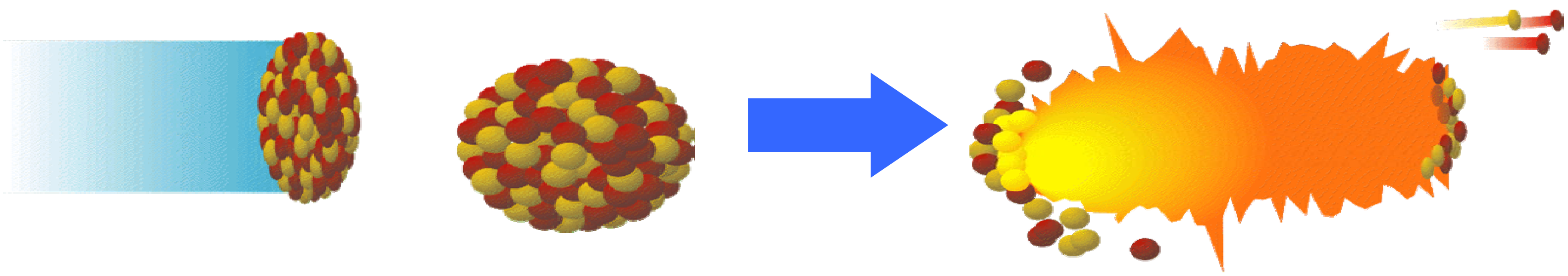
Relativistic Heavy-Ion Collisions: Recent Results from RHIC

David Hardtke

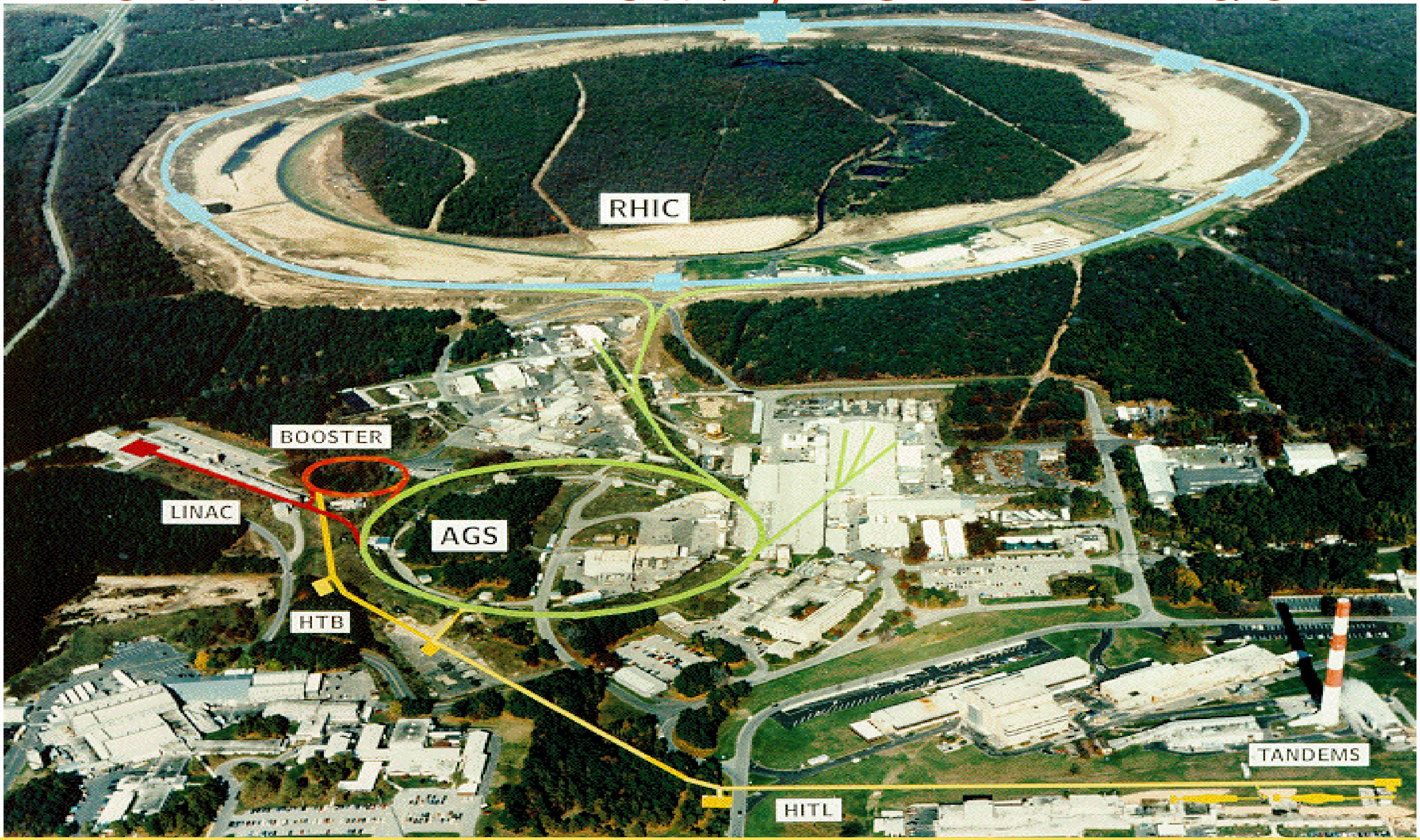
LBNL



Outline

- Why do we study high energy nucleus-nucleus collisions?
- Experimental Results from RHIC
  - Particle Multiplicities
  - "High" p_T phenomena and "jet quenching"
- Conclusions

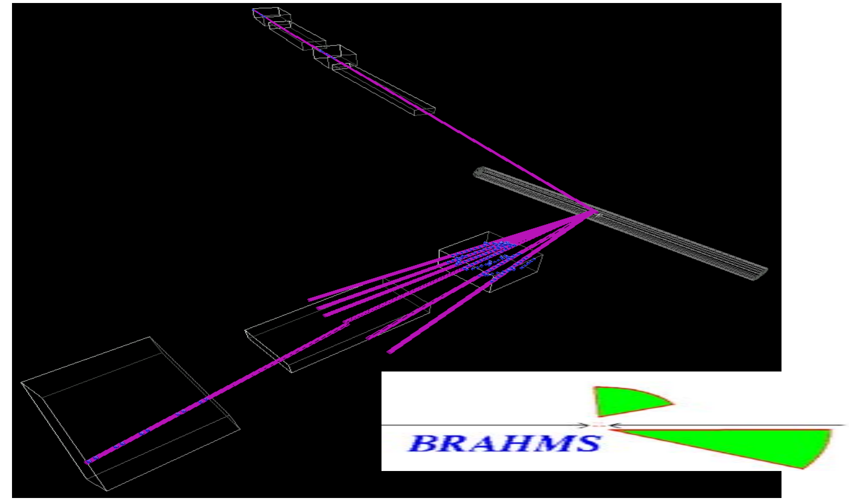
Relativistic Heavy Ion Collider

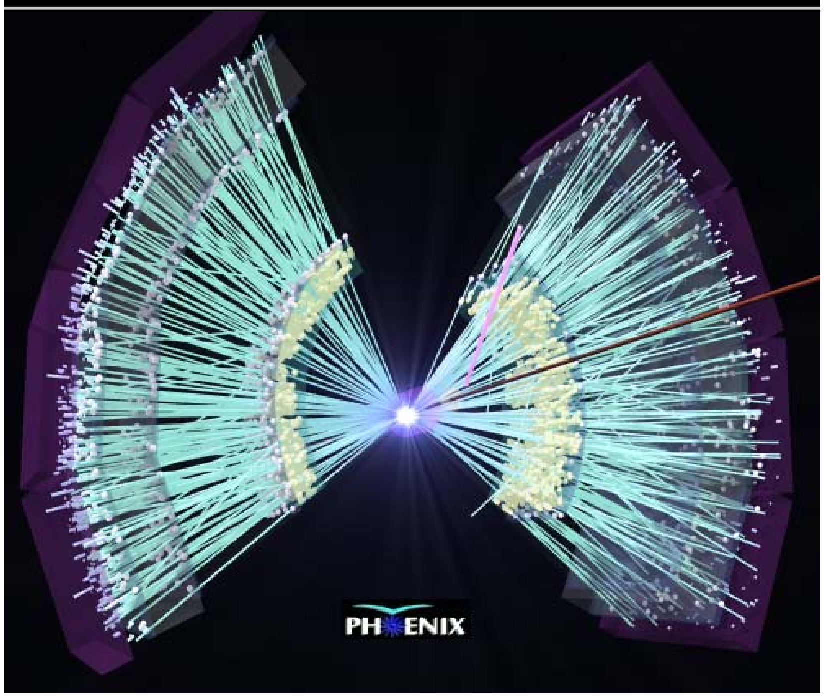


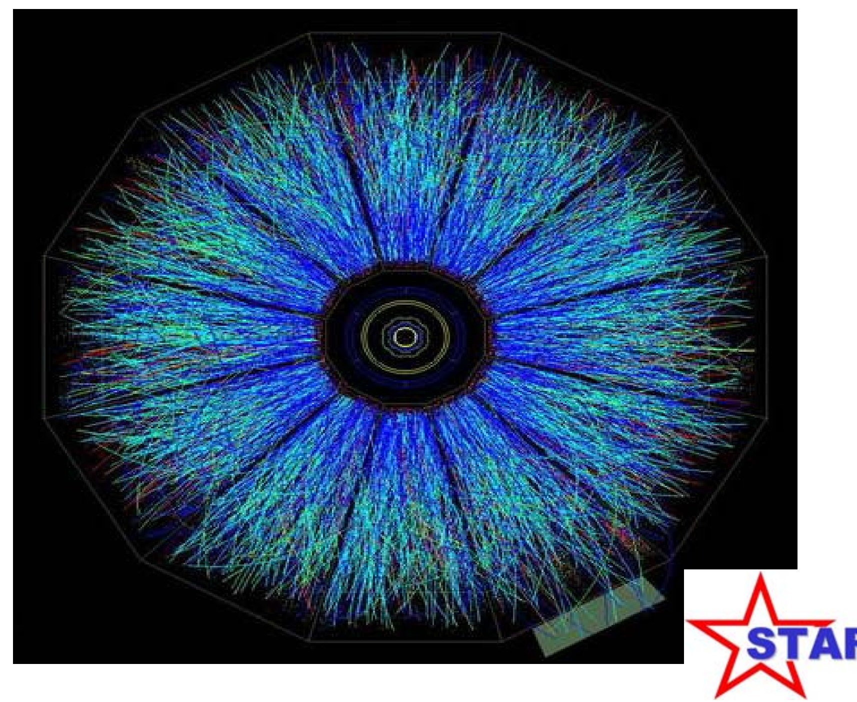
$p\uparrow + p\uparrow$ to Au+Au, $\sqrt{s}$ = 20 - 200 (Au+Au) - 500 (p+p) GeV/c

Today: p+p, d+Au, and Au+Au

The Experiments

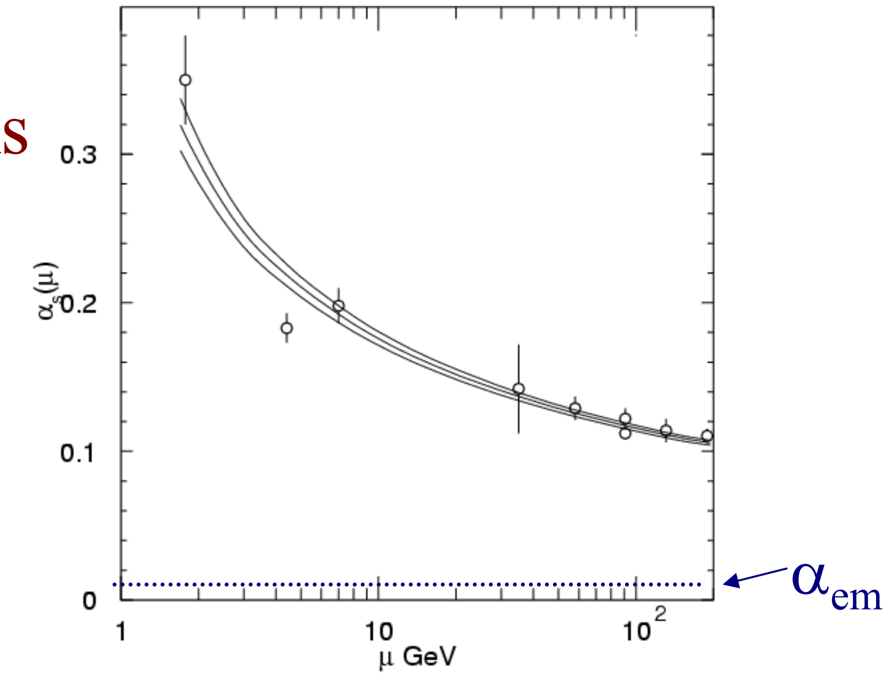






"Colorful" properties of QCD

- Running Coupling Constant ⇒ "Asymptotic Freedom"
  - Perturbation theory works well at large momentum transfer (large Q^2)
- Small Q^2 ⇒ "Confinement"
  - No free quarks

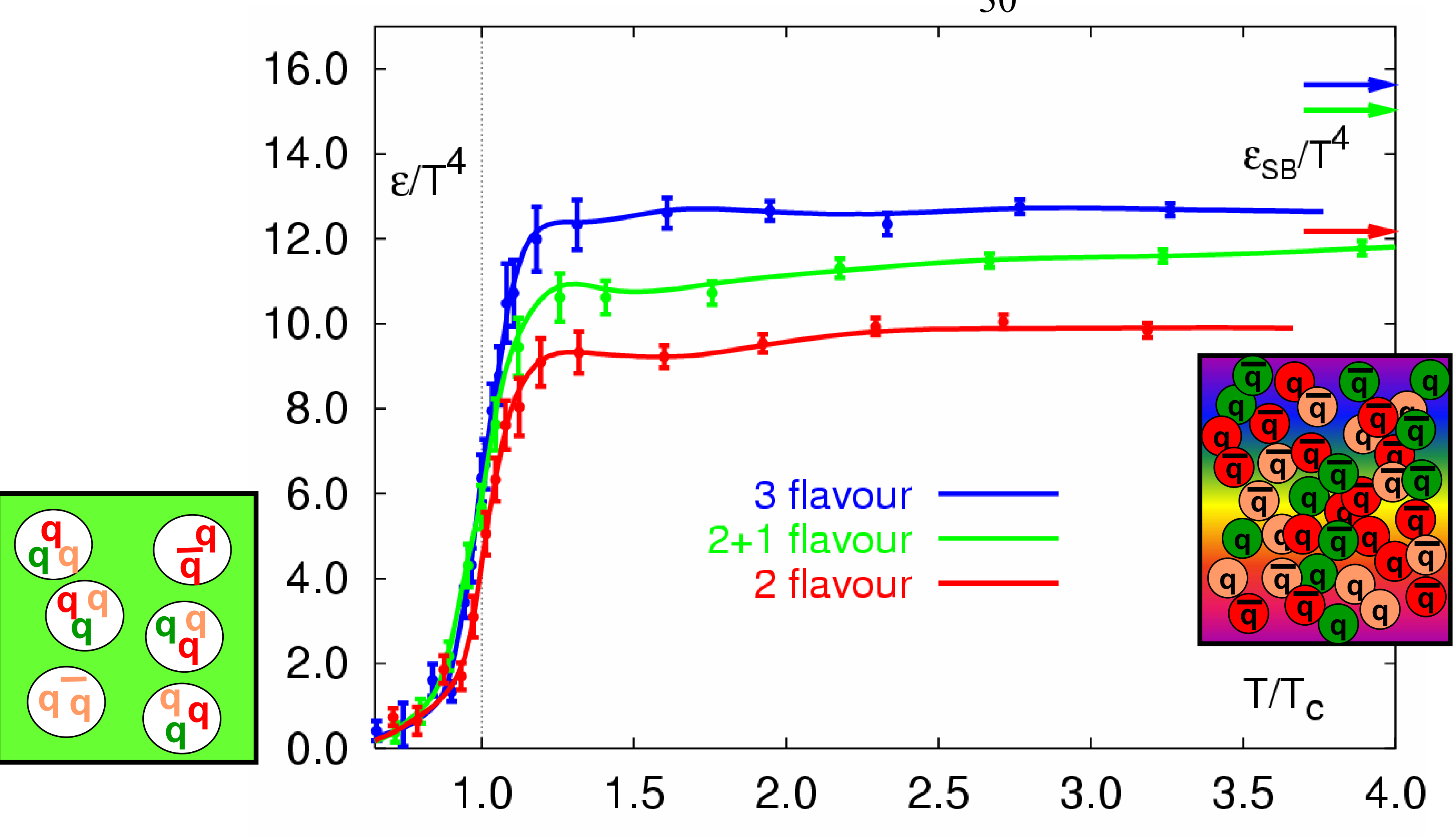


New path to weak coupling limit of QCD:

High Density or Temperature

Lattice QCD Calculations

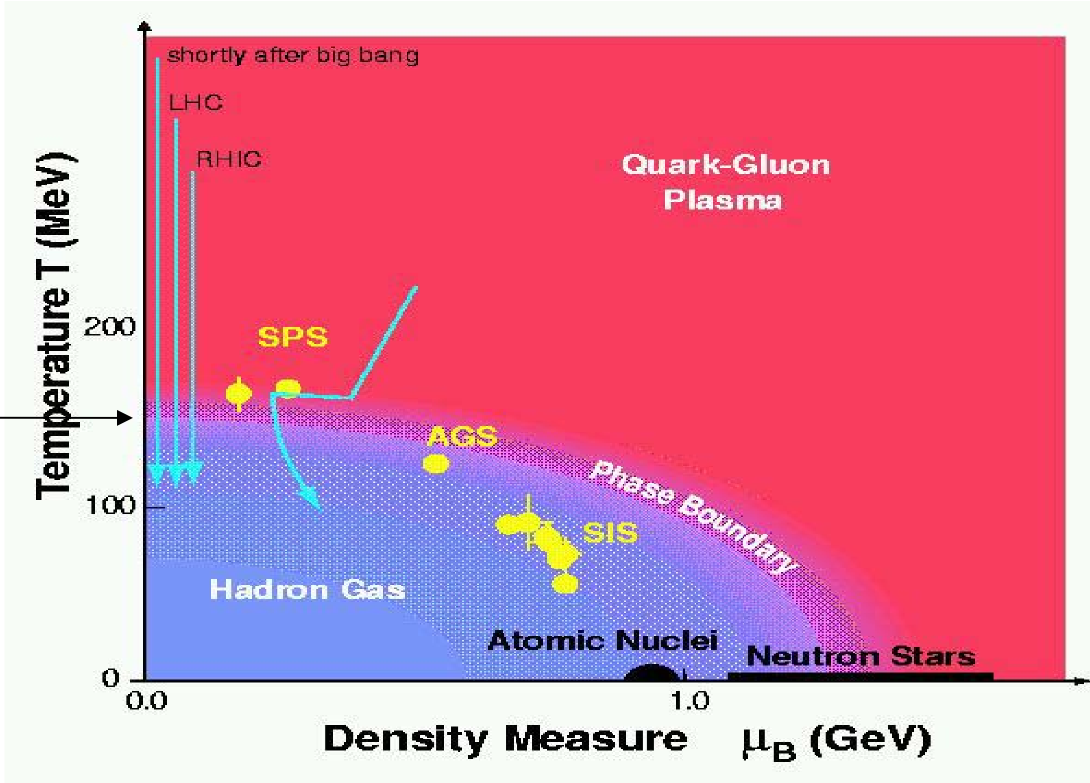
Massless ideal gas: $\varepsilon_{SB}(T) = \frac{\pi^2}{30}(N_{bosons} + 7/8\, N_{fermions})T^4$



Heavy-Ion Physics: The essential questions

- At high temperature, does nuclear matter undergo a phase transition?
- What are the properties of the deconfined phase?
  - quark mass : constituent mass (≈300 MeV) → current mass (few MeV) ?
  - Residual quark interactions?

150 MeV ≈ 10^{12} K



Lepton-Photon 2003

What's new with RHIC?

- Quark and gluon degrees of freedom shown to be important elsewhere:
  - "Evidence for Hadronic Deconfinement in pbar-p collisions at 1.8 TeV", E735 Collaboration, PLB (2002)
  - "New State of Matter Created at CERN", CERN Press Release (2000)
- RHIC → *bulk limit ?*
  - Thermodynamics of small systems difficult to understand
    - i.e. Tin nanoclusters

Shvarsburg and Jarrold, PRL 85

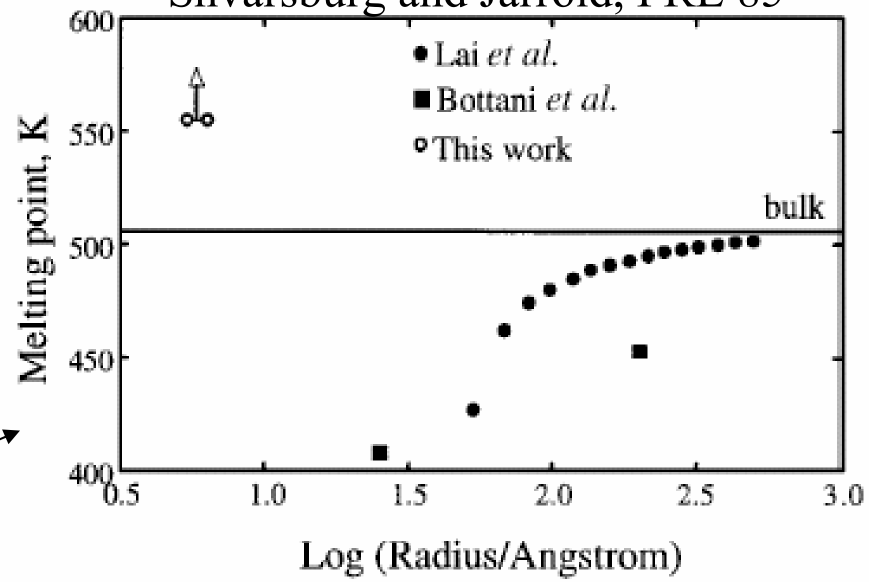
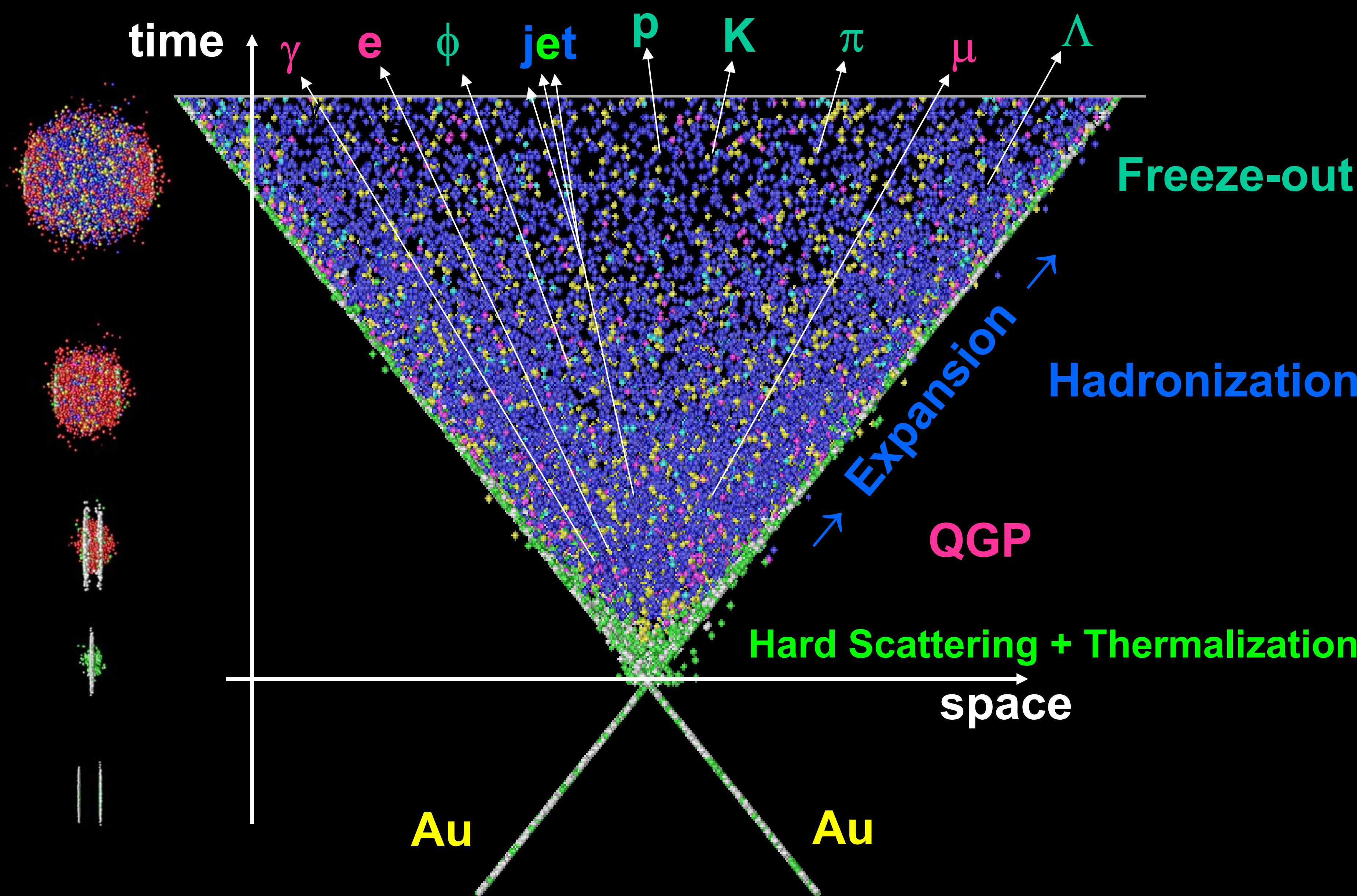


FIG. 2. Melting points of tin clusters as functions of the average cluster radius. ● Lai *et al.* [22] and ■ Bottani *et al.* [23] for mesoscopic tin particles, and ○ this work for clusters with 19–31 atoms.

Space-time Evolution of Collisions



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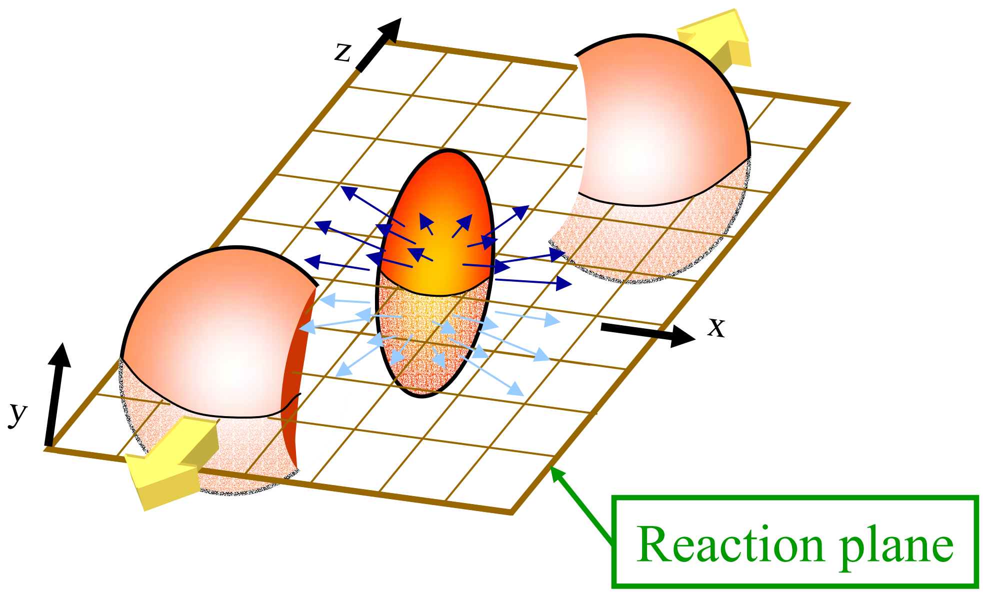
Geometry of Heavy Ion Collisions

Non-central Collisions



Number of participants: number of incoming nucleons (participants) in the overlap region

Number of binary collisions: number of equivalent inelastic nucleon-nucleon collisions

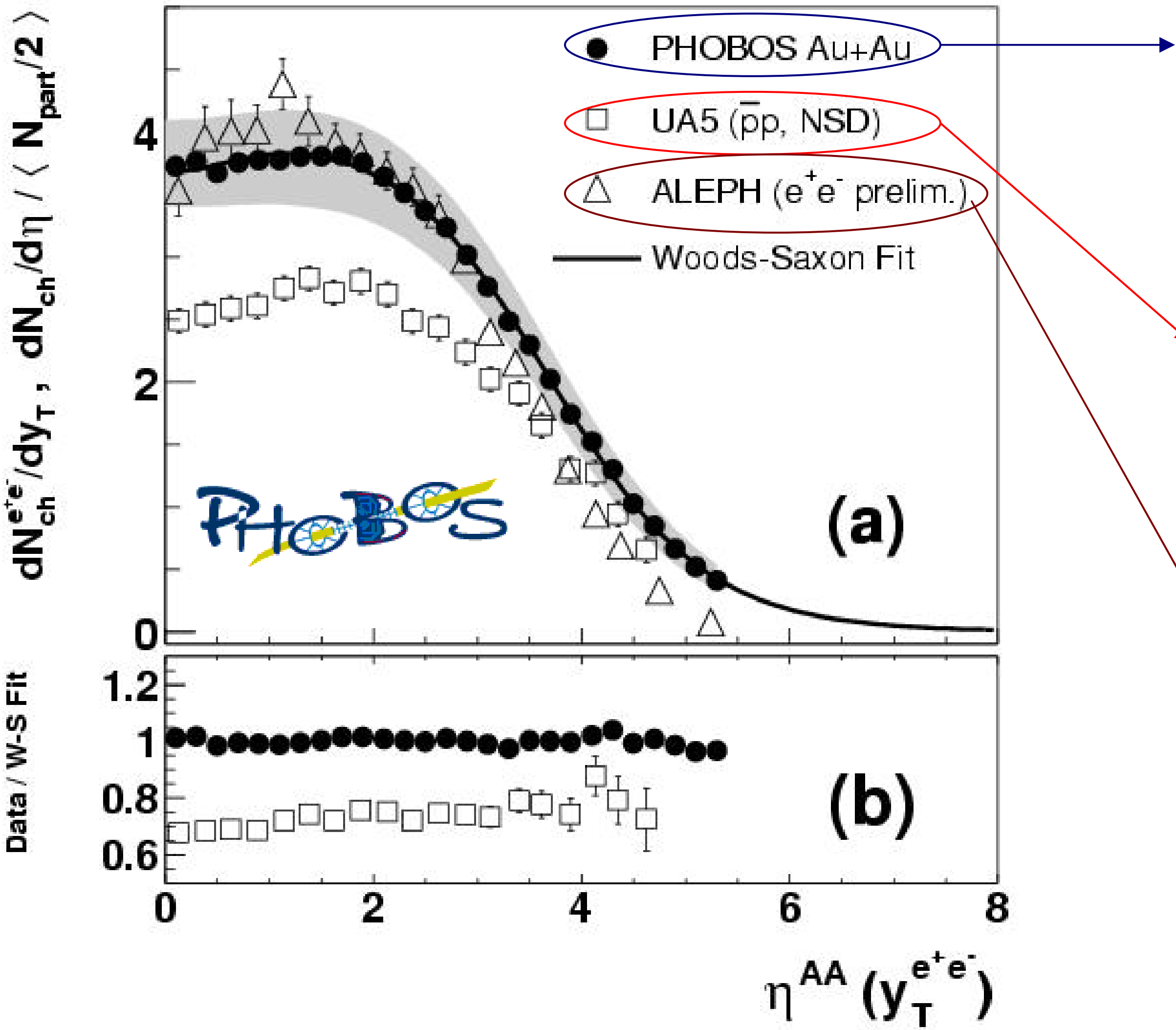
Total Multiplicity

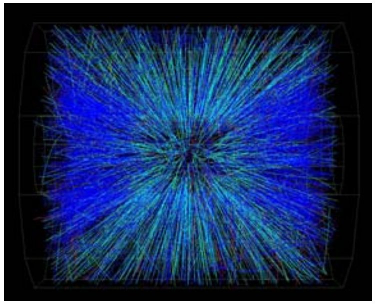
- Multiplicity $\propto$ Entropy
- *Ideal* Quark-Gluon Plasma should have high entropy density
  - quark and gluon vs. hadronic degrees of freedom

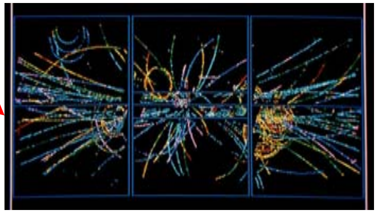
Can we see extra entropy production reflected in the particle multiplicity?

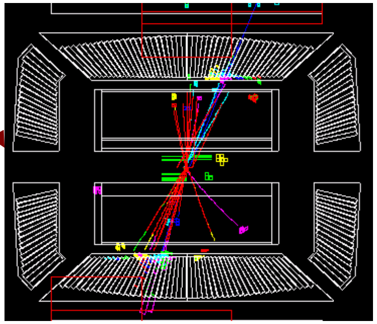
- Coherent nuclear phenomena may *reduce* total multiplicity
  - Shadowing of parton distributions
  - "Saturation" of nuclear gluon distributions

dN/dη per participant ($\sqrt{s}$ = 200 GeV)

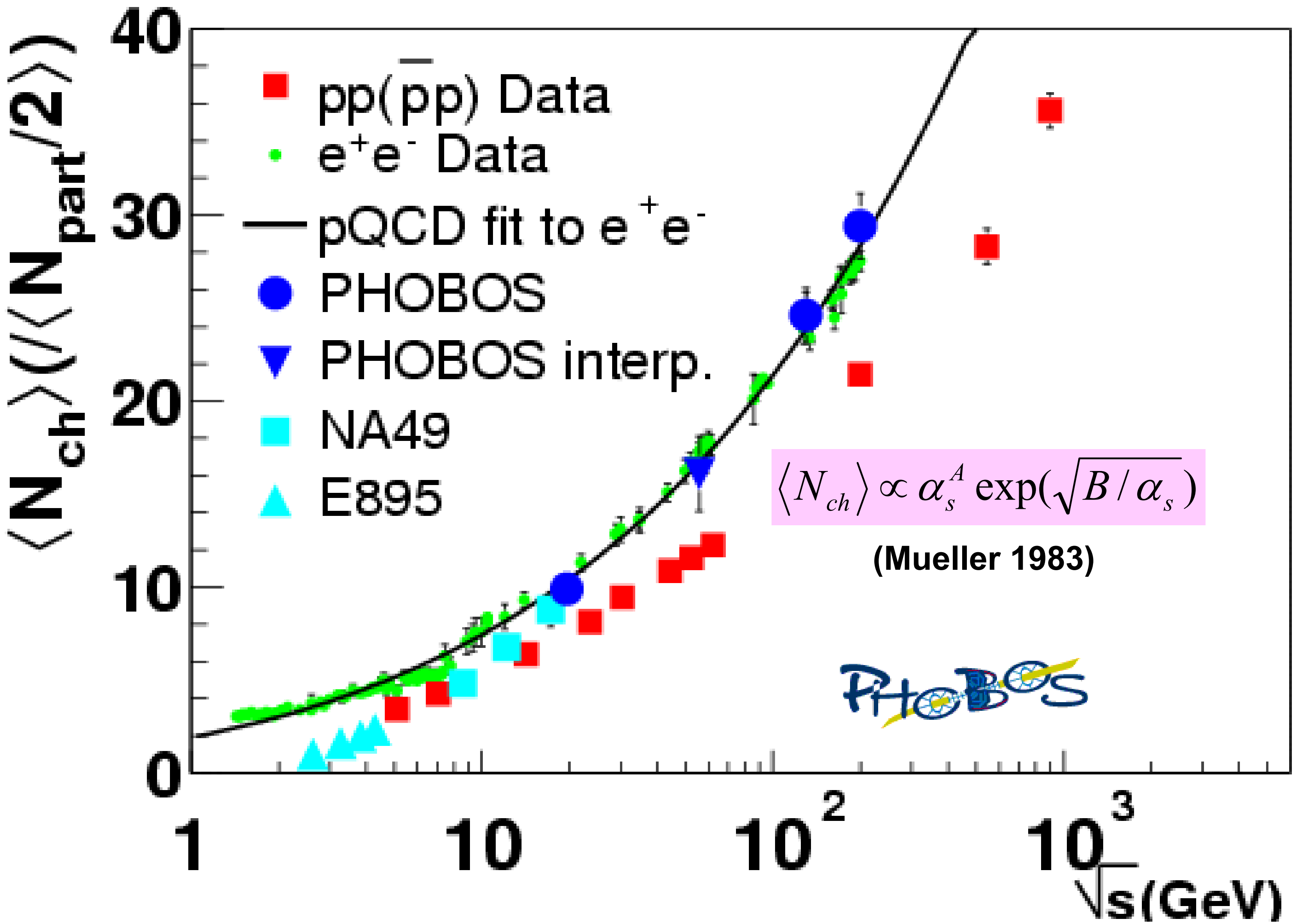






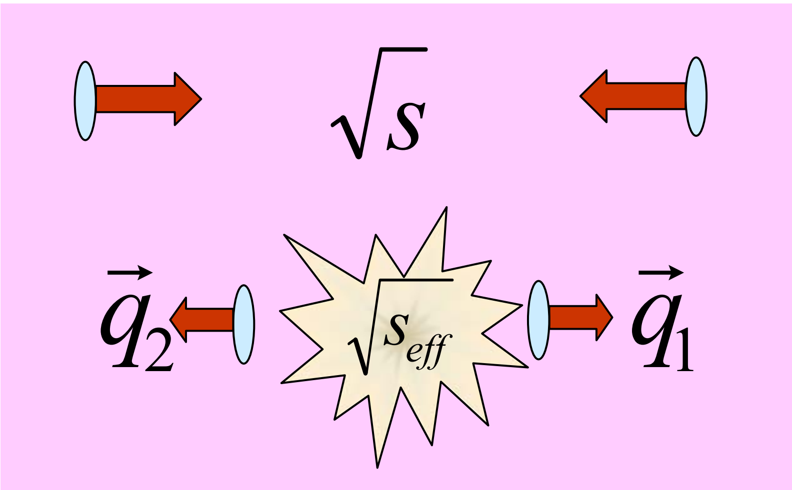


Total Multiplicity vs. √s



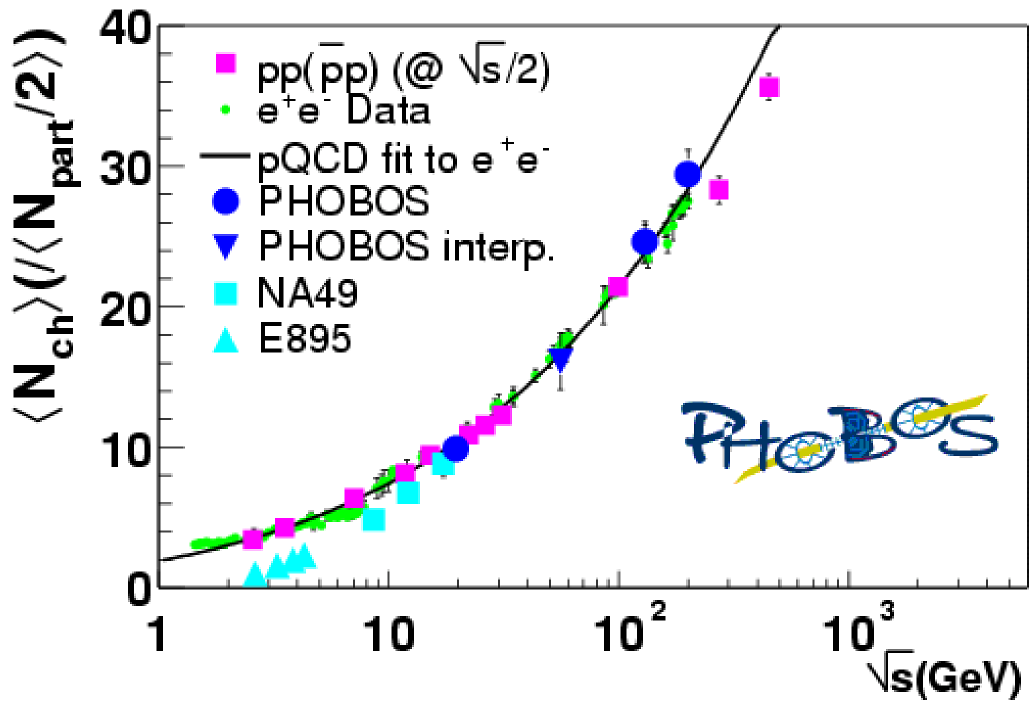
Why is p+p different?
Leading particle effect?

Basile et al., 1980



$$\sqrt{s_{eff}} = \sqrt{s - q_1^2 - q_2^2}$$

"effective energy" available for particle production



Universal Particle Production

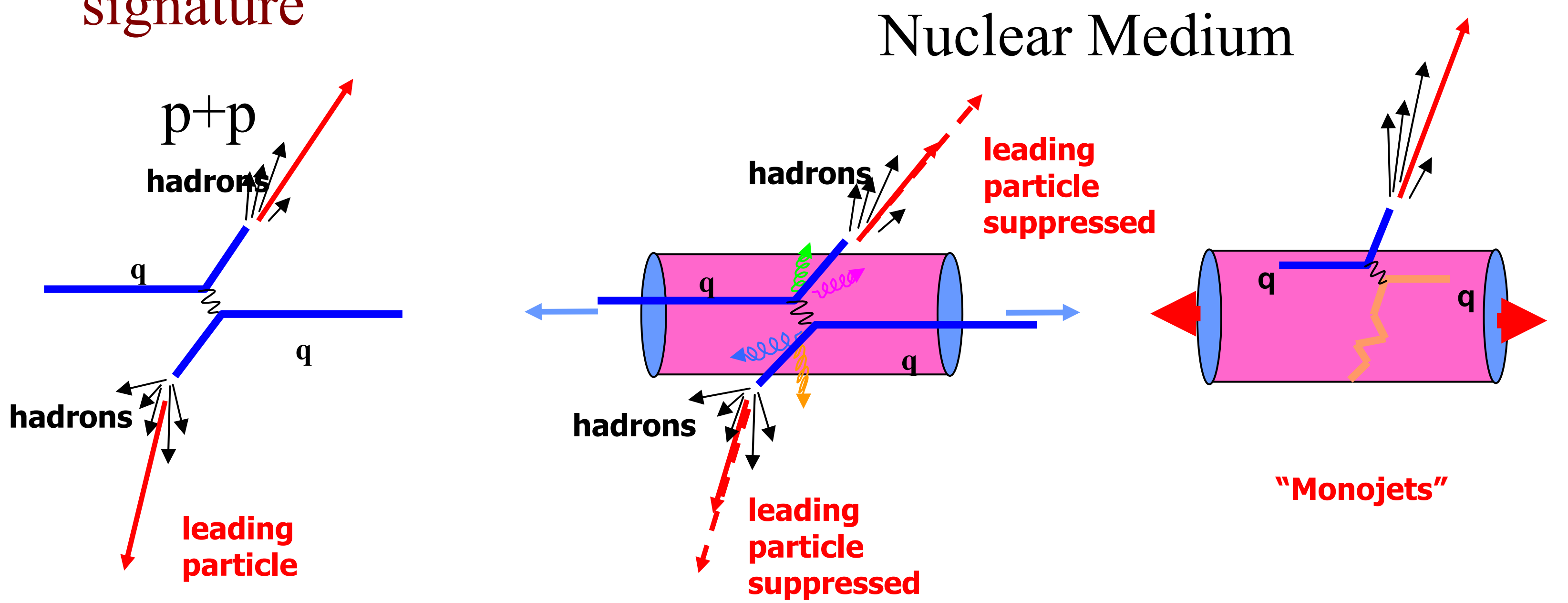
- Simple relation between e+e- and AA collisions:

$$N_{ch}^{AA} = N_{ch}^{e^+e^-}\left(\sqrt{s}\right)\times\frac{N_{part}}{2}$$

- (Any) excess entropy created in heavy-ion collisions *not* reflected in total multiplicity
- Will this relationship hold true at LHC?
  - Deeper into nuclear shadowing region of Bjorken x
- A mystery: Why is the total multiplicity unaffected by the complex dynamical evolution of a heavy-ion collision?

Jets in heavy-ion collisions

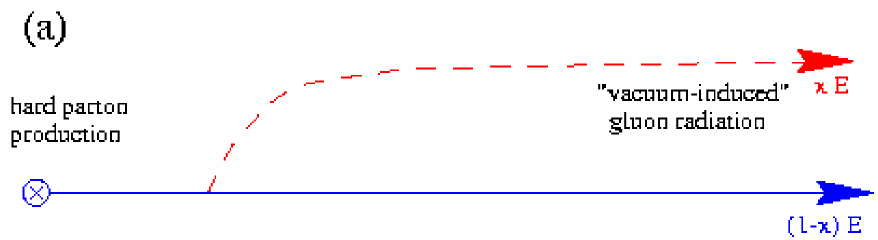
- Partons lose energy due to induced gluon radiation: "Jet Quenching"
  - Energy loss is measure of gluon density ⇒ Indirect QGP signature



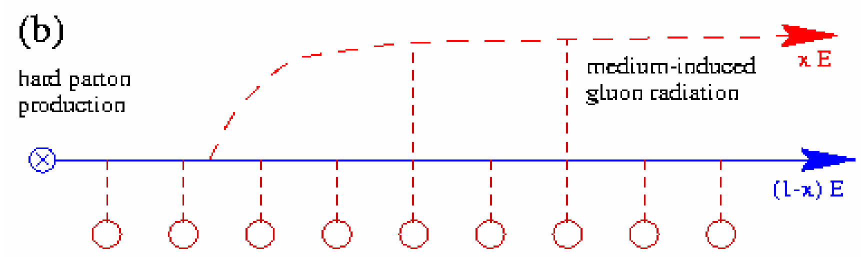
Probe energy loss via leading hadrons and di-hadron correlations

Energy Loss of Scattered Partons in Dense Matter

- elastic scattering of partons dE/dx ~ 0.1 GeV/fm



- nonlinear interaction of gluons dE/dx ~ few GeV/fm



$$\Delta E_{BDMS} \cong \frac{C_R \alpha_s^2}{4} L^2 \tilde{v} \rho_{glue}$$

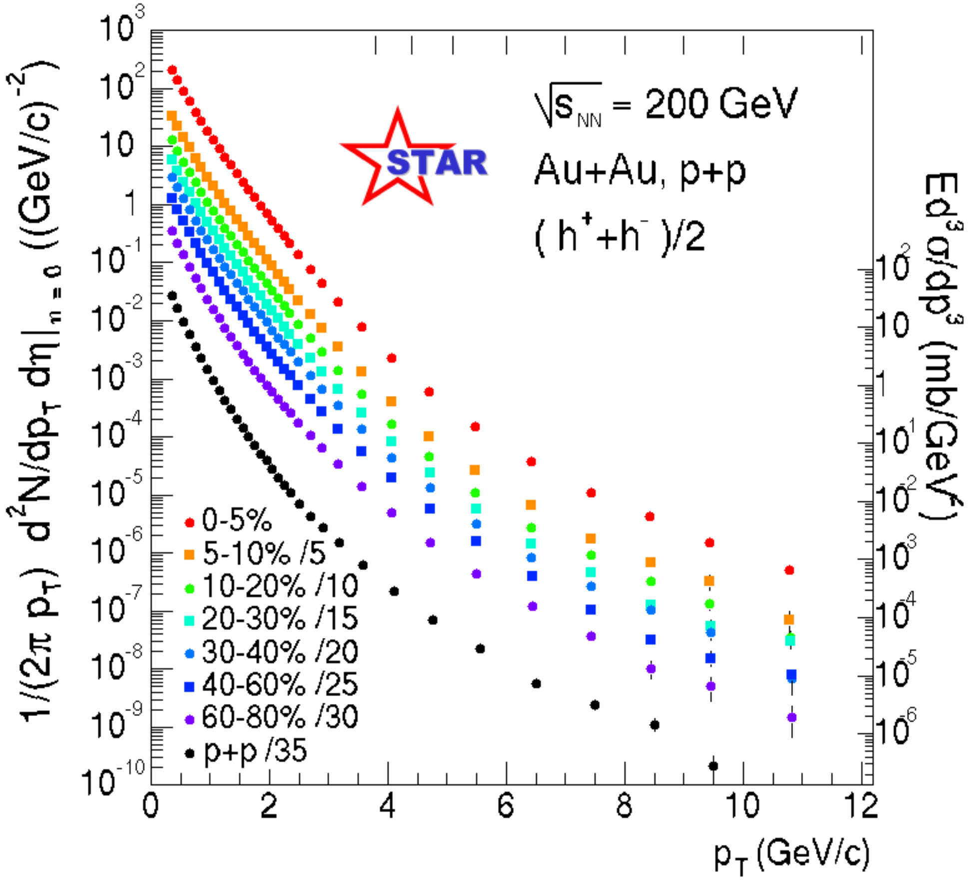
Linear dep. on gluon density

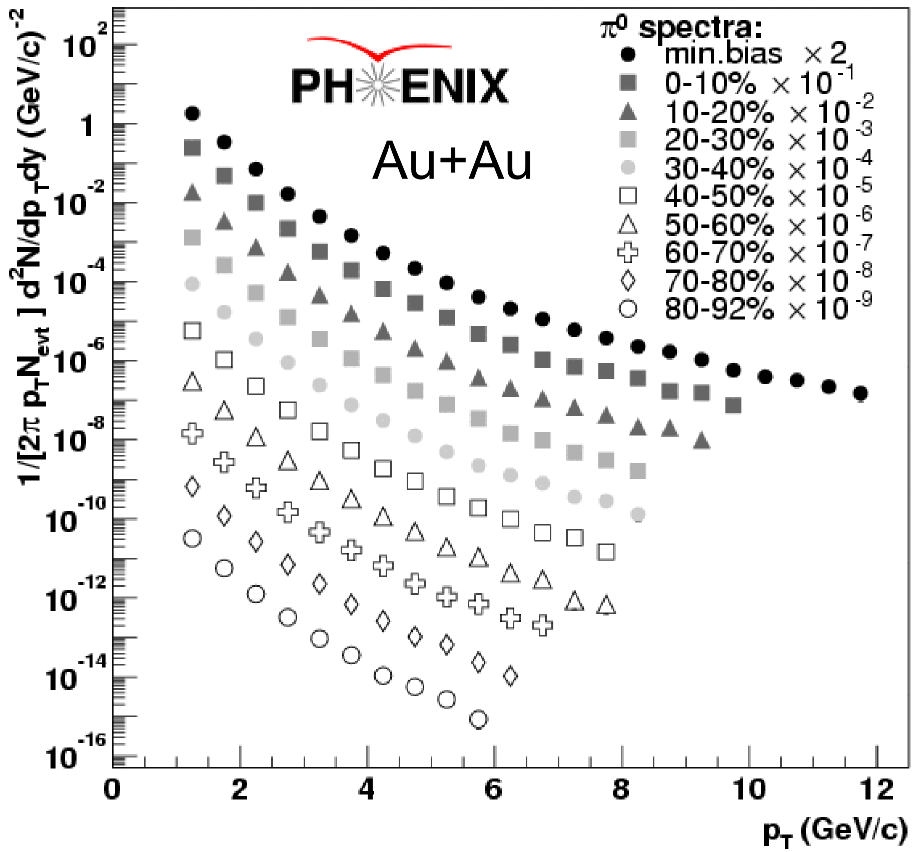
QCD LPM effect

- nonlinear interaction of gluons in thin plasma

$$\Delta E_{GLV} = C_R \alpha_S^3 \int d\tau \tau \rho_{glue}(\tau, r(\tau)) Log\left(\frac{2E_{jet}}{\mu^2 L}\right)$$

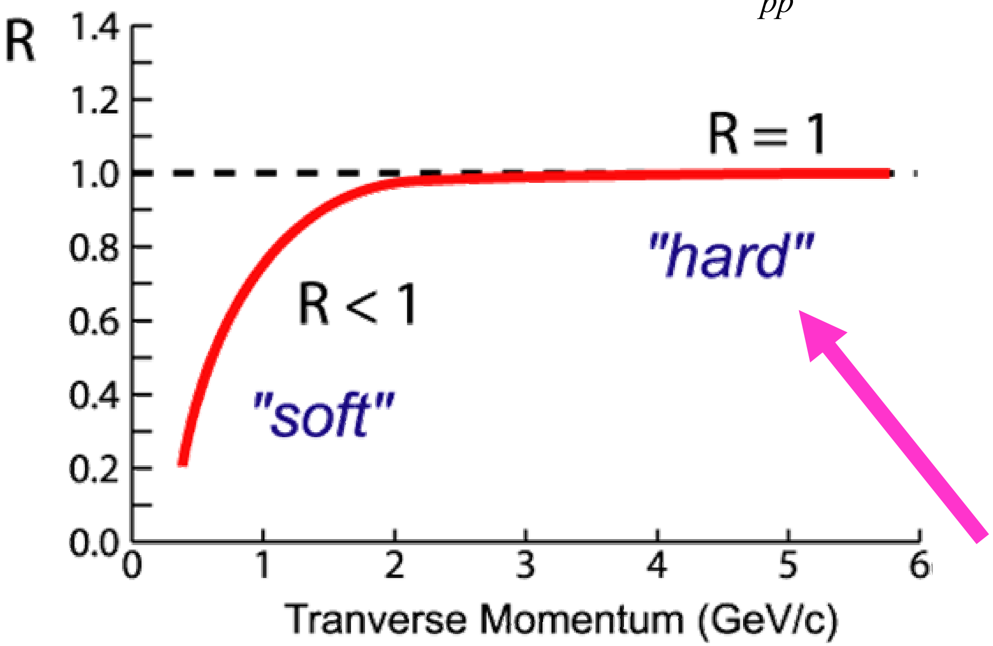
Mid-rapidity spectra





Nuclear Modification Factor R_{AA}

- Yield (p_T) in Au+Au and p+p collisions
- Number of binary collisions from Glauber
- Ratio: $$R_{AA}(p_T) = \frac{Yield_{AA} / \langle N_{binary} \rangle}{Yield_{pp}}$$



If no "effects":

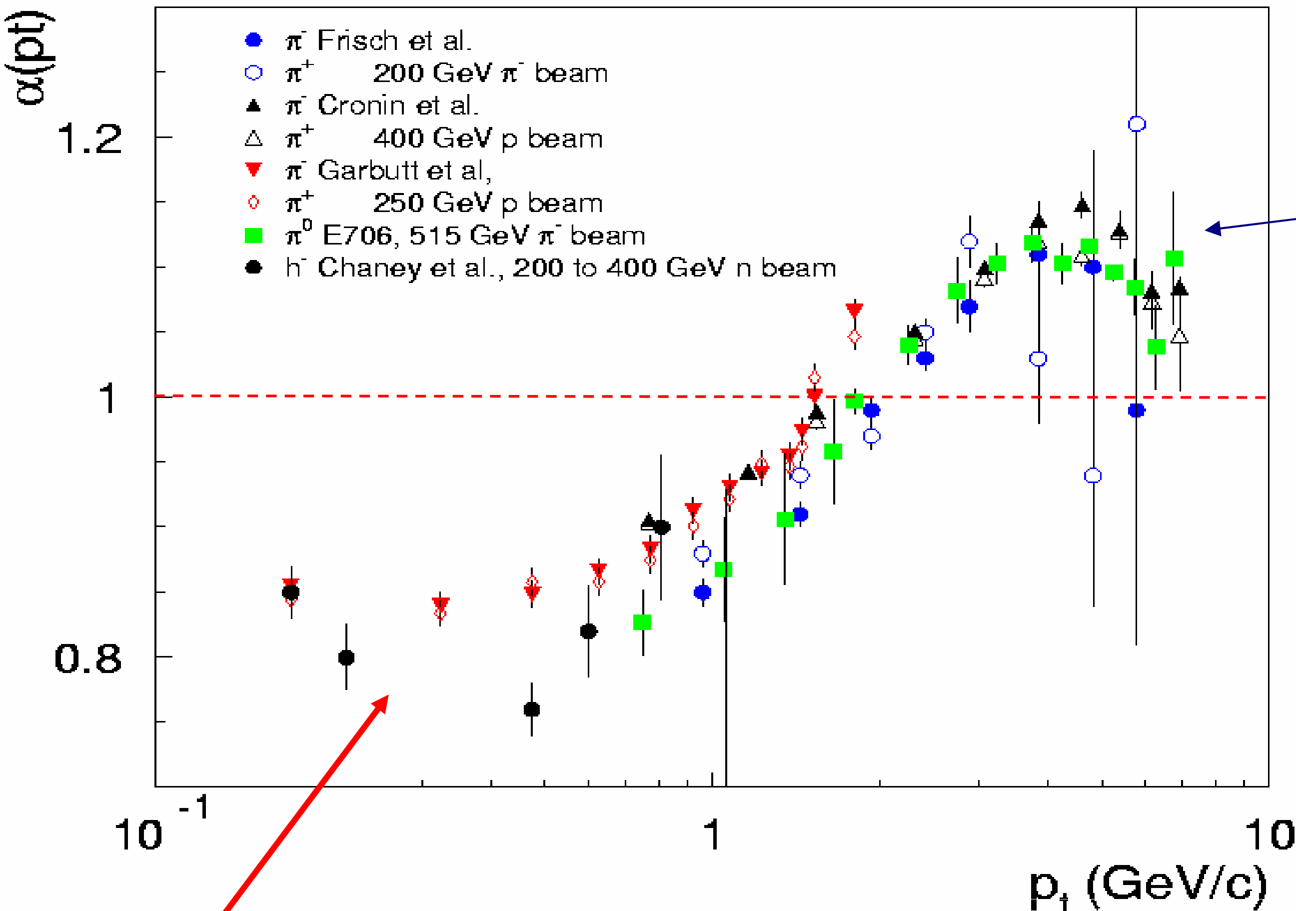
- R < 1 in regime of soft physics
- R = 1 at high-p_T where hard scattering dominates

Suppression ?

- Is R < 1 at high-p_T ?

Nuclear effects in pA collisions

$$\sigma_{pA} = A^{\alpha}\sigma_{pp}$$

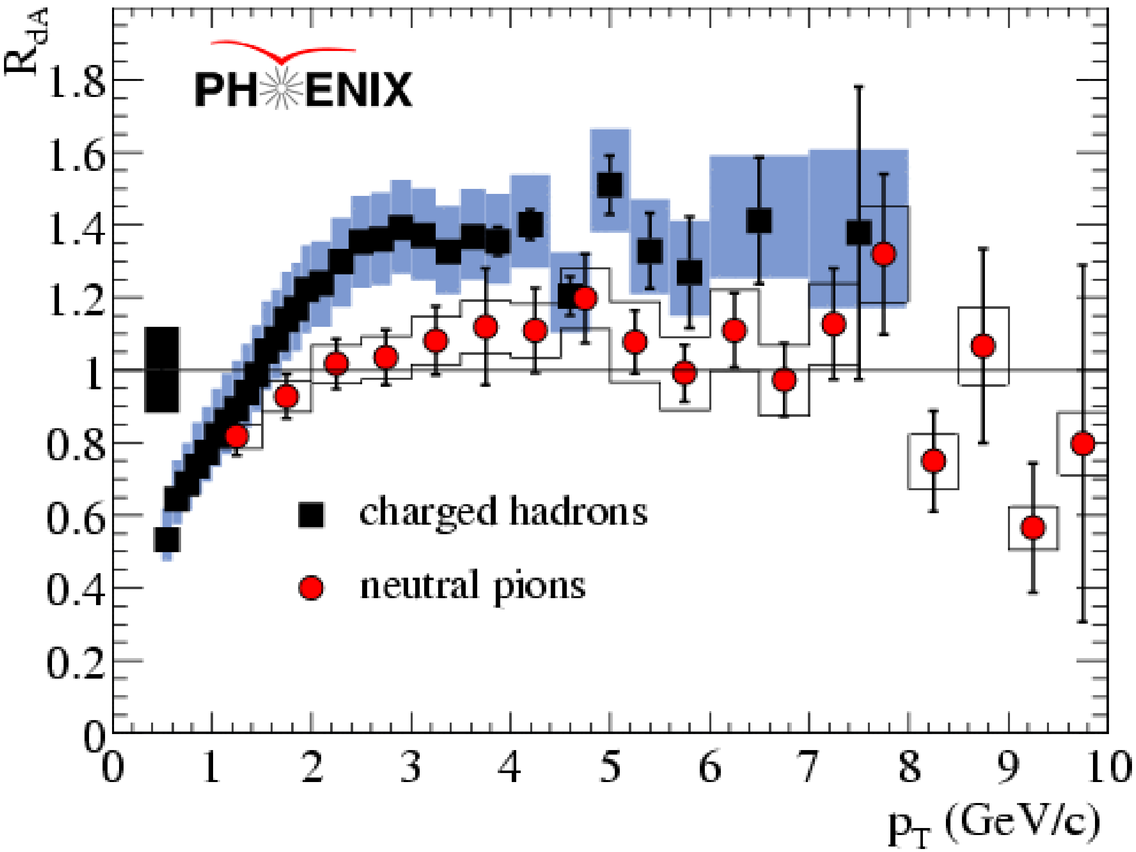


High p_T:
multiple scattering
$\alpha>1$
"Cronin Effect"

Low p_T: Coherent interactions and shadowing $\Rightarrow \alpha<1$

d+Au results from RHIC

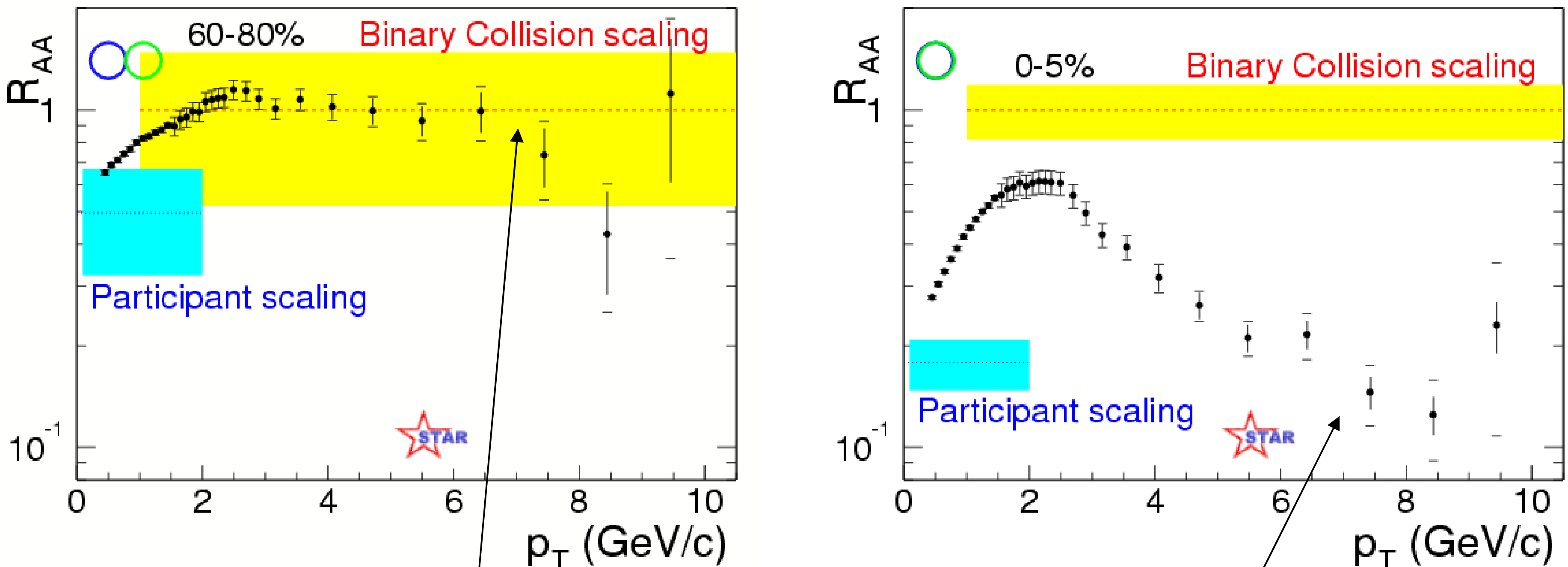
$$R_{dA}(p_T) = \frac{Yield_{dA} / \langle N_{binary} \rangle}{Yield_{pp}}$$



Expected "Cronin" enhancement observed by all four RHIC experiments in d+Au collisions

Nuclear modification R_{AA}

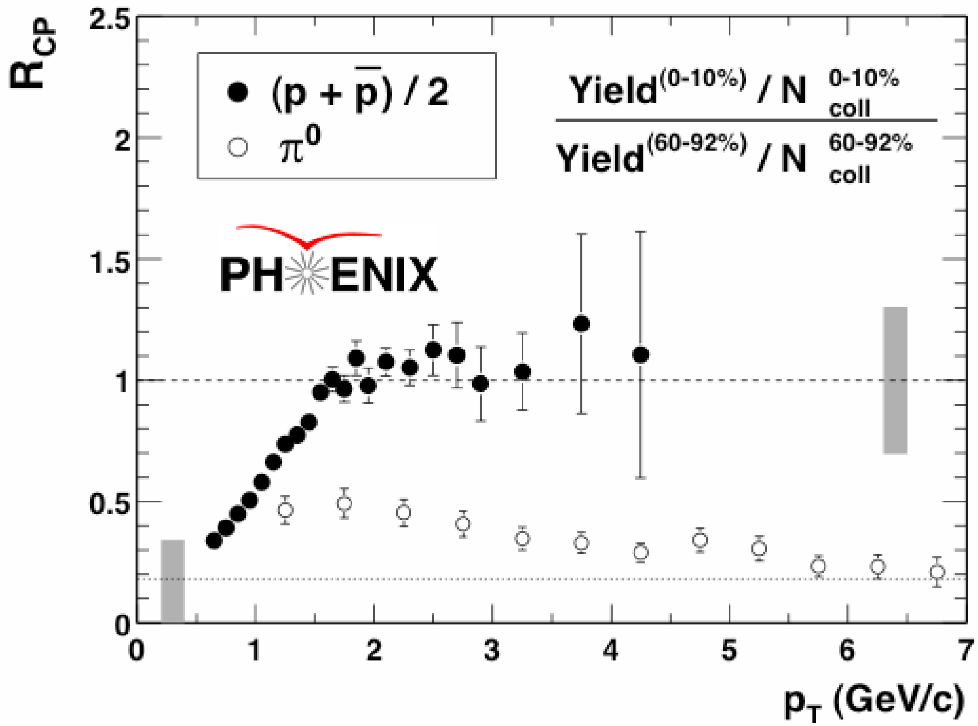
$$R_{AA}(p_T) = \frac{Yield_{AA} / \langle N_{binary} \rangle}{Yield_{pp}}$$

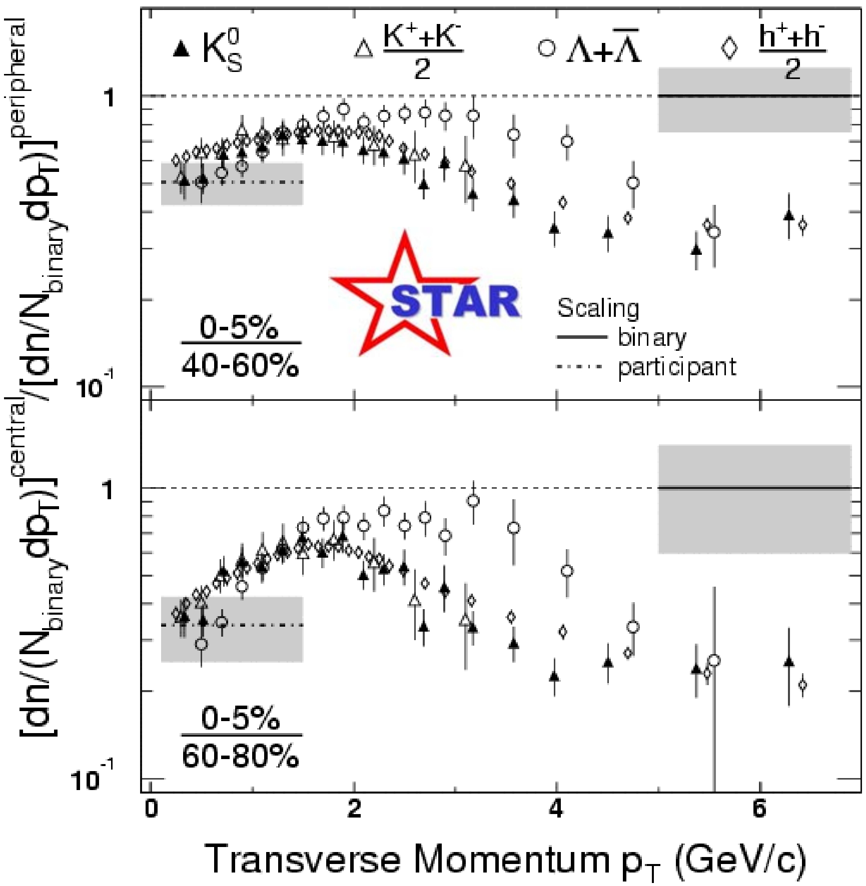


Peripheral (b≈10 fm): Binary Scaling

Central (b<3 fm): Factor ≈ 5 suppression

Flavor Dependence of Suppression





Baryons show binary collision scaling at intermediate p_T (2-4 GeV/c):

•Novel production mechanism?
Quark Coalescence: q+q+q → baryon

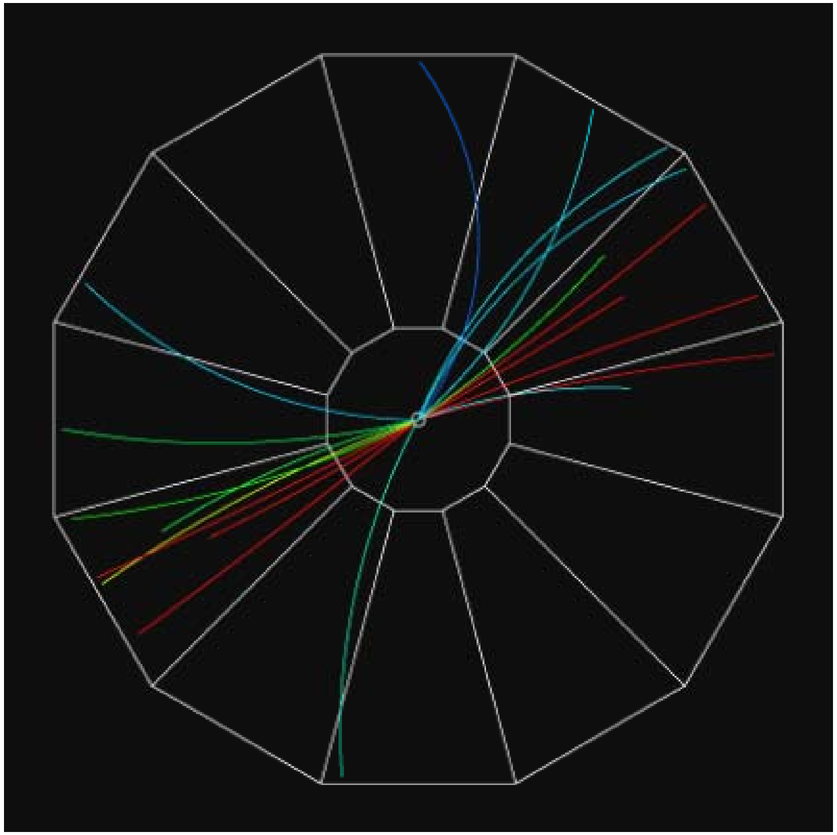
•Re-discovery of flavor dependence of

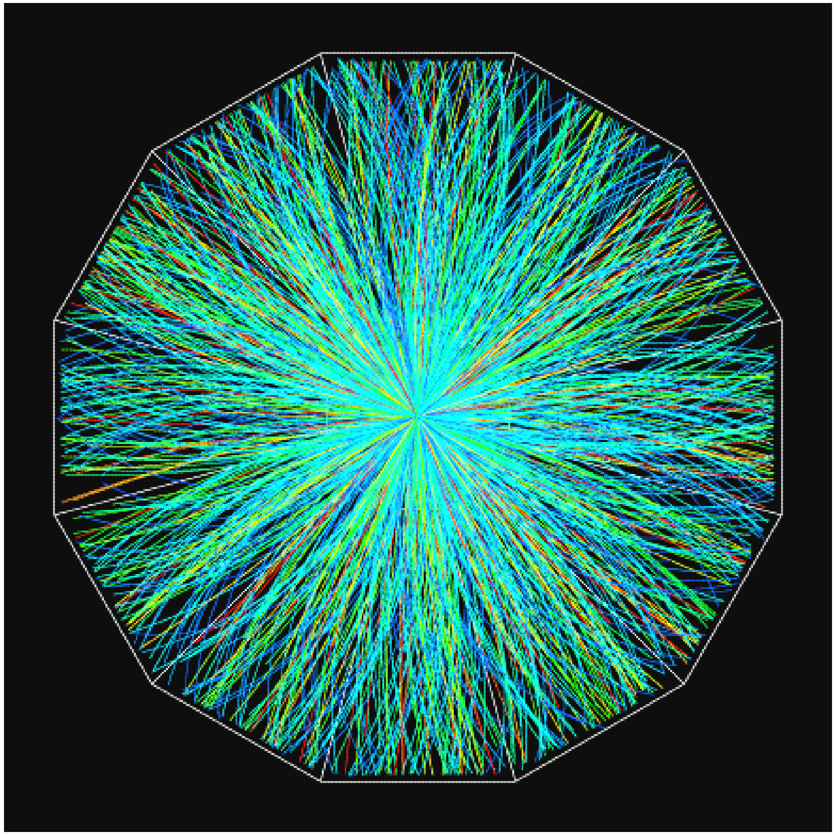
Jets in Au+Au? The Challenge

Find this ……………………………………….in here

p+p →dijet

Central Au+Au Event

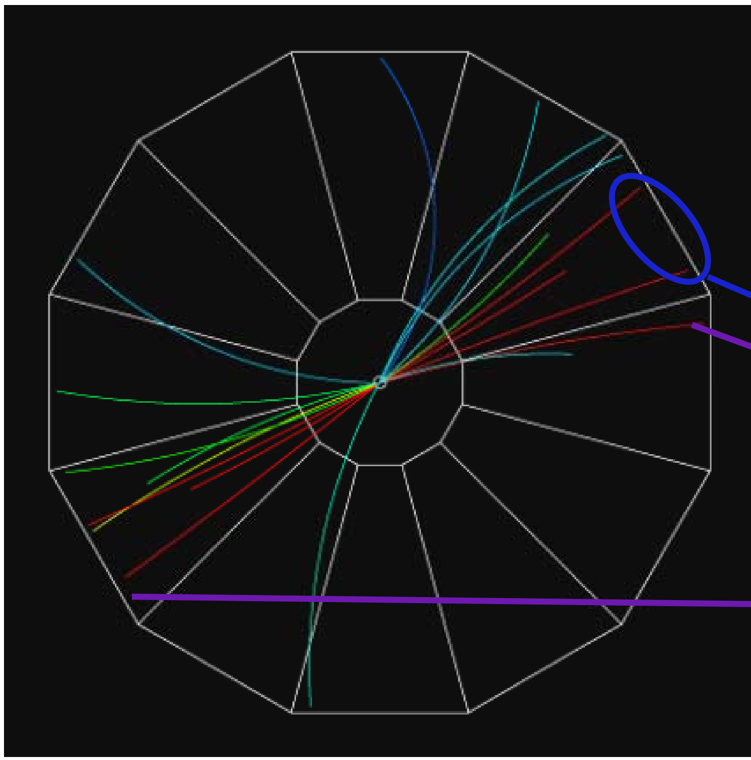




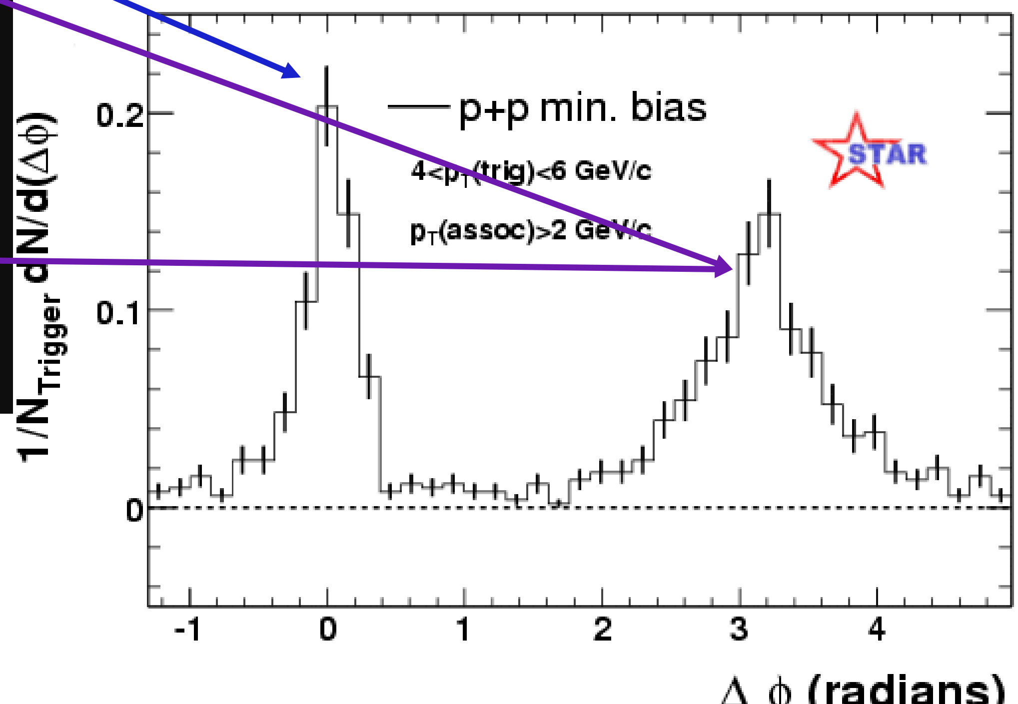
Jets in p+p collisions at RHIC

Two-particle azimuthal correlations:

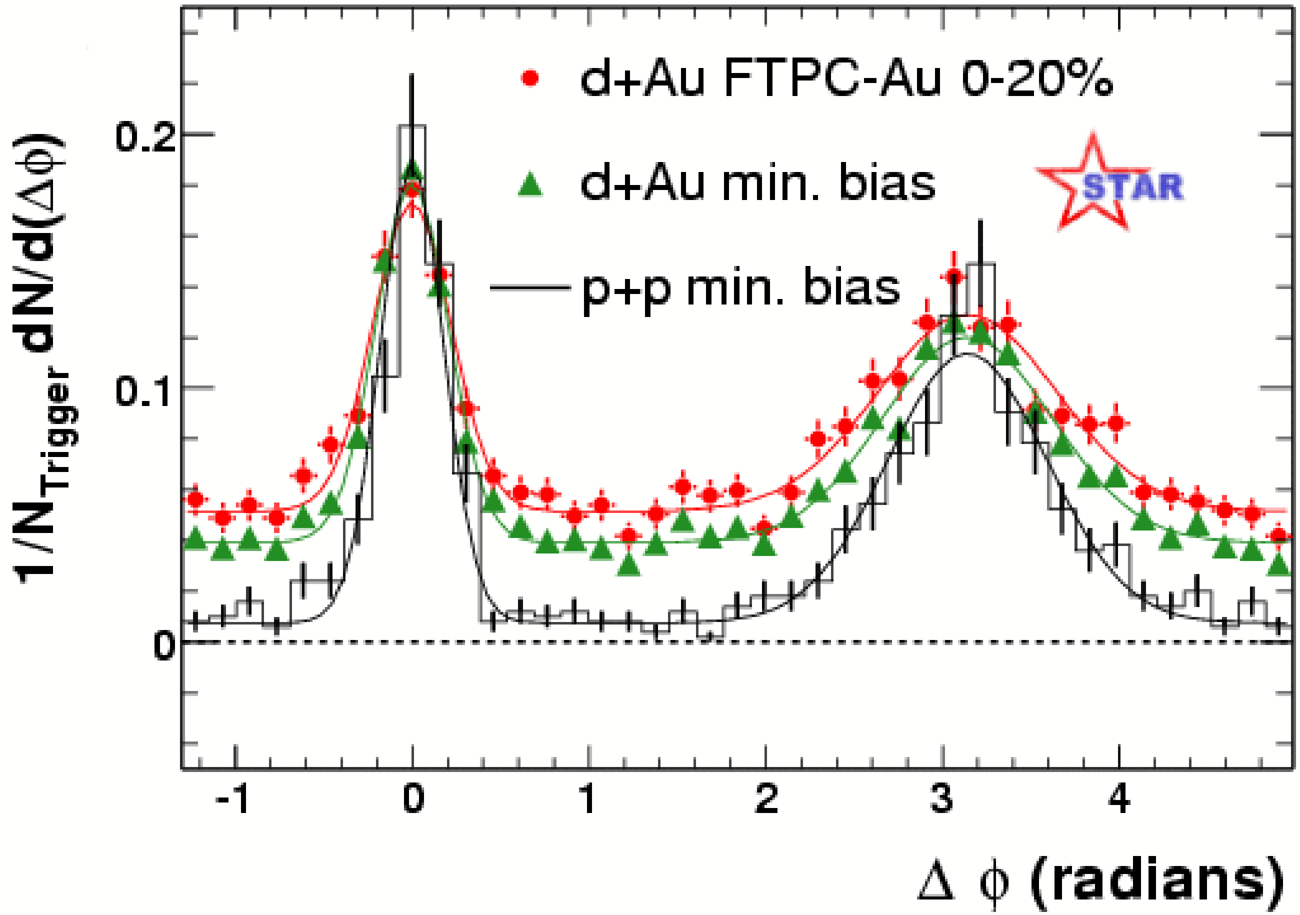
p+p → dijet



- p+p events with high p_T track (*maximally* biased jet finder)
- $\Delta\phi$ distribution of other tracks (p_T>2 GeV/c) in these events
- normalize to the # triggers …

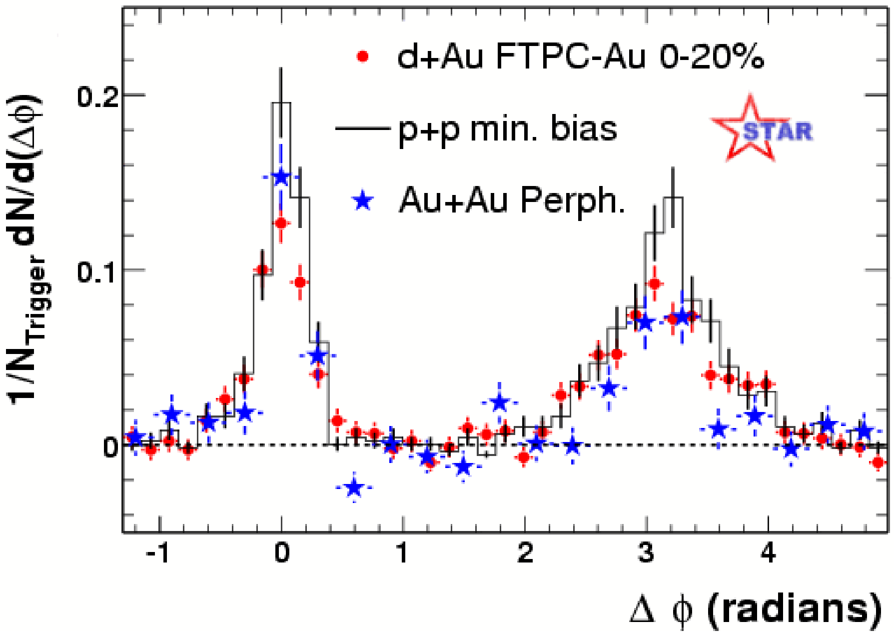


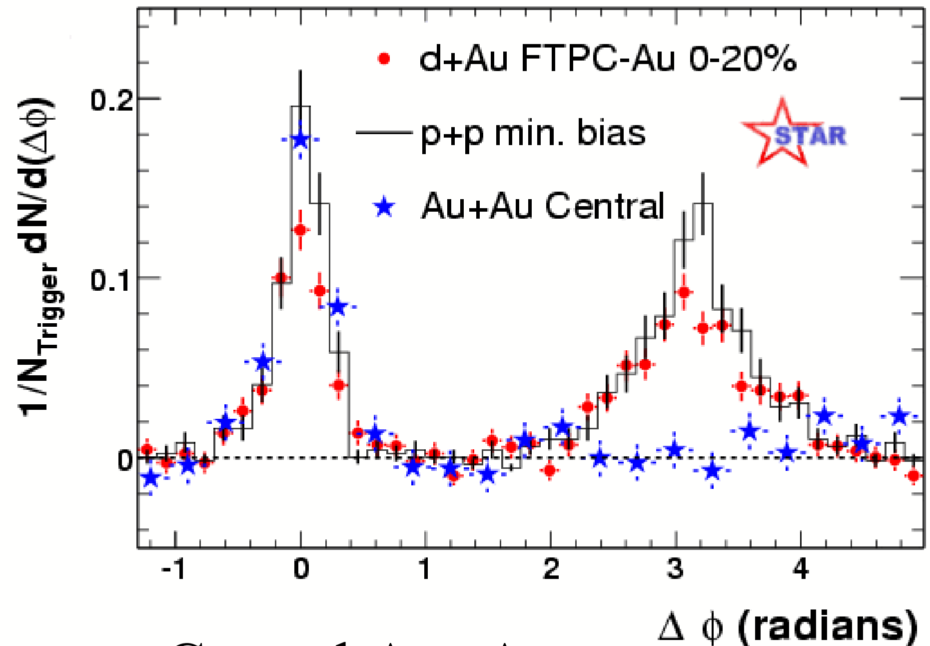
Jets in d+Au using Δφ correlations



- Similar near-angle and back-to-back correlations
- Increased "pedestal" from multiple interactions

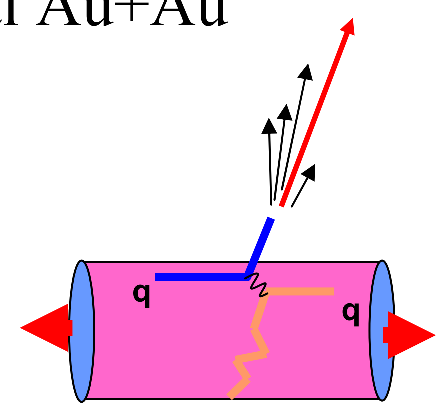
Jets in Au+Au collisions at RHIC





Central Au+Au

Peripheral Au+Au ≈ d+Au



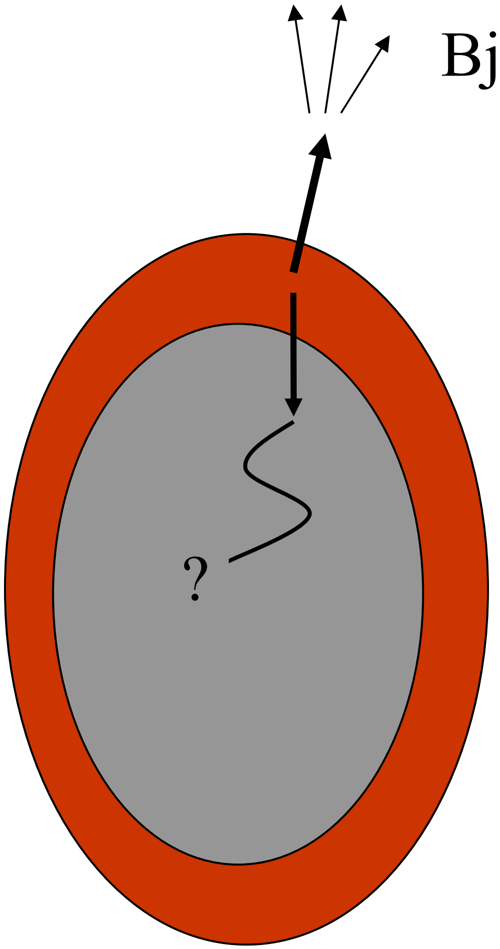
"Monojets"

High p_T particle production @ RHIC

- Suppression of inclusives compared to binary collision scaling
- High p_T charged hadrons dominated by jet fragments
- Suppression of back-to-back correlations in most central Au+Au collisions

Surface emission!

Bjorken '82



Theory Calculations

$dE/dx|_{t=0} = 7$ GeV/fm

$\rho_{t=0} \geq 30\ \rho_{nucleus}$

Jet Quenching ≠ Quark-Gluon Plasma

- Want Equation of State of hot nuclear matter:

$$\varepsilon_{SB}(T) = \frac{\pi^2}{30}\left(N_{bosons} + 7/8\, N_{fermions}\right)T^4$$

Jets, Dijets, γ-jet

Thermal photons?

Thermal dileptons?

J/Ψ?

Conclusions

- *Qualitatively* new physics in Au+Au collisions at RHIC:
  - Total multiplicity: Au+Au ≈ e^+e^- after accounting for geometry
  - Suppression of high p_T particle production
  - "monojets"
- High p_T Au+Au data consistent with "Jet Quenching" scenario
  - High gluon density: $\rho_{t=0} \geq 30\ \rho_{nucleus}$
  - Medium opaque to fast partons
- Essential question: Have we seen the Quark-Gluon Plasma at RHIC?
  - Density and temperature of system at or above predicted phase transition temperature, but …
  - No direct evidence for excess entropy production