Recent RHIC Results with AA

Mark D. Baker
Brookhaven National Laboratory

The Motivation

What have we learned about AA?

What have we learned about QCD?

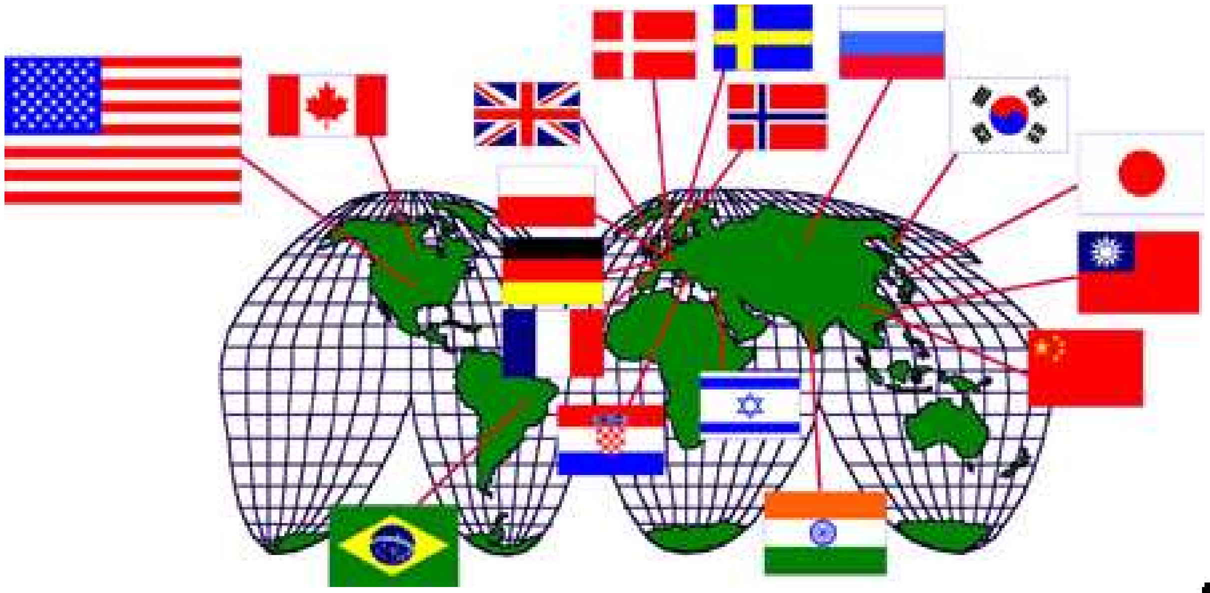
Conclusions

Many thanks to:
Peter Steinberg

BROOKHAVEN NATIONAL LABORATORY

The RHIC community

- >1000 people from around the world
  - Brazil, Canada, China, Croatia, Denmark, France, Germany, India, Israel, Japan, Korea, Norway, Poland, Russia, Sweden, Taiwan, UK, US




BNL
Brookhaven
National Laboratory


PHOBOS
10:00 o'clock
12:00 o'clock
BRAHMS & PP2PP ($\vec{p}$)
2:00 o'clock
RHIC
4:00 o'clock
PHENIX($\vec{p}$)
8:00 o'clock
STAR ($\vec{p}$)
6:00 o'clock
NASA - BAF
μ g-2
HEP/NP(p)
LINAC
BOOSTER
AGS
TANDEMS

There's a lot to summarize!

	Published	Submitted
130 GeV	16	4
200 GeV	1	2
Total	17	6

STAR:
PRL 86 (2001) 402
PRL 86 (2001) 4778
PRL 87 (2001) 082301
PRL 87 (2001) 112303
PRL 87 (2001) 182301
PRL 87 (2001) 262301
PRL 87 (2001) 262302
+ 1 more submitted

PHOBOS:
PRL 85 (2000) 3100
PRL 87 (2001) 102301
PRL 87 (2001) 102303
PRC 65 (2002) 031901
PRL 88 (2002) 022302
+ 1 more submitted

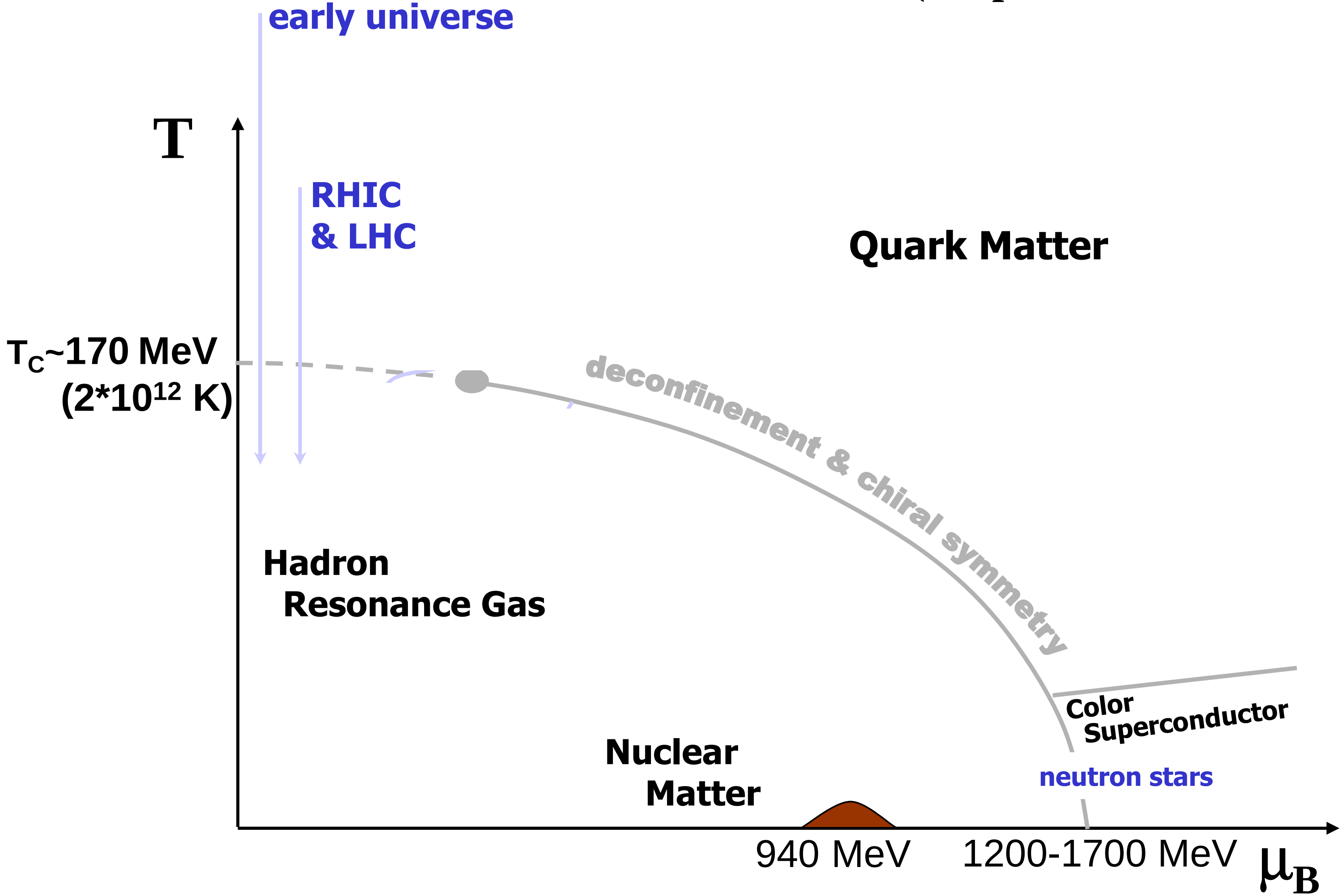
PHENIX:
PRL 86 (2001) 3500
PRL 87 (2001) 052301
PRL 88 (2002) 022301
+ 3 more submitted

BRAHMS:
PRL 87 (2001) 112305
PLB 523 (2001) 227
+ 1 more submitted

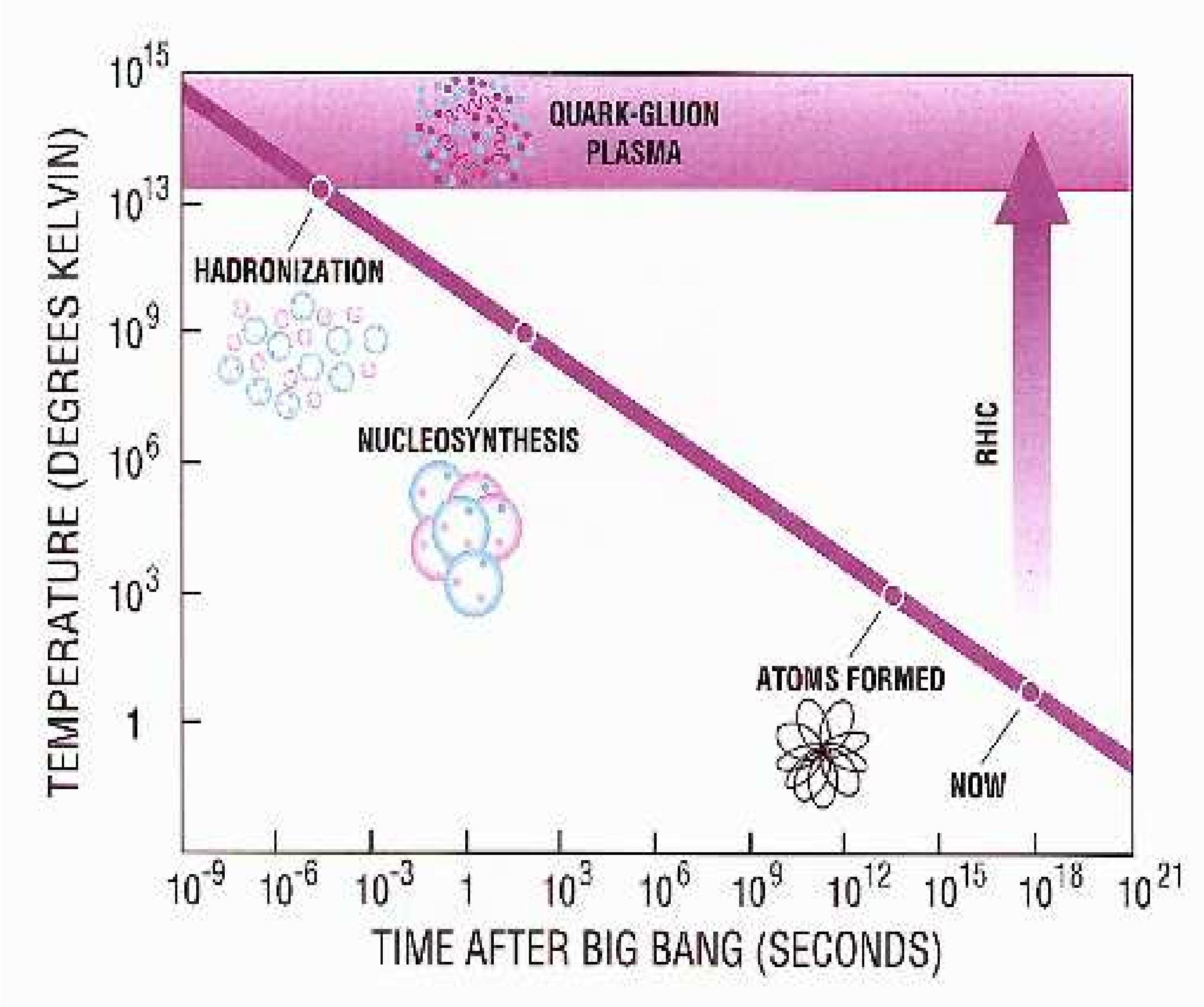
http://www.****.bnl.gov/**

The QCD Phase Diagram

(adapted from Axel Drees)

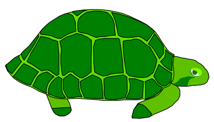


Heat is also a window back in time



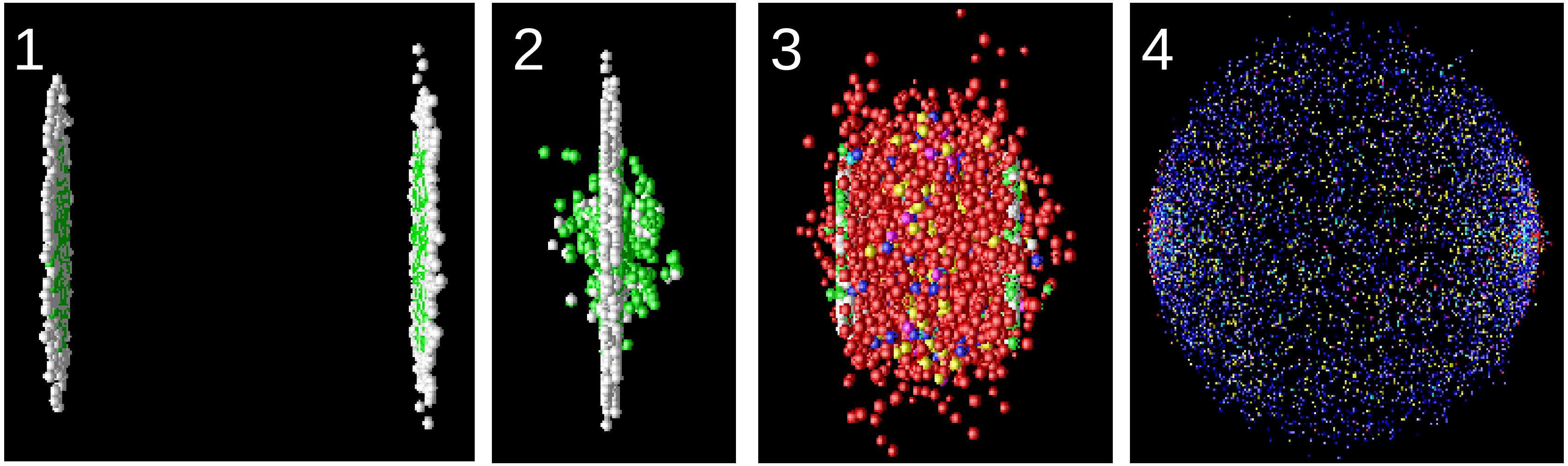
The plan of attack

- Collide gold nuclei at high energy
- Is it “strongly interacting bulk matter”?
  - – Initial State
  - – Collective motion
  - – Temperature, density
- Learn about the strong interaction
  - – Just beginning
  - – Confinement, Chiral Symmetry



Heavy-Ion Collisions

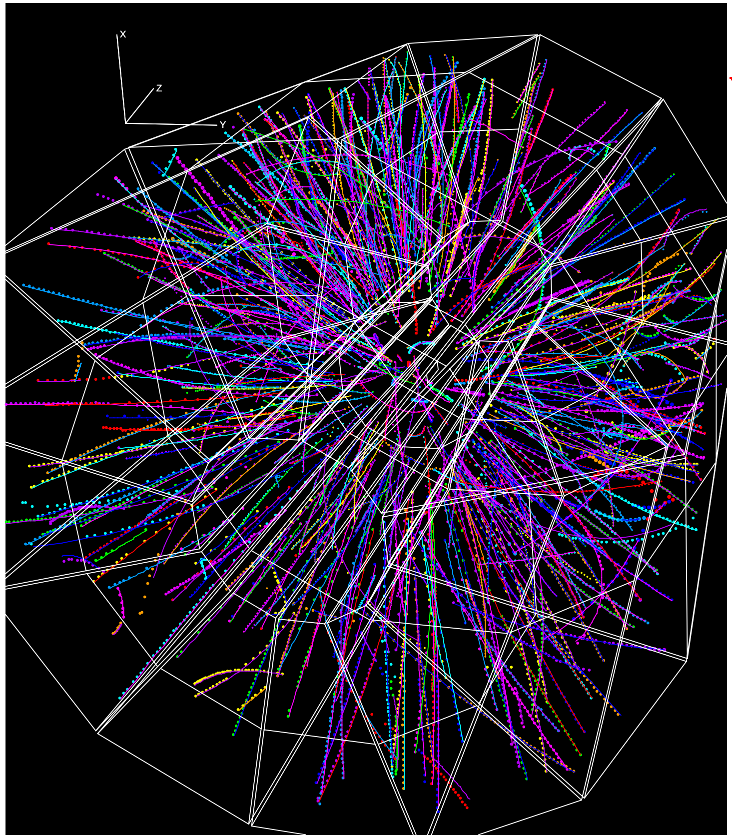
VNI Simulations: Geiger, Longacre, Srivastava, nucl-th/9806102

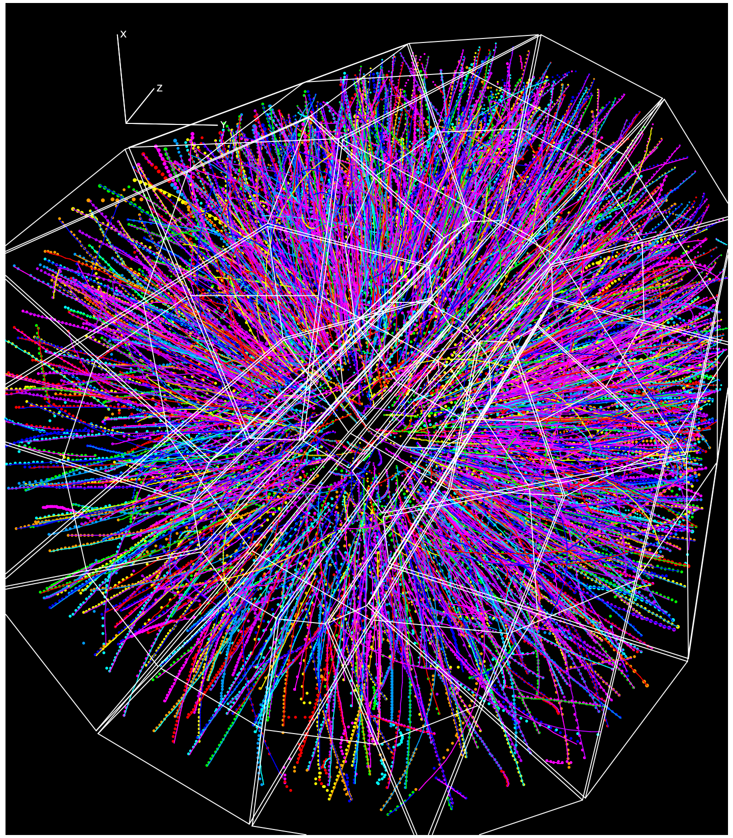


Colliding Nuclei | Hard Collisions | Parton Cascade | Hadron Gas & Freeze-out

- Entropy produced as system evolves
  - Where does most of it come from?
  - Initial, partonic or hadronic stage?

We have collisions

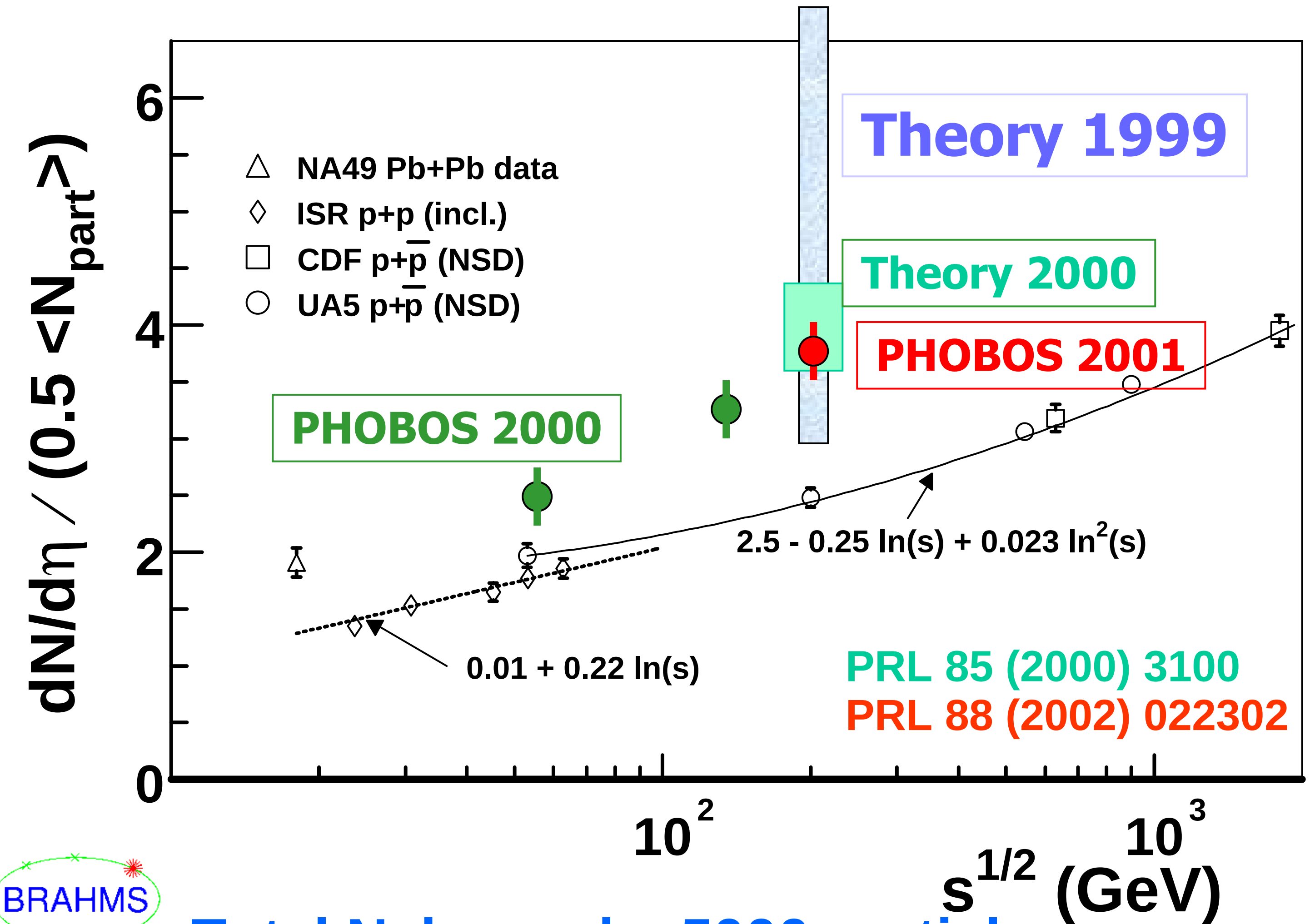




Year 2000: Au-Au $\sqrt{s}$ = (56) & 130 GeV

Year 2001: Au-Au $\sqrt{s}$ = 19.6 & 200 GeV

RHIC results at 200 GeV

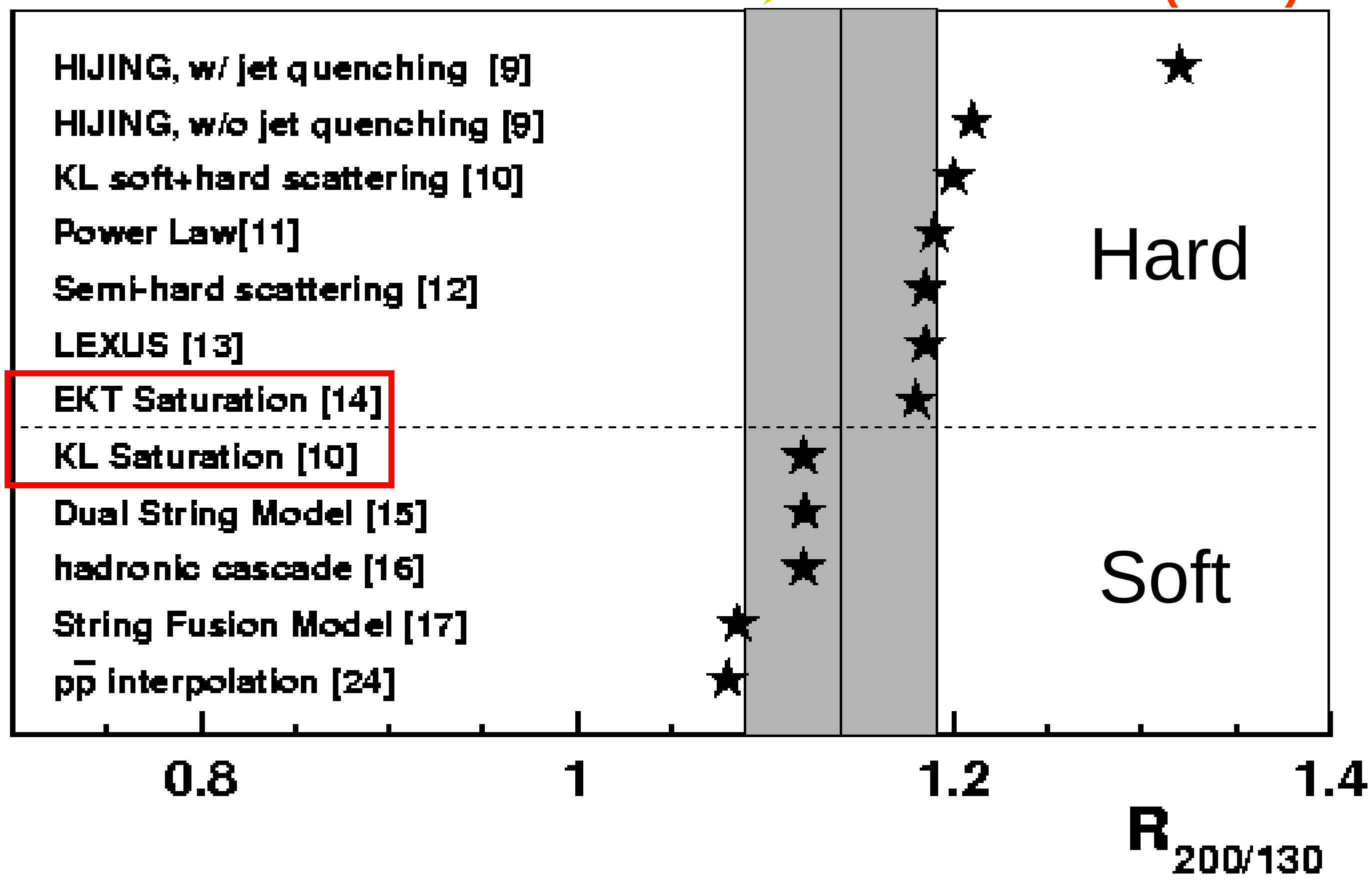


Total Ncharged ~ 5000 particles

Mark D. Baker

Energy Dependence

PRL 88 (2002) 022302

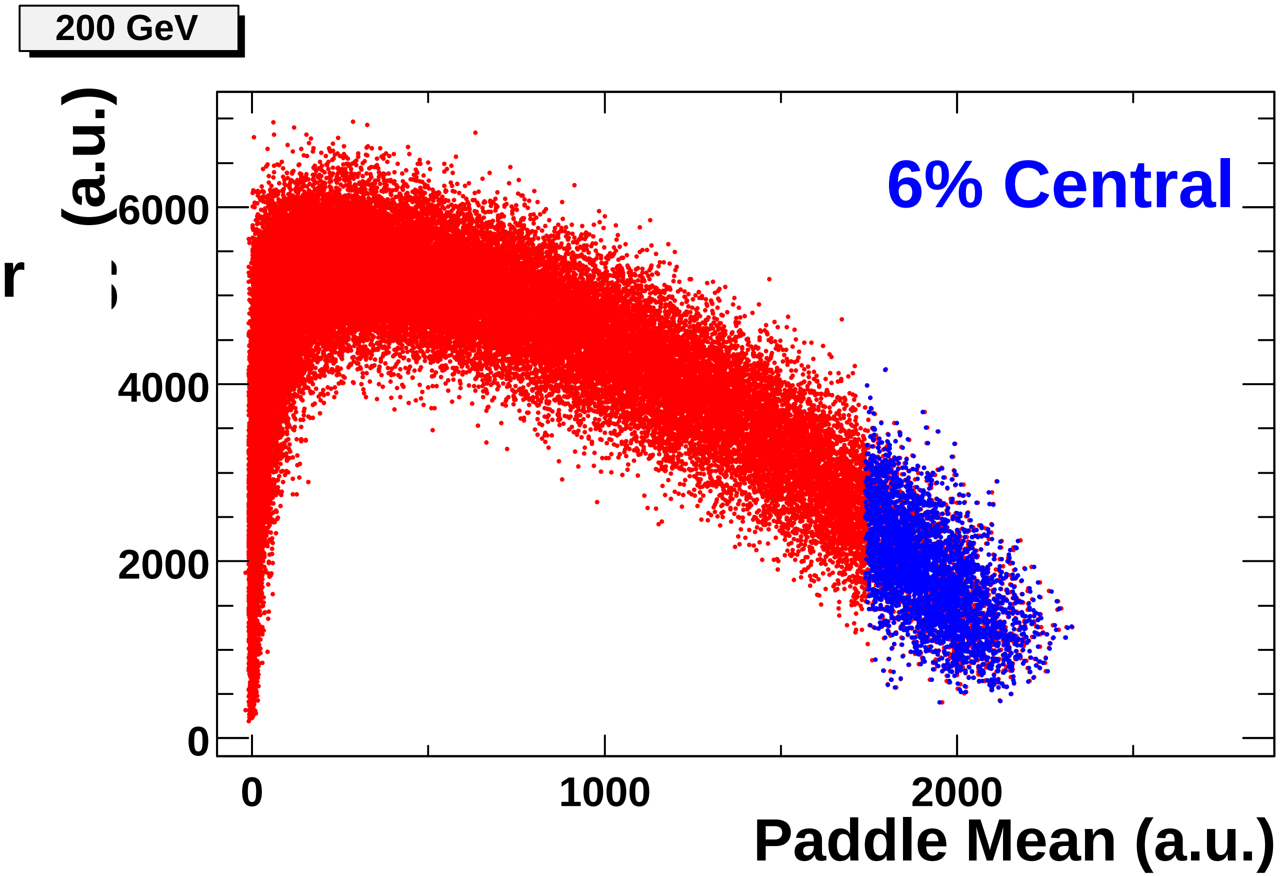


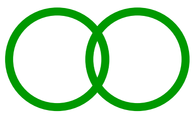
- Data favors models with minimal entropy production

Heavy Ion Collisions have a centrality

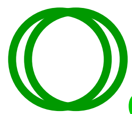
(impact parameter)

Forward
Spectator
Energy



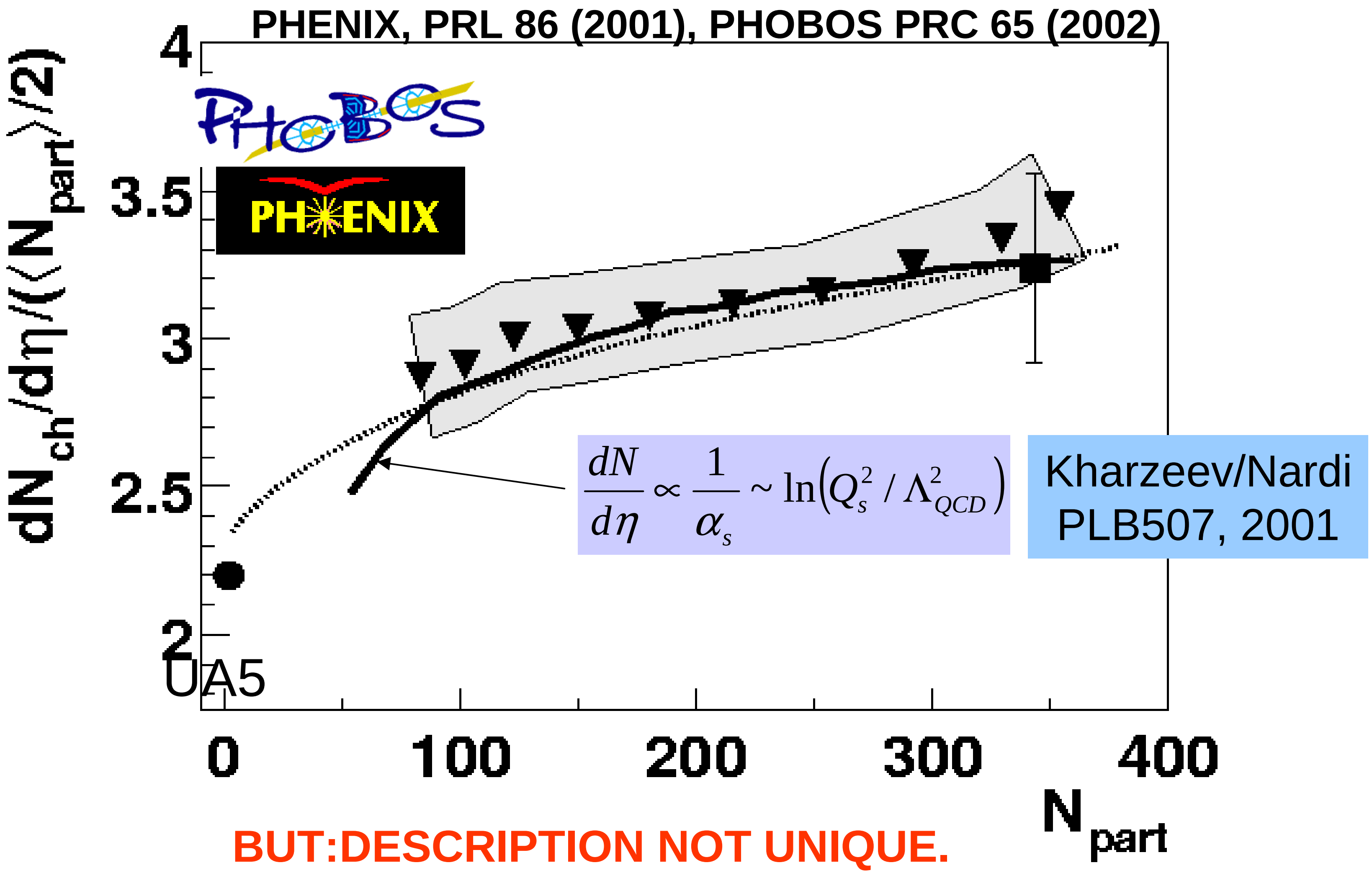


Peripheral



Central

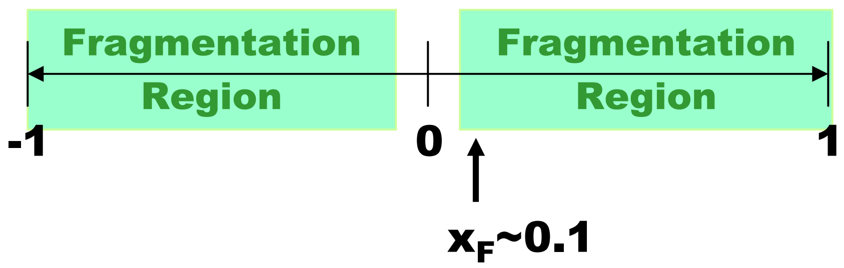
Parton Saturation Does Work



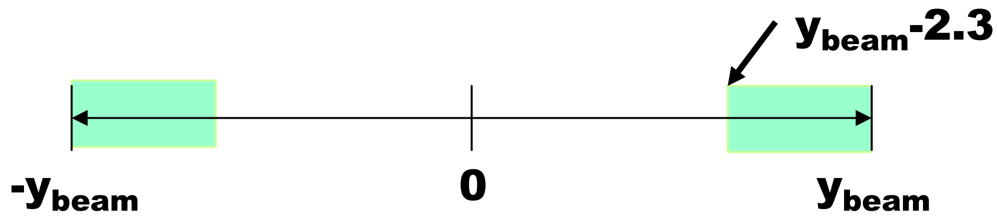
BUT:DESCRIPTION NOT UNIQUE.
We need an independent look at the saturation scale Q_s!

We like to think in “rapidity”

$$x_F \equiv p_z / p_{z-\max}$$



$$y \equiv \tanh^{-1}\left(p_z / E \right)$$



$$\eta \equiv \tanh^{-1}\left(p_z / p \right) = \tanh^{-1} \cos\theta$$

Parton Saturation may connect eA to AA

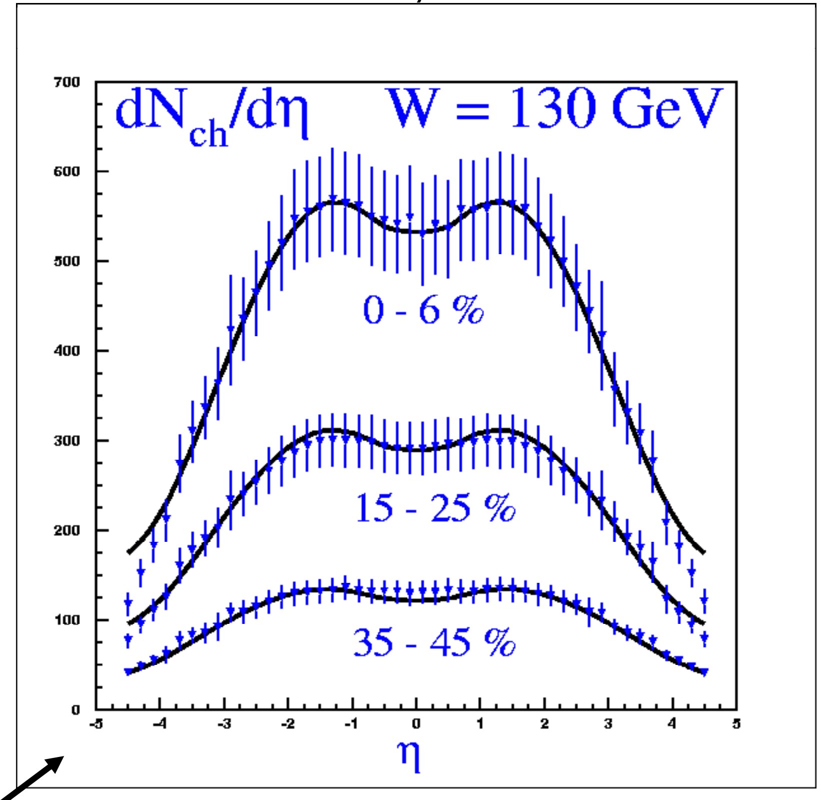
- Saturated initial state gives predictions about final state.

$$\Rightarrow N_h = c \times N_g$$

$$\frac{dN}{d\eta} \cong cN_{part}\left(\sqrt{s}\right)^{\lambda} f(\lambda|y|, Q_s)$$

λ~0.25 from fits to HERA data: $xG(x) \sim x^{-\lambda}$

Kharzeev & Levin, nucl-th/0108006



PHOBOS PRL 87 (2001)

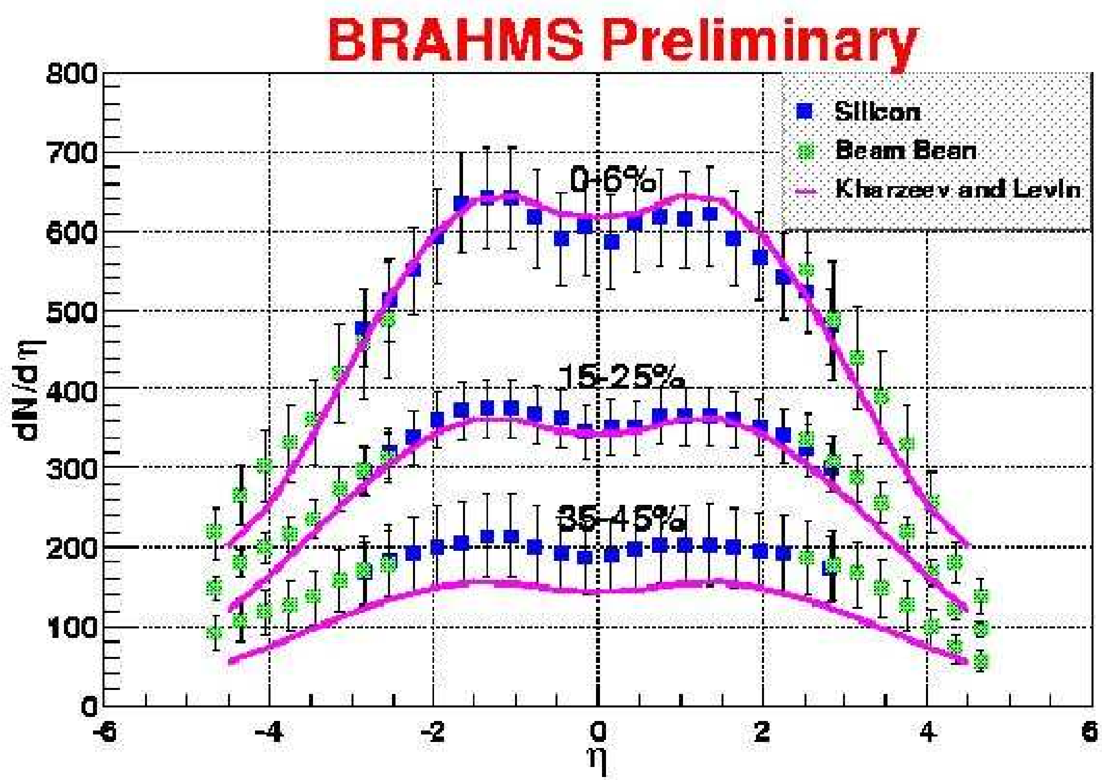
Fit PHOBOS data at 130 GeV to set c, Q_s

Saturation Works at 200 GeV

L. McLerran, DNP 2001

BRAHMS

nucl-ex/0112001



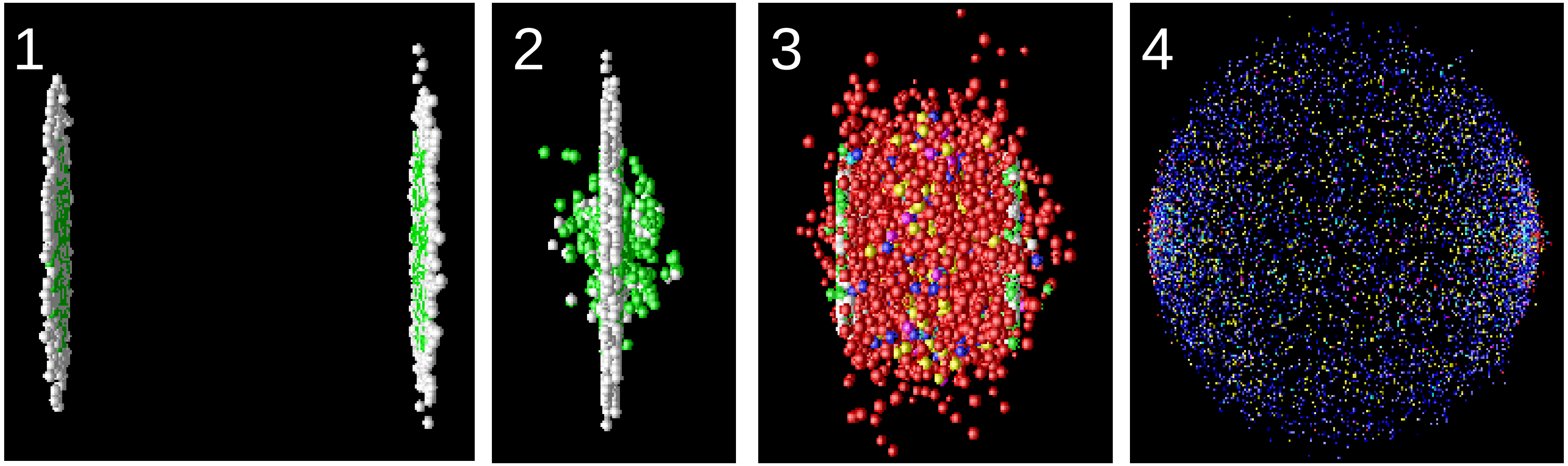
η

- Saturation models describe the data
  - Initial state parton density might be high enough to reach saturation regime

BROOKHAVEN NATIONAL LABORATORY

Implications:

- The initial state is dominated by soft physics
- Limited entropy production in late stages.



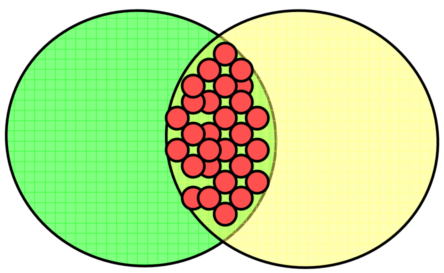
Colliding Nuclei | Hard Collisions | Parton Cascade | Hadron Gas & Freeze-out

Geometry/Saturation | QGP? / Fragmentation | Gentle Freeze-out

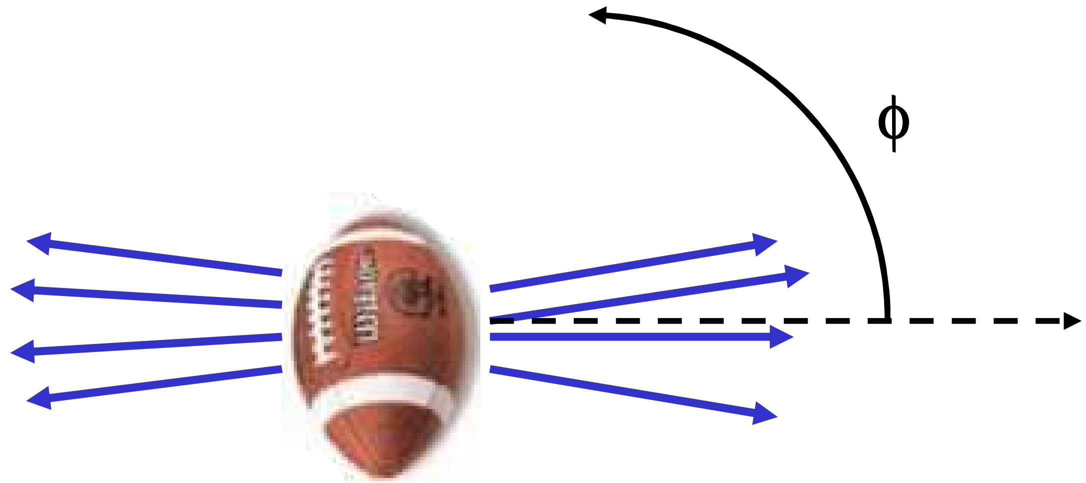
QCD

Elliptic Flow: A collective effect

Beam's eye view of a non-central collision:



Asymmetric particle distribution:

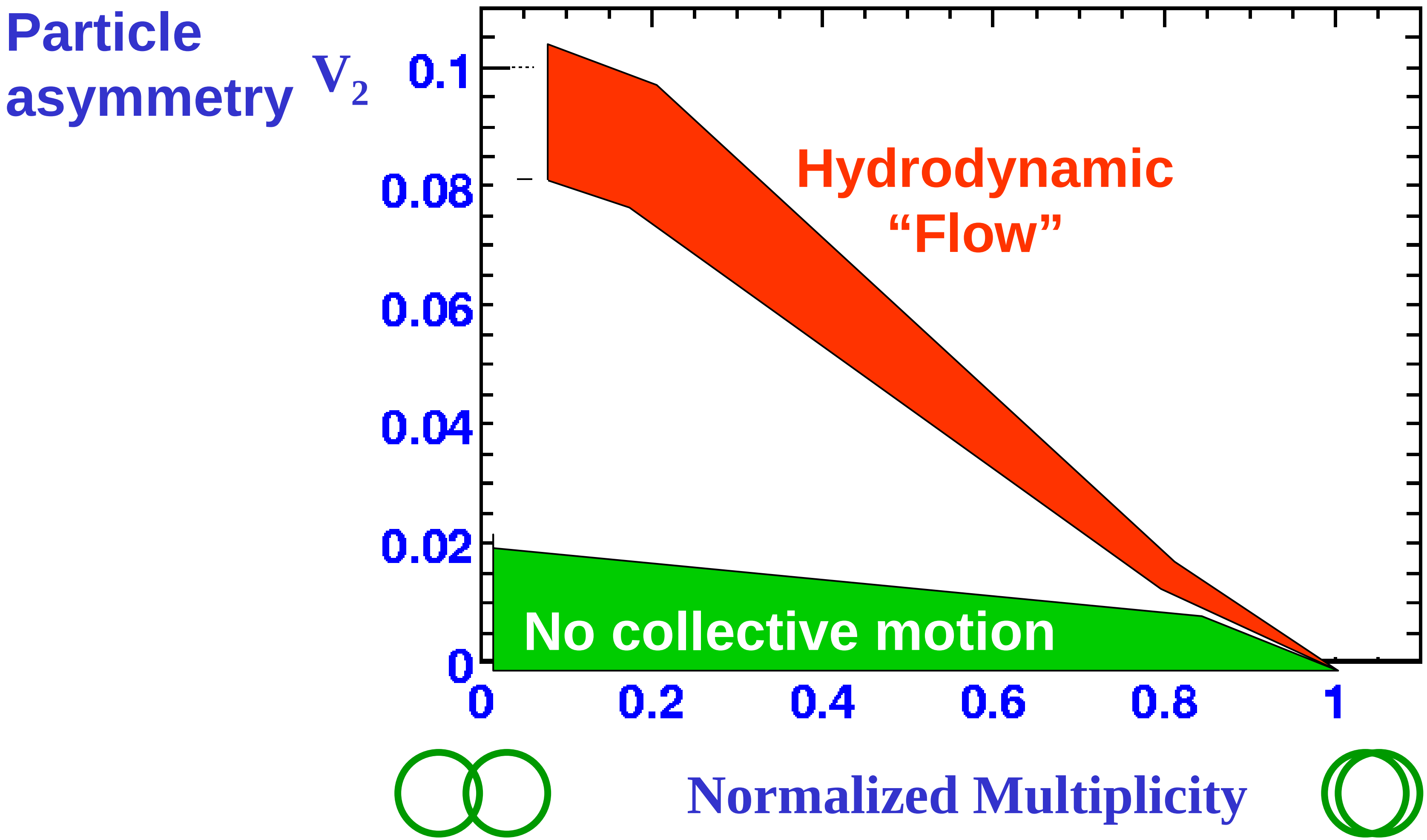


Particles prefer to be "in-plane"

$$dN/d(\phi - \Psi_R) = N_0 \left(1 + 2V_1 \cos(\phi - \Psi_R) + 2V_2 \cos(2(\phi - \Psi_R)) + \ldots\right)$$

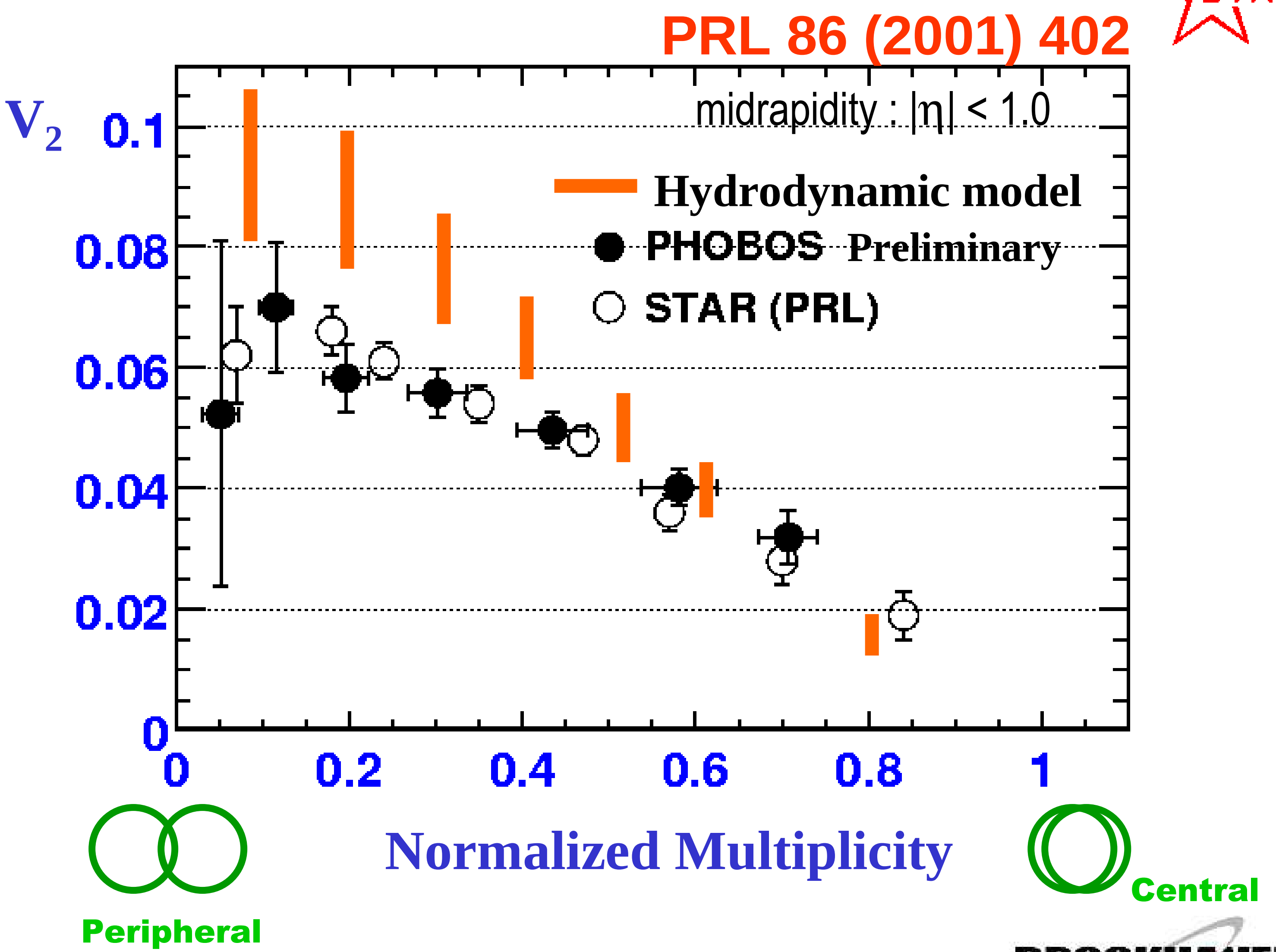
Elliptic flow

Elliptic Flow Expectations

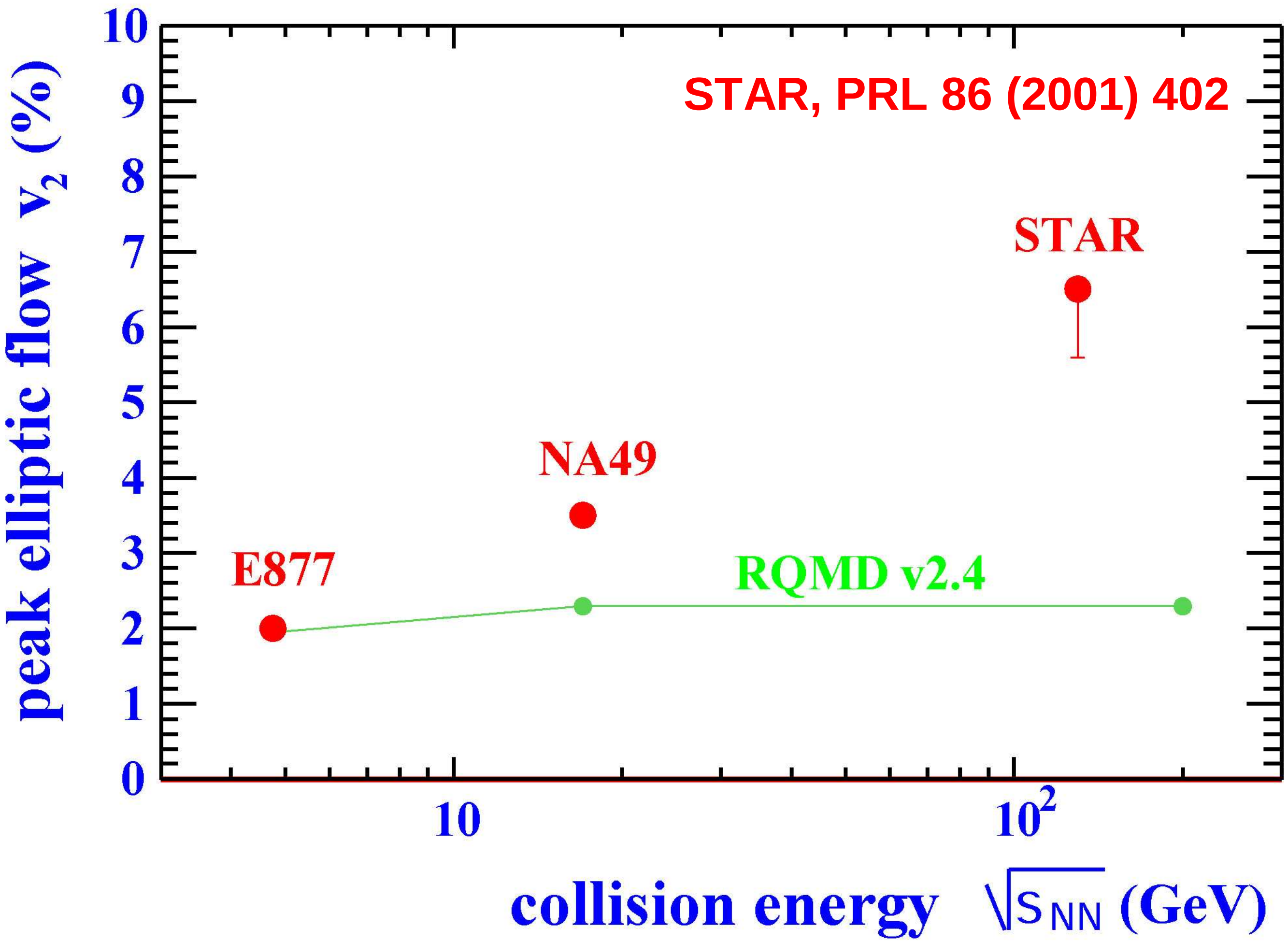


Elliptic Flow

Particle asymmetry

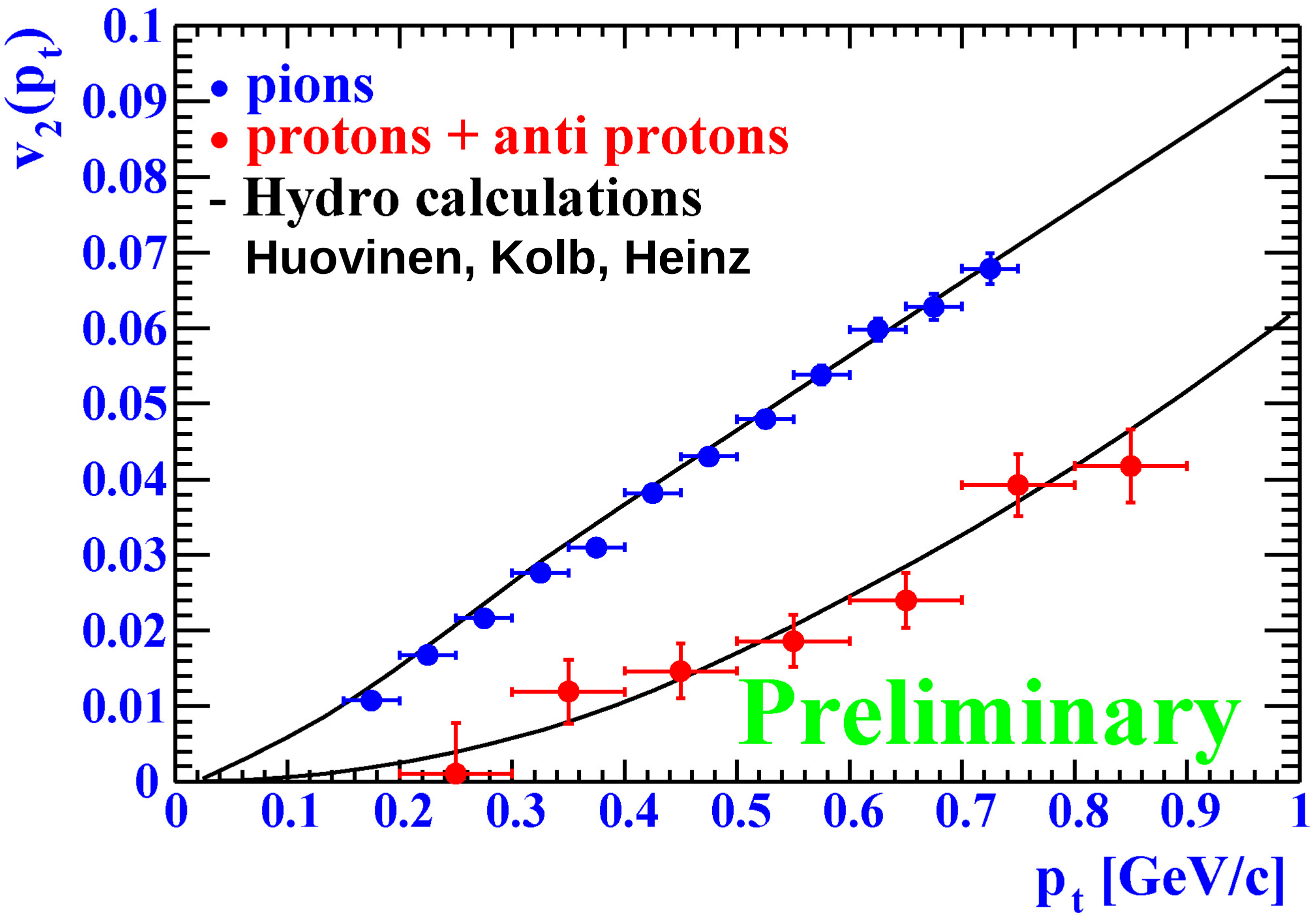


Collective motion largest at RHIC



It even makes sense in detail

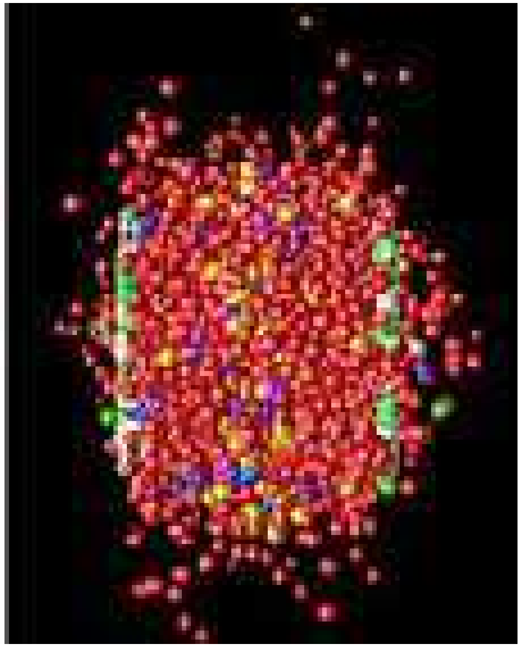
Particle asymmetry



We see the conditions at freezeout

(a lower limit to the maximum Temperature)

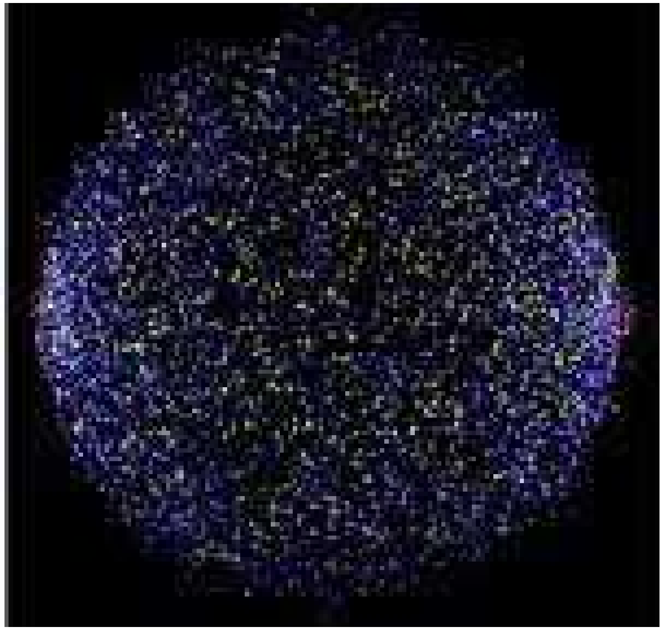
Hottest period



Expansion cooling

$$T \propto \frac{1}{R}$$

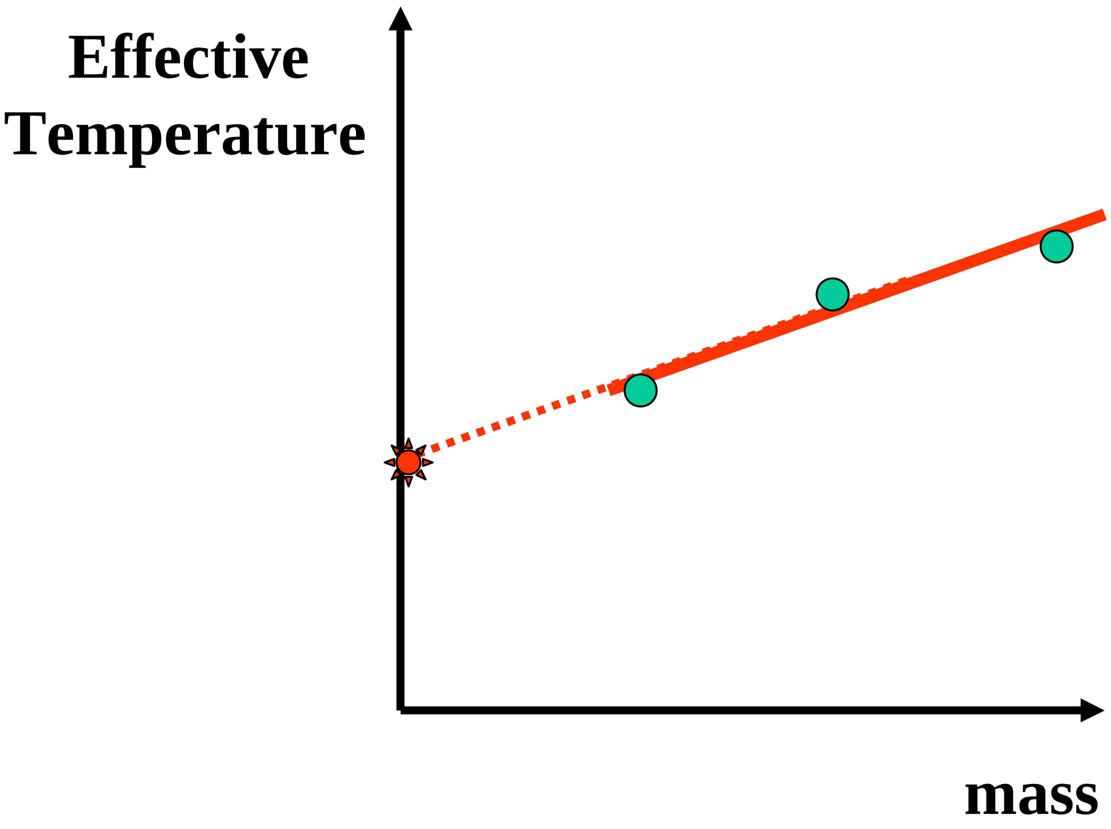
Freezeout



Separating Temperature & Expansion

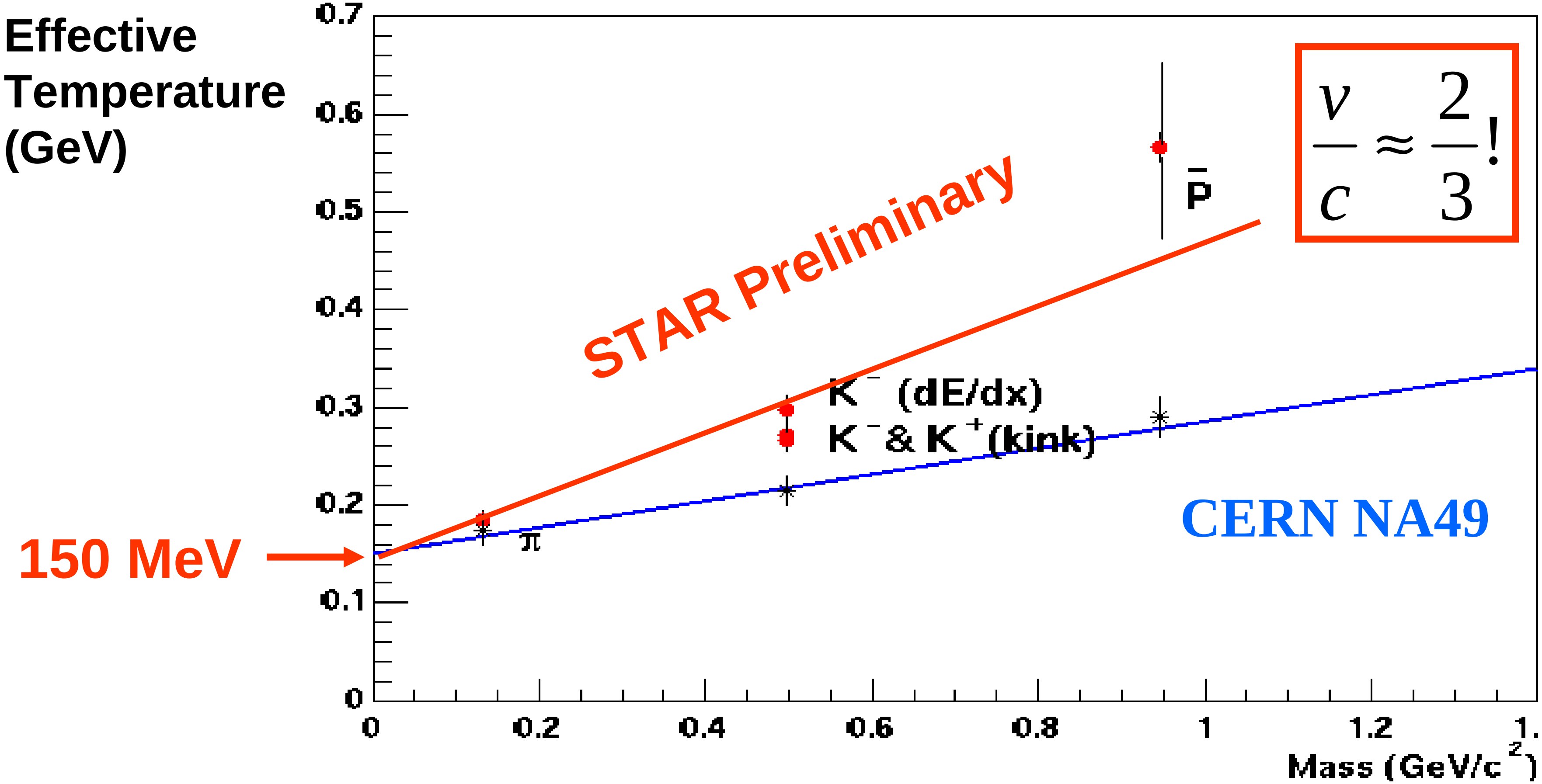
$$\frac{E}{N} \approx \frac{3}{2}T + \frac{m\langle v^2 \rangle}{2c^2}$$

$$T_{eff.} \approx T + \frac{m\langle v^2 \rangle}{3c^2}$$



Compare produced particles with different masses!

RHIC shows rapid expansion & a high temperature

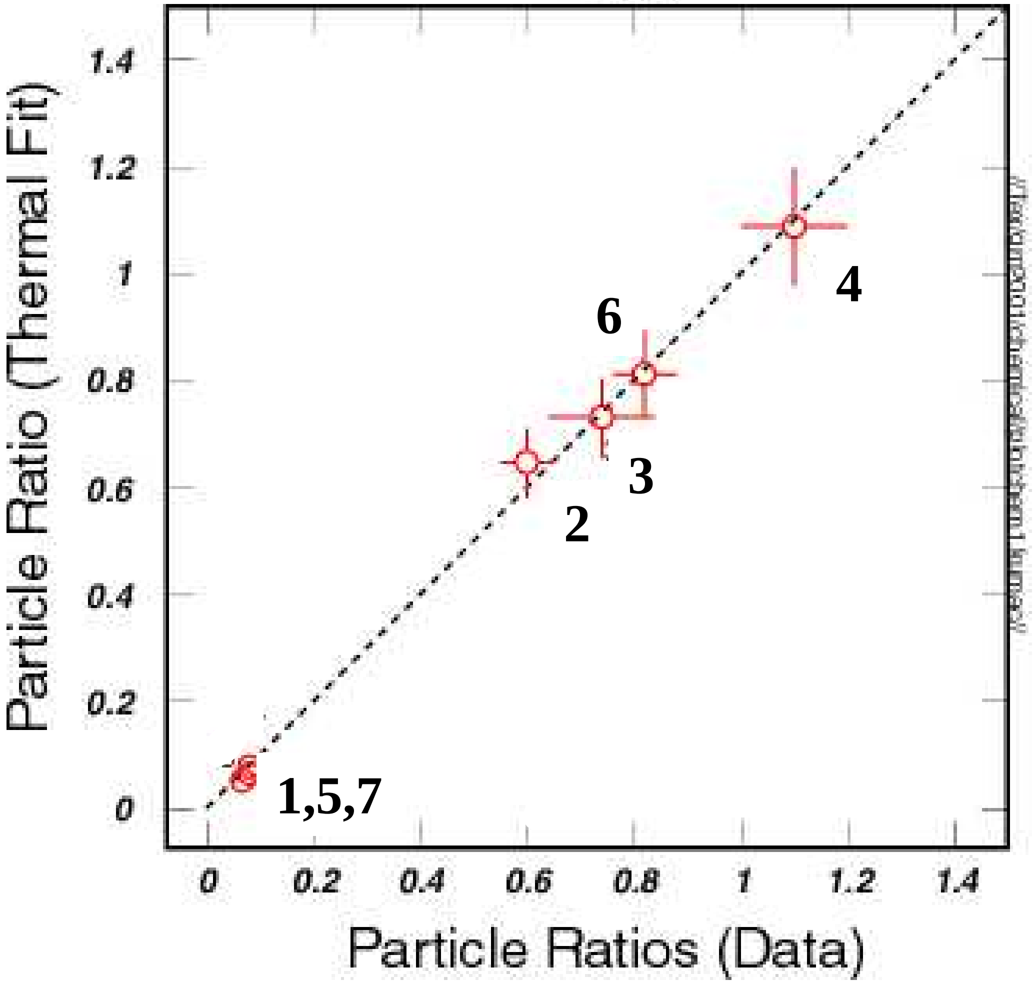


$$\frac{v}{c} \approx \frac{2}{3}!$$

PHENIX: p's and pbar's outnumber π's at p_t of 3 GeV/c!

Another “Thermometer”

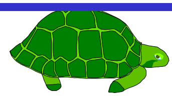
STAR Preliminary



T ~ 170-200 MeV

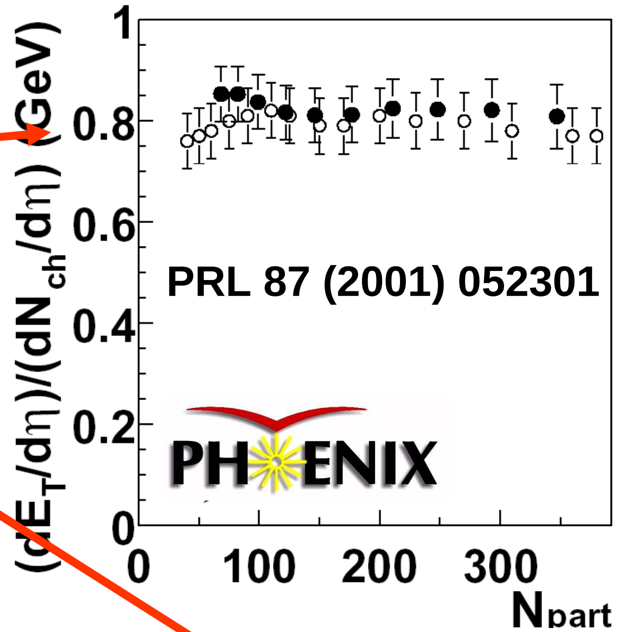
1. $K^- /(h^+ + h^-)$
2. $\bar{p} / p$
3. $\bar{\Lambda} / \Lambda$
4. K^+ / K^-
5. K_0^* / h^-
6. $\bar{\Xi}^- / \Xi^-$
7. $\bar{p} / \pi^-$

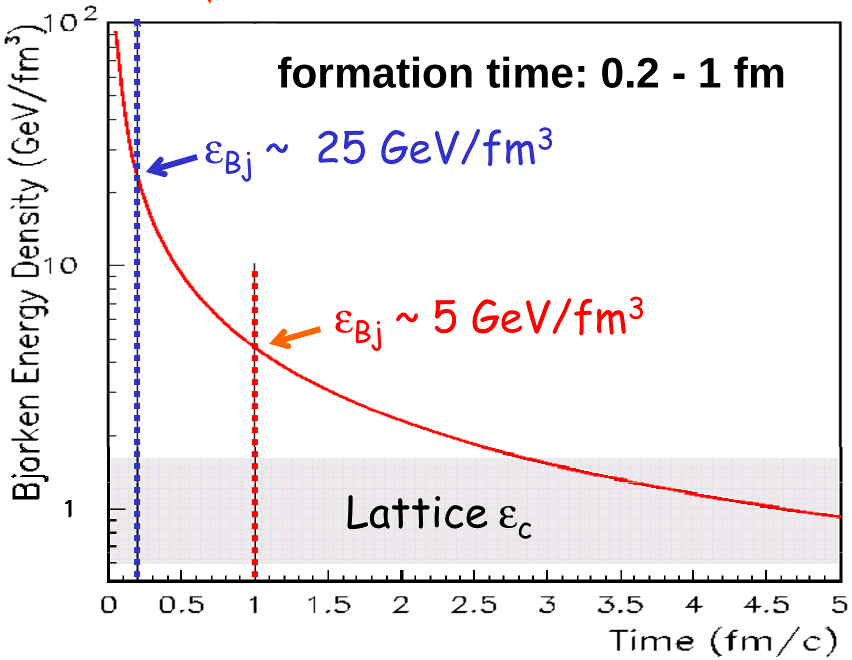
The plan of attack - where are we?

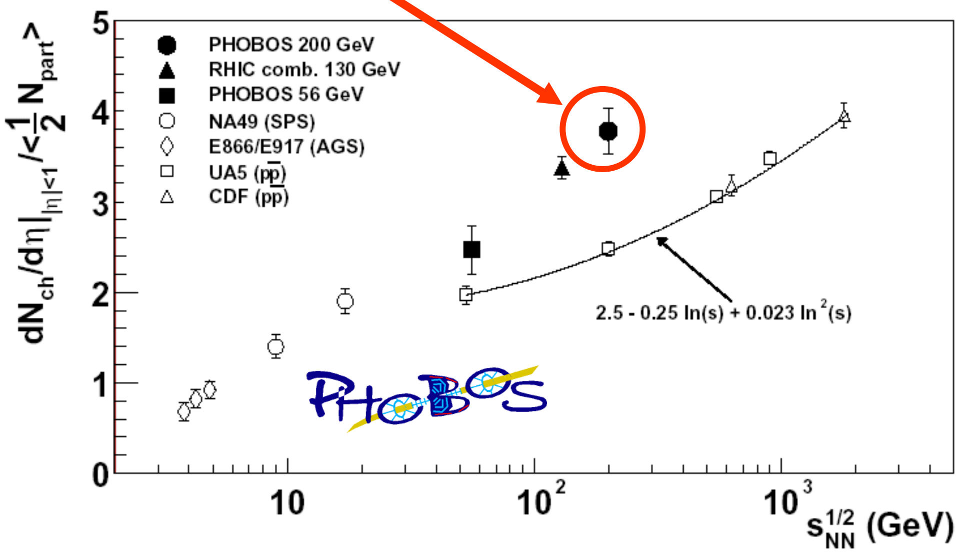
- Collide gold nuclei at high energy
- Is it “strongly interacting bulk matter”
  - Initial State
  - Collective motion
  - Temperature, density
- Learn about the strong interaction
  - Some good news
  - Some puzzles
  - Confinement, Chiral Symmetry 

Energy Density Estimate (Bj)

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

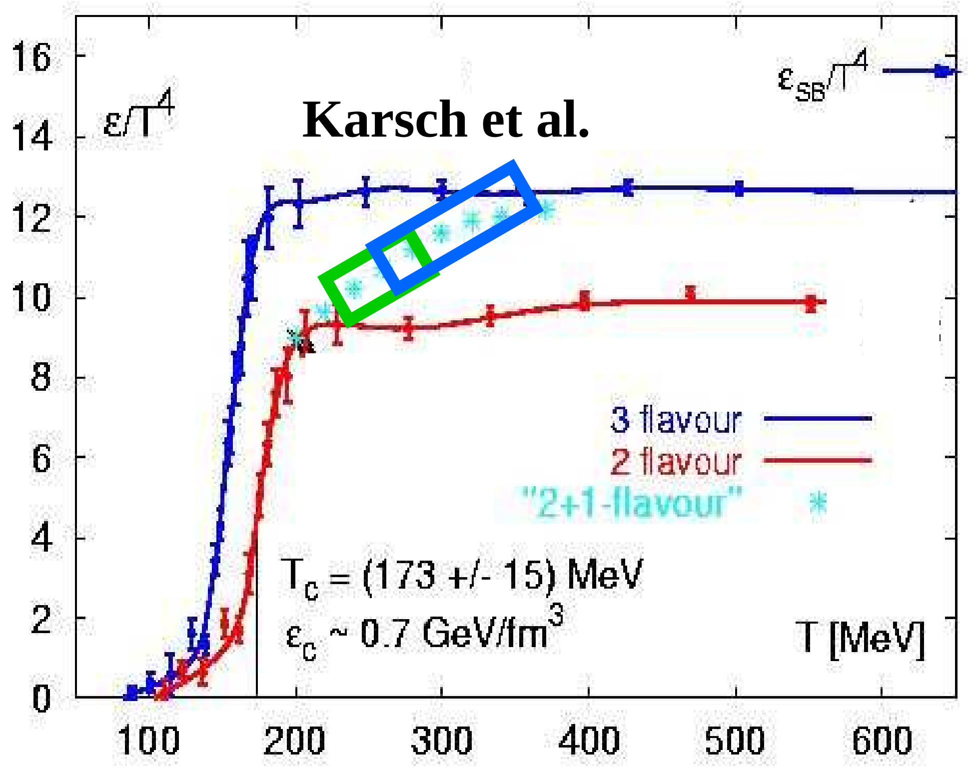






If you just believe the lattice...

$$\varepsilon(T) \Rightarrow T(\varepsilon)$$



CERN SPS (√s = 17 GeV)

ε_i ~ 3-10 GeV/fm^3

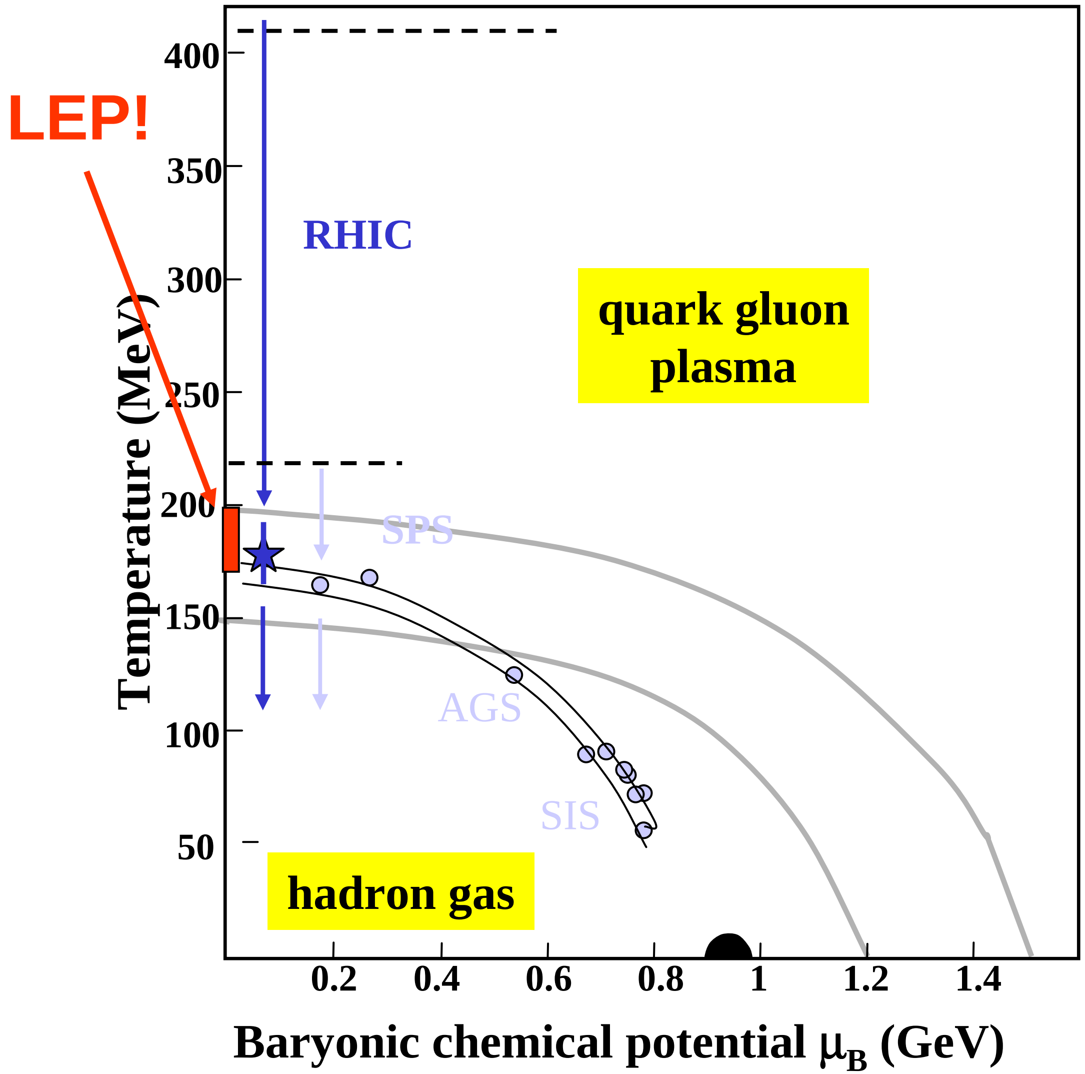
T_i ~ 220-290 MeV

BNL RHIC (√s = 200 GeV)

ε_i ~ 5-25 GeV/fm^3

T_i ~ 250-350 MeV

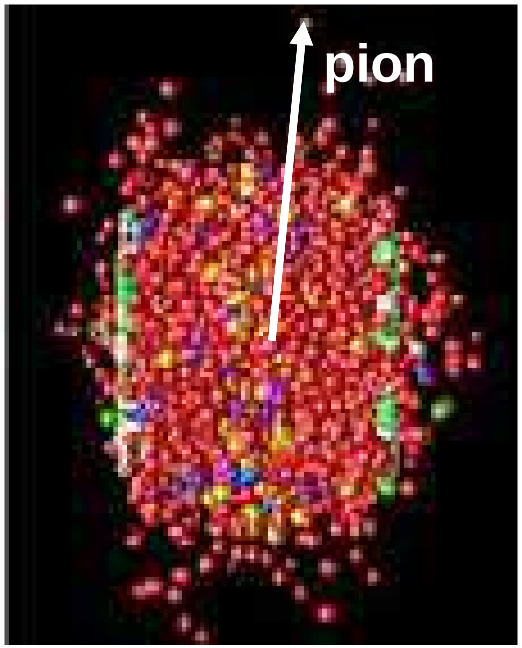
Putting it all together

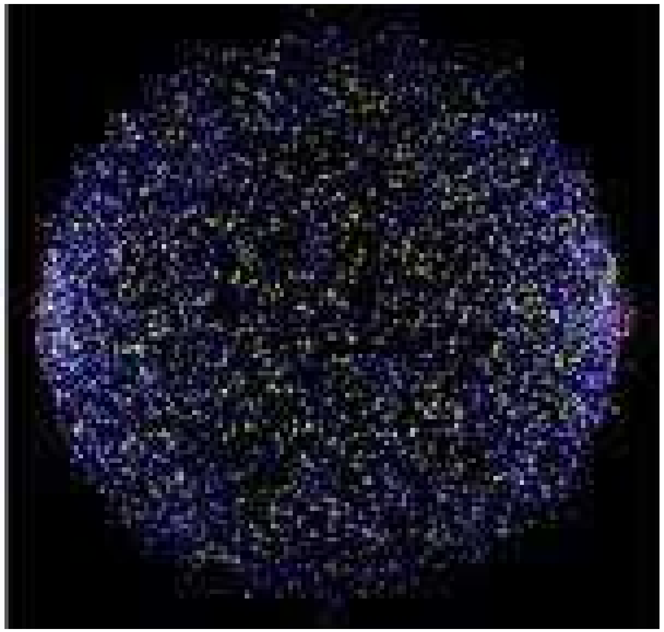


- Universal curve!
- RHIC:
  - "bulk" matter
  - high energy density
    $\varepsilon_{initial}$ ~ 5-25 GeV/fm^3
    (lattice ⇒ T_i >250 MeV)
  - freezeout near T_C
  - early collective expansion
    v_t ~ 0.65 c

What happens before freeze-out?

- Energetic particles come from quark or gluon “jets”.
- They interact with the dense medium, but can’t thermalize.
- Jet energy loss (“quenching”) is predicted (~1GeV/fm).
- Jet quenching measures the density early in the collision.

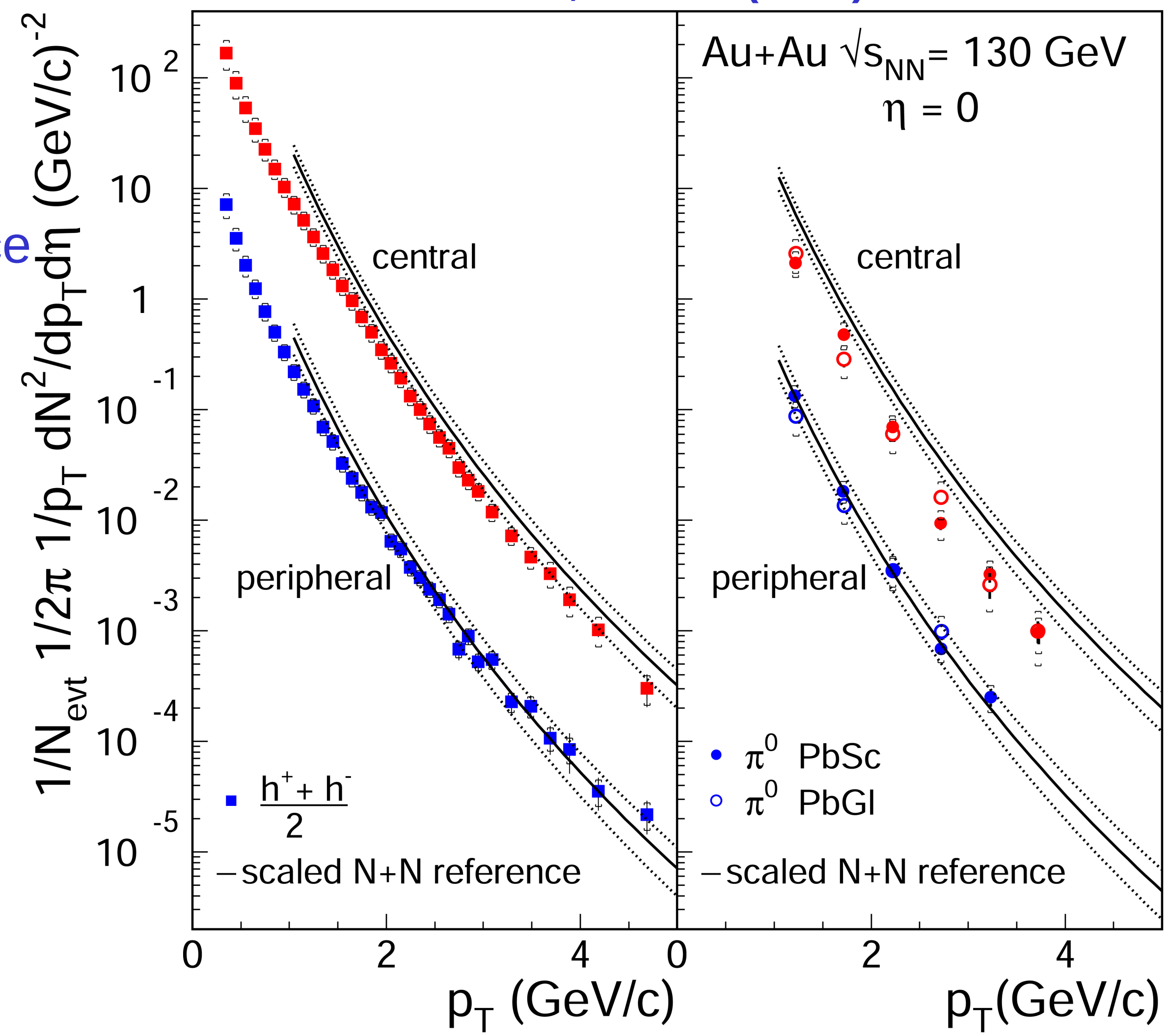




Suppression of High p_T Hadrons

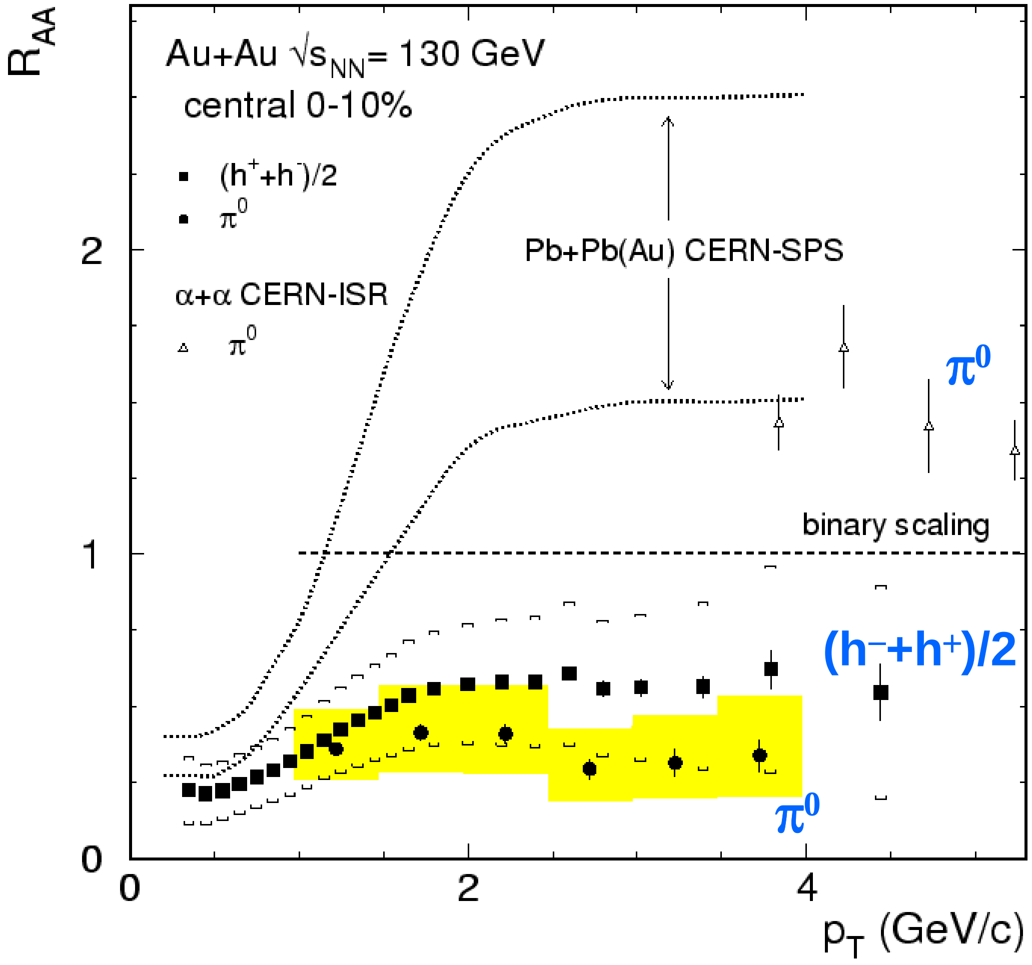
- AuAu data
  - central (0-10%) and peripheral (60-80%)
- compared to N-N reference
  - peripheral collisions
    - described at high p_T
  - central collision
    - suppressed at high p_T

PHENIX, PRL 88 (2002) 022301

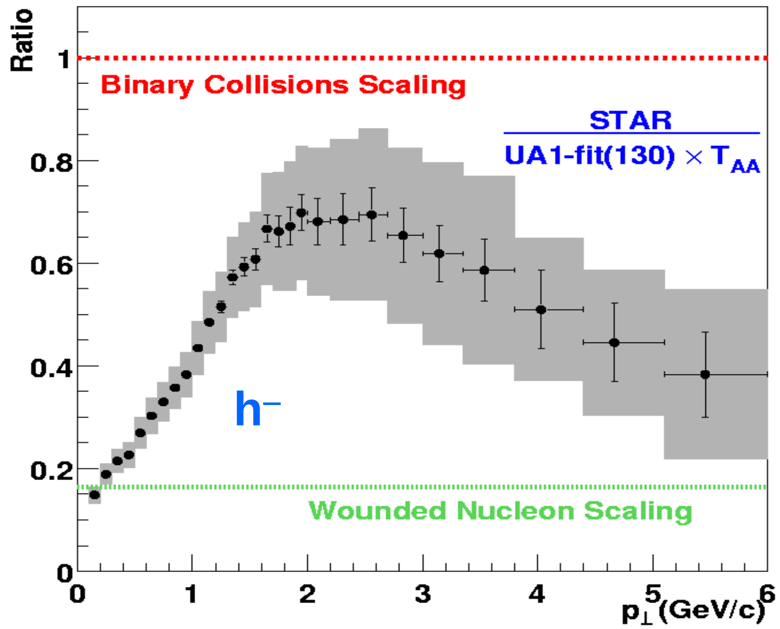


Scaling failure: might be quenching

PHENIX, PRL 88 (2002) 022301

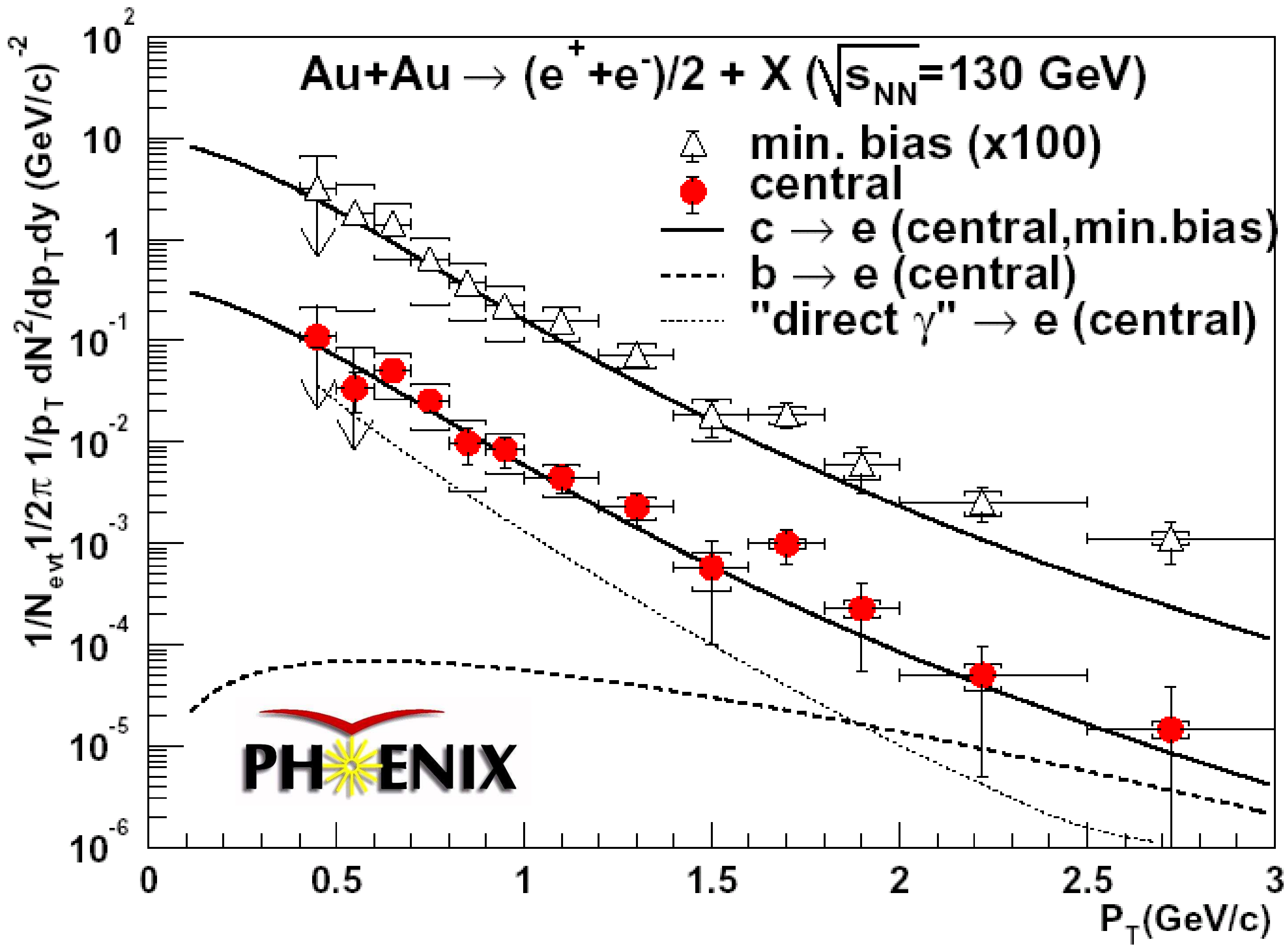


But it could be parton saturation



Charm Does Scale (doesn't quench)

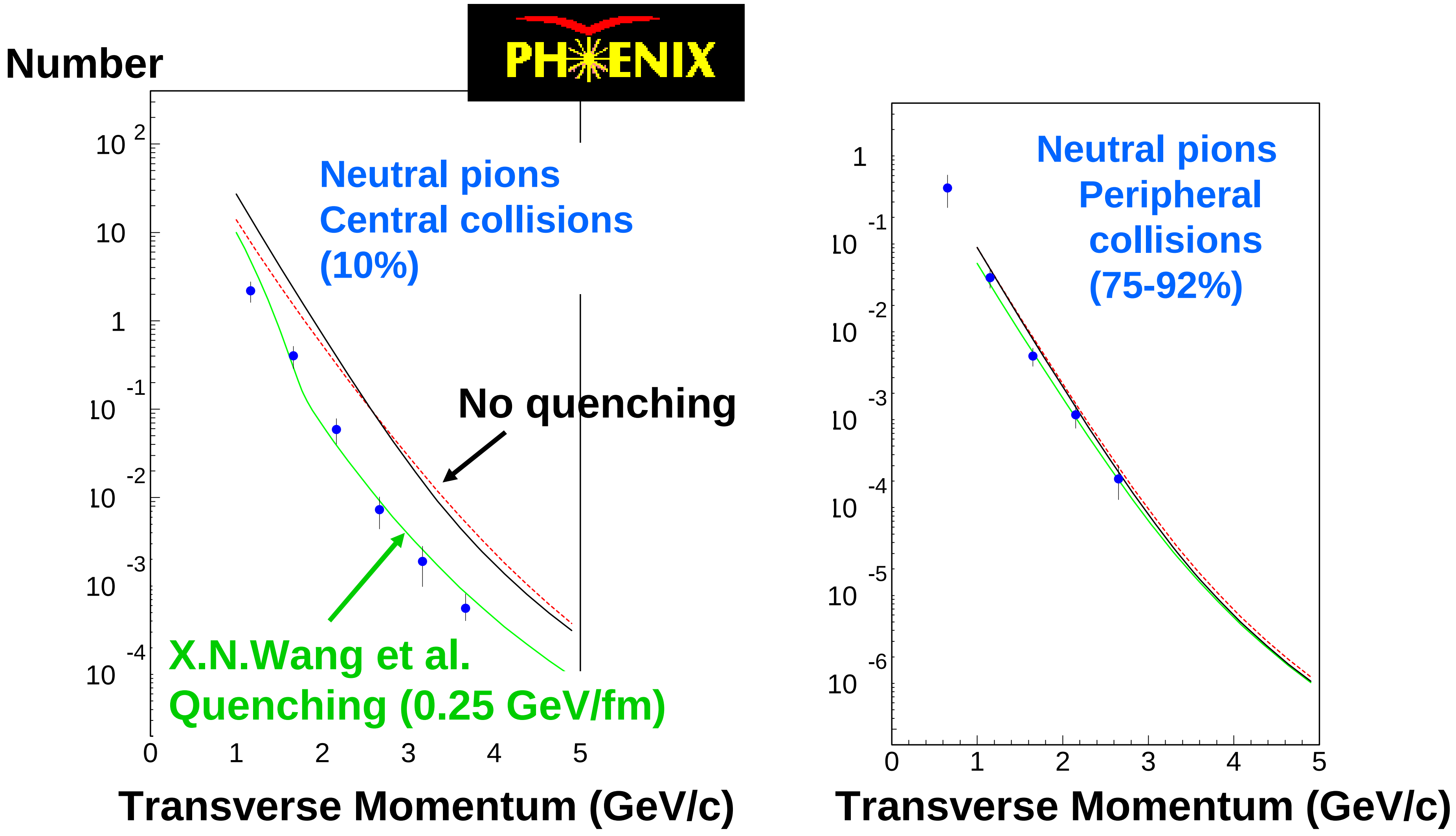
Favors quenching interpretation for pions.



Gluon radiation suppressed for heavy quarks.

Dokshitzer,Kharzeev hep-ph/0106202

Jet quenching at RHIC?



Summary

- We've learned a lot about the AA system
  - It is dense, hot & rapidly expanding.
  - Initial state soft effects dominate
    - Parton saturation?
- We are beginning to probe this state.
  - Universal freezeout/hadronization curve.
    - Including a clear "bulk" state for the first time
  - Possible first evidence of jet quenching!
    - Should lead to a measure of the density
    - Especially at higher p_T

Preliminary