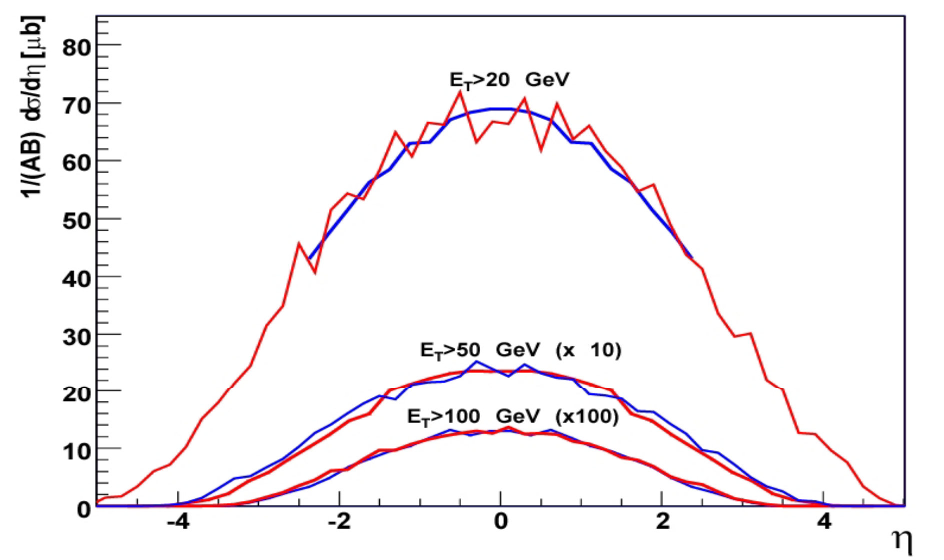
- **20 < E_T < 100 GeV**: jet rate high enough so that even with the limited read-out rate of TPC **> 10^4 jets measurable**. Good for FF and dependence of energy loss with L studies
=> 17% of the produced jet in the ALICE fiducial acceptance
=> 8.5% of the accepted jet events contain back-to-back di-jets

- **E_T > 100 GeV**: **triggering** will be **necessary** to be able to perform a fragmentation function analysis
(>10^4 jets are needed to study a FF close to z > 0.8)
Single jet acceptance = 26%
Di-jet acceptance = 13.5%

- to perform FF analysis, statistics **limit reached at ~ 250 GeV**



Jet Xsection in Pb-Pb collisions at LHC per binary collisions



Jet Xsection in Pb-Pb collisions at LHC per binary collisions vs pseudo-rapidity

The ALICE tools for jet reconstruction

- JETAN module in constant development in AliRoot to include different jet finders:

◈ First implementation: an iterative jet cone finder algorithm based on the UA1 cone method. Optimised for heavy-ion environment at LHC

✓ Uses combination of charged tracks and neutral digits/clusters in EMCal
✓ Analyses performed on a (η,ϕ) grid of size EMCal granularity in EMCal acceptance and varius size outside (ex: 0.015x0.015).
✓ Not infrared and collinear safe yet !

◈ Fast k_T recently interfaced: k_T algorithms are very slow in a heavy ion environment. New k_T algorithm (FASTJET) looks for nearest neighbours of each particle using the Voronoi diagram tool. G. Salam & M. Cacciari

◈ Project: SISCONE (Cone algorithm infrared and collinear safe) G. Salam & M. Cacciari

- Sub-methods extension of UA1-algorithm:

◈ Hadron correction
◈ In progress: remove energy counted twice from electrons
◈ Tools for background subtraction: 3 methods implemented for cone, statistical and ratio BG subtraction (vs $dN/d\eta$) [see later]

File production: PYTHIA & HIJING

Simulations for Jets:

- 3 mono-energetic jet samples in the EMCal acceptance (50, 75 and 100 GeV)
- 1 cross-section weighted sample (40 < p_THard < 240 GeV/c) – 11 energy ranges
- ALICE strategy to simulate hard and rare processes in Pb+Pb collisions:

=> embed p+p events in the UE of Pb+Pb
=> PYTHIA 6.214 + Central HIJING 1.36 (0 < b < 5 fm) & PYTHIA + Minbias HIJING

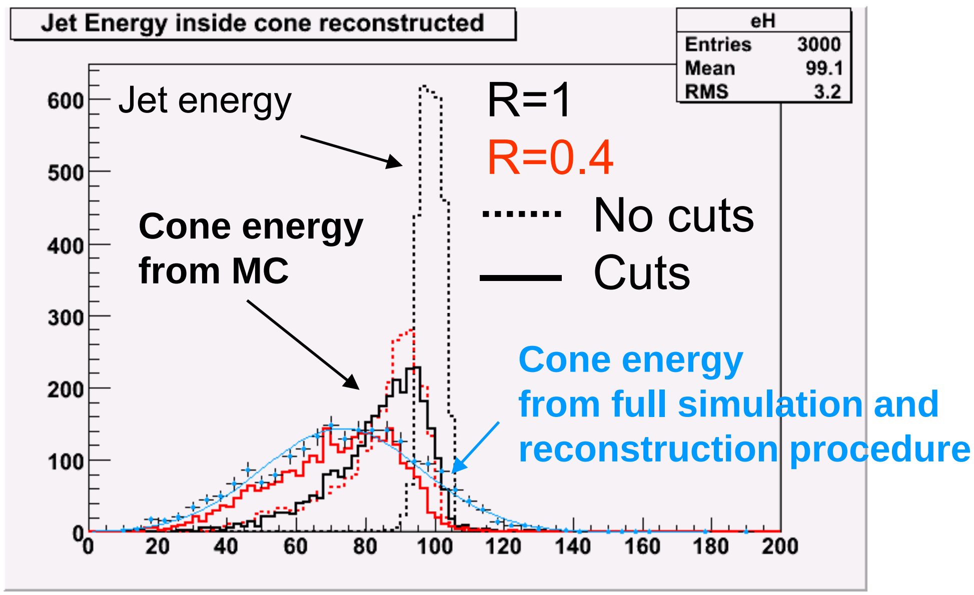
Detector simulation:

- Full GEANT3 response of ALICE and EMCal in original geometry:
  - TPC: $-0.9 < \eta < 0.9$, $0 < \phi < 2\pi$
  - EMCal: $-0.7 < \eta < 0.7$, $80° < \phi < 190°$
  - Jet reconstructed in the ALICE fiducial region

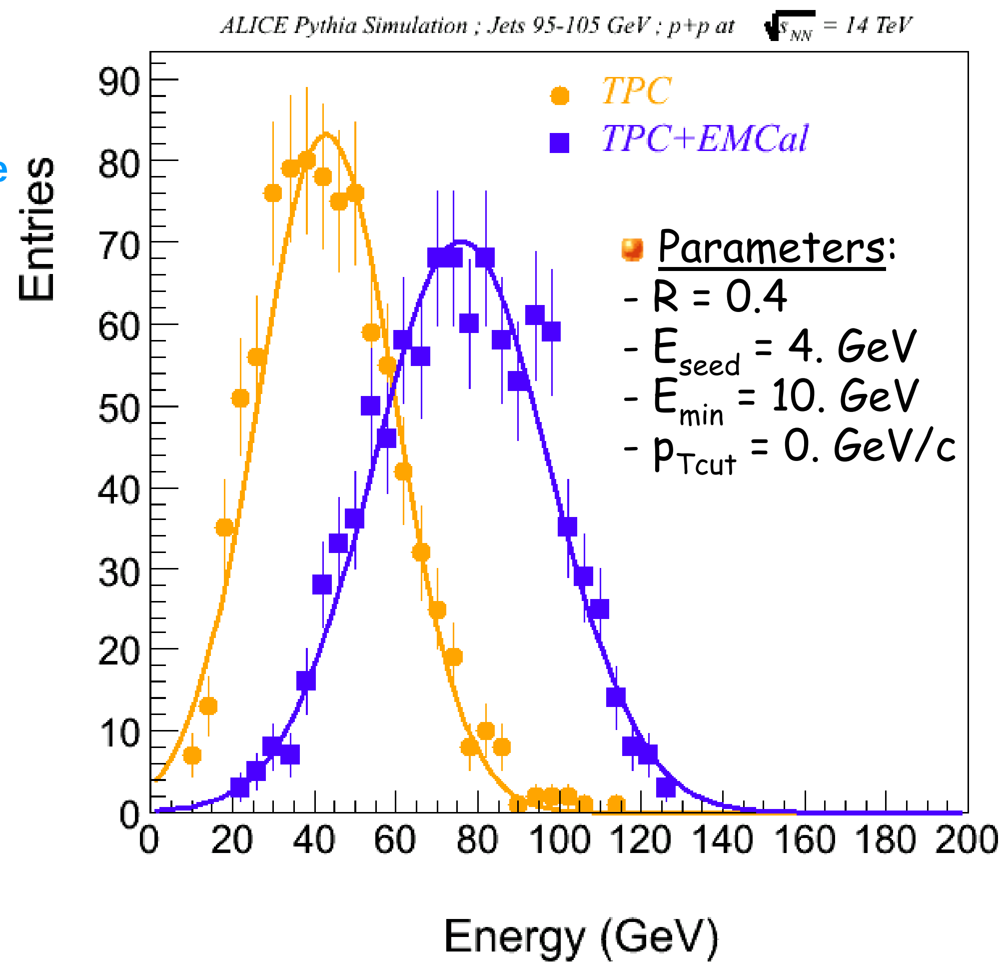
PYTHIA 6.214	
√sNN	5.5TeV
Hard processes	MSEL=1
Structure function	CTEQ5L
Jet quenching	Off/On
ISR/FSR	On
Multiple interactions	Off
Resonance decays	On

HIJING 1.36	
√sNN	5.5TeV
Jet quenching	On
Nuclear effects on PDF	On
ISR/FSR	On
Resonance decays	Off
Jet trigger	Off
Impact Parameter	0-5fm

Resolution improvement with the EMCal



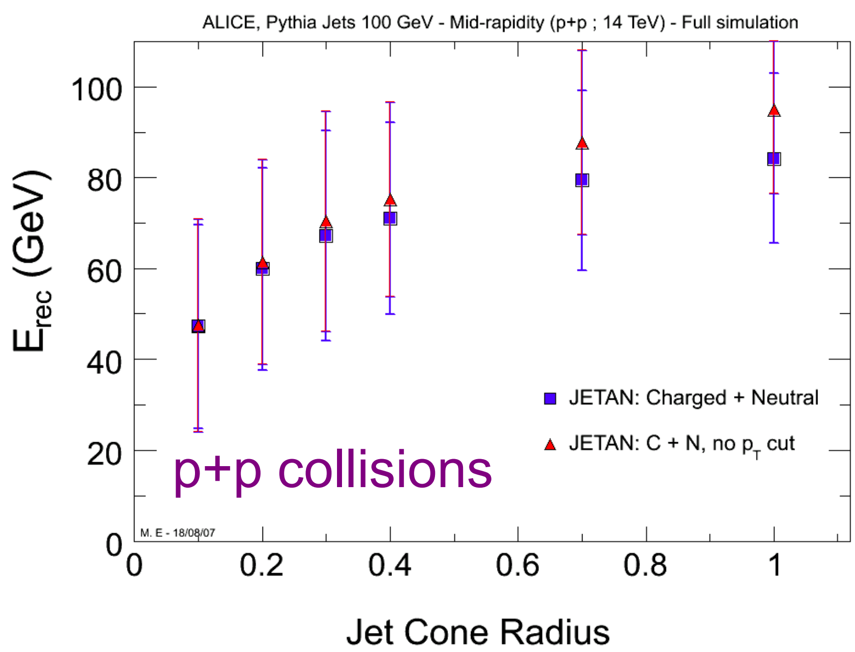
- Simulate 100 GeV @ 14TeV jets inside the EMCal acceptance (jets with R=0.4 totally included in the detector)
- Reconstruct jets inside the EMCal acceptance

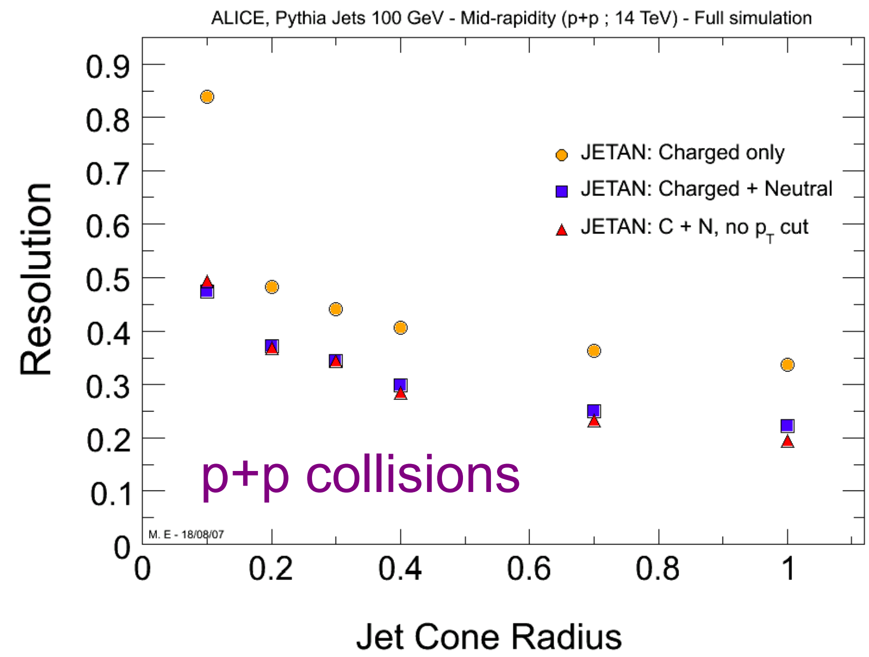


	TPC	TPC+EMCal
E_{mean} (GeV)	43.0+/-0.6	75.9+/-0.7
RMS (GeV)	16.9+/-0.5	21.7+/-0.6
Resolution	**39.3%***	**28.6%***

*Hadron correction not yet applied !

Cone energy and resolution systematics in p+p





E_{rec} = mean energy inside a cone of radius R
Resolution = RMS/E_{rec}

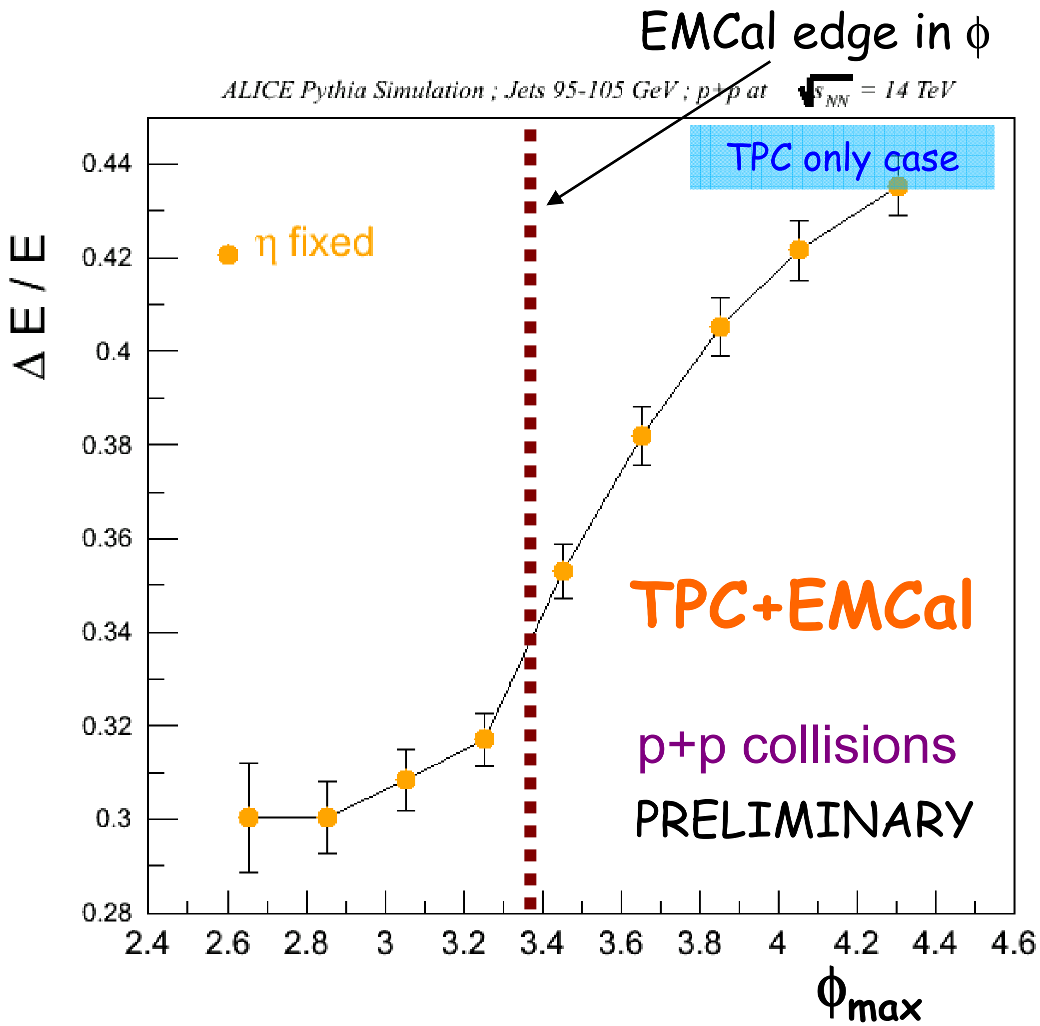
- The increase of the size of the jet cone radius or the inclusion of neutral particles in jet finding:
  ⇒ **improves** the reconstructed **cone energy**
  ⇒ **improves** the **resolution**
- Almost flat resolution with jet energy (R=0.4)
  ~ 40% (charged only)
  ~ 30% (charged + EMCal)

Acceptance effects and limitation

Resolution behaviour with ϕ_{max} ("leading")

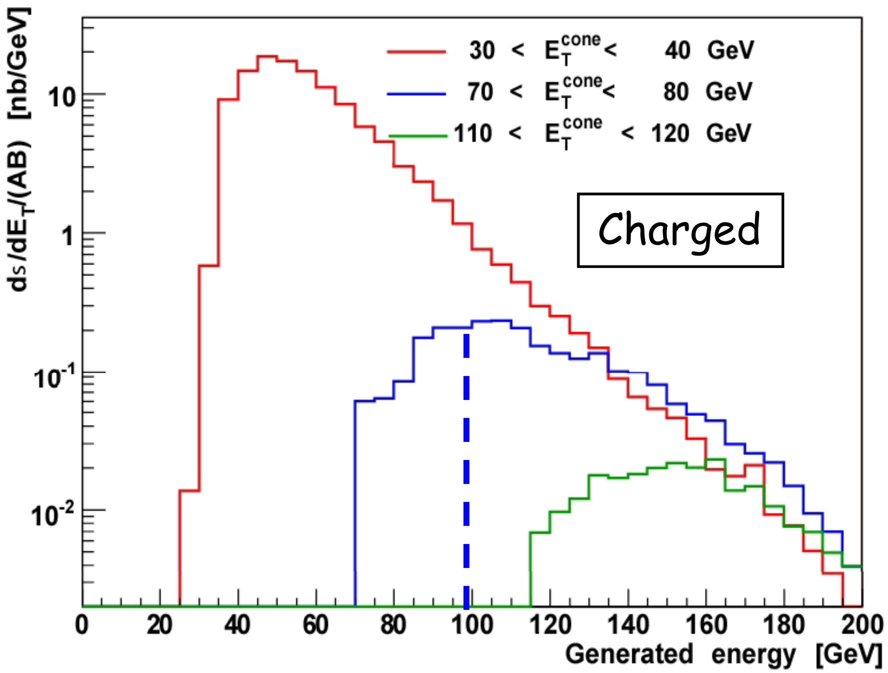
- 100 GeV jets simulated in TPC acceptance (Full simulation)
- Reconstruct jets with TPC+EMCal
- Select center of jets of radius R=0.4 in a given η-φ window:
  - In the following acceptance study, η taken in [-0.3,0.3].
  - Start with $\phi_{center\ of\ jet}$ in ϕ_{center} +/-0.3 and then open the window

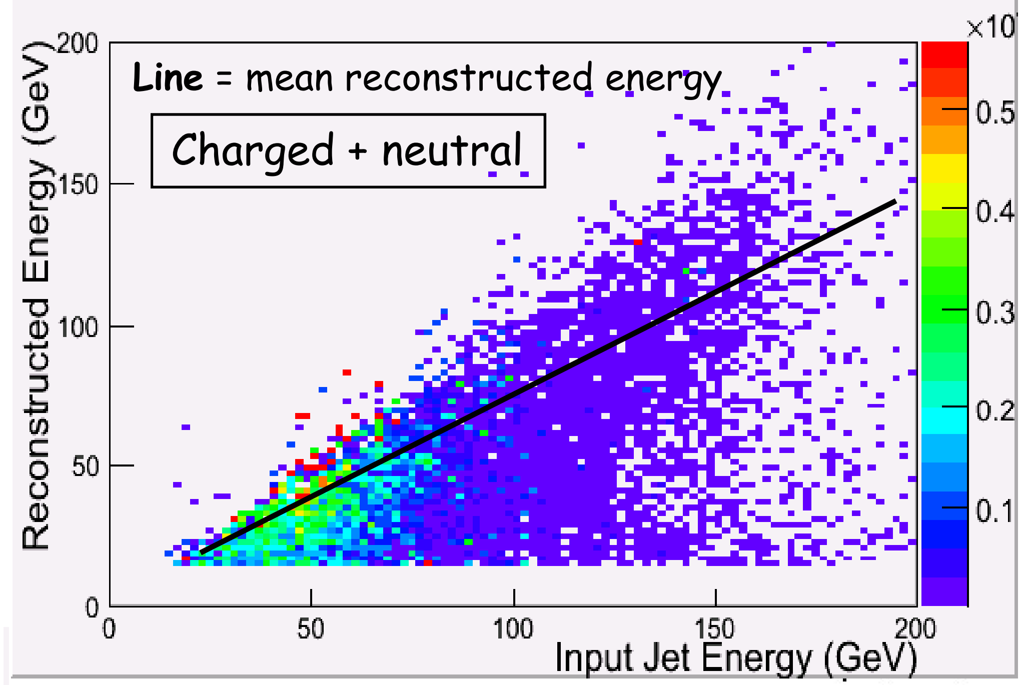
⇒ Look at the resolution

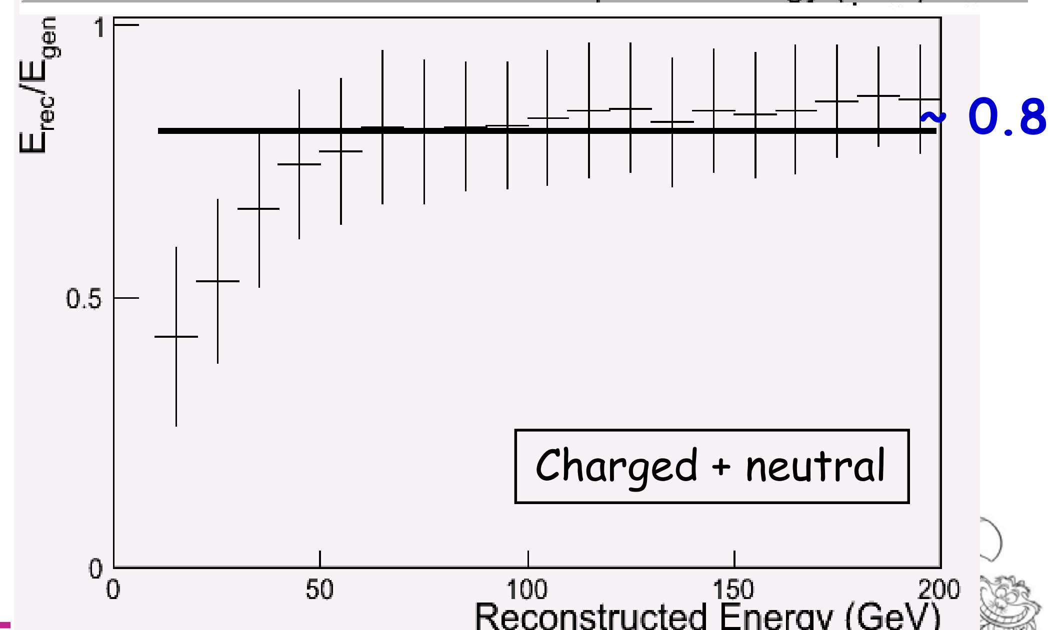


Center of the jet taken inside the calorimeter (until its edges):
⇒ resolution still better than 33%

Smearing function for jet energy correction

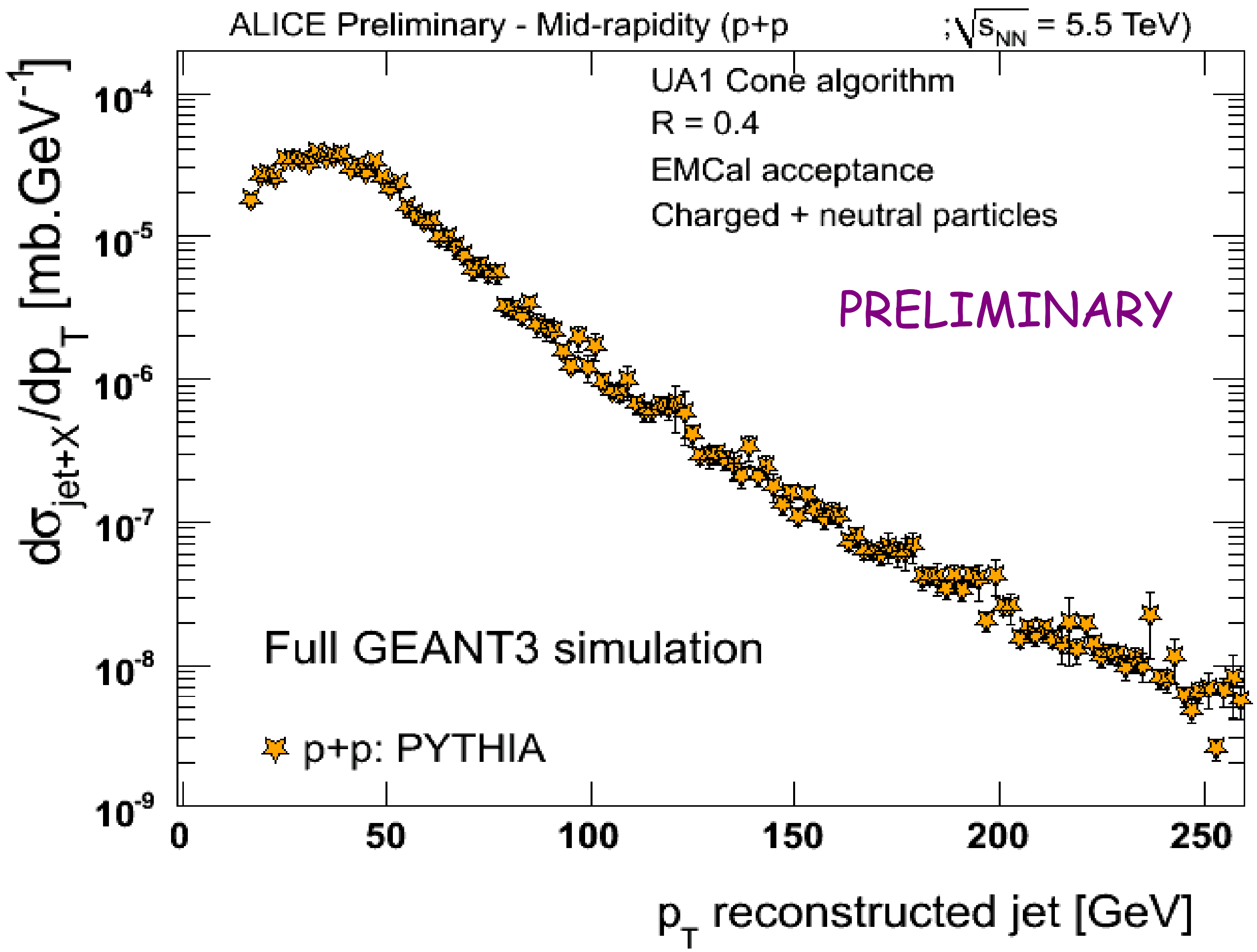






- Drop of E_{rec}/E_{gen} => artefact of the input spectrum simulation
- For E_T jet > 40 GeV, no special behaviour of the correction factor with the reconstructed jet energy.
- The reconstructed cone energy has been corrected according to this factor.

Full jet spectrum obtained from full simulation with GEANT3



Reconstructed energy dominated by the smearing of the spectrum

To be done: comparison to input PYTHIA

Background effects
in heavy ion collisions

A large background energy:

Multiple nucleon-nucleon interactions produce many particles of low energy
In a cone of radius R = 1
- RHIC: 300 GeV
- LHC: 1.5-2 TeV

…but large rate up to ~ 250 GeV !!! And jets are more collimated with increasing energy so that they « emerge » from the background more easily.

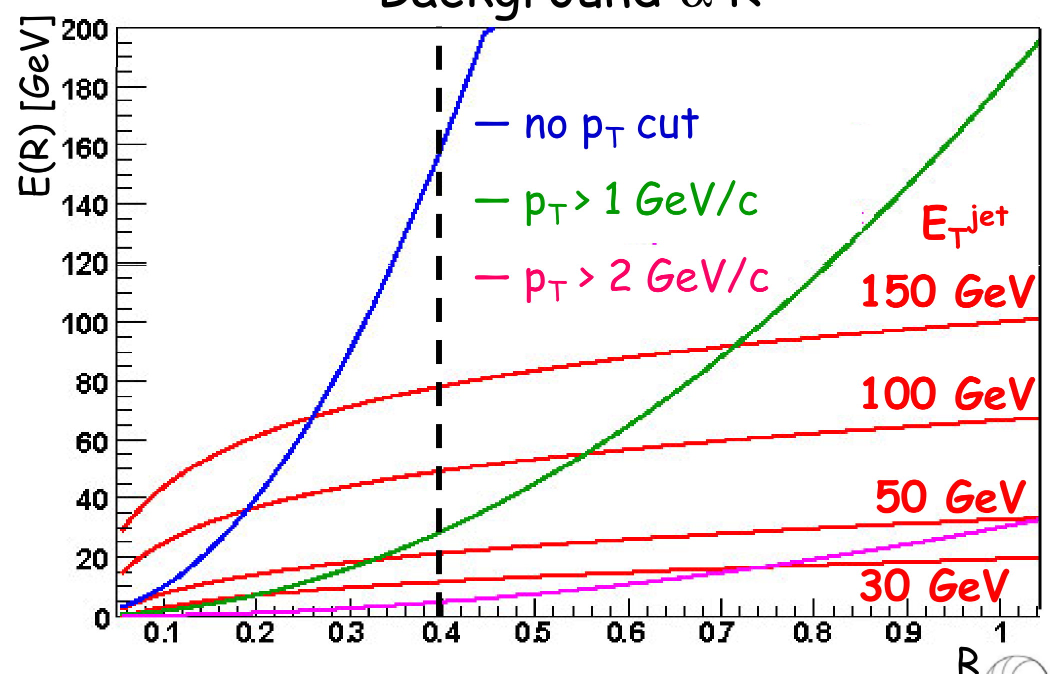
Ideas:

- look at domains in which $E_{mean} \gg \Delta E_{bg}$
- reduce the cone size.

Typically at LHC, 80% of the jet energy is included in a cone of R_c ~ 0.3 whereas BG and fluctuation of BG scale as R_c^2 and R_c reducing them to 170 GeV and 12 GeV.

- apply a low p_T cut

Background α R^2

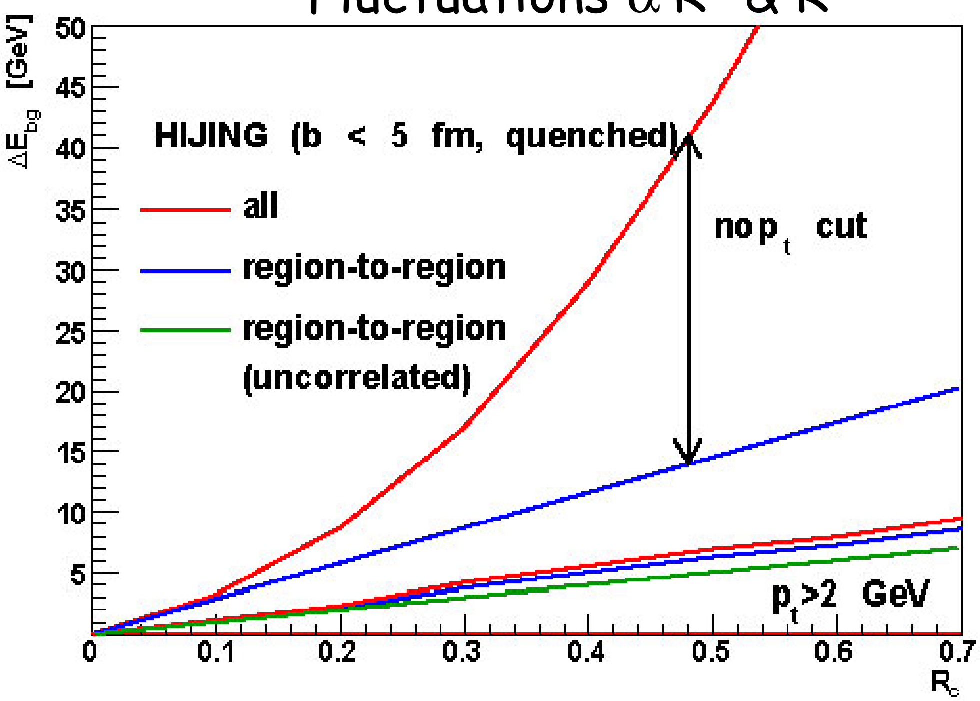


Jet reconstructed from charged particles

Characteristics of the background fluctuations

- Background fluctuations limit the energy resolution

Fluctuations α R^2 & R



HIJING simulations indicate that the optimal cone size is R = 0.4 and p_T cut = 1 or 2 GeV/c [lower poissonian limit reached]
=> Leads to signal fluctuations !

- Fluctuations caused by event-by-event variations of the impact parameter for a given centrality class (~R^2)

[Strong correlation between different regions in $\eta-\phi$ plane

Can be eliminated using impact parameter dependent background subtraction]

- Poissonian fluctuations of uncorrelated particles (~ R)

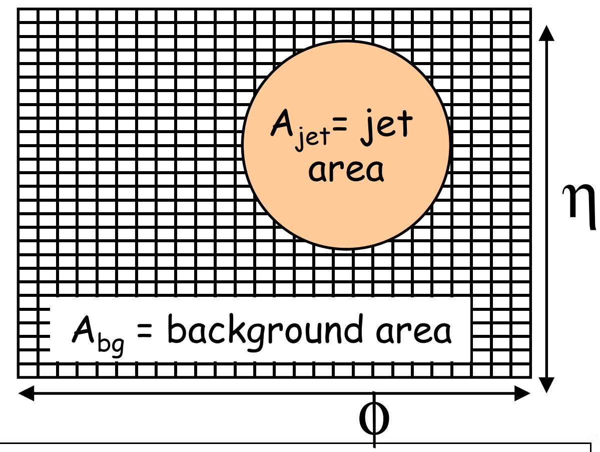
[dominate region-to-region fluctuations if no p_T cut]

- Correlated particles from common source (low-E_T jets) (~R)

[increase the fluctuation level to about 30% above the poissonian limit if p_T cut]

Background subtraction

The main jet finding modification consists in determining the mean cell energy from cells outside a jet cone. It is recalculated after each iteration and subtracted from the energy inside the jet area



- ✚ **Statistical method**: (from N jet-free events for different centrality) => limited by impact parameter fluctuations

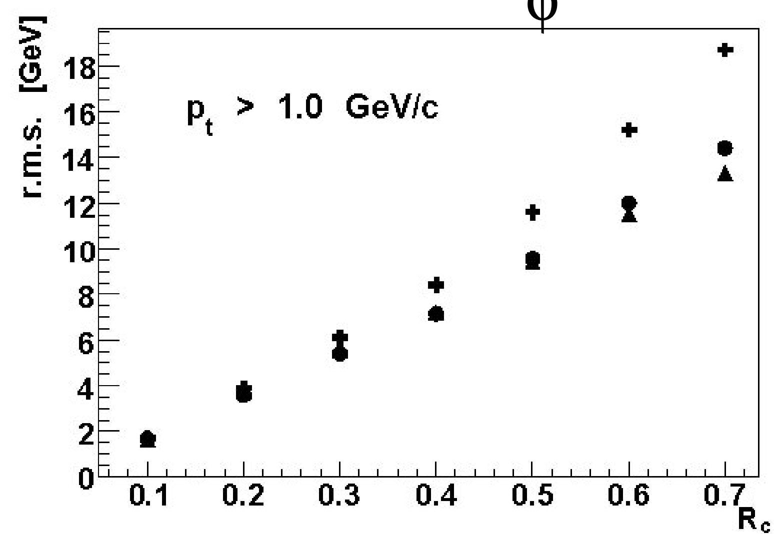
$$E_{bg}^{stat} = K \times \left\langle \sum_{p_t > p_t^{th}} p_t \right\rangle_N \qquad K = A_{jet}/A_{bg}$$

- ● **Cone method**: (event-by-event – Assumption: background energy uncorrelated with the jet)

$$E_{bg}^{cone} = K \times \sum_{p_t > p_t^{th}, R > R_c} p_t$$

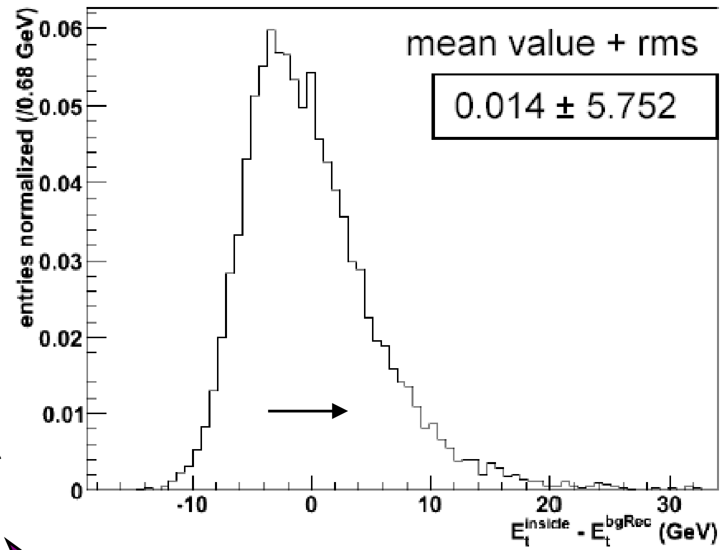
- ▲ **Ratio method**: (event by event except for F)

$$E_{bg}^{ratio} = F \times K \times \sum_{R > R_c} p_t \qquad F = \left\langle \sum_{p_t > p_t^{th}} p_t \right\rangle_N \Big/ \left\langle \sum p_t \right\rangle_N$$



r.m.s. of difference between estimated and real energy BG in jet cone.

Background subtraction bias on mono-energetic jets



Under-estimation of the background

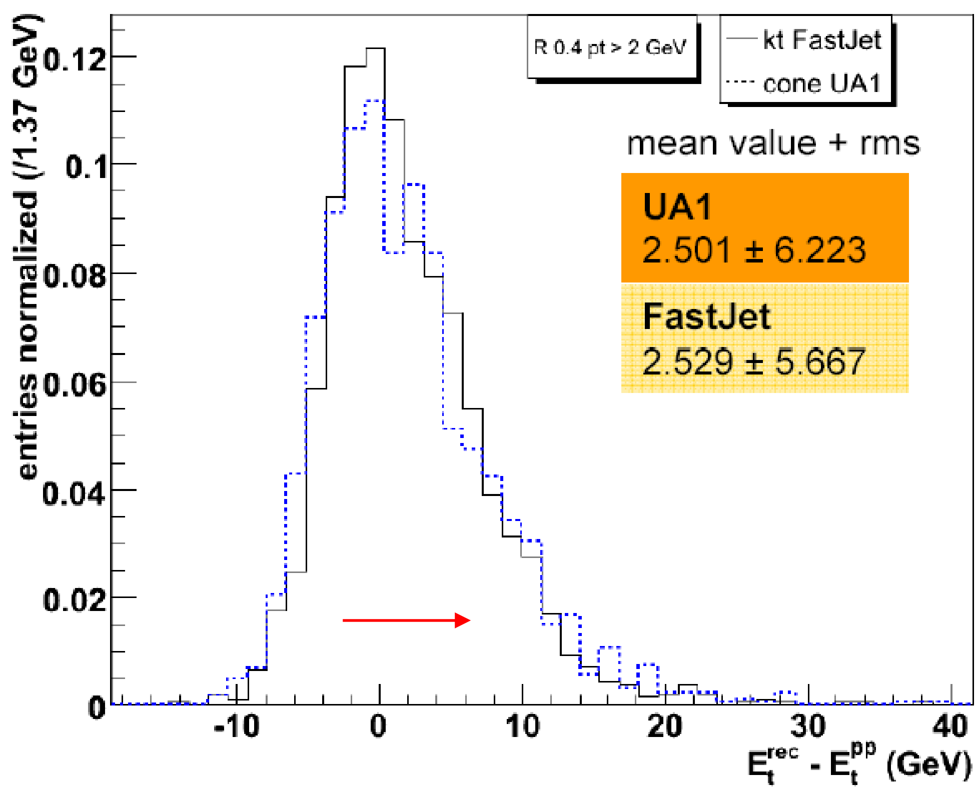
E_t^{inside} = Background energy summed in a cone taken randomly in $\eta \times \phi$ grid

E_t^{bgRec} = energy of the BG in the same cone but evaluate with the cone method

$E_t^{rec} = E_{cone} - E_{bgrec}$

E_{pp} = true jet energy

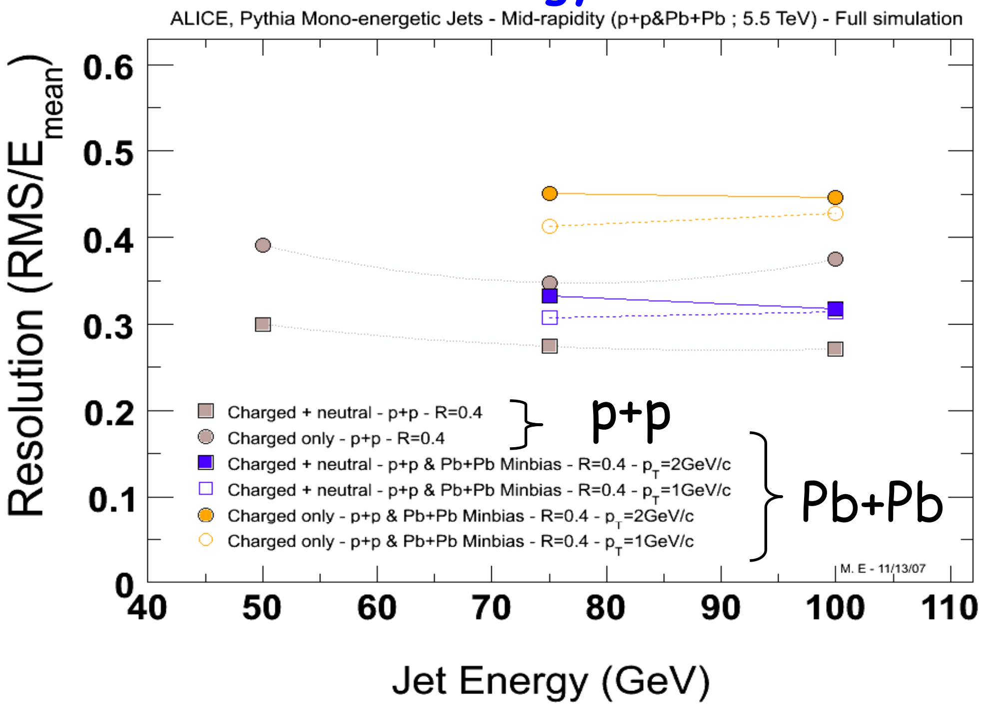
E_t^{input} = 45 GeV under Ideal detector response



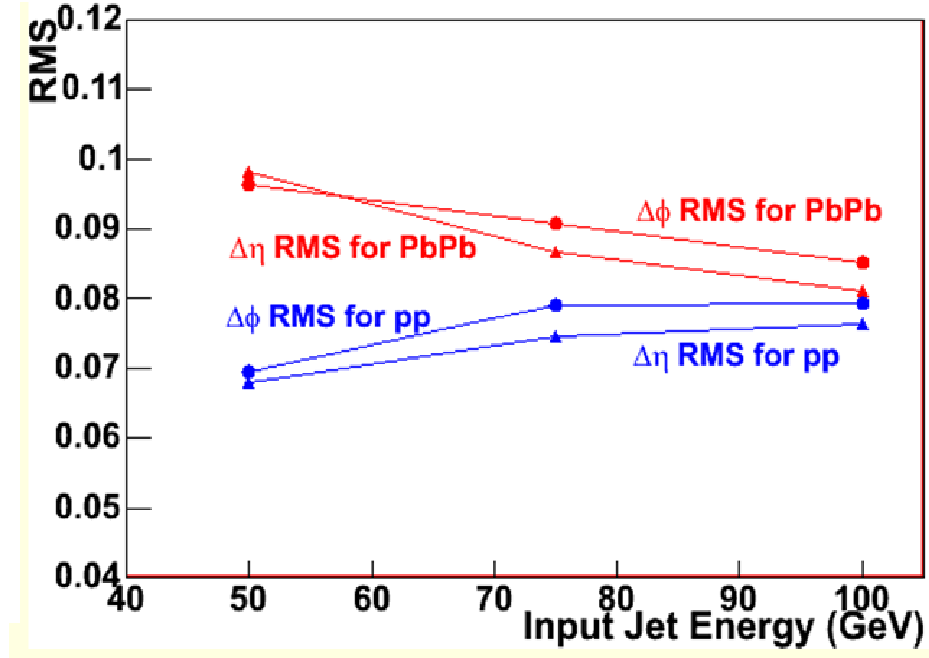
Over-estimation of the reconstructed energy !

Resolution from Full Simulation in Pb+Pb

Energy



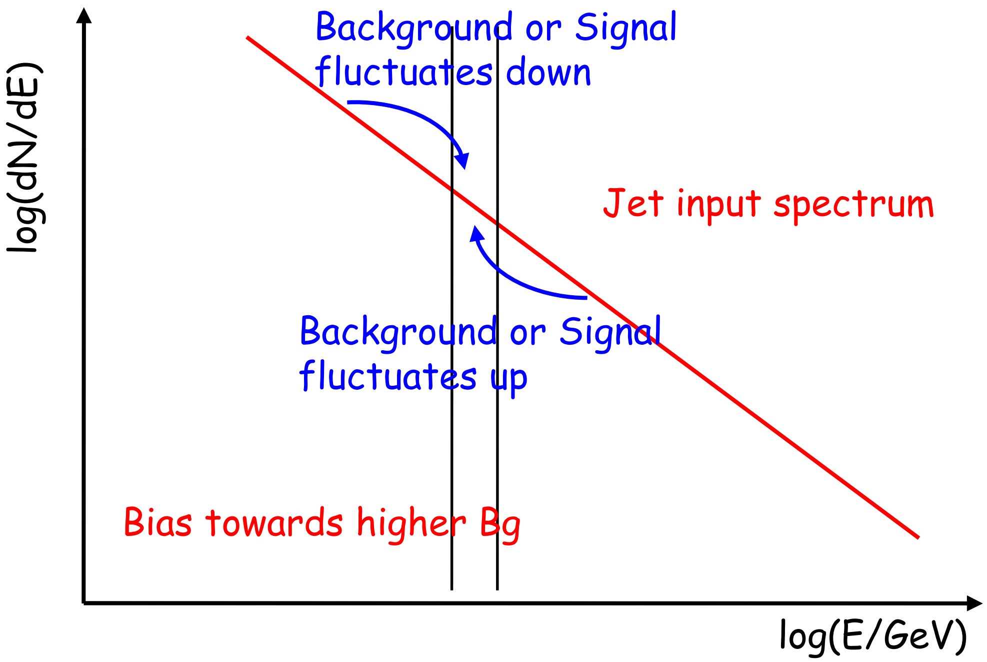
Direction (η,ϕ)



- Worth resolution than p+p alone
- $\Delta E/E$ (Charged+neutral) 30-35%
  (Charged only) ~ 45%
- Better resolution with smaller p_T cut on charged particles

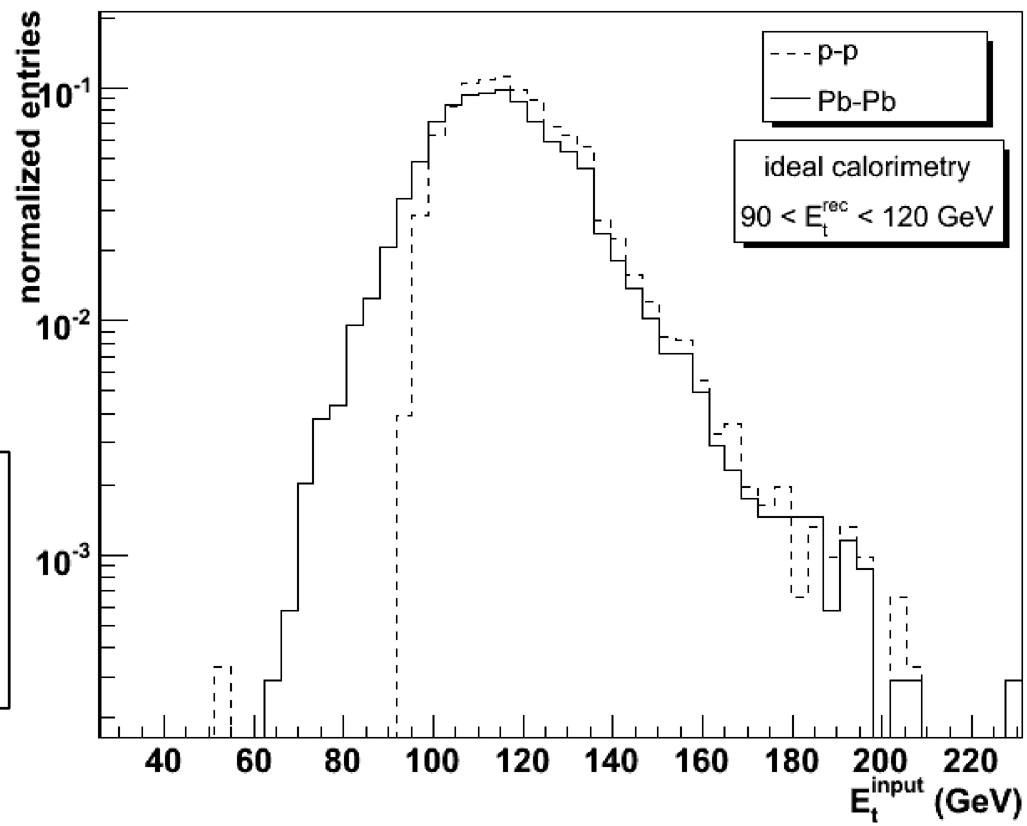
- Accurate jet direction recontruction in both p+p and Pb+Pb collisions

Background subtraction bias on full jet spectrum



	$\langle E_t^{input} \rangle$	$\langle E_t^{rec}/E_t^{input} \rangle$
p-p	**120.0±17.23**	**0.856±0.0815**
Pb-Pb	**116.2±19.21**	**0.894±0.1169**

- In Pb-Pb there are additional contributions from low energy jets overlapping with background fluctuations.

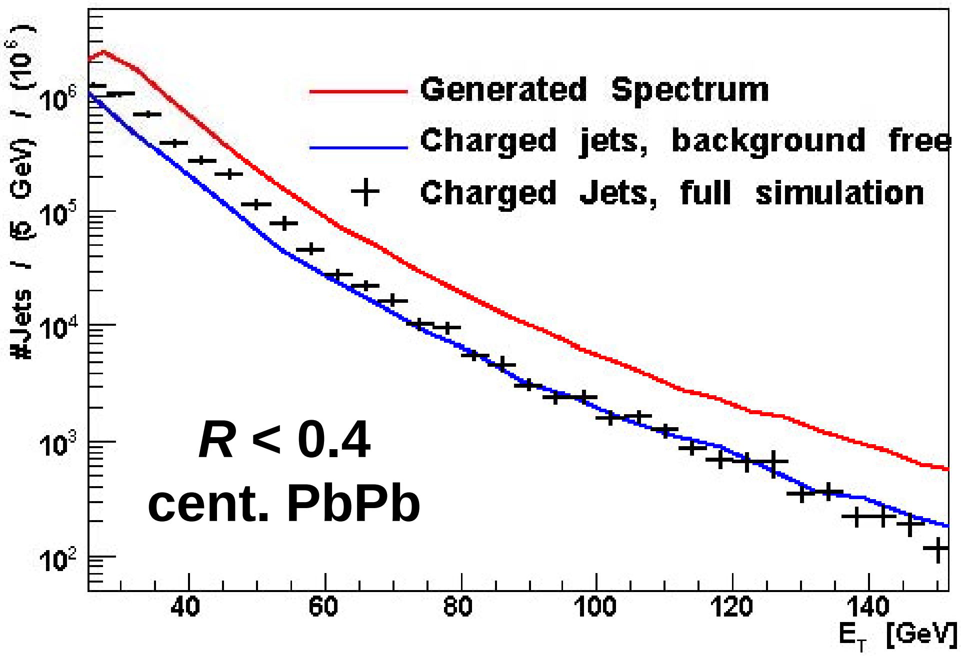


For a realistic input spectrum this effect is enhanced since the production rate for a jet with E_t+dE_t is lower than for E_t-dE_t

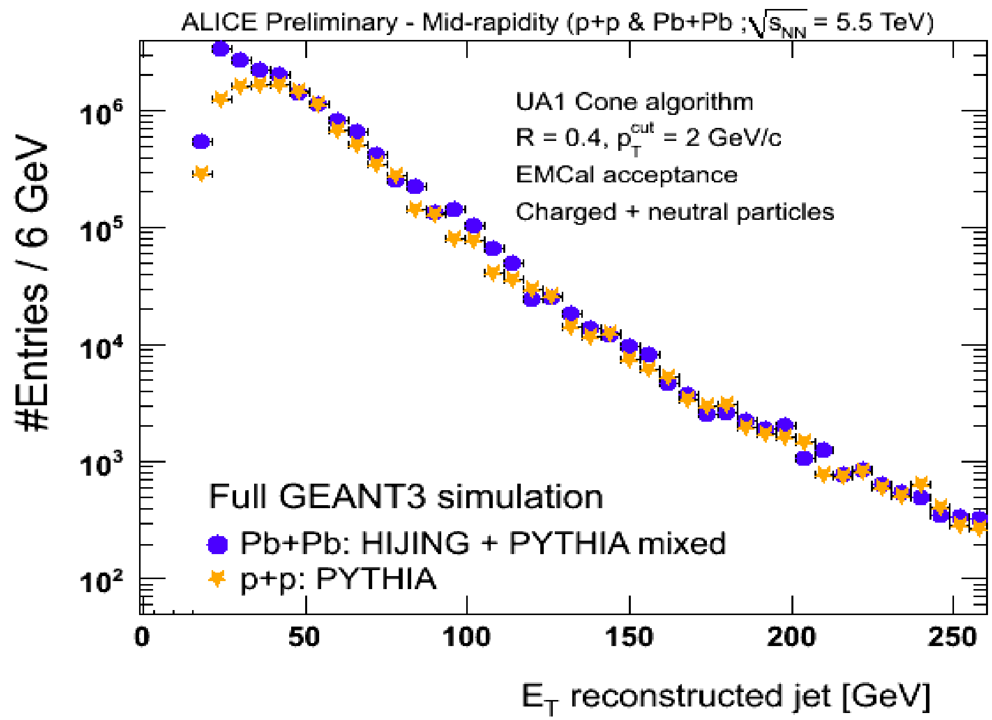
Full Simulation and Reconstruction Jet Spectra

Statistics for 1 month of Pb+Pb running (10^6 s)

Charged Jets

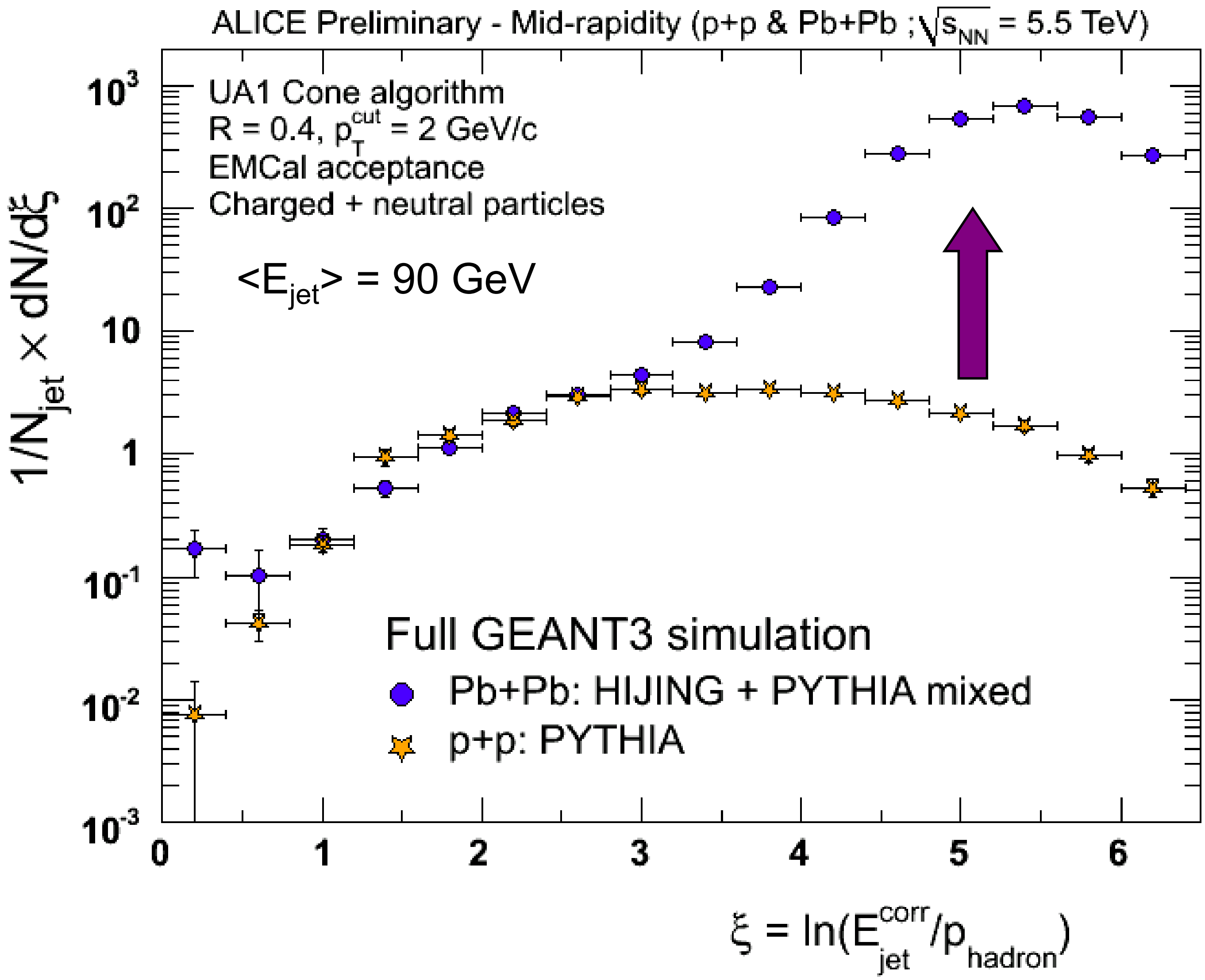


Charged + EMCal



Reconstruction efficiency dominated by smearing of the spectrum

Hump-backed plateau - no BG subtraction



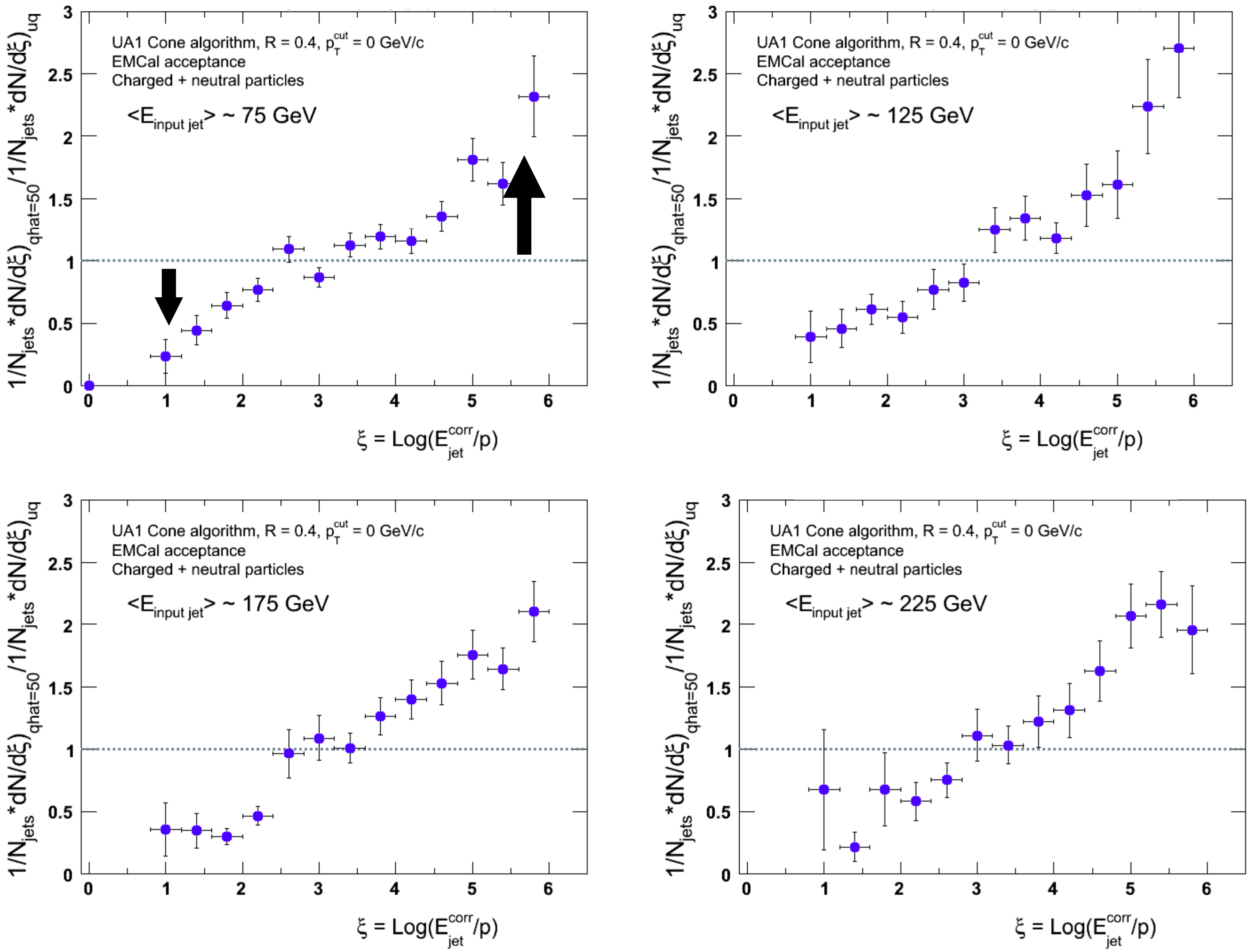
Understand background subtraction and relative energy calibration pp (14 TeV)/PbPb (5.5 TeV)!

- Extract the same 1/Njets.dN/dξ for the background only and then subtract to obtain a direct comparison to p+p data: $1/Njets.dN/d\xi]_{PbPb} - 1/Njets.dN/d\xi]_{PURE\ HIJING}$

=> in progress

In a quenching scenario…

- Ratio: FF(pp quenched)/FF(pp unquenched) vs ξ



- Energy loss: PQM model
- Many soft gluons emitted out-of-cone

Full simulation !

Comparison for different quenching scenarii under study

Conclusion

- Copious rates of jets at LHC
  - Reconstruction will be possible over the background from underlying event
  - Large energy range accessible from > 2. to ~ 250. GeV/c

- Quite good background substraction controlled (ongoing activity)
Good reconstruction of jet with R = 0.4 and p_T^{cut} = 2 GeV/c

- Algorithms initially written for pp systems are intensively tested for HIC application (not shown in this talk) : cone, k_T, fast k_T, …

- Jet structure observables will be measurable
  - In AA, high-p_T (calorimetry) and low-p_T capabilities needed for unbiased measurement of parton energy.
  - Strength of ALICE:
    - *Excellent low-p_T capabilities to measure particles from medium induced radiation.*
    - *PID to measure the particle composition of quenched jets*
    - *Dedicated pp experiments have larger E_T reach*
  - Background contribution and bias with neutrals still need to be studied as well as the smearing of the jet spectra and its consequences on energy calibration.

Extra