Jet physics at RHIC, lessons for LHC

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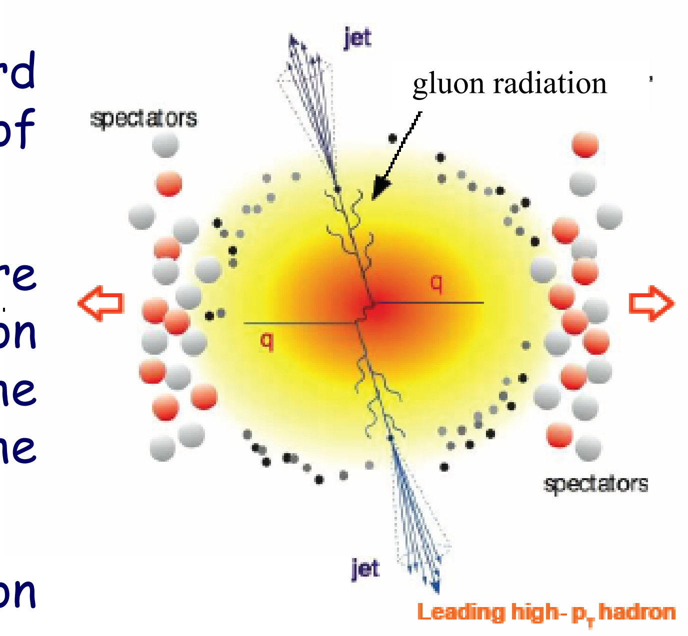
Physics motivation

- High energy partons, resulting from a initial hard scattering, will create a high energy cluster of particles → jets
- Partons traveling through a dense color medium are expected to loose energy via medium induced gluon radiation, "jet quenching", and the magnitude of the energy loss depends on the gluon density of the medium
- Parton showering and the subsequent hadronization are known as "parton fragmentation"



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

Measurement of the parton fragmentation products may reveal information about the QCD medium

I will talk about…

- Results from AuAu and pp collisions at $\sqrt{s_{NN}}$ = 200 GeV

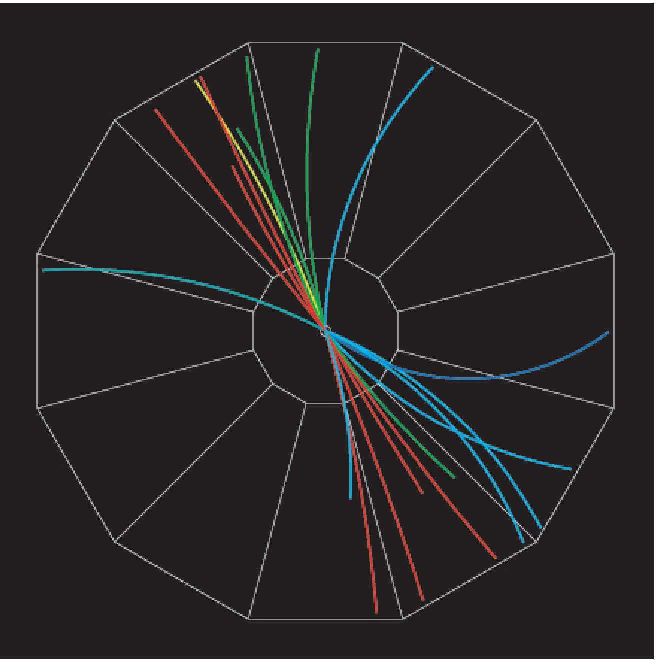
  what do they tell us?
- Results from dAu collisions

  initial or final state effects?
- Latest results
  - “real” high p_T
  - different systems, different energies
- Jets at LHC

This presentation features only a selection of results: an overview of the RHIC results, with emphasis on new results

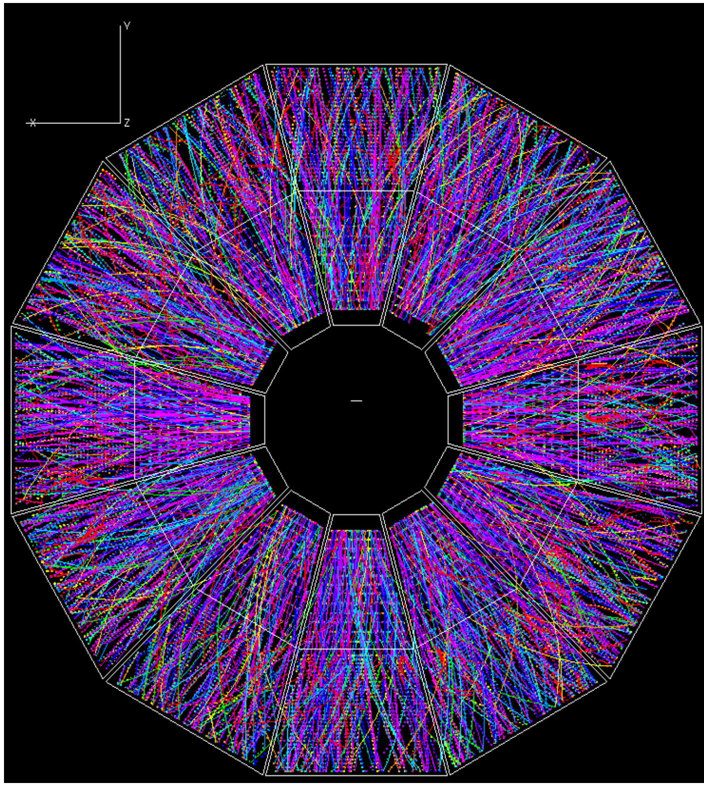
Finding jets

Find this…

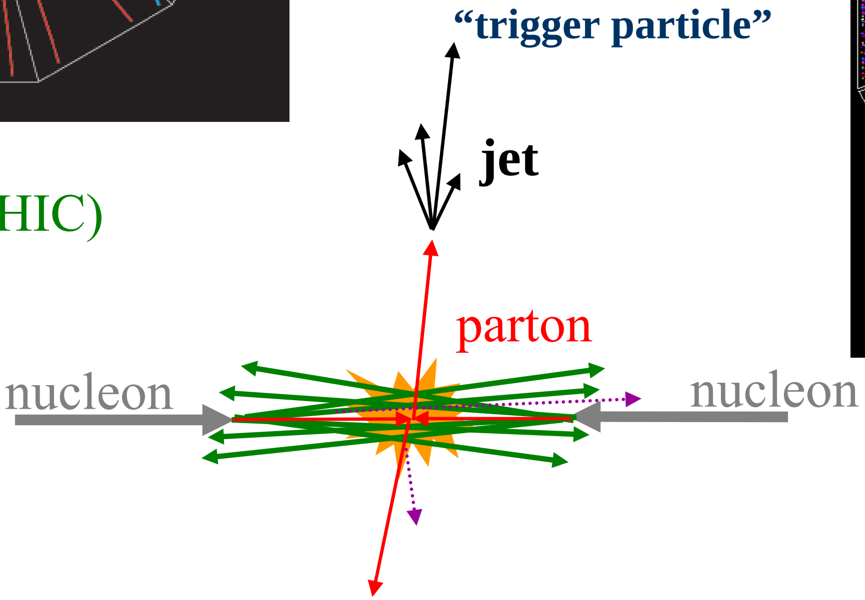


p+p
(STAR@RHIC)

… here:



Au+Au
(STAR@RHIC)



"trigger particle"

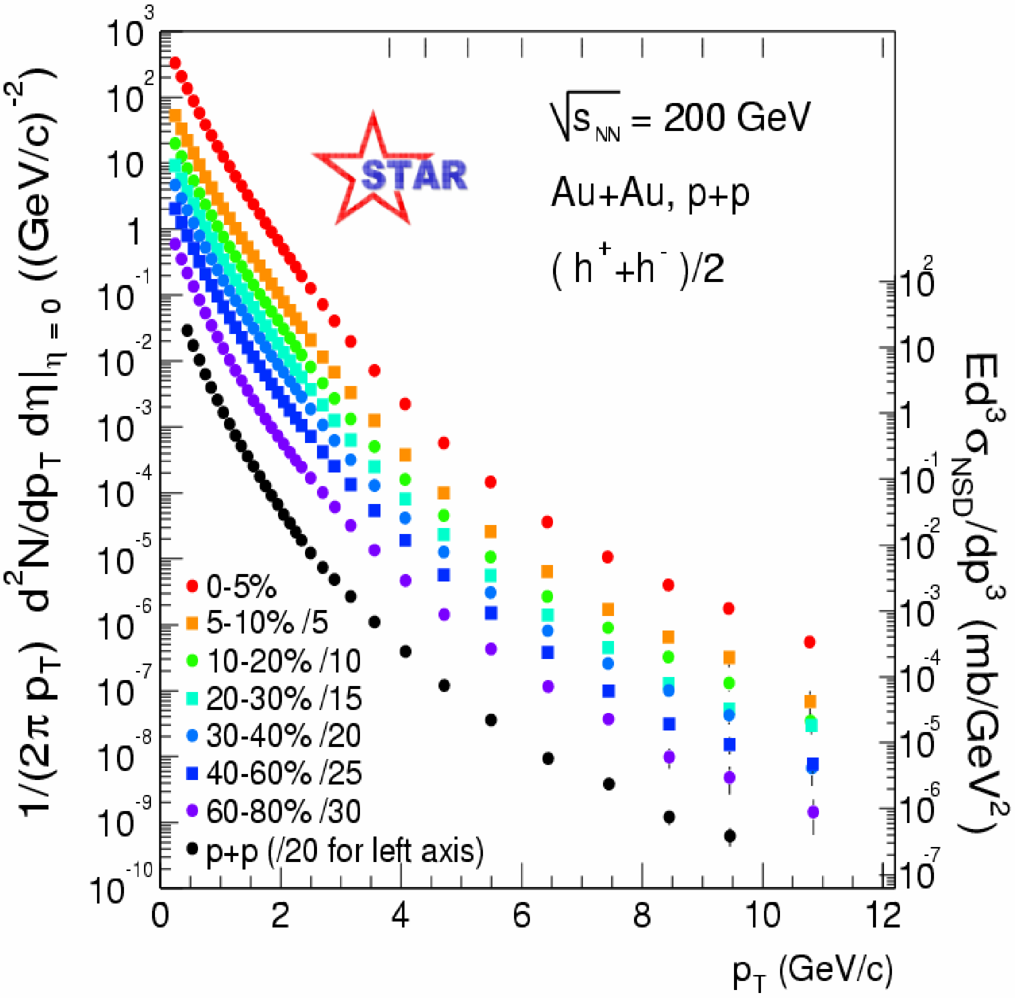
jet

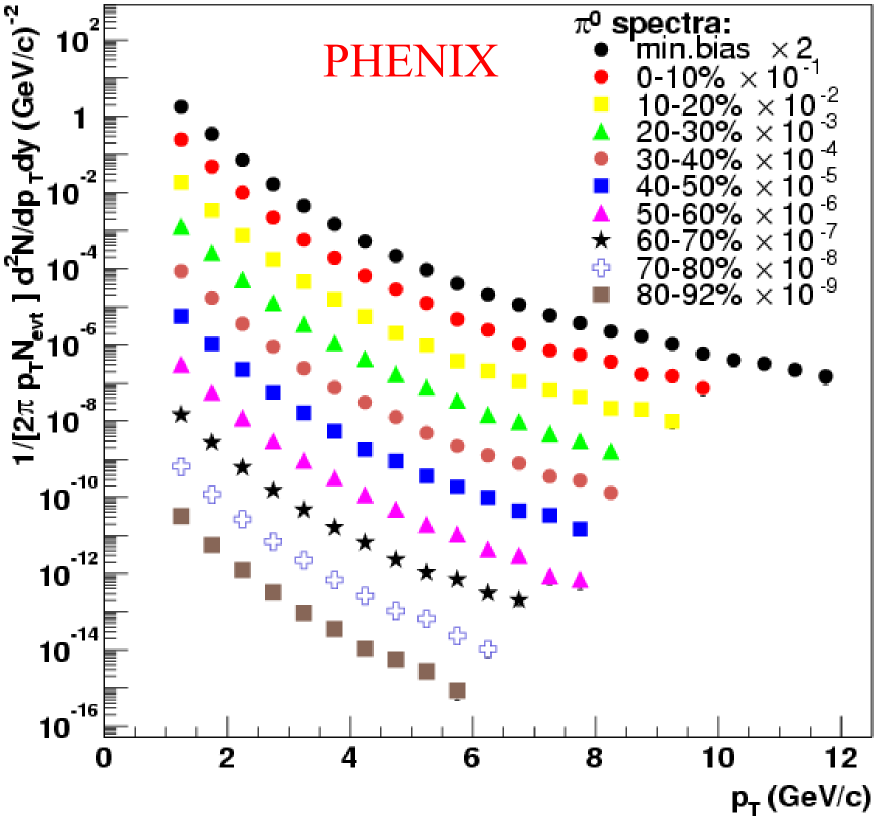
parton

nucleon

nucleon

Hadron spectra at $\sqrt{s_{NN}}$ = 200 GeV

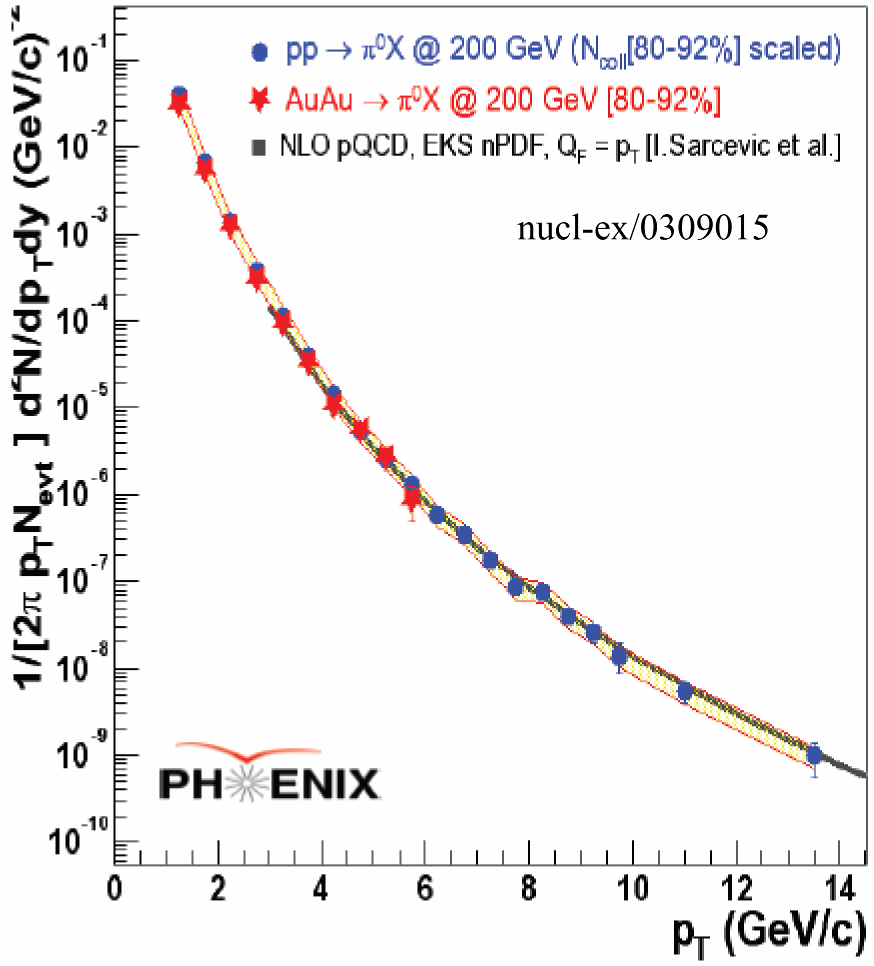




AuAu vs. pp

high-p_T production in pp provides the baseline "vacuum" reference to heavy-ion to study the QCD medium properties

$\sqrt{s_{NN}} = 200\ GeV$



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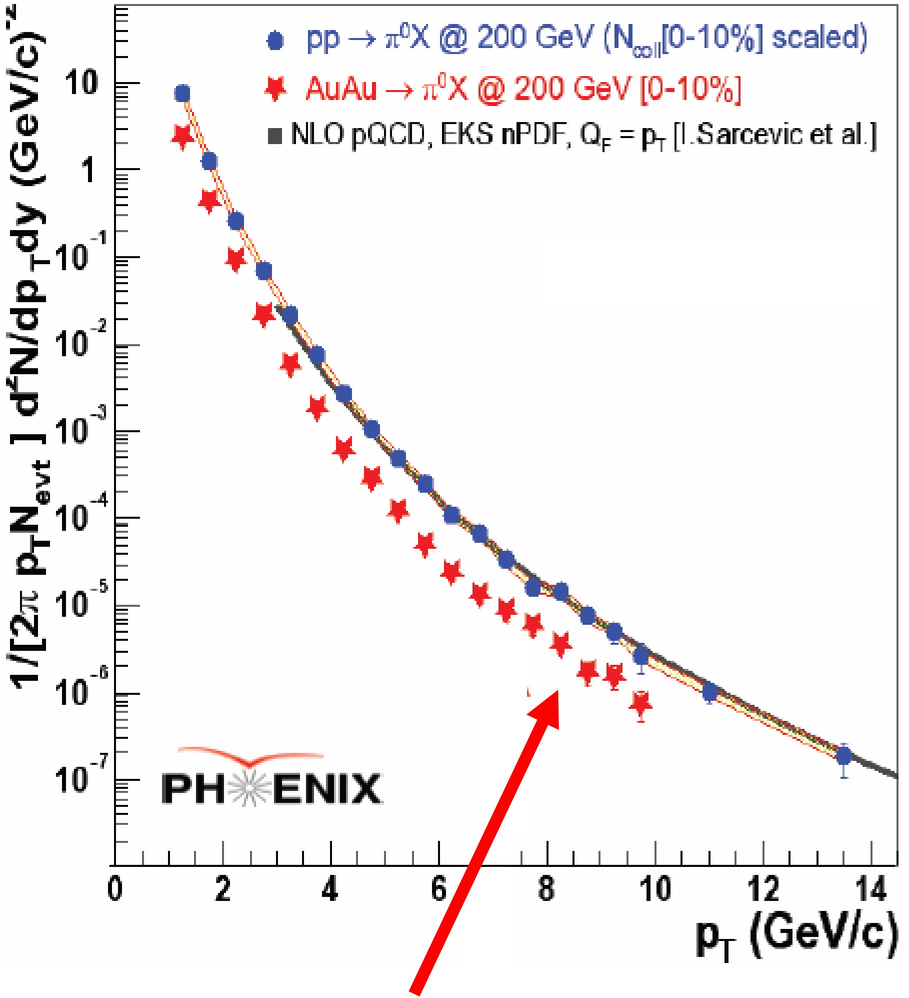


peripheral collisions agree with pp
(with the right scaling)

strong suppression in
central AuAu collisions

Nuclear modification factor R_{AB}

Are AuAu collisions just an incoherent superposition of pp ones?

We want to compare central AuAu collisions to pp collisions.

$$R_{AB} = \frac{1}{T_{AB}(b)} \frac{d^2N^{AB}/dp_T d\eta}{d^2\sigma^{pp}/dp_T d\eta}$$

It measures the deviation of the AB collision at a given centrality from a superposition of pp collision.

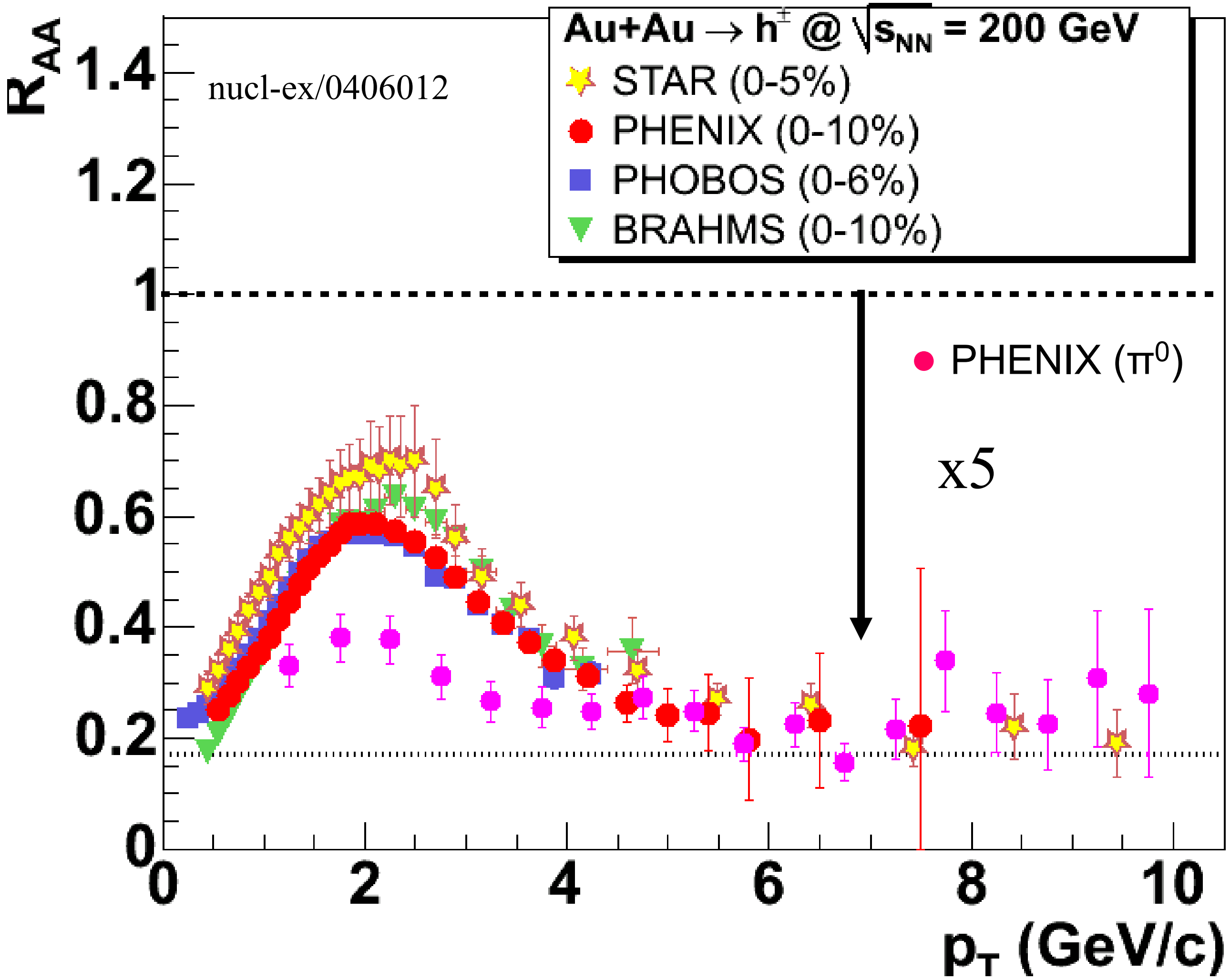
If at high p_T:

$R_{AB} = 1$ → no nuclear effects

$R_{AB} > 1$ → enhanced hadron production in AuAu

$R_{AB} < 1$ → suppressed hadron production in AuAu

R_{AA}



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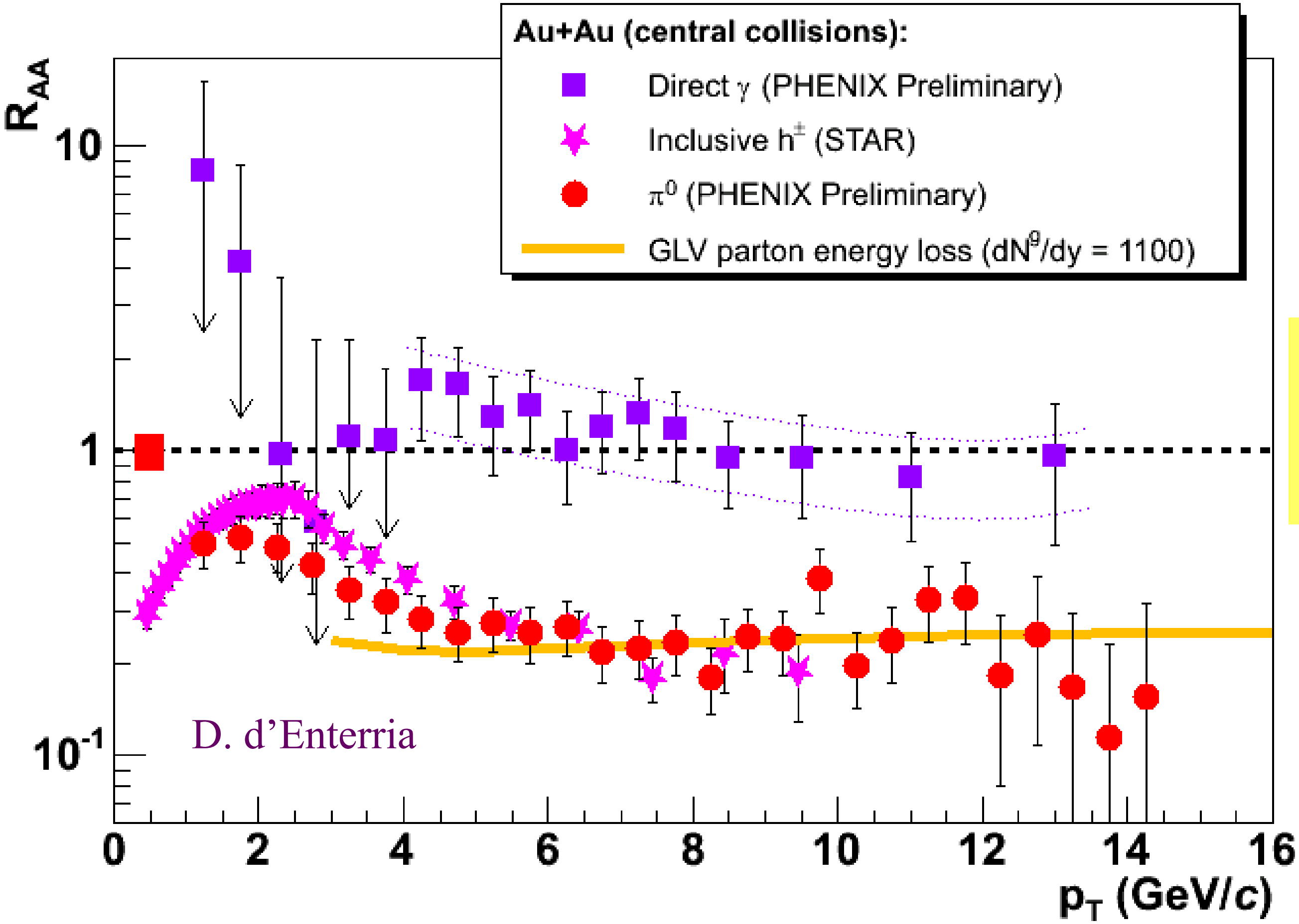
Strong high-p_T hadron suppression

But photons…



…are not suppressed

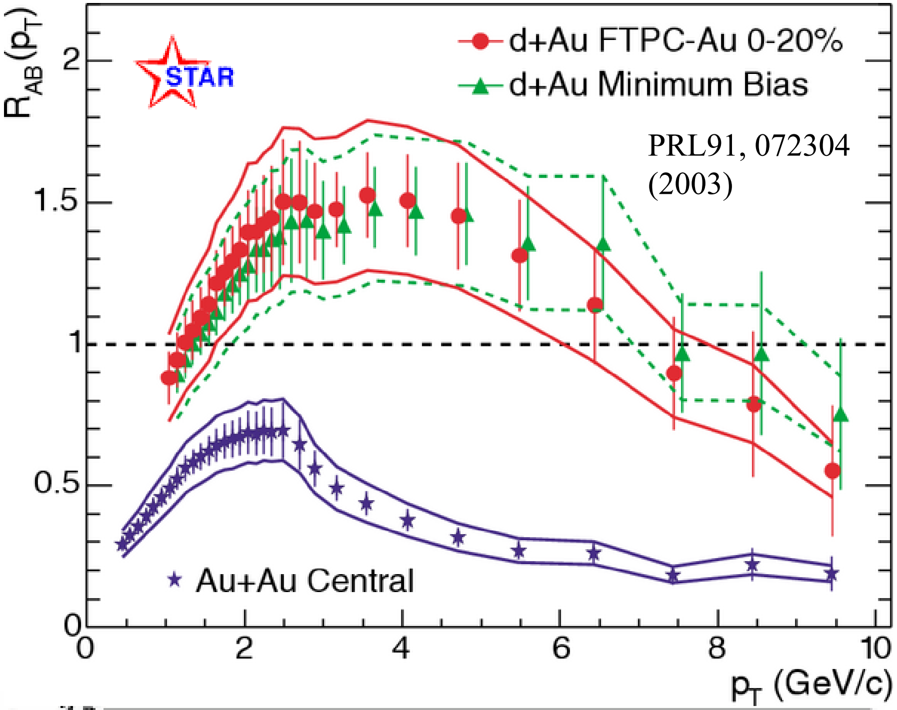
Interaction in a dense colored medium?

Why dAu?

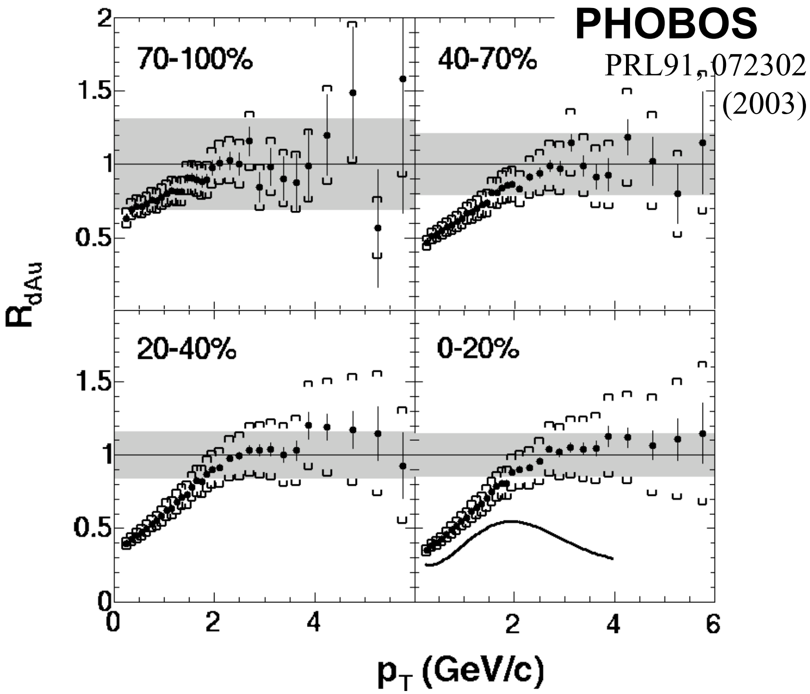
- High p_T suppression may be a result of:
  - **initial state effects** prior to hard scattering (such as saturation of gluon densities in the incoming nuclei) → **suppression would also be seen in dAu** collisions
  - **final state effects** due to interaction of partons with a dense medium → **suppression would not be observed in dAu** collisions

dAu: the control experiment

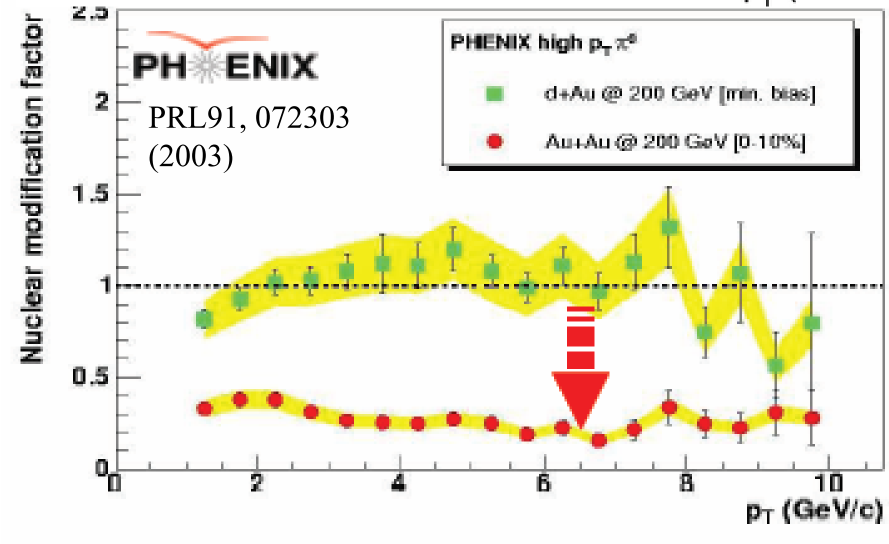
R_{AB} in dAu



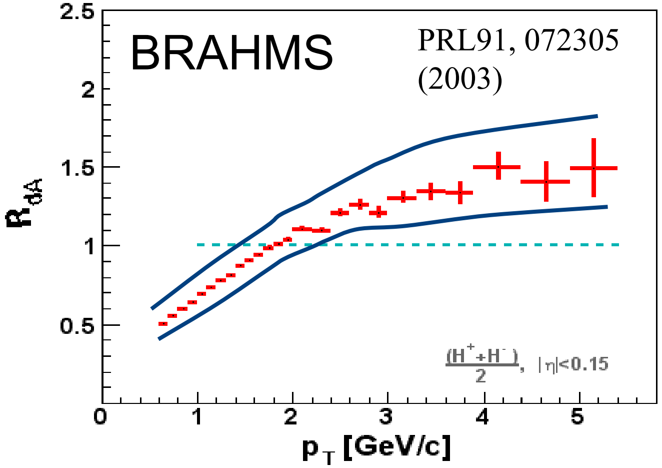
PRL91, 072304 (2003)



PRL91, 072302 (2003)



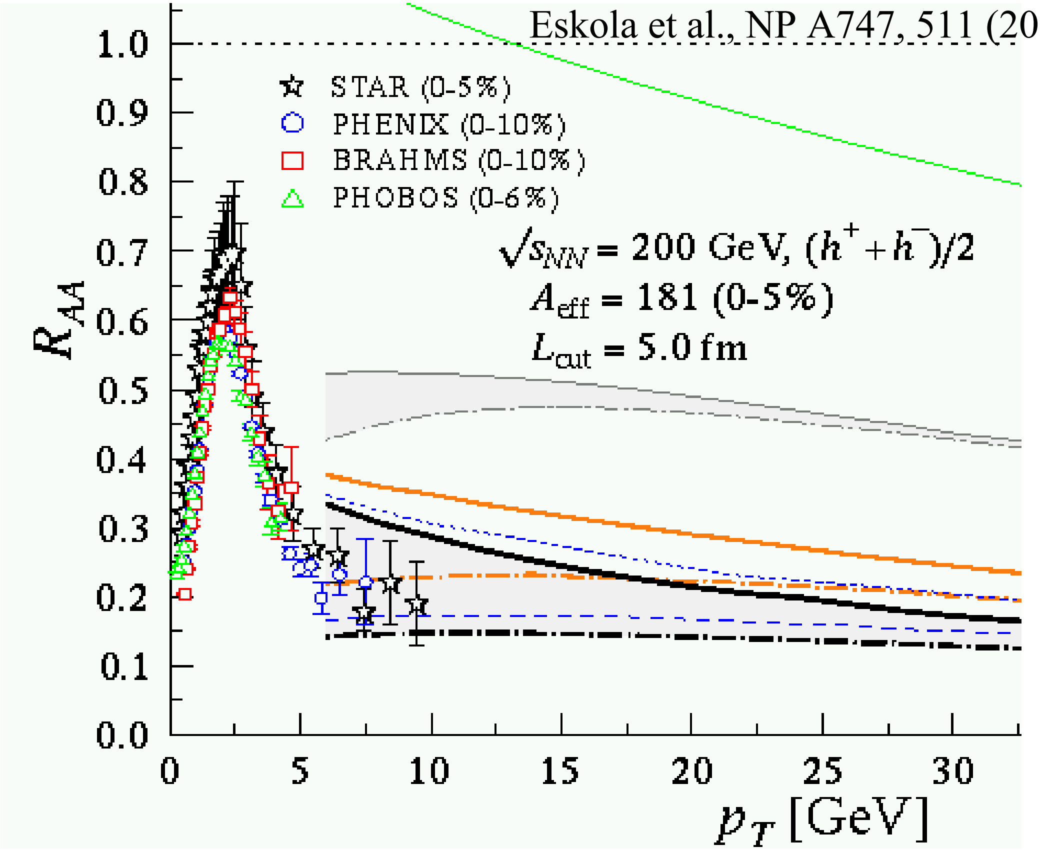
PRL91, 072303 (2003)



PRL91, 072305 (2003)

What do we learn from the suppression?

- It's a final state effect
- pQCD with energy loss calculations require initial density ~30-50 times cold nuclear matter density



Eskola et al., NP A747, 511 (2005)

$\hat{q} \propto density$

(time averaged)

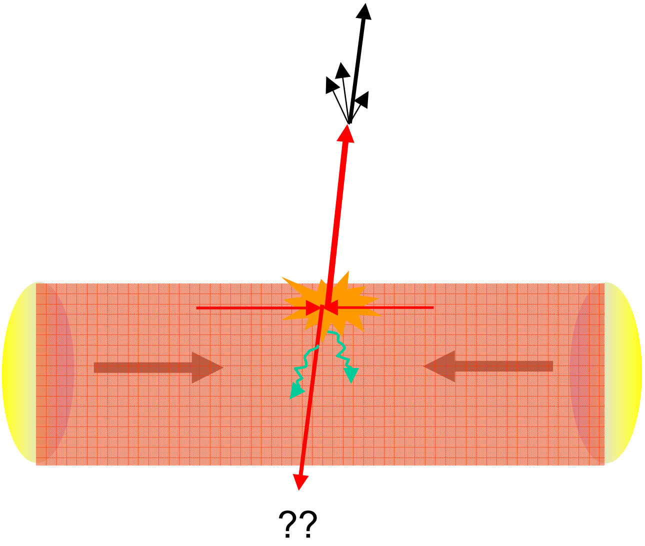
$\hat{q} = 0\, GeV^2 / fm$ (no medium)

$\hat{q} = 1\, GeV^2 / fm$

$\hat{q} = 5 - 15\, GeV^2 / fm$

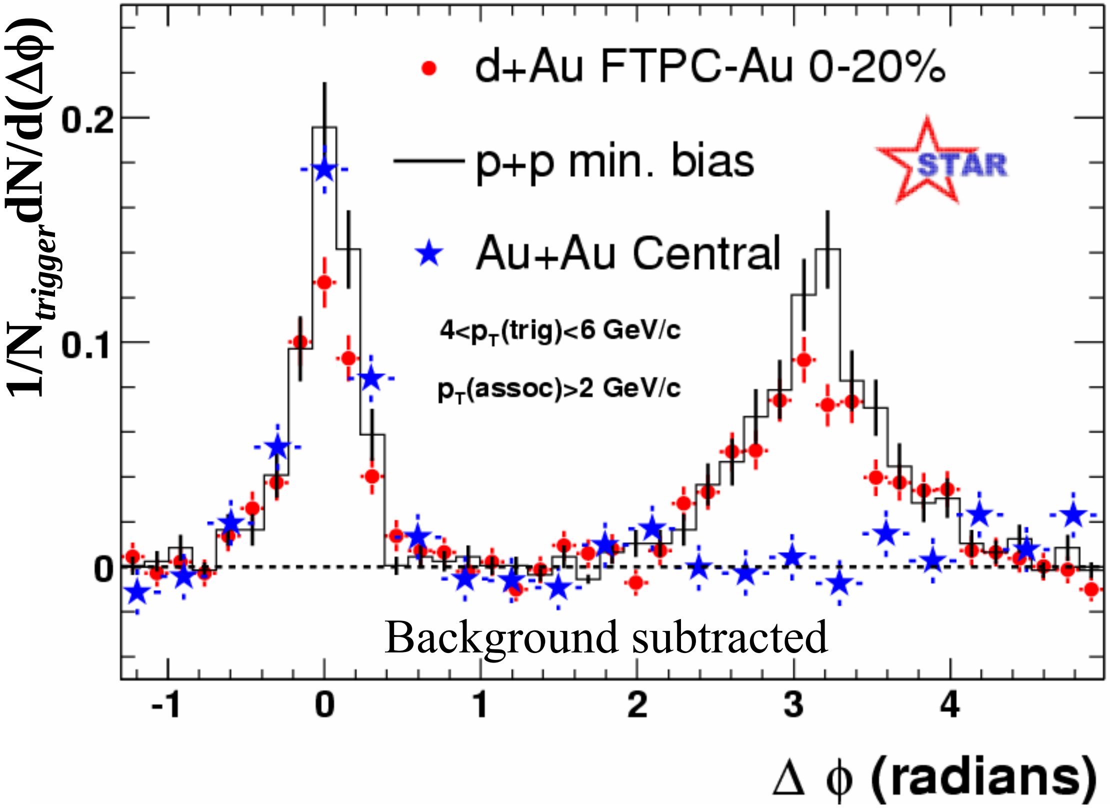
Suppression supplies a lower limit on the energy density

Back-to-back correlations



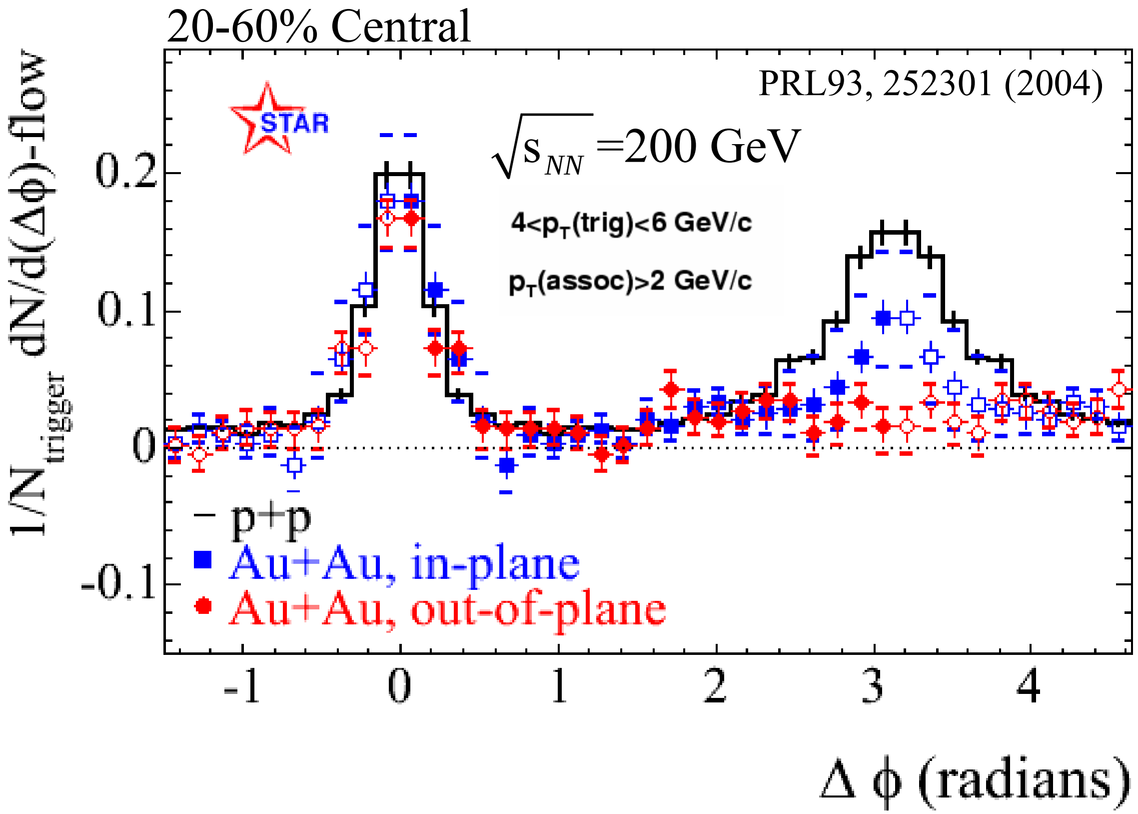
$p_T^{assoc.} < p_T^{trigger}$

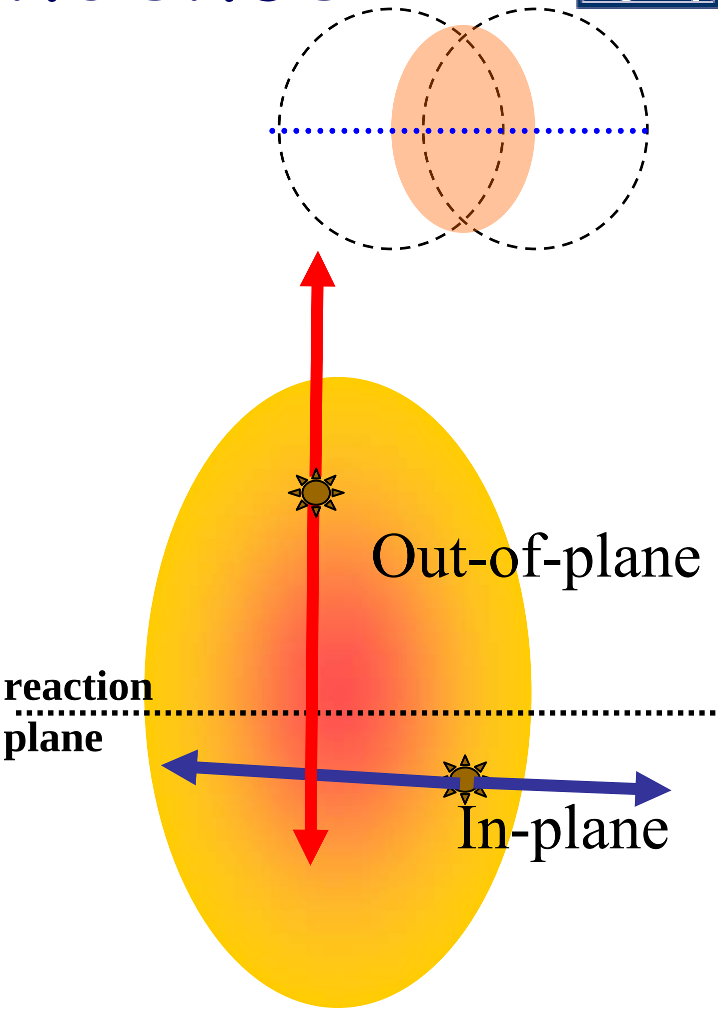
$$D(\Delta\phi) \equiv \frac{1}{N_{trigger}} \frac{dN}{d(\Delta\phi)}$$



PRL91, 072304 (2003)

Path length dependence





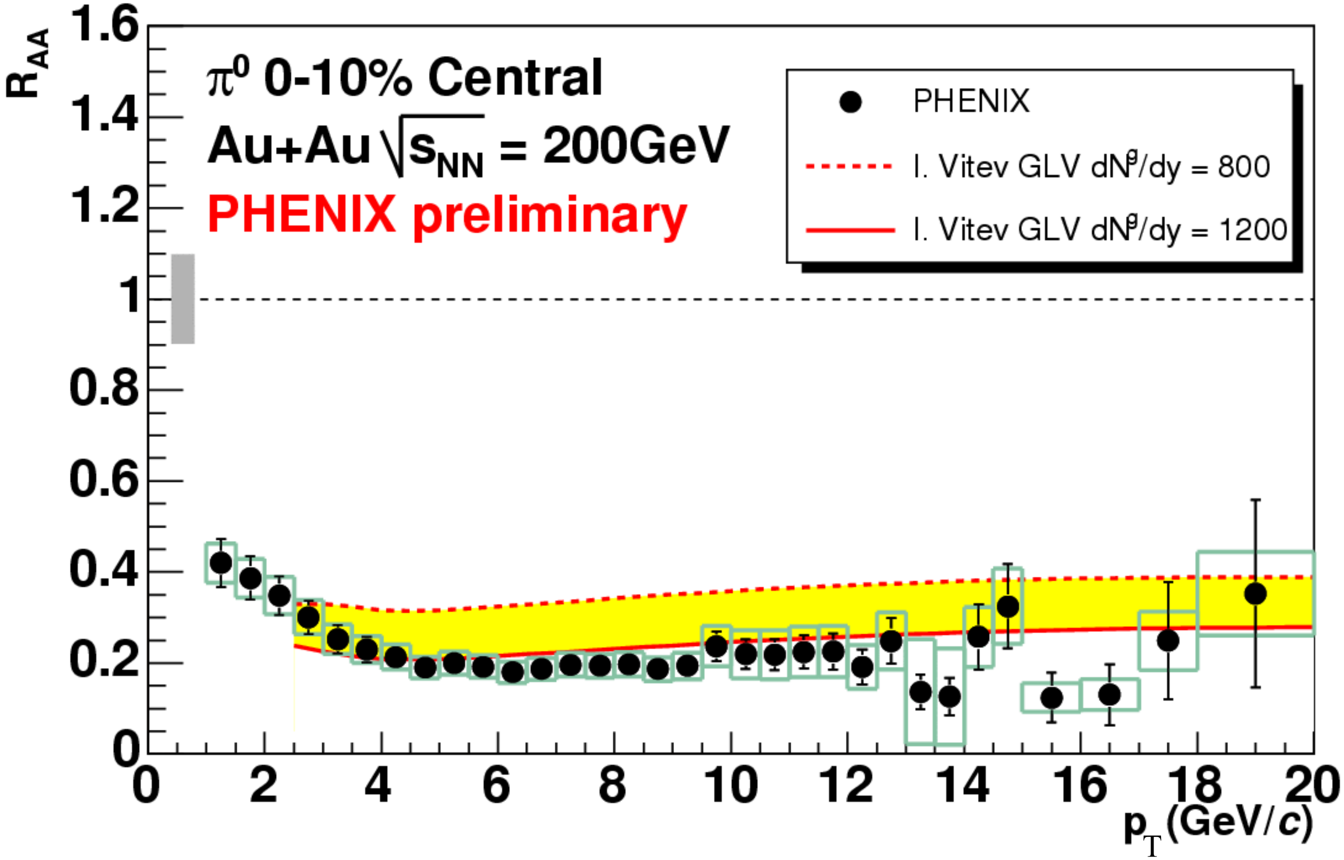
Clear indication of in-medium path length dependence of the hadron suppression

What we know until here…

- Modification of jet fragmentation from interaction of high energy partons with a dense (colored) medium prior to hadronization
  - high-p_T hadron suppression (factor of 5)
    - prompt photons are not suppressed
  - high-p_T recoiling jet suppressed
    - in-medium path length dependence

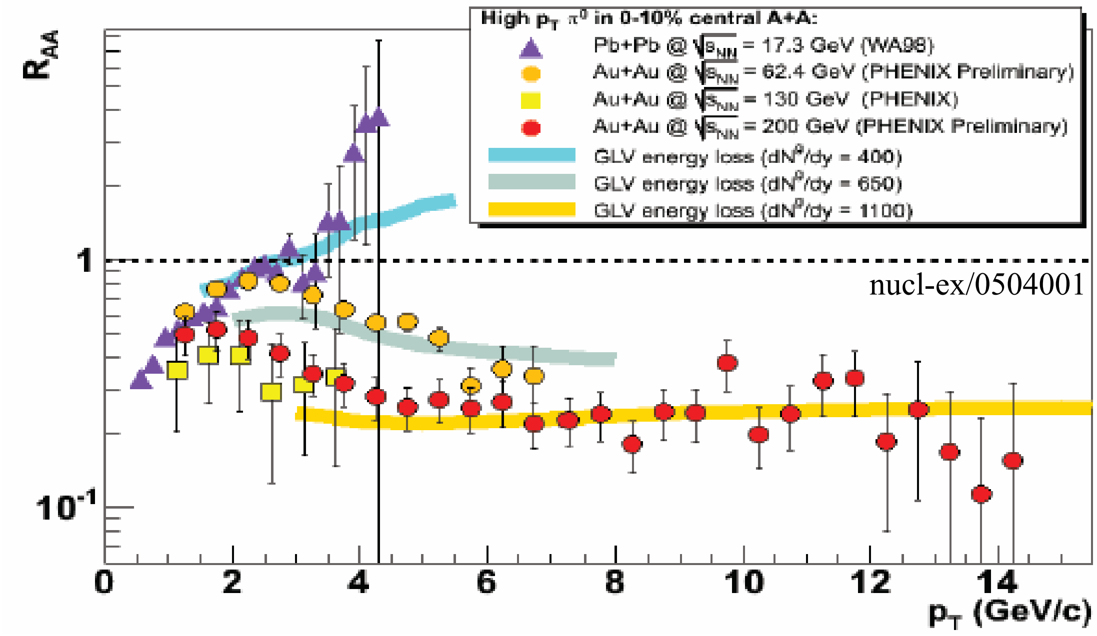
- pQCD -based calculations with medium-induced energy loss
  → density of the medium is high
  (30-50 times the one of cold nuclear matter)

R_{AA} independence of p_T



up to 20 GeV/c!

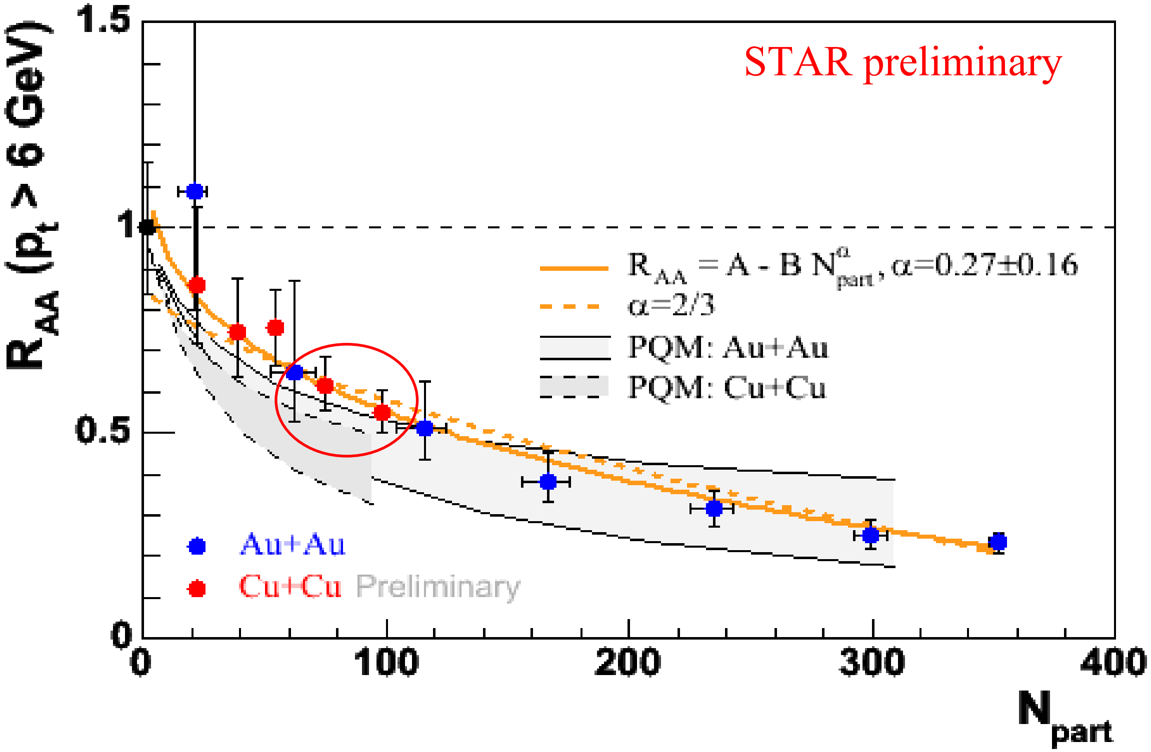
Energy dependence - R_{AA}



- Suppression observed for central AuAu at $\sqrt{s_{NN}}$ = 62.4 GeV
- Increasing suppression with $\sqrt{s_{NN}}$ consistent with increasing initial parton densities and longer duration of the dense medium

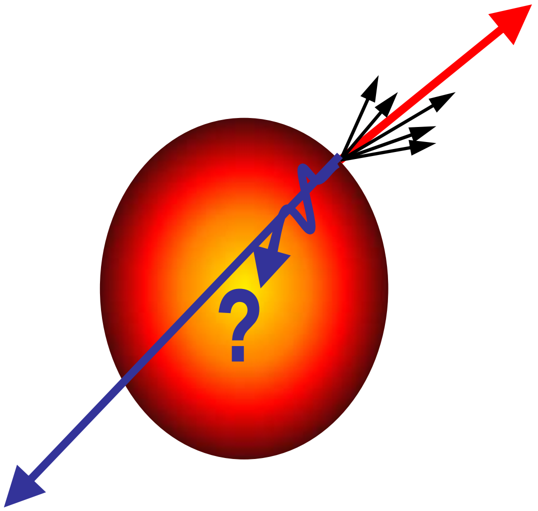
R_{AA} scales with N_{part}

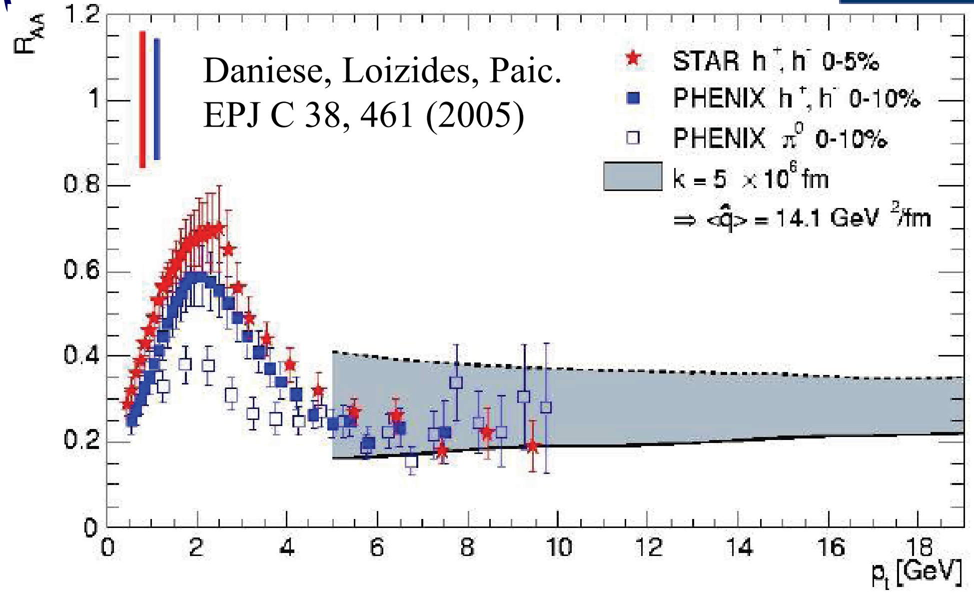
Suppression observed for central CuCu - “Testing” the L-dependence of ΔE

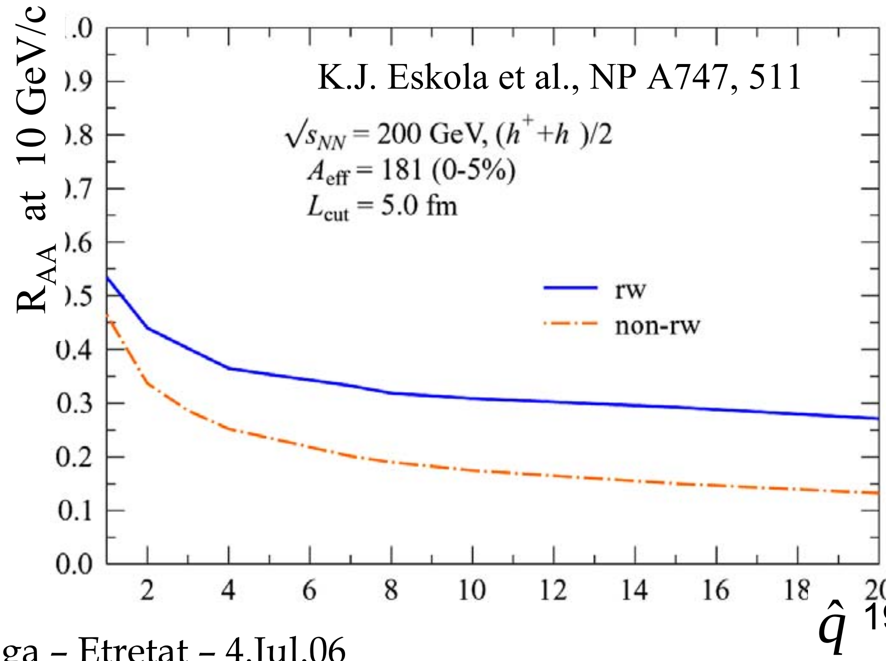


- CuCu adds significant precision at N_{part}~100
- Fit to N^{α}_{part} prefers α~1/3 (α~2/3 not completely excluded)

Limitations of R_{AA}




Daniese, Loizides, Paic.
EPJ C 38, 461 (2005)


K.J. Eskola et al., NP A747, 511

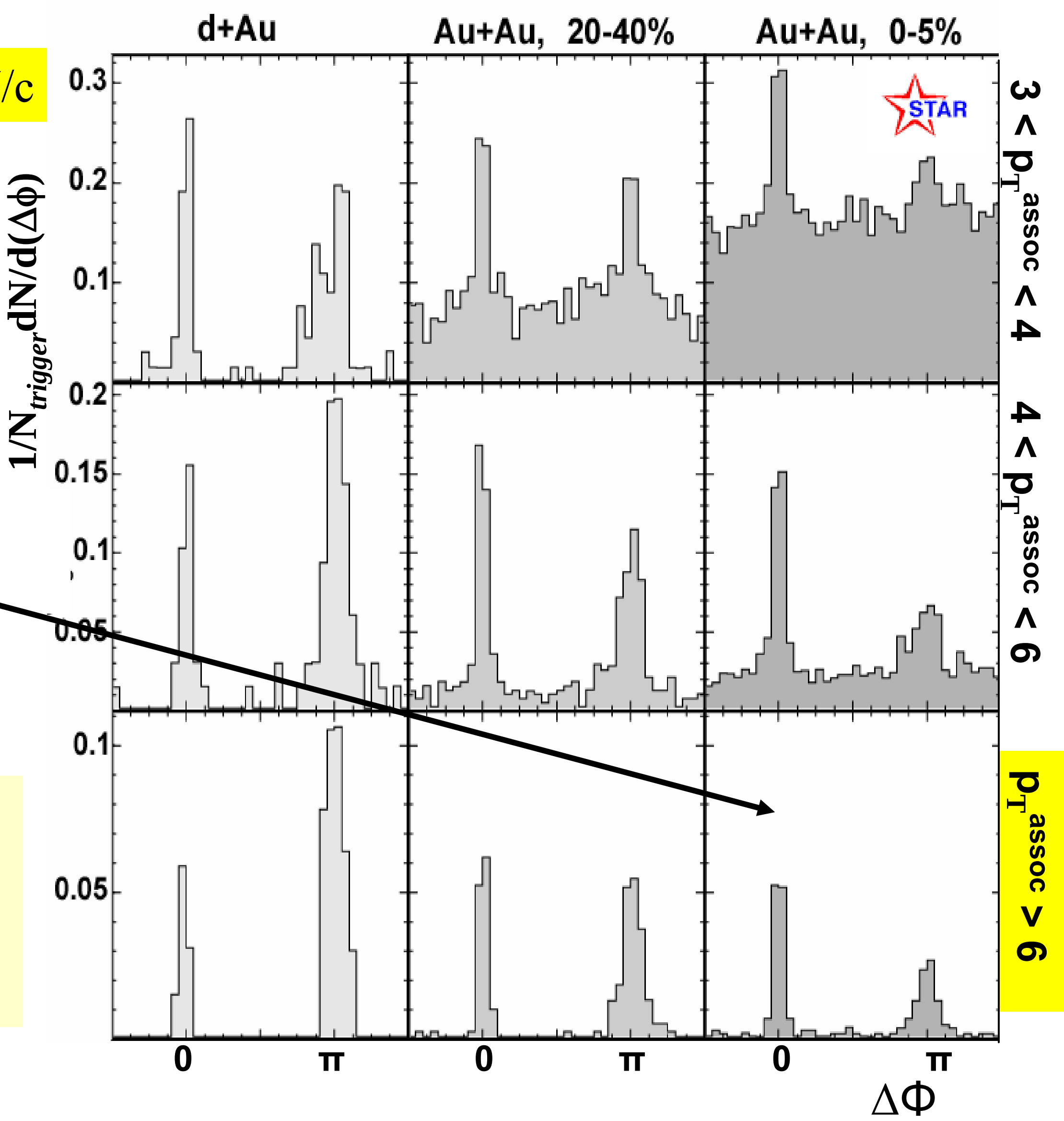
- Surface emission: leading hadrons preferentially arise from the surface
- $\hat{q} > 5$ GeV^2/fm: limited sensitivity to the region of highest energy density
- Need more penetrating probes

Azimuthal correlations at higher p_T

$8 < p_T^{trigger} < 15$ GeV/c

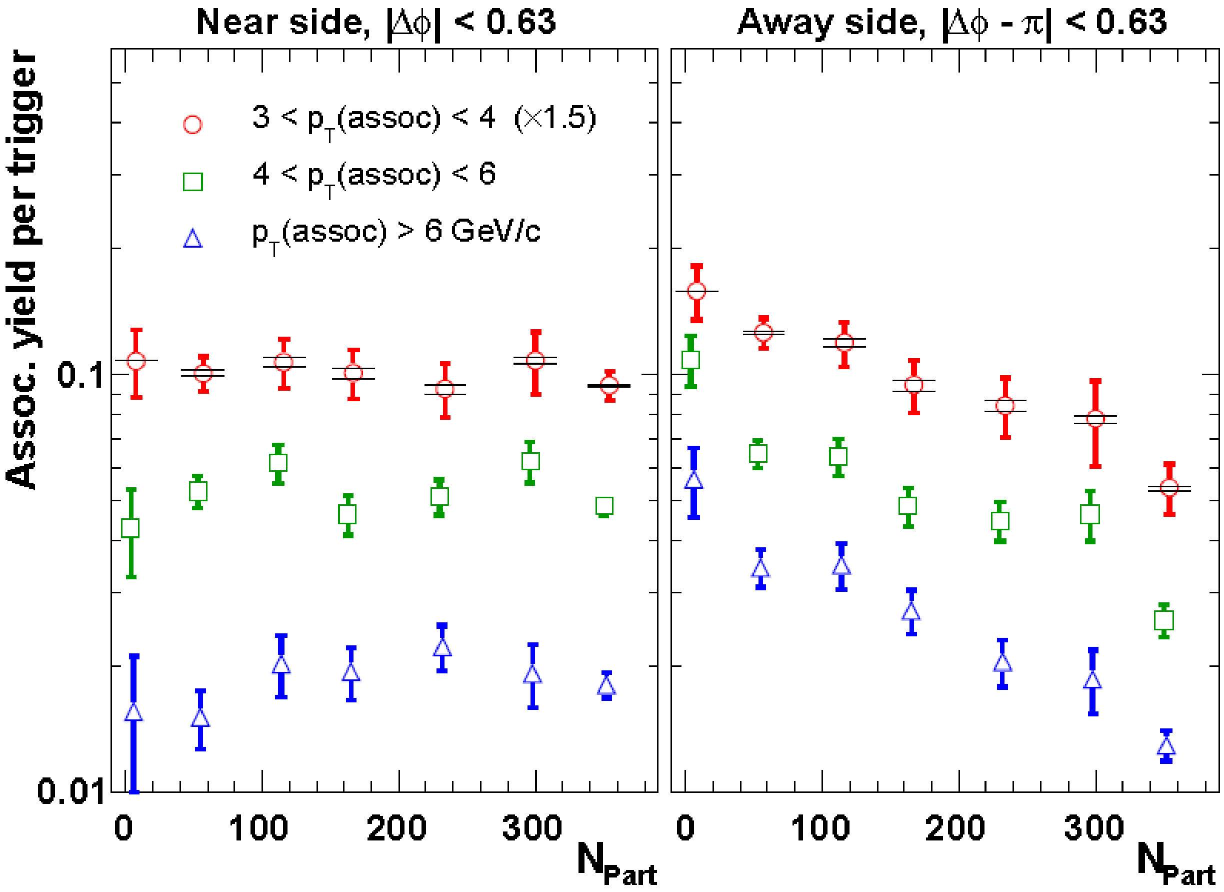
- Higher associated p_T
- Beyond "intermediate p_T" and into fragmentation region
- Combinatorial background is negligible

- Clear, unambiguous recoil peak: dijets in central collisions
- Away-side yield is suppressed but finite and measurable



nucl-ex/0604018

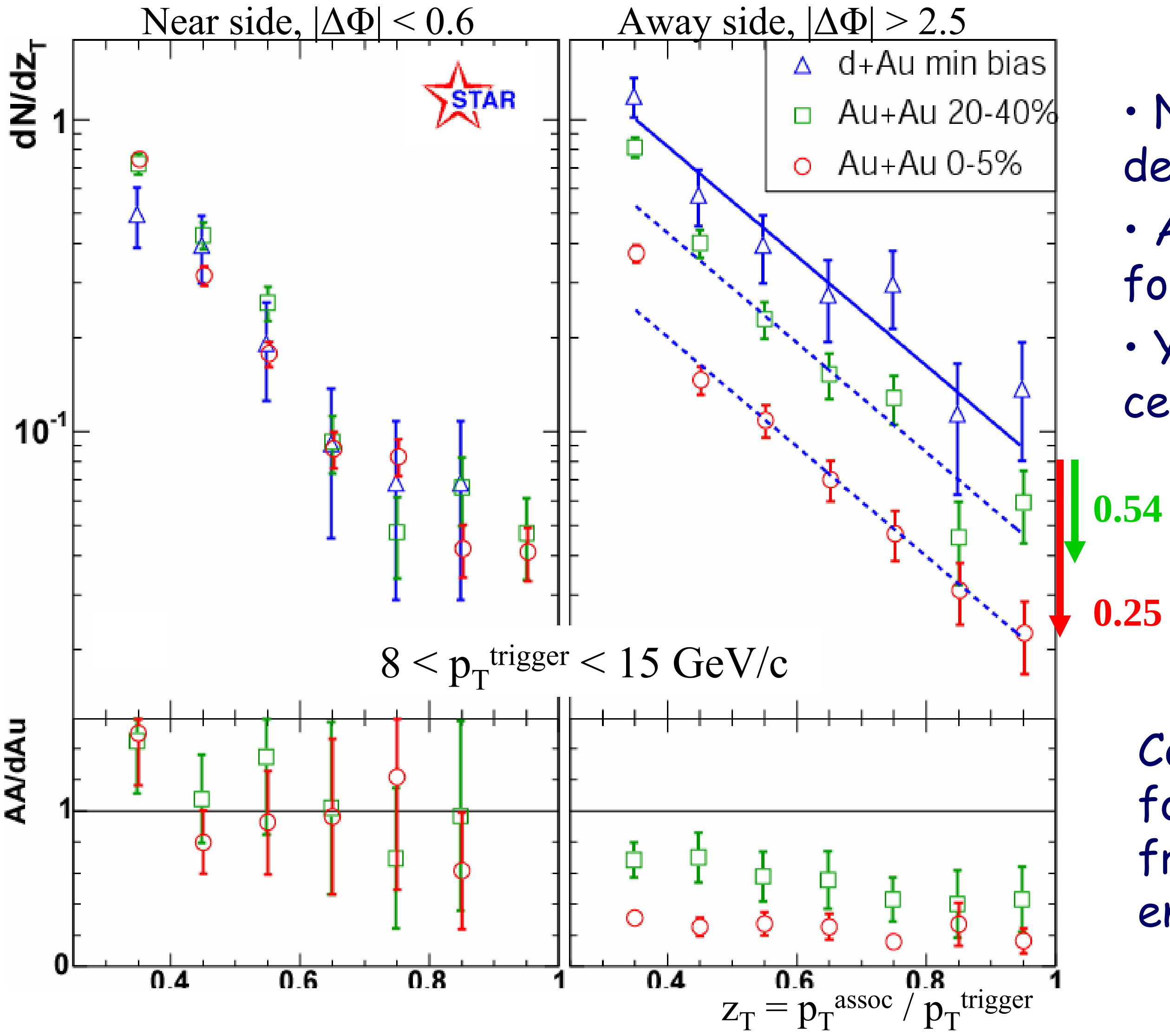
Jet yields at higher p_T



nucl-ex/0604018

- Near side: no significant suppression – little centrality dependence
- Away-side: suppressed - suppression pattern independent of p_T^{assoc}

Fragmentation function z_T



- Near-side: no system size dependence
- Away-side: similar shapes for the three systems
- Yield strongly suppressed in central AuAu (to level of R_{AA})

Consistent with calculations for medium-modified fragmentation due to energy loss

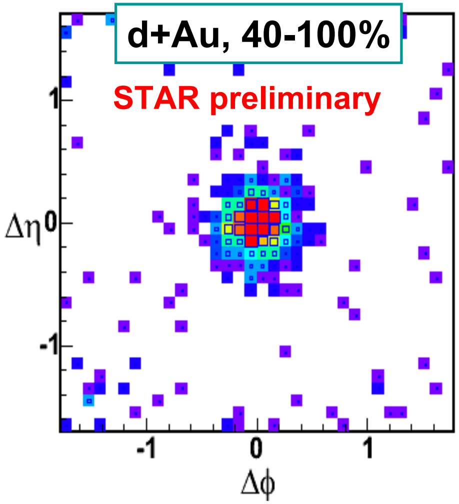
PLB 595, 165 (2004)

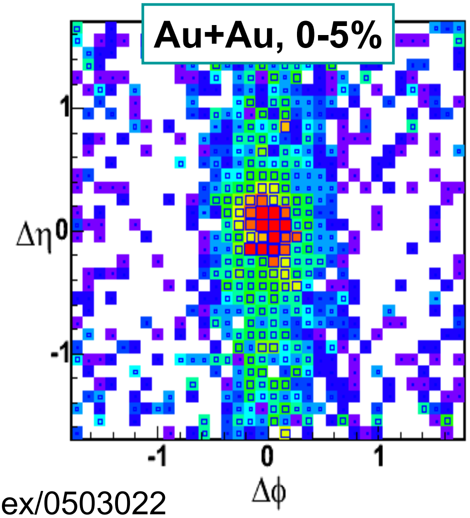
nucl-ex/0604018

$\Delta\eta$-$\Delta\phi$ near-side correlations

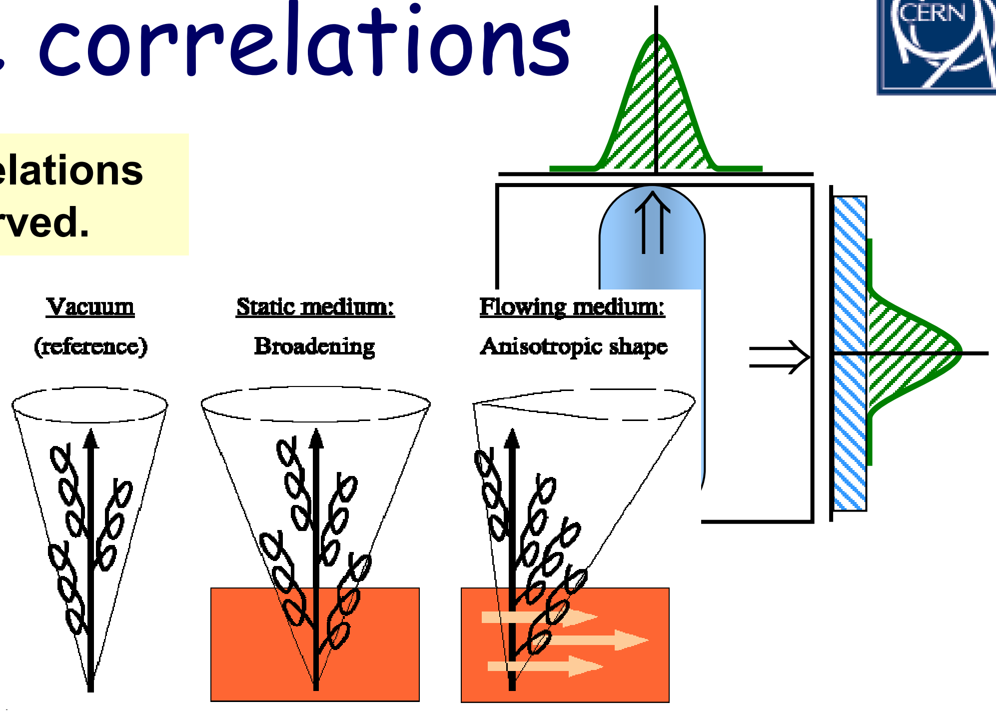
Additional near-side long range correlations in $\Delta\eta$ ("ridge like" correlations) observed.

$3 < p_{T,trig} < 6$ GeV
$2 < p_{T,assoc} < p_{T,}$





nucl-ex/0503022



Armesto et al, nucl-ex/0405301

a) Parton radiates energy before fragmenting and couples to the longitidunal flow (Armesto et al, nucl-ex/0405301)

b) Parton recombination (Chiu & Hwa Phys. Rev. C72:034903,2005)

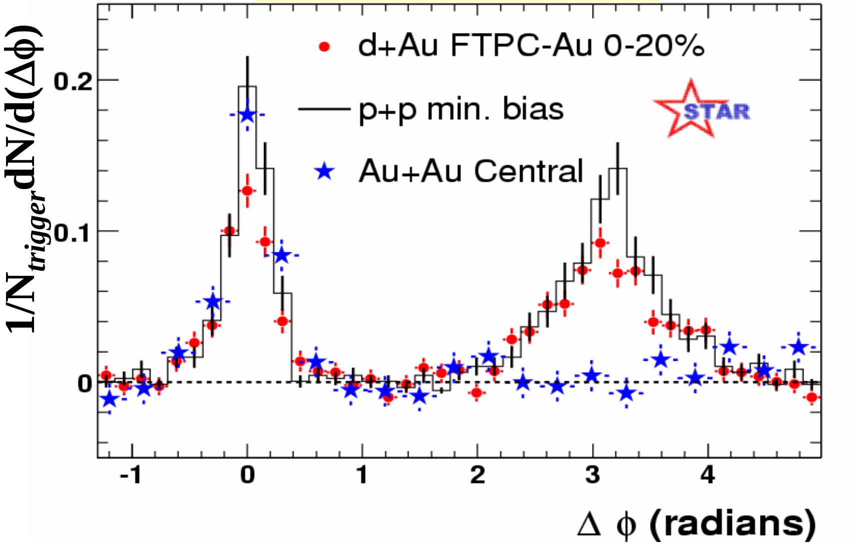
c) Radial flow + jet-queching (Voloshin nucl-th/0312065)

We might be seeing a direct effect of the jet coupling to the expanding medium, i.e. the effect of medium-induced energy loss on the jet

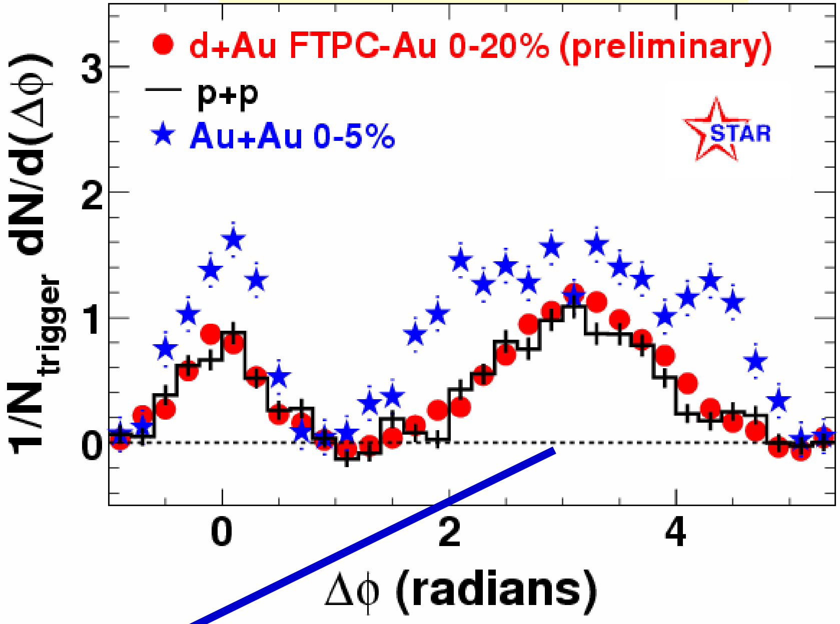
Lowering $p_T^{assoc.}$

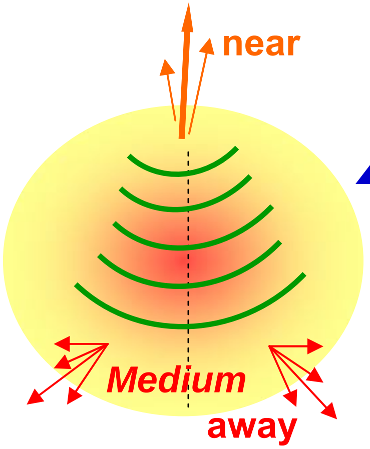
$4.0 < p_T^{trigger} < 6.0$ GeV/c

$2 < p_T^{assoc} < p_T^{trigger}$



$0.15 < p_T^{assoc} < 4.0$ GeV/c



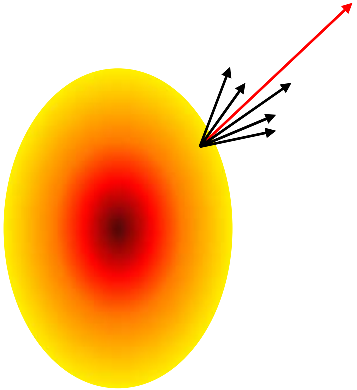


Mach cone?

hep-ph/0511263

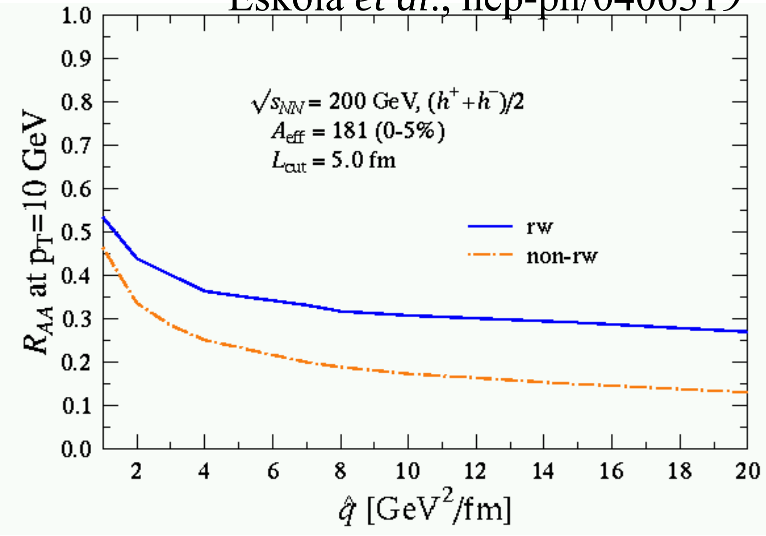
Full jet reconstruction at LHC

Leading Particle



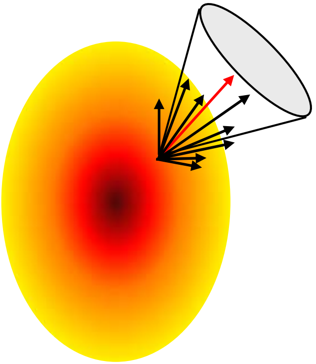
Leading particle becomes fragile as a probe

- Surface emission:
  - Small sensitivity of R_{AA} to medium properties.
- For increasing in medium path length L, the momentum of the leading particle is less and less correlated with the original parton 4-momentum.



Eskola *et al.*, hep-ph/0406319

Reconstructed Jet



Ideally, the analysis of reconstructed jets will allow us to measure the original parton 4-momentum and the jet structure.

→ Study the properties of the medium through modifications of the jet structure:

- Decrease of particles with high z, increase of particles with low z
- Broadening of the momentum distribution perpendicular to jet axis

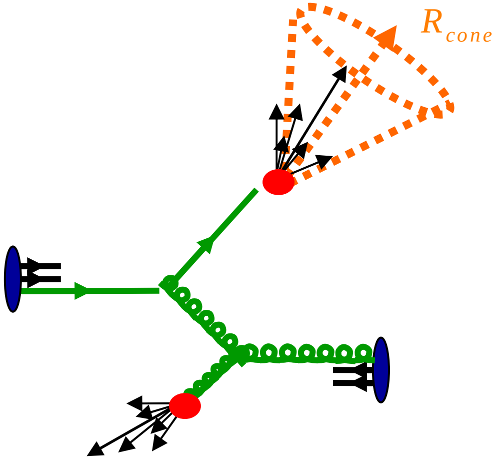
$$z = \frac{p_T}{E_T^{jet}}$$

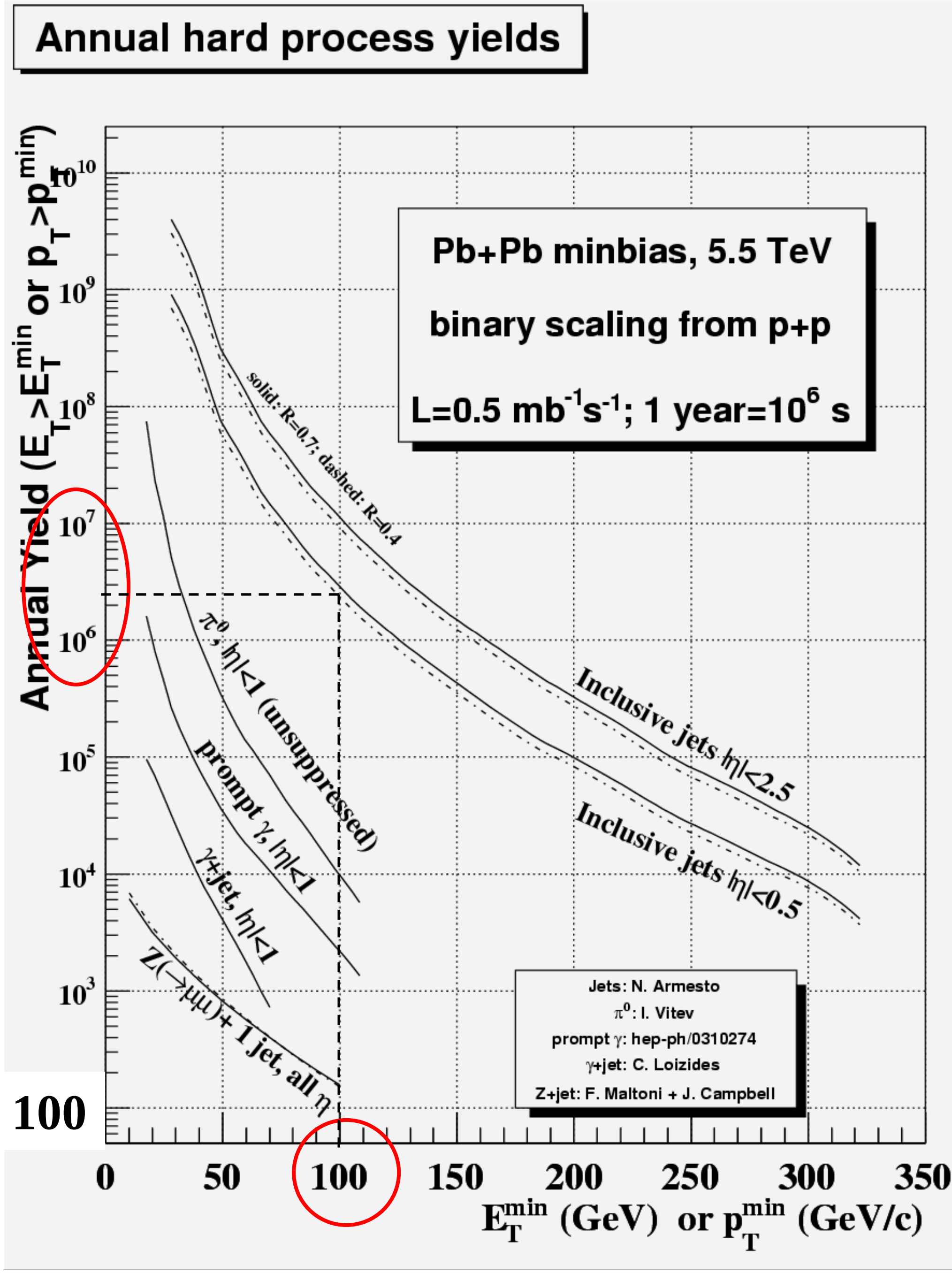
Jet rates at the LHC

Huge jet statistics from
E_T ~10 GeV to E_T~100 GeV

- Jets with E_T > 50 GeV will allow full reconstruction of hadronic jets, even in the underlying heavy-ion environment.

- Multijet production per event extents to ~ 20 GeV





Summary

- Evidence for partonic energy loss in nuclear collisions has been seen at RHIC.
  - Suppression of high-p_T hadrons in AuAu and CuCu (not in pp or dAu)
  - Suppression of leading recoiling hadron in back-to-back correlations
- Measurements are consistent with pQCD-based energy loss calculations and provide a lower bound to the initial density.
- R_{AA} scales with N_{part} (AuAu and CuCu)
- $R_{AA}(p_T)$: p_T-independent up to 20 GeV/c
  as expected by radiative energy loss models
- Reappearance of away-side jet at high p_T
- Interesting Physics ahead
  - Full reconstruction of high energy jets at LHC

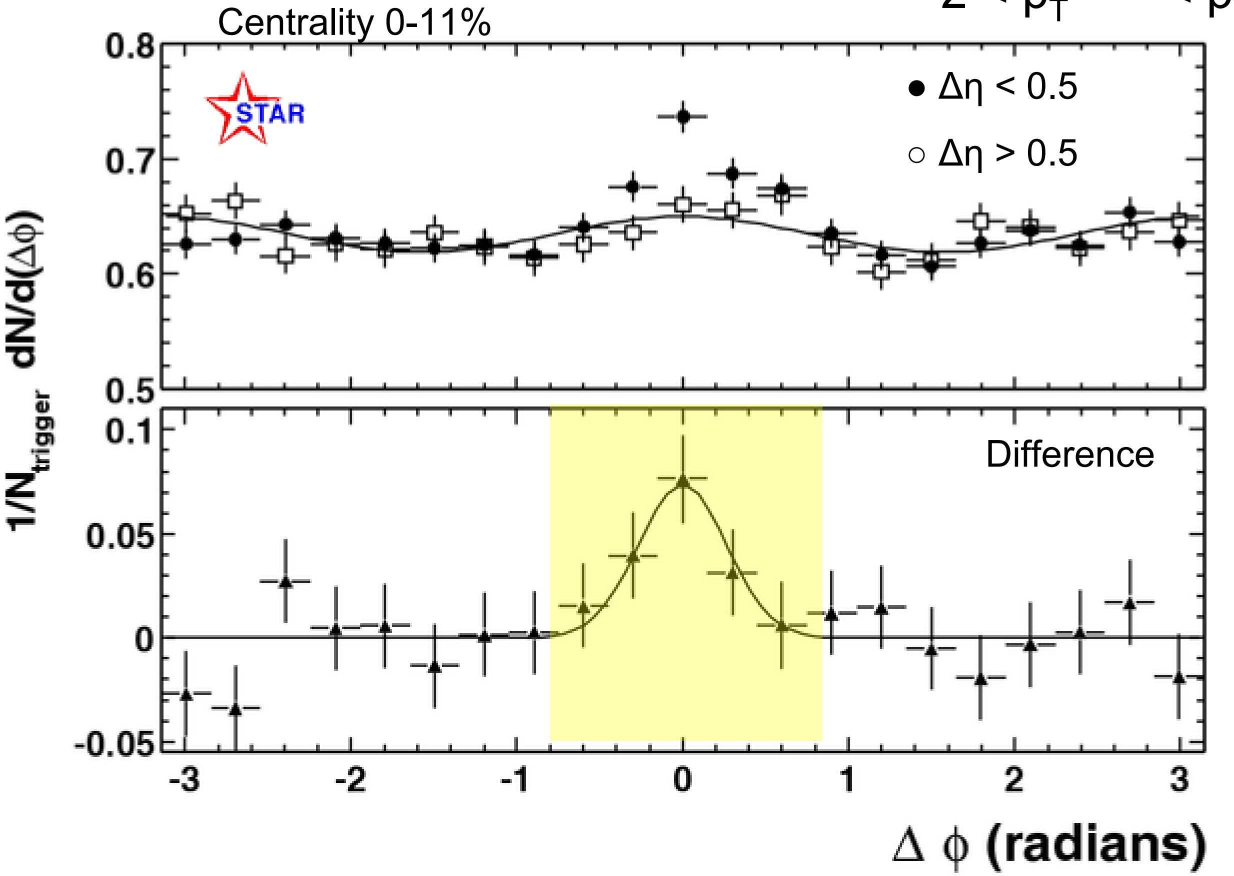
BACKUP SLIDES

First indications of jets…

$\sqrt{s_{NN}} = 130\,GeV$

$4 < p_T^{trigger} < 6$ GeV/c

$2 < p_T^{assoc} < p_T^{trigger}$

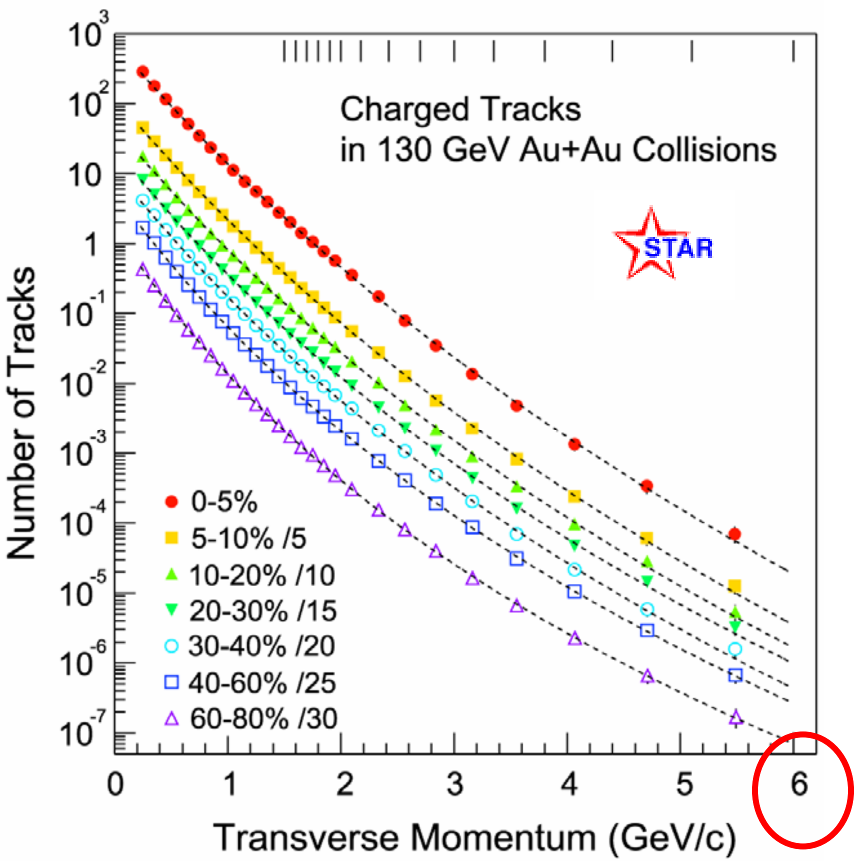


$$\frac{1}{N_{trigger}}\frac{dN}{d(\Delta\phi)} = \frac{1}{N_{trigger}}\frac{1}{\varepsilon}\int d\Delta\eta\, N(\Delta\phi,\Delta\eta)$$

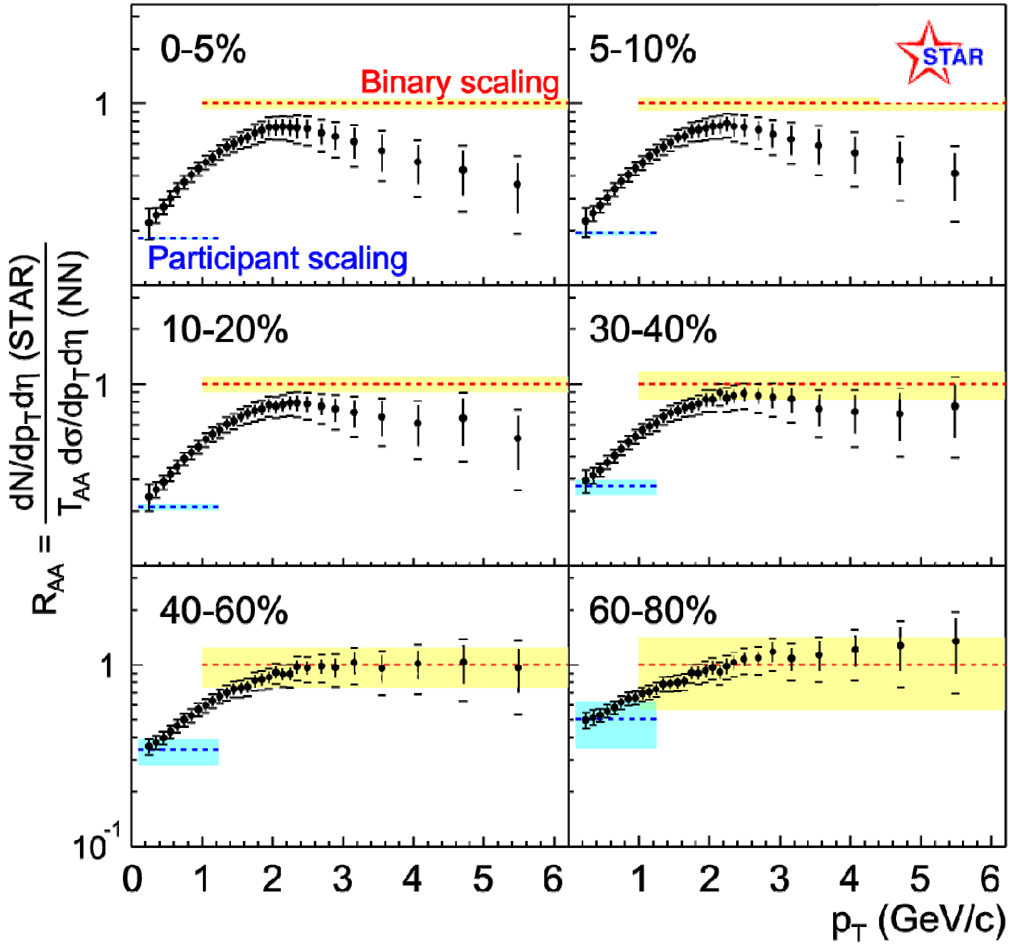
PRL 90, 032301 (2003)

…and of hadron suppression

$\sqrt{s_{NN}} = 130\ GeV$



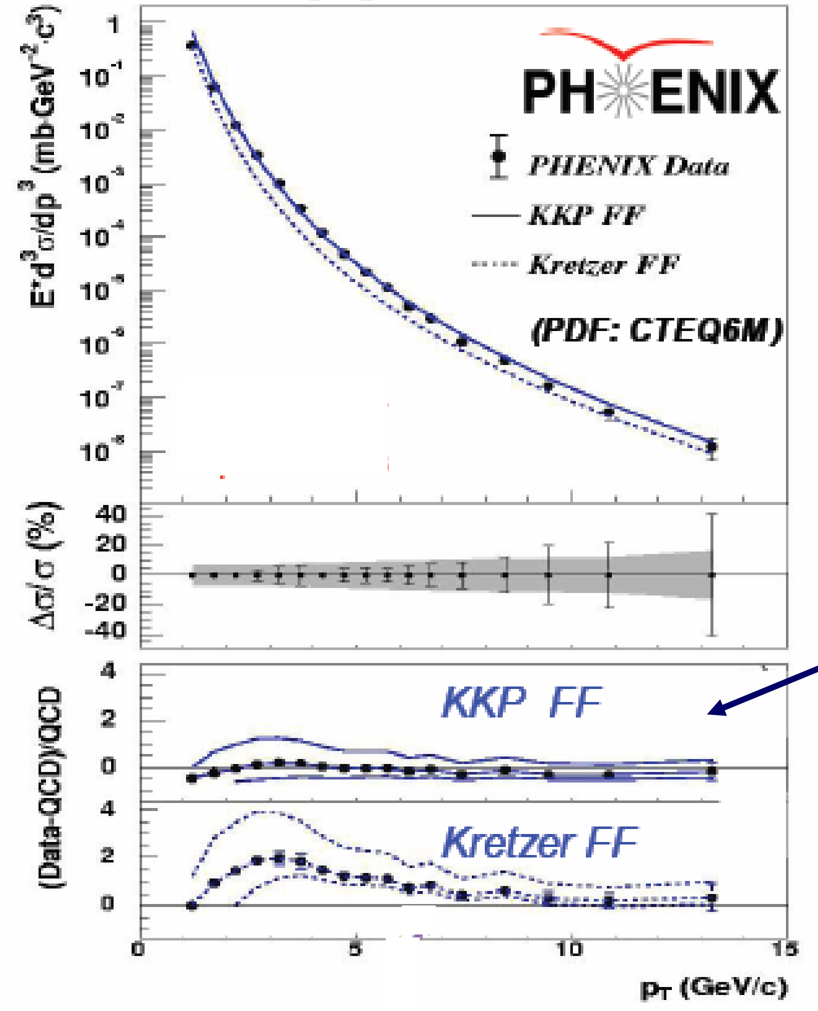
PRL 89, 202301 (2002)



(Reference: Scaled pp from UA1)

pp - baseline

$p+p \rightarrow \pi^0 X$



PRL91, 241803 (2003)

high-p_T production in pp provides the baseline "vacuum" reference to heavy-ion to study the QCD medium properties

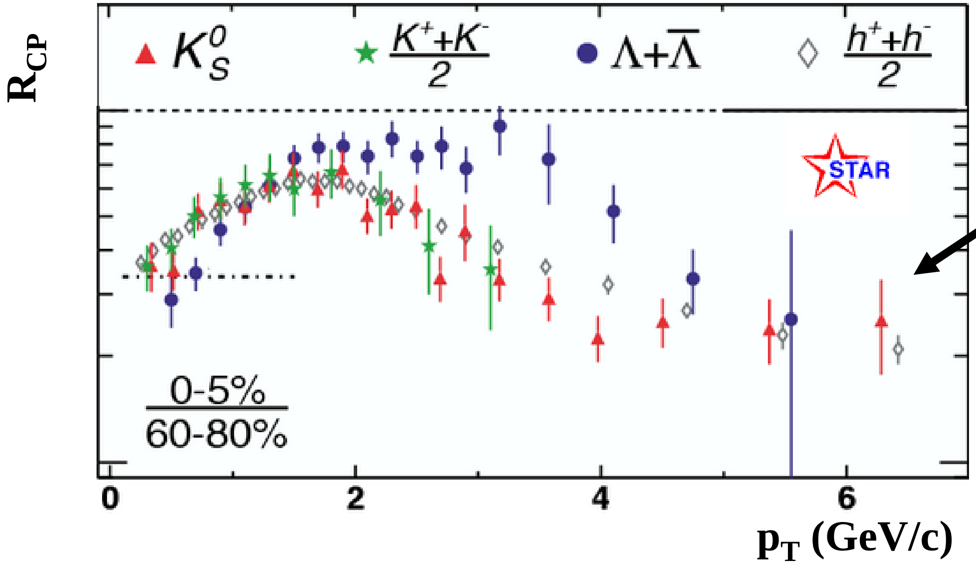
- pp results agree with NLO pQCD theoretical calculations for p_T >~ 5 GeV/c
- reference spectrum is well understood

"Higher" p_T, why?

- Intermediate p_T region ($2 < p_T < 5$ GeV/c)
  - mesons are more suppressed than baryons
  - elliptic flow v_2 larger for baryons than for mesons
  - this baryon/meson distinction does not depend on the mass

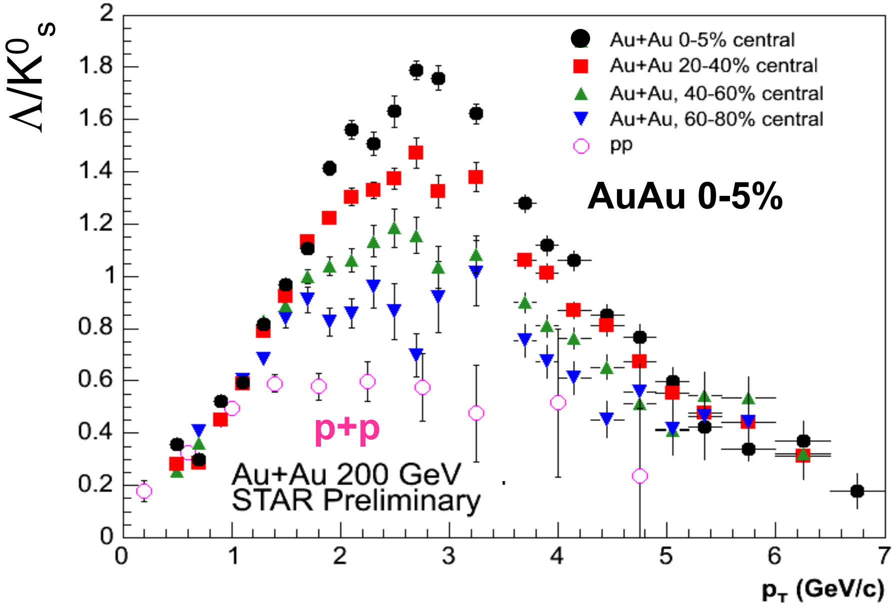
hadronization via coalescence or recombination of constituents quarks

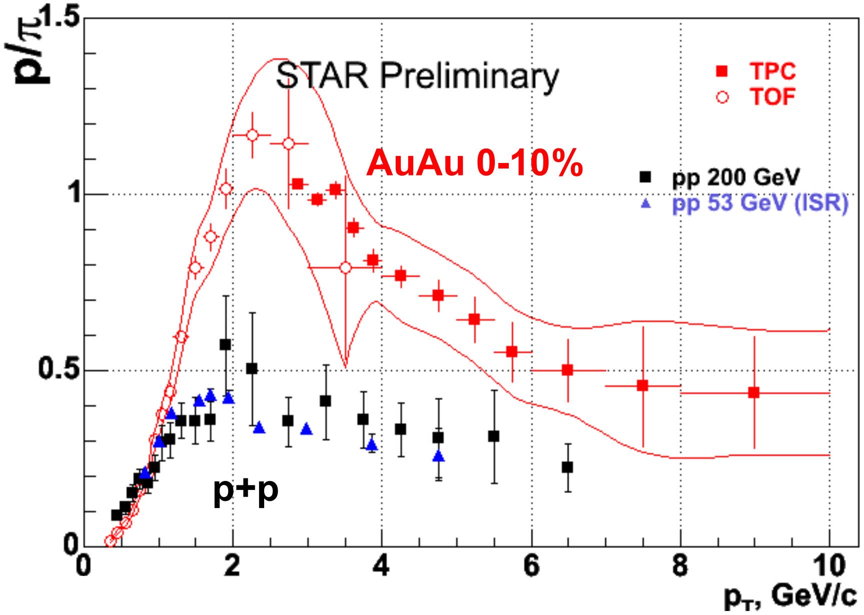
PRL 92, 052302 (2004)



Indications that the dependences on hadron species disappeared for $p_T > 5$ GeV/c?

Hadron production

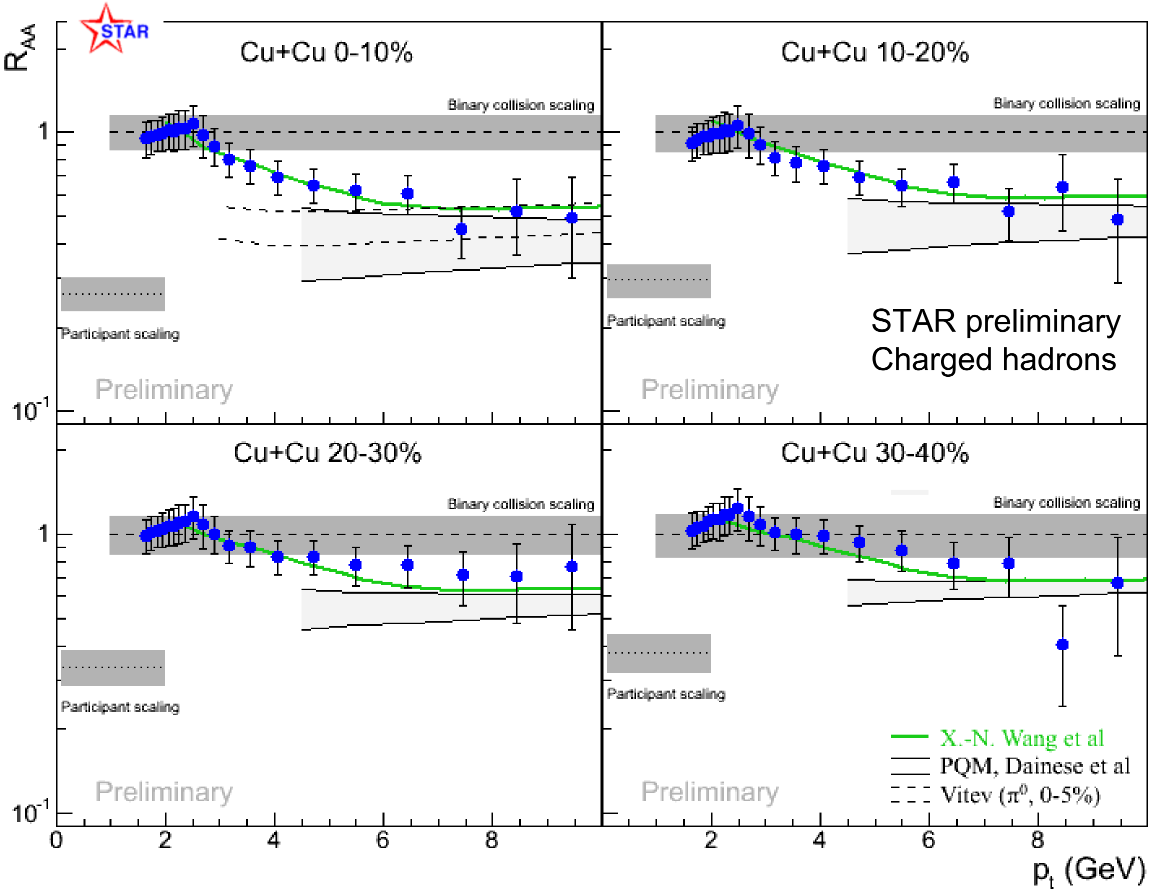




p_T <~ 5 GeV/c:
- deviation from vacuum fragmentation
- recombination picture

p_T > 5 GeV/c: fragmentation dominates

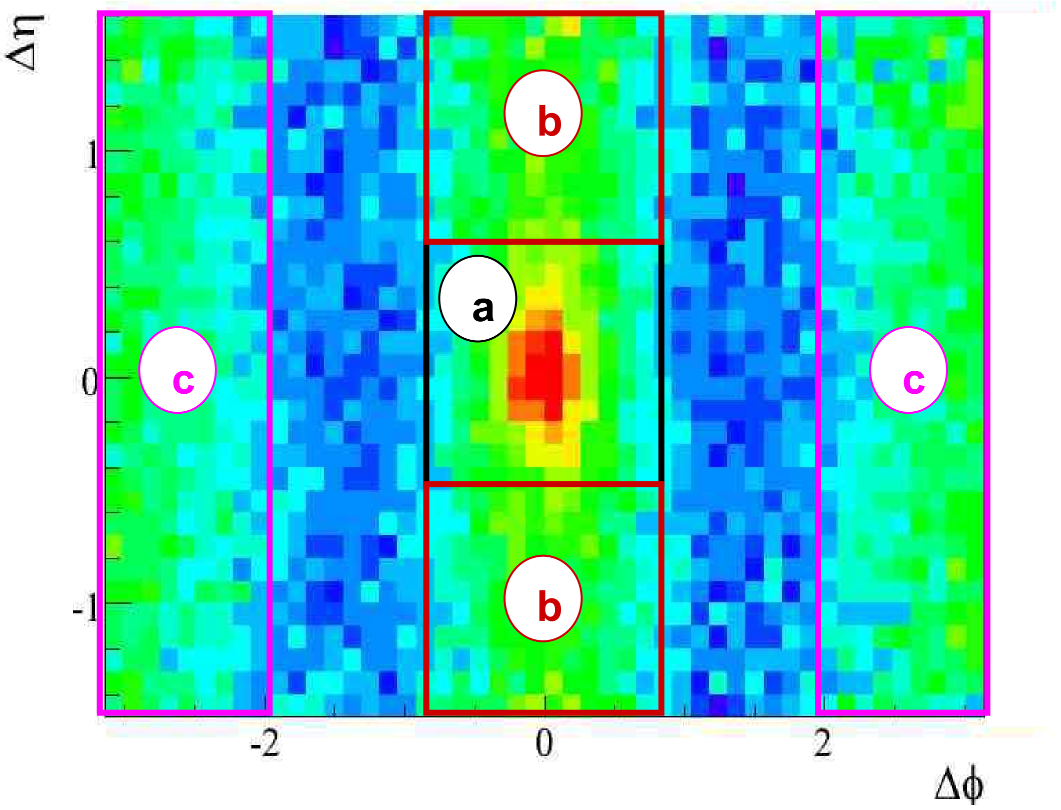
R_{AA} for CuCu



- “Testing” the L-dependence of ΔE
- Suppression observed for central CuCu

Components of $\Delta\eta\times\Delta\phi$ correlations

Au+Au 20-30%



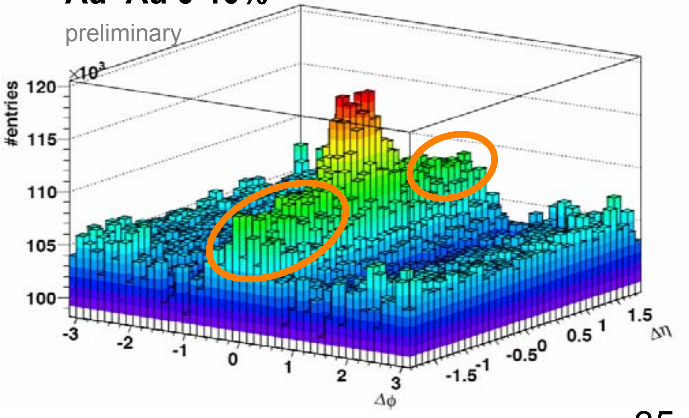
a) Near-side jet-like corrl.
+ ridge-like corrl.
+ v_2 modulated bkg.

b) Ridge-like corrl.
+ v_2 modulated bkg.

c) Away-side corrl.
+ v_2 modulated bkg.

Au+Au 0-10%

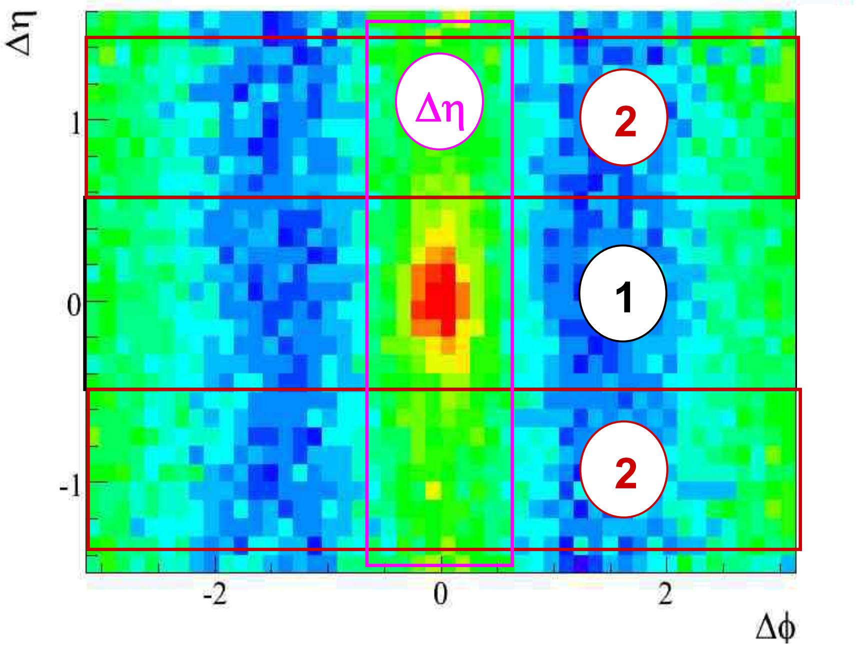
preliminary



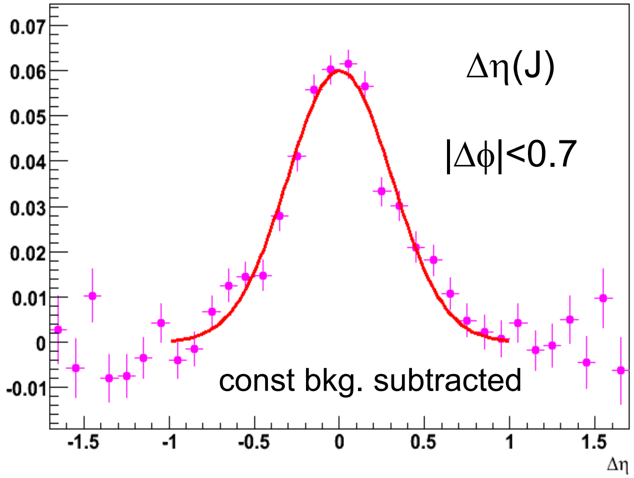
<u>Strategy:</u> Subtract $\Delta\eta$ from $\Delta\phi$ projection to isolate the ridge-like correlation

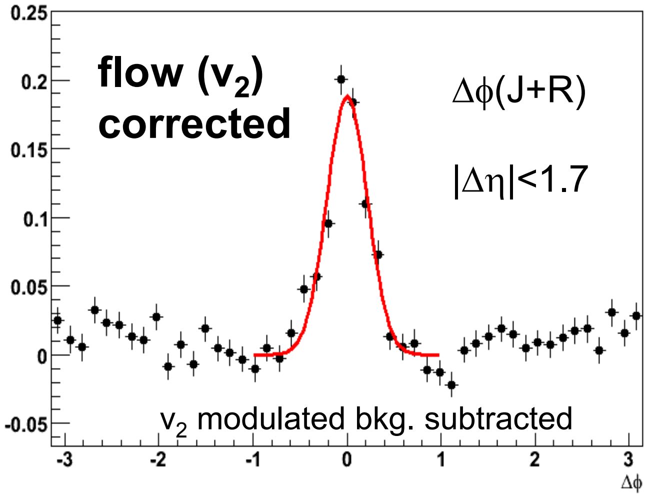
Extracting near-side "jet-like" yields

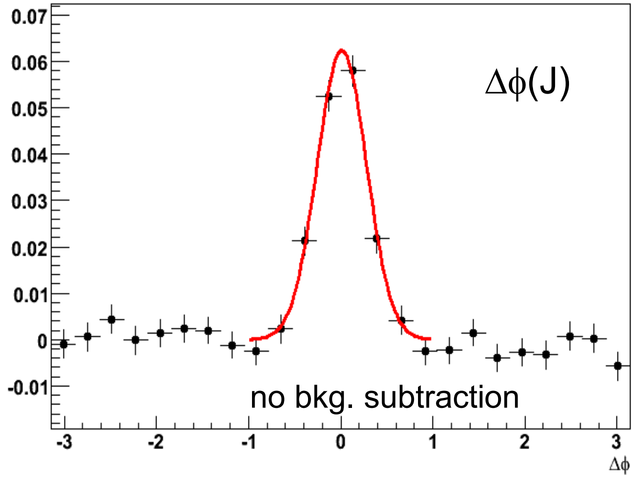
Au+Au 20-30%



J = near-side jet-like corrl.
R = "ridge"-like corrl.



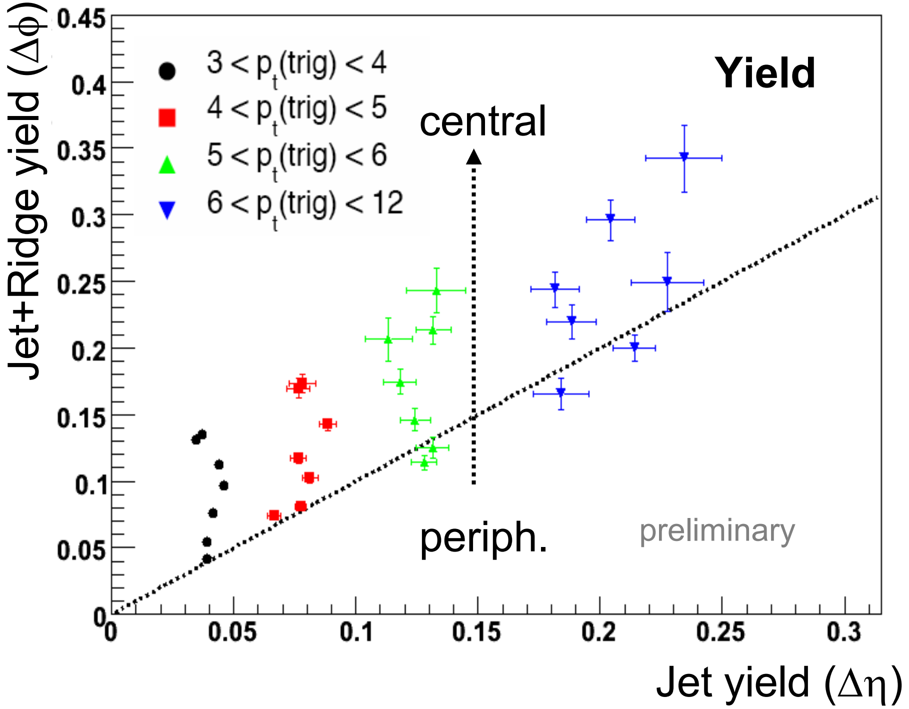




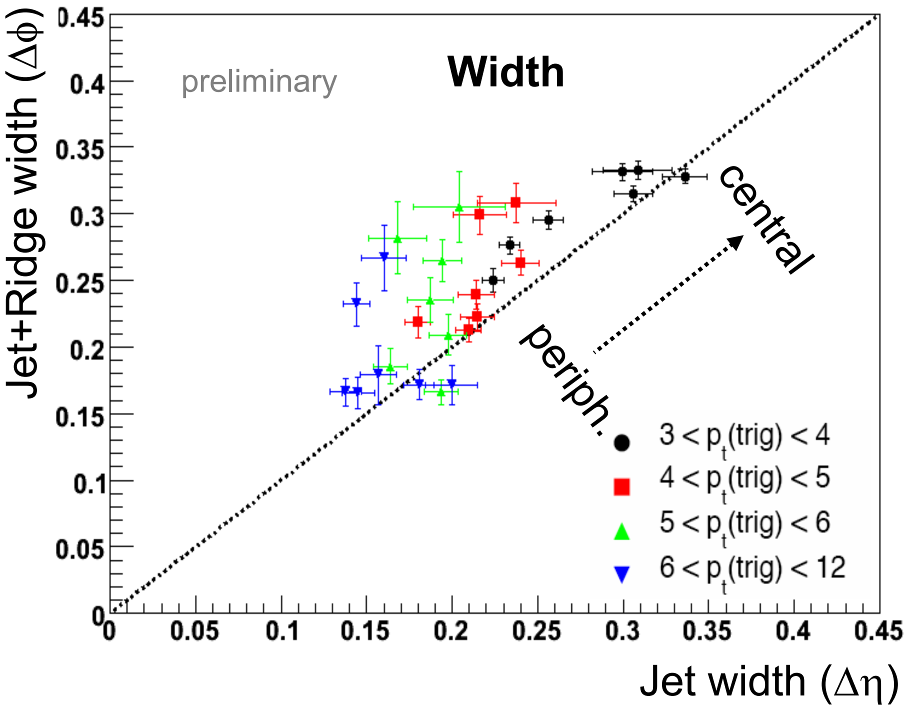
Jet and Jet+Ridge yields & widths

Correlate Jet ($\Delta\eta$(J)) and Jet+Ridge ($\Delta\phi$(J+R)) widths & yields via centrality

$p_{t,assoc.} > 2$ GeV



$p_{t,assoc.} > 2$ GeV

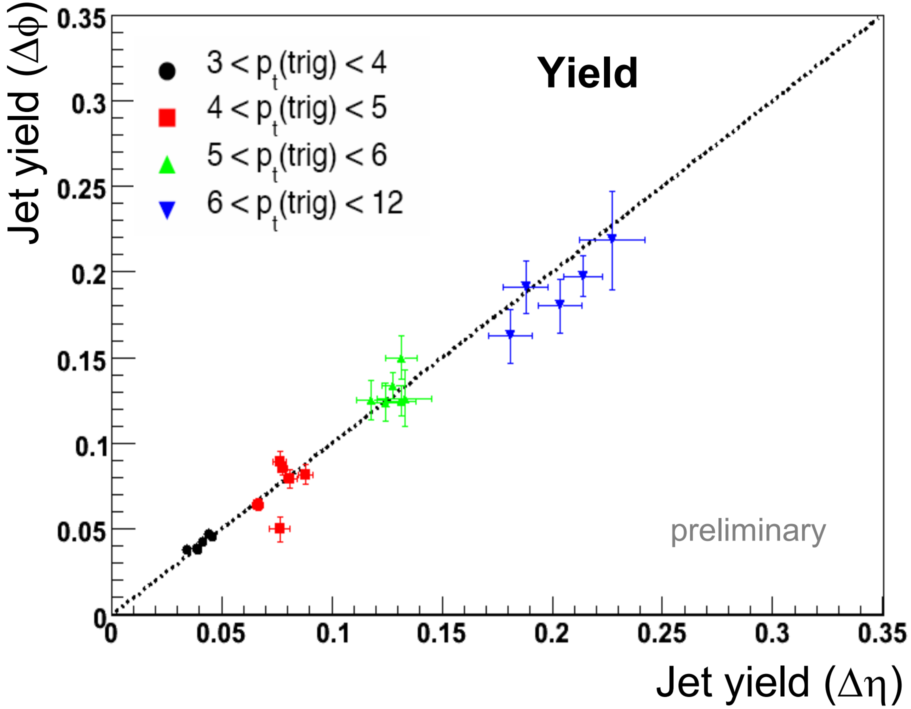


- Jet+Ridge yield increasing with centrality
- Jet+Ridge shape asymmetric in $\Delta\eta$ and $\Delta\phi$

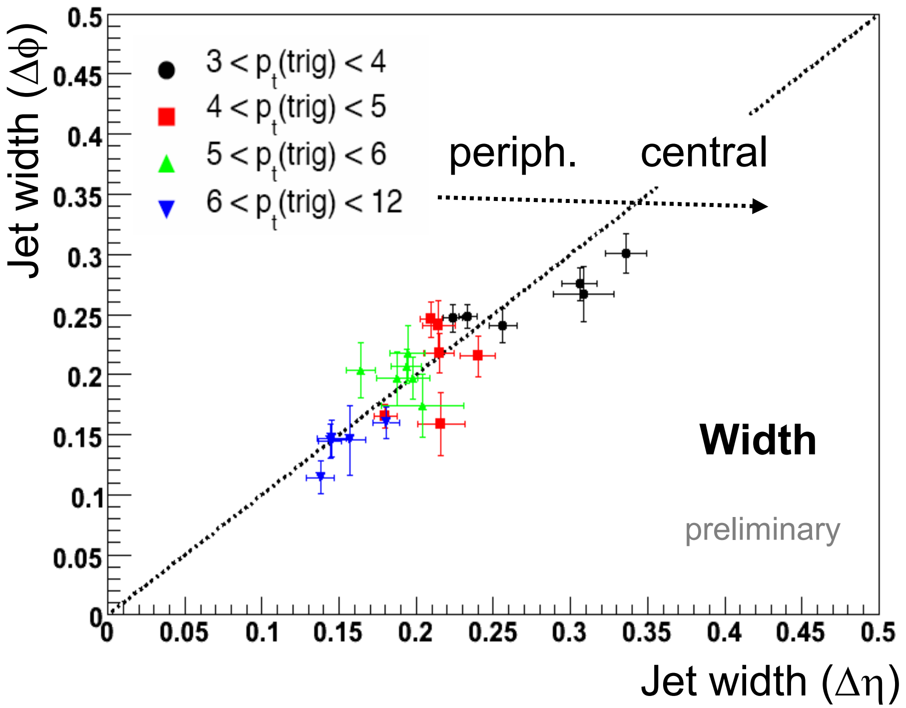
Jet yields & widths: $\Delta\eta$ vs. $\Delta\phi$

Correlate Jet ($\Delta\eta(J)$) and Jet ($\Delta\phi(J)$) widths and yields via centrality

$p_{t,assoc.} > 2$ GeV



$p_{t,assoc.} > 2$ GeV

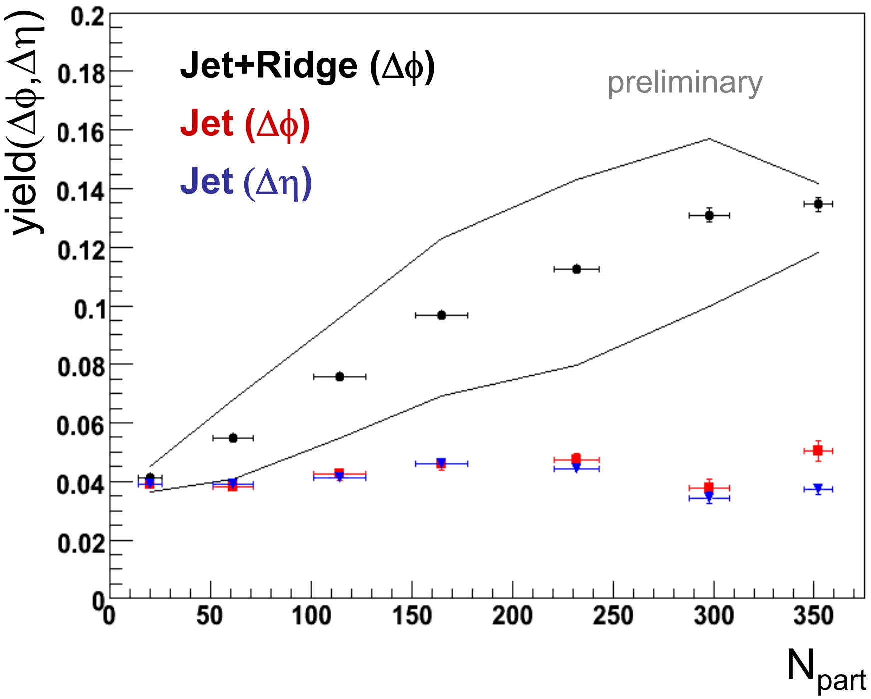


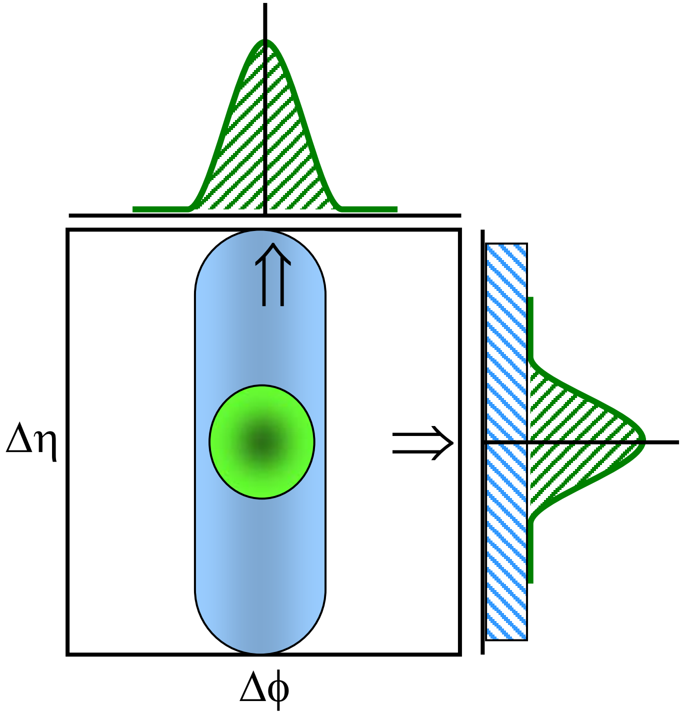
- Jet yield ~ symmetric in $\Delta\eta\times\Delta\phi$
- Jet shape ~ symmetric in $\Delta\eta\times\Delta\phi$ for $p_{t,trig} > 4$ GeV

(asymmetric in $\Delta\eta$ for $p_{t,trig} < 4$ GeV)

Extracting the ridge yield

$3 < p_{t,\mathrm{trigger}} < 4$ GeV and $p_{t,\mathrm{assoc.}} > 2$ GeV





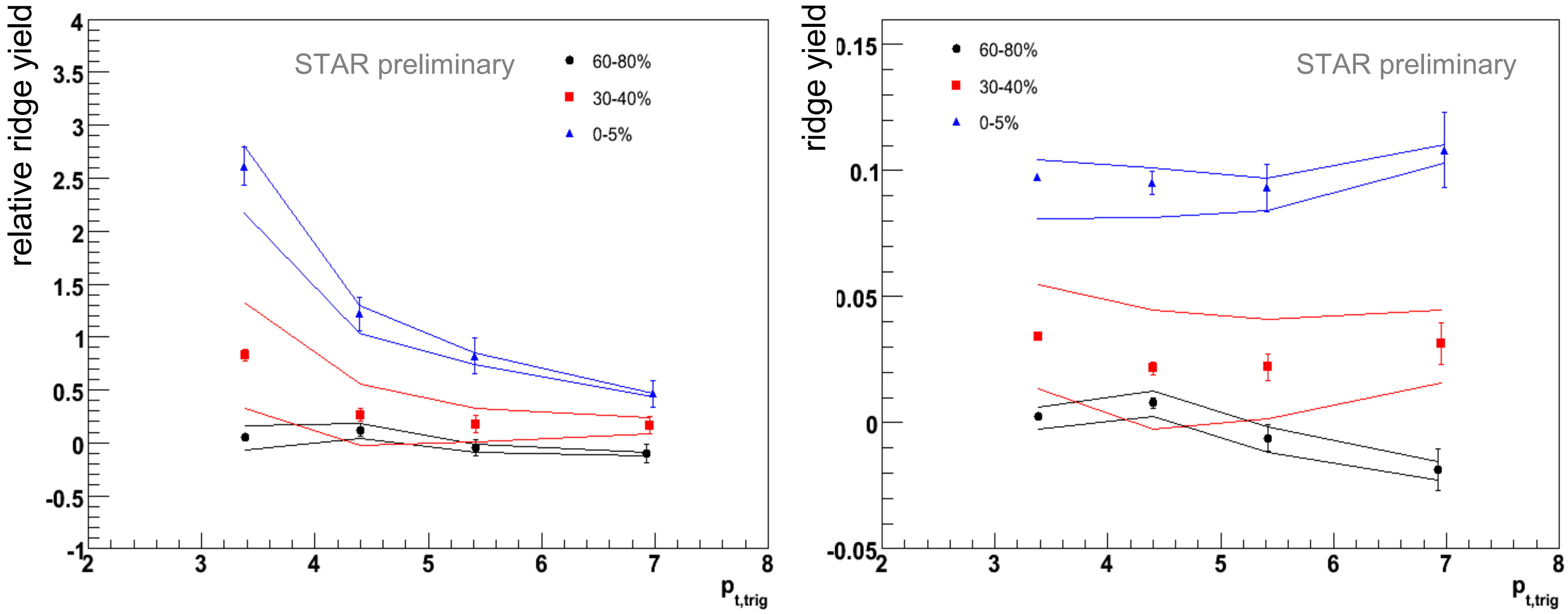
⇒ <u>Definition of “ridge yield”:</u>

i) ridge yield := Jet+Ridge($\Delta\phi$ – Jet($\Delta\eta$)

ii) relative ridge yield := ridge yield / Jet($\Delta\eta$)

Ridge yield in Au+Au I

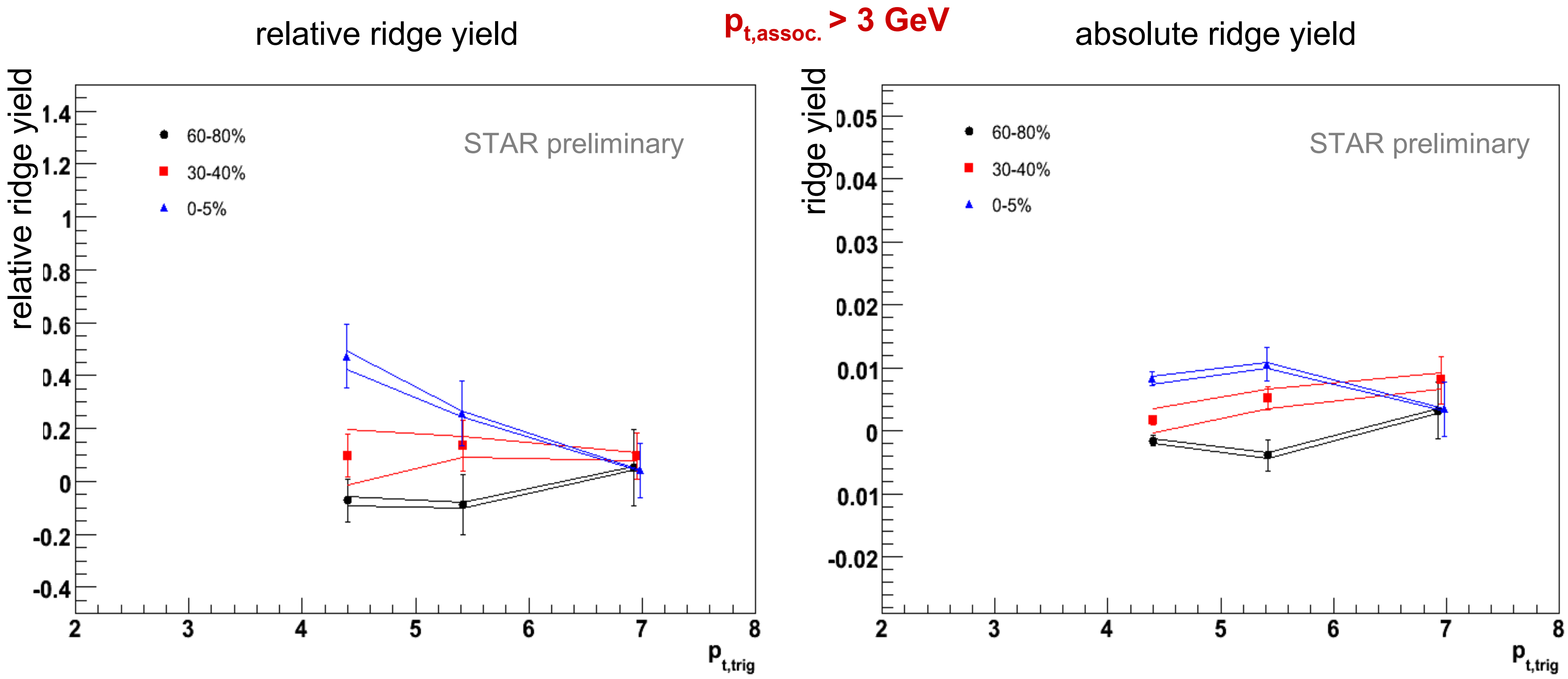
$p_{t,assoc.}$ > 2 GeV


relative ridge yield

absolute ridge yield

- Relative ridge yield decreasing with trigger p_t
- Absolute ridge yield constant as function of trigger p_t

Ridge yield in Au+Au II



relative ridge yield

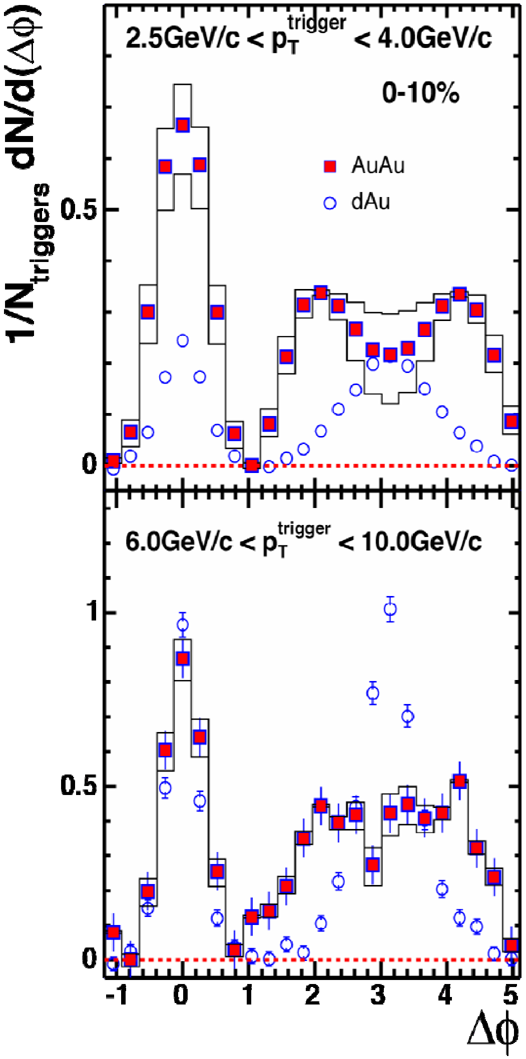
$p_{t,assoc.} > 3$ GeV

absolute ridge yield

Ridge contribution significantly suppressed for $p_{t,assoc.} > 3$ GeV

Two-Particle Correlations (Mach Cone?)

1 < p_T (assoc) < 2.5 GeV/c



- broad away-side distribution in central *Au+Au*
  - enhanced yield for lower p_T
  - consistent with two-peak structure
    - Mach cone or deflected jets? ▯ study 3-part. correlation
  - sensitive to elliptic flow subtraction
- dependence on trigger p_T?
- enhanced yield for near-side
  - quantitatively consistent with ridge
  - near-side enhancement only ridge? ▯ vacuum fragmentation?

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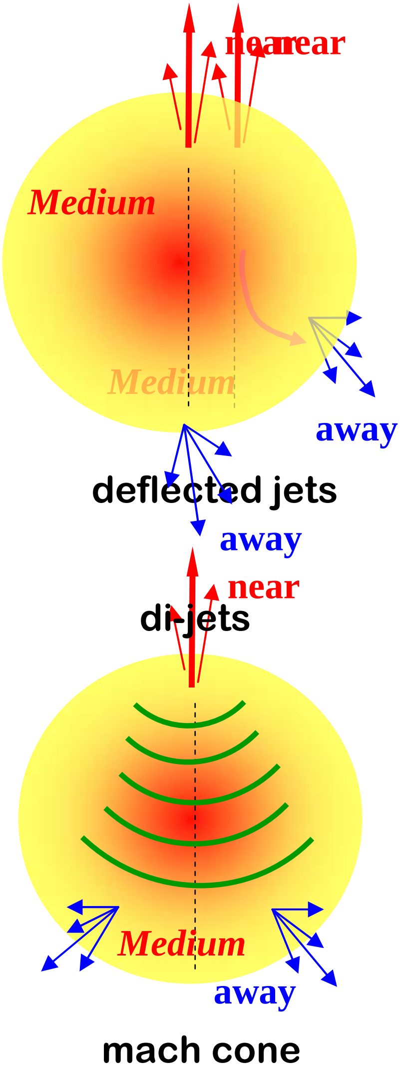
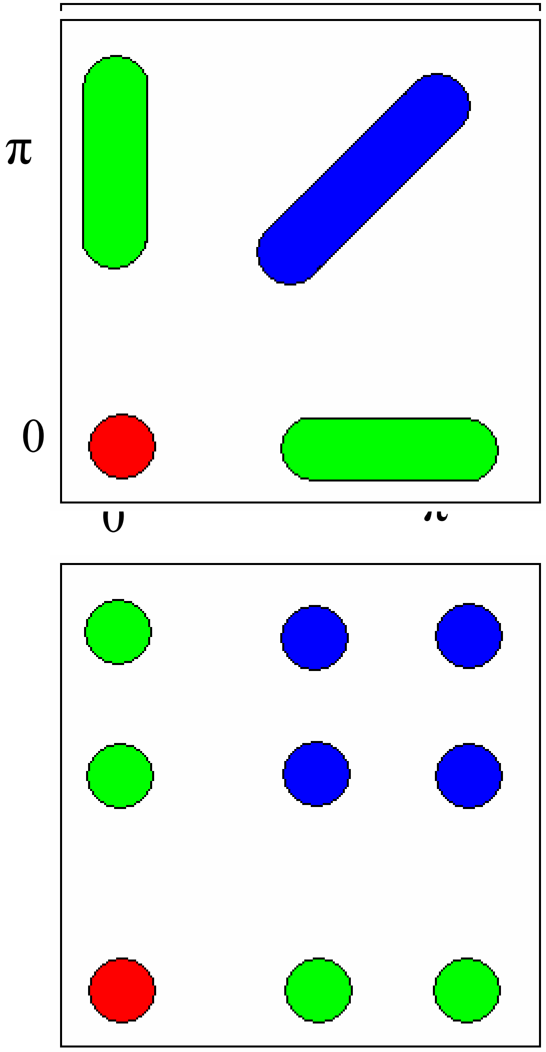
Poster

Conical Flow vs Deflected Jets





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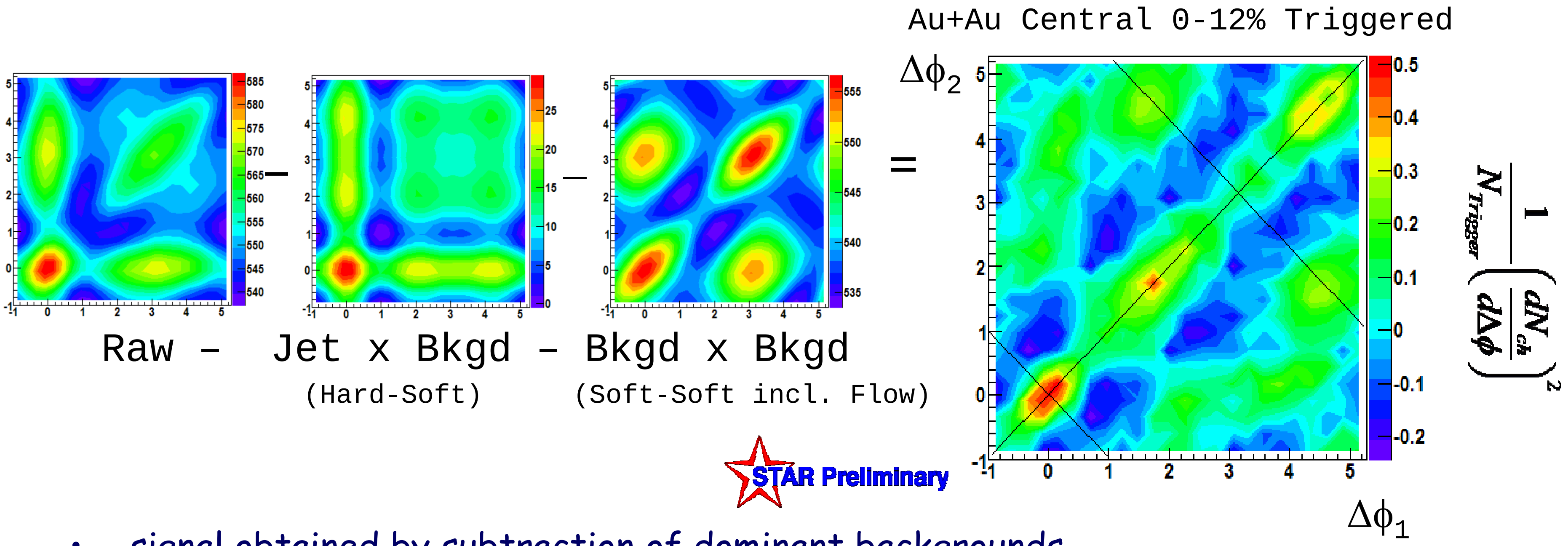
Three-Particle Correlations



Au+Au Central 0-12% Triggered

Raw – Jet x Bkgd – Bkgd x Bkgd =

(Hard-Soft) (Soft-Soft incl. Flow)

- signal obtained by subtraction of dominant backgrounds
  - flow components, jet-related two-particle correlation
- improved analysis compared to QM (e.g. high statistics)
  - additional check with cumulant analysis under way
  - careful: different assumptions on background normalisation!
- clear elongation (jet deflection)
- off-diagonal signal related to mach cone?

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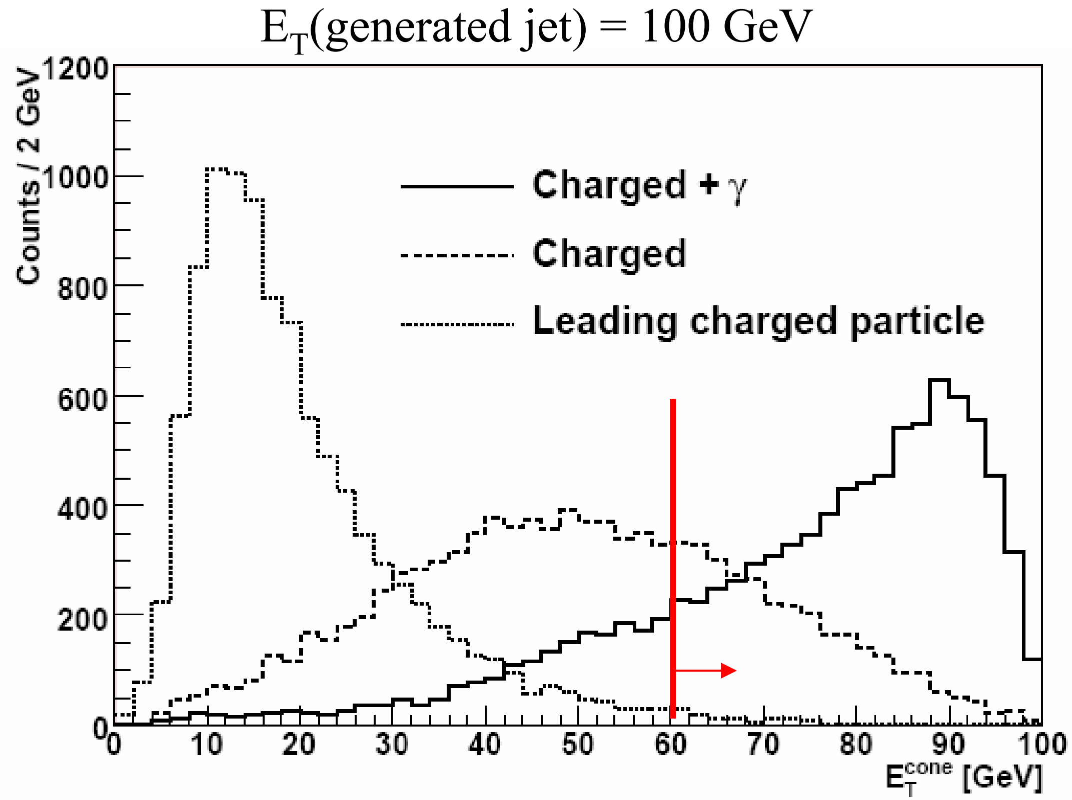
parallel talk

Full jet reconstruction at LHC

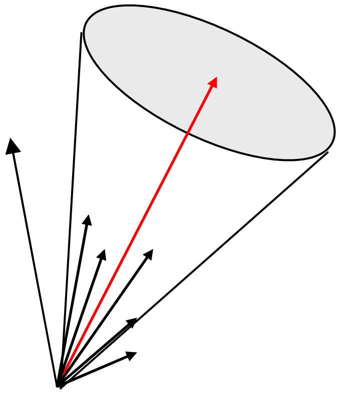
The leading particle as a probe becomes fragile in several respects.


E_T(generated jet) = 100 GeV

Ideally, the analysis of reconstructed jets will allow us to measure the original parton 4-momentum and the jet structure.

From this analysis a higher sensitivity to the medium parameters (transport coefficient) is expected.

Jet reconstruction in ALICE



$$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

- Collimation: ~ 80% energy around jet axis in $R < 0.3$
- Background energy in cone of size R is $\sim R^2$ and background fluctuations $\sim R$.

In **pp-collisions**

jets: excess of transverse energy within a typical cone of R = 1.

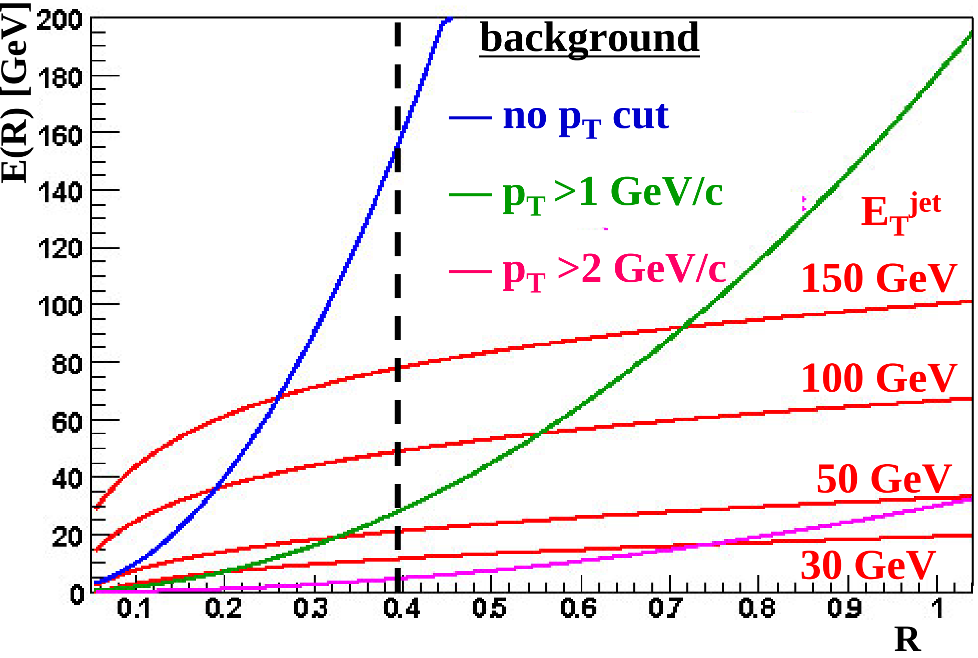
In **heavy-ion collisions**

- jets reconstructed using smaller cone sizes
- subtract energy from underlying event

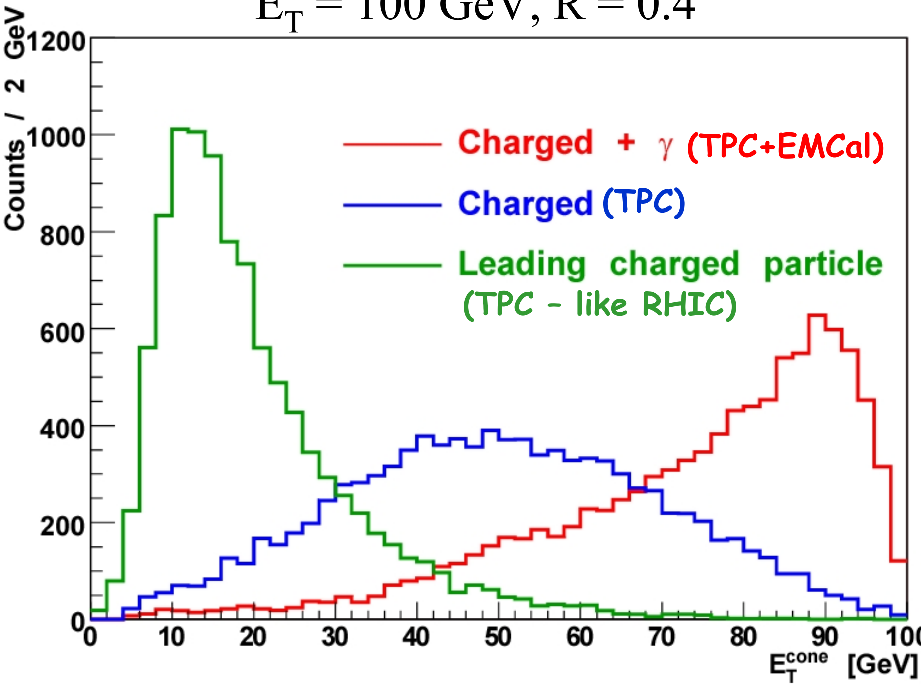
Main limitations:

- **Background energy**. Reduced by:
  - reducing the cone size (R = 0.3-0.4)
  - transverse momentum cut (p_T = 1-2 GeV/c)
- **Background energy fluctuations**:
  - event-by-event fluctuations
  - Poissonian fluctuations of uncorrelated particles
  - fluctuations of correlated particles

Intrinsic performance limits



E_T = 100 GeV, R = 0.4

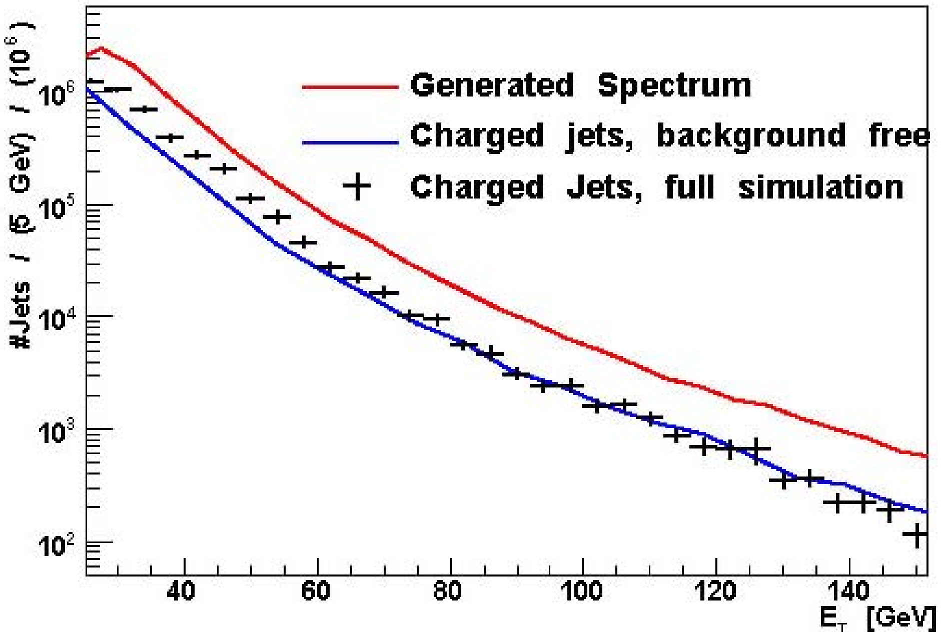


Energy contained in a subcone of radius R reduced by:

- reducing the cone size
- cutting on p_T

- Limited cone size leads to a low energy tail
- Charged reconstruction (TPC) dominated by charged to neutral fluctuations

Reconstructed jet



10^7 central events

R = 0.4

Charged jets

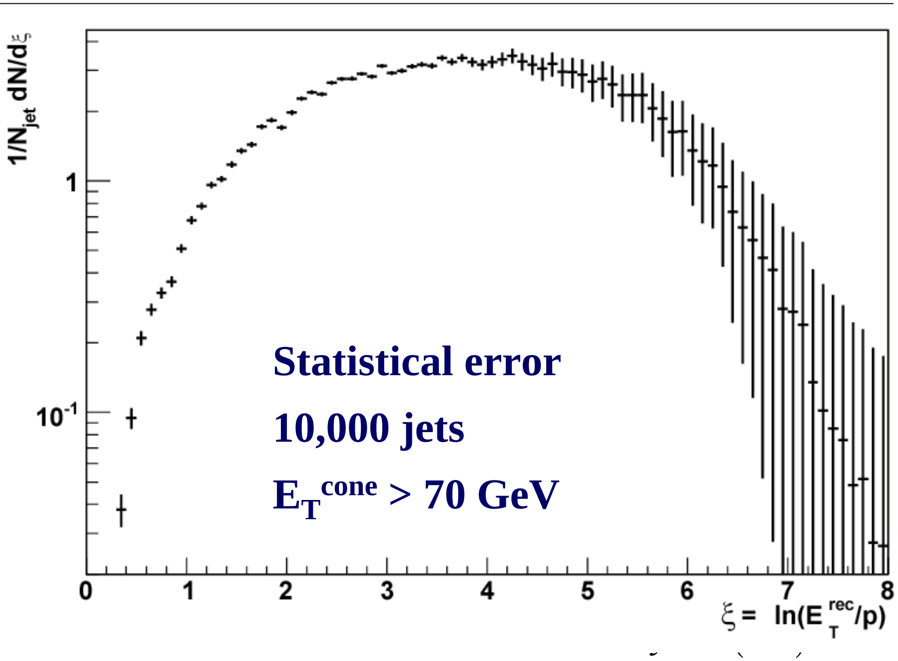
- Study properties of the medium through the modifications on the transverse jet structure

  Jet shape (dE/dr) and jet particle momentum perpendicular to jet axis (j_t) vs. reconstructed energy

- Study hard processes with low p_T observables by measuring the fragmentation function to low p_T. Energy loss and radiated energy

  Decrease of hadrons in the high-z part and increase of hadrons in the low-z region of fragmentation function ($z = p_T/E_T^{jet}$)

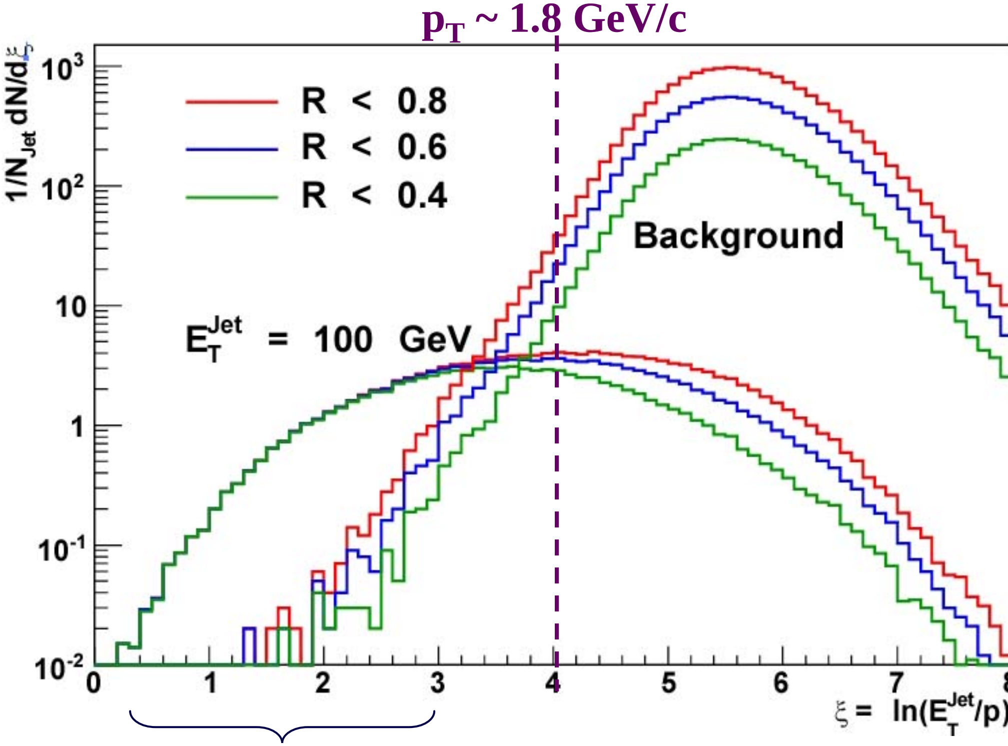
Jet-structure observables



Representing the fragmentation function: Hump-backed Plateau.

$$z = \frac{p_T}{E_T^{jet}}$$

Charged jets.



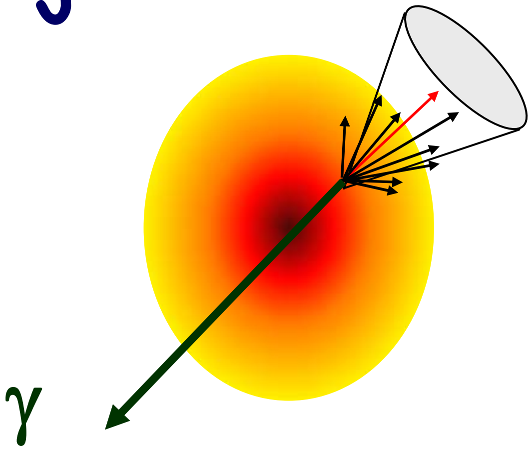
Leading Particles

S/B > 0.1

Particles from medium induced gluon radiation in $\xi \sim 4\text{-}6$

For $E_T \sim 100$ GeV, $S/B \sim 10^{-2}$

Photon-tagged jets



Dominant processes:

$$g + q \rightarrow \gamma + q \text{ (QCD Compton)}$$

$$q + \bar{q} \rightarrow \gamma + g \text{ (Annihilation)}$$

$p_T > 10$ GeV/c

γ-jet correlation

- $E_\gamma = E_{jet}$
- Opposite direction

- Direct photons are not perturbed by the medium
- Parton in-medium-modification through the fragmentation function