Jet Physics in Heavy Ion Collisions with ALICE

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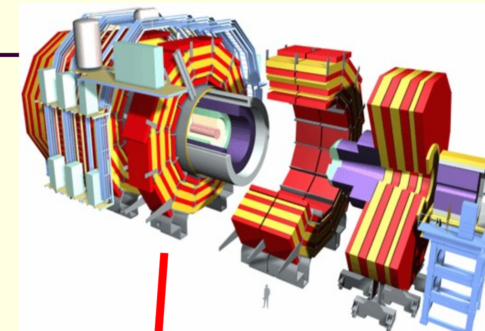
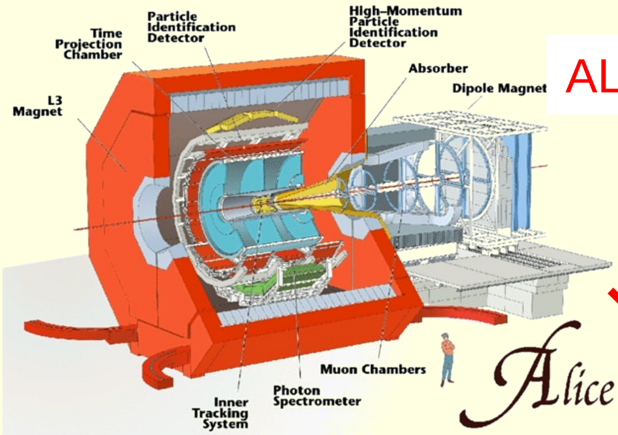
CERN
For the ALICE Collaboration

Sept 28, 2010

Heavy Ions at LHC: the actors ...

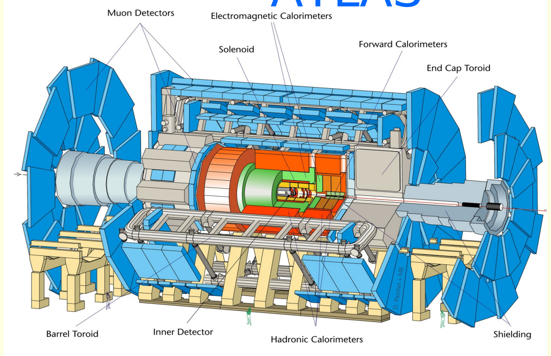
CMS





ALICE

ATLAS



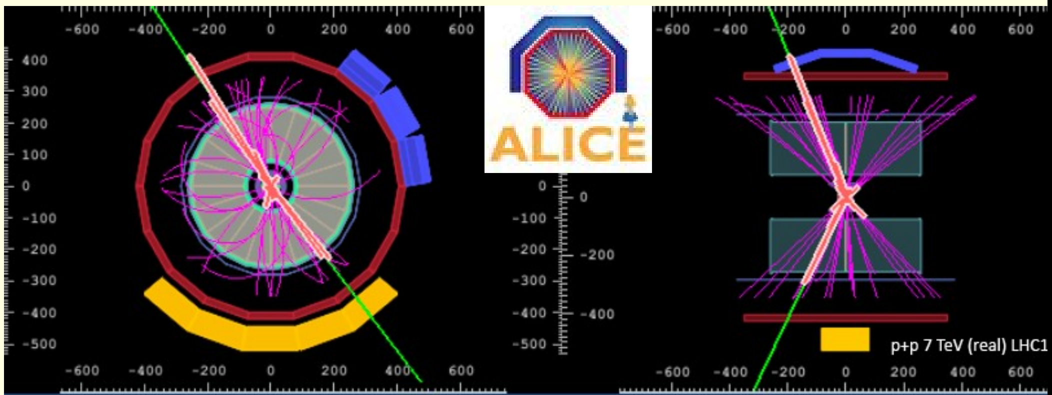
2010/11: p+p collisions @ 7 TeV

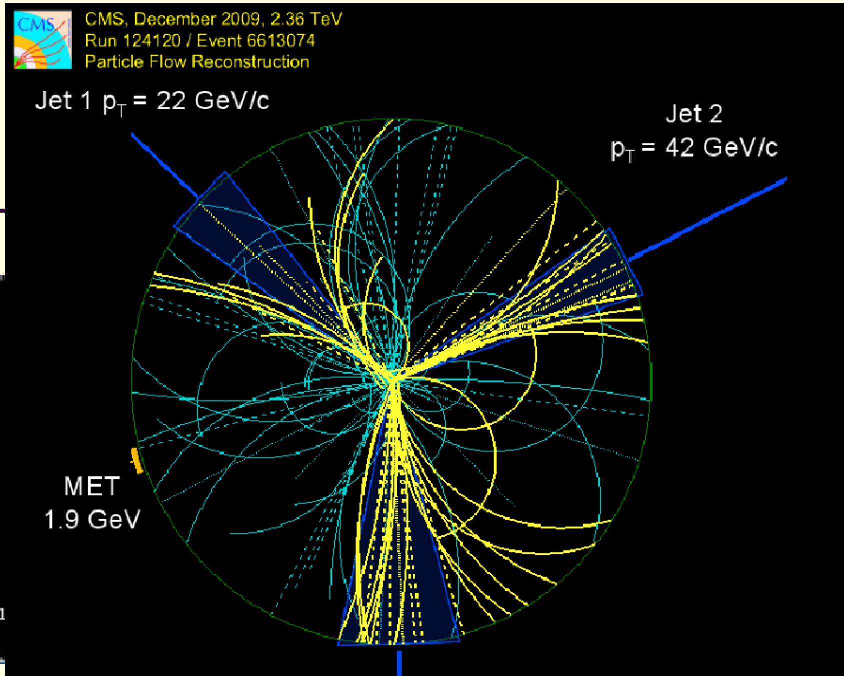
Nov 2010 hot switch to

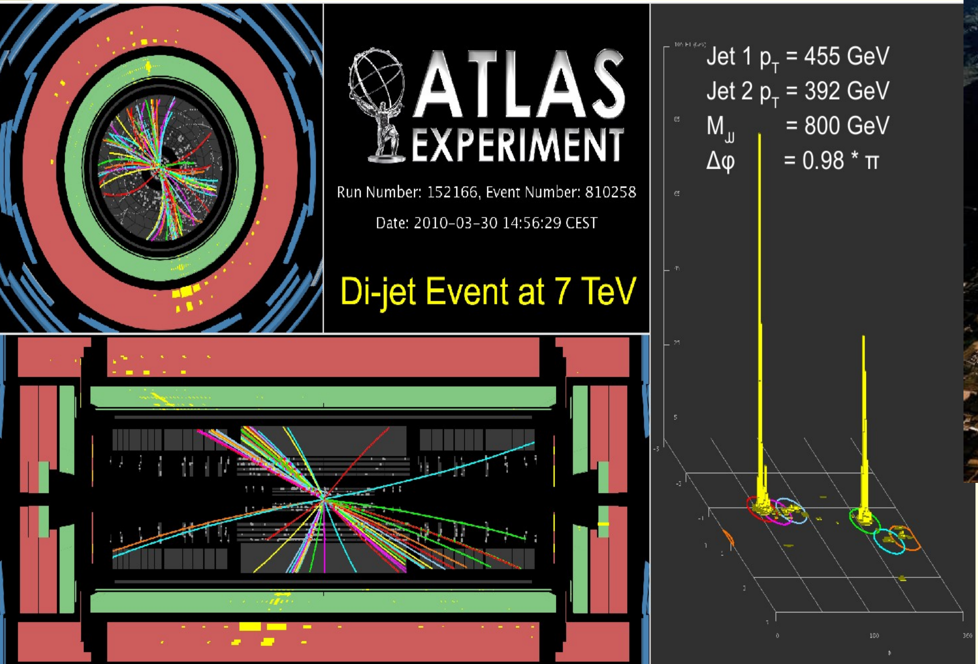
PbPb collisions @ 2.76 TeV

4 weeks in 2010 and 2011

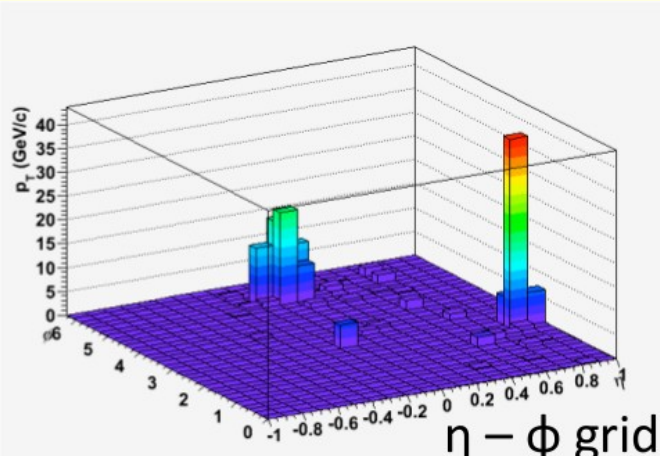
It is really happening



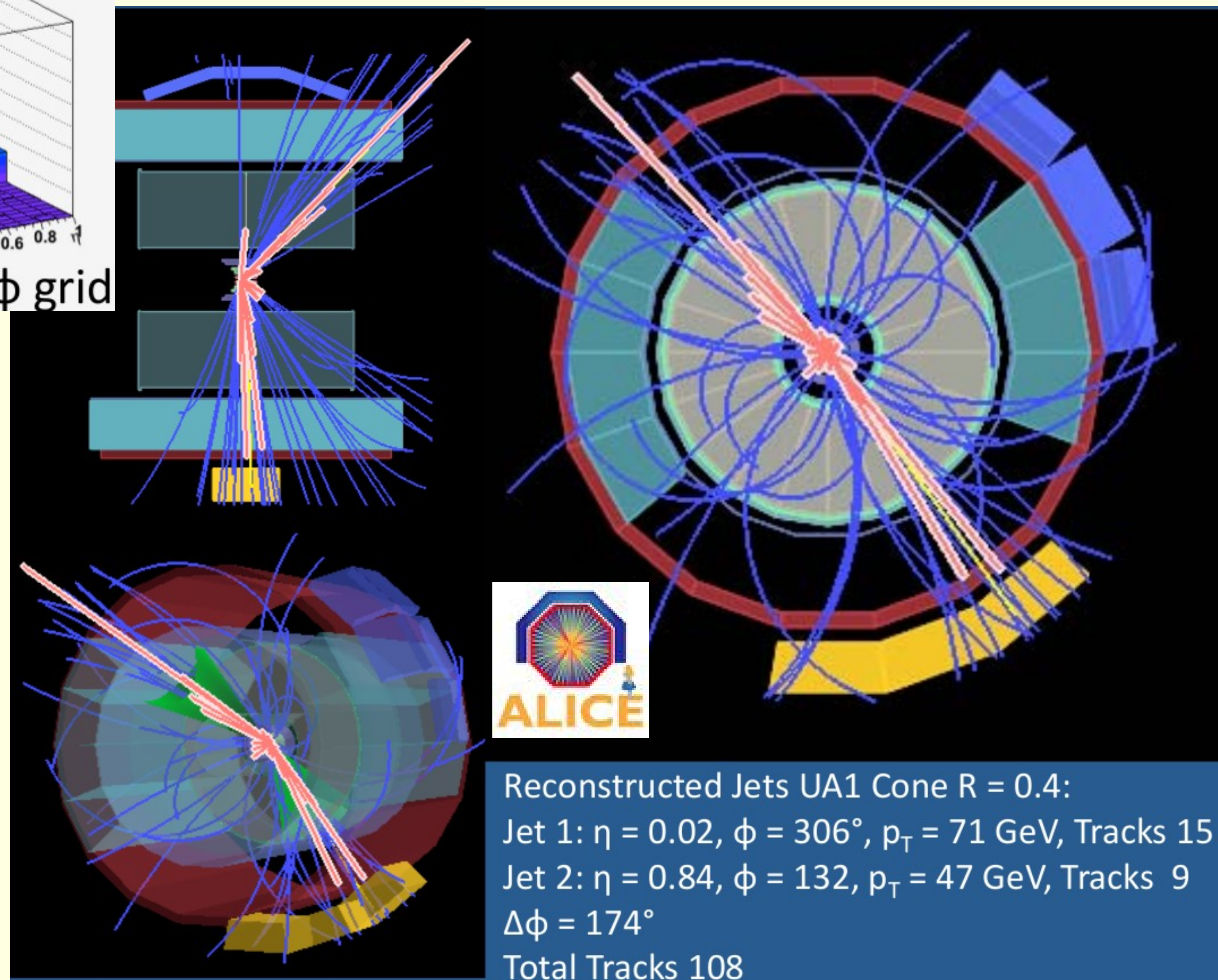




Di-Jet Event



p_T (GeV/c)
η – ϕ grid



ALICE
Reconstructed Jets UA1 Cone R = 0.4:
Jet 1: η = 0.02, ϕ = 306°, p_T = 71 GeV, Tracks 15
Jet 2: η = 0.84, ϕ = 132, p_T = 47 GeV, Tracks 9
Δϕ = 174°
Total Tracks 108

Some more patience needed: Early Heavy Ion Runs

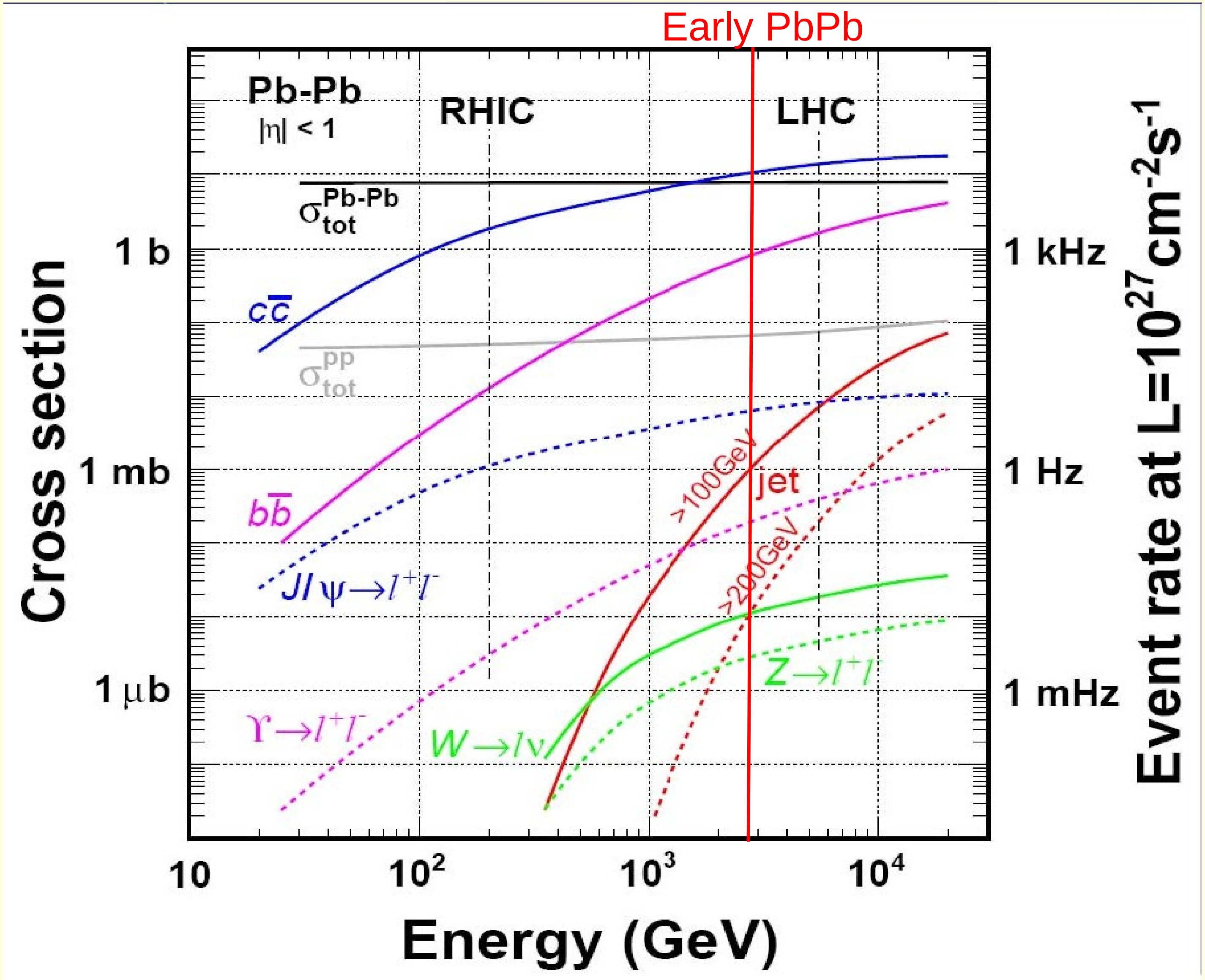
		Early (2010/11)	Nominal
$\sqrt{s_{NN}}$ (per colliding nucleon pair)	TeV	2.76	5.5
Number of bunches		62	592
Bunch spacing	ns	1350	99.8
β^*	m	2 → 3.5	0.5
Pb ions/bunch		7×10^7	7×10^7
Transverse norm. emittance	μm	1.5	1.5
Initial Luminosity (L_0)	$cm^{-2}s^{-1}$	(1.25→ 0.7) 10^{25}	10^{27}
Stored energy (W)	MJ	0.2	3.8
Luminosity half life (1,2,3 expts.)	h	τ_{IBS}=7-30	8, 4.5, 3

Initial interaction rate: 50 Hz (5 Hz central collisions $b = 0 – 5$ fm)

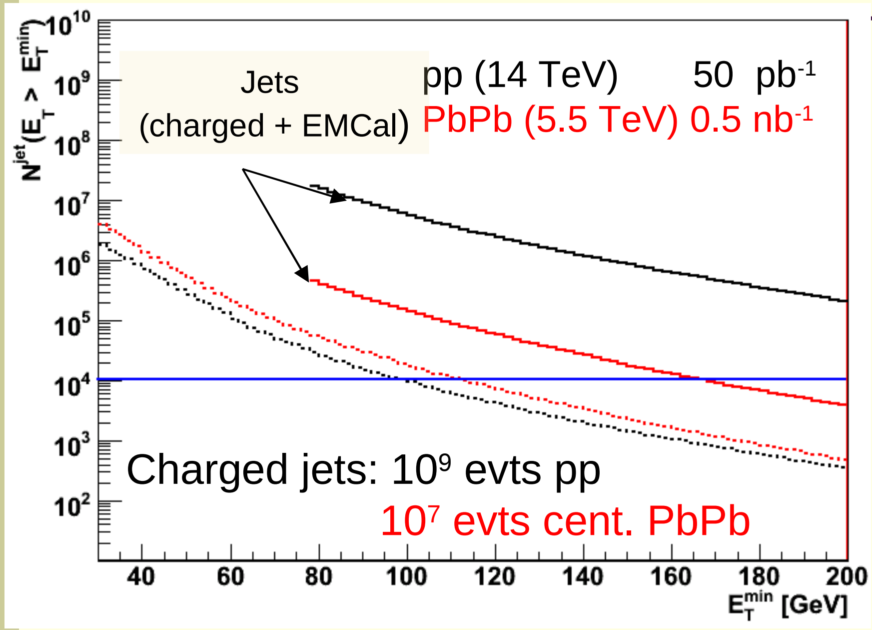
~5×10^7 interaction/10^6s (~1 month)

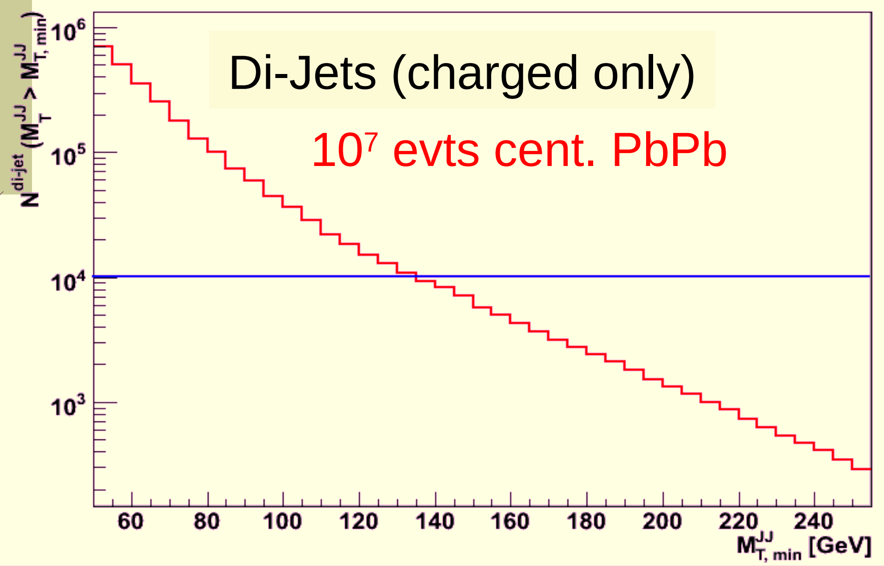
In 2010: integrated luminosity 1-3 μb^{-1}

The rare becomes profuse



Expected rates

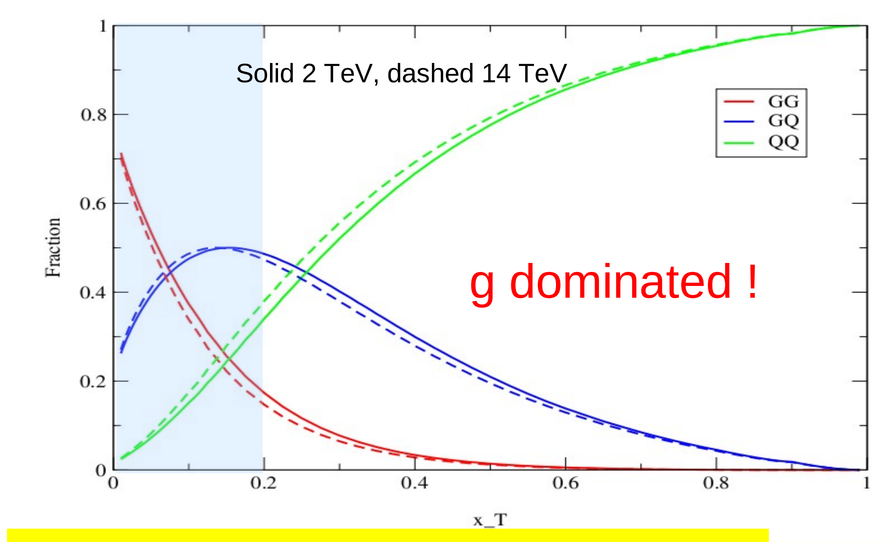




- First PbPb run at 2.76 TeV
  - Jet x-section reduced by factor 10
  - 10^6 central events
  - Measure R_{AA}^{Jet} up to 110 GeV
- 10^7 central events at 5.5 TeV
  - Measure R_{AA}^{Jet} up to 150 GeV
  - Jet structure up to 100 GeV
- Nominal 1month runs with EMCAL trigger
  - Jet structure up to 200 GeV
- Some important reference measurements only possible with EMCal trigger

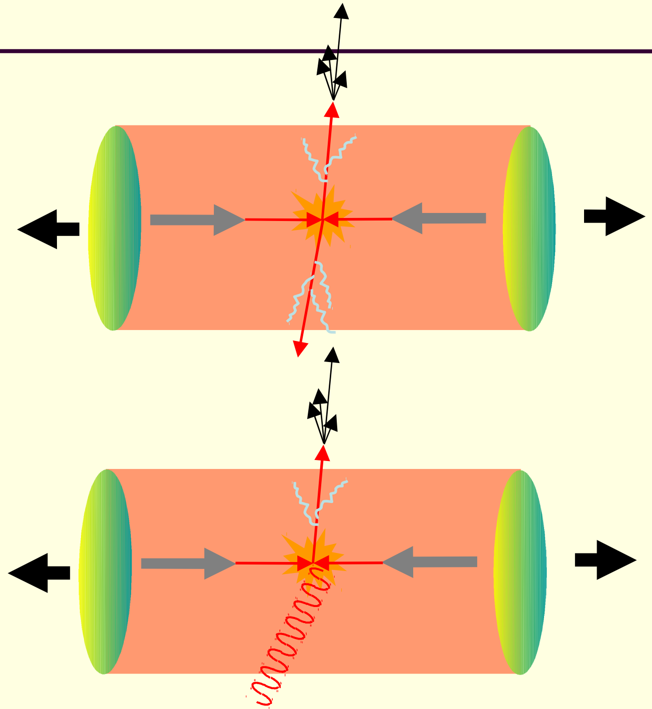
As compared to RHIC...

- Cross-section falls with a smaller (power-law) exponent
  - n = 5.9 (LHC) / 8 (RHIC)
  - Reduced sensitivity to energy scale
  - Reduced selection bias on fragmentation
- Different x_T range
  - LHC: 0.02 - 0.2
  - RHIC: 0.15 – 0.45
- LHC (RHIC) gluon (quark) dominated



N. Glover CTEQ-School, Rhodes, (2006)

Jets in Nucleus-Nucleus Collisions

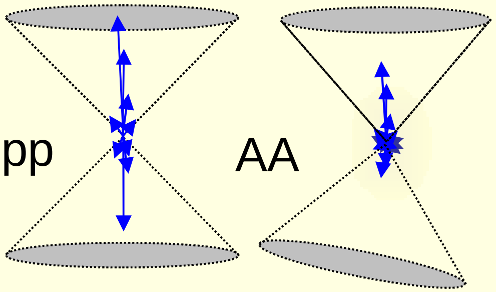


Ideal probe:
$t_{formation} \sim 1/Q \ll 1$ fm/c
History of interaction with medium imprinted into jet structure …

- High-p_T partons produced in hard interactions in the initial state of nucleus-nucleus collisions undergo multiple interaction inside the collision region prior to hadronisation.
- In particular they loose energy through medium induced gluon radiation and this so called “jet quenching” has been suggested to behave very differently in cold nuclear matter and in QGP.

$$\Delta E \propto \alpha_s C_R < \hat{q} > L^2 f(E, m_q)$$

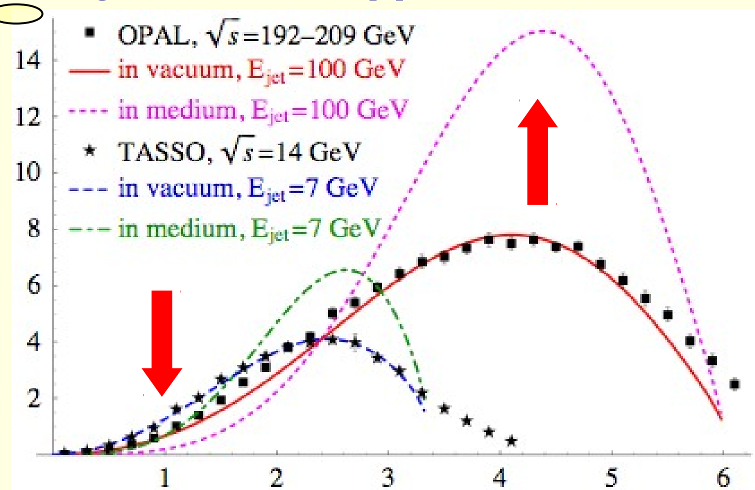
Consequences for the Jet Structure



Simplistically: Jet(E) → Jet(E-ΔE) + soft gluons (ΔE)

$1/N_{jet}$ dN/dξ also called the hump-backed plateau.
$\xi = ln(E^{jet}/p^{had})$

Borghini,Wiedemann, hep-ph/0506218



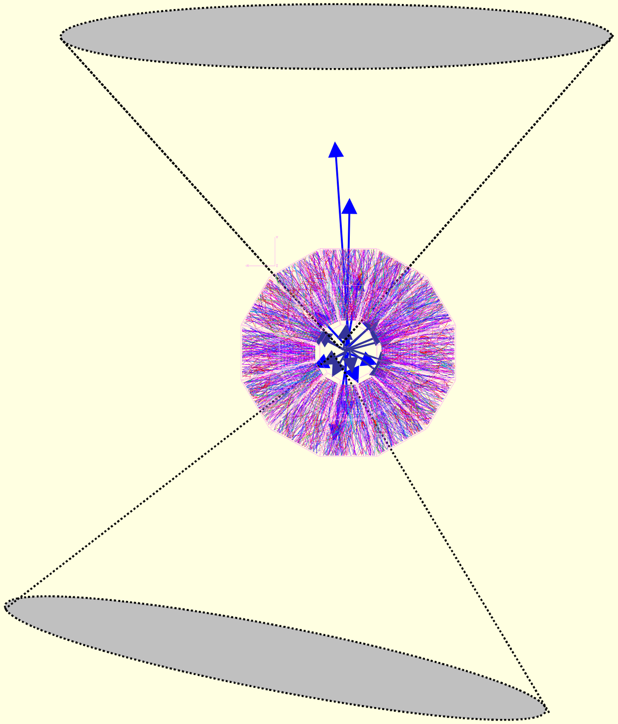
$$\xi = \ln(\frac{E}{p}) = \ln(\frac{1}{z})$$

- Decrease of leading particle p_T (energy loss)
- Increase of number of low momentum particles (radiated energy)
- Increase of p_T relative to jet axis (j_T)
  - Broadening of the jet
  - Out of cone radiation (decrease of jet rate)
- Increased di-jet energy imbalance and acoplanarity.

Background from the UE also important at LHC

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

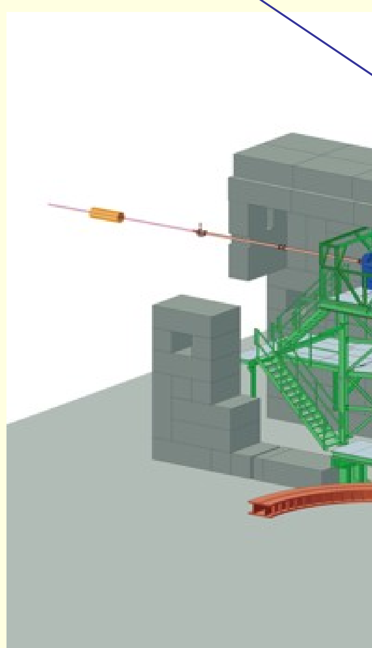
- … and this has important consequences for
  - Jet identification
  - Jet energy reconstruction
    - Resolution
    - Bias
  - Low-p_T background for the jet structure observables
- In Cone of R=1
  - 0.25 TeV (RHIC, cen. AuAu)
  - 0.8 - 1.9 TeV (LHC, cen. PbPb)
    - Higher bound from HIJING
  - High energy jets are more collimated



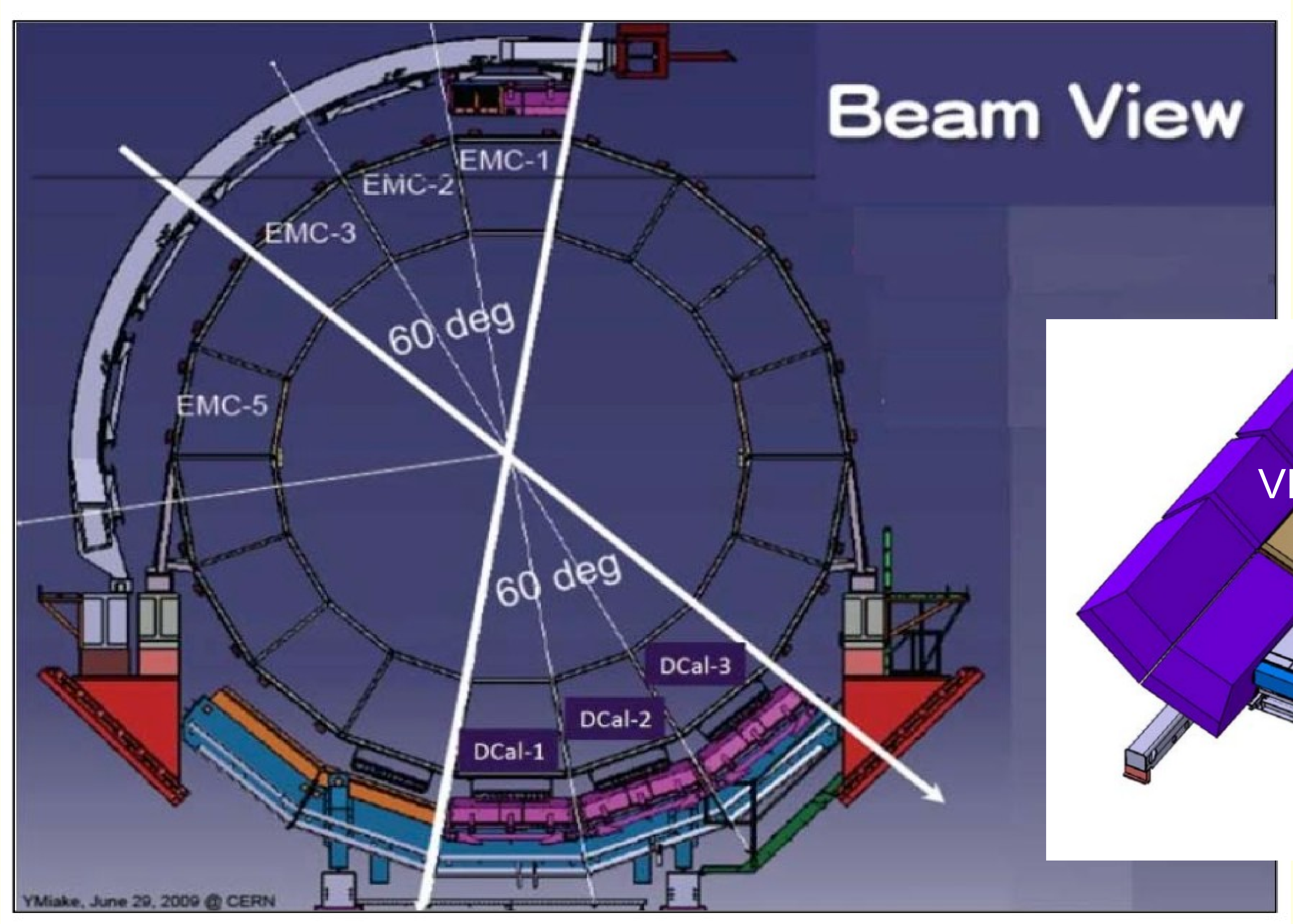
ALICE Detector Systems for Jet and γ-Identification

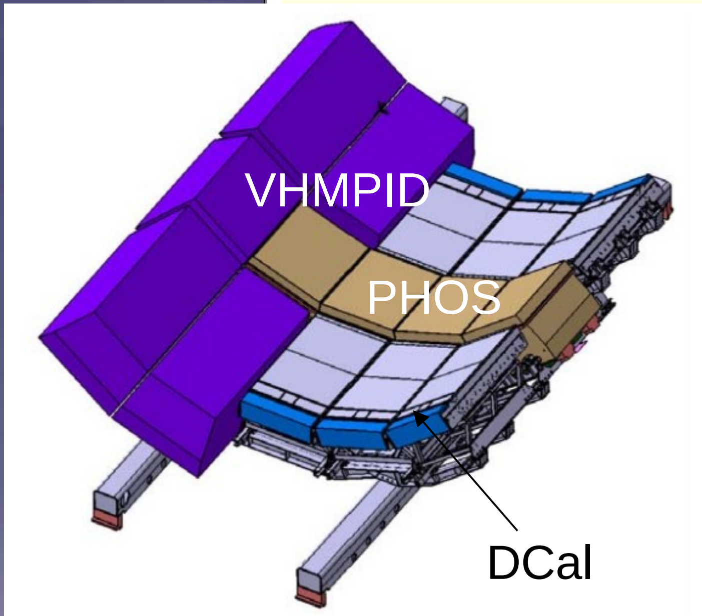
- ITS+TPC+(TOF, TRD)
  - Charged particles $|\eta| < 0.9$
  - Excellent momentum resolution up to 100 GeV/*c* ($\Delta p/p < 6\%$)
  - Tracking down to 100 MeV/*c*
  - Excellent Particle ID and heavy flavor tagging

- EMCal
  - Energy from neutral particles
  - Pb-scintillator, 13k towers
  - $\Delta\phi = 107°$, $|\eta| < 0.7$
  - *Energy resolution ~10%/√E_γ*
  - Trigger capabilities



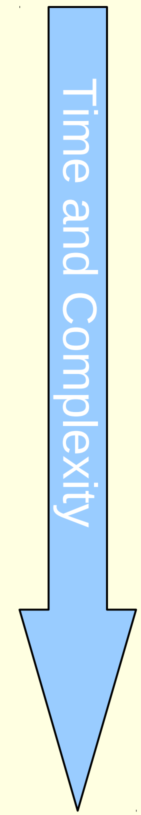
DCal complements EMCal for Dijet and hadron-Jet Correlation Measurements





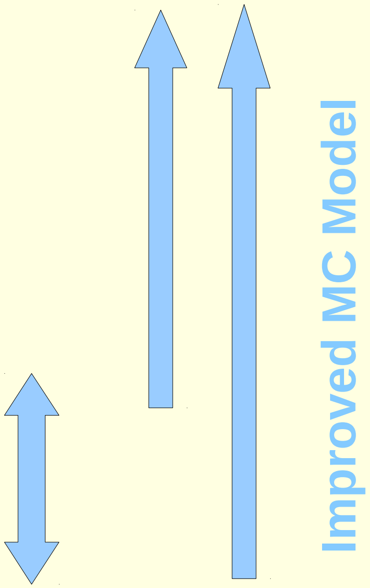
Sequence of key measurement

- Characterization of the soft background
  - Background fluctuations in typical jet cone areas
    - Correlated and uncorrelated
  - Elliptic flow
- Modification of the transverse jet structure
  - $R^{AA}_{Jet}(E_T, R)$
  - Jet shape $\psi(r)$
  - j_T
- Modification of the longitudinal jet structure
  - Fragmentation function $1/N_{jet}\, dN/dz$



More technically ...

- Determine Resolution Matrix $R(E_{rec} \mid E_{true}$;FF, JF, ...)
  - FF: Fragmentation
  - JF: Jet Finder
- Unfold measured spectrum
- Determine Smearing Matrix $R(E_{true}, E_{bg} \mid E_{rec}$;FF, JF, ...)
- Measure jet shape and correcting for soft BG (splash-in)
- Evaluate bias from splash-out
- Measure longitudinal fragmentation
  - Correct for splash in and splash out

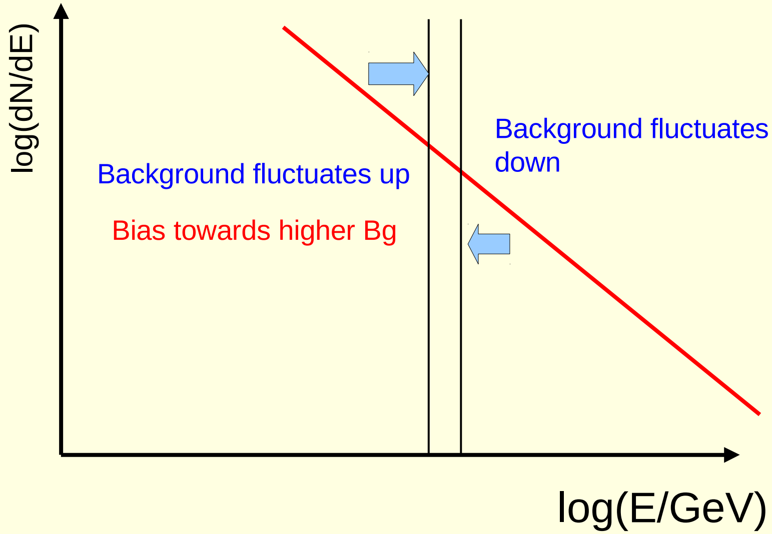


MC Consistency check

- Without modification standard jet finders used in pp (e^+e^-) collisions will not work in a heavy ion environment.
- The main modification consists in determining the mean underlying event cell energy from cells outside a jet cone. It is recalculated after each iteration and subtracted from the energy inside the jet area.
- Large interest and progress in Jet Reconstruction in high multiplicity environment
- FASTJet package (Cacciari, Salam)
  - Fast ($N \ln N$) implementation of k_T and Cambridge/Aachen
  - Implementation of an IRC safe cone algorithm (SIScone)
  - New soft-resilient algorithm: anti-k_T
  - Quantitative definition of jet area beyond leading order

Jet Reconstruction: Underlying Event

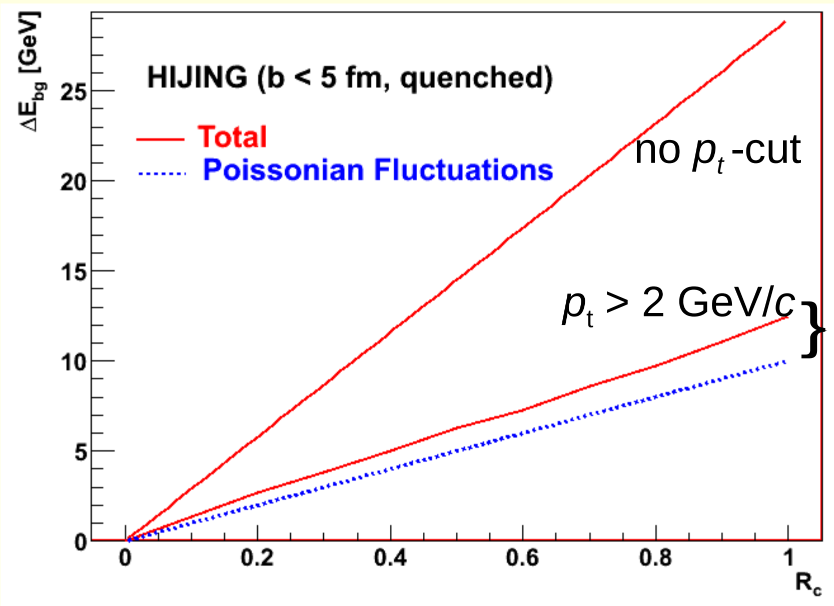
- Background energy fluctuations limit jet energy resolution at low energies
- In addition, they add a soft component to the jet structure observables (splash in)
- $\Delta E \sim \sqrt{\text{Jet Area}}$
  - Cone Algorithm: fixed area R^2
  - k_T : minimizes splash-out, however back-reaction from soft particles dominates systematics when comparing PbPb to more elementary collisions (pp, pA)
  - Anti-k_T: regular jet-areas, small back-reaction
- At LHC background has hard component
  - O(10) Jets > 10 GeV per central collision

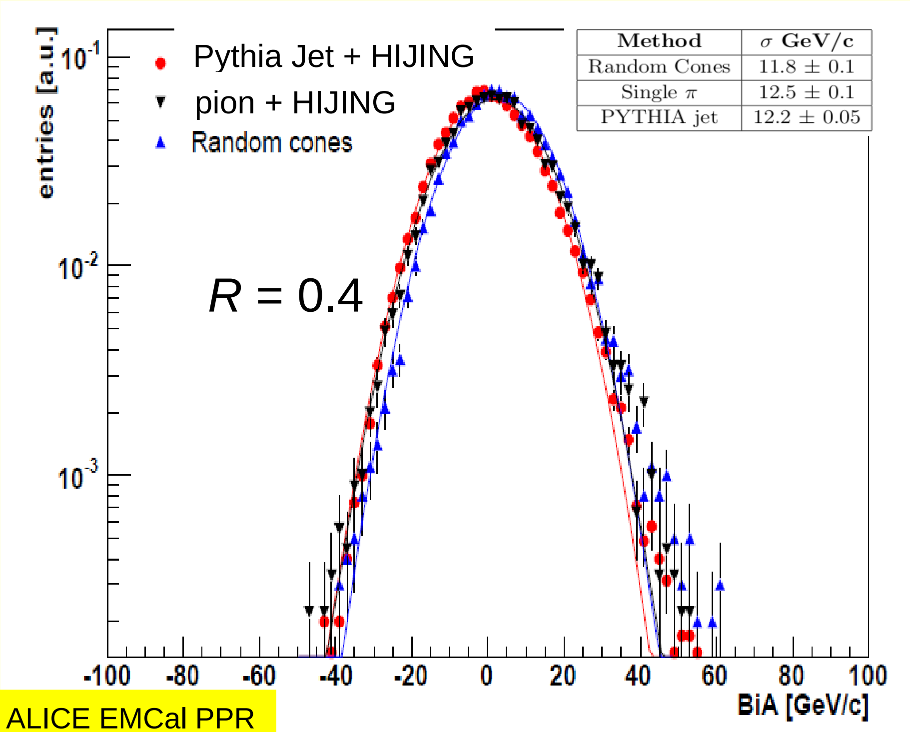


Splash-in can only be quantified once input spectrum has been measured and carries part of its systematic uncertainty.

Background Fluctuations

$\Delta E = \sqrt{N}\sqrt{[\langle p_T\rangle^2 + \Delta p_T^2]}$





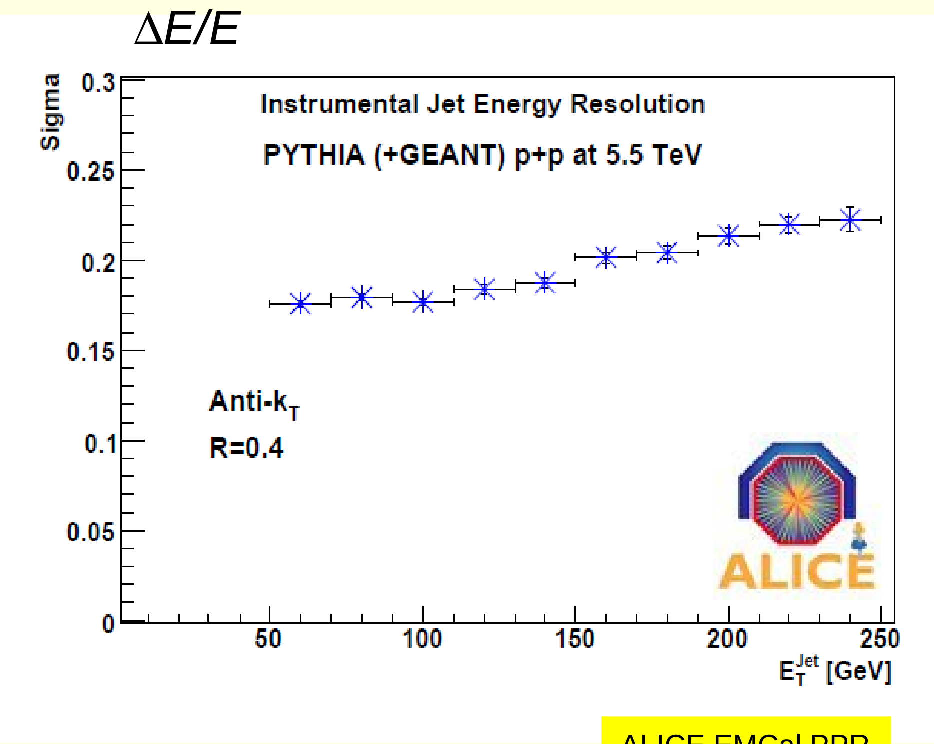
Method	σ GeV/c
Random Cones	11.8 ± 0.1
Single π	12.5 ± 0.1
PYTHIA jet	12.2 ± 0.05

ALICE EMCal PPR

Difference between real and estimated background energy
Jet Finder systematics with monochromatic jets.

- "non-Poissonian" behavior at medium pT and in the tails of the pdf
- Small but significant systematics of the mean value
- Characterization of the soft correlated and uncorrelated background for high E_T QCD jets is an important LHC day-1 measurement.

Energy Resolution: EMCAL+tracking

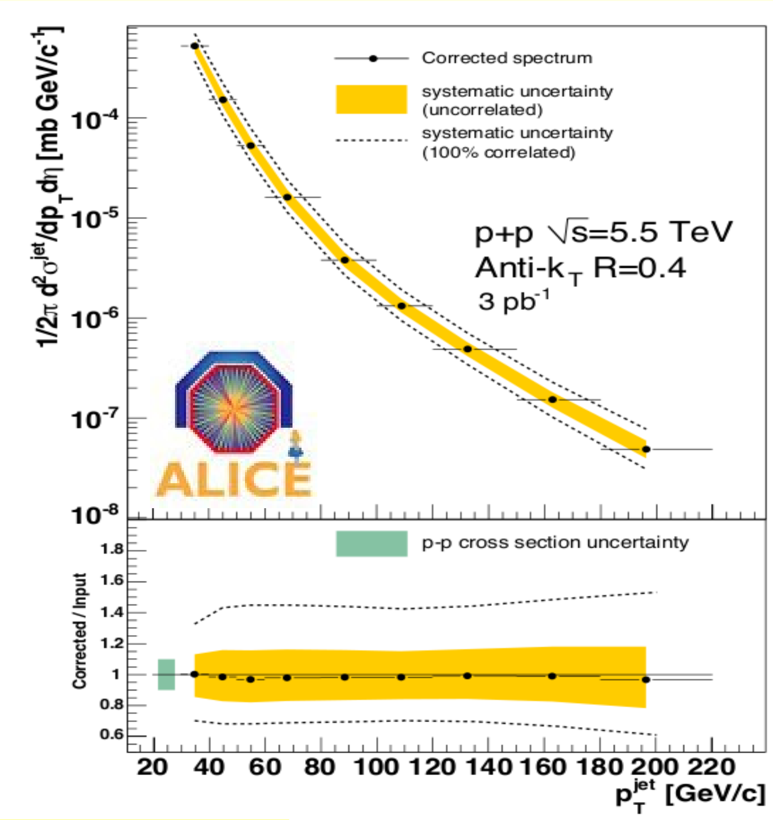


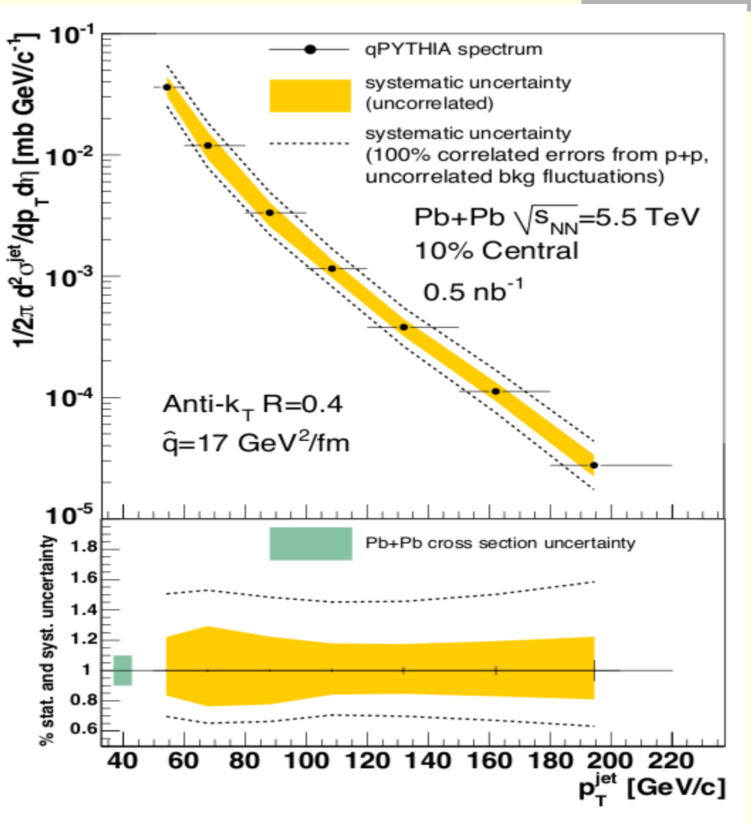
ALICE EMCal PPR

Underlying event (central Pb–Pb)	
Fluctuations	20% (75 GeV/c), 3% (150 GeV/c)
False Jets	small (>50 GeV/c)

Instrumental effects and fluctuating unmeasured contribution of K_0^L and neutrons.

Jet Cross-Section Measurement: Systematic Error





ALICE EMCal PPR

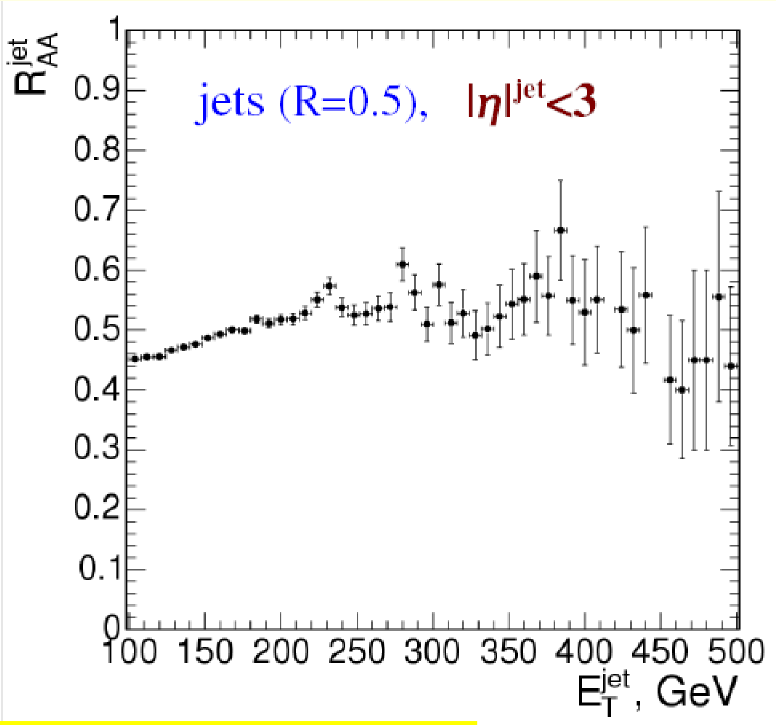
Systematic effect	Incl. cross section sys. uncert.
Common in p–p and A–A	
Tracking distortions (space charge etc.)	unknown
Tracking efficiency	1%
Hadronic and electron energy double counting	3-4%
EMCal energy scale	8-10%
Unobserved neutral energy	13-15%
Underlying event (central Pb–Pb)	
Fluctuations	20% (75 GeV/c), 3% (150 GeV/c)
False Jets	small (>50 GeV/c)

Reduced Jet Area (Splash-Out)

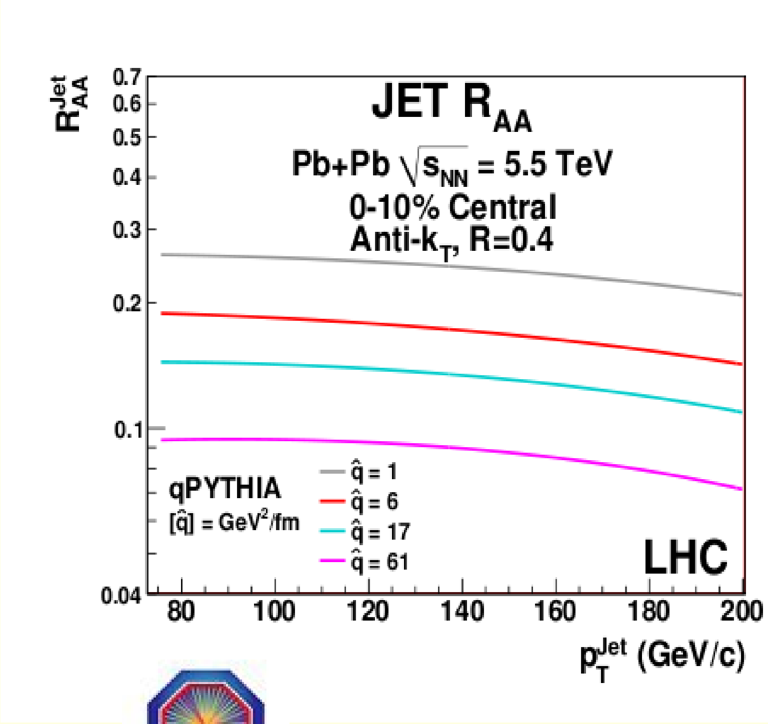
- Trigger bias towards more collimated jets
- Part of the medium induced soft radiation will be outside the jet cone and/or indistinguishable from the underlying event.
  - This introduces a systematic difference in the energy scale when comparing measurements in central PbPb to a baseline (pp or peripheral PbPb)
  - Energy scale enters directly into longitudinal fragmentation function($z = p_L/E_{jet}$)
  - Bias towards less quenched jets
- Measurement of the $R_{AA}^{Jet}(R)$ allows to quantify the effect
  - (see STAR and PHENIX)

Large Out-of-cone radiation also expected at LHC

$$R_{Jet}^{AA}(p_T) = \frac{d^2\sigma_{Jet}^{AA}/dp_T\,d\eta}{T_{AA}\,d^2\sigma_{Jet}^{pp}/dp_T\,d\eta}$$

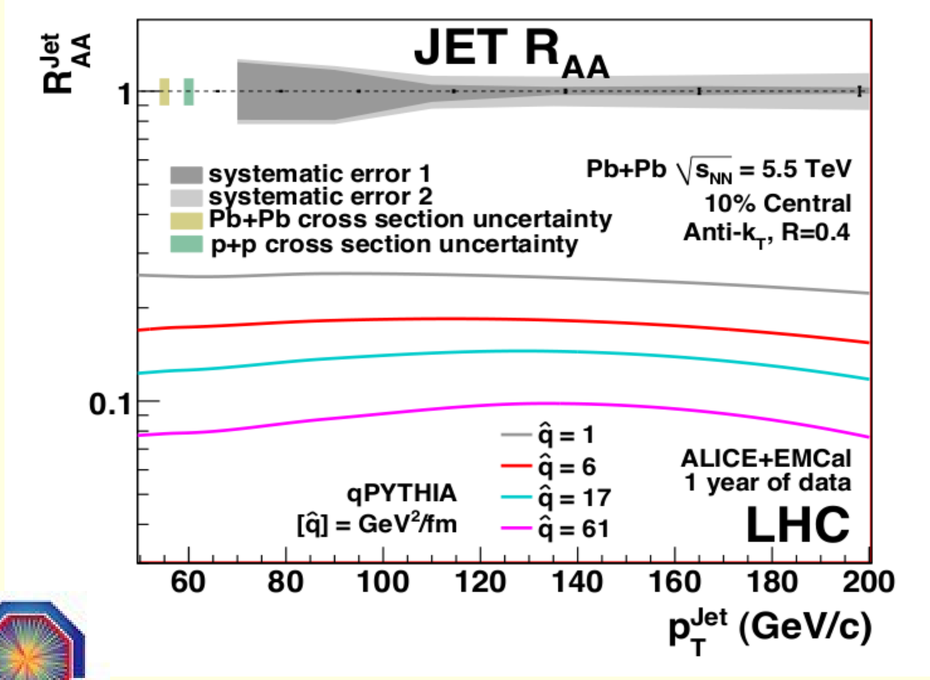


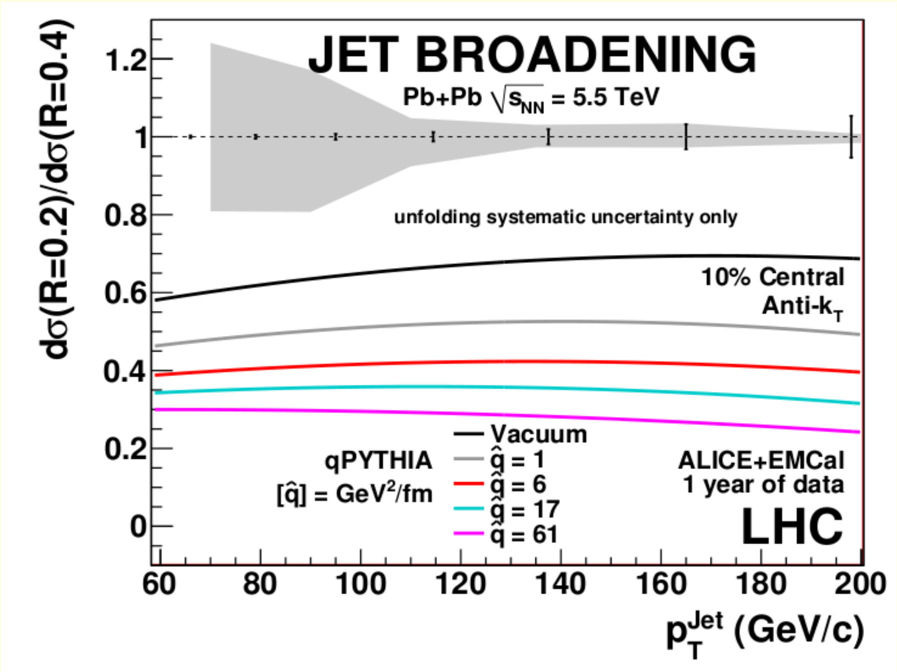
PYQUEN (I. Lokhtin)



ALICE

Jet R_{AA} and Jet Broadening

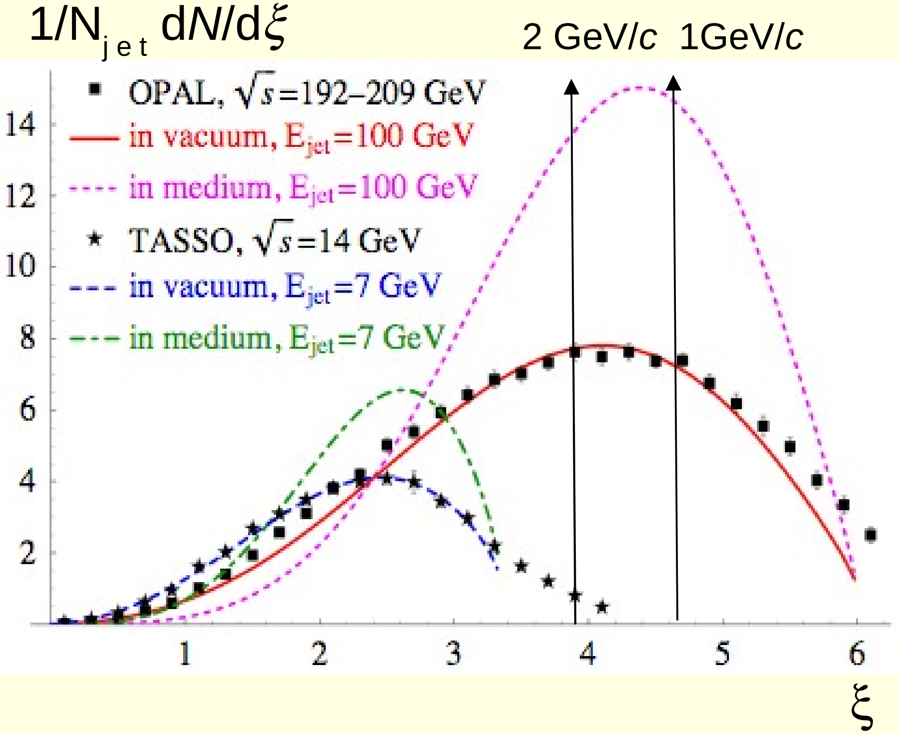




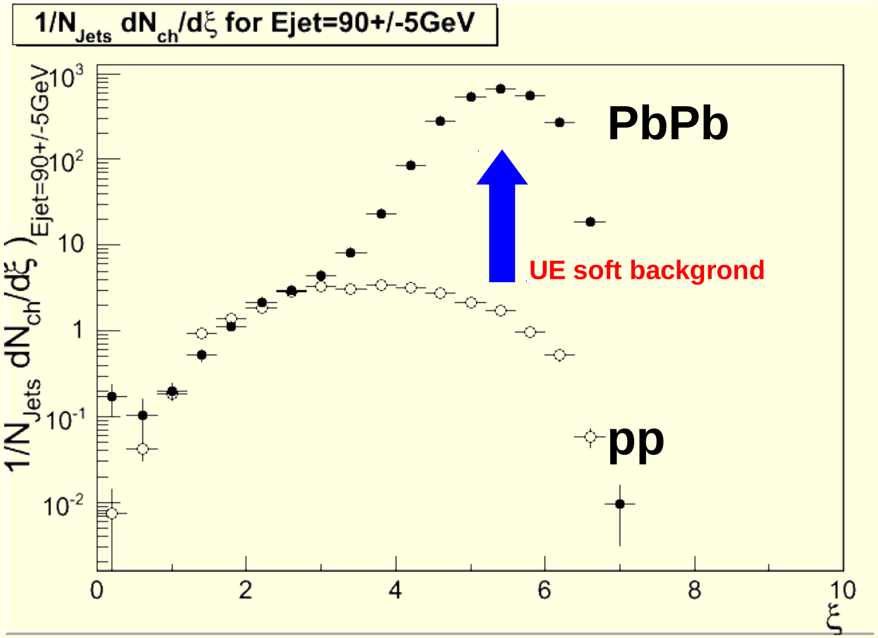
Splash in/out systematics on jet structure

- Splash-in
  - Softening, widening
  - Quench-bias
- Splash-out
  - Collimation, hardening
  - Anti-quench bias
- Examples on the following slides ...

Modification of the Fragmentation Function



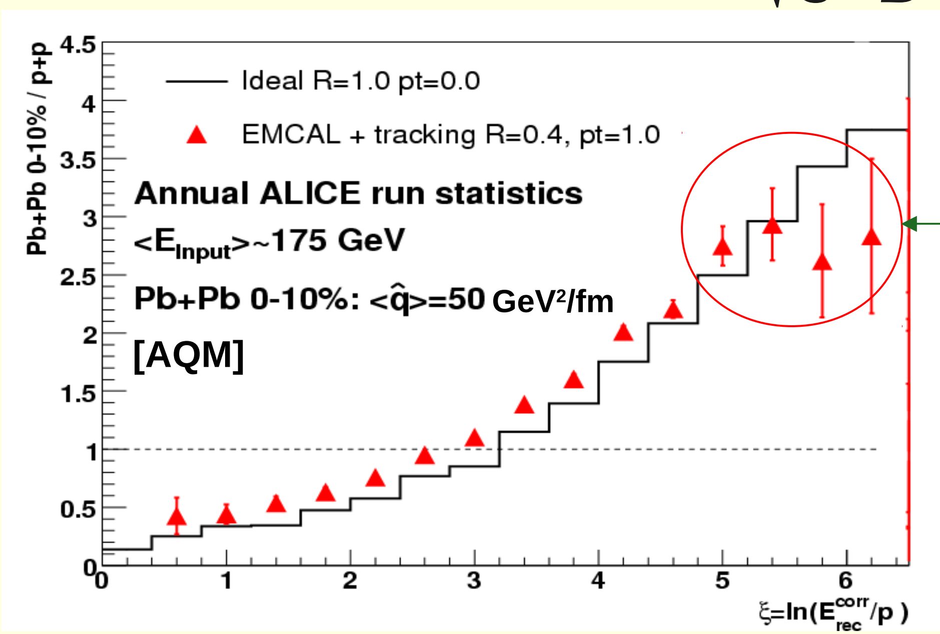
Ideal: No background

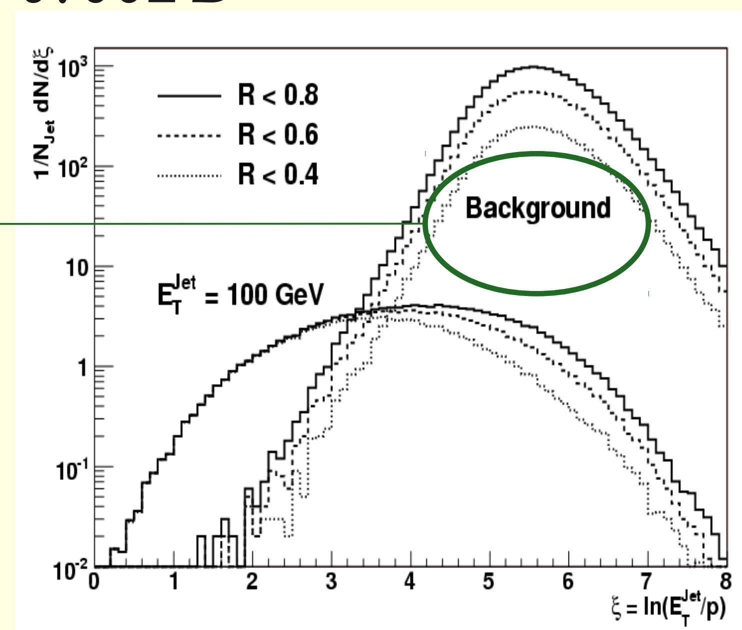


$R_{AA}(\xi)$

$$R_{AA}(\xi) = \frac{1/N_{jet}^{AA}\, dN^{AA}/d\xi}{1/N_{jet}^{pp}\, dN^{pp}/d\xi}$$

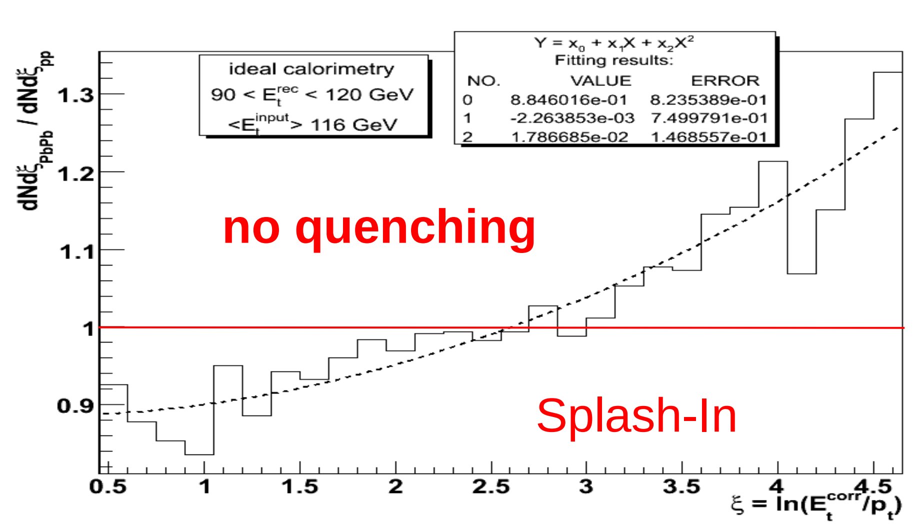
$$\sqrt{S+B} + 0.002\,B$$

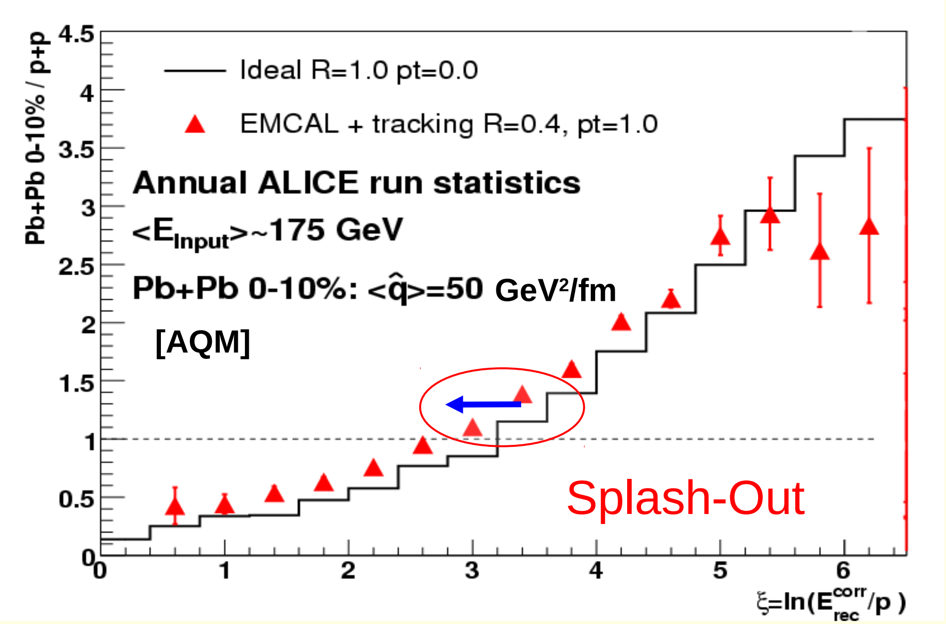




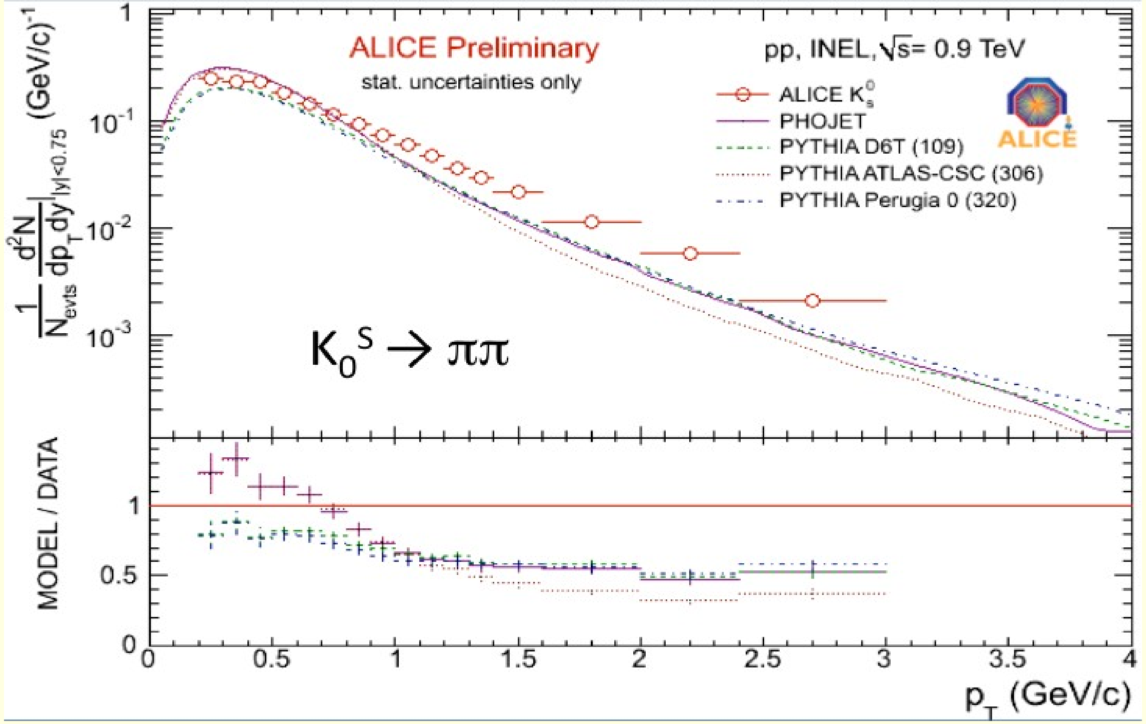
Systematic Effects

- Jet reconstruction pre-selects jets with larger than average soft UE contribution. Needs correction.
- Robust signal but underestimation of jet energy biases ξ to lower values.
  - Depends on cone size R and p_T cut
  - Measurement has to be complemented by measurement of the
    - jet shape (out of cone radiation)
    - $R_{AA}(E_{jet})$ and
    - Calibration using γ-jet events





PID and Jets

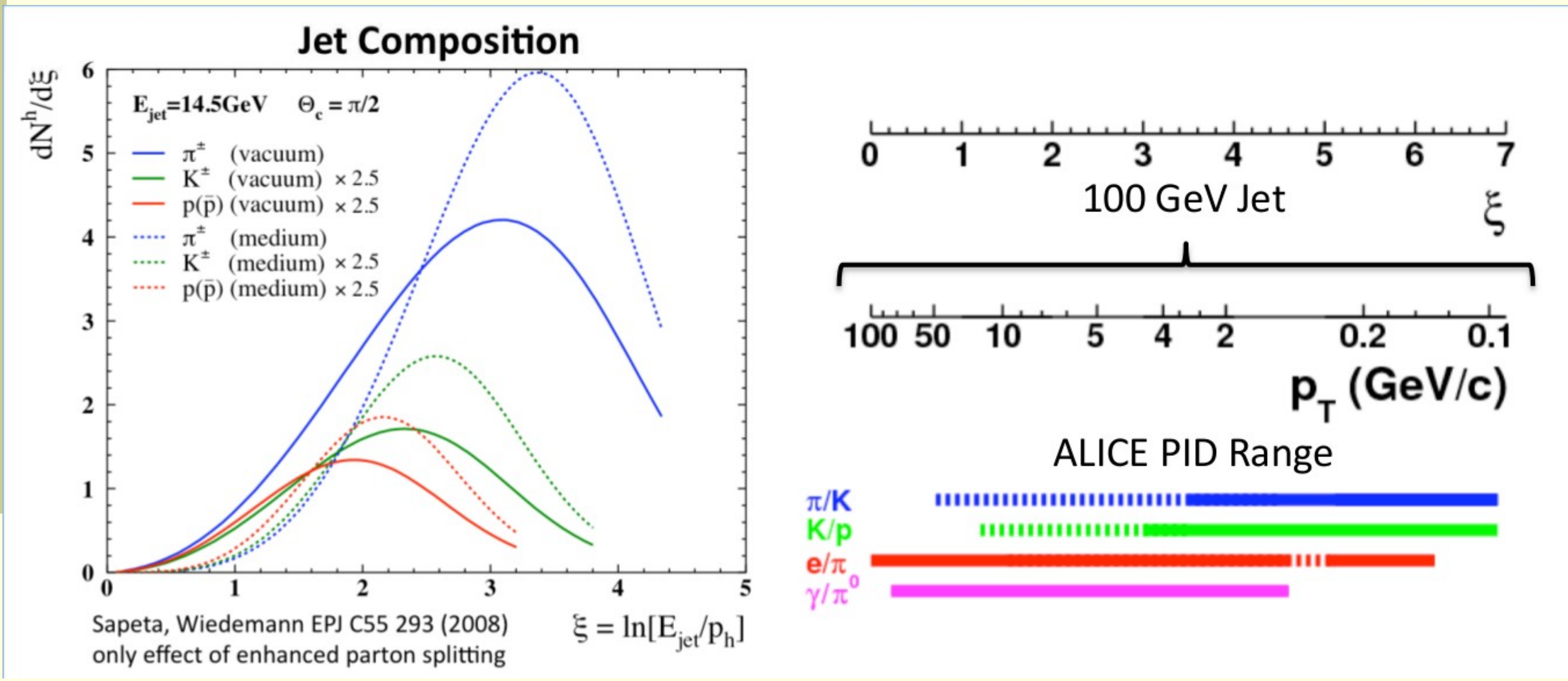


Measure K_0 spectrum much harder wrt to any Pythia Tune !

Look more differential into this effect:

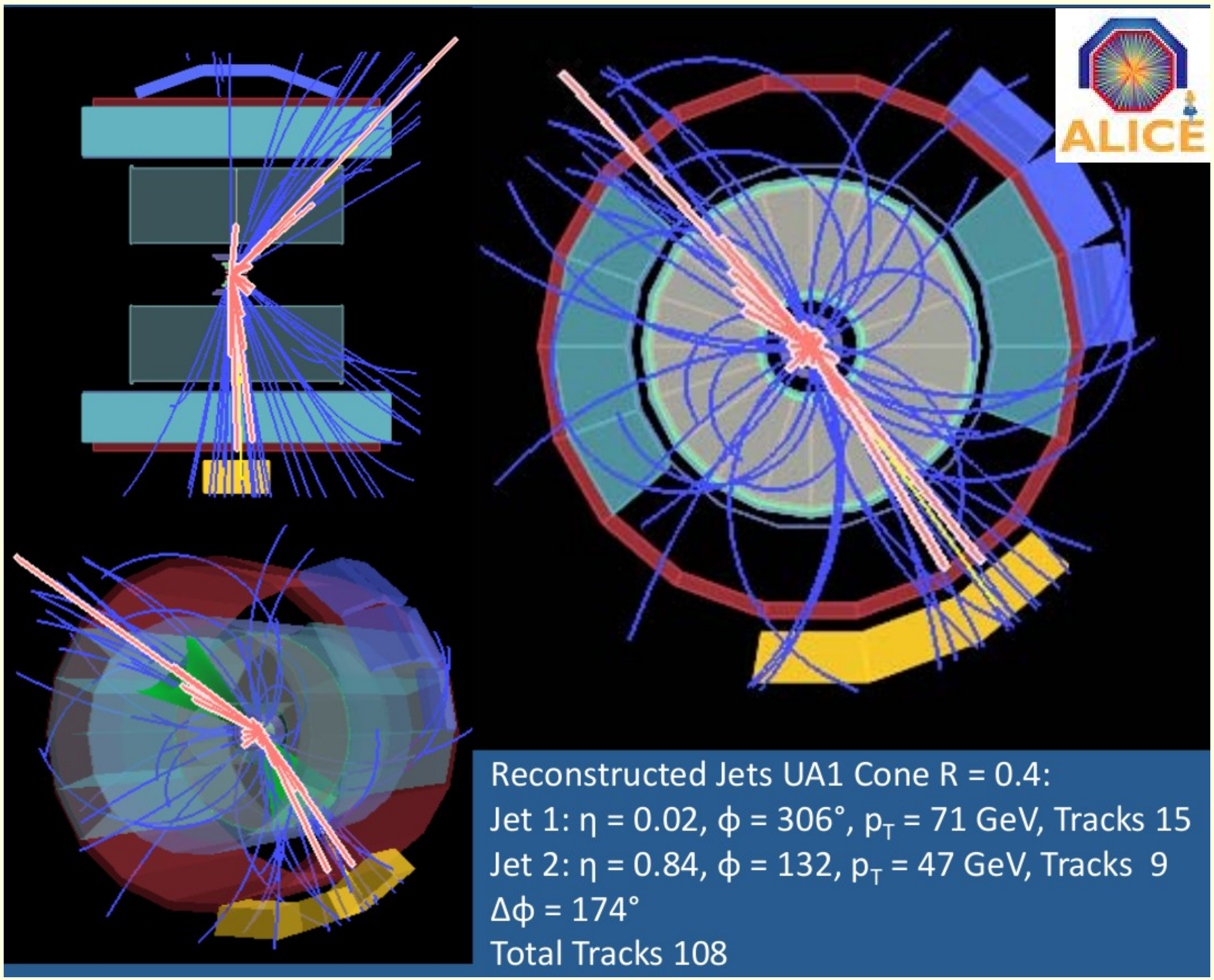
- K_0 yield inside jets
- K_0 in underlying event

PID and Jets



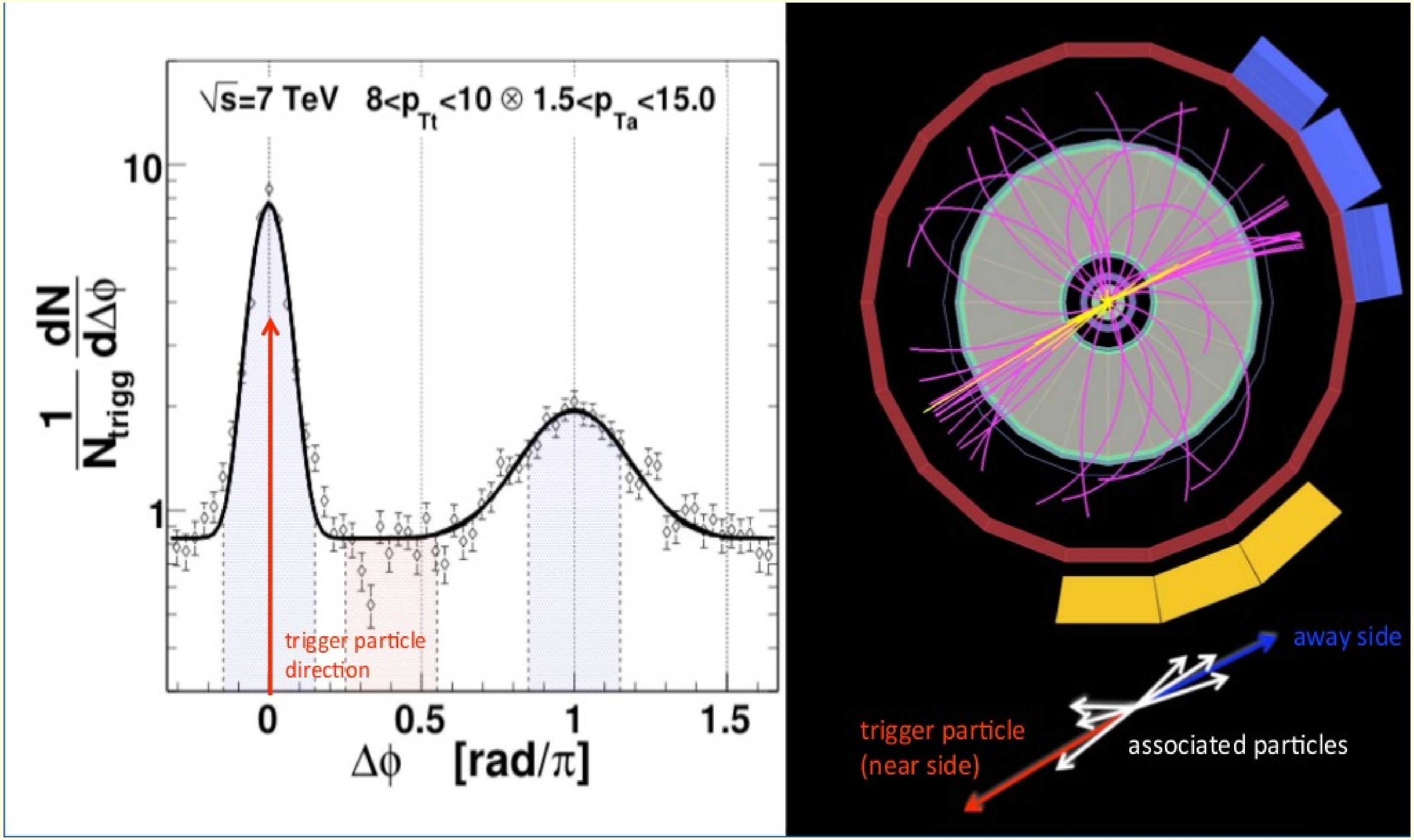
Jet Composition
E_{jet}=14.5GeV $\Theta_c = \pi/2$
$\pi^\pm$ (vacuum)
$K^\pm$ (vacuum) × 2.5
$p(\bar{p})$ (vacuum) × 2.5
$\pi^\pm$ (medium)
$K^\pm$ (medium) × 2.5
$p(\bar{p})$ (medium) × 2.5
$dN^h/d\xi$
0
1
2
3
4
5
6
0
1
2
3
4
5
$\xi = \ln[E_{jet}/p_h]$
Sapeta, Wiedemann EPJ C55 293 (2008)
only effect of enhanced parton splitting
0 1 2 3 4 5 6 7
100 GeV Jet
ξ
100 50 10 5 4 2 0.2 0.1
p_T (GeV/c)
ALICE PID Range
π/K
K/p
e/π
γ/π^0

Where do we stand today ?



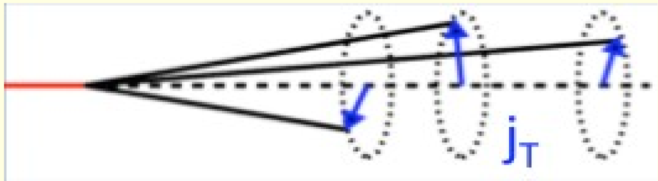
Di-Hadron Correlation

See talk J. Ulery

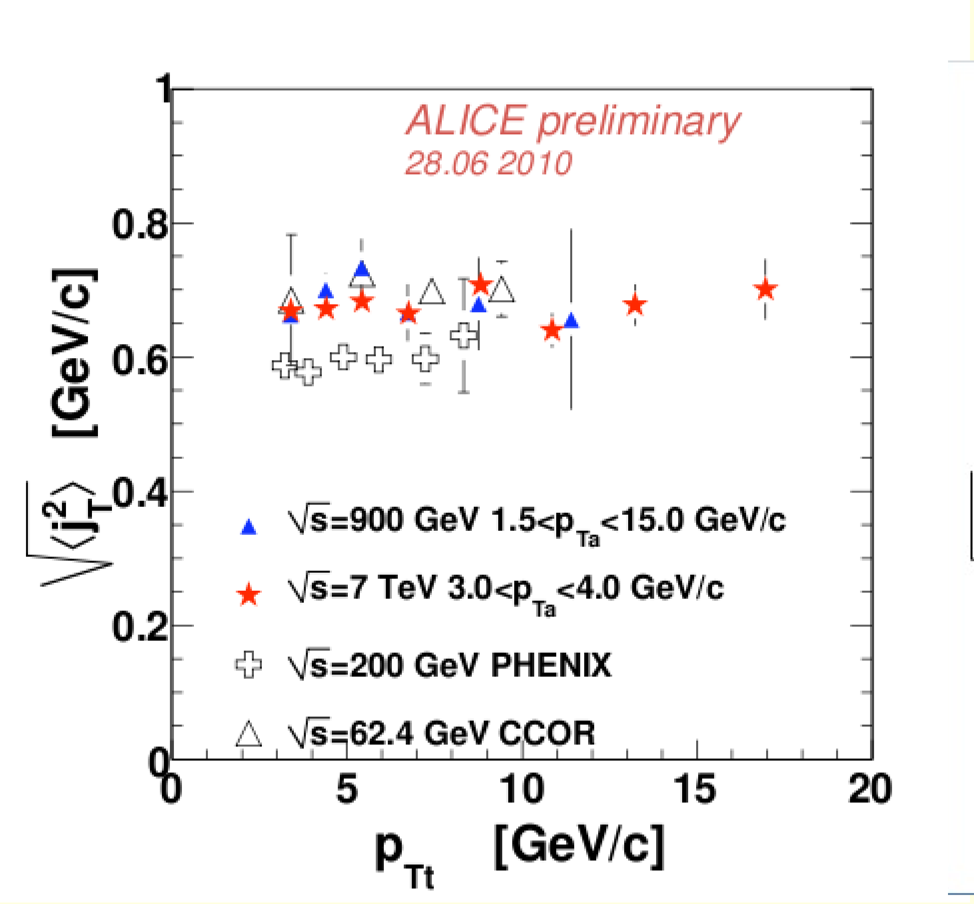


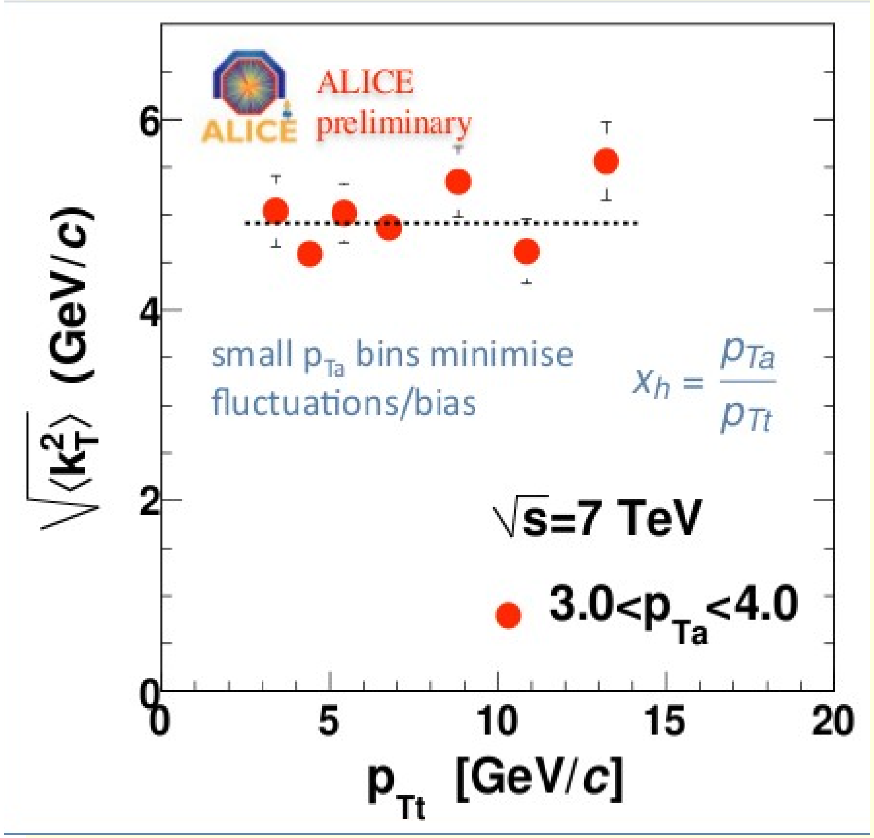
Jet-like properties from Di-Hadron Correlations

See talk J. Ulery

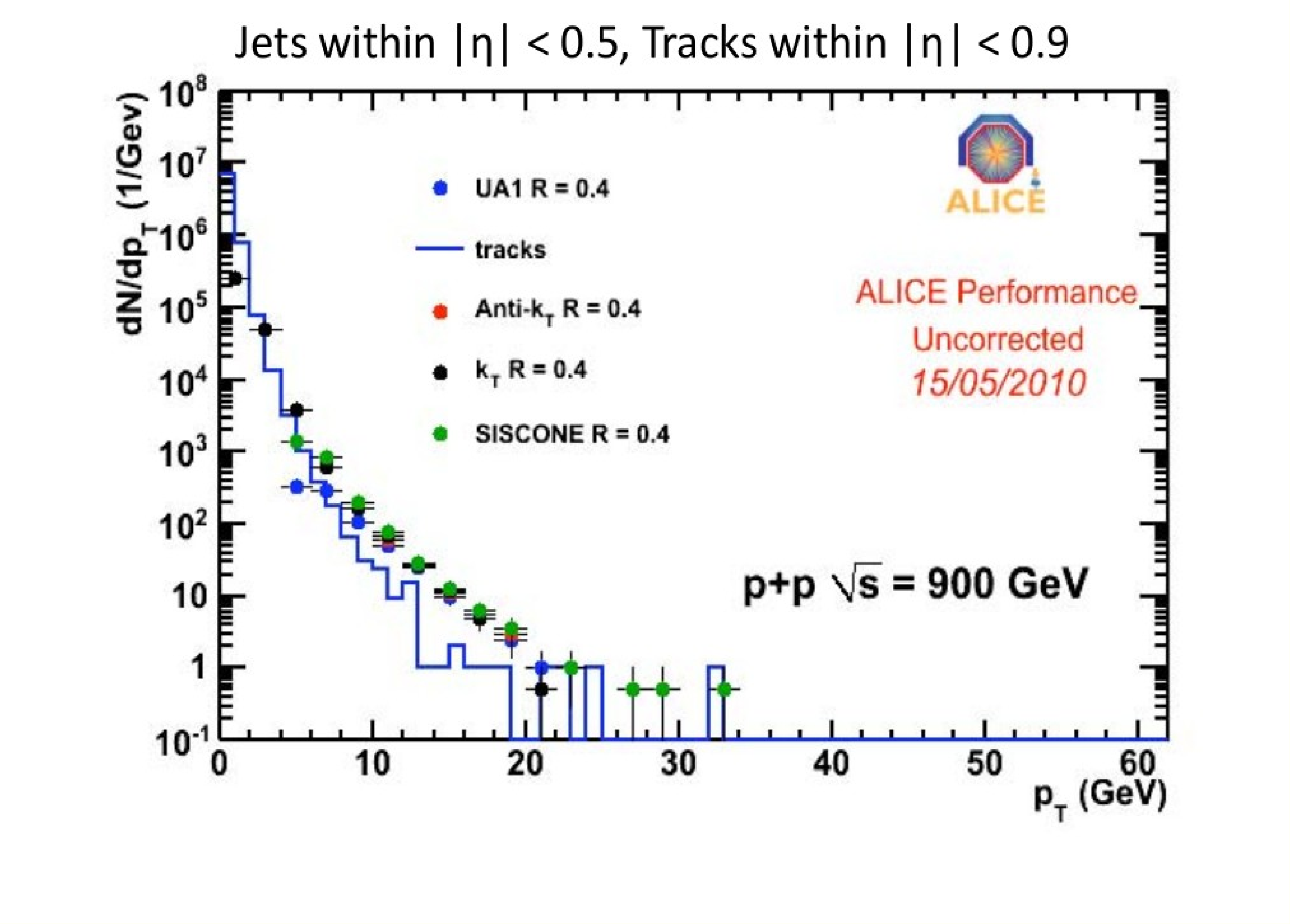


Di-Hadron p_T

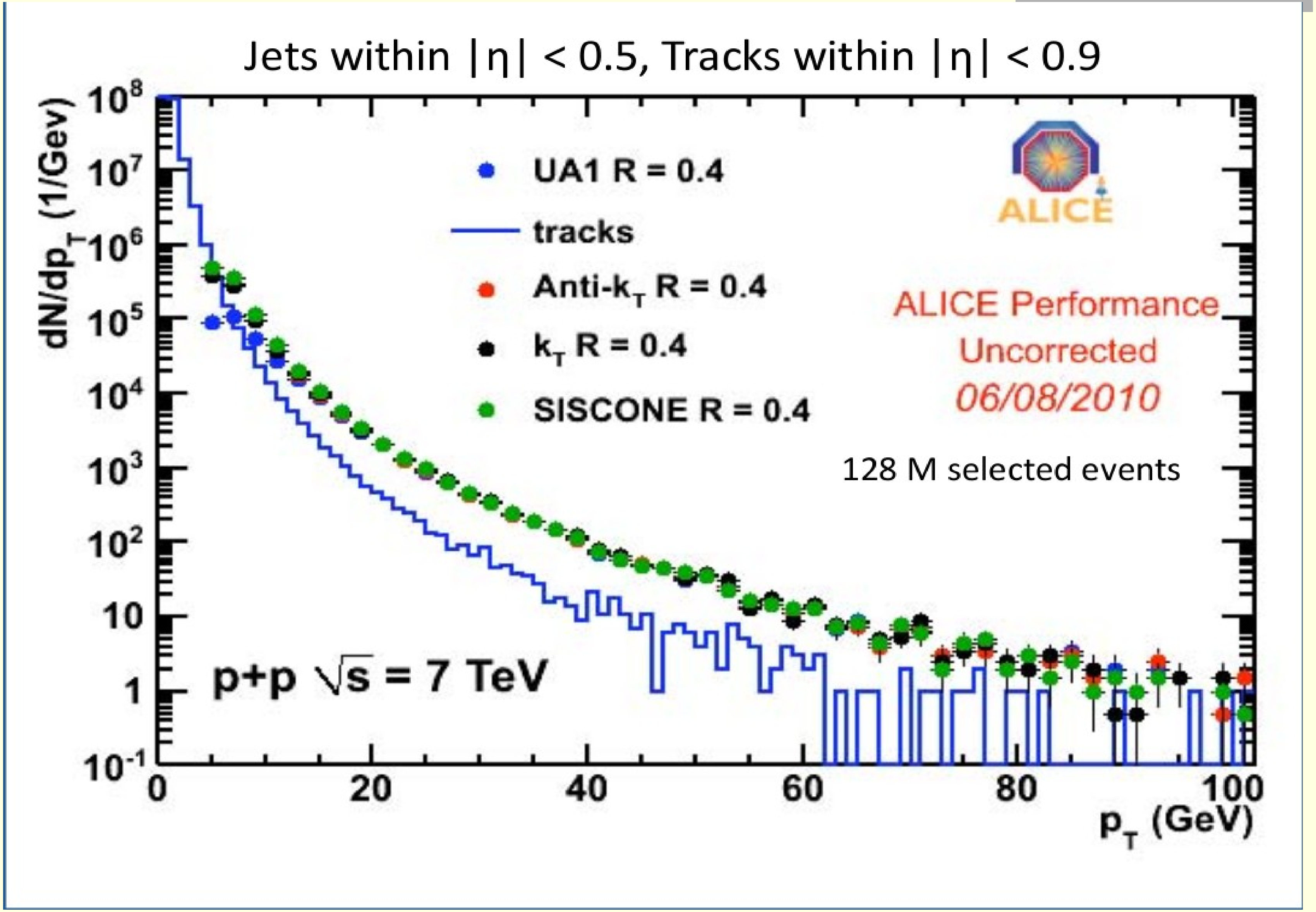




Raw Min Bias Jet Spectrum pp@900 GeV



Raw Min Bias Jet Spectrum pp@7 TeV

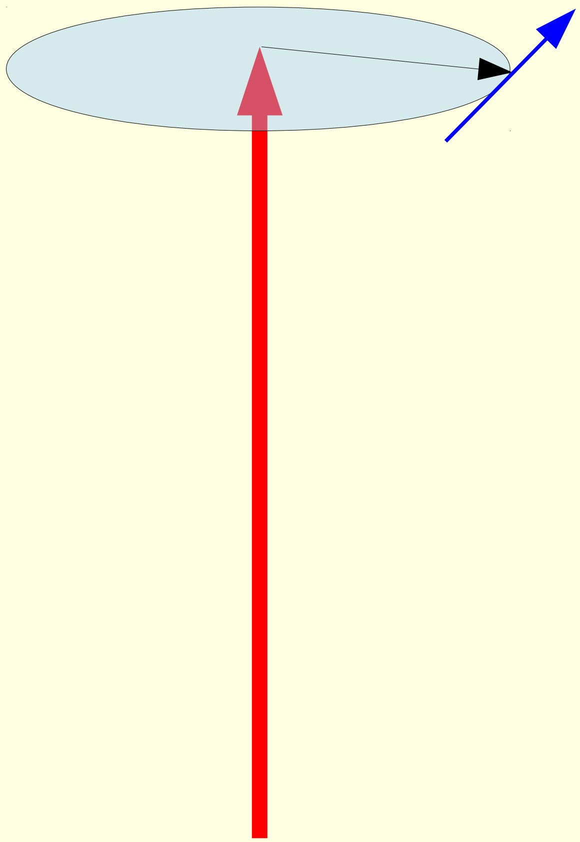


Some ideas for non-standard jet measurements

- Energy flow relative to thrust-major axis
- Jet mass modifications
- High j_T suppression

Energy flow relative to Thrust-Major

Jet axis ~ (single jet) Thrust



- Jet reconstruction sensitive to modifications of longitudinal and transverse energy flow. However, it should be insensitive to redistributions in the tangential direction.

- How to measure this ?
  - In parton showers ϕ-symmetry in plane perpendicular to jet axis is broken after first "hard" splitting. Defines Thrust Major Axis.
  - Determine this axis from particles near to the jet axis with relatively high p_t.
  - Look for correlations at higher R and lower p_T

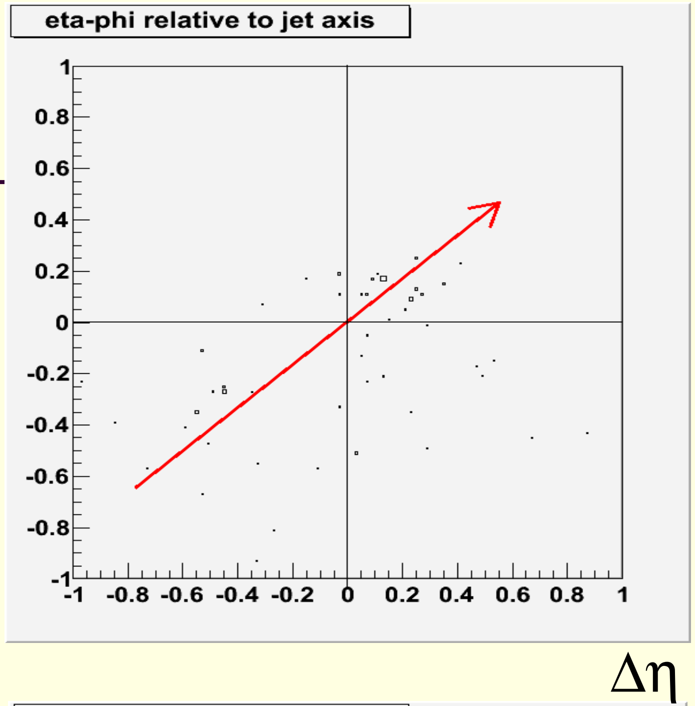
Sphericity Matrix in plane perpendicular to jet axis

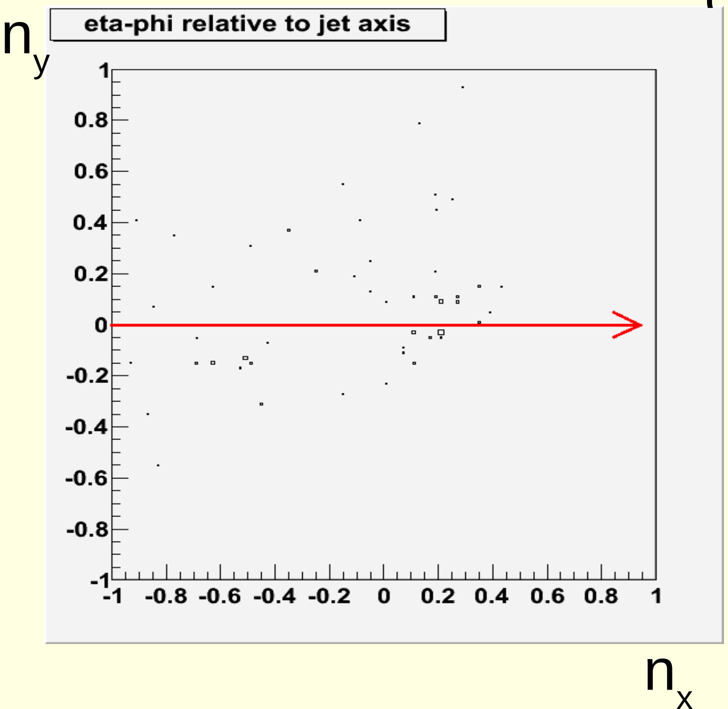
$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |p_i|^2}$$

$$p_i^x = p_T \cos(\delta)$$
$$p_i^y = p_T \sin(\delta)$$

$$\delta = \tan^{-1}(\Delta\Phi / \Delta\eta)$$

Find largest eigenvalue and corresponding eigenvector.
Eigenvector = x-axis of new coordinate system.

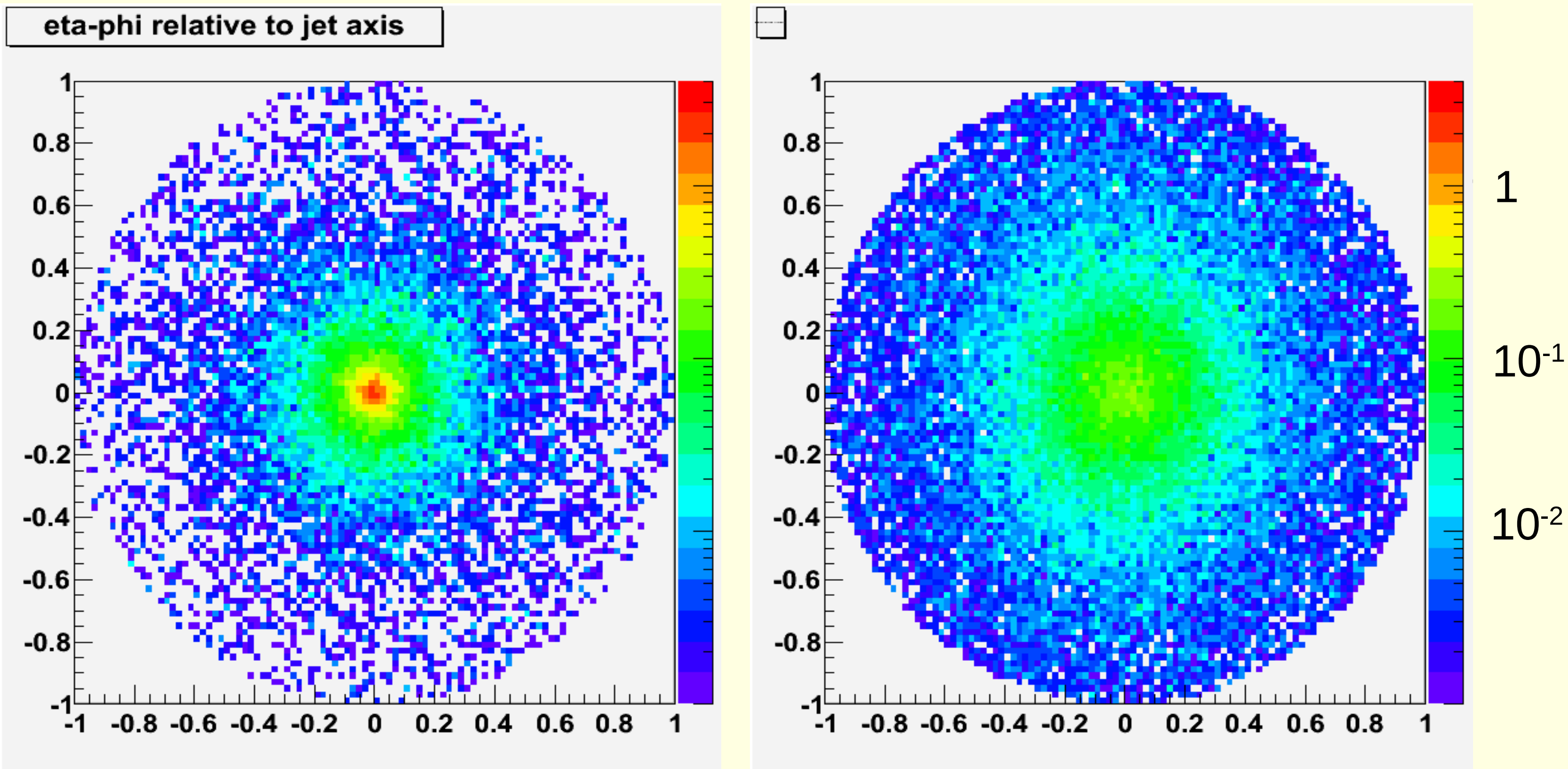




pp

Quenched (Q-Pythia)

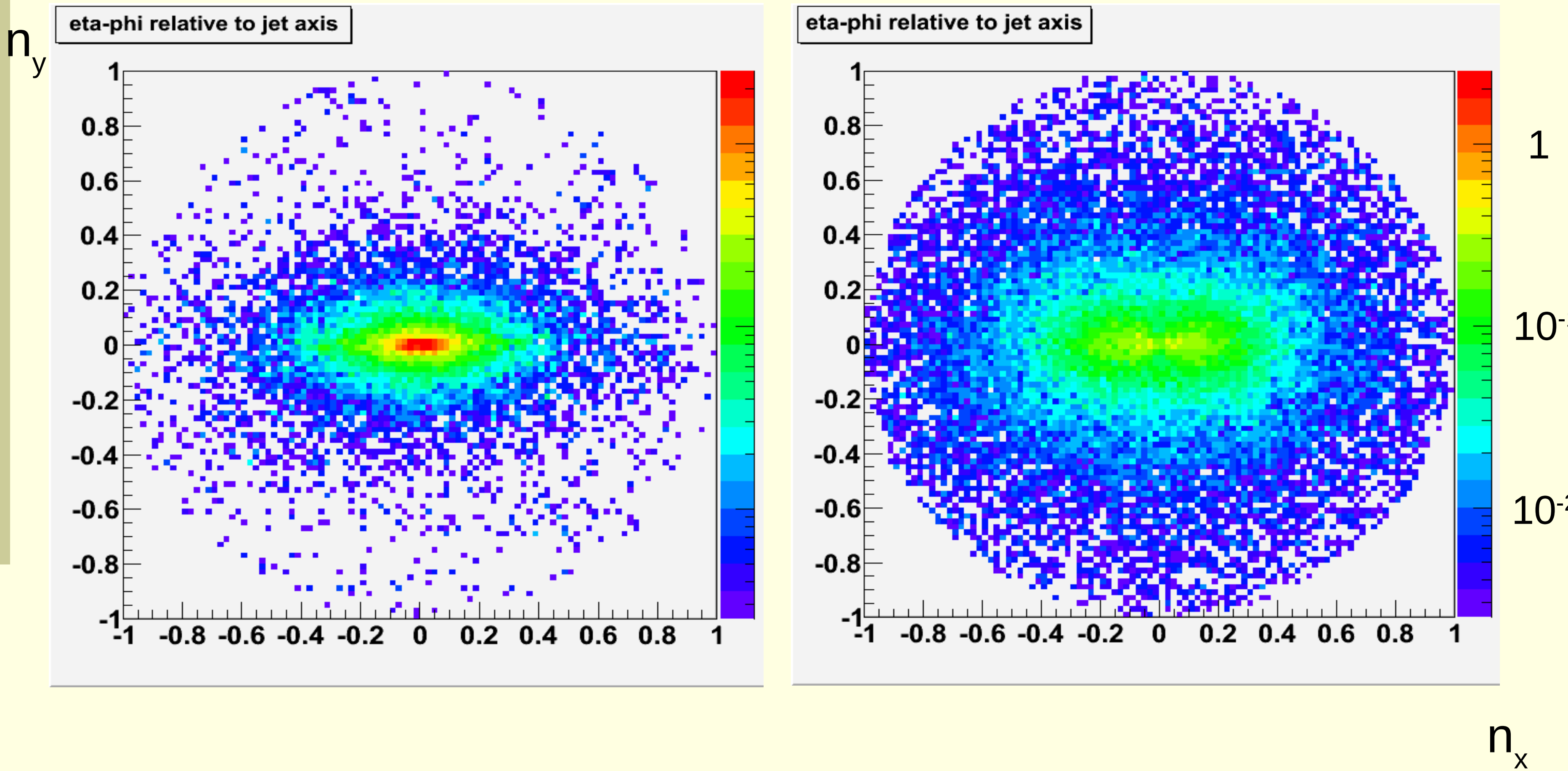
$\Delta\phi$

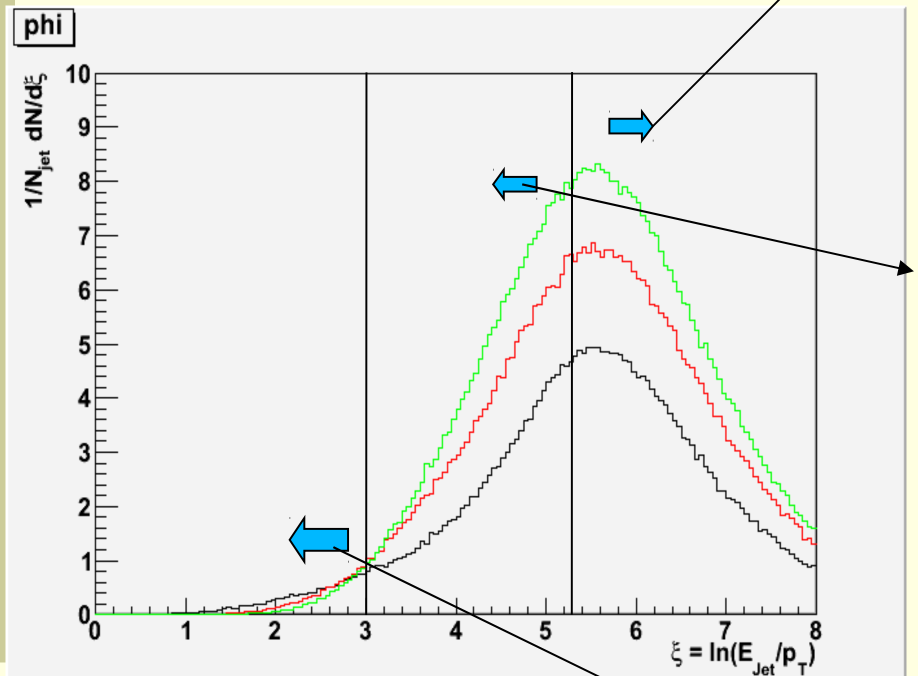


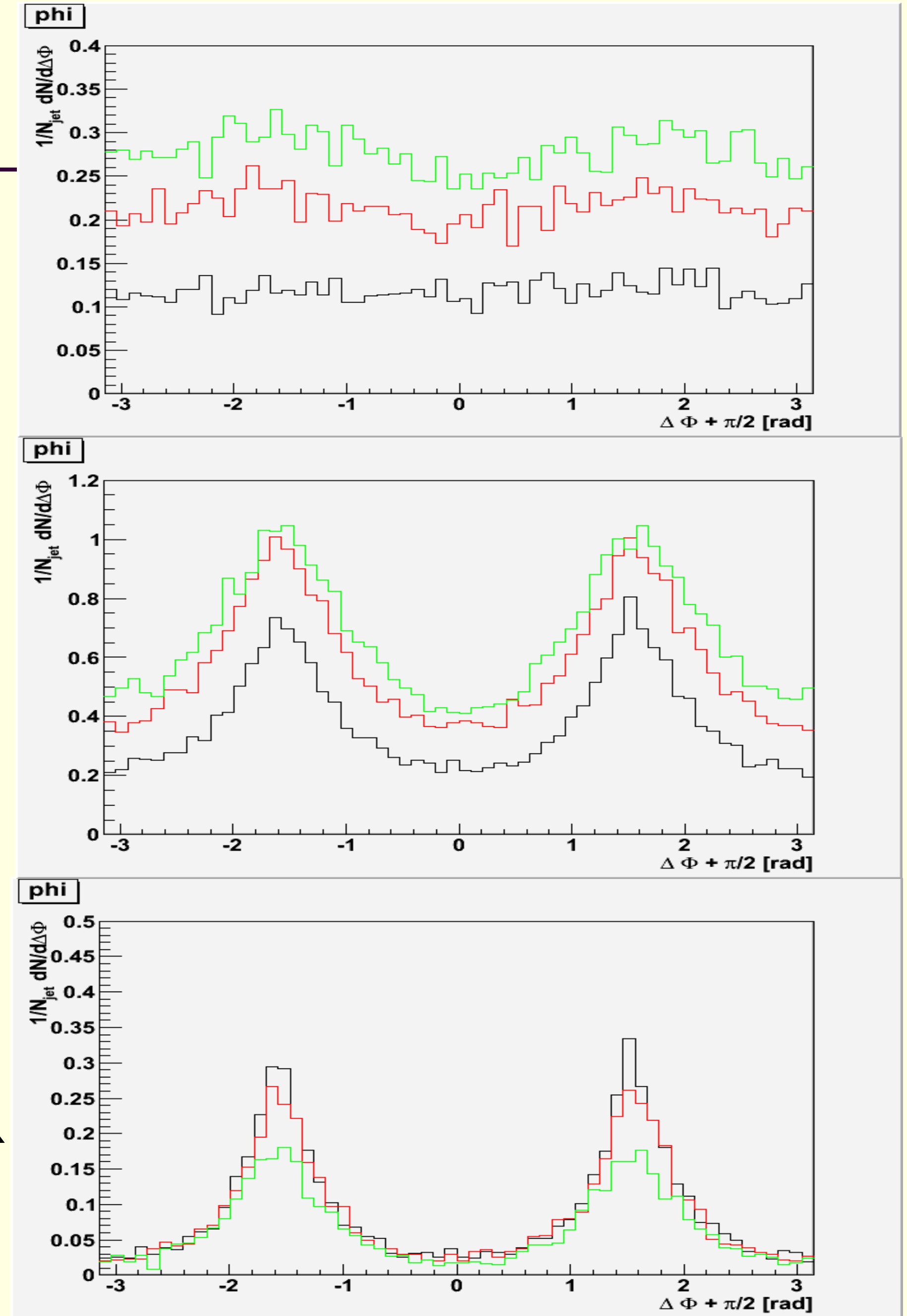
$\Delta\eta$

pp

Quenched (Q-Pythia)

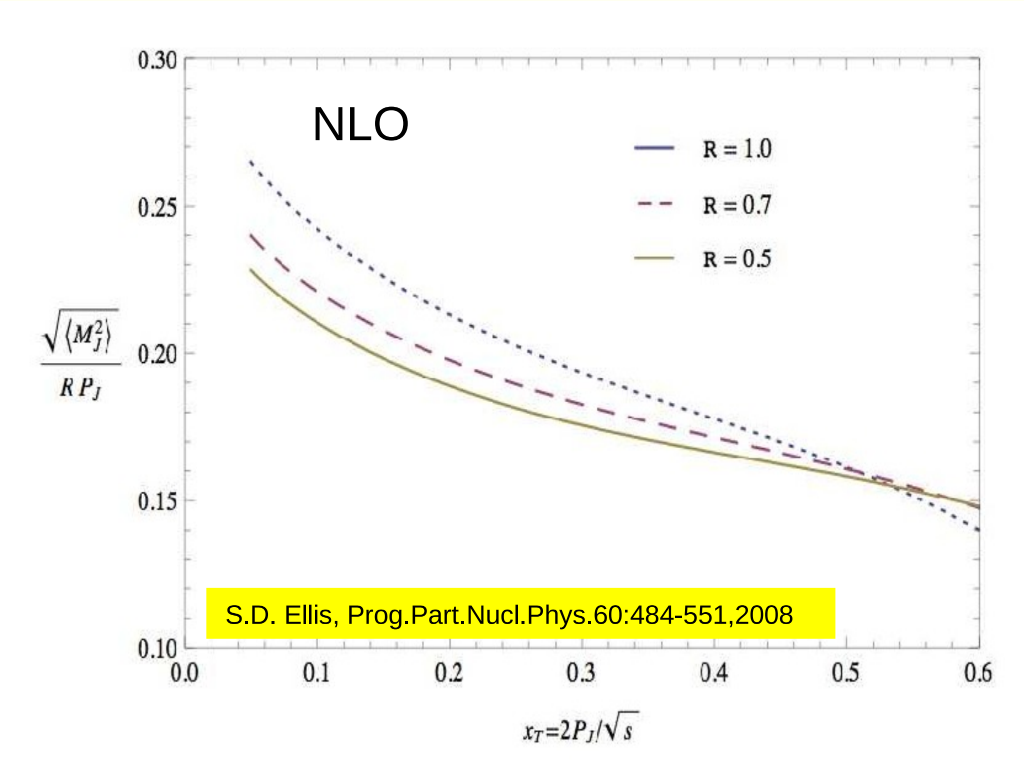






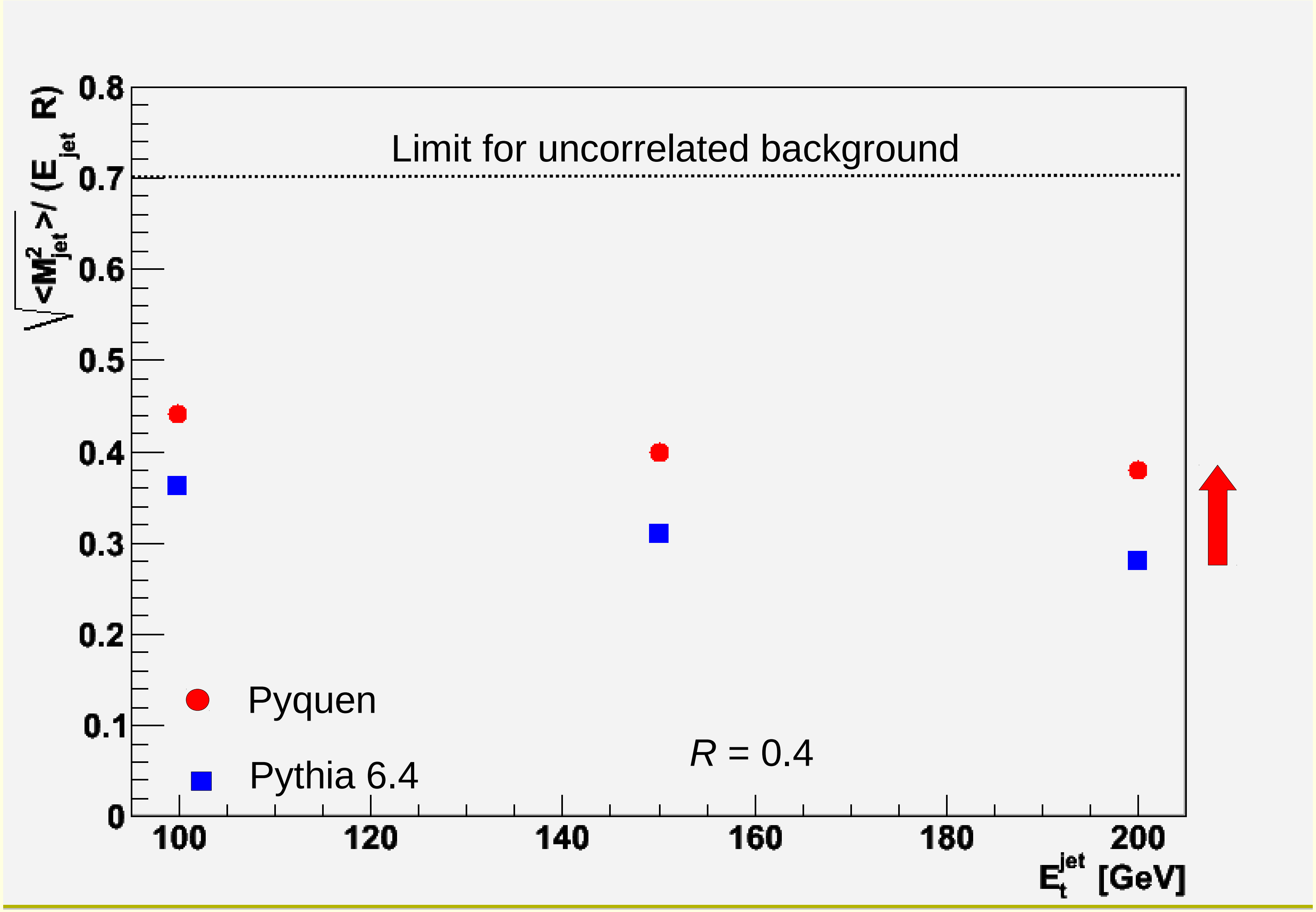
Effects intimately related to enhanced splitting !

Jet Mass



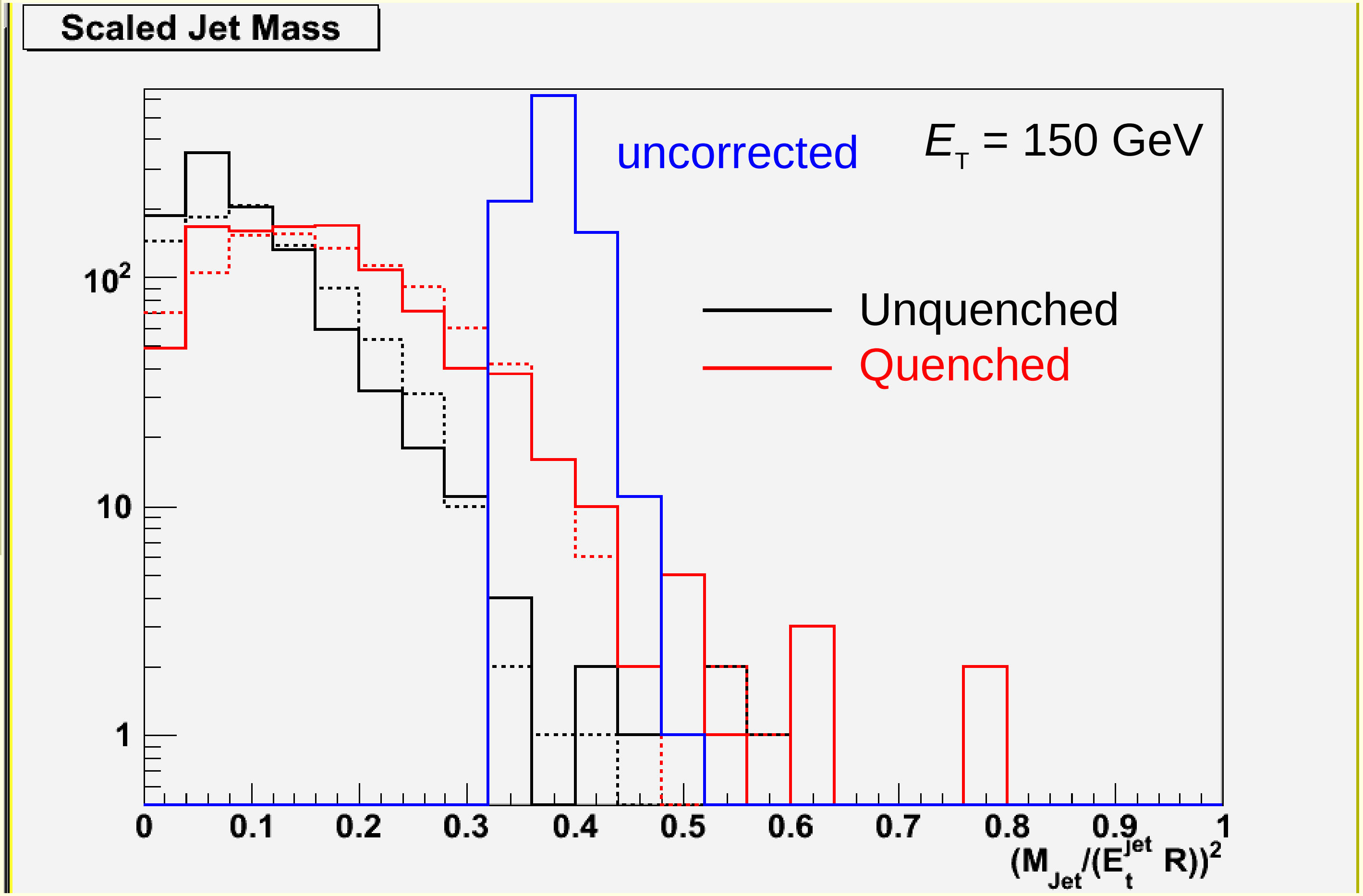
Will approximate scaling ~ RE_T persist in QGP ?

Possible LHC Scenario



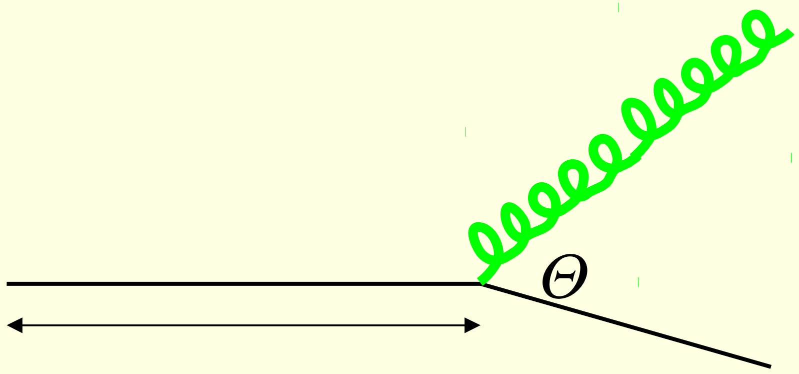
The Measurement: Background Correction

- Determine expected (E, p_x, 0, 0) at y = 0 from background
- Rotate and boost in the jet direction.
- Subtract jet by jet.



Solid: MC truth Dotted: Measured

Suppression of large j_T ?



$$t_{form} = 1/(\Theta j_T)$$

- 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 $\langle j_T \rangle$!

Summary

- We can look forward to very interesting physics with reconstructed jets in Heavy Ion collisions with ALICE
  - High rates providing sufficient energy lever-arm to map out the energy dependence of jet quenching.
  - Large effects: Jet structure changes due to energy loss and the additional radiated gluons.
  - Experiments suited for jet measurements in Heavy Ion Collisions
    - ATLAS and CMS: larger acceptance, higher energy reach
    - ALICE: excellent PID and low-p_T capabilities

- Three unconventional jet observables have been discussed. They might help to distinguish between different jet quenching models.
  - Energy flow relative to thrust-minor axis
  - Jet mass modifications
  - High j_T suppression