Jet Physics
in Heavy Ion Collisions at the LHC

Andreas Morsch (CERN)

- LHC Heavy Ion Program
- Jet Physics at LHC: Introduction and motivation
- Emphasis on expectations and requirements
  - Jet rates at the LHC
  - Energy resolution
  - Jet structure observables
- In short: The experiments.

Nuclear collisions at the LHC

- LHC on track for start-up of pp operations in April 2007
- Pb-Pb scheduled for 2008
  - Each year several weeks of HI beams (10^6 s effective running time)
- Future includes other ion species and pA collisions.
  - LHC is equipped with two separate timing systems.

System	$\mathcal{L}_0$ [$cm^{-2}s^{-1}$]	$\sqrt{s}_{NN\ max}$ [TeV]	Δy
Pb+Pb	$1\ 10^{27}$	5.5	0
Ar+Ar	$6\ 10^{28}$	6.3	0
O+O	$2\ 10^{29}$	7.0	0
pPb	$1\ 10^{30}$	8.8	0.5
pp	$1\ 10^{34}$	14	0

First 5-6 years

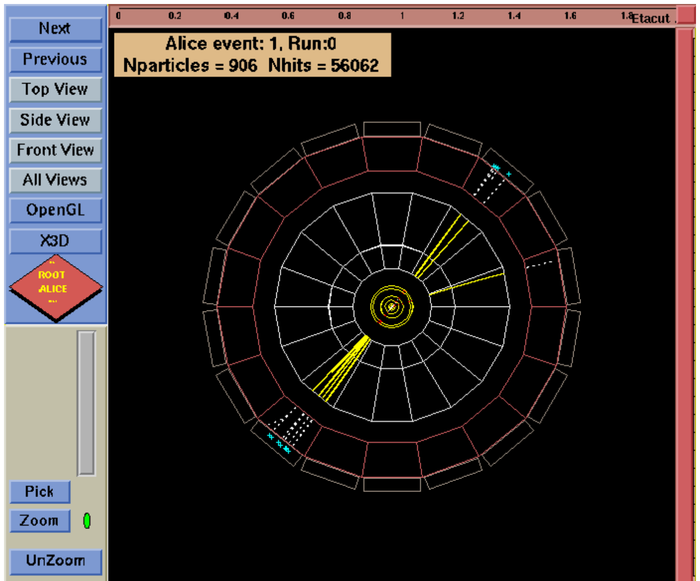
2-3y	Pb-Pb	(highest energy density)
2y	Ar-Ar	(vary energy density)
1y	p-Pb	(nucl. pdf, ref. data)

Pb-Pb Collisions at LHC

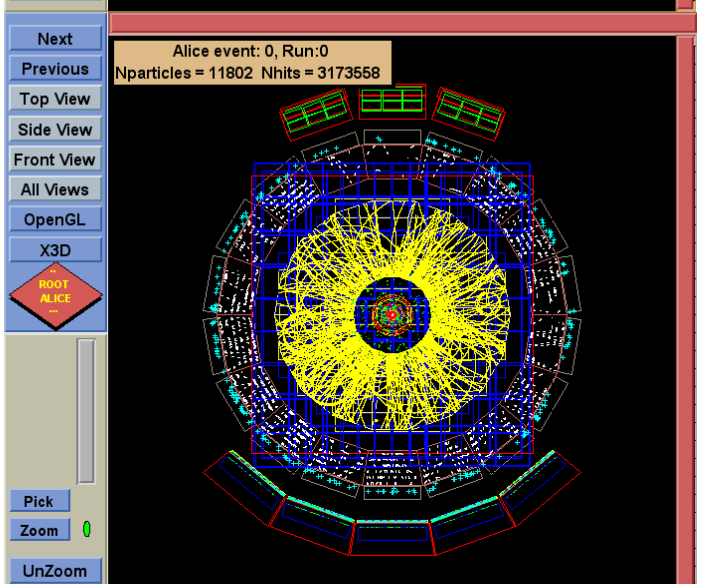
- As compared to RHIC
  - Energy density 4-10 higher
  - Larger volume (x 3)
  - Longer life-time (2.5 x)
- High rate of hard processes
  - Produced in on year of running for |y| < 1
    - $5\ 10^{10}$ Open charm pairs
    - $2\ 10^{9}$ Open beauty pairs
    - $1\ 10^{9}$ Jets (E_T > 20 GeV)

Central collisions	*SPS*	*RHIC*	*LHC*
$s^{1/2}$(GeV)	17	200	5500
dN_{ch}/dy	500	650	3-8 $\times 10^3$
ε (GeV/fm^3)	2.5	3.5	15-40
V_f(fm^3)	10^3	7×10^3	2×10^4
τ_{QGP} (fm/c)	<1	1.5-4.0	4-10
τ_0 (fm/c)	~1	~0.5	<0.2

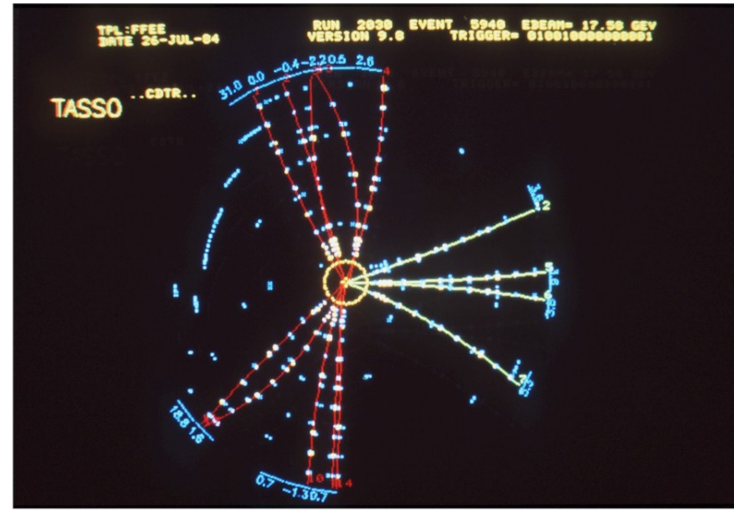
High rates, however challenging ...

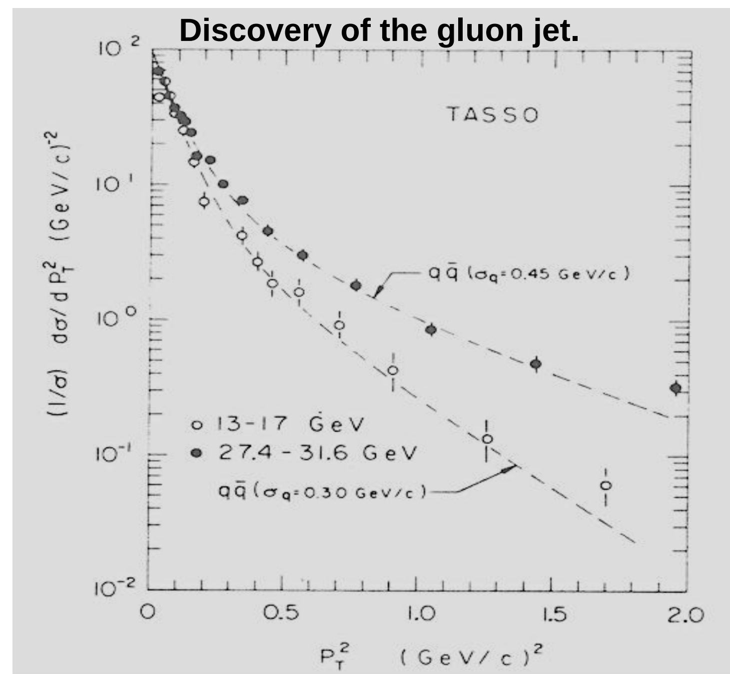


Study jet structure ...



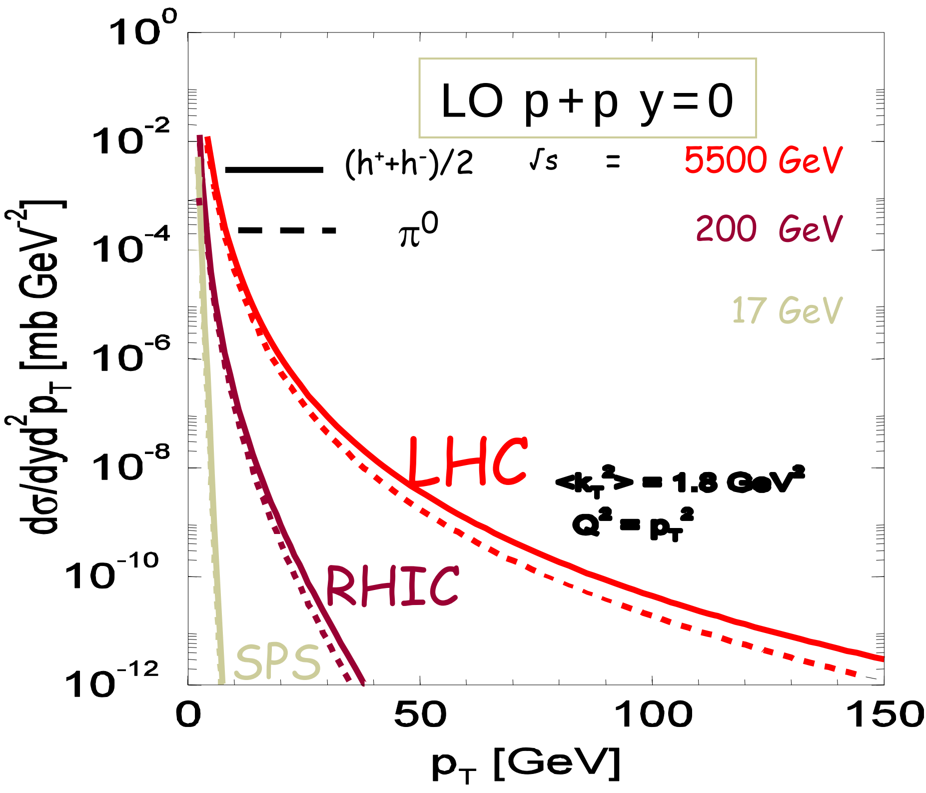
... inside the underlying event of a Pb-Pb collision.





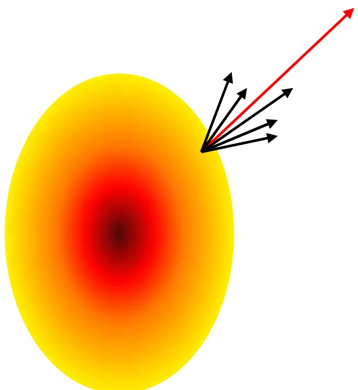
From RHIC to LHC

- Evidence for energy loss in nuclear collisions has been seen at RHIC.
  - Measurements are consistent with pQCD-based energy loss simulations and provide a lower bound to initial color charge density.
  - However, more detailed studies at higher p_T at RHIC and higher energies (LHC) are necessary to further constrain model parameters.
- This has triggered substantial interest in Jet Physics in nuclear collisions at the LHC at which
  - Medium and low-p_T
    - Dominated by hard processes
    - Several Jets E_T < 20 GeV / central PbPb collision
  - At high-p_T
    - Jet rates are high at energies at which jets can be identified over the background of the underlying event.

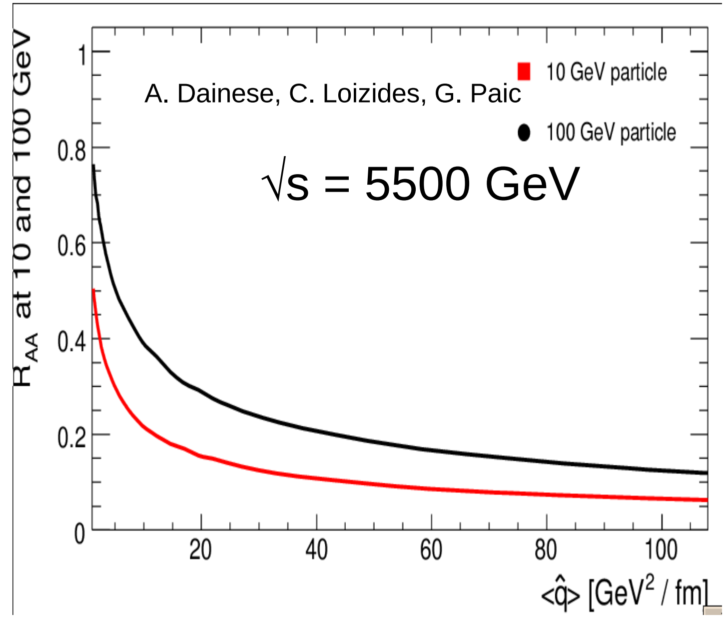


Naturally the next step: Reconstructed jets ...

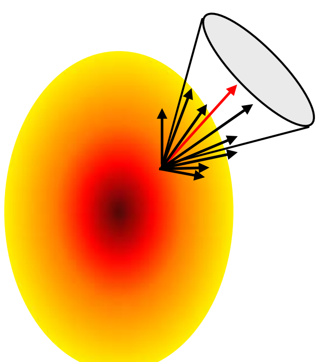
Leading Particle



- The leading particle as a probe becomes fragile in several respects:
- Surface emission "trigger bias" leading to
  - Small sensitivity of R_{AA} to variations of transport parameter q^{hat}.
  - Yields only lower limit on color charge density.
- For increasing in medium path length *L* leading particle is less and less correlated with jet 4-momentum.



Reconstructed Jet

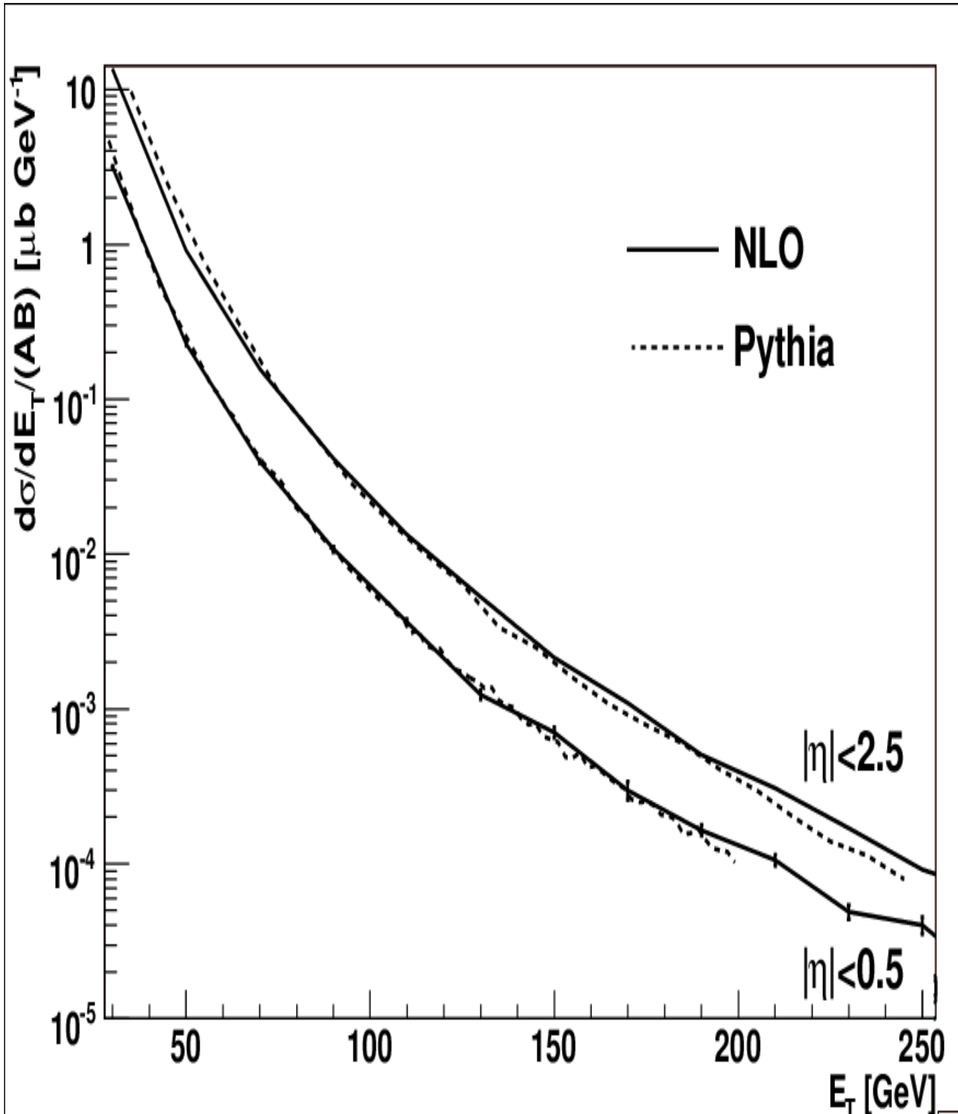


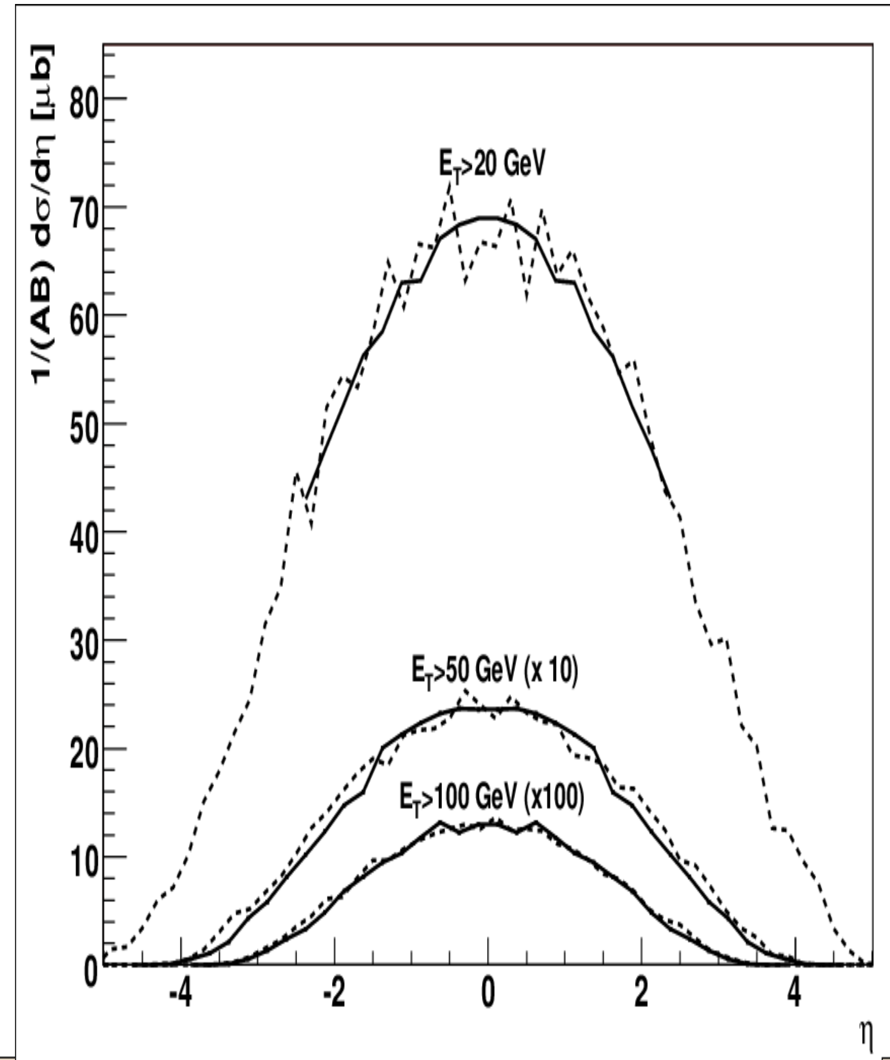
- Ideally, the analysis of reconstructed jets will allow us to measure the original parton 4-momentum and the jet structure (longitudinal and transverse). From this analysis a higher sensitivity to the medium parameters (transport coefficient) is expected.

Part II

- What are the expected jet production rates at the LHC ?
- How to identify jets knowing that a typical jet cone contains 1 TeV of energy from the underlying event ?
- What are the intrinsic limitations on the energy resolution ?

Jet rates at LHC



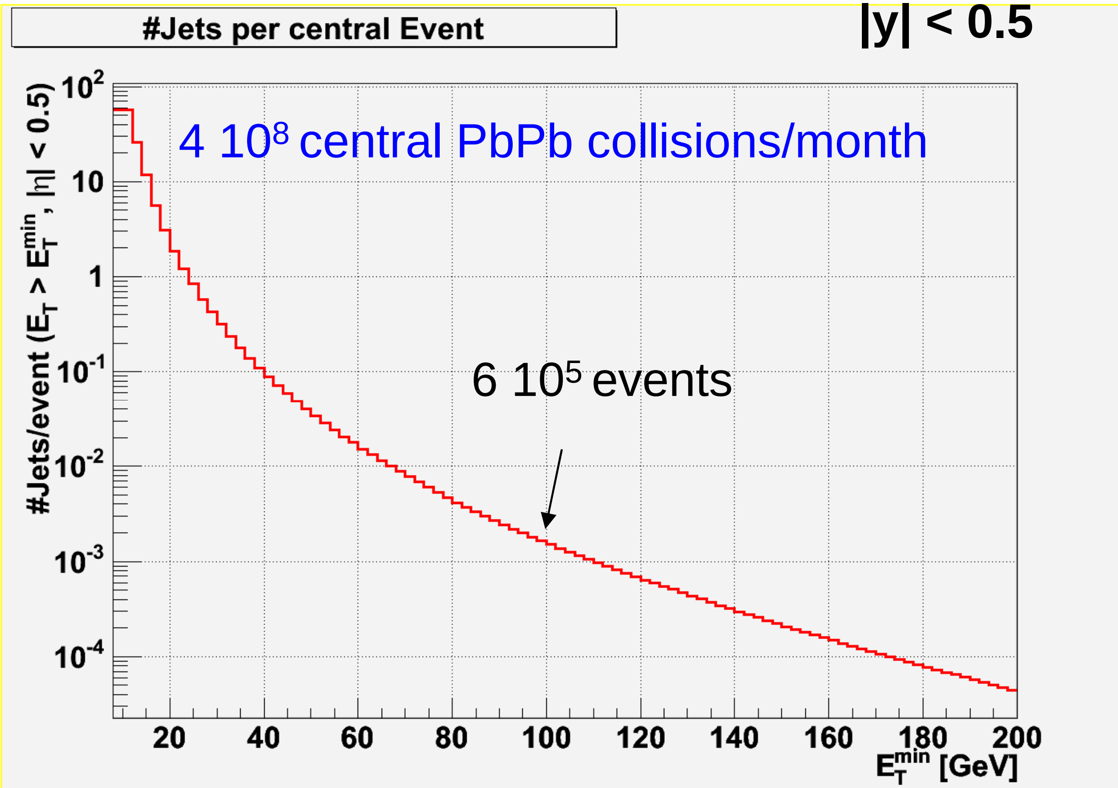


NLO by N. Arnesto

Jet rates at LHC

Copious production:

Several jets per central PbPb collisions for E_T > 20 GeV



E_T threshold	N_{jets}
50 GeV	2×10^7
100 GeV	6×10^5
150 GeV	1.2×10^5
200 GeV	2.0×10^4

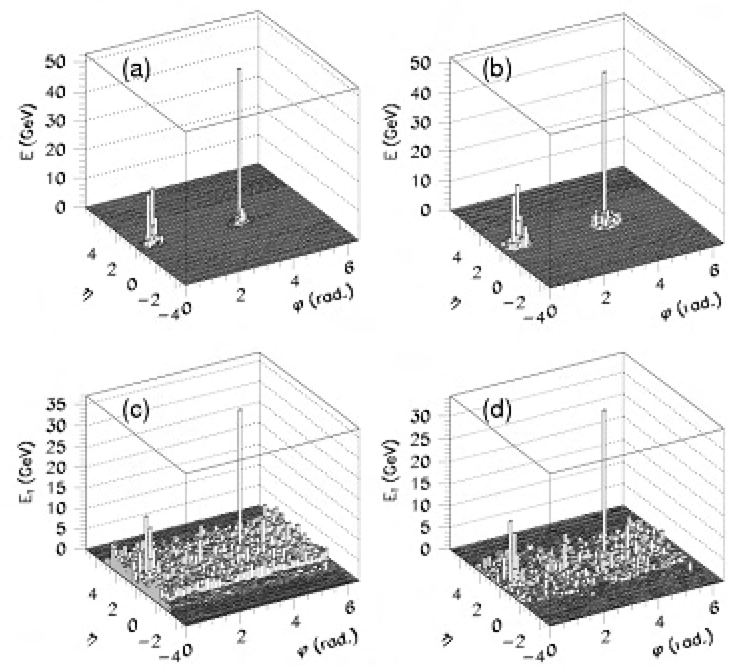
However, for measuring the jet fragmentation function close to $z = 1$, >10^4 jets are needed. In addition you want to bin, i.e. perform studies relative to reaction plane to map out L dependence.

Jet identification

- It has been shown (by embedding Pythia jets into HIJING) that even jets of moderate energies (E_T > 50 GeV) can be identified over the huge background energy of the underlying HIJING event of central PbPb.
  - Reasons:
    - Angular ordering: Sizable fraction (~50%) of the jet energy is concentrated around jet axis (R< 0.1).
    - Background energy in cone of size R is ~ R^2 and background fluctuations ~ R.

For dN_{ch}/dy = 5000:

Energy in $R = \sqrt{(\Delta\eta^2+\Delta\phi^2)} < 0.7$:
1 TeV !

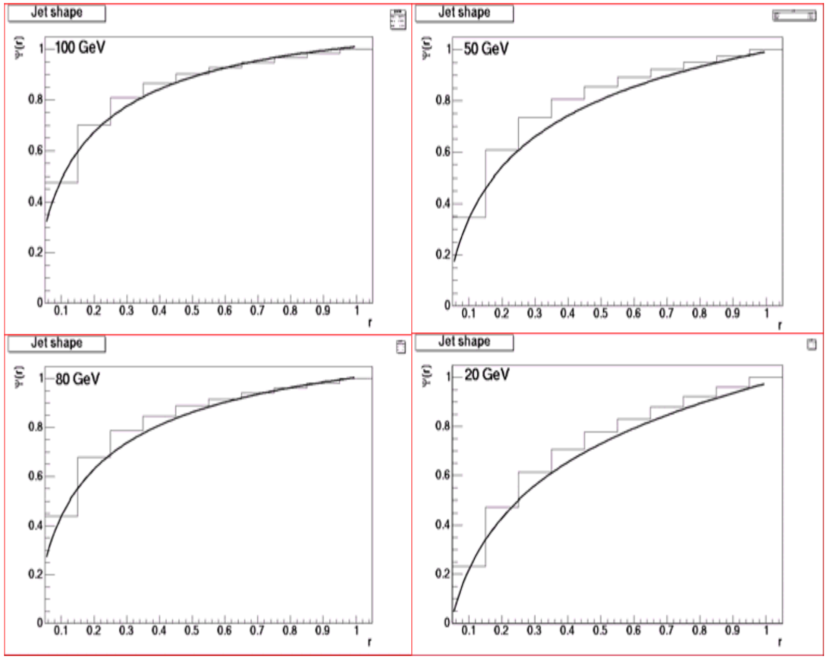


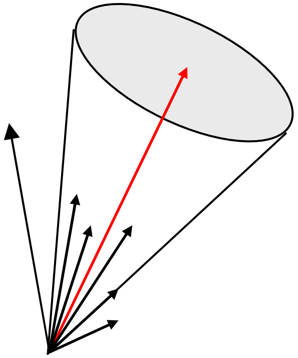
55 GeV jet

Jet Reconstruction with reduced cone-size

- Identify and reconstruct jets using small cone sizes R = 0.3 – 0.4 subtract energy from underlying event and correct using measured jet profiles.
- Reconstruction possible for $E_{jet} \gg \Delta E_{Bg}$
- Caveat:
  - The fact that energy is carried by a small number of particles and some is carried by hard final state radiation leads to out-of-cone fluctuation.
    - Reconstructed energy decreased.
    - Hence increase of $\Delta E/E$
  - Additional out-of-cone radiation due to medium induced radiation possible.

Jet profiles as measured by D0

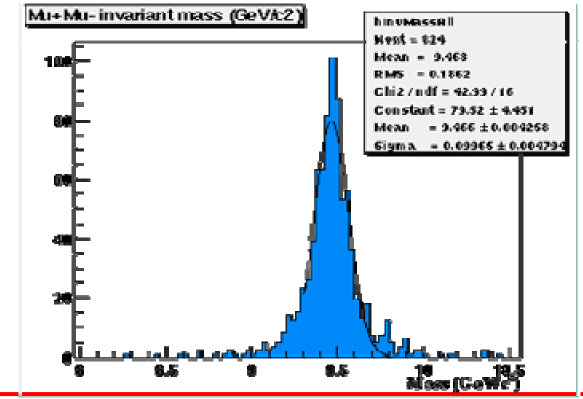




In analogy with heavy flavor physics:

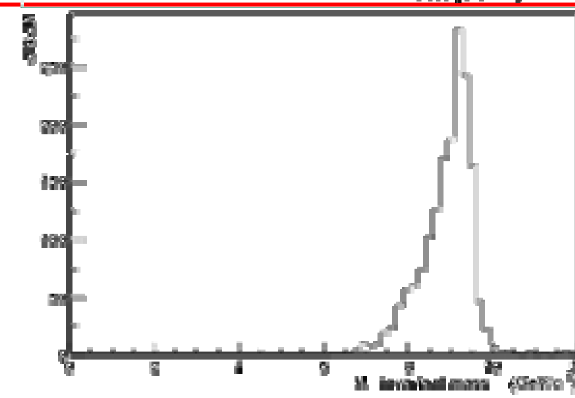
Fully contained jet.

Reconstructed resonance.



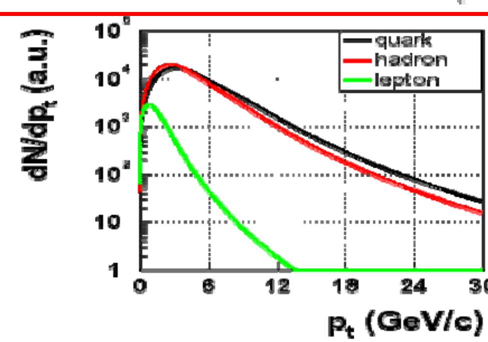
Hard final state radiation at large *R* lost.

Radiative losses, i.e. bremsstrahlung

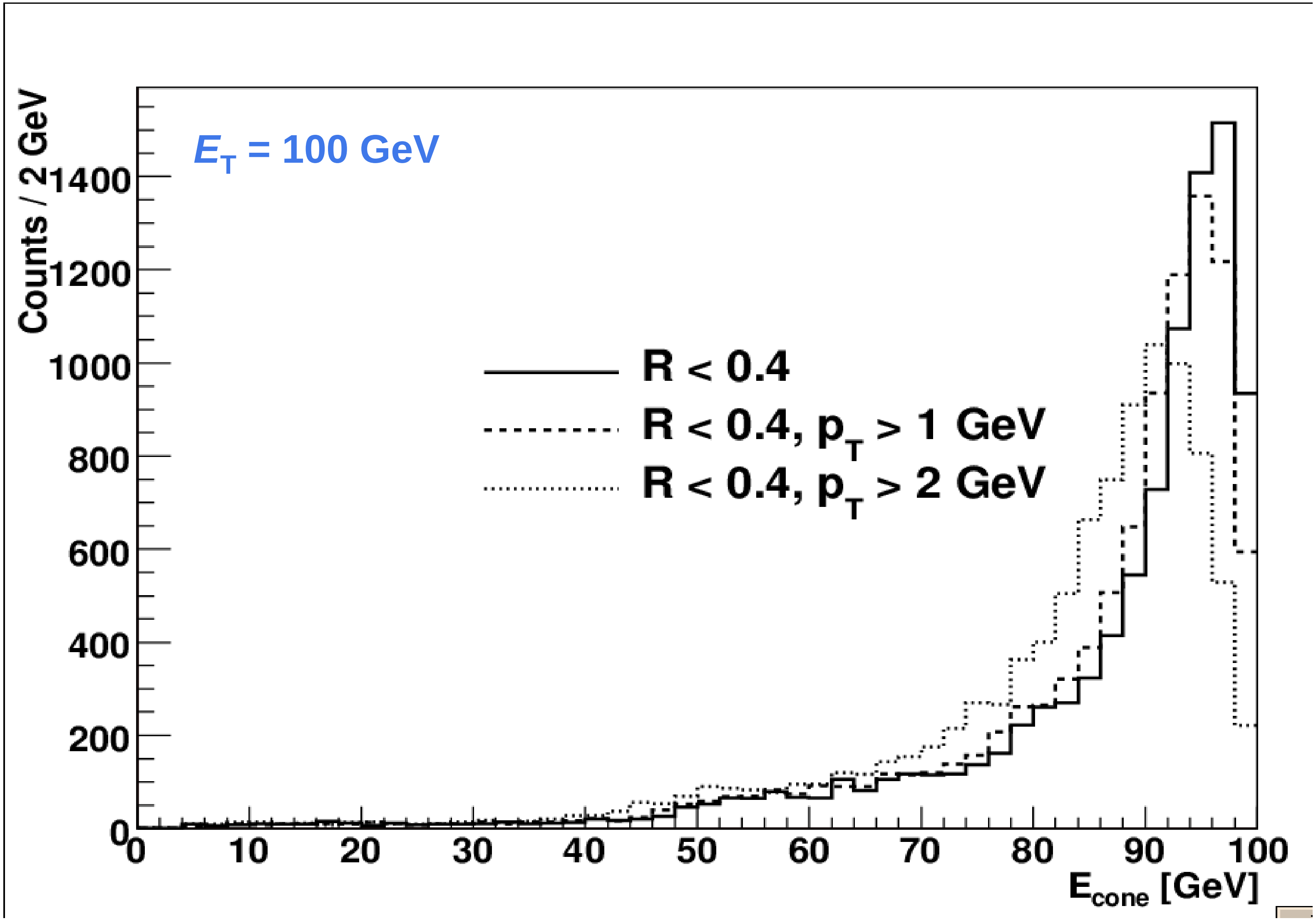


Leading particle analysis

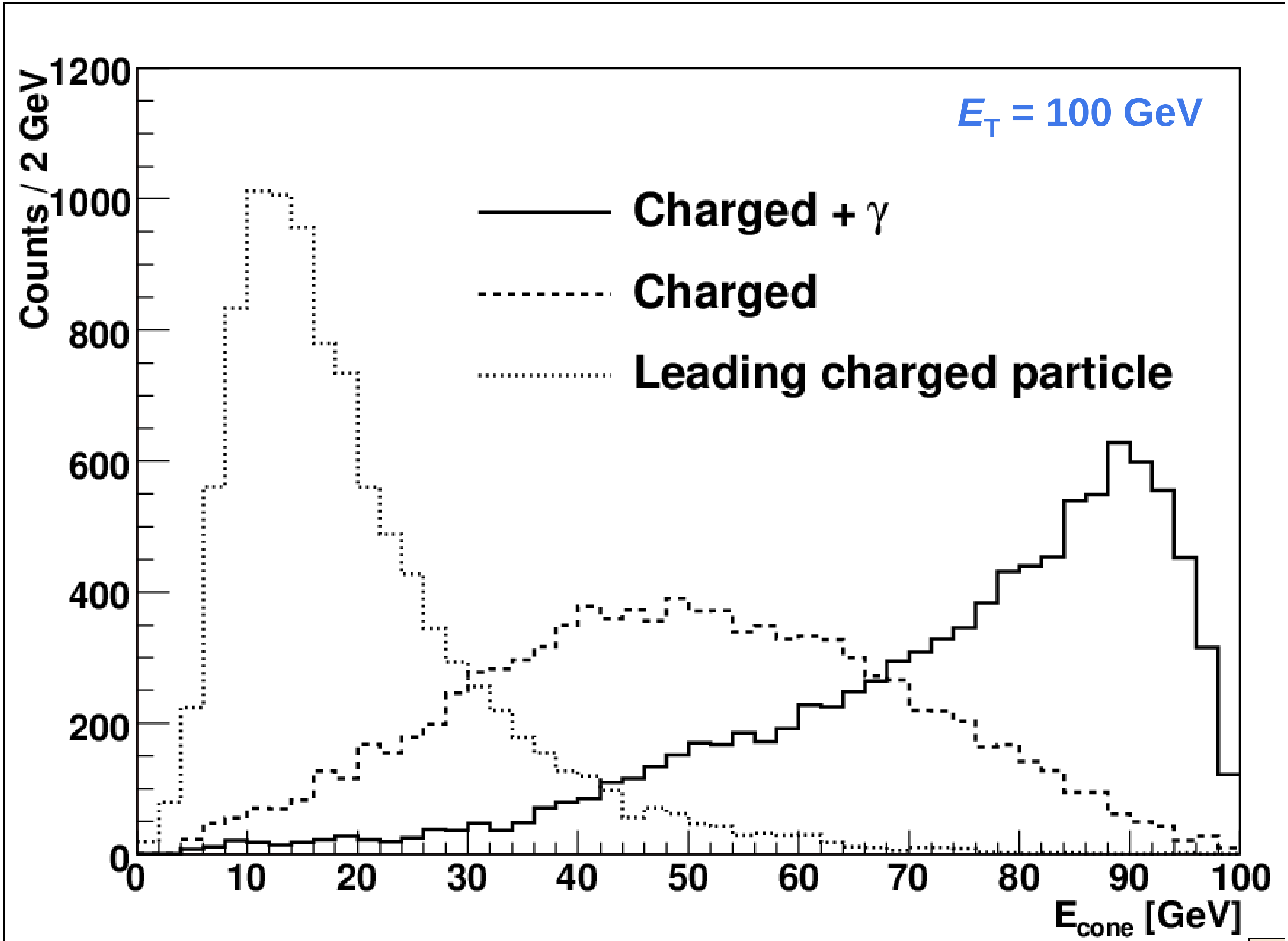
Semileptonic decays.



Intrinsic resolution: Effect of cuts

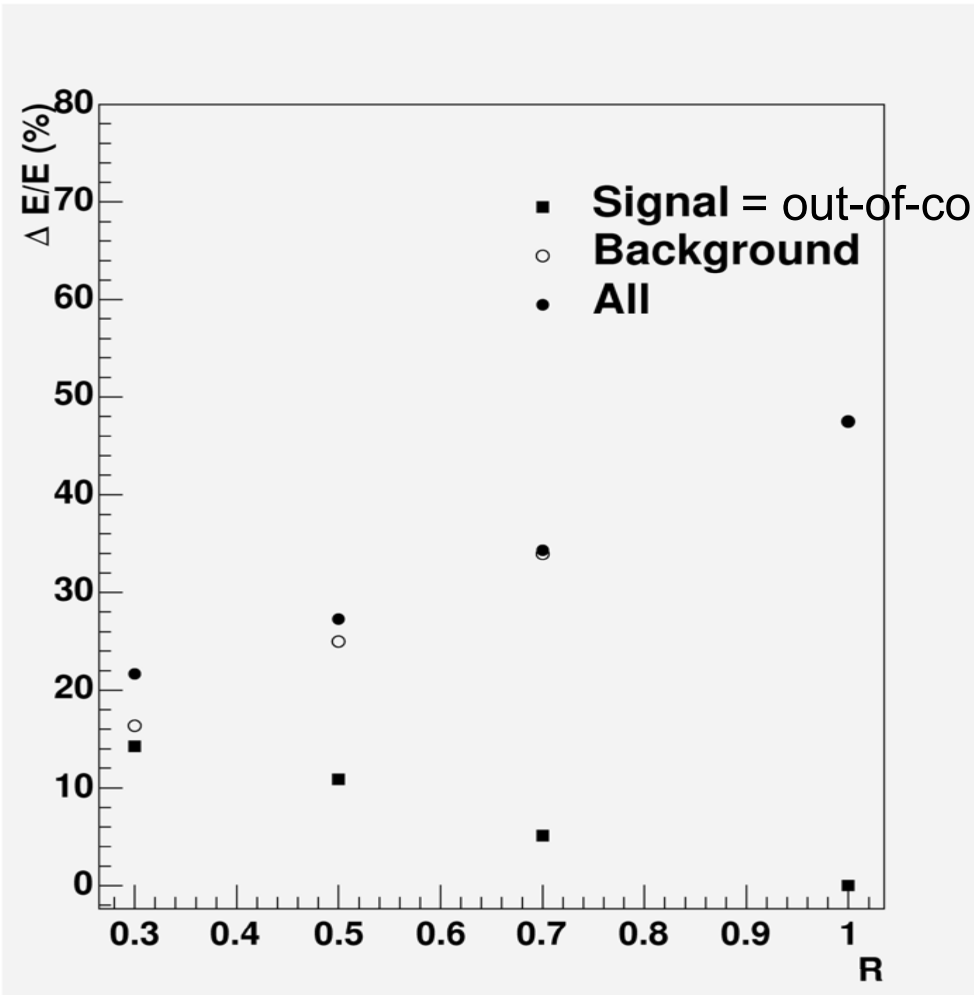


Intrinsic resolution



More quantitatively ...

Intrinsic resolution limit for E_T = 100 GeV



For R < 0.3:

$\Delta E/E$ = 16% from Background (conservative dN/dy = 5000)

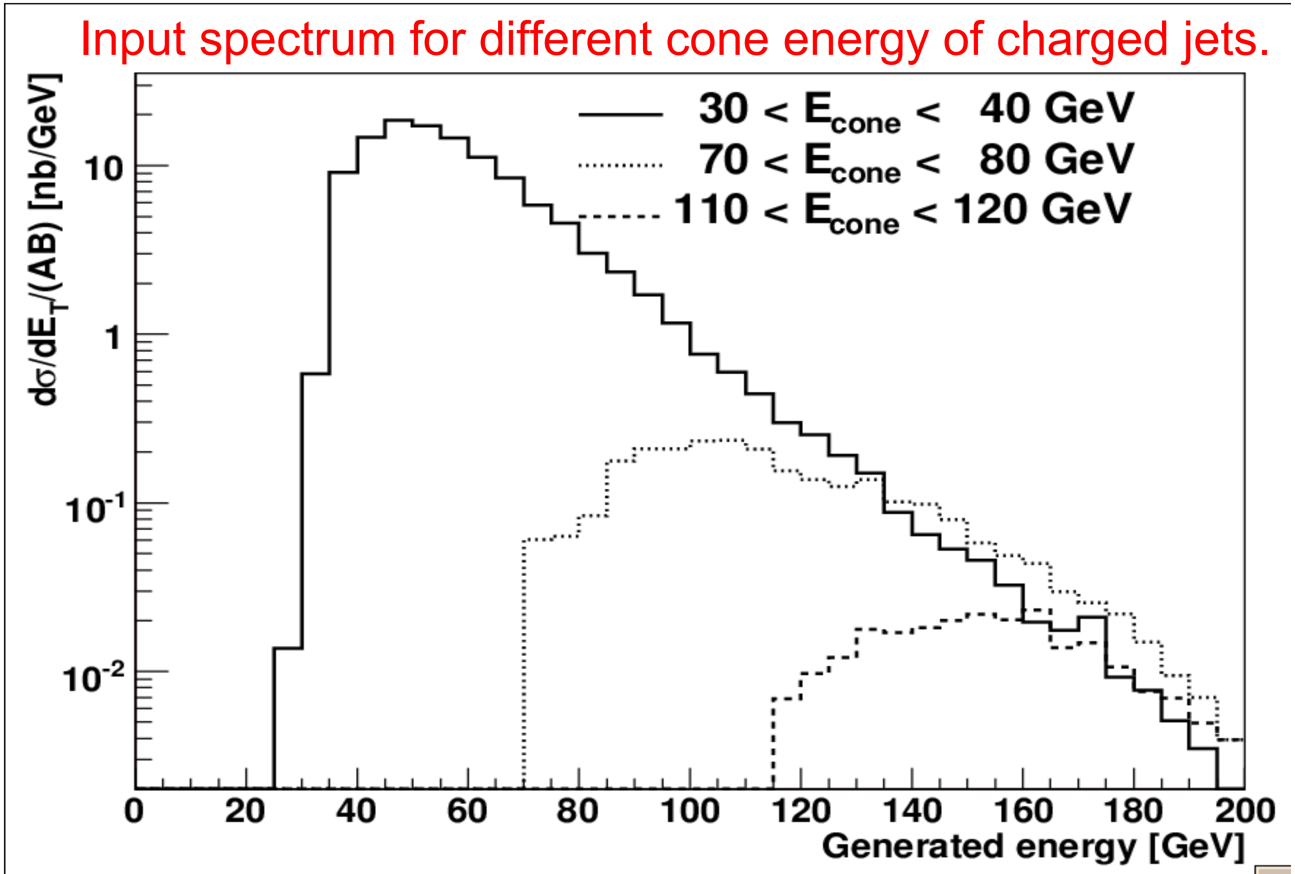
14% from out-of-cone fluctuations

Jet reconstruction for E_{Jet} > 50 GeV should be possible at LHC.

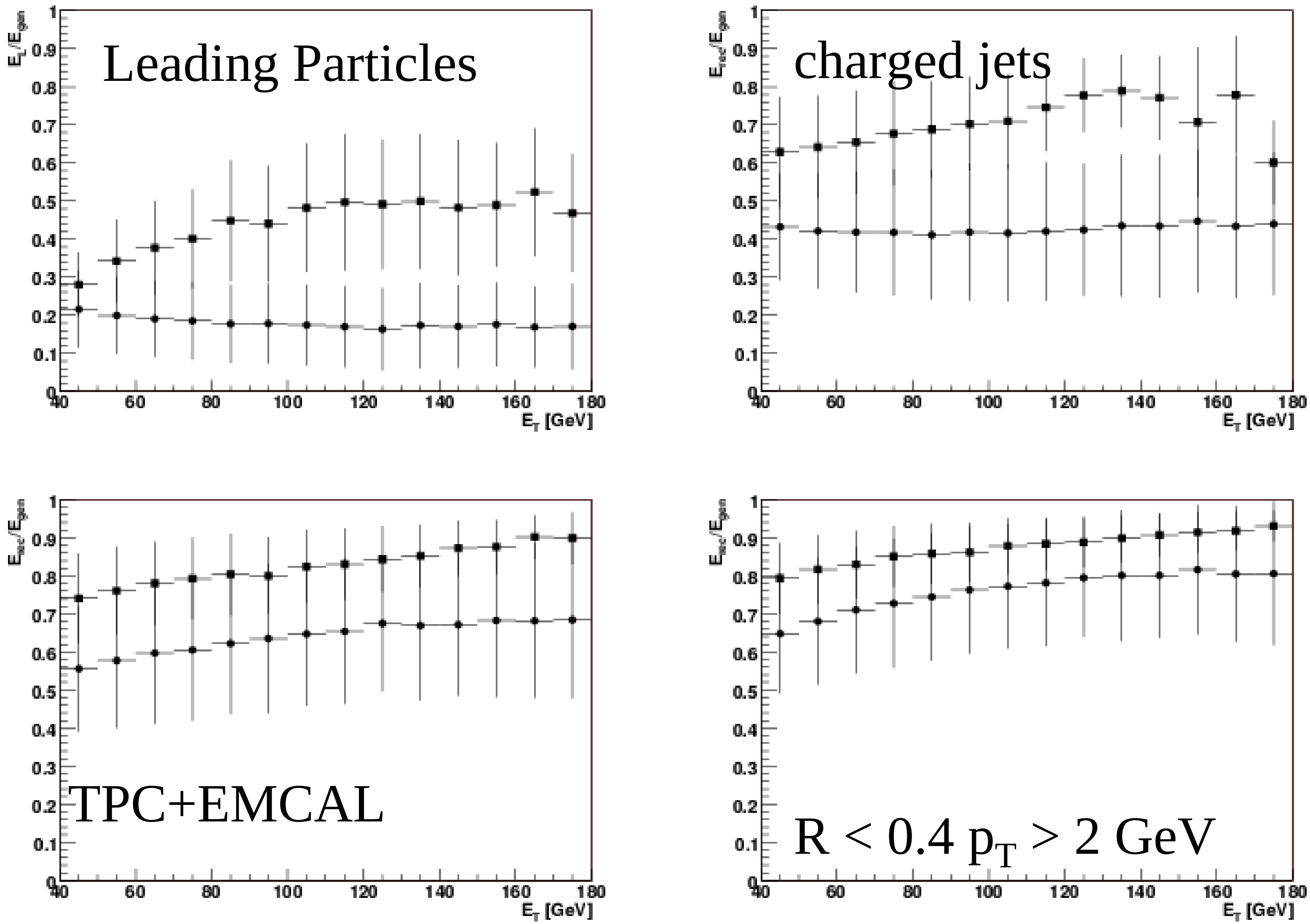
Not included in this estimate: Expected “quenching” or even thermalisation of the underlying event.

Production rate weighted resolution function

- Intrinsic resolution limited to $\Delta E/E$ ~ (15-20)%
- Production rate changes factor of 3 within ΔE
- Production rate weighted resolution function has to be studied.



Production spectrum induced bias



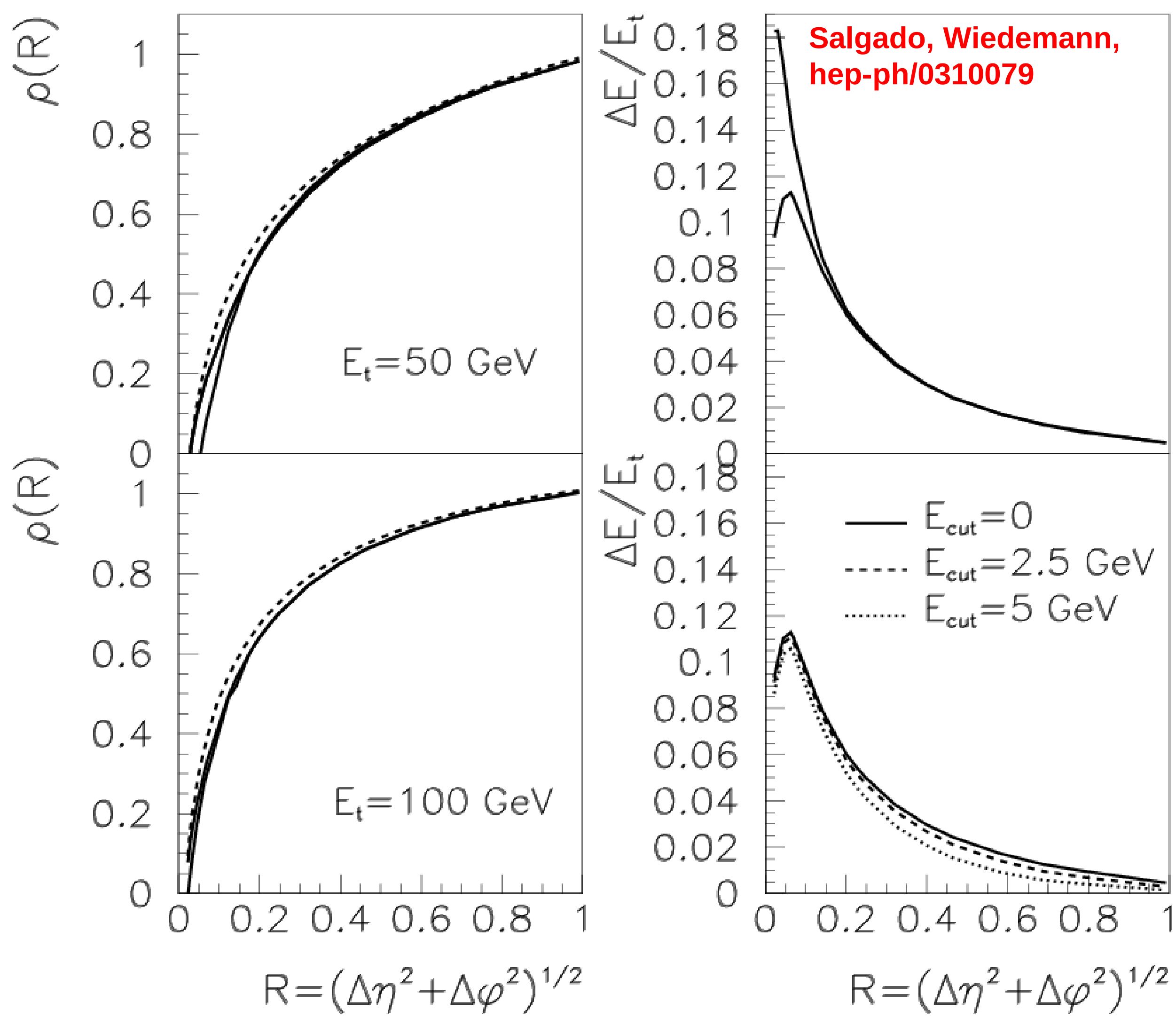
Part III

- The transverse structure
  - Do jets survive ?
  - Transverse Heating.
- Longitudinal structure
  - Leading parton remnant
  - Radiated energy

Transverse structure

- Central question
  - Does the collimated structure of the jets survive so that they can be reconstructed event by event ?
    - Study nuclear suppression factor $R_{AA}^{Jet}(E_T, R)$
    - Total suppression (i.e. surface emission only) or do we reconstruct modified jets ?
- Have the observed jets a modified transverse structure ?
  - Measure jet shape dE/dR
  - Measure momentum distribution perpendicular to the jet axis dN/dk_T ("Transverse Heating")

Transverse Structure



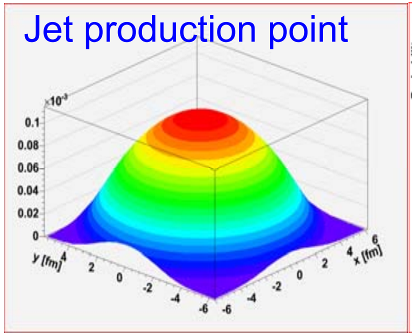
ΔE = 20 GeV

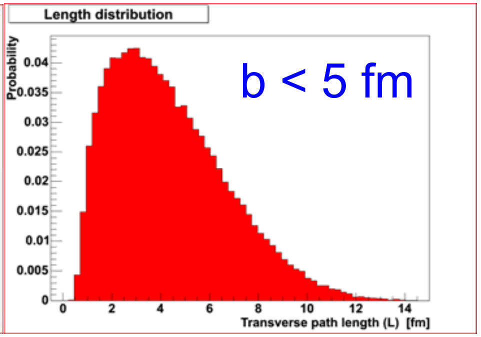
Longitudinal structure

- Measure parton energy as the energy of the reconstructed jet
- Measure energy loss
  - Remnant of leading partons in the high-z part of the fragmentation function
- Measure radiated energy
  - Additional low-z particles

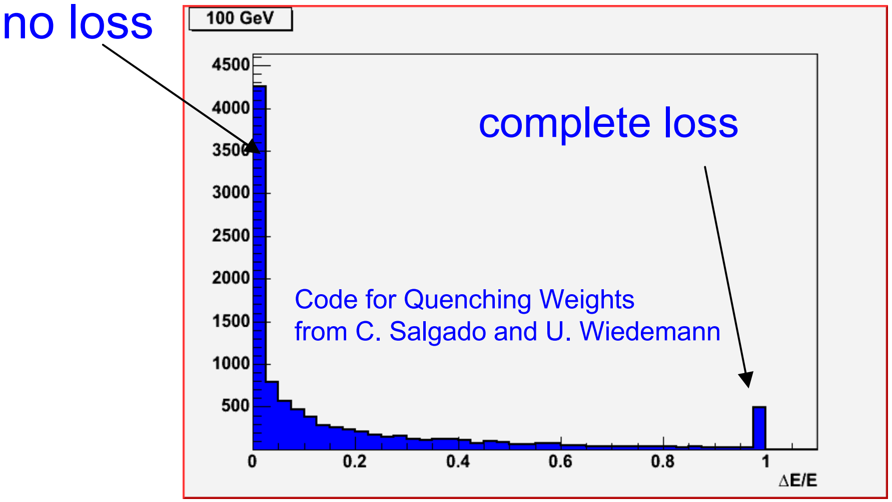
Longitudinal structure

- No trivial relation between energy loss and jet observables
  - Intrinsic to the system
    - Path length is not constant
    - Need measurements relative to reaction plane and as a function of *b*.
  - More importantly: Intrinsic to the physics
    - Finite probability to have no loss or on the contrary complete loss
  - Reduced cone size
    - Out-of-cone fluctuations and radiation
- To relate observables to energy loss we need shower MC combining consistently parton shower evolution and in-medium gluon radiation.

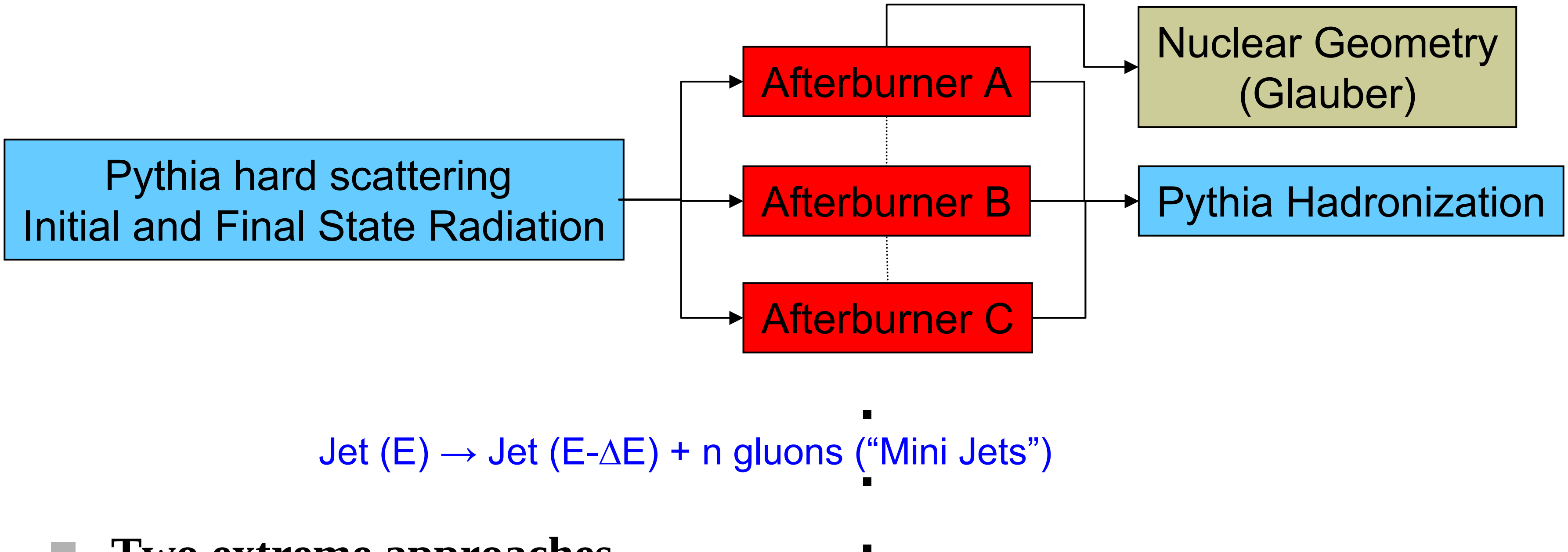




"Bremsstrahlung" Spectrum exemplified using results from Salgado and Wiedemann



Toy Models

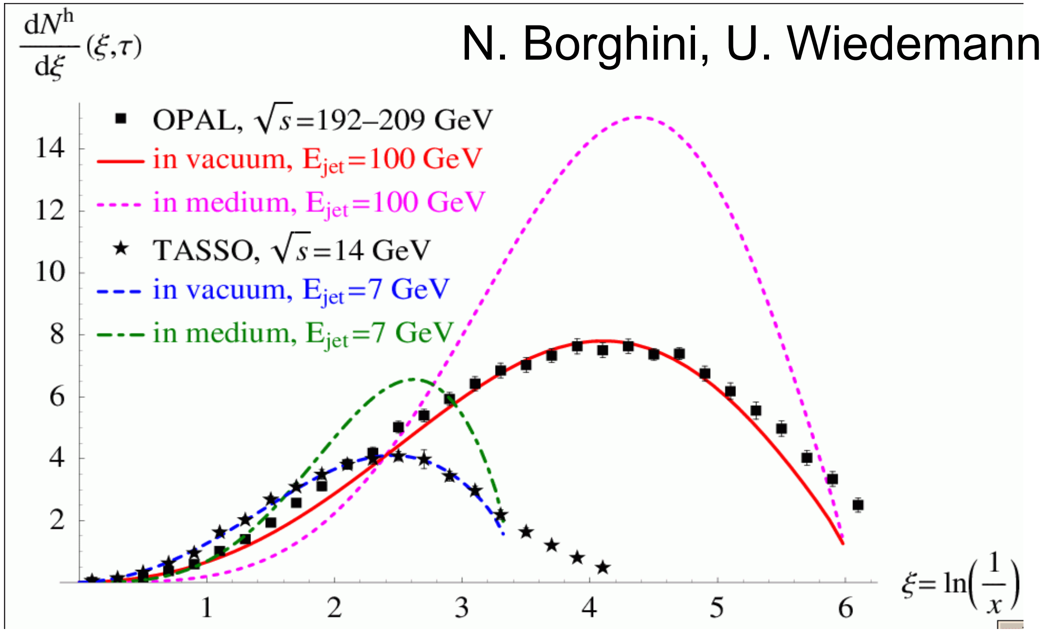


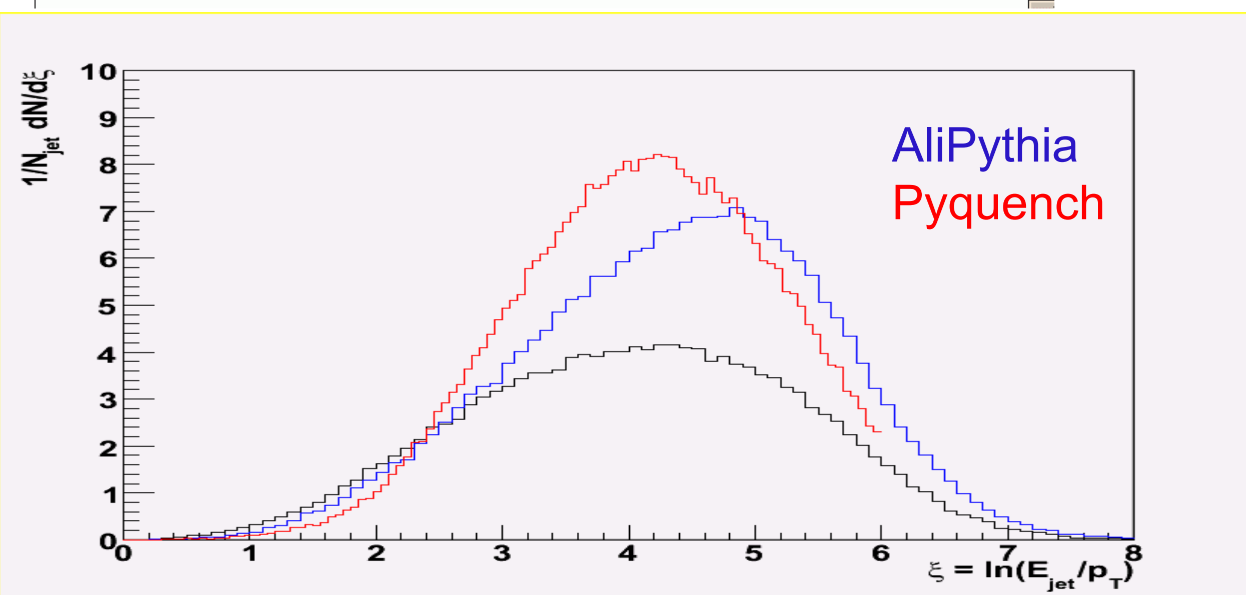
Jet (E) → Jet (E-ΔE) + n gluons ("Mini Jets")

- **Two extreme approaches**
  - Quenching of the final jet system and radiation of 1-5 gluons. (AliPythia::Quench + Salgado/Wiedemann - Quenching weights with q= 1.5 GeV^2/fm)
  - Quenching of all final state partons and radiation of many (~40) gluons (I. Lokhtin: Pyquen)*

)*I.P. Lokhtin et al., Eur. Phys. J C16 (2000) 527-536
I.P.Lokhtin et al., e-print hep-ph/0406038
http://lokhtin.home.cern.ch/lokhtin/pyquen/

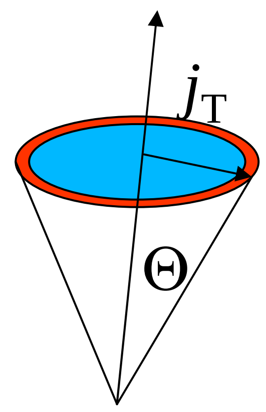
Example: Hump-backed Plateau



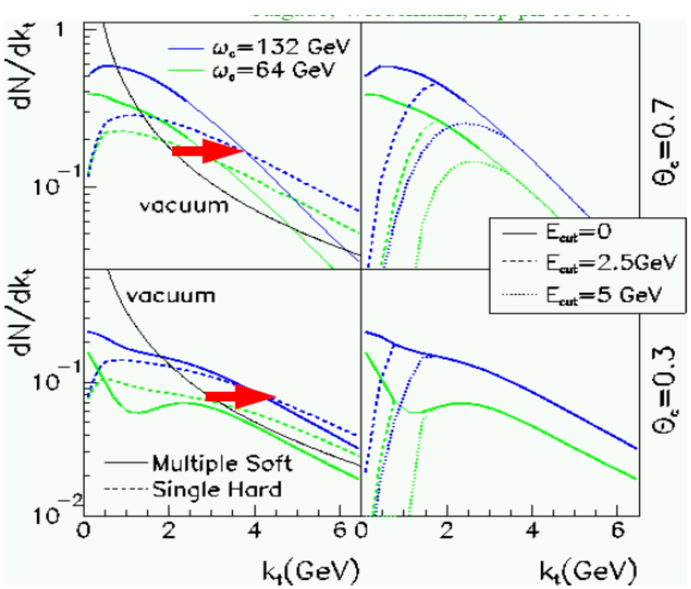


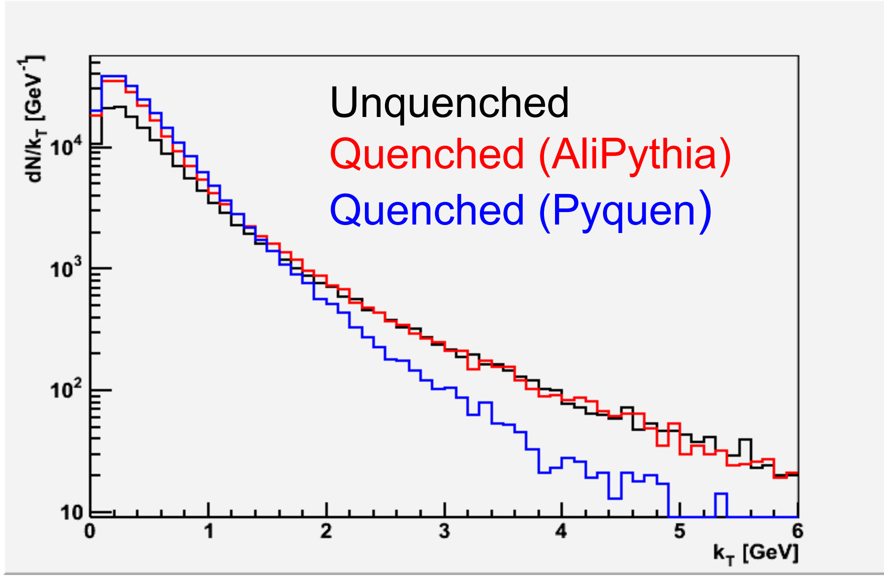
Transverse Heating: k_T - Broadening

- Unmodified jets characterized by $\langle k_T \rangle$ = 600 MeV ~ const(R).
- Partonic energy loss alone would lead to no effect or even a decrease of $\langle k_T \rangle$.
  - Transverse heating is an important signal on its own.



Salgado, Wiedemann, hep-ph/0310079





Suppression of large k_T ?

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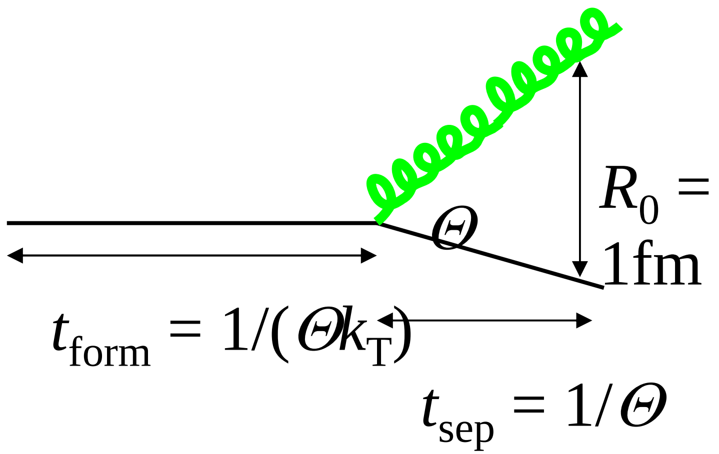
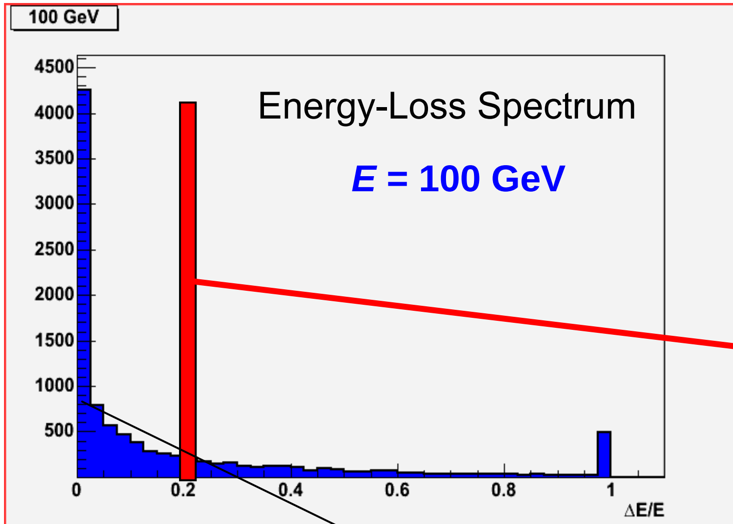
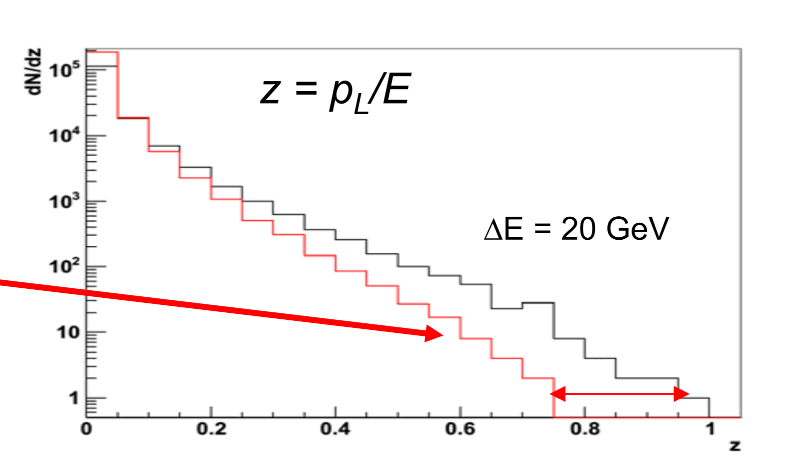
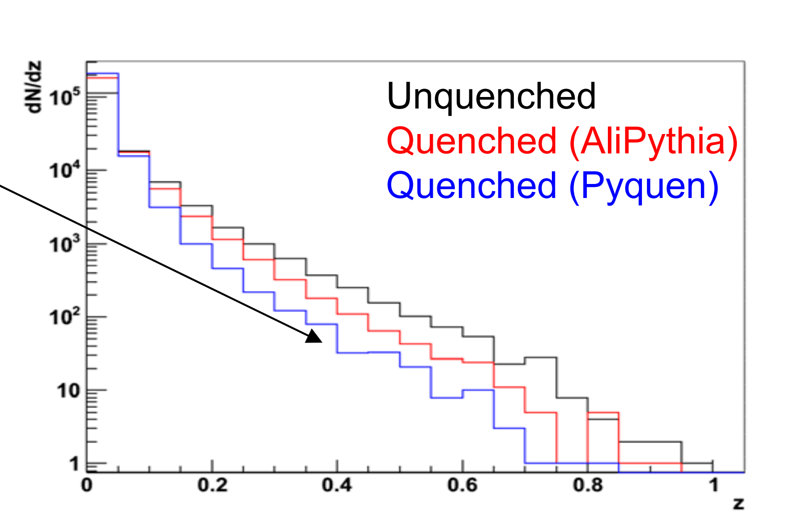


- Relation between R and formation time of hard final state radiation.
  - Early emitted final state radiation will also suffer energy loss.
  - Look for R – dependence of $\langle j_T \rangle$!

Interpretation of Fragmentation Functions



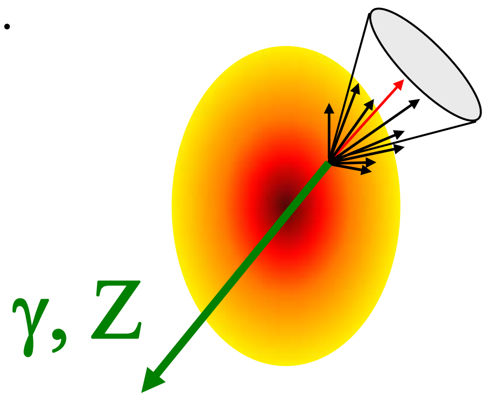




- Intrinsic limit on sensitivity due to higher moments of the expected $\Delta E/E$ distribution.
- Possible additional bias due to out-of-cone radiation.
  - $E_{rec} < E_{parton}$
  - $z_{rec} = p/E_{rec} > z_{hadron}$

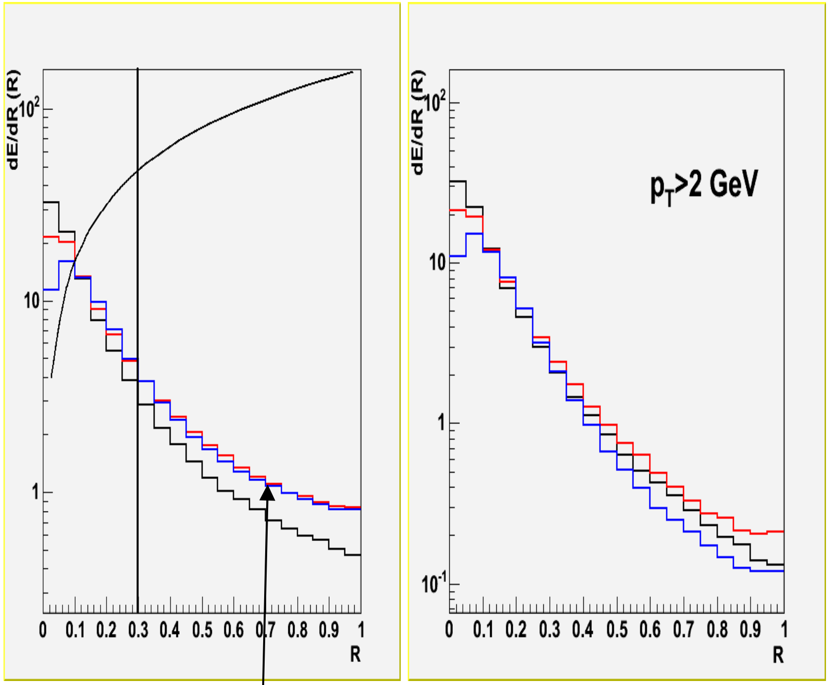
Limit experimental bias ...

- By measuring the jet profile inclusively.
  - Low-p_T capabilities are important since for quenched jets sizeable fraction of energy will be carried by particles with $p_T < 2$ GeV.



- Exploit γ-jet correlation
  - $E_\gamma = E_{jet}$
  - Caveat: limited statistics
    - O(10^3) smaller than jet production
  - Does the decreased systematic error compensate the increased statistical error ?
  - Certainly important in the intermediate energy region $20 < E_T < 50$ GeV.

Quenched (AliPythia)
Quenched (Pyquen)



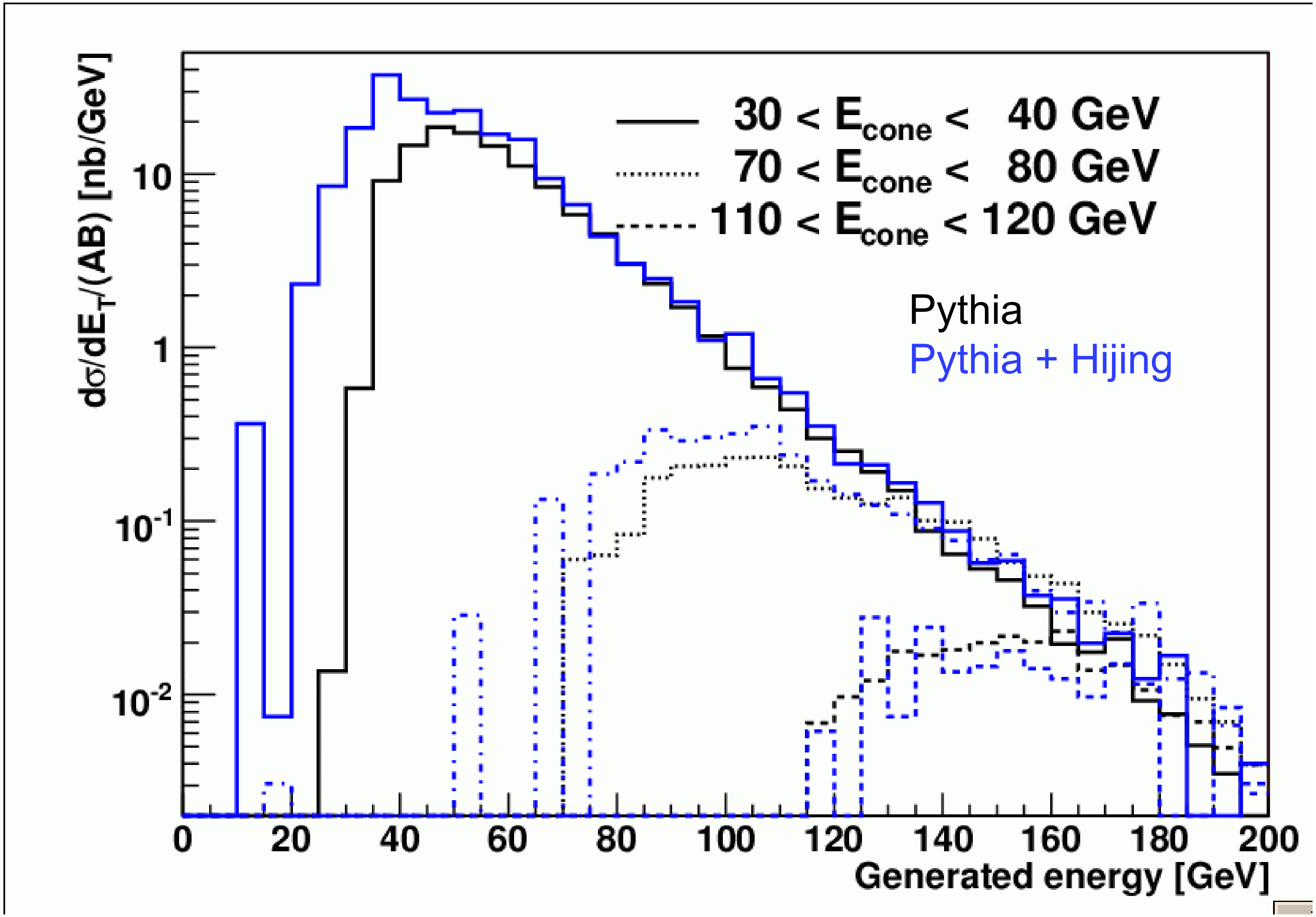
Energy radiated outside core

Not visible after p_T-cut.

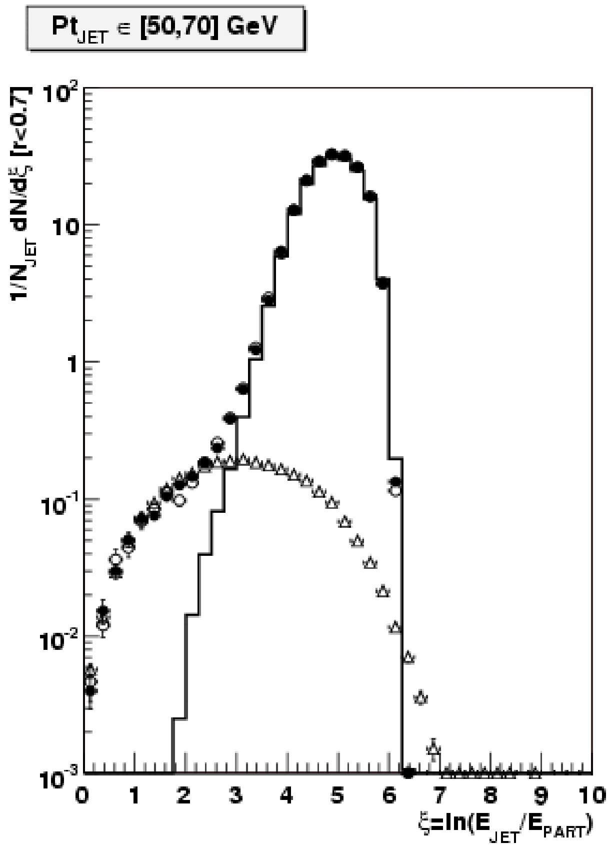
ALICE Jet Data Challenge

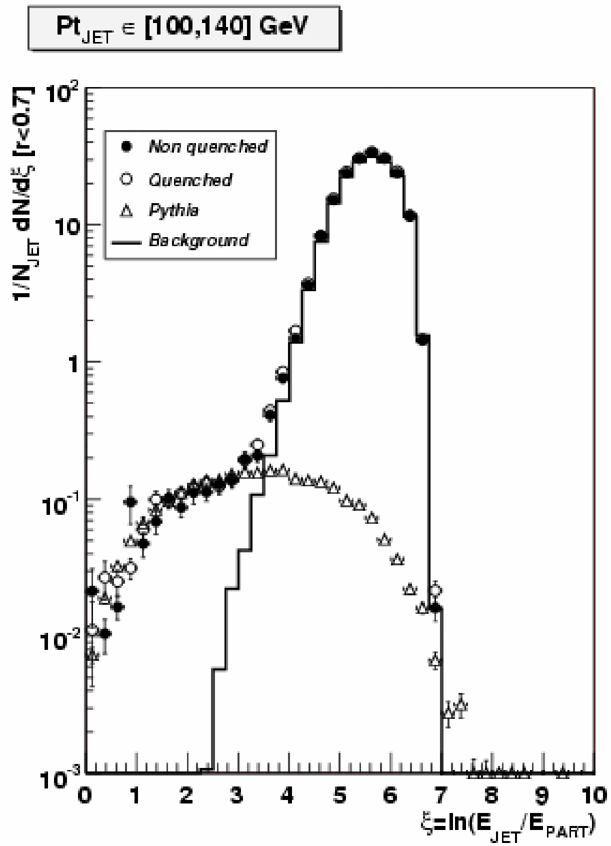
- Embed Pythia jets in central Pb-Pb HIJING events
- Pass through full detector simulation
  - Geant3 transport and detailed detector simulation
- Reconstruct tracks in central detectors
- Reconstruct charged jets (E_T > 10GeV)
  - Statistics: ~ 3000 jets for E_T > 100 GeV
  - ~1 month, un-triggered
- Study jet structure

ALICE Jet Data Challenge



Hump-backed plateau



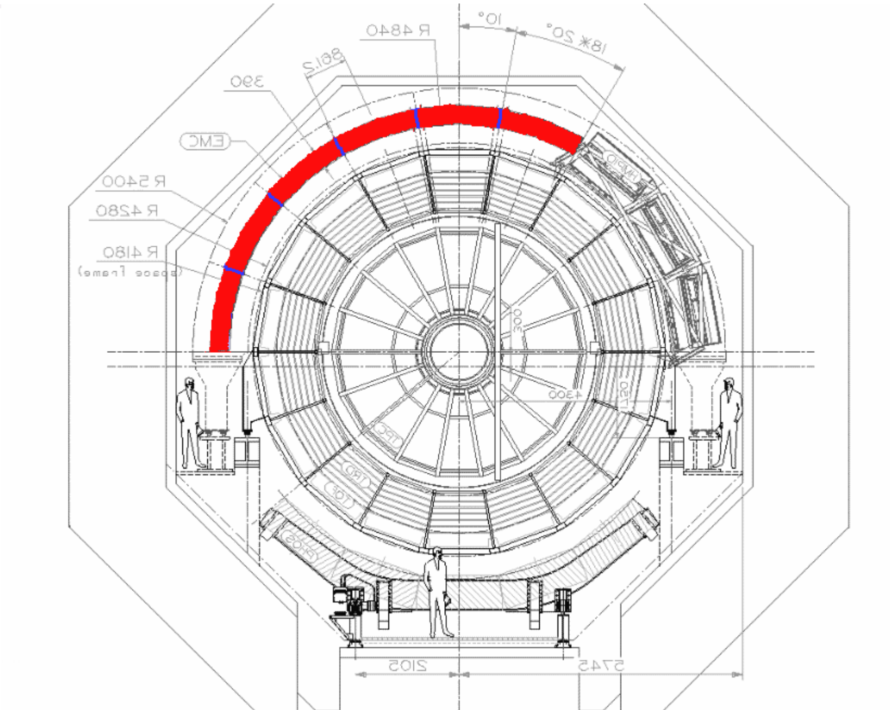


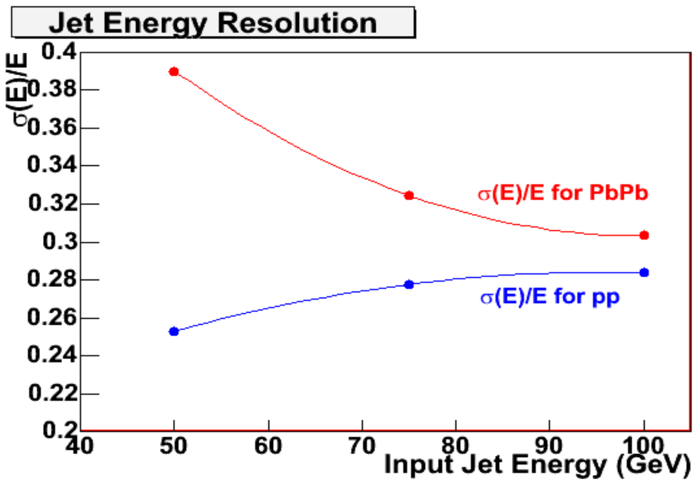
G. Contreras, M. Lopez

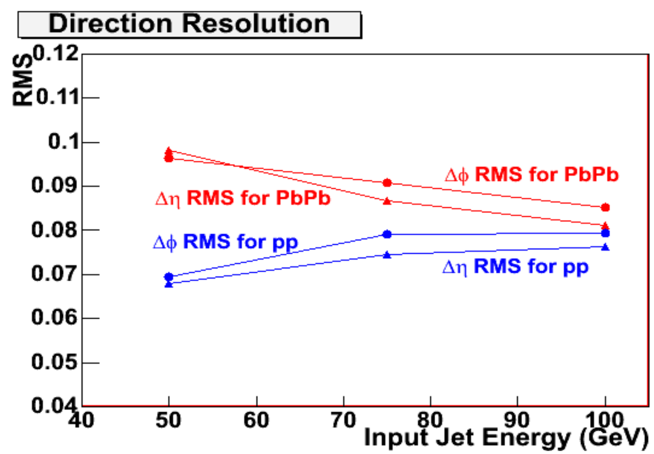
High z (low ξ): Needs good resolution

Low z (high ξ): Systematics is a challenge, needs reliable tracking. Also good statistics (trigger is needed)

EMCAL for ALICE



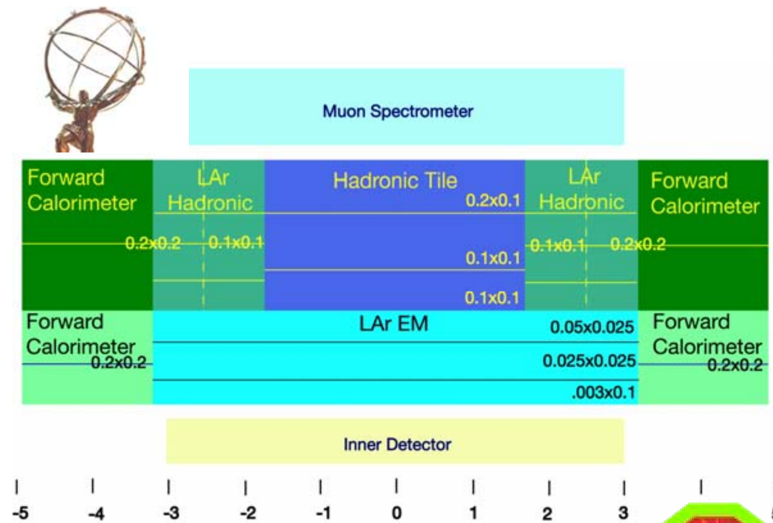


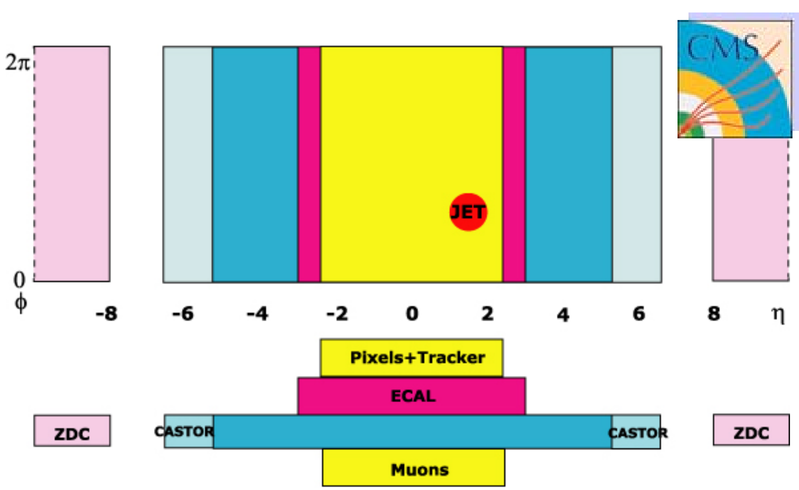


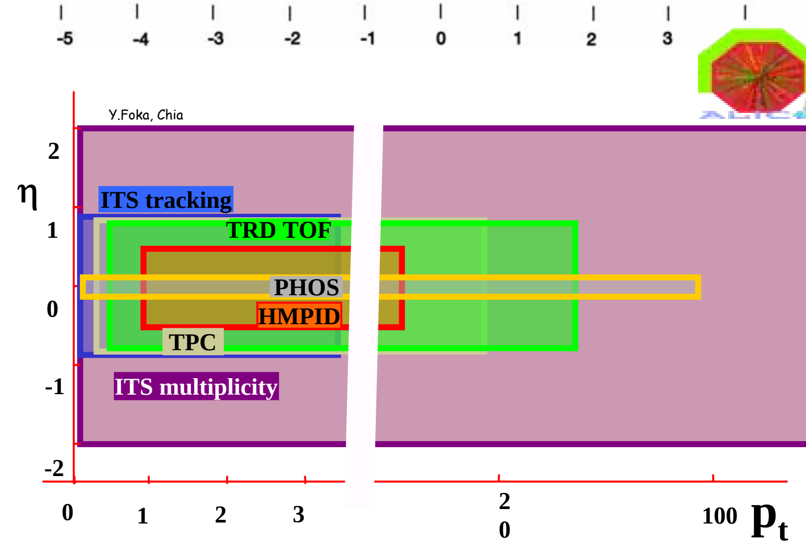
- *EM Sampling Calorimeter (STAR Design)*
- *Pb-scintillator linear response*
  - $-0.7 < \eta < 0.7$
  - $\pi/3 < \Phi < \pi$
- *12 super-modules*
- **19152** *towers*
- *Energy resolution ~15%/√E*

Complementarities and Redundancy

- ATLAS, CMS
  - Full calorimetry
  - Large coverage (hermeticity)
  - Optimized for high-p_T
- ALICE
  - TPC + proposed EMCAL
  - Low- and high-p_T capability
    - 100 MeV – 100 GeV
  - Particle identification







Conclusions

- Copious production of jets in PbPb collisions at the LHC
  - < 20 GeV many overlapping jets/event
    - Inclusive leading particle correlation
- Background conditions require jet identification and reconstruction in reduced cone $R < 0.3$-0.5
- At LHC we will measure jet structure observables (k_T, fragmentation function, jet-shape) for reconstructed jets.
  - High-p_T capabilities (calorimetry) needed to reconstruct parton energy
  - Good low-p_T capabilities are needed to measure particles from medium induced radiation.

- ALICE needs calorimetry (EMCAL) for triggering and jet reconstruction
  - ... and this would make it the ideal detector for jet physics at the LHC covering the needed low and high-p_T capabilities + particle ID.
- Community needs MC combining consistently in medium energy loss and parton showers.