News (and thoughts) from QM2005

Alberto Accardi (Iowa State U.)

ISU nuclear seminar, Sep. 8th, 2005

- **The Quark-Gluon Liquid:**
  - “Cones” ⇒ properties of the liquid
  - Lessons from QED plasmas
- **From discovery to tests of energy loss**
  - confirmations and new puzzles
- **Everything scales as Npart! (?)**
  - Single particle observables
  - Are we seeing the CGC? (speculative)

I. The Quark-Gluon Liquid

QGL - the "perfect" fluid

- RHIC announced formation of a "perfect fluid", i.e.,
  a strongly interacting plasma-like nuclear matter with an extremely small ratio of shear viscosity to entropy

- The fluid is partonic:
  - $T = O(10) \times T_c$ (Extrapolated from E_T, jet quenching, ...)
  - strong collective flow - also non-γ $e^{\pm}$ $\Rightarrow$ heavy quarks
  - hydro with QGP EOS reproduces v2 fairly well (soft p_T<2 GeV)
  - quark number scaling
  - also ϕ flows - too strongly for hadronic rescattering mechanisms
  - ...

Let's call it Quark-Gluon Liquid!

- The fluid is strongly coupled
  - lattice ⇒ plasma is not perturbative at $T < 2\ T_c$
  - what states does it contain?
    - ✔ coloured partonic bound states (Shuryak, Koch, Karsch)

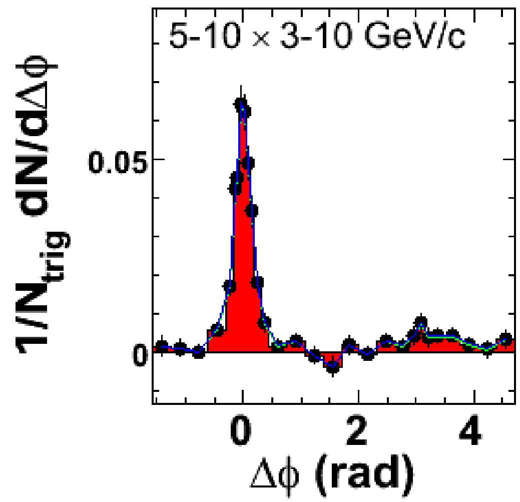
Some prefer to call it a strongly coplud QGP: sQGP

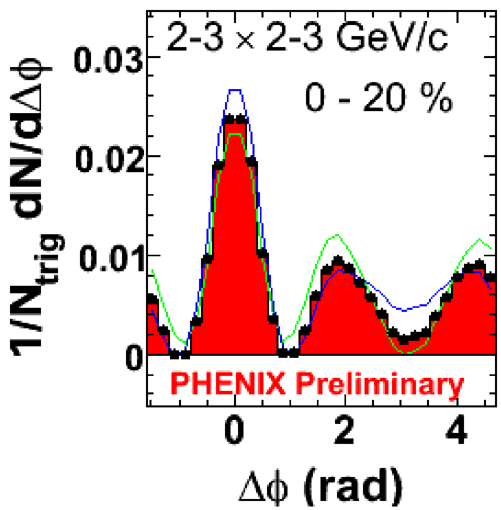
- The task is now to study its properties

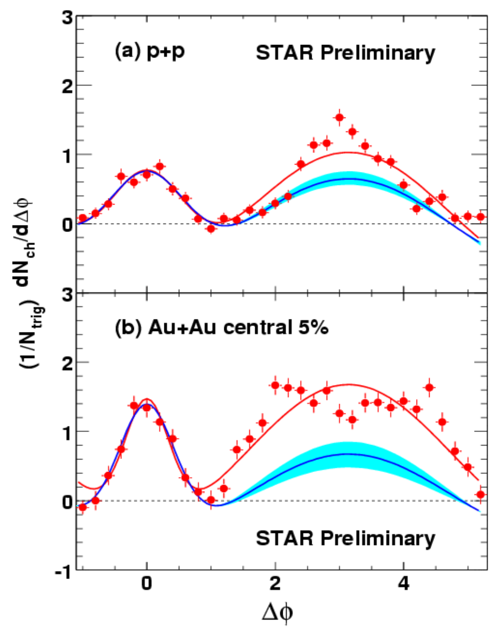
- Need new approaches, e.g.,
  - conical waves: "cones" in the soft hadron sector
    ⇒ properties such as speed of sound, (color) dieletric constant
    (Shuryak, Ruppert, Dremin, Majumder)
  - guidance from QED plasmas (Thoma)

I.1 “Cones”

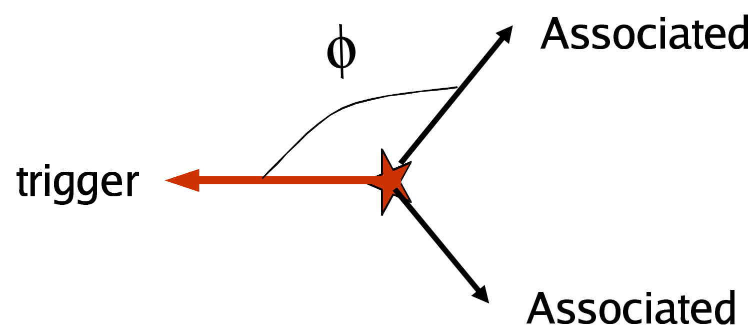
The reappearance of the away-side jet







2-particle correlations



Explanations

(see also Focus talk of J.Ruppert)

- Jet energy is redistributed into excitations of
  1) colorless (hydrodynamical) modes => Mach cones

     J. Casalderray, E. Shuryak, D. Teaney, (2004) hep-ph/0411315,

     Ulrich Heinz in preparation

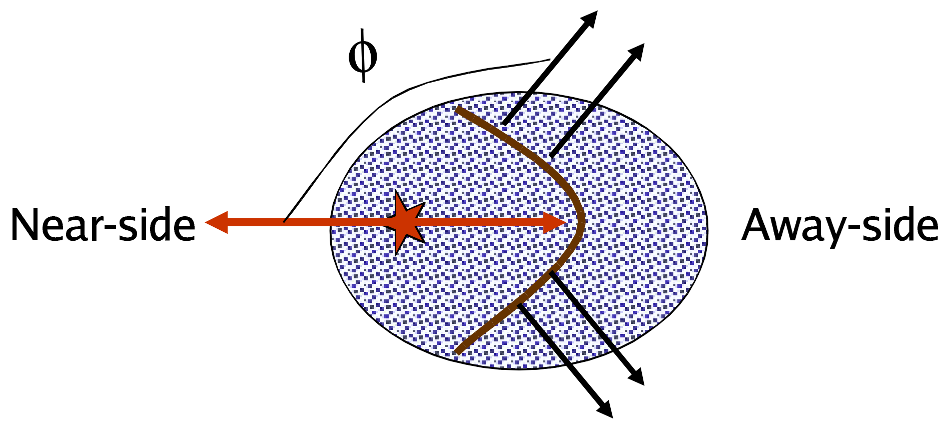
  2) colorful modes:

     2.1) longitudinal modes => Mach cones

     H. Stöcker, Nucl. Phys. A750, (2005) 121,
     J. Ruppert, B. Müller, Phys. Lett. B618 (2005) 123

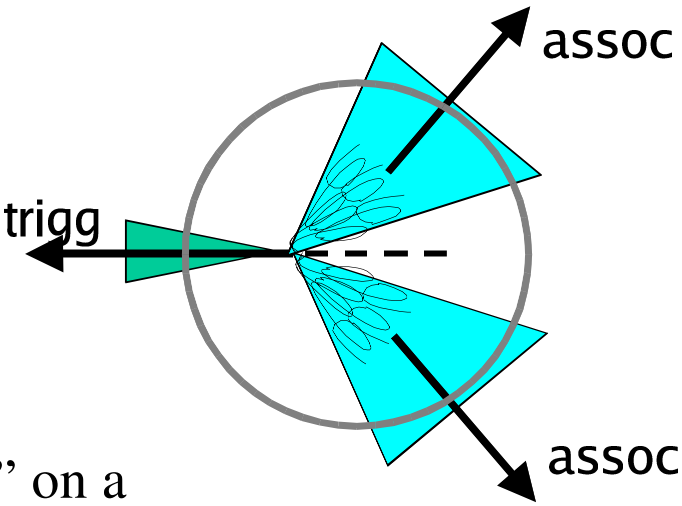
     2.2) transverse modes =>Cherenkov (like) radiation

     I. Dremin, JETP Lett.30, (1979) 140 and I. Dremin, hep-ph/0507167,
     A. Majumder and X.-N. Wang, nucl-th/0507062



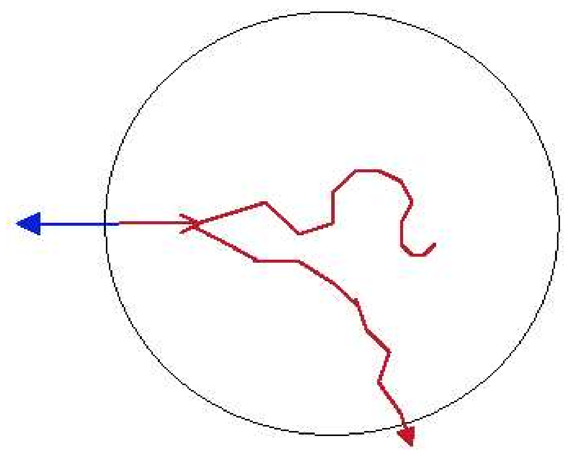
- LPM interference depletes radiated gluons along parton's direction

I.Vitev, hep-ph/....



- Bent jets R.Hwa's talk
  - soft parton makes “random walk” on a circular mound; step size ∝ medium density
  - most walks absorbed in the medium

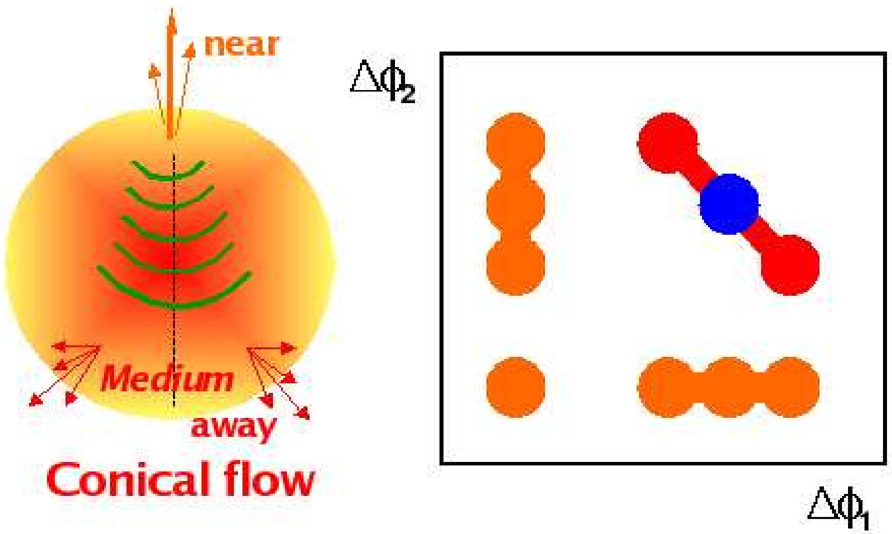
No conical flow!



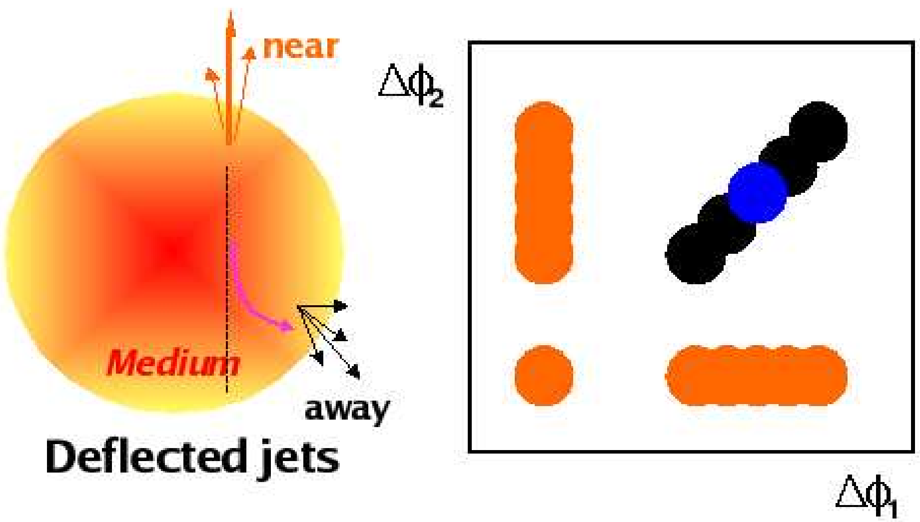
  - cone angle in non central collsions should depend also on trigger orientation

3-particle correlations

- Should distinguish a “cone” from a “bent jet”



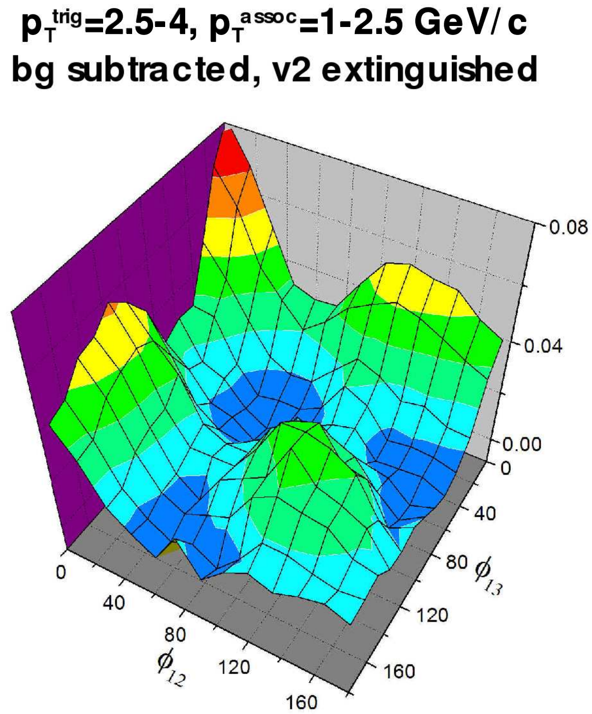
- Does a shock wave form?
- Three-particle correlations
  - **Conical flow**: associated particles may appear on opposite sides of $\Delta\phi=\pi$



  - **Deflected jets**: associated particles on the same side of $\Delta\phi=\pi$

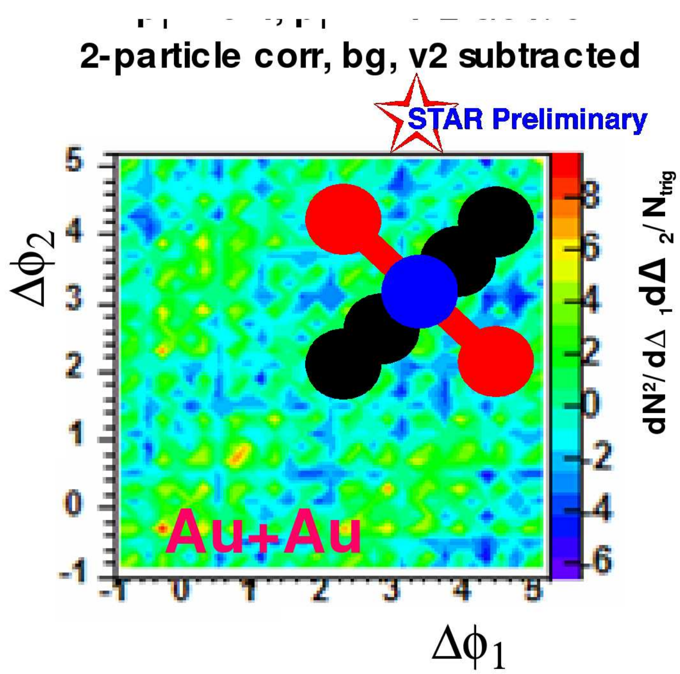
Casalderrey-Solana, Shuryak and Teaney, hep-ph/0411315
Stocker, NP A750, 121
Ruppert and Muller, PL B618, 123

PHENIX



Clear conical flow!

STAR



Conical flow is not seen!

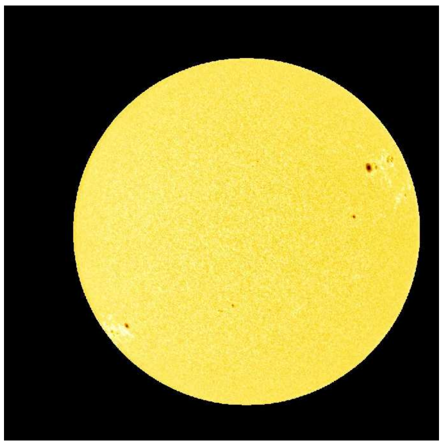
I.2 Lessons from QED plasmas

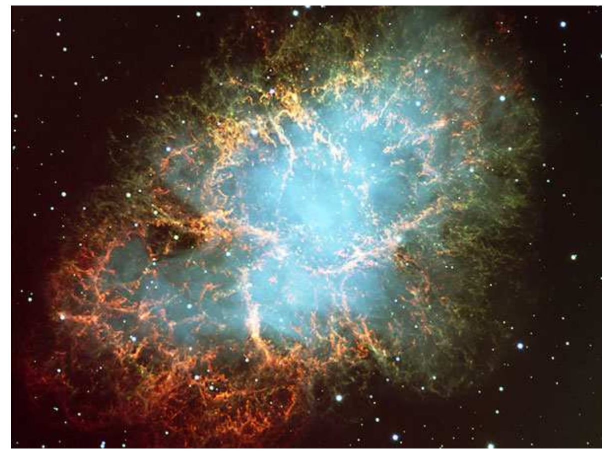
(transparencies adapted from M.Thoma's talk)

1. Strongly Coupled Plasmas

Plasma = ionized gas, 99% of visible matter in Universe

Plasmas generated by high temperatures, electric fields, or radiation





Classifications:

2. Non-relativistic – relativistic plasmas (pair plasmas, QGP)
3. Classical – quantum plasmas (white dwarfs, QGP)
4. Ideal – strongly coupled plasmas (complex plasmas, QGP)

Coulomb coupling parameter

$$\Gamma = \frac{Q^2}{dT}$$

Q: charge of plasma particles
d: inter particle distance
T: plasma temperature

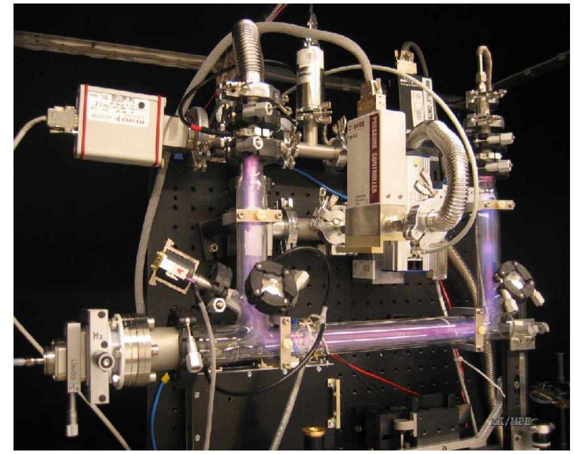
Ideal plasmas: $\Gamma << 1$ (most plasmas: $\Gamma < 10^{-3}$)

Strongly coupled plasmas: $\Gamma > O(1)$

Examples: ion component in white dwarfs, high-density plasmas at GSI

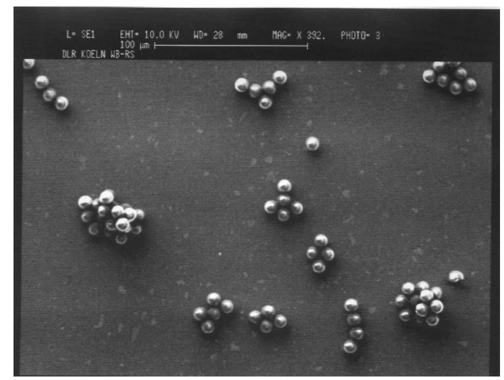
Non-perturbative description, e.g., molecular dynamics

2. Complex Plasmas



Dusty or complex plasmas = multi component plasmas with ions, electrons, neutral gas, and microparticles (dust)

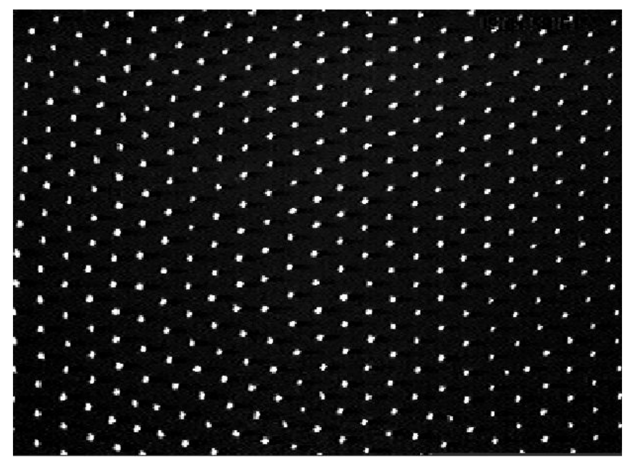
E.g.: low temperature neon plasma in a dc- or rf discharge



Injection of microparticles with diameter 1 – 10 μm

- Microparticles collect electrons on surface ⇒ large negative charge: $Q = 10^3 - 10^5\, e$
- Inter particle distance about 200 μm

⇒ plasma crystal (predicted 1986, discovered 1994 at MPE)



Observation: illumination by laser sheet and recorded by CCD camera

3. Phases of the plasmas

Melting of plasma crystal by pressure reduction; less neutral gas friction; temperature increase; decrease of Coulomb coupling parameter $\Gamma = Q^2/(dT)$

long range order (crystalline phase) → short range order (liquid phase) → disordered phase (gas)

Quantitive analysis of equation of state and determination of Γ:
pair correlation function

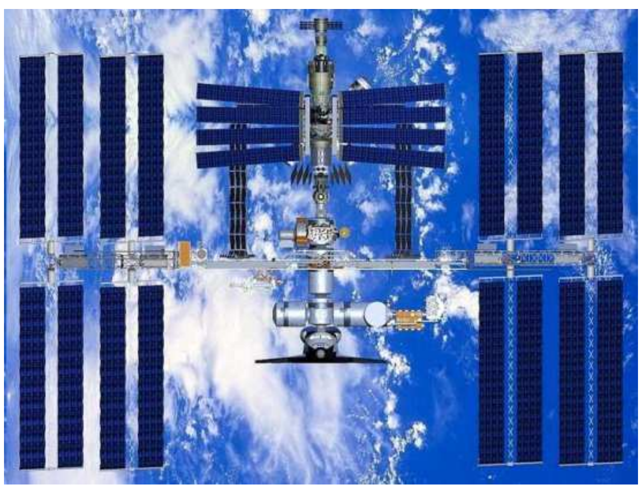
4. Collective phenomena

Mach cones induced by a laser beam have been observed

5. The fun part of this business

Gravity has strong influence on microparticles → microgravity experiments

M.Thoma !!



6. Applications to the Quark-Gluon Plasma

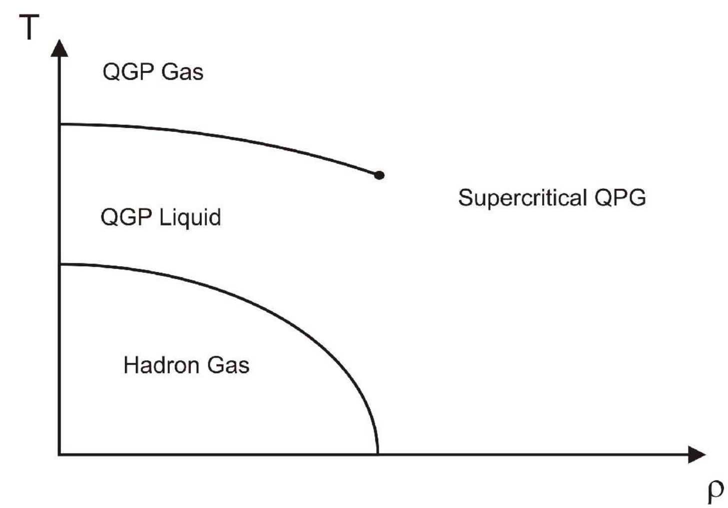
Estimate of interaction parameter $\Gamma \simeq 2 \frac{C\ \ s}{dT}$

C = 4/3 (quarks), C = 3 (gluons)
T = 200 MeV □α_S = 0.3 - 0.5
d = 0.5 fm
Ultrarelativistic plasma: magnetic interaction as important as electric

□Γ = 1.5 – 6 γ QGP Liquid?

RHIC data (hydrodynamical description with small viscosity, fast thermalization) indicate QGP Liquid

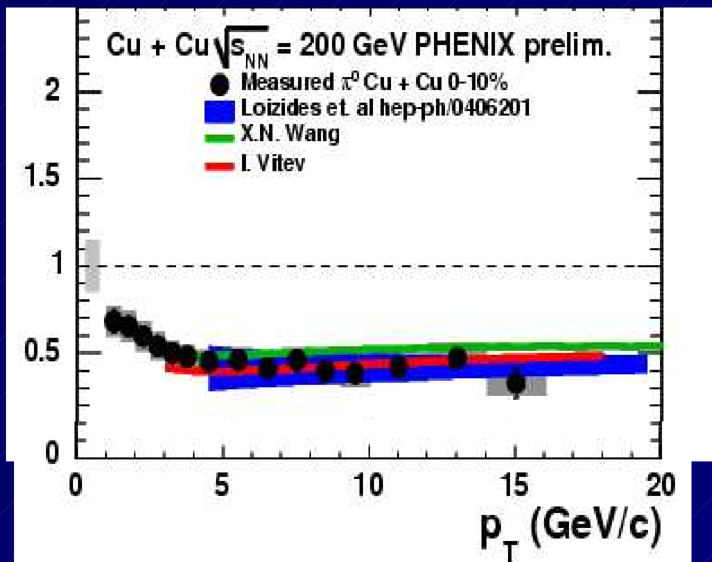
Attractive and repulsive interaction □ gas-liquid transition at a temperature of a few hundred MeV

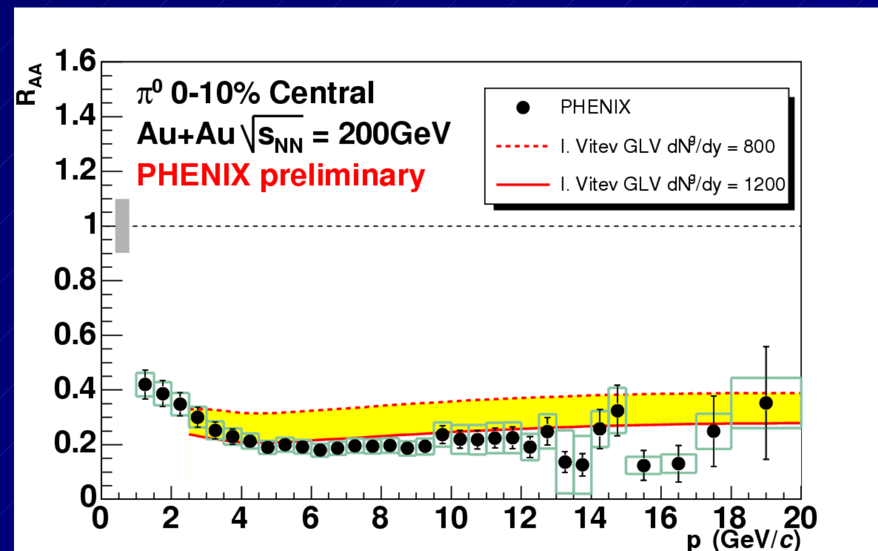


II. 2001-2005: from discovery to tests of partonic energy loss

(adapted from I.Tserruya, B.Cole, M.Djordjevic, N.Grau)

Suppression persists all the way till 20 GeV/c...
...as predicted by energy loss models



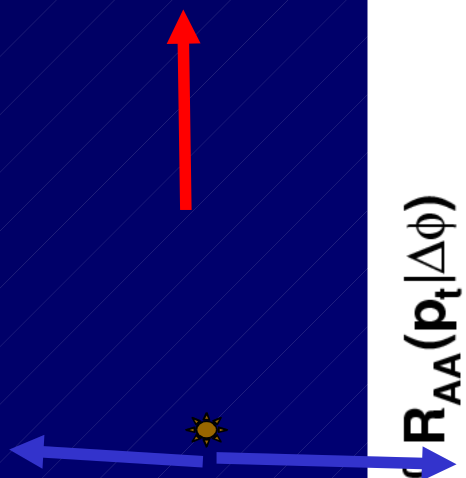


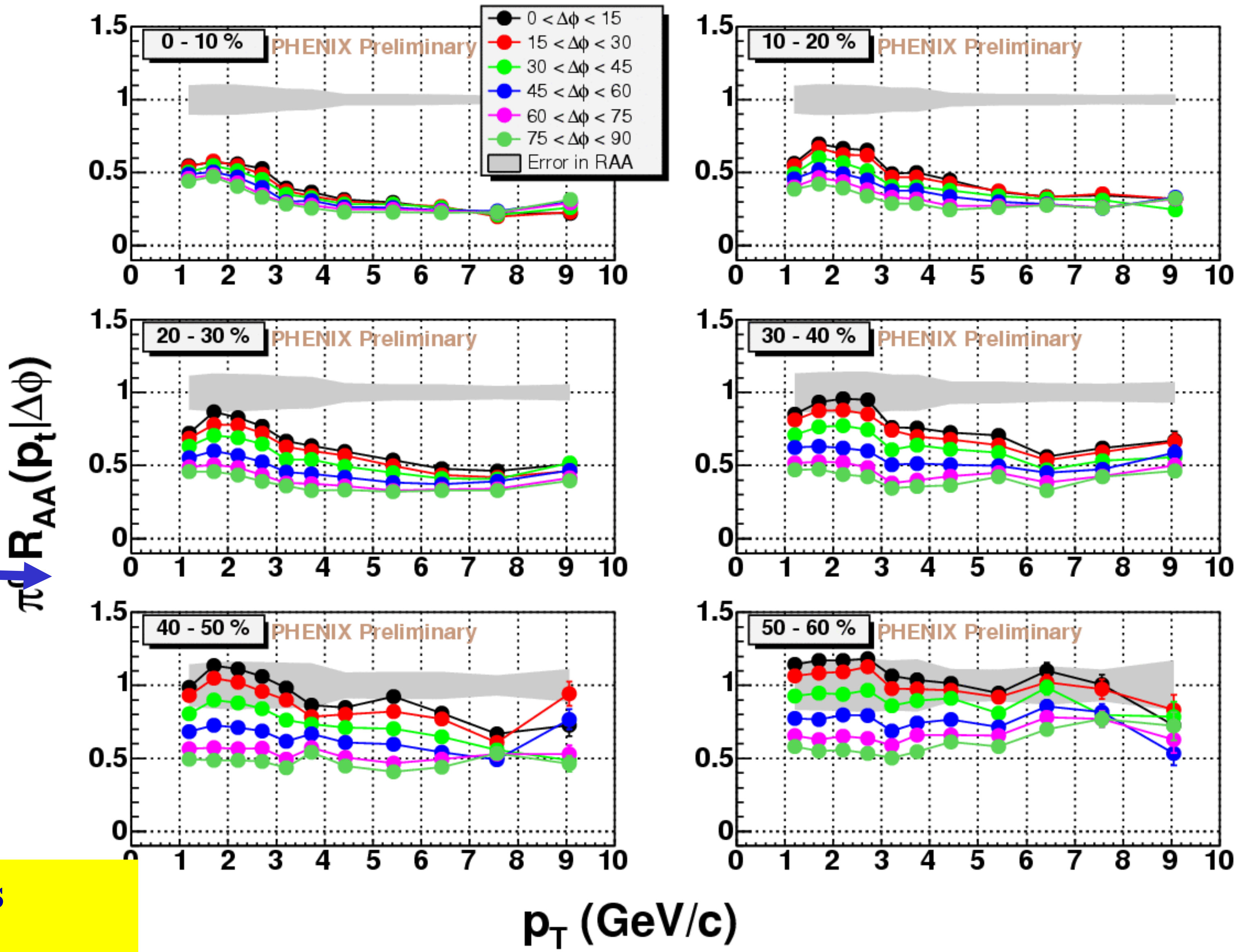
To quote B.Cole:

- "We have excellent agreement between models and data for both Au+Au AND Cu+Cu! This is good, right? **Wrong!** "

  - Different models yield different medium opacity
  - Loizides et al.: "Surface emission"
  - GLV: energy fluctuations leave the medium more transparent

R_{AA} wrt reaction plane



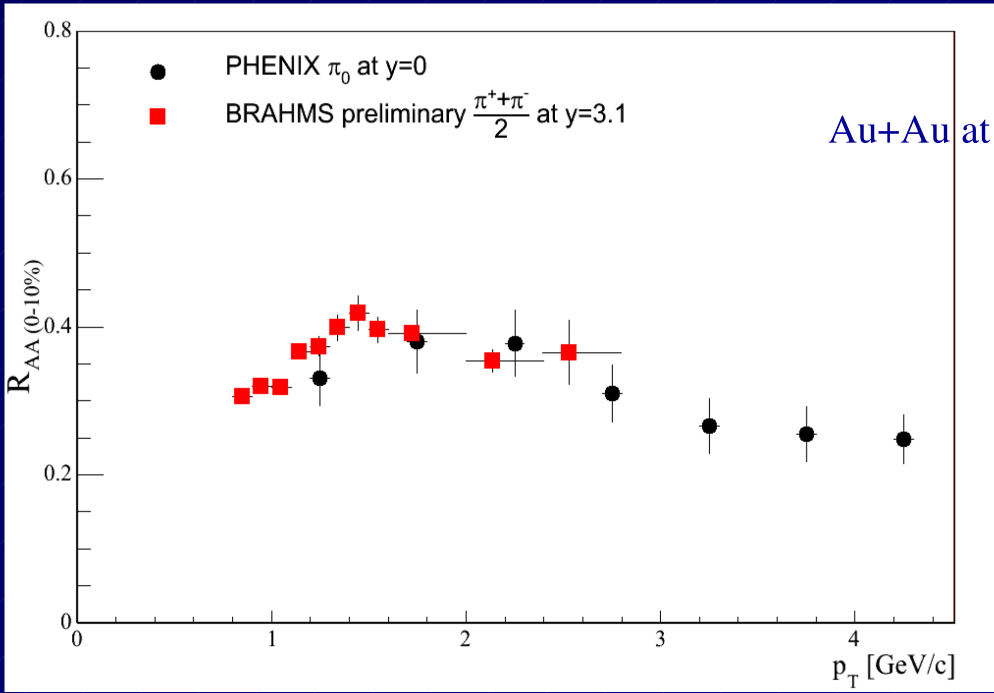


Energy loss depends on the path-length

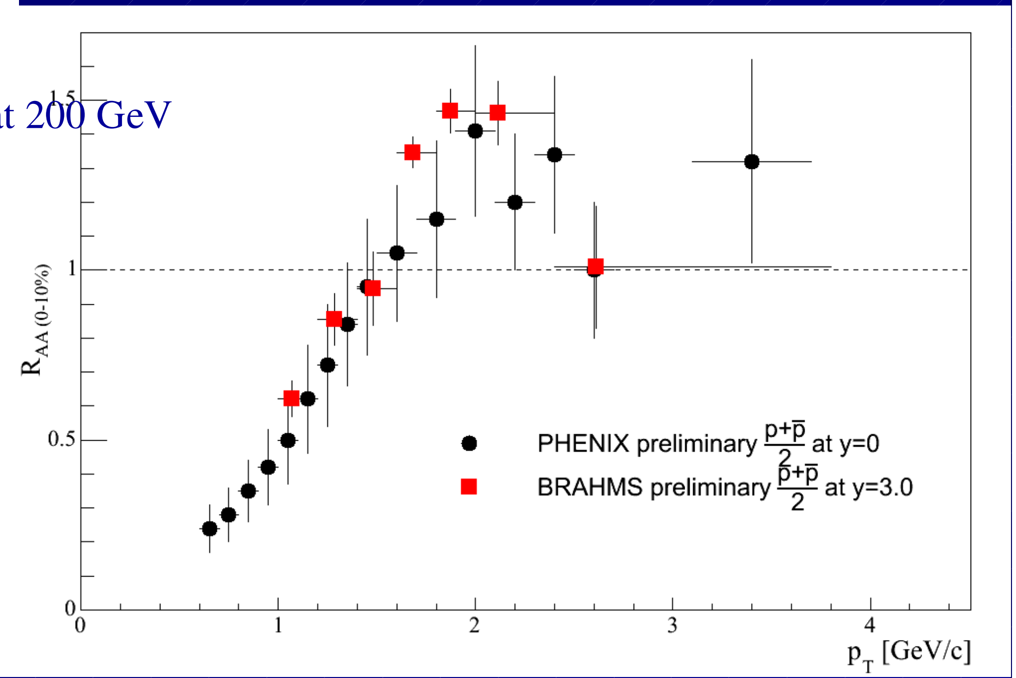
R_{AuAu} of identified hadrons vs rapidity

Pions y=0 and y=3.1

Protons y=0 and y=3

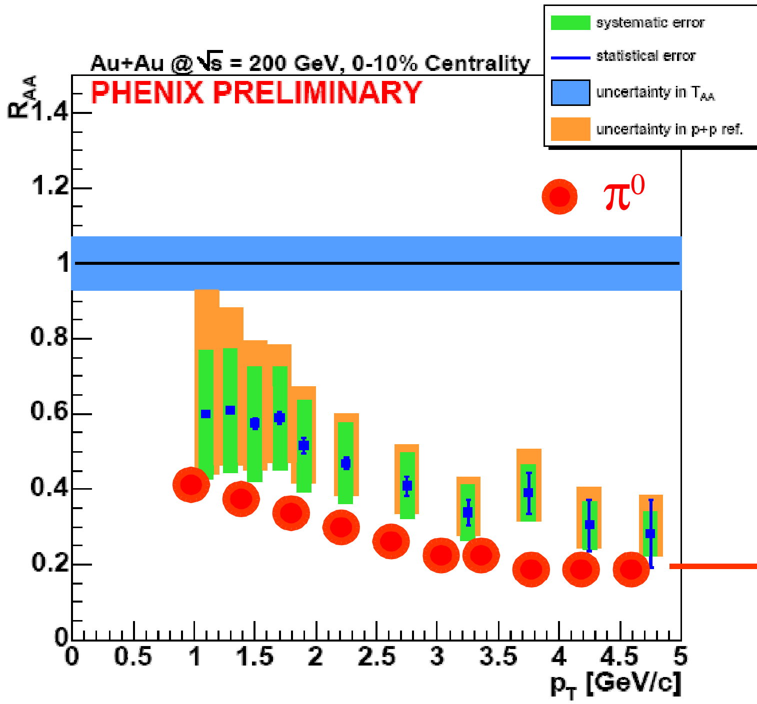


Au+Au at 200 GeV

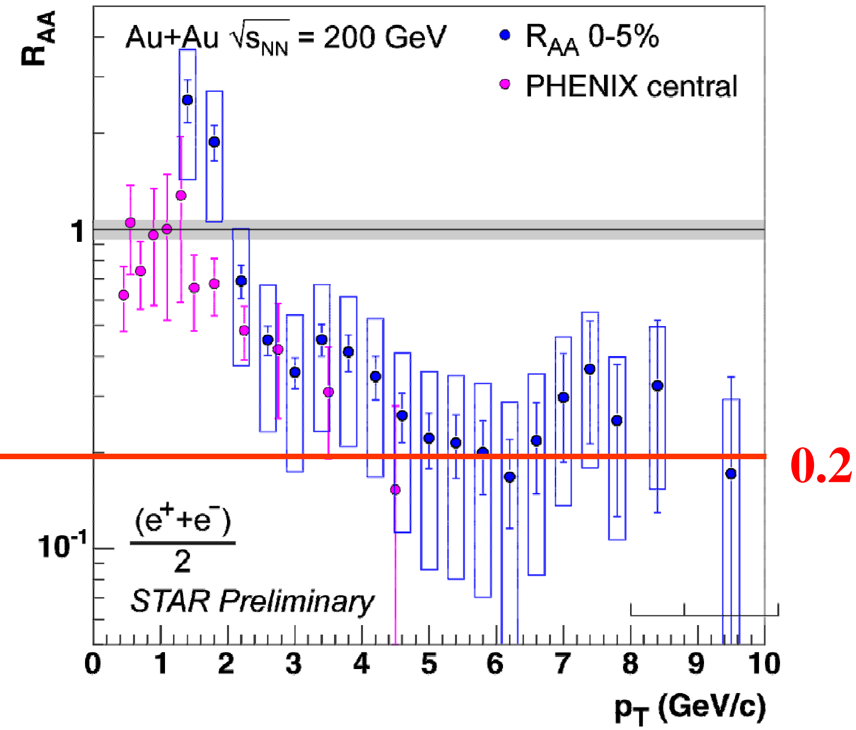


- NO change of R_{AuAu} with rapidity

Single electron suppression measurements

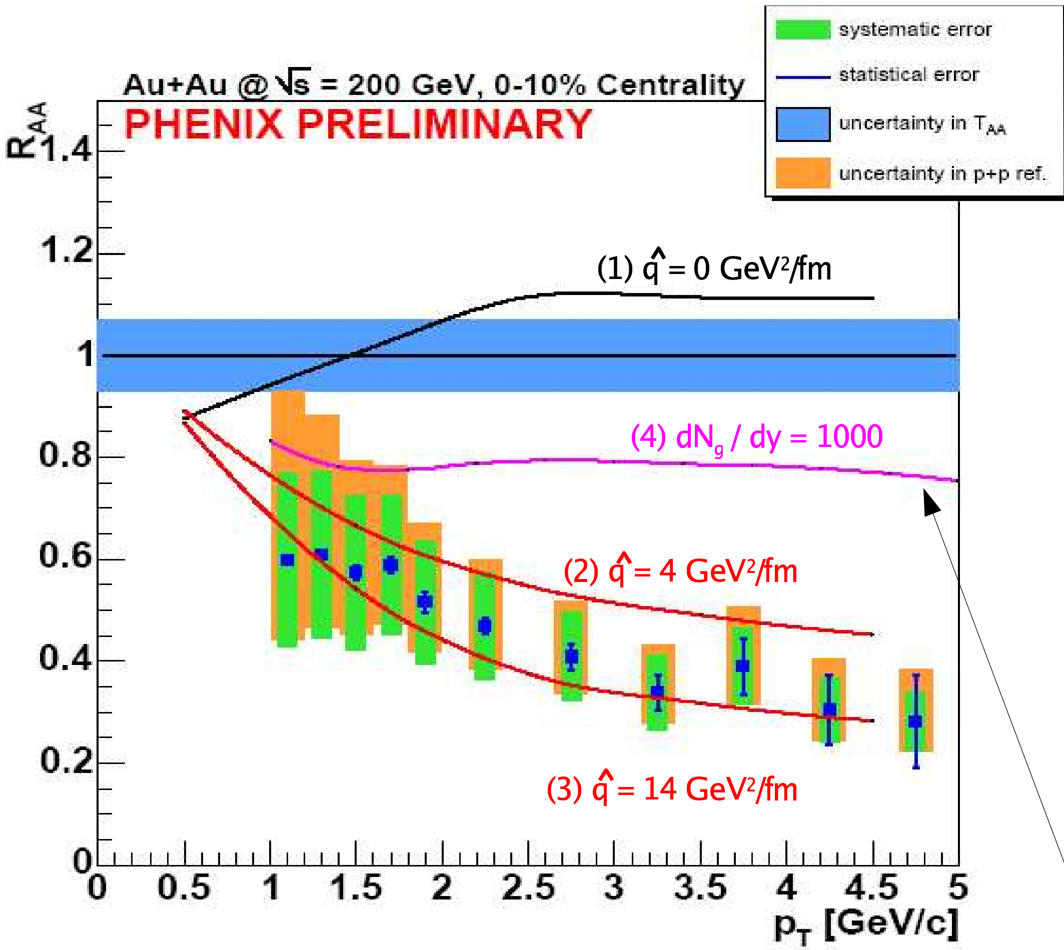


V. Greene, S. Butsyk, QM2005



Significant reduction at high pT suggest sizable energy loss!

Comparison to Theory – A New Puzzle



Theory curves
(1-3) from N. Armesto, *et al.*, PRD 71, 054027
(4) M. Djordjevic, M. Gyulassy and S. Wicks, Phys. Rev. Lett. 94, 112301 (2005);

M. Djordievic QM2005 talks:

Theoretically, single electron suppression has to be at least two times smaller than pion suppression.

$e^{\pm}$ suppression compatible with charm suppression; using NLO pQCD cocktail of c & b yields curve (4)

single hadron suppression vs. v2 : another puzzle

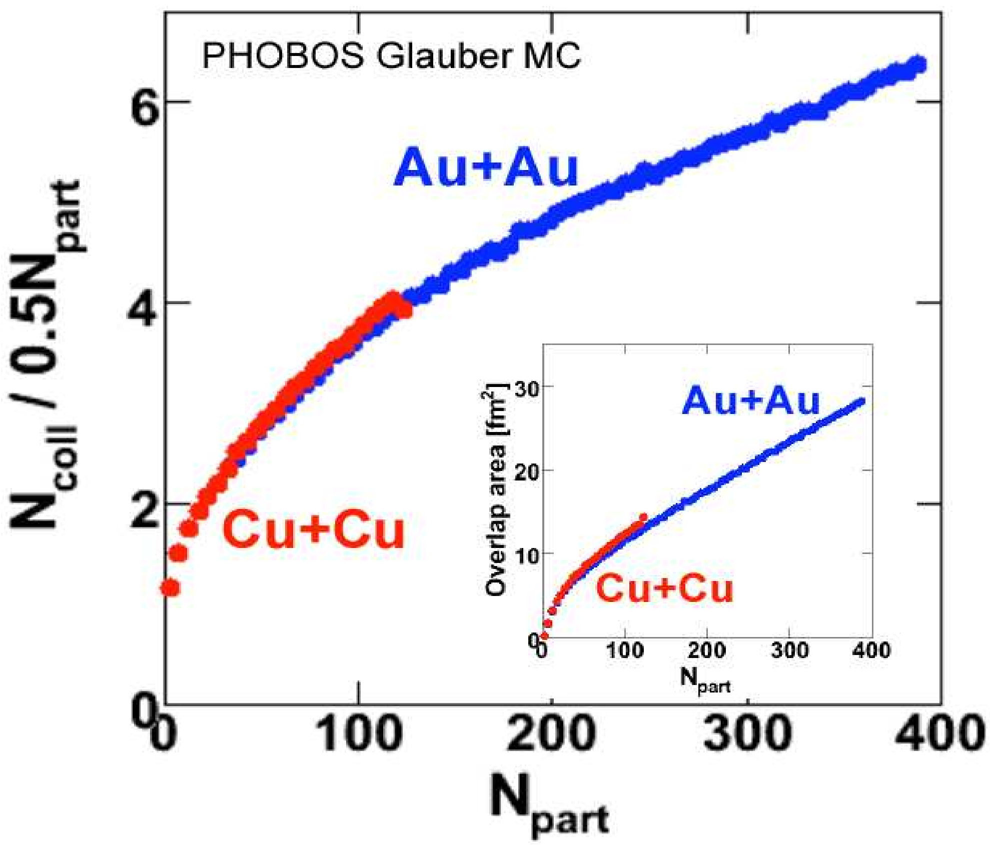
Energy loss models tuned to single hadron quenching, undepredict high-pT v2

If tuned to v2 they overpredcit single hadron quenching.

Solving the puzzle promising for advance of the field.

III. Everything scales as N_{part}

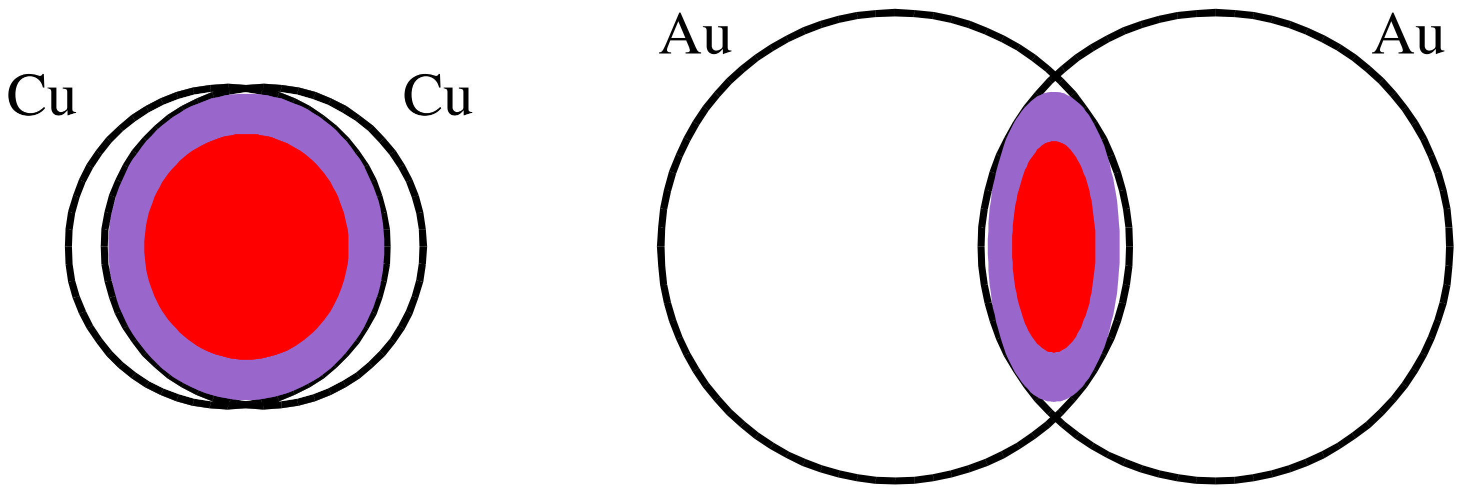
New at QM2005: Cu+Cu vs. Au+Au collisions



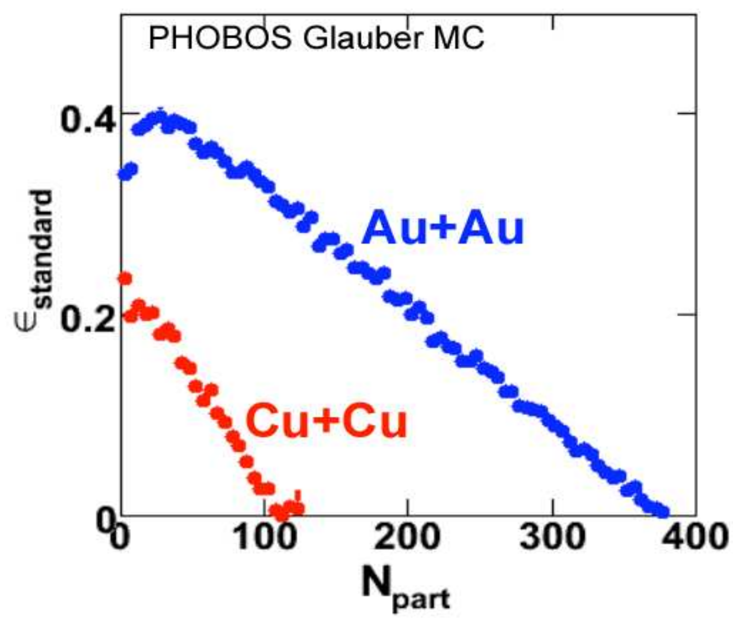
- Cu+Cu comparable to Au+Au
- Cu+Cu: smaller system ⇒ less background, smaller errorbars
- Better accuracy than AuAu peripheral

Interplay of density and geometry

e.g., fix Npart ~ 100, same √s

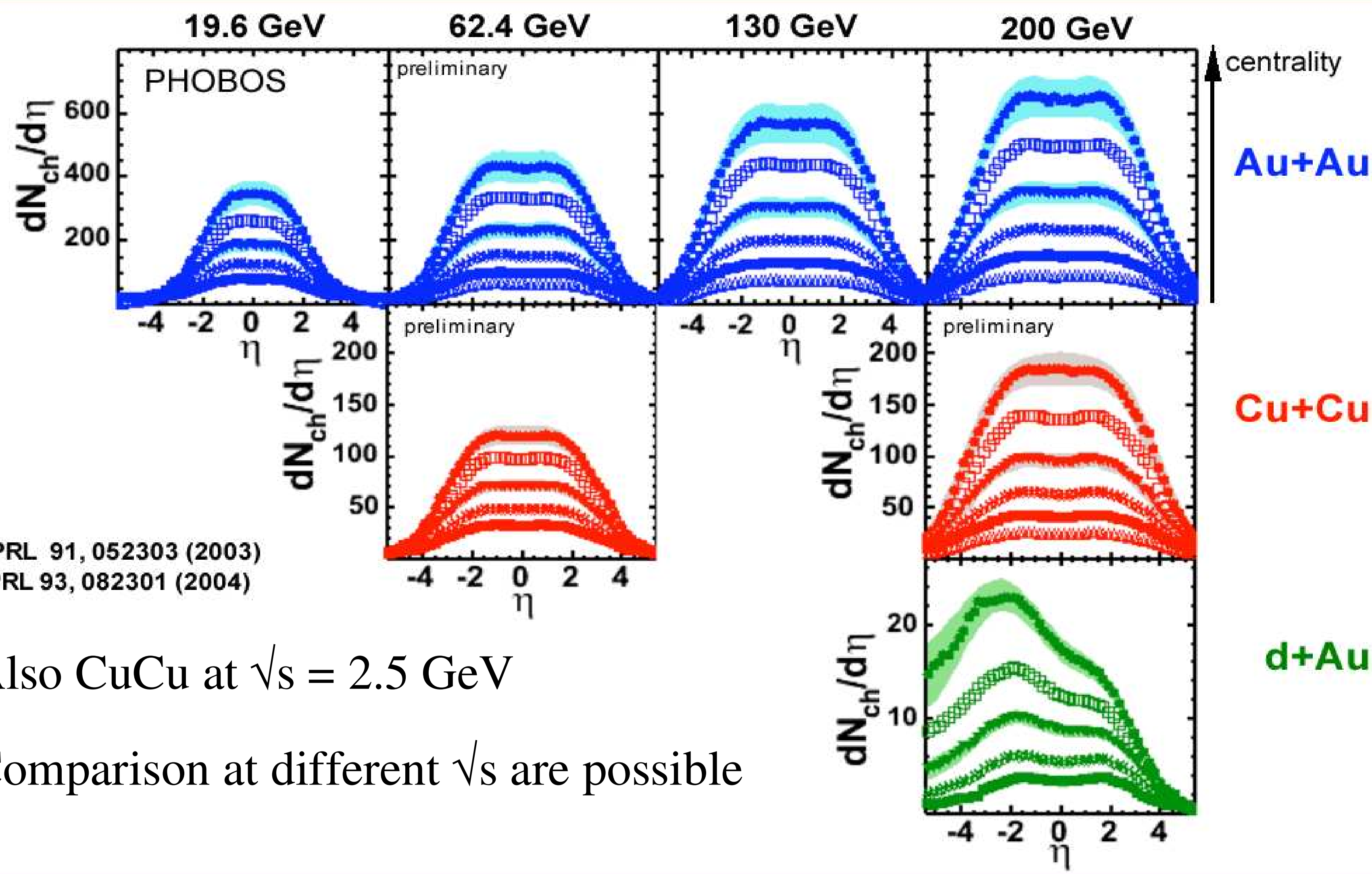


- eccentricity: $\varepsilon_{CuCu} << \varepsilon_{AuAu}$
- medium density: $\delta_{CuCu} = \delta_{AuAu}$
- surface/volume: $S/V_{CuCu} << S/V_{AuAu}$



Available systems / energies

Charged Hadron dN/dη

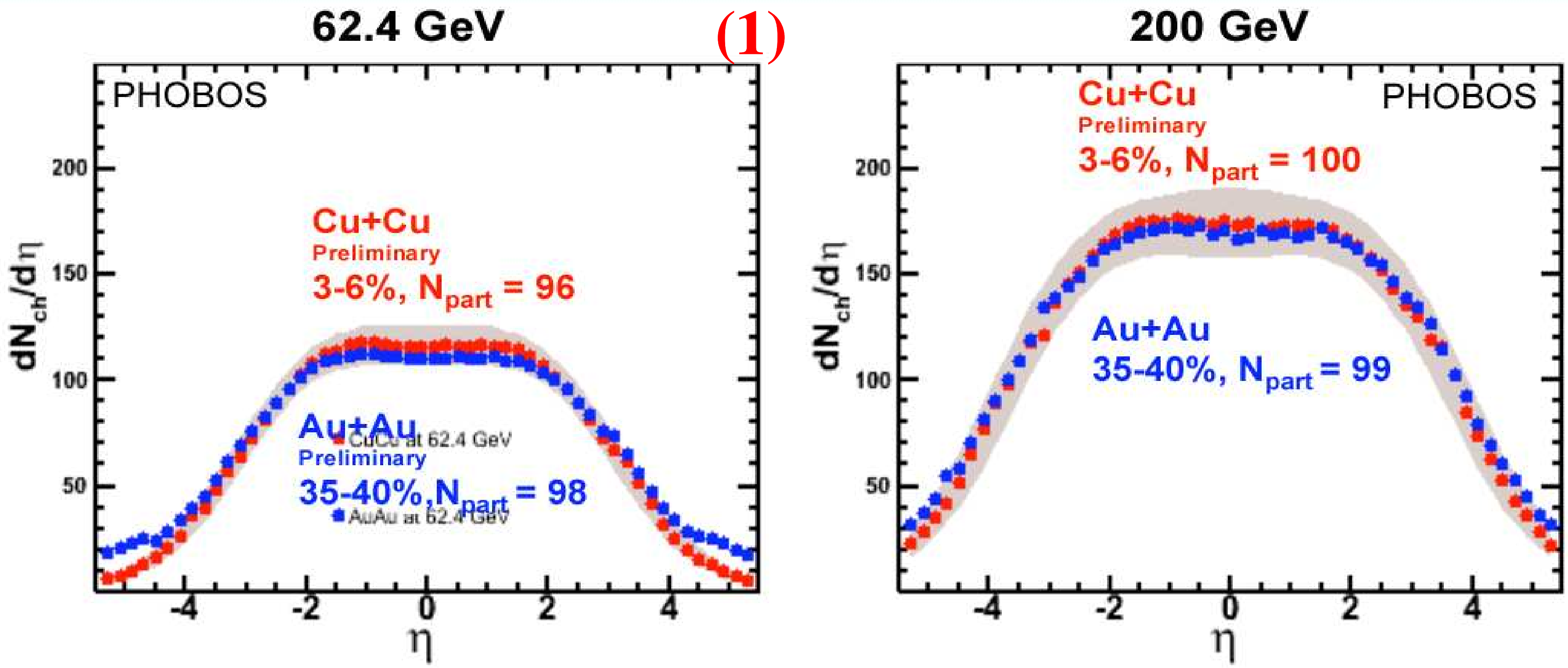


Au+Au : PRL 91, 052303 (2003)
d+Au : PRL 93, 082301 (2004)

- Also CuCu at $\sqrt{s}$ = 2.5 GeV
- Comparison at different $\sqrt{s}$ are possible

III.1 $dN_{ch}/d\eta$

dN/dη in Cu+Cu vs Au+Au

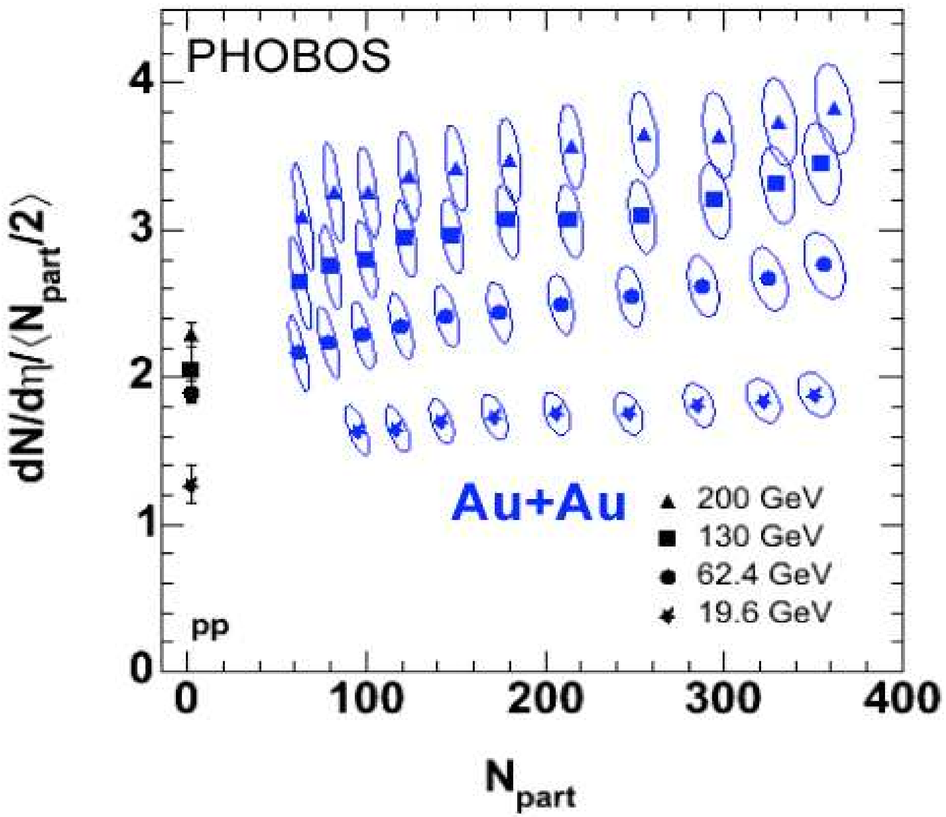


Unscaled dN/dη very similar for Au+Au and Cu+Cu at same N_{part}

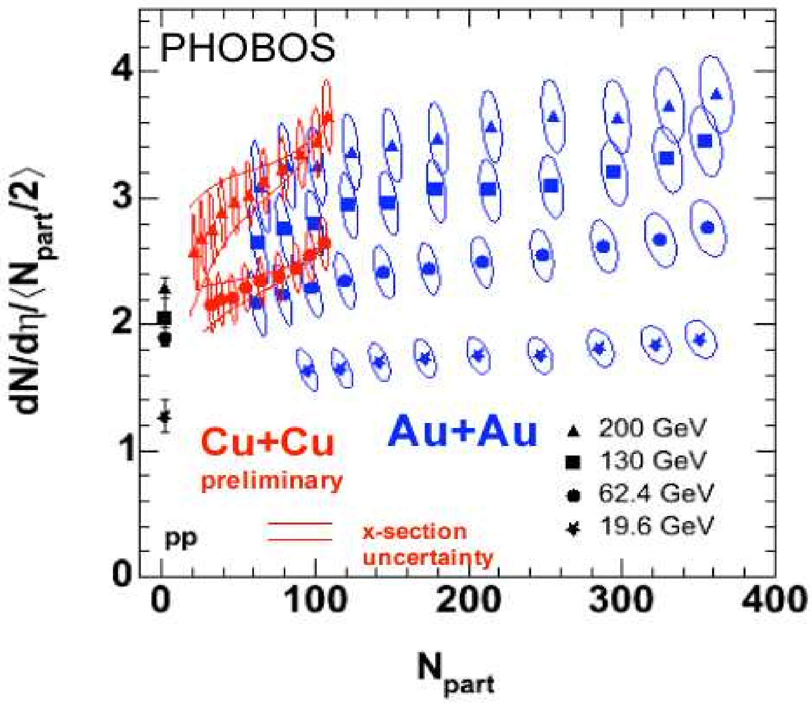
See poster by Richard Hollis

- We can understand it in terms of the wounded parton model:
  - Soft particles yield proportional to Npart

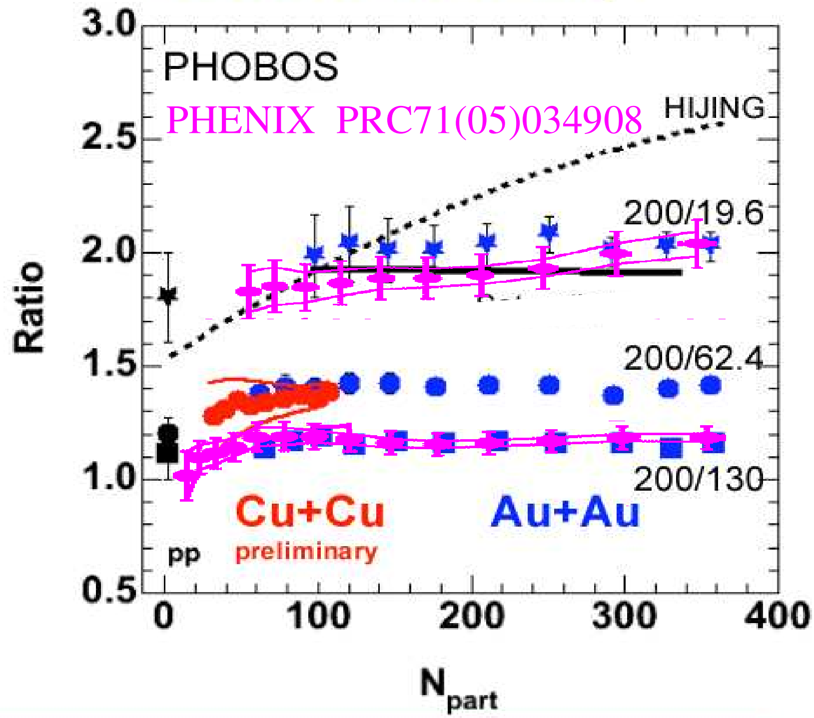
- As energy is changed, though particle production increases:



Energy/Centrality Factorization



Ratio of dN/dη @ η=0 relative to 200 GeV vs centrality



Factorization of energy and centrality dependence

Initial state effect?

Au+Au: Phys. Rev. C70, 021902(R) (2004) + prel. 62.4 GeV

c.f. Armesto, Salgado, Wiedemann hep-ph/0407018

Energy/Centrality factorization

see, Armesto, Salgado, Wiedamann PRL94(05)022002

- from "saturation physics" $\left.\frac{dN^{AA}}{dy}\right|_{y\sim 0}^{minijet} \propto Q^2_{\mathrm{sat,A}}\,\pi R_A^2$
  - CGC
  - EKRT
  - but also pQCD rescatterings (AA)

- Ansatz: $Q^2_{\mathrm{sat,A}} = Q^2_{\mathrm{sat,p}} \left(\frac{A\pi R_p^2}{\pi R_A^2}\right)^{\frac{1}{\delta}}$
  (δ fitted to nuclear DIS data)

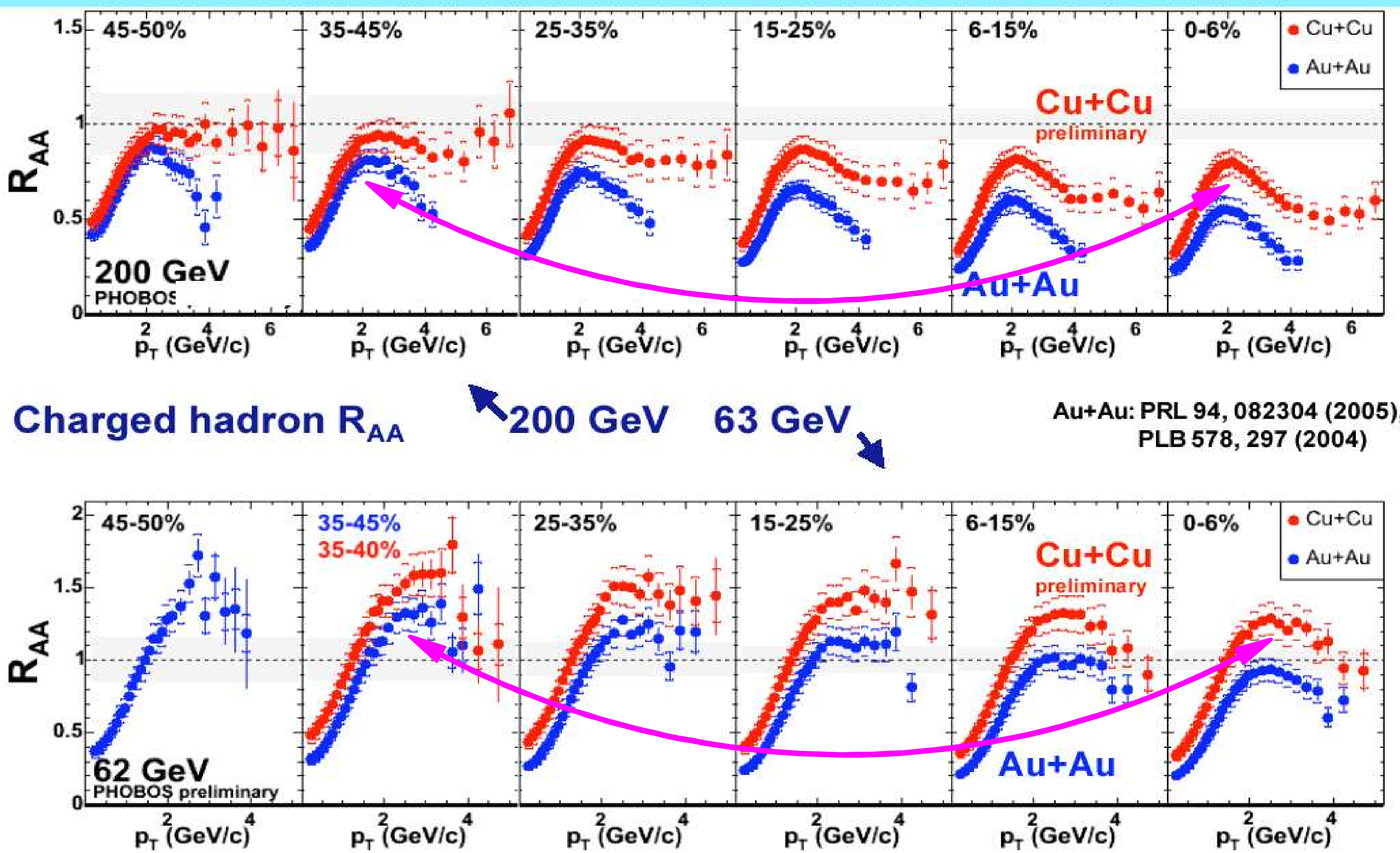
- In terms of N_{part}: $\left.\frac{1}{N_{\mathrm{part}}}\frac{dN^{AA}}{d\eta}\right|_{\eta\sim 0} = C \left.\frac{1}{N_{\mathrm{part}}}\frac{dN^{AA}}{d\eta}\right|_{\eta\sim 0}^{minijet} = N_0 \sqrt{s}^{\lambda} N_{\mathrm{part}}^{\frac{1-\delta}{3\delta}}$

Energy/Centrality factorization

NB: parton-hadron duality is assumed here

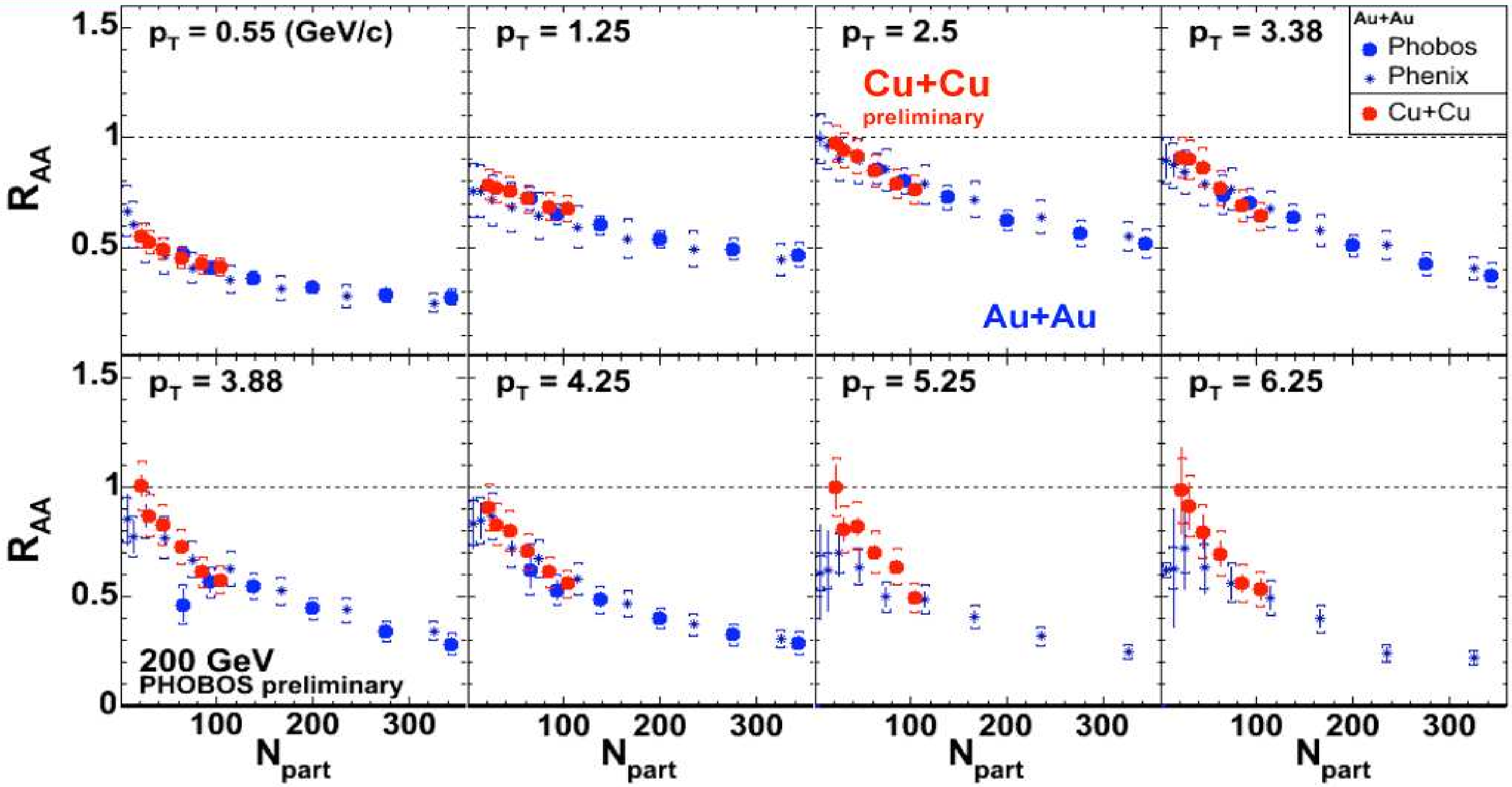
III.2 Jet quenching - R_{AA} and R_{cp}

(2) Particle Production vs p_T



N_{part}^{CuCu} (0-3%) ~ N_{part}^{AuAu} (35-45%) ~ 100

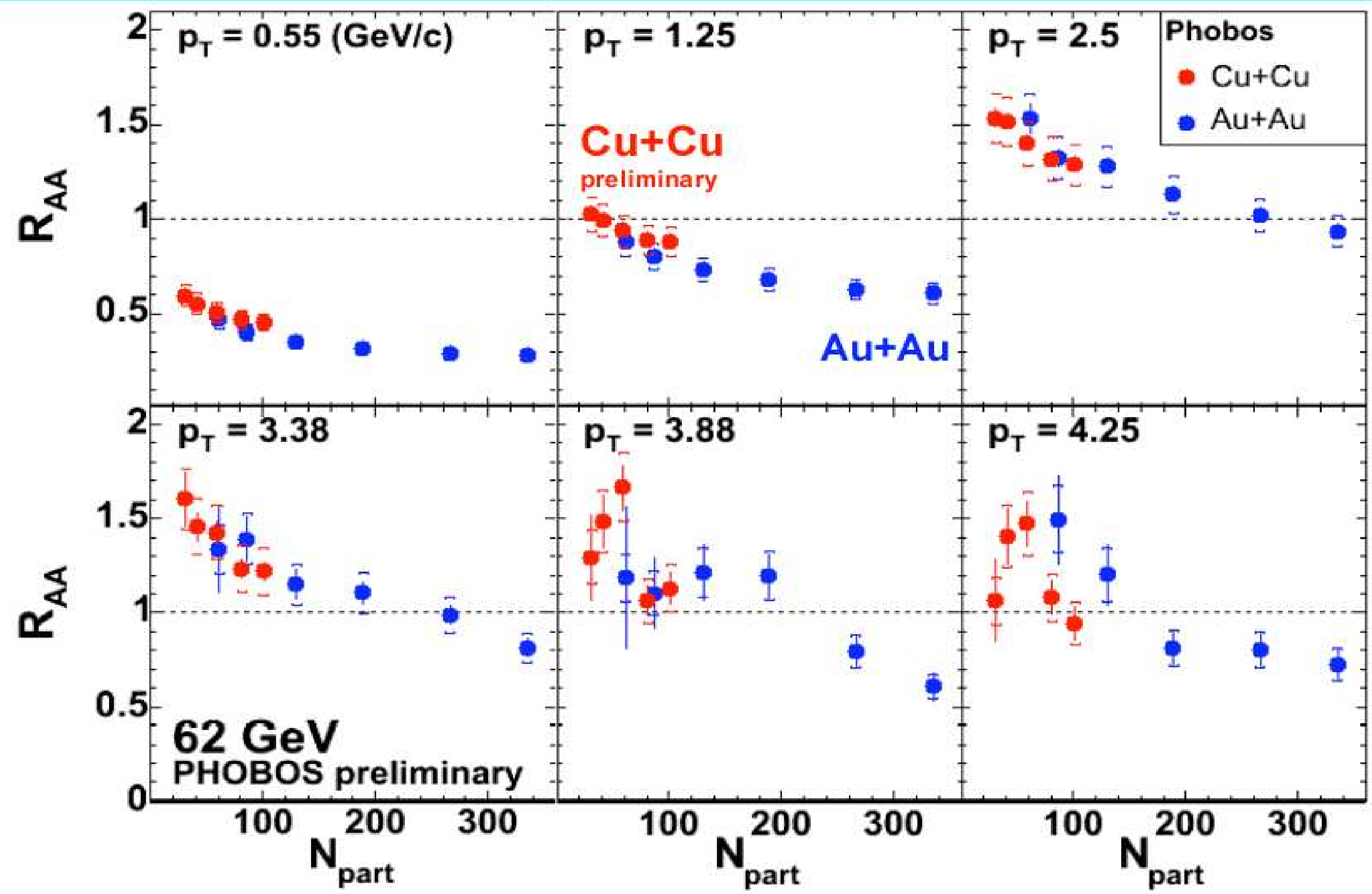
Yields vs N_{part}, 200 GeV



Au+Au: PRL 94, 082304 (2005), PLB 578, 297 (2004)

See poster by Gerrit van Nieuwenhuizen

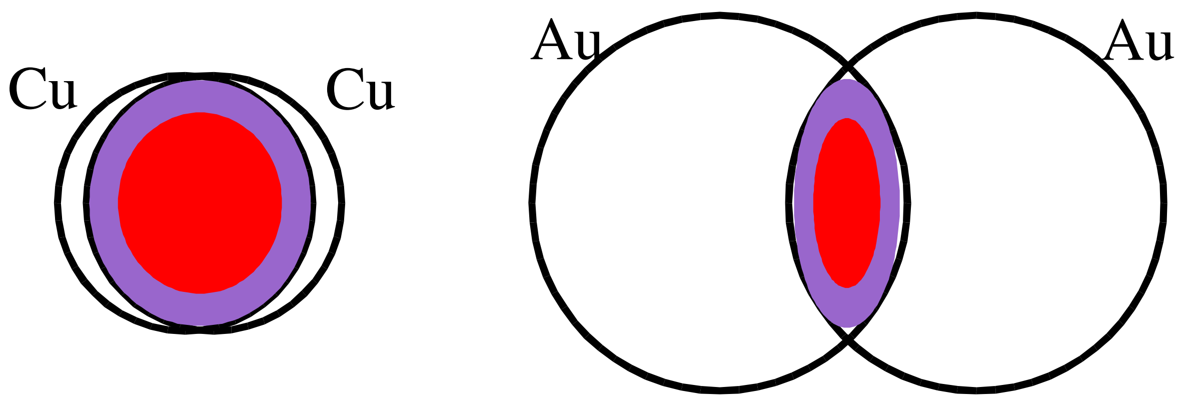
Yields vs N_{part}, 62 GeV



Au+Au: PRL 94, 082304 (2005)

- RAA in CuCu and AuAu comparable at same N_{part}
- Is this a surprise? In a sense no:
  - medium density $\delta \sim N_{part}$
  - same medium suppression independently of system size

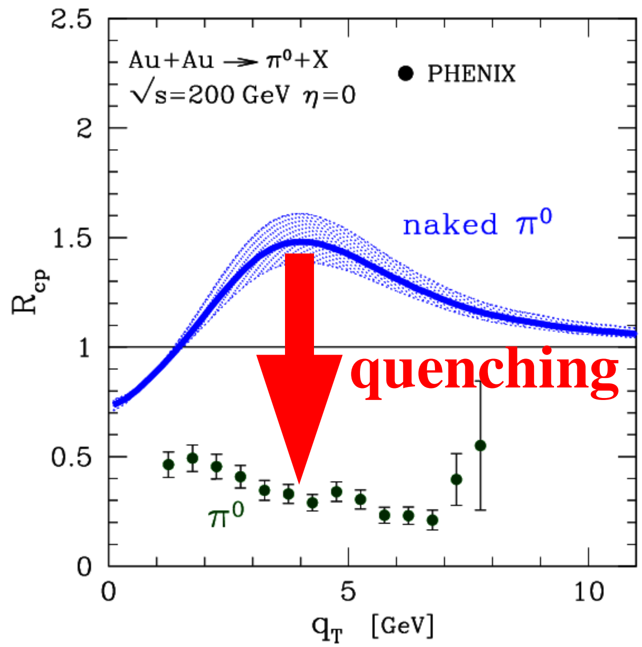
- But..
  what about the idea of "Quenching = surface emission" ??

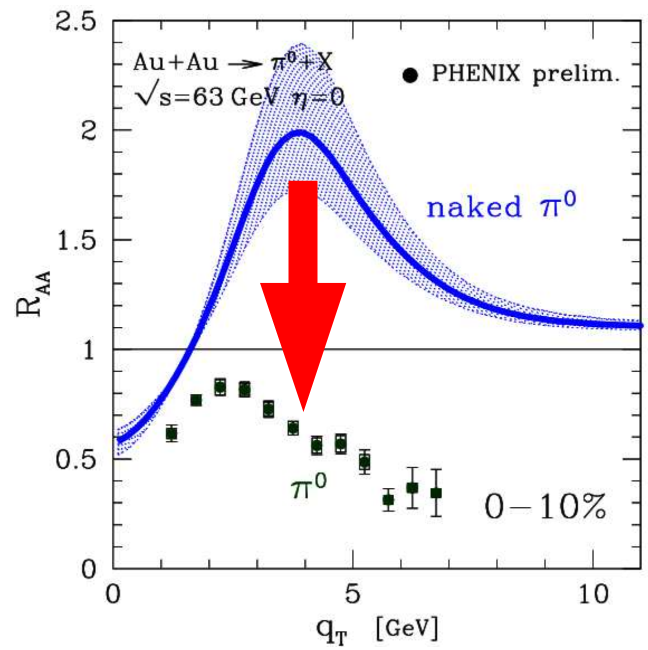


CuCu should quench more than AuAu!

Comparing quenching at different √s

- We have so far compared small/large systems at fixed **√s**
- Let's do the opposite: **AuAu @ 200 vs. 62 geV**





~ same quenching at 2 different energies!

Would expect increase with √s as density ~ $(dN/dy)_{200\ GeV} > (dN/dy)_{62\ GeV}$

Attention: medium is partonic, quoted densities are of charged hadrons

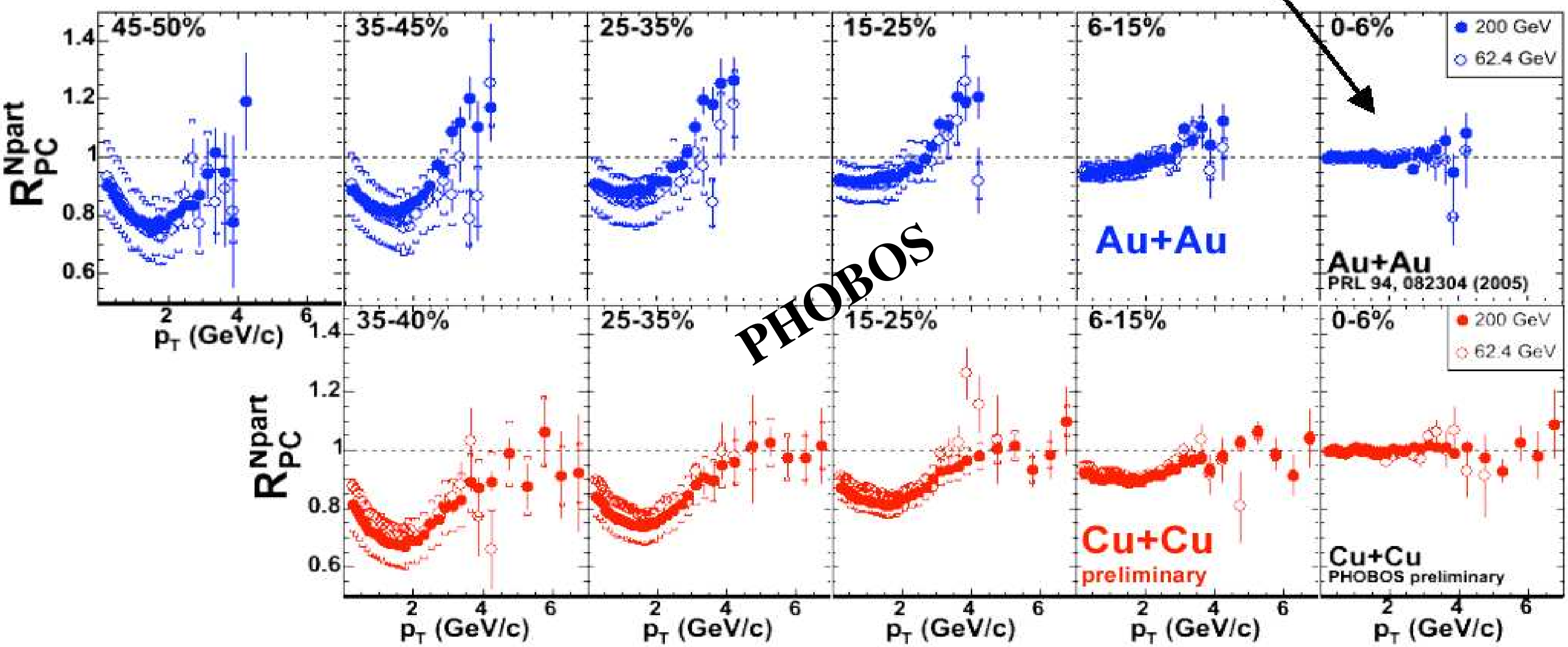
(Note:
At 200 GeV, I'm using R_{cp} as a proxy for central R_{AA} : quenching should increase slightly using the latter)

- Previous argument may sound fishy:
  - Cronin enhancement depends on slope of dN/dp_T in p+p collisions (the steeper the higher the Cronin enhancement)
  - Quenching depends on slope, as well (at fixed $\Delta\varepsilon$, quenching is larger for steeper dN/dp_T)
  - Same quenching maybe just a coincindence

- Let's ask the experimental data, then:
  - Consider the central/peripheral ratio R_{cp}
  - the underlying p+p slope is the same
  - increase of effects with slope compensate in the ratio (at least partially)

- Compare 200 Gev and 62 GeV data

Normalized for central events



$$R_{PC}^{N_{part}} = \frac{\langle N_{part}^{0-6\%} \rangle}{\langle N_{part} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 N_{AA}^{0-6\%}/dp_T d\eta}$$

Peripheral/Central ratio...

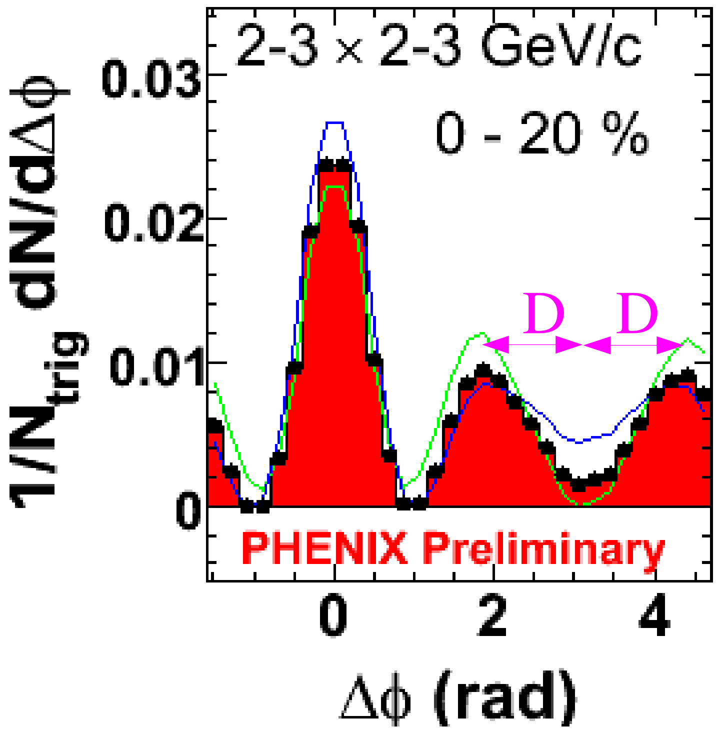
normalizing with Ncoll gives < 10% relative change between 200 and 62 GeV

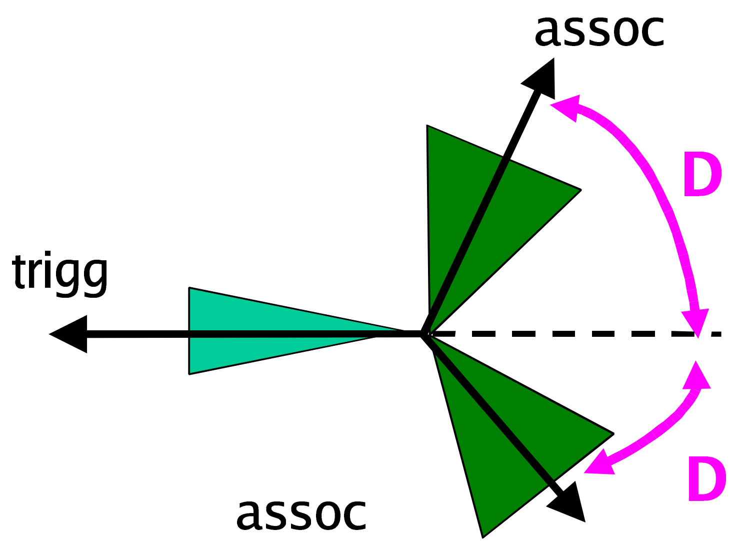
same quenching at 62 and 200 GeV

⇒ same medium ??

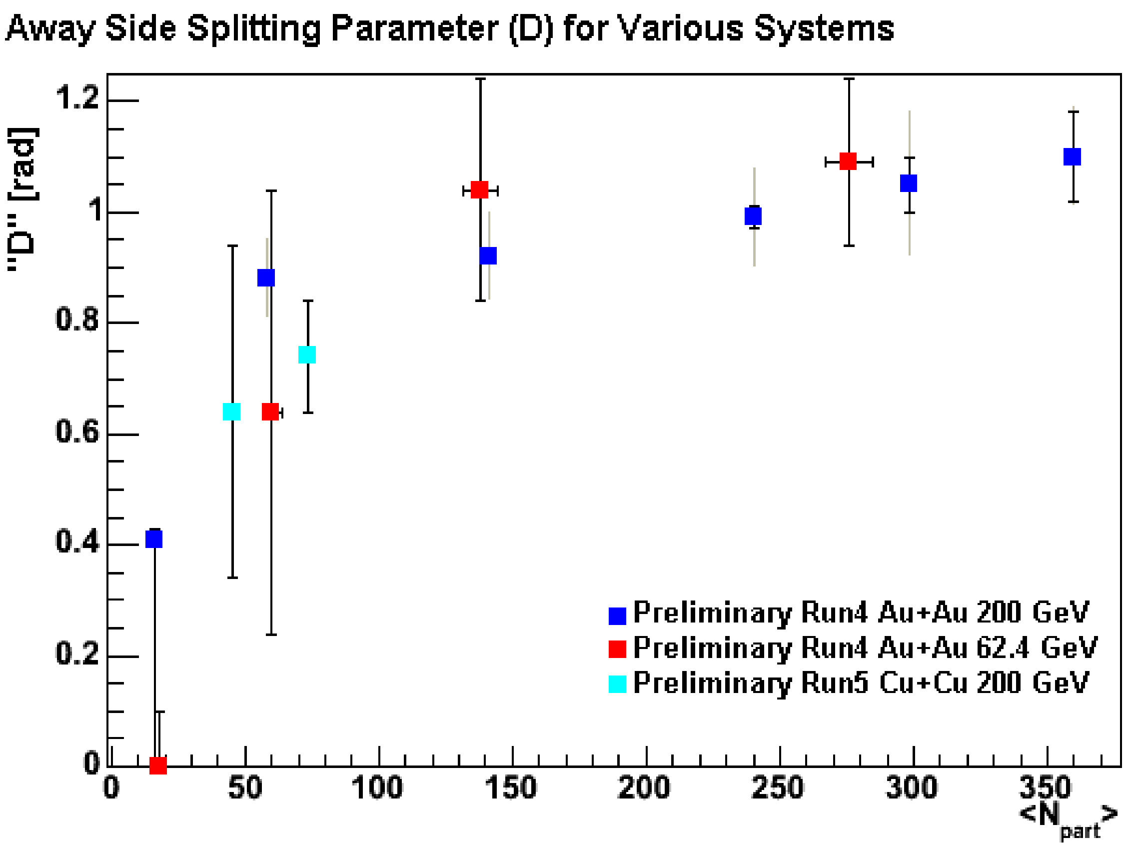
III.3 "Cone" angles

The away-side splitting D



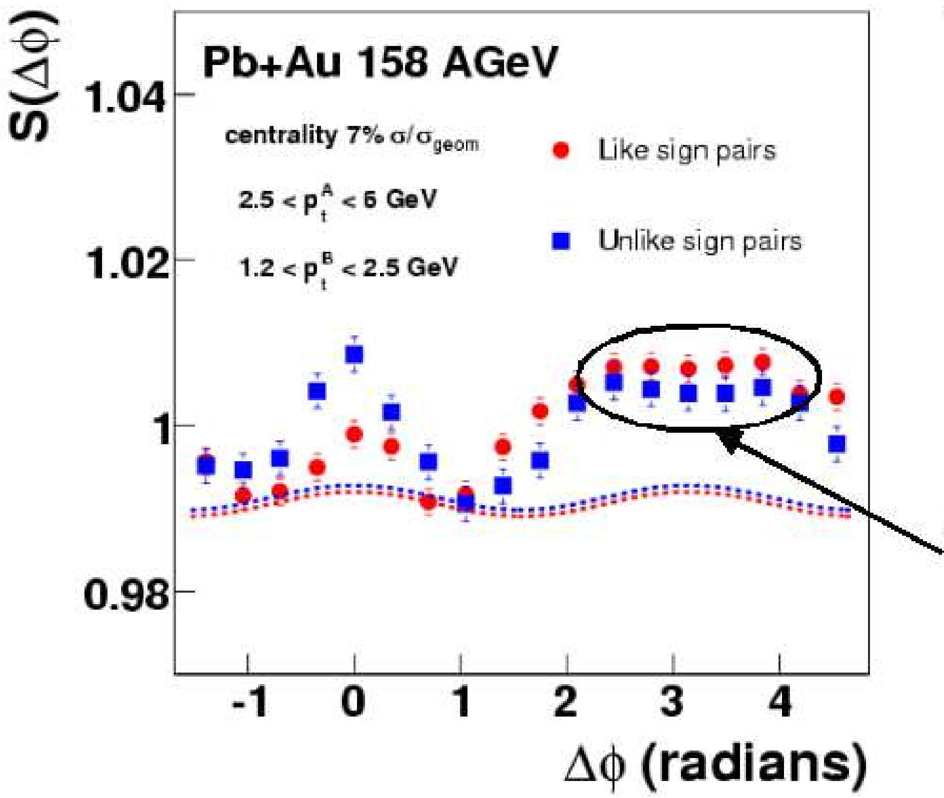


Parameterize the away-side shape as 2 Gaussians that are offset symmetrically around $\Delta\phi = \pi$ by fit parameter D.



- D is independent of energy and system size!
  Scales with N_{part}!
  - Not reconcilable with Mach or Cerenkov cones, or bent jet...
  - ...**unless the medium is the same in all cases!**
- Need to reduce error bars to test the scaling

Dip Persists at SPS

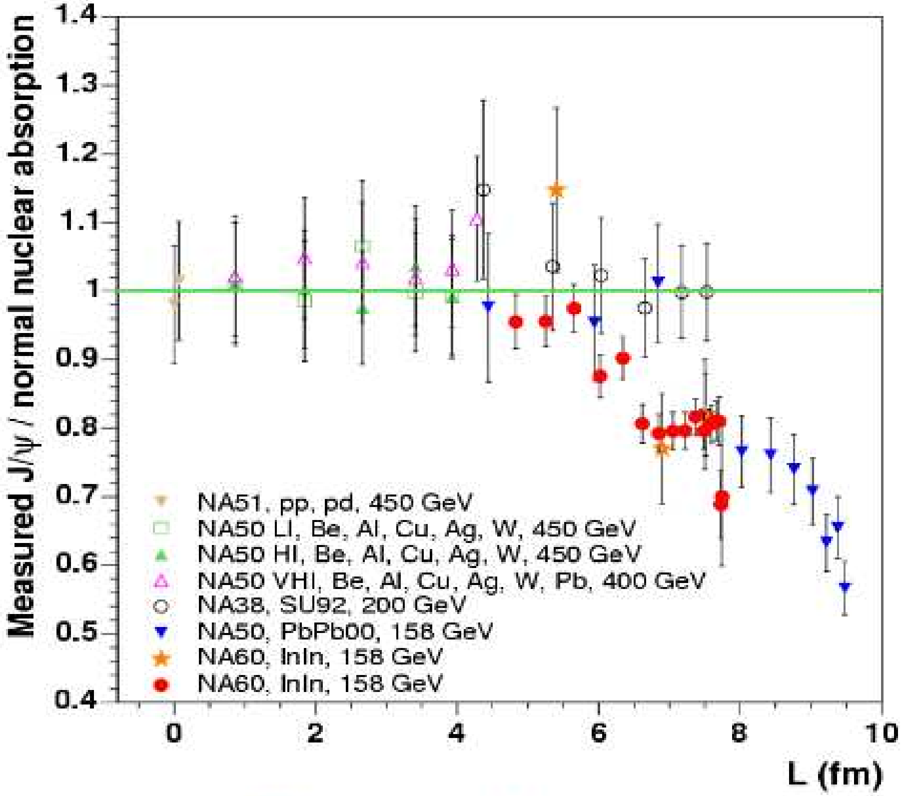


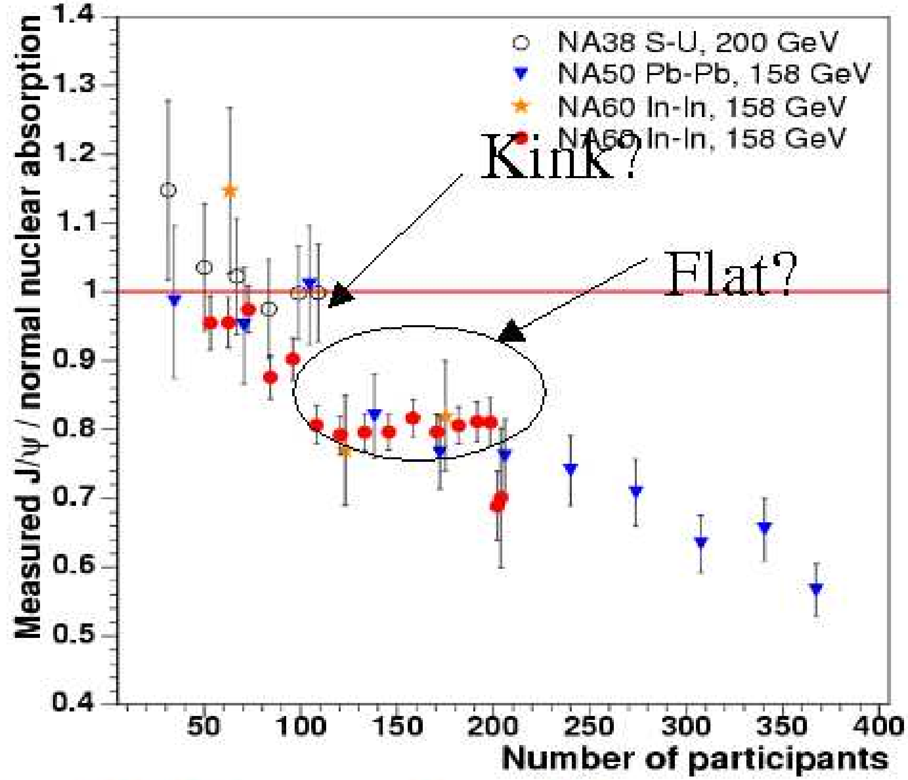
- CERES data at much lower root-s but similar trigger and associated p_T ranges
  - higher $x_T \Rightarrow$ quark jet dominated
- Correlation is flat at far angles $\Rightarrow$ dip present at SPS at a smaller level!

Does D_{SPS} scale as Npart together with D_{RHIC}??

III.4 J/ψ suppression

Ratio of Measured/Expected

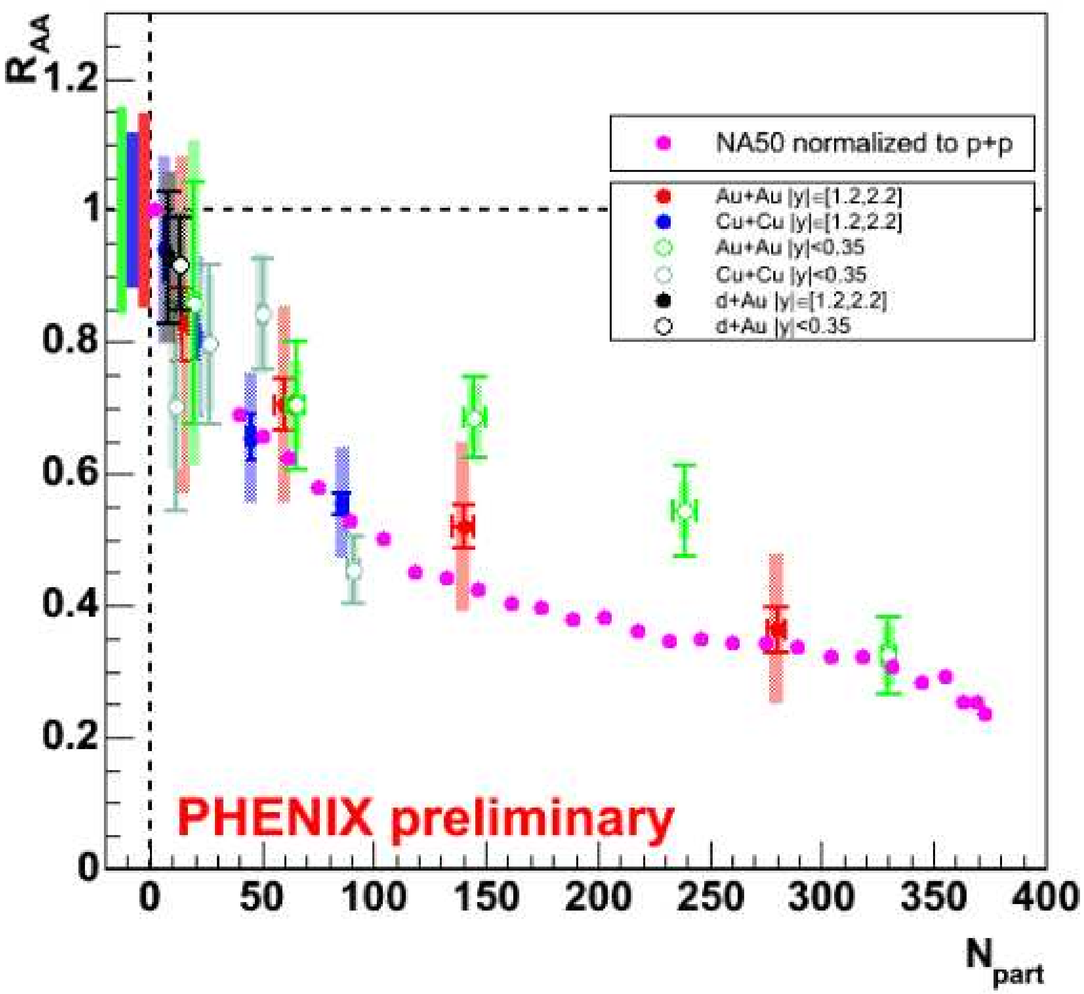




Suppression seems to scale with Npart and not L!

Comparison to SPS

J/ψ nuclear modification factor R_{AA}



A similar suppression pattern as seen by NA50!?!

Scaling with Npart?

Difference in energy and rapidity coverage.

Need MUCH more statistics at RHIC?

III.5 Why does everything scale as N_{part}?

Naively very natural

- Initial state rescatterings $\propto T_A(b) \propto N_{part}$
- Final state effects $\propto \rho_{medium} \propto N_{part}$

But! Conventional wisdom: parton-hadron duality + wounded nucleons

$$\rho_{medium} \propto N_{partons} = const \times N_{hadrons} \propto C(\sqrt{s})\, N_{part}$$

"dynamics" "geometry"

Medium is partonic, so **larger density at larger $\sqrt{s}$**

⇒ **why are observables similar at 62 GeV and 200 GeV with same Npart ??**

A possible scenario

- Medium = partons liberated in the collision ("minijet plasma")
- Parton production such that:

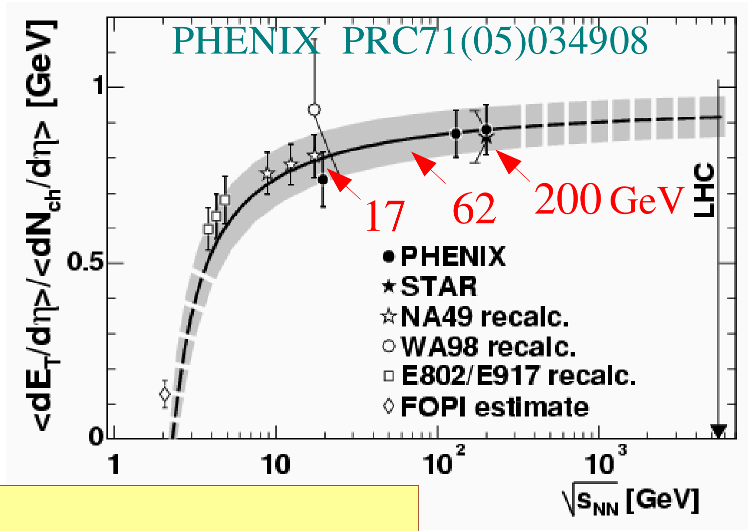
$$N_{partons}(200) = N_{partons}(62)$$
$$(E/N)_{partons}(200) > (E/N)_{partons}(62)$$

- Because of larger E/N, the minijet plasma fragments into more hadrons at 200 GeV than at 62 GeV:

$$(dN/dy)_{had}(200) > (dN/dy)_{had}(62)$$

  - naturally we expect

$$(E/N)_{had}(200) \approx (E/N)_{had}(62)$$



- In this scenario $\rho_{medium}(200) \approx \rho_{medium}(62)$ and medium effects are almost independent of $\sqrt{s}$
- ρ_{medium} doesn't change much from SPS to RHIC to LHC!

- The statements above amount to say that
  the minijet plasma is made of saturated partons liberated in the collision

- $x \approx 2 \langle p_T \rangle / \sqrt{s}$ can be small enough for soft partons to be in the saturation region

- Increasing $\sqrt{s}$ one decreases x, the no. of partons cannot increase
  $\Rightarrow$ partons are created with larger energy.

The medium is made of saturated partons: CGC!

- Standard hadronization picture challenged
  - no parton-hadron duality
  - **saturation of phase space for hadron formation??**

- "Factorization of energy and centrality" holds but for different reasons than commonly thought:

Conclusions

- **If we really have a QGL, better take it seriously**
  - seek and study probes that inetract with it
  - look for collective effects (e.g. the "cones")
  - New approaches: "forget" past illusions, build new ones! (e.g. lessons from QED plasmas)

- **Energy loss can be quantitatively compared to data**
  - we can check the details
  - new puzzles -> new discoveries?

- **Pervasive Npart scaling**
  - Provides evidence for CGC in the soft sector
  - Challenges common views on hadronization
  - worth pursuing, but without excessively pushing the concept