Experimental Highlights since QM02

Thomas K Hemmick
Stony Brook University

Thanks to B.V. Jacak and D. d'Enterria

The Opening Act

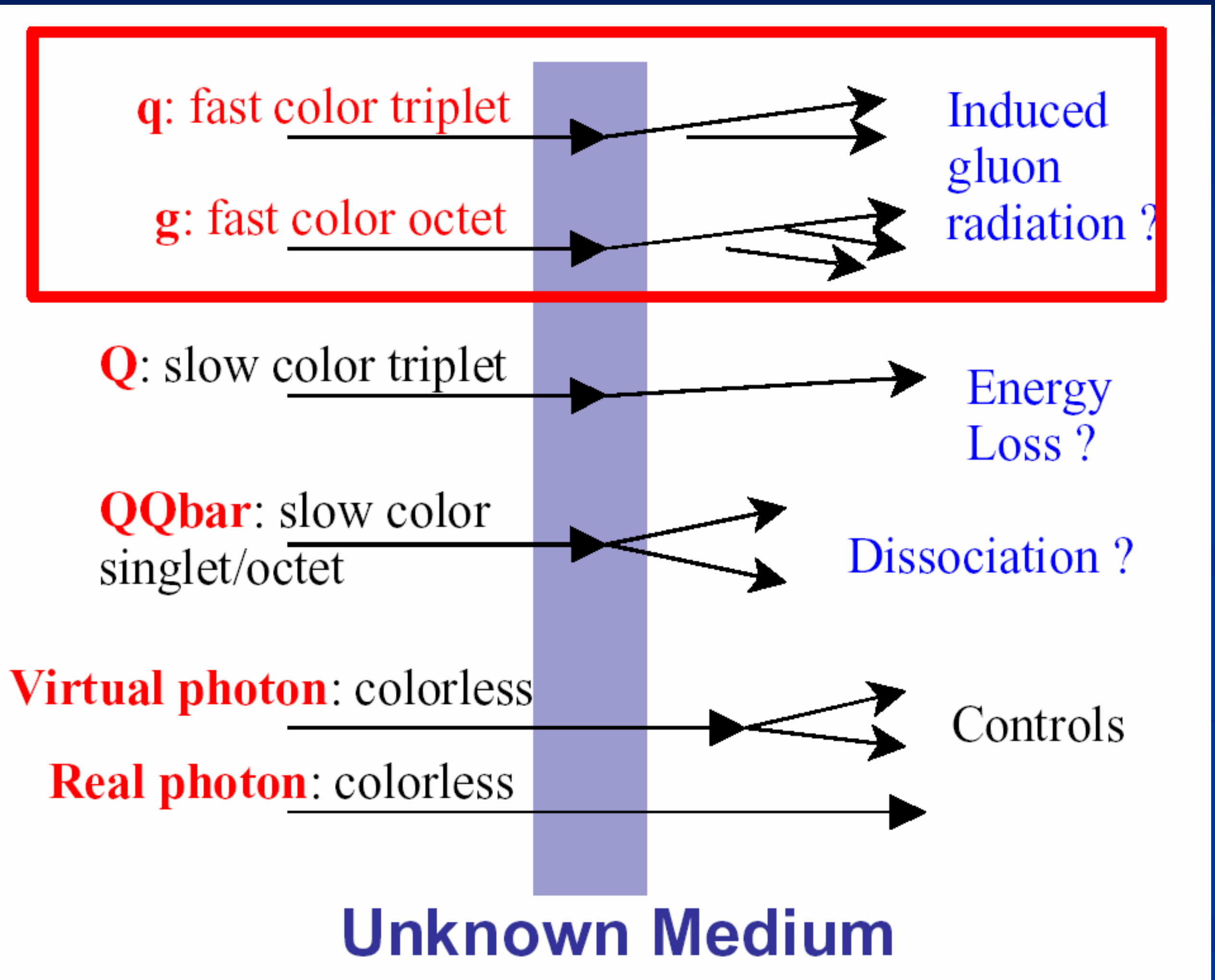
- In music, an opening act is a lesser band that performs first and mostly serves to increase the audience's desire for hearing the headline act.
- My charge is to present "progress in the field" since we last met at QM02, but not to preempt the conference.
- I will, however, indicate results to look for and my personal charge to you.

WARNING: The Surgeon General has determined that overview talks contain biased and incomplete reports that may be detrimental to the health and mental wellbeing of individuals who expect or demand otherwise.

The Paradigm

- We accelerate nuclei to high energies with the hope and intent of utilizing the beam energy to driving a phase transition to QGP.
- The collision must not only utilize the energy effectively, but generate the signatures of the new phase for us.
- I will make an artificial distinction as follows:
  - Medium: The bulk of the particles; dominantly soft production and possibly exhibiting some phase.
  - Probe: Particles whose production is calculable, measurable, and thermally incompatible with (distinct from) the medium.

The Probes Gallery:



Jet Suppression

charm/bottom dynamics

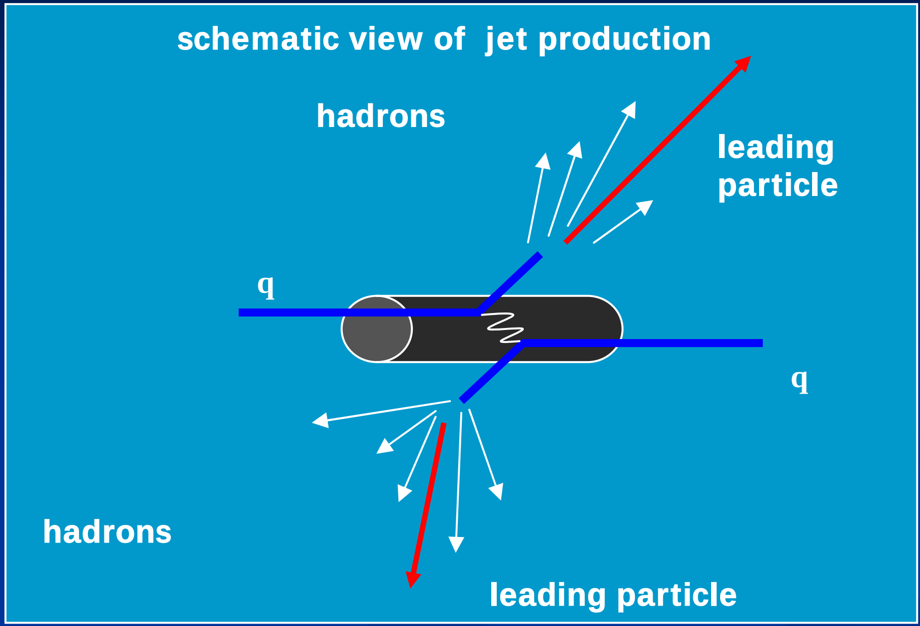
J/Ψ & Y

direct photons
CONTROL

The importance of the control measurement(s) cannot be overstated!

q/g jets as probe of hot medium

Jets from hard scattered quarks observed via fast leading particles or azimuthal correlations between the leading particles

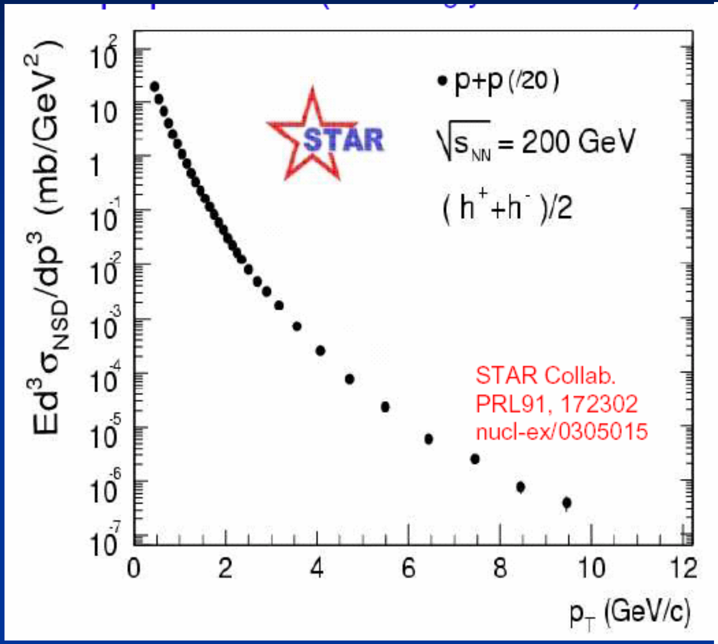


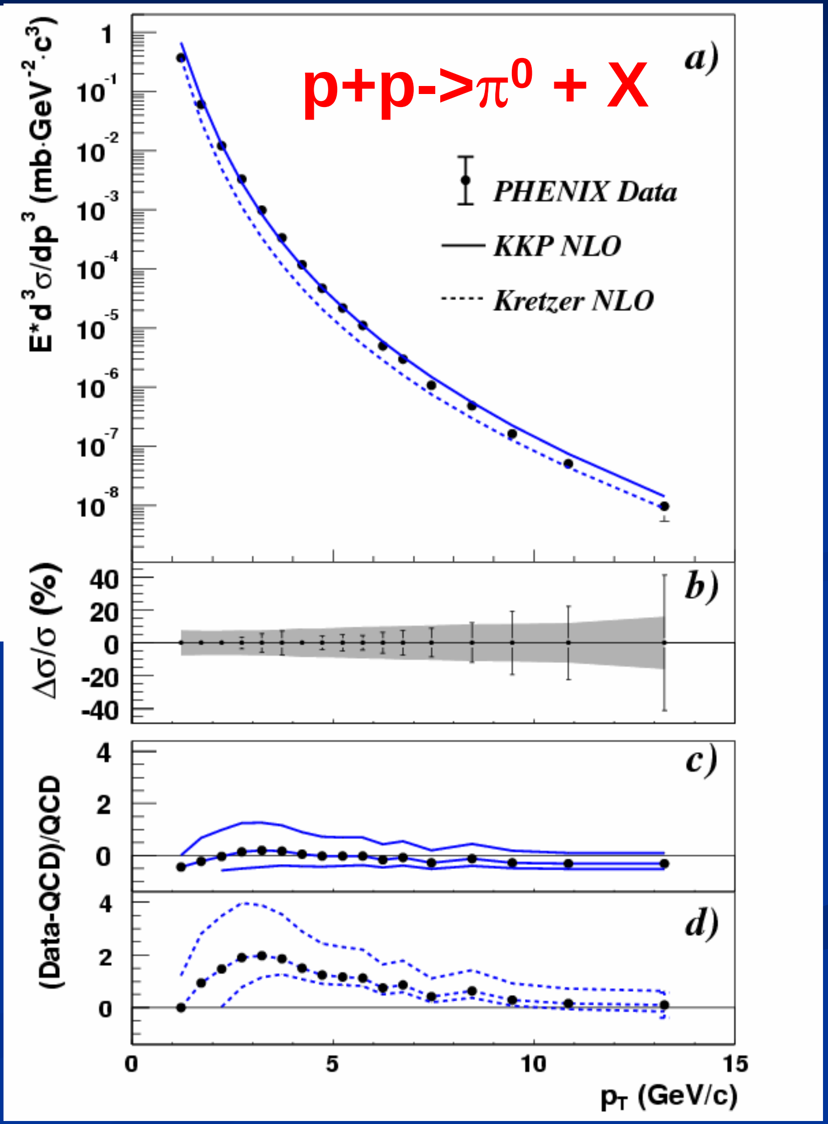
However, before they create jets, the scattered quarks radiate energy (~ GeV/fm) in the colored medium

→decreases their momentum (fewer high p_T particles)
→"kills" jet partner on other side

Jet Quenching

Calibrating the Probe(s)

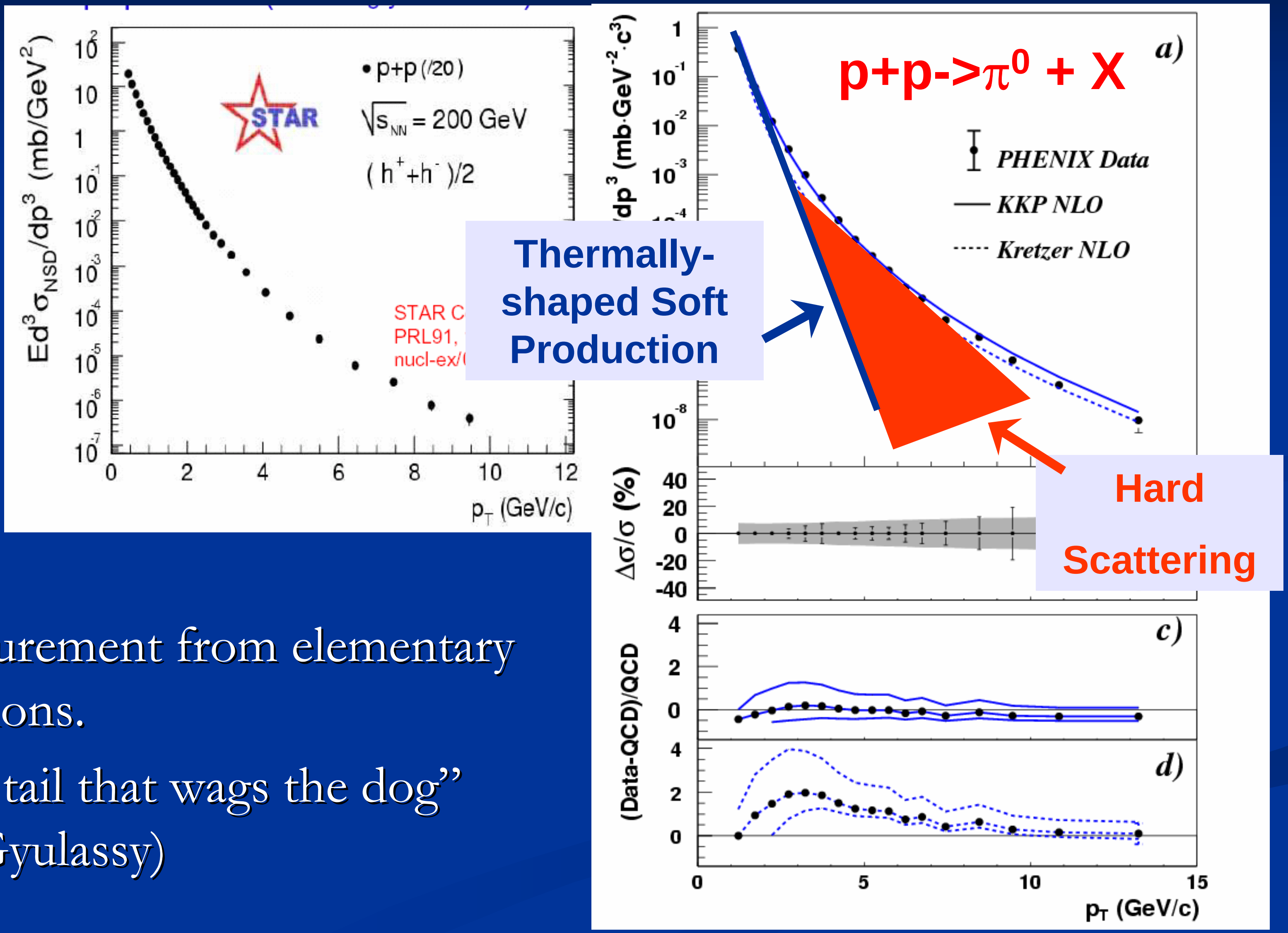




- Measurement from elementary collisions.
- "The tail that wags the dog" (M. Gyulassy)

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

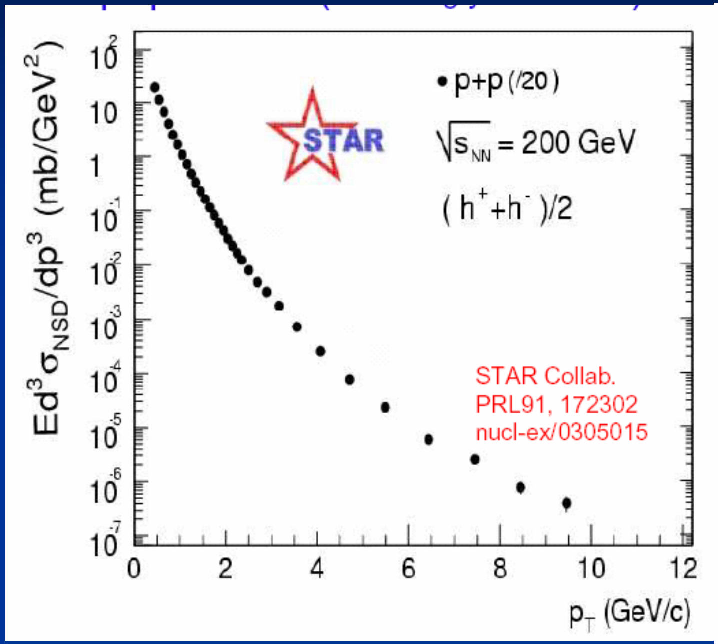
Calibrating the Probe(s)

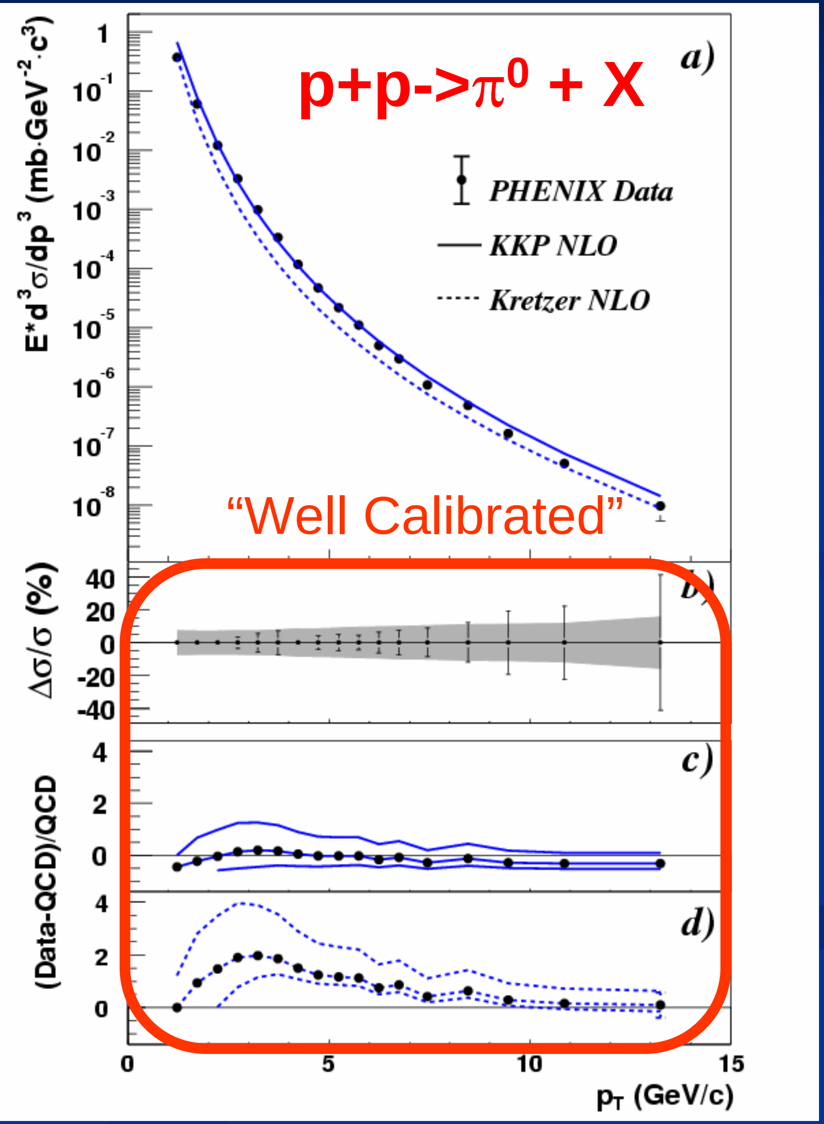


- Measurement from elementary collisions.
- "The tail that wags the dog" (M. Gyulassy)

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

Calibrating the Probe(s)

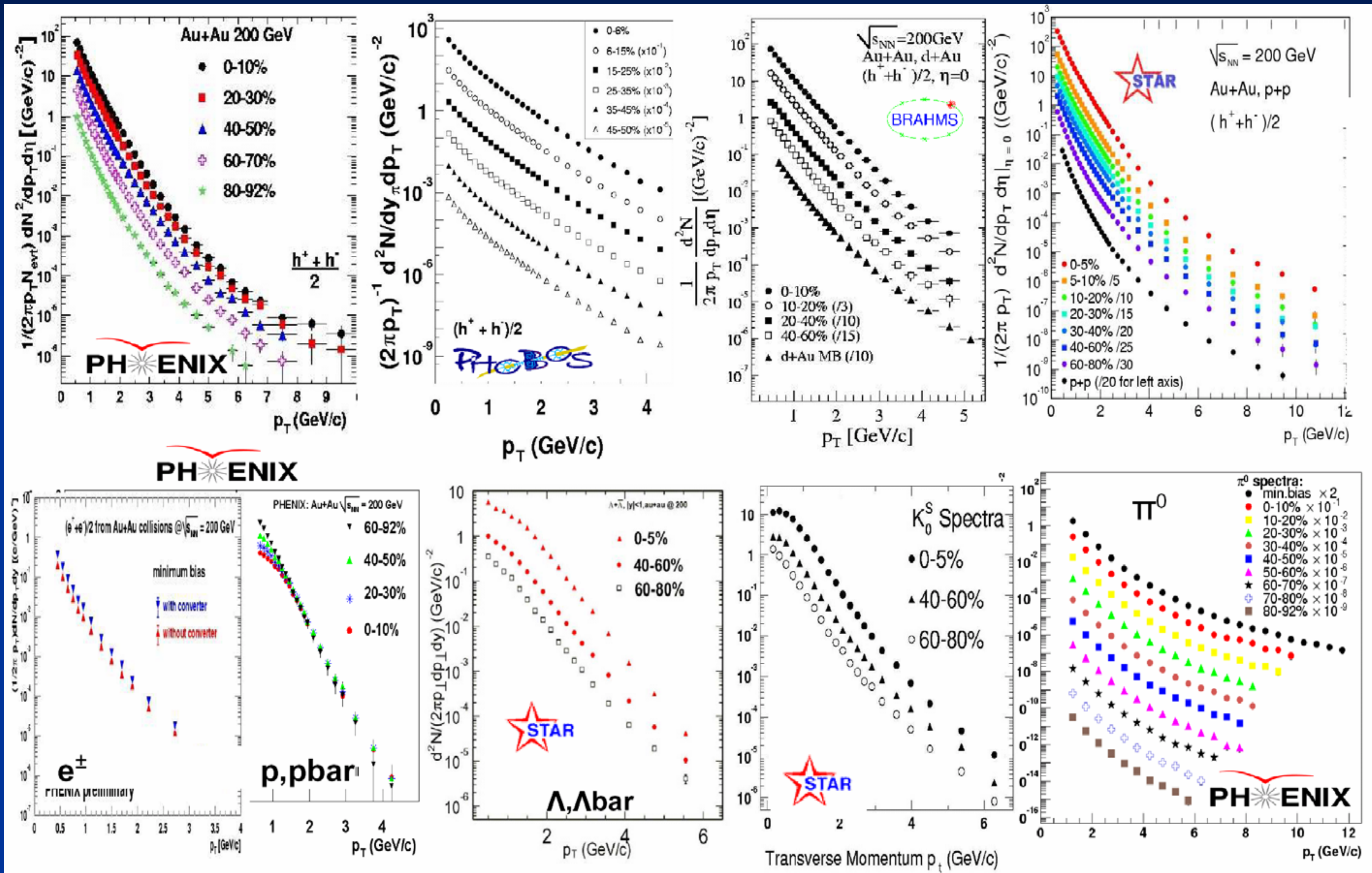




- Measurement from elementary collisions.
- "The tail that wags the dog" (M. Gyulassy)

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

Many measurements measure at high p_T(!)



R_{AA} Normalization

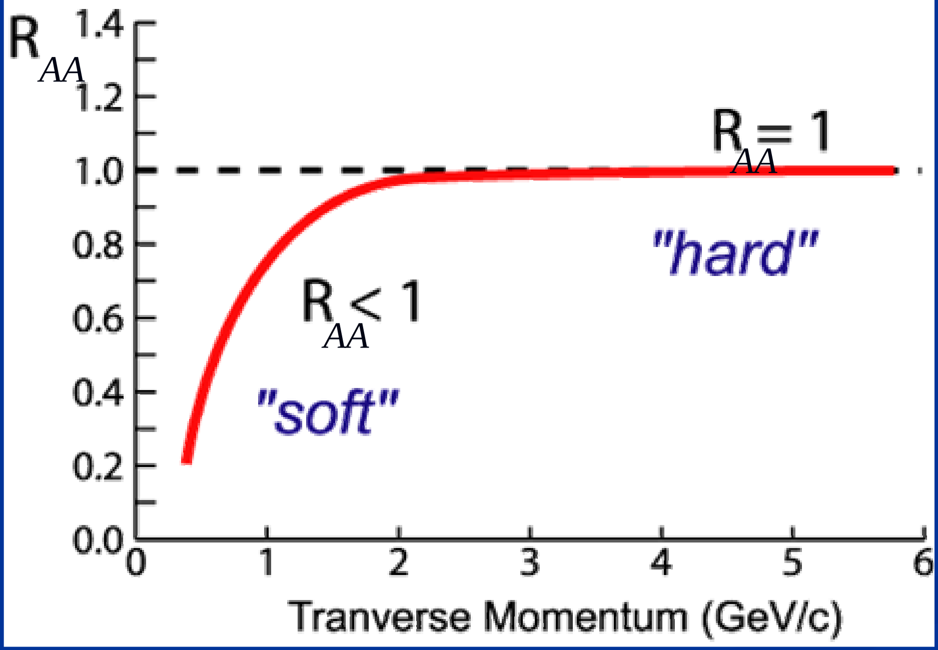
1. Compare Au+Au to nucleon-nucleon cross sections
2. Compare Au+Au central/peripheral

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:

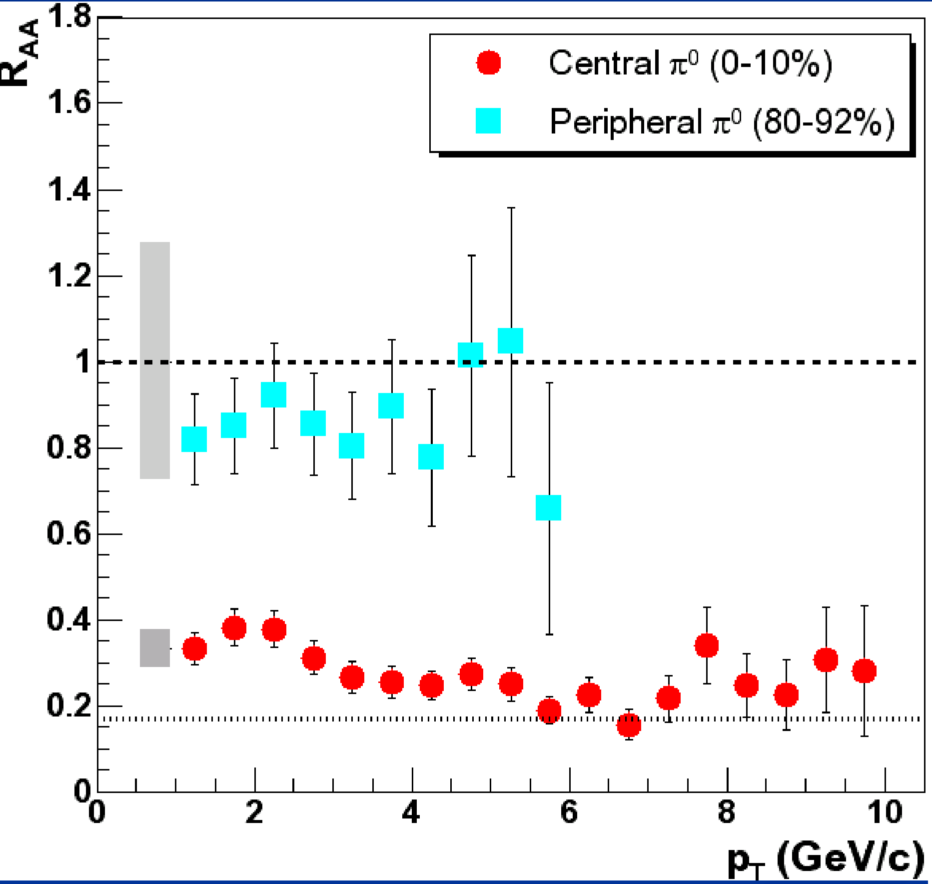
$R_{AA} < 1$ at high-p_T

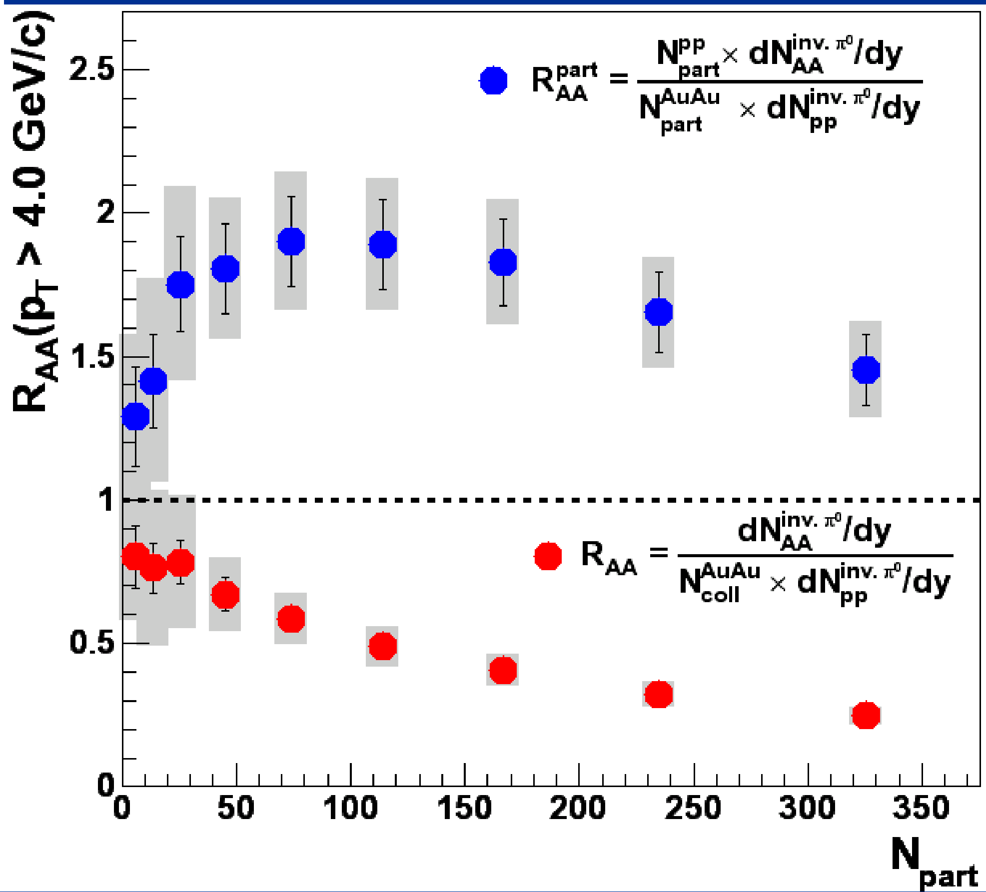
Au-Au $\sqrt{s}$ = 200 GeV: high p_T suppression!

PRL91, 072301(2003)

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

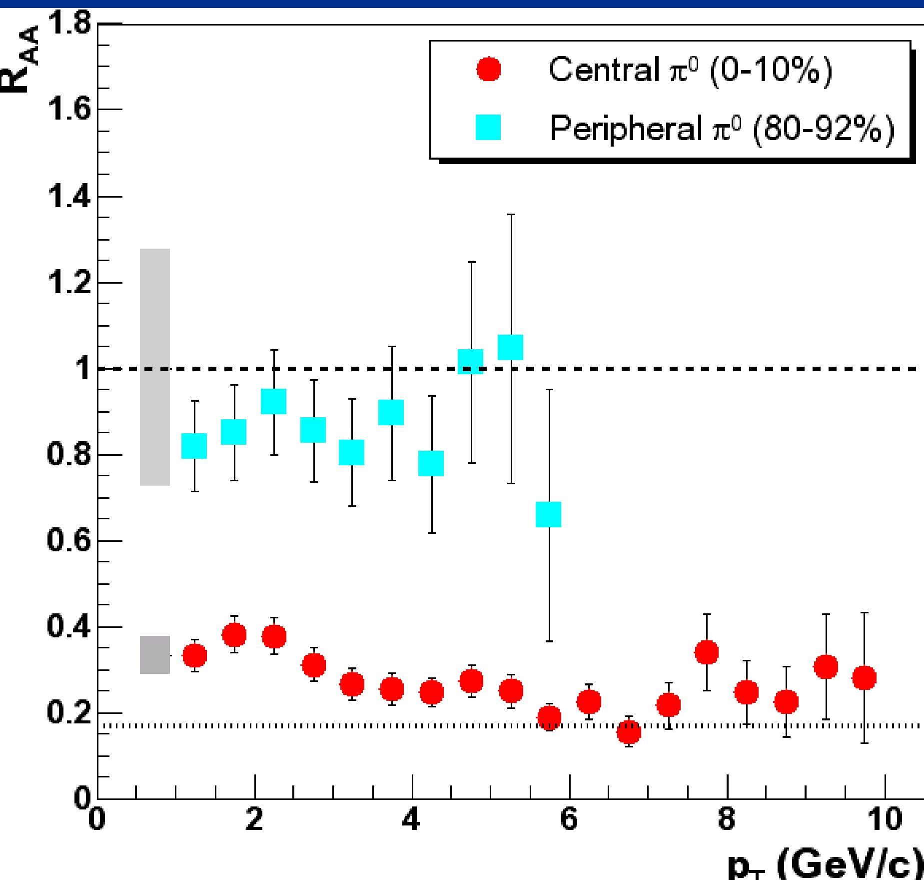
$$R_{AA}^{part} = \frac{\text{Yield}_{AuAu} / \langle N_{part} \rangle_{AuAu}}{\text{Yield}_{pp} / 2}$$

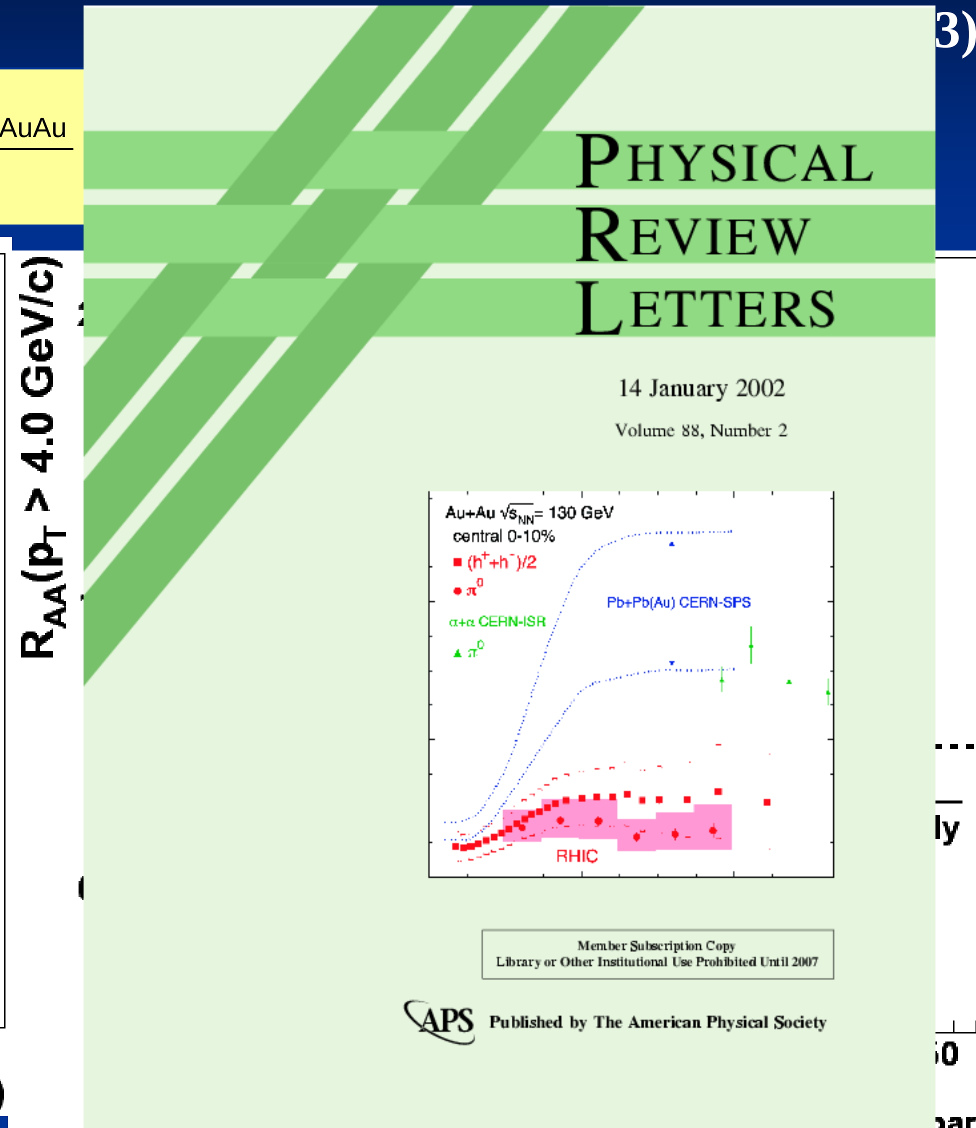




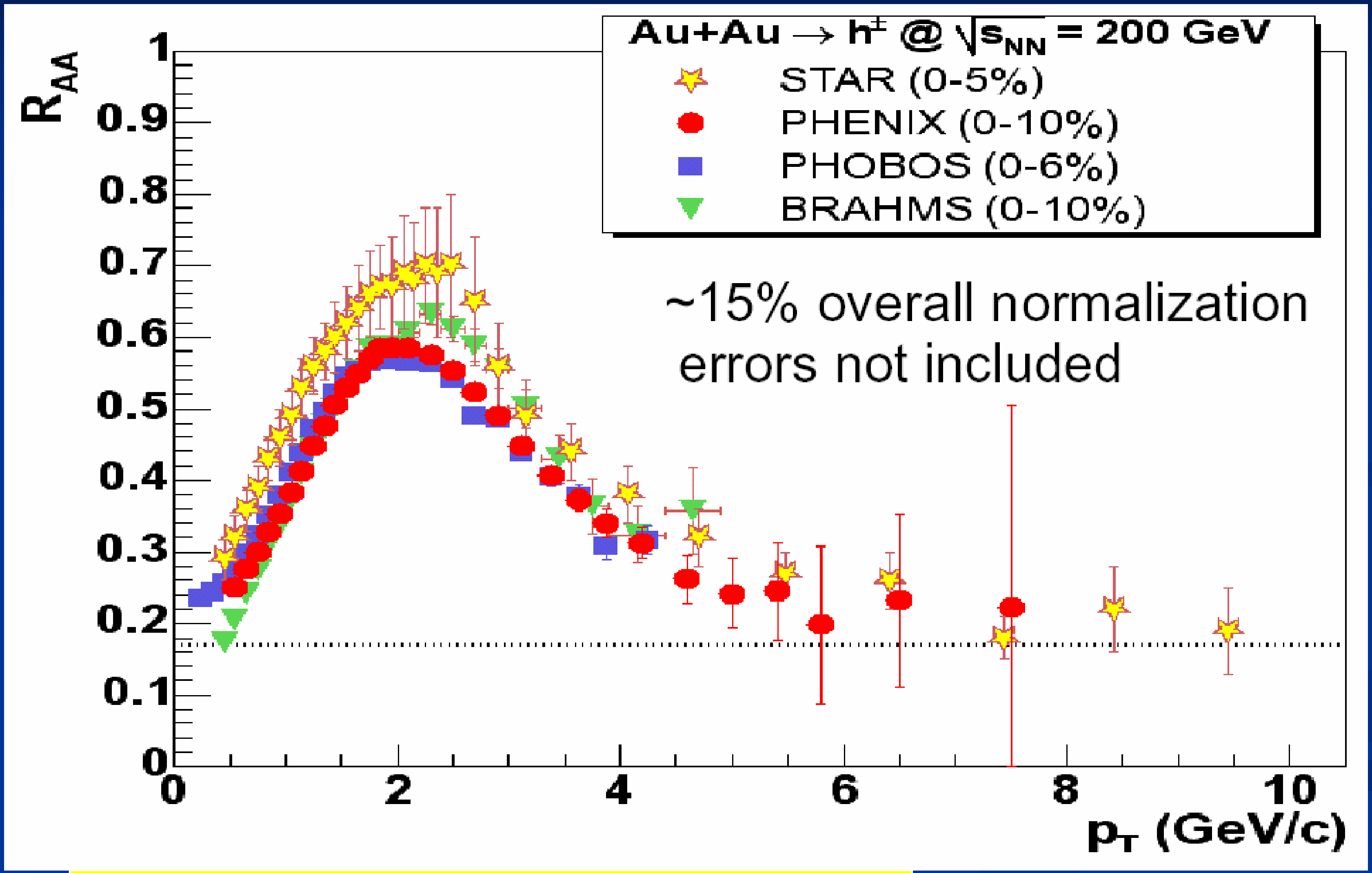
Au-Au $\sqrt{s}$ = 200 GeV: high p_T suppression!

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





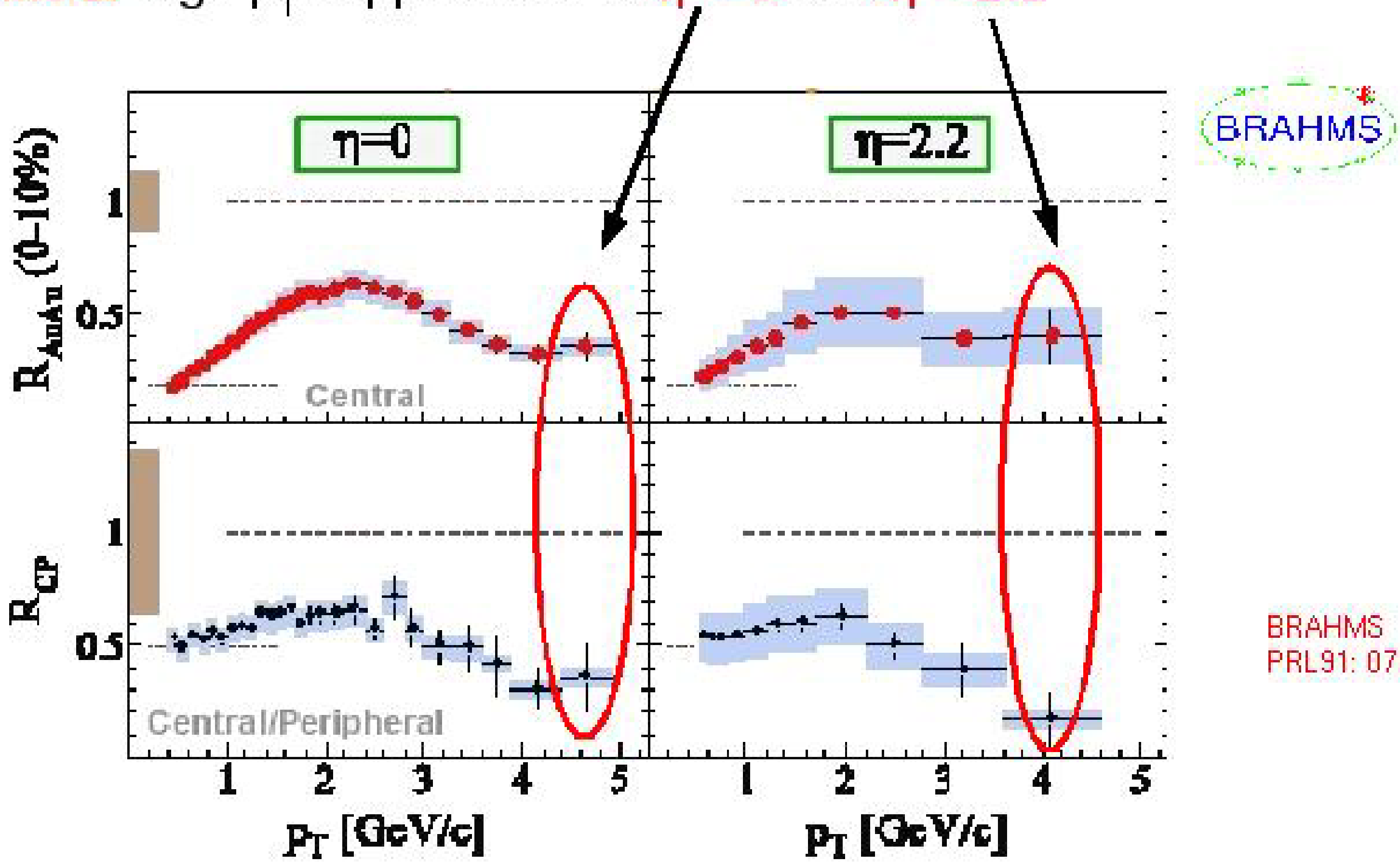
Quantitative Agreement Across Experiments



Effect is real…Final or Initial State Effect?

Suppression similar at η=2.2

- Similar high p_T suppression at $\eta = 0$ and $\eta = 2.2$

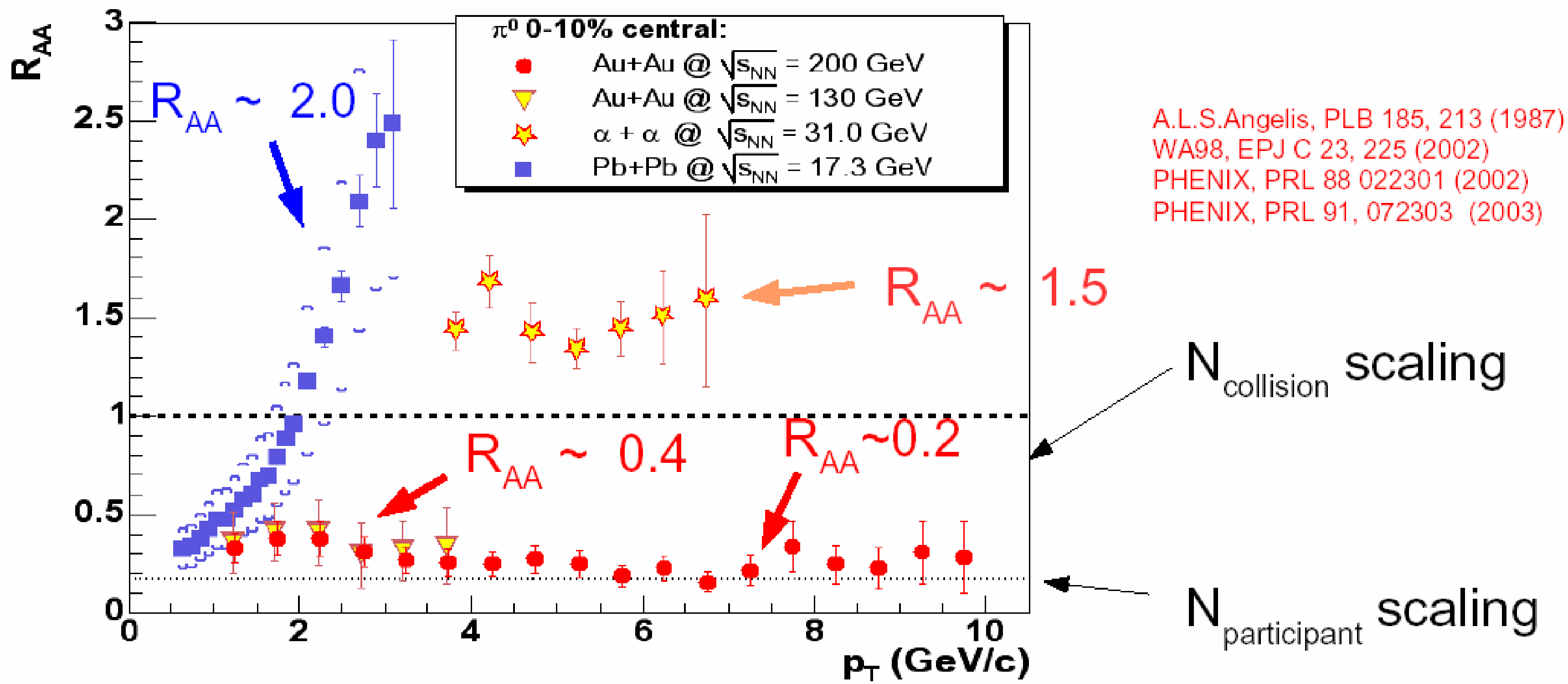


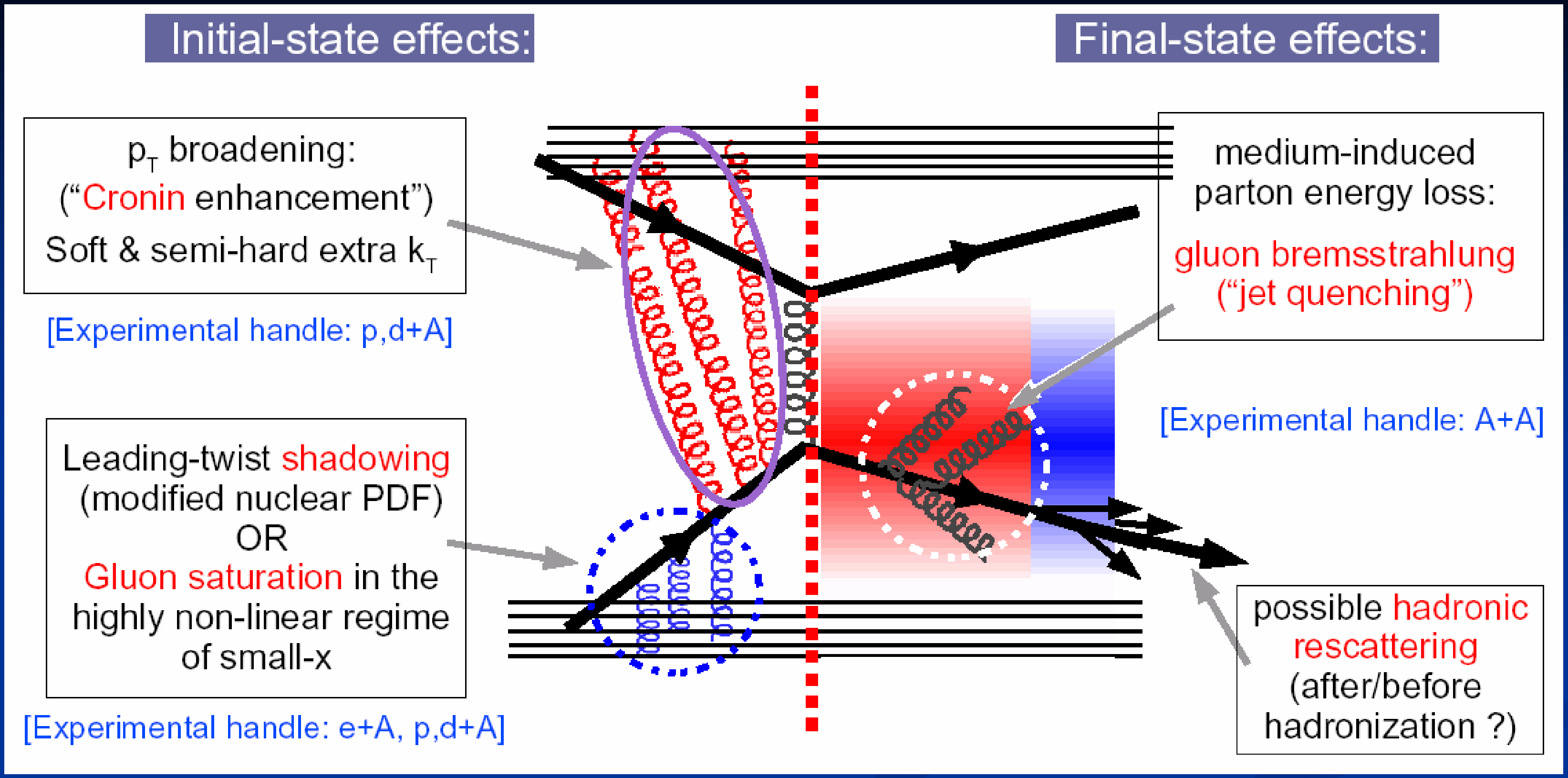
BRAHMS
PRL91: 072305(2003)

- *The "quenching" medium extends also in the* *longitudinal direction*.

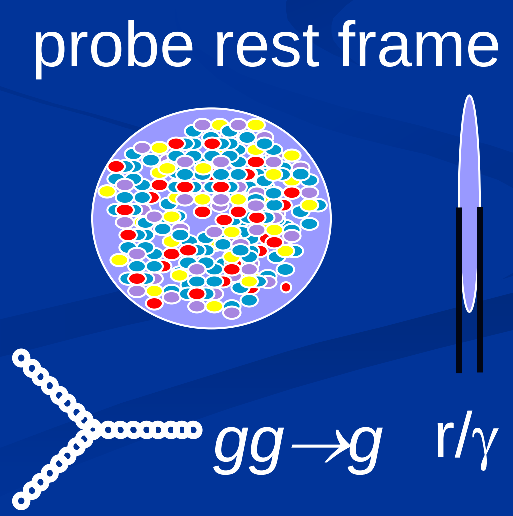
Suppression vs Collision Energy

- CERN: Pb+Pb ($\sqrt{s_{NN}}$ ~ 17 GeV), α+α ($\sqrt{s_{NN}}$~31 GeV): Cronin enhancement
- RHIC: Au+Au ($\sqrt{s_{NN}}$ ~ 130, 200 GeV): x4-5 suppression with respect to N_{coll}

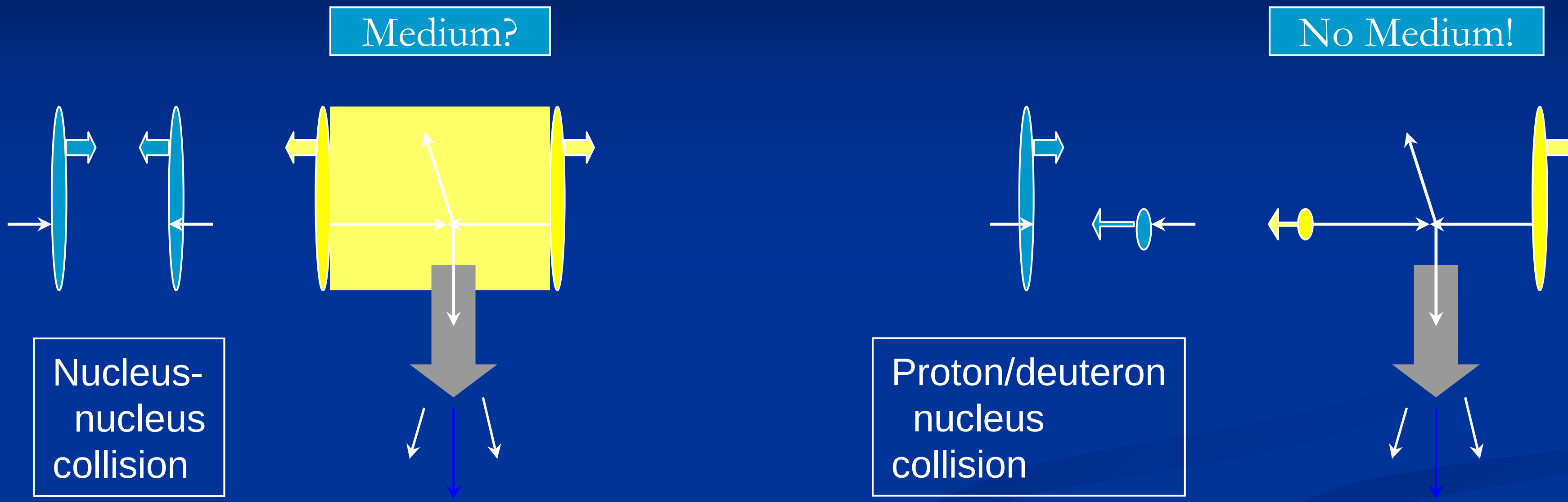




- Color Glass Condensate
- Gluon fusion reduces number of scattering centers in initial state.
- Theoretically attractive; limits DGLAP evolution/restores unitarity

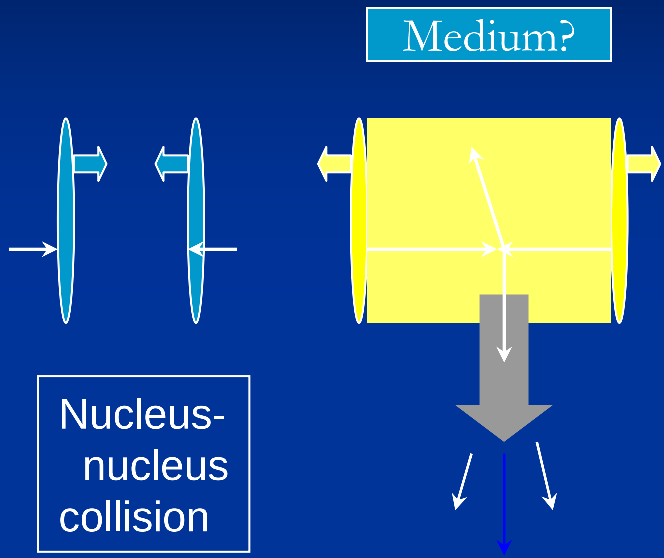


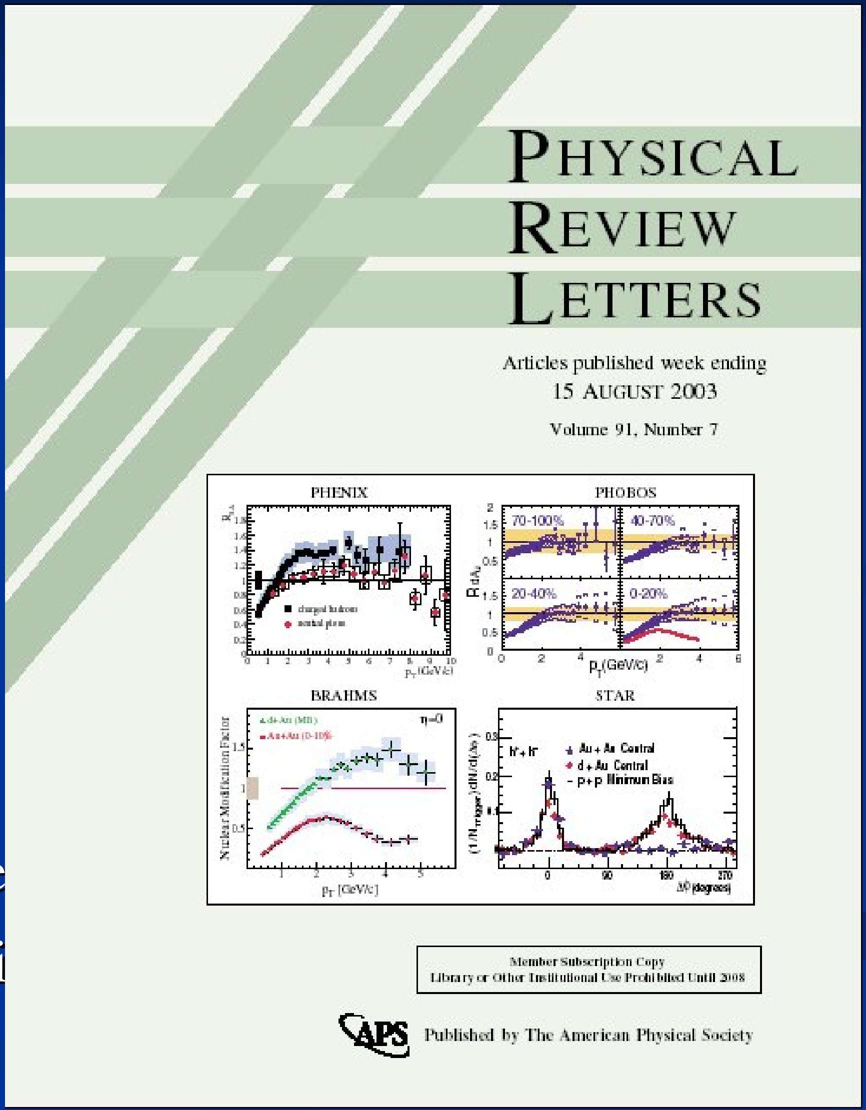
Control Experiment



- Collisions of small with large nuclei quantify all cold nuclear effects.
- Small + Large distinguishes all initial and final state effects.

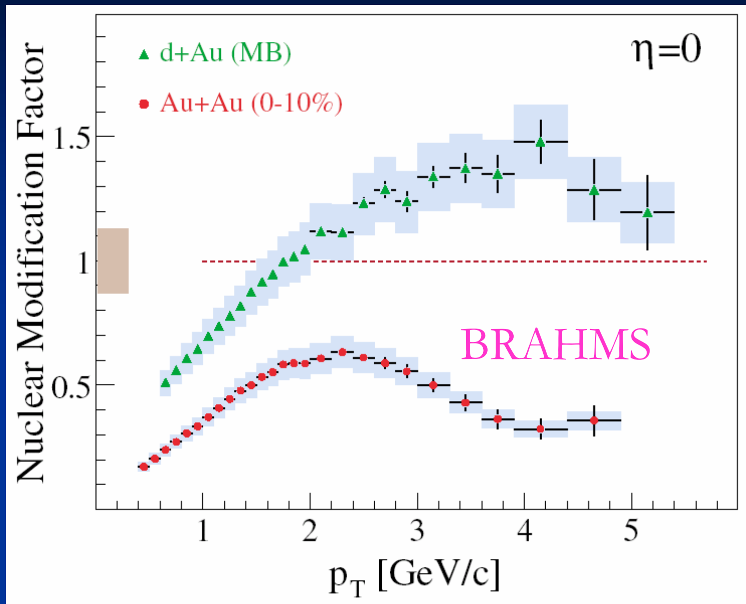
Control Experiment

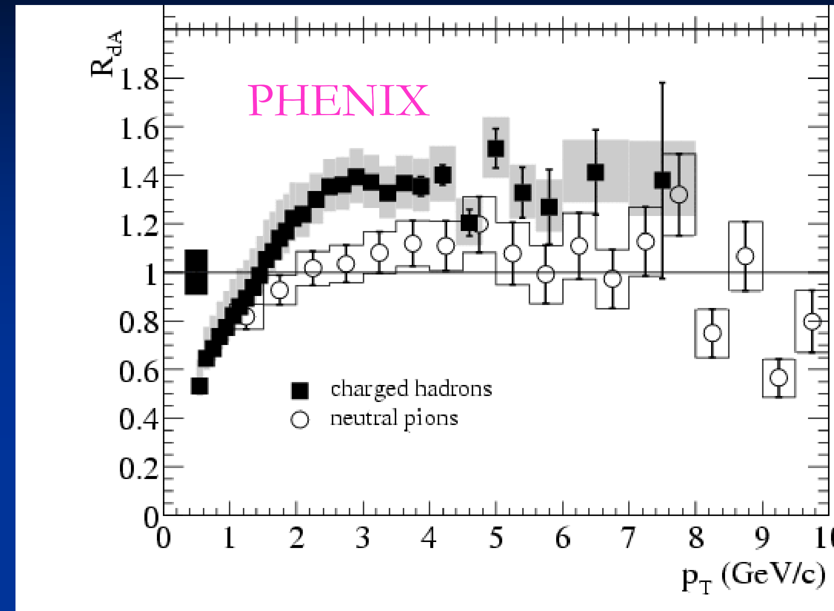


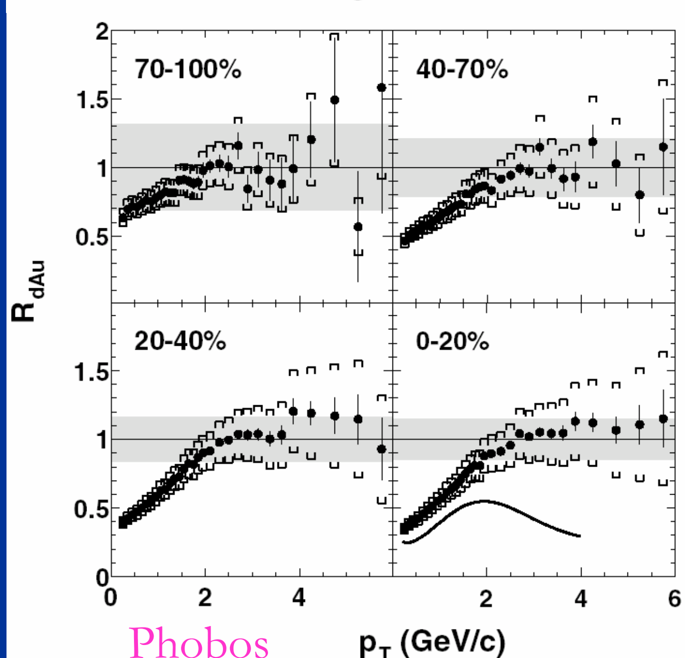


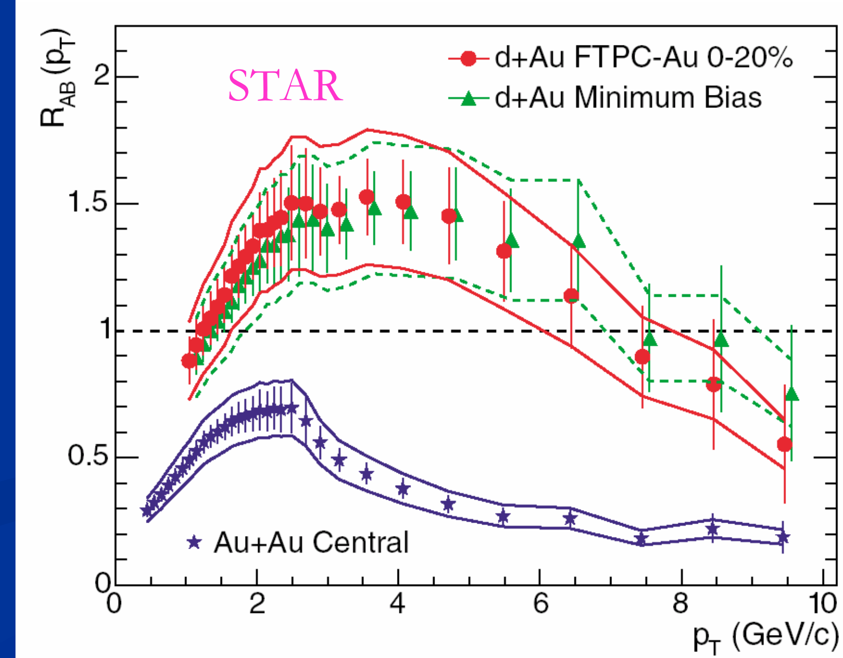
- Collisions of small with large nucle
- Small + Large distinguishes all initi

NO suppression in d+Au!



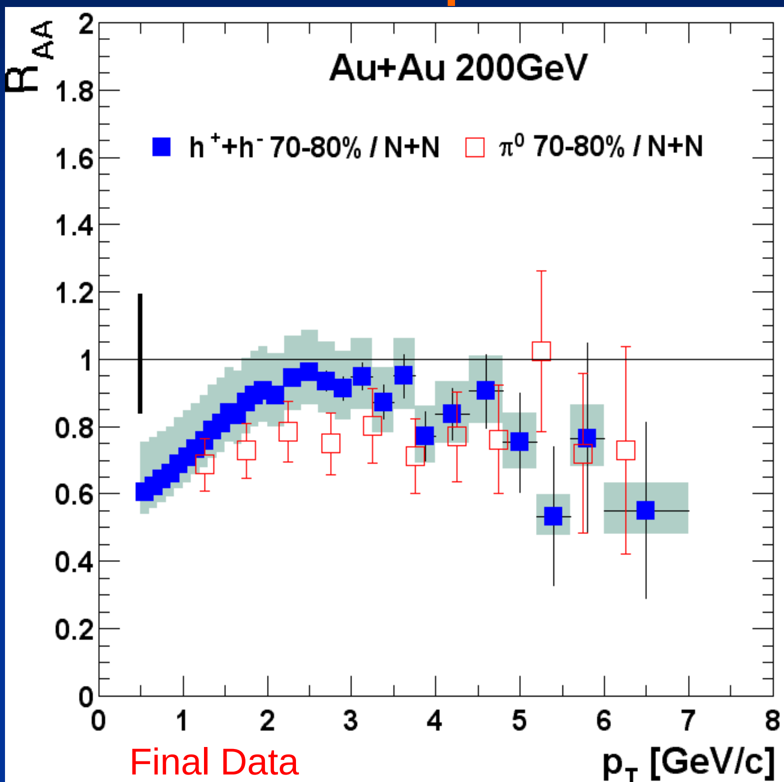


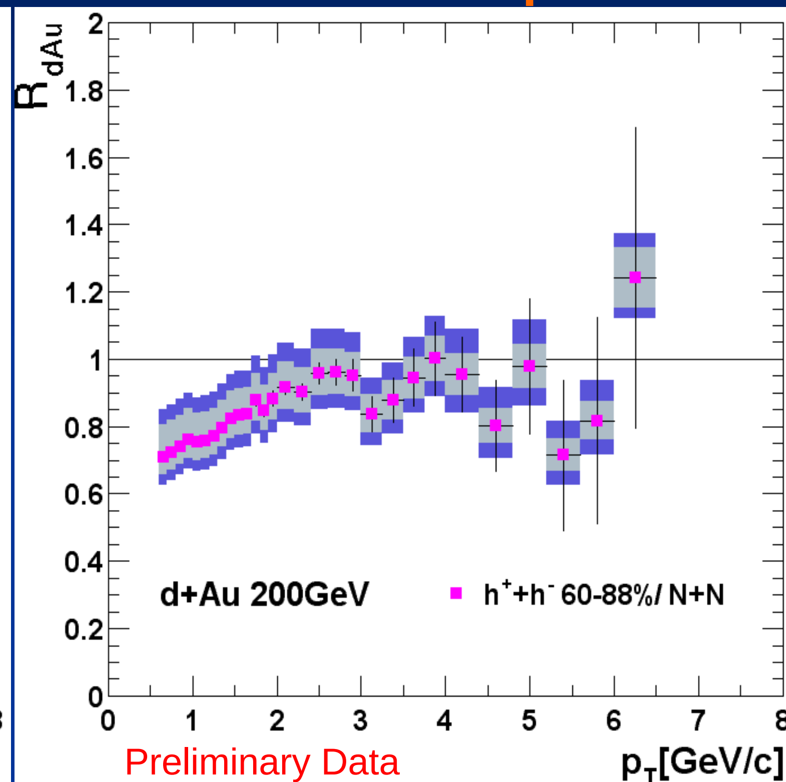




Centrality Dependence

Au + Au Experiment | **d + Au Control Experiment**

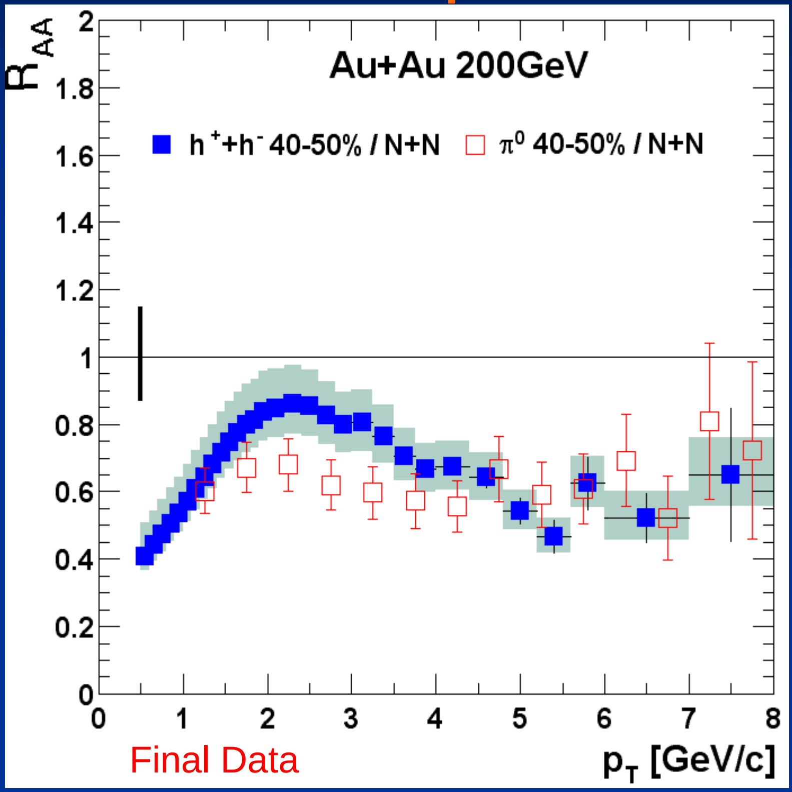




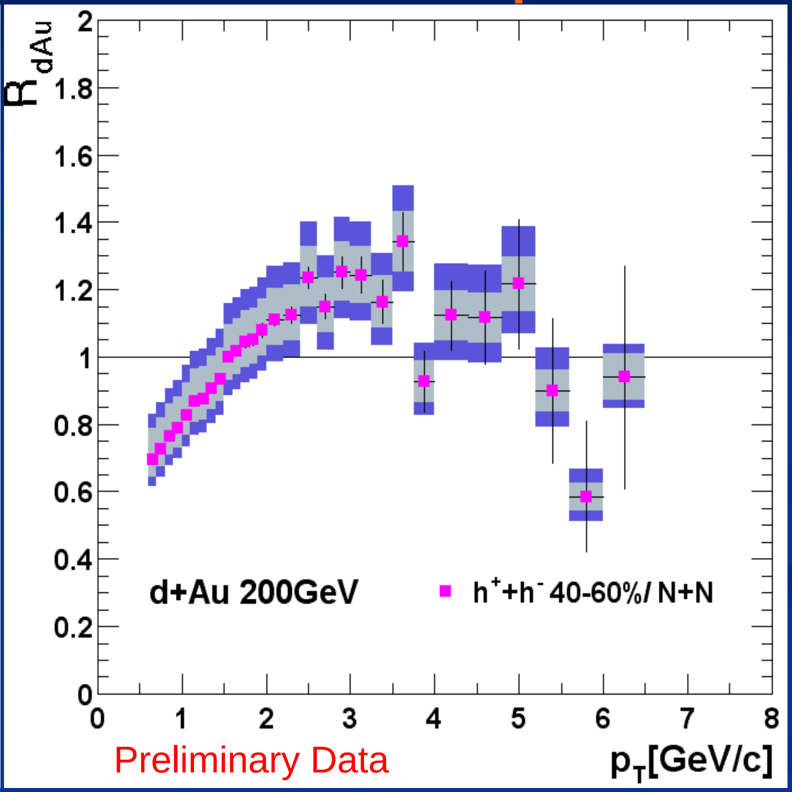
- Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.
- Jet Suppression is clearly a final state effect.

Centrality Dependence

Au + Au Experiment



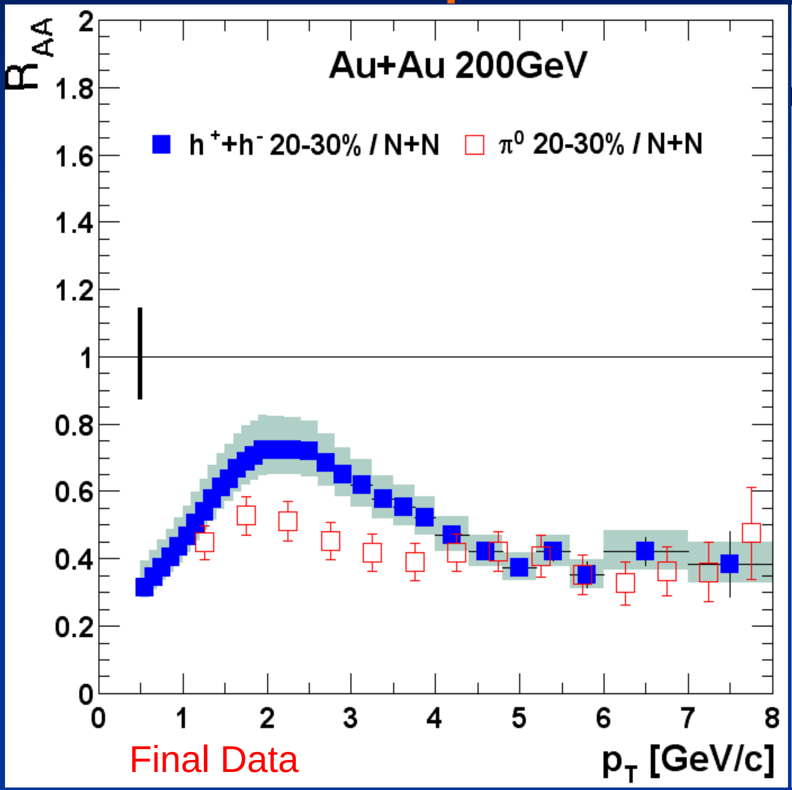
d + Au Control Experiment



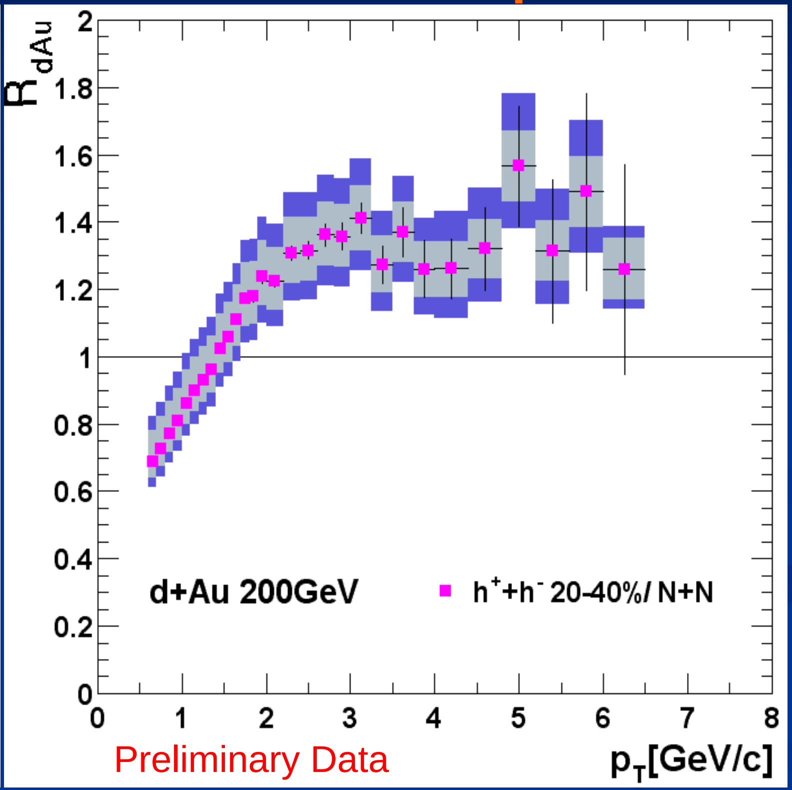
- Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.
- Jet Suppression is clearly a final state effect.

Centrality Dependence

Au + Au Experiment



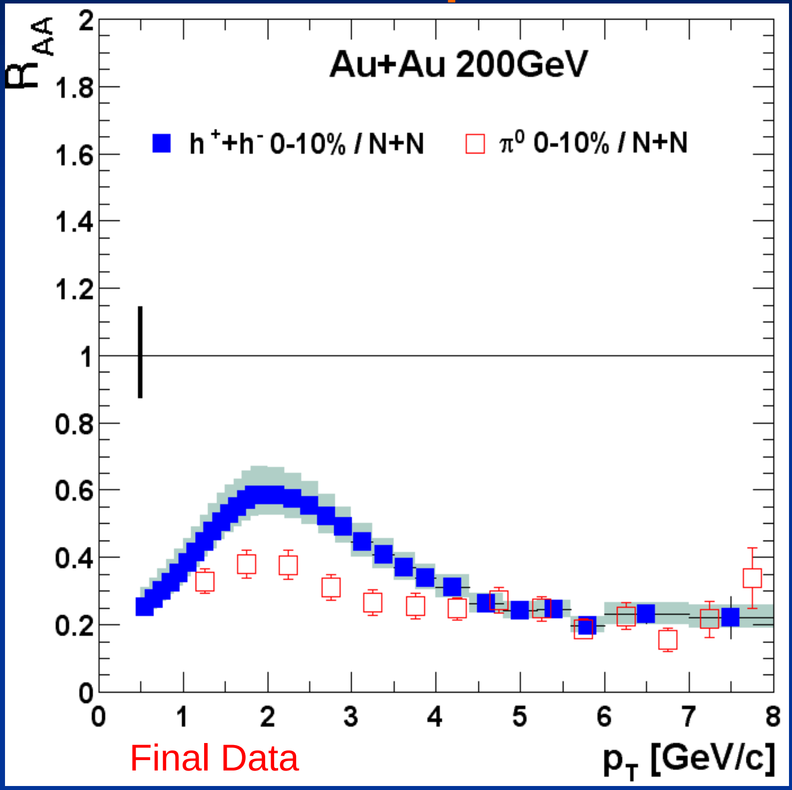
d + Au Control Experiment



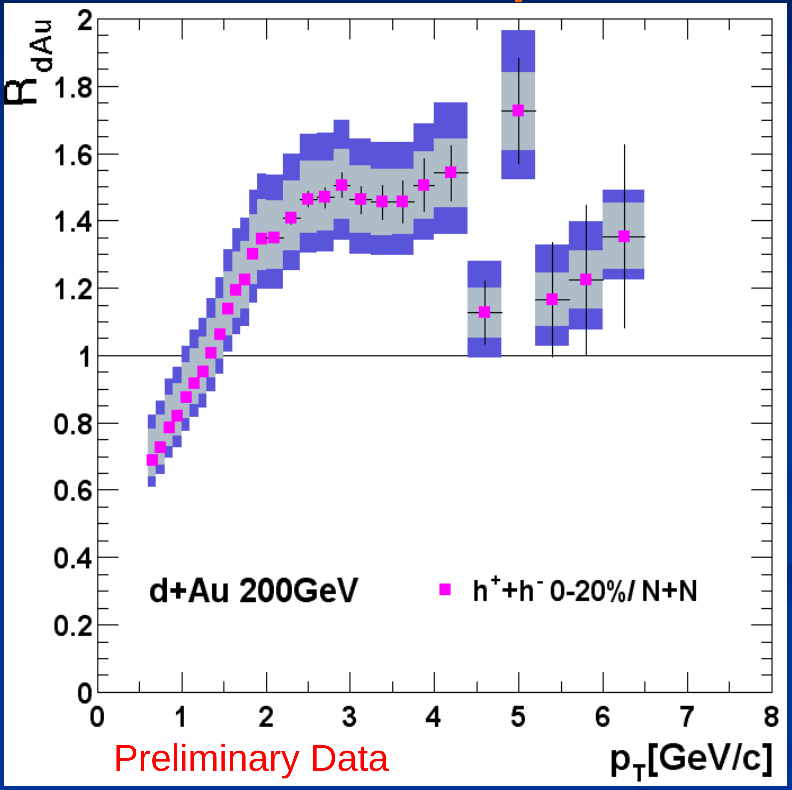
- Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.
- Jet Suppression is clearly a final state effect.

Centrality Dependence

Au + Au Experiment



d + Au Control Experiment



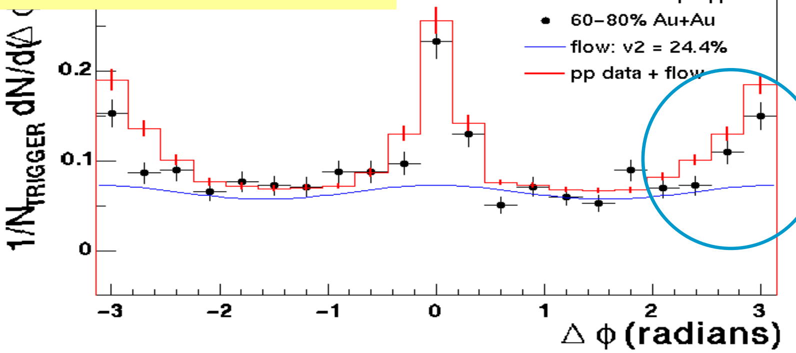
- Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.
- Jet Suppression is clearly a final state effect.

Jet Tomography

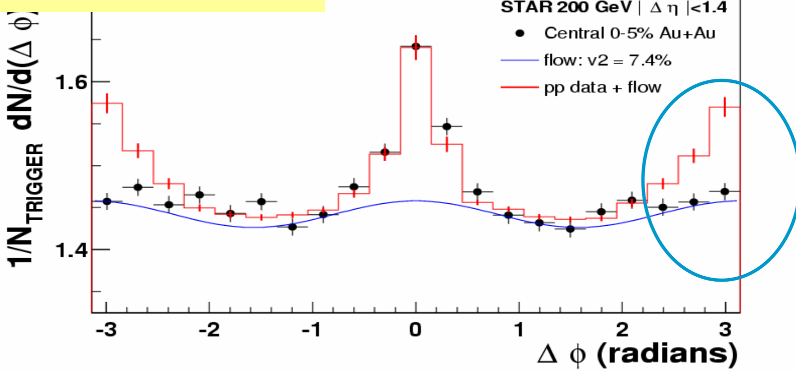
- Moving forward from high p_T suppression to real tomography requires several steps:
  - Map the dynamics of Near-Side and Away-Side jets.
  - Study the composition of the jets.
  - Vary the reaction plane orientation.
  - Account for momentum balance.
- Technical Challenges in separation of harmonic flow from jet contributions to angular correlations.

Back-to-back jets

Peripheral Au + Au

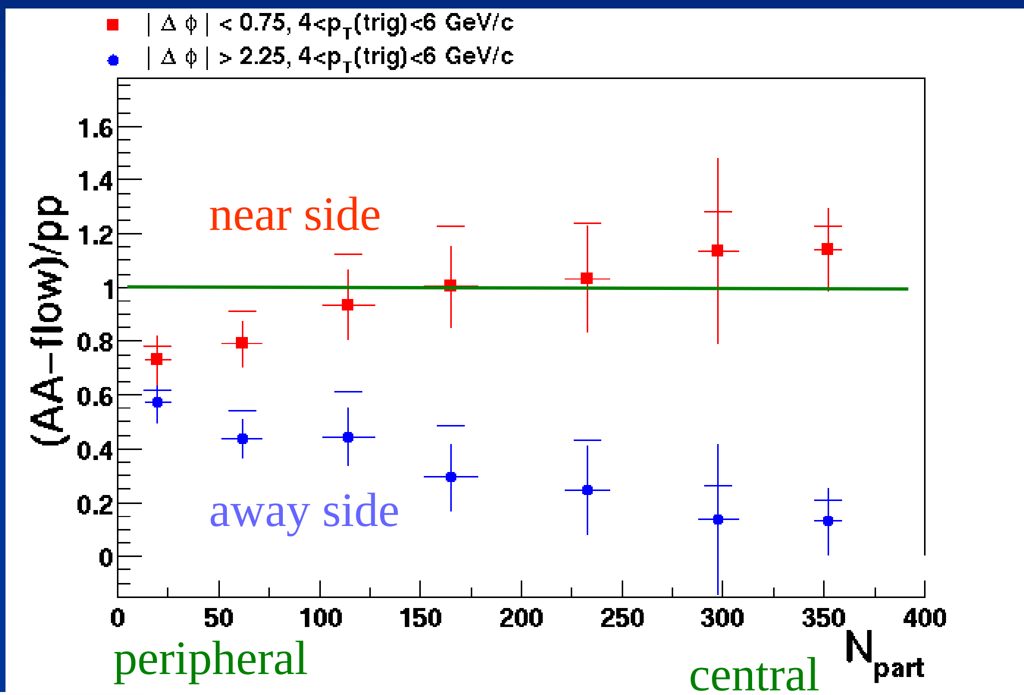


Central Au + Au

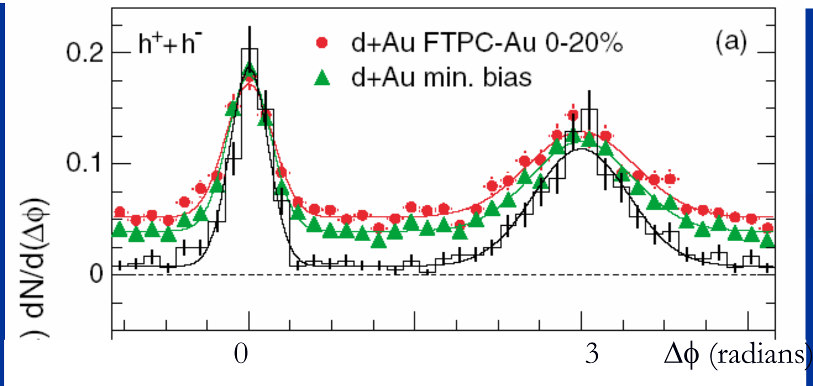


STAR PRL 90, 082302 (2003)

$$D_2(Au+Au) = D_2(p+p) + B(1+v_2^2\cos(2\Delta\phi))$$



d + Au control



- Away-side obviously sensitive to precise v_2 value.
- Desire precision technique to disentangle

Two-Part Correlation Functions wrt Reaction Plane

- Formulate two-particle correlation in two cases:
  - Trigger particle in reaction plane.
  - Trigger particle out of reaction plane.
- Harmonic component changes sign!
- Determine amplitude of harmonic by equalizing near side jets

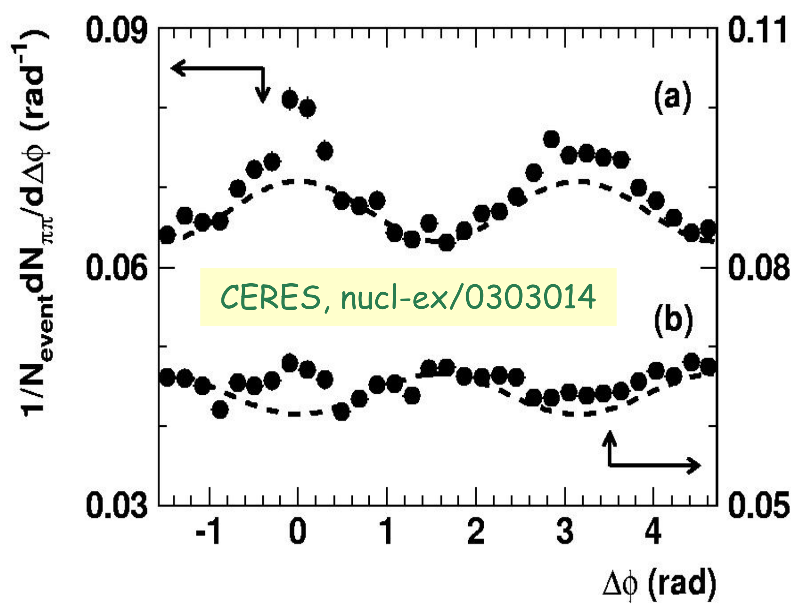
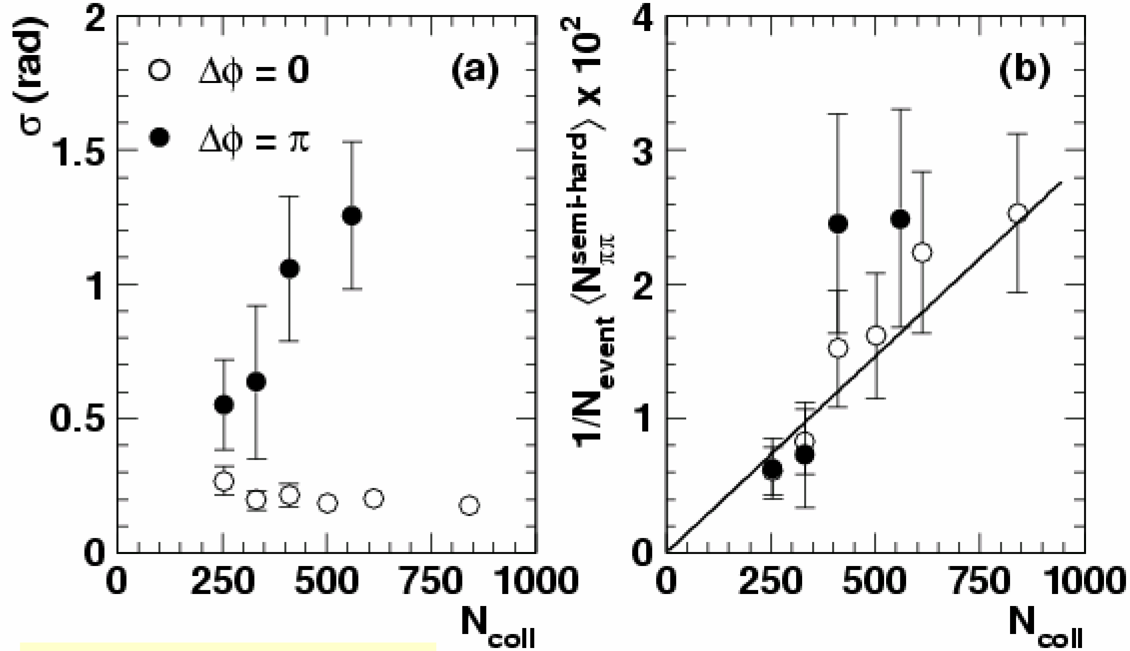


FIG. 5: In-plane (a) and out-of-plane (b) two-pion opening angle distributions. Dashed lines are calculated for pure elliptic flow as measured by the EP method and corrected for HBT correlations. Data are for centrality 15-30%, $p_T \geq 1.2$ GeV/c, a cut on $\Delta\theta \geq 20$ mrad, and are efficiency corrected. Observe different ordinates as indicated by arrows.

see also: J. Bielcikova, P. Wurm, K. Filimonov, S. Esumi, S.V. nucl-ex/0311007

Apparent yield loss attributed to broadening!!

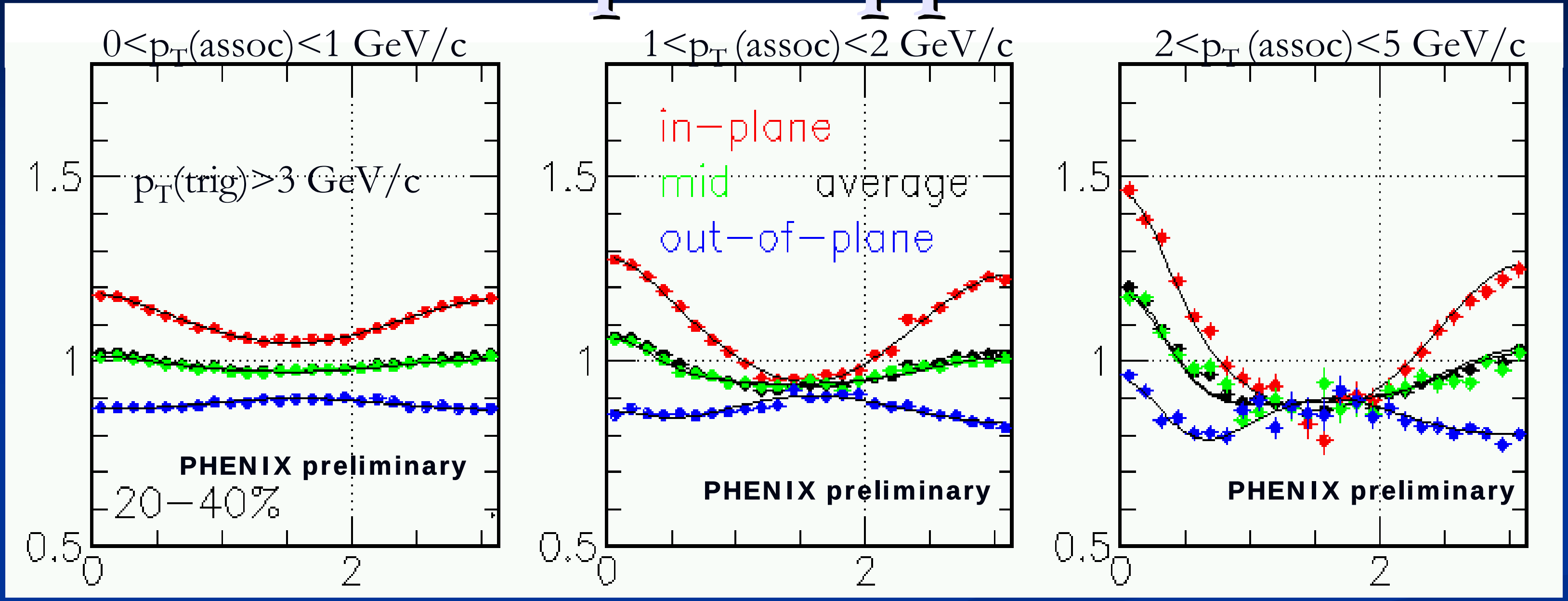
- Significant broadening of away-side peak nearly exactly compensates for height reduction.
- Away-side and near side yields exhibit binary scaling.

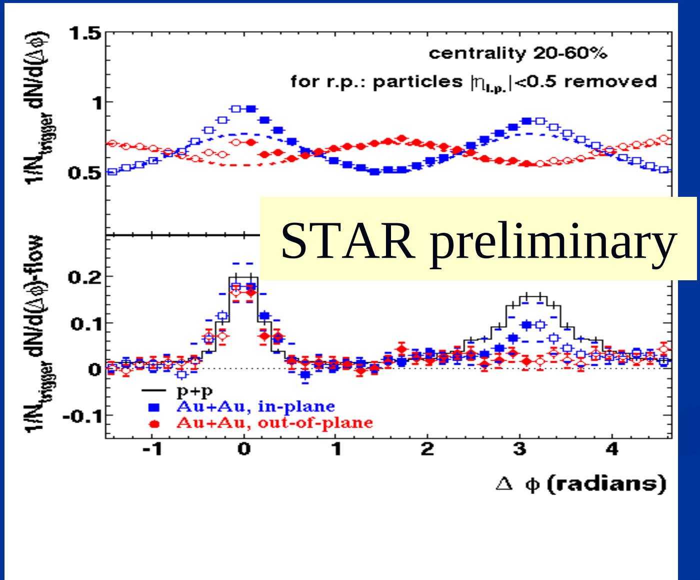


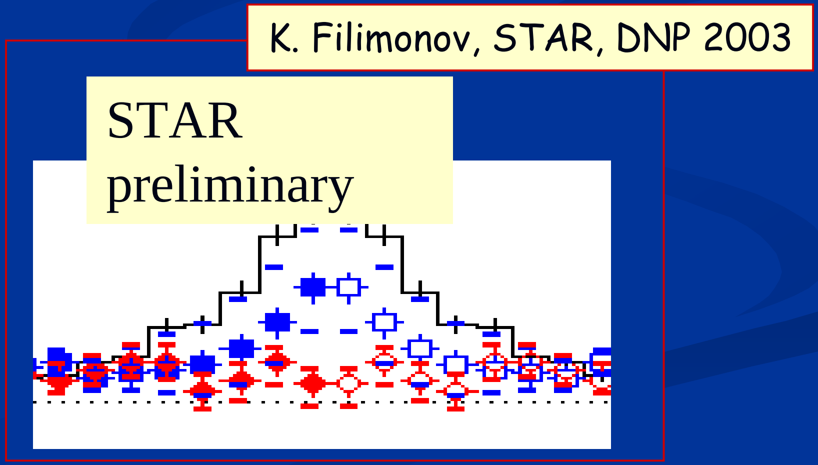
CERES, nucl-ex/0303014

FIG. 4: Centrality dependence of the Gaussian widths of the correlation peaks at $\Delta\phi = 0, \pi$ (a) and of the areas under the Gaussian peaks, both from fits (b). The loss in pair acceptance due to the cut $\Delta\theta \geq 20$ mrad has not been corrected.

Similar Techniques Applied at RHIC

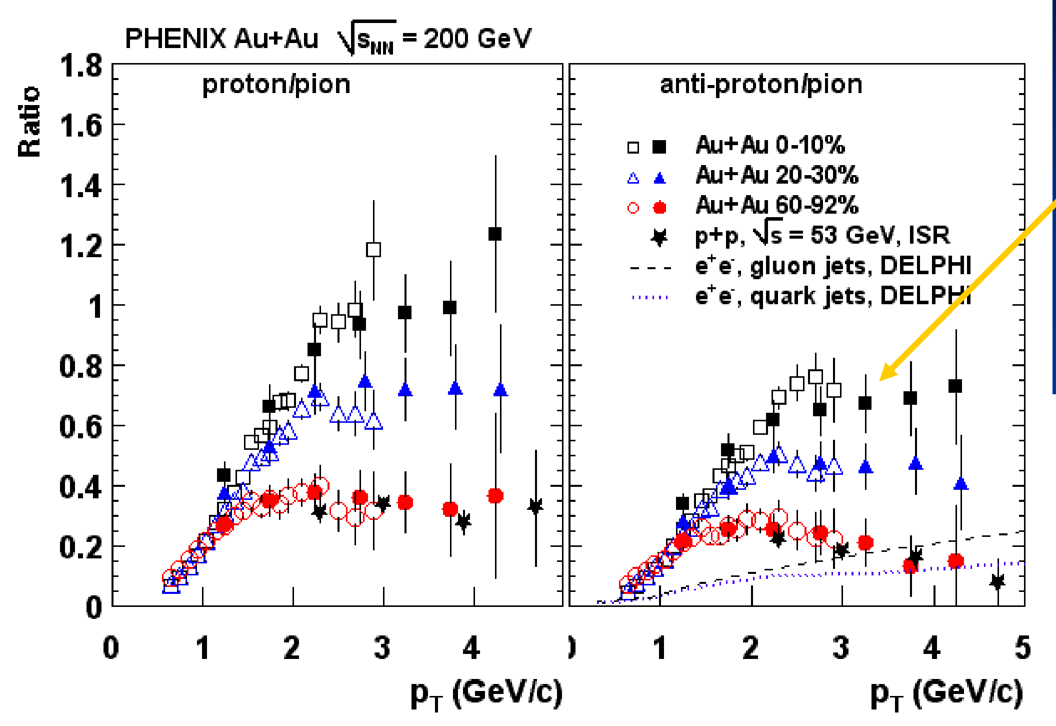






Particle composition

nucl-ex/0305036 (PRL)



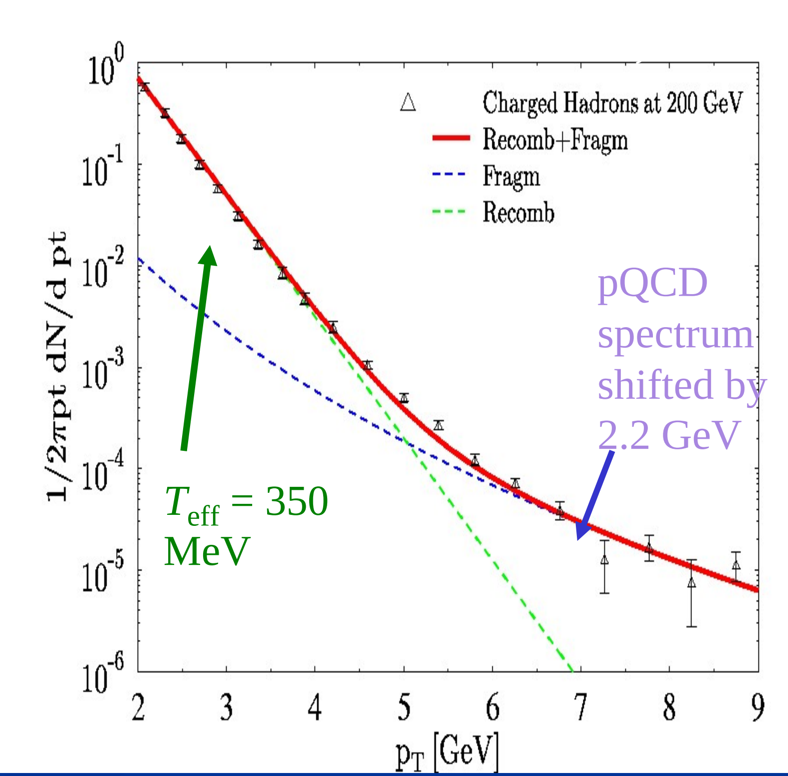
p/π ~1 at high p_T in central collisions

Higher than in p+p or jets in e+e-

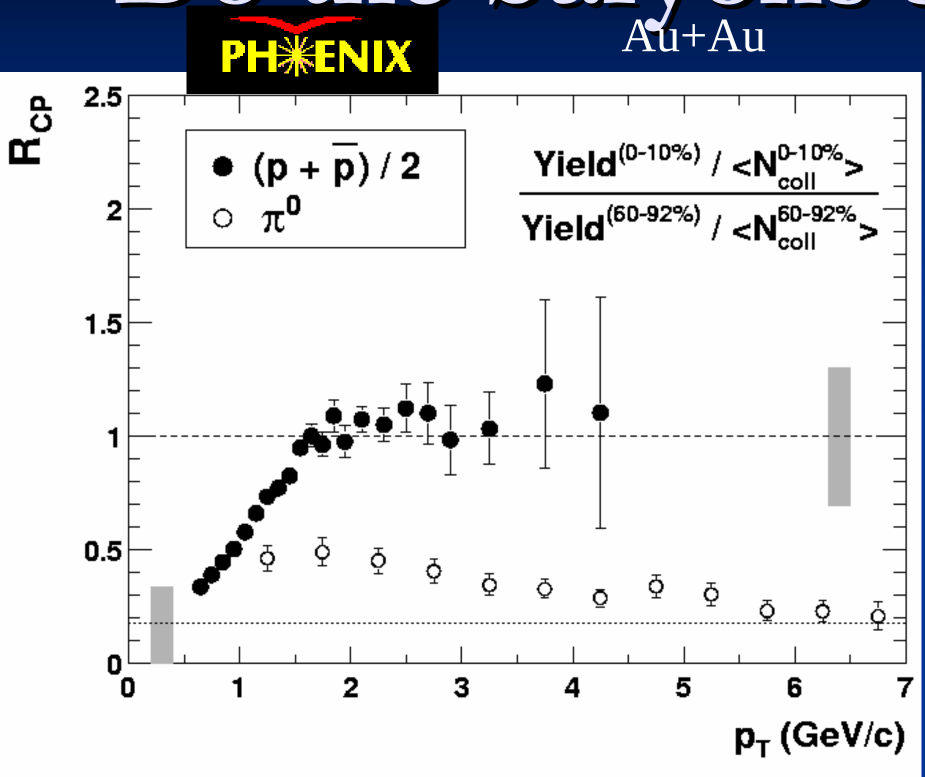
Hydro. expansion at low p_T + jet quenching at high p_T:

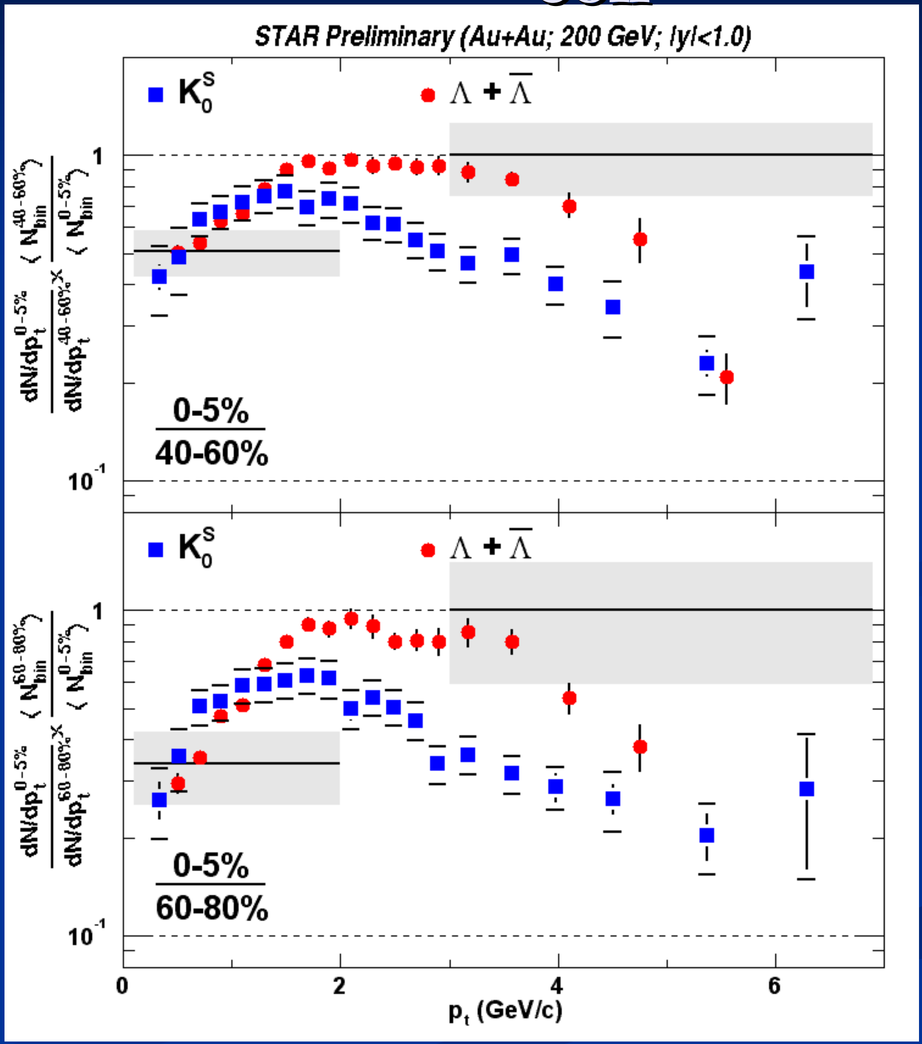
Recombination of boosted q's?

Modified fragmentation function INSIDE the medium?



Do the baryons scale with N_{coll}?





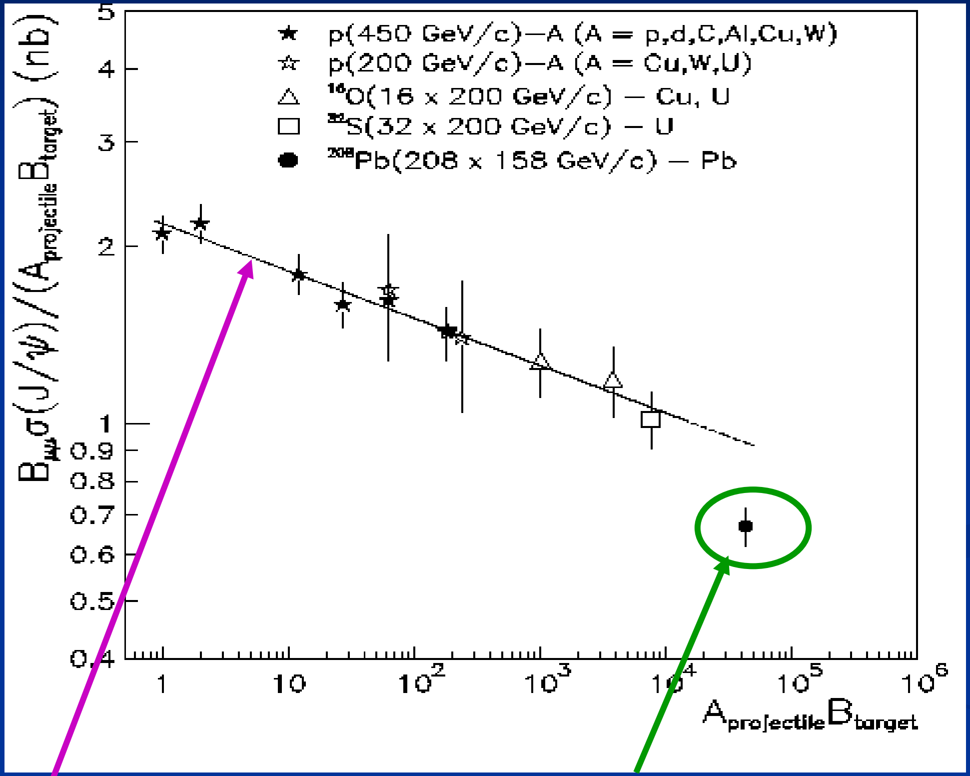
Baryon yields *not* suppresed

$\propto N_{coll}$ at $p_T = 2 - 4$ GeV/c

Unlikely that energy loss is affected by subsequent fragmentation!

J/Ψ suppression was observed at CERN at √s=18 GeV/A

J/Ψ
yield



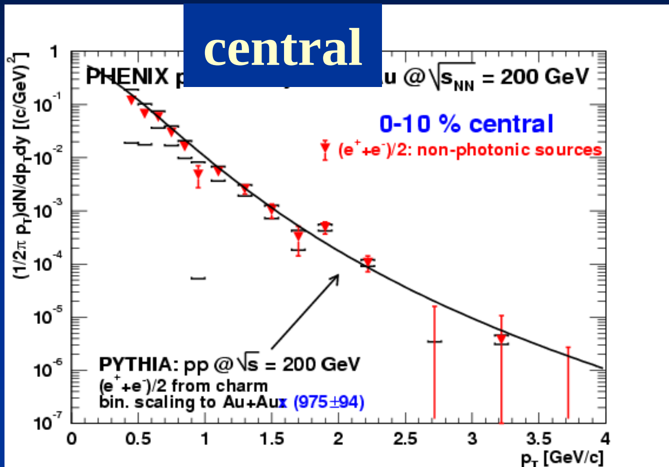
NA50 collaboration

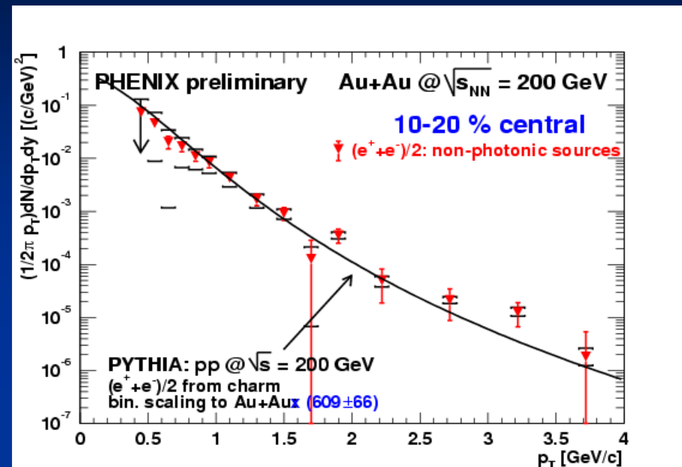
- Complementary baseline measurement is open charm rate.
- NA60 has had a very successful run designed specifically to answer the question.

Fewer J/Ψ in Pb+Pb than expected!
Interpret as color screening of c-cbar by the medium

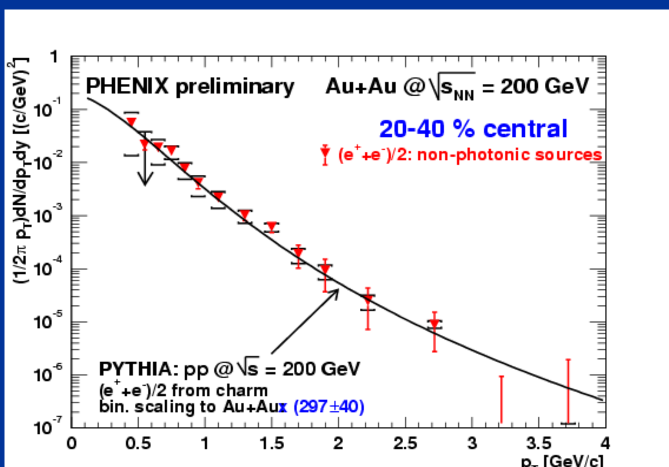
Initial state processes affect J/Ψ too so interpretation is still debated...

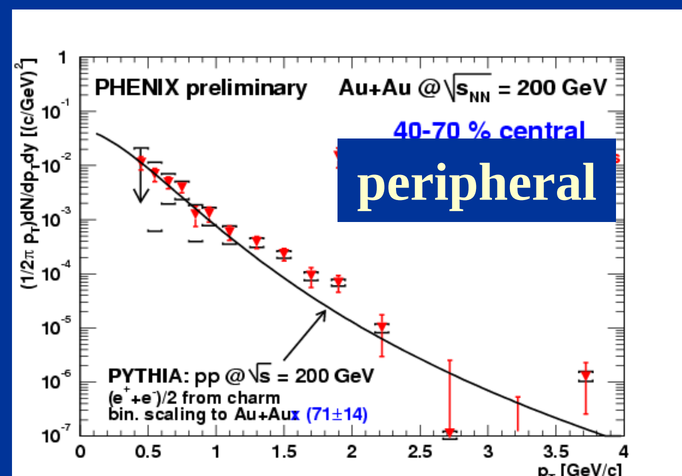
Centrality dependence of open charm in Au+Au





Compare to (PYTHIA) an event generator tuned for pp collisions…





no large suppression- unlike light quarks!

Spectra of electrons from c→ e± + anything photonic sources are subtracted

Comparison to pp should be available this week.

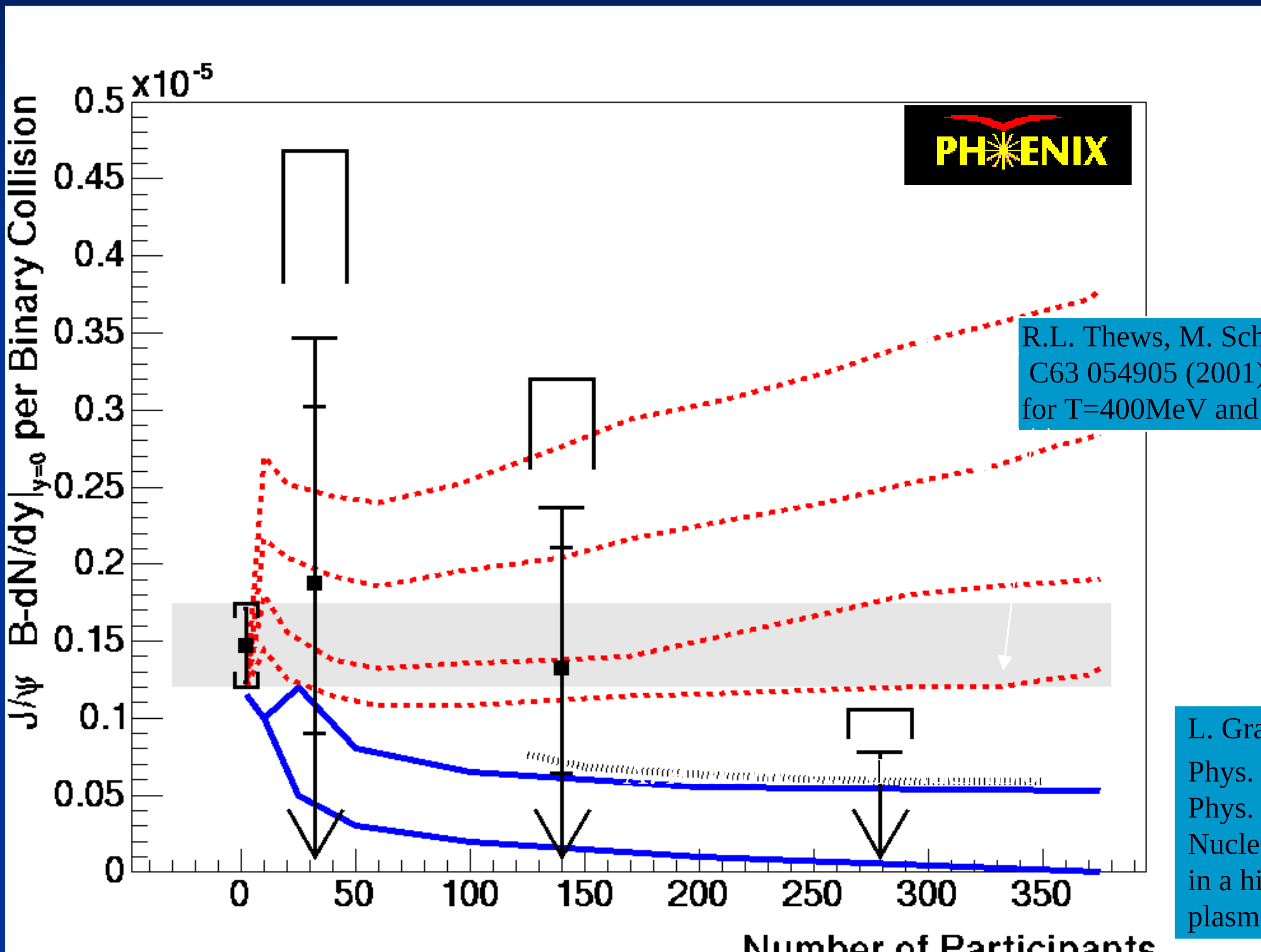
Why no energy loss for charm quarks?

- "dead cone" predicted by Kharzeev and Dokshitzer, Phys. Lett. B519, 199 (1991)
- Gluon bremsstrahlung:
  - $k_T^2 = \mu^2 t_{form}/\lambda$ transverse momentum of radiated gluon
  - $\mu = p_T$ in single scatt. λ = mean free path
  - $\theta \sim k_T / \omega$ ω = gluon energy
- But radiation is suppressed below angles $\theta_0 = M_q/E_q$
  soft gluon distribution is
  $dP = \alpha_s C_F/\pi \, d\omega/\omega \, k_T^2 \, dk_T^2/(k_T^2 + \omega^2 \theta_0^2)^2$
- Fully stopped in *FLOWING* medium (S. Batsouli, S.Kelly, M.Gyulassi, J.Nagle Phys.Lett. B557 (2003) 26-32)

J/Ψ: Is there deconfinement at RHIC?

Does colored medium screen c+cbar?

nucl-ex/0305030



R.L. Thews, M. Schroedter, J. Rafelski Phys. Rev. C63 054905 (2001): Plasma coalesence model for T=400MeV and y_{charm}=1.0,2.0, 3.0 and 4.0.

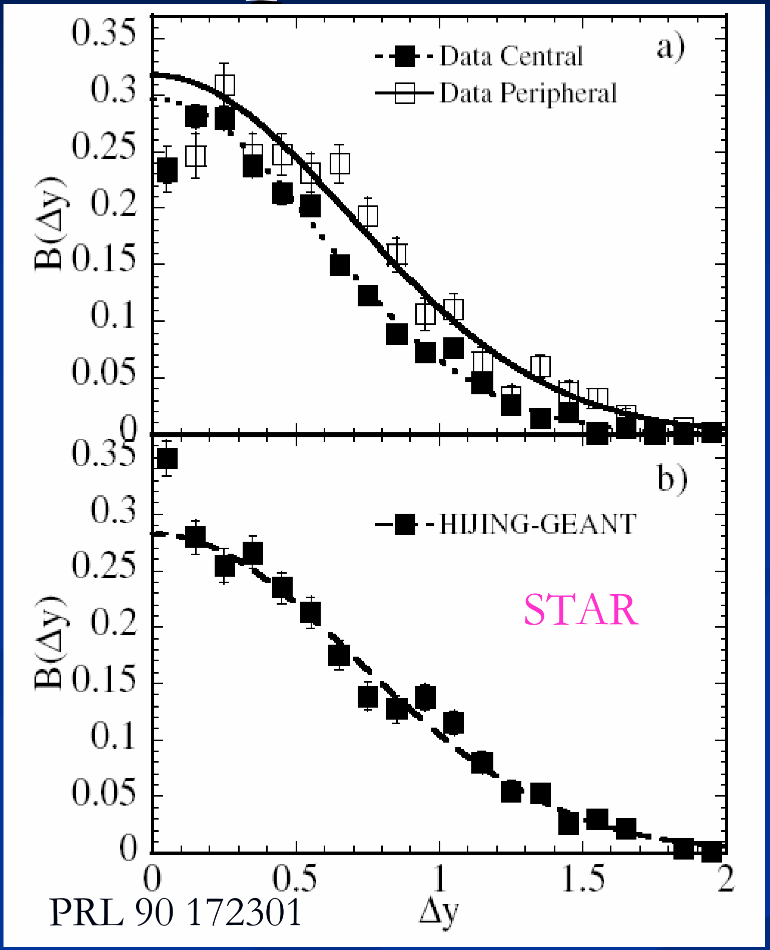
L. Grandchamp, R. Rapp Nucl. Phys. A&09, 415 (2002) and Phys. Lett. B 523, 50 (2001): Nuclear Absorption+ absoption in a high temperature quark gluon plasma

Need run 4 data to determine J/Psi fate.

IRONY: Baseline is ready!

Jet Story—Future Developments

- Quantify near and far jet in terms of widths and full yields.
- Measure PID content of JET (not simply high p_T)
- Account for momentum balance:
  - By momentum conservation a jet cannot "disappear", it's momentum balance must appear in the final state.
  - Not such a small needle in our haystack.
- NEED CONTROL (direct gamma)

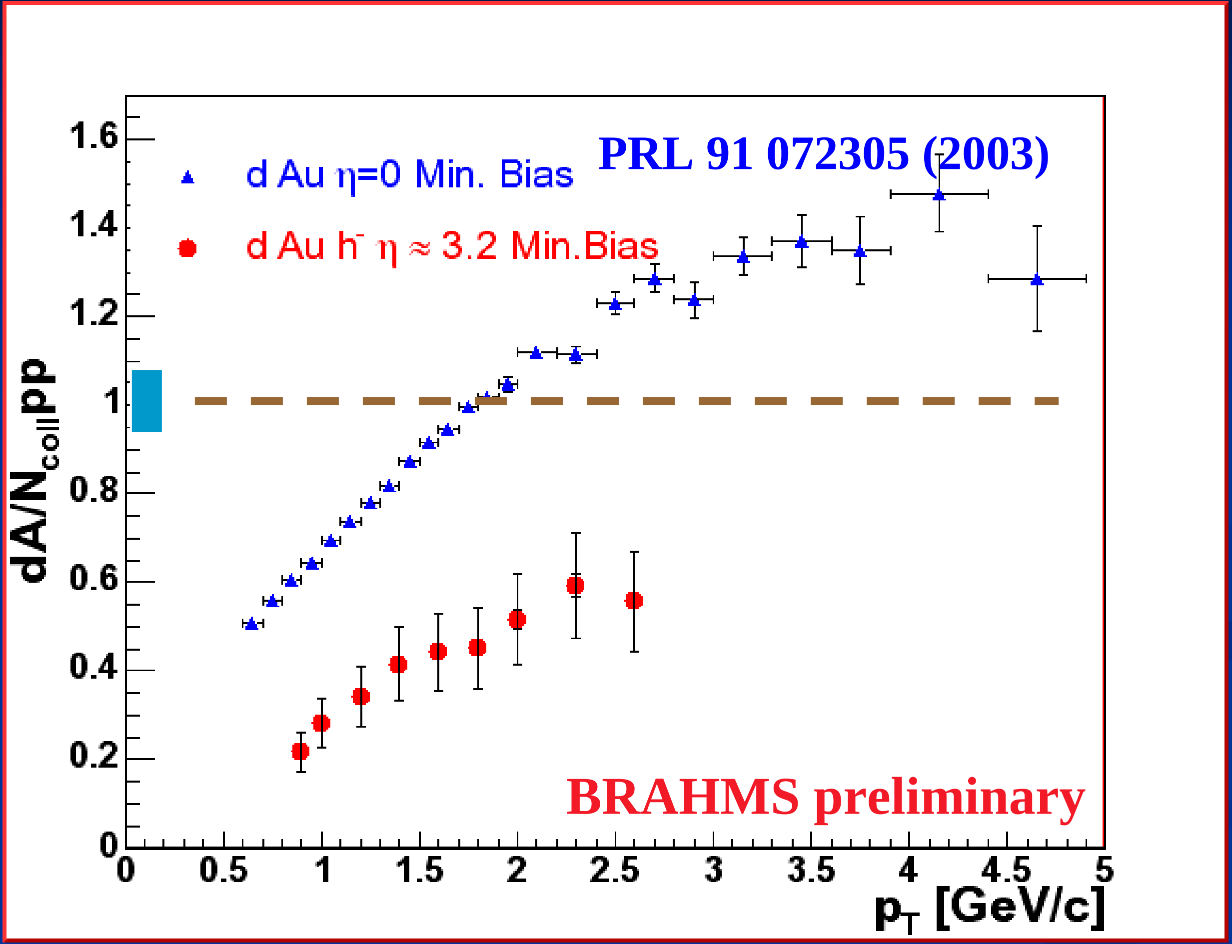


Balance Function finds SINGLE associated particle in central AuAu

Is the CGC dead?

- NO. The arguments for gluon saturation are very solid theoretically.
- The results from mid-rapidity and high p_T have certainly been proven to utilize a high enough x range that the gluon saturation effects are not significant.
- Nonetheless when probed at sufficiently low-x the the Au wave function should exhibit saturation (fewer scattering centers).
- Collisions involving a low-x parton from Au and a high-x parton from d, will be highly forward focussed:
  - Prediction $R_{AA}<1$ at high forward rapidity.

BRAHMS results:



- Qualitative agreement with CGC tendencies.
- Also qualitative agreement with shadowing.
- Look for quantitative results from all RHIC experiments.

The medium itself is also instructive

- Pioneering work at AGS/SPS energies into thermal descriptions (Braun-Munzinger, Stachel, Redlich, Heinz, many others…) produces simple, few parameter models that successfully describe particle ratios and spectra at all measured energies.
- There exists a stunning wealth of excitation function data accumulated recently at SPS that is simply too broad and rich to give justice to in this short summary.
- Recent improvements in Coulomb correction (so-called partial coulomb correction) help to resolve R_{out}/R_{side} puzzle.

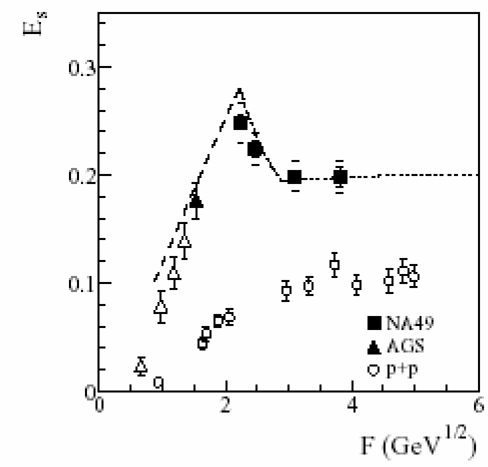


Figure 6: Dependence of the strangeness to pion ratio E_s on the collision energy $F \approx s^{1/4}$ (see text). Also shown is the expectation within the Statistical Model of The Early Stage (lines).[10]

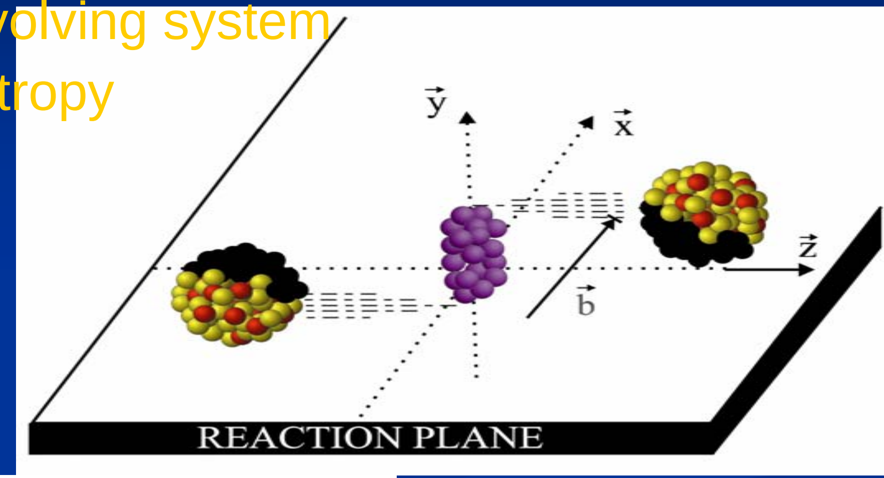
• One plot that has generated intrigue and controversy concerns the excitation function of the K+/π+ excitation function.

•Is it more than the shift of the production mechanism from Λ-associated production to direct pair production?

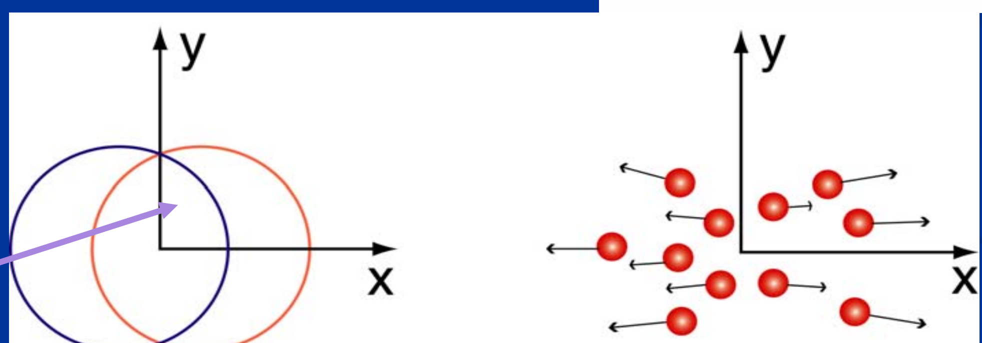
Pressure? “elliptic flow” barometer

Origin: spatial anisotropy of the system when created, followed by multiple scattering of particles in the evolving system

spatial anisotropy $\rightarrow$ momentum anisotropy



v_2: 2nd harmonic *Fourier coefficient* in azimuthal distribution of particles with respect to the reaction plane



Almond shape overlap region in coordinate space

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

$$v_2 = \langle \cos 2\phi \rangle$$

$$\phi = \operatorname{atan} \frac{p_y}{p_x}$$

Now the jet is the background

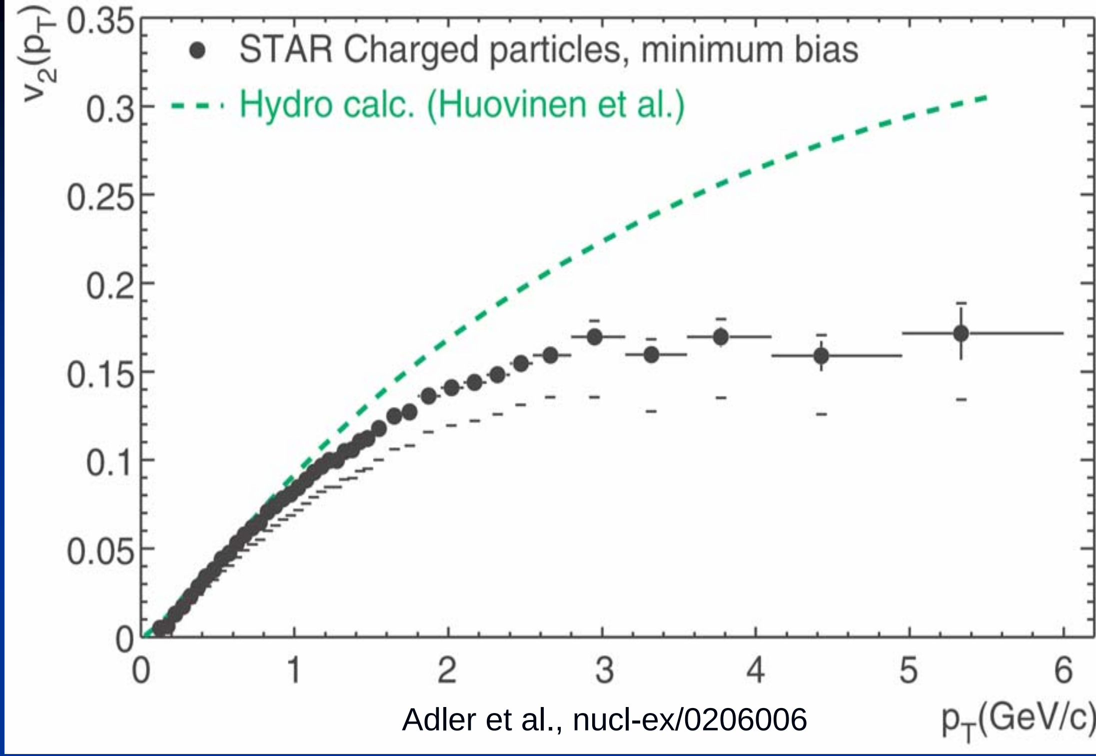
- Many advances in technique to verify that indeed collective motion is NOT an artifact of other correlations:
  - Cumulant analysis. (Ollitrault)
  - Multiplicity Independent Moments (Voloshin)

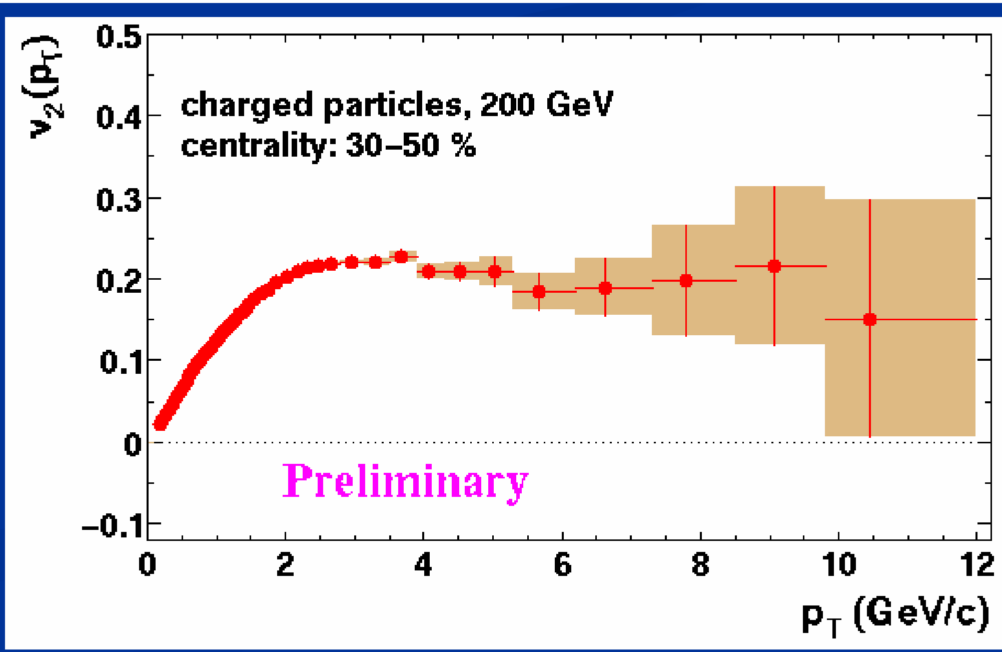
$$\langle u_b Q^* \rangle^{AA} \approx v_b v_p M^{AA} + \langle u_b Q^* \rangle^{pp}$$

- Flow is indeed collective.
- Amazing fact is how strong is the flow.

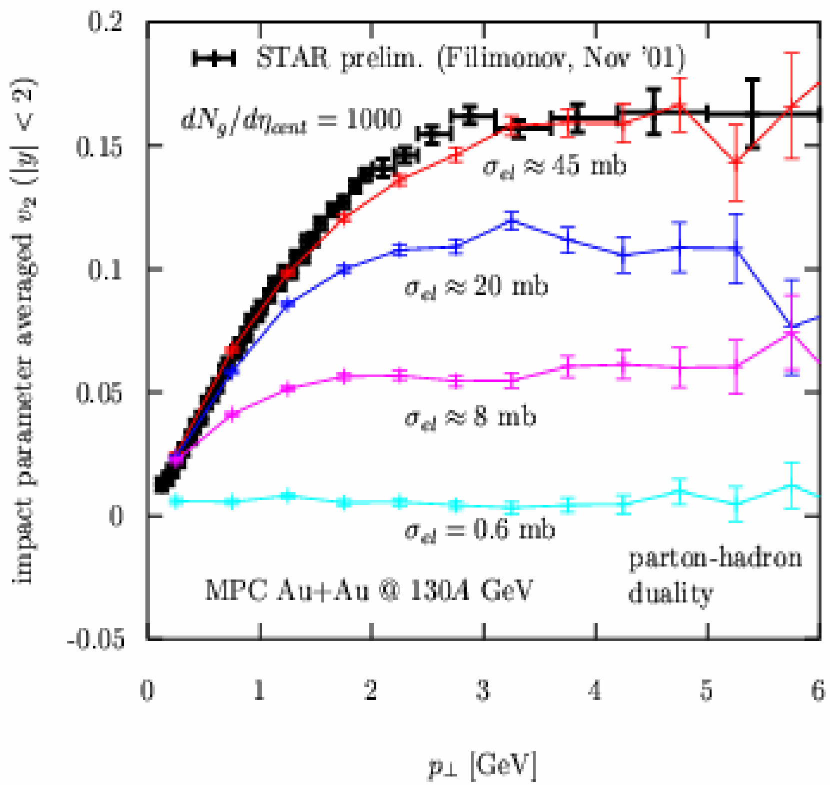
Large v_2

- Hydrodynamic limit exhausted at RHIC for low p_T particles.
- Can microscopic models work as well?
- Is this a consequence of jet suppression?
  - NO, measured v_2 even in excess of "Geometrical Almond" limit (Shuryak).





What is needed to reproduce magnitude of v_2?



parton transport solutions via MPC 1.6.0 [D.M. & Gyulassy, NPA 697 ('02)]

$$p^\mu \partial_\mu f_i = S_i + C_i^{2\to 2}[f] + \ldots$$

minijet initial conditions

$1g \to 1\pi$ hadronization

Huge cross sections!!

- **saturation pattern can be reproduced with elastic $2 \to 2$ interactions,**

  requires large opacities $\sigma_{el} \times dN_g/d\eta \approx 45000$ **mb** $\gg$ **pQCD** (3 **mb** $\times 1000$)

  - large opacities also suggested by pion HBT data [D.M & Gyulassy, nucl-th/0211017]

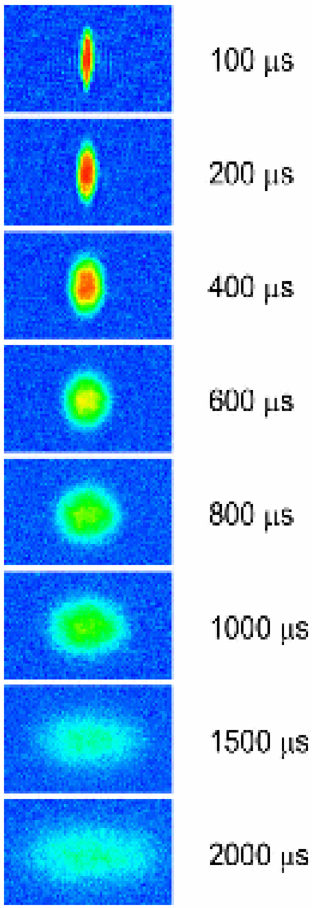
How to get 50 times pQCD σ?

- We suspect that hadrons don't all melt at Tc
  - π, σ survive as resonances *Schaefer & Shuryak, PLB 356 , 147(1995)*
  - η_c bound at 1.5 Tc *Asakawa & Hatsuda, hep-lat/0309001*
  - charmonium bound states at T>Tc *Karsch*
- all q,g have thermal masses at high T, maybe α_s keeps running up at T>Tc (Shuryak and Zahed)
  - would cause strong rescattering qqbar ⇔ meson
- Huge cross section causes pressure and elliptic flow
  - Same phenomenon observed in trapped Li atoms

Elliptic flow with trapped Li^6 atoms:

K.M.O'Hara et al, Science 298,2179, 2002

T.Bourdel et al, PRL 91 020402 , July 11 2003



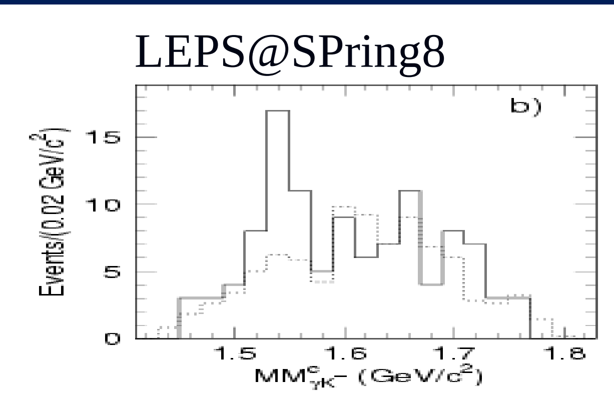
Magnetic field $B \sim 800G$ shifts (via the Feschbach resonance $|f = 1/2, m_f = 1/2 > <=> |f = 1/2, m_f = -1/2 >$) and makes the 38-th vibrational Li_2 state to exactly zero energy => infinite scattering length a, very large size and lifetime ~ 1 sec.

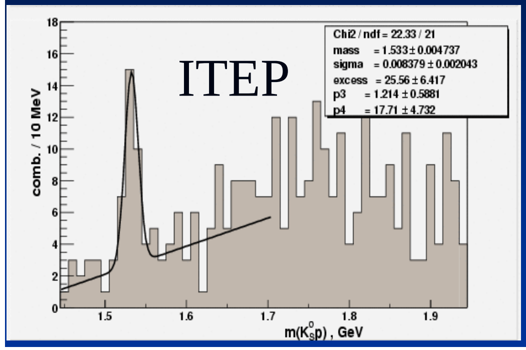
Normally gas is transparent, $l \ll L$, and expands without collisions isotropically

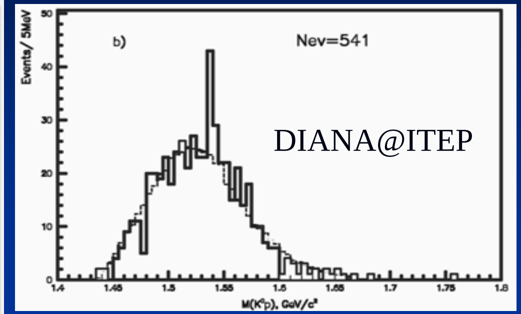
But in the strong coupling regime $l \ll L$ it explodes hydrodynamically !, see the figure

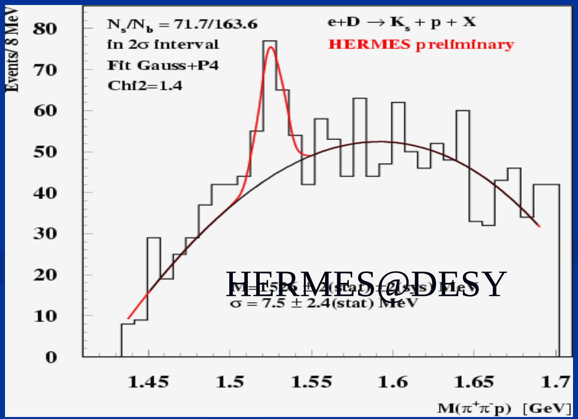
Cross section can be changed by many orders of magnitude, but the EoS changes by $\sim 20\%$ only ! (like in QGP and CFT... why?)

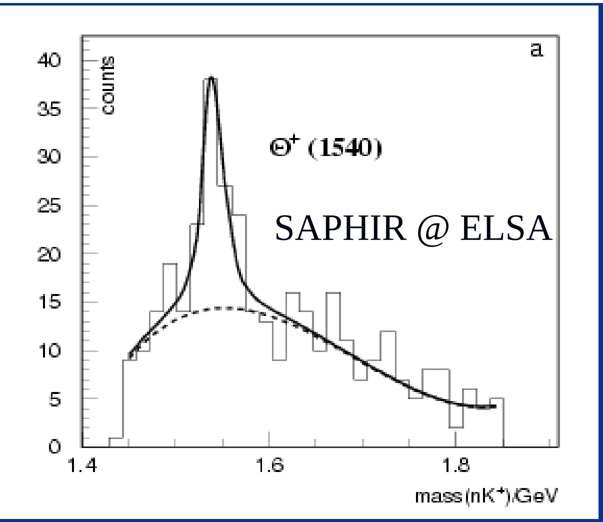
NA49 results on exotic quark states

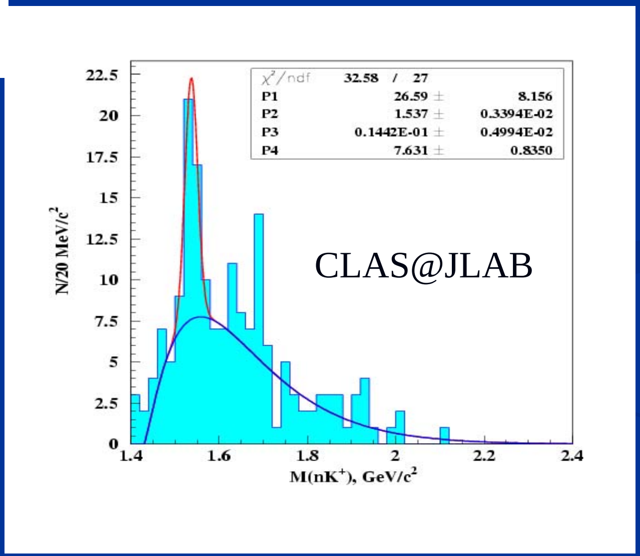






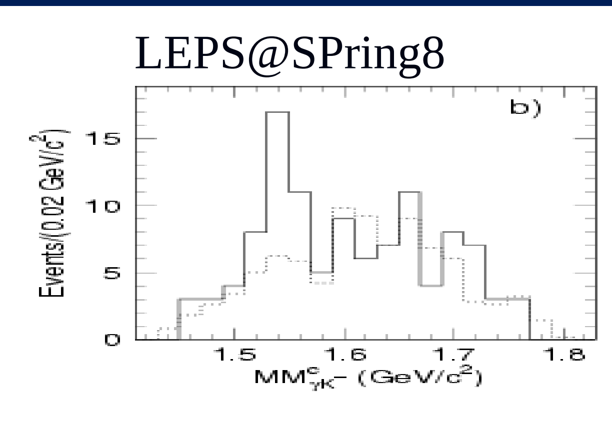


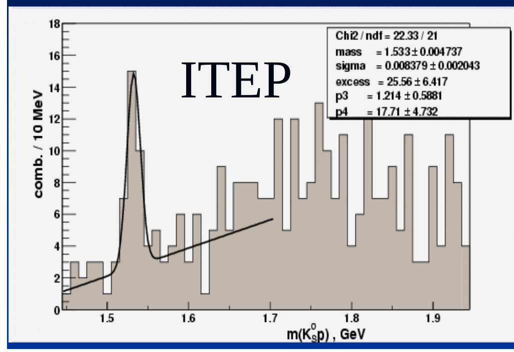


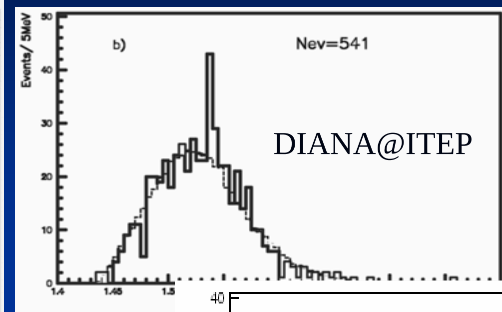


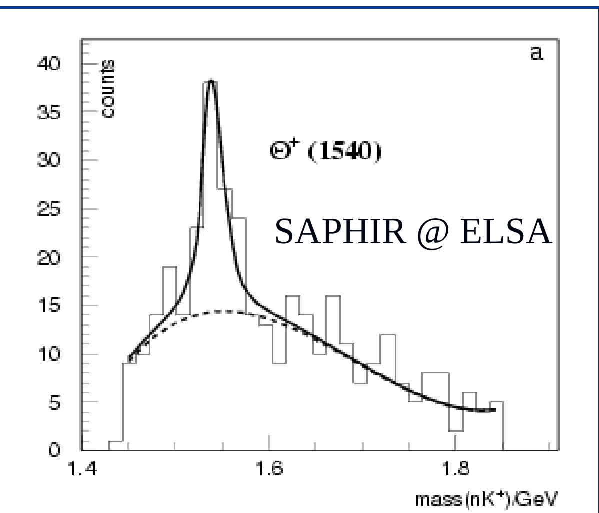
- Noone scrambles quarks like us!
- All the ingredients for discovery.
- Look for additional results throughout the conference!

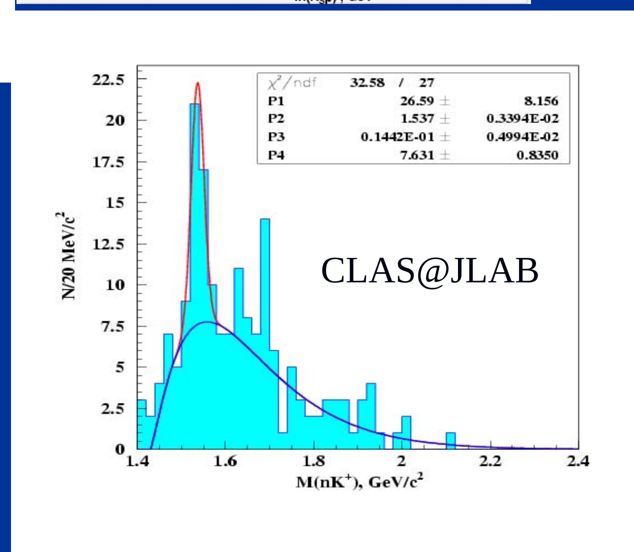
NA49 results on exotic quark states

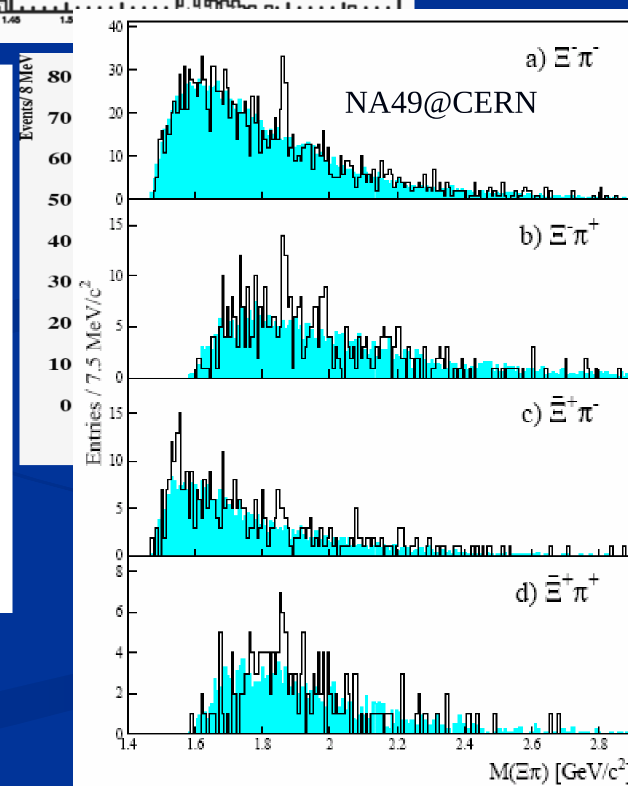












- Noone scrambles quarks like us!
- All the ingredients for discovery.
- Look for additional results throughout the conference!

Conclusion: properties of the medium

- Equilibrates rapidly!
  - Strong pressure gradients, hydrodynamics works
  - *EOS is not hadronic*
- Constituent scattering cross section is very large
- The hot matter is "sticky" – it absorbs energy & seems to
    - transport it efficiently
  - See energy loss/jet quenching
  - d+Au data says: *final state*, not initial state effect
- So, the stuff is dense, hot, ~ equilibrated, looks like liquid
- QGP discovery? It's *NOT* a perturbative plasma…
- Some say it is a liquid.

Why a liquid?

- Mean free path is very short
  - Smaller than size of system
  - Must be so to get large energy loss
- Interaction among gluons is quite strong
- Have a (residual) correlation among partons until $T>>T_c$

All are liquid-like properties!

What we may see this week.

- Tomography:
  - Find the lost jet in phase space, it's balance is somewhere.
  - Unlock the chemistry of the jet.
  - Reaction Plane.
  - Complete the probe set (CONTROLS TOO).
- Explore Saturation Regime.
- Look for exotic quark combinations.
- Extend lower energy strangeness studies to more multiply strange particles.
- Measure open charm baseline at CERN.
- High mass resolution e^+e^- from SPS.

Some Lore and My Charge to You

- When Rutherford lead the Cavendish Laboratory, the scientists were thrown out and the doors padlocked promptly at 6:00 PM.
  - Charge to the scientists: Go Home and THINK!
- When the Professor and two students shared the three wishes from the Genie of the Lamp:
  - Student 1: I wish to be the RICH and powerful ruler of a nation.
  - Student 2: I wish to live on a tropical isle with beautiful people and no cares in the world.
  - Professor: I want them back in the lab by nightfall.
- My charges to you:
  - STAY OFF COMPUTER; Sit in your seat and THINK.
  - I want you back in the lab Monday next.