Heavy Ion Physics at RHIC

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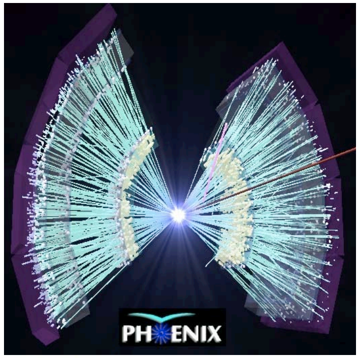
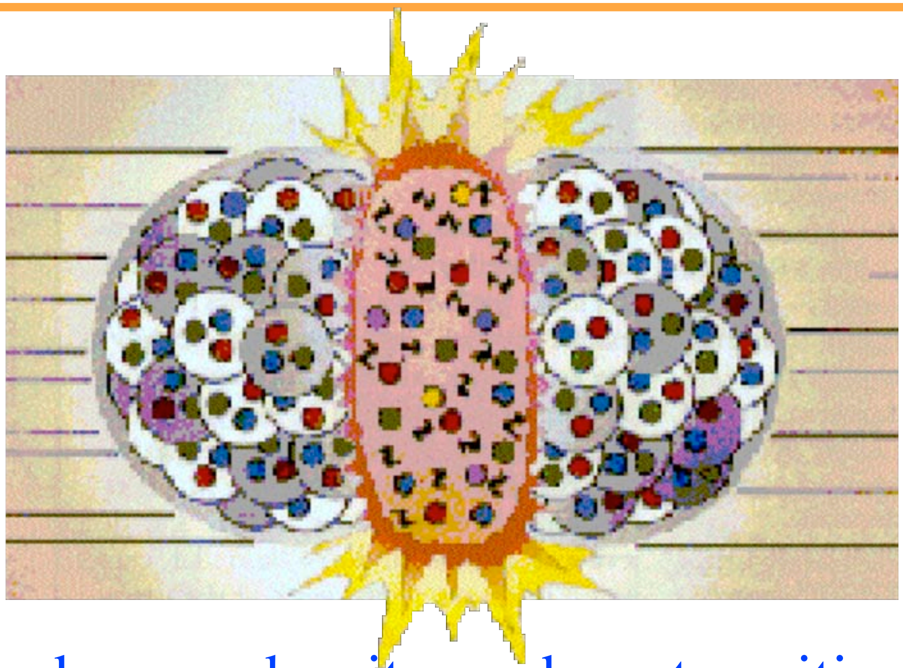
See references:
Rep. Prog. Phys. 69, 2005 (2006)
Nucl. Phys. A 757, 1-283 (2005)



Symposium, 50+ Years of
High Energy Physics @UB
October 21, 2006

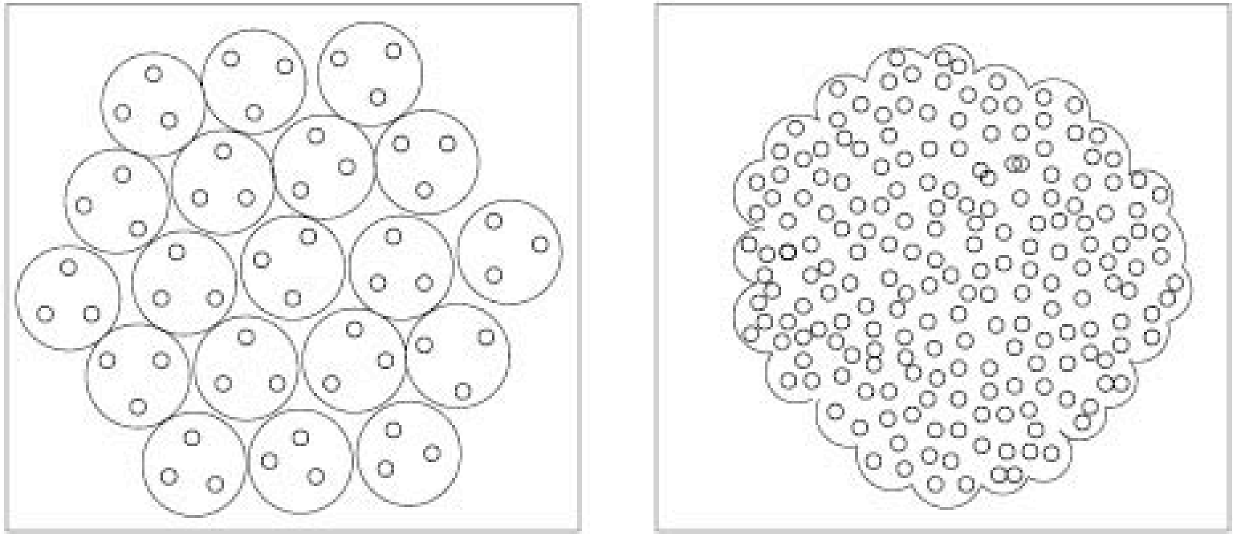
High Energy Nucleus-Collisions provide the means of creating Nuclear Matter in conditions of Extreme Temperature and Density



- At large energy or baryon density, a phase transition is expected from a state of nucleons containing confined quarks and gluons to a state of "deconfined" (from their individual nucleons) quarks and gluons covering a volume that is many units of the confinement length scale.

One Big Grape

H Satz Rep. Prog. Phys. **63** (2000) 1511



a b

Figure 1. Strongly interacting matter as nuclear matter at a density of closely packed nucleons (*a*) and as quark matter at much higher density (*b*).

The Quark Gluon Plasma (QGP)

- The QCD confinement scale---when the string breaks---is order:

$$1/\Lambda_{QCD} \sim 1/m_{\pi} = 1.4 \text{ fm}$$

- With increasing temperature, T, in analogy to increasing Q^2, $\alpha_s(T)$ becomes smaller, reducing the binding energy, and the string tension $\sigma(T)$ becomes smaller, increasing the confinement radius, effectively screening the potential

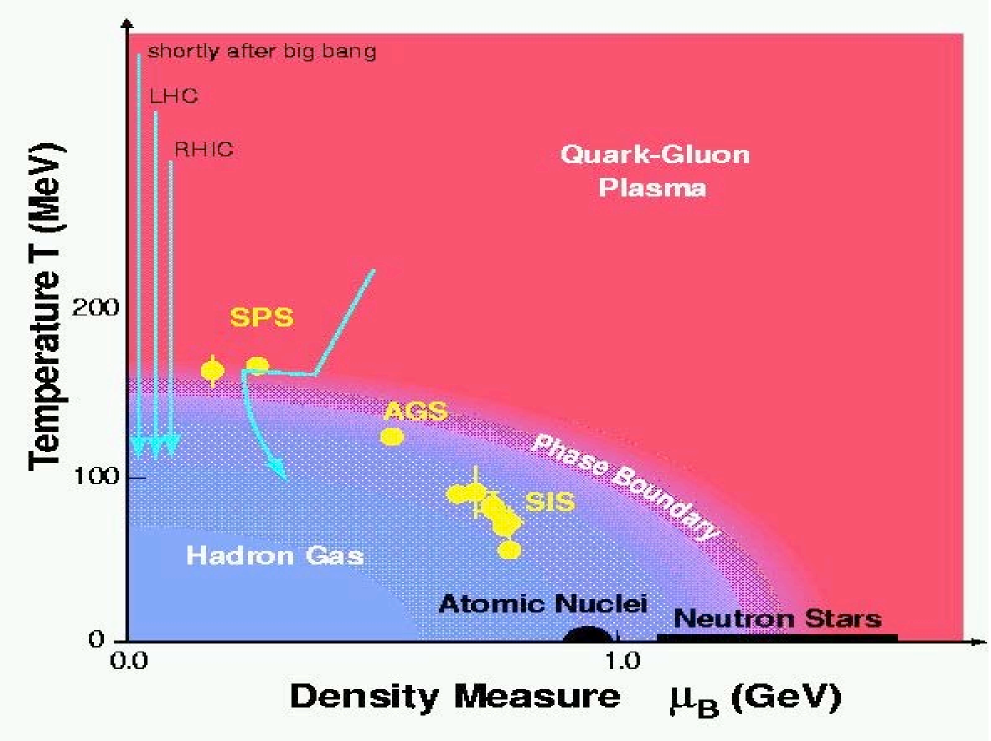
$$V = \frac{-4\,\alpha_s}{3\ \ r} + \sigma\, r \Rightarrow \frac{-4\,\alpha_s}{3\ \ r}\, e^{-\mu(T)r} + \sigma\,\frac{(1 - e^{-\mu(T)r})}{\mu(T)}$$

- For $r < 1/\mu$ a quark does feel the full color charge but for $r > 1/\mu$ the quark is free of the potential, effectively deconfined

The Quark Gluon Plasma (QGP)

- The state should be in chemical (particle type) and thermal equilibrium $\langle p_T \rangle \sim T$

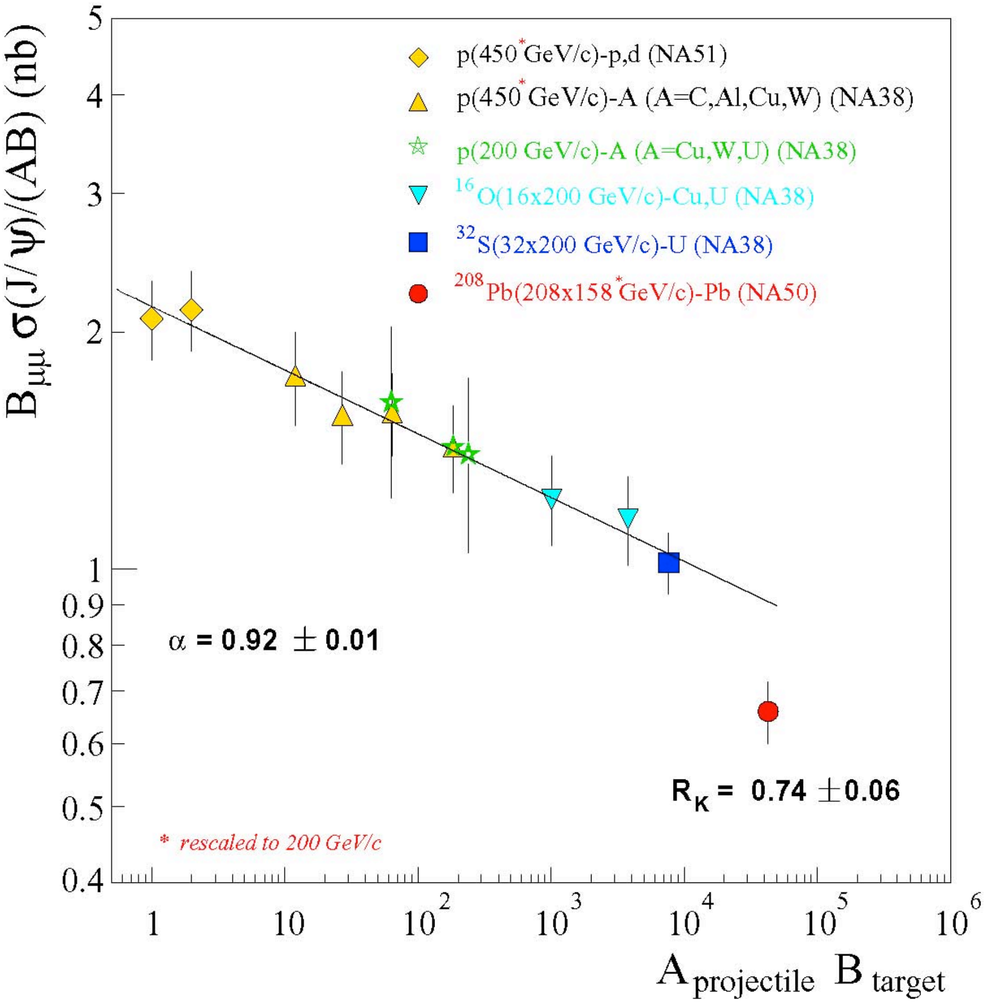
- The major problem is to relate the thermodynamic properties, Temperature, energy density, entropy of the QGP or hot nuclear matter to properties that can be measured in the lab.



The gold-plated signature for the QGP J/ψ Suppression

- In 1986, T. Matsui & H. Satz PL **B178**, 416 (1987) said that due to the Debye screening of the color potential in a QGP, charmonium production would be suppressed since the cc-bar couldn't bind.

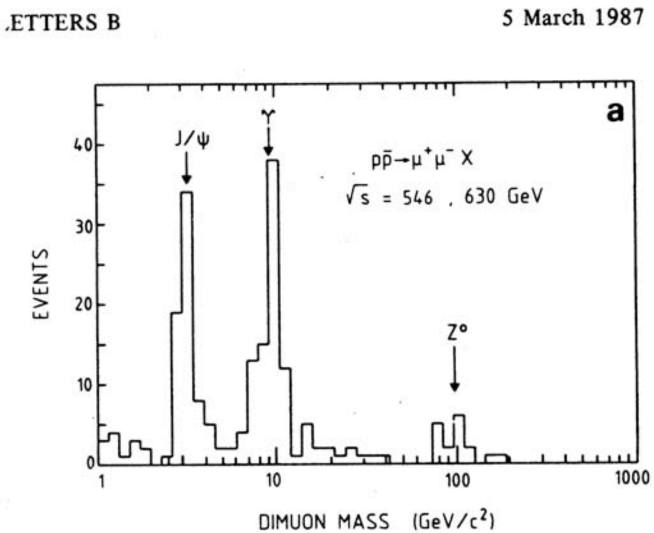
- This is CERN's claim to fame: but the situation is complicated because J/ψ are suppressed in p+A collisions. [NA50 collaboration, M.C. Abreu, et al., PL**B 477**, 28 (2000)]



How to discover the QGP-1990-91

- The Classical road to success in RHI Physics: J/Ψ Suppression

The Road To Success in HEP

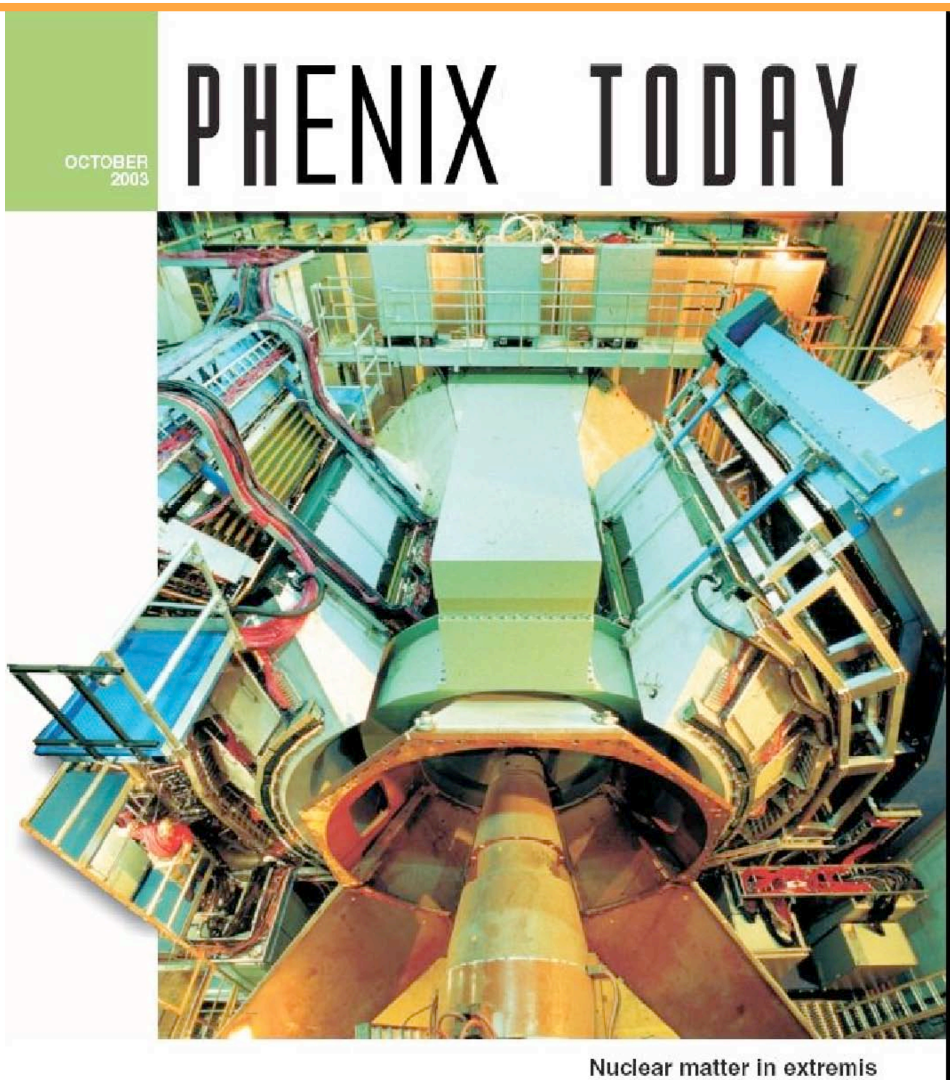


$p_T(\mu) \geq 3$ GeV/c, UA1 Phys. Lett. **B186**, 237 (1987)

The Road To Success in HIP

- Major background for e± detection is photons and conversions from π^0. but more importantly
- Need an electron trigger for full J/Ψ detection ⇒ EMCal plus electron ID at trigger level.
- High p_T π^0 and direct γ production and two-particle correlations are the way to measure hard-scattering in RHI collisions where jets can not be detected directly---> segmentation of EMCal must be sufficient to distinguish π^0 and direct γ up to 25 GeV/c (also vital for spin)
- Charm measurement via single e± (Discovered by CCRS experiment at CERN ISR)
- So we designed PHENIX to make these measurements

"Mike, is there a `real collider detector' at RHIC?---J. Steinberger "



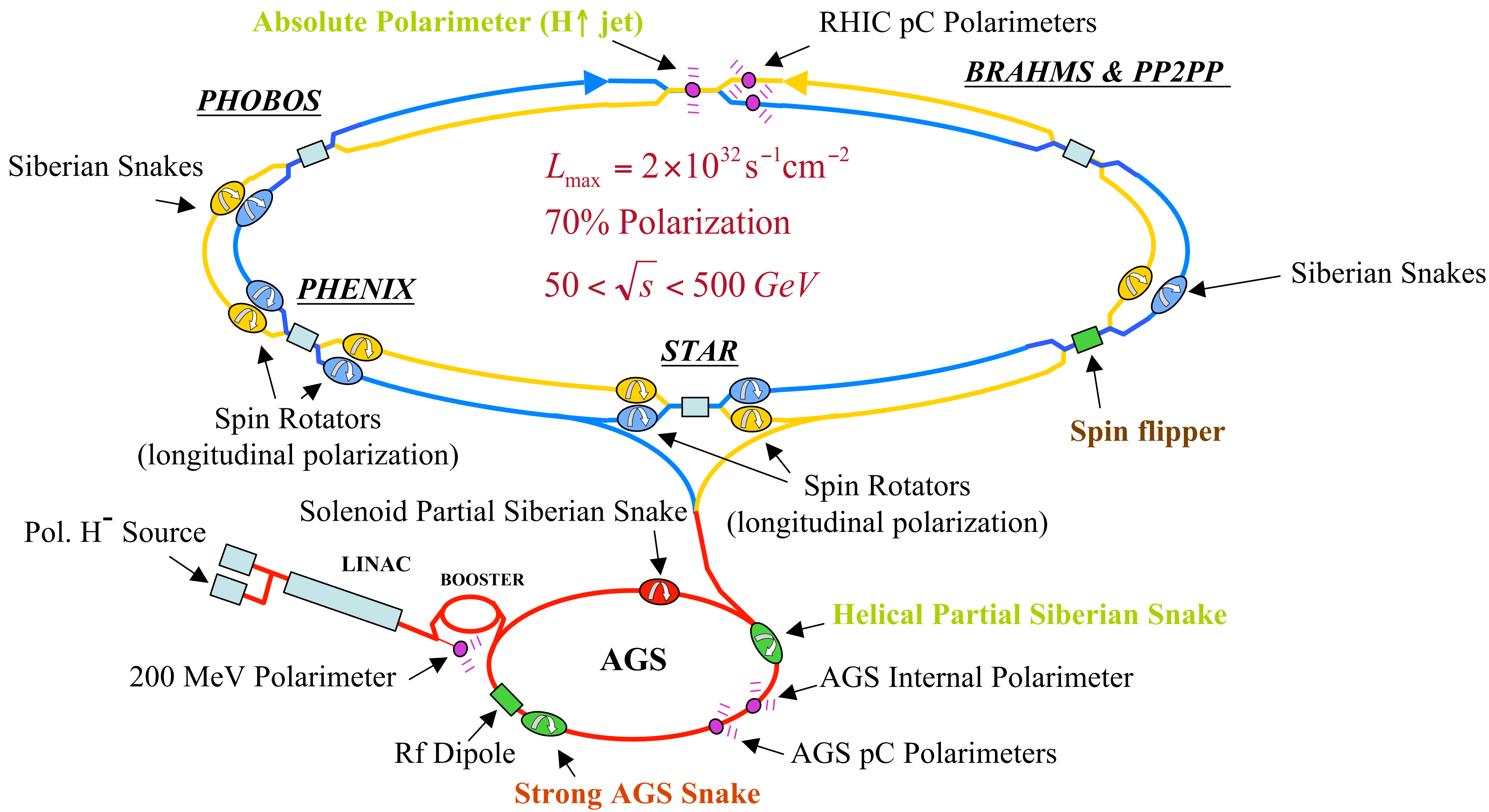
- **PHENIX is picturesque because it is not your father's solenoid collider detector**
- **Special purpose detector designed and built to measure *rare processes* involving *leptons and photons* at the *highest luminosities.***

Where Is RHIC?

Where Is RHIC?

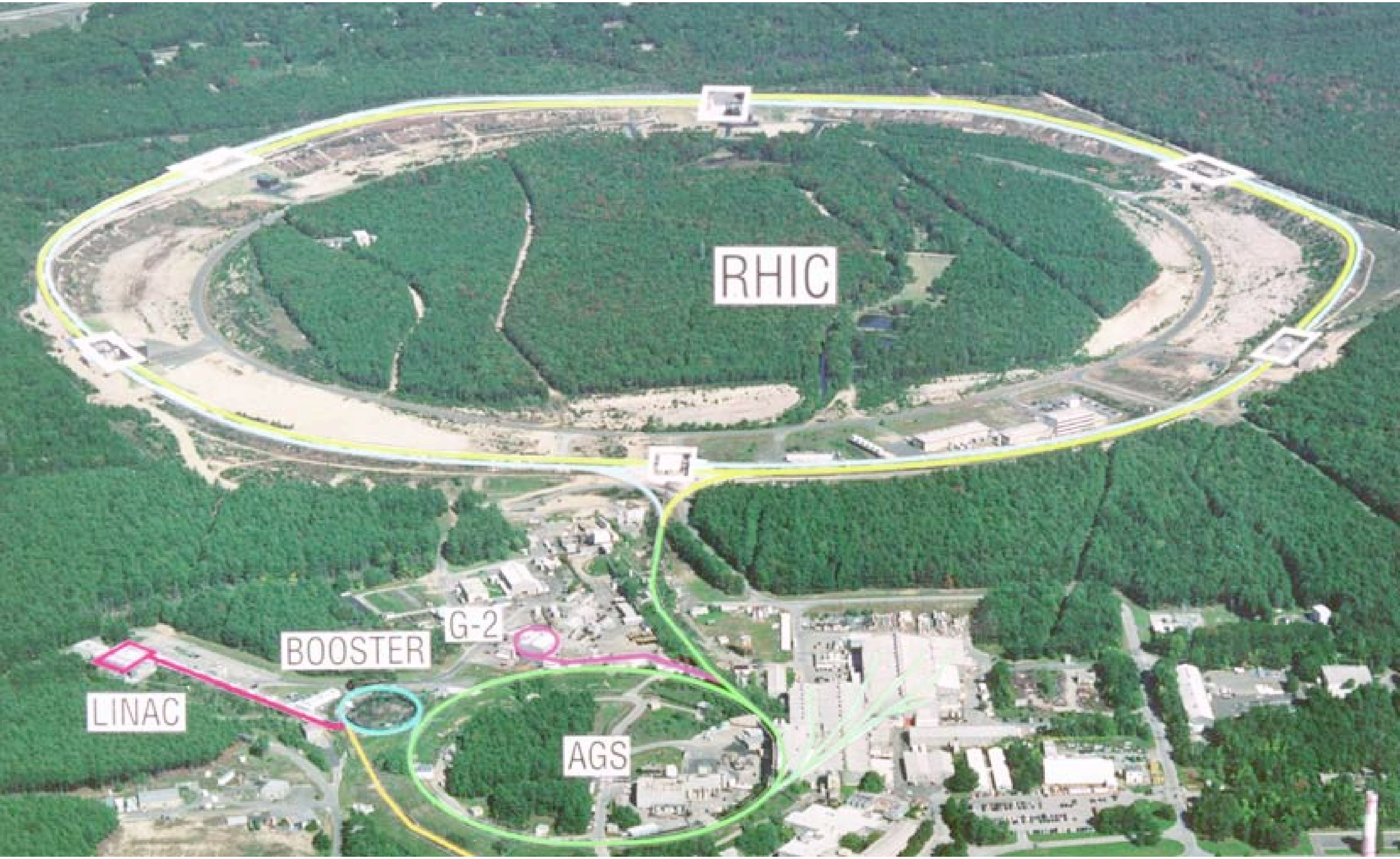

RHIC
G-2
BOOSTER
LINAC
AGS
TANDEMS

RHIC: RHI+polarized p-p collider

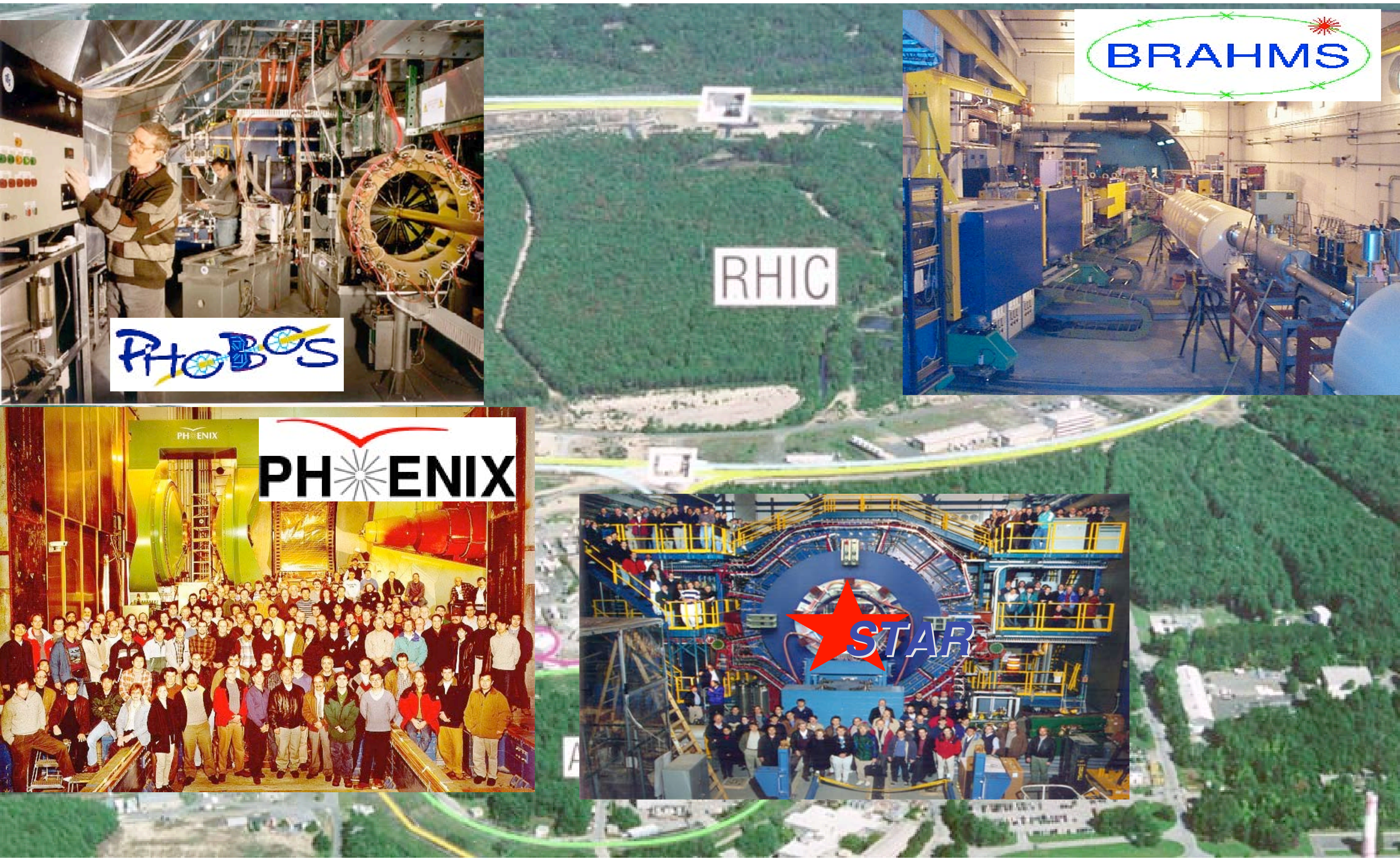


- Installed and commissioned during FY04 run
- Plan to be commissioned during FY05 run
- Installed and plan to be commissioned during FY05 run

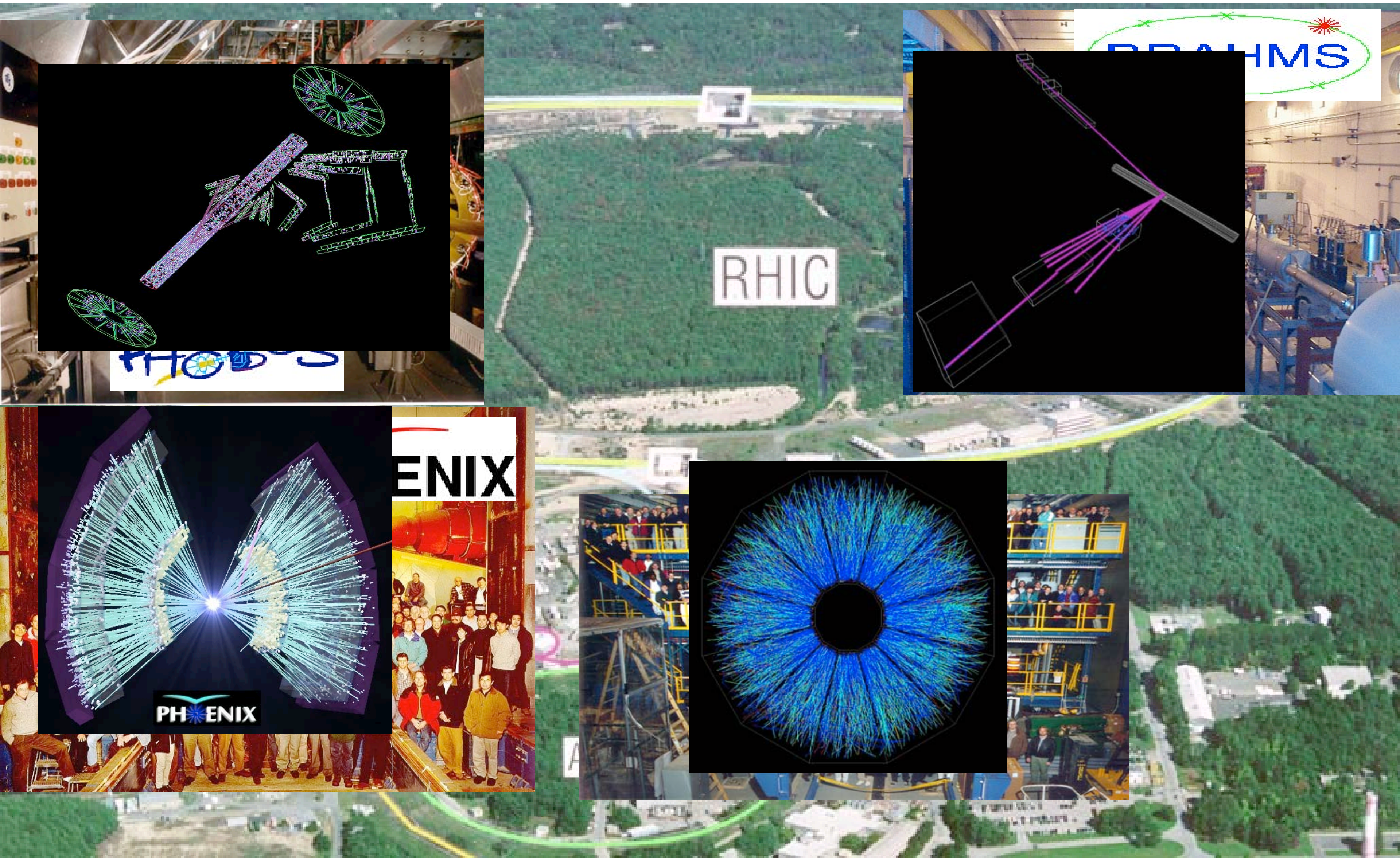
RHIC: Experiments



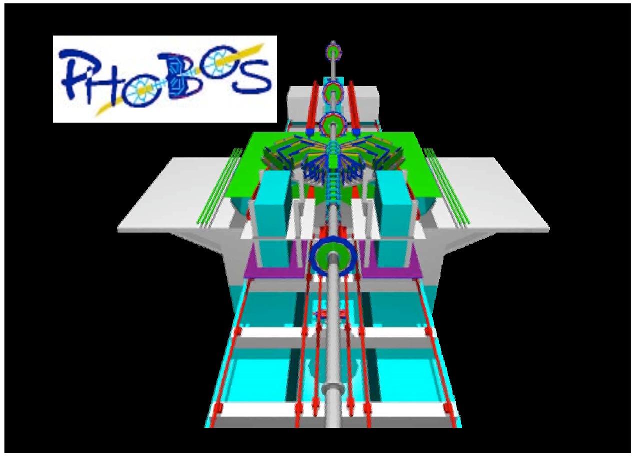
RHIC: Experiments



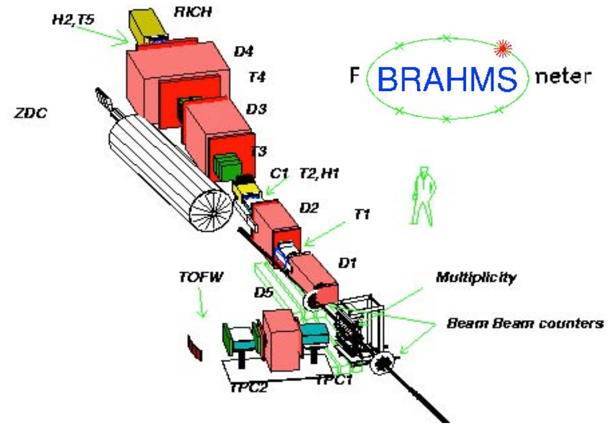
RHIC: Experiments



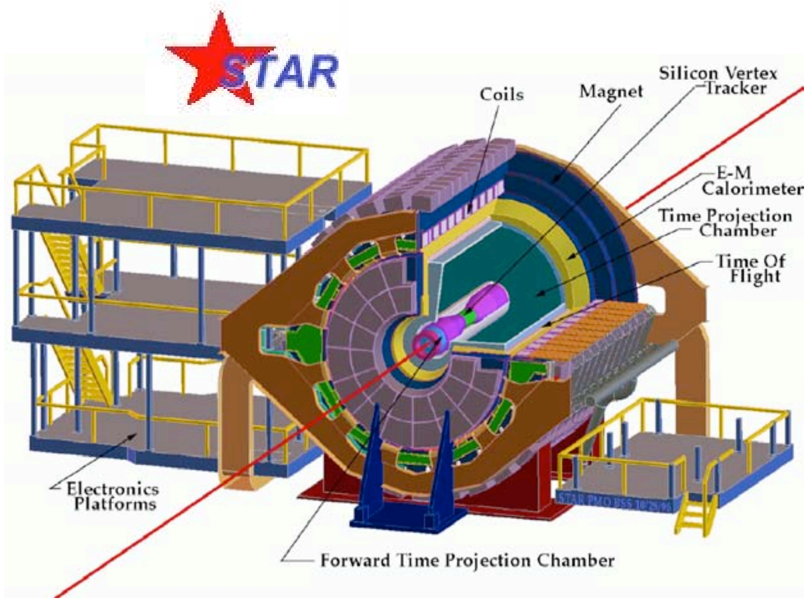
4 Detectors at a glance



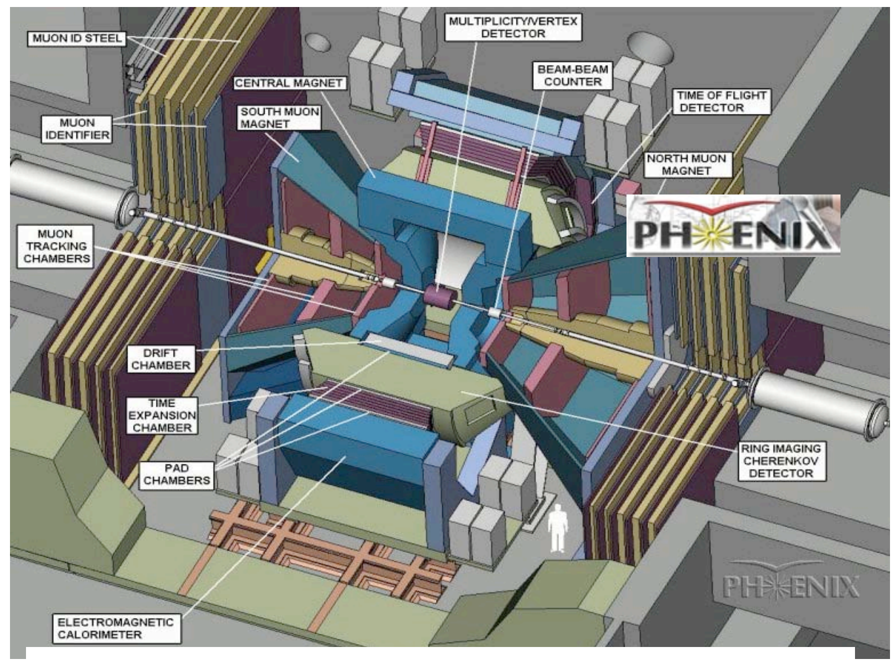
Si-strip tracking, PMT-based TOF



Two magnetic dipole spectrometers in "classic" fixed-target configuration



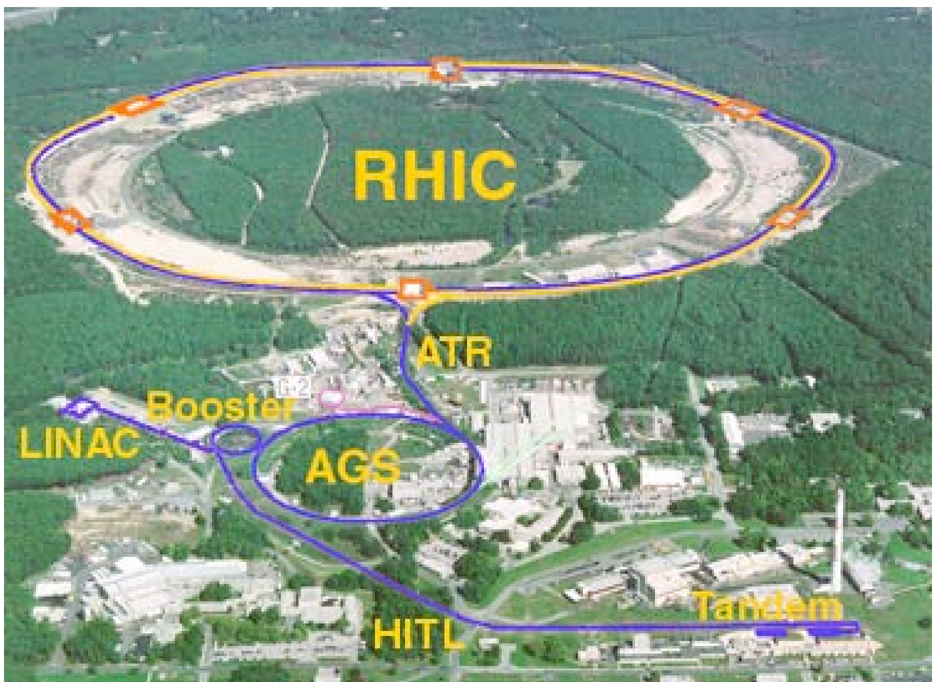
TPC's, silicon, calorimeters
Large acceptance

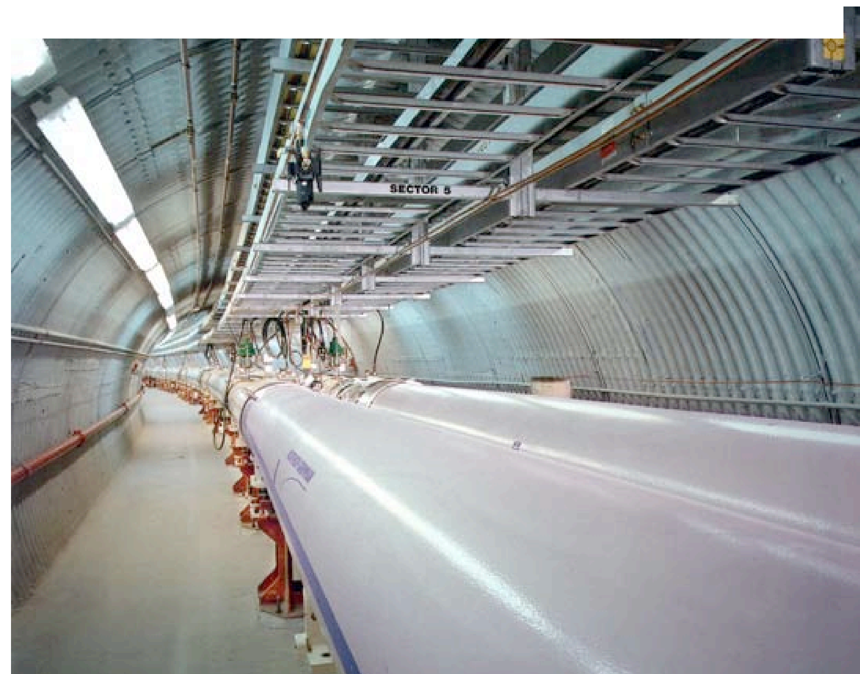


Hadrons, electrons, muons, photons
Rare & penetrating probes

PHENIX = Pioneering High Energy Nuclear Interaction eXperiment

A large, multi-purpose nuclear physics experiment at the Relativistic Heavy-Ion Collider (RHIC): $1 \leq A \leq 197$.
For Au+Au: $19 \leq \sqrt{s_{NN}} \leq 200$ GeV $L_{max} = 2 \times 10^{26}$ cm^{-2} s^{-1}
two independent rings ---> p+Au, d+Au, etc.





PHENIX

- University of São Paulo, São Paulo, Brazil
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- Peking University, Beijing, P. R. China
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- KEK, Institute for High Energy Physics, Tsukuba, Japan
- Kyoto University, Kyoto, Japan
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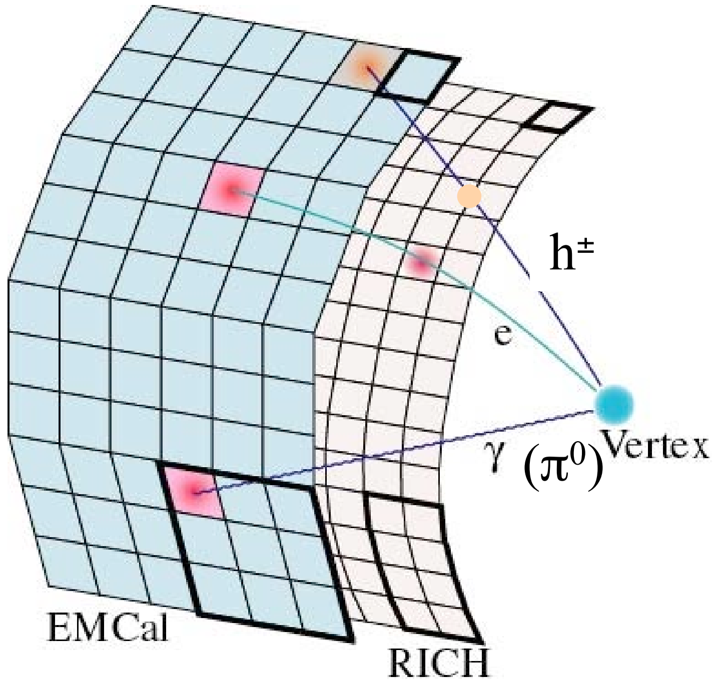
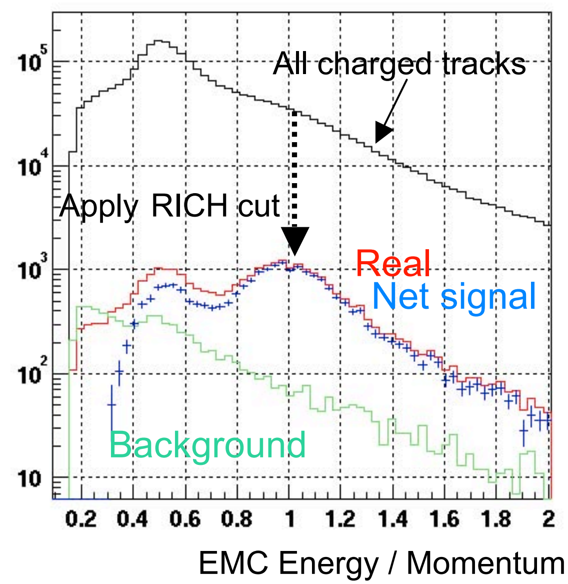
*as of March 2005

Detecting electrons means detecting all particles=PHENIX





- **ElectroMagnetic Calorimeter** measures Energy of photons and electrons
    - reconstructs π^0 from 2 photons. Measures decent Time of Flight
    - hadrons deposit Minimum Ionization, or higher if they interact
- **For electron ID require RICH (cerenkov) and matching energy in EMCal**
    - Electron and photon energy can be matched to < 1%--No nonlinearity problem
- momentum +TOF=charged particle ID
- High Resolution TOF completes the picture giving excellent charged hadron PID

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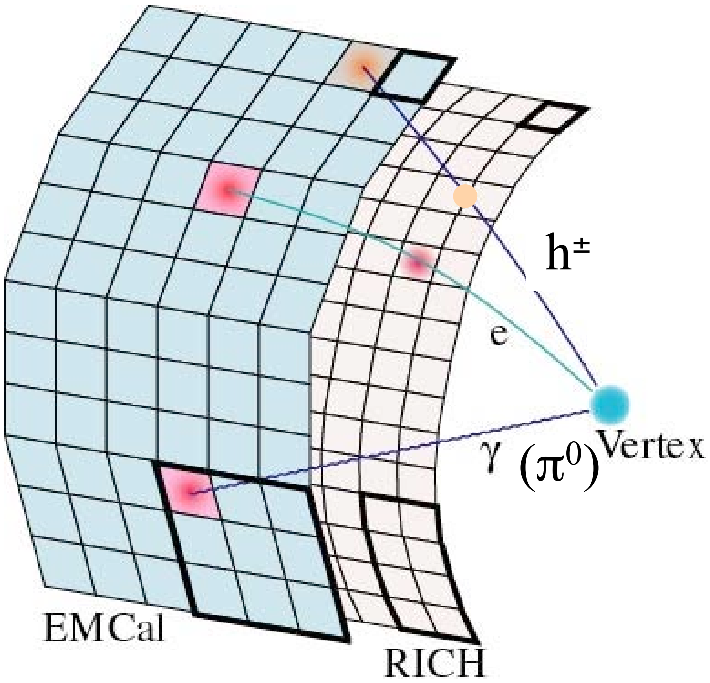

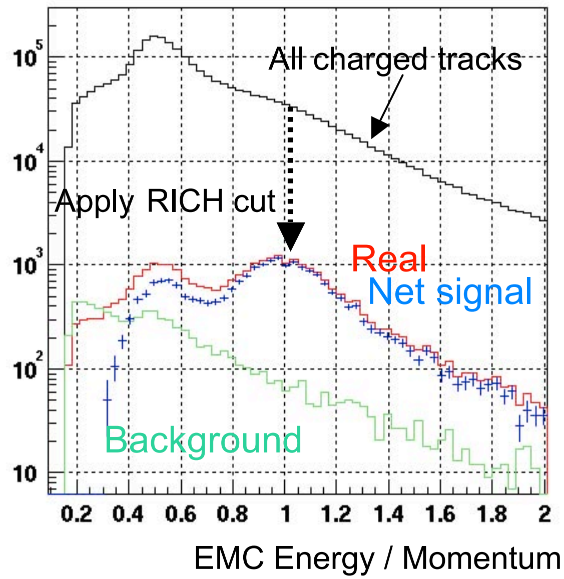

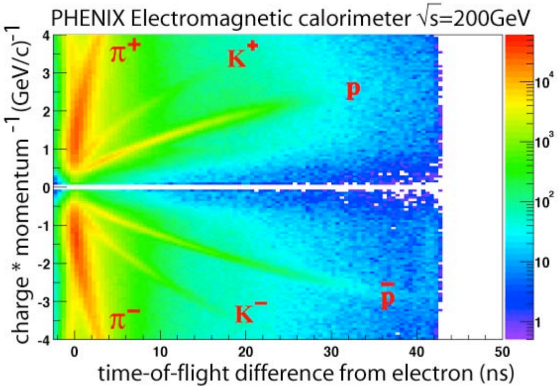

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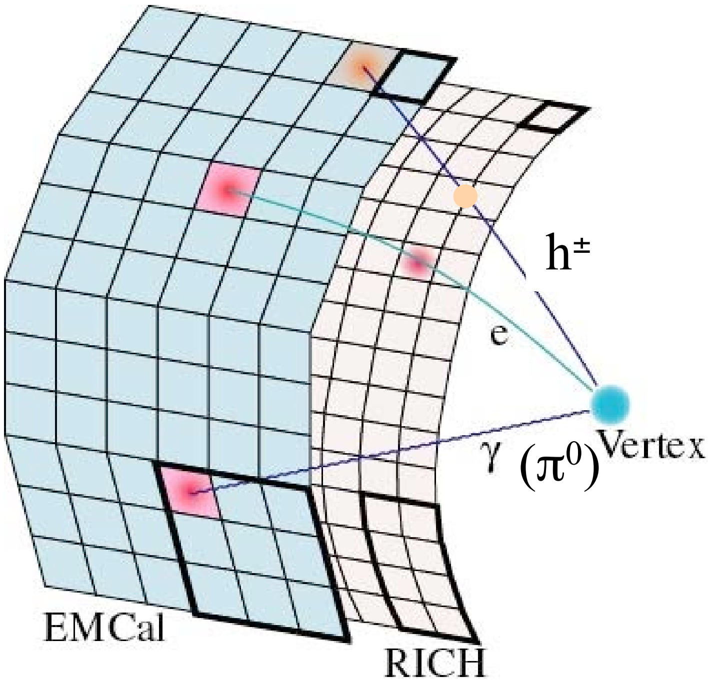

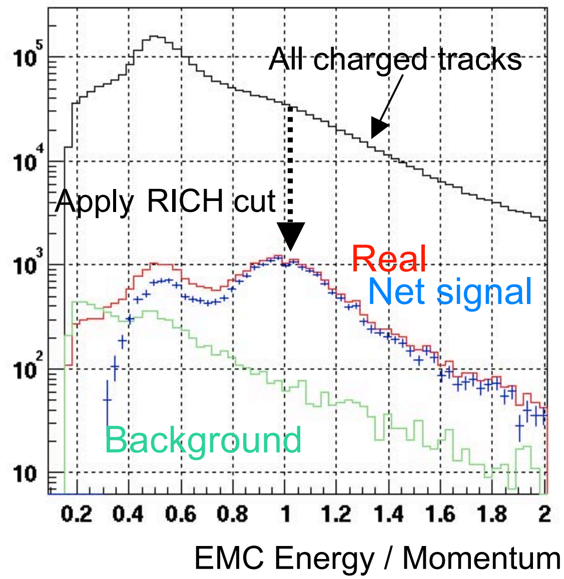

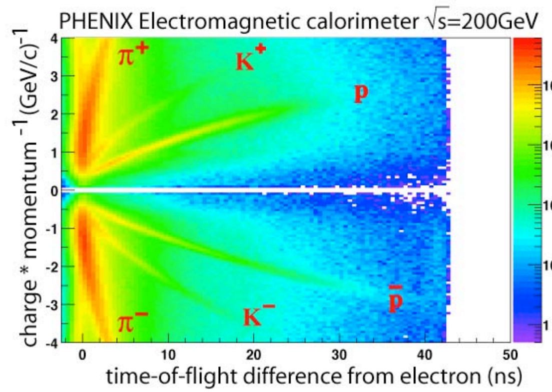

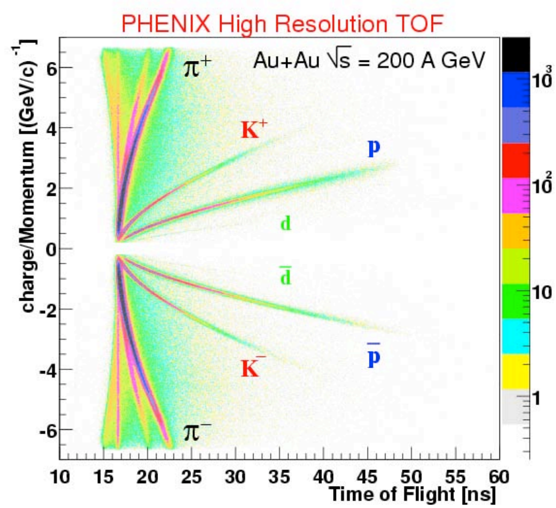

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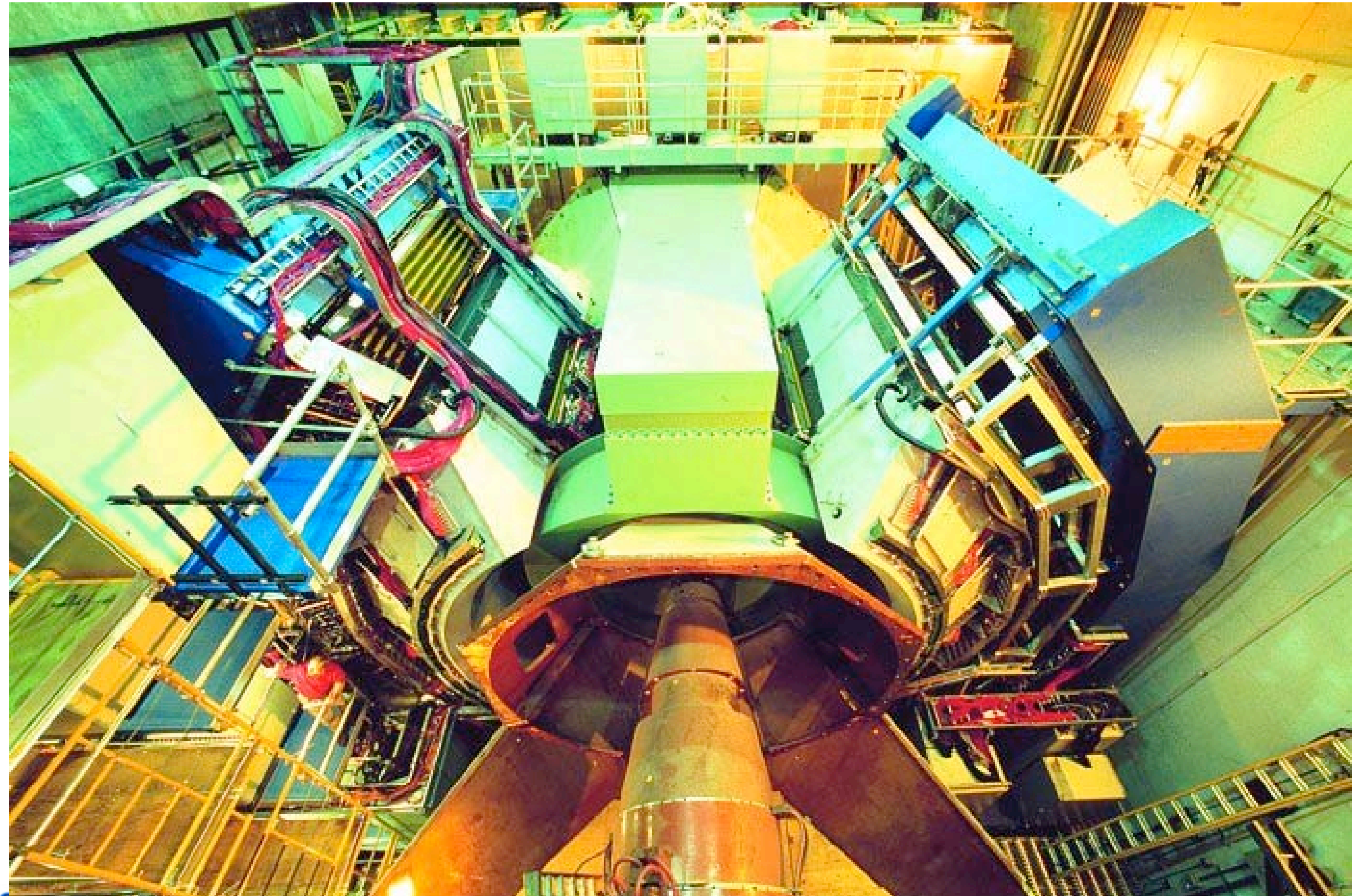
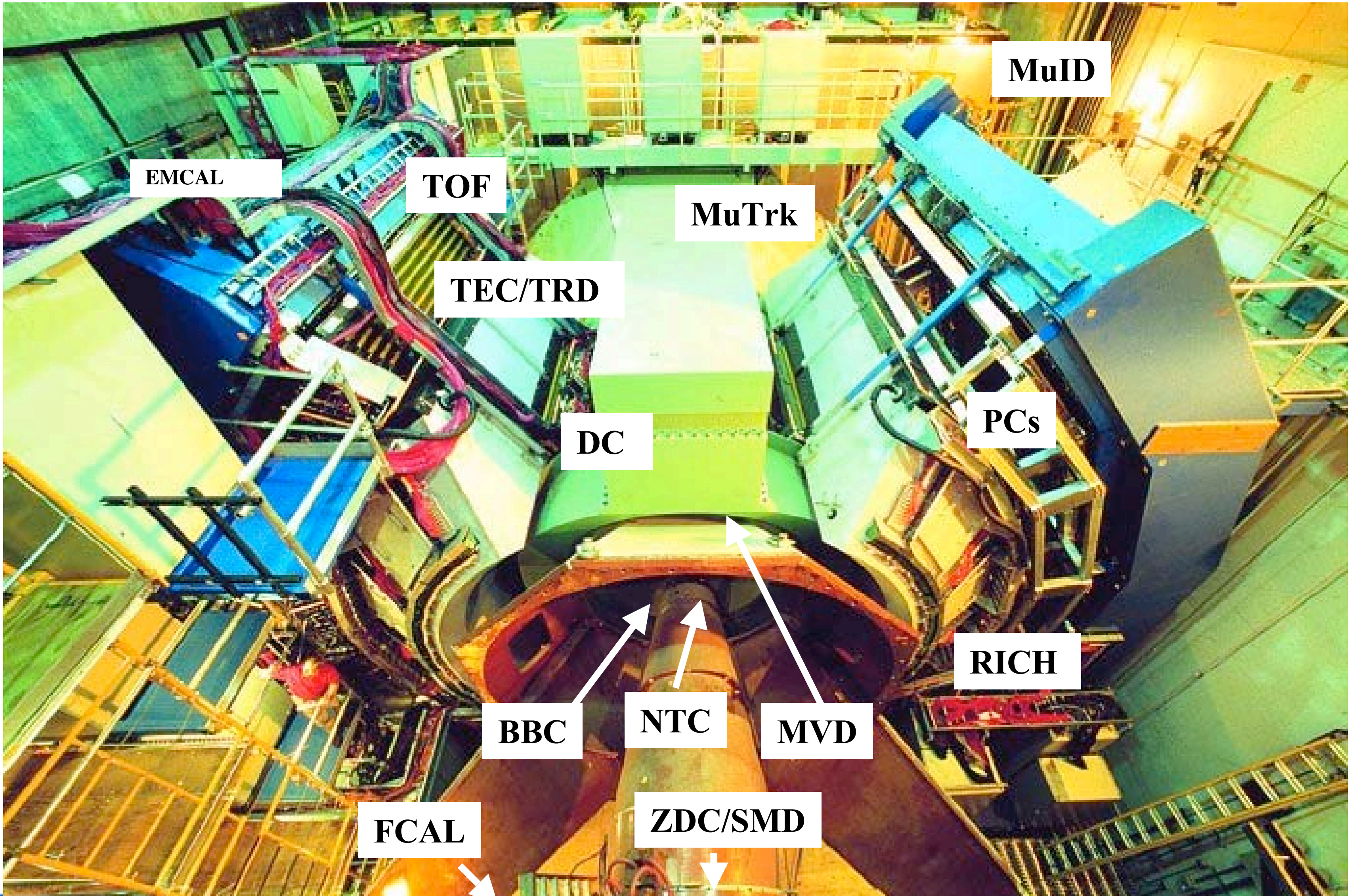
Annotated View--13 Subsystems !#%



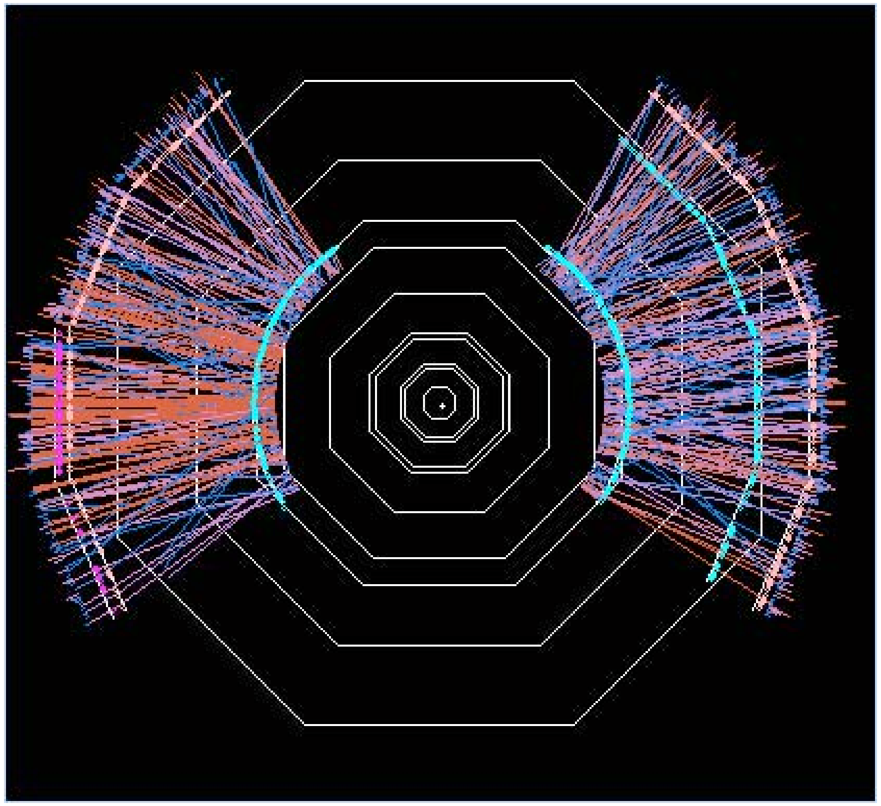
Annotated View--13 Subsystems !#%

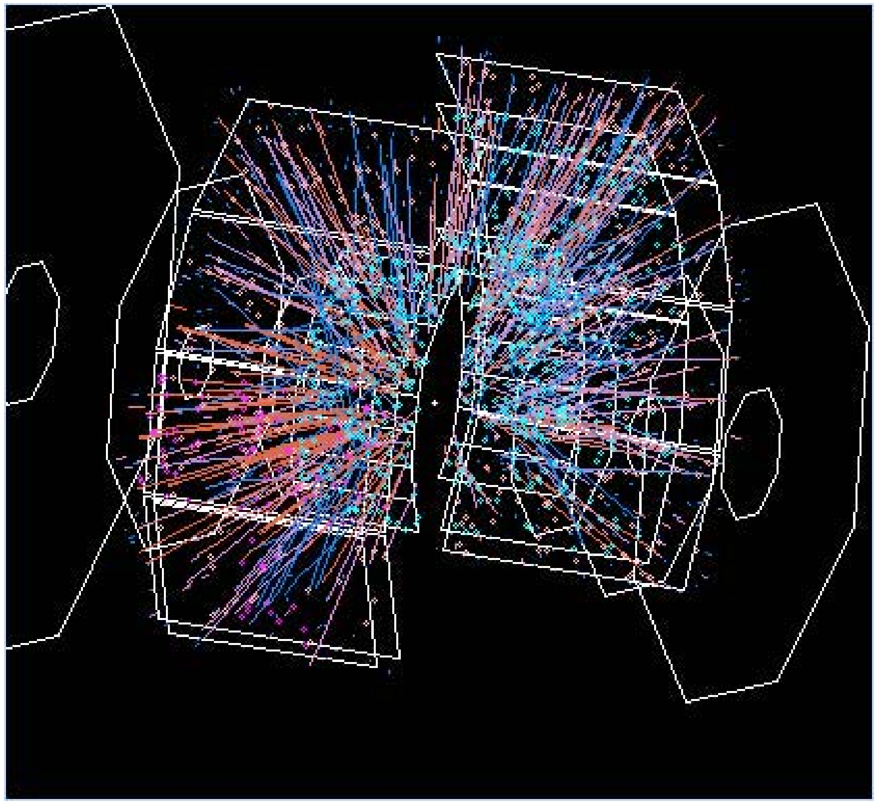


Example of a central Au+Au event at $\sqrt{s_{nn}}$ =200 GeV

$dn_{ch}/d\eta|_{\eta=0}$ =700 for central Au+Au collisions

=2.5 for p-p collisions



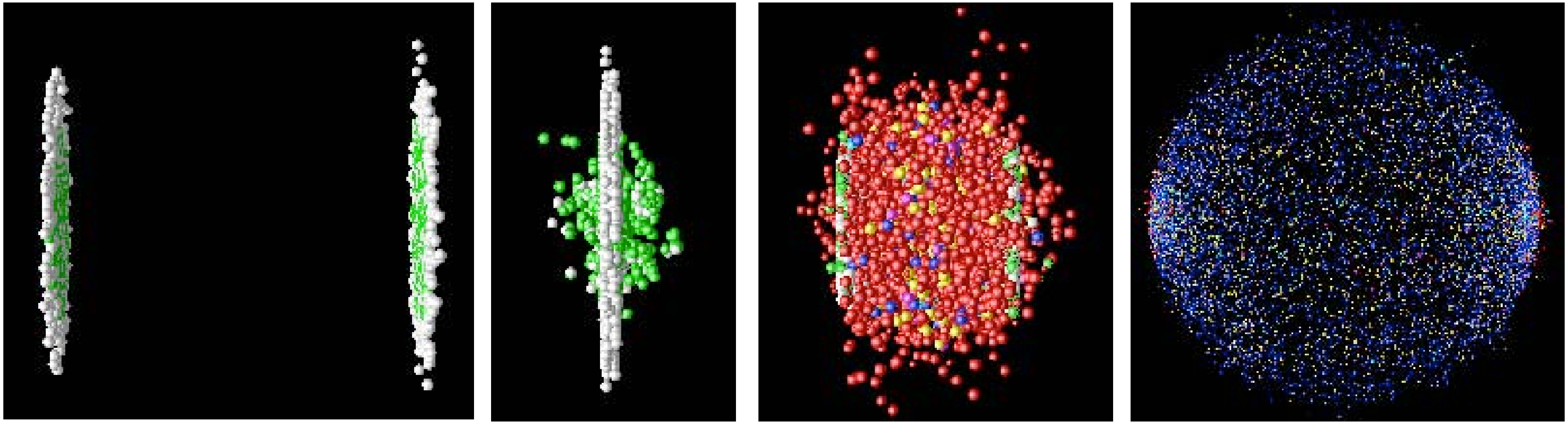


Run-1 to Run-6 Capsule History

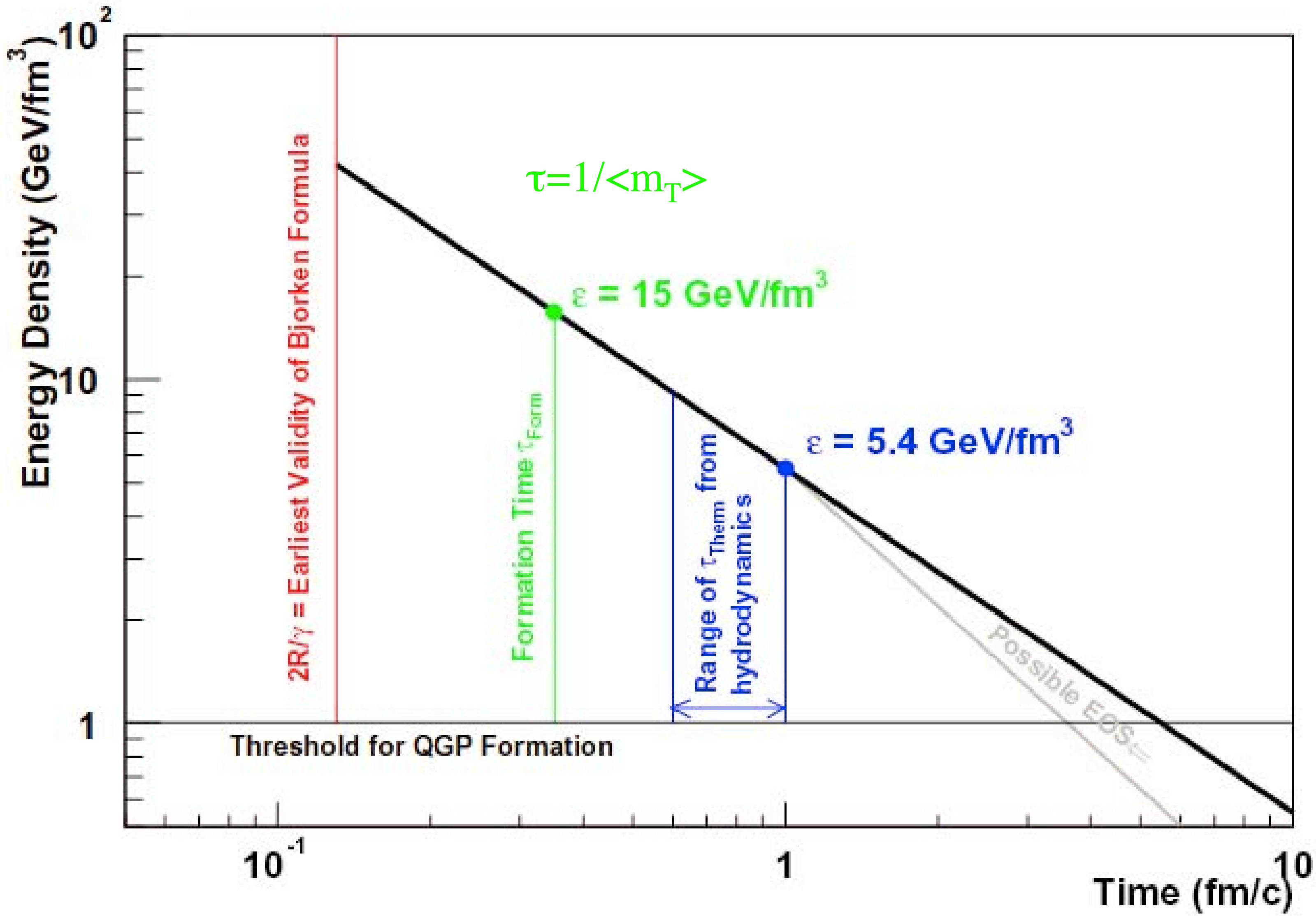
Run	Year	Species	$s^{1/2}$ [GeV]	$\int Ldt$	N_{Tot}	p-p Equivalent	Data Size
01	2000	Au+Au	130	1 μb^{-1}	10M	0.04 pb^{-1}	3 TB
02	2001/2002	Au+Au	200	24 μb^{-1}	170M	1.0 pb^{-1}	10 TB
		p+p	200	0.15 pb^{-1}	3.7G	0.15 pb^{-1}	20 TB
03	2002/2003	d+Au	200	2.74 nb^{-1}	5.5G	1.1 pb^{-1}	46 TB
		p+p	200	0.35 pb^{-1}	6.6G	0.35 pb^{-1}	35 TB
04	2003/2004	Au+Au	200	241 μb^{-1}	1.5G	10.0 pb^{-1}	270 TB
		Au+Au	62	9 μb^{-1}	58M	0.36 pb^{-1}	10 TB
05	2004/2005	Cu+Cu	200	3 nb^{-1}	8.6G	11.9 pb^{-1}	173 TB
		Cu+Cu	62	0.19 nb^{-1}	0.6G	0.8 pb^{-1}	48 TB
		Cu+Cu	22.5	2.7 μb^{-1}	9M	0.01 pb^{-1}	1 TB
		p+p	200	3.8 pb^{-1}	85B	3.8 pb^{-1}	270 TB
06	2006	p+p	200	10.7 pb^{-1}	230B	10.7 pb^{-1}	310 TB
		p+p	62	0.1 pb^{-1}	28B	0.1 pb^{-1}	25 TB

PHYSICS

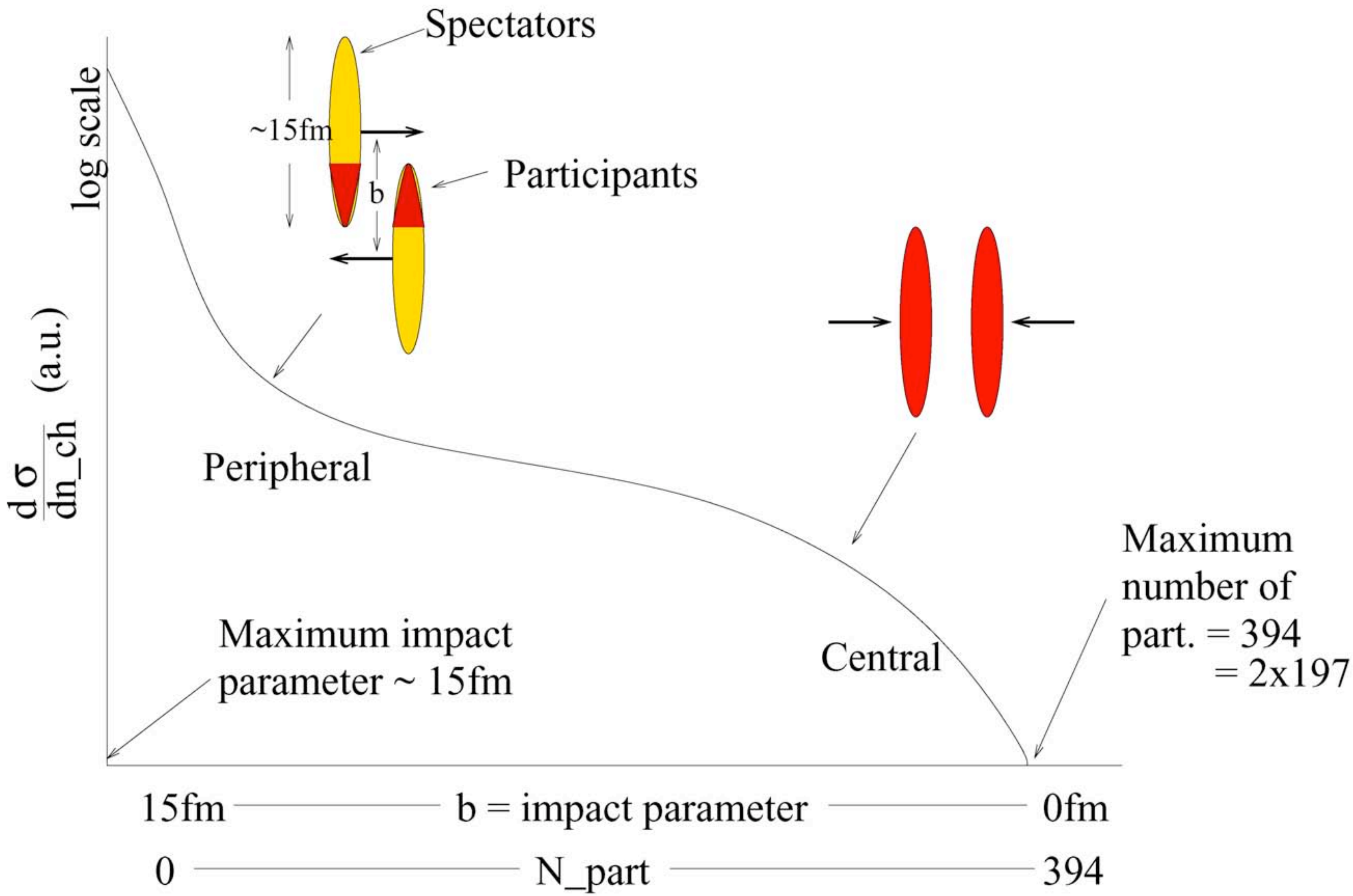
Spacetime evolution is important



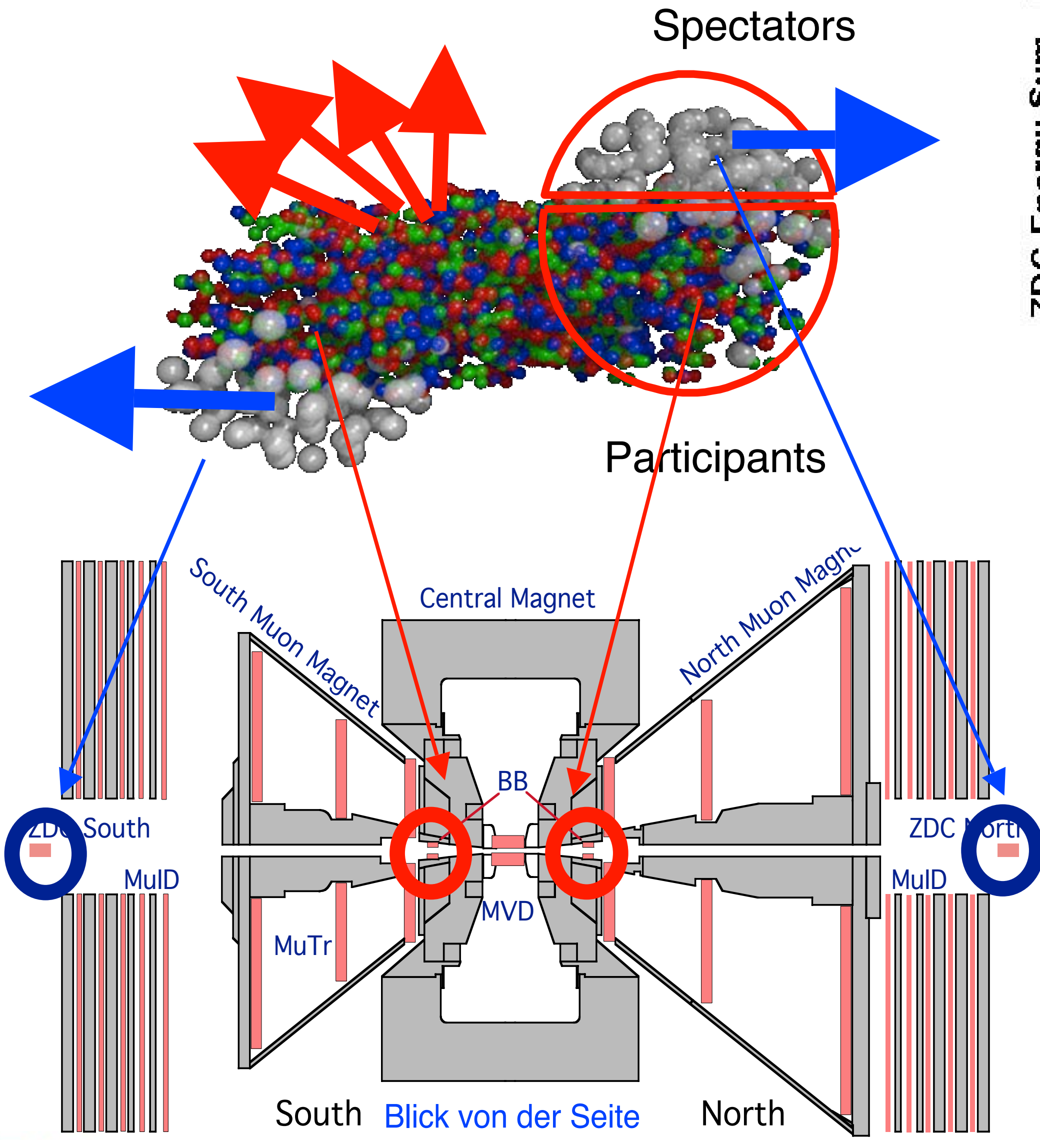
Spacetime evolution is important

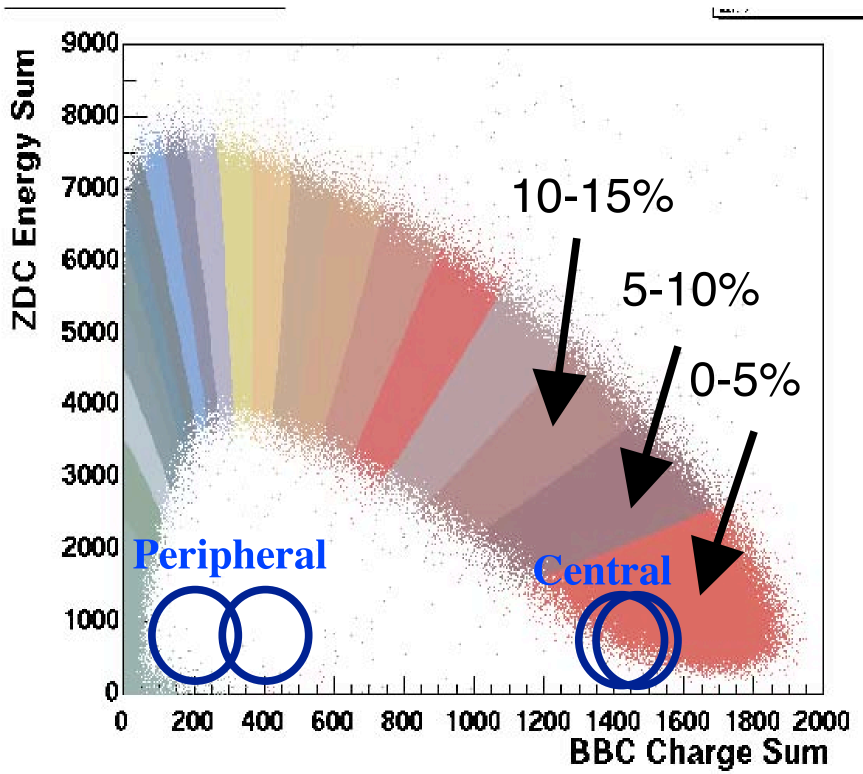


Schematic Au+Au collision



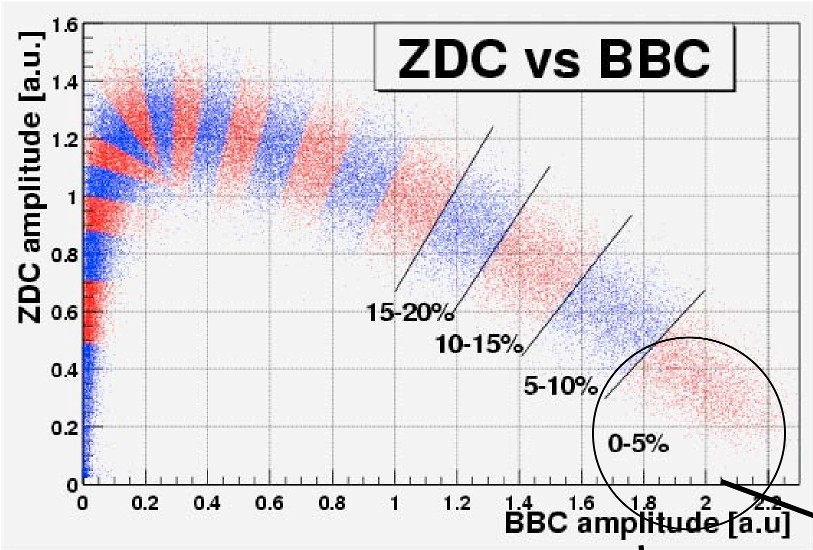
Collision Centrality Determination



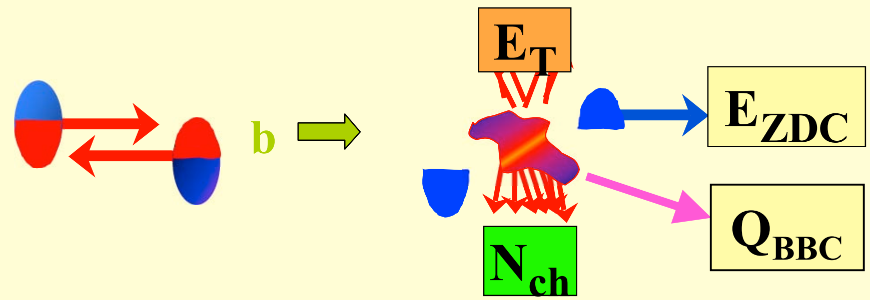


- Centrality selection : Sum of Beam-Beam Counter (BBC, |η|=3~4) and energy of Zero-degree calorimeter (ZDC)
- Extracted N_{coll} and N_{part} based on Glauber model.

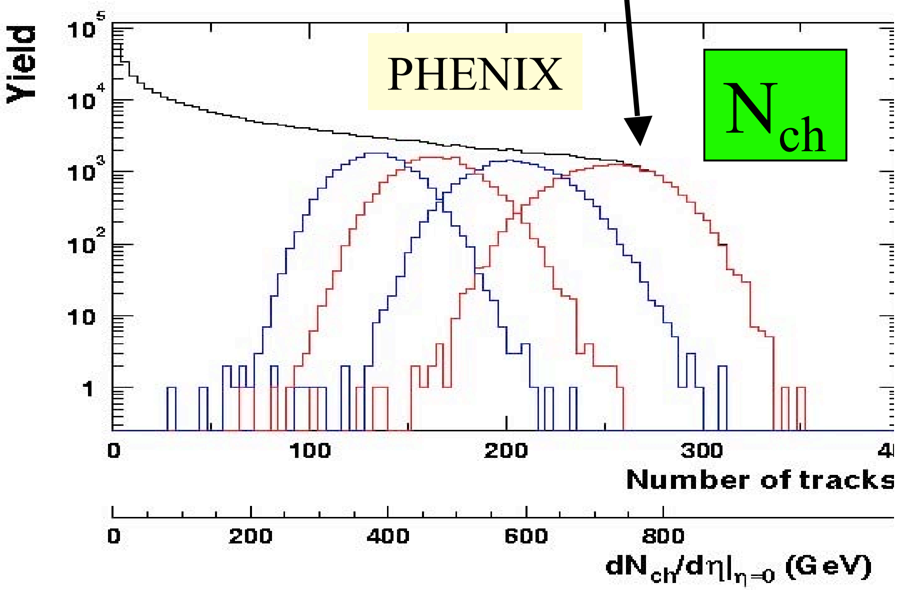
$N_{charged}$, E_T exhibit(&could determine) the Nuclear Geometry

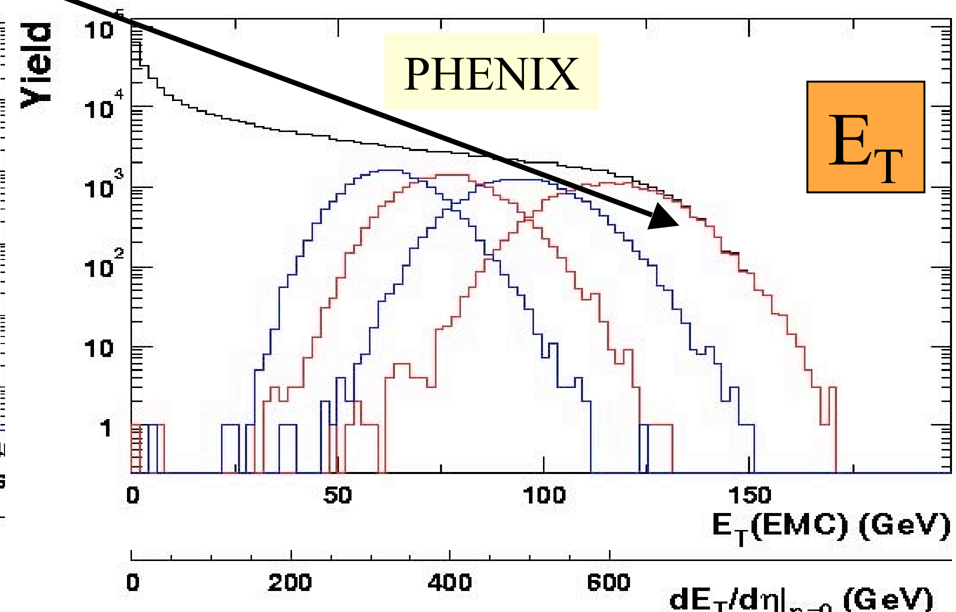


Define centrality classes: ZDC vs BBC



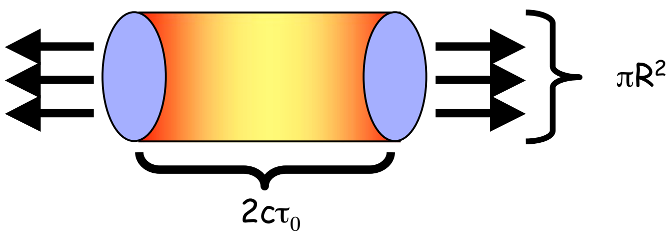
Extract N participants: Glauber model





Is the energy density high enough?

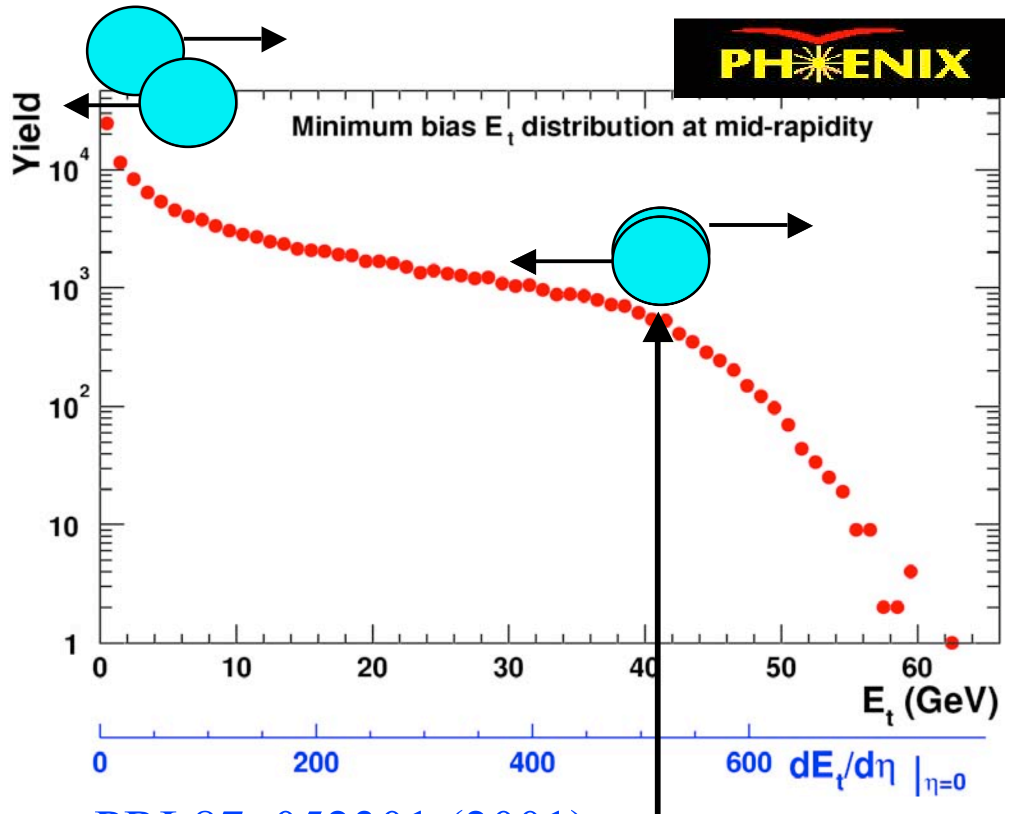
Colliding system expands:



Energy ⊥ to beam direction

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{c\tau_0}\left(\frac{dE_T}{dy}\right)$$

per unit velocity || to beam



PRL87, 052301 (2001)

→ε ≥ *4.6 GeV/fm³* (130 GeV Au+Au)

5.5 *GeV/fm³* (200 GeV Au+Au)

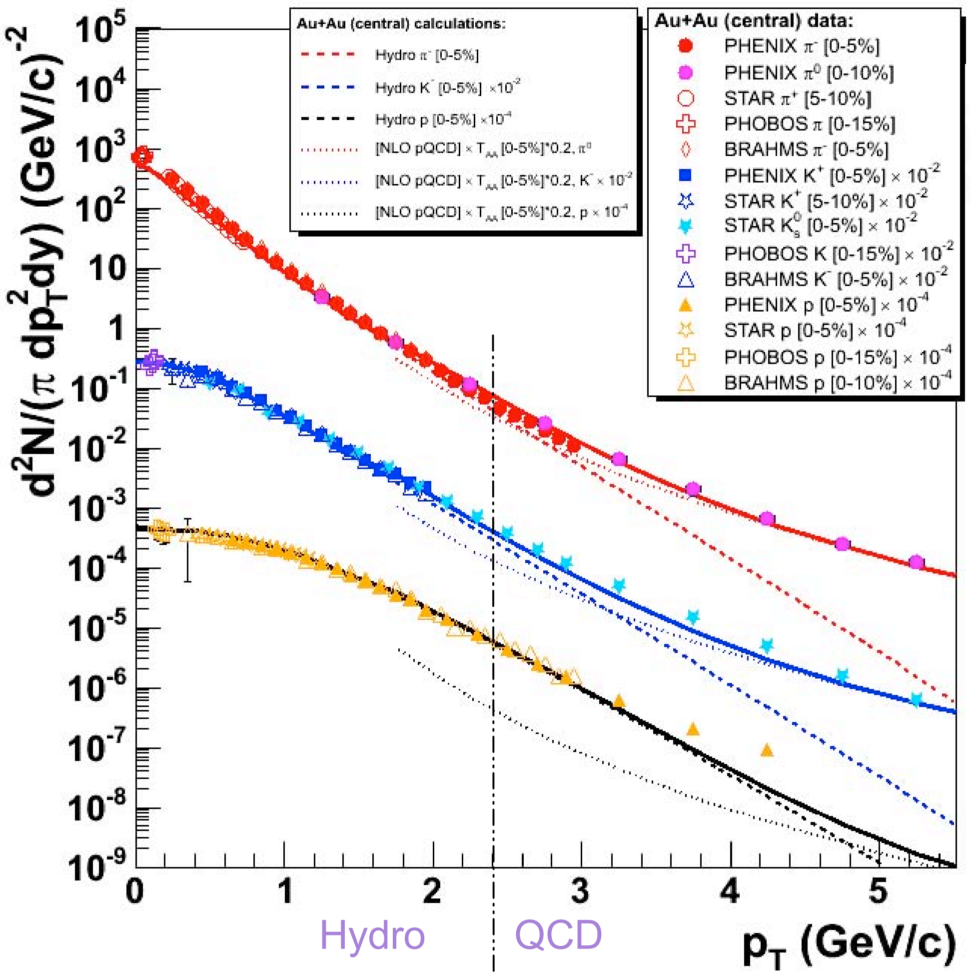
well above predicted transition!

EMCal measures ε_{Bj}

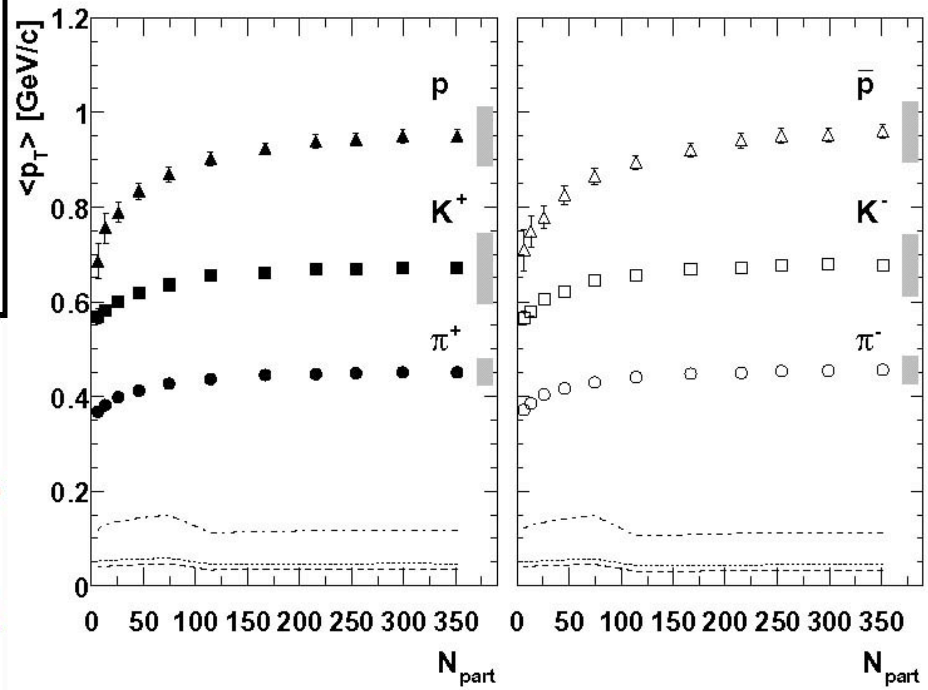
Particle Production

Semi-Inclusive soft particle spectra

Au+Au central (b < 2.6 fm)



D.d'Enterria &D. Peressounko
nucl-th/0503054

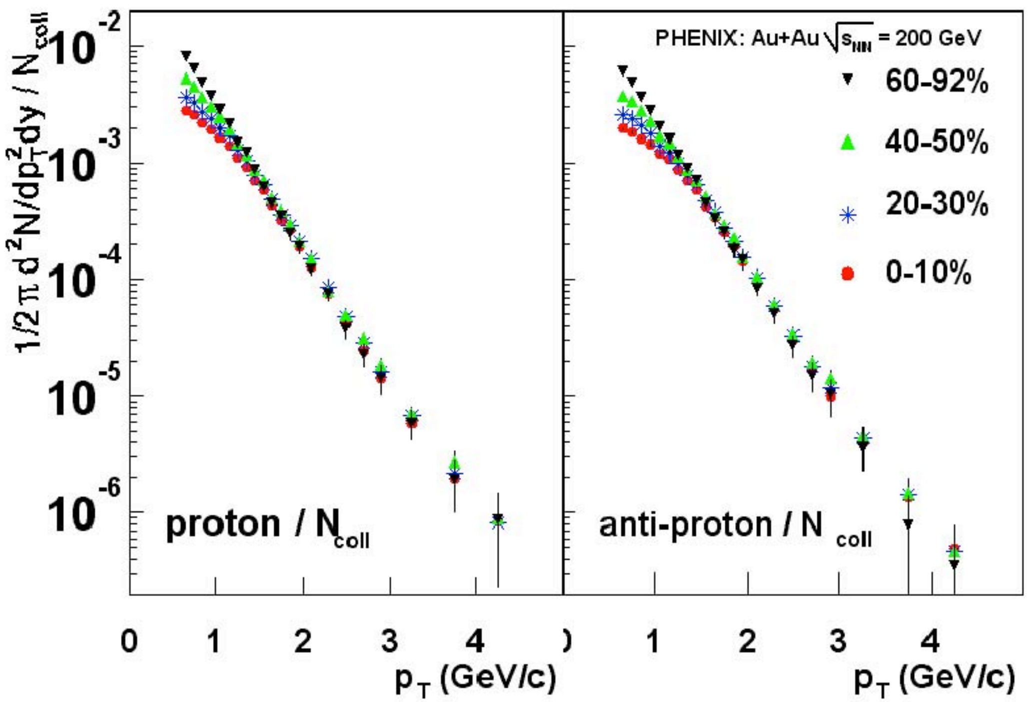


- <pT>: π < K < p
- 25% (π) to 40% (p) increase from peripheral to central

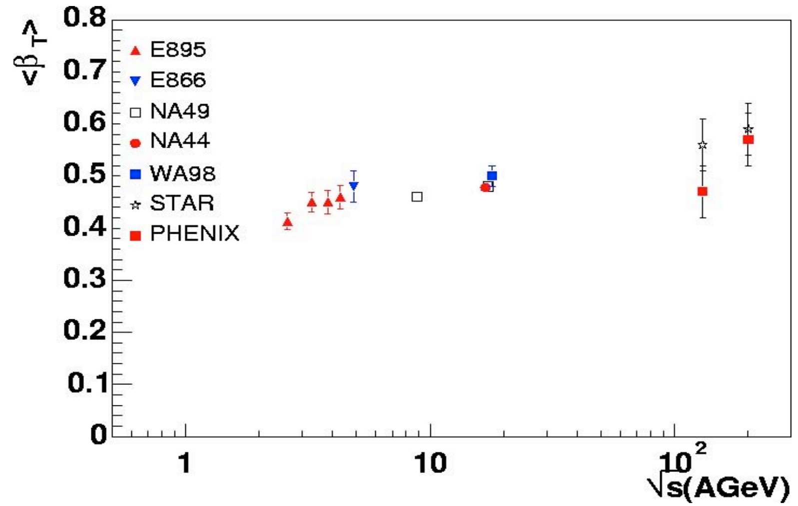
Increase of $\langle p_T \rangle$ with centrality--radial flow

- $p_T \sim \gamma_T \beta_T m$

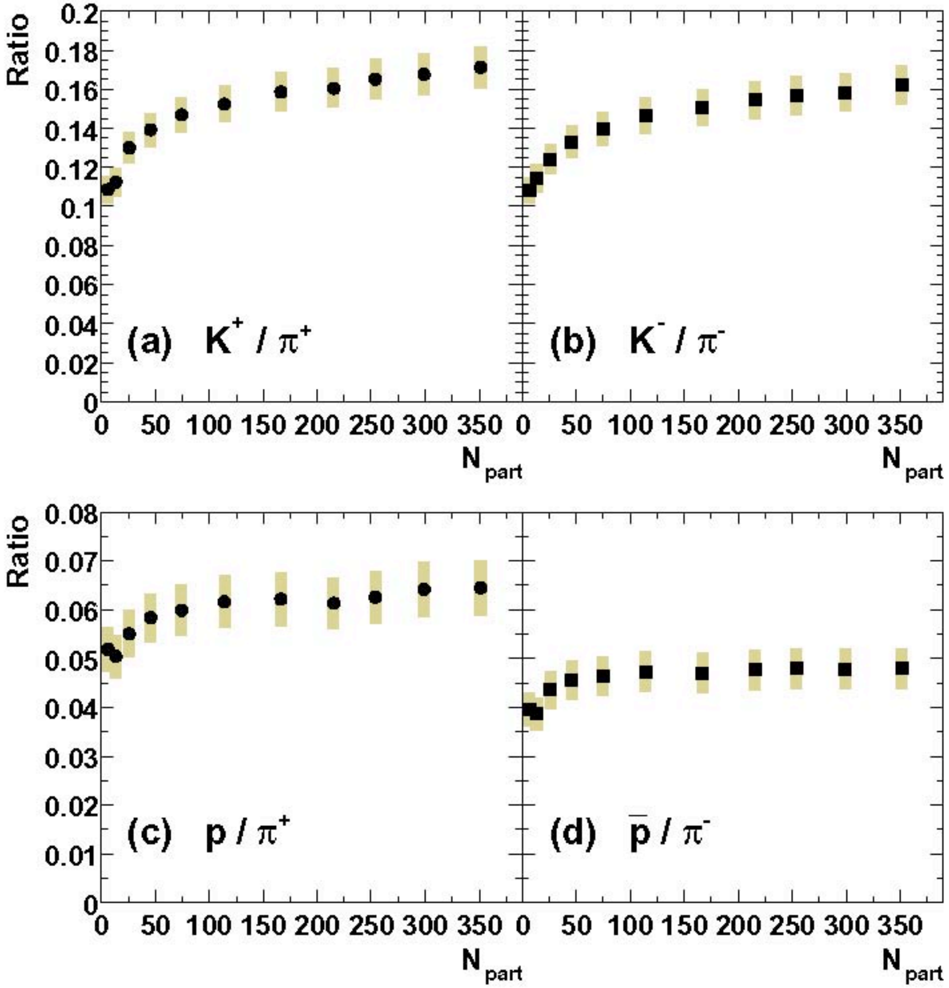
$$m_T = \sqrt{p_T^2 + m^2} = \gamma_T m$$



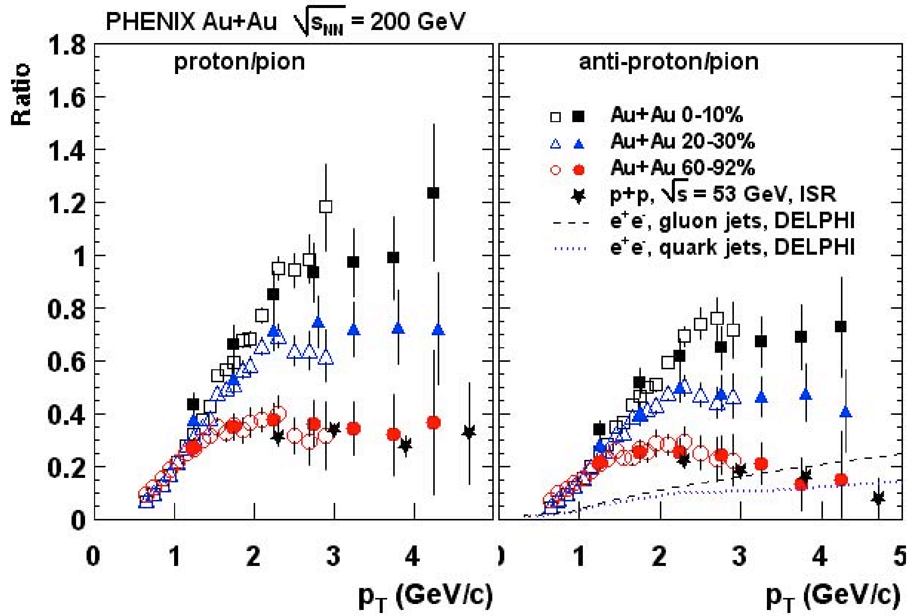
Strong radial collective flow built-up at freeze-out: $\langle \beta_T \rangle \approx 0.6$



Particle ratios---inclusive and at high p_T



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



dramatic with centrality vs p_T

inclusive vs centrality-nothing much

Low p_T (inclusive) ratios consistent with ``Thermal''--but so are pp and $e^+ e^-$

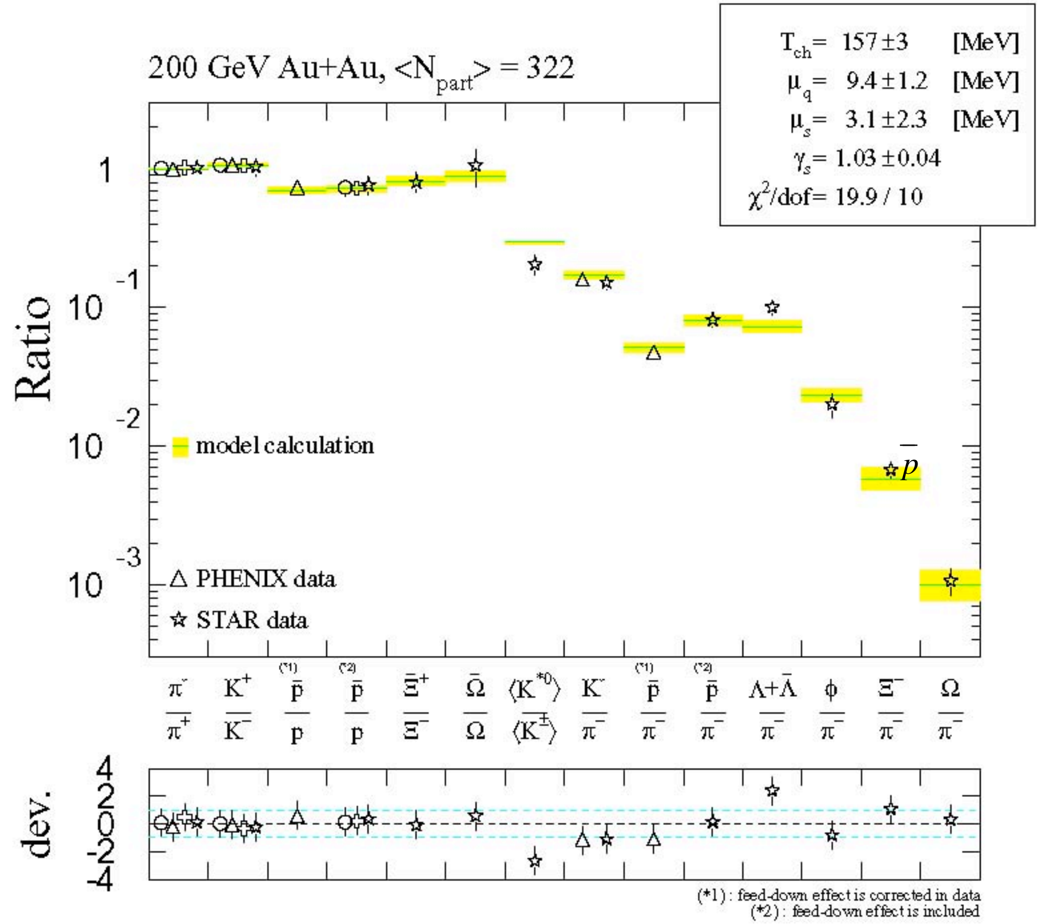


Fig. 10. Comparison of PHENIX (triangles), STAR (stars), BRAHMS (circles), and PHOBOS (crosses) particle ratios from central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity. The thermal model descriptions from Kaneta [78] are also shown as lines. See Kaneta [78] for the experimental references.

- Assume all distrib. described by one T and one μ:

$$dN \sim e^{-(E-\mu)/T} d^3p$$

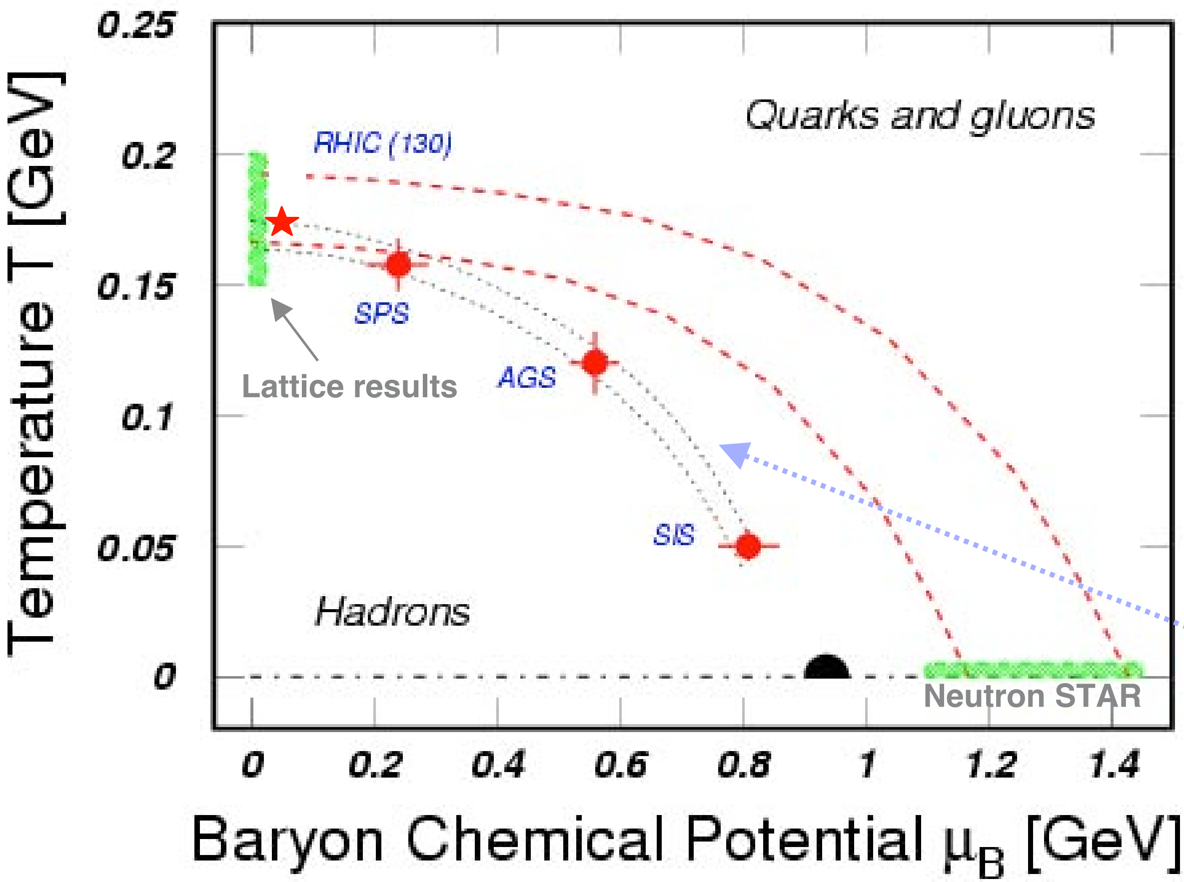
- 1 ratio (e.g. $\bar{p}/p$) determines μ/T

$$\bar{p}/p \sim e^{-(E+\mu)/T} / e^{-(E-\mu)/T} = e^{-2\mu/T}$$

- 2^{nd} ratio (e.g. K/pi) provides T,μ.

- Then predict all other hadronic yields and ratios
- n.b strangeness not suppressed γ_s=1

Phase Diagram from Thermal Fit of particle ratios---``chemical"

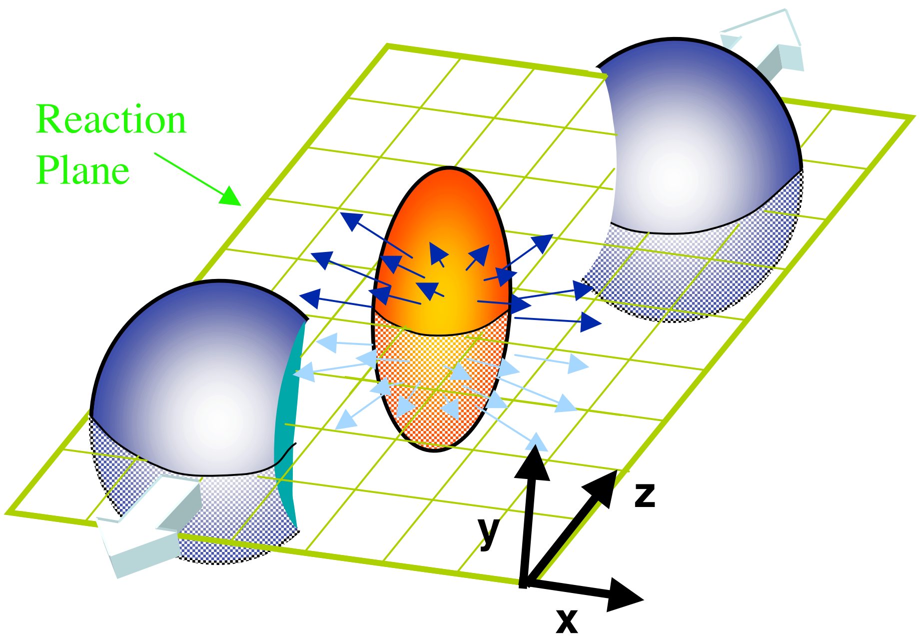


- **Final-state analysis suggests RHIC reaches the phase boundary**
- **Hadron resonance ideal gas** (M. Kaneta and N. Xu, nucl-ex/0104021 & QM02)
  - **T_{CH} = 175 ± 10 MeV**
  - **μ_B = 40 ± 10 MeV**
- **<E>/N ~ 1 GeV**

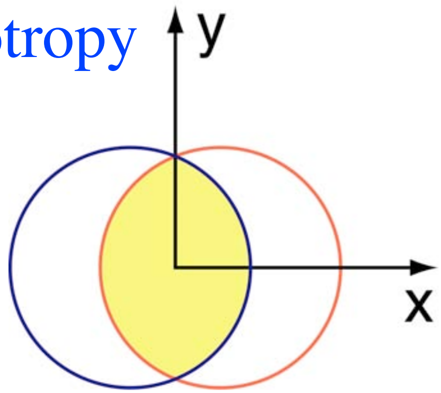
(J. Cleymans and K. Redlich, Phys.Rev.C, 60, 054908, 1999)

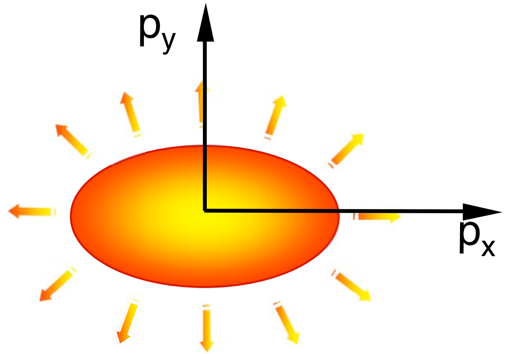
- Where is the QGP critical point?

Anisotropic (Elliptic) Transverse Flow--an Interesting complication in AA collisions



- spatial anisotropy⇒ momentum anisotropy



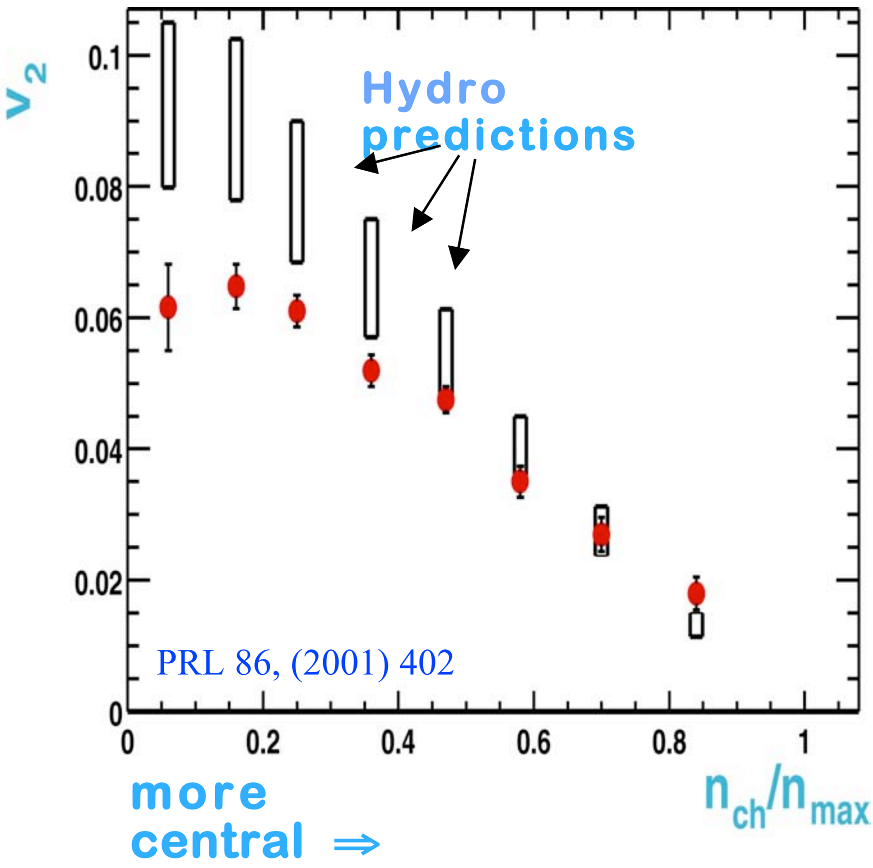


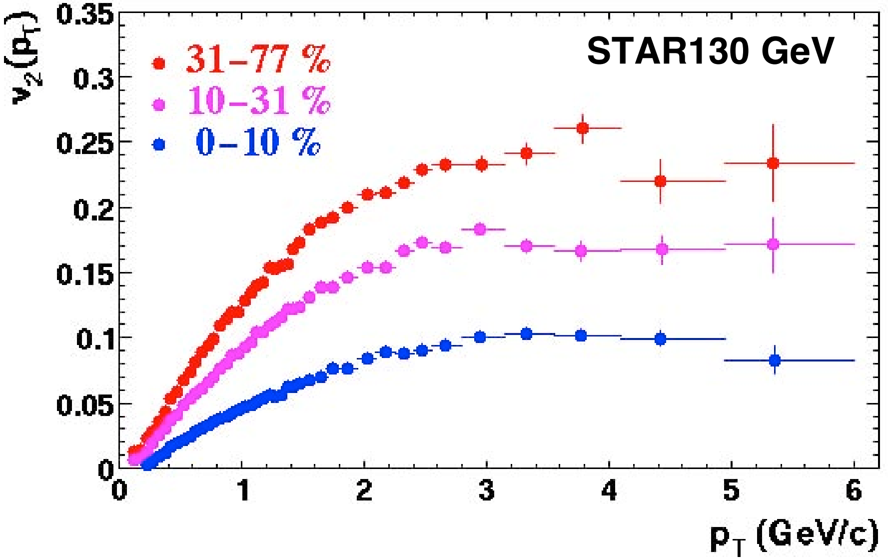
- Perform a Fourier decomposition of the momentum space particle distributions in the x-y plane
  - ✓ v_2 is the 2nd harmonic Fourier coefficient of the distribution of particles with respect to the reaction plane

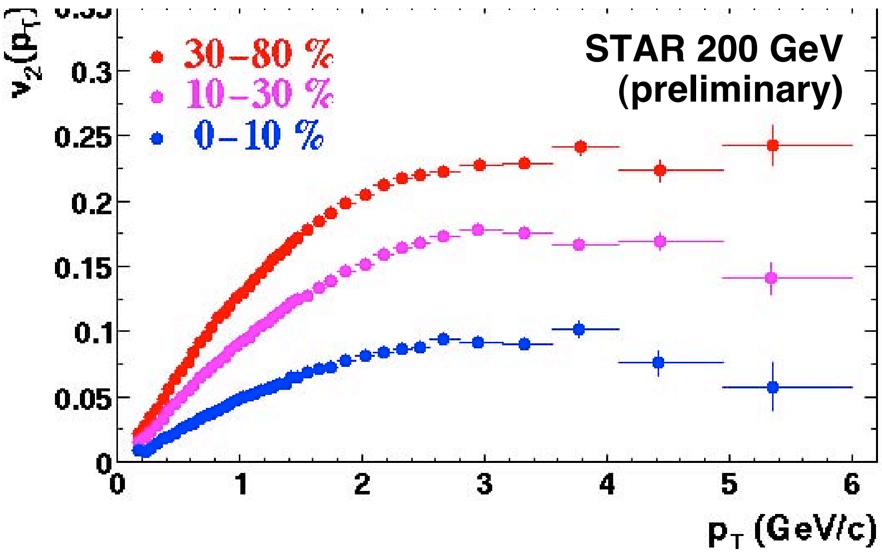
$$v_2 = \langle \cos 2\phi \rangle \qquad \phi = \mathrm{atan}\frac{p_y}{p_x}$$

Centrality and p_T dependence of v_2

unidentified charged hadrons

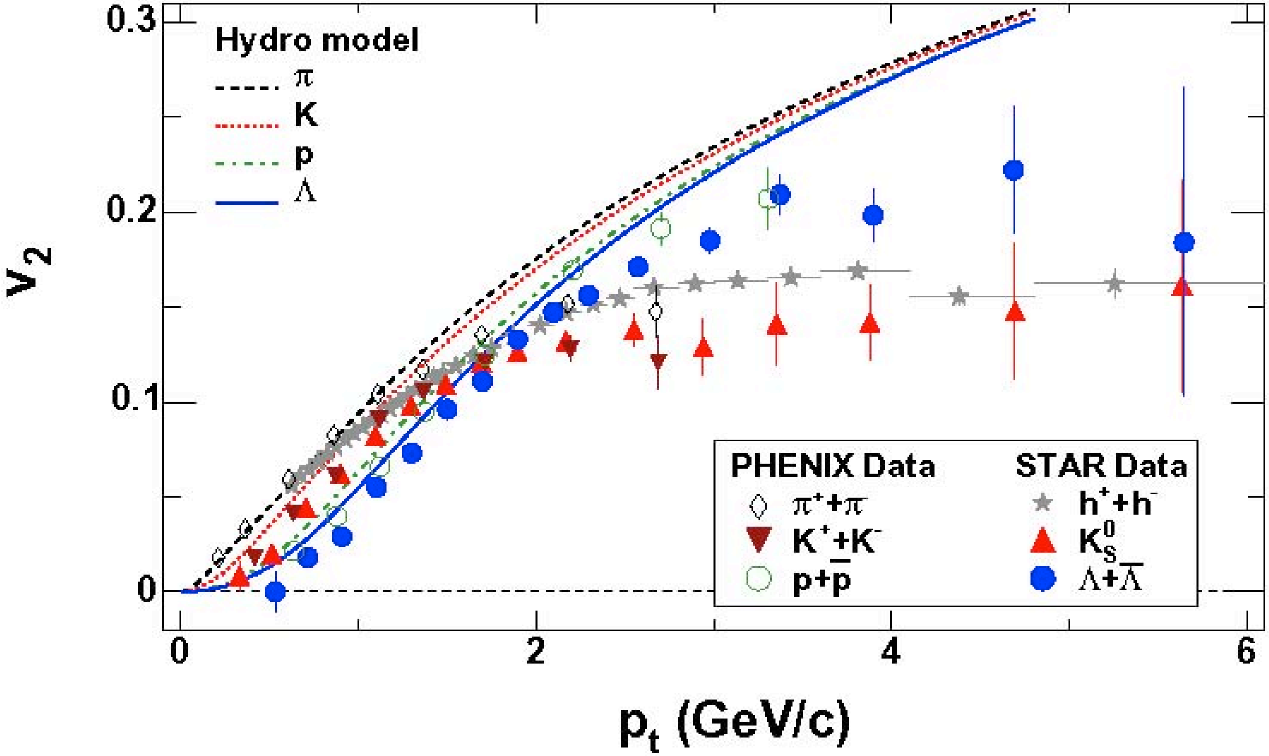




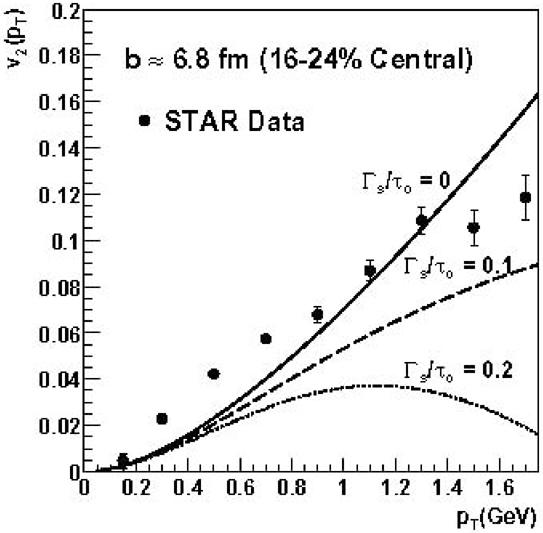


- follows eccentricity of almond
- saturates for pT >2 GeV/c

Detailed comparison to hydrodynamics with identified particles--The perfect fluid (?)

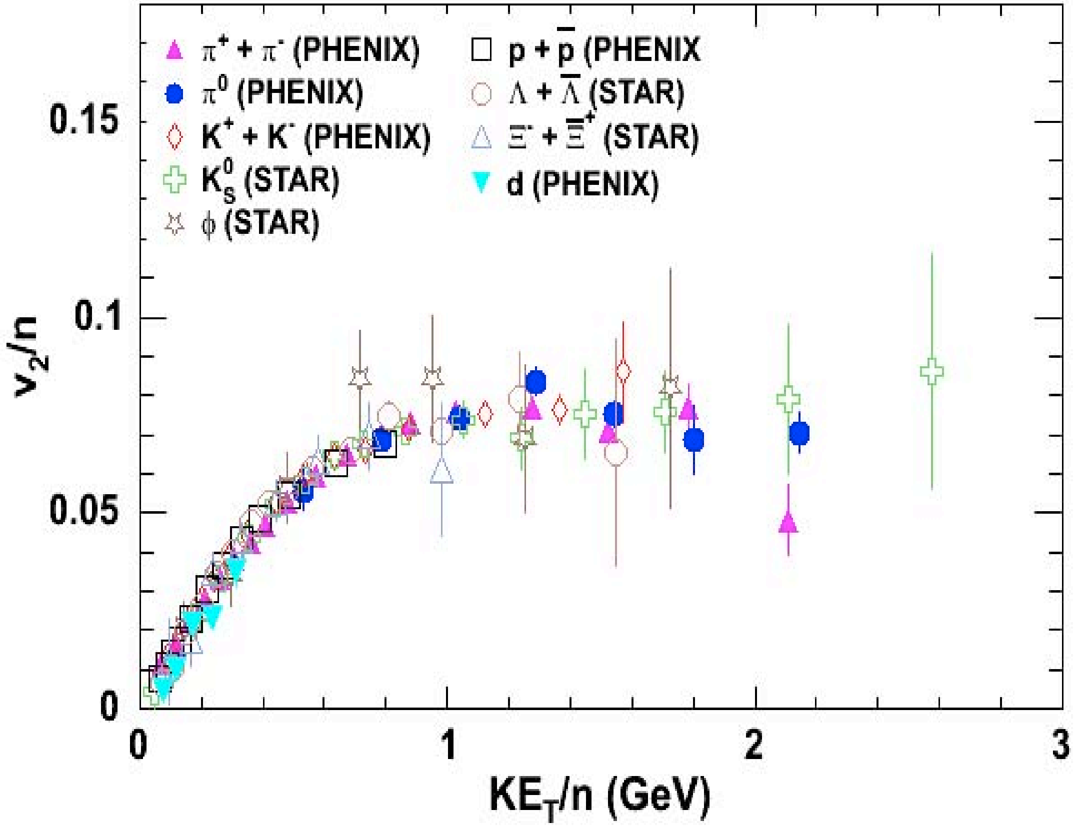


STAR-PRC72, 014904 (2005)



D.Teaney,
PRC**68**, 034913 (2003)

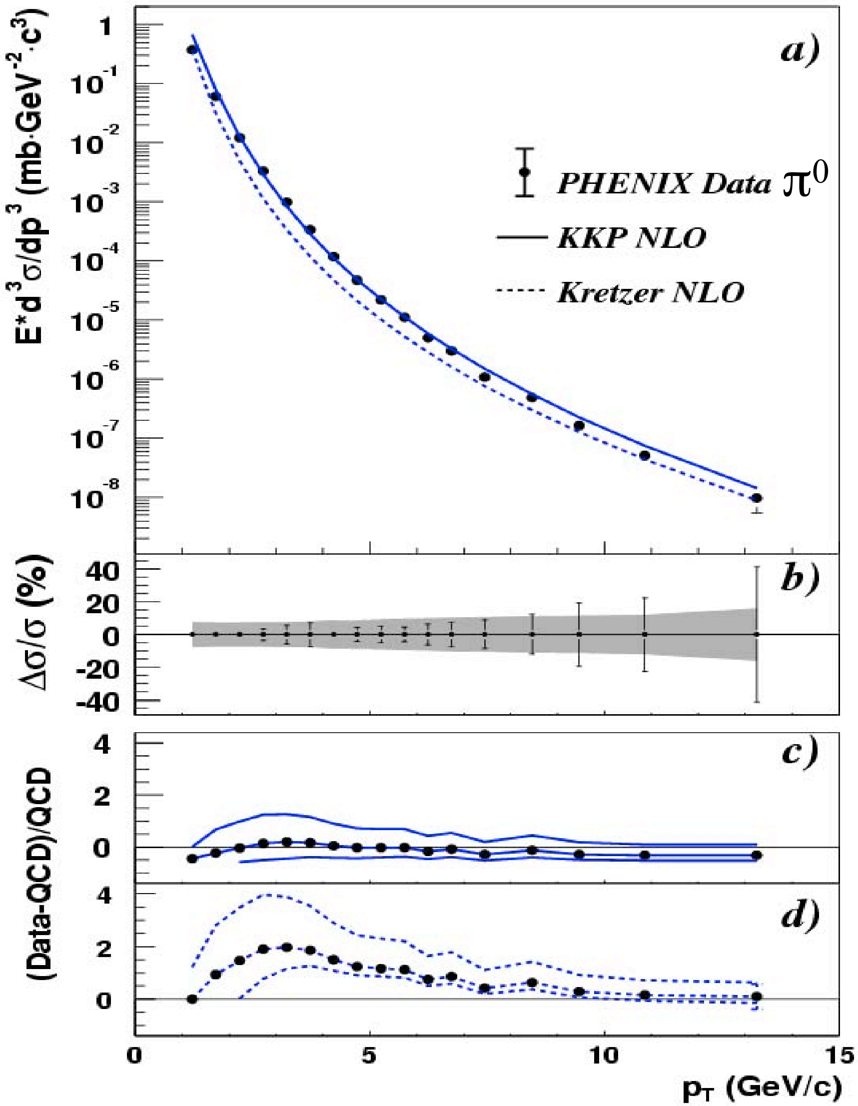
All particles scale in v2/n vs KE_T/n ⇒ constituent quarks flow



v_2 per quark vs Kinetic Energy per quark scaling works for a broad set of particles
φ flow and scaling--evidence for partonic flow due to small φ hadronic cross section

Hard-Scattering: Jet (π^0) Suppression

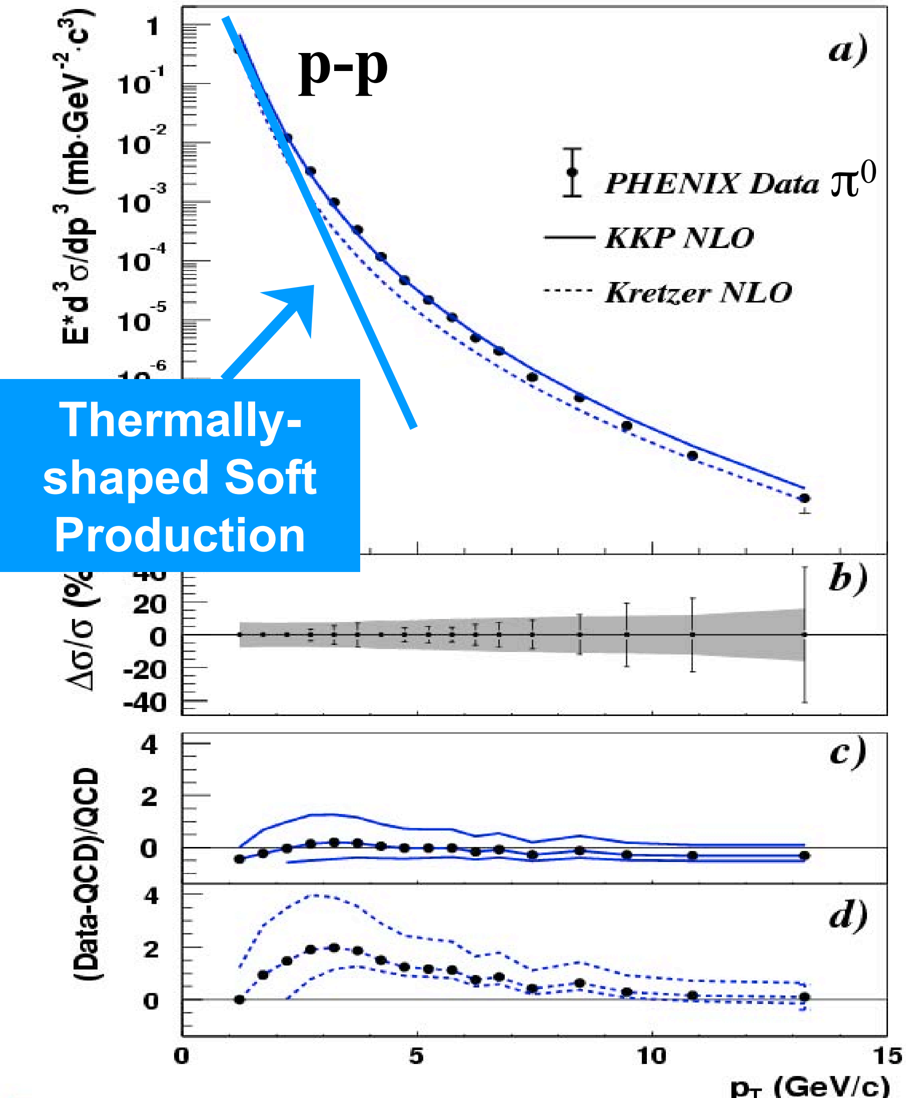
RHIC pp spectra √s=200 GeV nicely illustrate hard scattering phenomenology



- Good agreement with NLO pQCD
  - ✓ this is no surprise for `old timers' (like me) since single particle inclusive spectra were what proved QCD in the late 1970's before jets.
- **Reference for A+A and p+A spectra**
  - ✓ π^0 measurement in same experiment allows us the study of nuclear effect with less systematic uncertainties.

PHENIX (p+p) PRL 91, 241803 (2003)

RHIC pp spectra √s=200 GeV nicely illustrate hard scattering phenomenology



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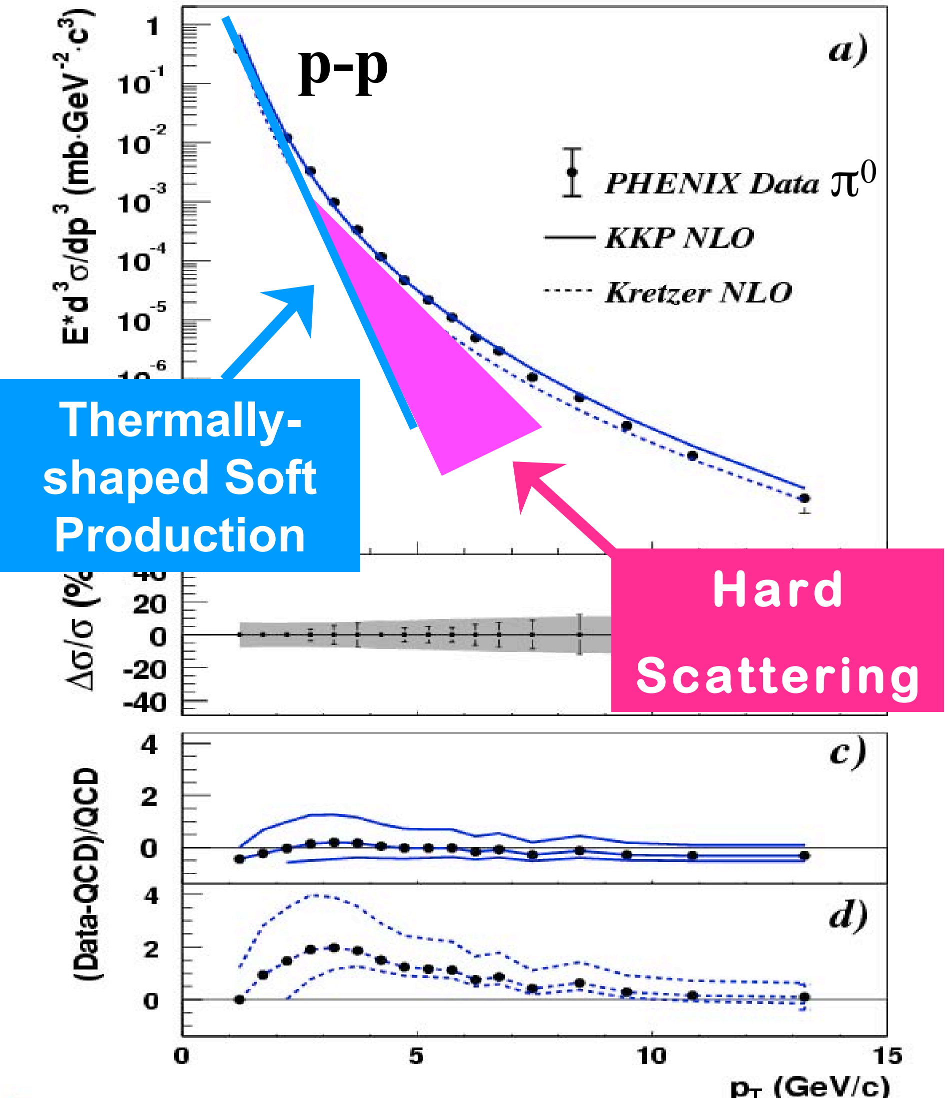

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PHENIX (p+p) PRL 91, 241803 (2003)

μ-A DIS at AGS (1973)--Hard-Scattering is pointlike

E. Gabathuler, Total cross-section

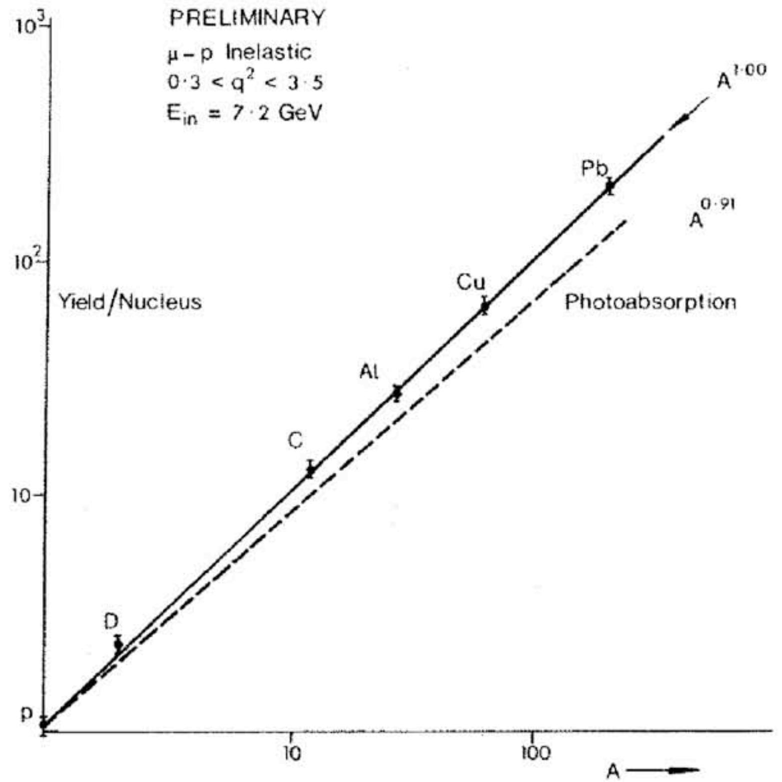
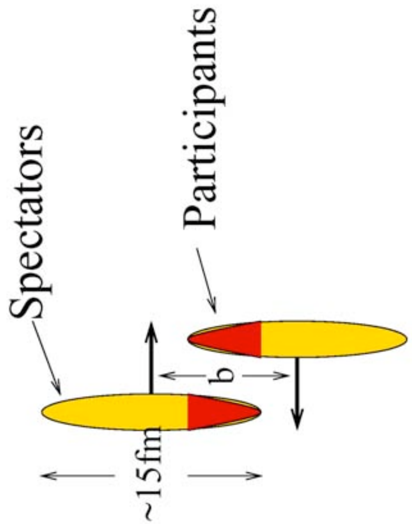


Fig. 14. The *A* dependence of the inelastic muon cross-section as presented by Tannenbaum (see discussion).

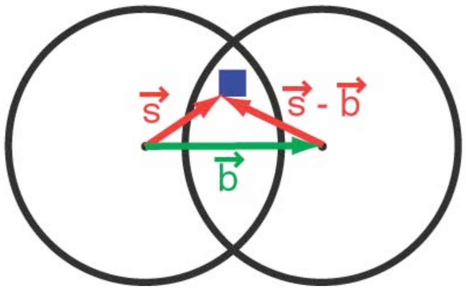
AGS $\mu - A$ scattering data, from E. Gabathuler's talk, [Proc. 6th Int. Symposium on Electron and Photon Interactions at High Energies, Bonn (1973)].

- ♡ DIS is pointlike $A^{1.00}$ even at modest q^2—no shadowing.
- ♡ Photoproduction is shadowed—$A^{0.91}$

High p_T in A+B collisions---T_{AB} Scaling



looking down



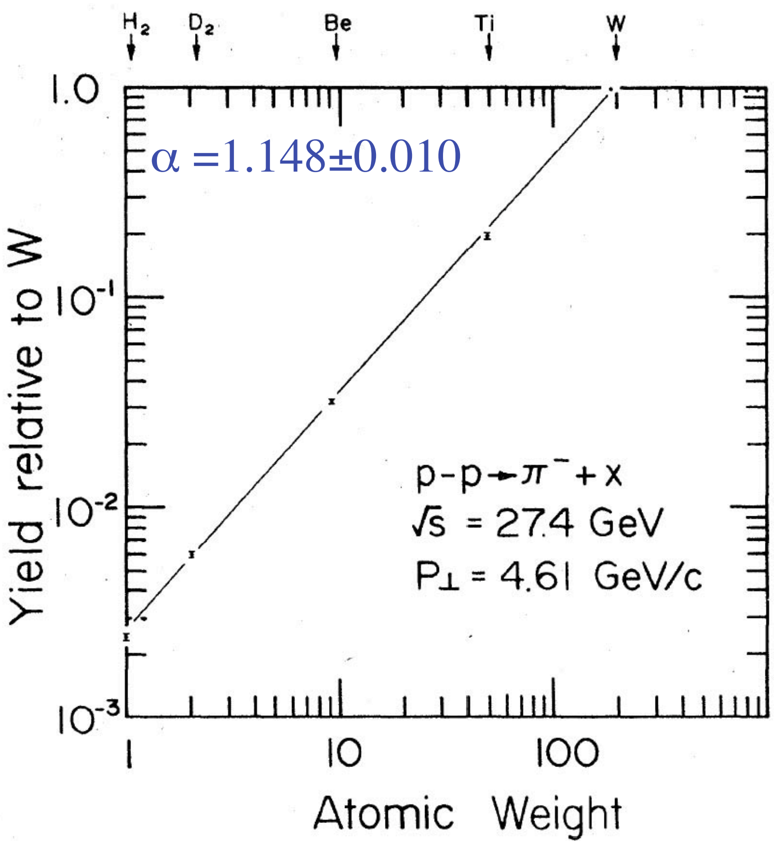
view along beam axis

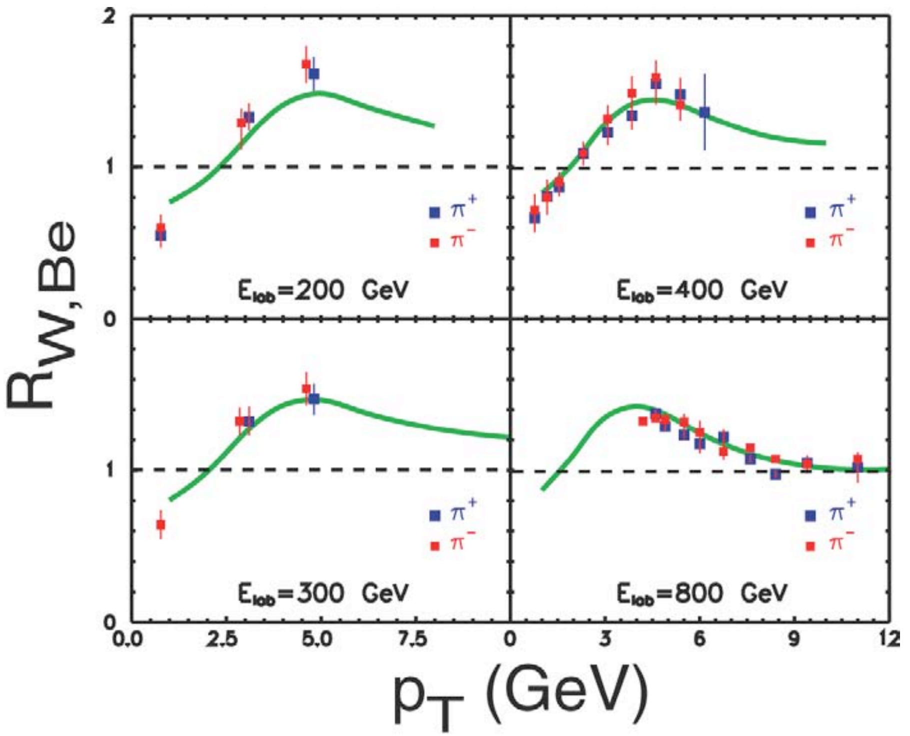
- For point-like processes, the cross section in p+A or A+B collisions compared to p-p is simply proportional to the relative number of possible pointlike encounters
  - ✓ A for p+A, AB for A+B for the total rate
  - ✓ T_{AB} the overlap integral of the nuclear profile functions, as a function of impact parameter b

What really Happens for p+A: $R_A > 1$!

The anomalous nuclear enhancement a.k.a. the Cronin effect-- due to multiple scattering of initial nucleons (or constituents)

- Known since 1975 that yields increase as A^{α}, $\alpha > 1$



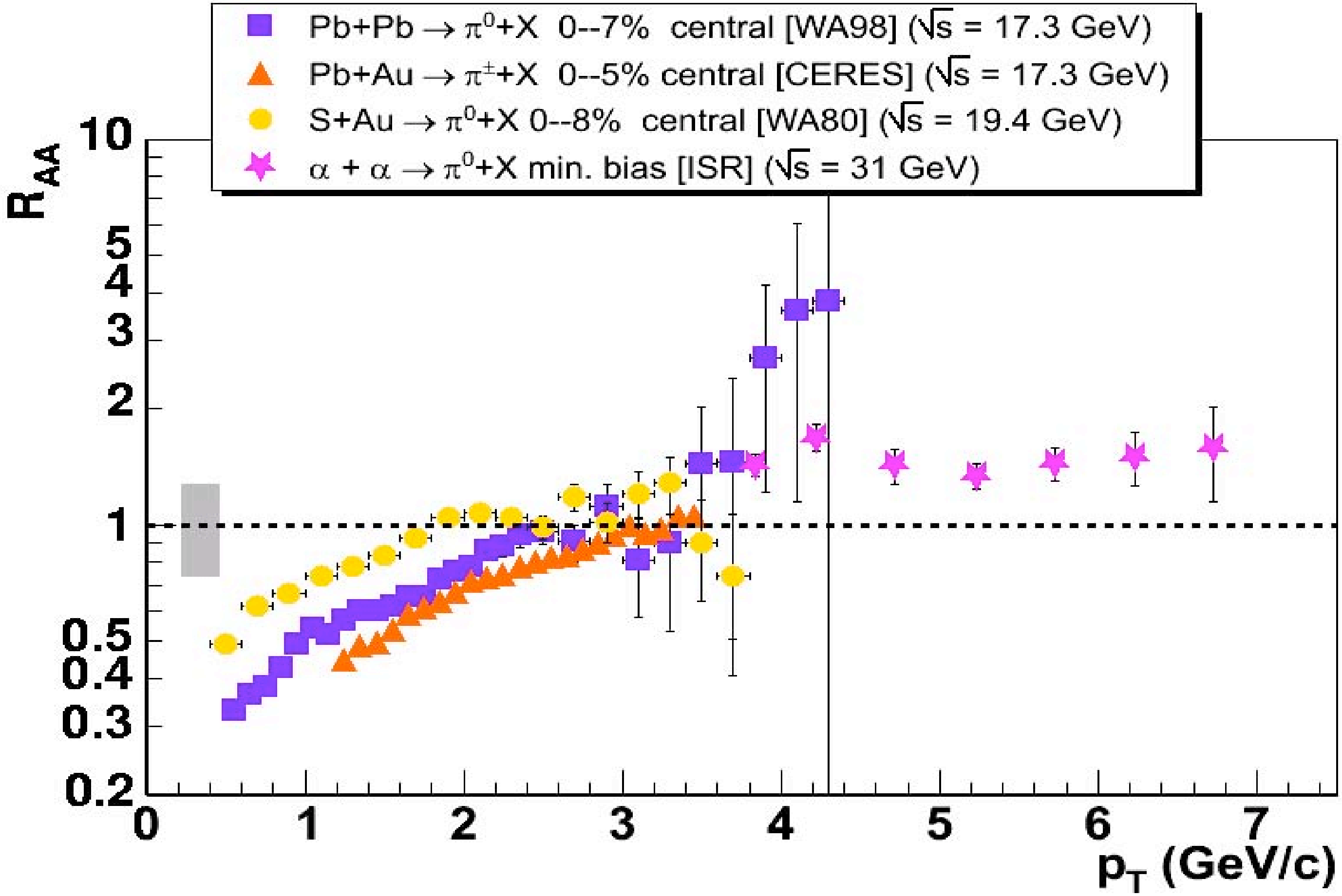


- J.W. Cronin et al., Phys. Rev. **D11**, 3105 (1975)
- D. Antreasyan et al., Phys. Rev. **D19**, 764 (1979)

Same for A+A at $\sqrt{s_{NN}}$= 17, 31 GeV

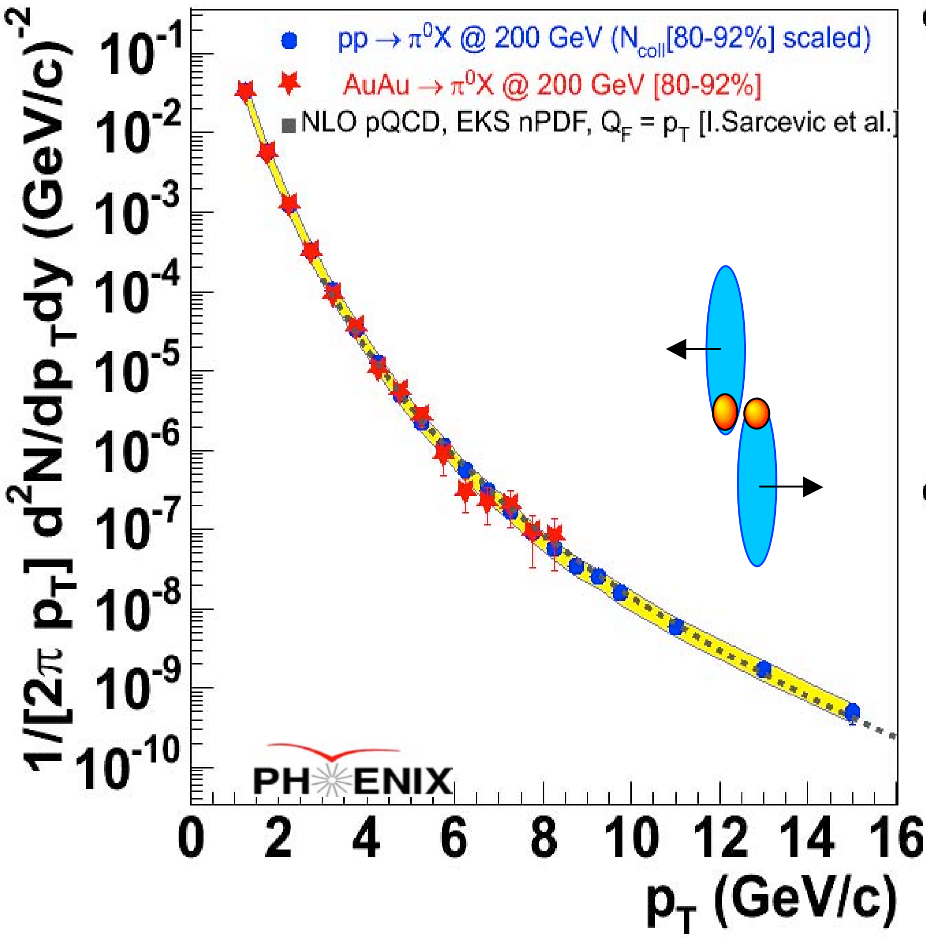
Nuclear Modification Factor:

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

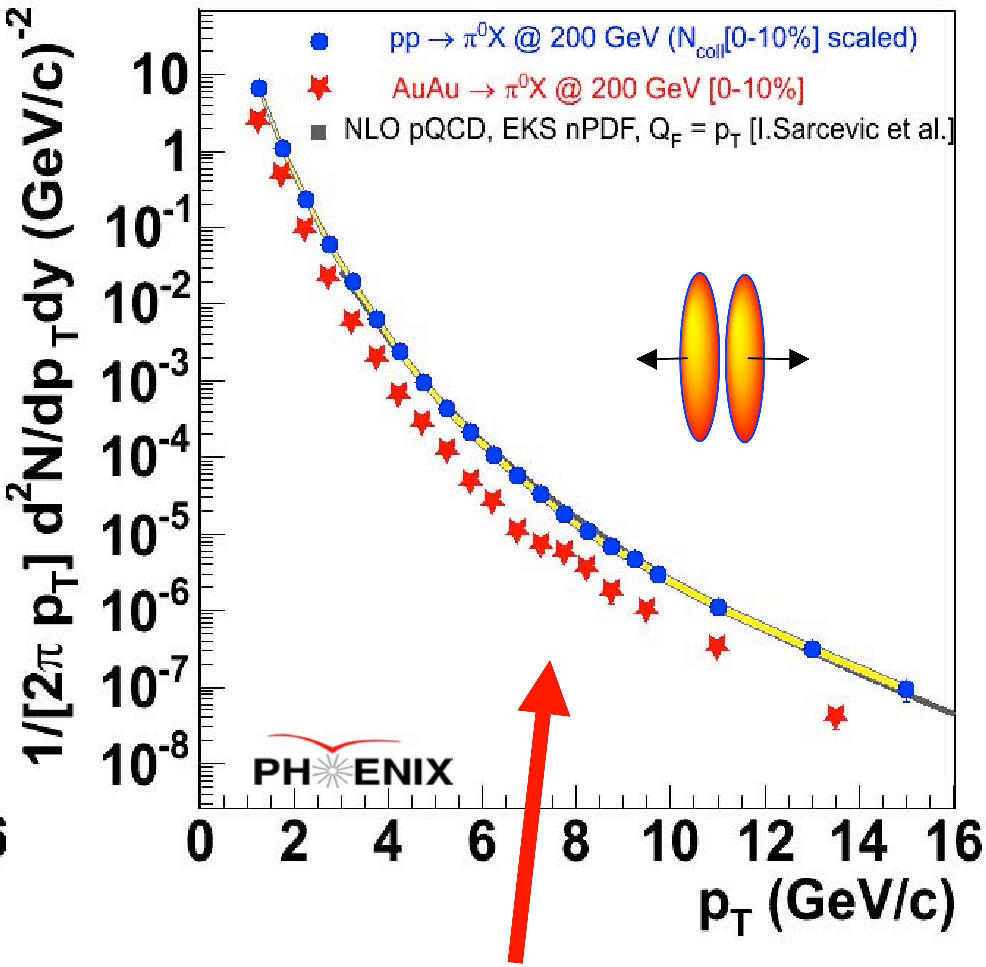


For Au+Au at RHIC--strong suppression !

Au+Au→ π^0 X (peripheral)



Au+Au→ π^0 X (central)



Peripheral data agree well with p+p (data & pQCD) scaled by T_{AB} (N_{coll}-)

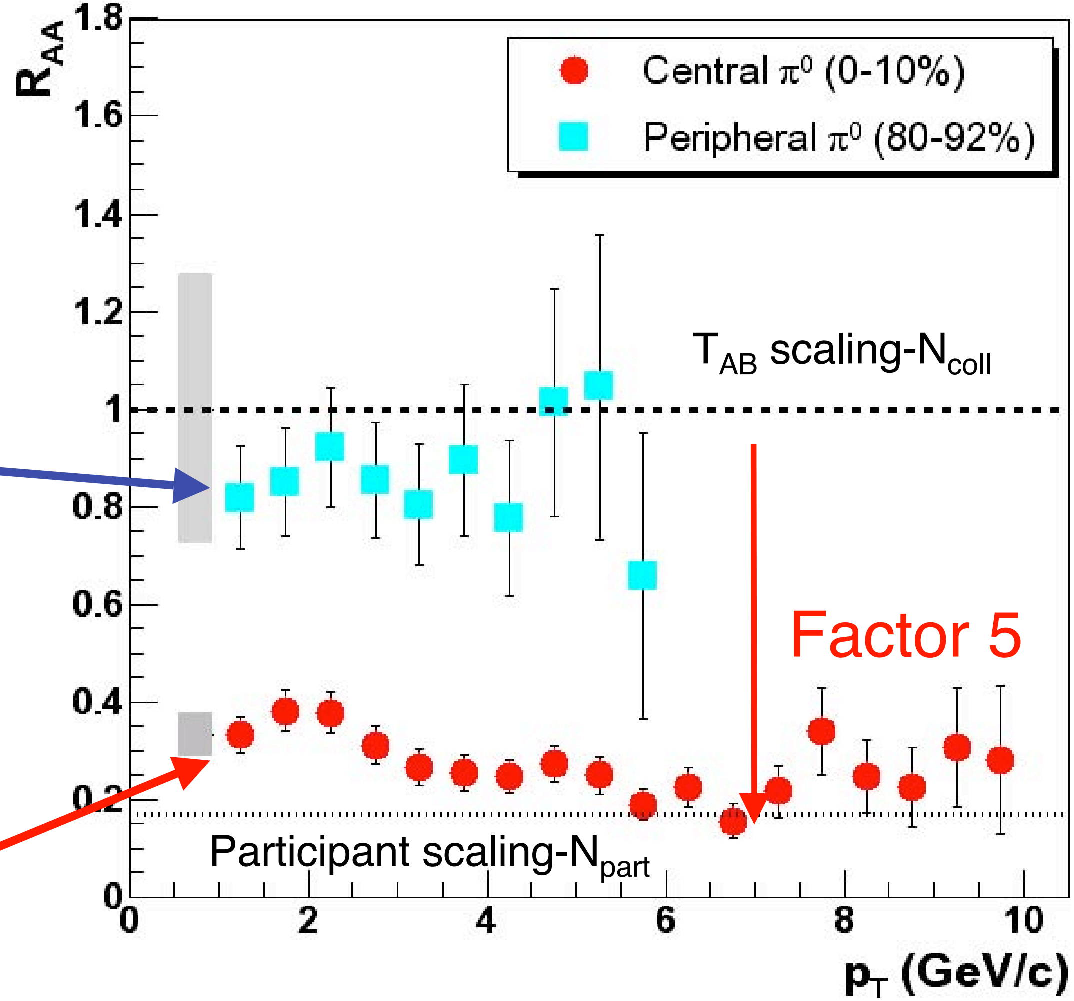
Strong suppression in central Au+Au collisions

R_{AA} (π^0) AuAu:pp 200GeV
High p_T Suppression flat from 3 to 10 GeV/c !

$$R_{AA} = \frac{\text{Yield}_{AuAu}(p_T)}{\langle T_{AB}\rangle_{AuAu} \times \sigma_{pp}(p_T)}$$

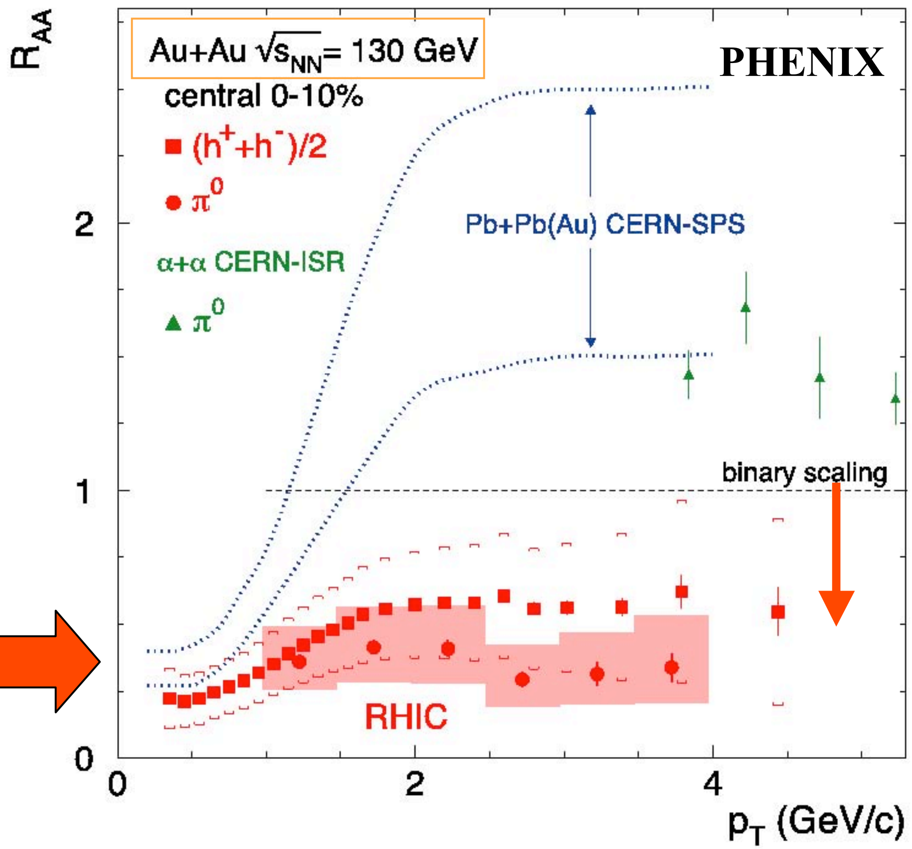
Peripheral AuAu - consistent with N_{coll} scaling (large systematic error)

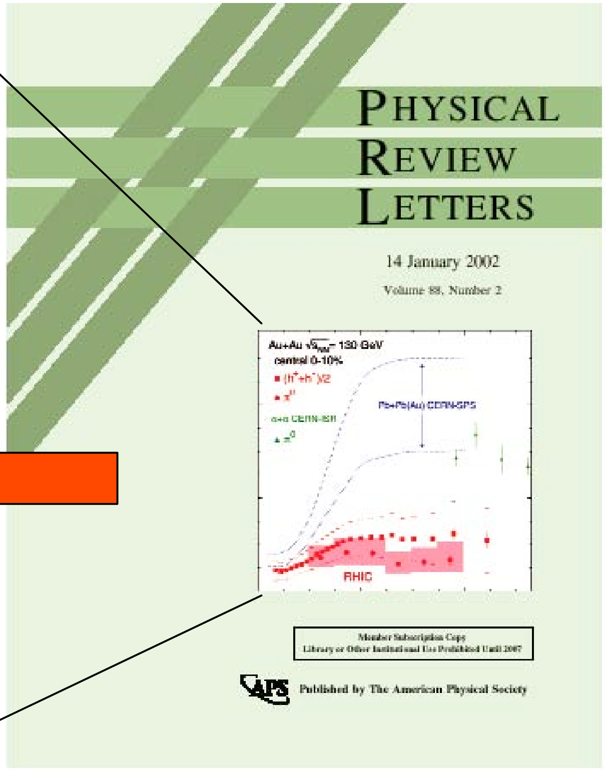
Large suppression in central AuAu - close to participant scaling at high P_T



PRL 91, 072301 (2003)

Run-1: RHIC Headline News … January 2002
THE major discovery at RHIC (so far)





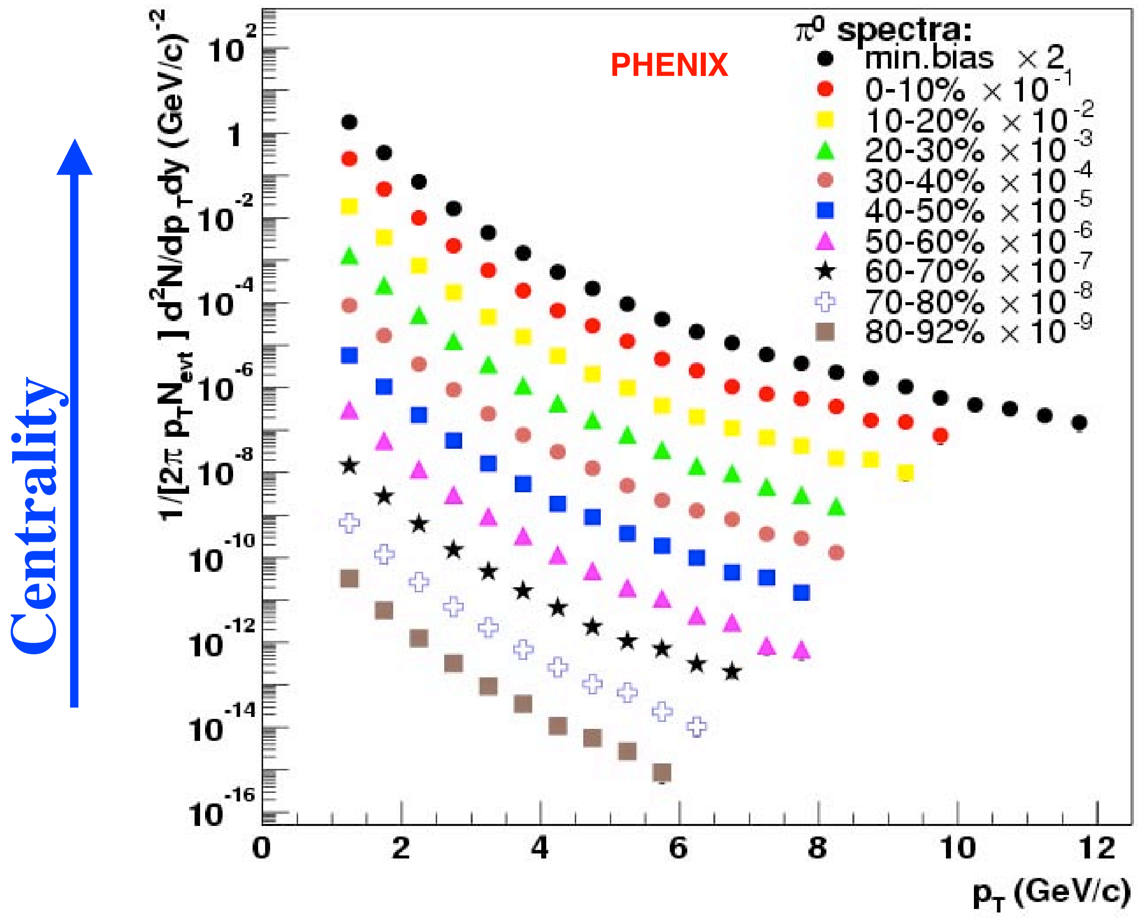
PHENIX PRL 88, 022301 (2002)

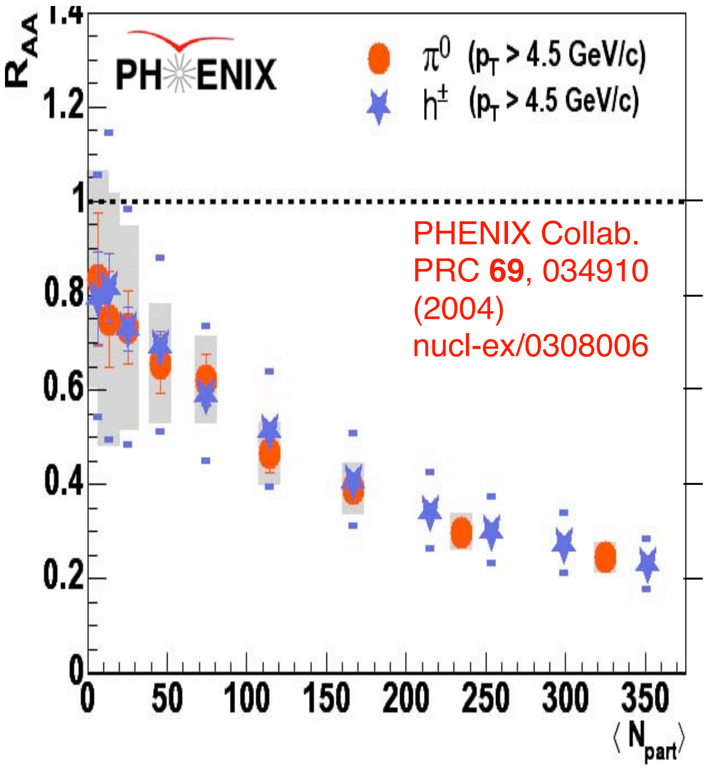
First observation of *large* suppression of high p_T hadron yields

"Jet Quenching"? == Quark Gluon Plasma?

RHIC Run 2 $\sqrt{s}$=200 GeV: Comprehensive π^0 data vs centrality in Au+Au + π^0 reference in p-p

Au-Au nucl-ex/0304022 Phys. Rev. Letters **91**, 072301 (2003)

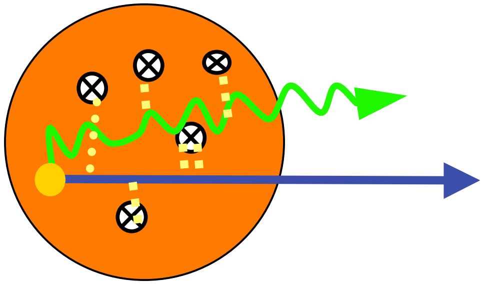




Suppression: Final State Effect?

- **Hadronic absorption of fragments:**
  - ✓ Gallmeister, et al. PRC67,044905(2003)
  - ✓ Fragments formed inside hadronic medium
- **Parton recombination (up to moderate p_T)**
  - ✓ Fries, Muller, Nonaka, Bass nucl-th/0301078
  - ✓ Lin & Ko, PRL89,202302(2002)
- **Energy loss of partons in dense matter**
  - ✓ Gyulassy, Wang, Vitev, Baier, Wiedemann…

  See nucl-th/0302077 for a review.



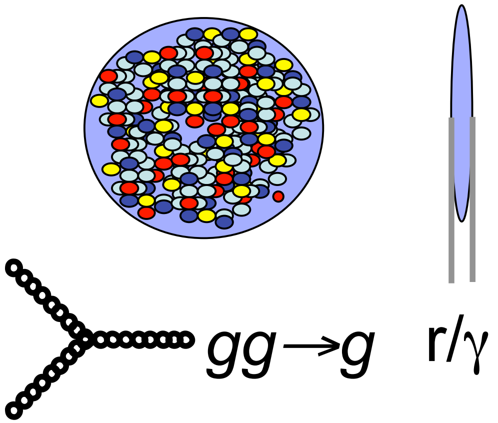
Alternative: Initial Effects

- **Gluon Saturation**
  ✓ **(color glass condensate: CGC)**

Wave function of low x gluons overlap; the self-coupling gluons fuse, saturating the density of gluons in the initial state.

(gets N_{ch} right!)

hep-ph/0212316; D. Kharzeev, E. Levin, M. Nardi

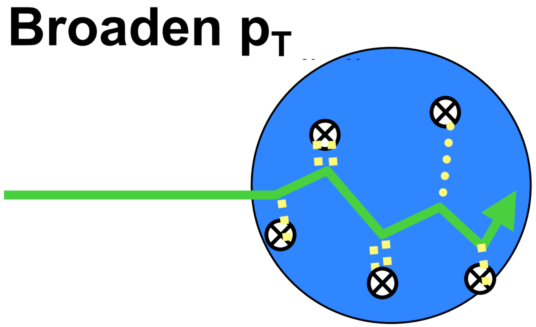


D.Kharzeev et al., PLB 561 (2003) 93

- **Multiple elastic scatterings**

(Cronin effect)

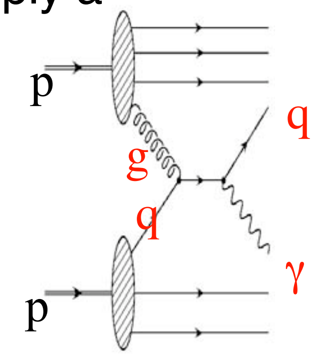
Wang, Kopeliovich, Levai, Accardi

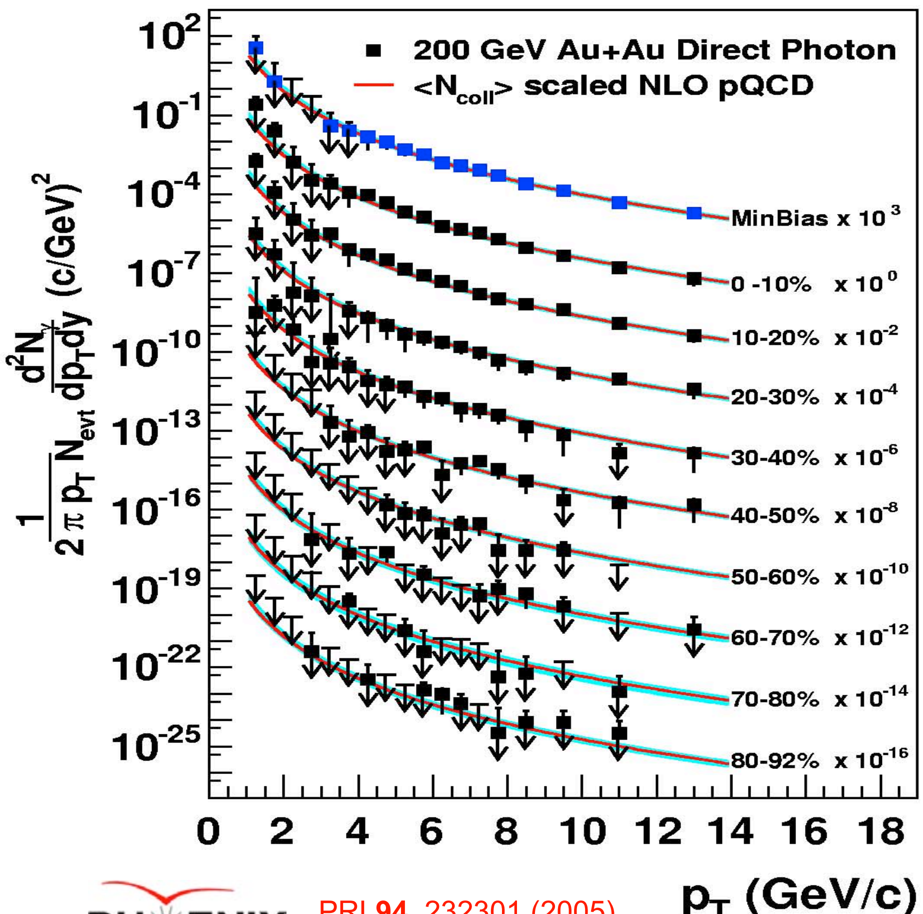


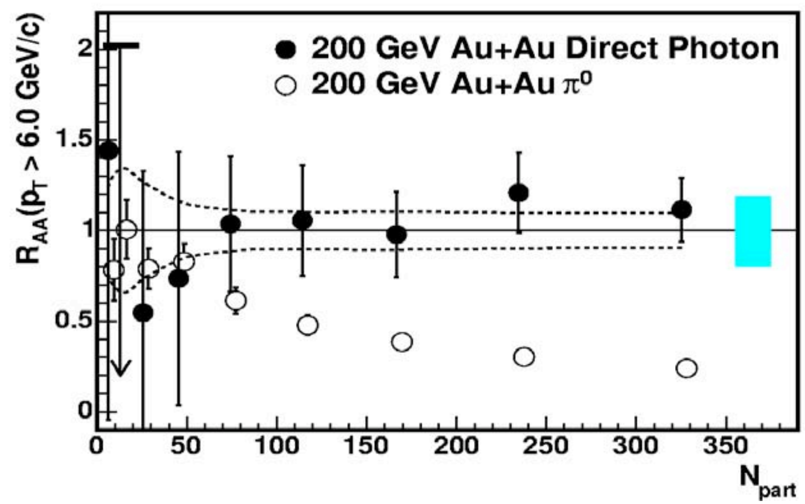
- **Nuclear shadowing**

2004--Direct Photons in Au+Au 200 GeV: follow T_{AB} scaling from p-p for all centralities-no suppression

- Direct photon production in Au+Au (all centralities) consistent w/ "T_{AB}-scaled" pQCD. Proves that initial state Au structure function is simply a superposition of p-p structure functions including g(x).





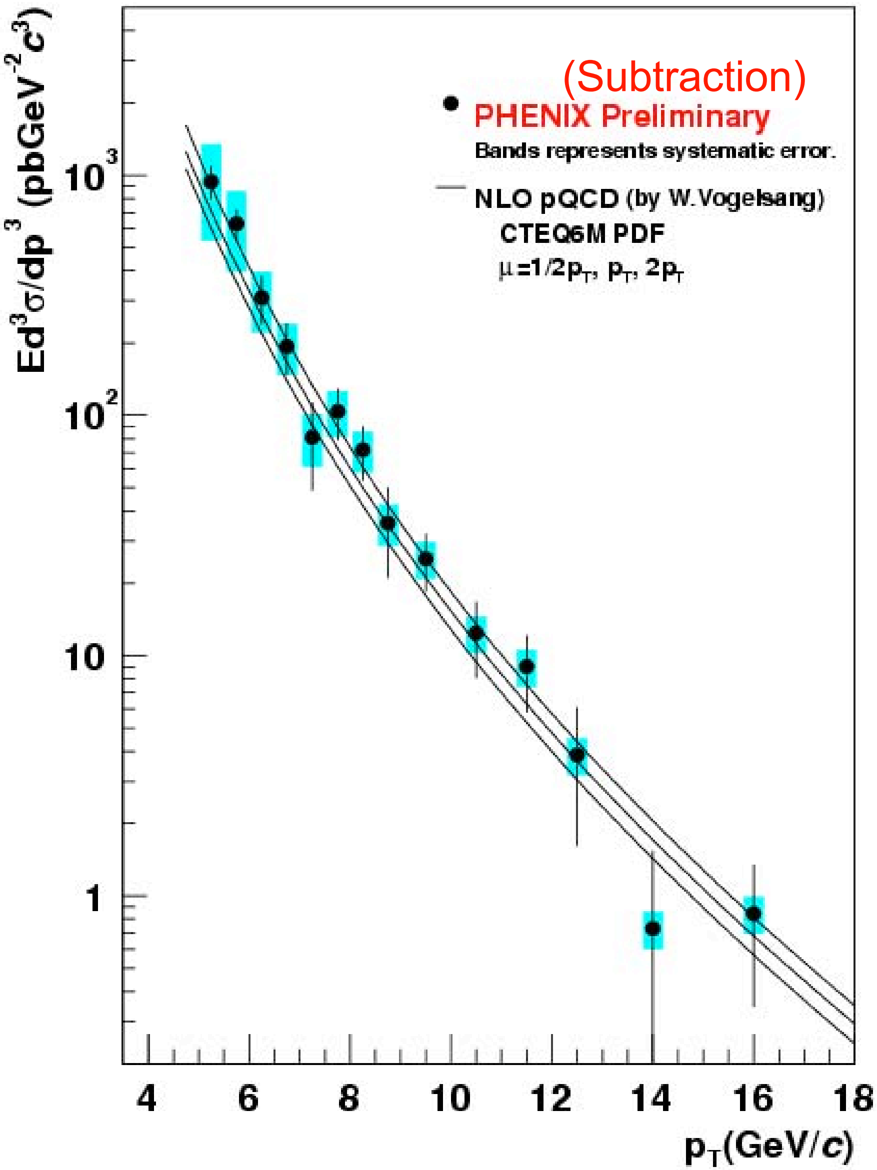


- outgoing Direct photons unaffected by QCD medium in Au+Au → π^0 **suppression is medium effect**

PHENIX

PRL**94**, 232301 (2005)
nucl-ex/0503003

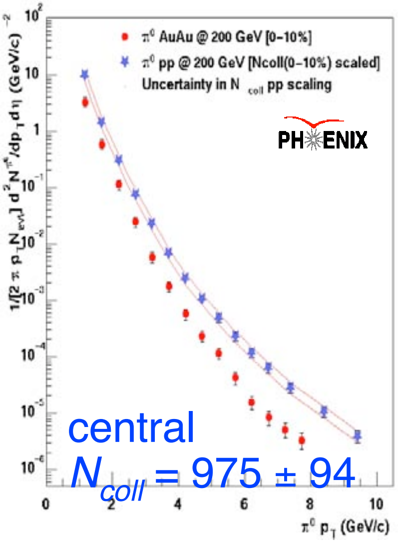
Direct-γ measurement in √s=200 GeV p-p



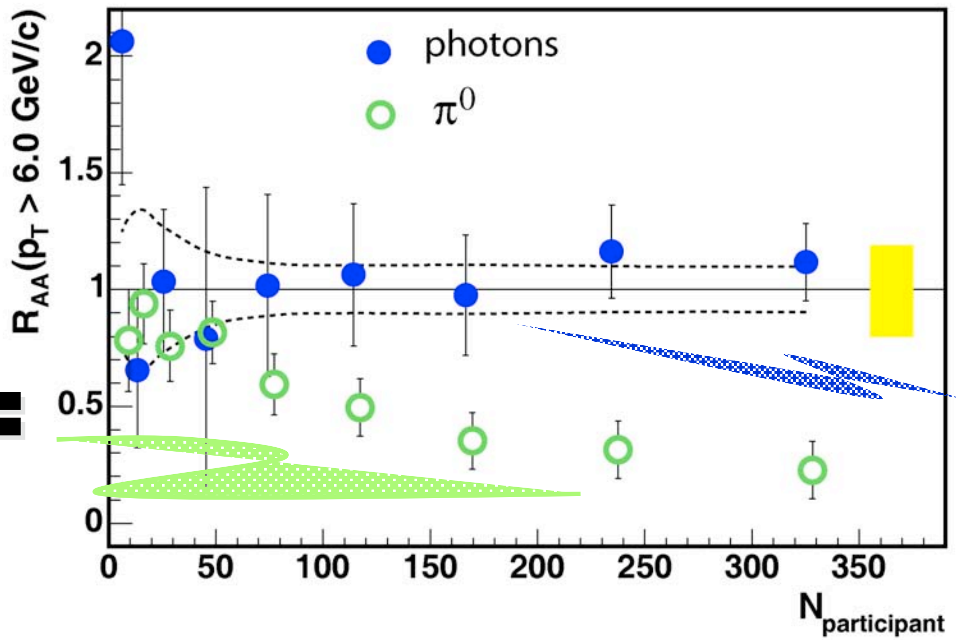
- NLO-pQCD calculation
  - ✓ Private communication with W.Vogelsang
  - ✓ CTEQ6M PDF.
  - ✓ direct photon + fragmentation photon
  - ✓ Set Renormalization scale and factorization scale pT/2,pT,2pT

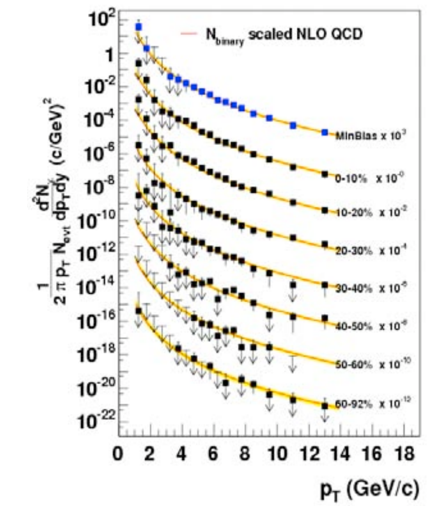
- The theory calculation shows a good agreement with our result
- Confirms use of theoretical result as Au+Au comparison
- Opens the way for measurement of gluon spin structure function from A_{LL}

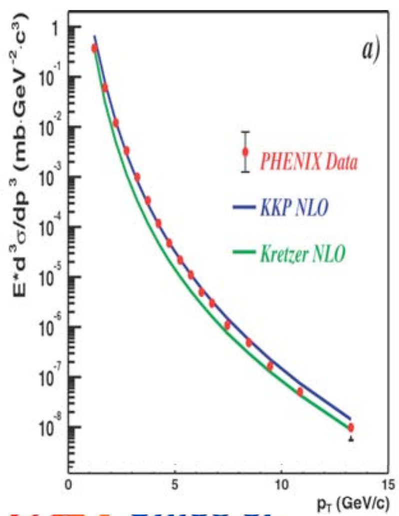
RHIC Physics is Precision Science



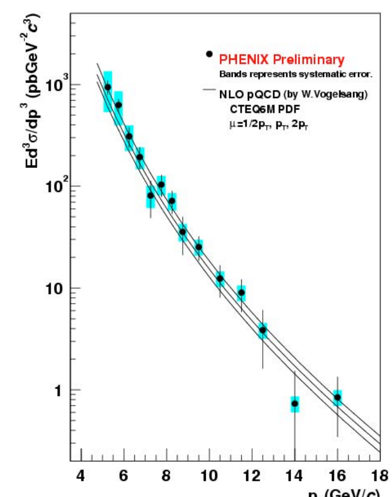
- This one figure encodes rigorous control of systematics



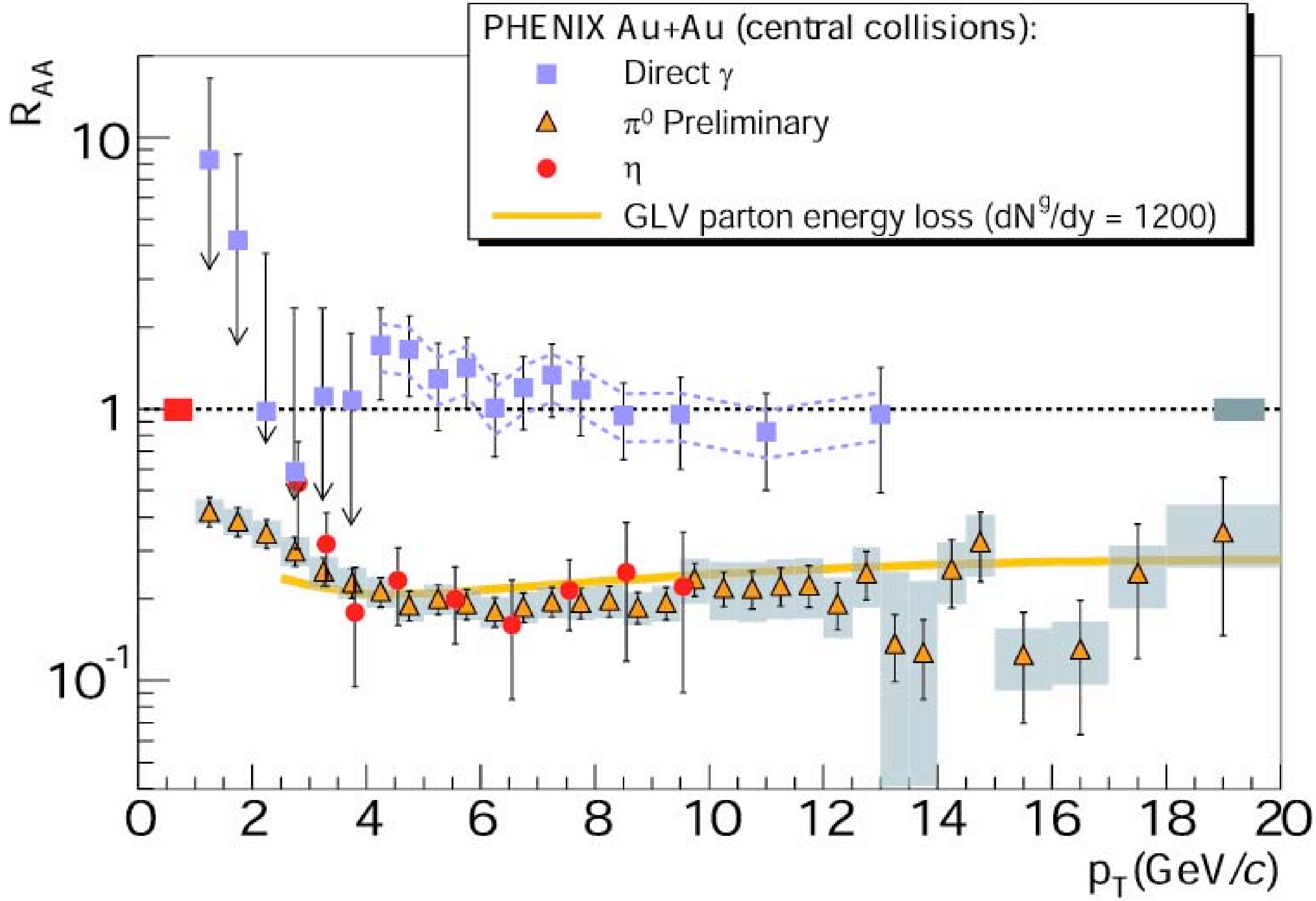




- in four different measurements over many orders of magnitude

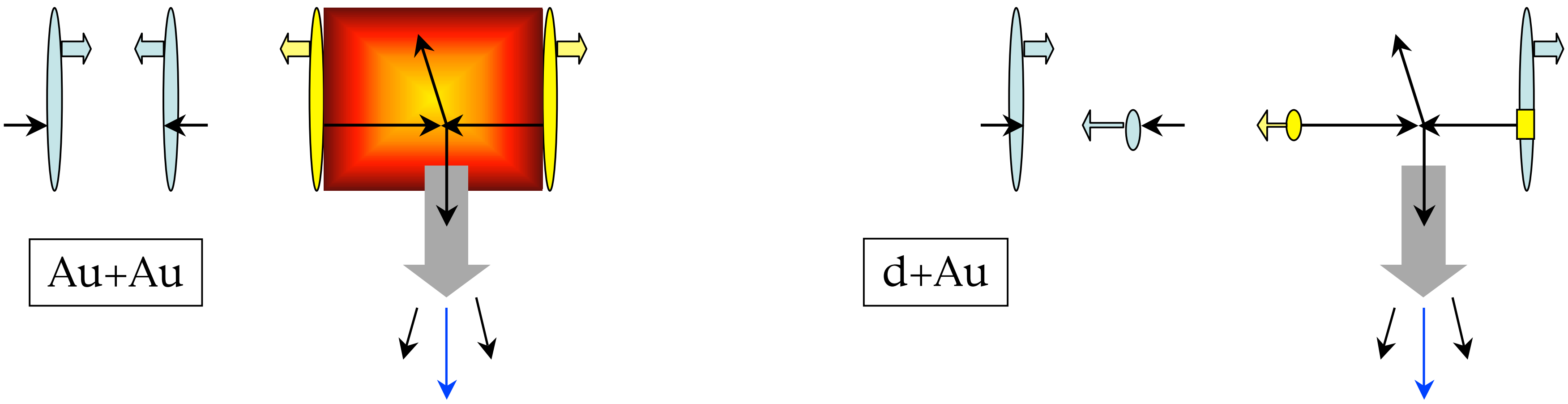


Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV



Direct γ are not suppressed. π^0 and η suppressed even at high p_T
Implies a strong medium effect (energy loss) since γ not affected.
Suppression is flat at high p_T. Are data flatter than theory?

d+Au: Control Experiment to prove the Au+Au discovery



= hot and dense medium

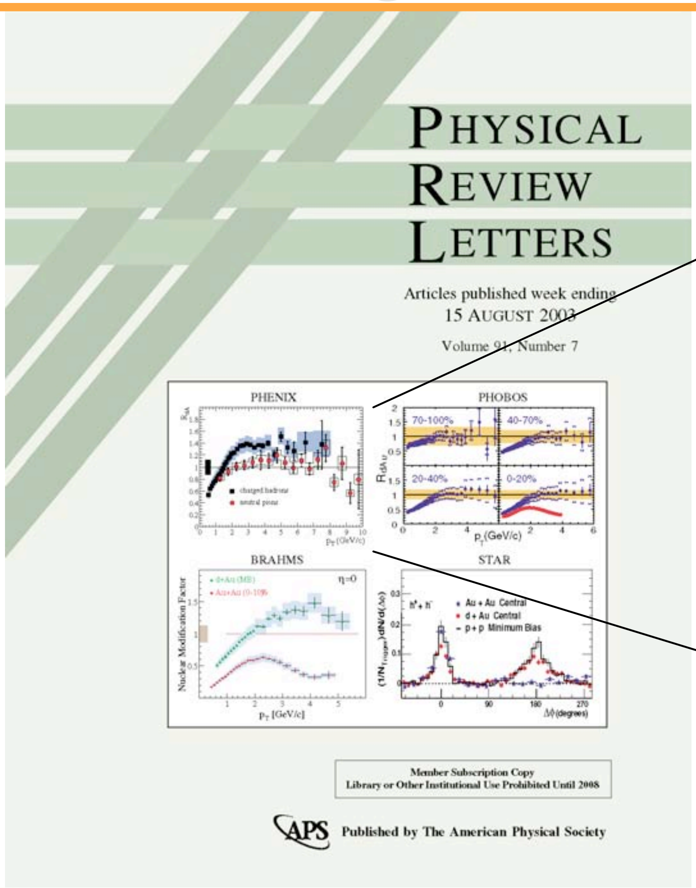
Initial + Final State Effects

= cold medium

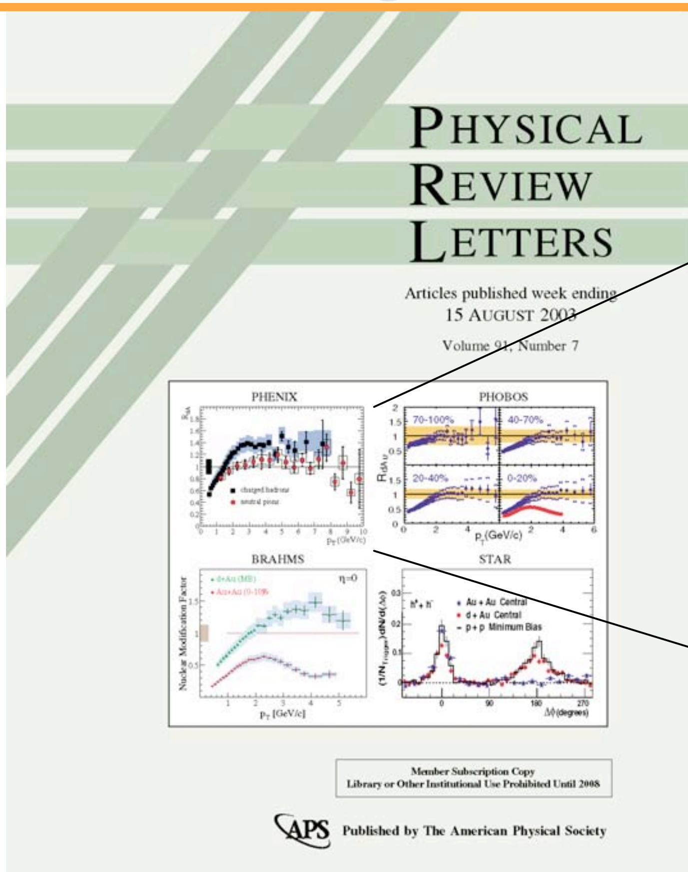
Initial State Effects Only

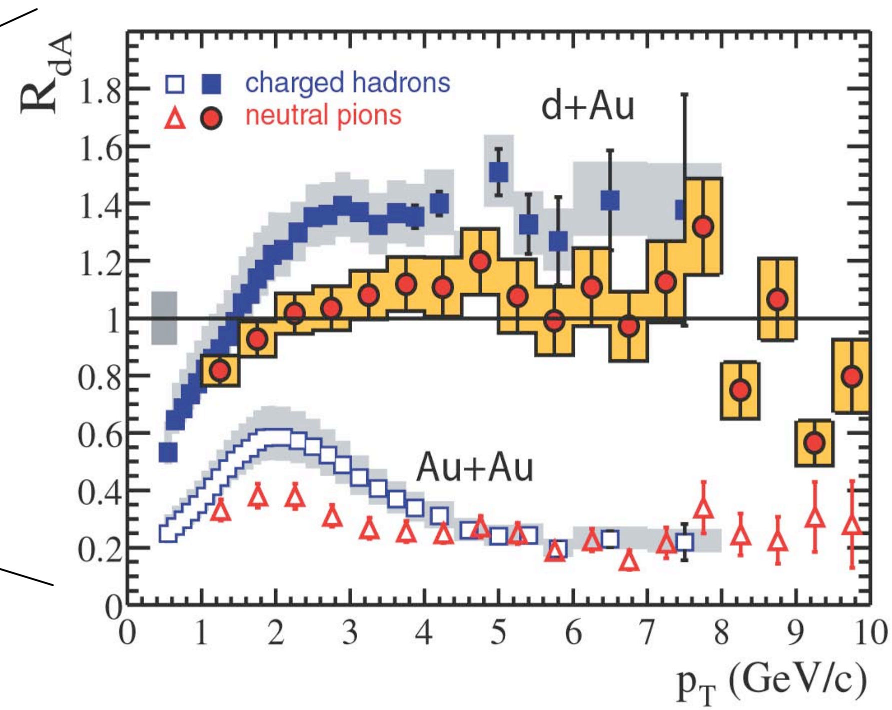
- The “Color Glass Condensate” model predicts the suppression in **both Au+Au and d+Au** (due to the initial state effect).
- **The d+Au experiment tells us that the observed hadron suppression at high p_T central Au+A is a final state effect.**
- This diagram also explains why we can’t measure jets directly in Au+Au central collisions: all nucleons participate so charged multiplicity is ~200 times larger than a p-p collision→ 300 GeV in standard jet cone.

Cronin effect observed in d+Au at RHIC $\sqrt{s_{NN}}$=200 GeV, confirms x is a good variable This leads to our second PRL cover, our first being the original Au+Au discovery



Cronin effect observed in d+Au at RHIC $\sqrt{s_{NN}}$=200 GeV, confirms x is a good variable This leads to our second PRL cover, our first being the original Au+Au discovery





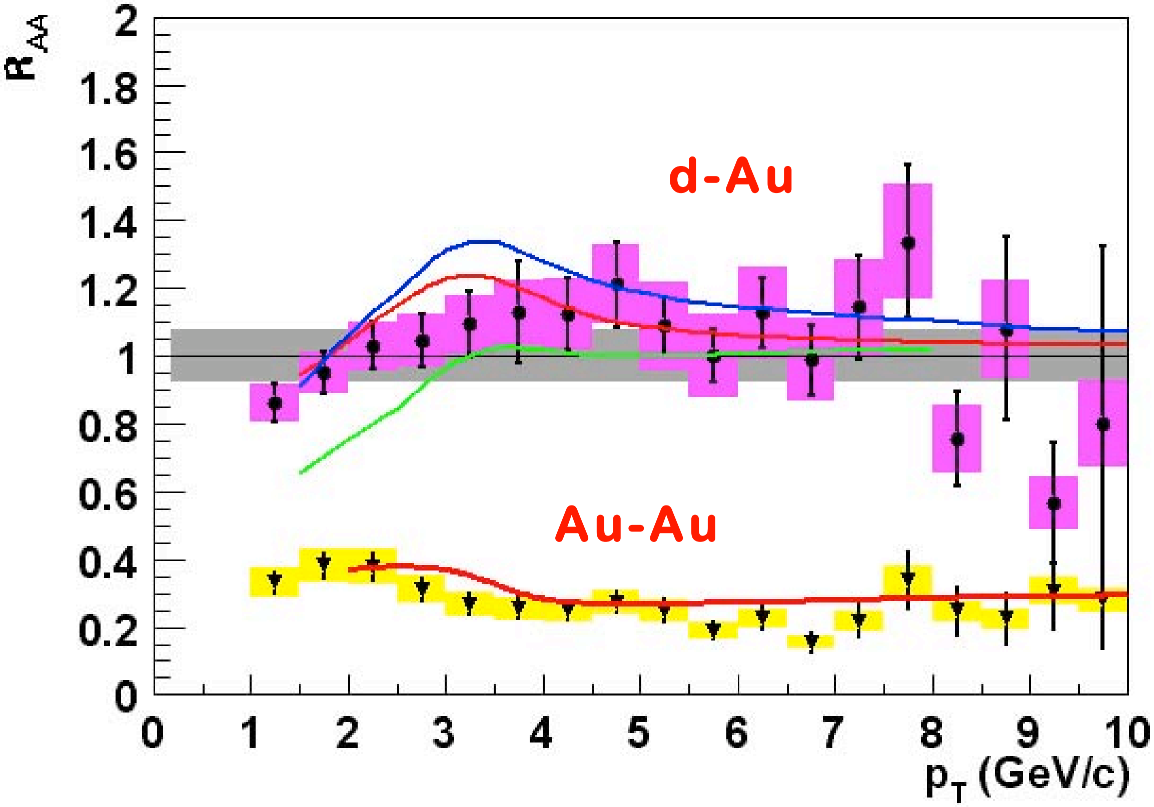
Theoretical Understanding?--the winner is:

Both

- ✓ Au-Au suppression (**I. Vitev and M. Gyulassy, hep-ph/0208108)**
- ✓ d-Au enhancement (**I. Vitev, nucl-th/0302002**)

understood in an approach that combines multiple scattering with absorption in *a dense partonic medium* See nucl-th/0302077 for a review.

➡ Our high p_T probes have been calibrated and are now being used to explore the precise properties of the medium



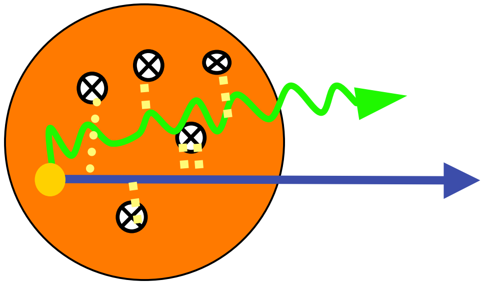
Suppression is a Final State Medium Effect

- **Energy loss of partons in dense matter--A medium effect predicted in QCD---Energy loss by colored parton in medium composed of unscreened color charges with thermal mass μ by gluon bremsstrahlung--LPM radiation-of gluons**
  - ✓ Gyulassy, Wang, Vitev, Baier, Wiedemann…

  See nucl-th/0302077 for a review.
  - ✓ Baier, Dokshitzer, Mueller, Peigne, Shiff, NPB483, 291(1997), PLB345, 277(1995), Baier hep-ph/0209038,

- From Vitev nucl-th/0404052:

$$\frac{\langle \Delta E \rangle}{E} \approx \frac{9 C_R \pi \alpha_s^3}{4} \frac{1}{A_\perp} \frac{dN^g}{dy} L \frac{1}{E} \ln \frac{2E}{\mu^2 L} + \cdots$$



$\varepsilon_{Bj} \Rightarrow \varepsilon$=15 GeV/fm^3=10 x larger unscreened color charge density than in a nucleon

Baier, et al: Screened Coulomb potential MJT: μ^2 plays role of t_{min}

Secondly, an averaging over momentum transfers $q_{\perp\ell}$ should be performed with the distribution corresponding to the screened Coulomb potential scattering:

$$\prod_{\ell=1}^{n+2} dV(\boldsymbol{q}_\ell)\,; \quad dV(\boldsymbol{q}_\ell) = \frac{\mu^2\, d^2 q_\ell}{\pi(q_\ell^2 + \mu^2)^2}\,;$$

...

Straightforward algebra leads to

$$\frac{\omega\, dI}{d\omega\, dz} =$$

$$= \frac{N_c \alpha_s}{\pi\lambda} \int_0^\infty \frac{\mu^4\, dk_\perp^2}{k_\perp^2 (k_\perp^2 + \mu^2)^2} \left[1 + \left(\frac{N_c}{2C_F}\frac{\tau}{\lambda}\right)^2\right]^{-1}$$

μ= 0.5 GeV/c=1/0.4 fm

One Big Grape-but size of a nucleon

H Satz Rep. Prog. Phys. **63** (2000) 1511

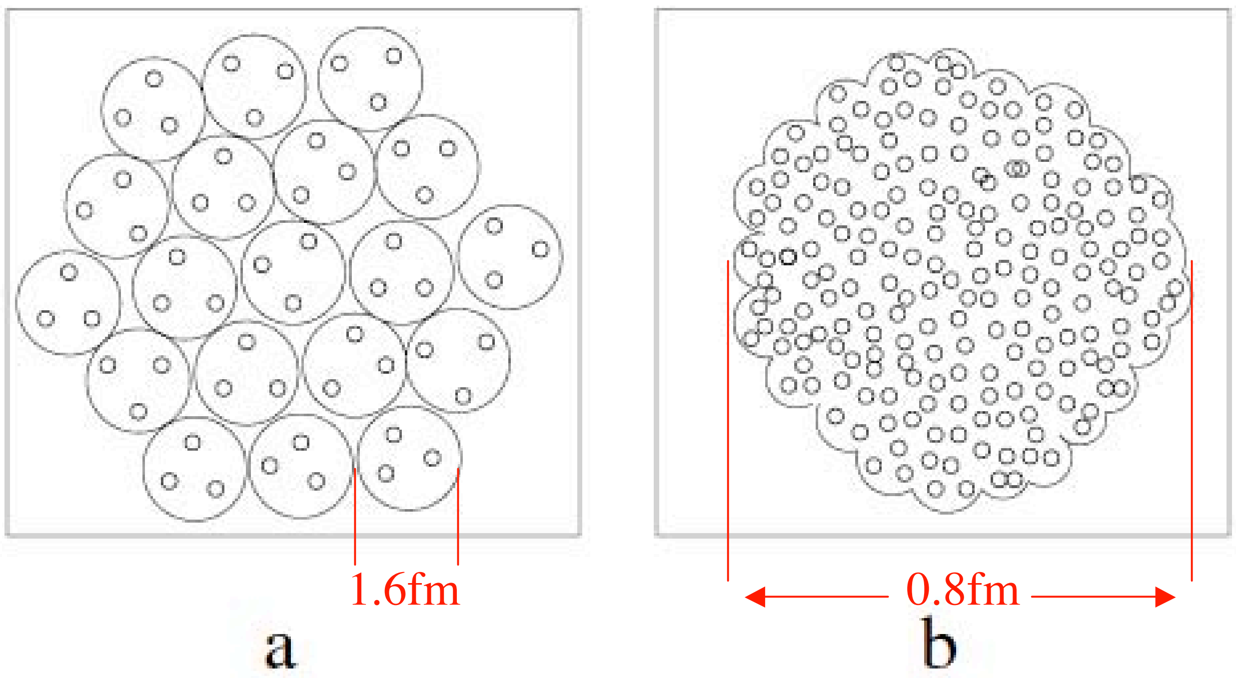
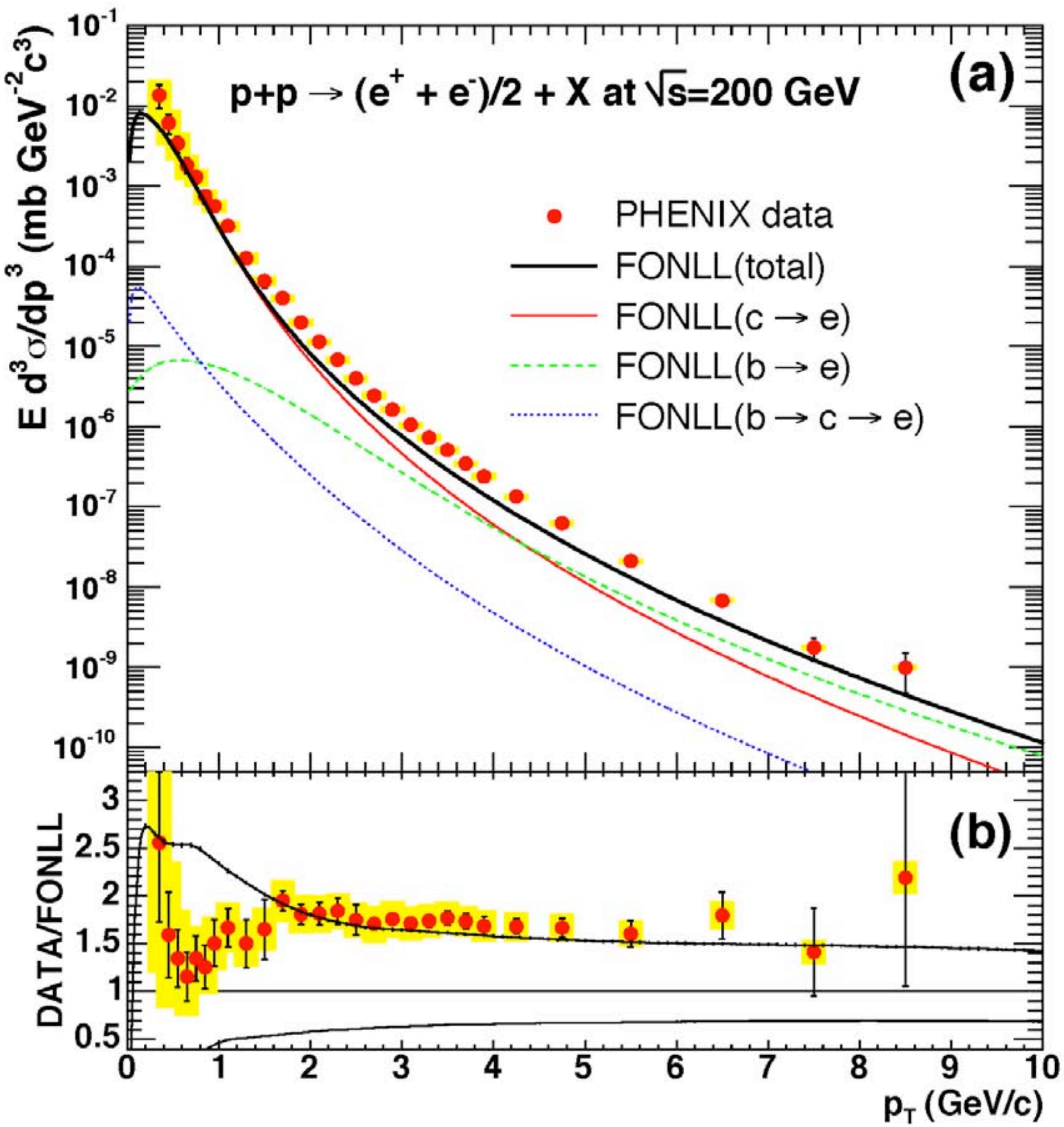


Figure 1. Strongly interacting matter as nuclear matter at a density of closely packed nucleons (*a*) and as quark matter at much higher density (*b*).

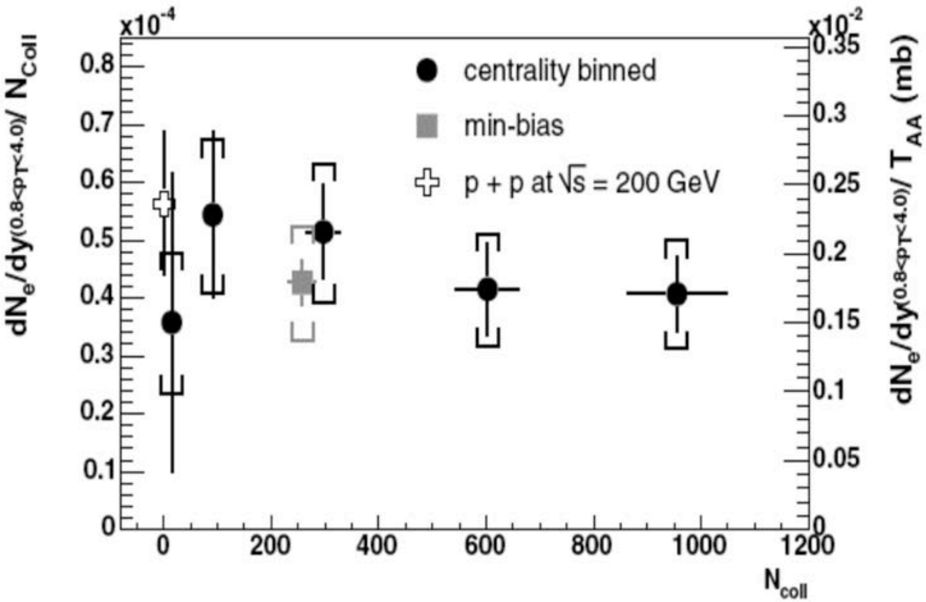
Charm via direct single e in p-p collisions



PHENIX hep-ex/0609010

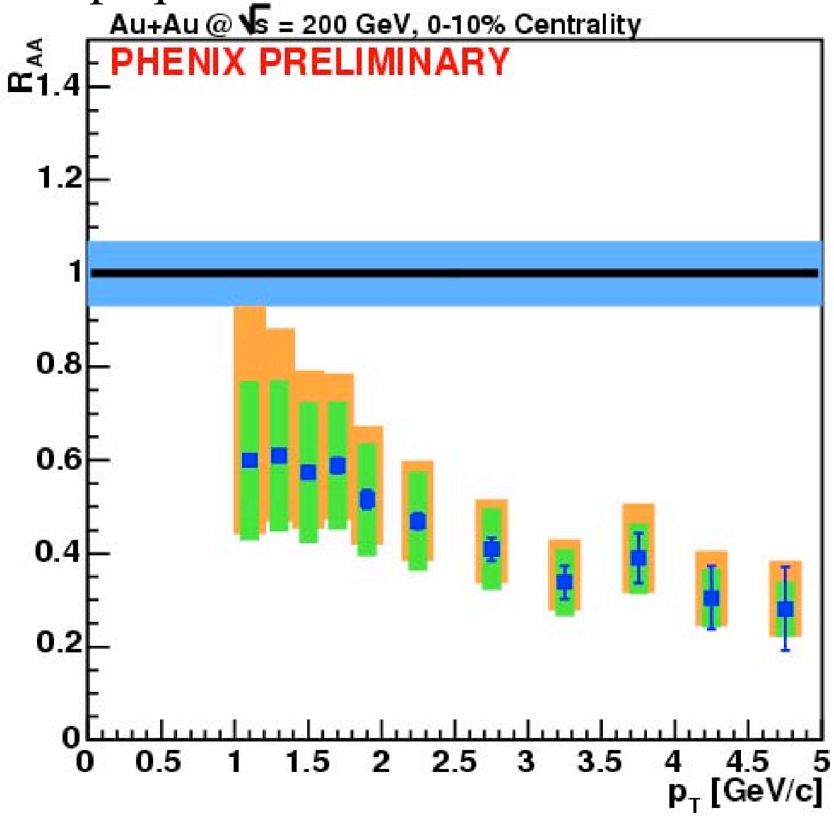
Production of charm is pointlike but p_T spectrum shows suppression

- charm yield determined from single electron spectrum
  - ✓ charm decay dominant source of intermediate p_T electrons



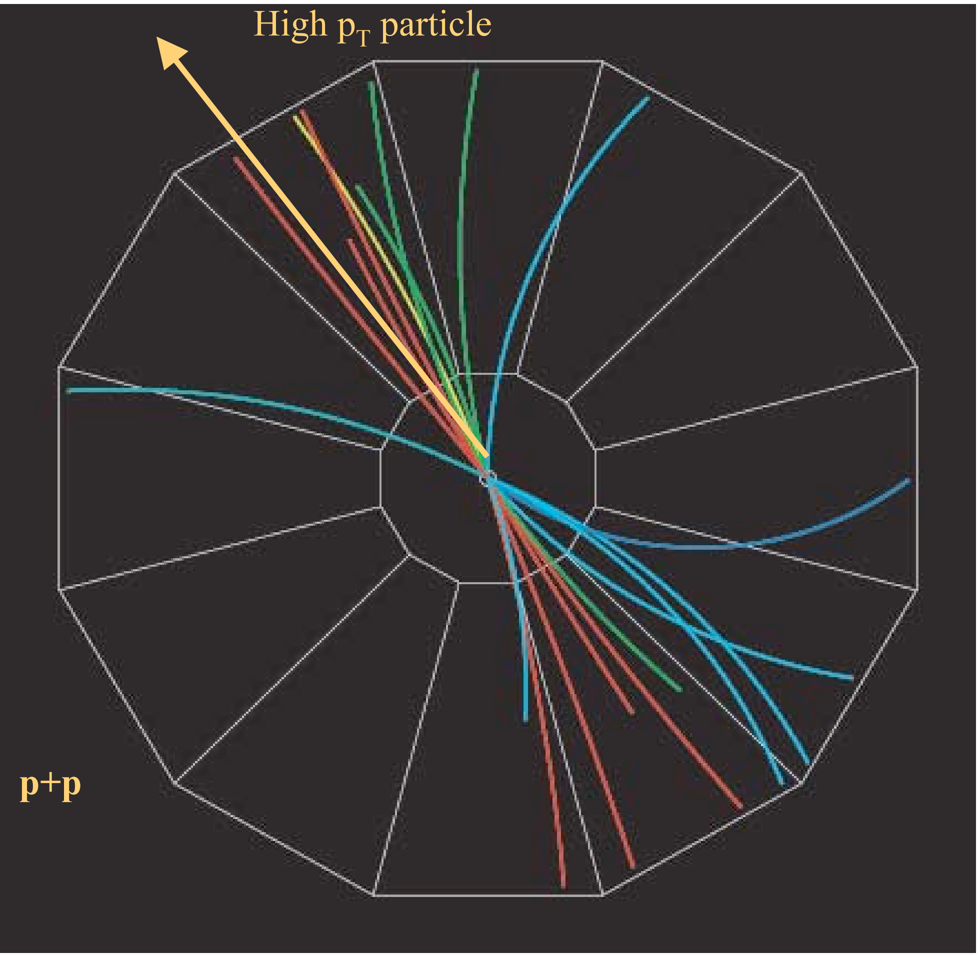
PRL 94, 082301 (2005)

- not only very high p_T but also very heavy quarks lose tremendous energy trying to escape system: very opaque

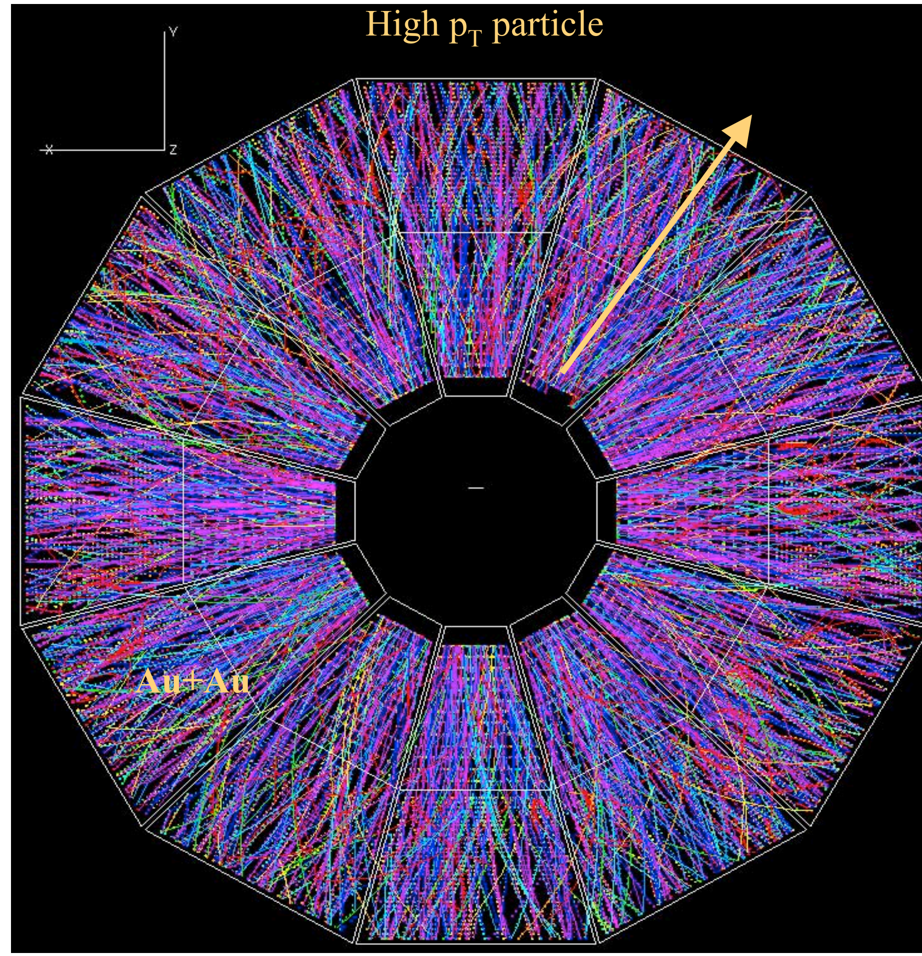


Jet Physics …jets in AuAu "difficult"--but

STAR-Jet event in pp collision

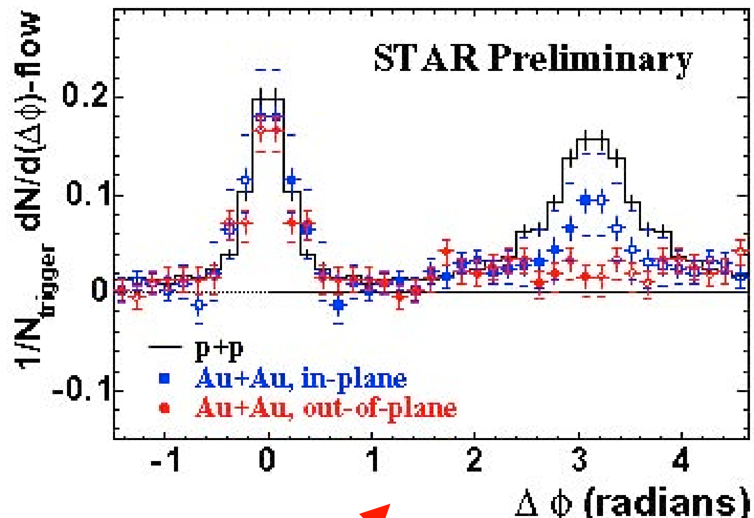


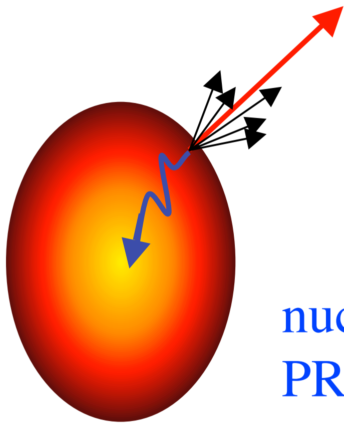
STAR Au+Au collision

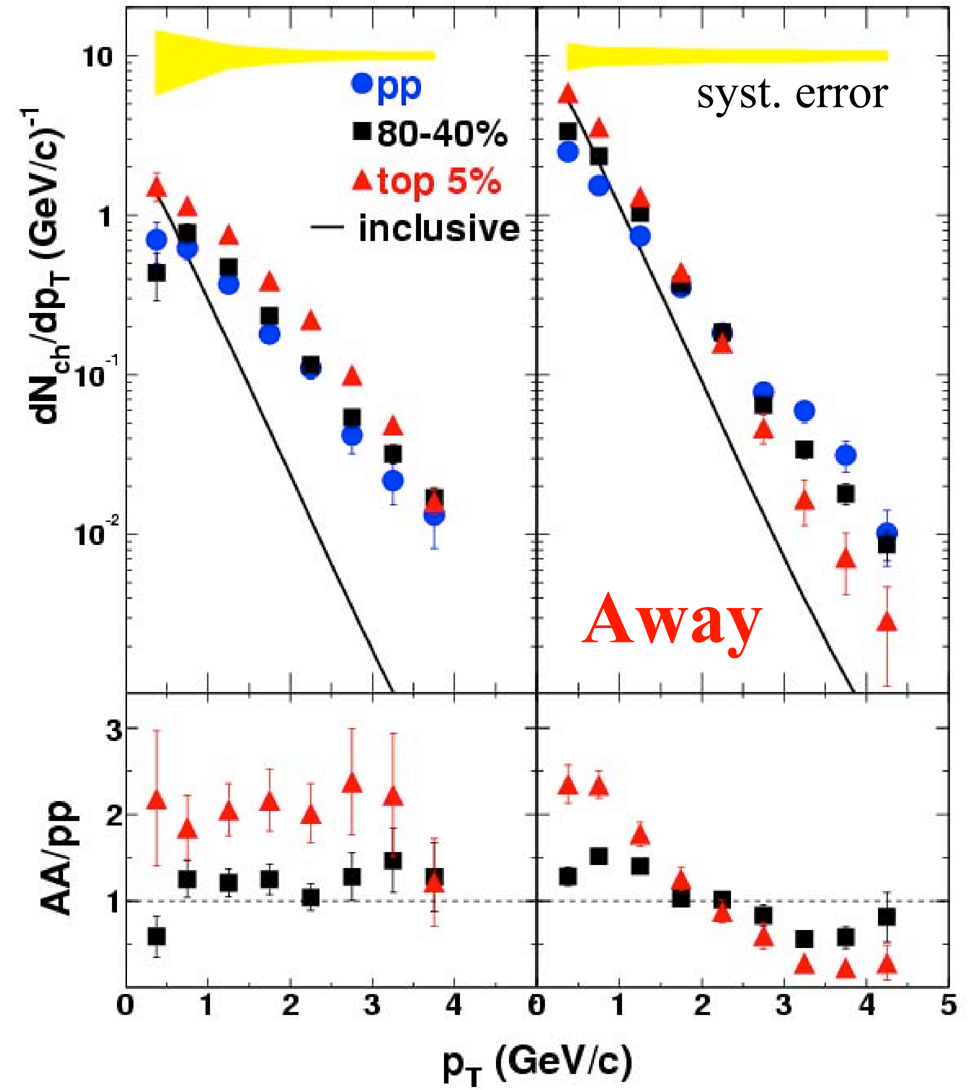


STAR--Away jet is suppressed--consistent with energy loss

- Select a ``trigger'' particle $4<p_T<6$ GeV/c
  $2< p_T^{assoc} < 4$ GeV/c







nucl-ex-0501009
PRL**95**, 152301 (2005)

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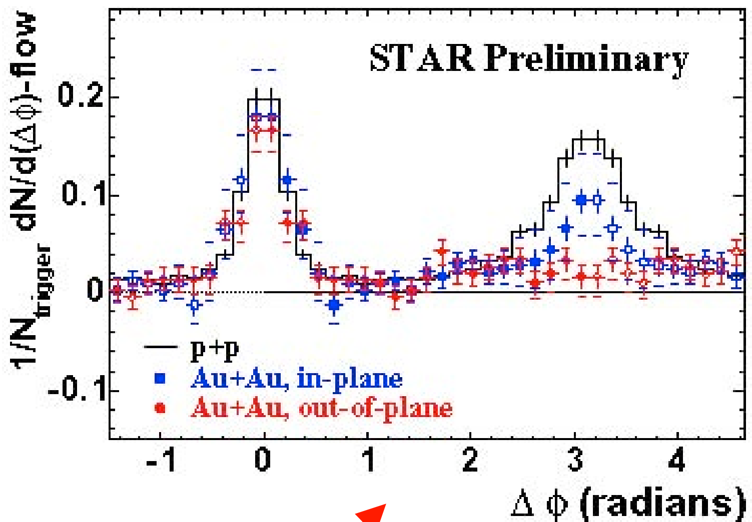
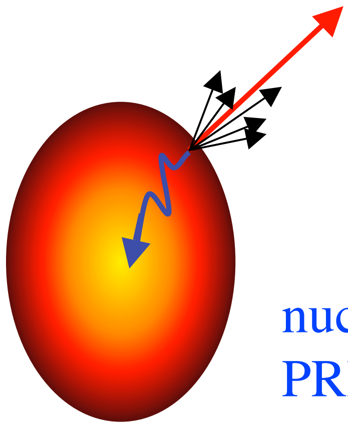
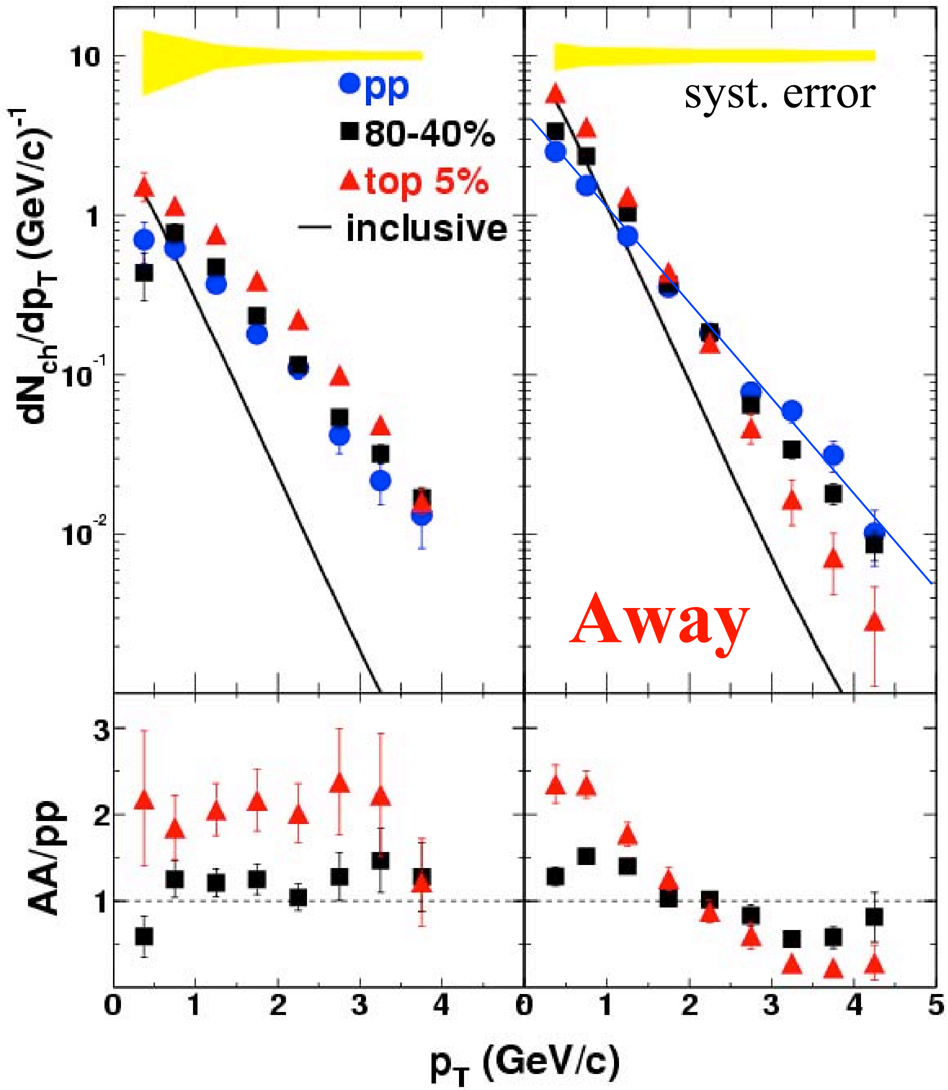




nucl-ex-0501009
PRL**95**, 152301 (2005)



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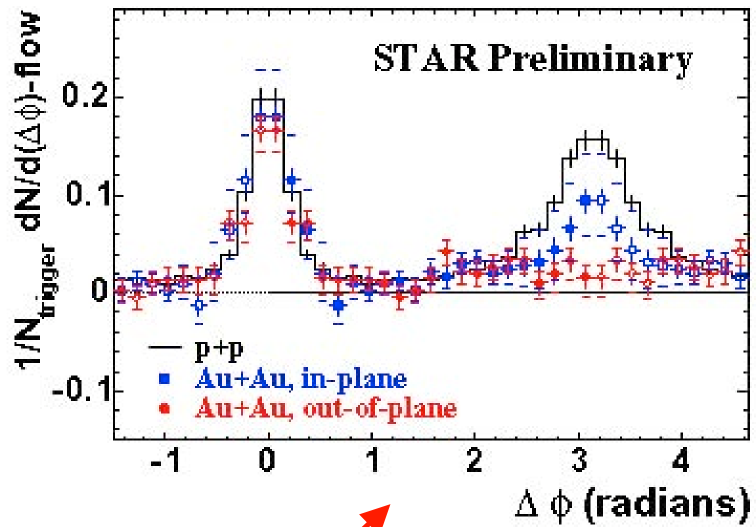

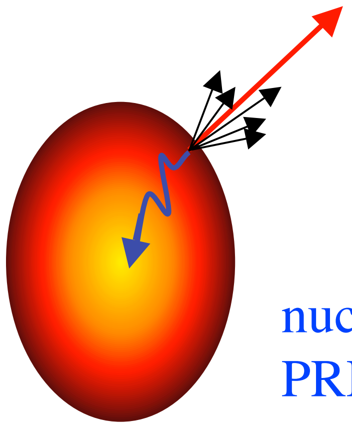

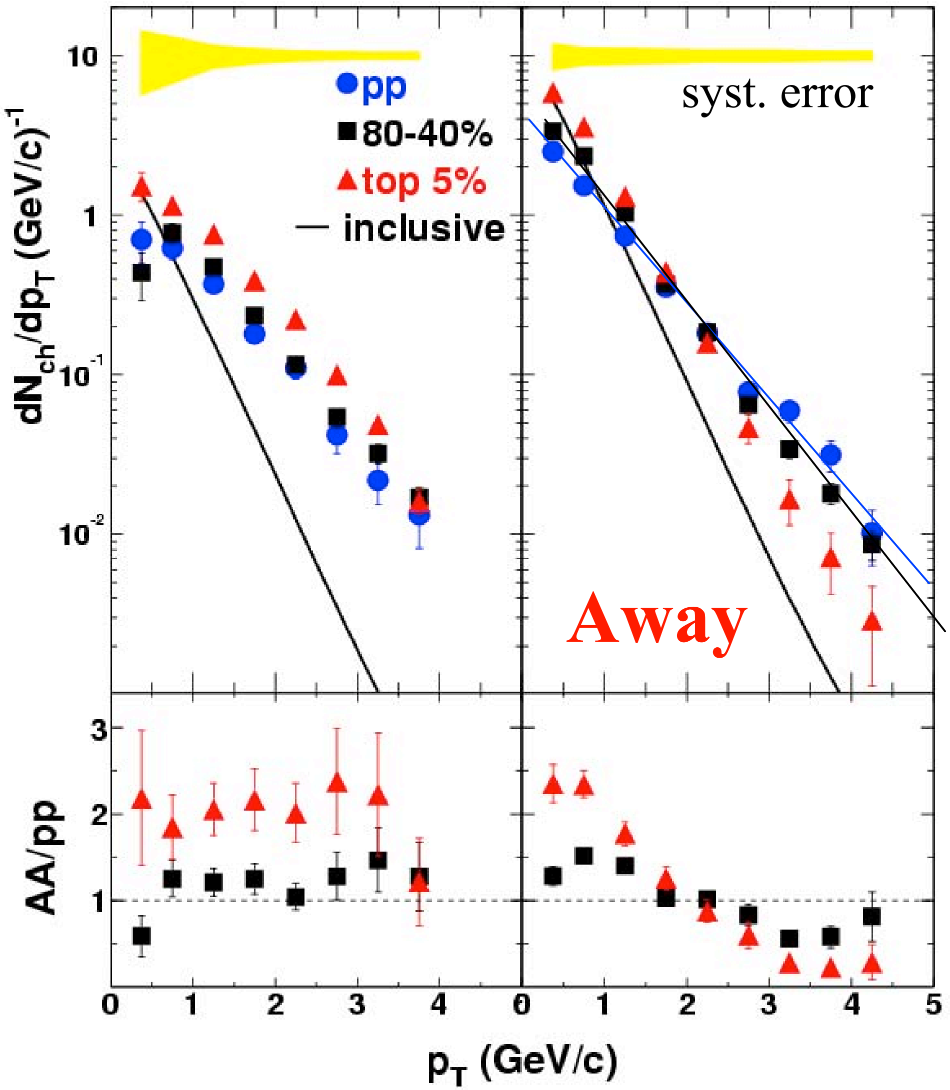

nucl-ex-0501009
PRL**95**, 152301 (2005)

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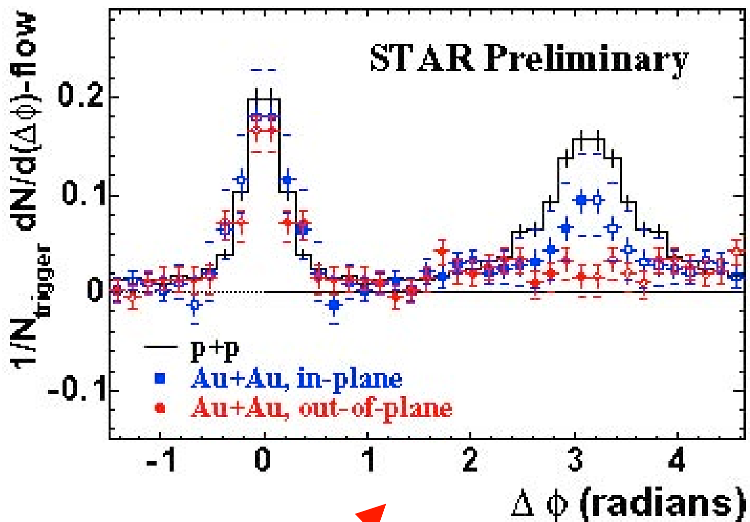
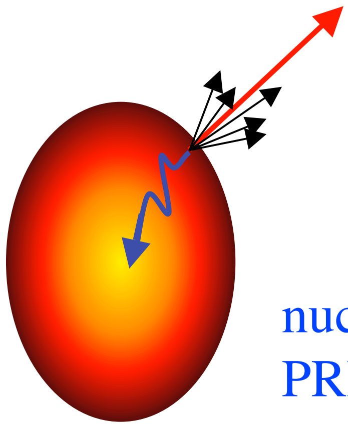
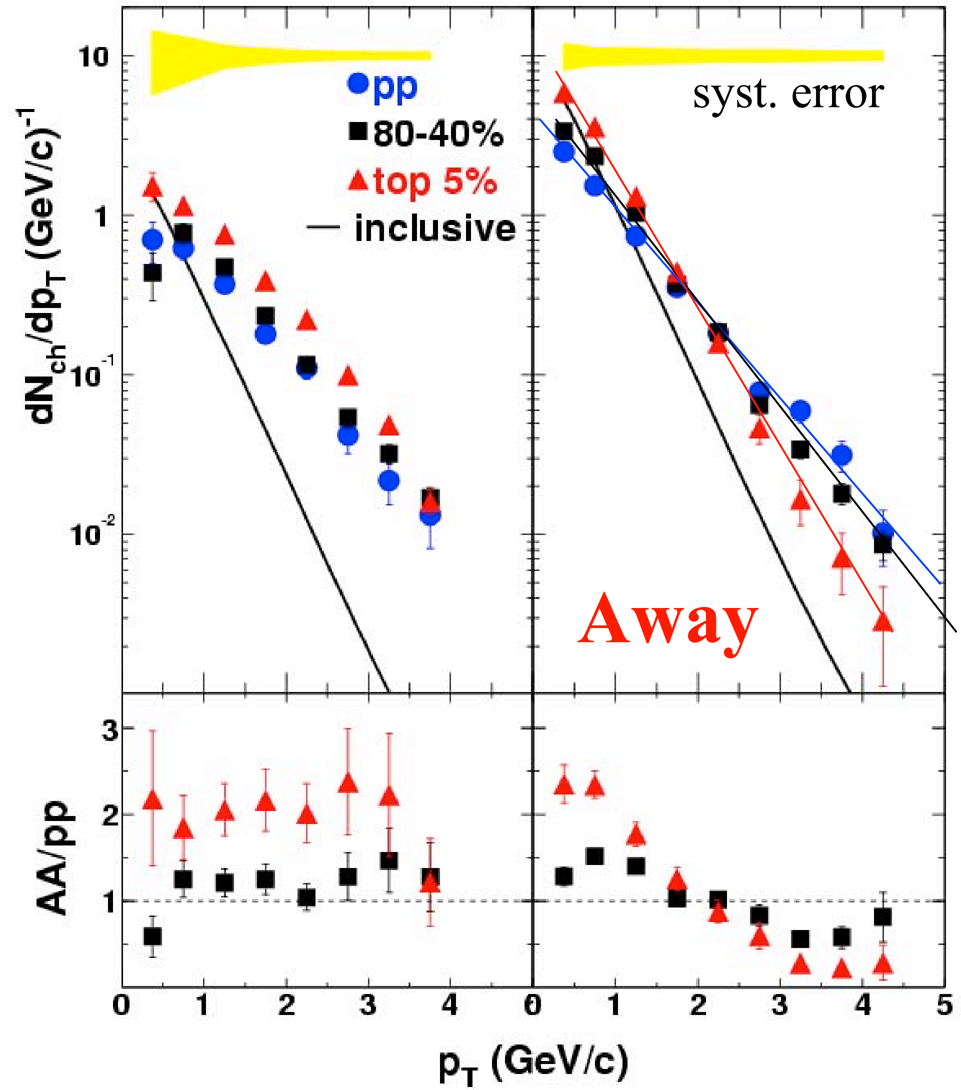
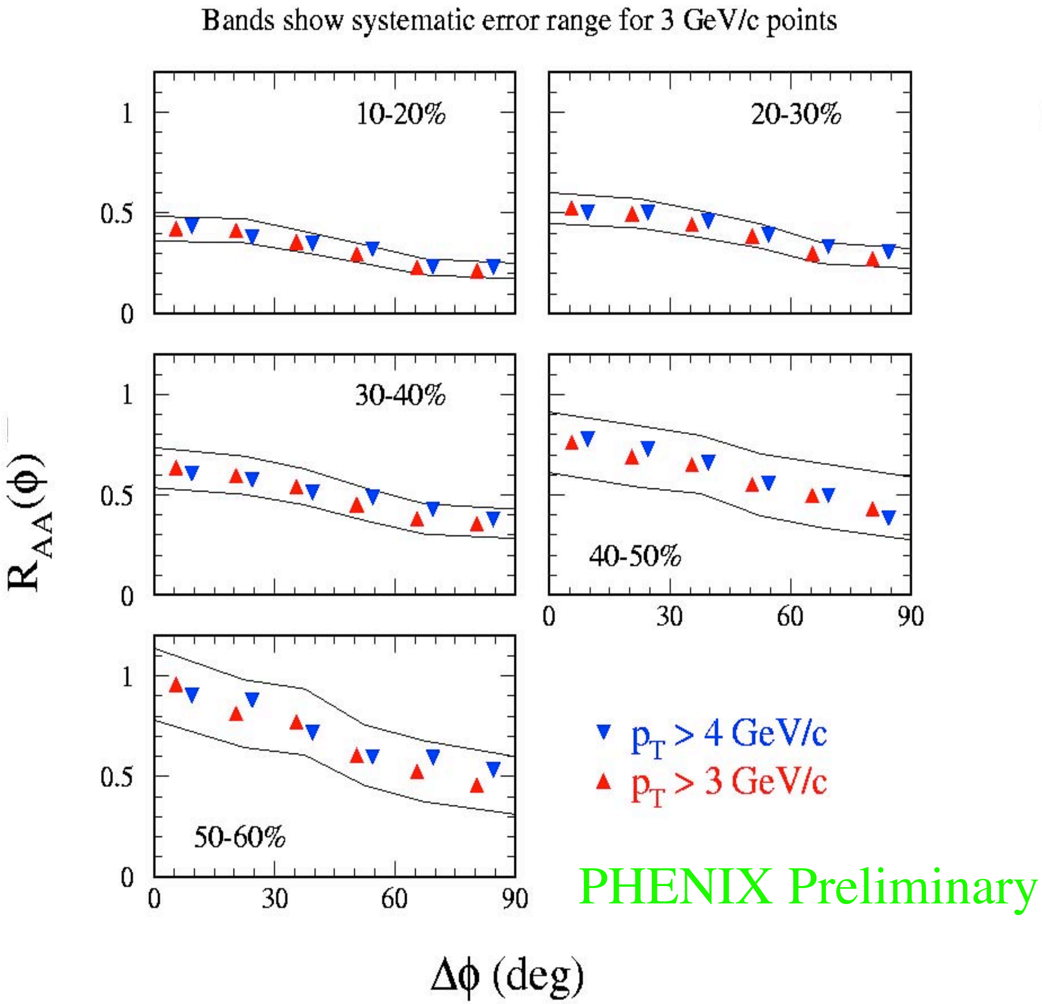


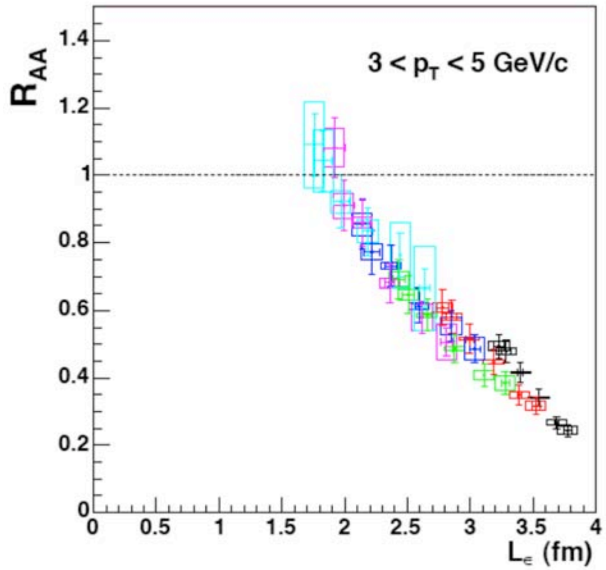


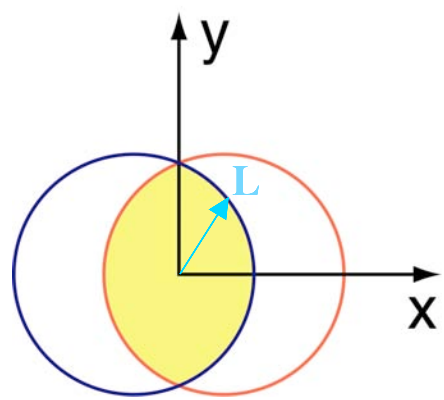


nucl-ex-0501009
PRL **95**, 152301 (2005)

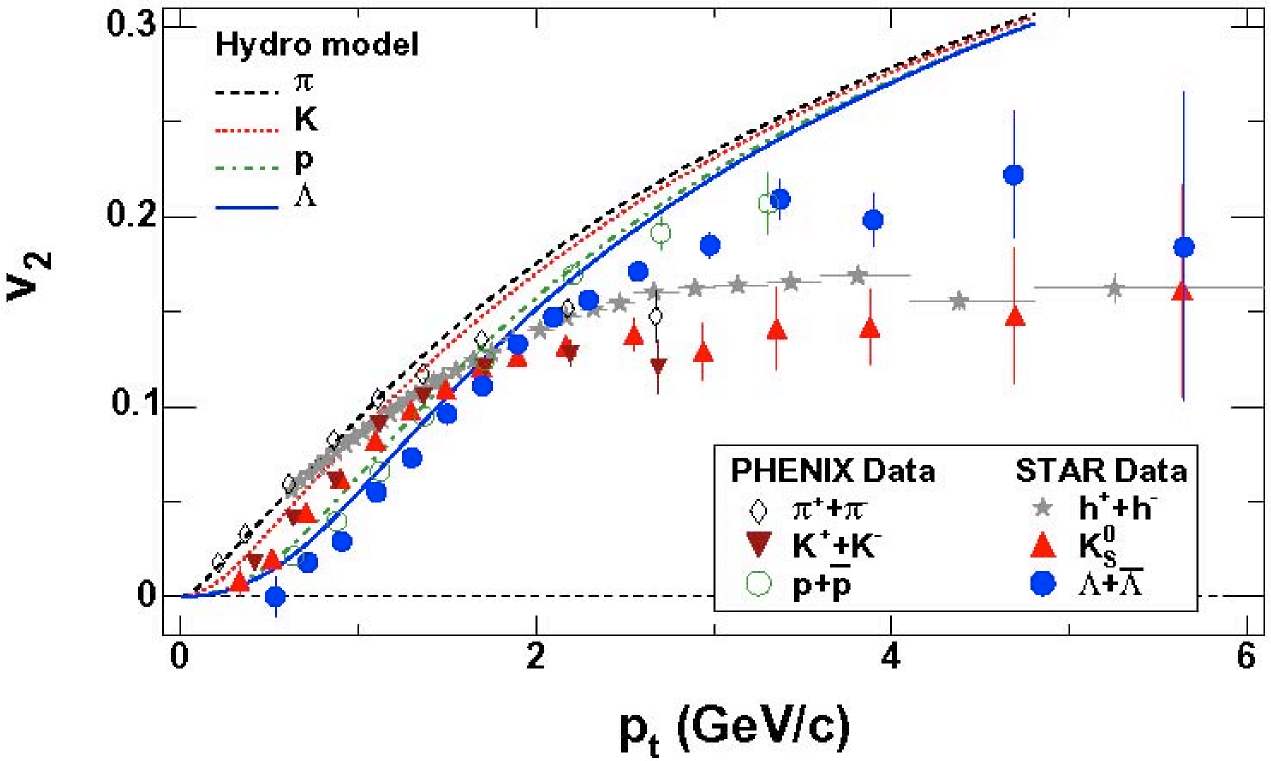
Implies that v_2 p_T> 2 GeV/c is due to anisotropic energy loss (L>2fm)



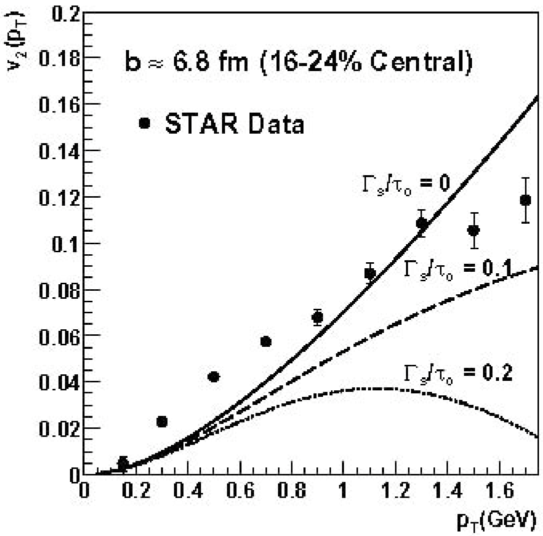




Nobody believes that v_2 p_T>2 GeV/c is entirely due to hydro pressure--perfect fluid (?)



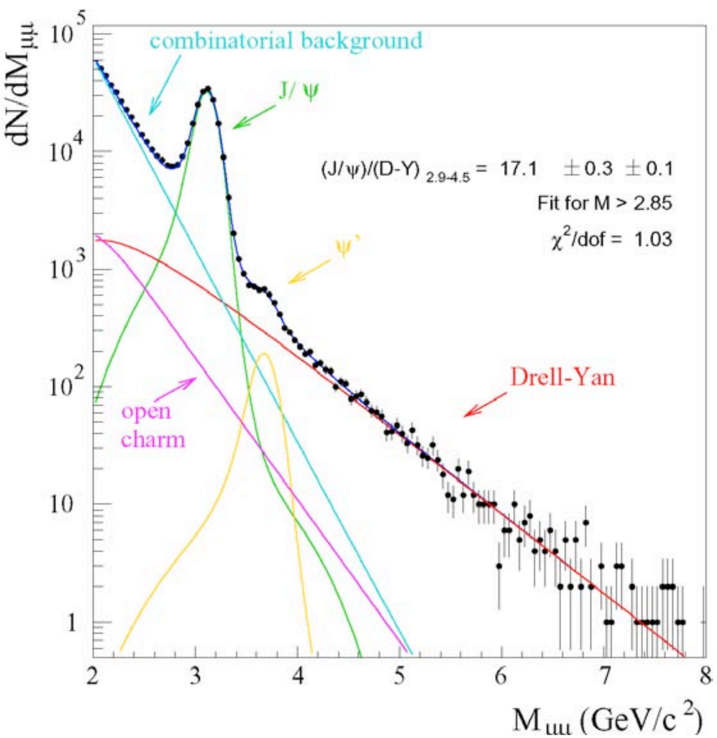
STAR-PRC-nucl-ex/0409033



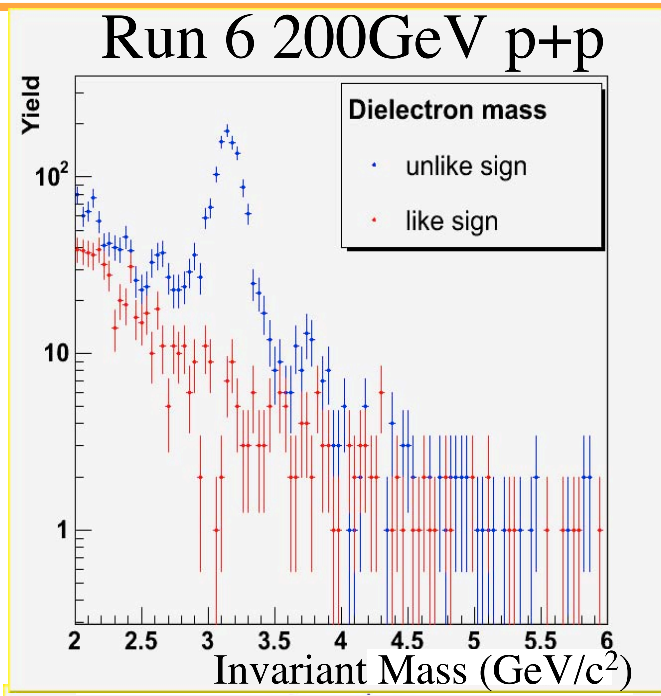
D.Teaney, PRC**68**, 034913 (2003)

J/Ψ Suppression

NA50-CERN

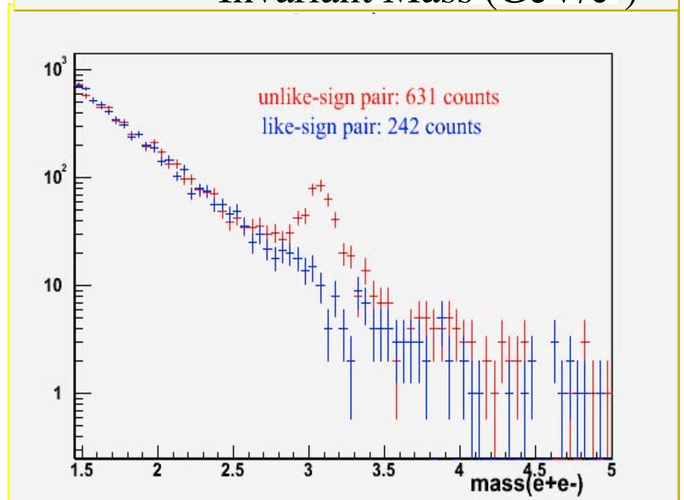


NA50 PL**B 477**, 28 (2000)-PbPb
hep-ex/0101052~100-200K events



PHENIX

p-p~few K

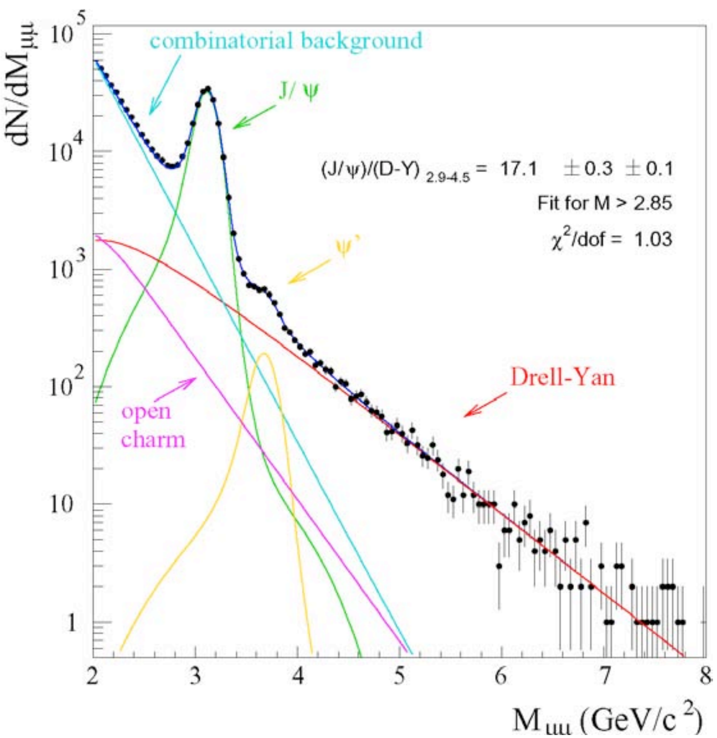


PHENIX

AuAu 0-20%
few 100

J/Ψ Suppression

NA50-CERN



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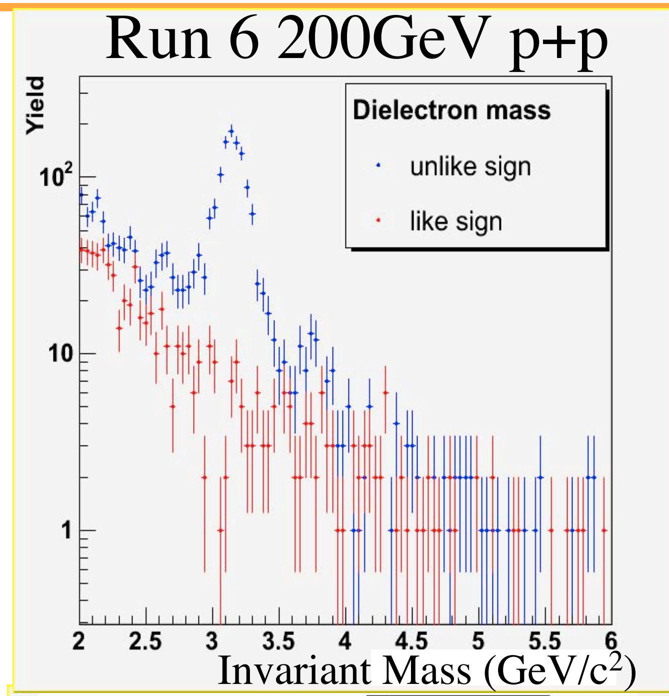

PHENIX

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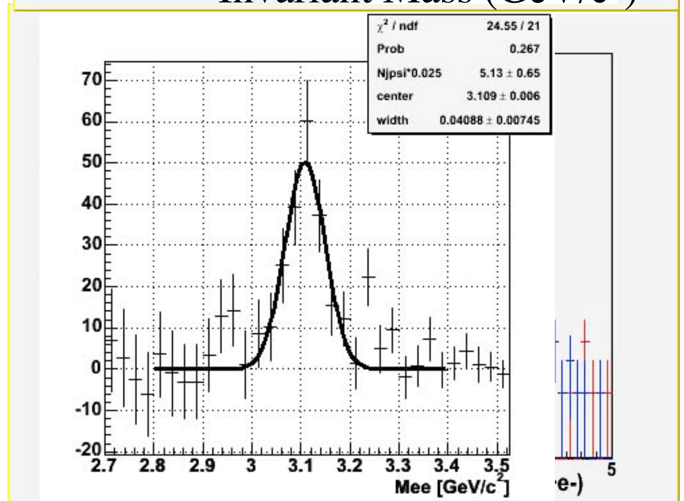
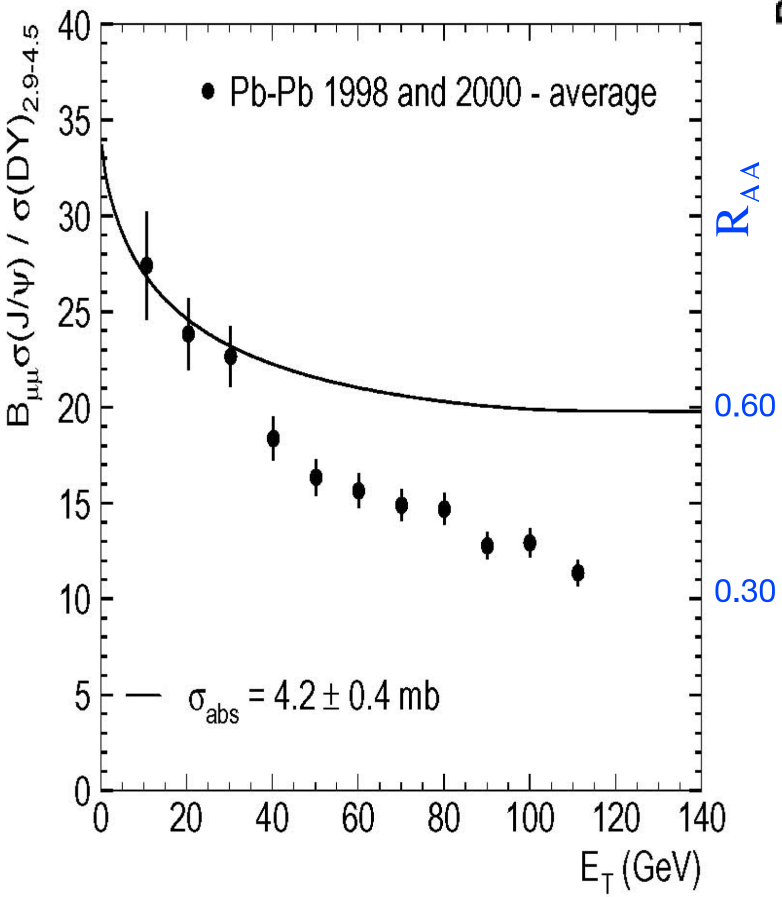


PHENIX

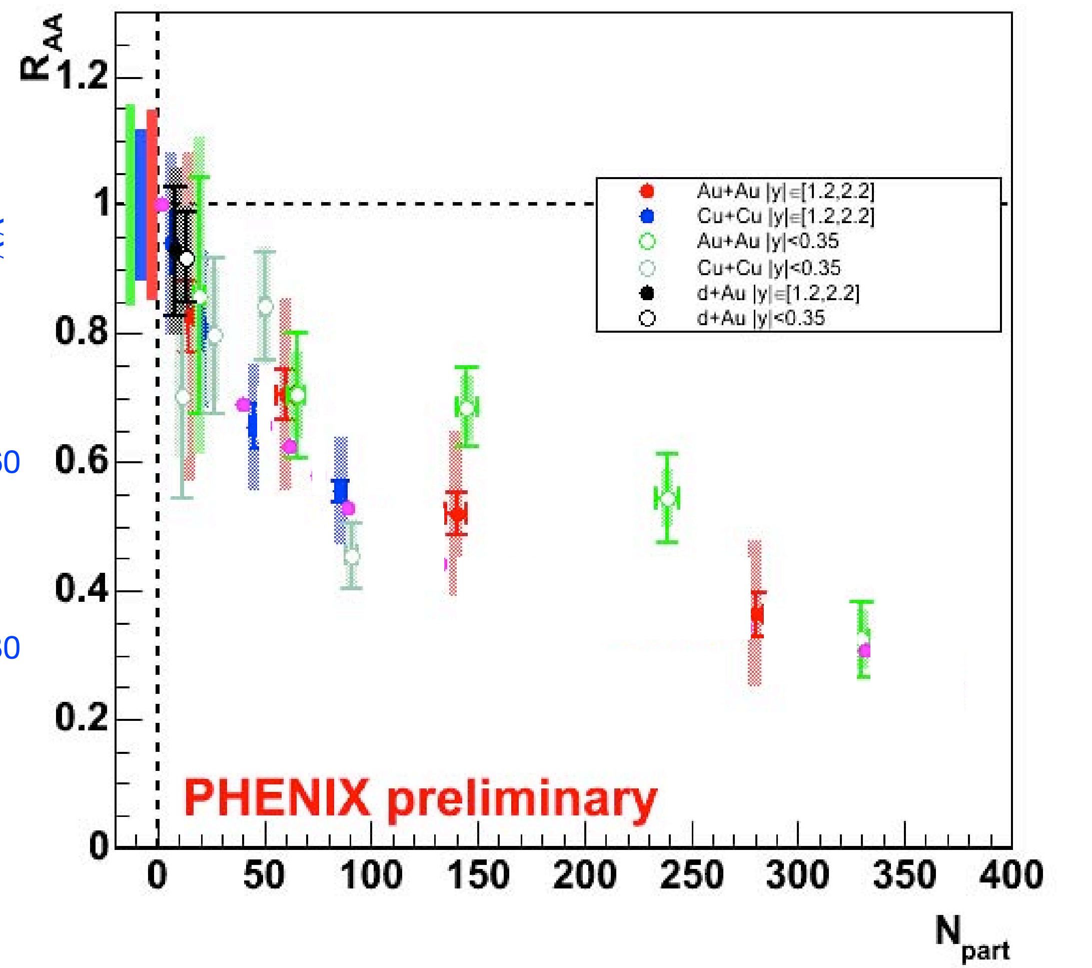
AuAu 0-20%
few 100

J/Ψ No longer the Gold-Standard?

NA50-CERN

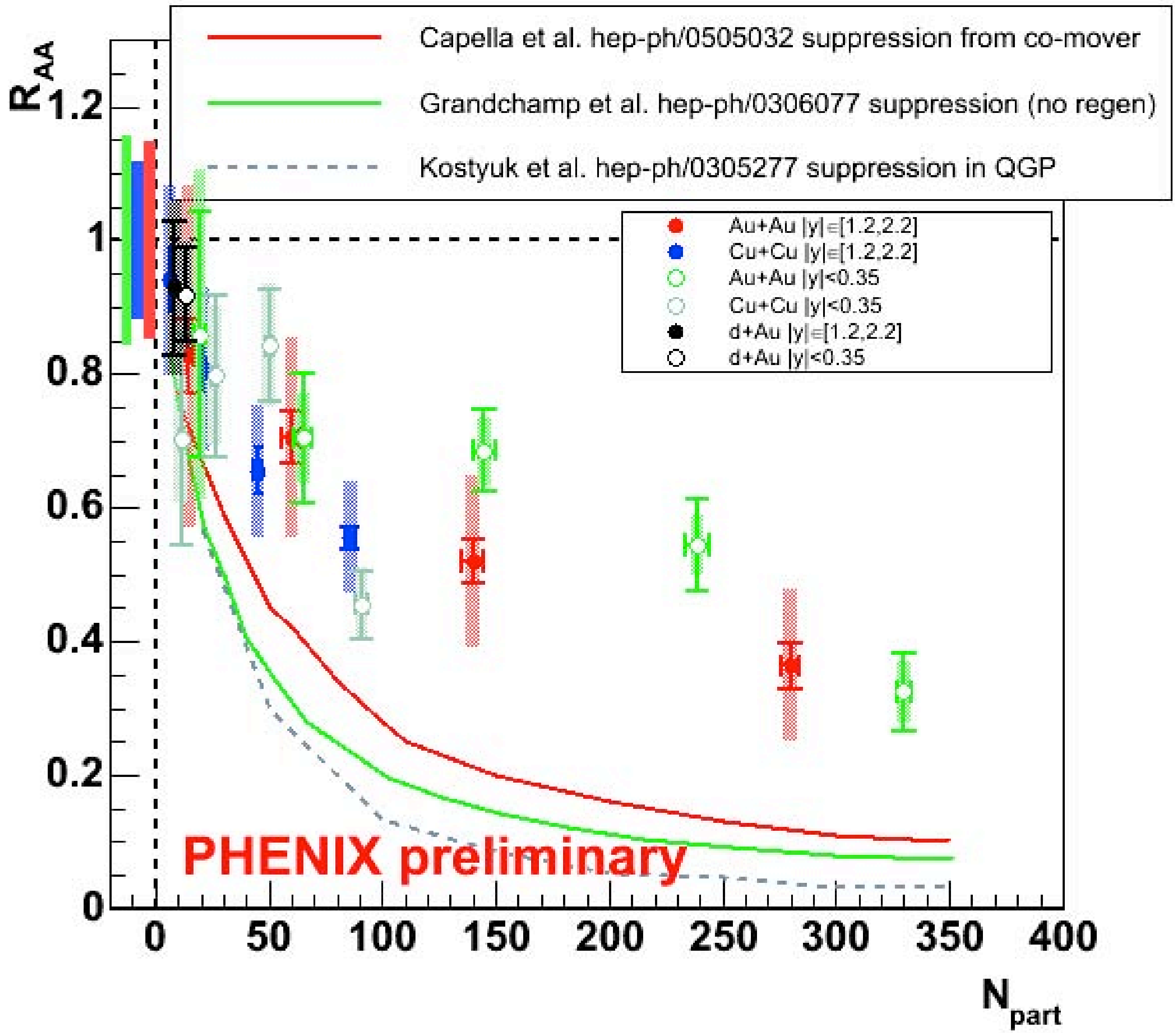


J/ψ nuclear modification factor R_{AA}

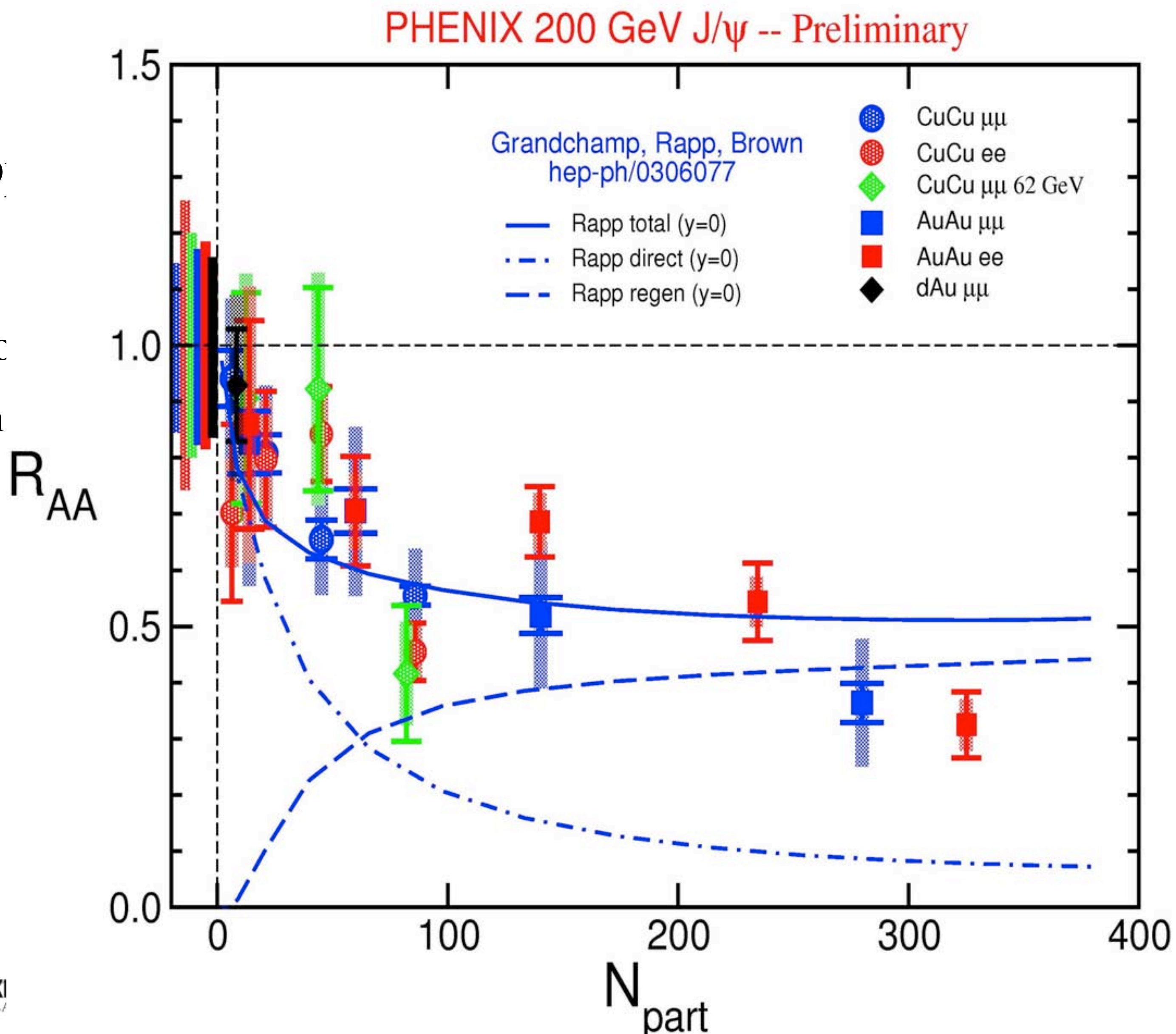


J/ψ nuclear modification factor R_{AA}

- Compare to models which fit NA50 results.



- Many new Explanations.
- One example: Grandchamp, Rap Brown; PRL 92, 212301 (2003)
  - ✓ In-media dissolutic
  - ✦ Plus regeneration from "off-diagonal" c-cbar pairs



Conclusions

- the nuclear matter produced in central Au+Au collisions at RHIC appears to be a nearly perfect quark-gluon "liquid" instead of behaving like a gas of free quarks and gluons.

- No signs of a rapid phase transition have been seen---consistent with latest ideas that transition is a cross-over at RHIC energies.

- The medium at RHIC is characterized by very high energy densities, density of unscreened color charges ten times that of a nucleon, large cross sections for the interaction between strongly interacting particles, strong collective flow which implies early thermalization.

- This state of matter is not describable in terms of ordinary color-neutral hadrons, because there is no known self-consistent theory of matter composed of ordinary hadrons at the measured densities.

But there is more

- Hydro totally fails for Bose-Einstein (Hanbury-Brown Twiss)(GGLP) correlations.
- In the range $2 < p_T < 4.5$ GeV/c baryons are not suppressed. This has spawned a whole new idea called Recombination, which so far fails to explain same associated jet correlations for p and π triggers.
- J/Psi measurements in p-p collisions are consistent with total cross section measurements at lower $\sqrt{s}$, but Au+Au measurements exhibit the same suppression as at CERN, not more as expected. Is it recombination?
- Test whether the LPM energy loss formalism is correct in detail (e.g. Light vs heavy quarks?) If correct, can measure properties of medium.
- Charm quarks flow and are suppressed. Do J/Psi flow? • • •

Lattice Gauge Predictions-Charmonium

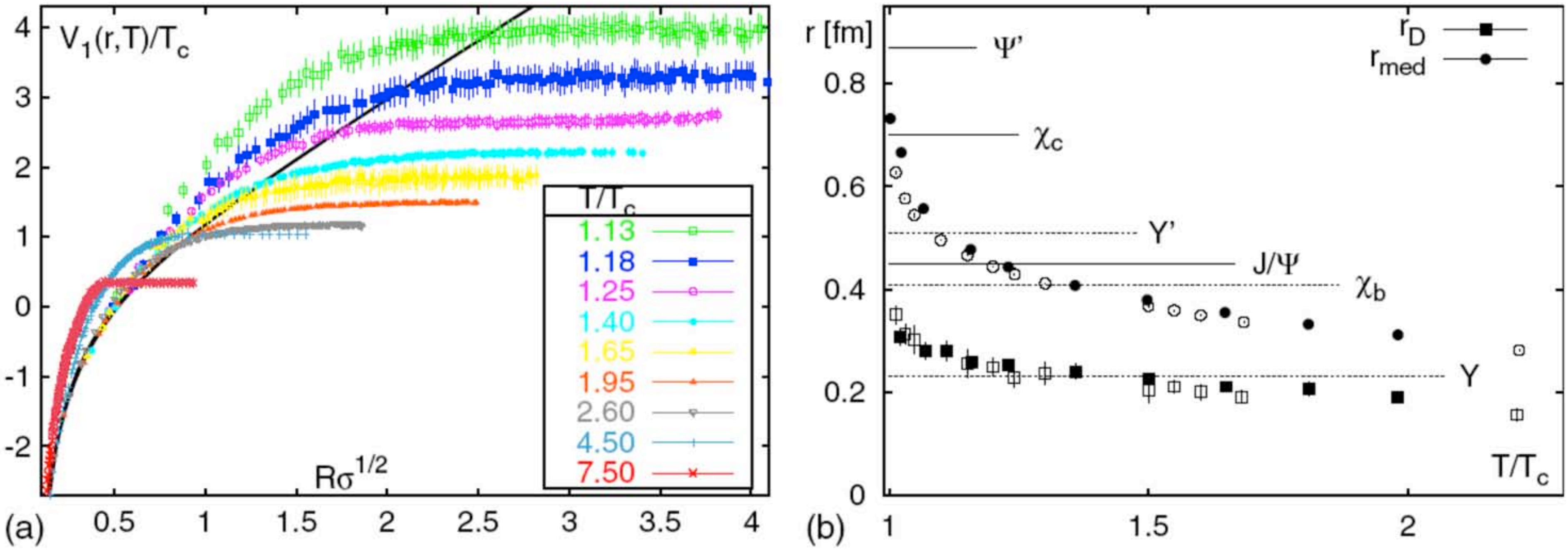
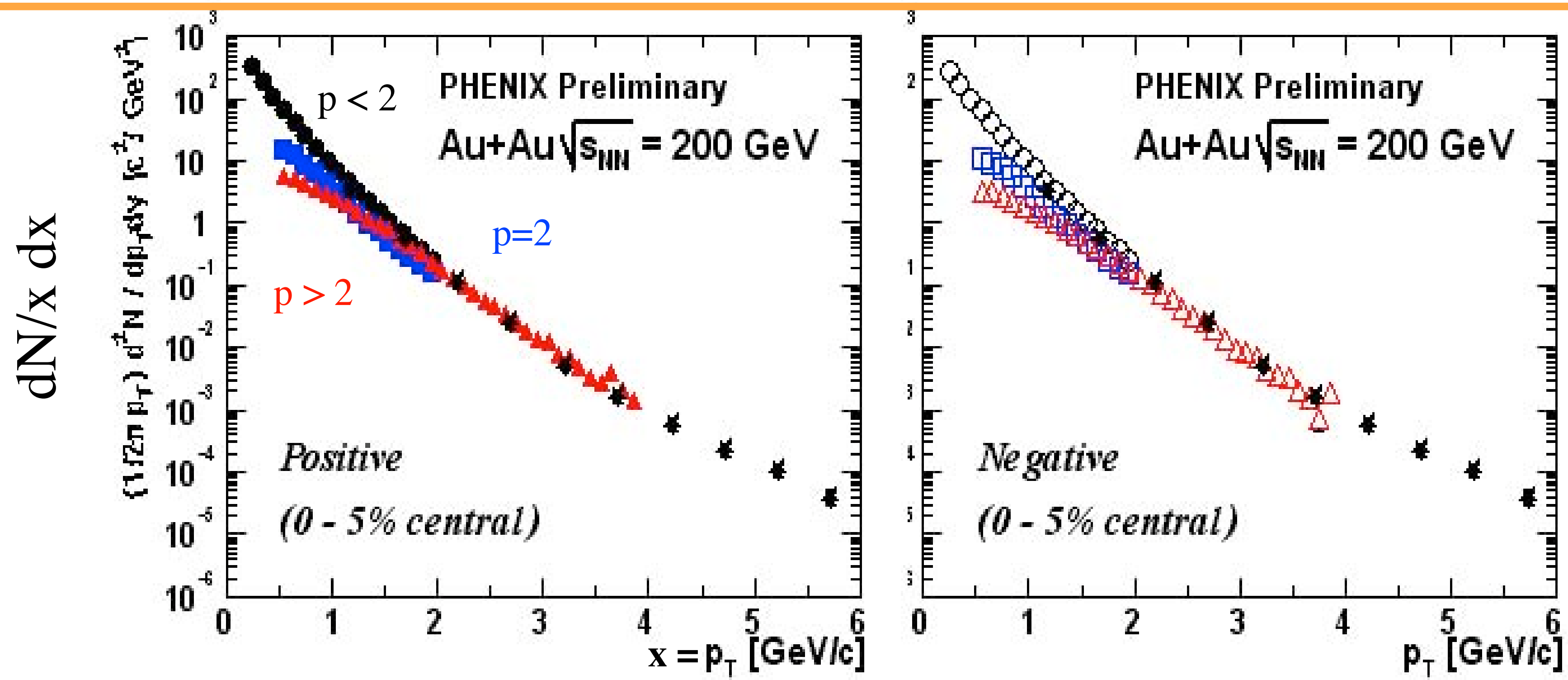


Figure 8. (*a*) Lattice gauge calculations of heavy quark potential $V(r)$ as a function of T/T_c [116]. The solid line is the normal ($T = 0$) potential. (*b*) Estimate [50] of r_{med}, the distance beyond which the force between a static quark and an anti–quark pair is strongly modified by temperature effects, is compared with the Debye screening radius, $r_D = 1/\mu$, and the mean square charge radii of $c\bar{c}$ and $b\bar{b}$ bound states (lines). Note that the actual melting points of the Ψ', χ_c and J/Ψ are no longer expected to be ~0.2,0.7 and 1.1 T_c as in the calculation illustrated [50], but rather 1.1, 1.1 and ~2 T_c by more recent calculations [117–119].

Inclusive p_T spectra are Gamma Distributions

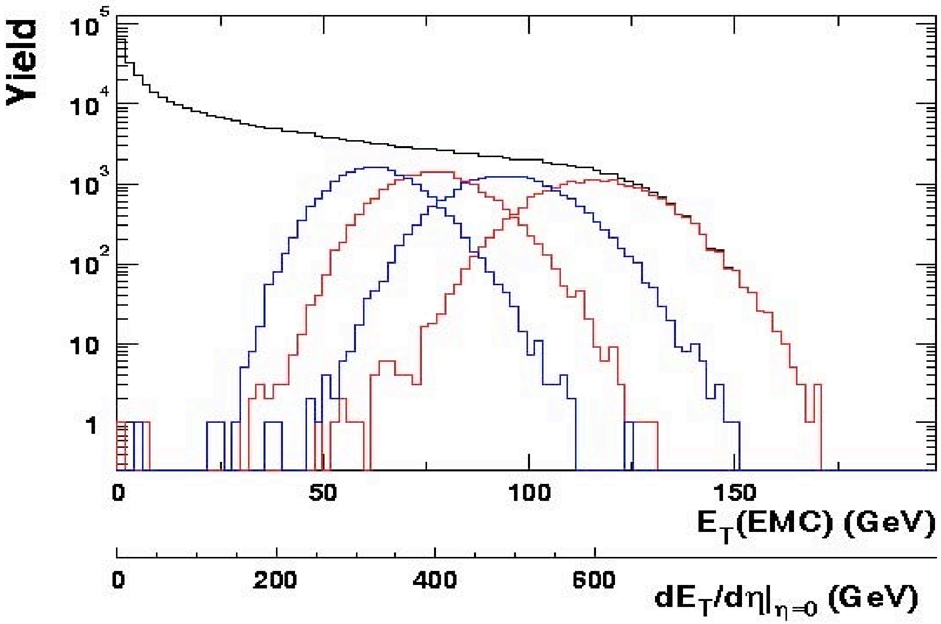


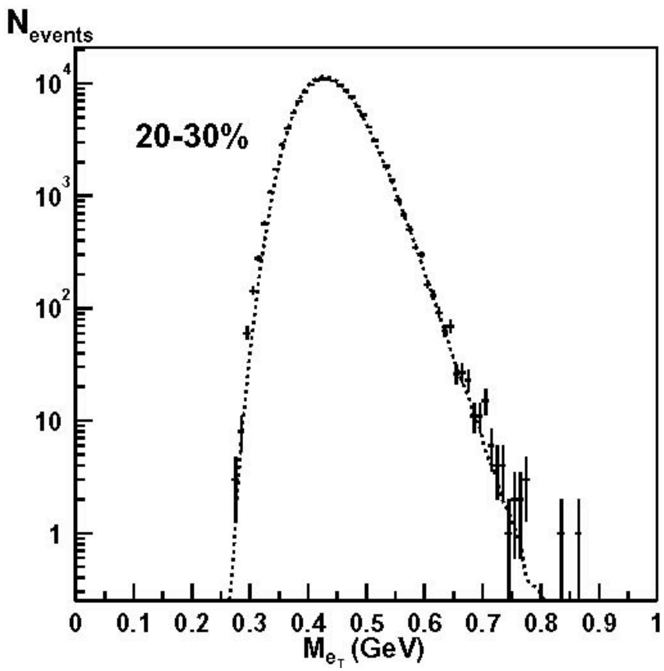
$$\frac{dN}{dx} = f_\Gamma(x,p,b) = \frac{b}{\Gamma(p)}(bx)^{p-1}e^{-bx}$$

$$\langle x \rangle = \frac{p}{b} \equiv \mu \qquad \sigma_x^2 = \frac{p}{b^2} \qquad \frac{\sigma^2}{\mu^2} = \frac{1}{p} \qquad \frac{\sigma^2}{\mu} = \frac{1}{b}$$

$$p \sim 2 \quad b \sim 6\ (\mathrm{GeV/c})^{-1}$$

Are there fluctuations beyond random?





- Event-by-event average p_T (M_{pT}) is closely related to E_T

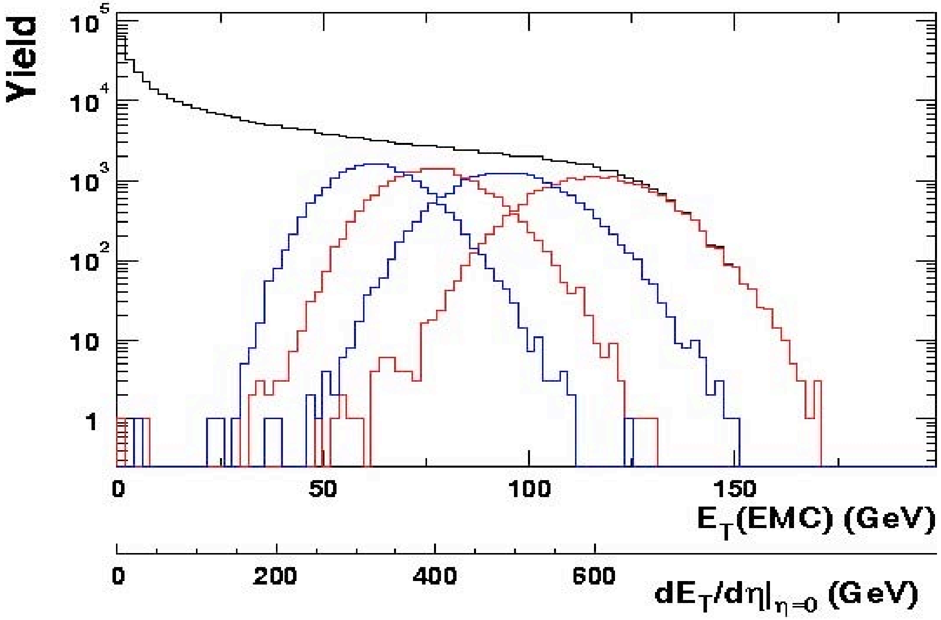
$$M_{p_T} = \overline{p_T}_{(n)} = \frac{1}{n}\sum_{i=1}^{n} p_{T_i} = \frac{1}{n} E_{Tc}$$

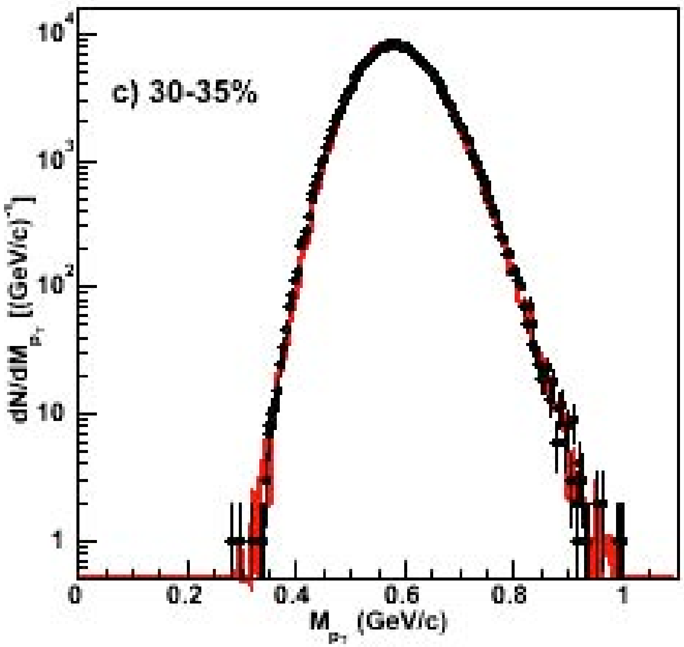
- compare Data to Mixed events for random.
- deviation expressed as:

$Fp_T = \sigma_{MpTdata} / \sigma_{MpTmixed} - 1 \;\sim$ few %

- due to jets see PRL **93**, 092301(04)

Are there fluctuations beyond random?





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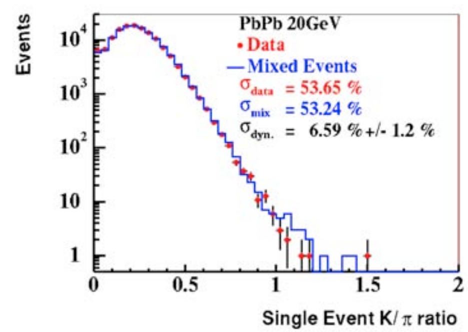
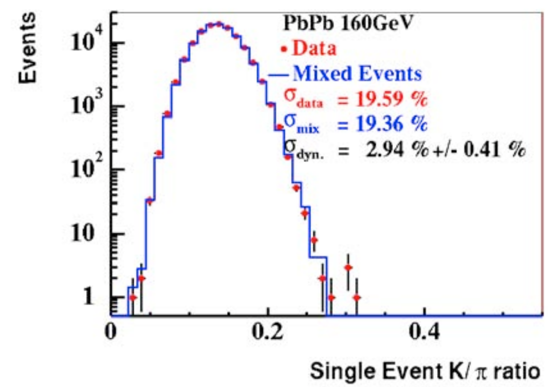
What e-by-e tells you that you don't learn from the inclusive average

- e-by-e averages separate classes of events with different average properties, for instance 17% of events could be all kaons, and 83% all pions---see C. Roland QM2004, e-by-e K/π consistent with random.





- A nice example I like is by R. Korus, et al, PRC **64**, 054908 (2004): The temperature T~1/b varies event by event with ⟨T⟩ and σ_T.

$$\frac{\sigma^2_{M_{p_T}}}{\mu^2} - \frac{1}{n}\frac{\sigma^2_{p_T}}{\mu^2} = \left(1-\frac{1}{n}\right)\frac{\sigma^2_T}{\langle T\rangle^2} = \Sigma^2_{p_T} \qquad \text{CERES}$$

Assuming all fluctuations are from $\sigma_T/\langle T\rangle$
Very small and relatively constant with $\sqrt{s_{NN}}$

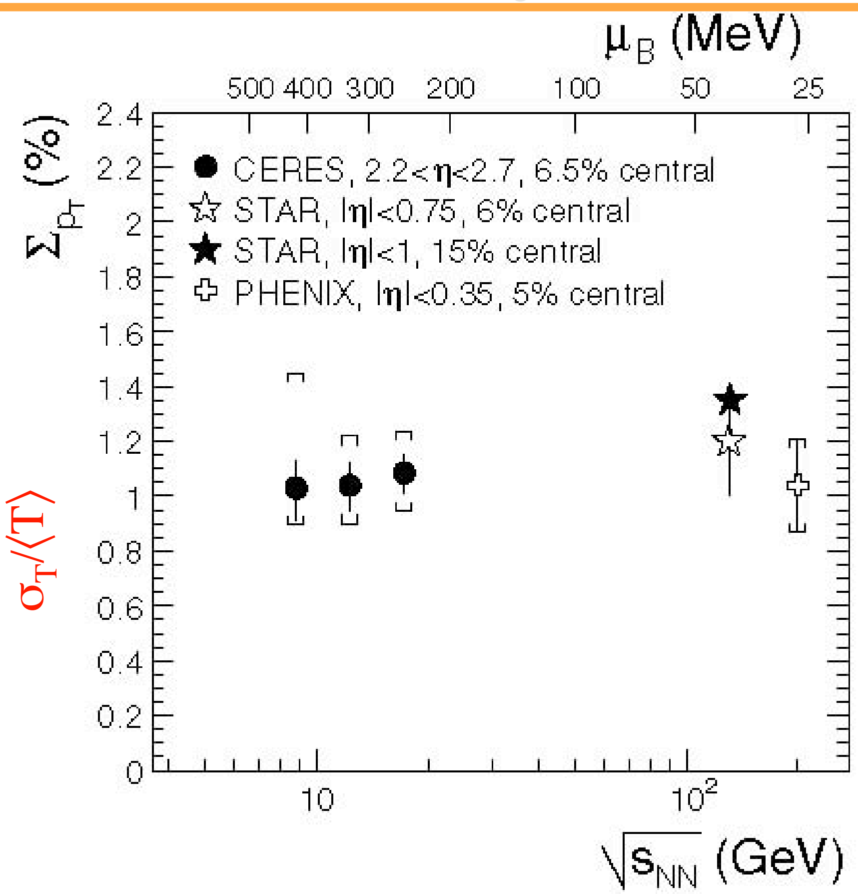


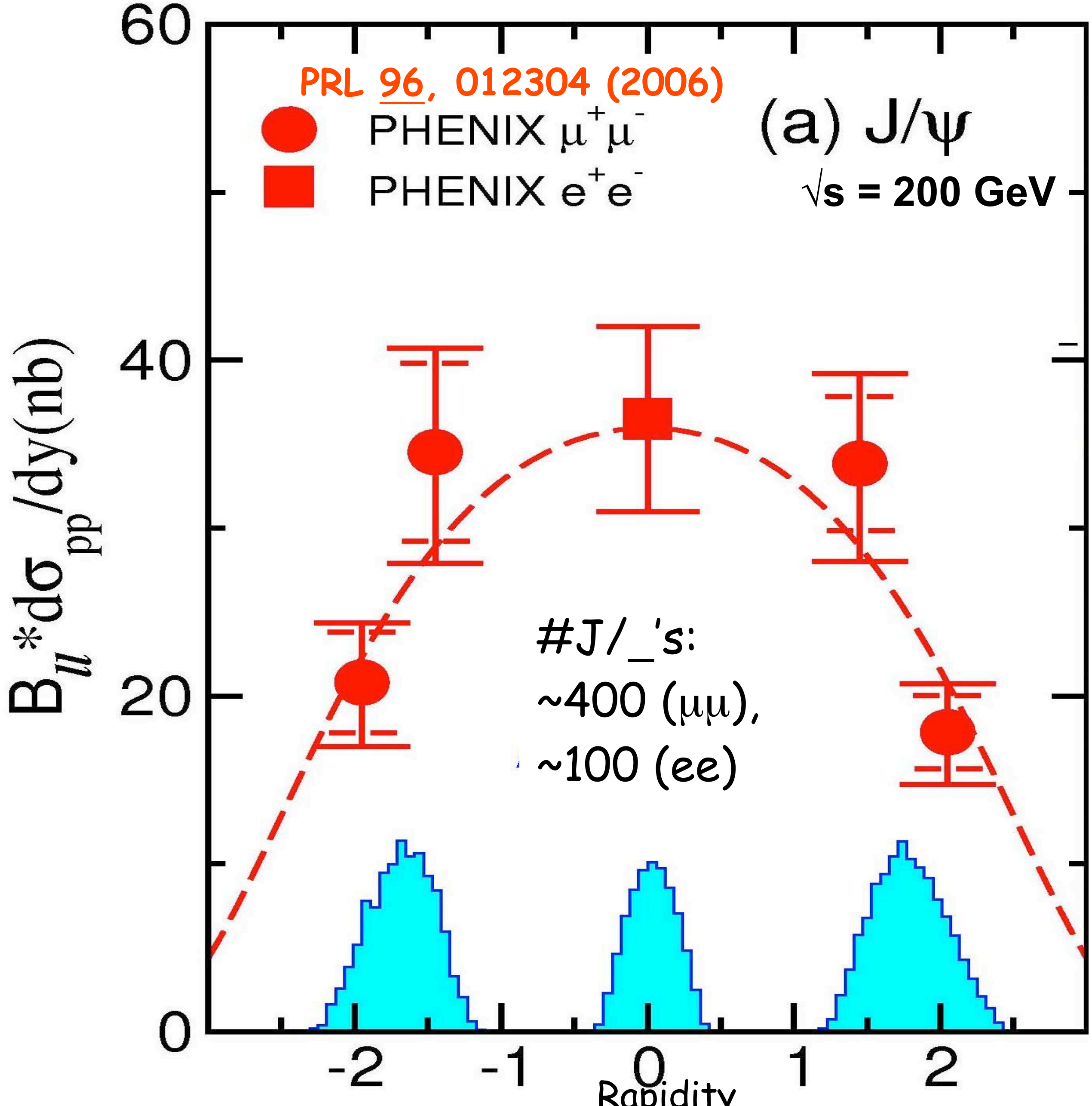
Figure 2. Σ_{p_T} as a function of $\sqrt{s_{NN}}$ in central events.

CERES tabulation H.Sako, et al, JPG 30, S1371 (04)

Where is the critical point?

$$\Sigma^2_{p_T} = \frac{\sigma^2_{p_T,dyn}}{\mu^2} = \frac{\sigma^2_{M_{p_T}}}{\mu^2} - \frac{1}{\langle n\rangle}\frac{\sigma^2_{p_T}}{\mu^2} = \frac{\sigma^2_T}{\langle T\rangle^2}$$

Cross section vs Rapidity (p+p)-e+e- and μ+μ-



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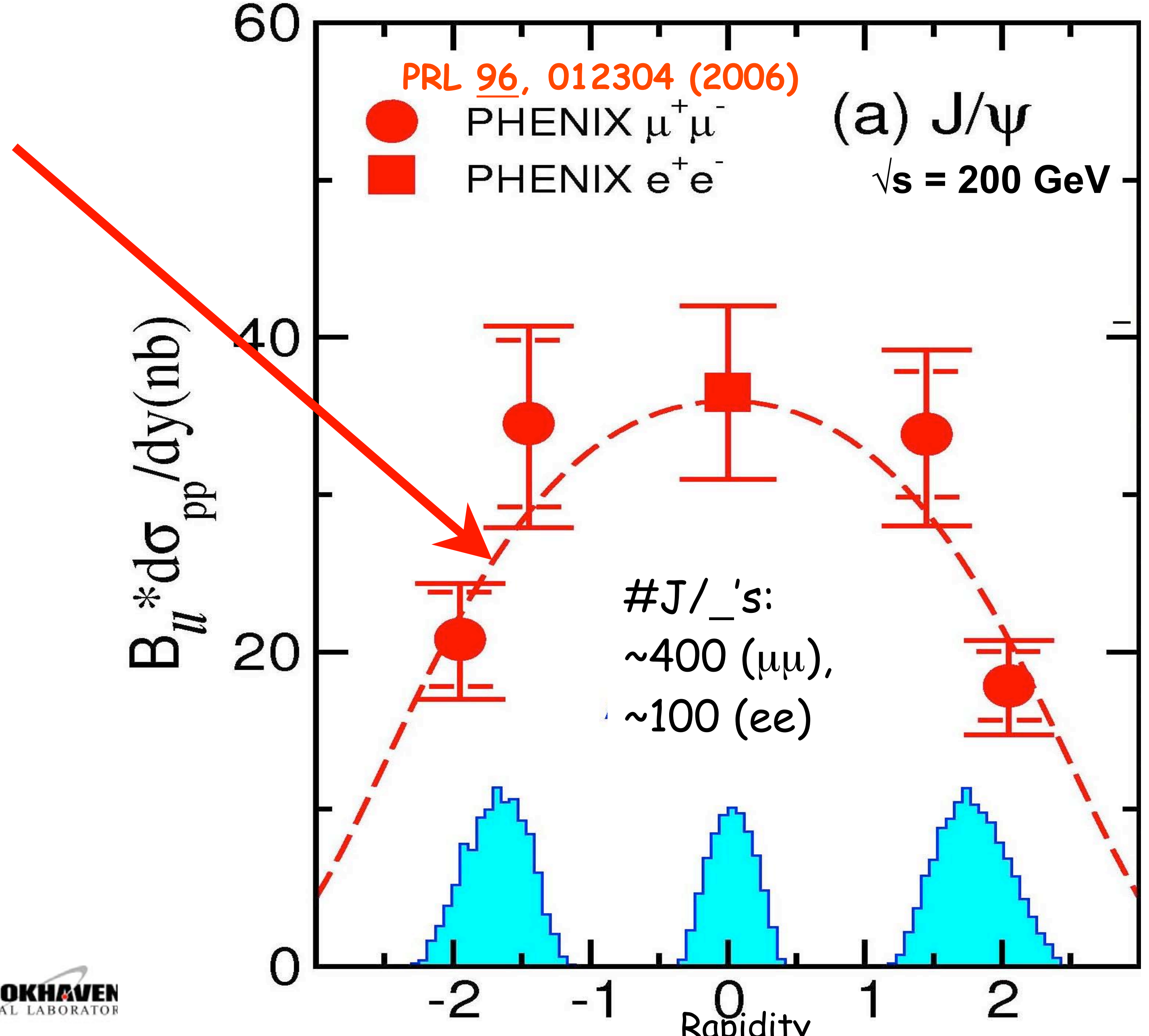
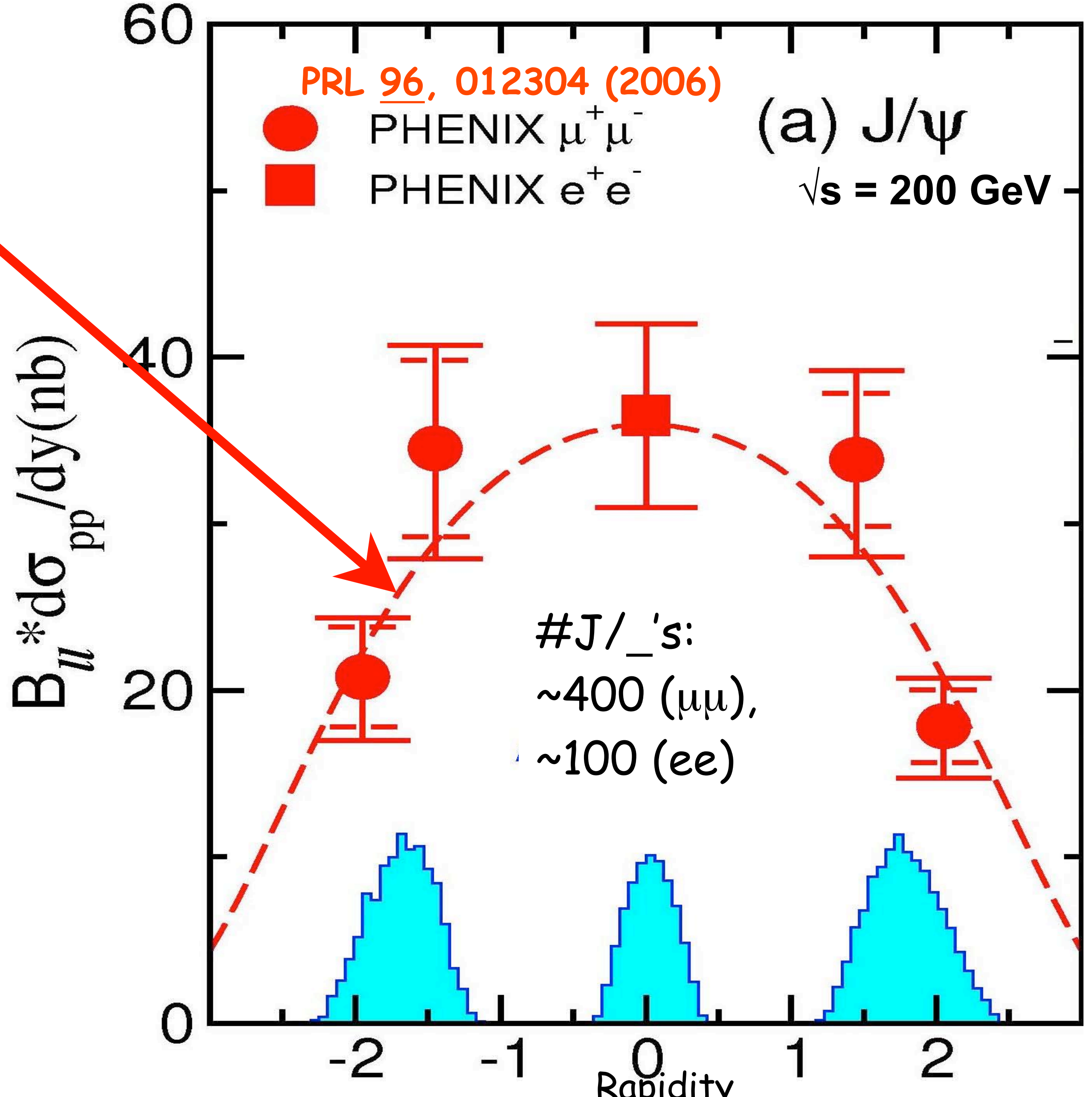
Cross section vs Rapidity (p+p)-e+e- and μ+μ-



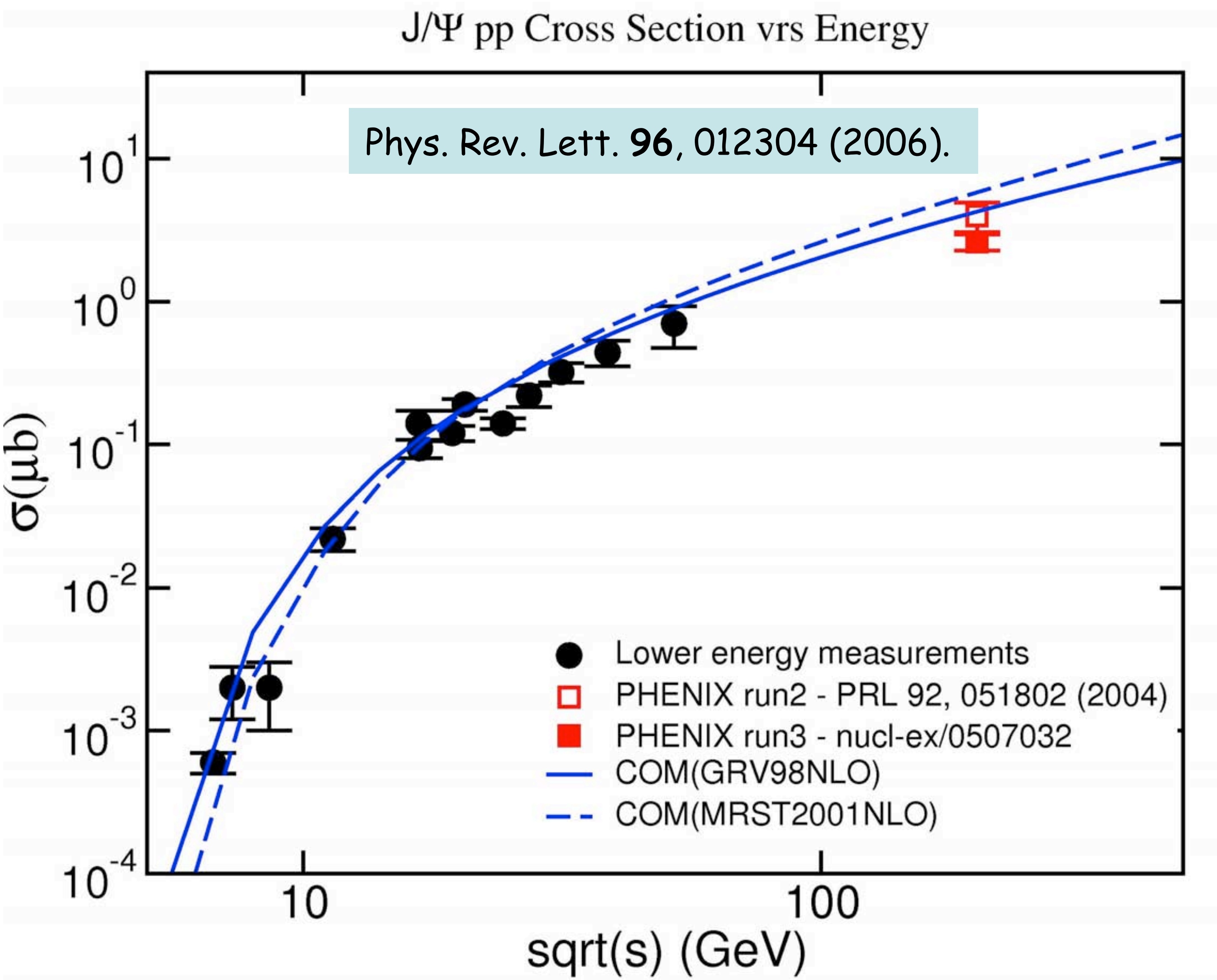
Cross section vs Rapidity (p+p)-e+e- and μ+μ-

- Good agreement with PYTHIA shape
- These are Run-3 data
- Run-5: ~ x 10
- Run-6: ~ Run-5 today, expected to double



p+p Reference is consistent

- Consistent with trend of world's data
- ~Consistent with at least one COM (Color Octet Model) calculation



Not Suppressing the J/ψ (!)

- Karsch, Kharzeev, Satz; hep-ph/0512239 :
  - ✓ Based on LQCD results suggesting $T_{J/\psi} \sim 2\ T_C$
  - ✓ Suppression (only) of Ψ' and χ_C
  - ✓ See talk(s) to follow

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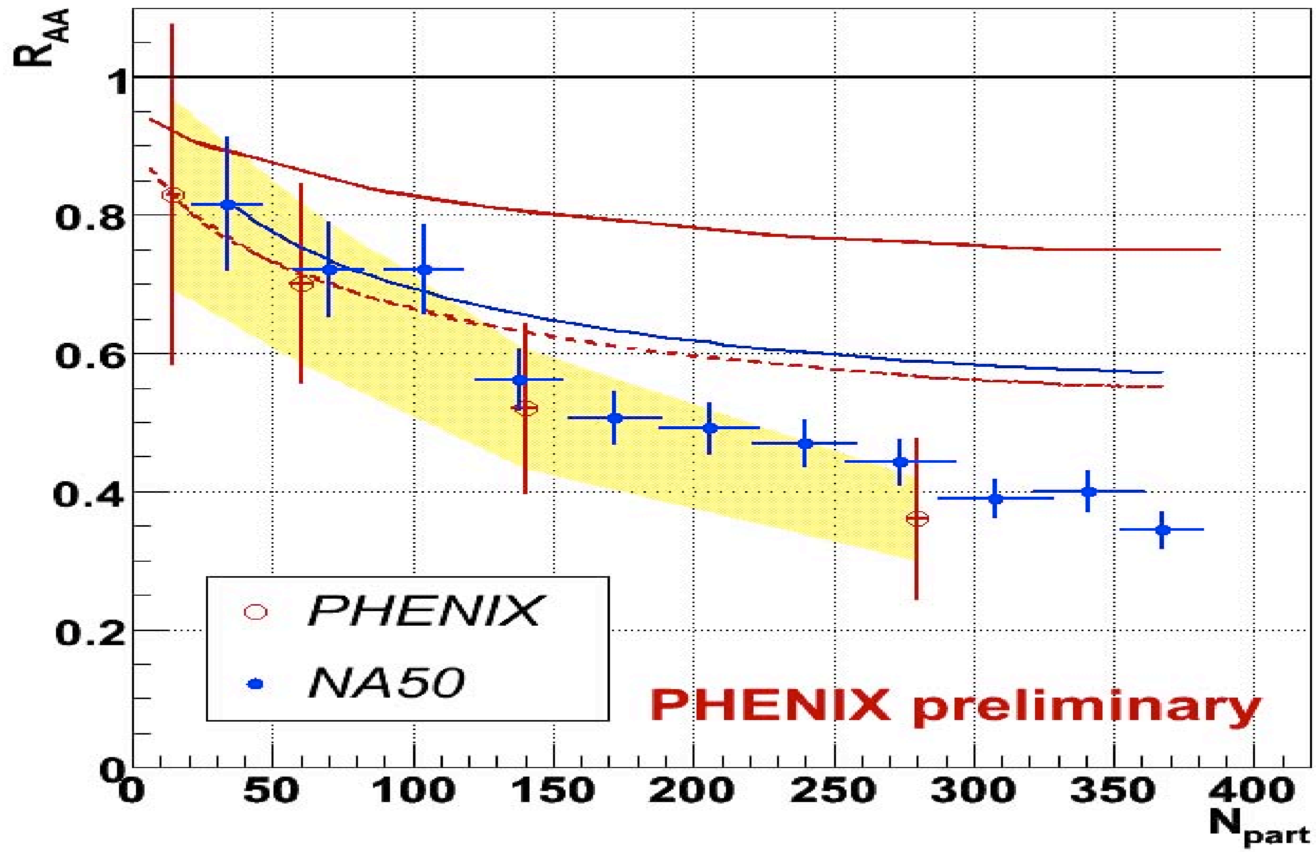
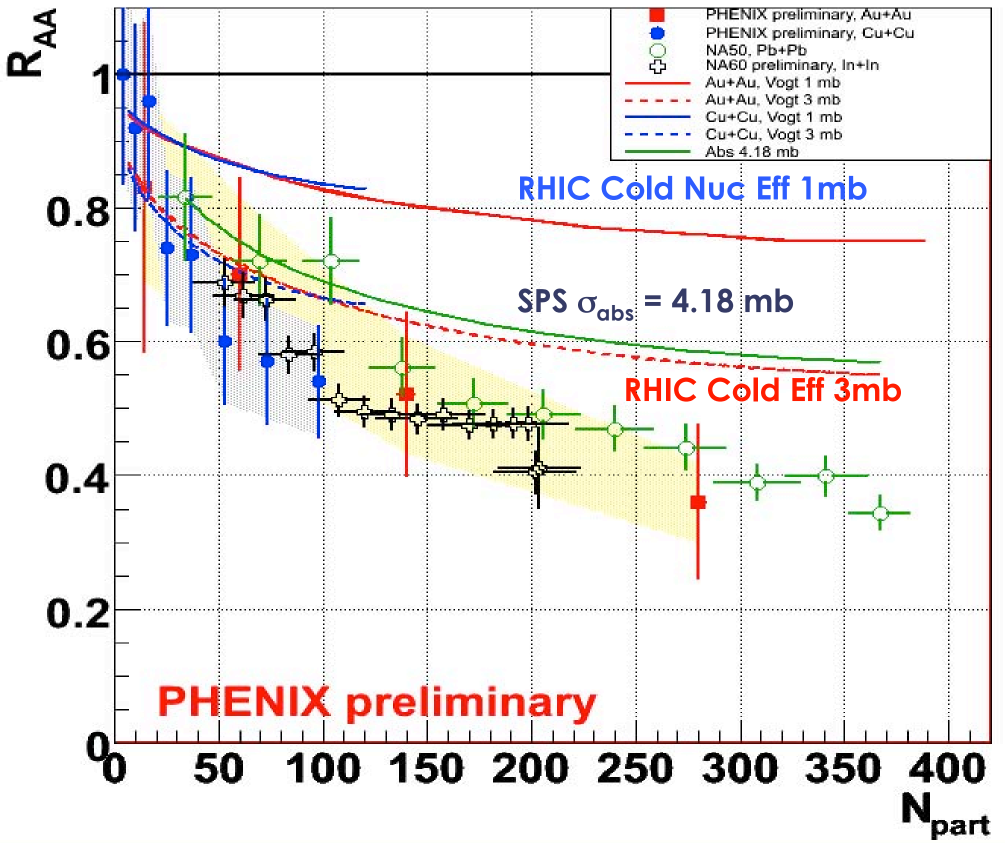
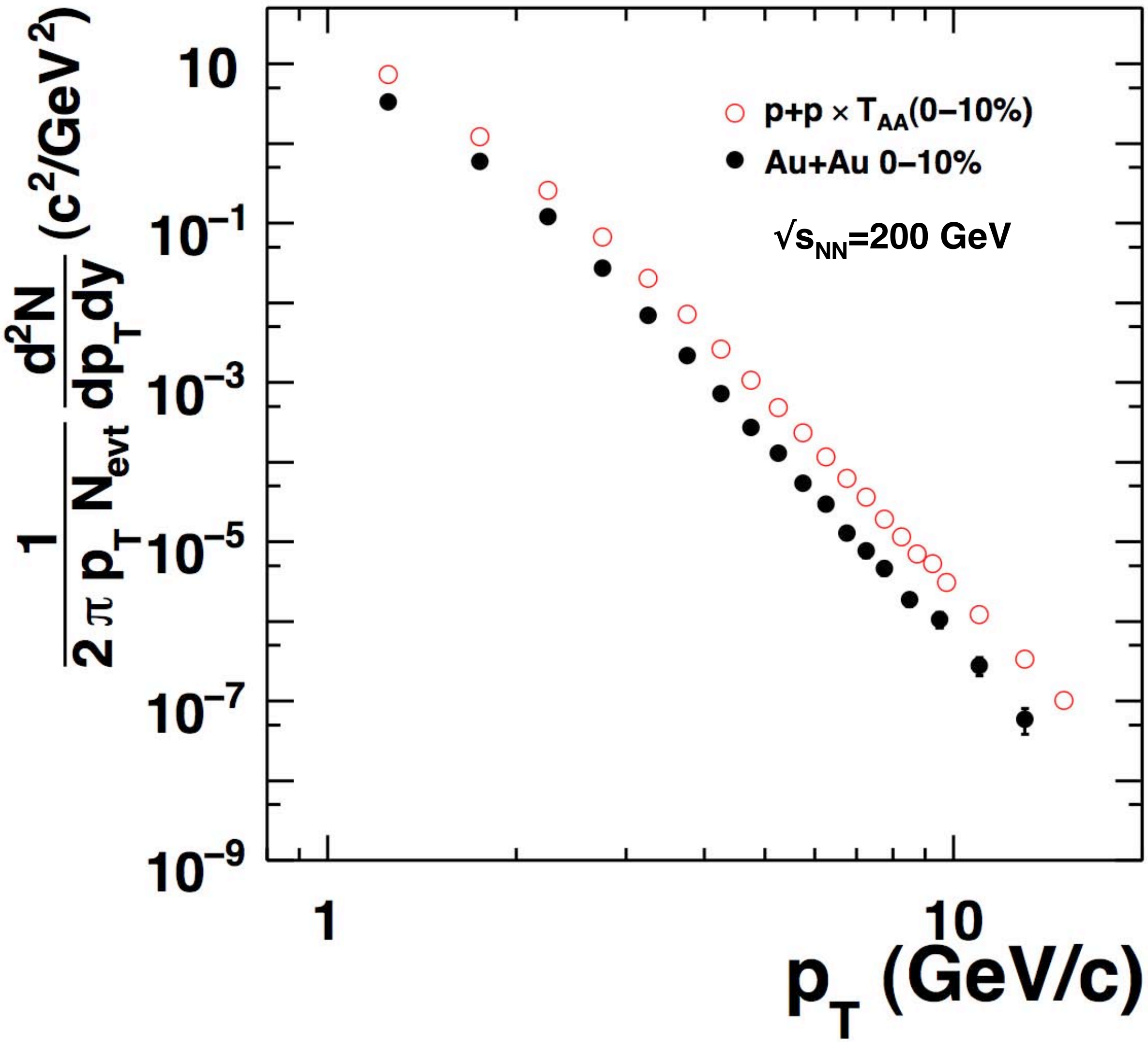




R_{AA}
PHENIX preliminary, Au+Au
PHENIX preliminary, Cu+Cu
NA50, Pb+Pb
NA60 preliminary, In+In
Au+Au, Vogt 1 mb
Au+Au, Vogt 3 mb
Cu+Cu, Vogt 1 mb
Cu+Cu, Vogt 3 mb
Abs 4.18 mb
RHIC Cold Nuc Eff 1mb
SPS σ_{abs} = 4.18 mb
RHIC Cold Eff 3mb
PHENIX preliminary
N_{part}

Inclusive invariant π^0 spectrum is power law for $p_T \geq 3$ GeV/c n=8.1±0.1 in p+p and Au+Au



Nuclear Modification Factor

$$R_{BA} = \frac{\left[d^2N^{\pi}_{BA}/dp_T dy dN^{inel}_{BA}\right]}{\langle T_{BA}\rangle \times \left[d^2\sigma^{\pi}_{pp}/dp_T dy\right]}$$

$$R_{BA} = \frac{\left[d^2N^{\pi}_{BA}/dp_T dy dN^{inel}_{BA}\right]}{\langle N_{coll}\rangle / \sigma^{inel}_{pp} \times \left[d^2\sigma^{\pi}_{pp}/dp_T dy\right]}$$

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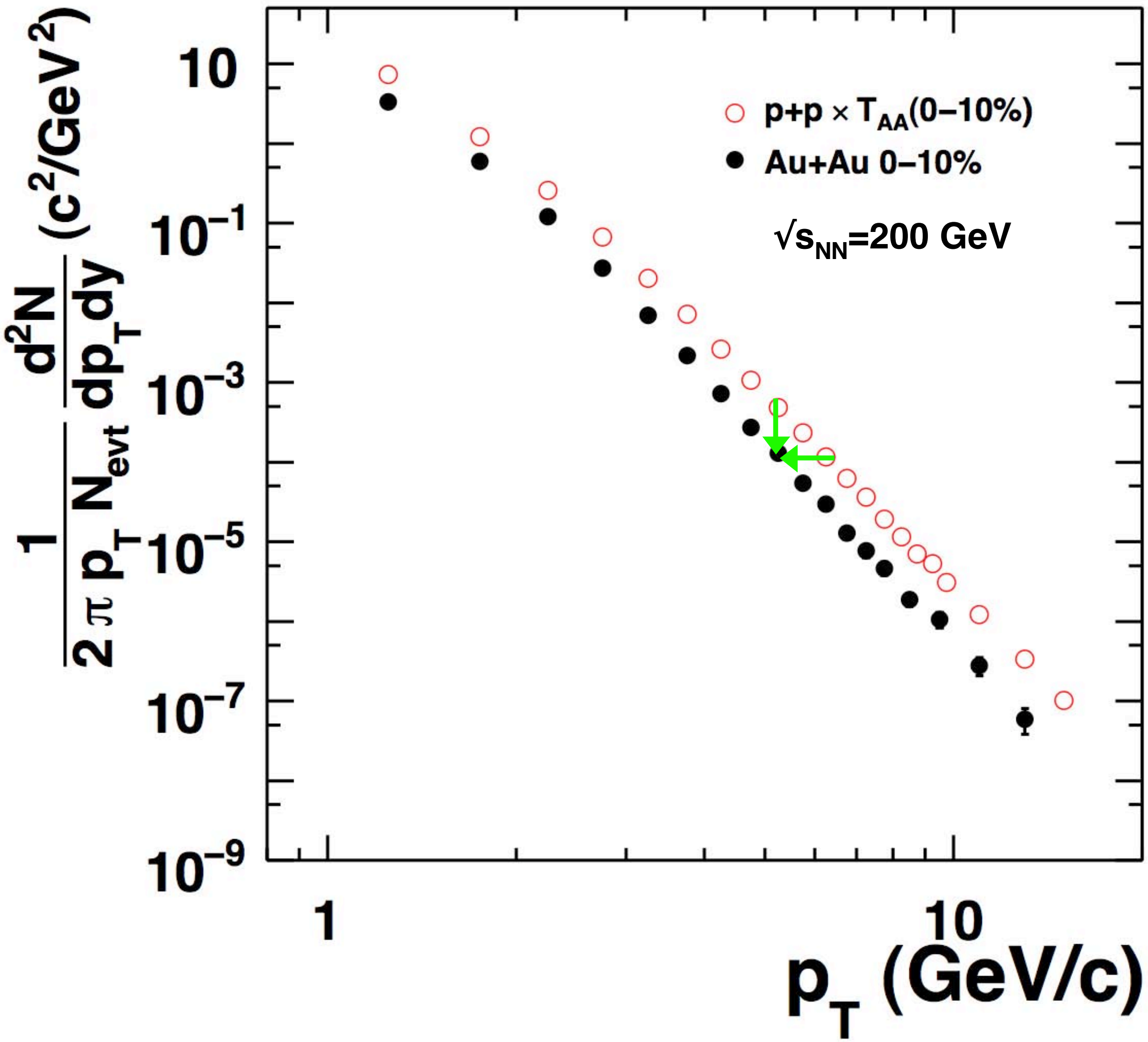

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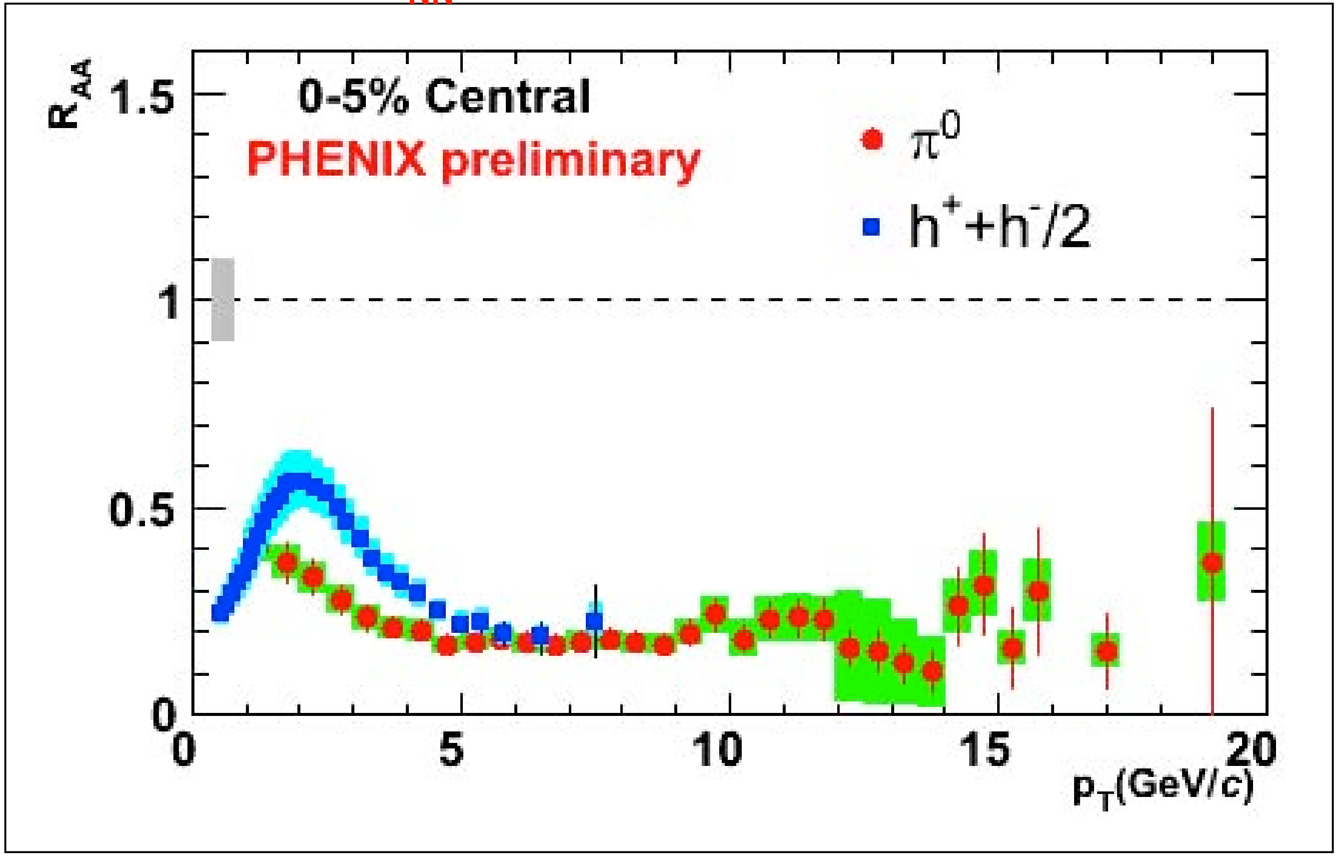
Impossible to distinguish reduction in the number of partons (due to e.g. stopping in medium) from fractional downshift in spectrum (due to e.g. energy loss of parton in medium)

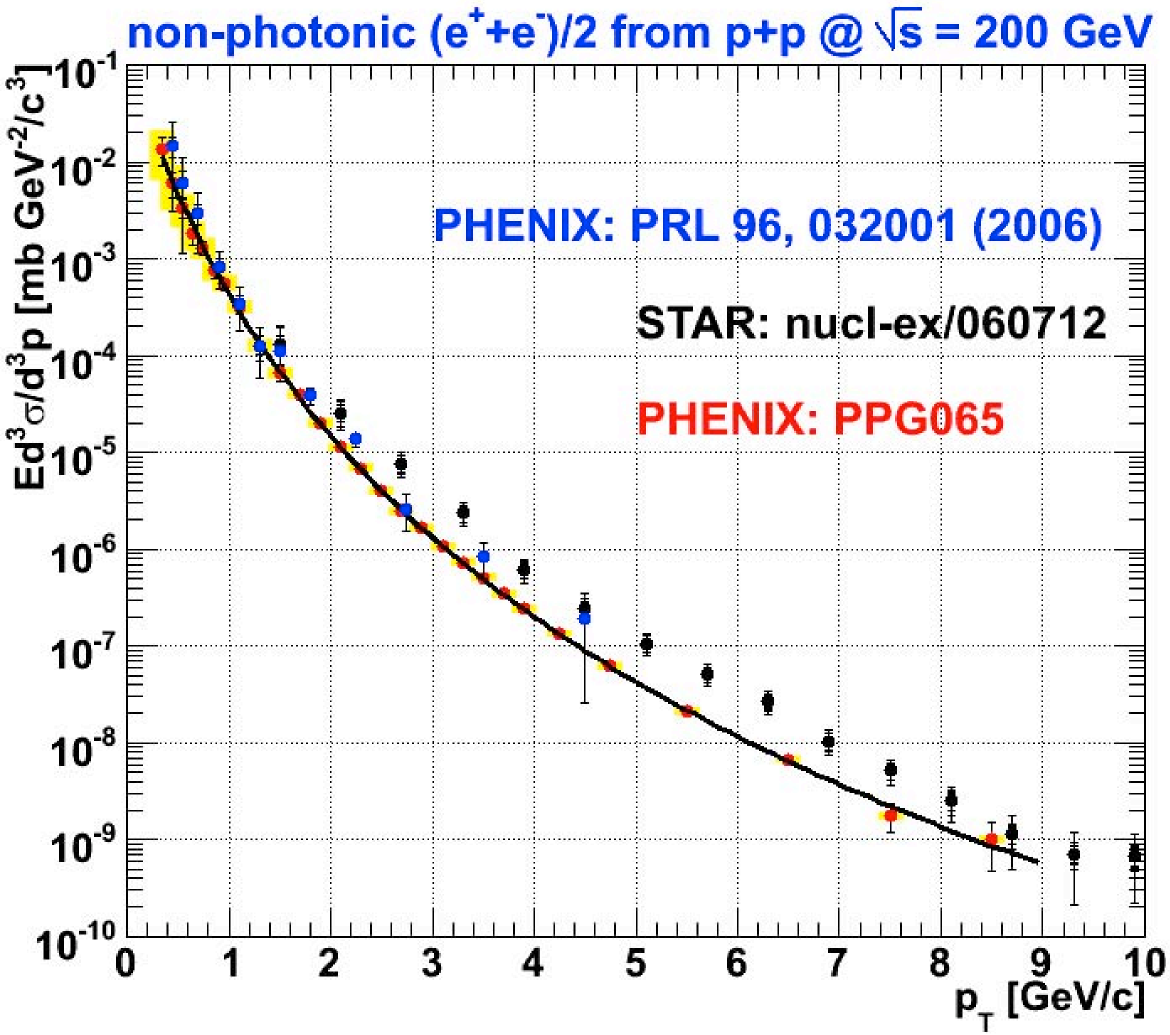
R_{AA}: π^0 and non-identified charged are different

Au Au $\sqrt{s_{NN}}$=200 Gev-run 4

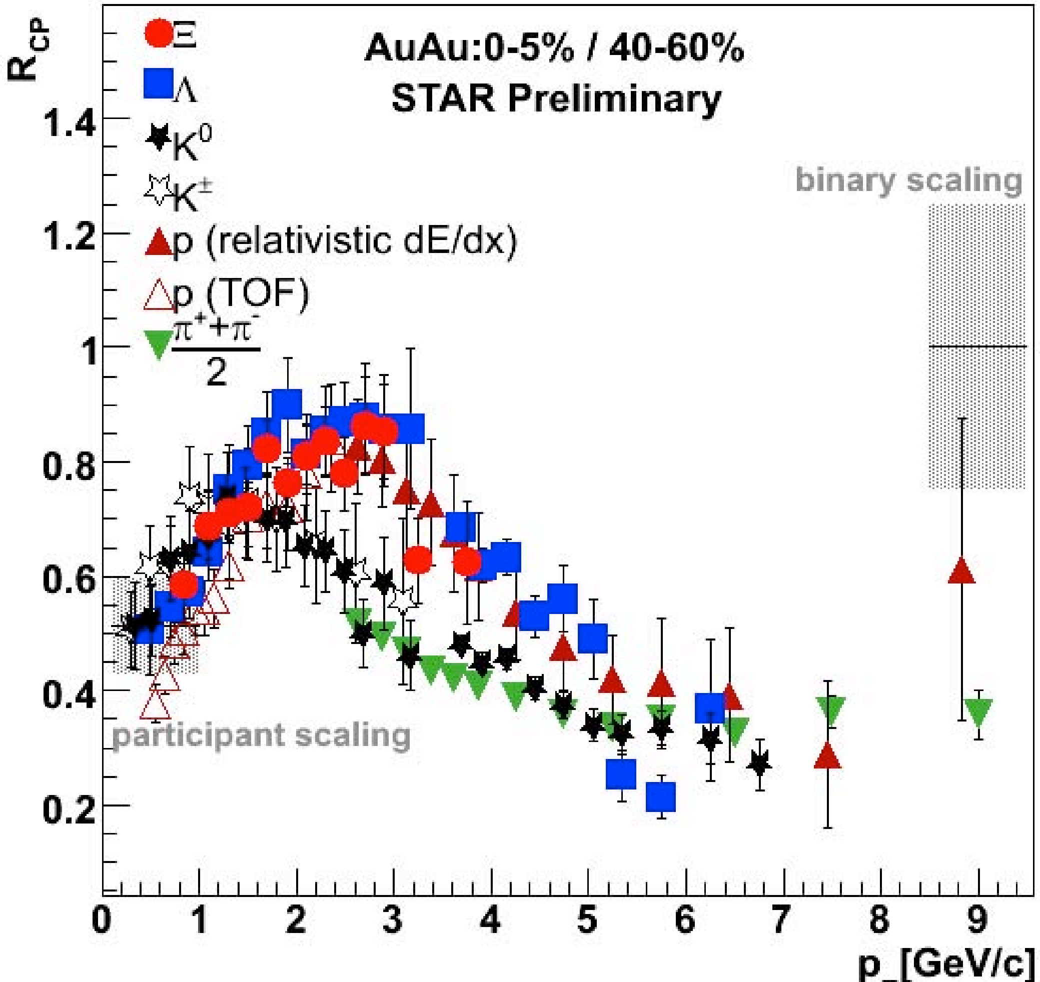


Does either obey QCD? We tried x_T scaling AuAu 200 cf 130 GeV

STAR PHENIX disagreement on charm
Are the electrons really non-photonic?



Rcp of Baryons & mesons become equal (⇒fragmentation) for p_T>6 GeV/c at 200 GeV



STAR-Jana Bielcikova Hard Probes 2006

- In agreement with recombination predictions
- Balance between recombination and fragmentation should be different at LHC

- Hwa & Yang nucl-th/0603053 predict p/π~10 out to p_T~20 GeV/c at LHC due to recombination of partons from the many jets produced⇒ *p* have no associated jet structure !!

- Very important to measure at LHC--needs pid over a large p_T range