Jet quenching

Hard-scattering probes

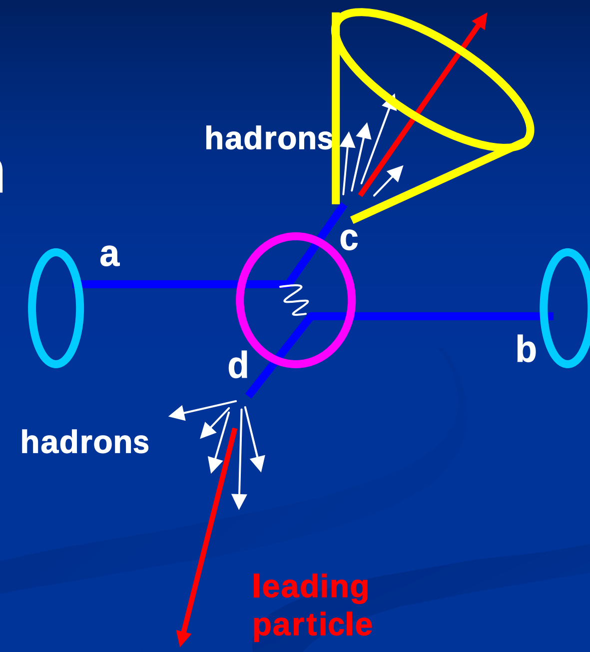
Probing the medium

- I will make an artificial distinction of the "medium" and "the probe"
- In fact: both are produced in the collision
  - Medium: The bulk of the particles; dominantly soft production and possibly exhibiting some phase.
  - <u>Probe</u>: Particles whose production is calculable, measurable, and thermally incompatible with (distinct from) the medium.
- The basic idea:

- Things to learn
  - Measure the density of the medium
  - Is the medium colored (i.e. deconfined) ? Specific pQCD predictions for induced gluon radiation since 1990s

High p_T Particle Production in pp

Jet: A localized collection of hadrons which come from a fragmenting parton



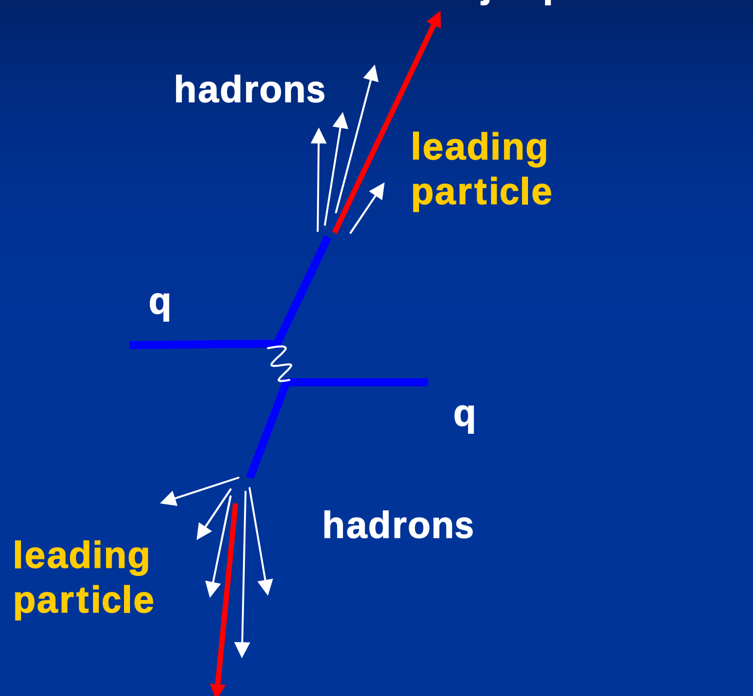
Parton Distribution Functions
Hard-scattering cross-section
Fragmentation Function

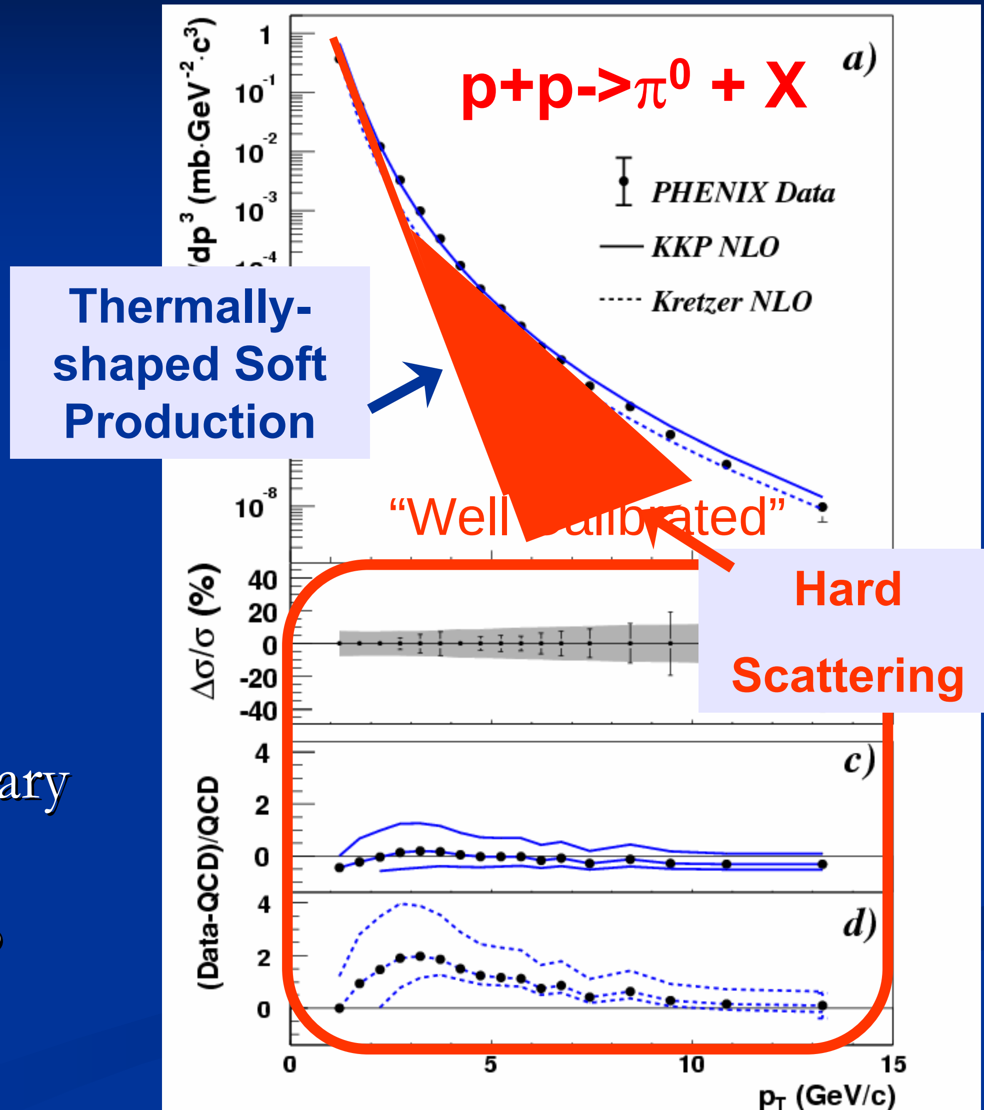
"Collinear factorization"

$$\frac{d\sigma_{pp}^{h}}{dyd^2p_T} = K\sum_{abcd}\int dx_a dx_b\, f_a(x_a,Q^2)\, f_b(x_b,Q^2)\, \frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)\, \frac{D_{h/c}^{0}}{\pi z_c}$$

Calibrating the Probe(s)

schematic view of jet production



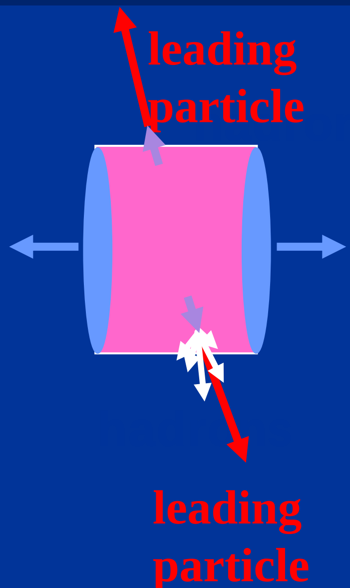


- Measurement from elementary collisions. Leading particles spectra used as a "proxy" to jets.

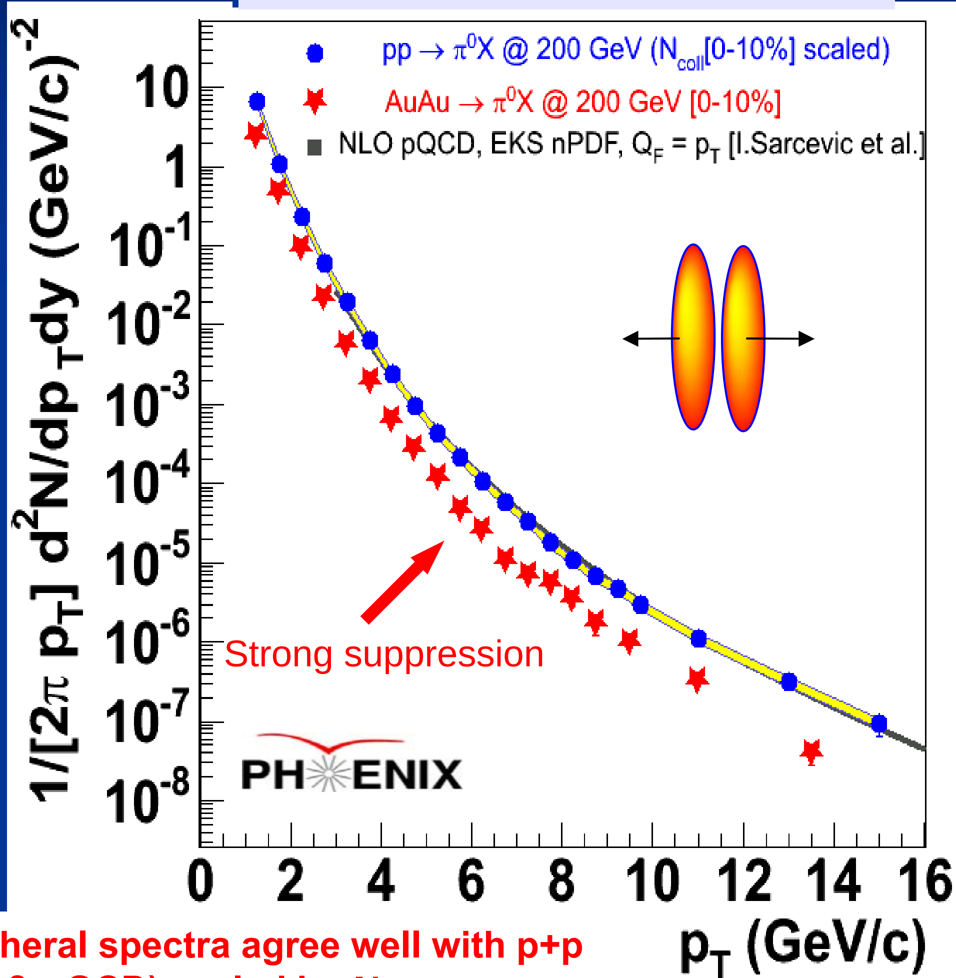
hep-ex/0305013 S.S. Adler et al.

Calibrate the probe and then use it !

- Single-particle spectrum and QCD predictions



Au+Au → π^0 + *X* (central)



Peripheral spectra agree well with p+p (data & pQCD) scaled by *N_{coll}*

Central data exhibits suppression!

Quantifying the nuclear effect

$$R_{AA} = \frac{\text{yield in A+A/number of equivalent p+p collisions}}{\text{yield in p+p}}$$

$$= \frac{1}{\langle n_{coll} \rangle} \frac{d^2N_{AB}/dy\,dp_T}{d^2N_{pp}/dy\,dp_T} = \frac{1}{\sigma_{pp} \langle T_{AB} \rangle} \frac{d^2N_{AB}/dy\,dp_T}{d^2N_{pp}/dy\,dp_T}$$

R_{AA} Normalization

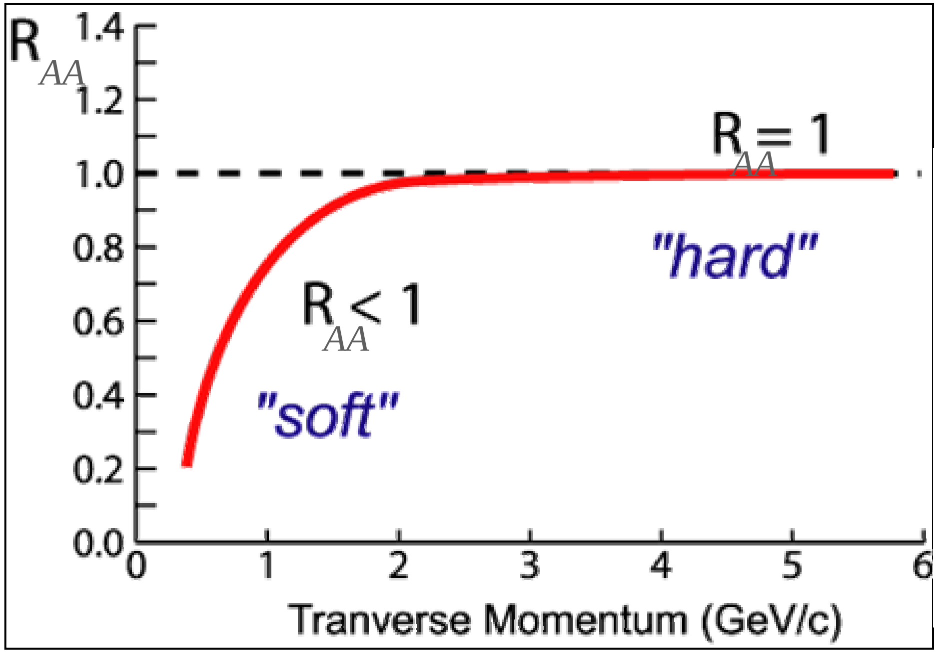
1. Compare Au+Au to nucleon-nucleon cross sections
2. Compare Au+Au central/peripheral

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

nucleon-nucleon cross section

$\langle N_{binary}\rangle/\sigma_{inel}^{p+p}$



If no "effects":

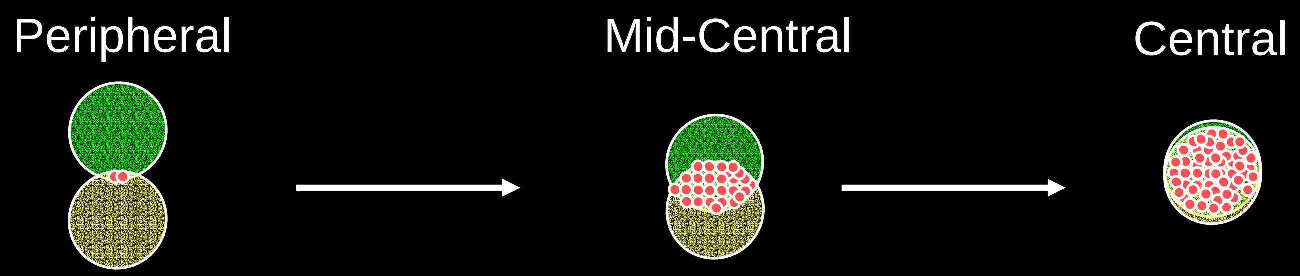
$R_{AA} < 1$ in regime of soft physics

$R_{AA} = 1$ at high-p_T where hard scattering dominates

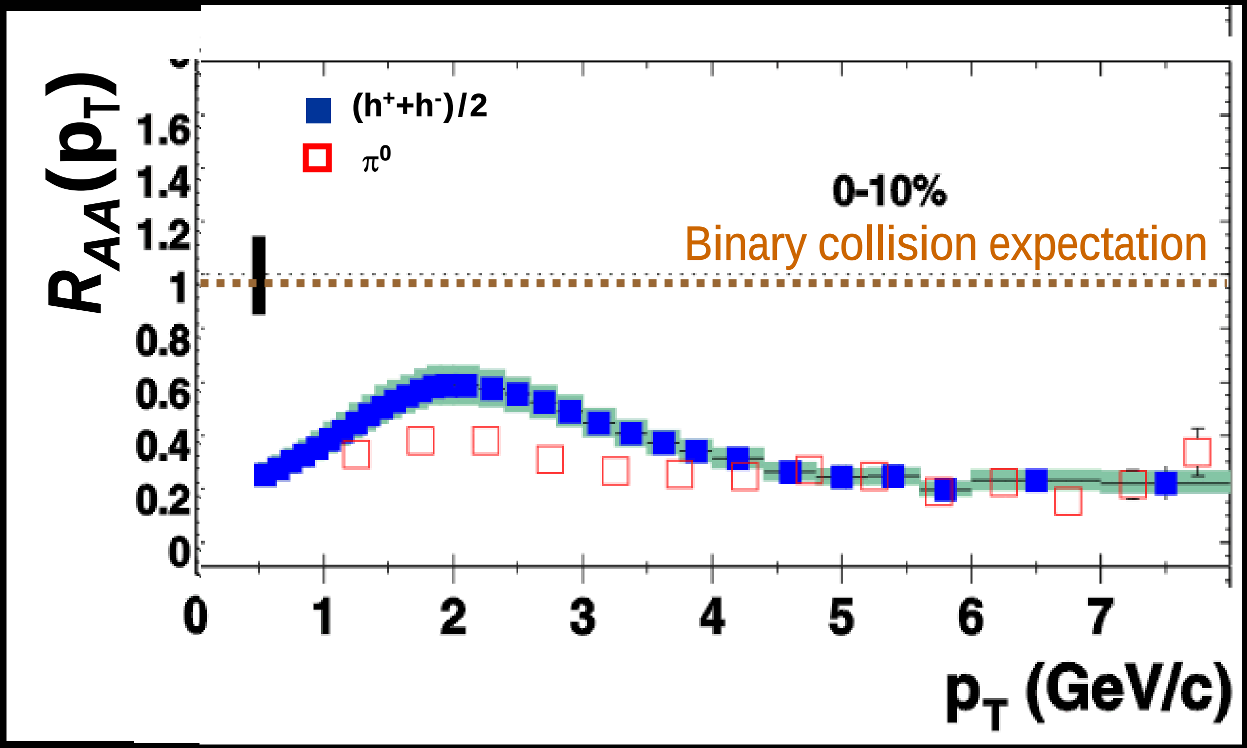
Suppression:

$R_{AA} < 1$ at high-p_T

Suppression of high-p_T hadrons in AuAu collisions



$$R_{AA} = \frac{\text{Yield}_{AuAu}}{\langle N_{binary} \rangle_{AuAu} \text{Yield}_{pp}}$$



Phenix: Phys.Rev. C69 (2004) 034910

→ See a strong suppression of high p_T yields in AuAu Central Collisions

High p_T Particle Production in A+A: why suppressed?

$$\frac{dN^h_{AB}}{dy\,d^2p_T} = ABK \sum_{abcd} \int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b$$

(pQCD context...)

$$\otimes\, f_{a/A}(x_a,Q^2)\, f_{b/B}(x_b,Q^2)$$

Parton Distribution Functions

$$\otimes\, g(\mathbf{k}_a)\, g(\mathbf{k}_b)$$

Intrinsic k_T , Cronin Effect

$$\otimes\, S_A(x_a,Q_a^2)\, S_B(x_b,Q_b^2)$$

Shadowing, EMC Effect

$$\otimes\, \frac{d\sigma}{d\hat{t}}(ab \to cd)$$

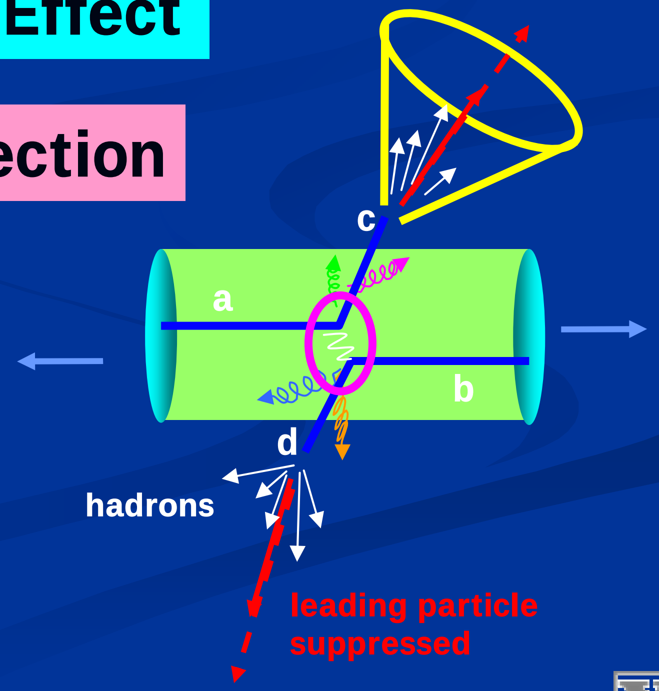
Hard-scattering cross-section

$$\otimes \int_0^1 d\varepsilon P(\varepsilon) \frac{z_c^*}{z_c}$$

Partonic Energy Loss

$$\otimes\, \frac{D^0_{h/c}(z_c^*,Q_c^2)}{\pi z_c}$$

Fragmentation Function

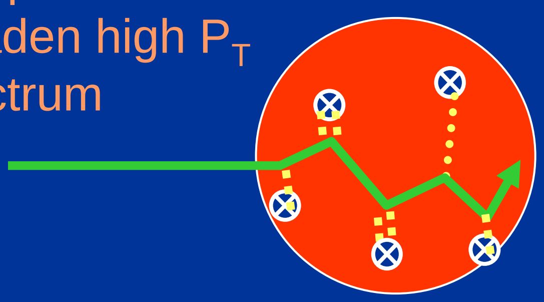


Initial state effect I: Cronin enhancement

- Multiple scattering in the initial state leads to p_T smearing and then enhancement

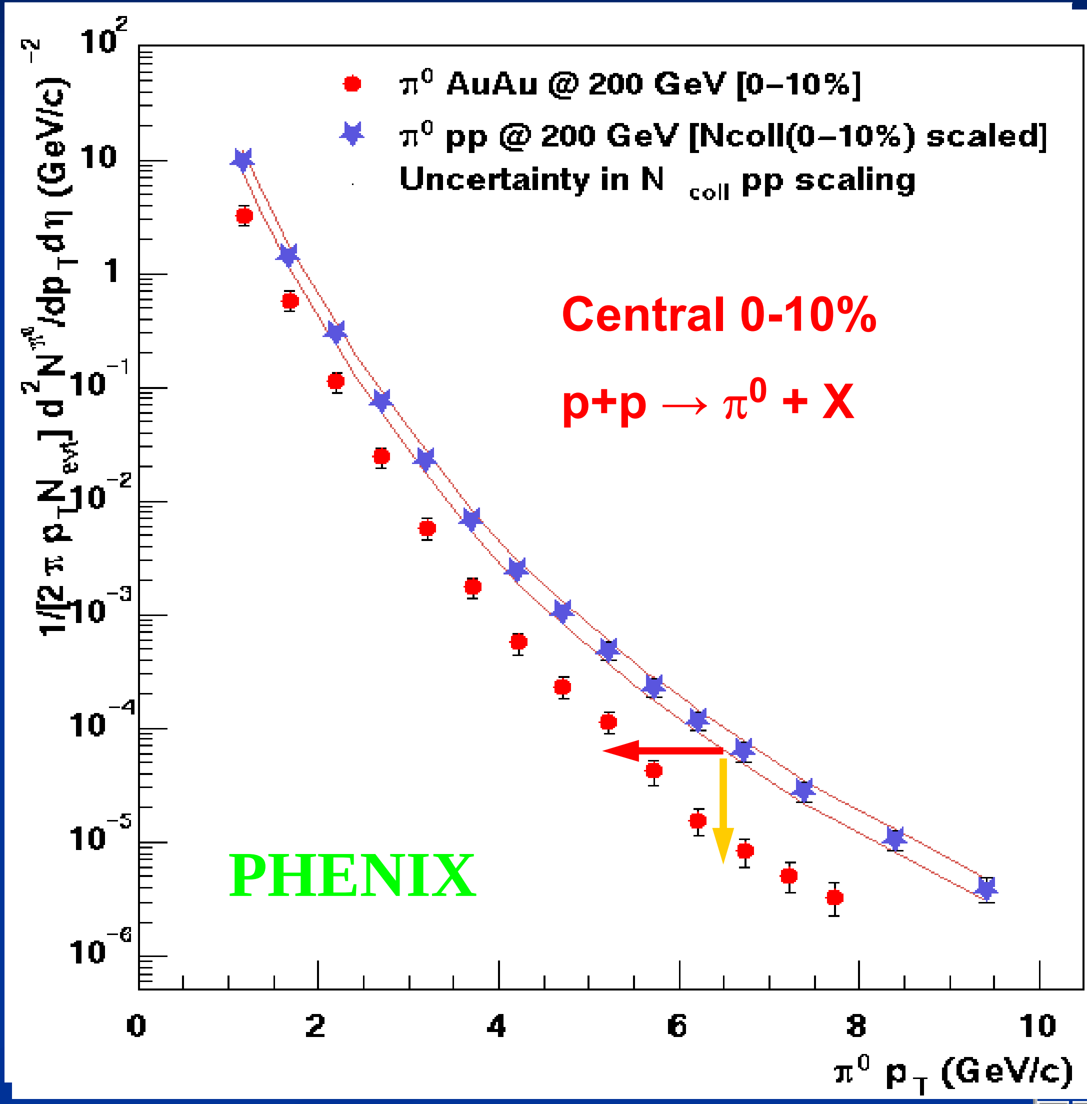
Cronin Effect:

Multiple Collisions broaden high P_T spectrum

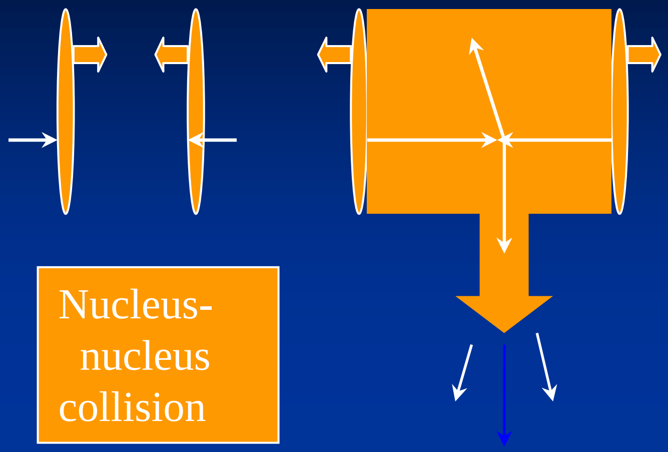


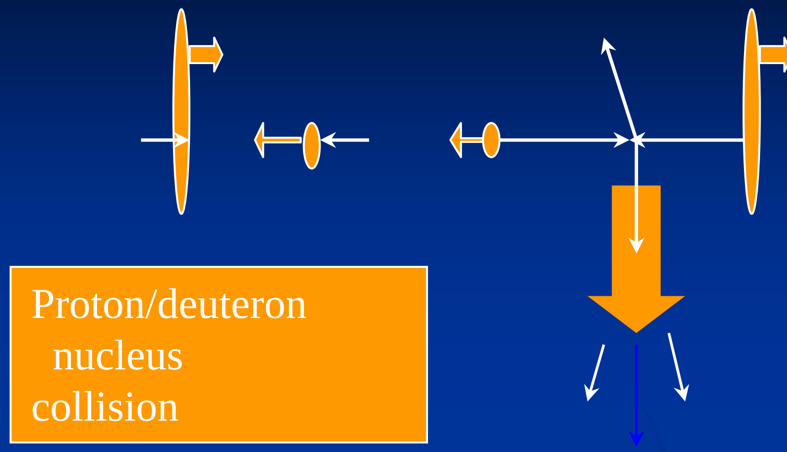
Initial vs final state suppression

- Calibrating the probes-pp reference data
  -agrees with NLO pQCD
- Peripheral Collisions
  -Scale with Ncoll
- Central Collisions
  DO NOT SCALE!
- Is it
  - Suppression of low-x gluons in the initial state?
  - Energy loss in a new state of matter?



d+Au Control Experiment



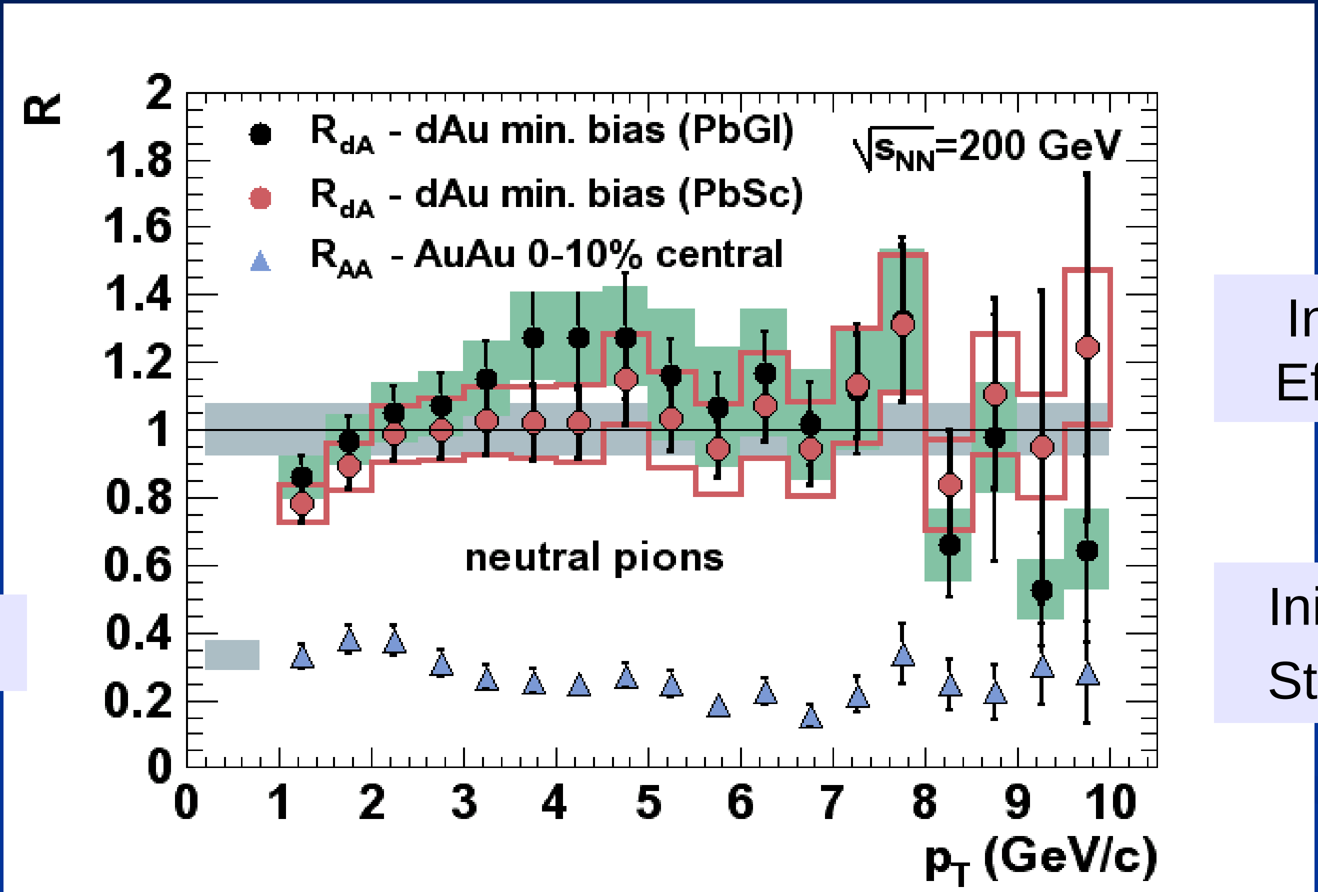


- Collisions of small with large nuclei were always foreseen as necessary to quantify cold nuclear matter effects.
- Recent theoretical work on the "Color Glass Condensate" model provides alternative explanation of data:
  - Jets are not quenched, but are a priori made in fewer numbers.
  - Color Glass Condensate hep-ph/0212316; Kharzeev, Levin, Nardi, Gribov, Ryshkin, Mueller, Qiu, McLerran, Venugopalan, Balitsky, Kovchegov, Kovner, Iancu
- Small + Large distinguishes all initial and final state effects.

R_{AA} vs. R_{dA} for Identified π^0

d+Au

Au+Au



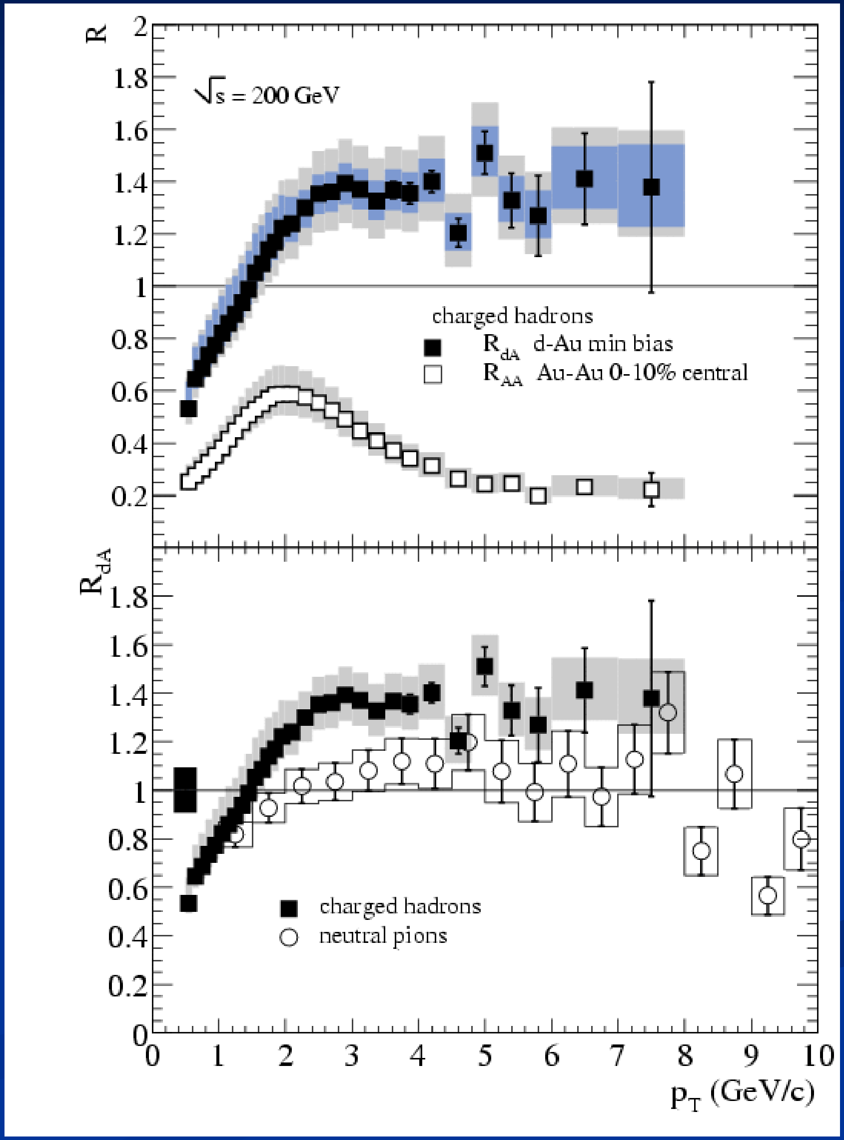
Initial State Effects Only

Initial + Final State Effects

d-Au results rule out CGC as the explanation for Jet Suppression at Central Rapidity and high p_T

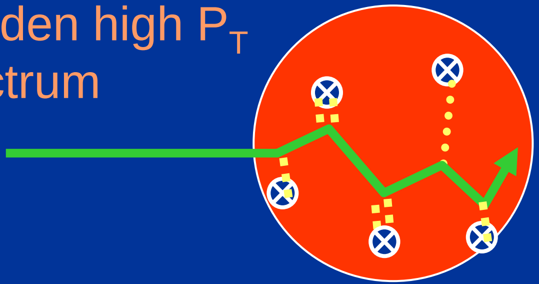
Charged Hadron Results

- Striking difference of d+Au and Au+Au results.
- Charged Hadrons higher than neutral pions.



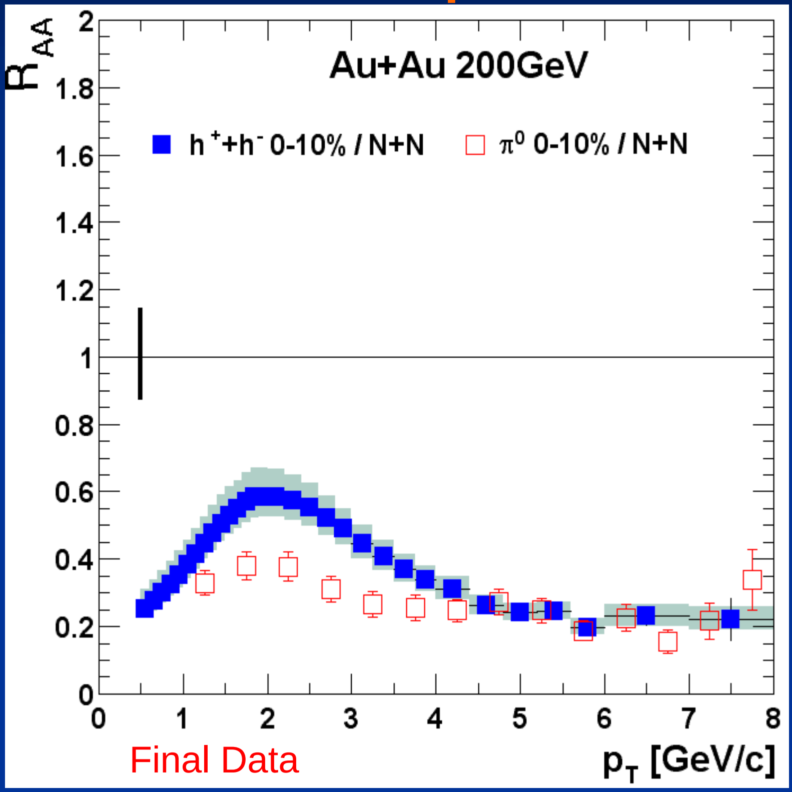
Cronin Effect:

Multiple Collisions broaden high P_T spectrum

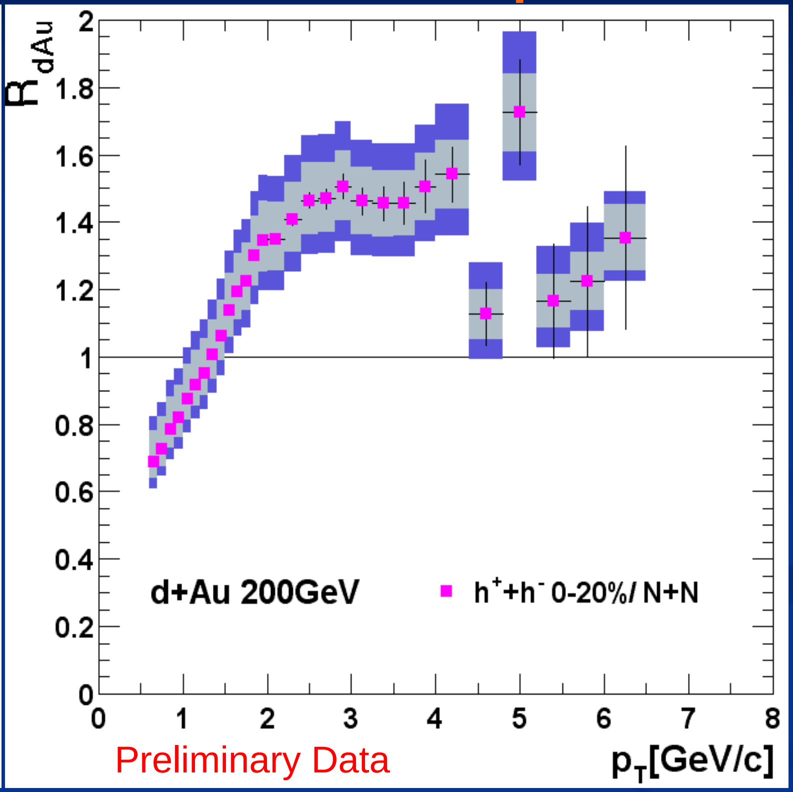


Centrality Dependence

Au + Au Experiment

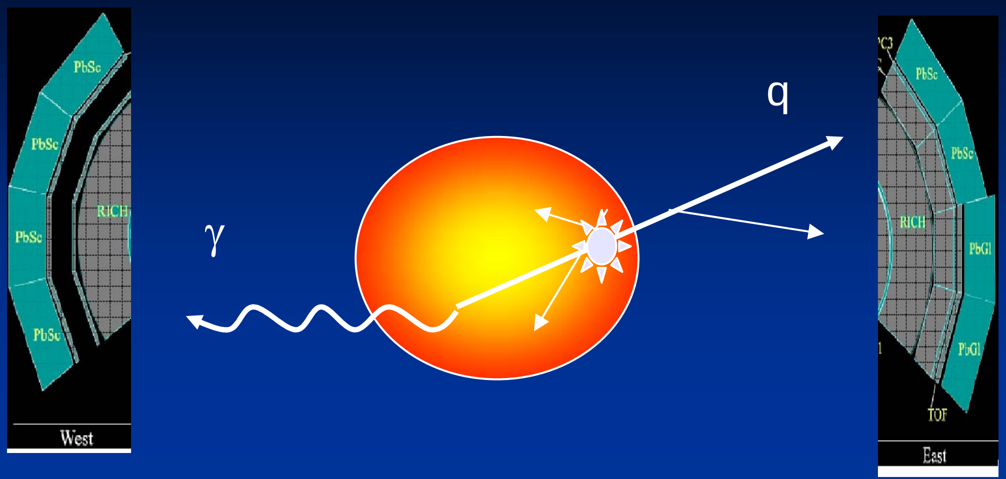


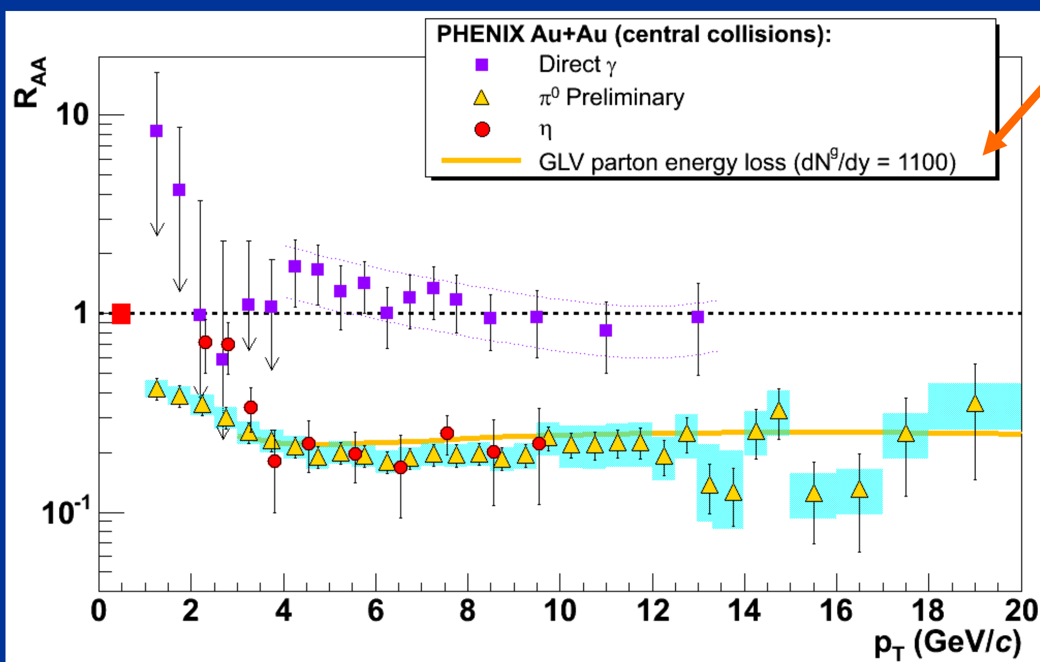
d + Au Control Experiment



- Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.
- Jet Suppression is clearly a final state effect.

Control experiment: colorless probe





Confirm that jet quenching is due to energy loss in the medium. Deduce the medium density.

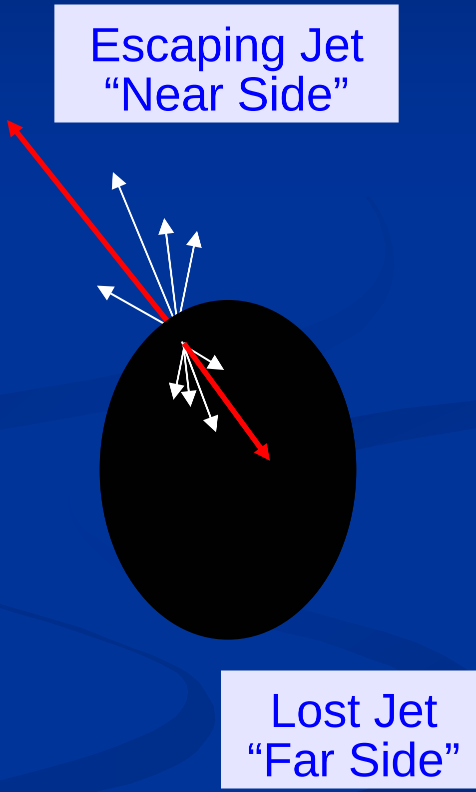
Photons shine !

Pions and etas – suppressed !

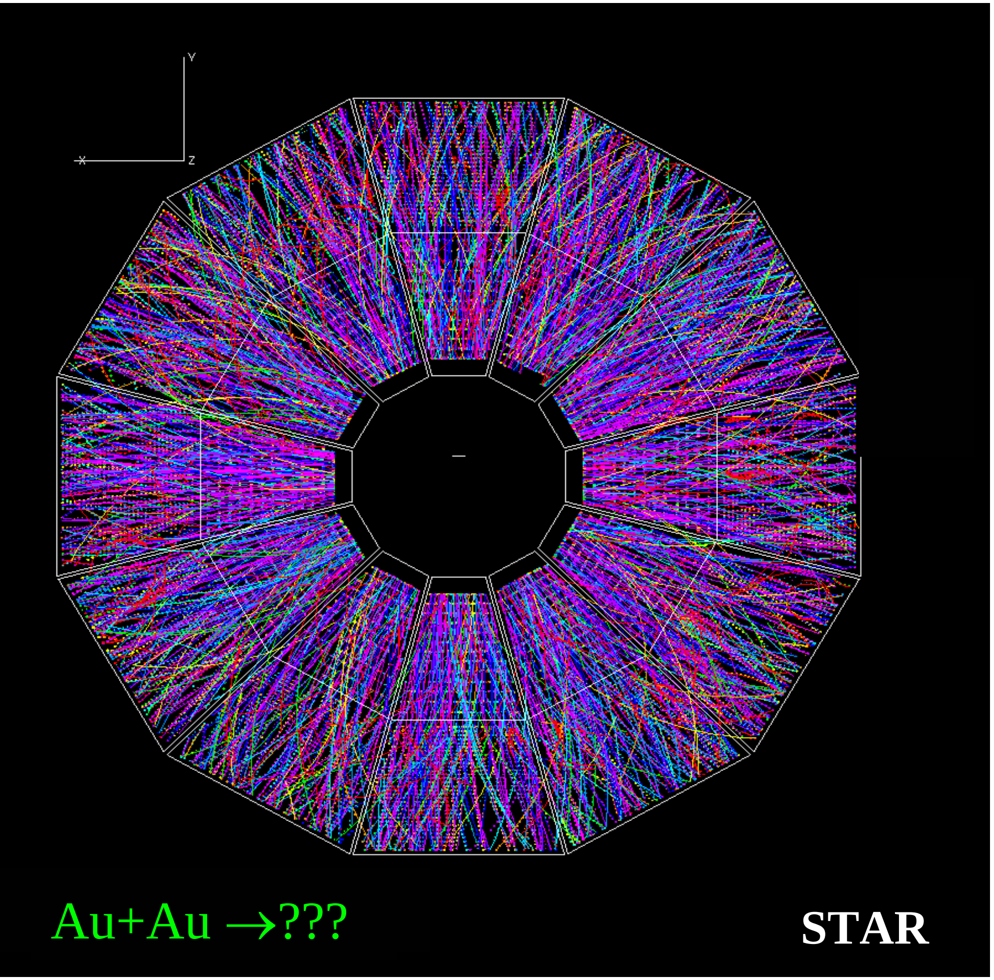
Back to back jets (di-jets)

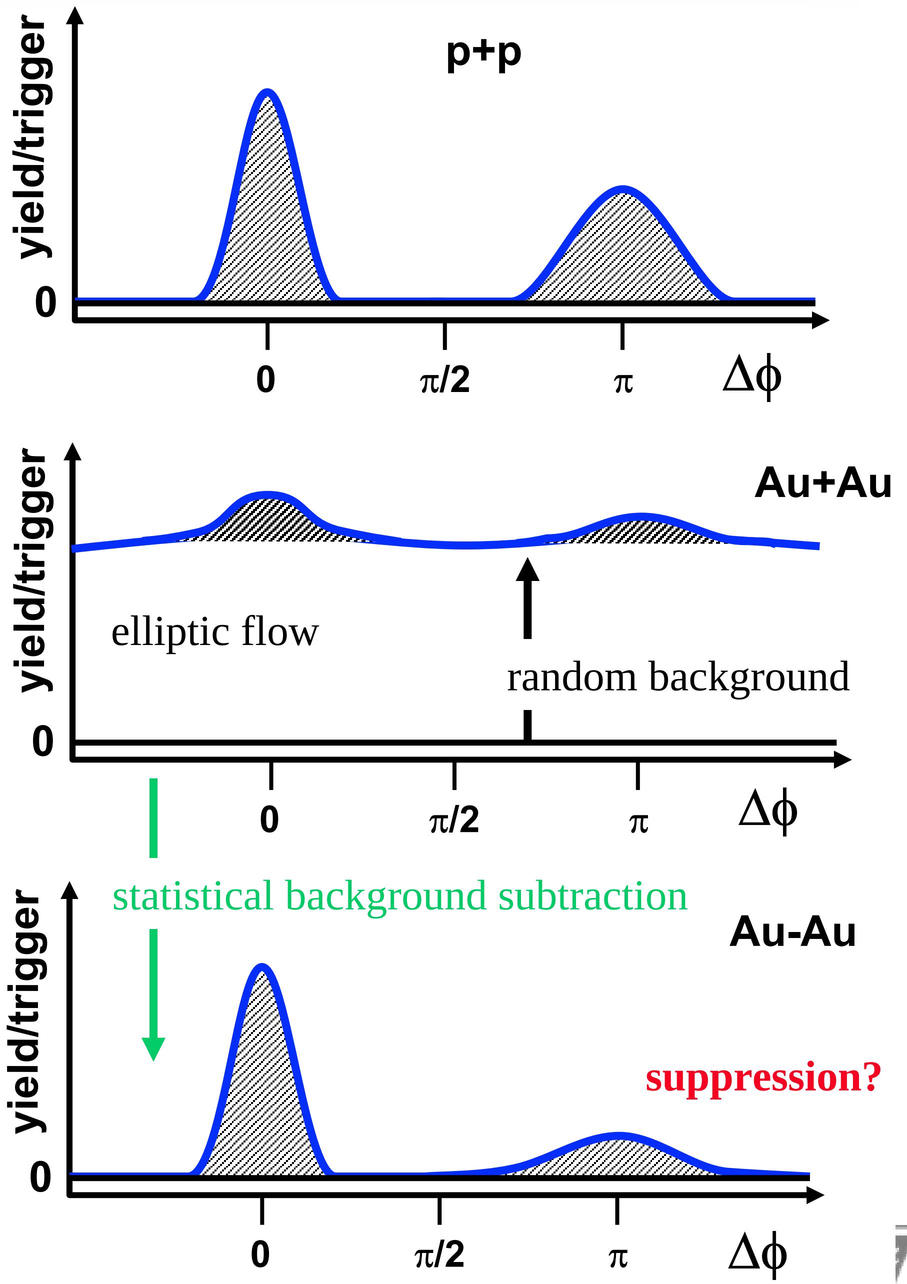
single particle spectra tell you a lot, but you should be able to learn even more from di-jets

Tomographic information on the medium



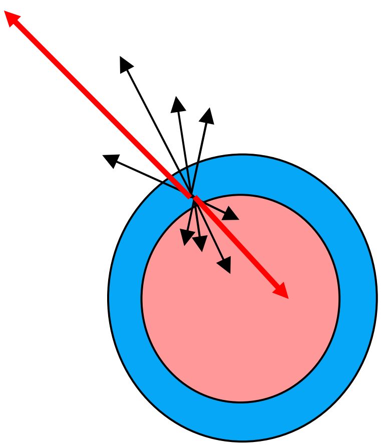
Azimuthal Correlations from Jets



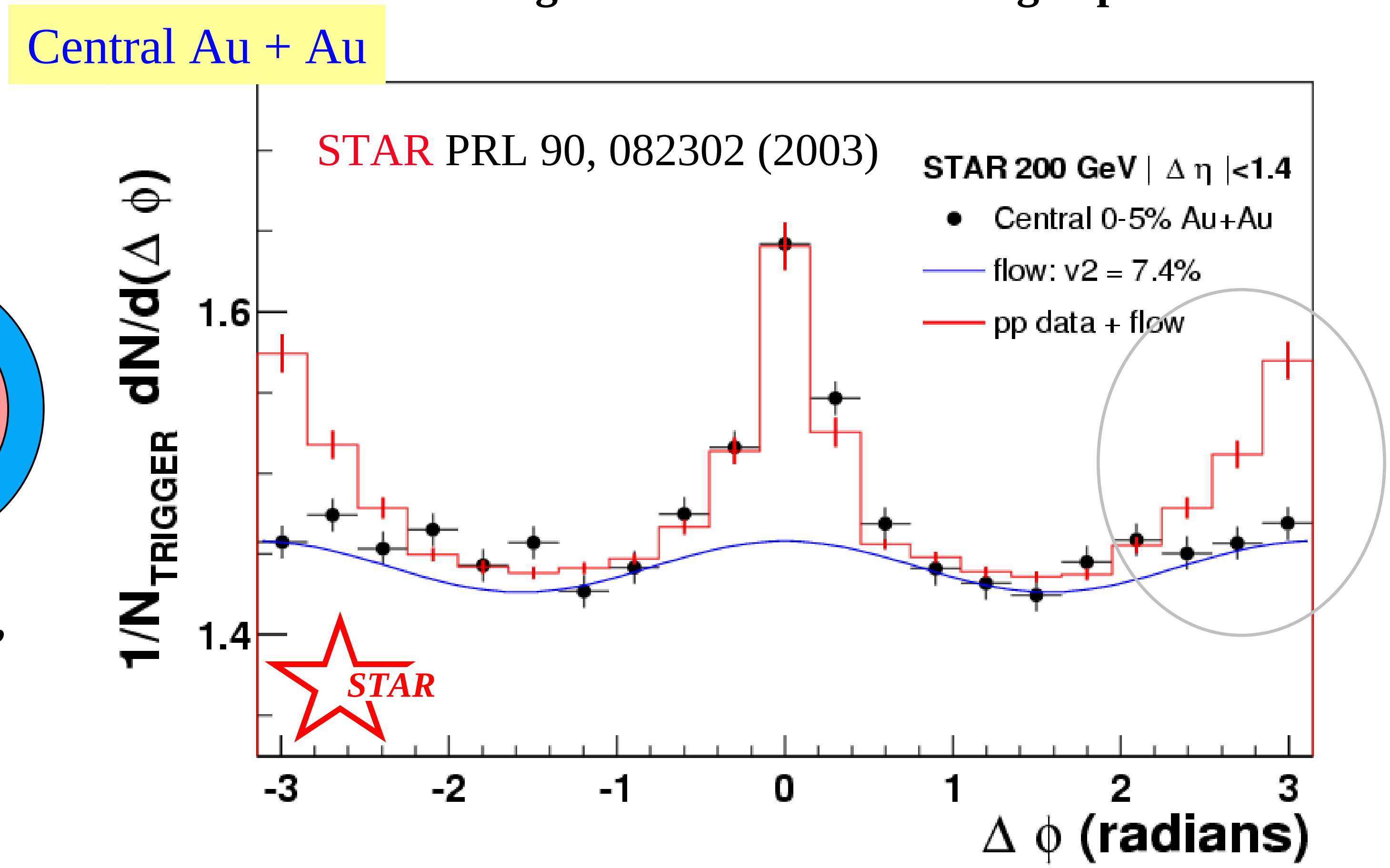


Jet correlations in Au-Au via statistical background subtraction

Disappearance of the "Away-Side" Jet



Azimuthal angular correlation of charged particles



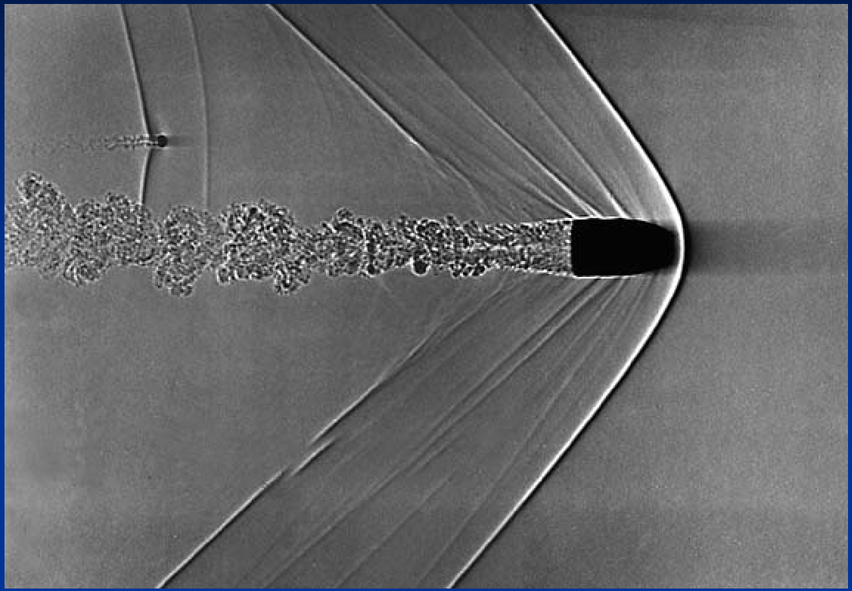
Suppression of away side jet in central Au+Au collisions

Jet quenching: conclusions

- Strong suppression of high-p_T hadrons and disappearance of the away-side jet in central AuAu
- No such effects in dAu
- No suppression of photons in AuAu
- => Jet quenching is due to final state (the presence of medium)
- The medium is extremely dense : dN/dy(gluons) ~ 1000 – indicative of QGP

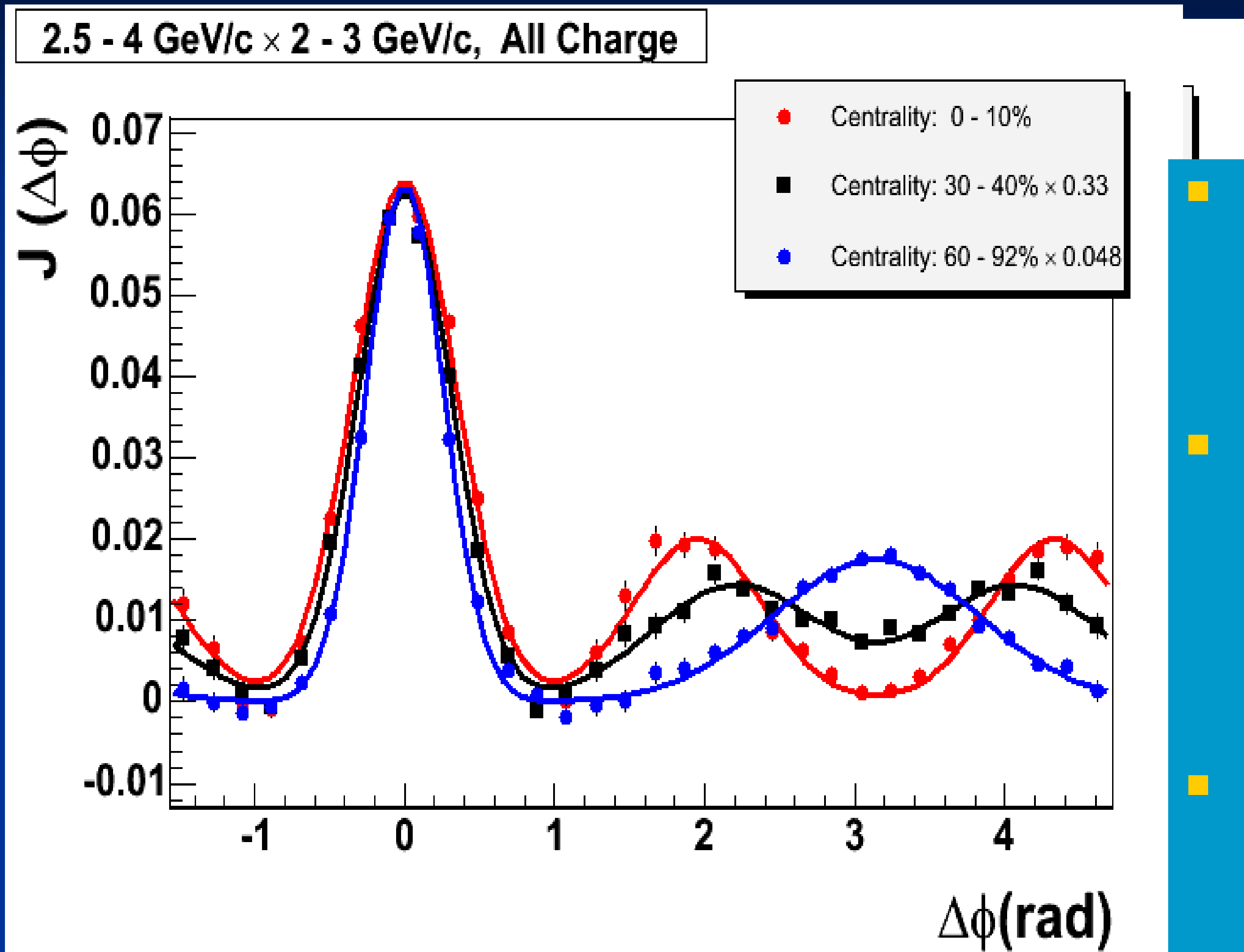
Splash!

Shock waves ?

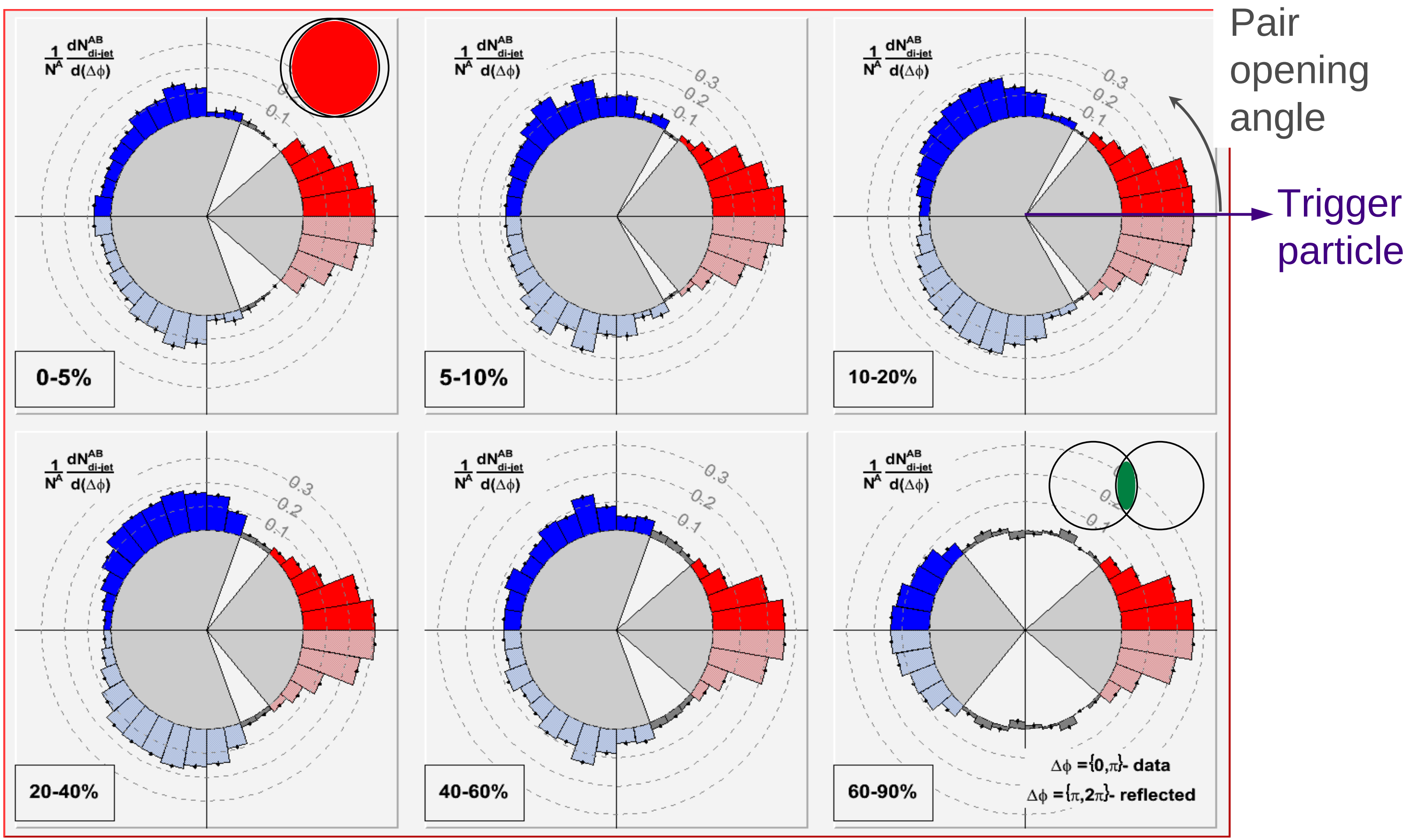


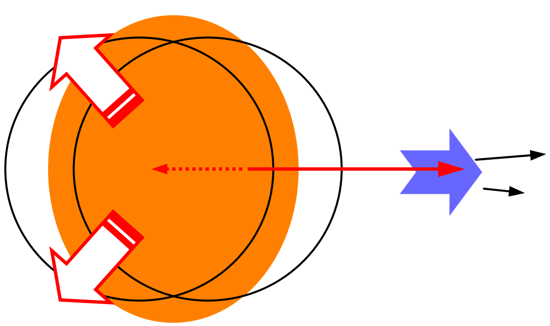
- It looks like the medium quenches the jets, but it also responds to the propagation of the fast moving parton
- If you look closely, you will find the lost energy at lower momenta !
- And … it looks like we have a tool to measure the speed of sound in QGP !

Here is what the data look like



- The shapes of jets are modified by the matter.
  - Mach cone?
  - Cerenkov?
- Can the properties of the matter be measured from the shape?
  - Sound velocity
  - Di-electric constant
- Di-jet tomography is a powerful tool to probe the matter

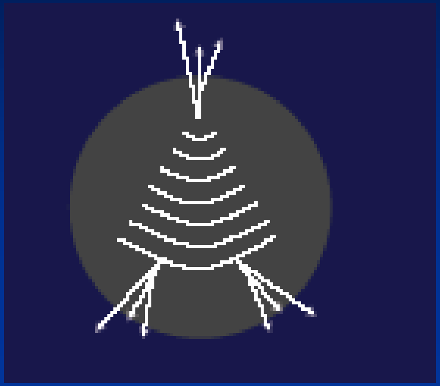


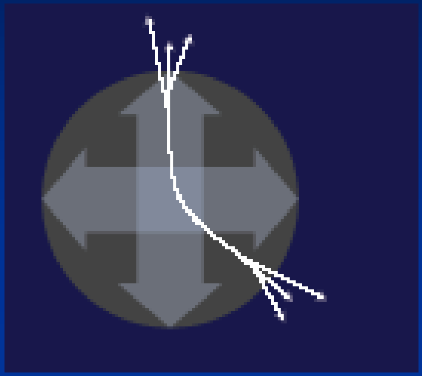


Suggestive of…

Cherenkov cones?
Mach cones?

Other ideas: shock waves vs bent jets





- Jets maybe deflected due to the radiual flow in the medium
- Testable via 3-particle correlations
- Present data (not yet conclusively) supports Mach cones