Title: Probing the Properties of the Quark-Gluon Plasma and the Studying QCD in the Strong-field Limit in Heavy Ion Collisions at RHIC and the LHC

Date: Feb 07, 2007 02:00 PM

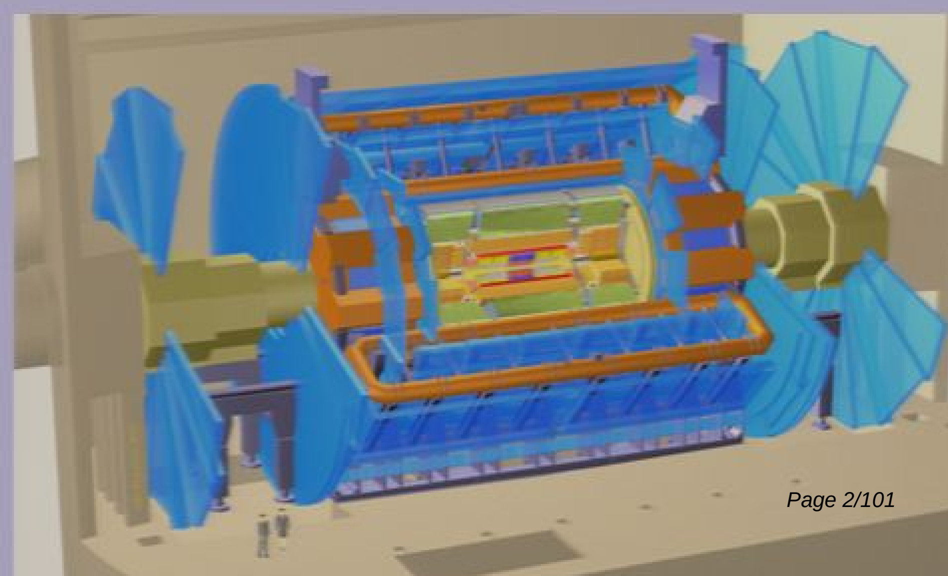
URL: http://pirsa.org/07020000

Abstract: Soon after Quantum Chromodynamics (QCD) was shown to exhibit asymptotic freedom at short distances, it was realized that it might be possible to create a new form of matter at high temperatures (T Â„d 150 MeV) in which hadrons dissolve and quarks and gluons become locally deconfined. Experiments have been carried out for the last two decades attempting to create this new form of matter, called Â¡Â§quark-gluon plasmaÂ¡Â¨ (QGP), via high-energy collisions of large nuclei. In 2000, the Relativistic Heavy Ion Collider (RHIC) started operation at Brookhaven National Laboratory in the US and results obtained from the first five years of RHIC operation provide the first convincing evidence for creation of the quark-gluon plasma in the laboratory. Measurements at RHIC show that the QGP is opaque to the passage of high-energy quarks and gluons and that interactions between the quarks and gluons in the QGP appears to be much stronger than initially expected. The estimated viscosity to entropy ratio of the QGP has been interpreted as showing that the QGP produced at RHIC is the most perfect fluid ever observed in the laboratory. Measurements from RHIC also suggest that the strong, coherent gluon fields in the incident nuclei play a significant role in the initial particle production and early evolution of the quark gluon plasma. Within the next few years, the large hadron collider will provide Pb+Pb collisions at a nucleon-nucleon center of mass energy of 5.5 TeV, thus opening a new frontier in the study of the QGP. I will provide a summary of the key experimental observables at RHIC, a discussion of their canonical interpretation and then discuss how measurements at the LHC can be used to test these interpretations.

Probing the Properties of the Quark-Gluon Plasma and Studying Strong-Field QCD in Heavy Ion Collisions @ RHIC and the LHC

Prof. Brian A. Cole.
Columbia University

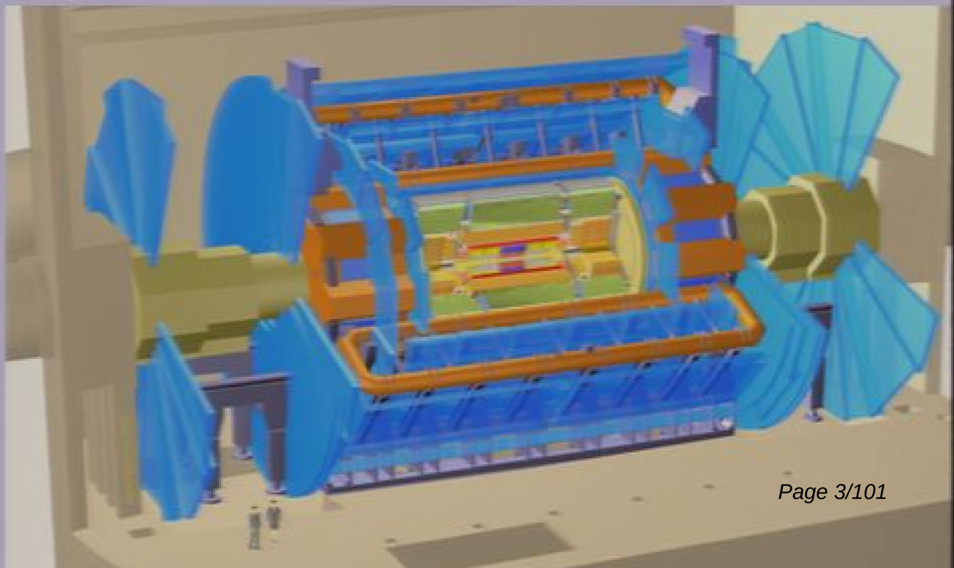
PHENIX and ATLAS



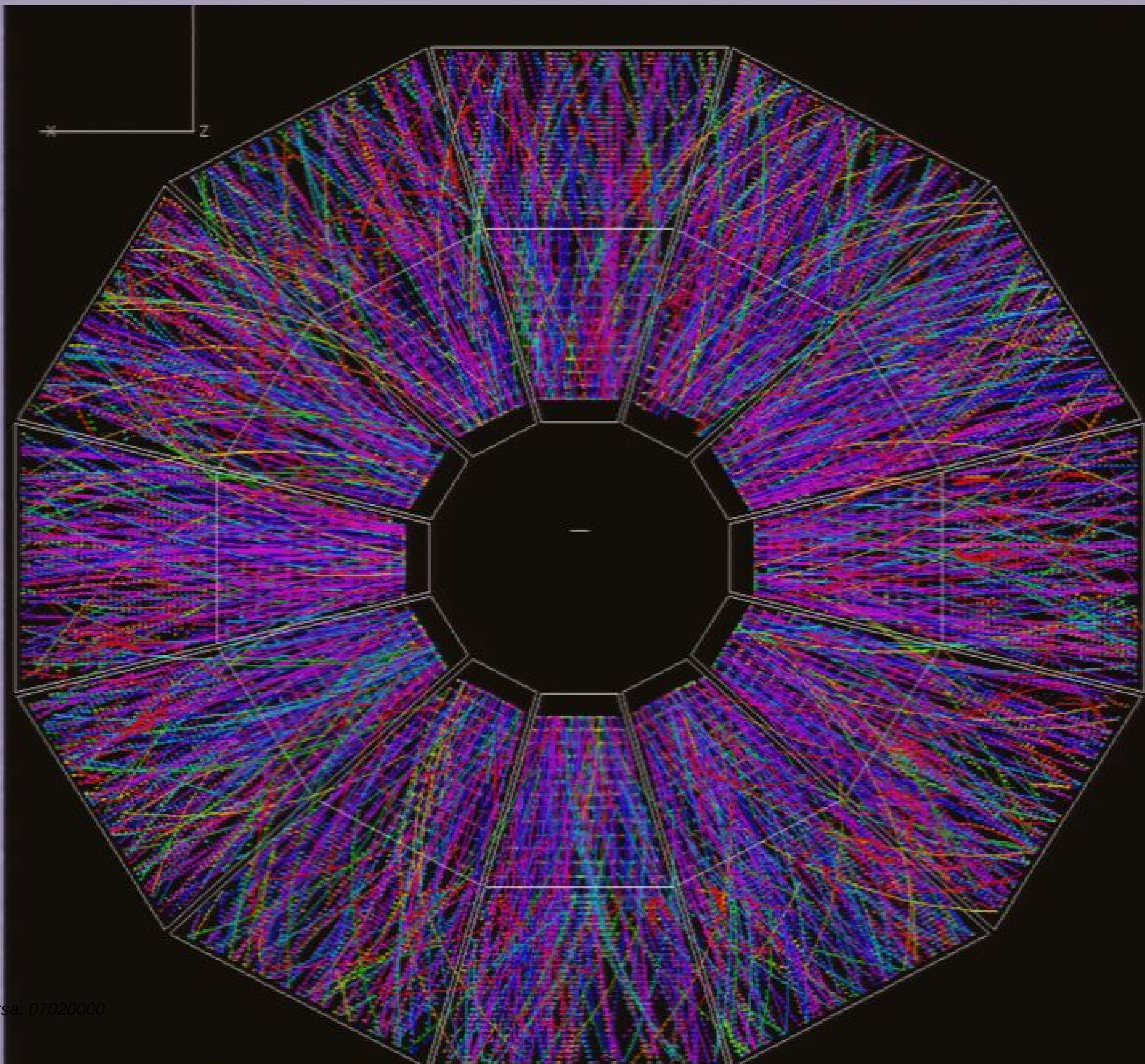
Probing the Properties of the Quark-Gluon Plasma and Studying Strong-Field QCD in Heavy Ion Collisions @ RHIC and the LHC

Prof. Brian A. Cole.
Columbia University

PHENIX and ATLAS



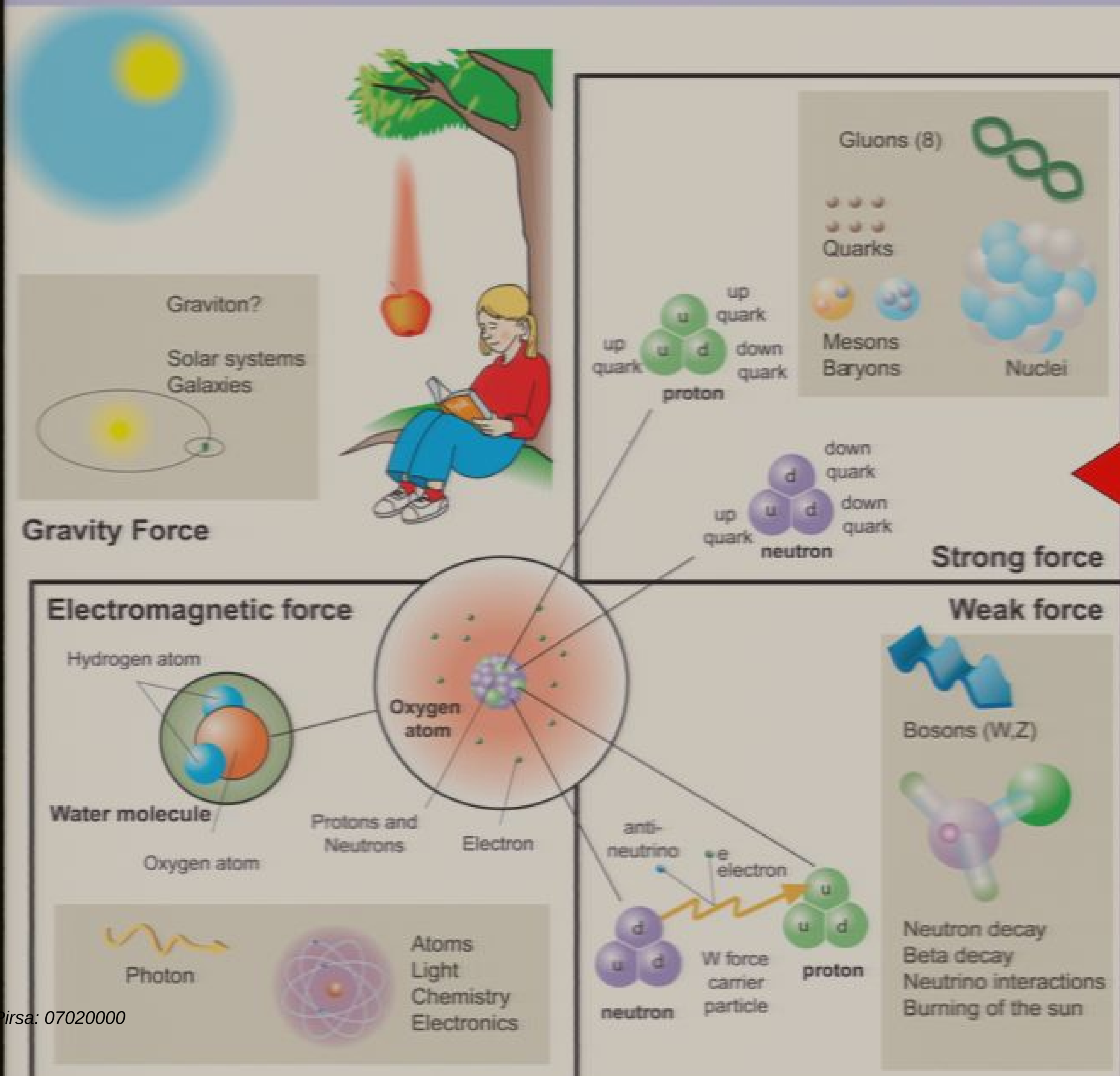
The “Big Picture”



Heavy Ion (Au+Au) collision as seen by the STAR time-projection chamber.

Why???

Fundamental Interactions



Matter usually studied in the lab has properties determined by EM interactions.

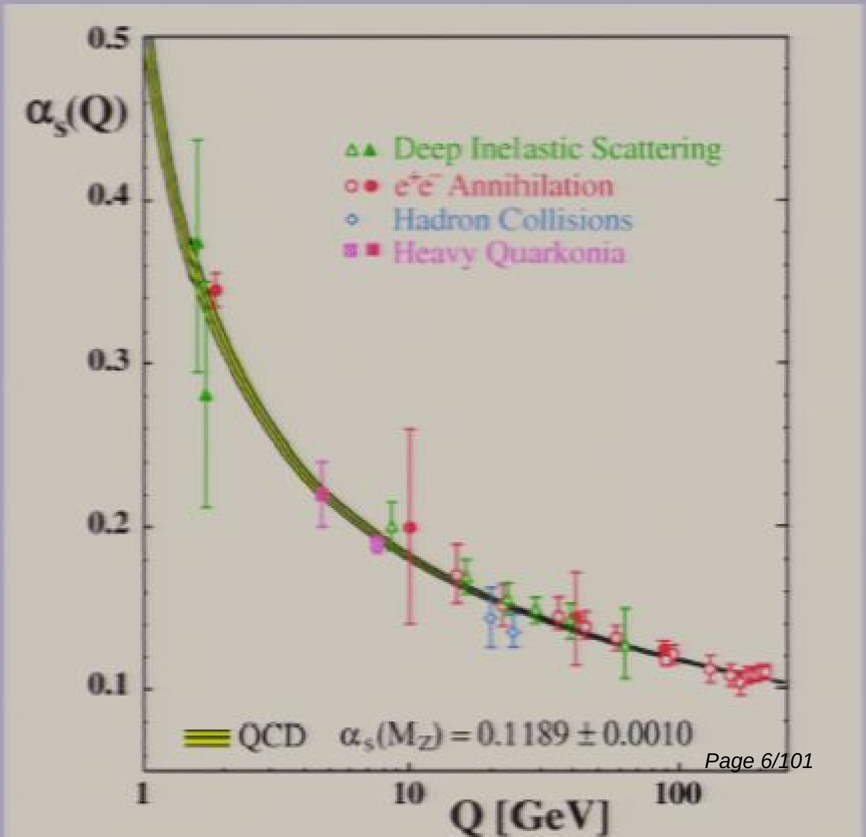
How would non-Abelian matter be different?

The Big Picture

- We have a fundamental theory of strong interactions

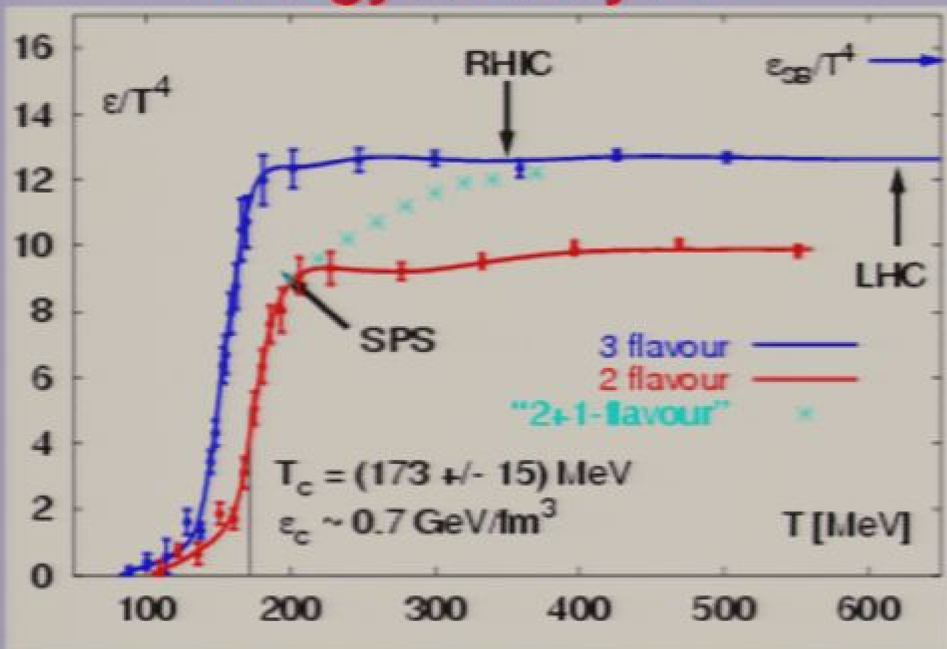
$$L_{QCD} = -\frac{1}{4} F^{\alpha}_{\mu\nu} F^{\mu\nu}_{\alpha} - \sum_n \overline{\psi}_n \left(\partial\!\!\!/ - ig\gamma^{\mu} A^{\alpha}_{\mu} t_{\alpha} - m_n \right) \psi_n$$

- exhibits asymptotic freedom at large momentum transfer.
- What about other limits of QCD?
  - **High temperature**
  - **High field strength**

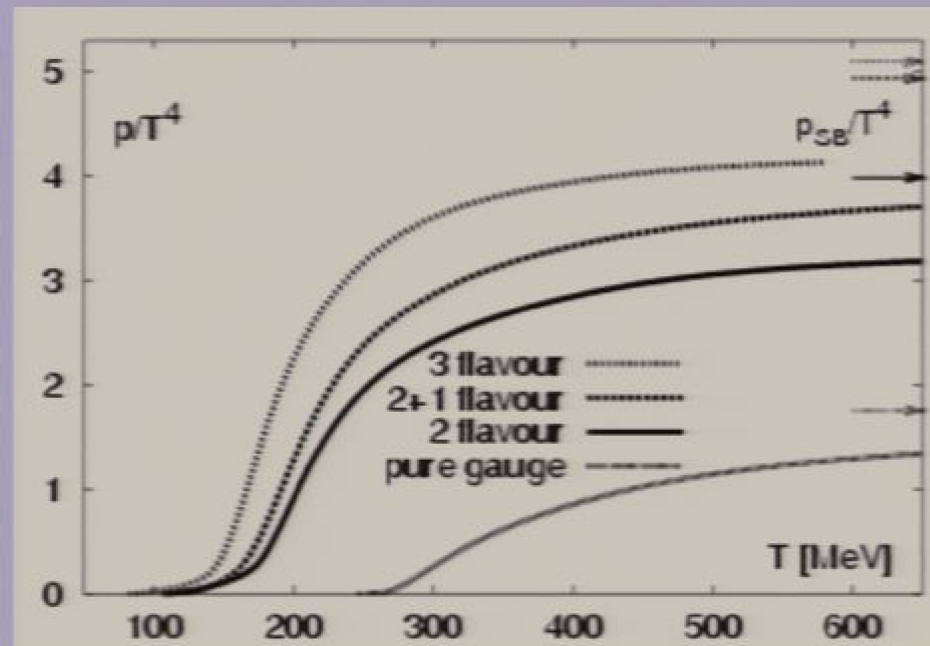


QCD Thermodynamics (on Lattice)

Energy Density / T^4



Pressure / T^4



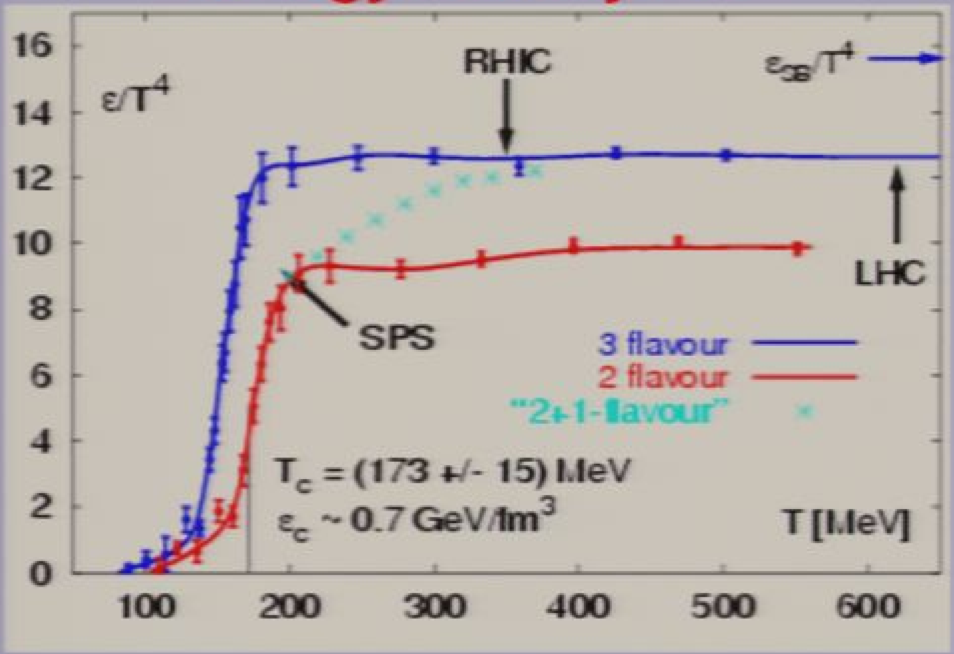
- Rapid cross-over from "hadronic matter" to "Quark-Gluon Plasma" at T ~ 170 MeV
  - ⇒Energy density, $\varepsilon \sim 1\ GeV/fm^3$.
- **Only fundamental "phase transition" that can be studied in the laboratory.**
  - –**Is the QGP weakly interacting??**

Relativistic Heavy Ion Collider

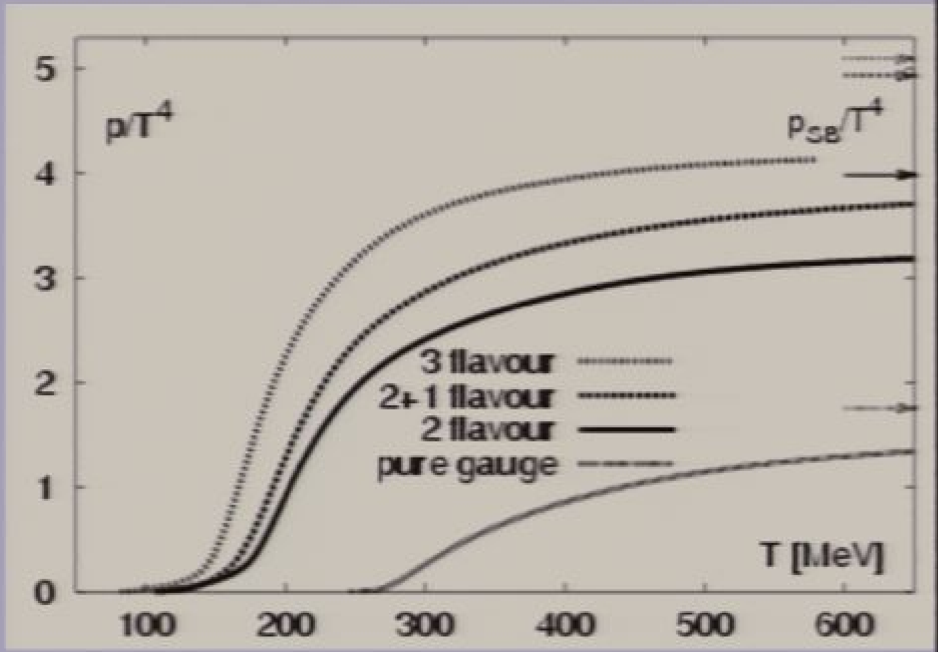
- Run 1 (2000): Au-Au $\sqrt{S_{NN}}$ = 130 GeV
- Run 2 (2001): Au-Au, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 3 (2003): d-Au, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 4 (2004): Au-Au $\sqrt{S_{NN}}$ = 200, 64 GeV, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 5 (2005): Cu-Cu $\sqrt{S_{NN}}$ = 200, 64 GeV, p-p $\sqrt{S_{NN}}$ = 200 GeV

QCD Thermodynamics (on Lattice)

Energy Density / T^4



Pressure / T^4



- Rapid cross-over from "hadronic matter" to "Quark-Gluon Plasma" at T ~ 170 MeV

  ⇒Energy density, $\varepsilon \sim 1$ GeV/fm^3.

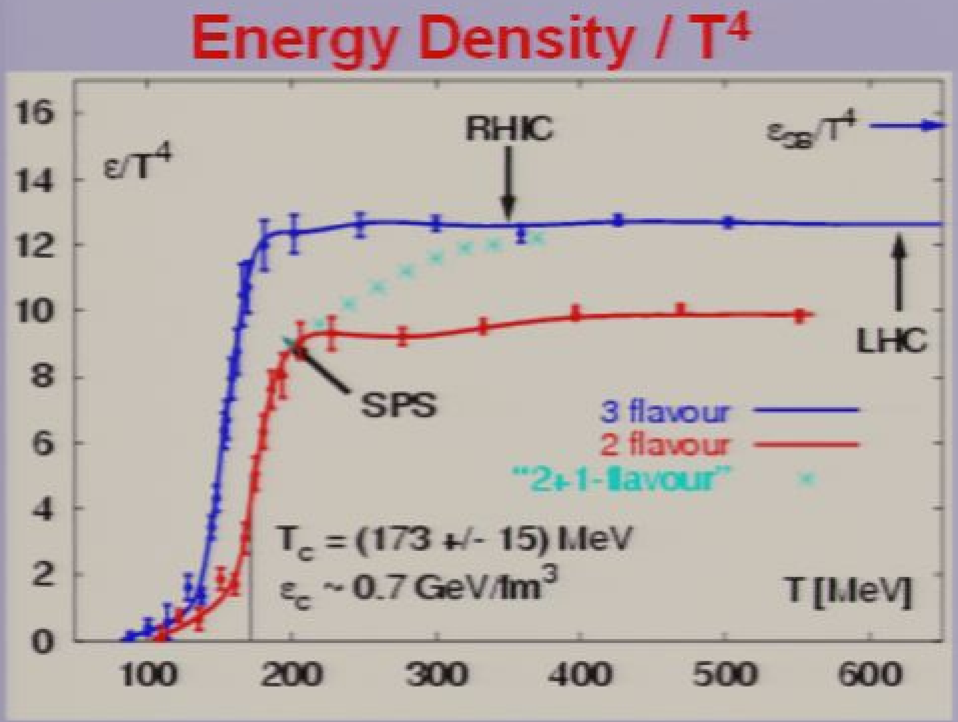
- **Only fundamental "phase transition" that can be studied in the laboratory**.

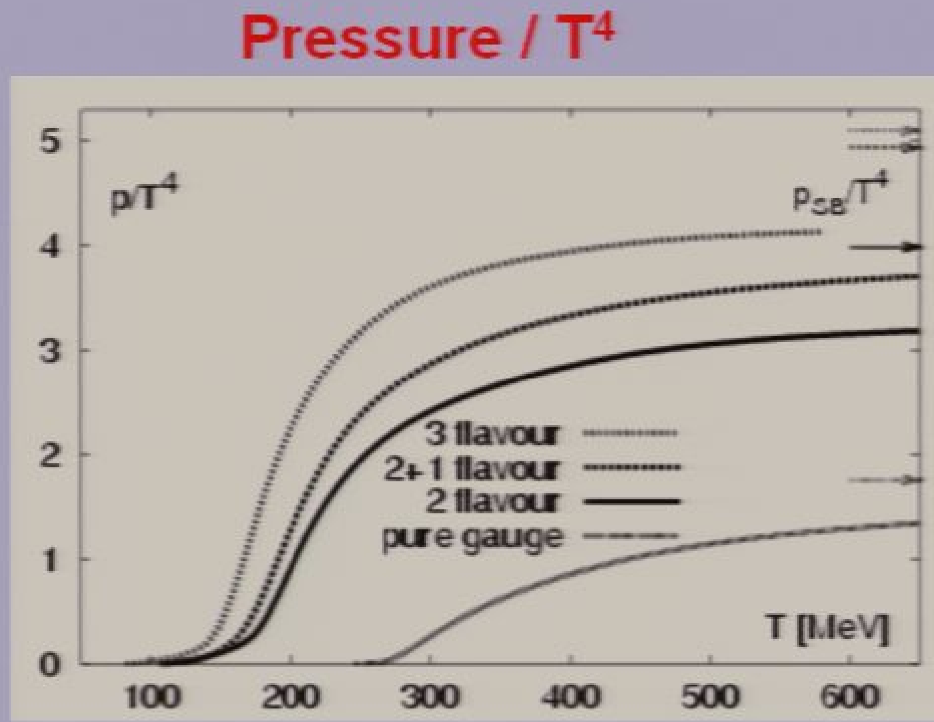
  –**Is the QGP weakly interacting??**

Relativistic Heavy Ion Collider

- ➢Run 1 (2000): Au-Au $\sqrt{S_{NN}}$ = 130 GeV
- ➢Run 2 (2001): Au-Au, p-p $\sqrt{S_{NN}}$ = 200 GeV
- ➢Run 3 (2003): d-Au, p-p $\sqrt{S_{NN}}$ = 200 GeV
- ➢Run 4 (2004): Au-Au $\sqrt{S_{NN}}$ = 200, 64 GeV, p-p $\sqrt{S_{NN}}$ = 200 GeV
- ➢Run 5 (2005): Cu-Cu $\sqrt{S_{NN}}$ = 200, 64 GeV, p-p $\sqrt{S_{NN}}$ = 200 GeV

QCD Thermodynamics (on Lattice)





- Rapid cross-over from "hadronic matter" to "Quark-Gluon Plasma" at T ~ 170 MeV

  ⇒Energy density, $\varepsilon \sim 1$ GeV/fm^3.

- **Only fundamental "phase transition" that can be studied in the laboratory**.

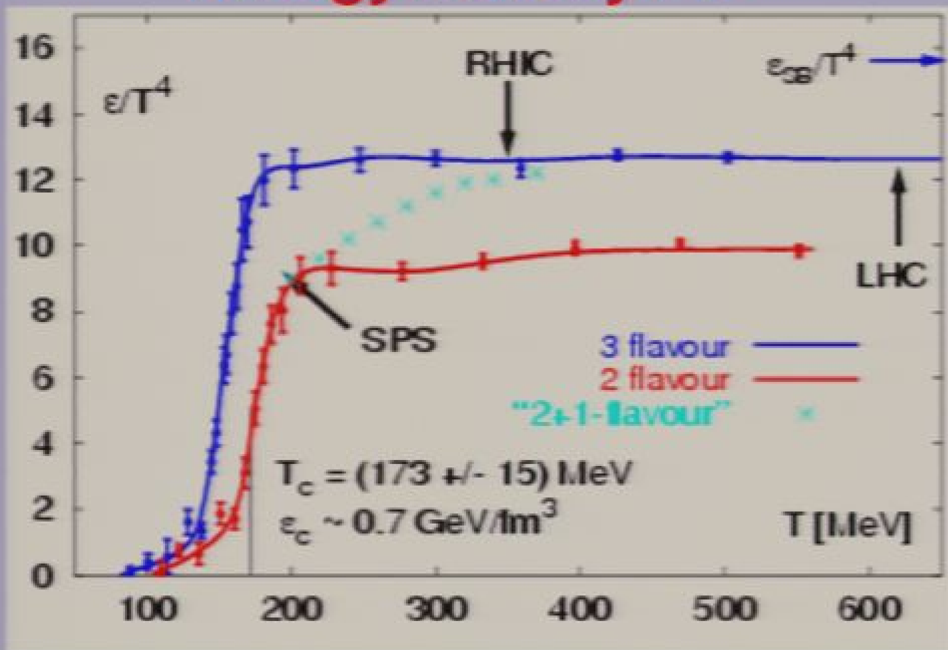
–Is the QGP weakly interacting??

Relativistic Heavy Ion Collider

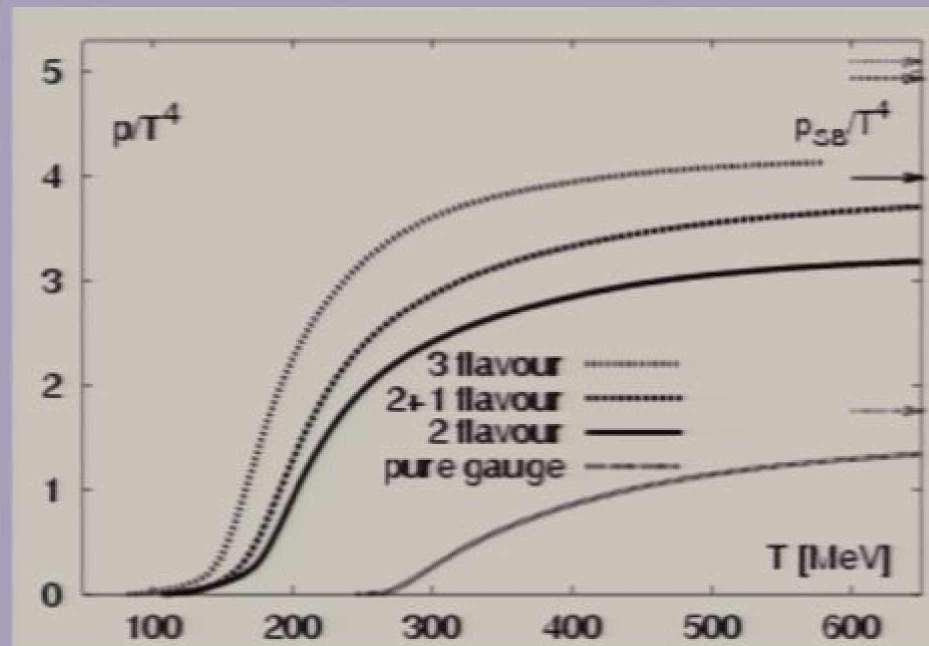
- Run 1 (2000): Au-Au $\sqrt{S_{NN}}$ = 130 GeV
- Run 2 (2001): Au-Au, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 3 (2003): d-Au, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 4 (2004): Au-Au $\sqrt{S_{NN}}$ = 200, 64 GeV, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 5 (2005): Cu-Cu $\sqrt{S_{NN}}$ = 200, 64 GeV, p-p $\sqrt{S_{NN}}$ = 200 GeV

QCD Thermodynamics (on Lattice)

Energy Density / T^4



Pressure / T^4



- Rapid cross-over from "hadronic matter" to "Quark-Gluon Plasma" at T ~ 170 MeV

  ⇒Energy density, $\varepsilon \sim 1$ GeV/fm^3.

- **Only fundamental "phase transition" that can be studied in the laboratory**.

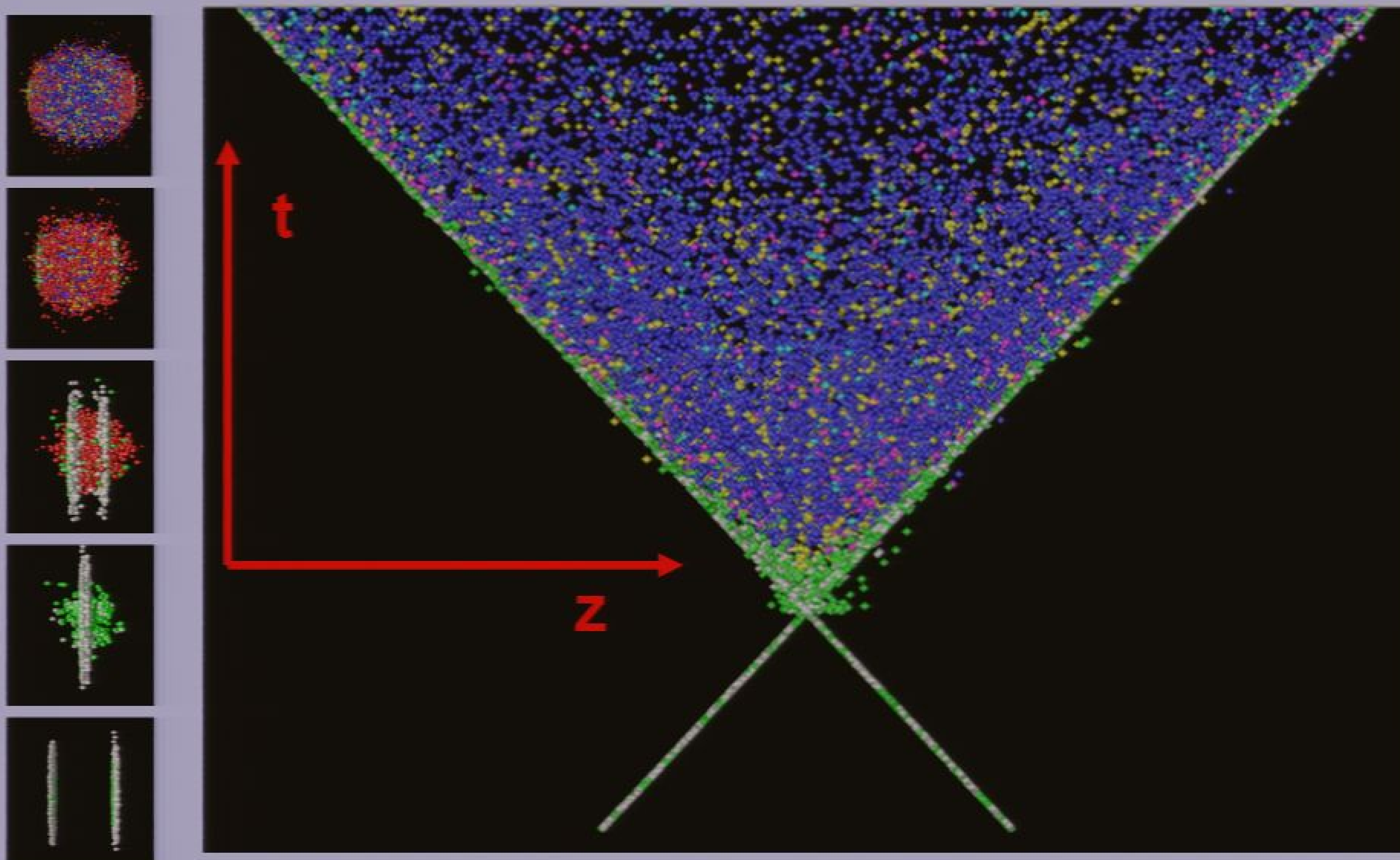
  –**Is the QGP weakly interacting??**

Relativistic Heavy Ion Collider

- Run 1 (2000): Au-Au $\sqrt{S_{NN}}$ = 130 GeV
- Run 2 (2001): Au-Au, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 3 (2003): d-Au, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 4 (2004): Au-Au $\sqrt{S_{NN}}$ = 200, 64 GeV, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 5 (2005): Cu-Cu $\sqrt{S_{NN}}$ = 200, 64 GeV, p-p $\sqrt{S_{NN}}$ = 200 GeV

Heavy Ion Collision Time History

RHIC collision space-time history in "parton cascade" model

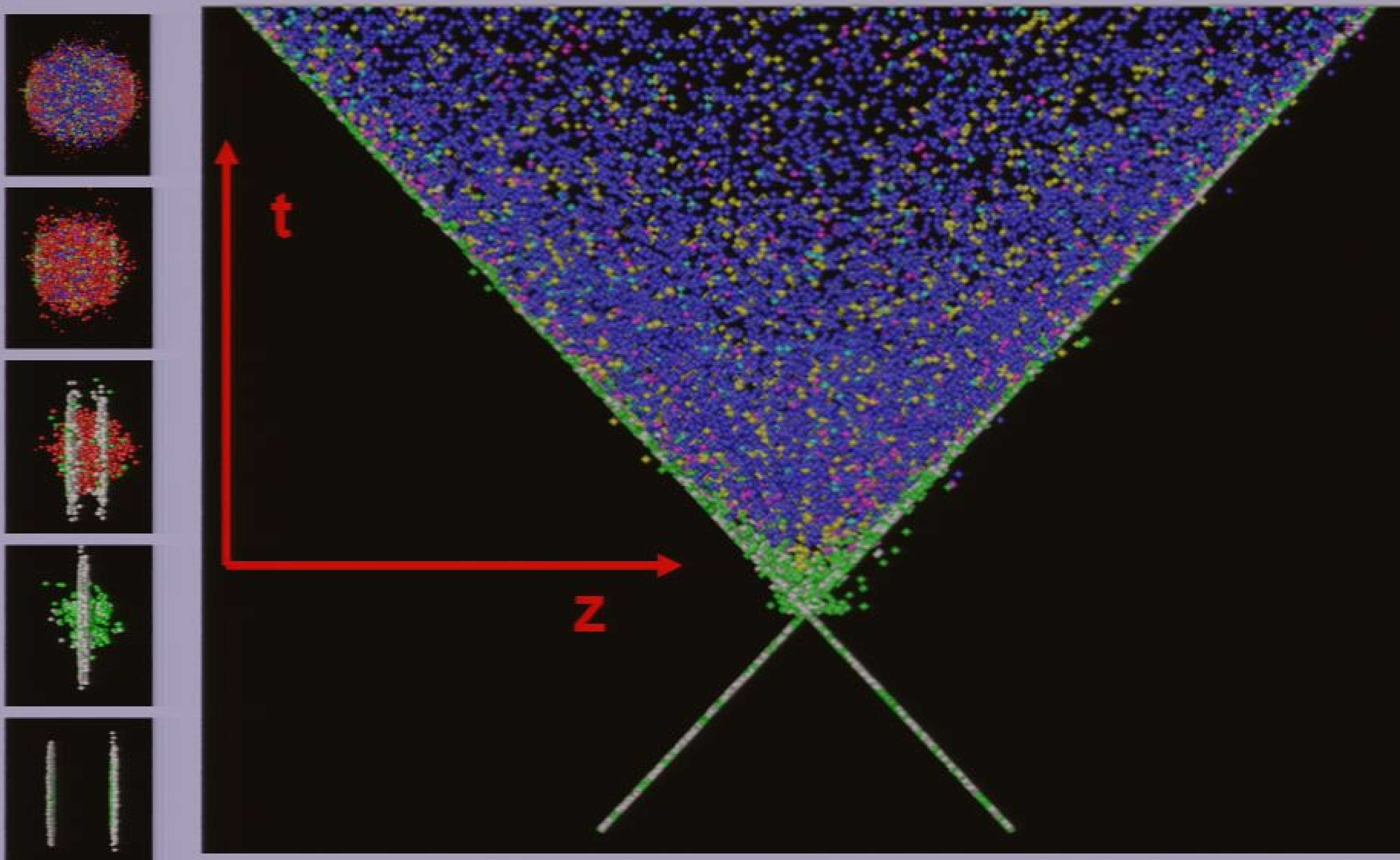


Relativistic Heavy Ion Collider

- Run 1 (2000): Au-Au $\sqrt{S_{NN}}$ = 130 GeV
- Run 2 (2001): Au-Au, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 3 (2003): d-Au, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 4 (2004): Au-Au $\sqrt{S_{NN}}$ = 200, 64 GeV, p-p $\sqrt{S_{NN}}$ = 200 GeV
- Run 5 (2005): Cu-Cu $\sqrt{S_{NN}}$ = 200, 64 GeV, p-p $\sqrt{S_{NN}}$ = 200 GeV

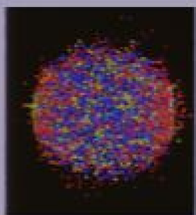
Heavy Ion Collision Time History

RHIC collision space-time history in "parton cascade" model

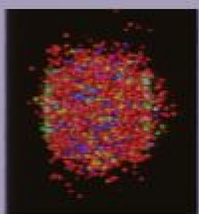


Heavy Ion Collision Time History

RHIC collision space-time history in "parton cascade" model

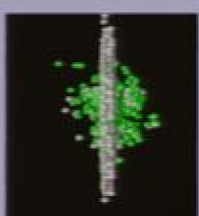


Hadronization (interesting but I won't cover)



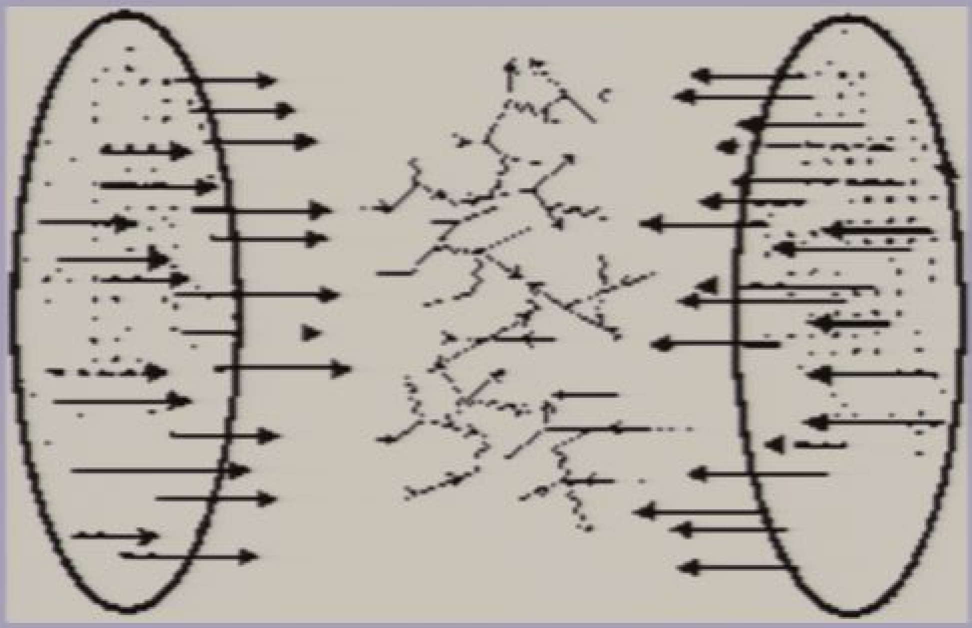
"Hydrodynamic" evolution

Rapid thermalization



Initial particle production from strong fields

RHIC Initial Conditions



- Au+Au @ 200 GeV per nucleon, γ = **E/m ≈ 100**.
  - –Au diameter, **d ≈ 14 fm,** contracted **d/γ ≈ 0.2 fm**
    - ⇒ Crossing time **< 0.2 fm/c**.
- Add quantum mechanics: **$\Delta E \geq \hbar c / \Delta t$**
  - –Fluctuations with **ΔE > 1 GeV** are "on shell"
    - ⇒These are primarily gluons (**~ 200/collision**)
    - ⇒**RHIC is a gluon collider!** (10 GeV/fm^3)

"Saturation" @ low x

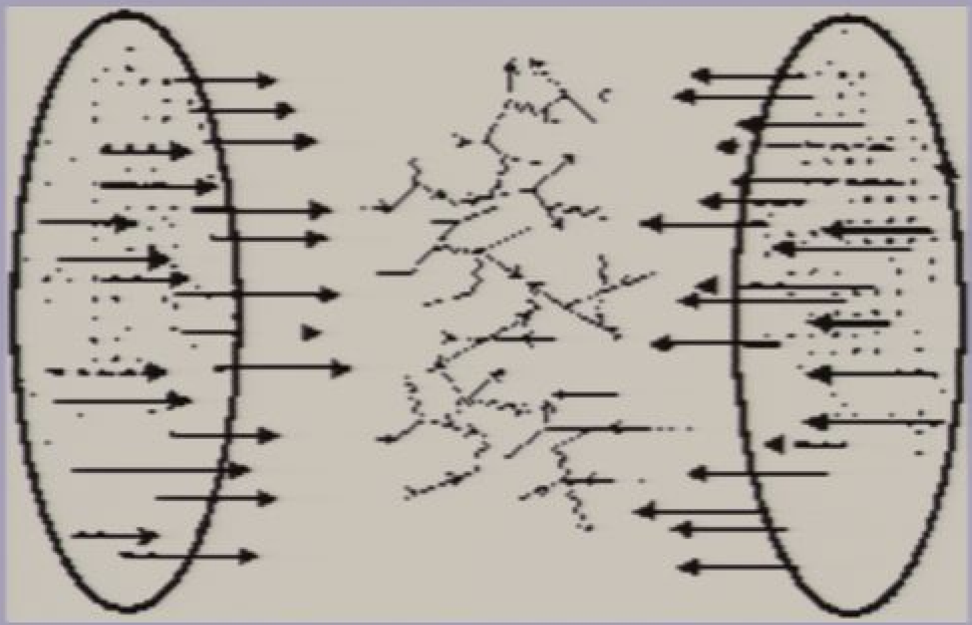
- @ High energy nuclei are highly Lorentz contracted
  - Except for soft gluons
  - Which overlap longitudinally
  - **And recombine producing broadened k_T distribution**

    ⇒Generates a new scale: $\mathbf{Q_s}$

    ⇒**Typical k_T of gluons**
- If $Q_s >> \Lambda_{QCD}$, perturbative calculations possible.

    ⇒Large occupation #s for $k_T<Q_s$ ⇒ classcial fields
- Saturation is a result of unitarity in QCD

RHIC Initial Conditions



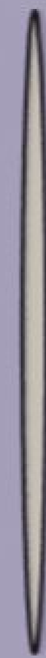
- Au+Au @ 200 GeV per nucleon, γ **= E/m ≈ 100**.
  - Au diameter, **d ≈ 14 fm,** contracted **d/γ ≈ 0.2 fm**
    - ⇒ Crossing time **< 0.2 fm/c**.
- Add quantum mechanics: **$\Delta E \geq \hbar c / \Delta t$**
  - Fluctuations with **ΔE > 1 GeV** are "on shell"
    - ⇒These are primarily gluons (**~ 200/collision**)
    - ⇒**RHIC is a gluon collider!** (10 GeV/fm^3)

"Saturation" @ low x

- @ High energy nuclei are highly Lorentz contracted
  - Except for soft gluons
  - Which overlap longitudinally
  - **And recombine producing broadened k_T distribution**
    - ⇒Generates a new scale: **Q_s**
    - **⇒Typical k_T of gluons**
- If $Q_s >> \Lambda_{QCD}$, perturbative calculations possible.
    - ⇒Large occupation #s for $k_T < Q_s \Rightarrow$ classcial fields
- Saturation is a result of unitarity in QCD

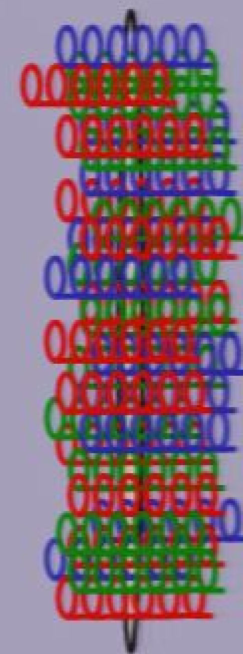
"Saturation" @ low x

- @ High energy nuclei are highly Lorentz contracted
  - Except for soft gluons
  - Which overlap longitudinally
  - **And recombine producing broadened k_T distribution**
    - ⇒Generates a new scale: $\mathbf{Q_s}$
    - **⇒Typical k_T of gluons**
- If $Q_s >> \Lambda_{QCD}$, perturbative calculations possible.
  - ⇒Large occupation #s for $k_T < Q_s \Rightarrow$ classcial fields
- Saturation is a result of unitarity in QCD



“Saturation” @ low x

- @ High energy nuclei are highly Lorentz contracted
  - Except for soft gluons
  - Which overlap longitudinally
  - **And recombine producing broadened k_T distribution**
    - $\Rightarrow$Generates a new scale: $\mathbf{Q_s}$
    - $\Rightarrow$**Typical k_T of gluons**



- If $Q_s >> \Lambda_{QCD}$, perturbative calculations possible.
  - $\Rightarrow$Large occupation #s for $k_T<Q_s \Rightarrow$ classcial fields
- Saturation is a result of unitarity in QCD

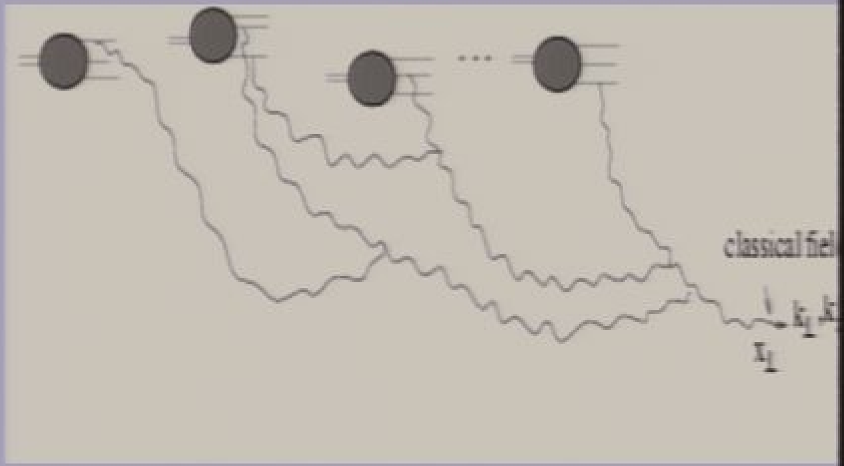
"Saturation" @ low x

- @ High energy nuclei are highly Lorentz contracted
  - Except for soft gluons
  - Which overlap longitudinally
  - **And recombine producing broadened k_T distribution**

    ⇒Generates a new scale: **Q_s**

    ⇒**Typical k_T of gluons**
- If $Q_s >> \Lambda_{QCD}$, perturbative calculations possible.

  ⇒Large occupation #s for $k_T < Q_s$ ⇒ classcial fields
- Saturation is a result of unitarity in QCD

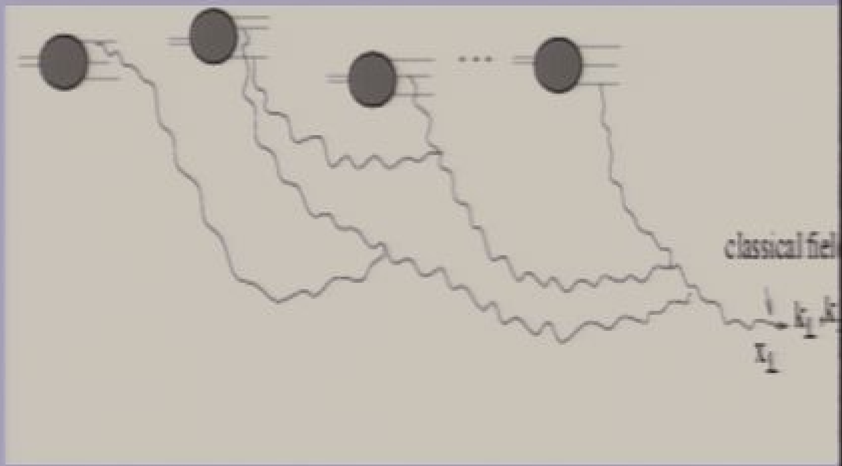


"Saturation" @ low x

- @ High energy nuclei are highly Lorentz contracted
  - Except for soft gluons
  - Which overlap longitudinally
  - And recombine producing broadened k_T distribution

    ⇒Generates a new scale: Q_s

    ⇒Typical k_T of gluons



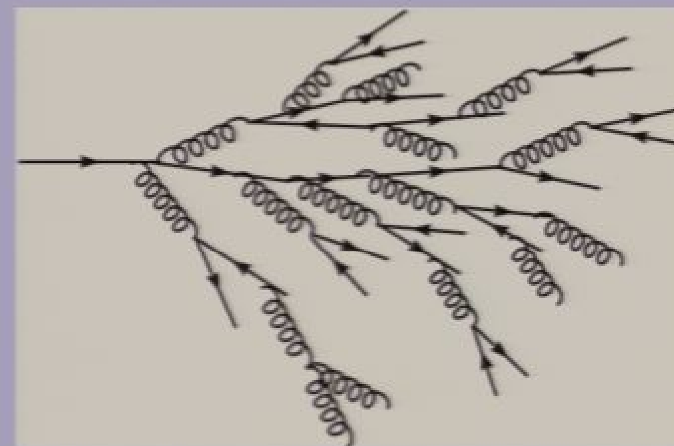
- If $Q_s >> \Lambda_{QCD}$, perturbative calculations possible.

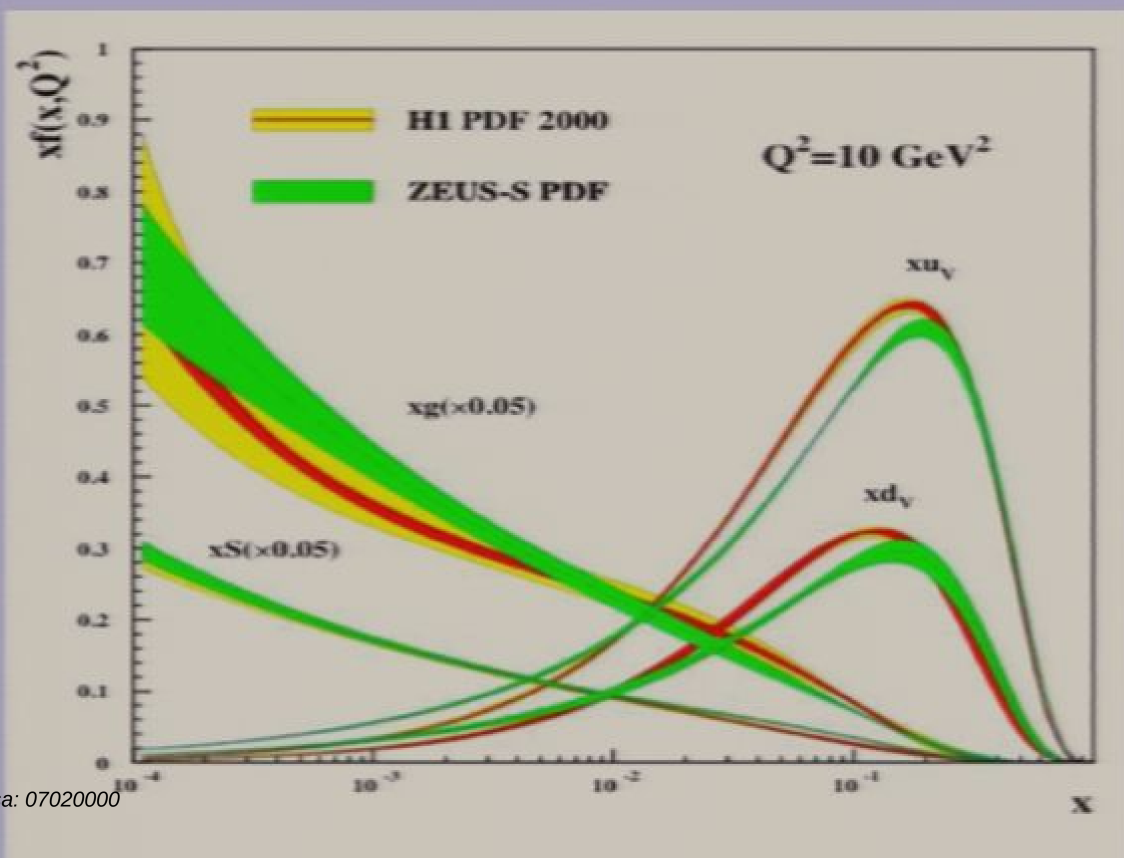
    ⇒Large occupation #s for $k_T<Q_s$ ⇒ classcial fields

- Saturation is a result of unitarity in QCD

QCD: Evolution

- Quarks radiate copiously
  - ⇒ Evolution of proton (e.g.) parton distribution functions
  - ⇒ Growth of gluon distribution @ low x



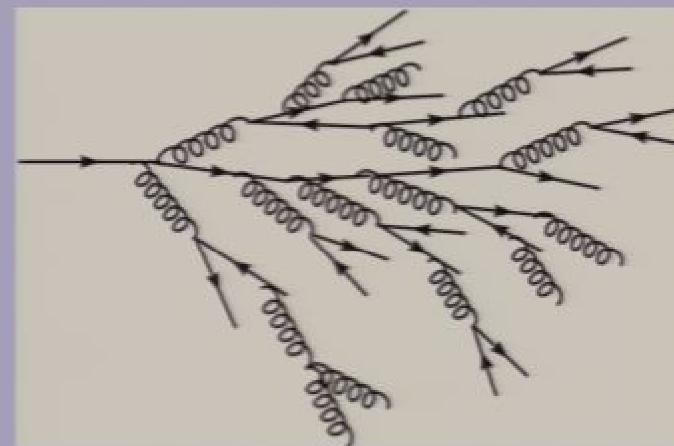


- @ high gluon density recombination starts to limit growth.
- Q_s - resolution scale where recombination starts to dominate
- Limiting density ∝ Q_s^2/α_s

–~ Classical field

QCD: Evolution

- Quarks radiate copiously
  - ⇒ Evolution of proton (e.g.) parton distribution functions
  - ⇒ Growth of gluon distribution @ low x



- Number of gluons per unit area:

$$\rho \sim \frac{xG_A(x, Q^2)}{\pi R_A^2}$$

- Recombination cross-section:

$$\sigma_{gg\to g} \sim \frac{\alpha_s}{Q^2}$$

- Recombination happens if $\rho\sigma_{gg\to g} \gtrsim 1$, i.e. $Q^2 \lesssim Q_s^2$, with:

$$Q_s^2 \sim \frac{\alpha_s x G_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3}\frac{1}{x^{0.3}}$$

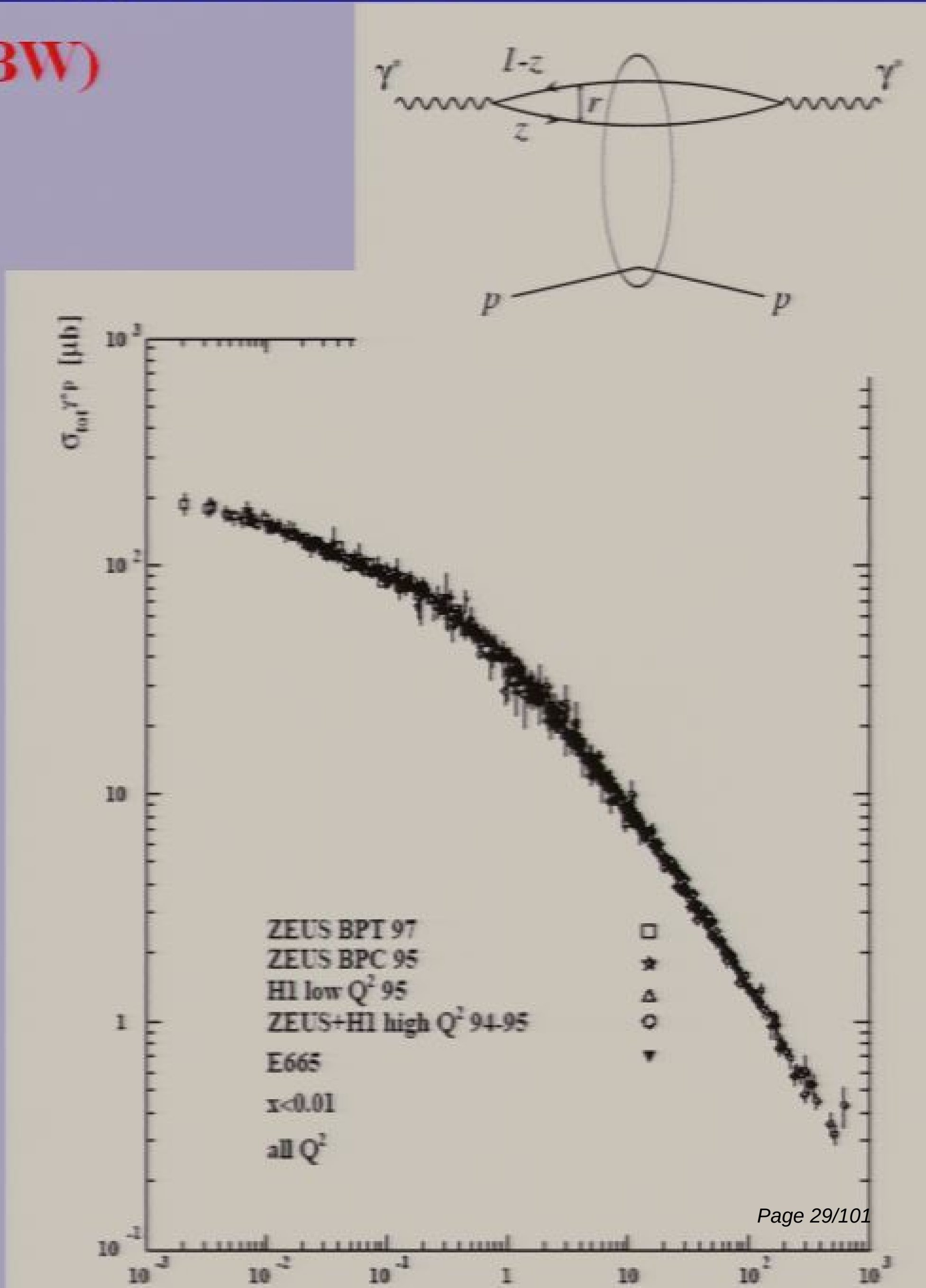
- @ high gluon density recombination starts to limit growth.
- Q_s - resolution scale where recombination starts to dominate
- Limiting density ∝ Q_s^2/α_s

–~ Classical field

Saturation @ HERA?

Golec-Biernat and Wusthoff (GBW) Saturation Model (empirical)

- Measurements of DIS cross-section vs x, Q^2 for x < 0.01.
- Plotted vs $\tau \equiv \frac{Q^2}{Q_s^2(x)}$
- All x dependence in the saturation scale.
  - "Geometric scaling"
- Precursor to saturation in PDF evolution



QCD: Evolution

- Quarks radiate copiously
  - ⇒ Evolution of proton (e.g.) parton distribution functions
  - ⇒ Growth of gluon distribution @ low x

- Number of gluons per unit area:

$$\rho \sim \frac{xG_A(x, Q^2)}{\pi R_A^2}$$

- Recombination cross-section:

$$\sigma_{gg \to g} \sim \frac{\alpha_s}{Q^2}$$

- Recombination happens if $\rho \sigma_{gg \to g} \gtrsim 1$, i.e. $Q^2 \lesssim Q_s^2$, with:

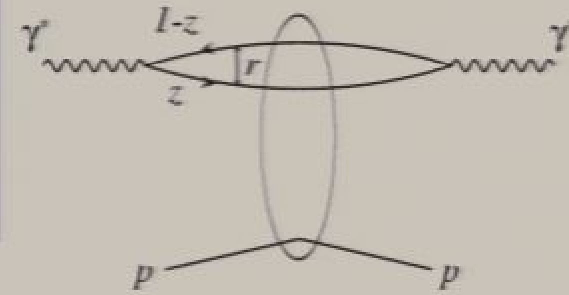
$$Q_s^2 \sim \frac{\alpha_s xG_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3} \frac{1}{x^{0.3}}$$

- @ high gluon density recombination starts to limit growth.
- Q_s - resolution scale where recombination starts to dominate
- Limiting density ∝ Q_s^2/α_s

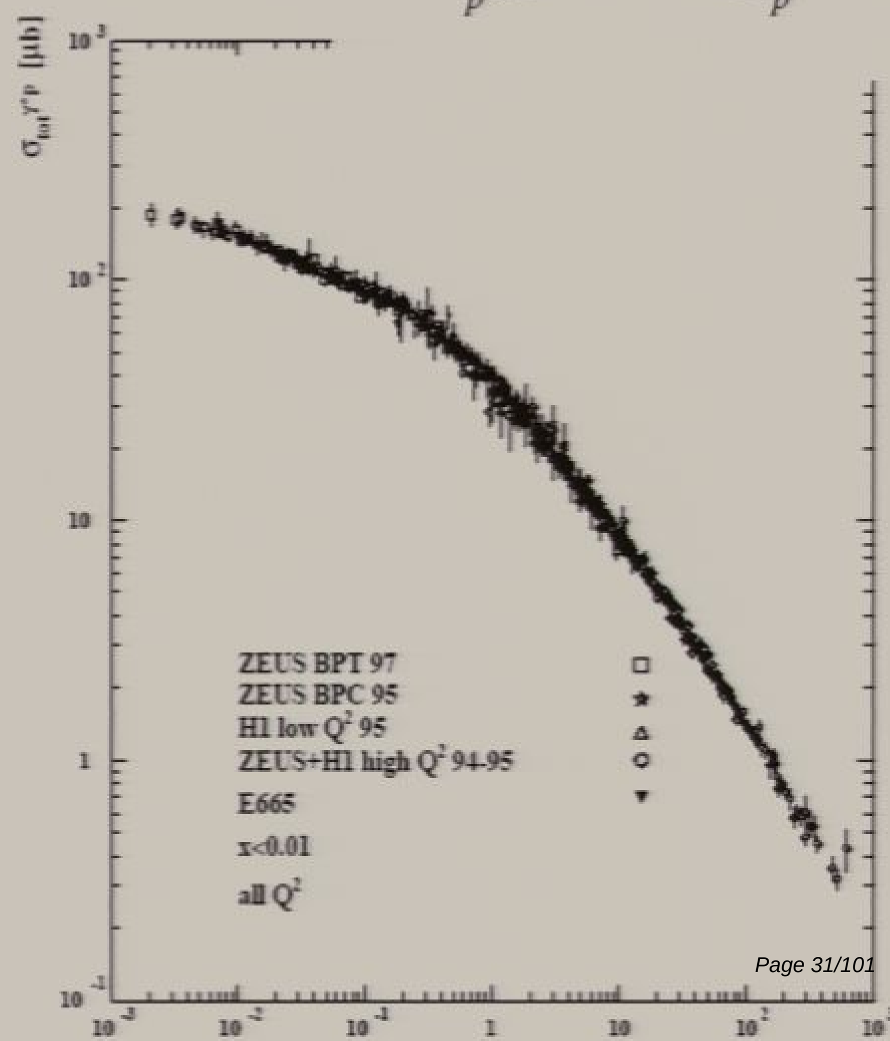
–~ Classical field

Saturation @ HERA?

Golec-Biernat and Wusthoff (GBW) Saturation Model (empirical)

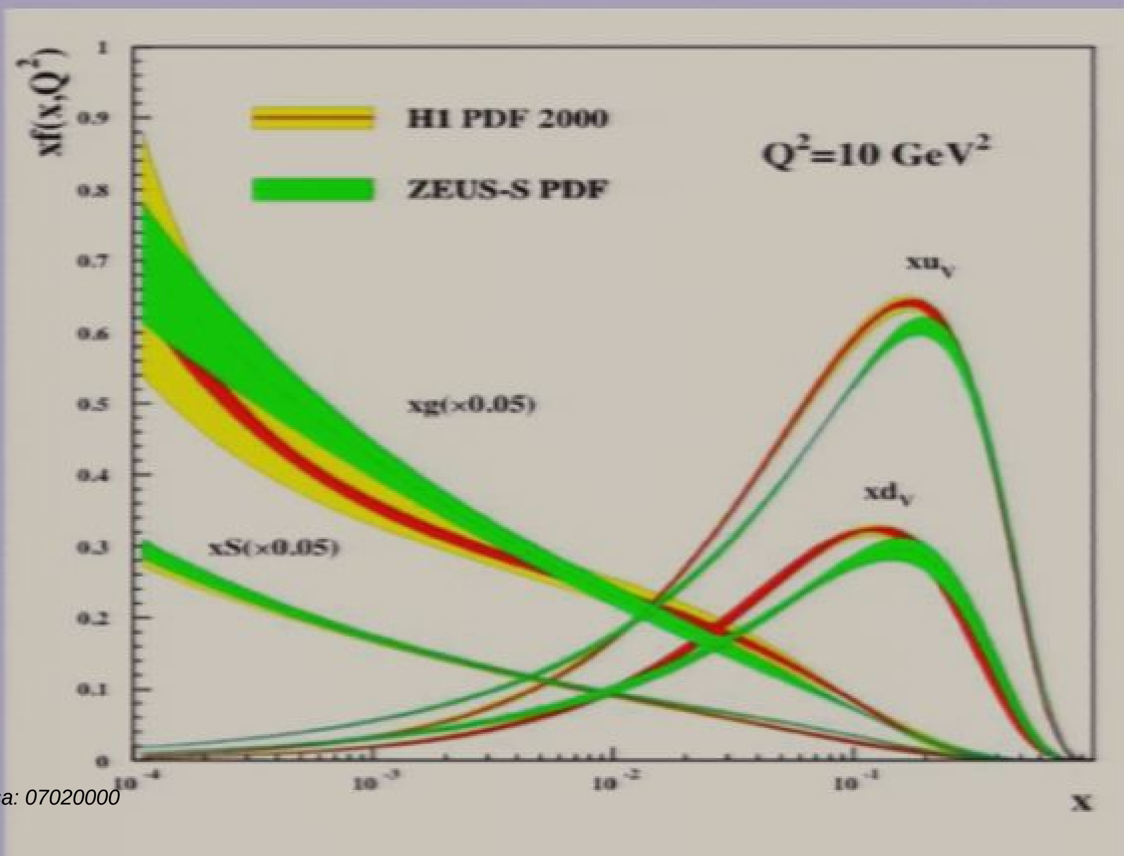


- Measurements of DIS cross-section vs x, Q^2 for x < 0.01.
- Plotted vs $\tau \equiv \frac{Q^2}{Q_s^2(x)}$
- All x dependence in the saturation scale.
  - "Geometric scaling"
- Precursor to saturation in PDF evolution



QCD: Evolution

- Quarks radiate copiously
  - ⇒ Evolution of proton (e.g.) parton distribution functions
  - ⇒ Growth of gluon distribution @ low x



- @ high gluon density recombination starts to limit growth.
- Q_s - resolution scale where recombination starts to dominate
- Limiting density ∝ Q_s^2/α_s

–~ Classical field

QCD: Evolution

- Quarks radiate copiously
  - ⇒ Evolution of proton (e.g.) parton distribution functions
  - ⇒ Growth of gluon distribution @ low x

- Number of gluons per unit area:

$$\rho \sim \frac{xG_A(x, Q^2)}{\pi R_A^2}$$

- Recombination cross-section:

$$\sigma_{gg \to g} \sim \frac{\alpha_s}{Q^2}$$

- Recombination happens if $\rho\sigma_{gg\to g} \gtrsim 1$, i.e. $Q^2 \lesssim Q_s^2$, with:

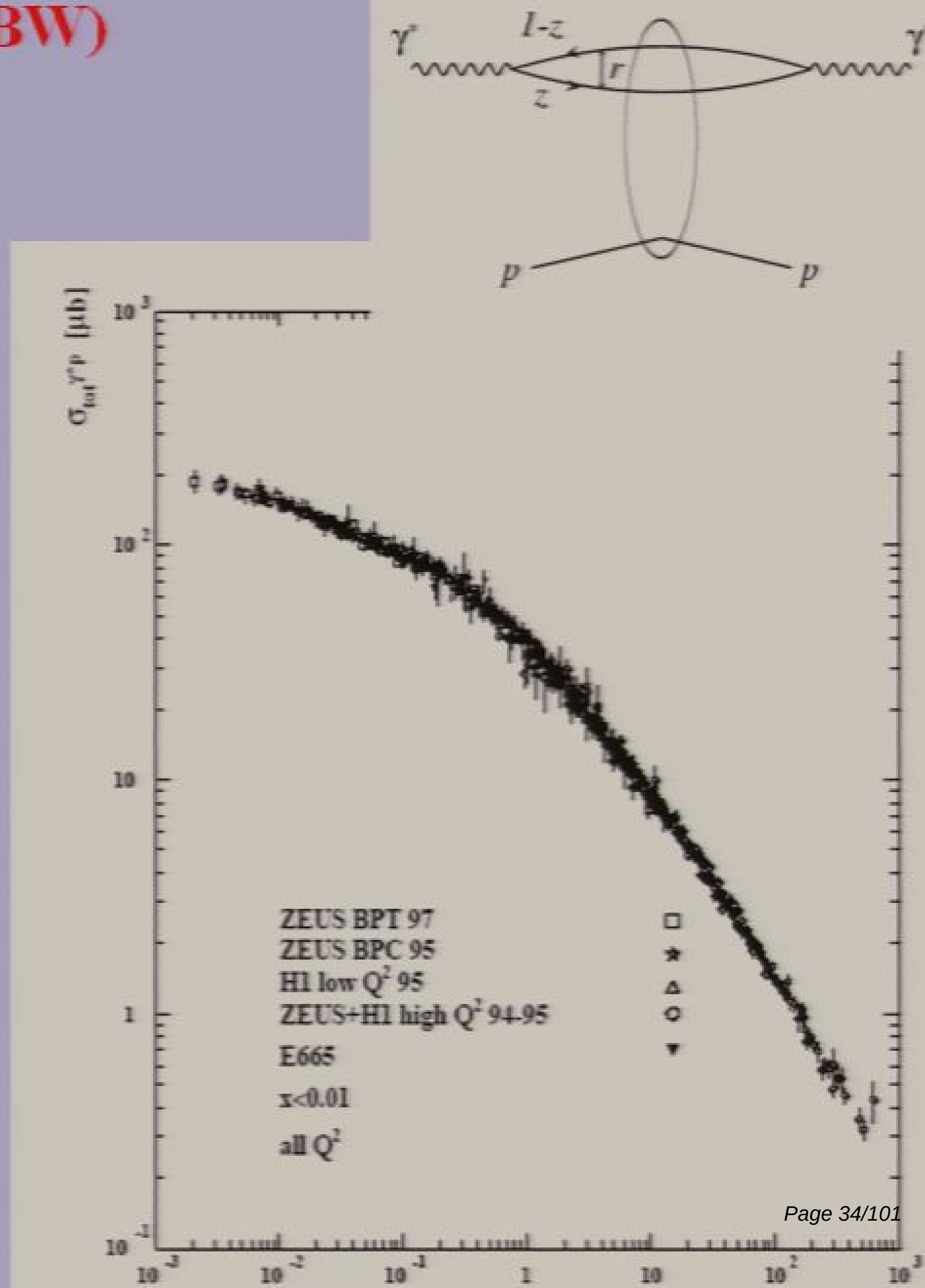
$$Q_s^2 \sim \frac{\alpha_s xG_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3}\frac{1}{x^{0.3}}$$

- @ high gluon density recombination starts to limit growth.
- Q_s - resolution scale where recombination starts to dominate
- Limiting density ∝ Q_s^2/α_s

–~ Classical field

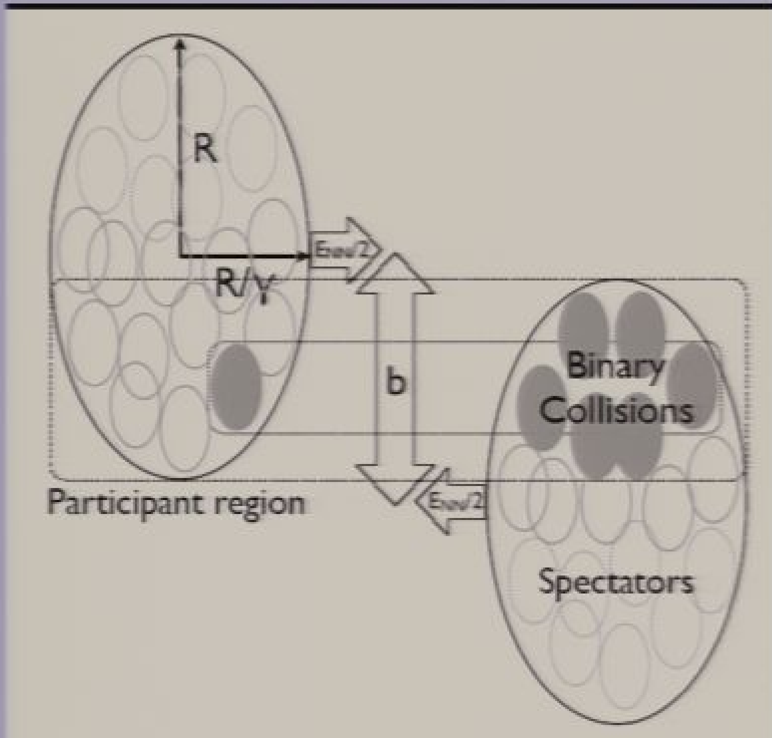
Saturation @ HERA?

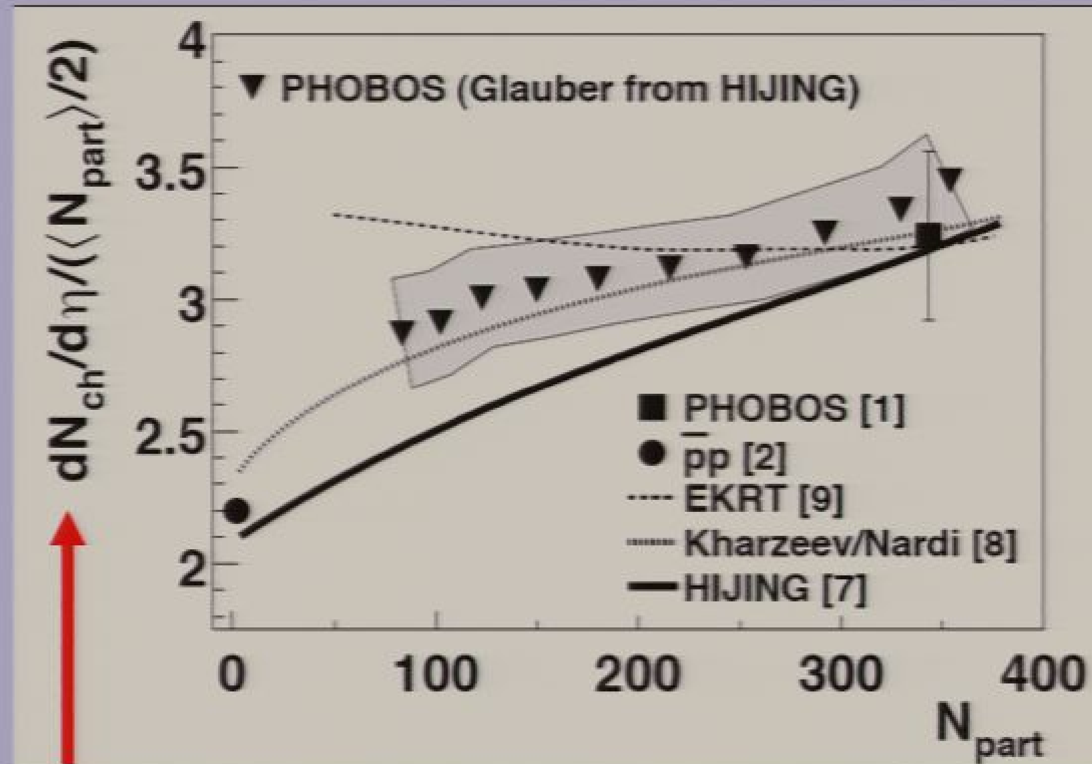
Golec-Biernat and Wusthoff (GBW) Saturation Model (empirical)



- Measurements of DIS cross-section vs x, Q^2 for x < 0.01.
- Plotted vs $\tau \equiv \frac{Q^2}{Q_s^2(x)}$
- All x dependence in the saturation scale.
  - "Geometric scaling"
- Precursor to saturation in PDF evolution

RHIC Particle Multiplicities

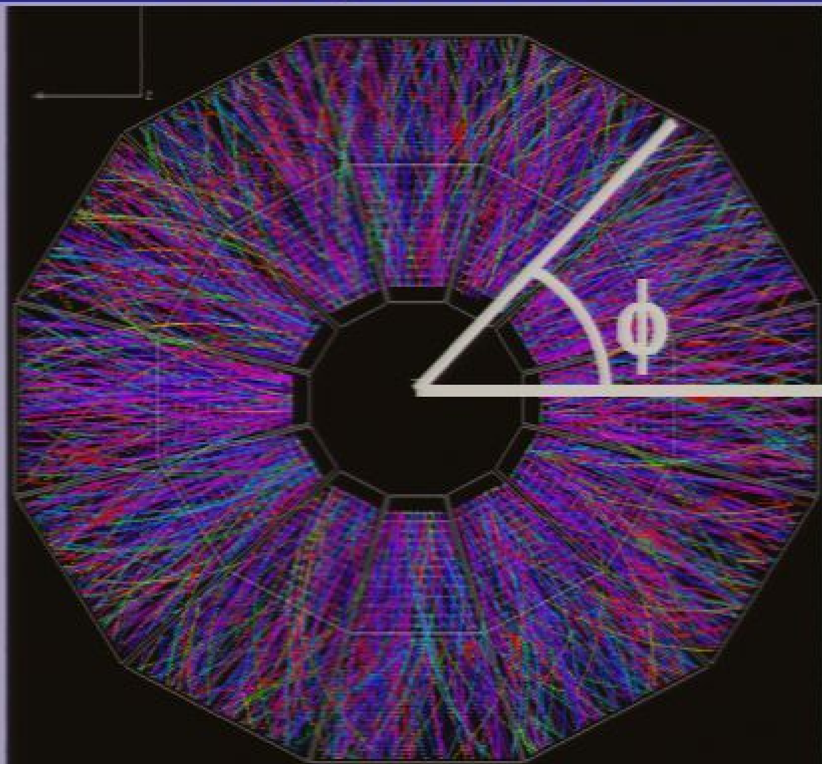


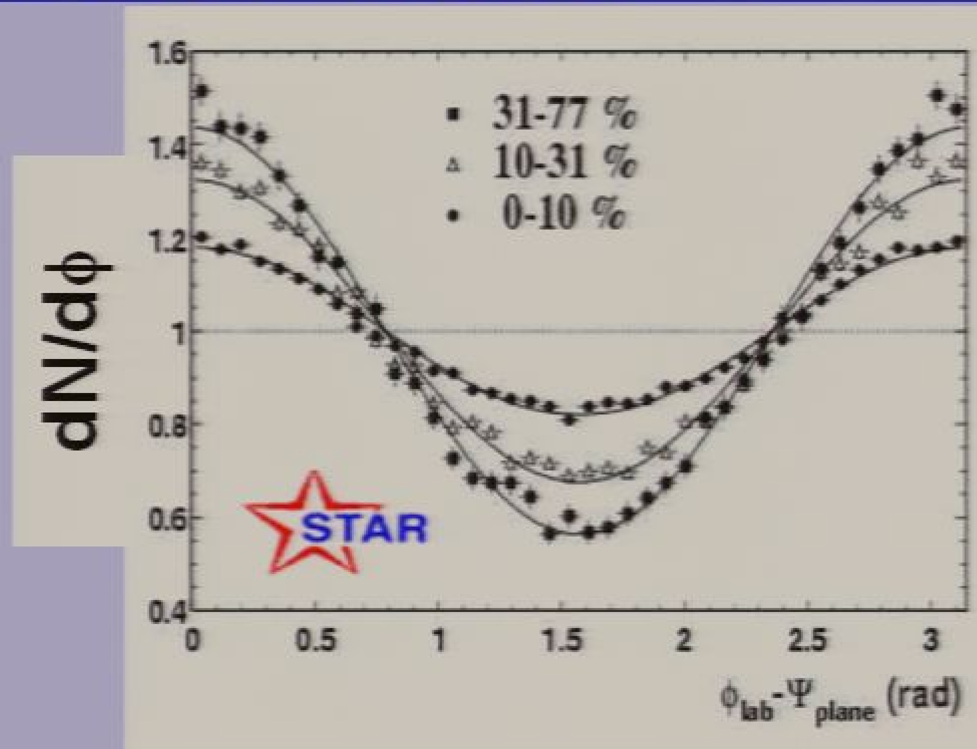


Multiplicity per colliding nucleon pair

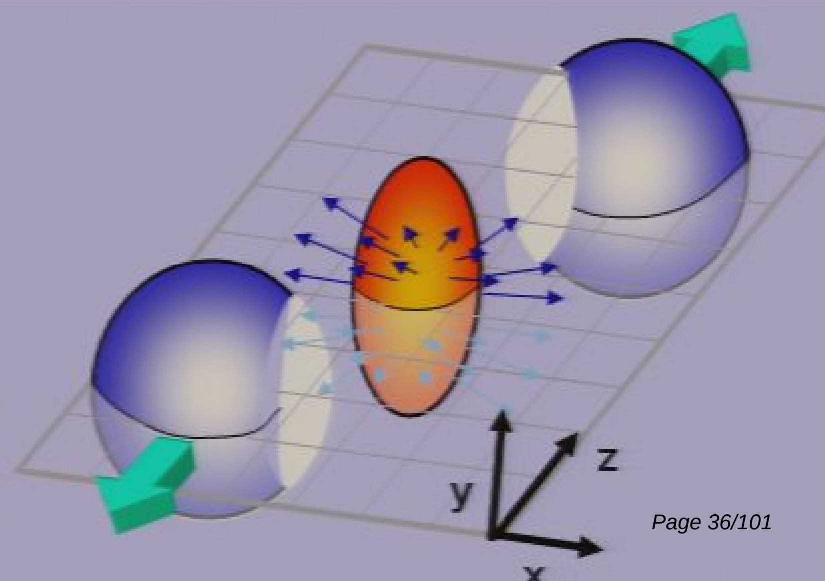
- Multiplicity @ RHIC on low end of predicted range
- Slow growth with impact parameter (N_{part})
  - Inconsistent with factorized mini-jet production
  - Best described by saturation <u>model</u>

But, Have We Created "Matter" ?

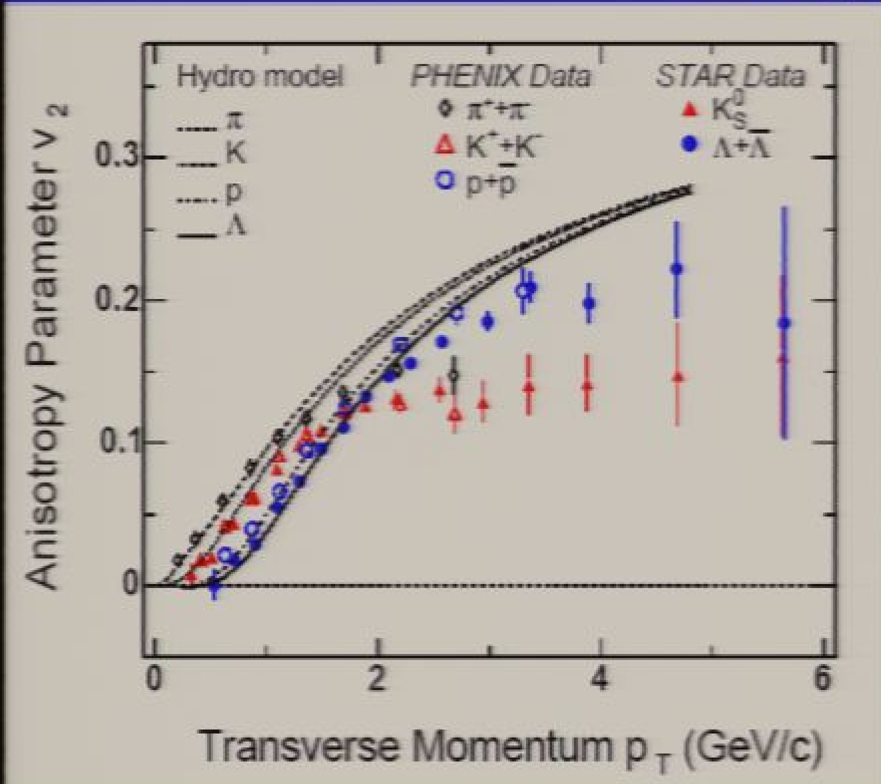


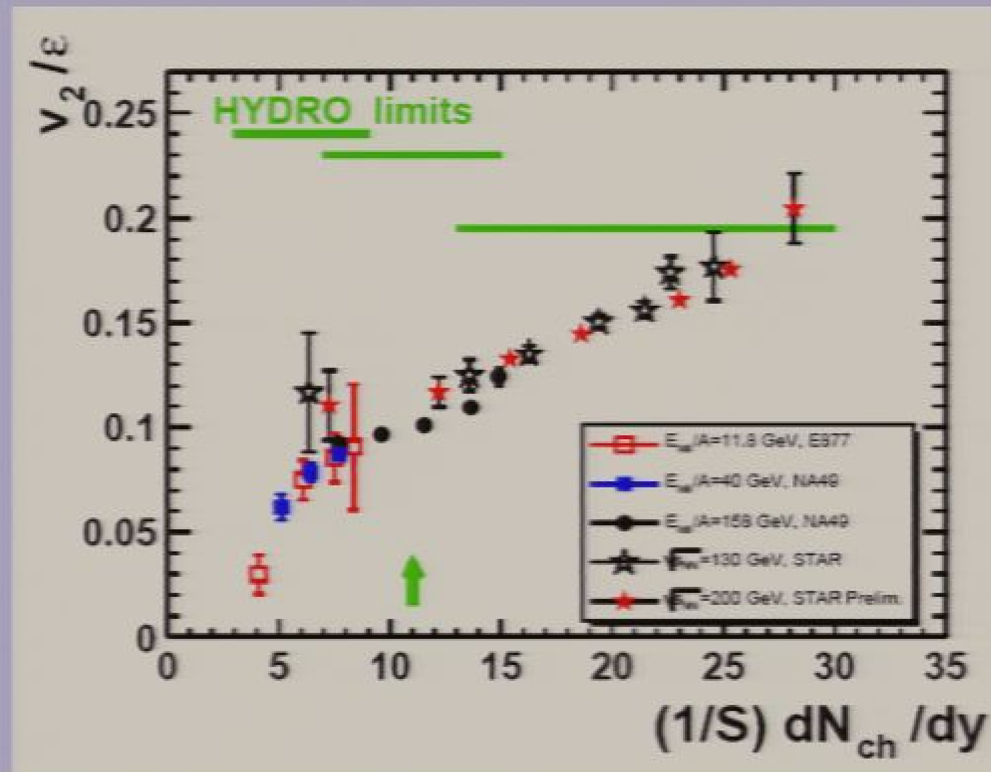


- "Pressure" converts spatial anisotropy to momentum anisotropy.
- Requires early thermalization.
- Unique to heavy ion collisions
- Answer: yes



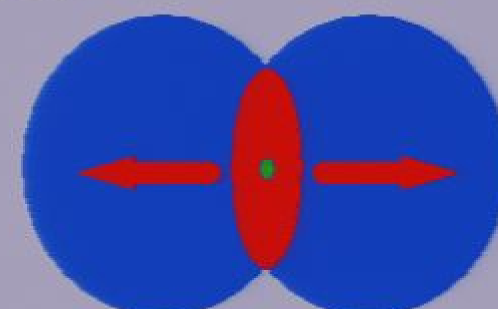
"Elliptic Flow"





- Parameterize φ variation by "v_2" parameter
  - $\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi)$
- Compare to "eccentricity":

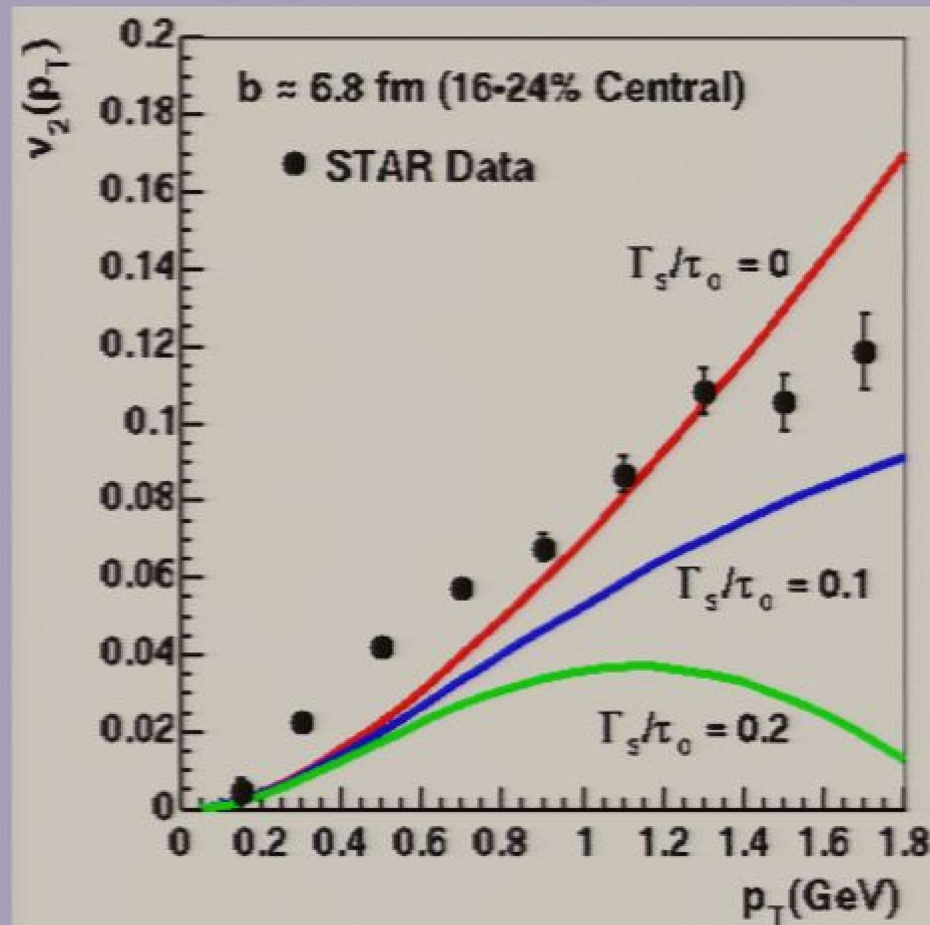
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



- **Data consistent w/ hydrodynamic calculations**

Estimating the (Shear) Viscosity

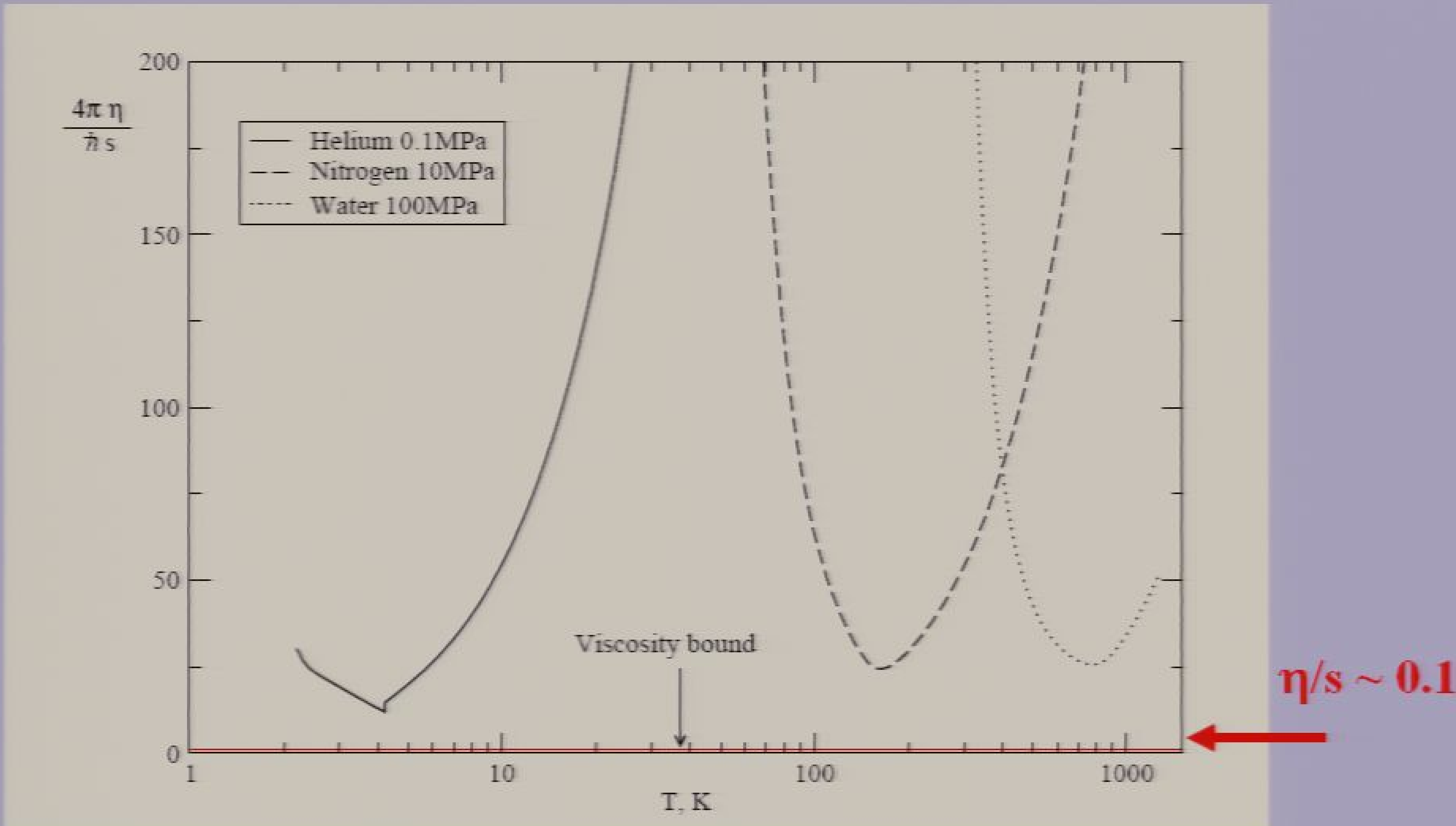
- Relevant parameter for determining collective motion of quark-gluon plasma
  - viscosity to entropy ratio: η/s.
- Finite viscosity leads to dependence of flow strength on p_T.
  - Correction $\propto (\eta/s)\, p_T^2$
- From data shown to right, obtain estimate:
  - $\eta/s \sim 0.1$
  - Very small!



Γ_s is "sound attenuation length" $\propto$ mean free path

$$\Gamma_s = \frac{4}{3}\frac{\eta}{sT}$$

Comparison to "Typical" Vicosities

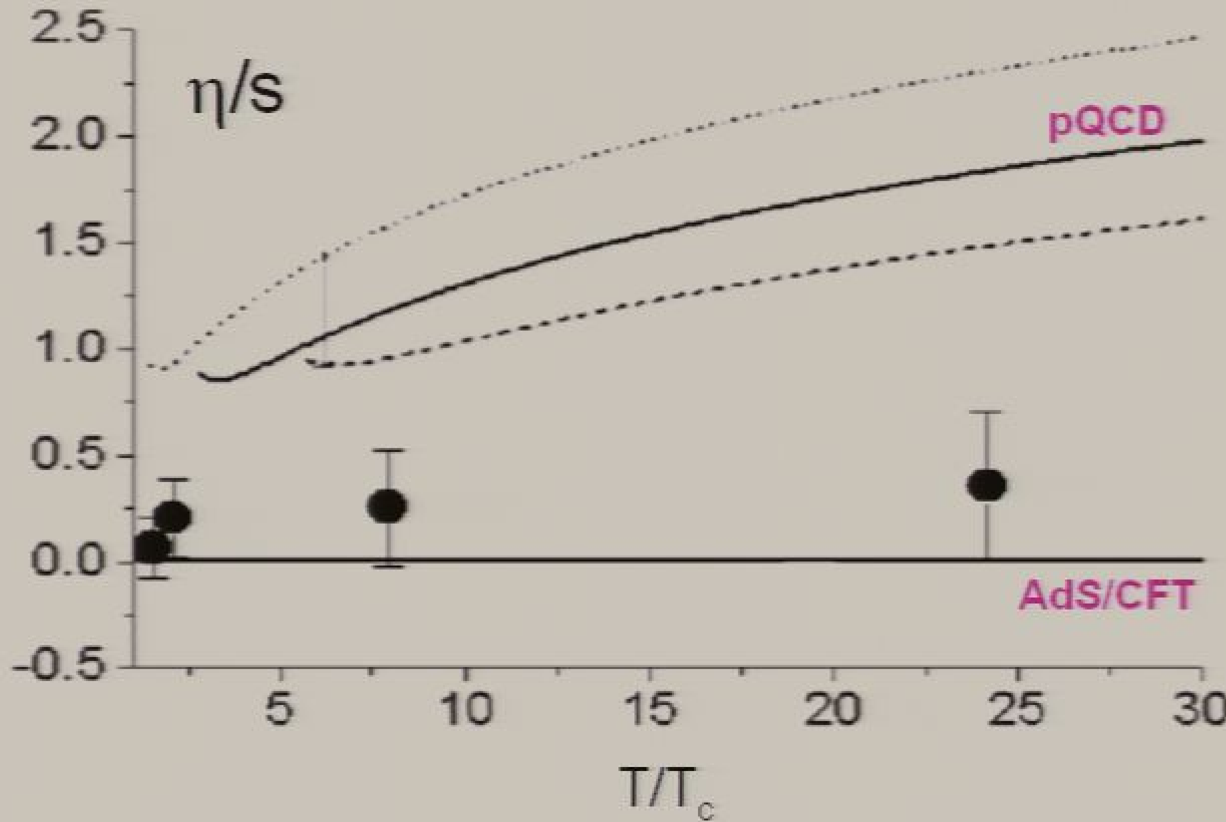


- Thus the statement:
  - –QGP is most perfect fluid every created

Lattice QCD Estimate of η/s

Lattice QCD Estimate of η/s

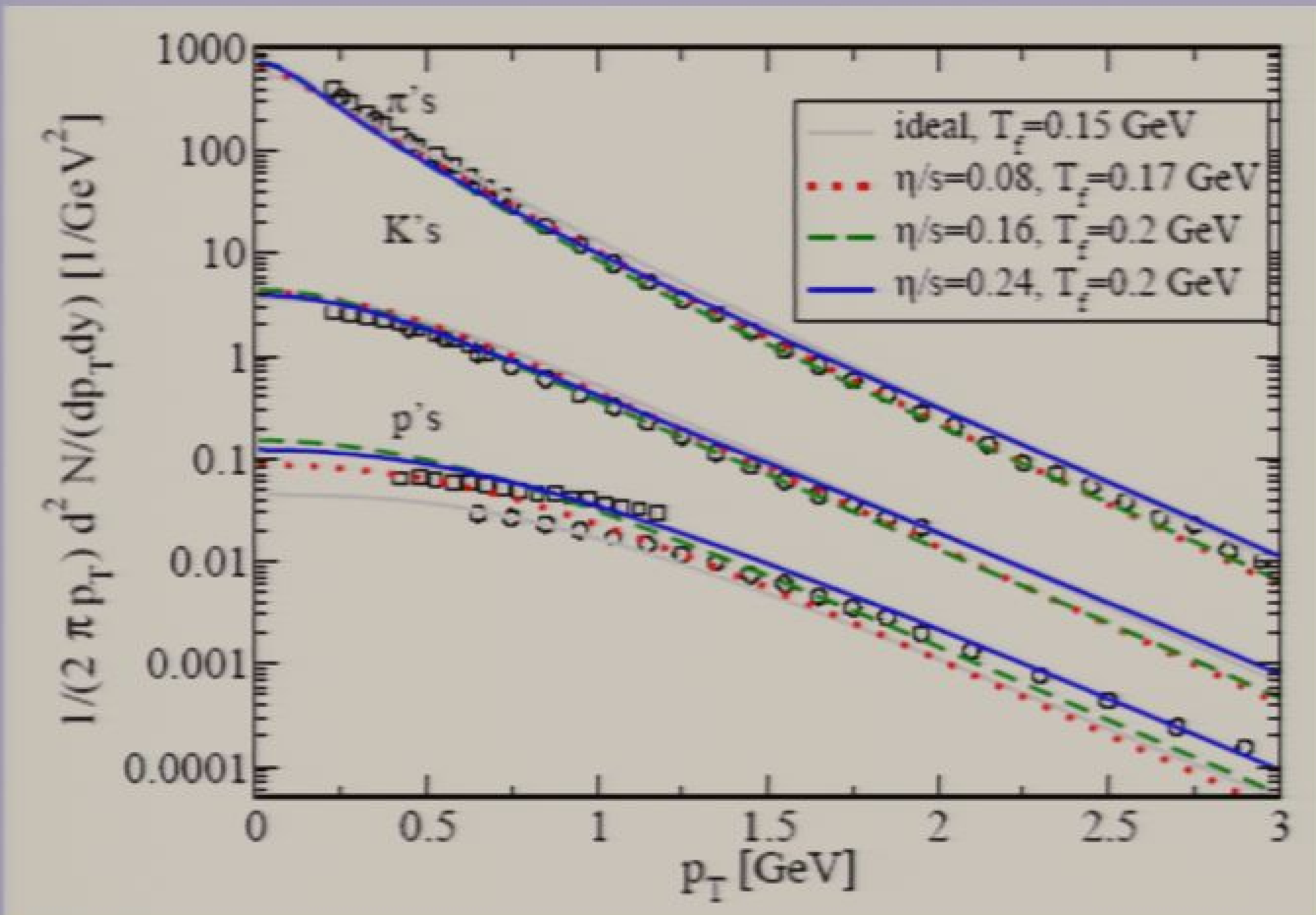
Shear viscosity in quenched QCD $\eta = \pi \lim_{\omega \to 0} \rho_\Theta(\omega)/\omega$



Nakamura & Sakai. hep-lat/0510100

"Casual" Viscous Hydrodynamics

P. Romatschke nucl-th/0701032

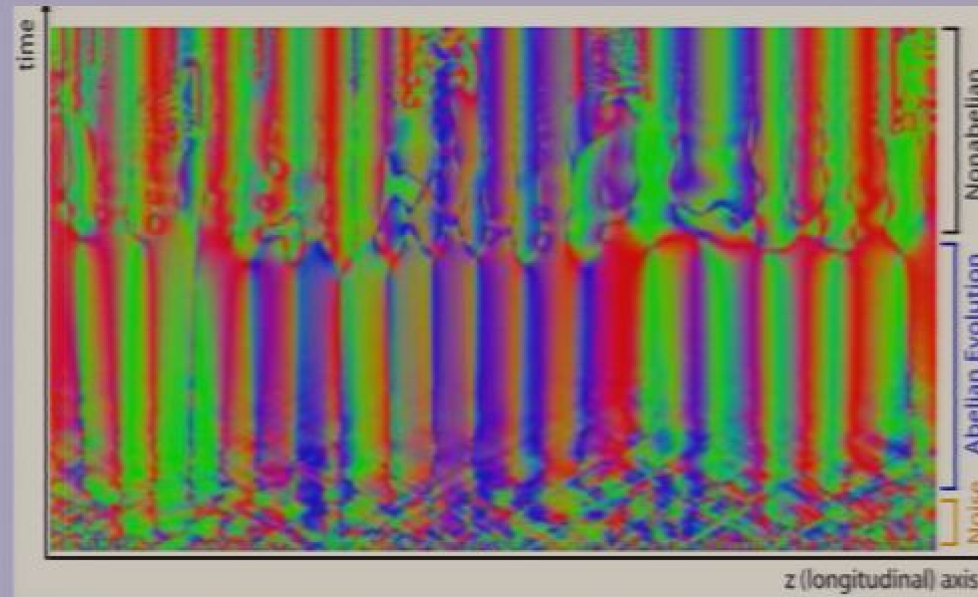


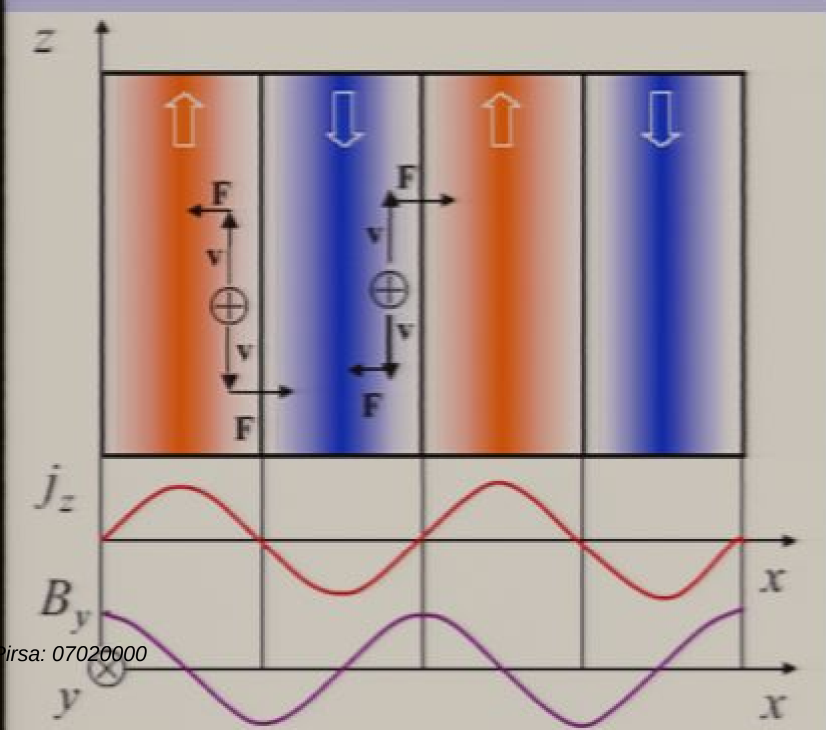
Comparison of viscous hydro results to meson spectra from PHENIX

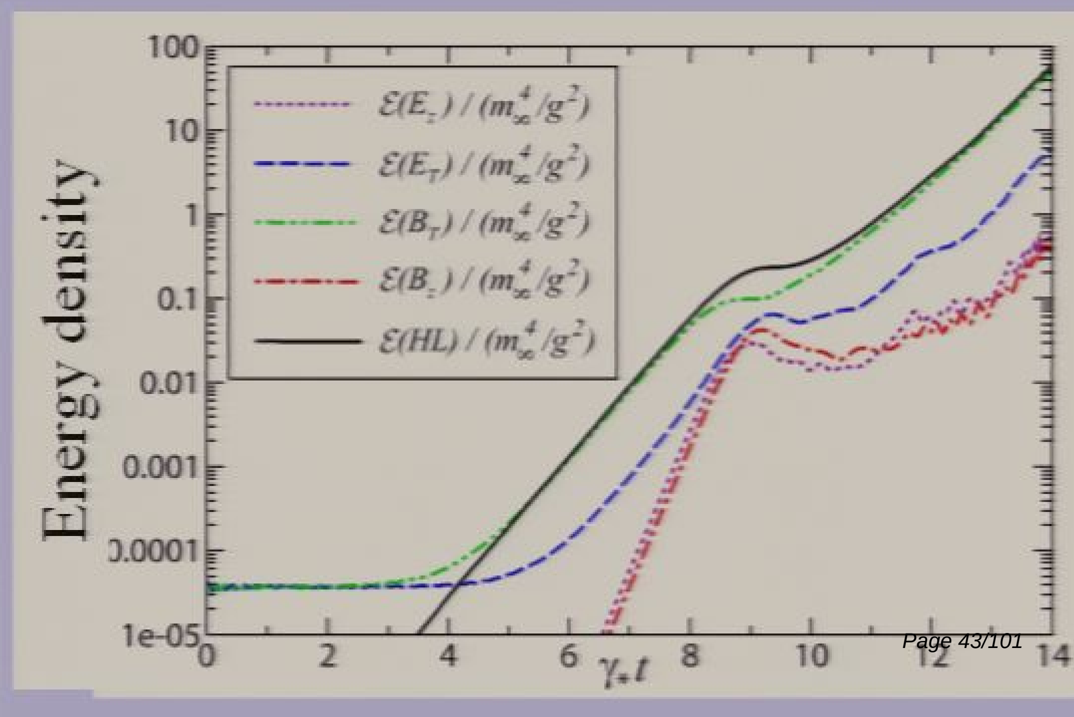
- Causal fix introduces a new scale, τ_Π, relaxation time. Uncertainty in τ_Π weakens η/s constraint
  - –Concludes η/s < 0.5, but elliptic flow?

Thermalization via Plasma Instabilities?

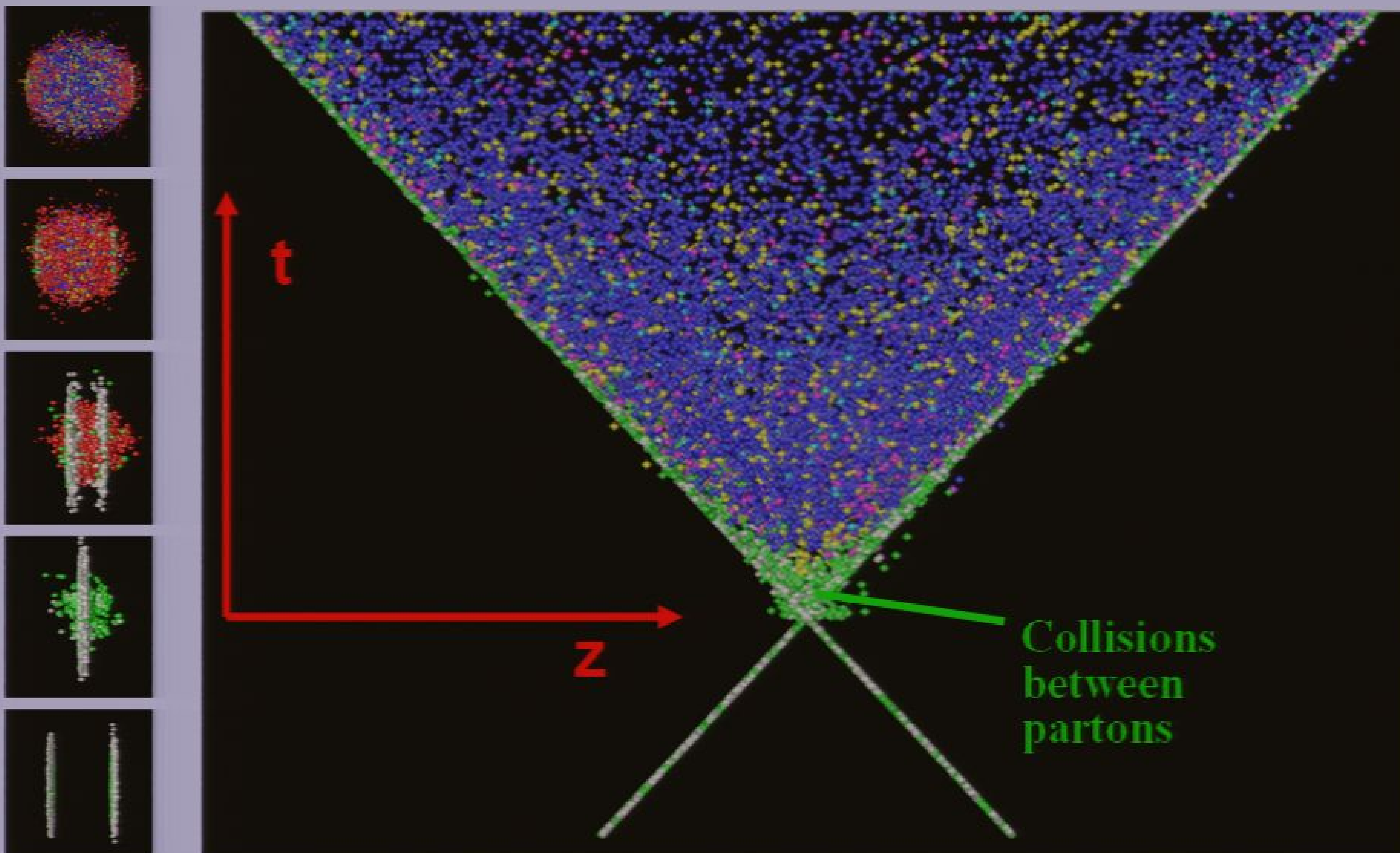
- p_T vs p_z anisotropy
  - Generates strong local chromo-magnetic fields
  - Lorentz forces produce rapid isotropization.
- Pressure from macro-scopic color fields?!



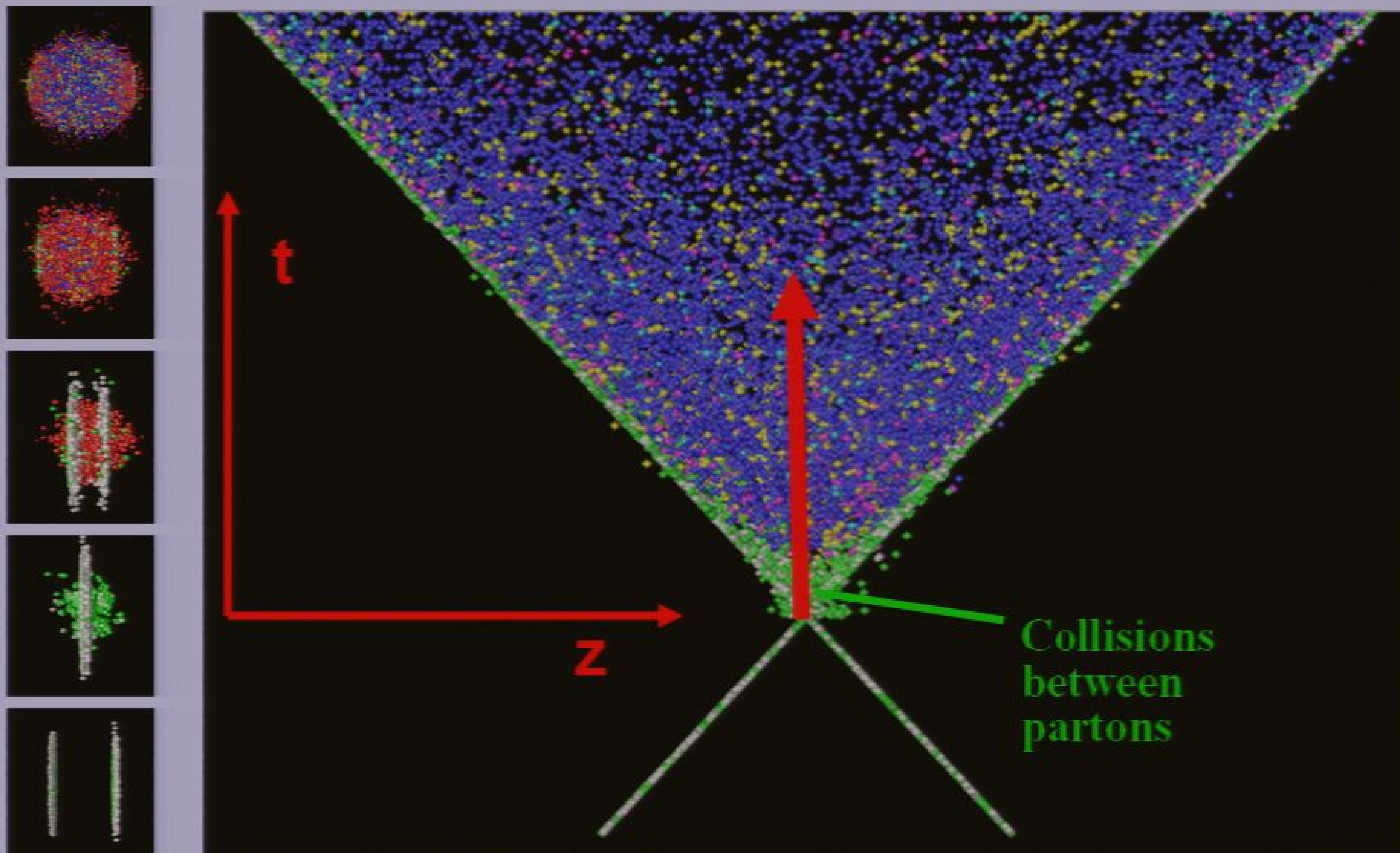




Penetrating Probes of Created Matter



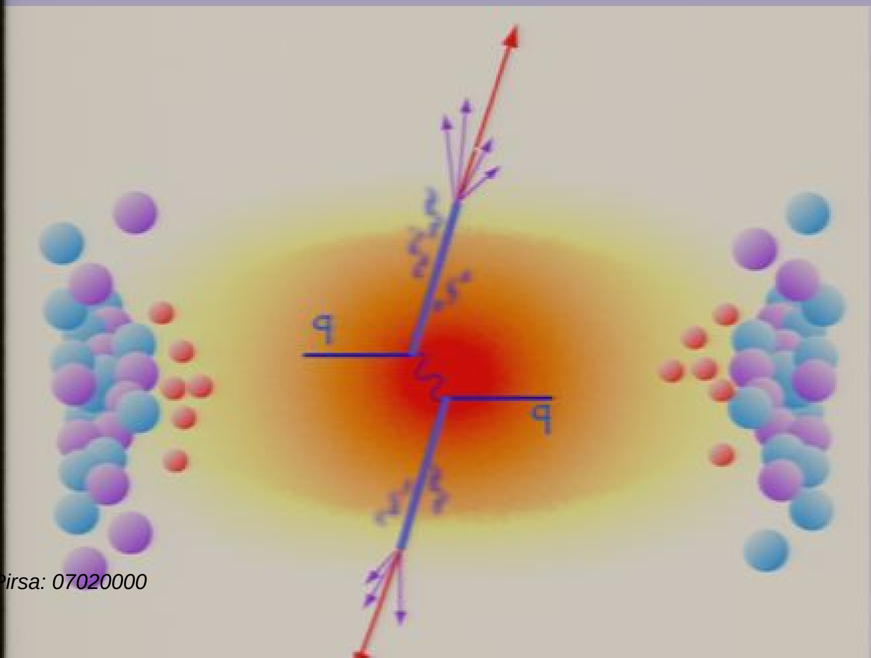
Penetrating Probes of Created Matter



- Use self-generated quarks/gluons/photons as probes of the medium (classic physics technique!)

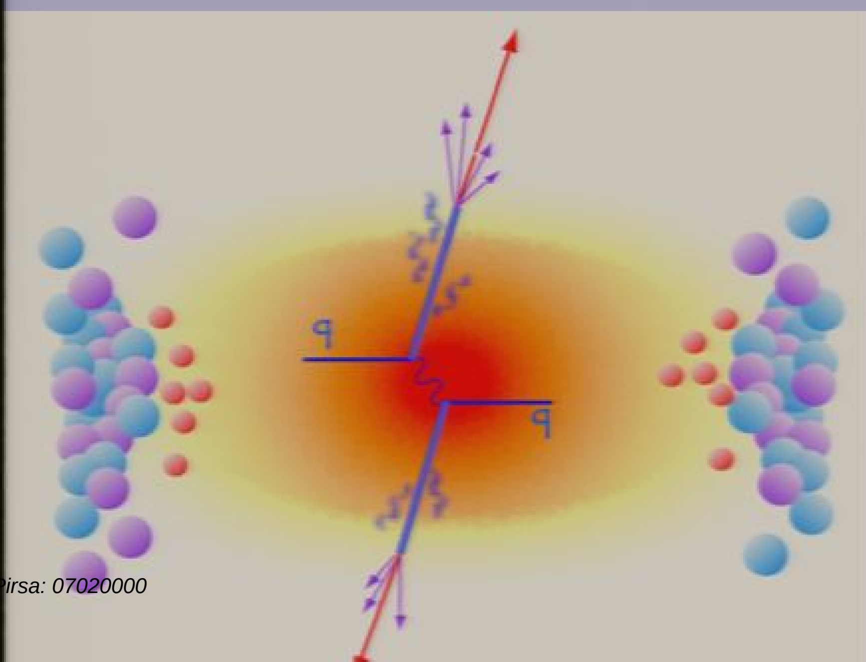
How to directly probe medium ?

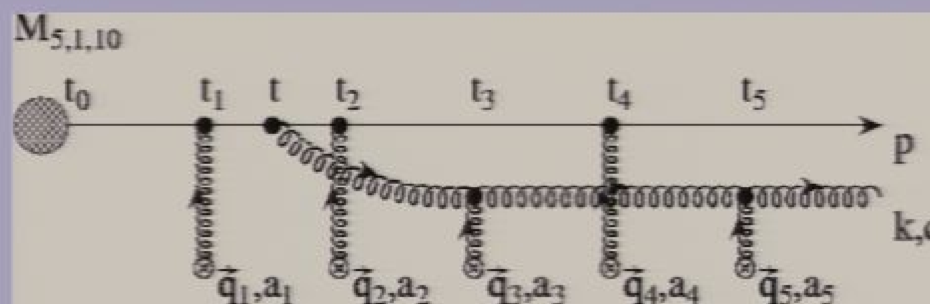
- Use quarks & gluons from high-Q^2 scattering
  - "Created" at very early times (~ 0.1 fm).
  - Propagate through earliest, highest ε matter.
- (QCD) Energy loss of (color) charged particle
  - ~ Entirely due to radiation
  - Virtual gluon(s) of quark multiply scatter.
- e.g. GLV (Gyulassy, Levai, Vitev) formalism



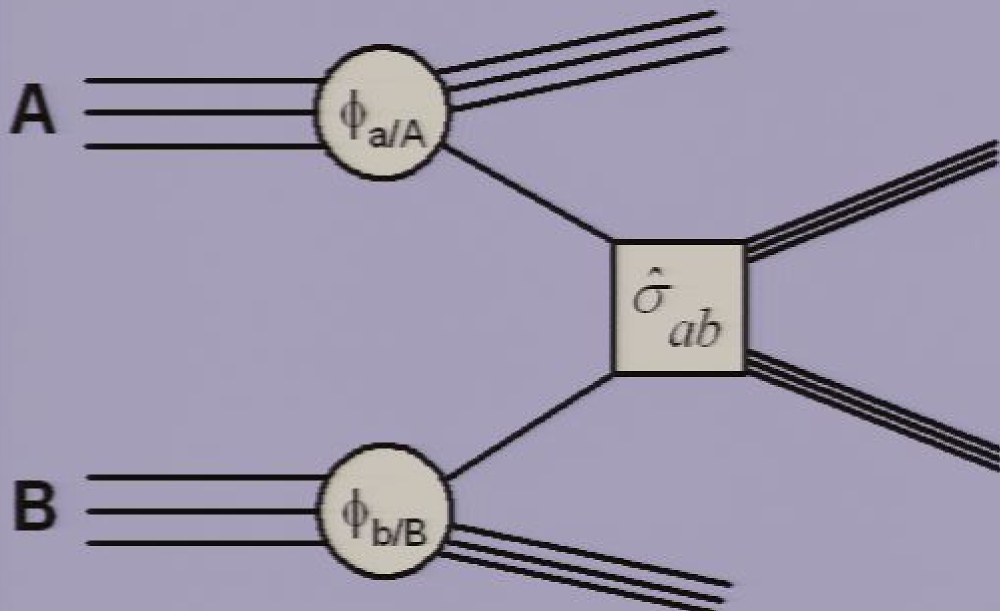
How to directly probe medium ?

- Use quarks & gluons from high-Q^2 scattering
  - "Created" at very early times (~ 0.1 fm).
  - Propagate through earliest, highest ε matter.
- (QCD) Energy loss of (color) charged particle
  - ~ Entirely due to radiation
  - Virtual gluon(s) of quark multiply scatter.
- e.g. GLV (Gyulassy, Levai, Vitev) formalism





Perturbative quantum chromo-dynamics



From **Collins, Soper, Sterman**
Phys. Lett. B438:184-192, 1998

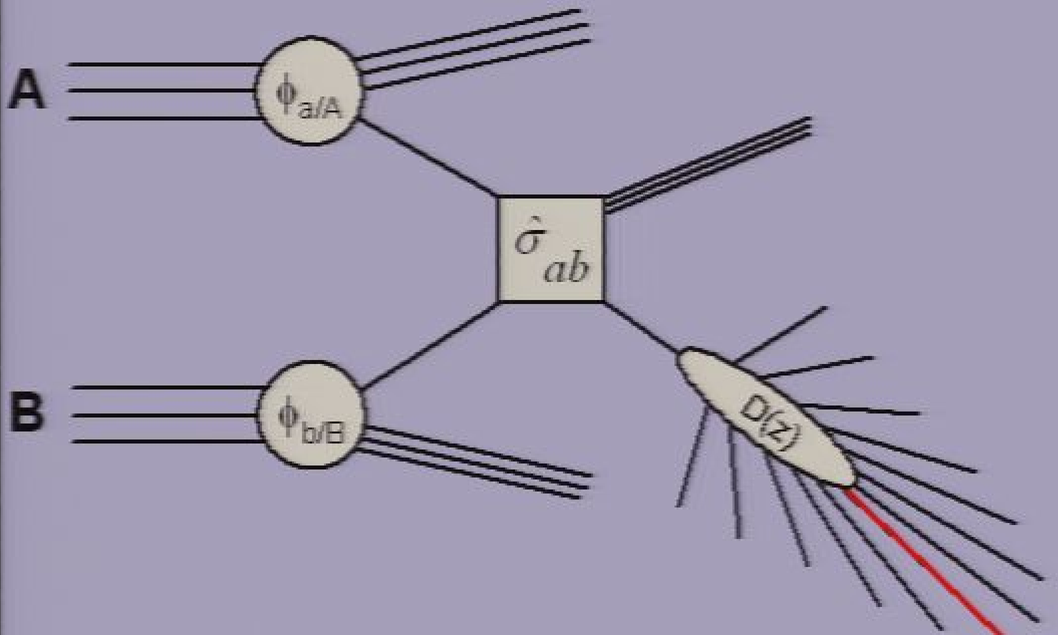
$$\sigma_{AB} = \sum_{ab} \int dx_a dx_b\, \phi_{a/A}(x_a, \mu^2)\, \phi_{b/B}(x_b, \mu^2)\, \hat{\sigma}_{ab}\left(\frac{Q^2}{x_a x_b s}, \frac{Q}{\mu}, \alpha_s(\mu)\right) \left(1 + \mathcal{O}\left(\frac{1}{Q^P}\right)\right)$$

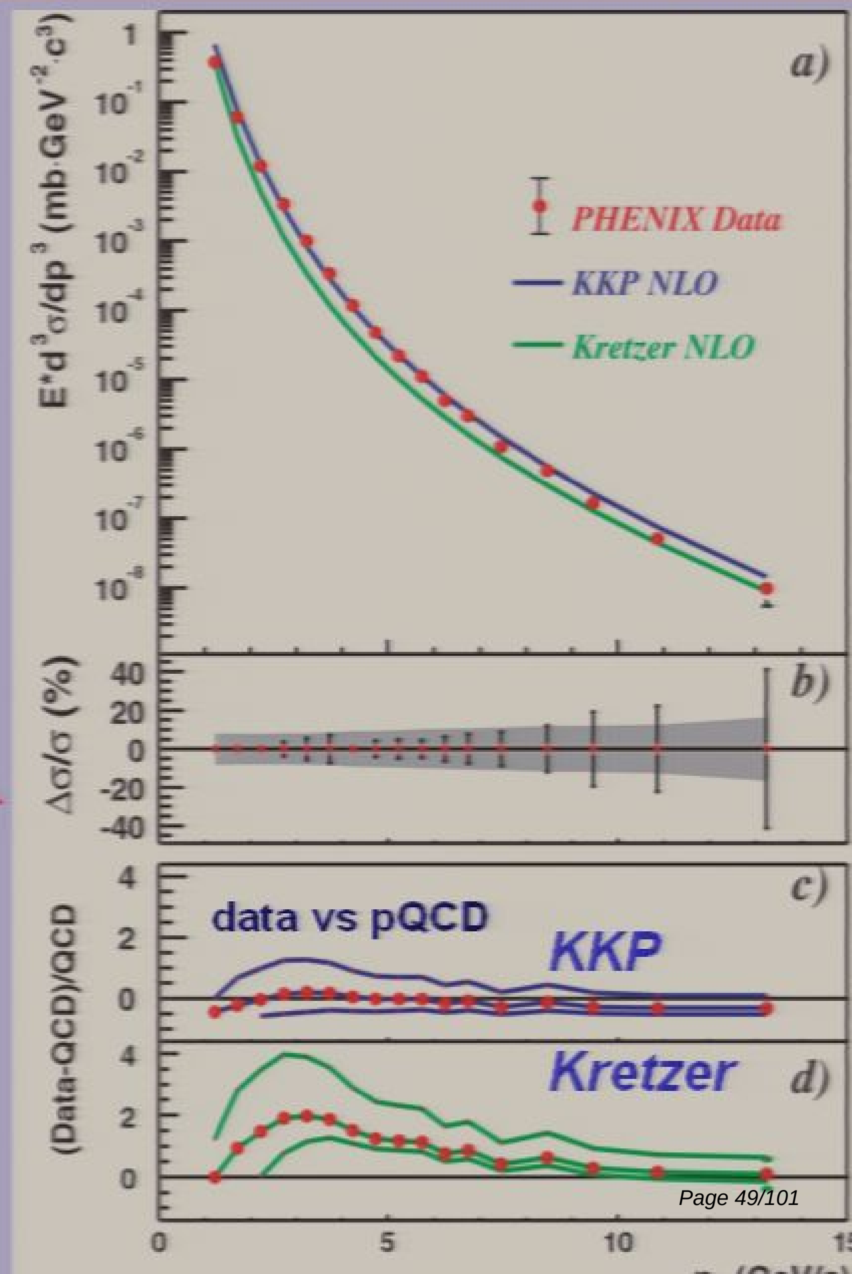
- Factorization: separation of σ into
  - Short-distance physics: $\hat{\sigma}$ – calculable using perturbation theory**
  - Long-distance physics: ϕ's – universal, measured separately.
- Valid @ large momentum transfer – high p_T particles

pQCD – Single Hadron Production

Phys. Rev. Lett. 91, 241803 (2003)

Add fragmentation to hadrons



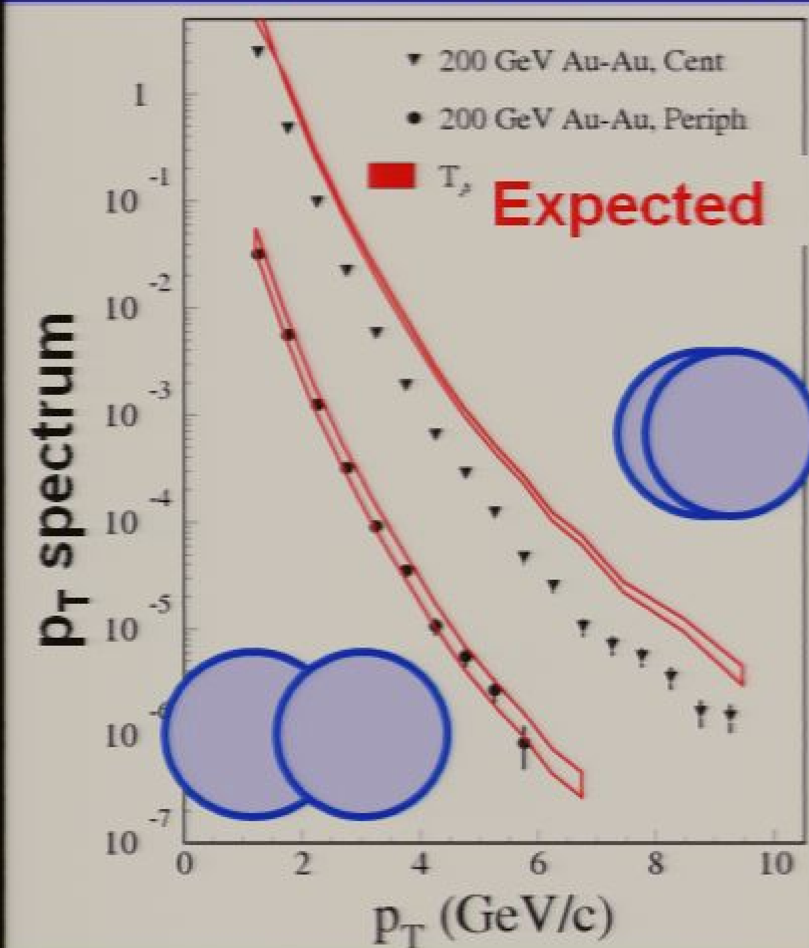


$$E\frac{d^3\sigma}{dp^3} = \sum_{abc}\int dx_a dx_b\, \phi_{a/A}(x_a,Q^2,\mu)\,\phi_{b/B}(x_a,Q^2,\mu)$$

$$\times \frac{D_{\pi^0/c}(z,Q^2,\mu)}{z\pi}\,\frac{d\hat\sigma}{dt}$$

- D(z) – fractional momentum distribution of particles in “jet”

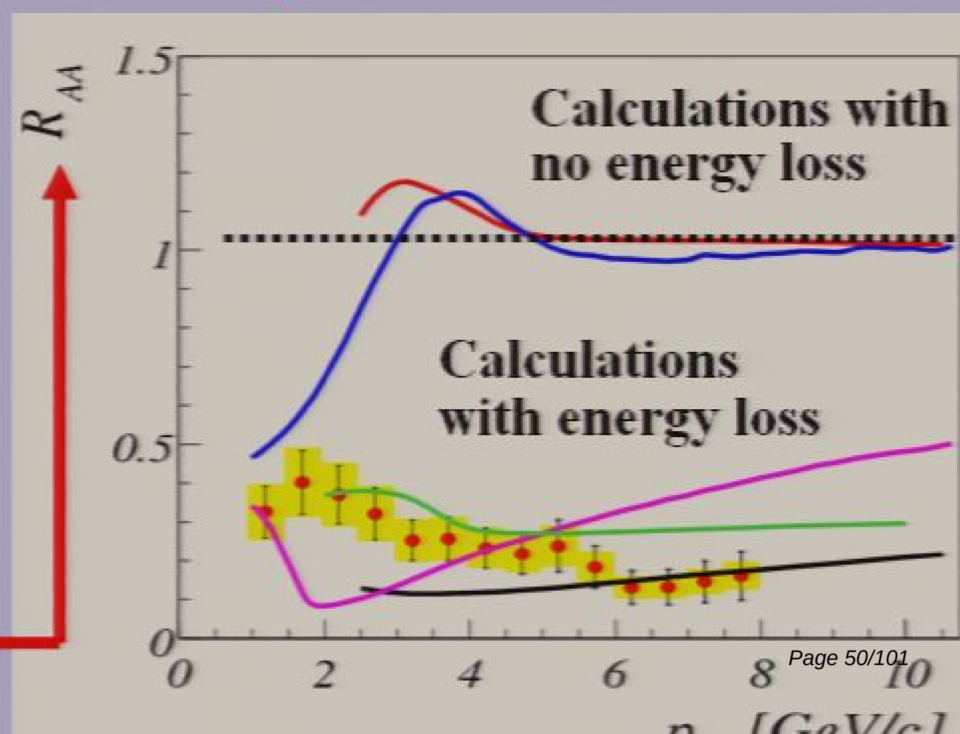
PHENIX Au-Au π^0 Spectra



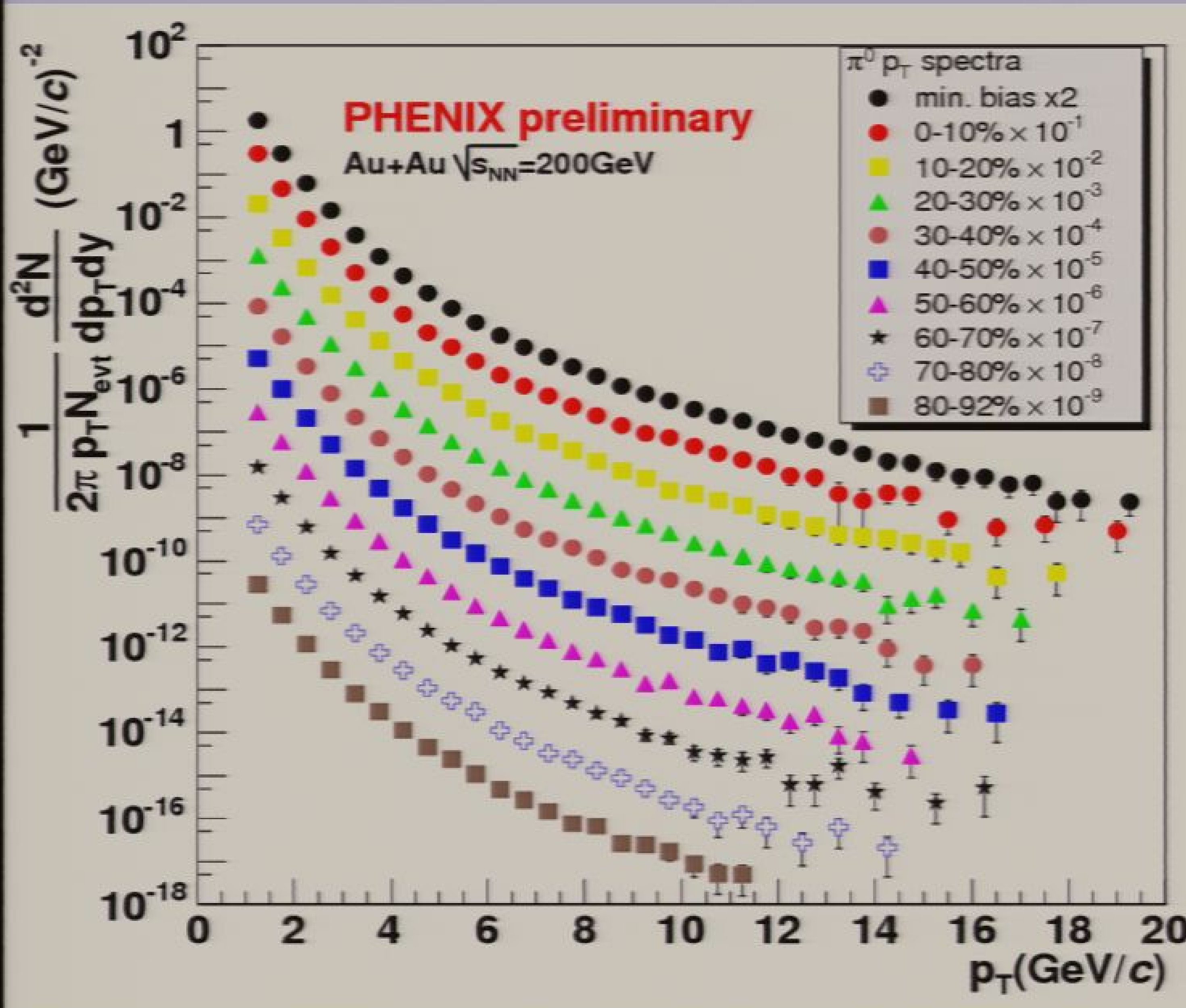
- Observe **20%** of expected yield @ high p_T
  - ⇒ Deduce energy density ε ~15 Gev/fm^3
  - ⇒ Compare ε_{crit} ~ 1 GeV/fm^3
  - ⇒ 100 x normal nucleus energy density!

$R_{AA} \equiv$ Observed/Expected

Using p-p data as baseline

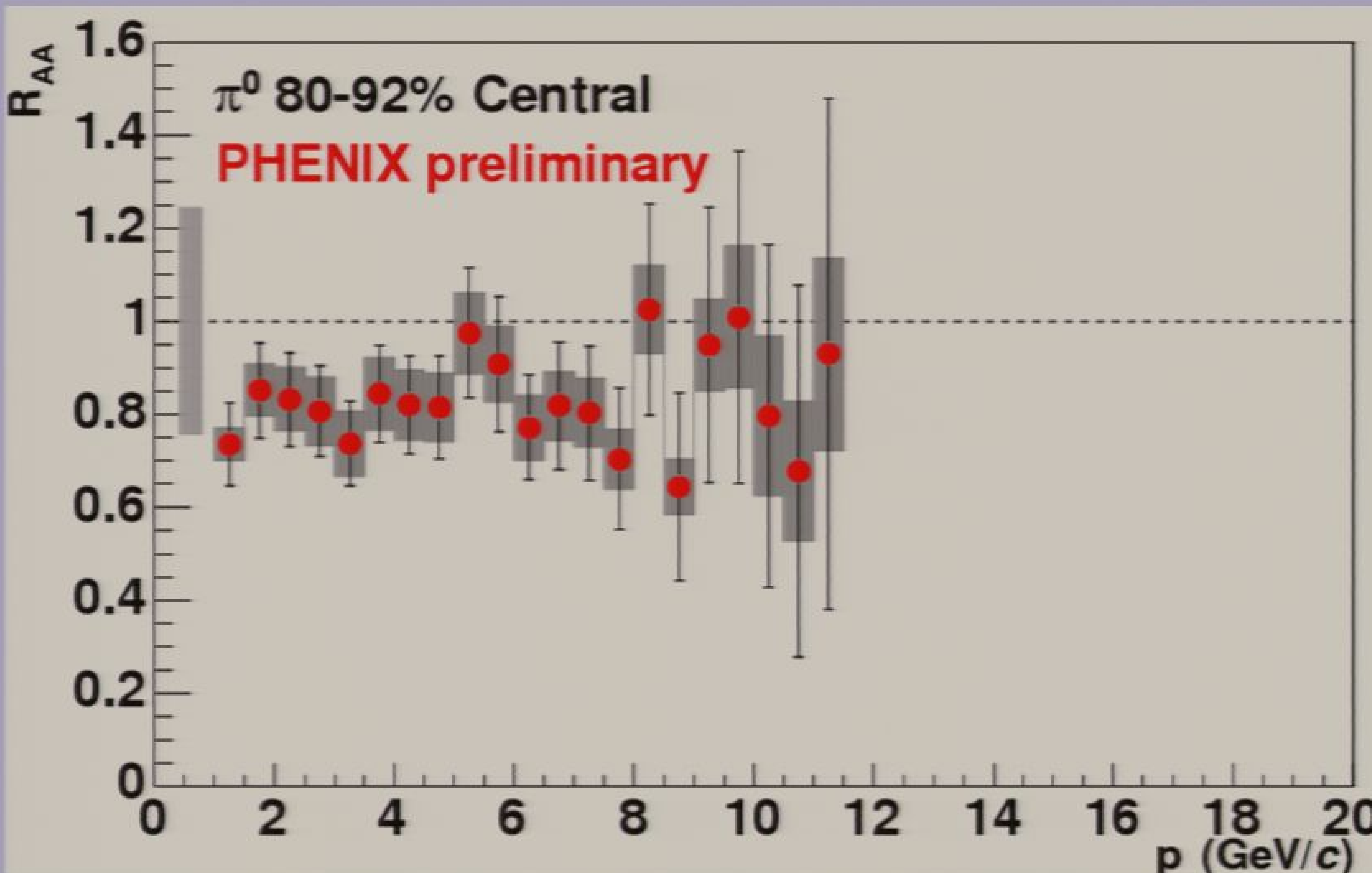


PHENIX: Au-Au High-p_T π^0 Suppression

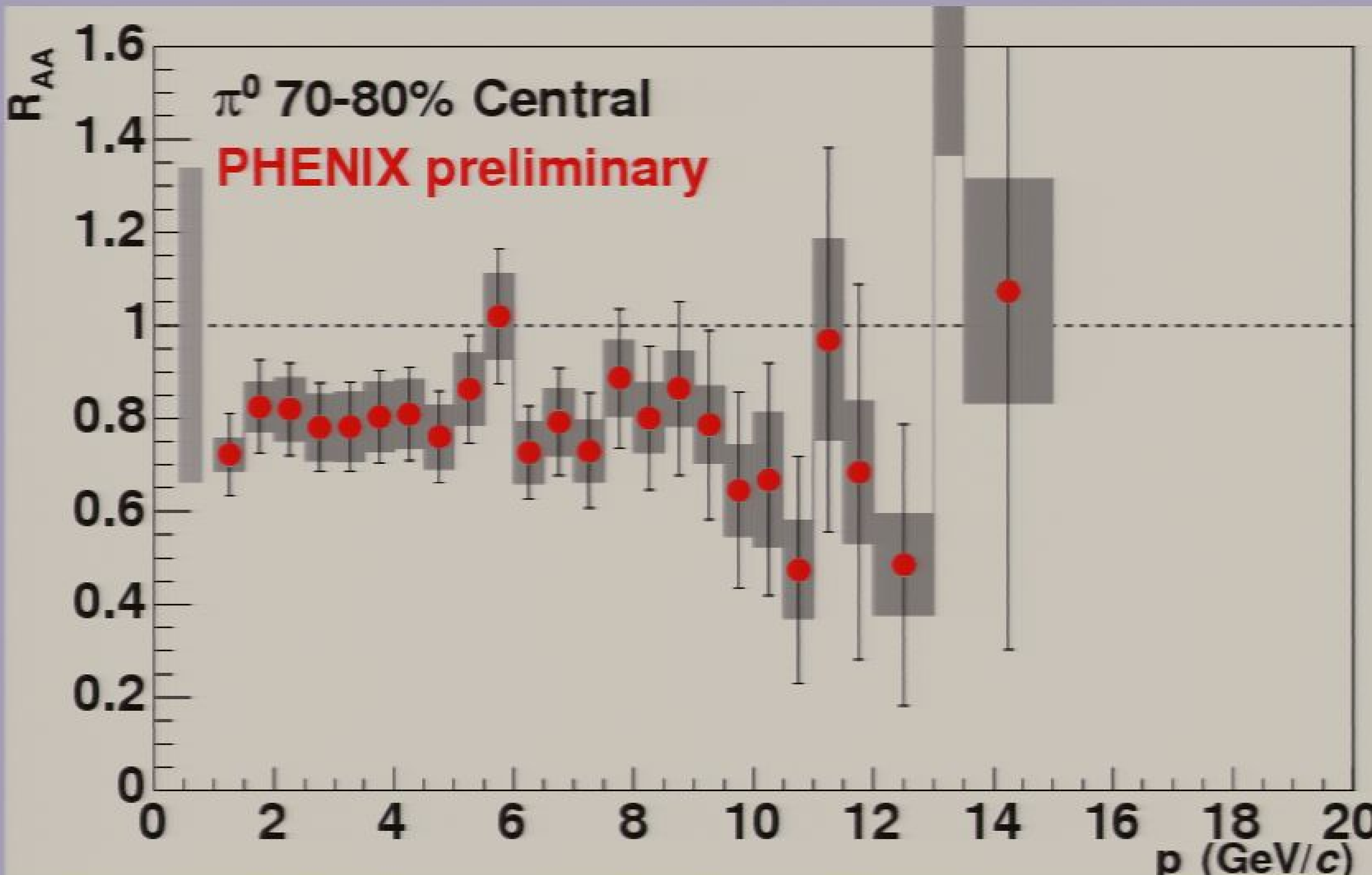


PHENIX: Au-Au High-p_T π^0 Suppression

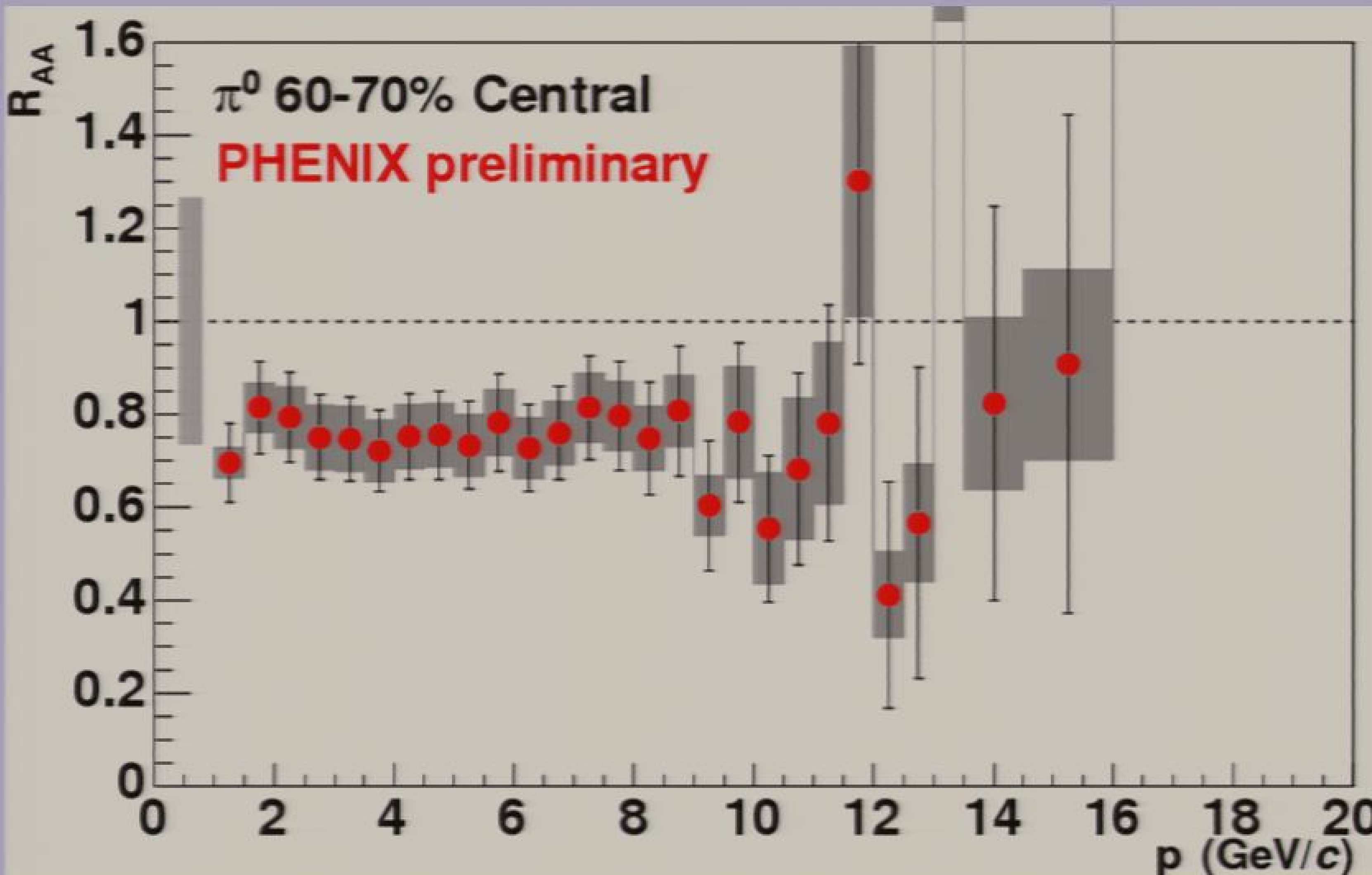
PHENIX: Au-Au High-p_T π^0 Suppression



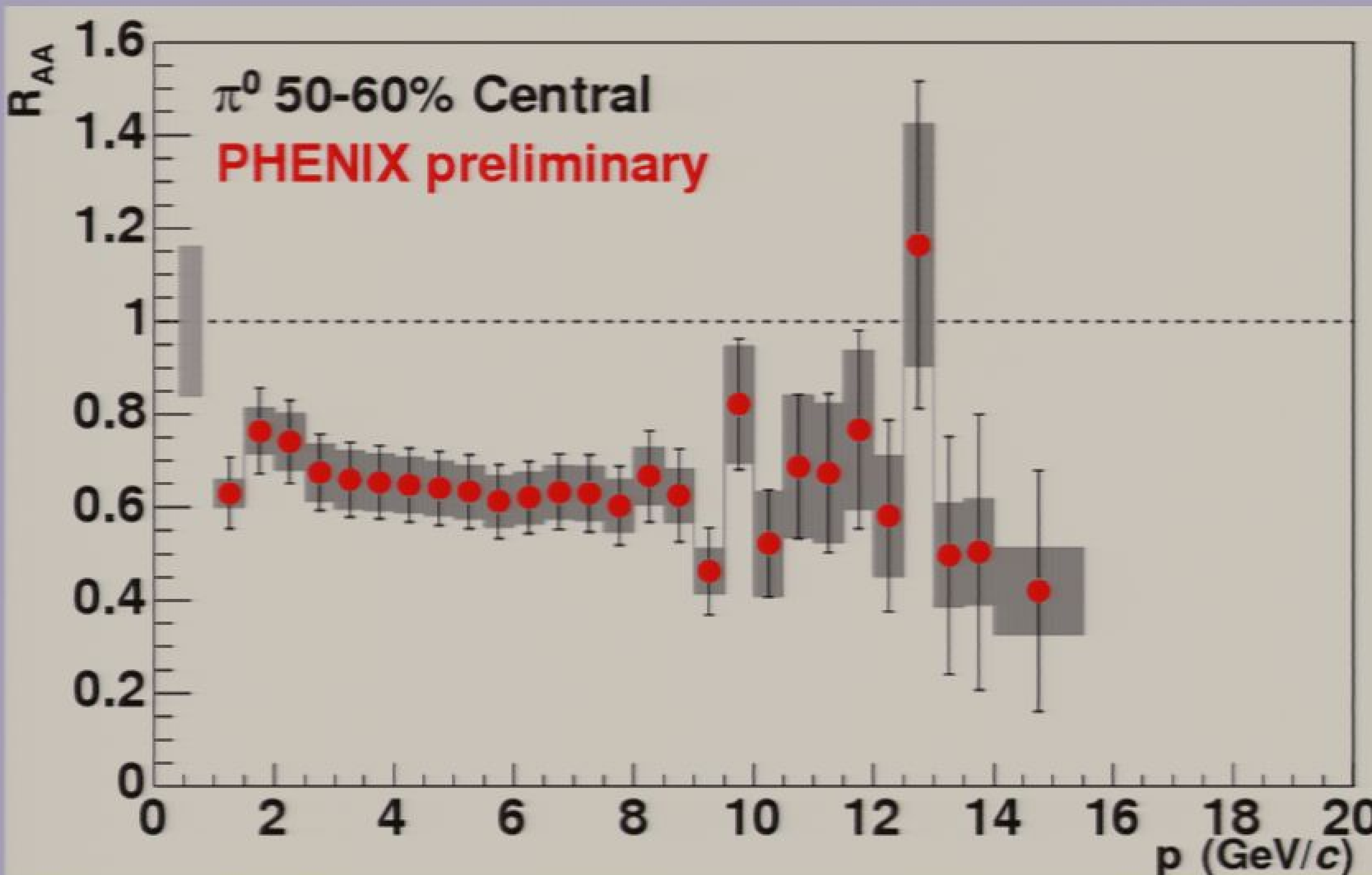
PHENIX: Au-Au High-p_T π^0 Suppression



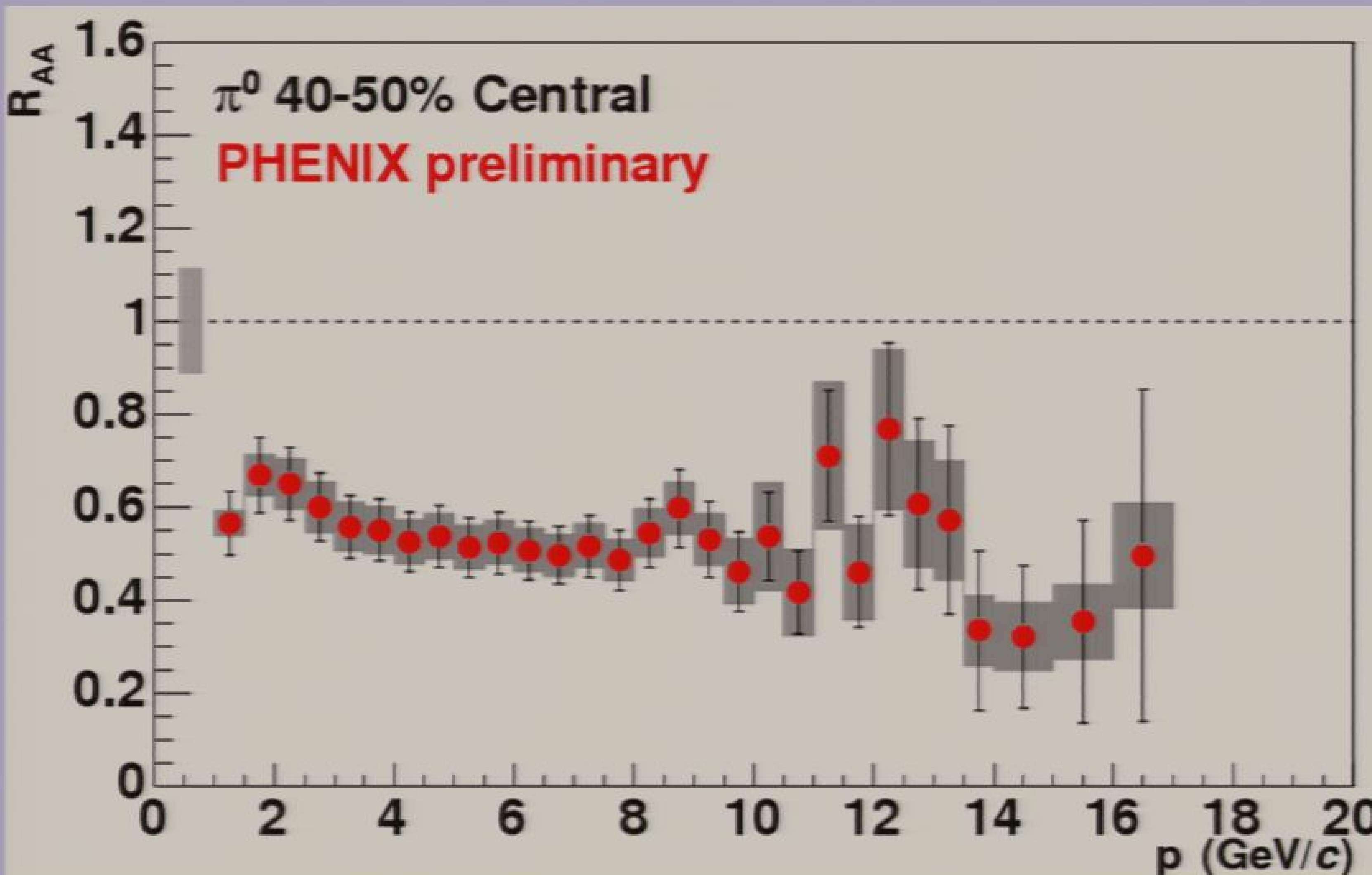
PHENIX: Au-Au High-p_T π^0 Suppression



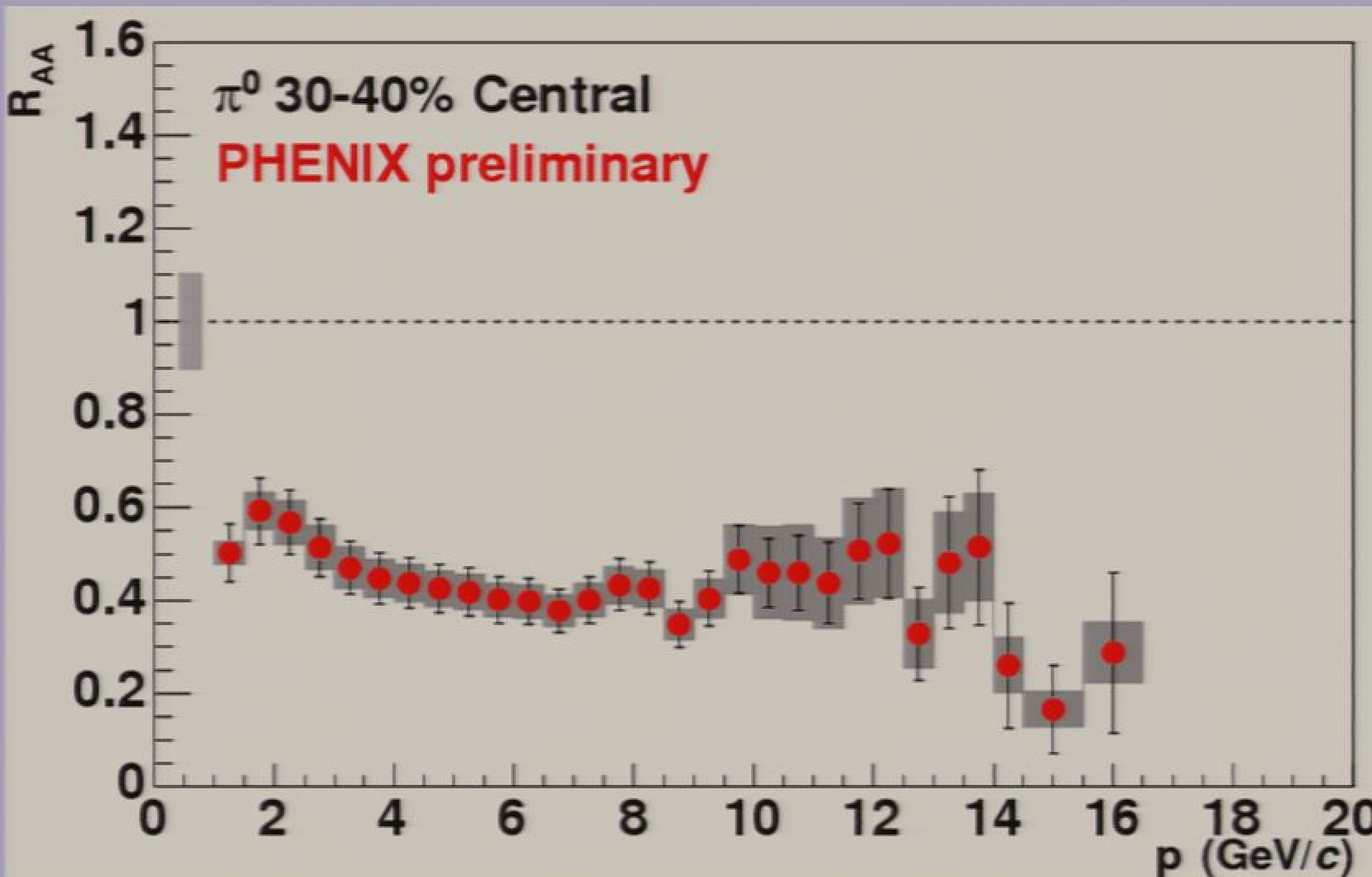
PHENIX: Au-Au High-p_T π^0 Suppression



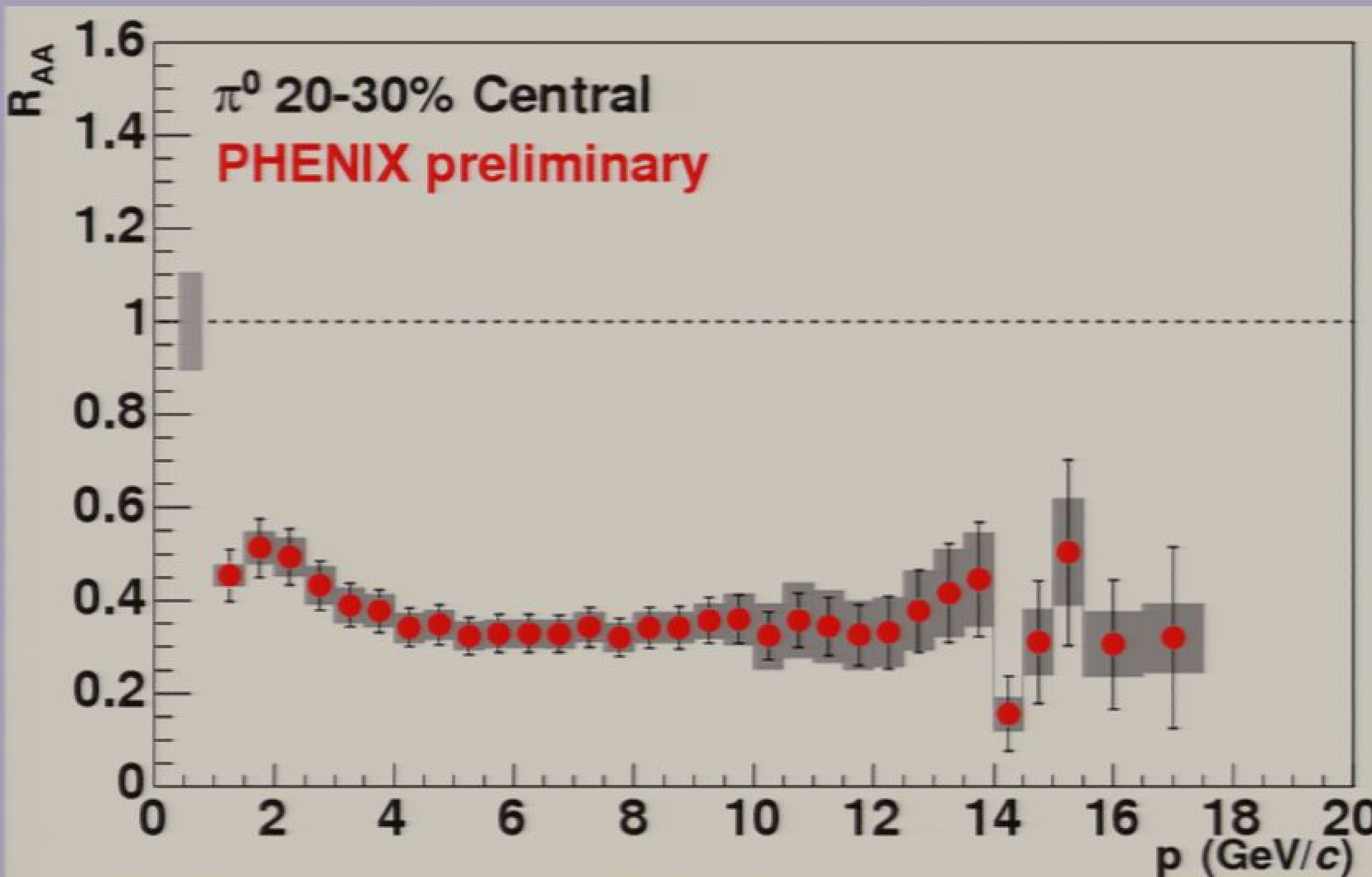
PHENIX: Au-Au High-p_T π^0 Suppression



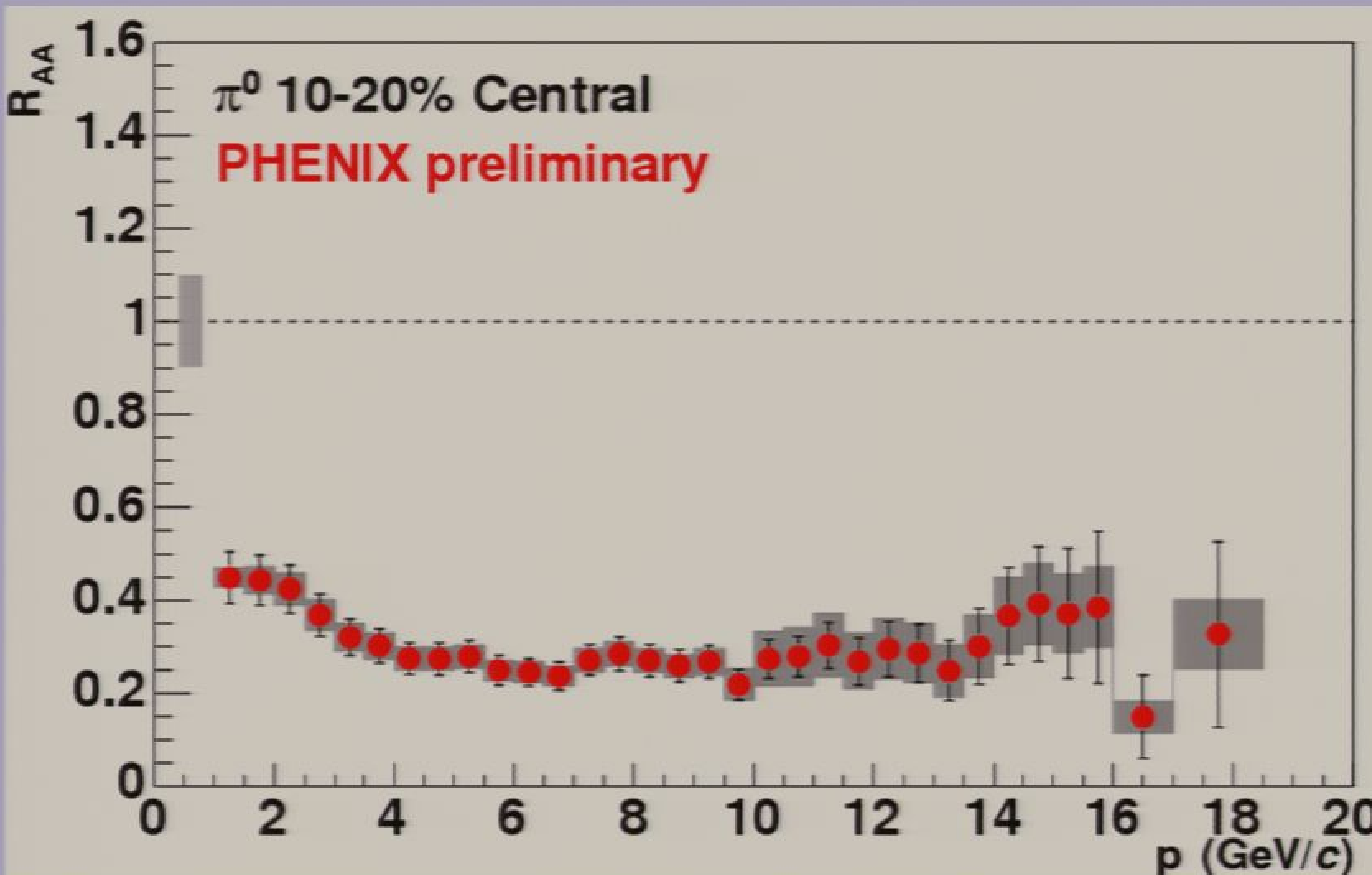
PHENIX: Au-Au High-p_T π^0 Suppression



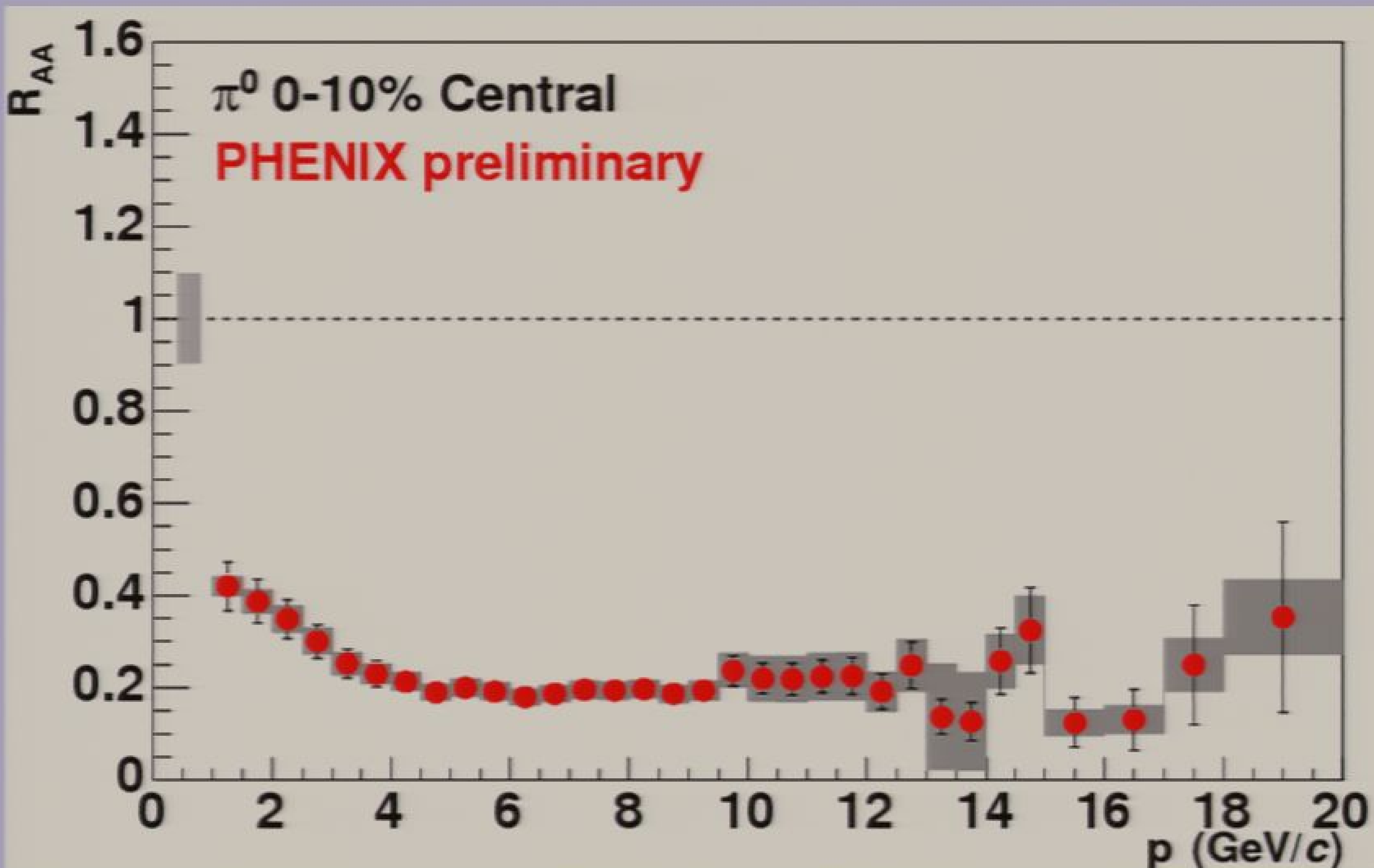
PHENIX: Au-Au High-p_T π^0 Suppression



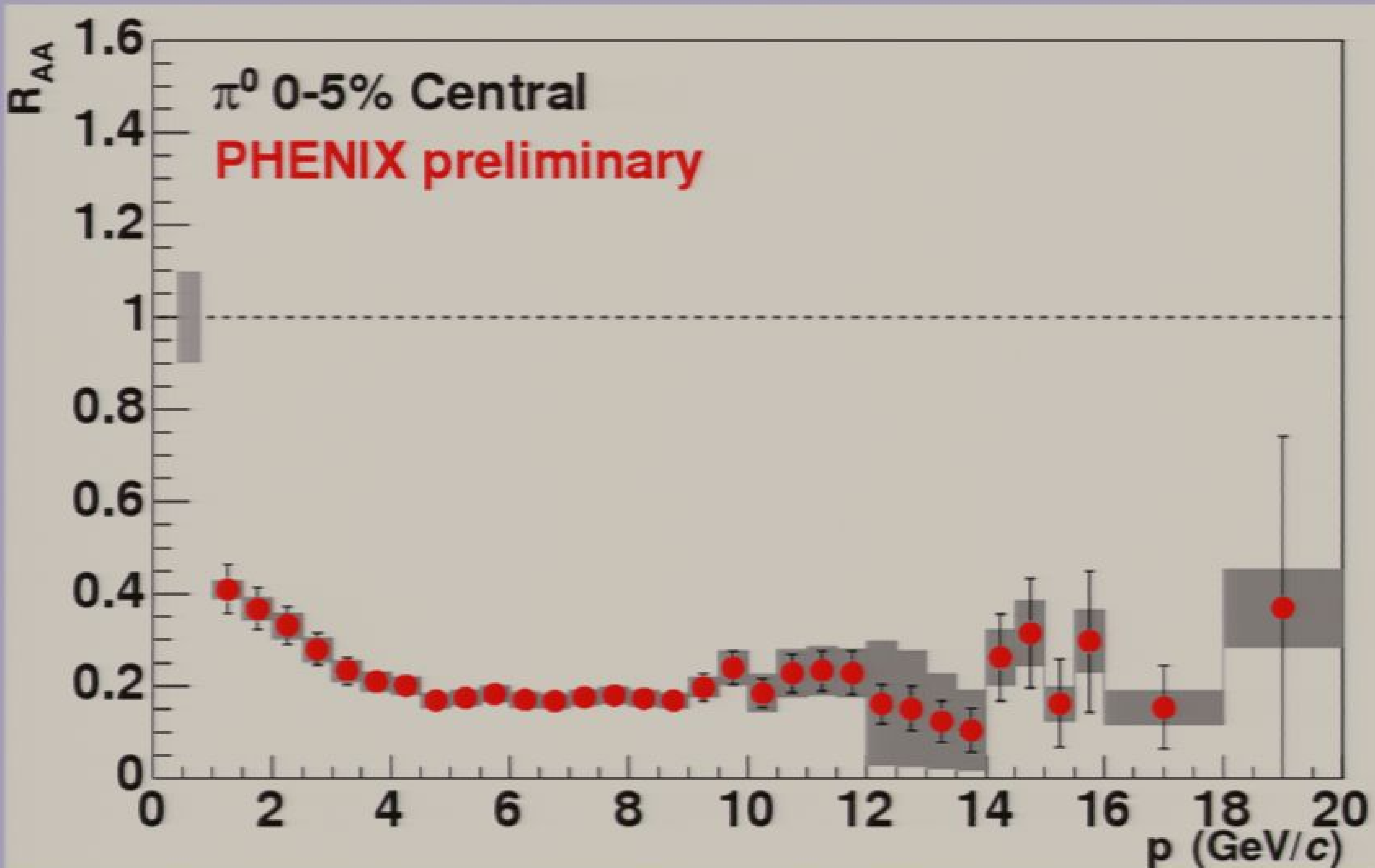
PHENIX: Au-Au High-p_T π^0 Suppression



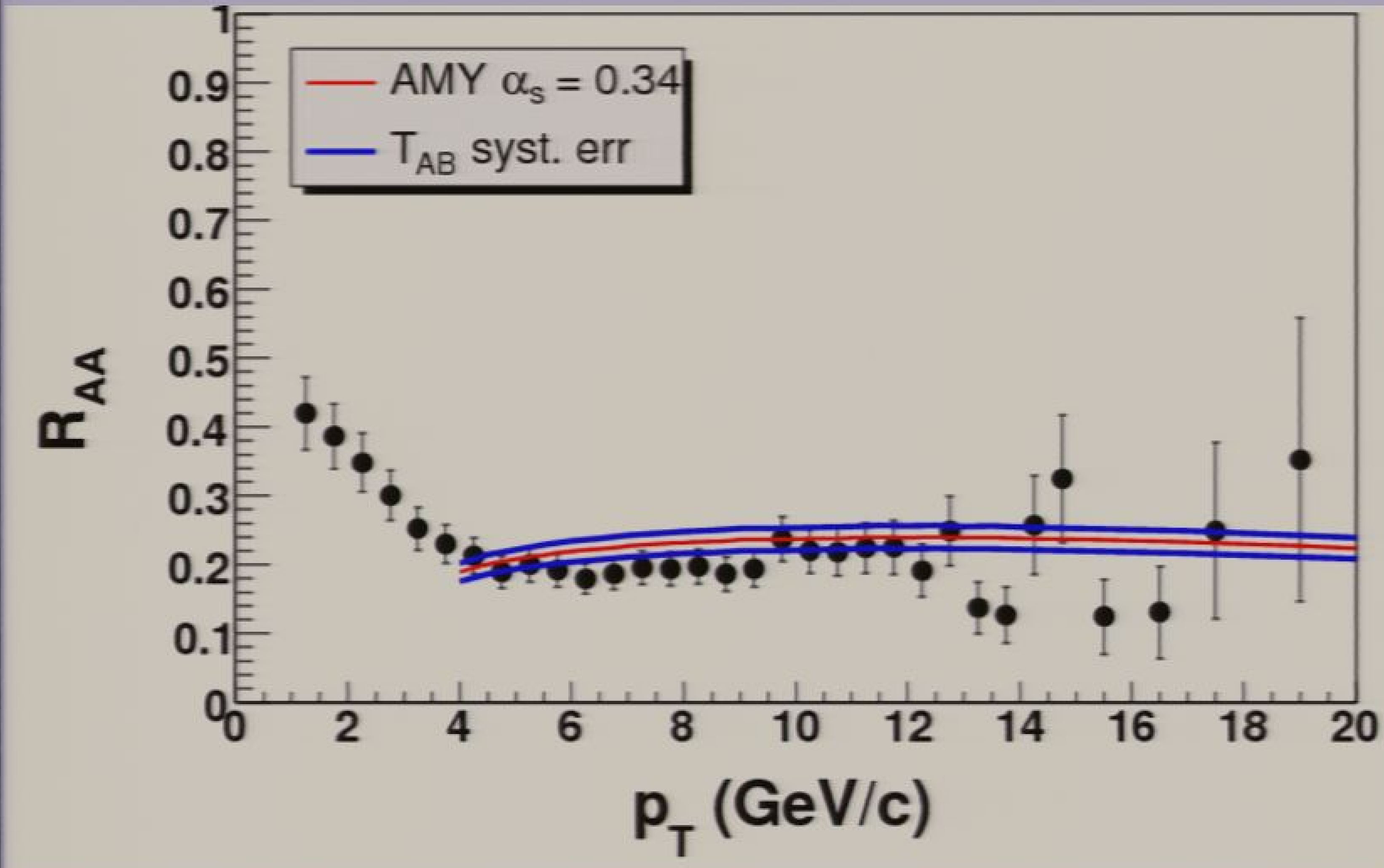
PHENIX: Au-Au High-p_T π^0 Suppression



PHENIX: Au-Au High-p_T π^0 Suppression

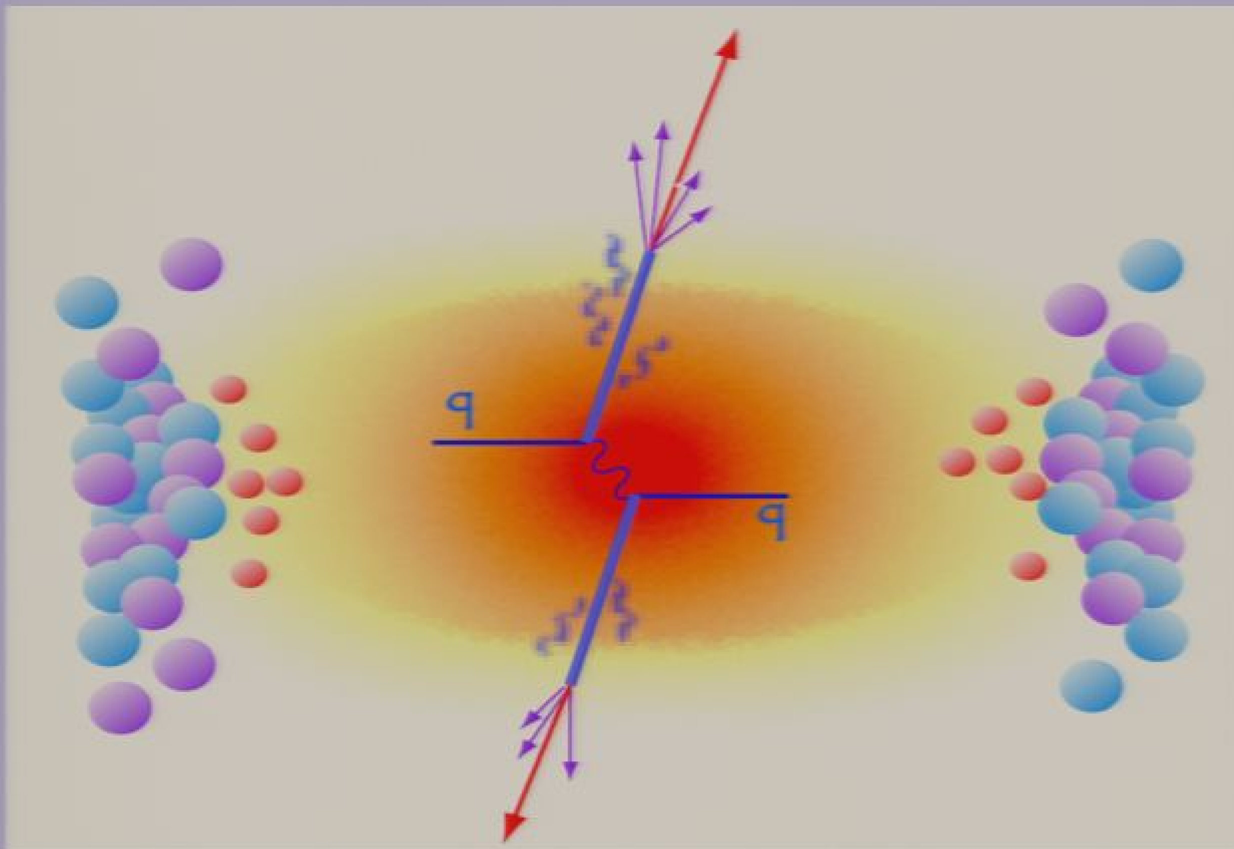


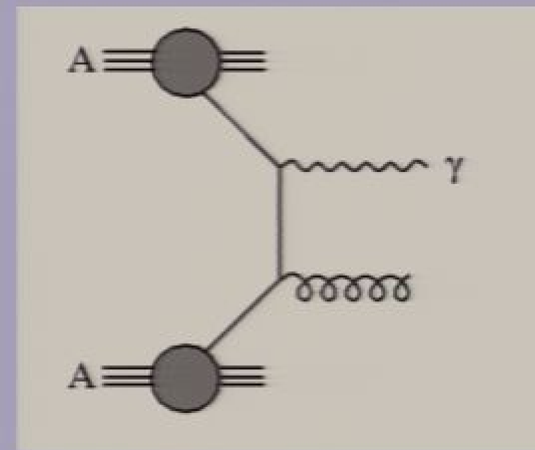
π^0 Suppression: dE/dx Comparisons

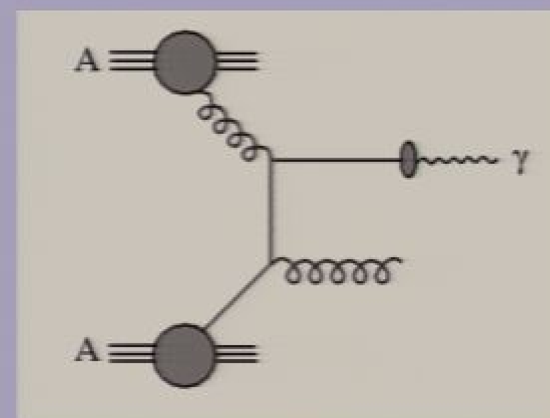


- Quark & gluon dE/dx analysis: *Turbide et al* (McGill)
  - **Essentially an *ab initio* calculation**
  - **Compared to precision (relatively) data**

Prompt Photon Production

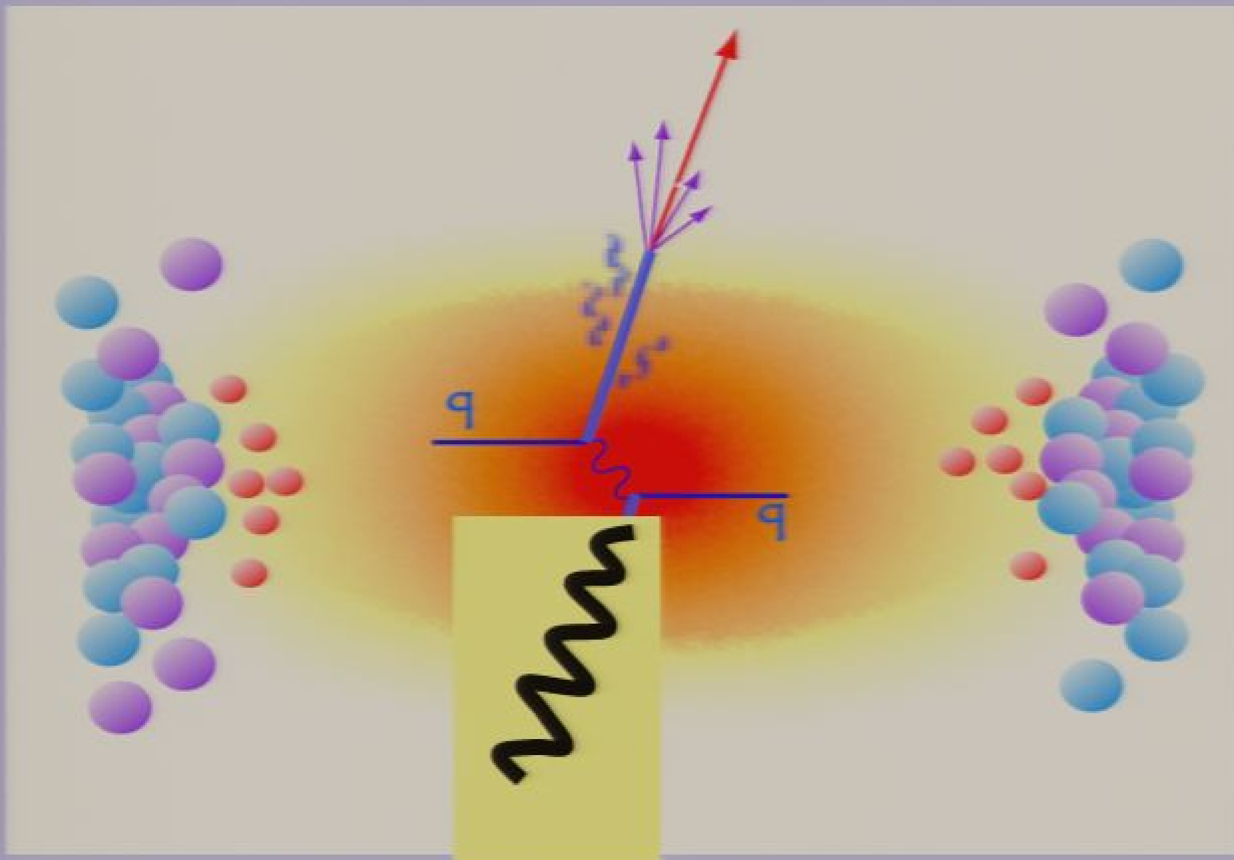


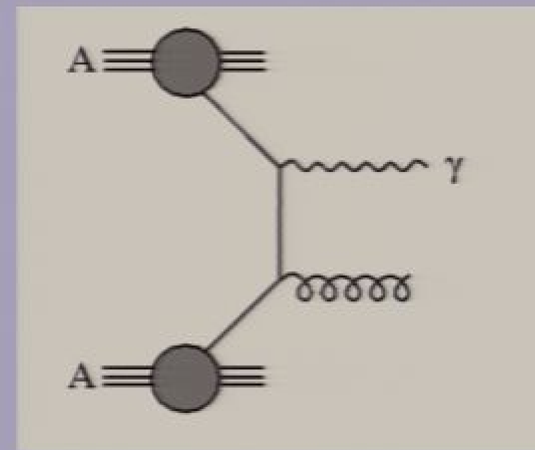


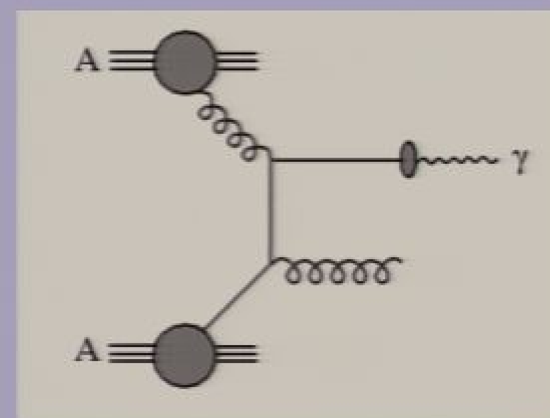


- Prompt photons provide an independent control measurement for jet quenching.
  - Produced in hard scattering processes
  - But, no final-state effects (???)

Prompt Photon Production





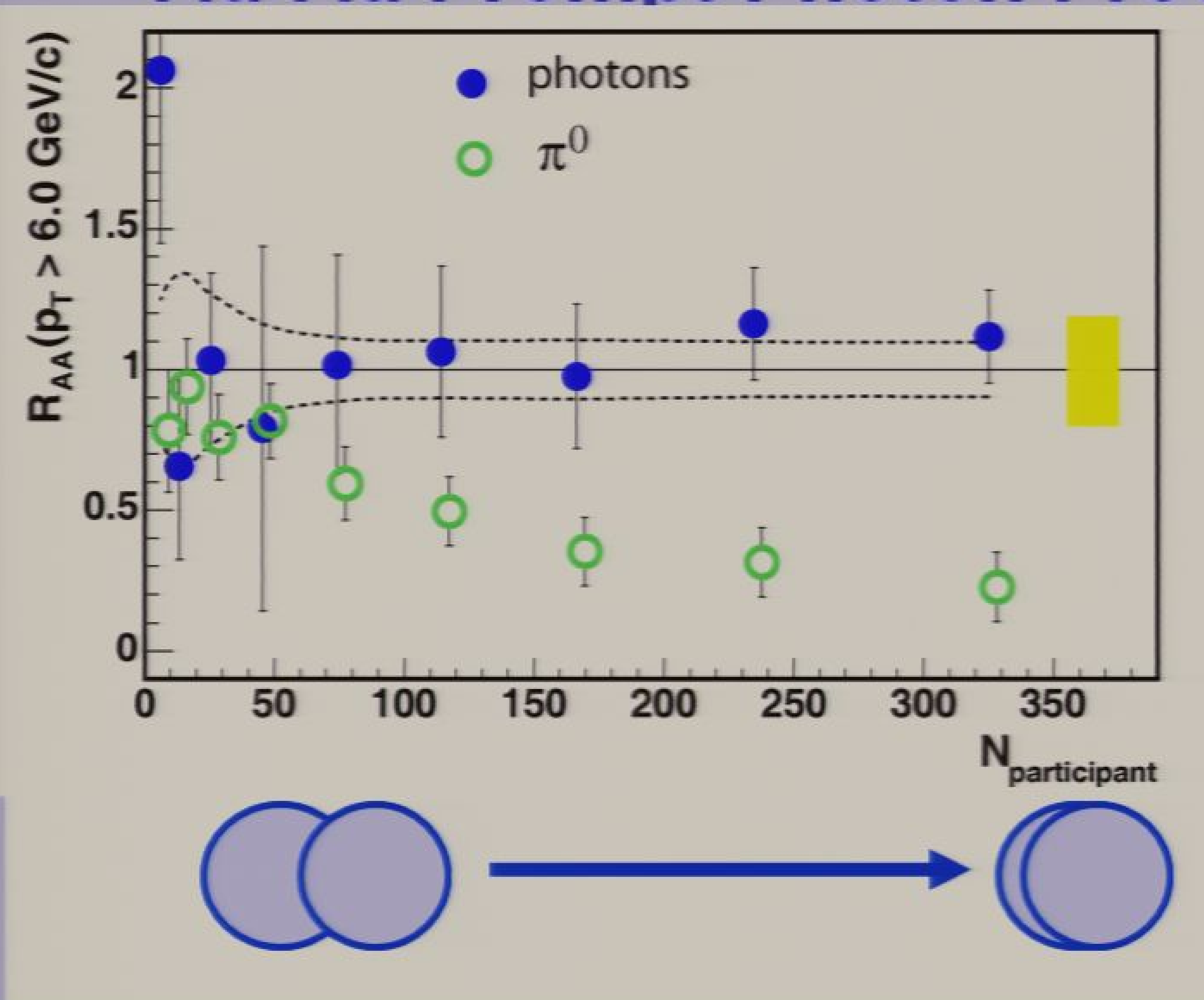


- Prompt photons provide an independent control measurement for jet quenching.
  - Produced in hard scattering processes
  - But, no final-state effects (???)

Au-Au Prompt Photon Production

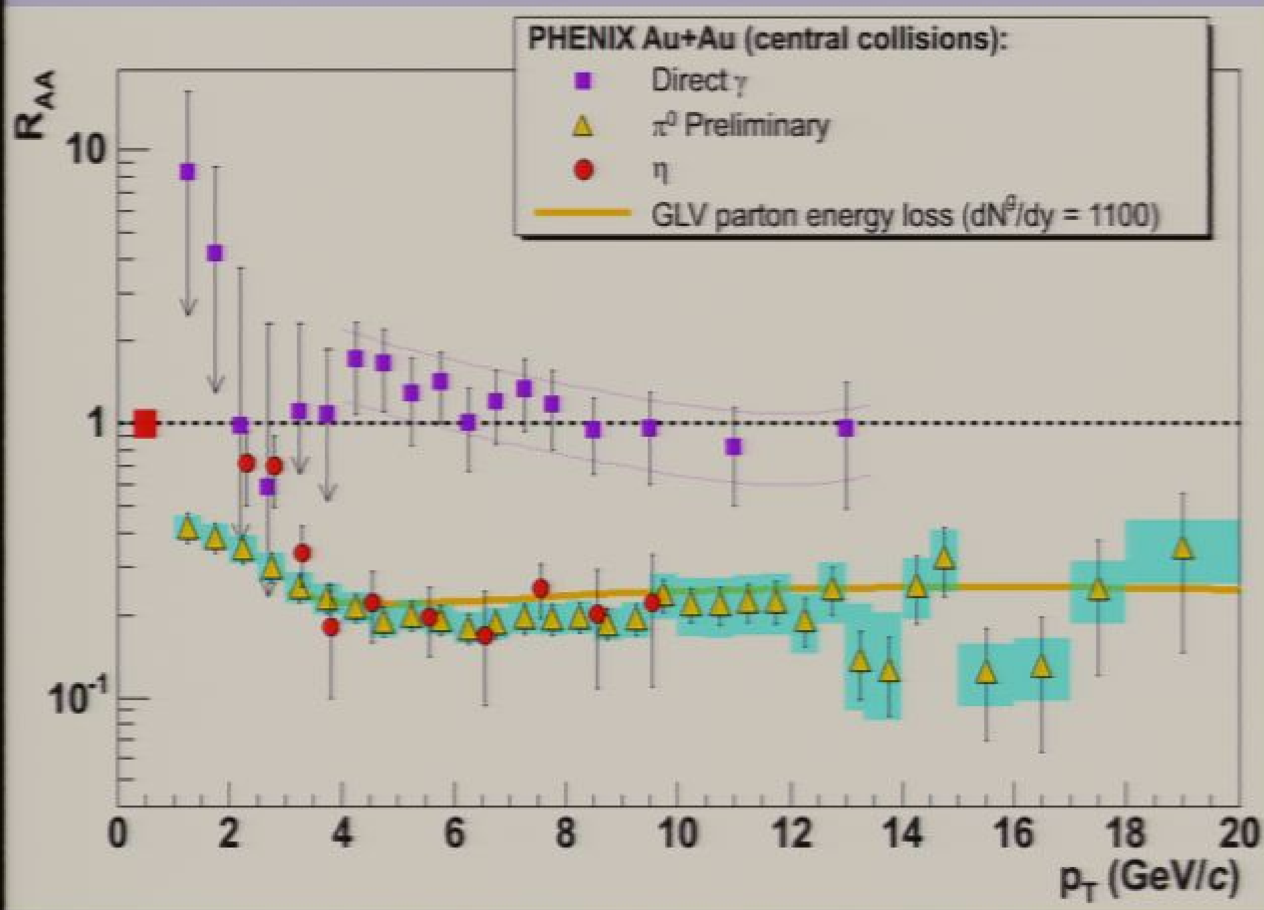
- Photon control measurement shows no quenching
- pQCD calculations OK, **quenching a final-state effect**

Au-Au Prompt Photon Production



- Photon control measurement shows no quenching
- pQCD calculations OK, **quenching a final-state effect**

High-p_T Single Particle Summary



To explain data:

Unscreened color charge dn/dy~1000

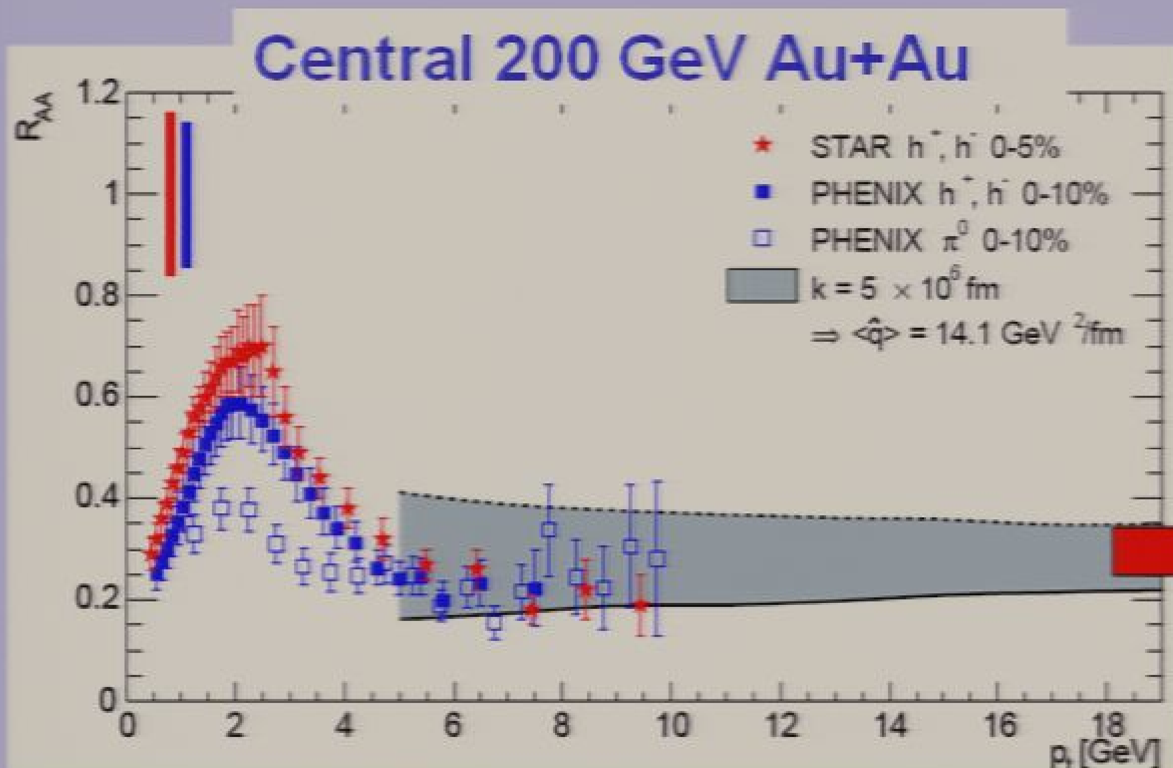
Energy density ~15 GeV/fm^3

> ×10 "critical" energy density

- ×5 violation of factorization up to 20 GeV/c
  - –In hadron production (jets), **but not prompt γ**
    - ⇒Hard scatterings occur at expected rates
    - ⇒Suppression **from final-state energy loss**

Analysis of Single Hadron Data: BDMS-Z-SW

- "Thick medium" energy loss calculation



Transport coefficient:

$$\hat{q} = \langle p_T^{\,2} \rangle / length$$

for radiated gluon

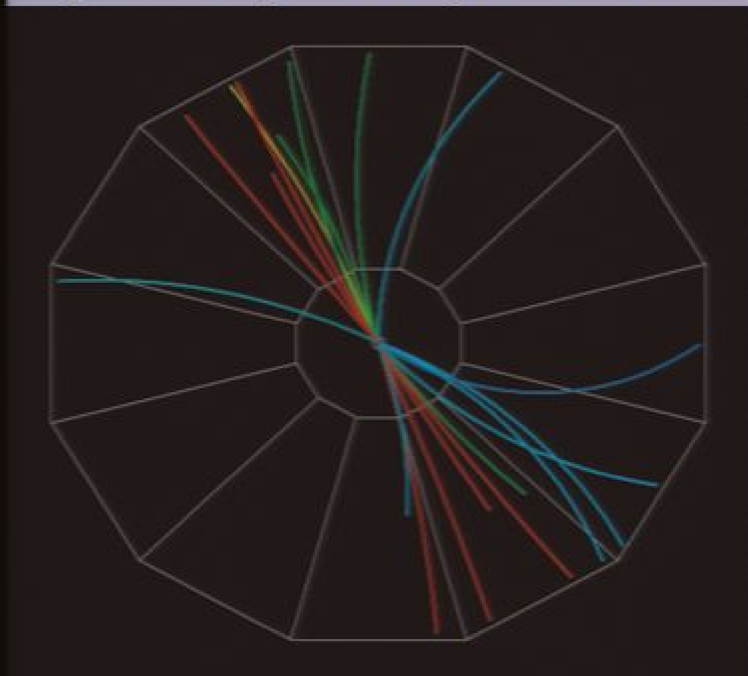
$$\hat{q} \sim 14\ \mathrm{GeV}^2/\mathrm{fm}$$

- Baier [Nucl. Phys. A715, 209 (2003)]: $\hat{q} \approx c\varepsilon^{3/4}$
  - **C = 2 expected for ideal QGP**
  - **14 GeV/fm² ⇒ *c = 8-10*!!**

⇒Strong coupling [Eskola et al, Nucl. Phys. A747, 511 (2005)]

STAR Experiment: "Jet" Observations

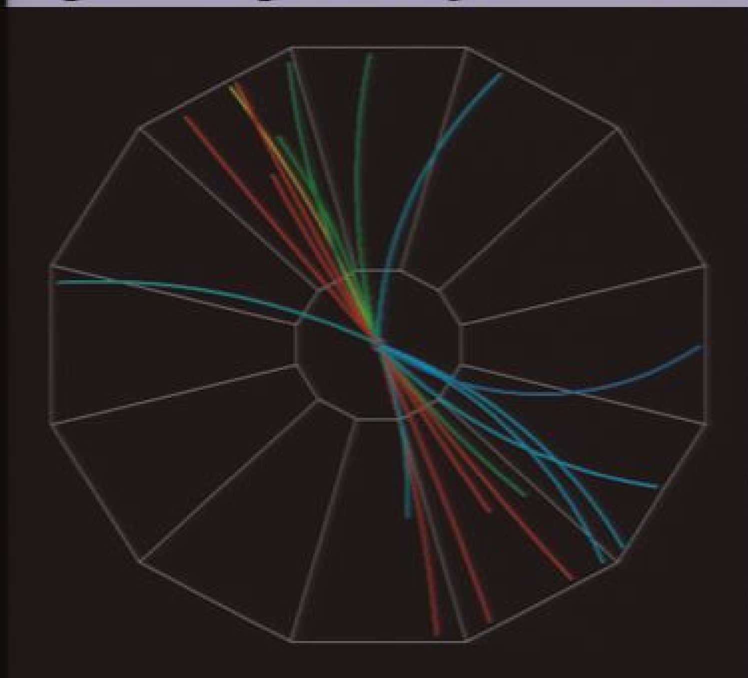
proton-proton jet event



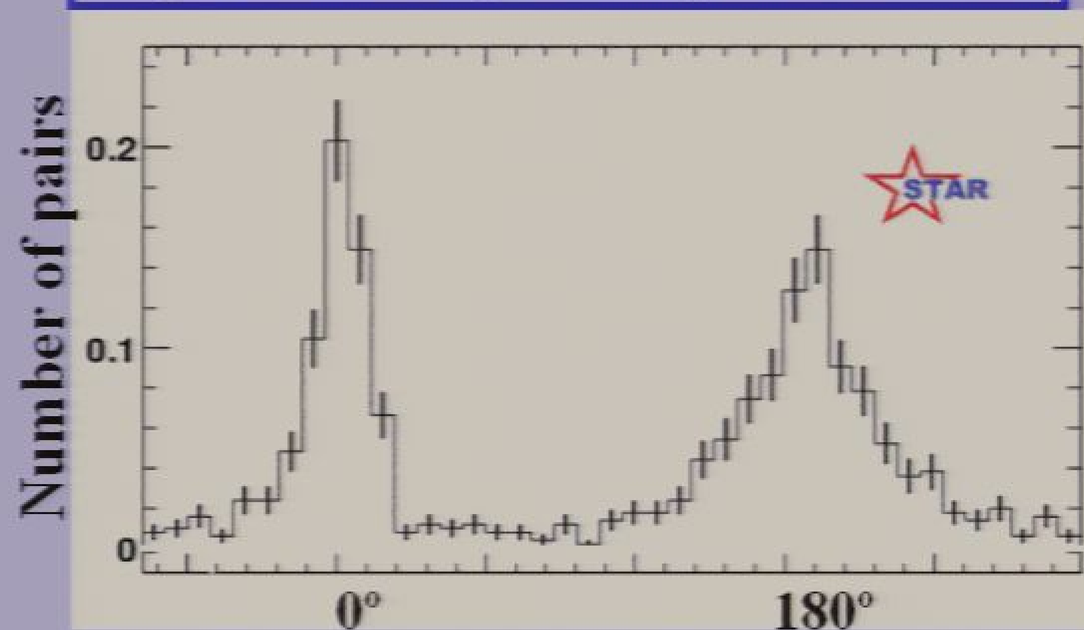
Analyze by measuring (azimuthal) angle between pairs of particles

STAR Experiment: "Jet" Observations

proton-proton jet event



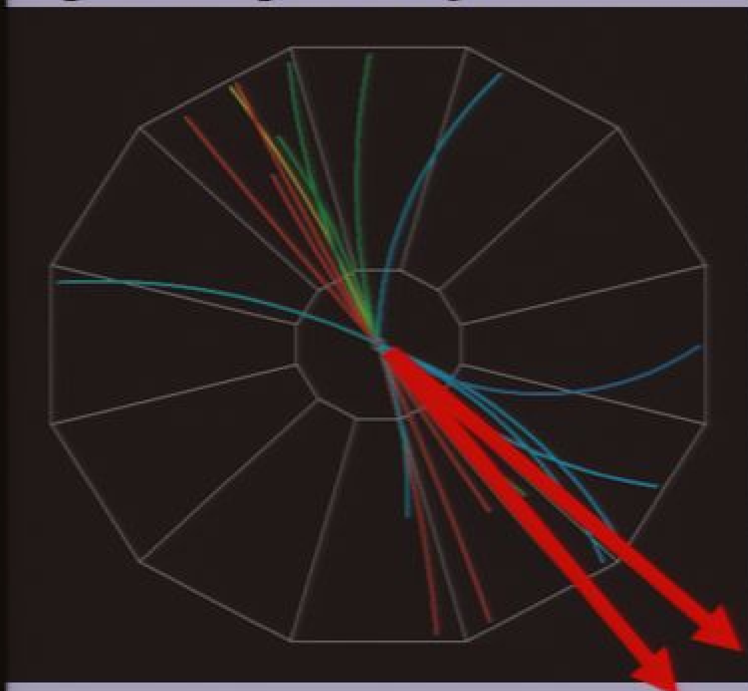
Analyze by measuring (azimuthal) angle between pairs of particles



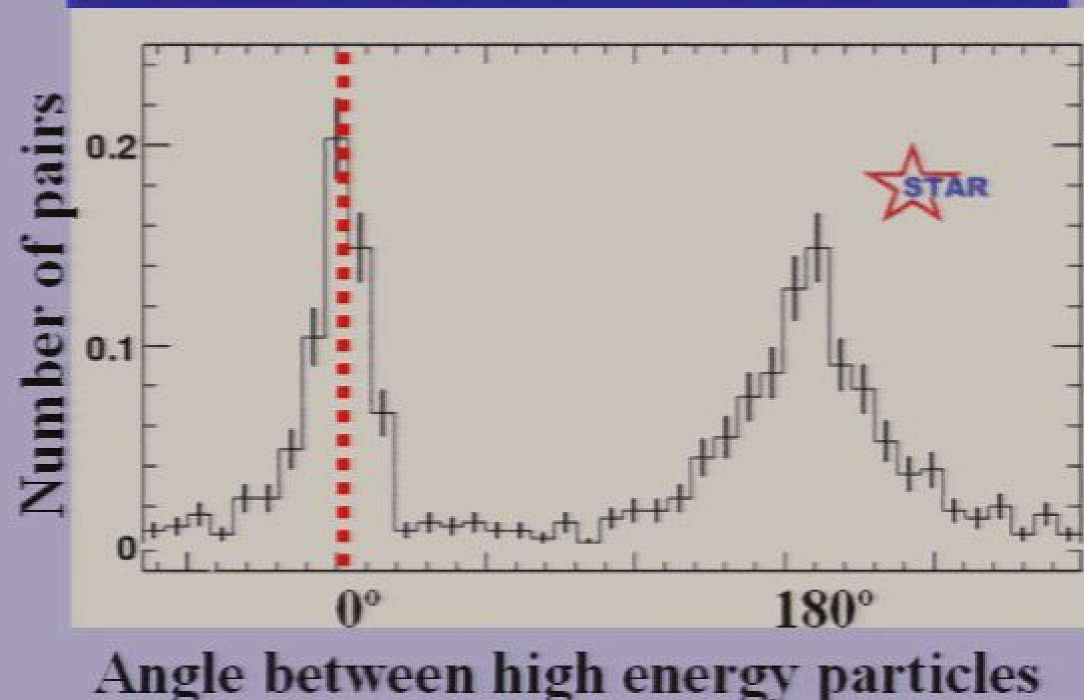
Angle between high energy particles

STAR Experiment: "Jet" Observations

proton-proton jet event

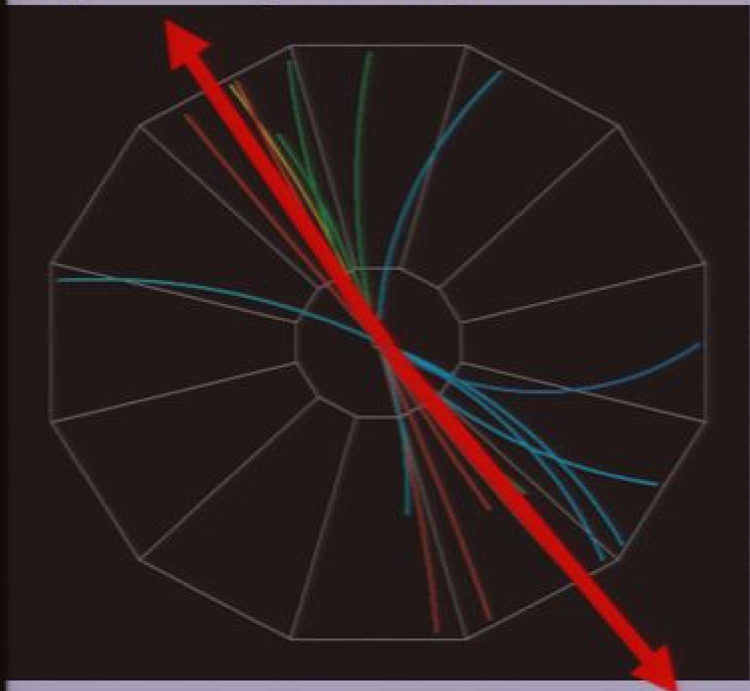


Analyze by measuring (azimuthal) angle between pairs of particles

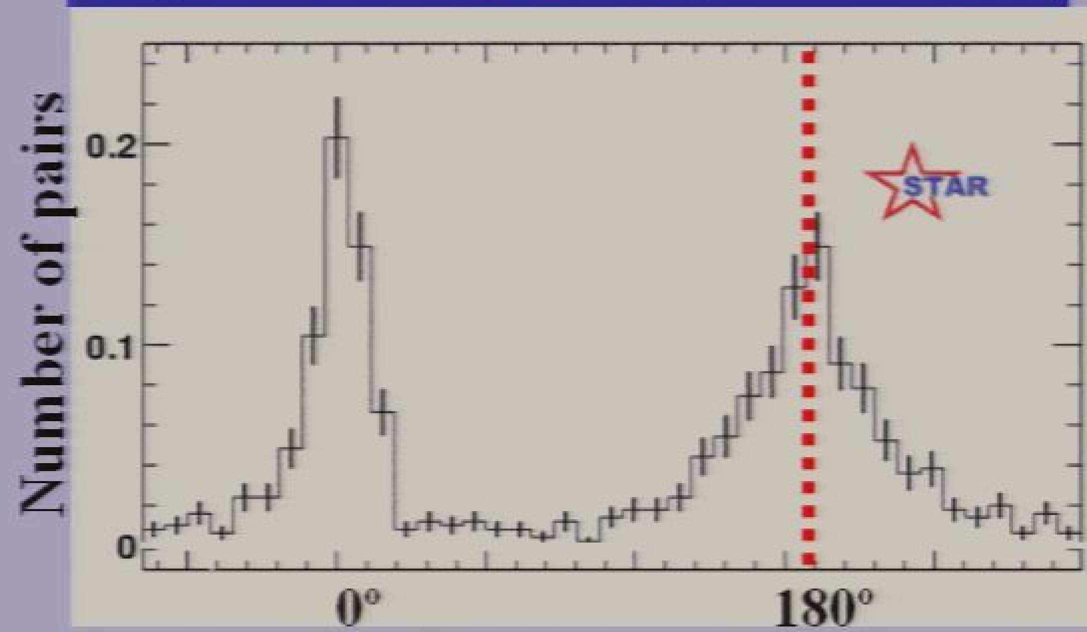


STAR Experiment: "Jet" Observations

proton-proton jet event



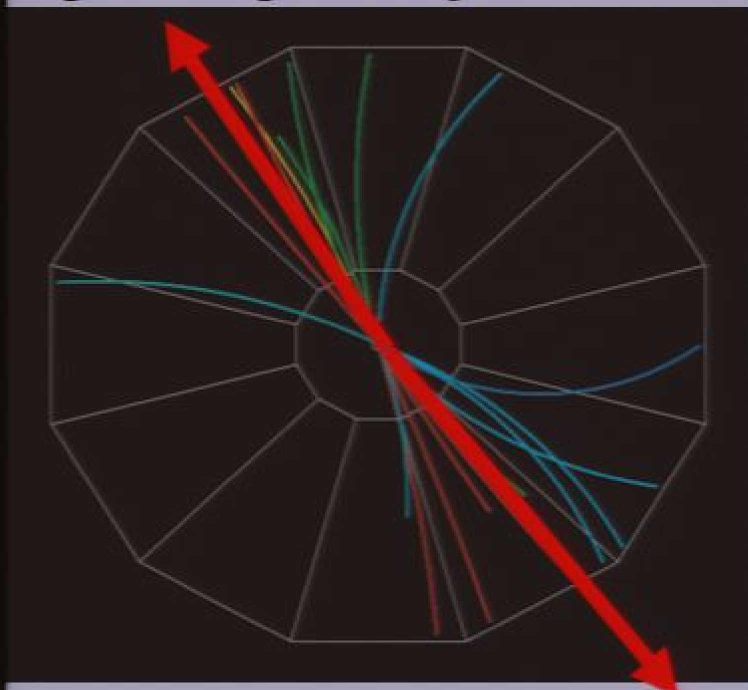
Analyze by measuring (azimuthal) angle between pairs of particles



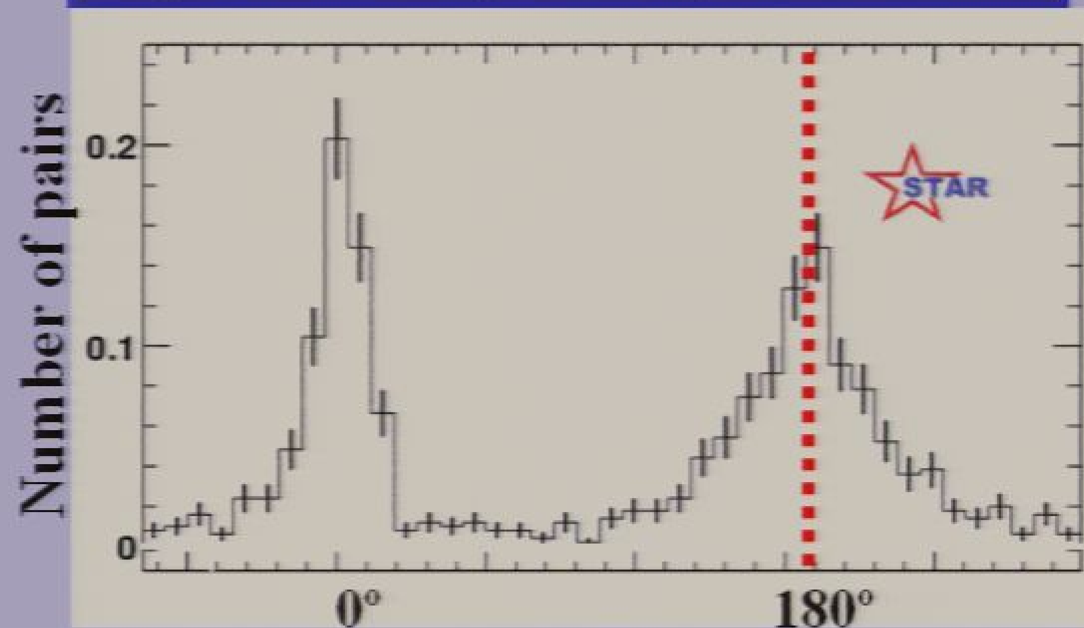
Angle between high energy particles

STAR Experiment: "Jet" Observations

proton-proton jet event



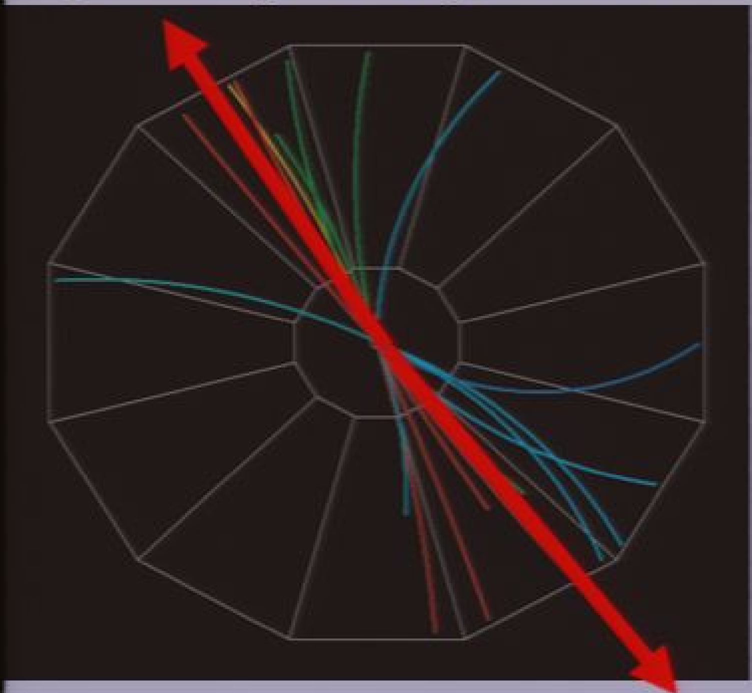
Analyze by measuring (azimuthal) angle between pairs of particles



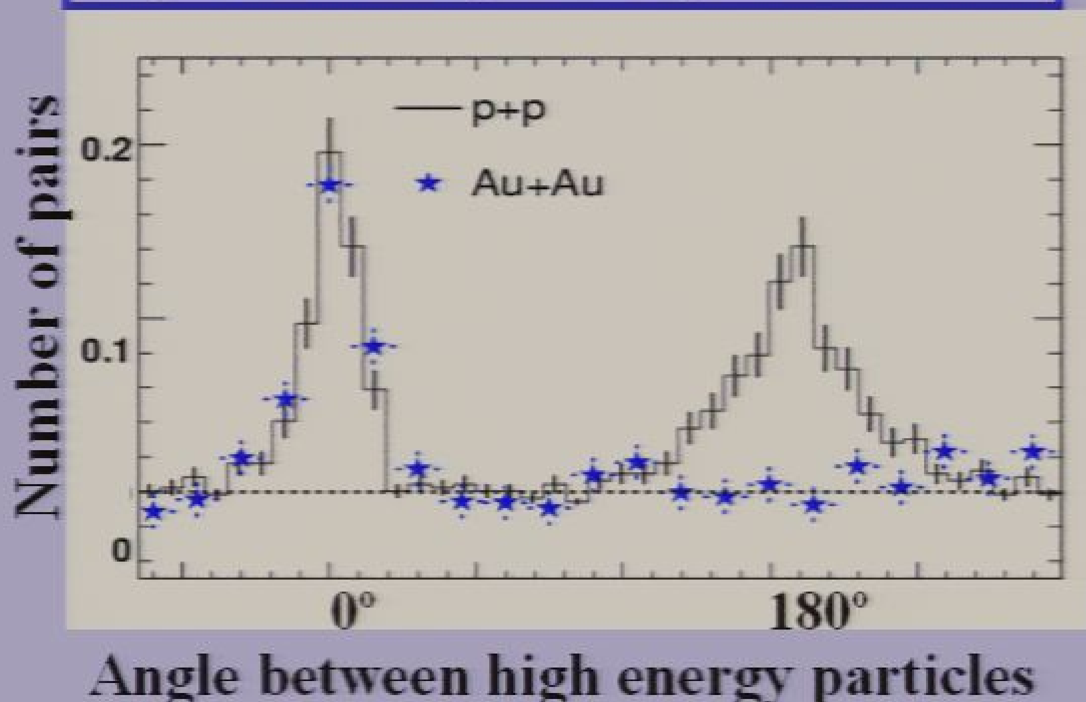
Angle between high energy particles

STAR Experiment: “Jet” Observations

proton-proton jet event

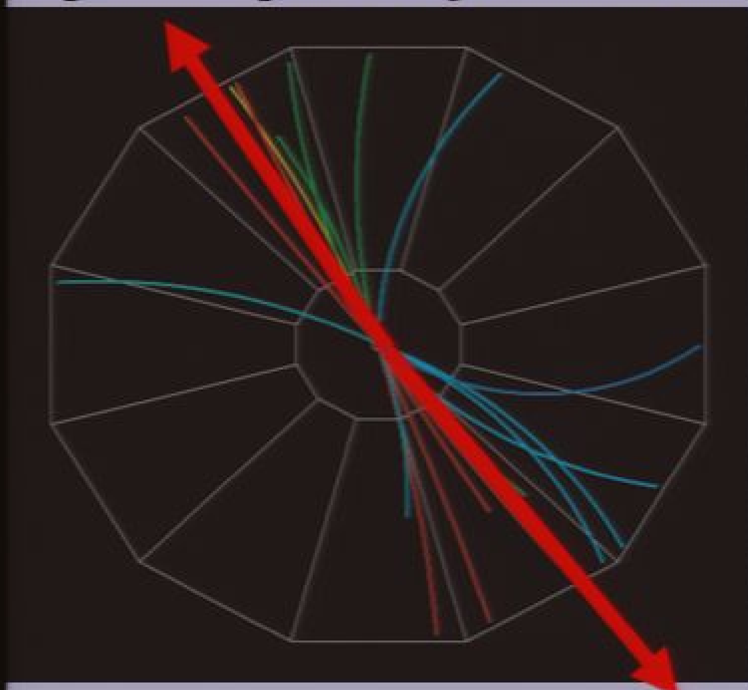


Analyze by measuring (azimuthal) angle between pairs of particles

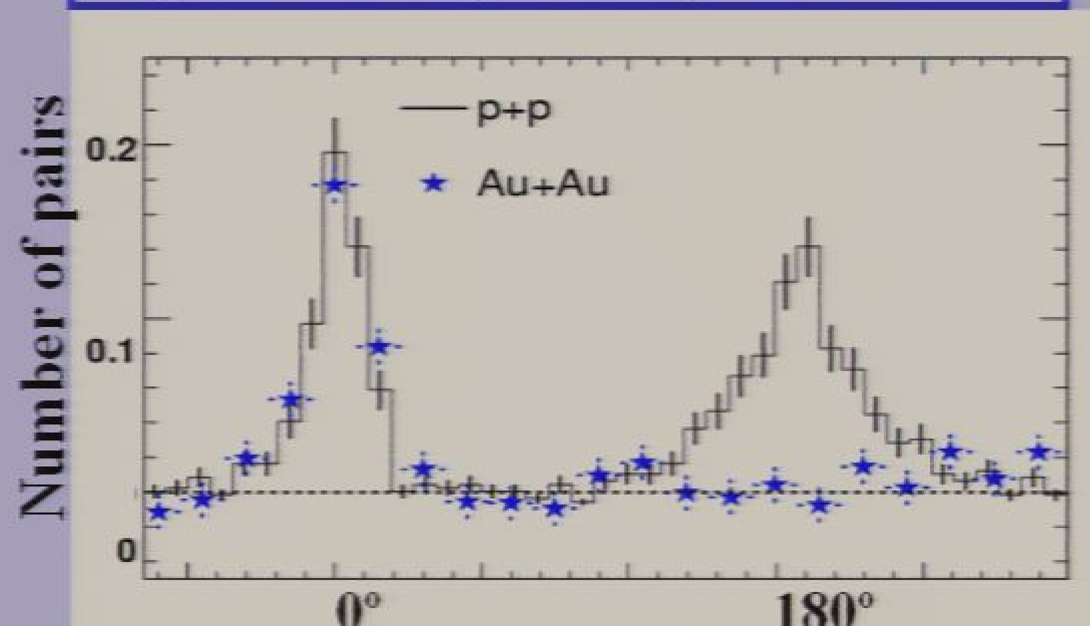


STAR Experiment: "Jet" Observations

proton-proton jet event



Analyze by measuring (azimuthal) angle between pairs of particles

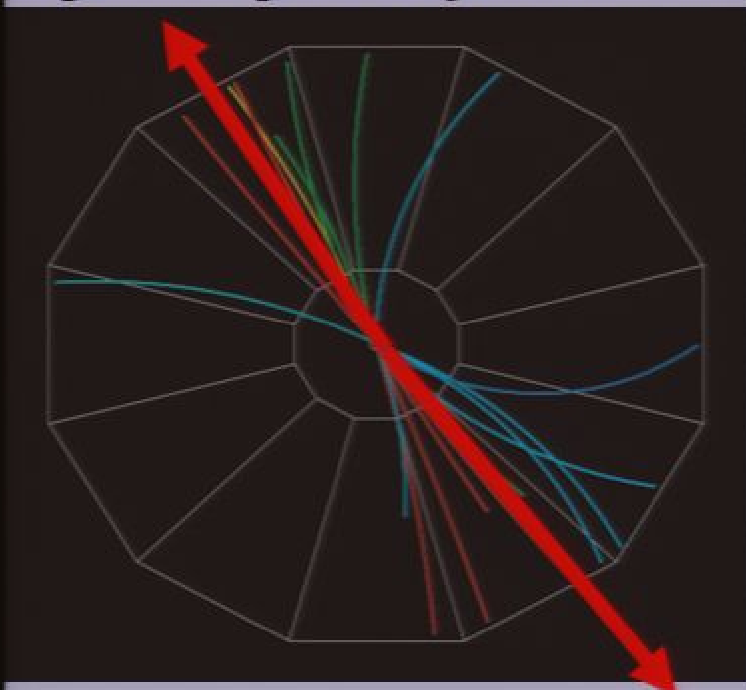


Angle between high energy particles

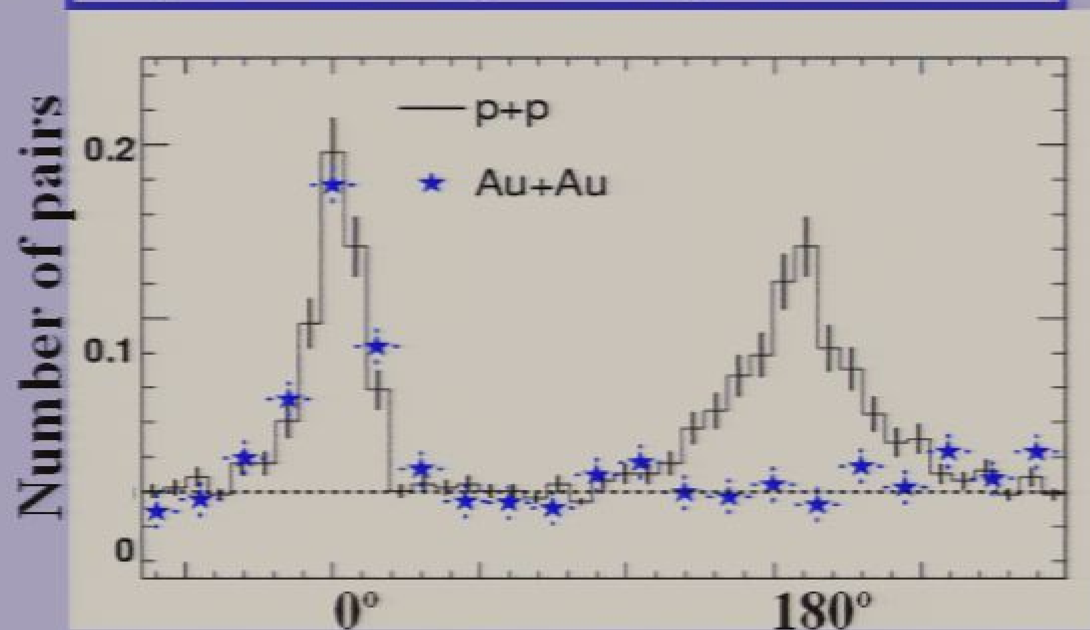
- In Au-Au collisions we see **only one "jet" at a time** !
- How can this happen ?
- Jet quenching!

STAR Experiment: "Jet" Observations

proton-proton jet event

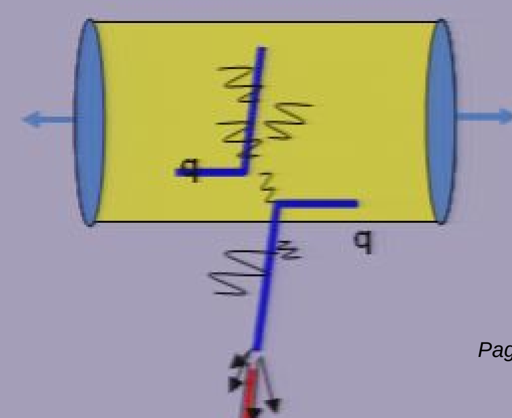


Analyze by measuring (azimuthal) angle between pairs of particles



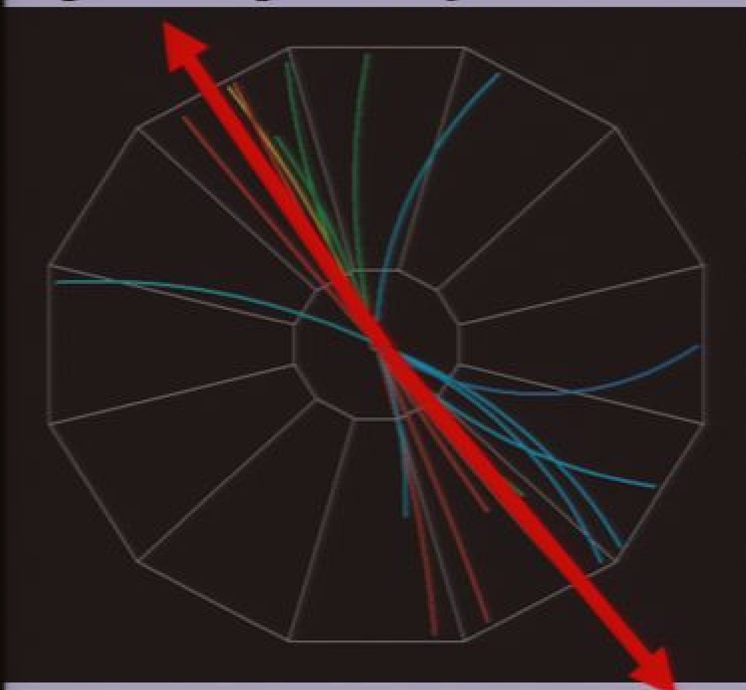
Angle between high energy particles

- **In Au-Au collisions we see only one "jet" at a time !**
- **How can this happen ?**
- **Jet quenching!**

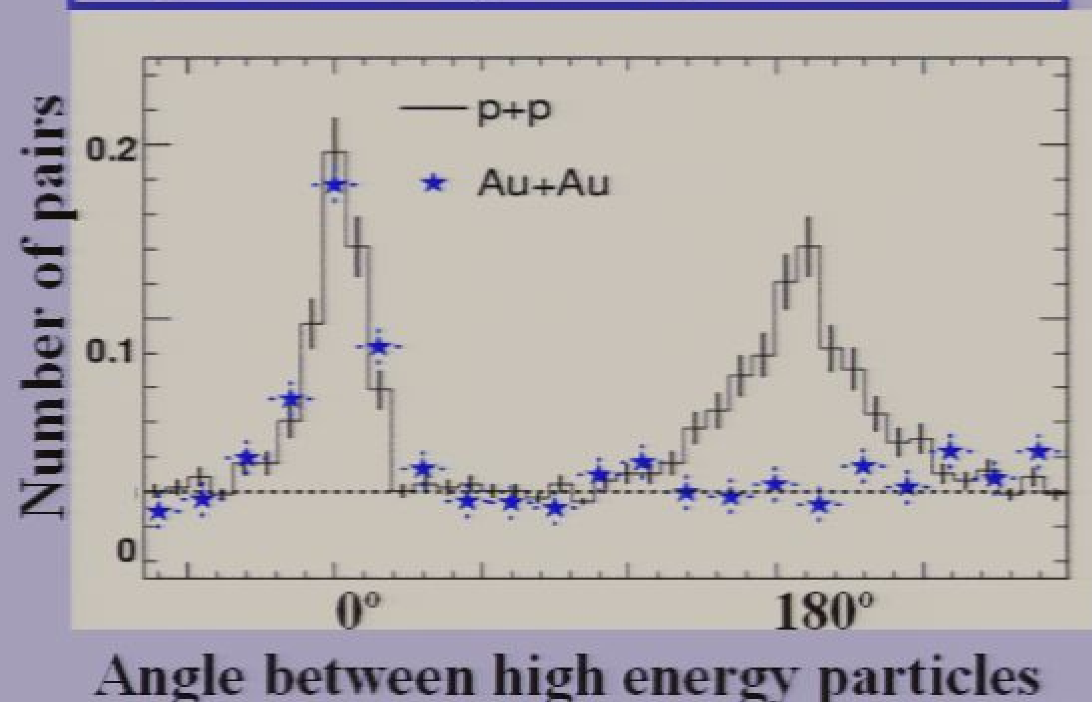


STAR Experiment: "Jet" Observations

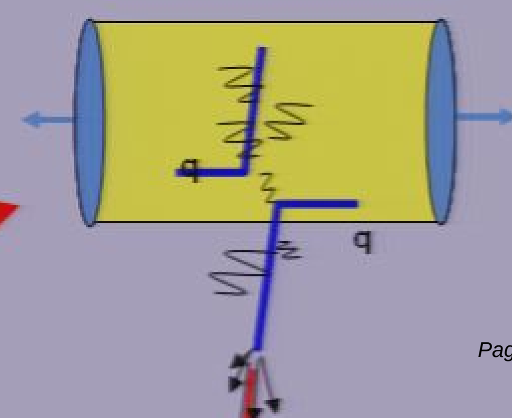
proton-proton jet event



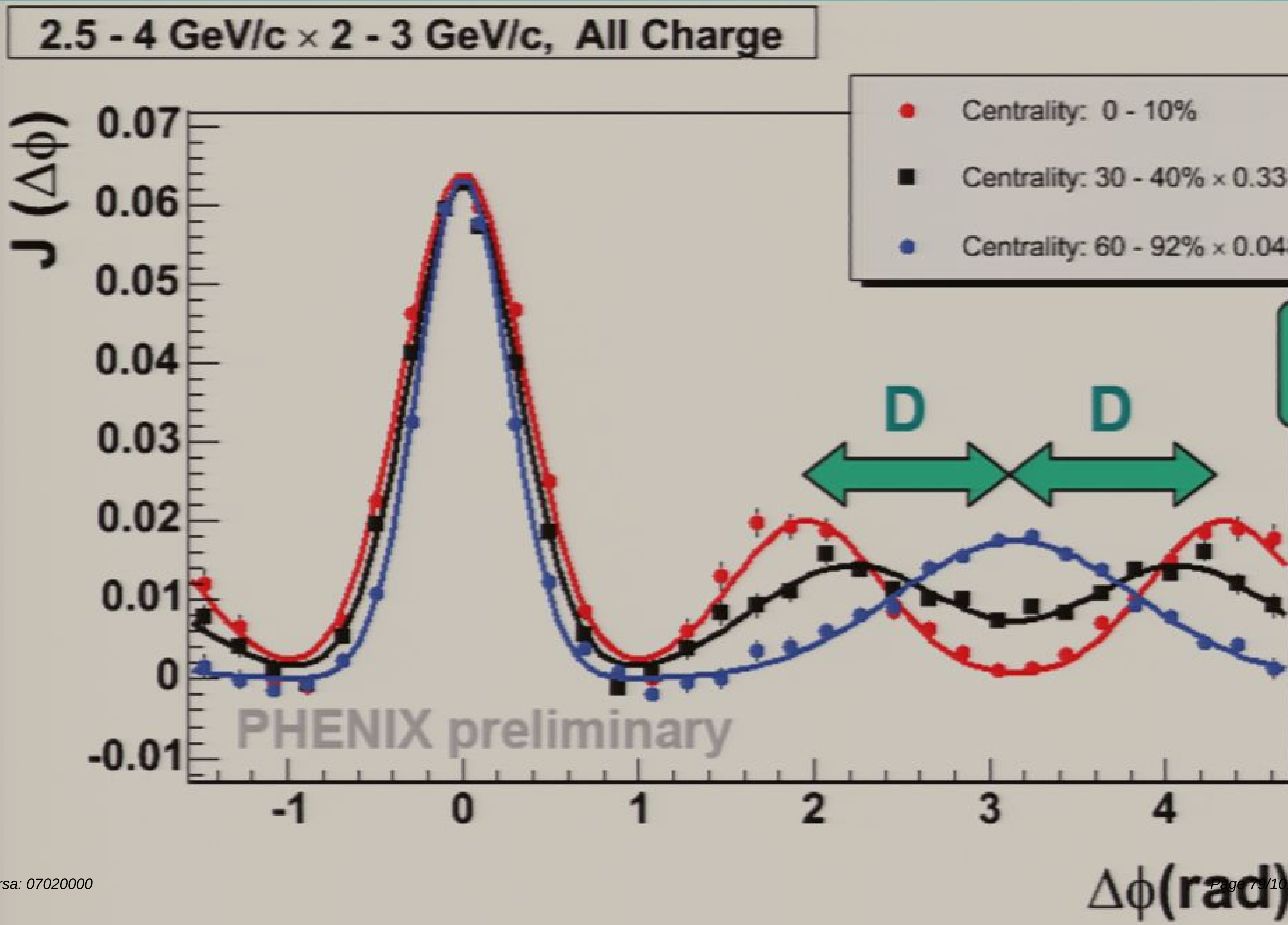
Analyze by measuring (azimuthal) angle between pairs of particles



- In Au-Au collisions we see only one "jet" at a time !
- How can this happen ?
- Jet quenching!

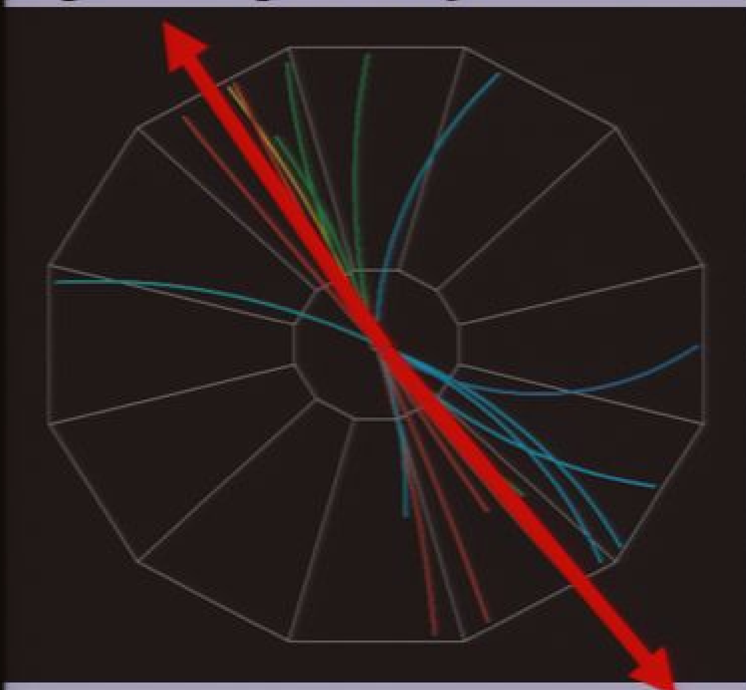


Di-jet Distortion vs "Impact Parameter"

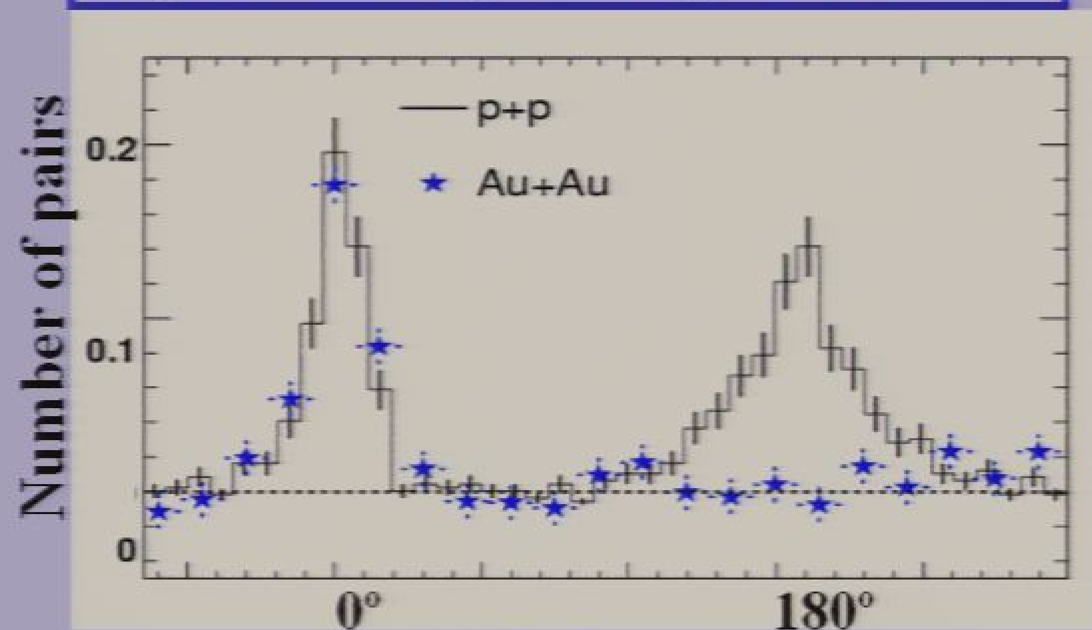


STAR Experiment: "Jet" Observations

proton-proton jet event

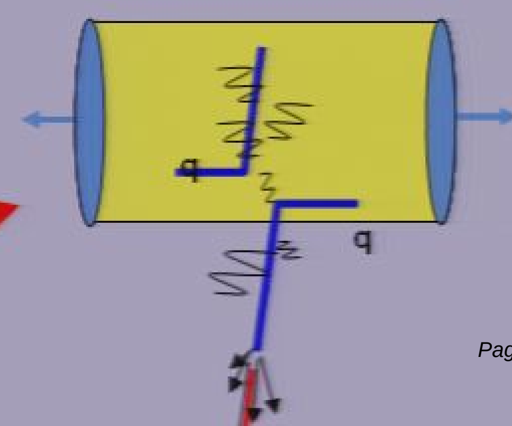


Analyze by measuring (azimuthal) angle between pairs of particles

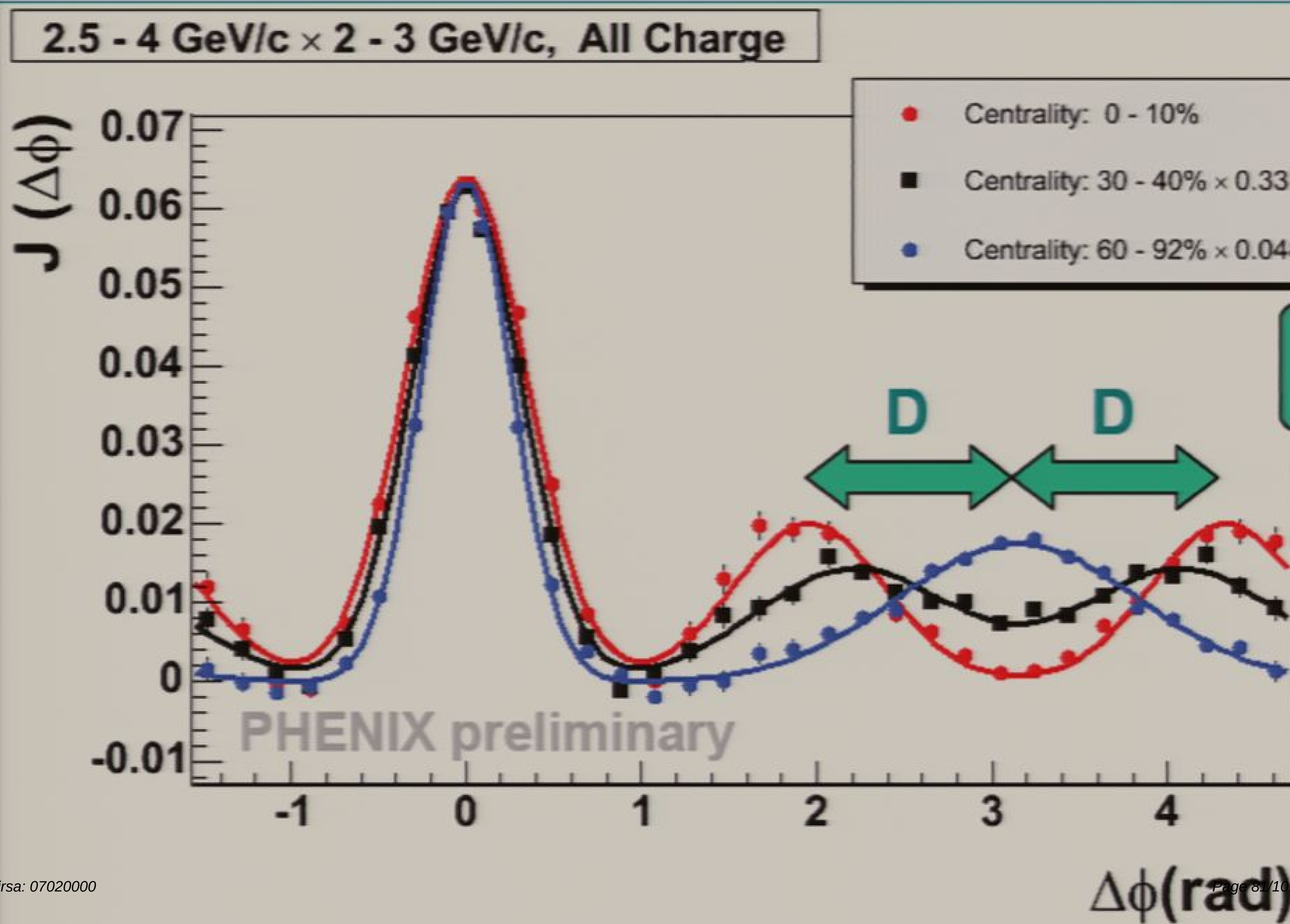


Angle between high energy particles

- In Au-Au collisions we see only one "jet" at a time !
- How can this happen ?
- Jet quenching!

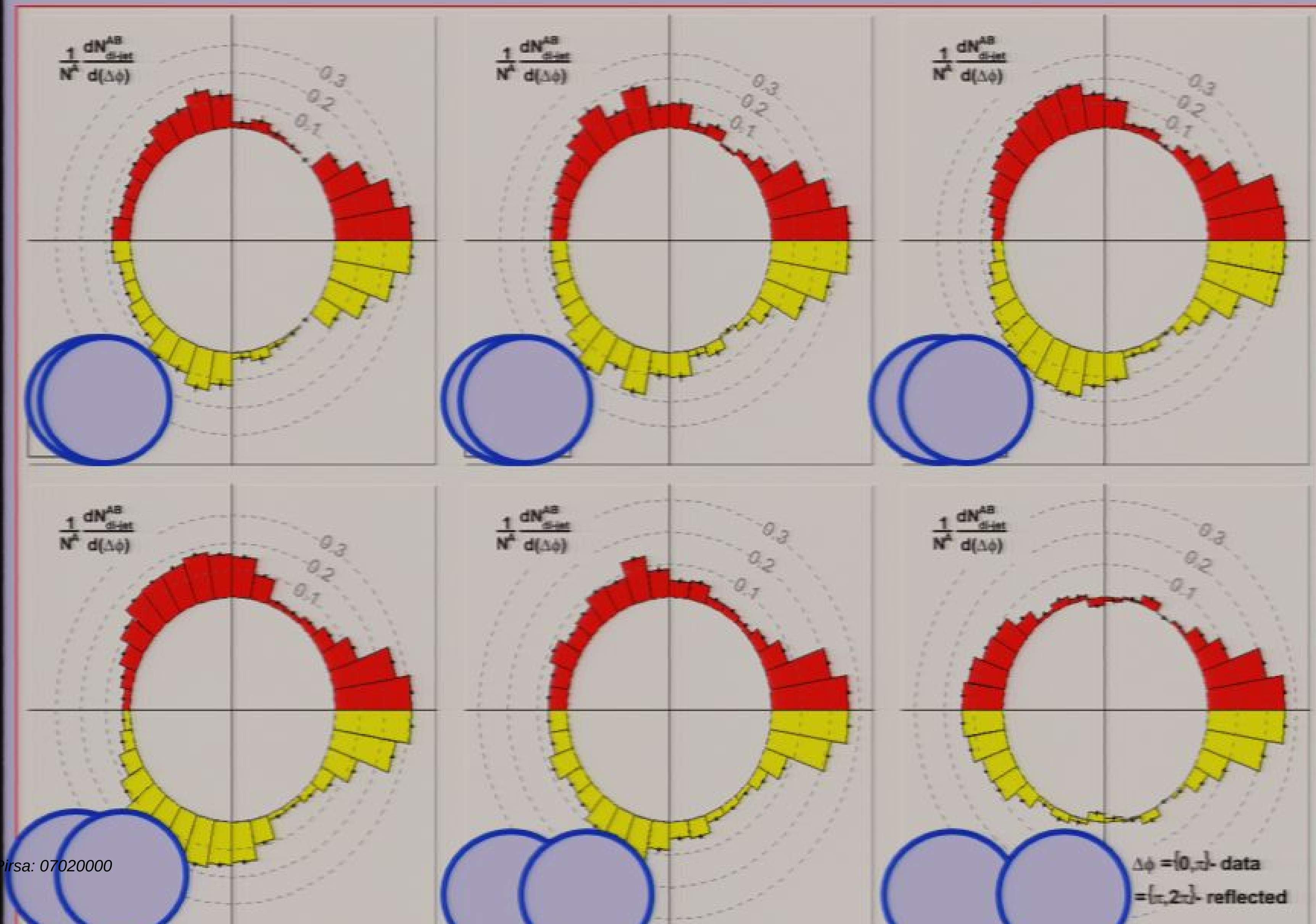


Di-jet Distortion vs "Impact Parameter"



(di)Jet Angular Correlations (PHENIX)

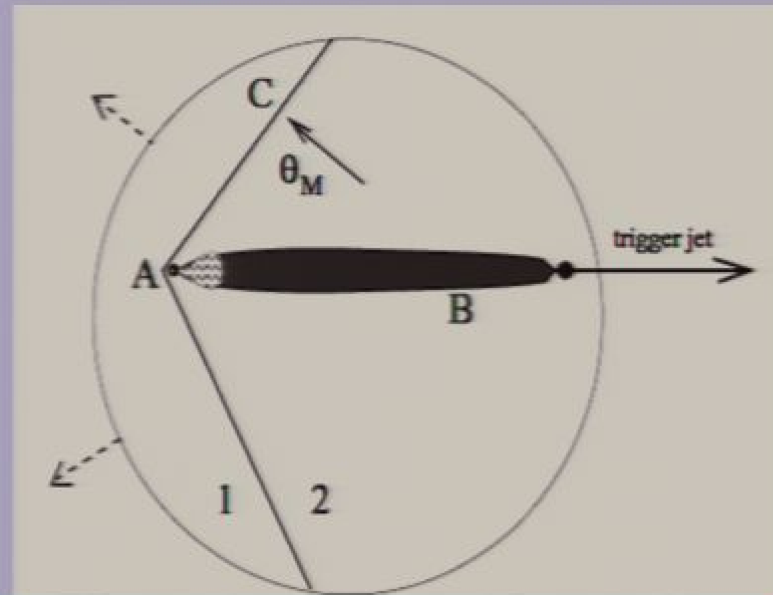
- PHENIX (nucl-ex/0507004): **moderate p_T**

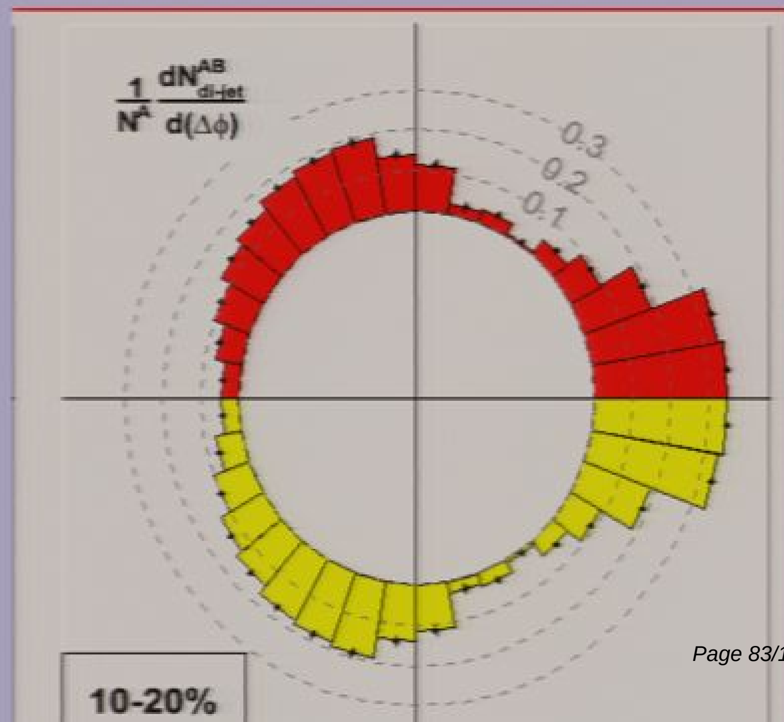


Origin of di-jet Distortion?

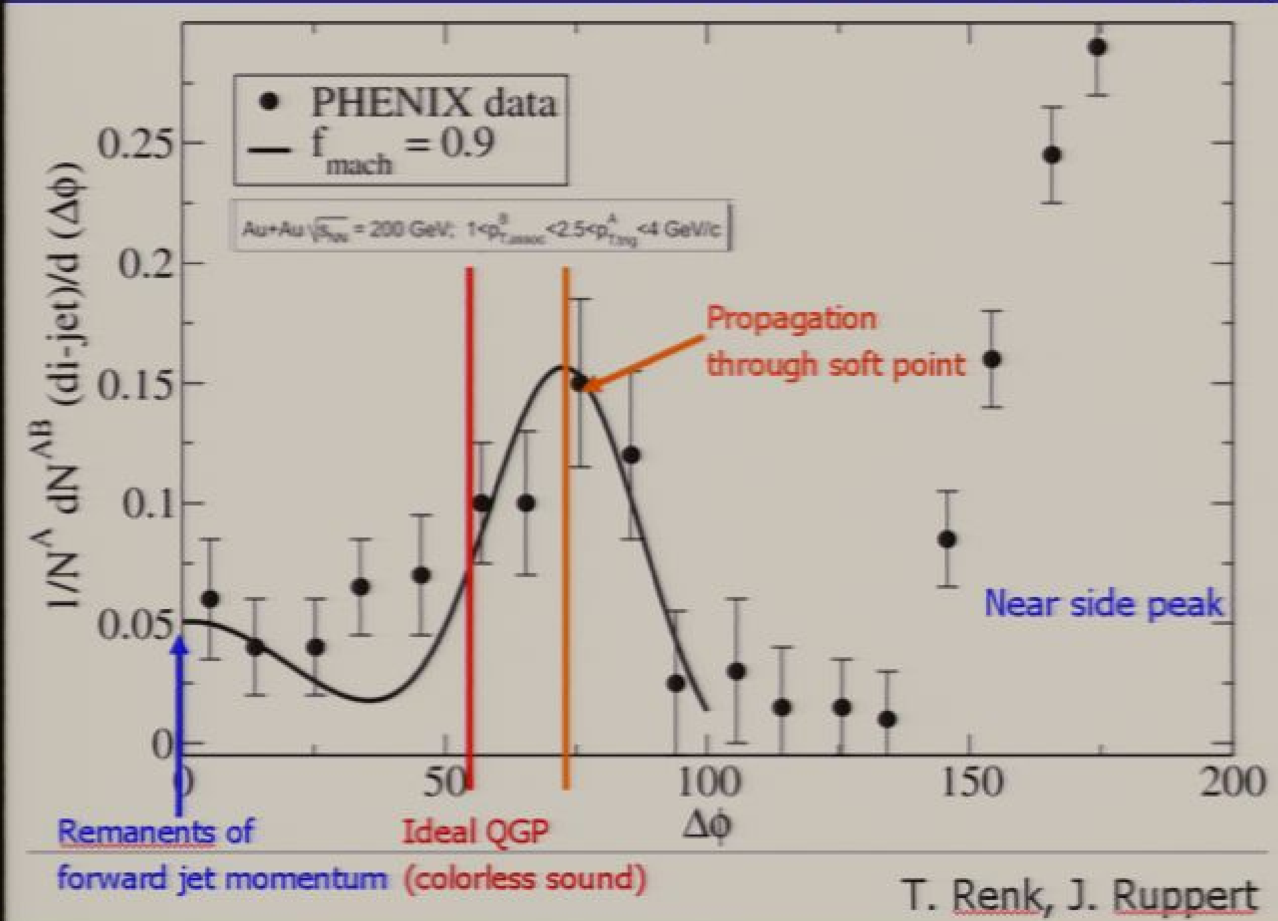
Mach cone?

- Jets may travel faster than the speed of sound in the medium.
- While depositing energy via gluon radiation.
- QCD "sonic boom"





Mach Cone (2)



- Ideal QGP, $c_s^2 = 1/3$
- $\cos \theta_M = c_s$

$\Rightarrow$ **$\theta_M = 55^o$**

- Detailed calculation taking into account evolving speed of (gluon) sound from hydrodynamics.
  - $c_s^2 = \partial p / \partial \varepsilon$

- But, other possible mechanisms proposed.

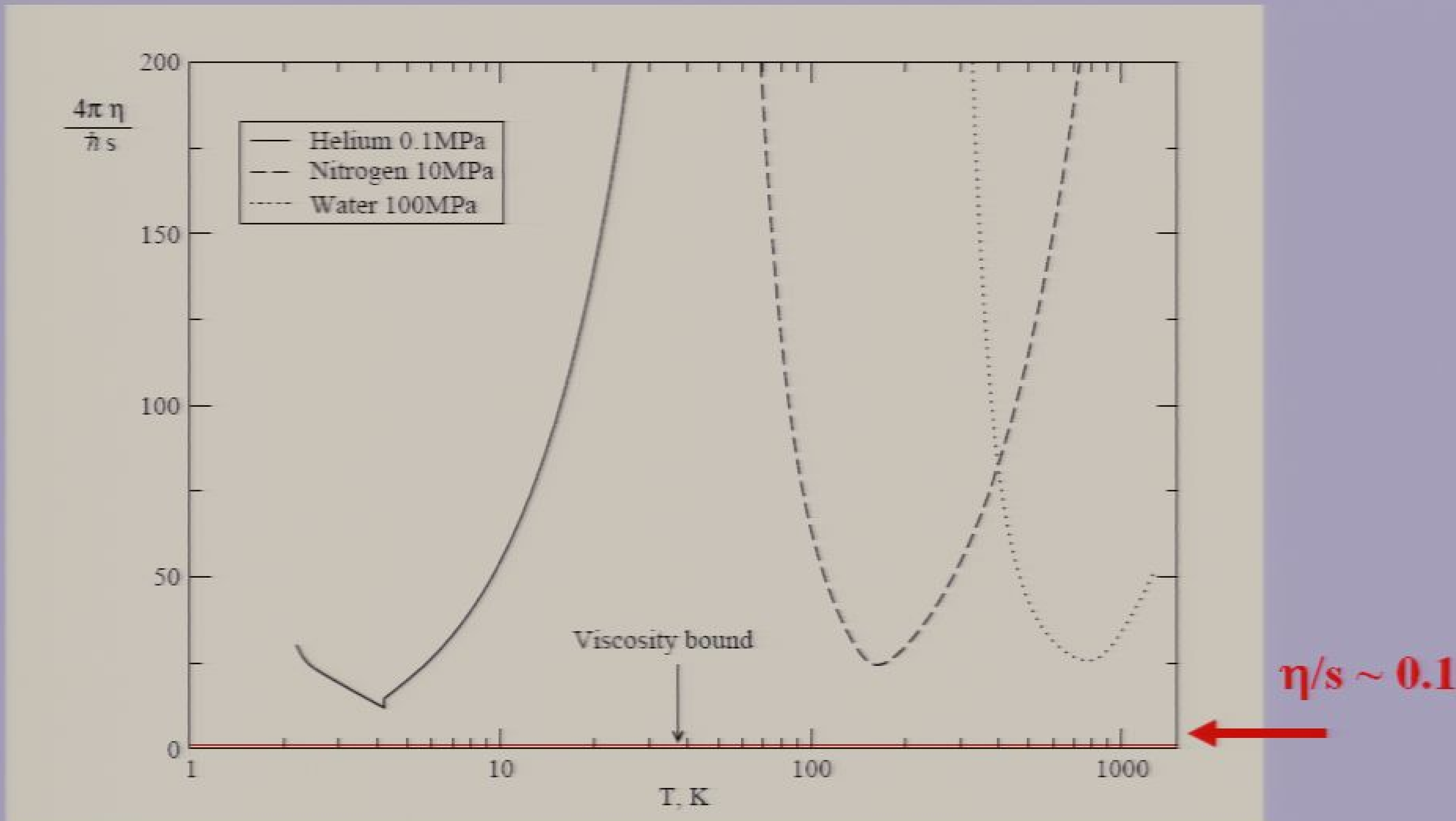
What I Didn't Show You

- Charm quarks also are quenched
  - And show rapid thermalization!
- Large charm quark elliptic flow signal
  - Can only be established at the quark level.
- Large baryon excess for $2 < p_T < 5$ GeV/c
  - Hadron formation by quark recombination
- We see final state particle flavor distributions consistent with "freeze-out" from chemically equilibrated system.
  - We are rapidly approaching stage where QGP is ONLY viable interpretation of data

RHIC Physics

- Since start of RHIC, substantial progress on development of a rigorous foundation for understanding stages of a heavy ion collision:
  - Particle production from strong gluon fields
  - Thermalization (ideas but not yet understood)
  - Hydrodynamic evolution
  - Hadronization
- With jets as calibrated probe
  - But jet quenching is still not completely understood
- We are probing the properties of the QGP – with surprising results
  - Strong coupling – why?
  - Speed of sound?

Comparison to "Typical" Vicosities



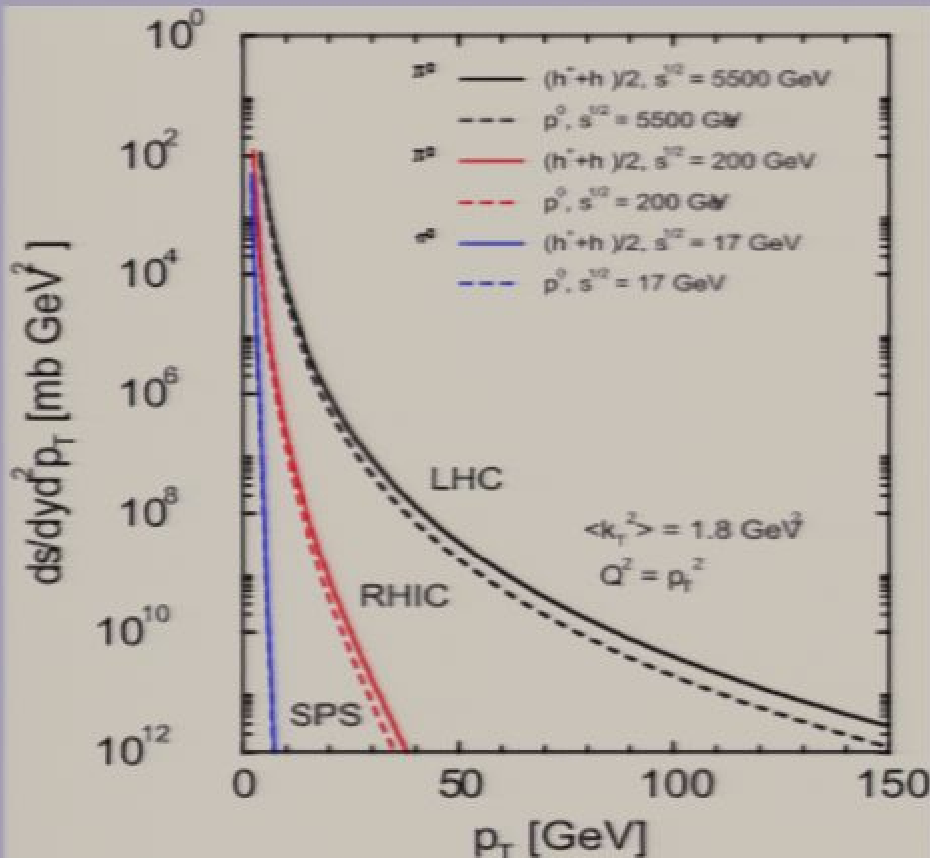
- But what is this "viscosity bound"?
  - Calculation of viscosity using string theory
  - Huh????

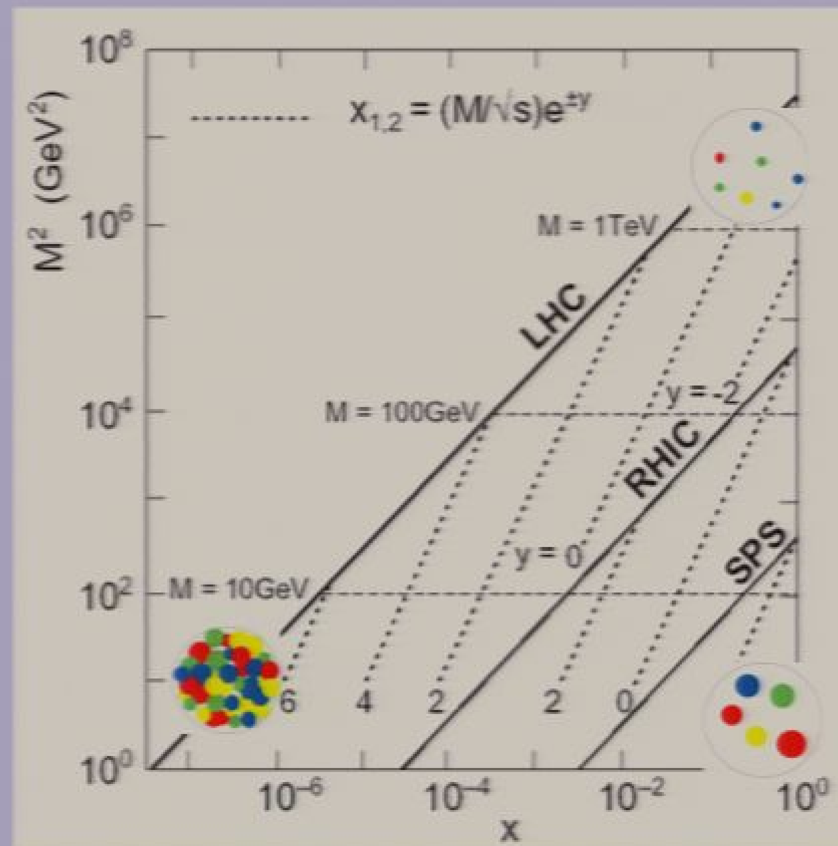
AdS/CFT Correspondence

Main idea

- Duality between string theory in anti-DeSitter space and conformal field theories.
  - Weakly coupled string theory $\rightarrow$ strongly coupled CFT
- Example conformal theory:
  - N=4 supersymmetric Yang-Mills
  - Which is not QCD (e.g. no running of α_s)
  - But similar enough??
- **AdS/CFT now being applied to many apsects of RHIC physics**
  - Viscosity, **η/s.**
  - Jet quenching
  - "Sound" waves

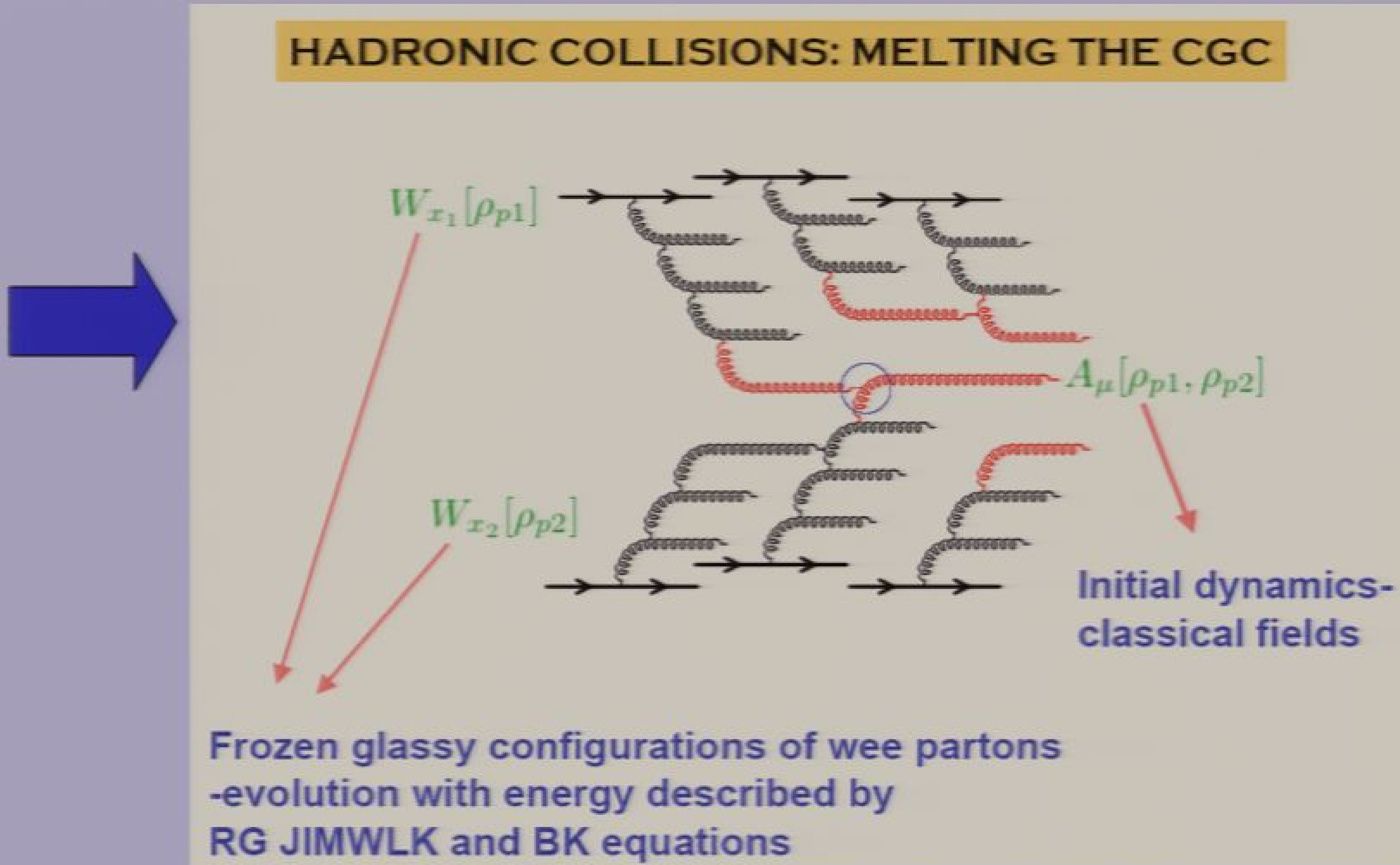
Why Heavy Ions @ LHC?





- **Low x** – Gluon production from saturated initial state
- **Energy density** – ~ 50 GeV/fm^3 (?)
- **Rate** – “copious” jet production above 100 GeV
- **Jets** – Full jet reconstruction
- **Detector** – necessary detector “for free”!

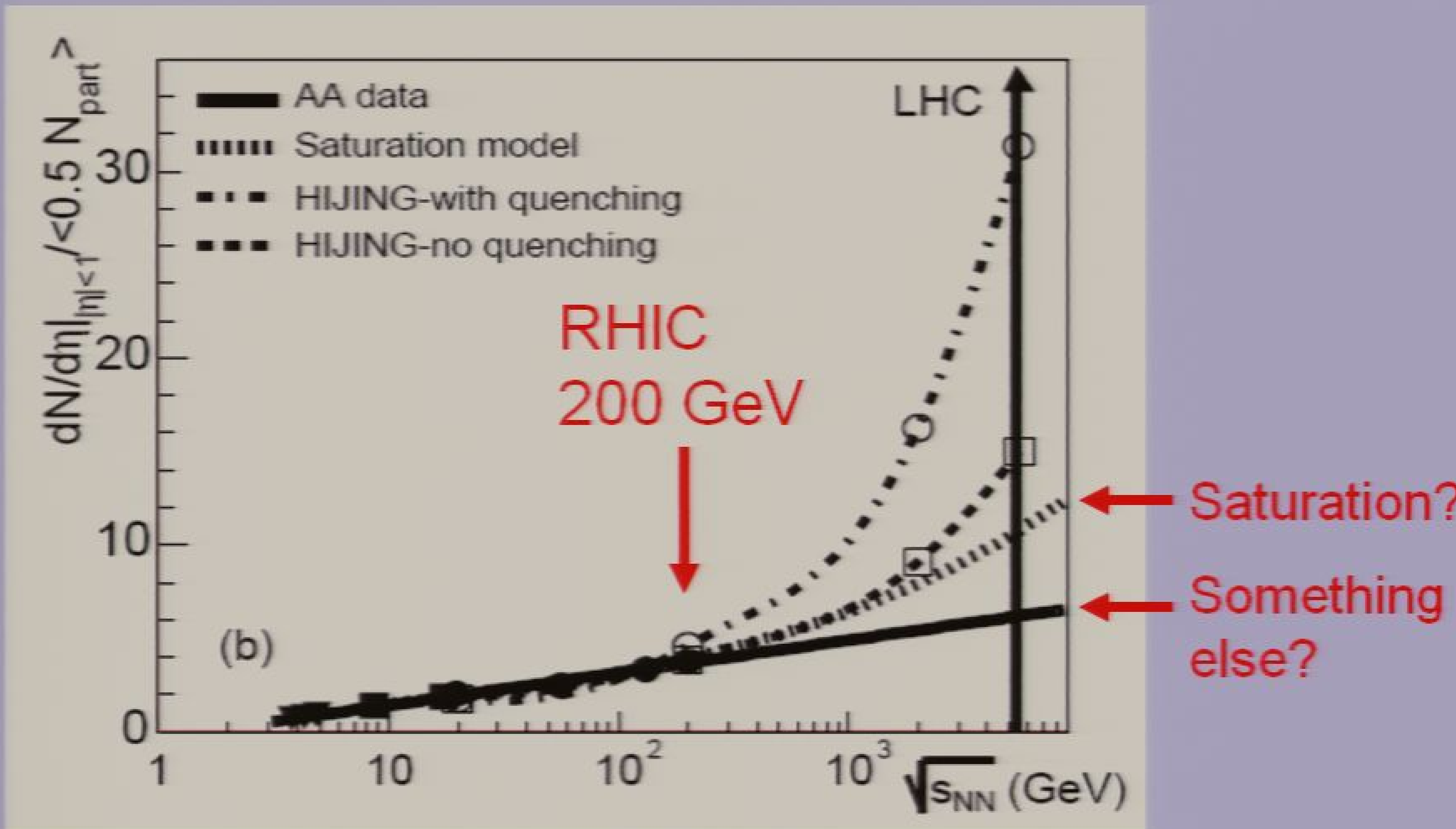
Heavy Ion Initial Conditions: Modern



- At LHC we (think we) will be able to study "classical" gluon fields in nuclei

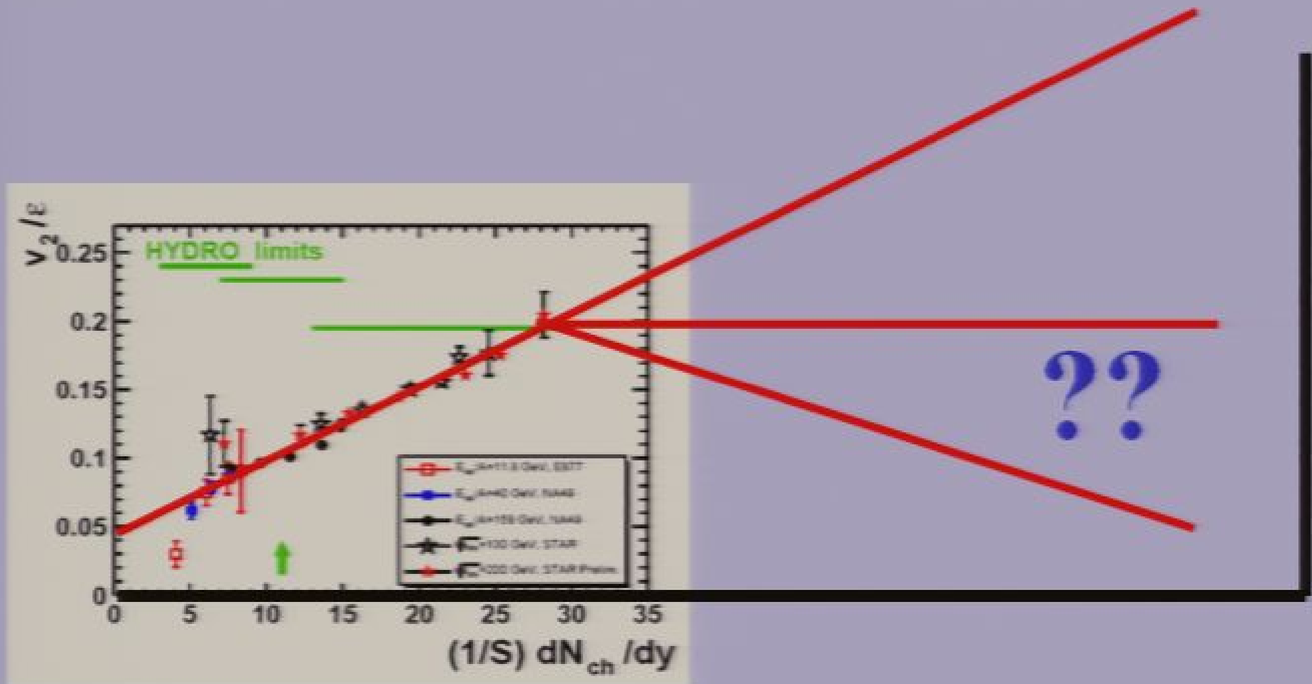
–And their quantum evolution

A+A Multiplicity vs Energy



- LHC measurements will provide an essential test of whether we understand the mechanism responsible for bulk particle production.
  - e.g. does saturation correctly extrapolate?

Elliptic Flow @ LHC

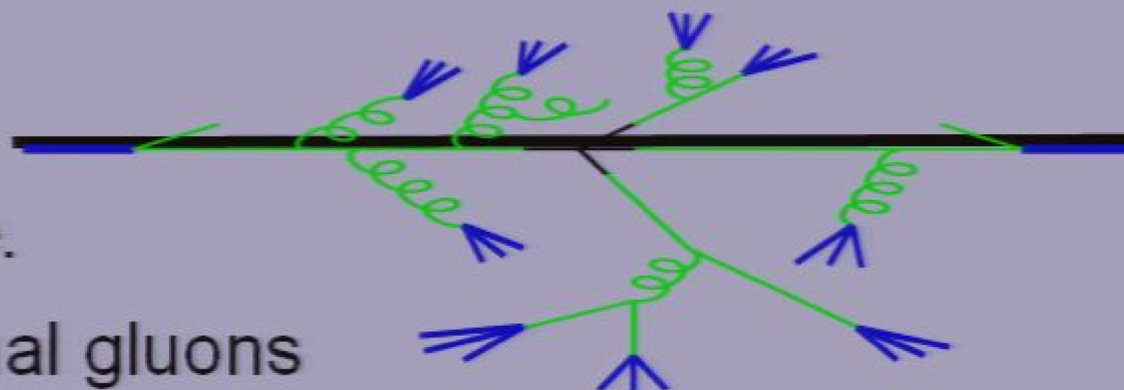


Can change horizontal scale by x2 @ LHC

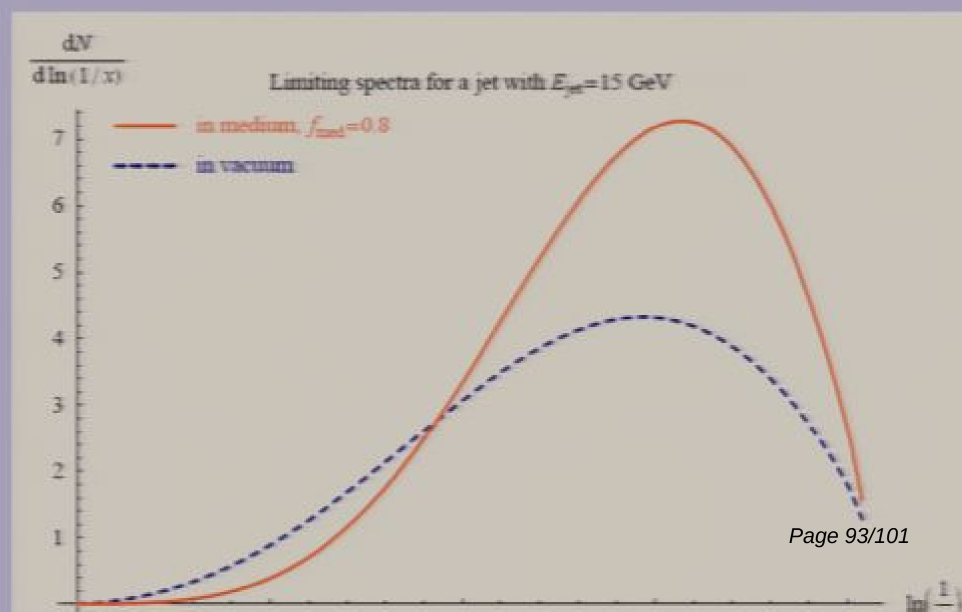
- LHC data will provide an essential test of our understanding of elliptic flow data @ RHIC
  - And test whether QGP is still strongly coupled
  - Extremely high priority given the possible relevance of AdS/CFT.
- **Large ATLAS acceptance a big advantage**

Jets as Color Antennas

- A high-energy quark/gluon acts like a "color antenna"
- In vacuum, radiation strongly affected by quantum interference.



- But, in medium thermal gluons "regulate" radiation.
- **Studies of modified jets in heavy ion collisions may shed light on a "fundamental" problem in (particle) physcs**



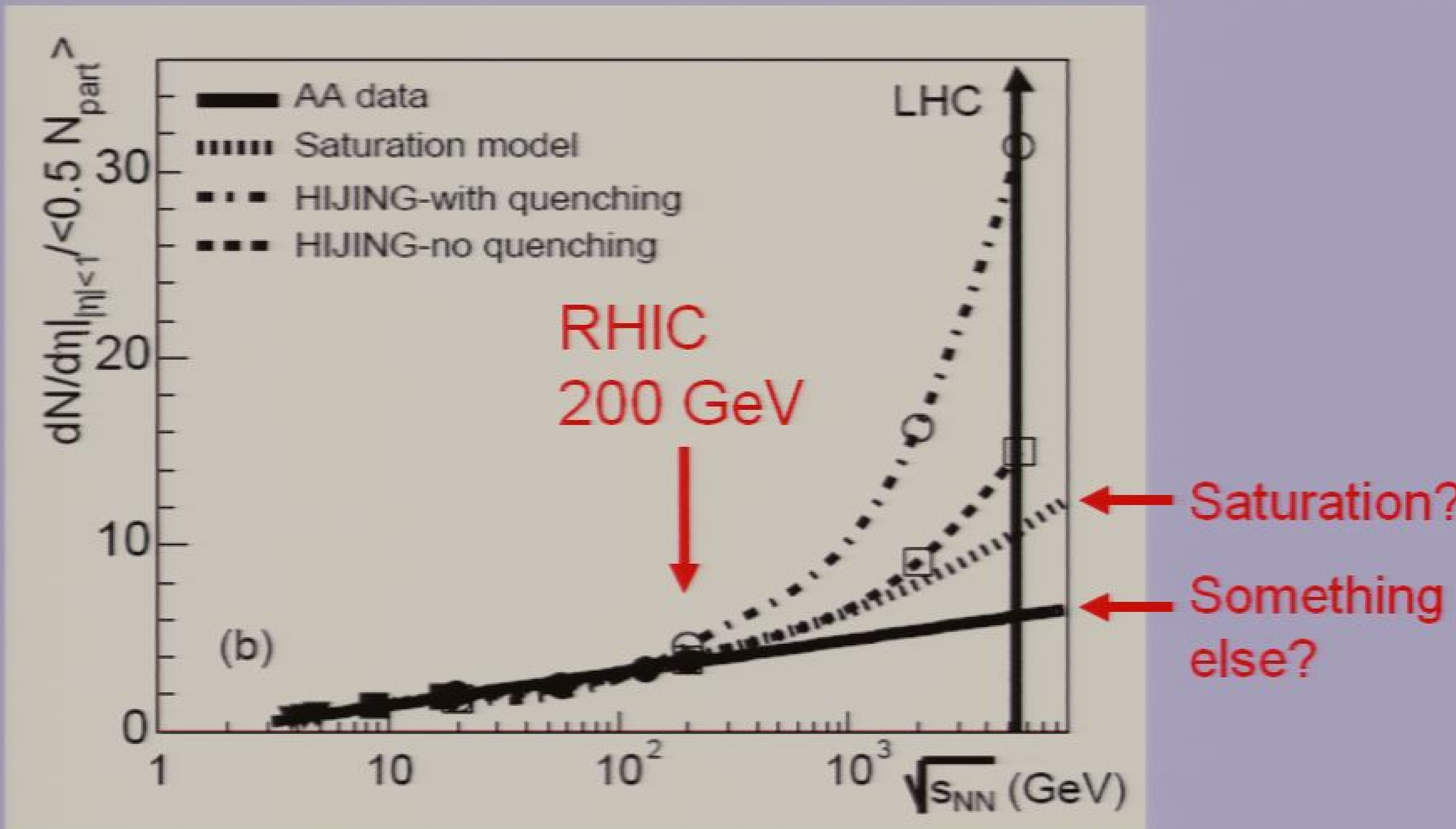
LHC Physics Opportunity

- Create & study quark-gluon plasma at T = 0.8~GeV
- Study particle production from strong gluon fields.
- New program with w/ new discoveries ~ guaranteed
  - If RHIC is any guide …
- p_T reach, rates, detector capabilities at LHC allow for qualitatively different (better!) measurements.
- Overlap w/ many other sub-fields of physics
  - ➢ Particle physics
  - ➢ Plasma physics
  - ➢ Fluid/hydro dynamics
  - ➢ Thermal field theory, lattice & non-lattice
  - ➢ String theory (!?) – AdS-CFT correspondence
  - ➢ General relativity (gluon production as Unruh radiation?)

Jets as Color Antennas

- A high-energy quark/gluon acts like a "color antenna"
- In vacuum, radiation strongly affected by quantum interference.
- But, in medium thermal gluons "regulate" radiation.
- **Studies of modified jets in heavy ion collisions may shed light on a "fundamental" problem in (particle) physcs**

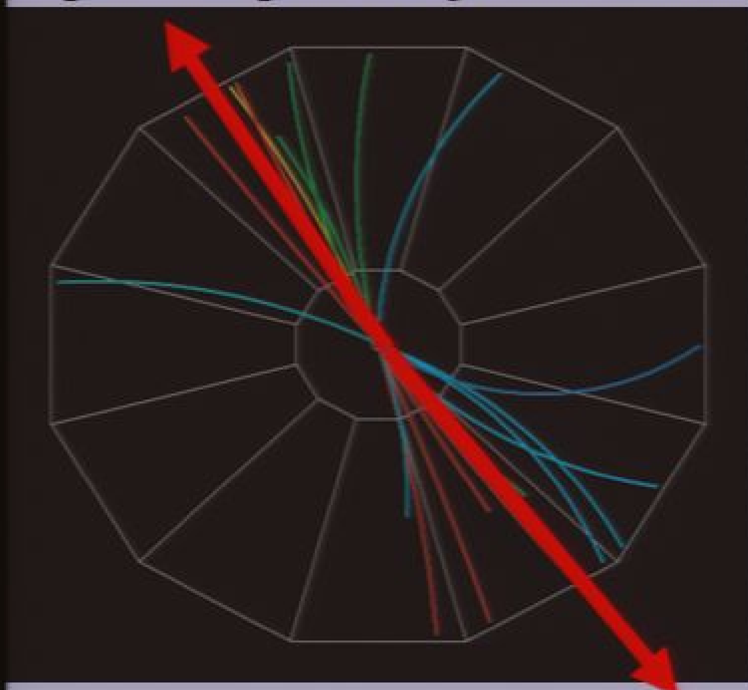
A+A Multiplicity vs Energy



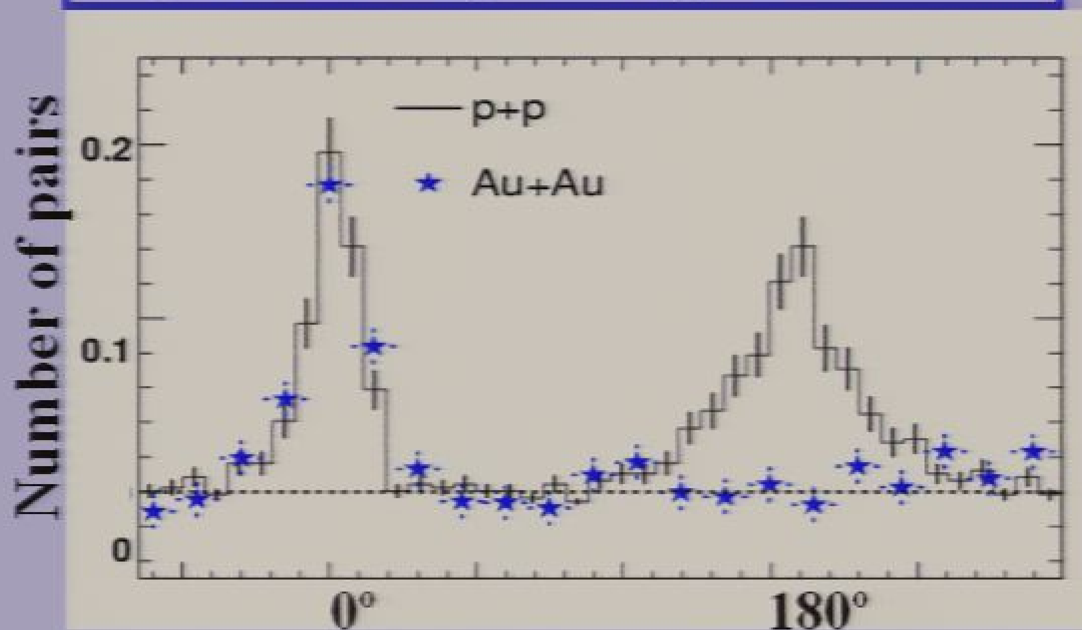
- LHC measurements will provide an essential test of whether we understand the mechanism responsible for bulk particle production.
  - e.g. does saturation correctly extrapolate?

STAR Experiment: "Jet" Observations

proton-proton jet event

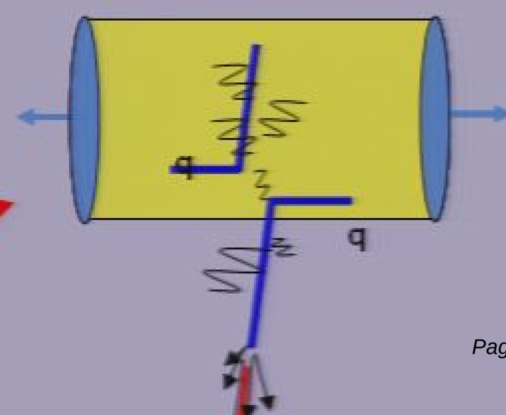


Analyze by measuring (azimuthal) angle between pairs of particles



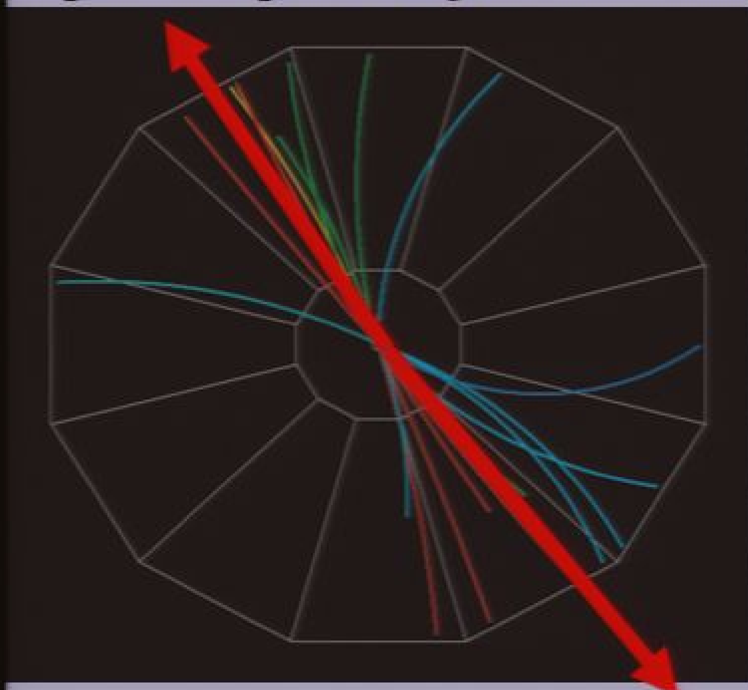
Angle between high energy particles

- **In Au-Au collisions we see only one "jet" at a time !**
- **How can this happen ?**
- **Jet quenching!**

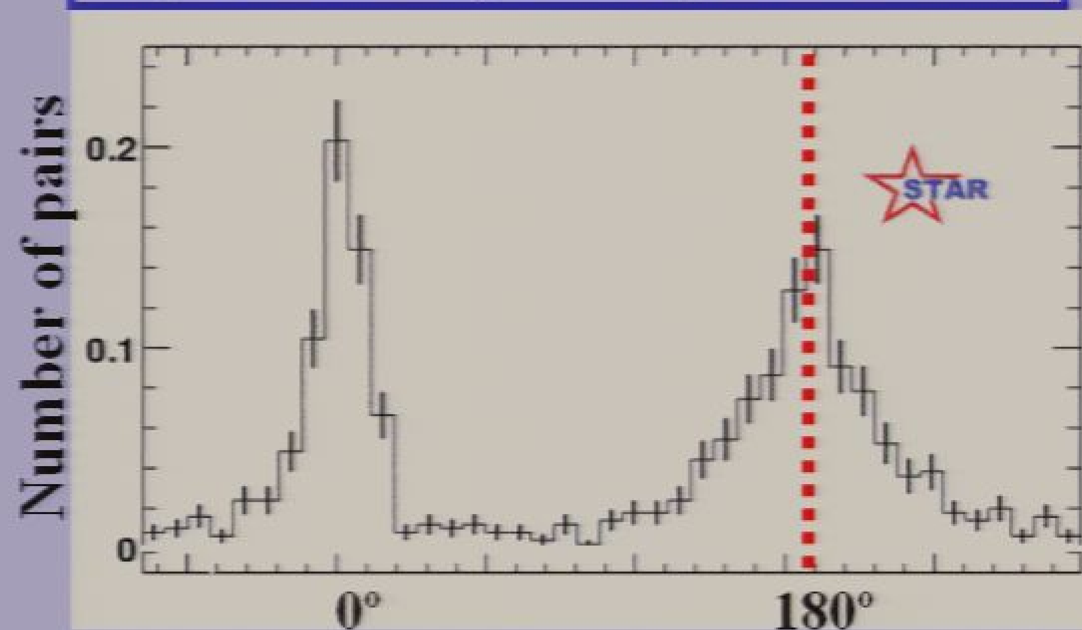


STAR Experiment: "Jet" Observations

proton-proton jet event

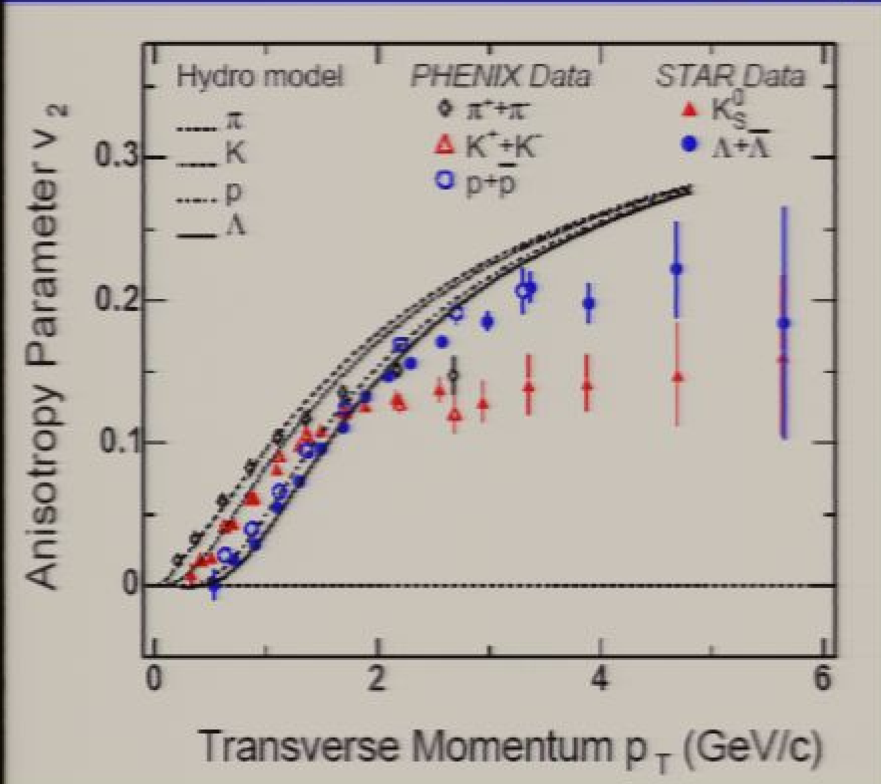


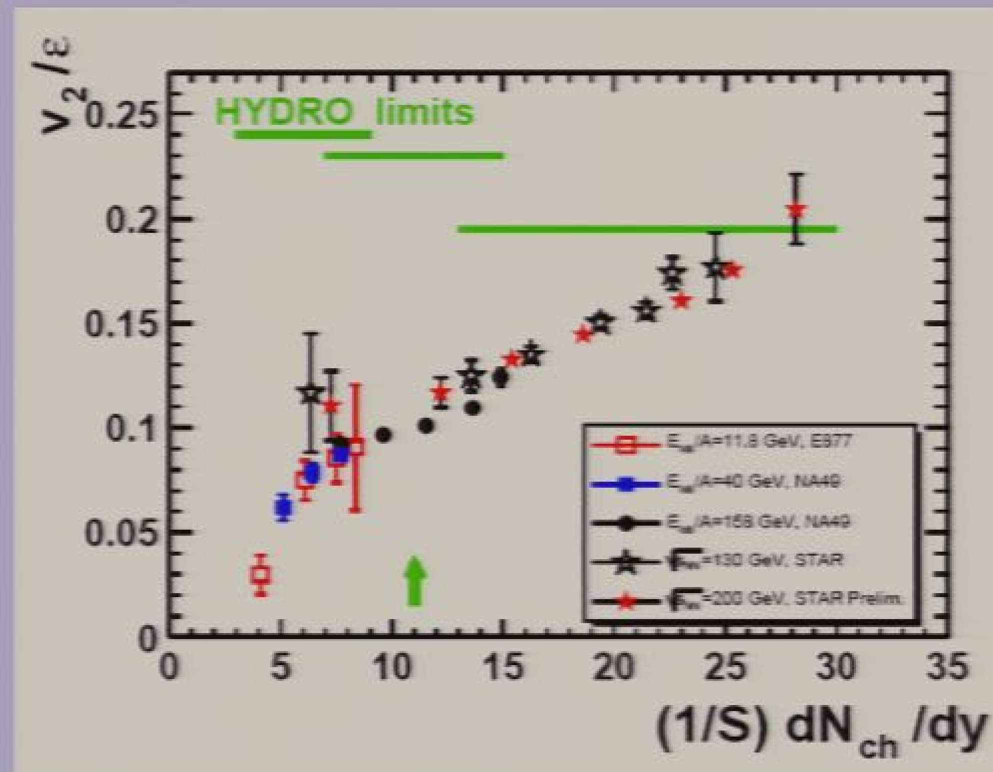
Analyze by measuring (azimuthal) angle between pairs of particles



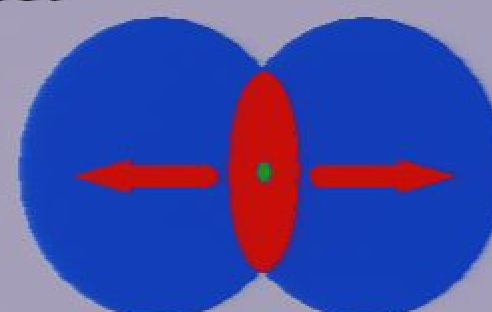
Angle between high energy particles

"Elliptic Flow"





- Parameterize ϕ variation by "v_2" parameter
  - $$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi)$$
- Compare to "eccentricity": $$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



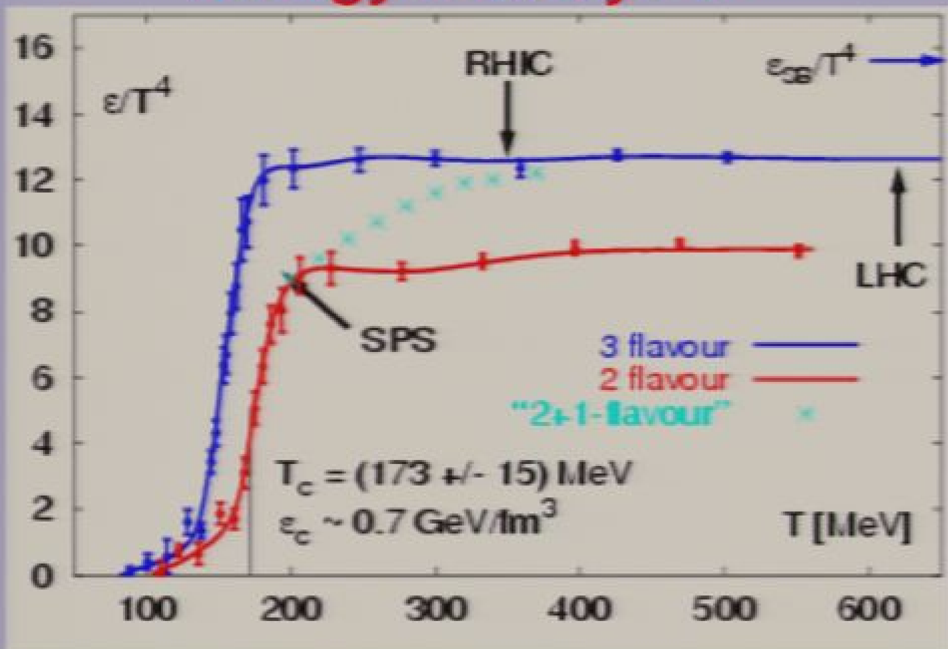
- **Data consistent w/ hydrodynamic calculations**

Relativistic Heavy Ion Collider

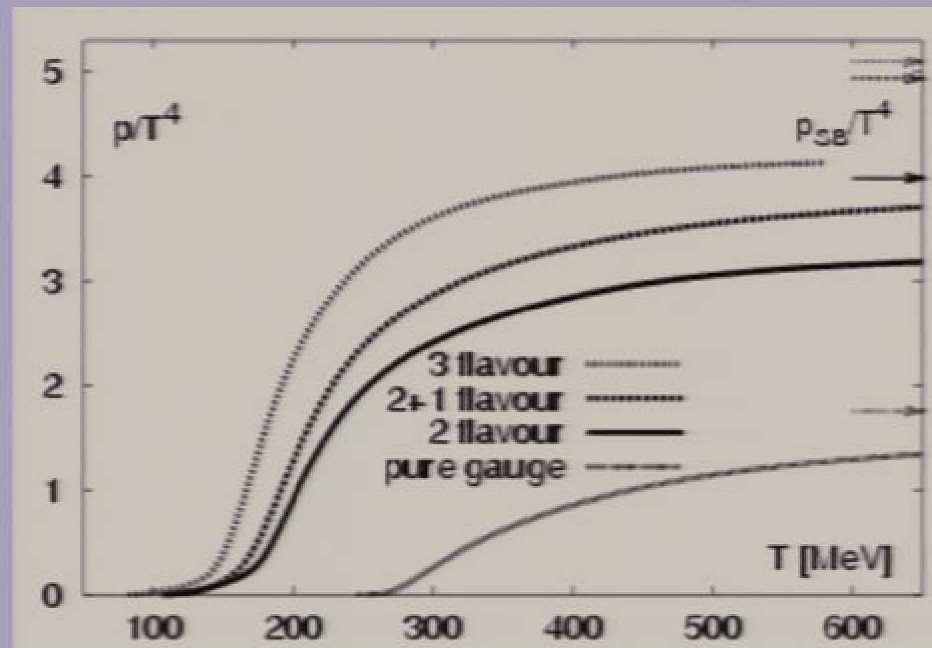
- ➢Run 1 (2000): Au-Au $\sqrt{S_{NN}}$ = 130 GeV
- ➢Run 2 (2001): Au-Au, p-p $\sqrt{S_{NN}}$ = 200 GeV
- [redacted]

QCD Thermodynamics (on Lattice)

Energy Density / T^4



Pressure / T^4



- Rapid cross-over from "hadronic matter" to "Quark-Gluon Plasma" at T ~ 170 MeV

  ⇒Energy density, $\varepsilon \sim 1$ GeV/fm^3.

- **Only fundamental "phase transition" that can be studied in the laboratory.**

  –Is the QGP weakly interacting??