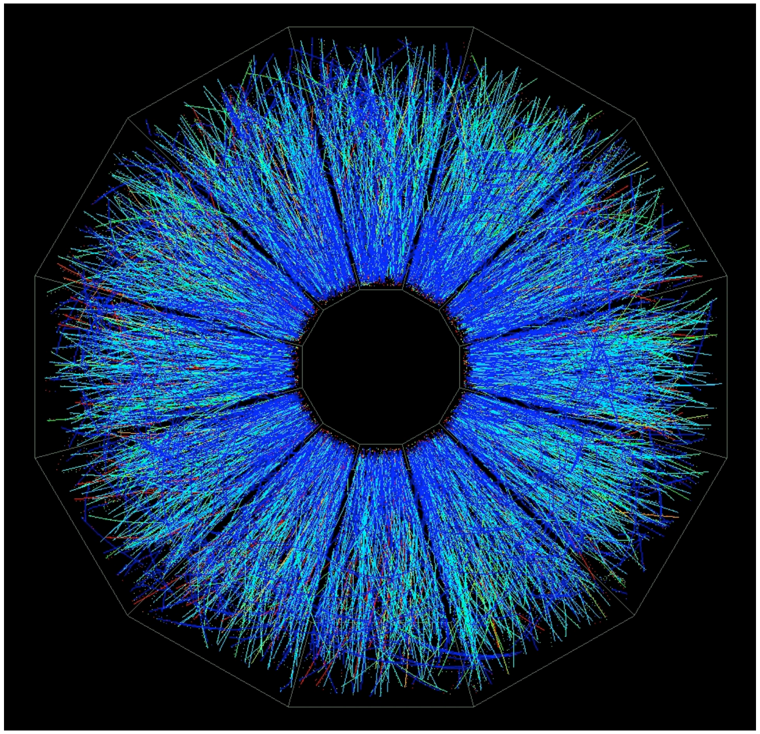
Recent Results from RHIC:
On the trail of the Quark-Gluon Plasma



Single Au+Au Collision
seen by STAR@RHIC

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für Physik
(Werner-Heisenberg-Institut)

July 15 2003

SPIEGEL ONLINE

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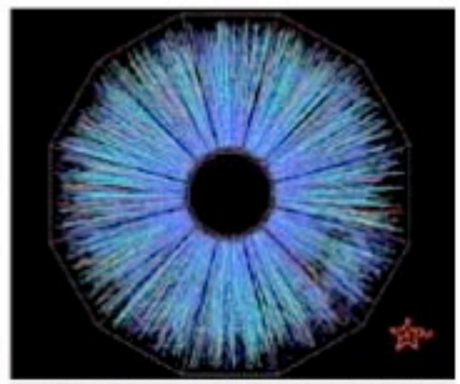
TEILCHENPHYSIK

Die Ursuppe lässt grüßen

Physiker haben möglicherweise Materie vom Anbeginn der Zeiten rekonstruiert: In ihrem Beschleuniger könnte eine Ursuppe aus Quarks und Gluonen entstanden sein, wie sie unmittelbar nach dem Big Bang existierte.

Am Anfang war das Quark-Gluonen-Plasma: In den ersten Mikrosekunden nach dem Urknall gab es keine Atome. Nicht einmal ihre Kernbausteine, die Protonen und Neutronen, waren geboren. Im Universum schwirrten lediglich deren Bestandteile ungebunden umher: Quarks und ihre Klebeteilchen, die Gluonen.

Die Freiheit währte jedoch nur Sekundenbruchteile. Während die Temperatur des Alls rapide absank, organisierten sich Quarks und Gluonen zunächst zu Protonen und Neutronen. Daraus entstanden kurz darauf Atomkerne, die schließlich zu leichten Atomen wurden. Etwa 13 Milliarden Jahren später haben Physiker begonnen, diesen Prozess zumindest in Teilchenbeschleunigern wieder umzukehren.

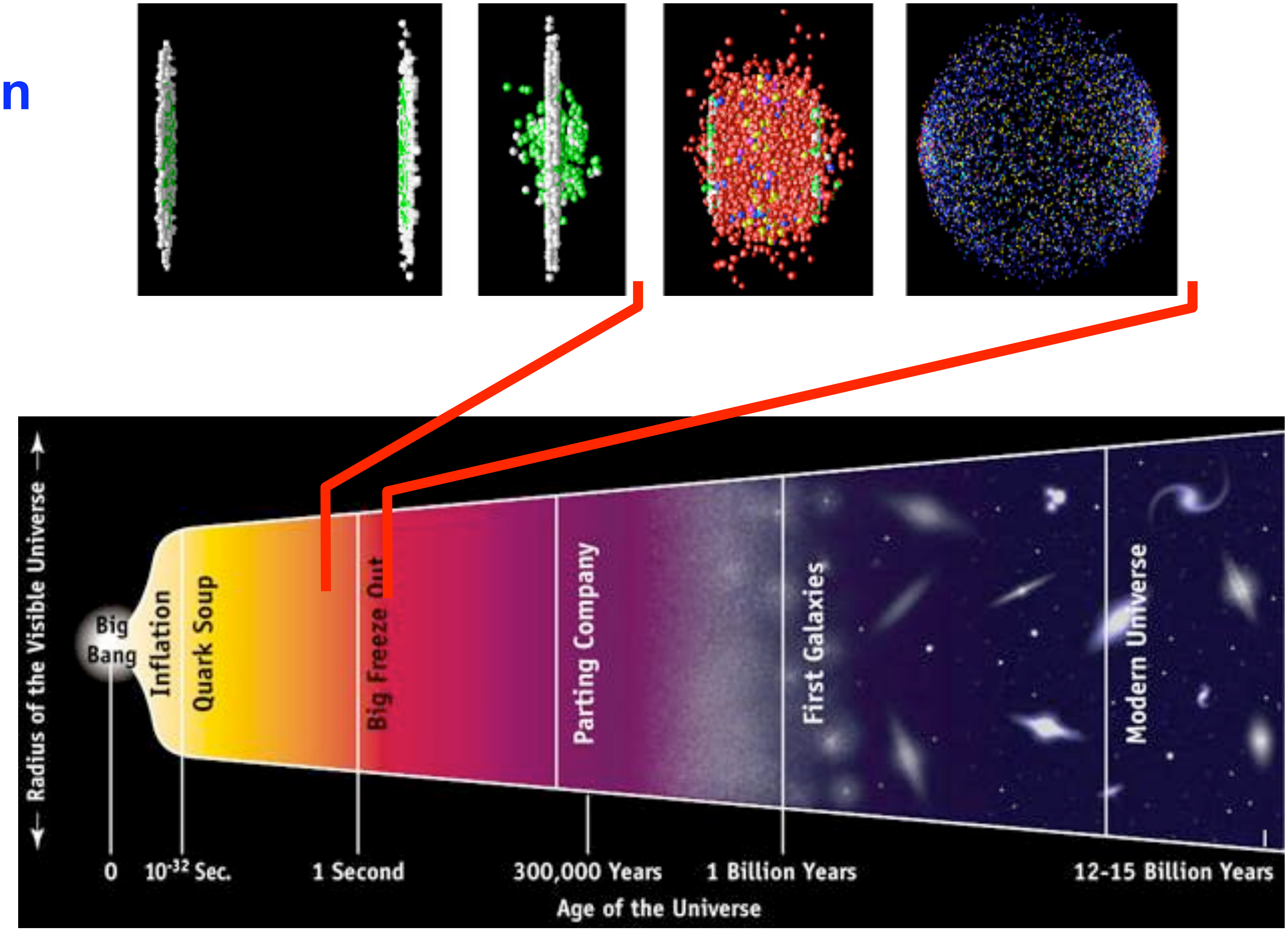


Brookhaven National Laboratory

Ergebnis der Kollision zweier Goldionen-Ströme im RHIC: Extreme Energie

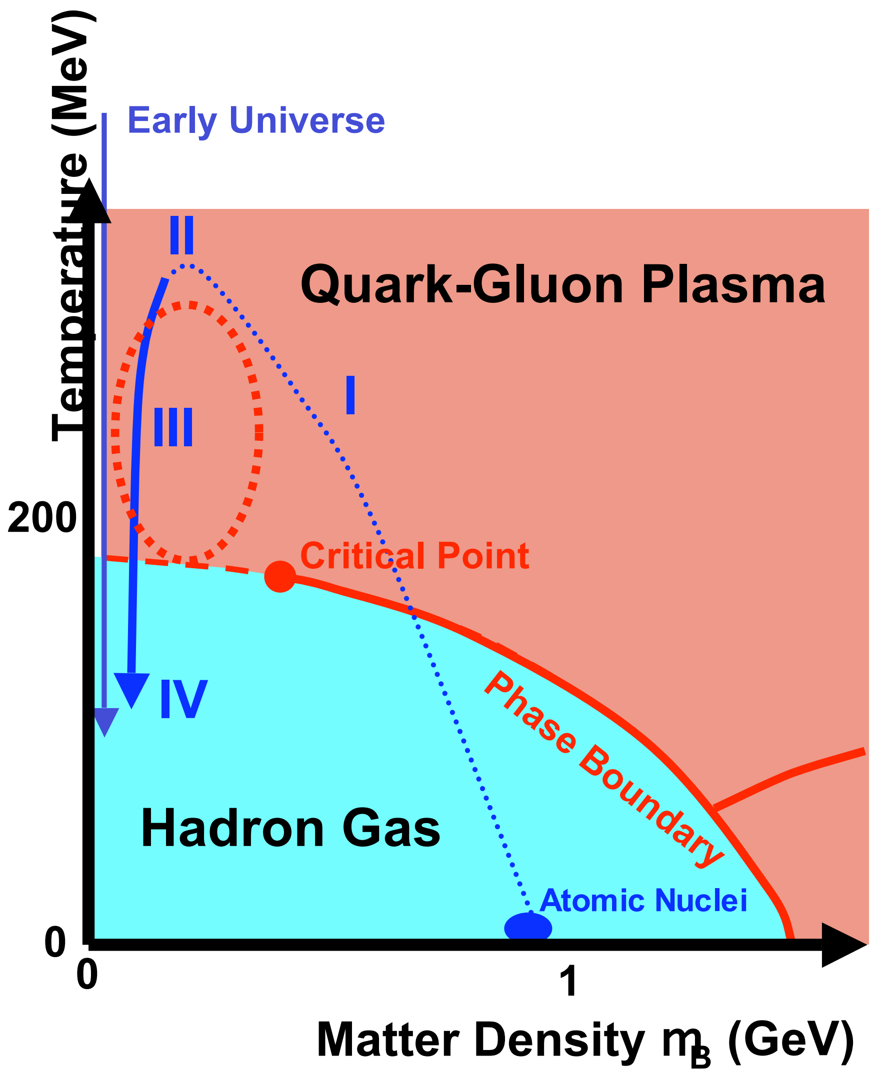
Cooking Quark Soup

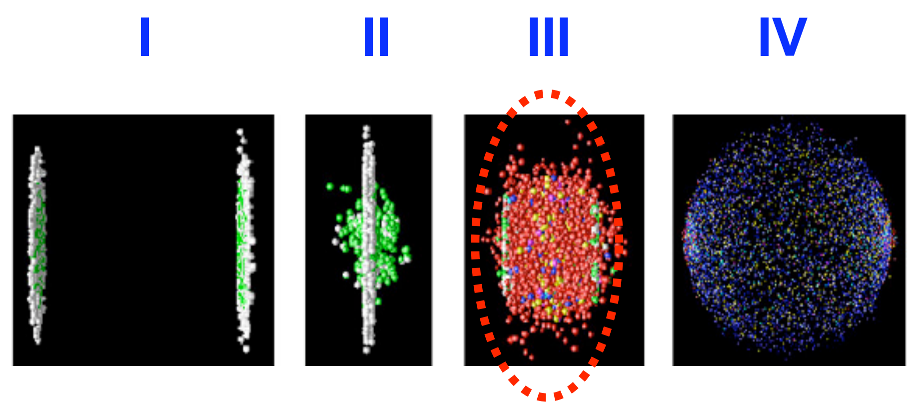
Heavy-Ion Collision



Universe

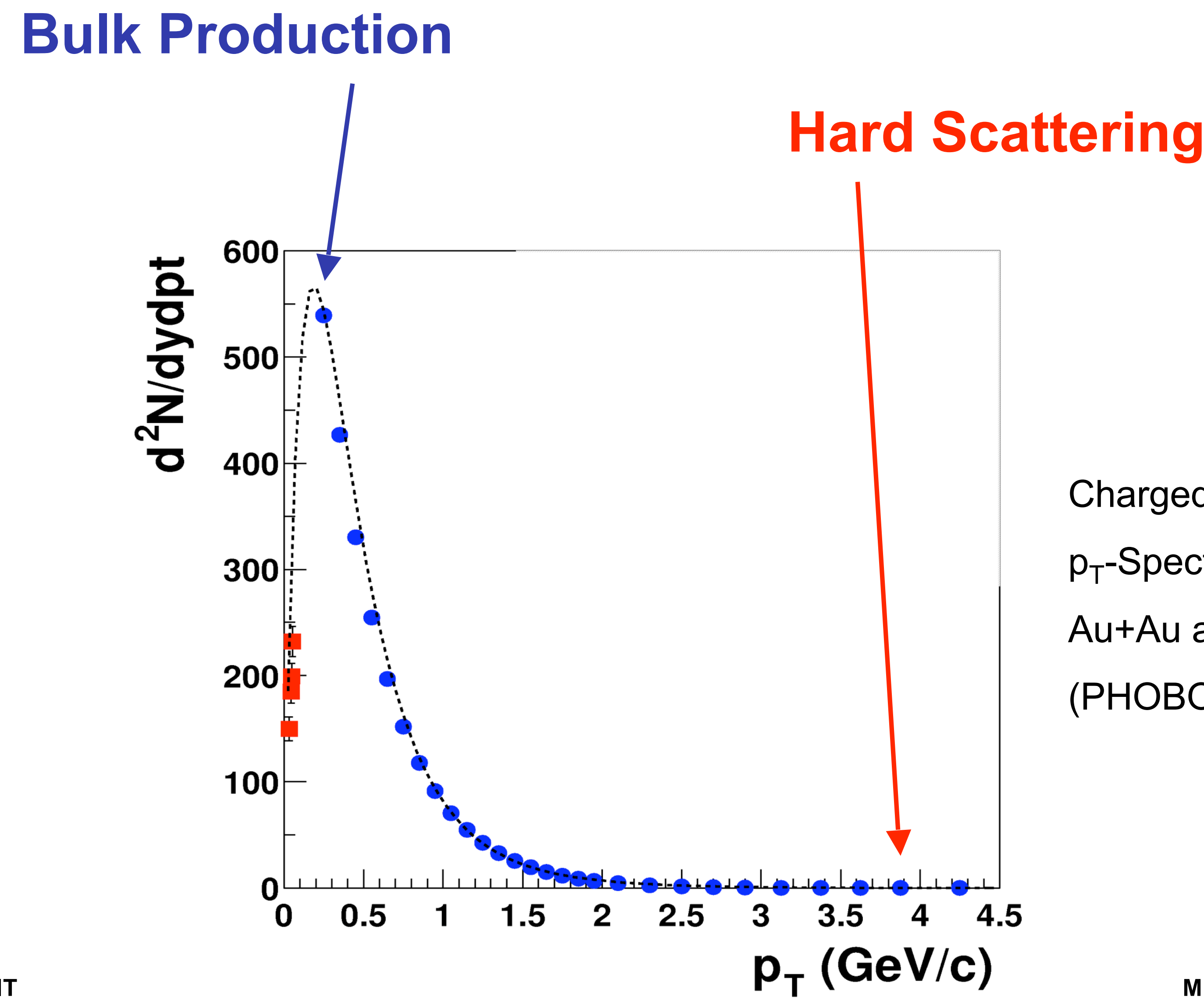
Exploring QCD with Heavy Ions





- Structure of Relativistic Nuclei
- Mechanism of Entropy Production
- QCD phase diagram
- Properties of QGP

Particle Production at RHIC

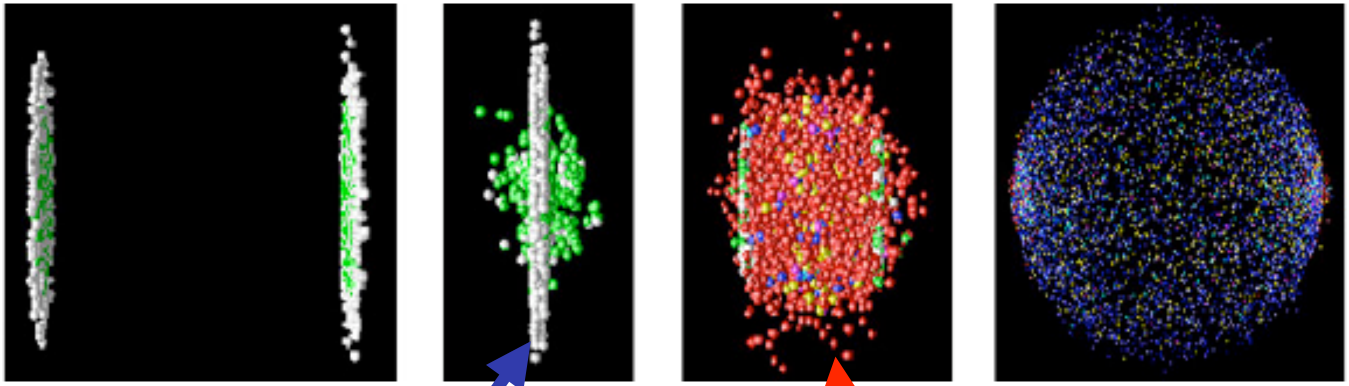


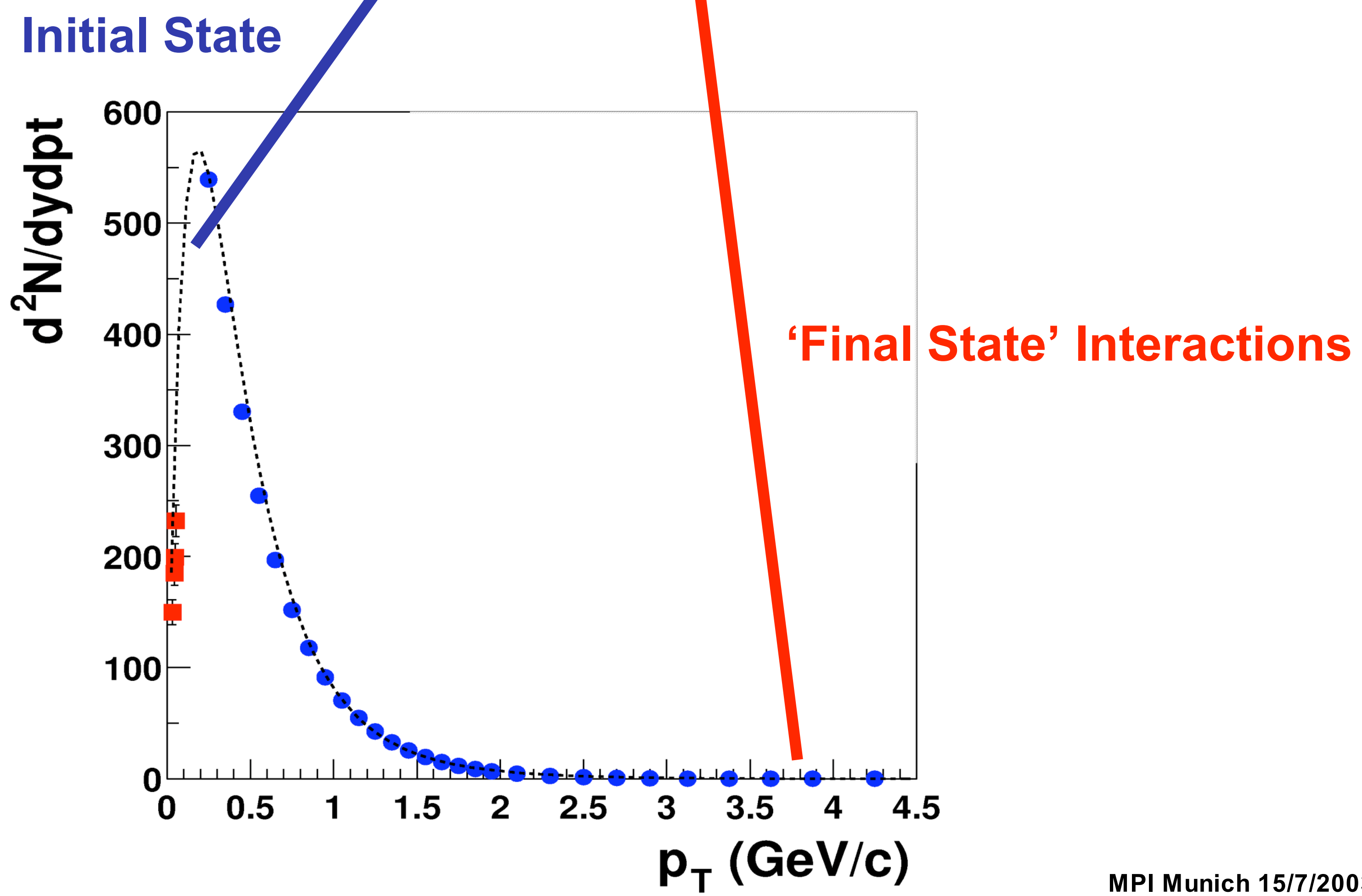
Charged Hadron

p_T-Spectrum in

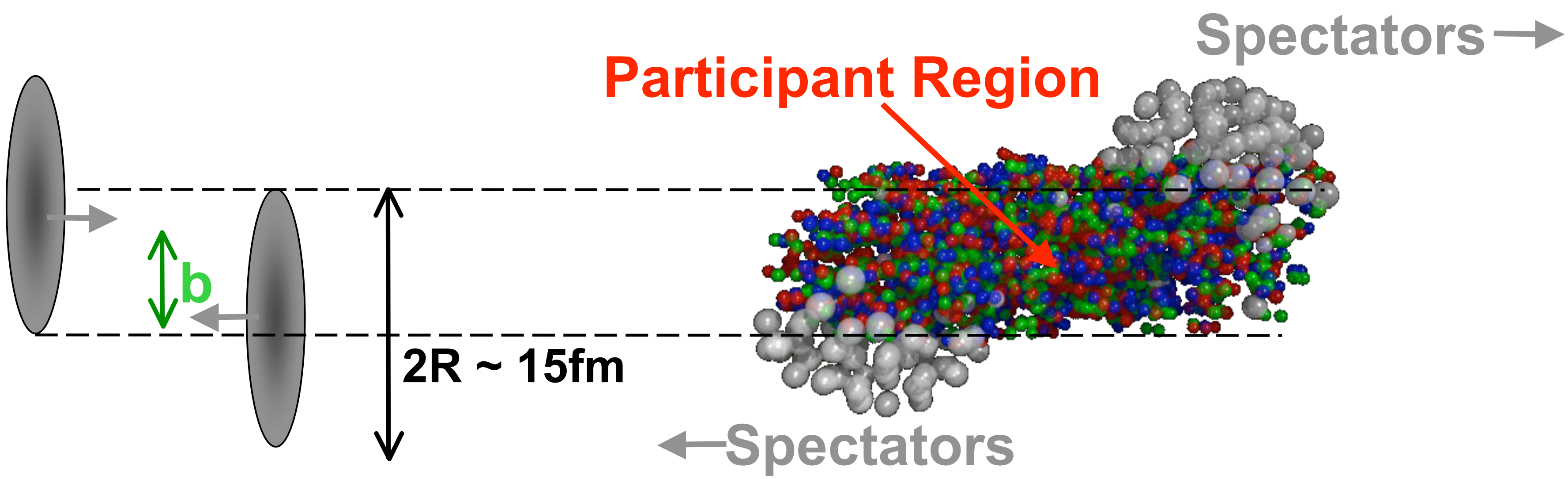
Au+Au at RHIC

(PHOBOS)




Initial State
'Final State' Interactions
600
500
400
300
200
100
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
$d^2N/dydpt$
p_T (GeV/c)

Control Parameters: Centrality



Smaller Impact Parameter b

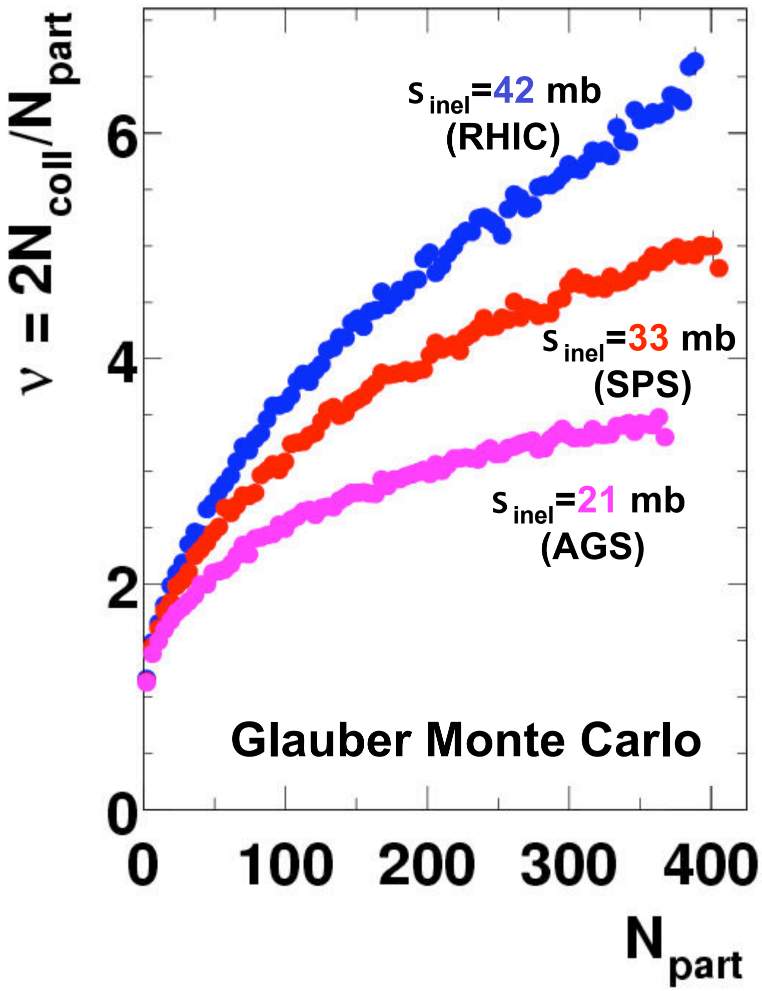
↕

More Participants (N_{part}) = *Wounded Nucleons*

↕

Bigger Collision System

Control Parameters: Centrality



- Centrality controls
  - Volume (N_{part})
  - No. of binary collisions (N_{coll})
  - Shape of interaction region
- N_{part} vs N_{coll}
  - soft vs hard processes
  - coherent vs incoherent production

Relativistic Heavy Ion Collider

First Physics in ‘00

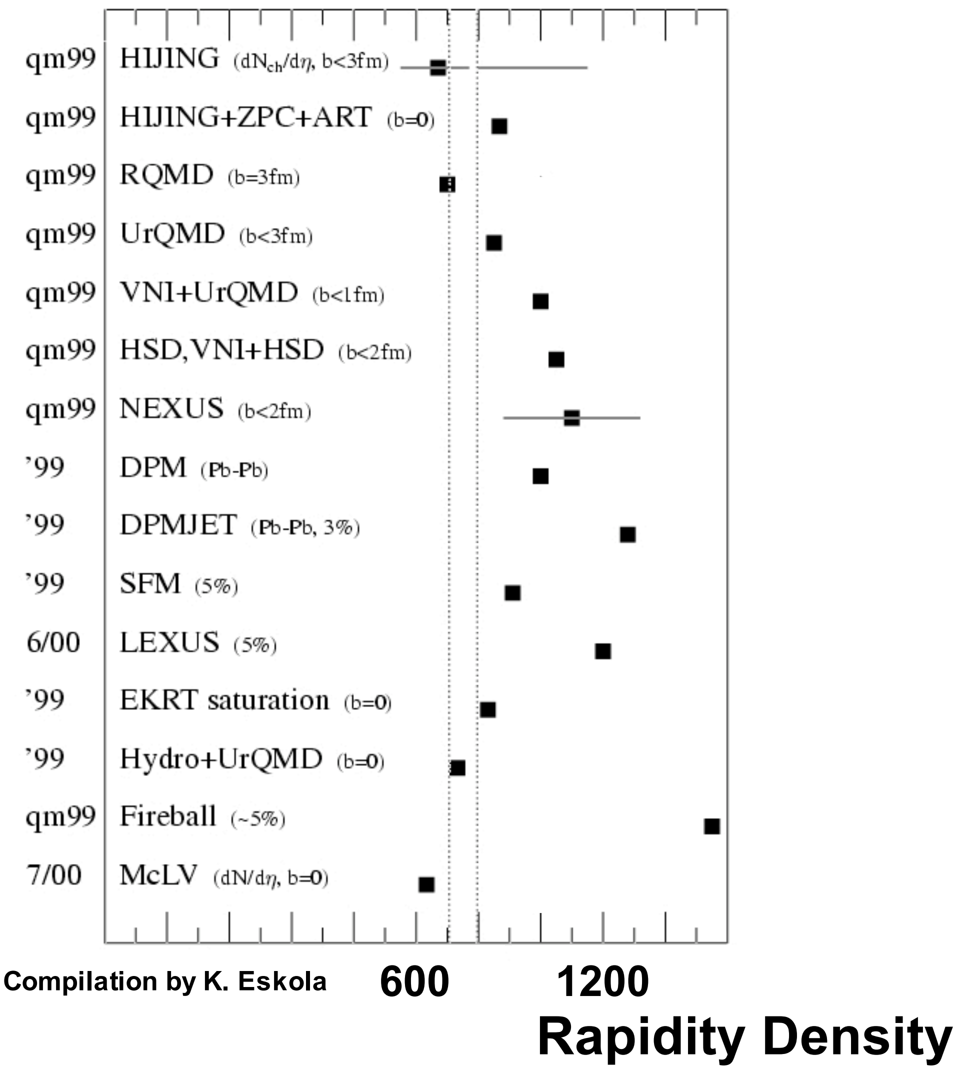
Versatile machine

- Au+Au (‘00-’02)
  - 19.6 GeV
  - 56 GeV
  - 130 GeV
  - 200 GeV
- p+p (‘02,’03)
  - 200 GeV polarized
- d+Au (‘03)
  - 200 GeV

- 4 Experiments
  - 2 big
  - 2 small
- Complementary capabilities

Initial State of the Collision

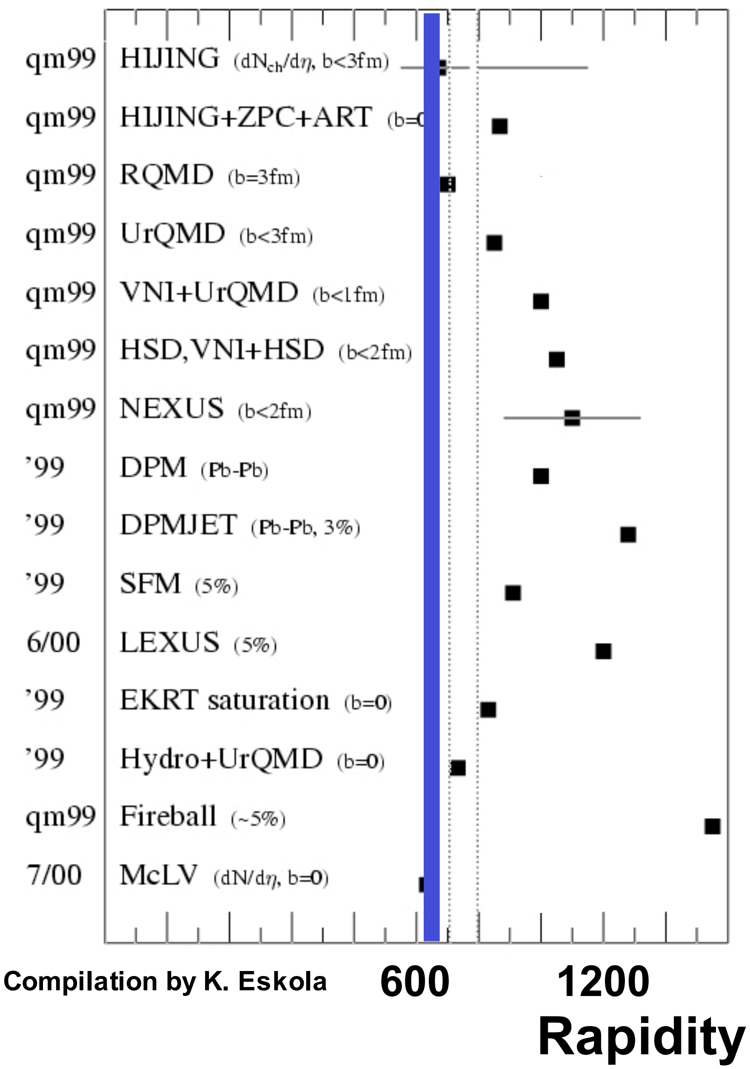
Particle Multiplicity at RHIC



Compilation by K. Eskola

Particle Multiplicity at RHIC

PHOBOS Central Au+Au (200 GeV)

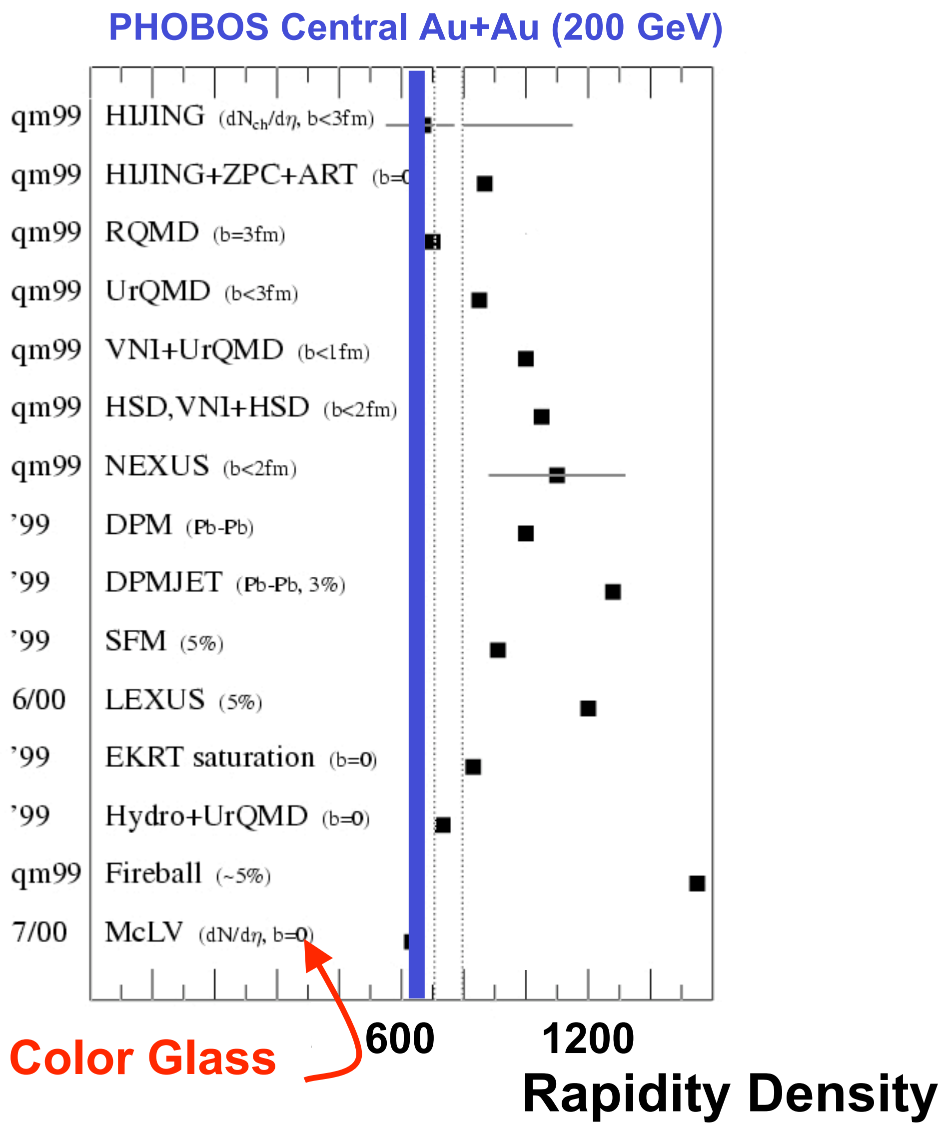


Compilation by K. Eskola

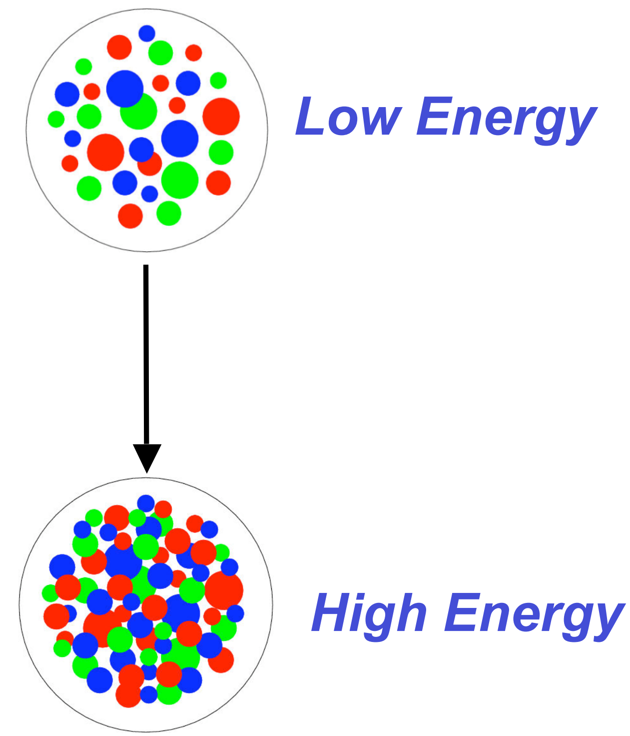
- *Multiplicity at low end of range*
  - *But: Energy density 30x nuclear matter*
- *Most models didn't do so well*

Data: PHOBOS
Phys. Rev. Lett. 85 , 3100 (2000)
Phys. Rev. Lett. 87, 102303 (2001)
Phys.Rev. Lett. 88 , 22302 (2002)

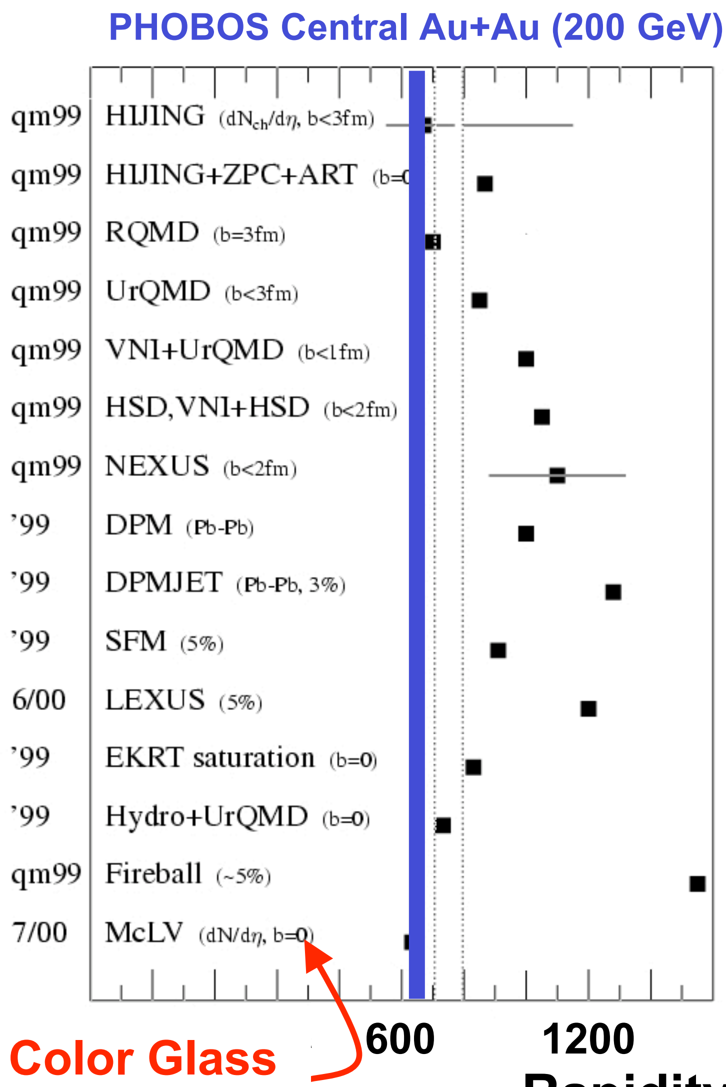
Particle Multiplicity at RHIC



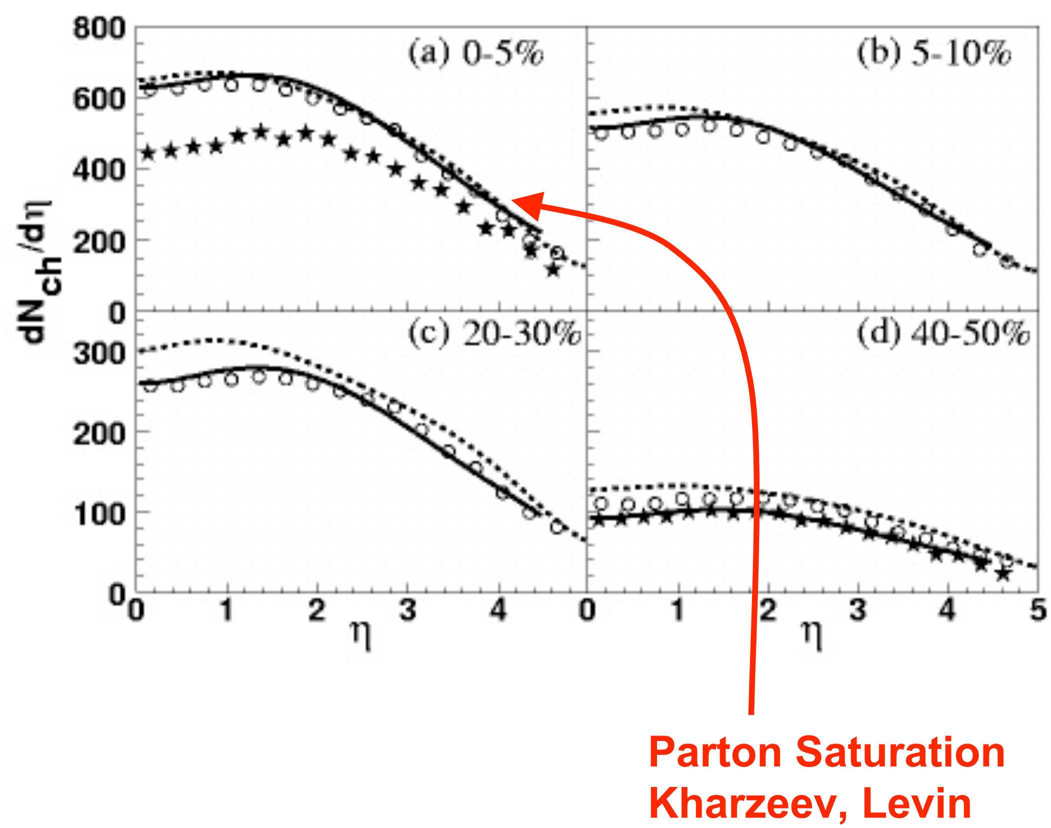
Parton Saturation



Particle Multiplicity at RHIC



Hadron multiplicities at RHIC well described by Parton Saturation

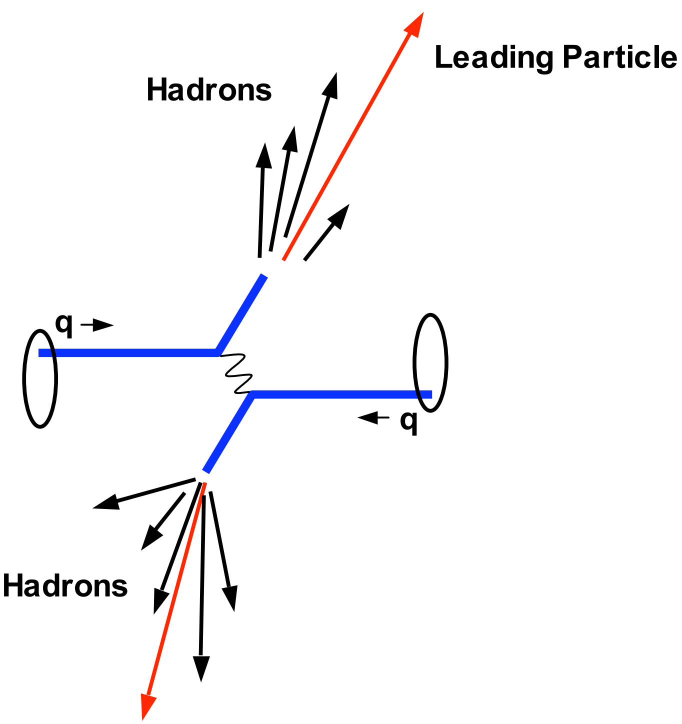


Kharzeev & Levin, Phys. Lett. B523 (2001) 79
Data: BRAHMS, PRL 88, 202301 (2002)

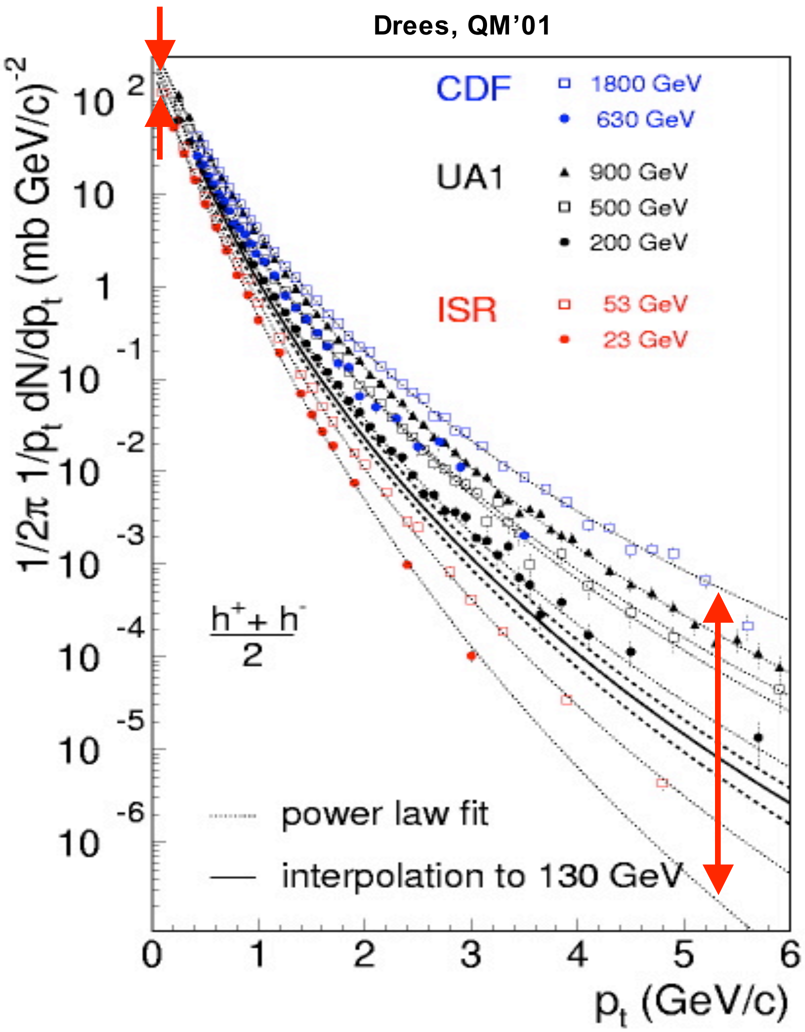
Hot, Dense *Matter*?

Hard Probes of Dense Matter

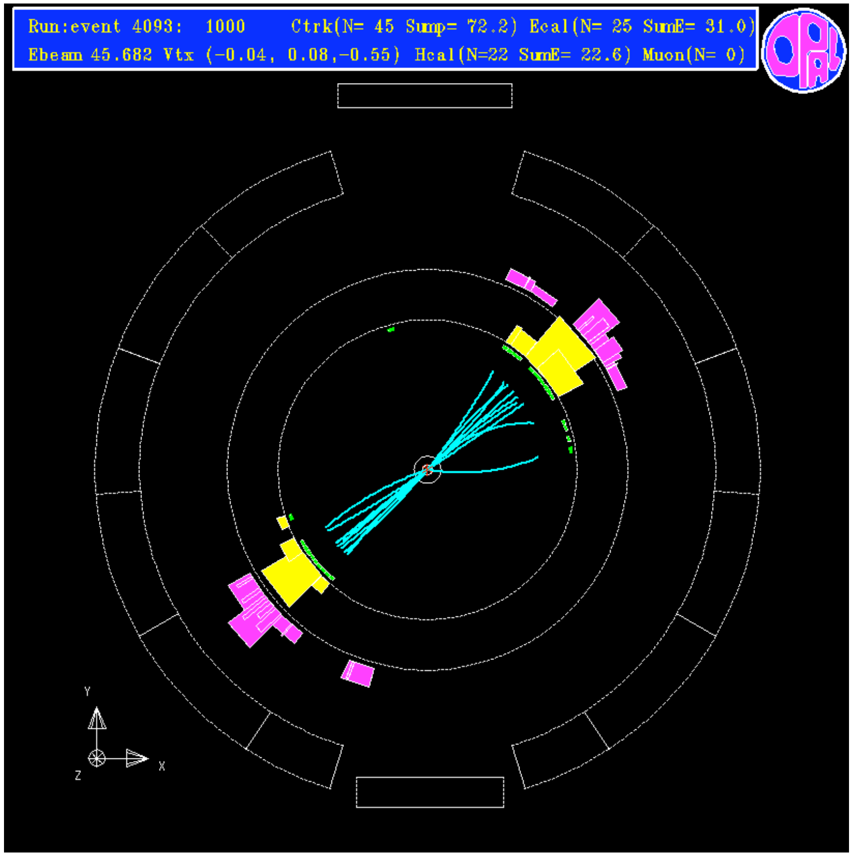
Jet cross-section calculable in QCD



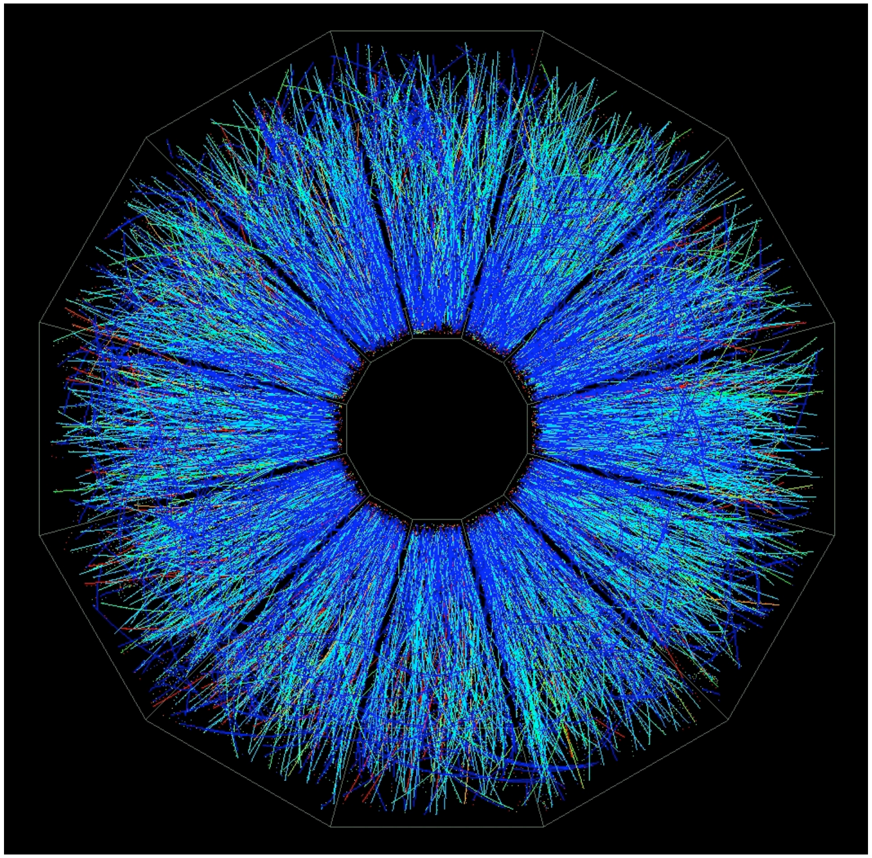
Drees, QM'01



Opal e^+e^-

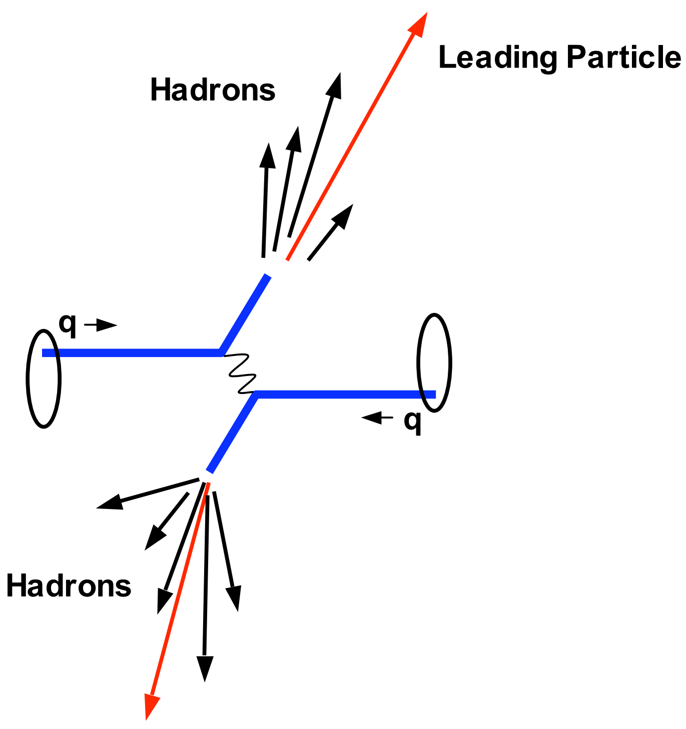


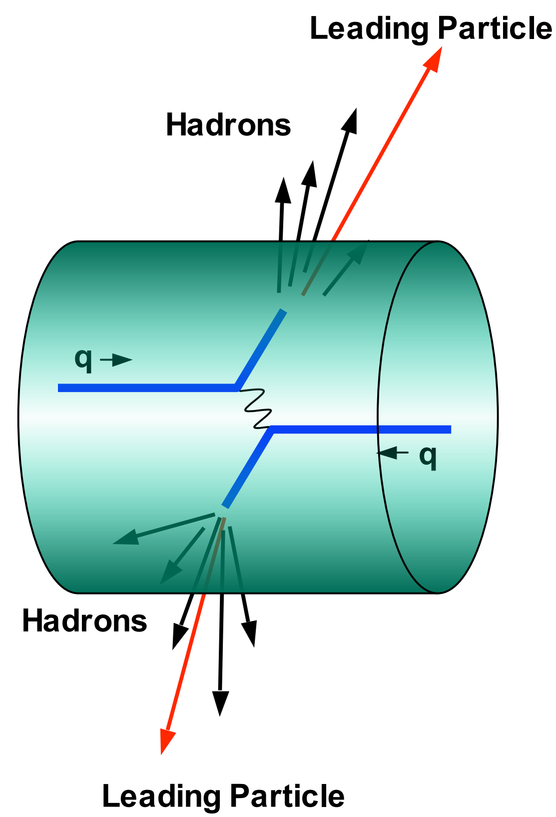
STAR Au+Au



Hard Probes of Dense Matter

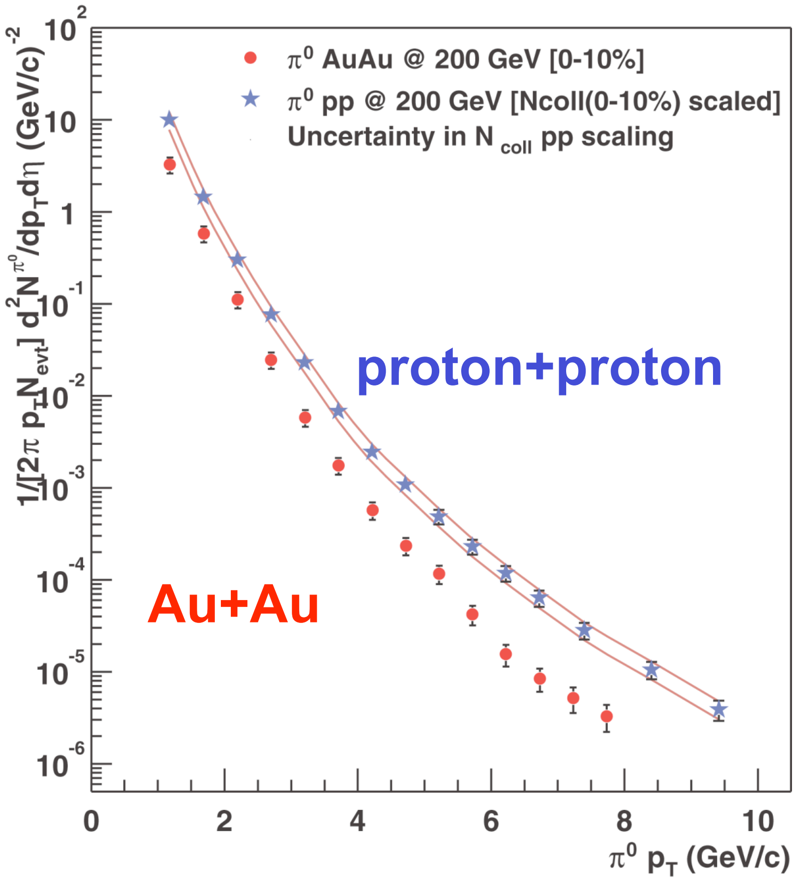
Jet cross-section calculable in QCD → Study fate of jets in dense matter in Au+Au

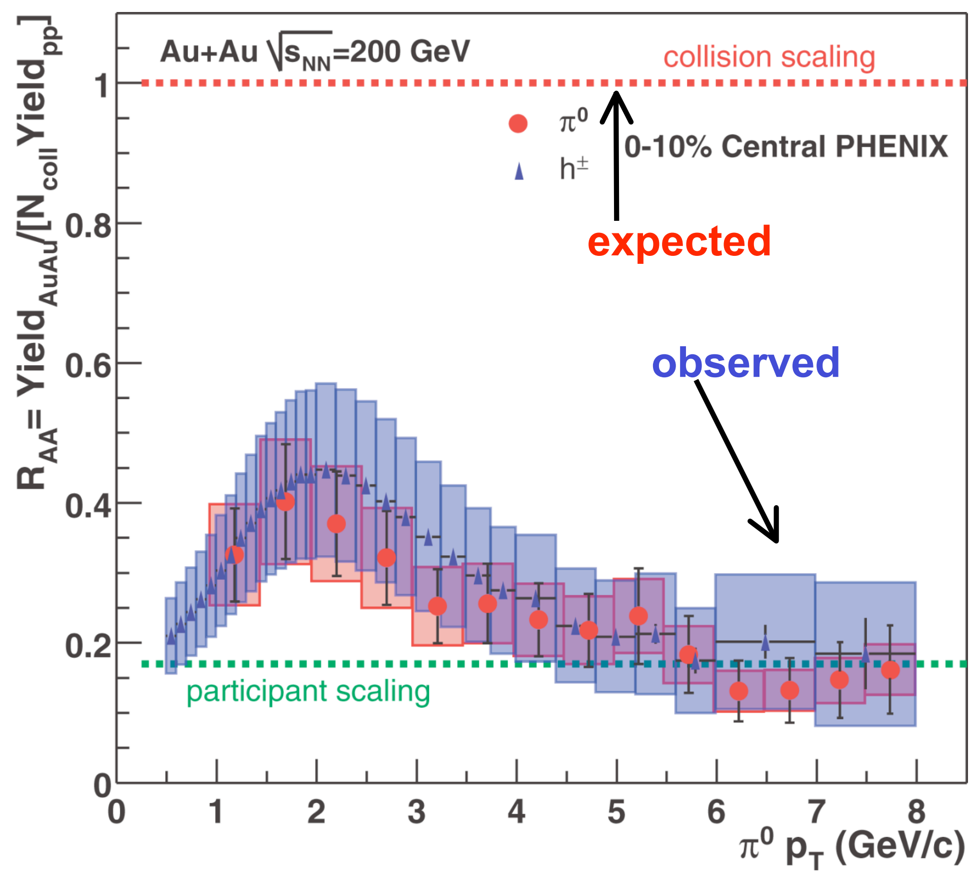




Poor man's jet: Leading Particles

"Jet Quenching" at High p_T





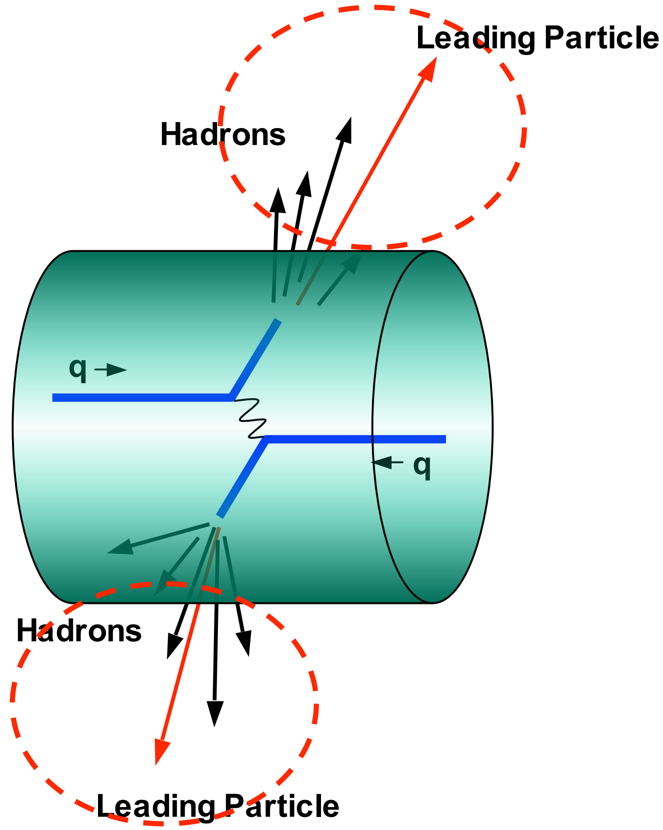
Yield at high p_T in AA is 6 times smaller than expected

Jets in Dense Matter

Are we really looking at jets?

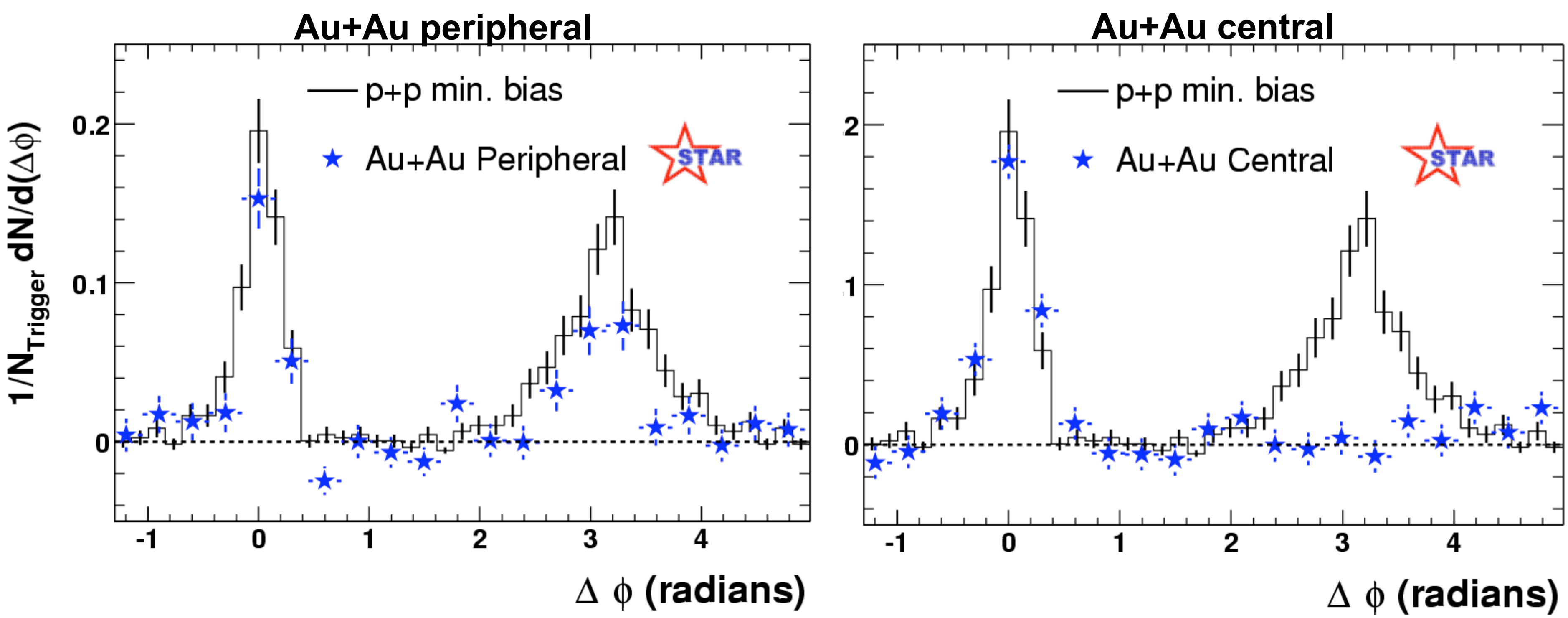
- Look for jet structure by measuring
  - Small angle correlations
  - Back-to-back correlations

  relative to high p_T leading particle



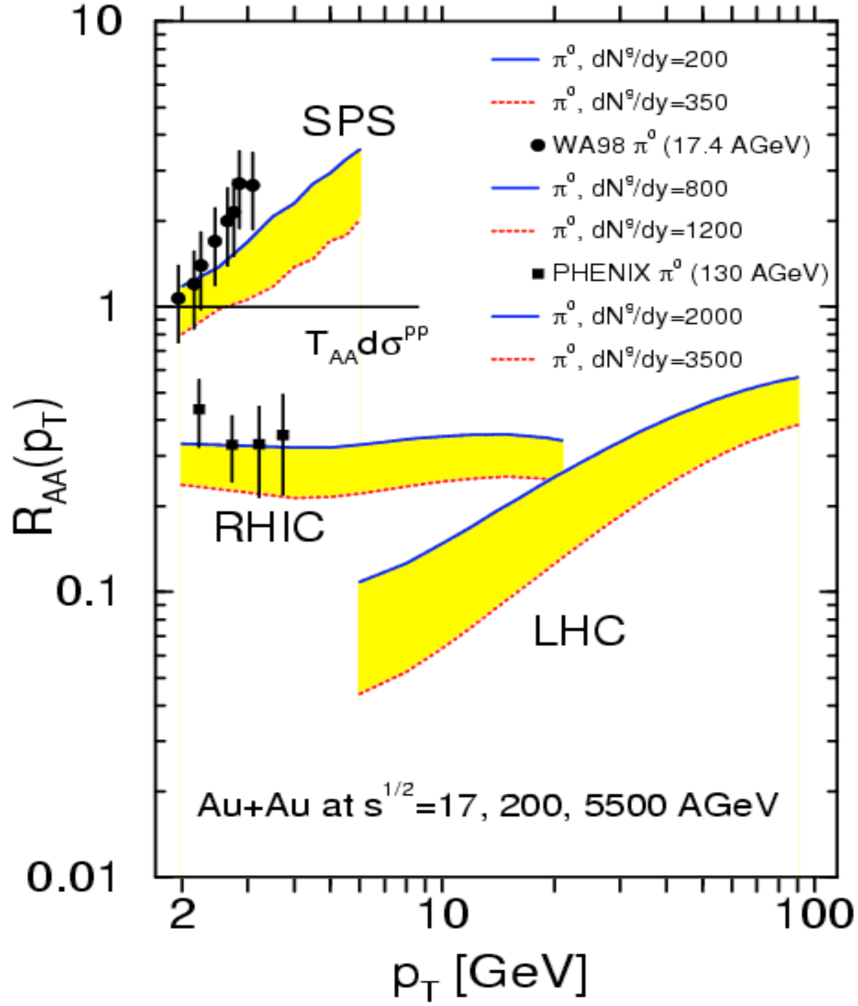
Jets in Au+Au data

PRL 90, 082302



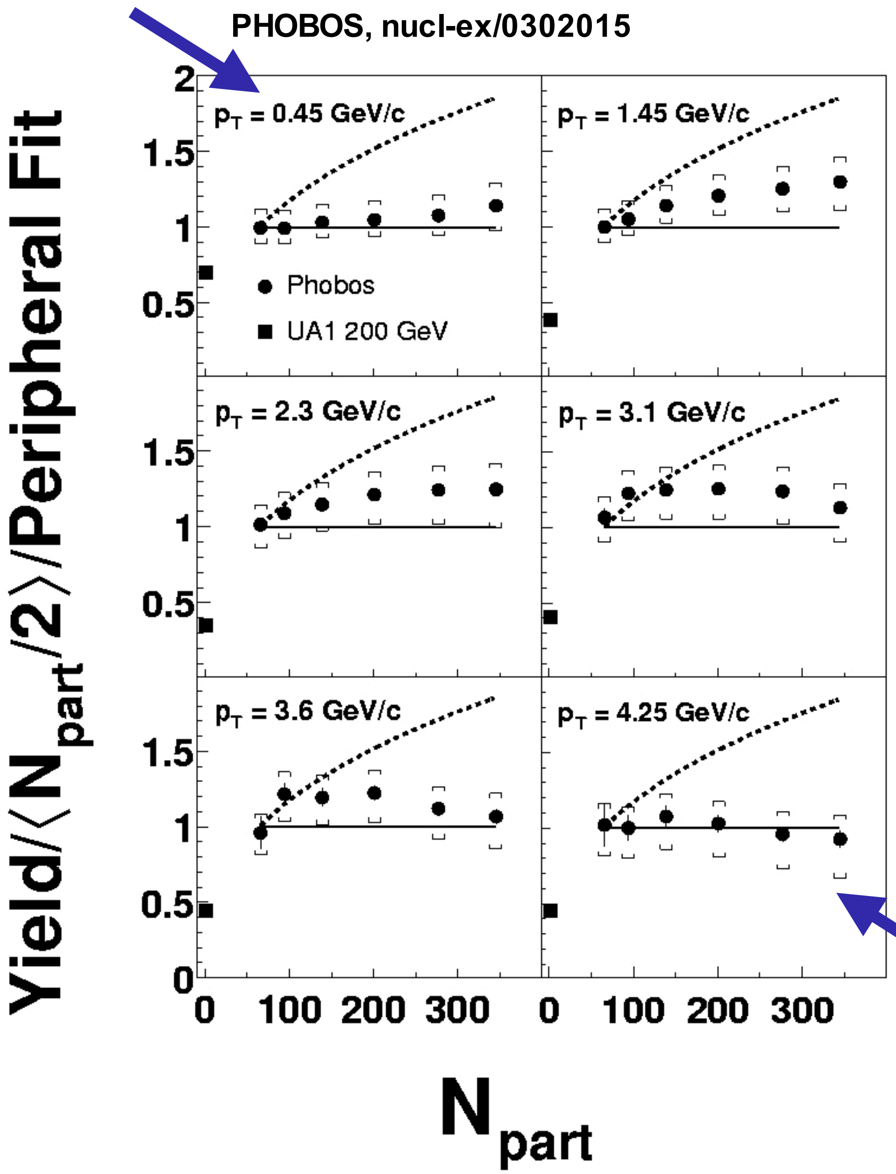
Jet suppression via Energy Loss

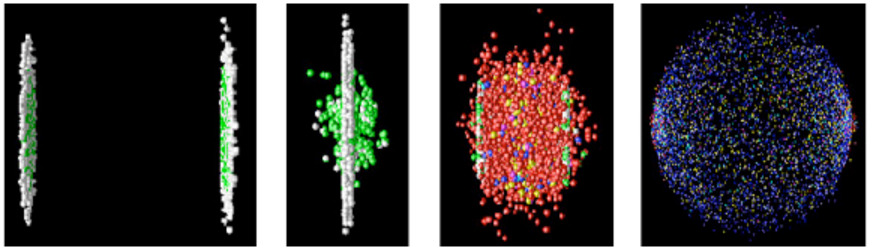
Vitev, Gyulassy, PRL 89 (2002)



Suppression due to the energy loss of fast partons in plasma via induced gluon radiation

Centrality Dependence vs p_T





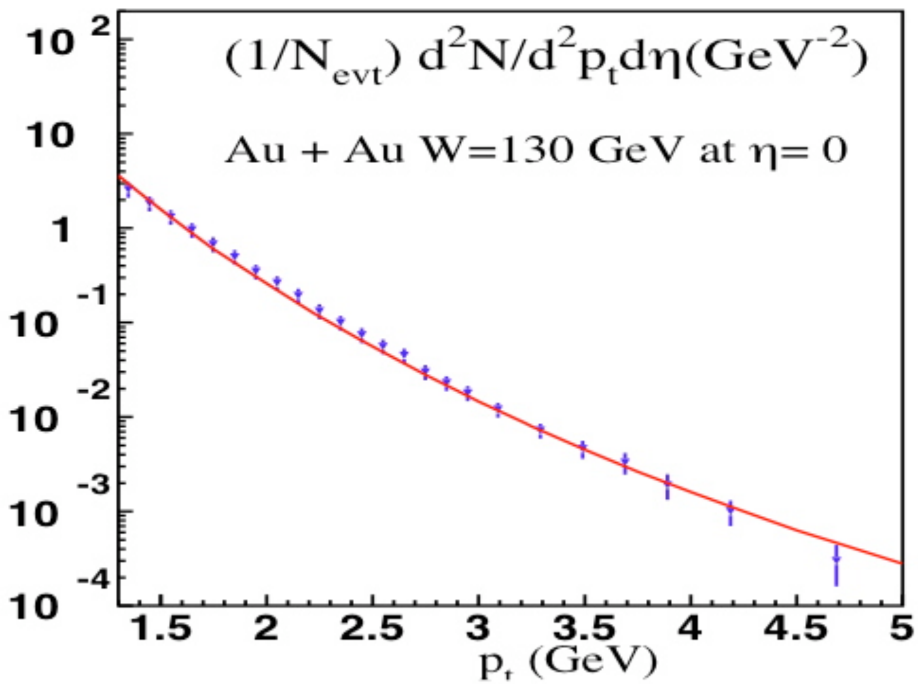
Initial State Coherence?

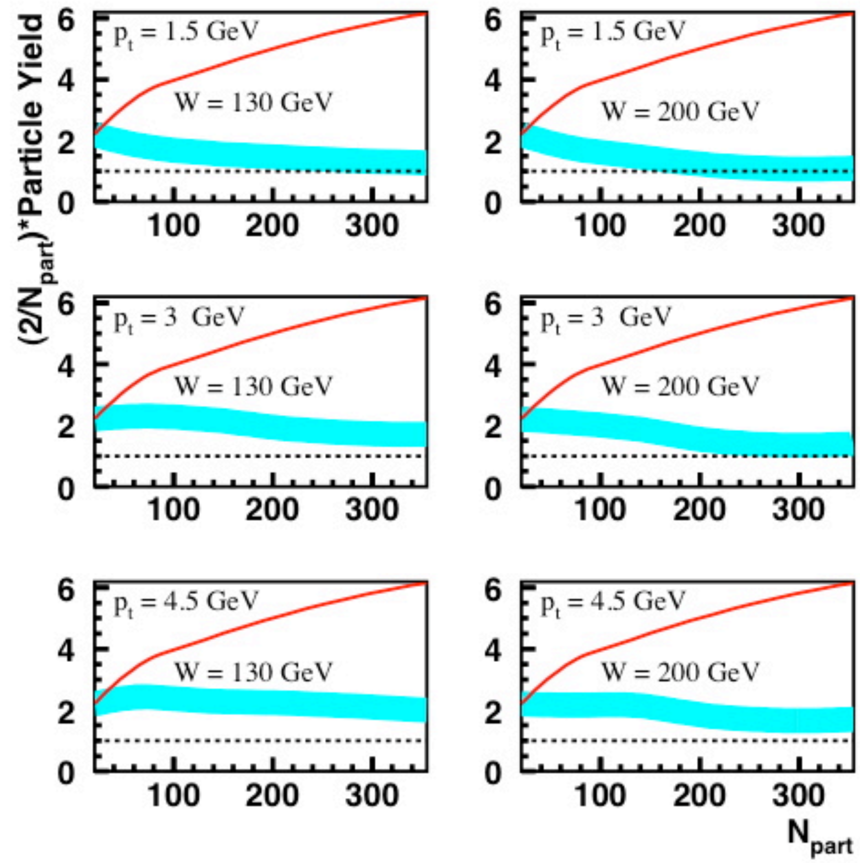
Interaction in Dense Medium?

Similar centrality dependence at p_T = 0.5 and 4 GeV/c !

N_{part} Scaling in Saturation Model

Kharzeev, Levin, McLerran, hep-ph/021332





High p_T suppression as an initial state effect:
Parton saturation breaks incoherence

Predictions for d+Au

Parton Saturation

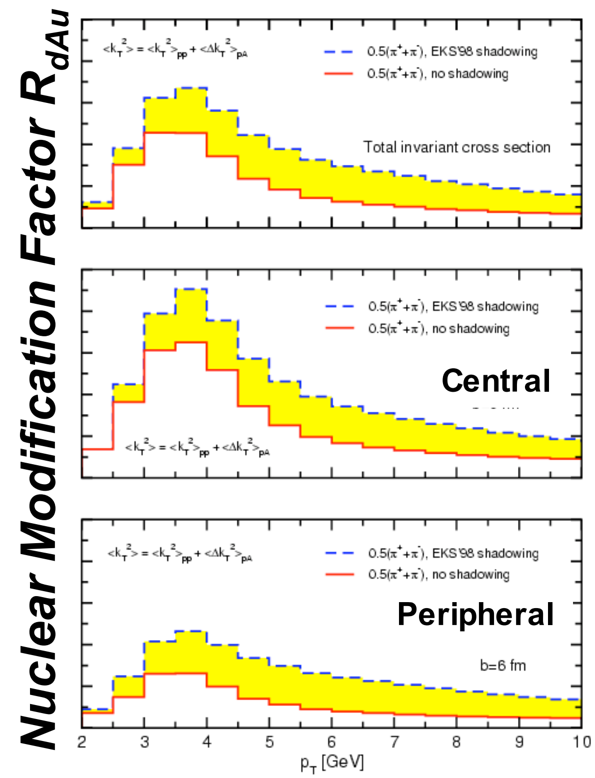
pQCD

Kharzeev, Levin, McLerran, hep-ph/021332

the number of collisions expected in perturbative QCD. We expect the saturation effects to set in around $N^{Au}_{part} \simeq 6$, corresponding to the impact parameter of dAu collision $b = 5 \div 6$ fm [53]. We thus predict that around $N^{Au}_{part} \simeq 6$ the yields of high p_t particles would begin to deviate from the scaling with the number of collisions $N_{coll} \sim N^{Au}_{part}$; the yield per participant will start to decrease as $(N^{Au}_{part})^{-1/2}$. In 15% most central dAu events, where $N^{Au}_{part} \simeq 12$ [53], we therefore expect to see the normalized yield of $(6/12)^{1/2} \simeq 0.7$, corresponding to $\simeq$ 30% suppression of high p_t particles†. The scaling of semi–hard processes in dAu collisions with centrality at

"~30%suppression of high p_T particles"
(central vs peripheral)

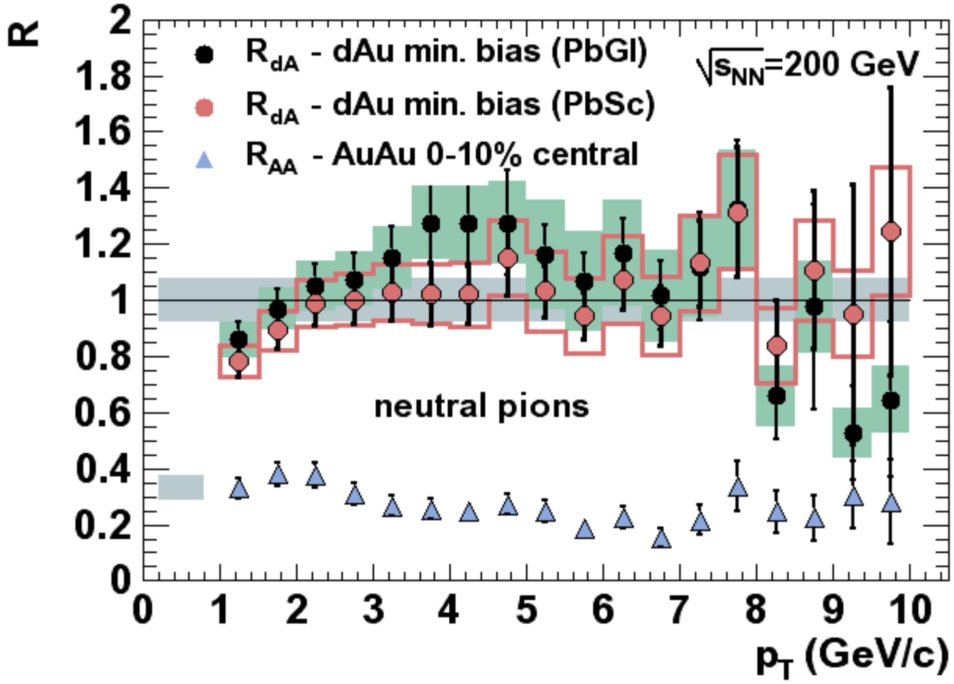
Vitev, nucl-th/0302002, Phys.Lett.B in press
Vitev and M.Gyulassy, Phys.Rev.Lett. 89 (2002)



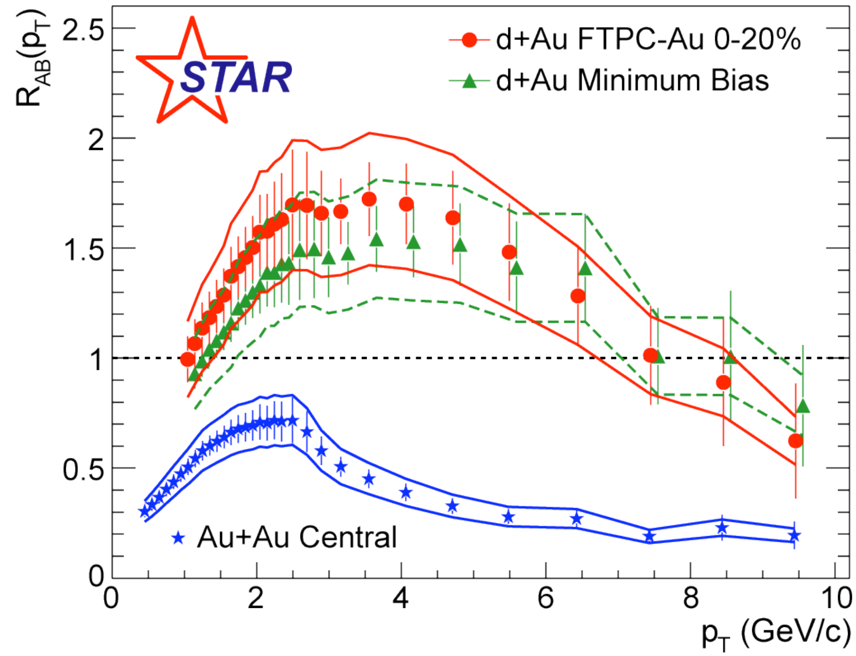
16% increase central vs peripheral

Results for d+Au

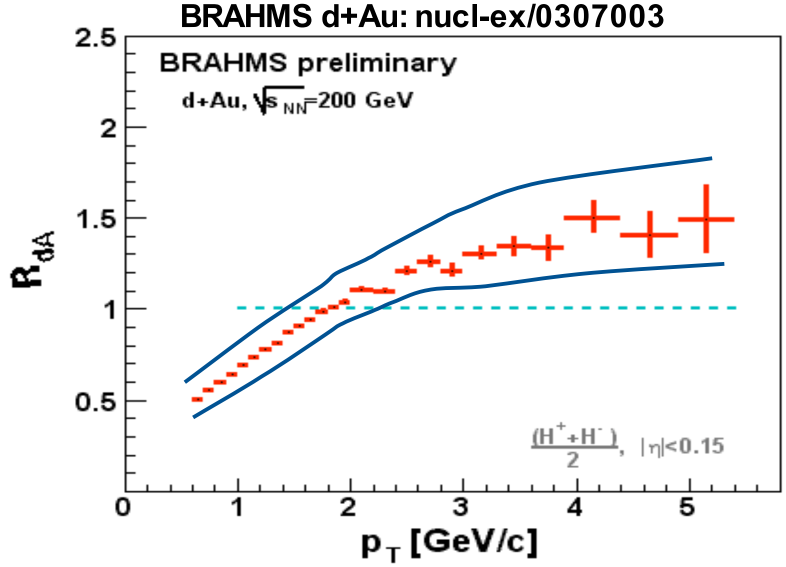
PHENIX d+Au: nucl-ex/0306021



STAR d+Au: nucl-ex/0306024



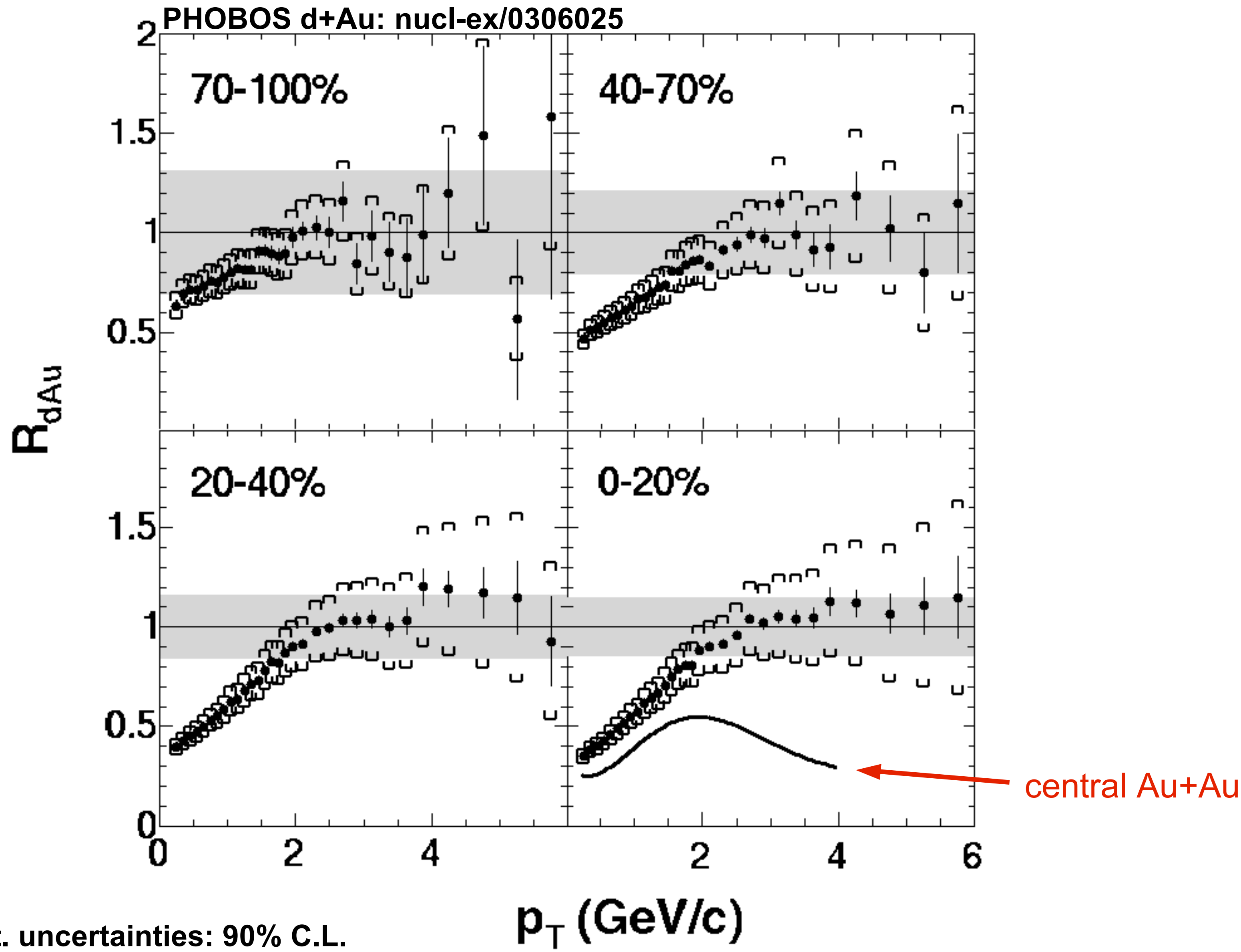
BRAHMS d+Au: nucl-ex/0307003



Min-bias d+Au data (relative to p+p * N_{coll})

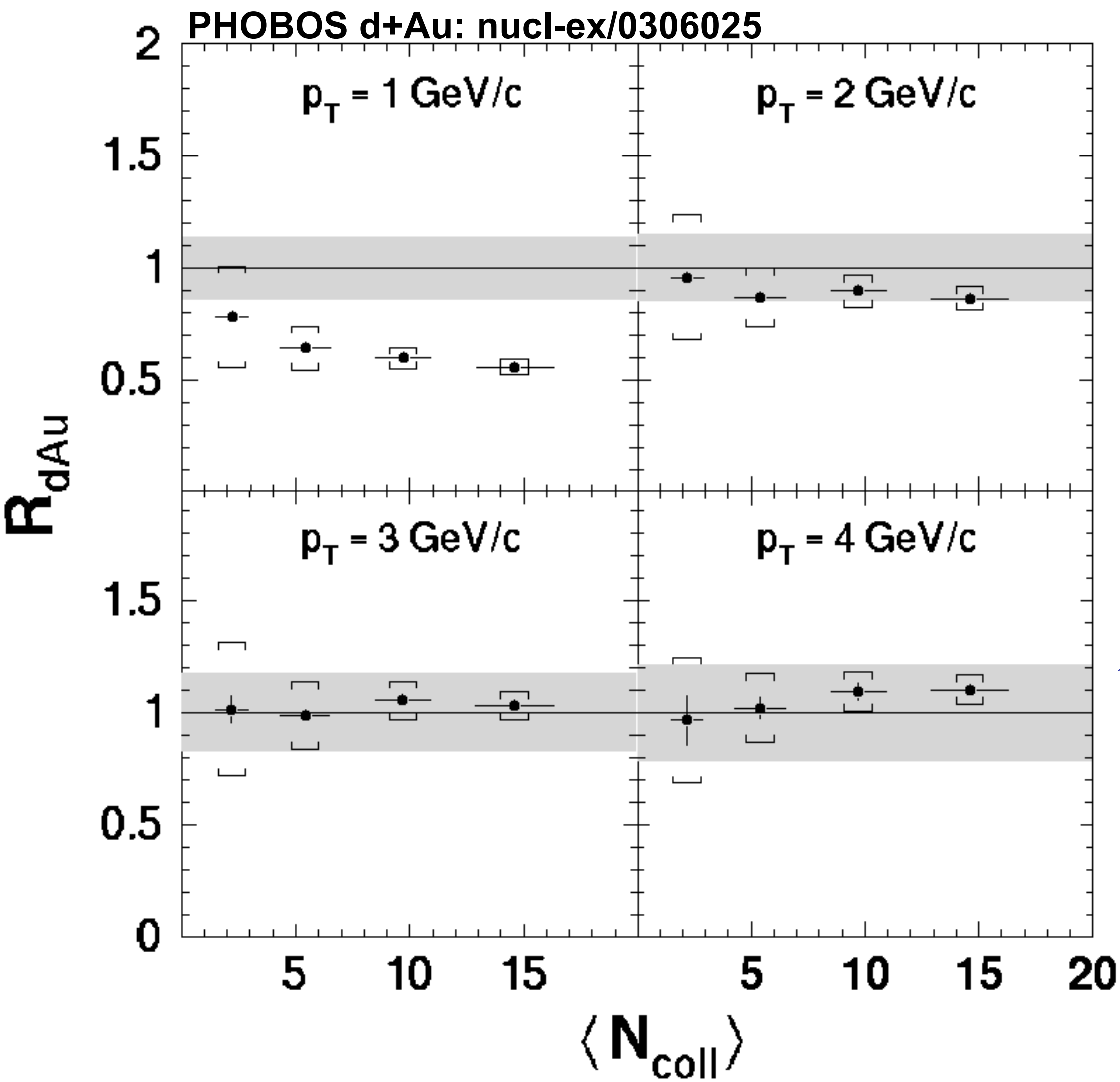
- Similar to low-energy data (Cronin effect)
- No suppression

R_{dAu} vs p_T



All syst. uncertainties: 90% C.L.

Centrality dependence of R_{dAu}

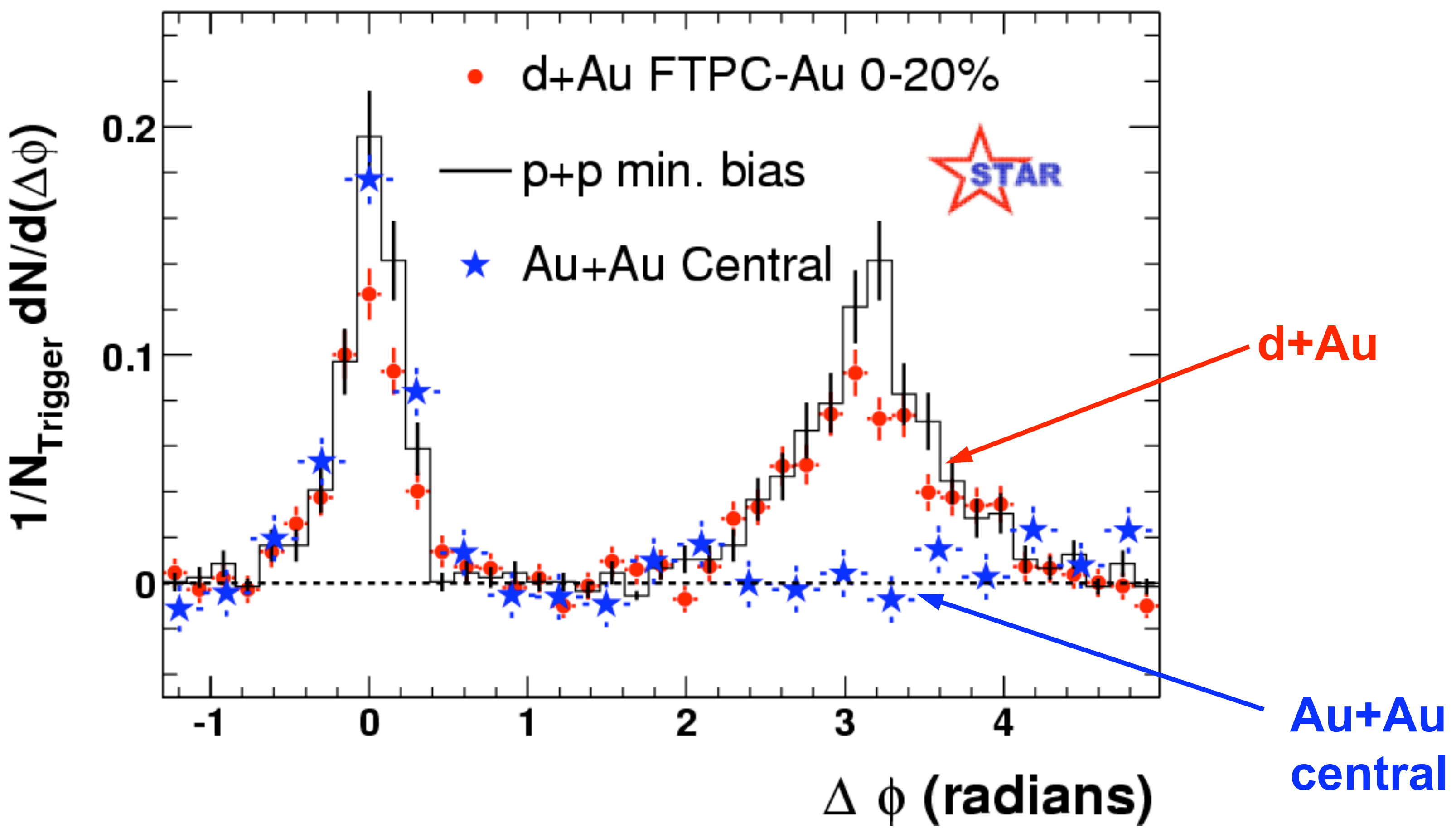


Data disfavor initial state interpretation of Au+Au high-p_T suppression

N.B. Smaller s_{pp}^{inel} would increase R_{dAu} central vs R_{dAu} peripheral

All syst. uncertainties: 90% C.L.

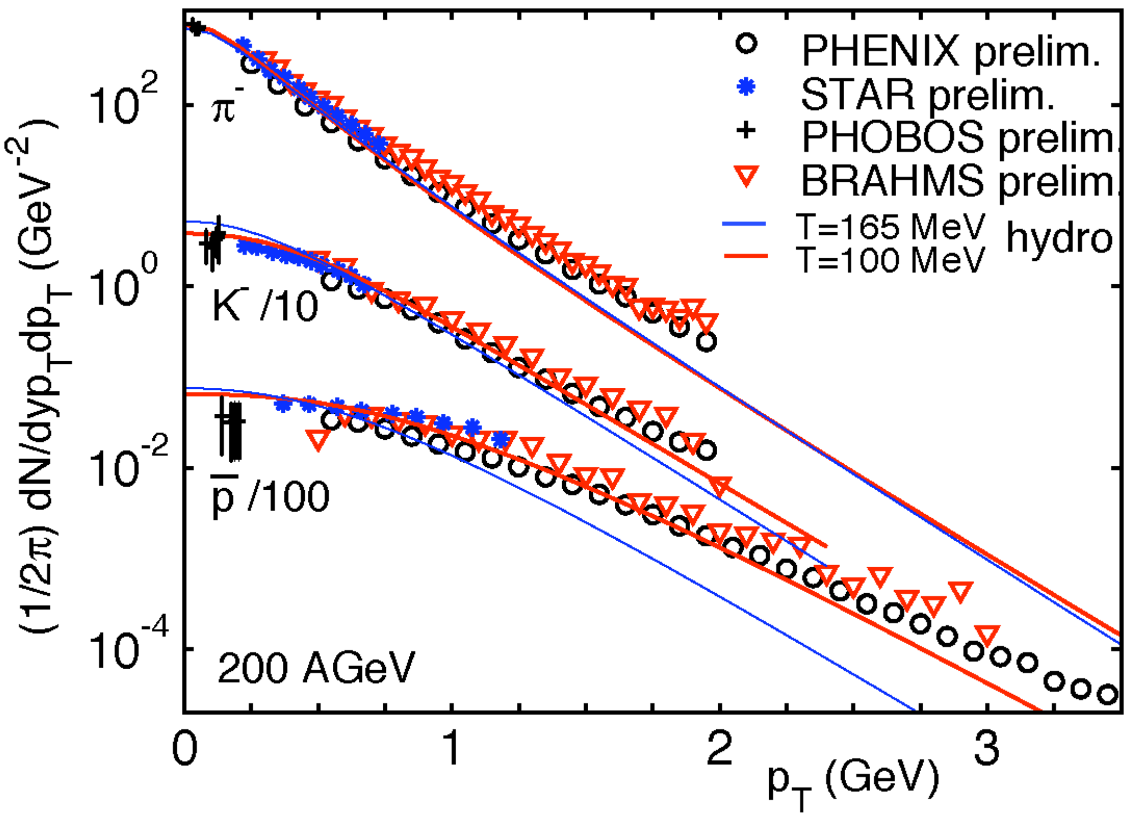
Back-to-back ‘Jets’ in d+Au



Properties of the Dense Matter

Hydrodynamics and Spectra

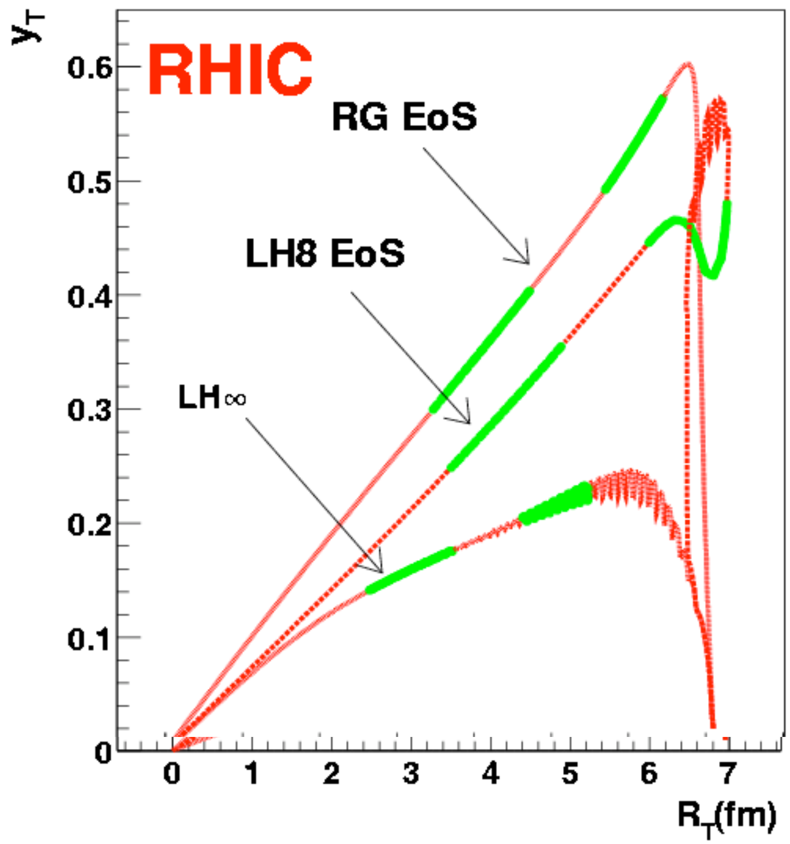
Kolb, Rapp, Phys. Rev. C 67 (03) 044903



Parameters:
τ_0 = 0.6 fm/c
s_0 = 110 fm^{-3}
s_0/n_0 = 250
$T_{crit}=T_{chem}$=165 MeV
T_{dec}=100 MeV

Transverse Expansion

Teaney, Lauret & Shuryak, nucl-th/0110037

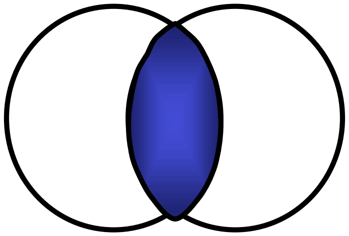


from Mike Lisa, CIPANP'03

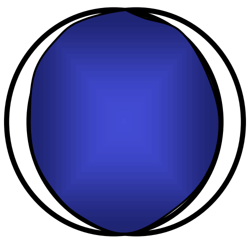
Azimuthal Anisotropy

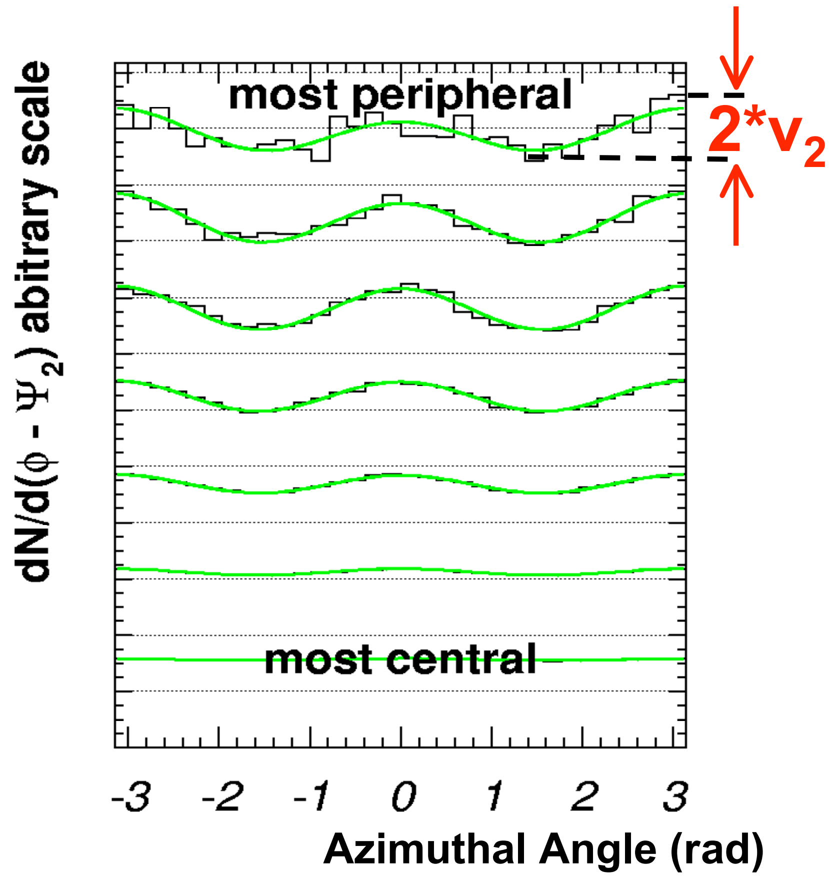
"Head on" view of colliding nuclei

Peripheral



Central



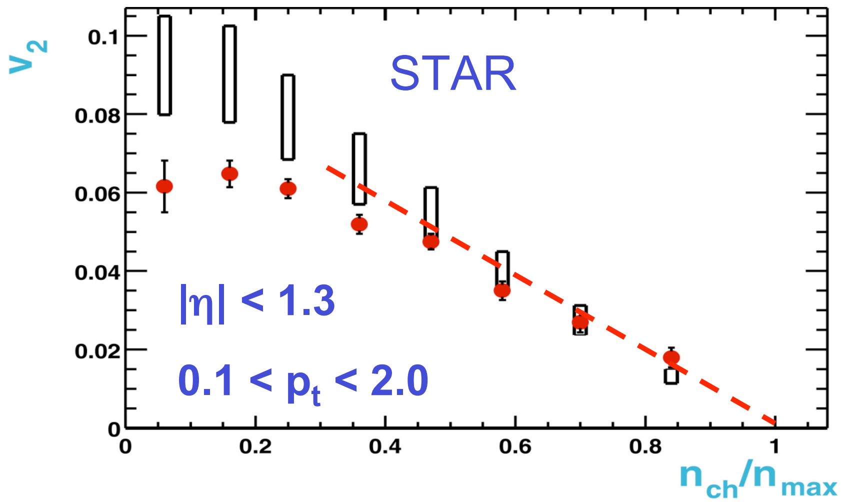


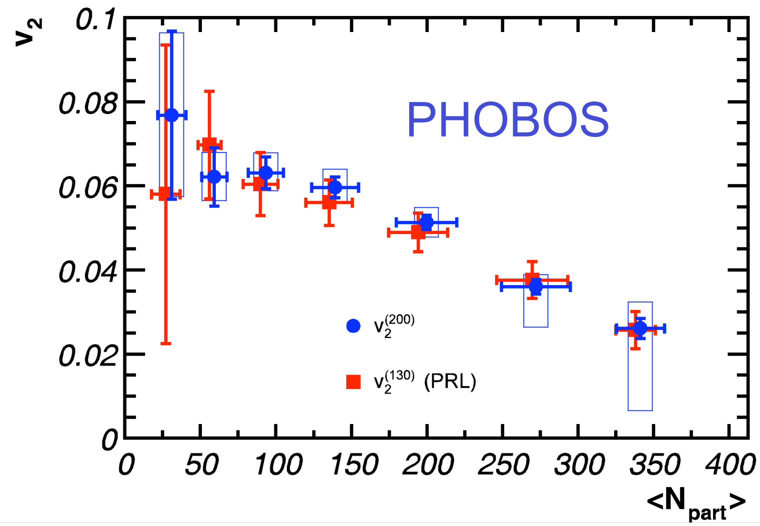
Interaction!

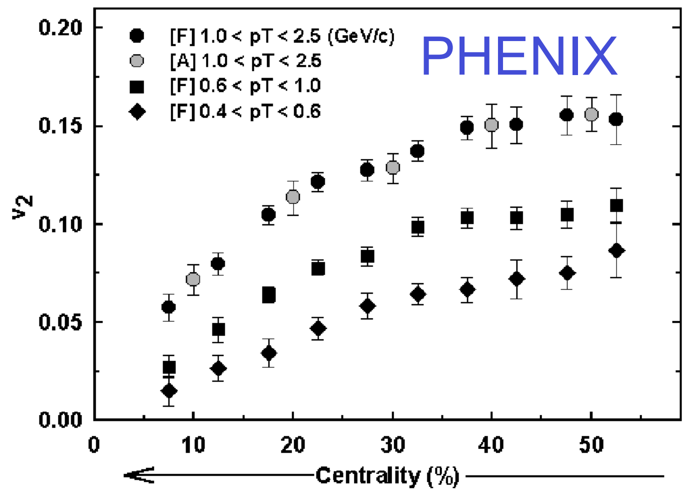
Initial State Anisotropy
Coordinate Space

Final State Anisotropy
Momentum Space

Anisotropy v_2 vs Centrality



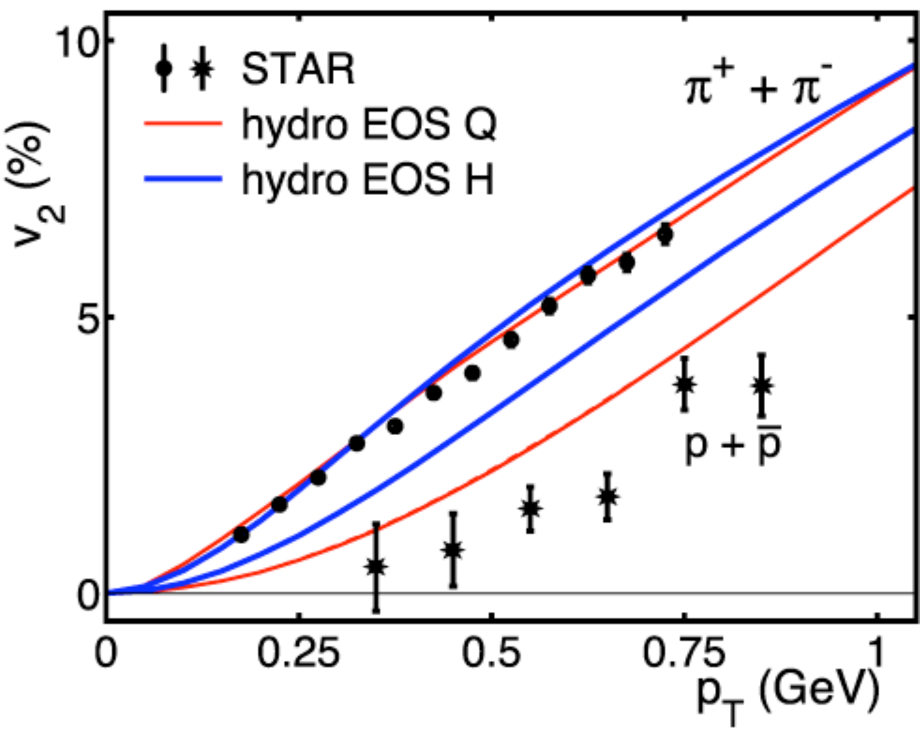




Up to mid-central collisions, v_2 reaches hydro limit

Hydrodynamics and v_2

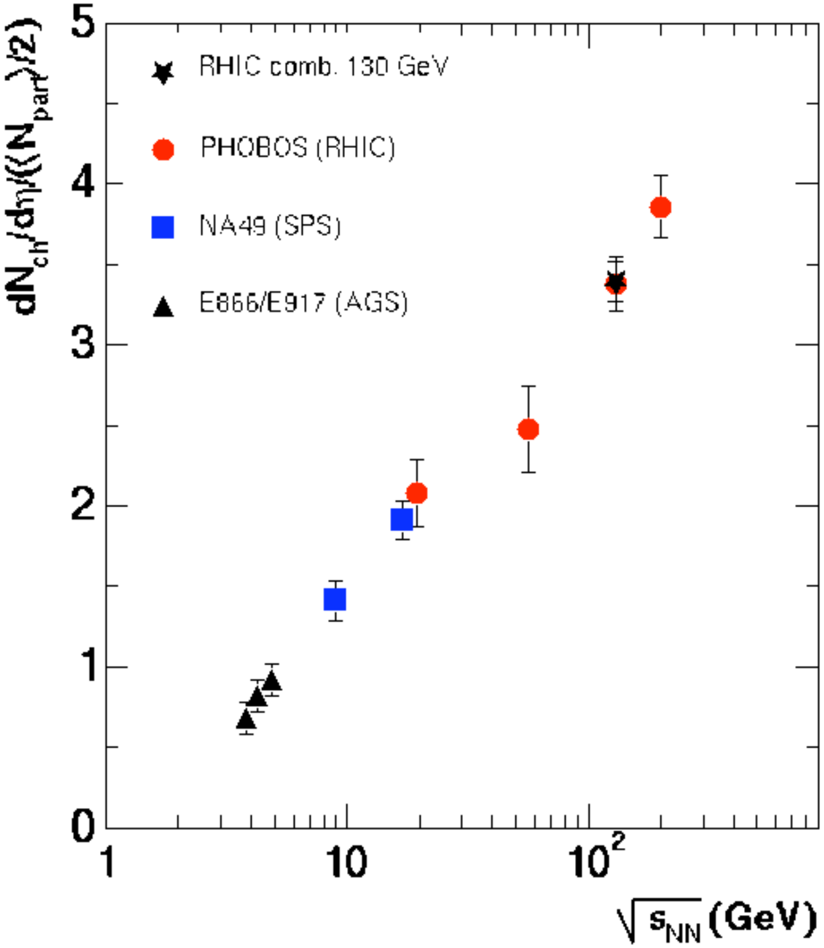
Kolb, Heinz, nucl-ex/0204061

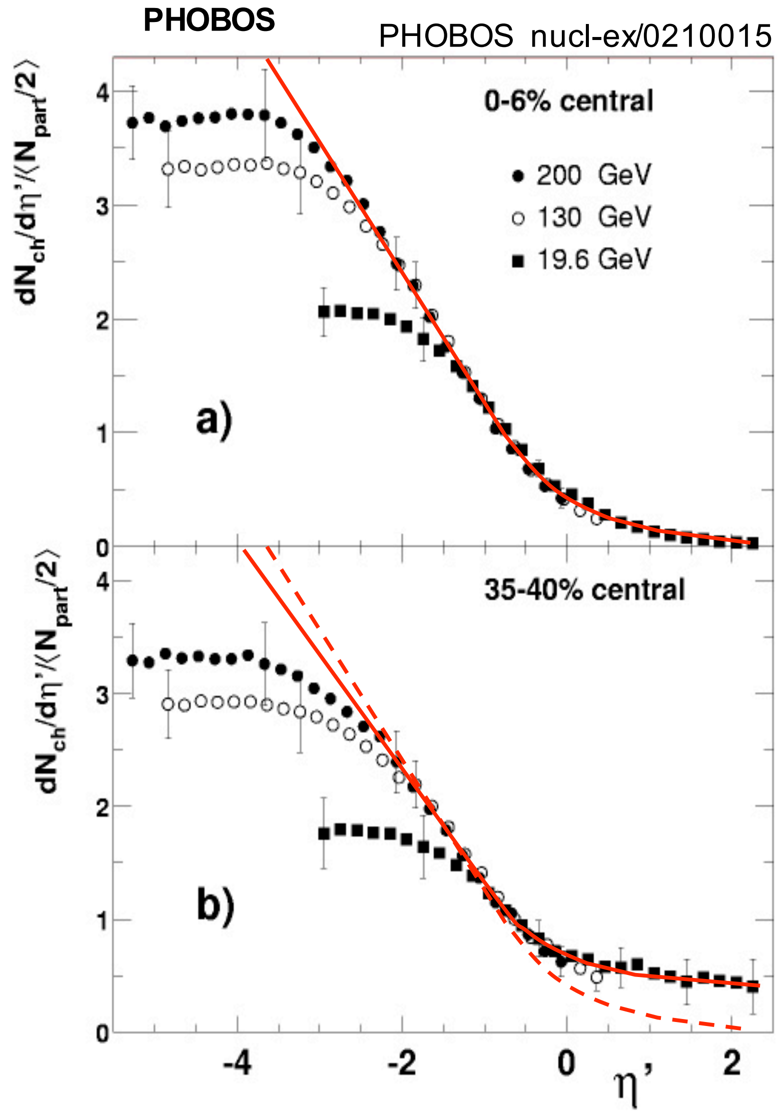


- Data consistent with hydro calculations
- Sensitivity to EoS

New New Form of Matter
vs
Old New Form of Matter

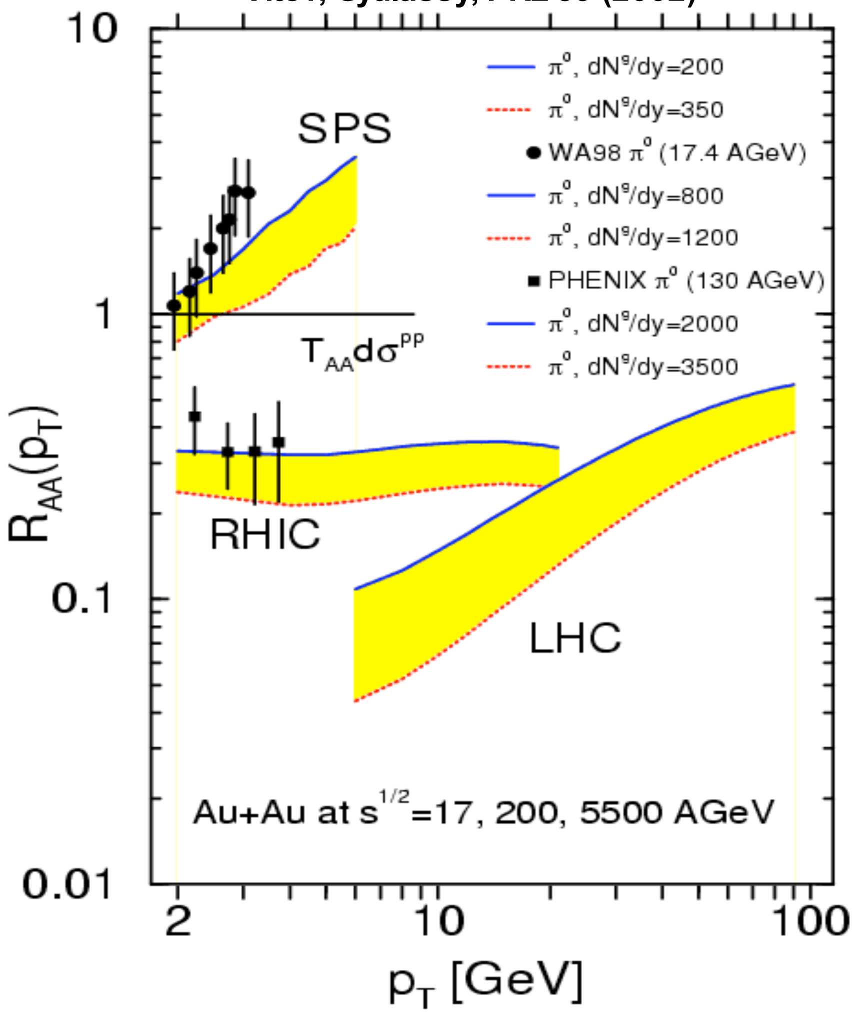
Particle density near midrapidity





Jet suppression via Energy Loss

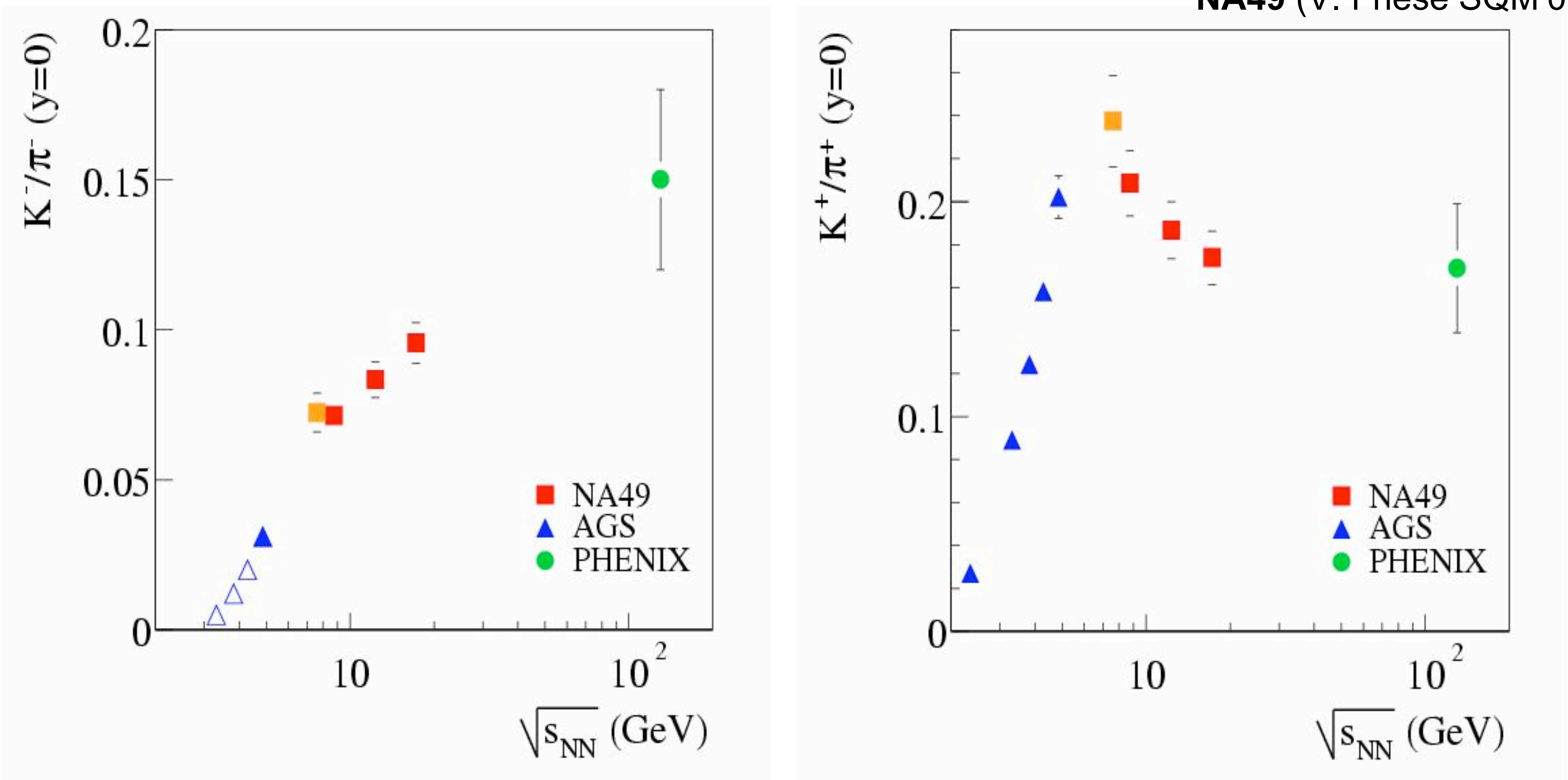
Vitev, Gyulassy, PRL 89 (2002)



Suppression due to the energy loss of fast partons in plasma via induced gluon radiation

Mid-Rapidity K/π

NA49 (V. Friese SQM'03)



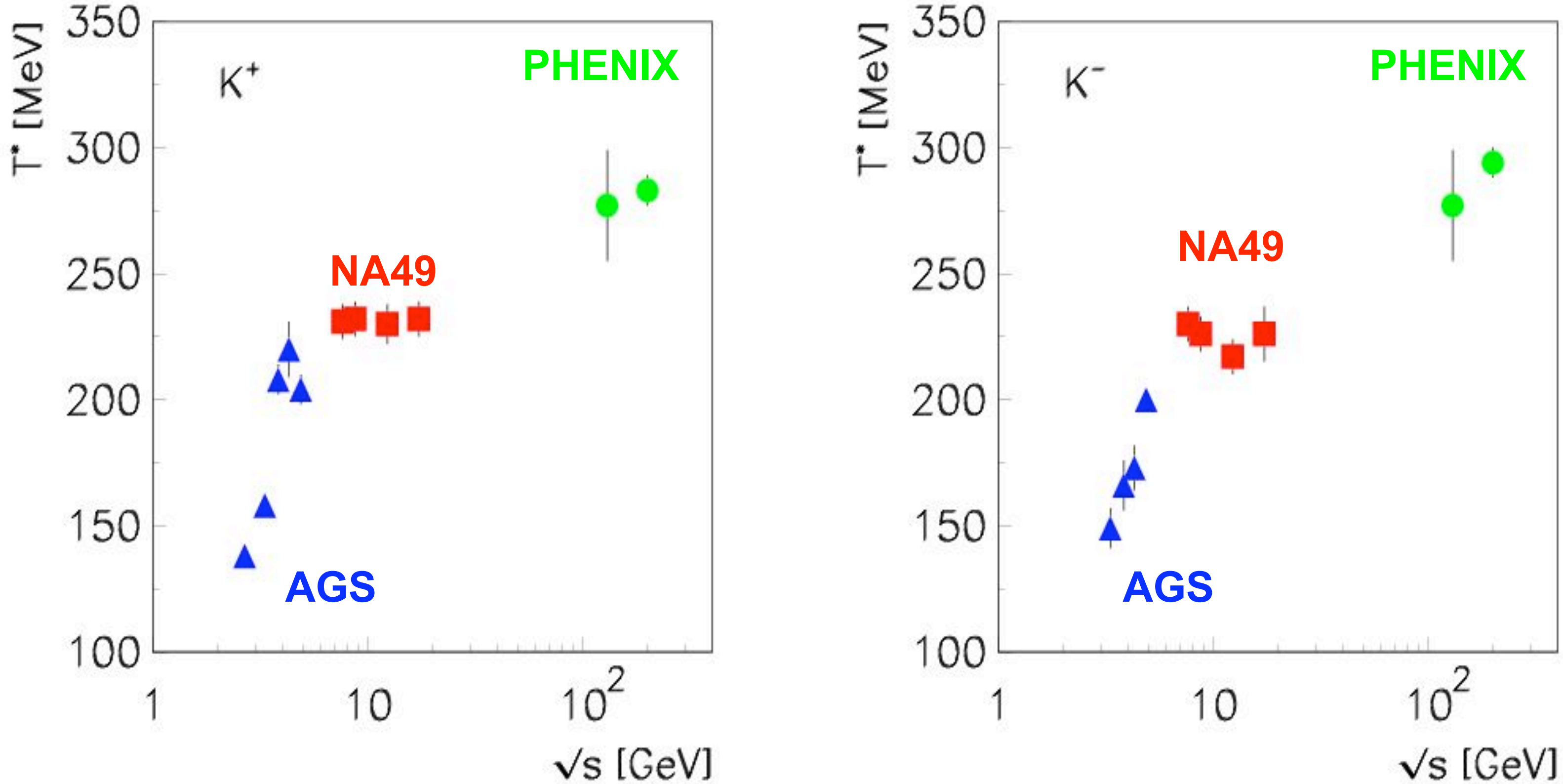
Non-monotonic Evolution!

Oeschler, PBM, Redlich: **Thresholds vs Baryo-chemical potential**

Too kinky!

Kaon Slope Parameters

NA49 (V. Friese SQM'03)



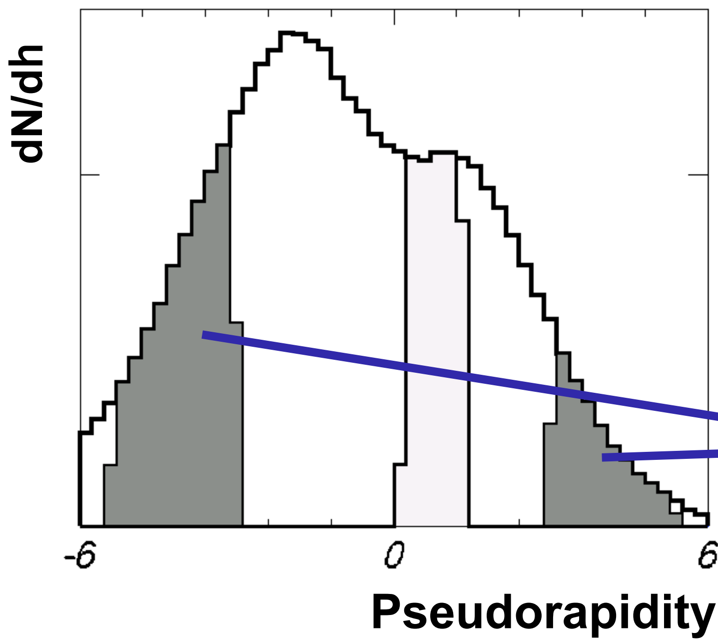
Summary

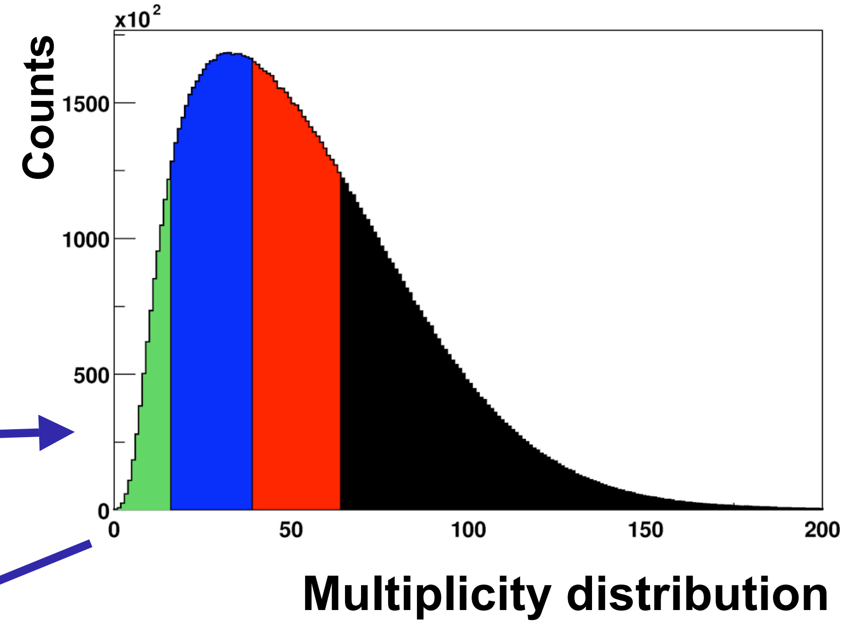
- Extensive and Consistent Data Set
  - BRAHMS, PHENIX, PHOBOS, STAR
  - AGS, SPS, RHIC
- Multiplicity, Parton Energy Loss, Elliptic Flow
  - Hot and Dense Matter
  - 50-100x normal nuclear matter density
  - Opaque to fast partons
  - Small mean free path
- Challenge: *Consistent Dynamical Scenario*
  - Energy Dependence
  - Soft vs Hard particle Production

Back-up Material

Centrality Determination in d+Au

HIJING Simulation



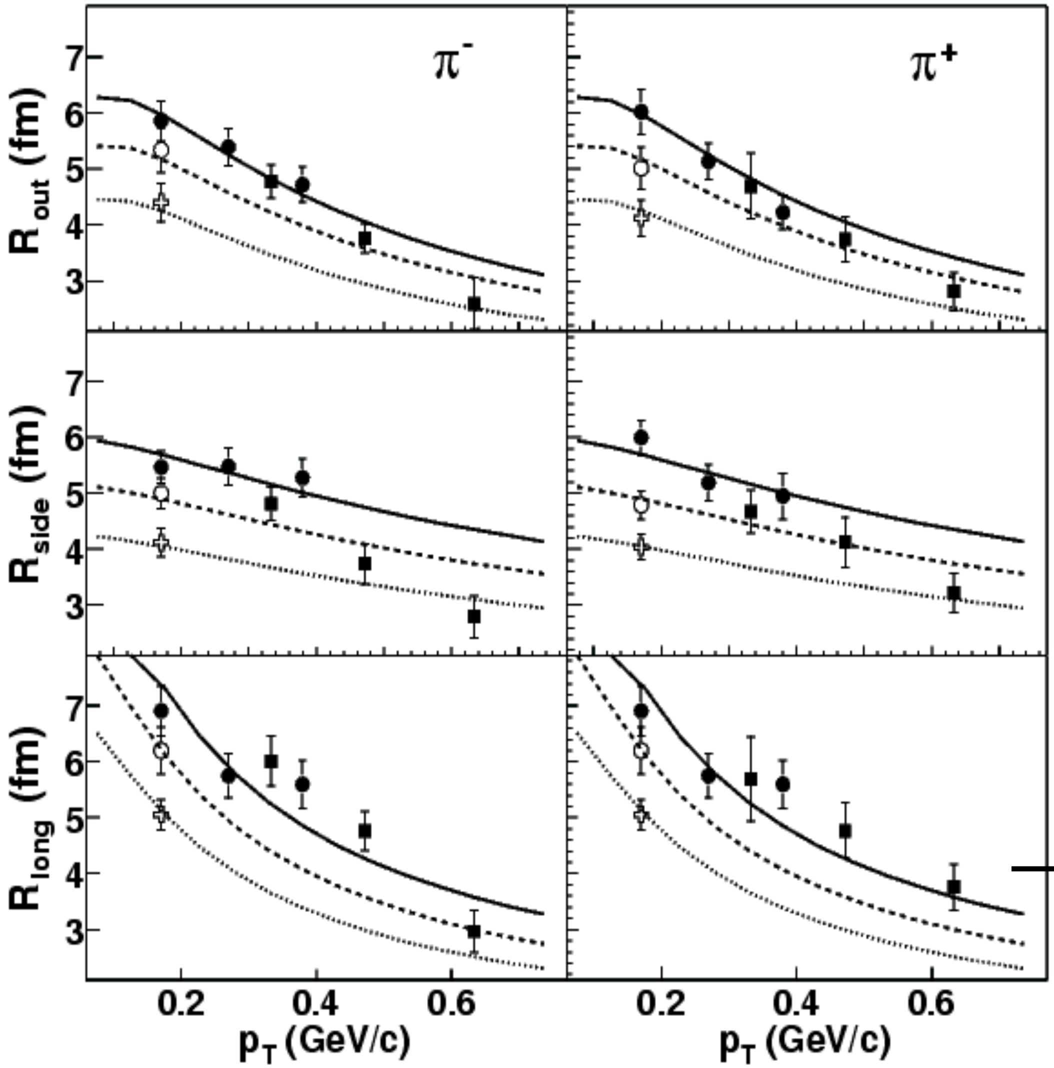


Glauber Calculation

- Hijing 1.383
  - Hulthen w.f.
  - 41mb inelastic cross-section
- Full GEANT Simulation

Centrality Selection	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$	Efficiency
0–20%	15.5 ± 1.0	14.6 ± 0.9	82%
20–40%	10.9 ± 0.9	9.7 ± 0.8	73%
40–70%	6.7 ± 0.9	5.4 ± 0.8	49%
70–100%	3.3 ± 0.7	2.2 ± 0.6	14%

Blast Wave & Bose-Einstein Correlations



Particle Emisson over few fm/c

Lifetime ~ 10 fm/c

Fabrice Retiere SQM '03, Mike Lisa