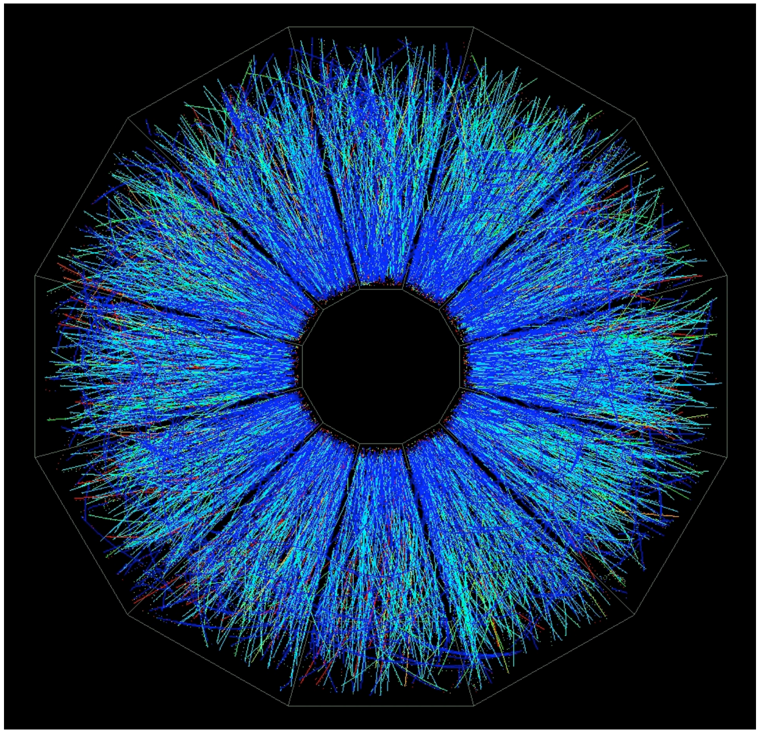
Physics Results from RHIC

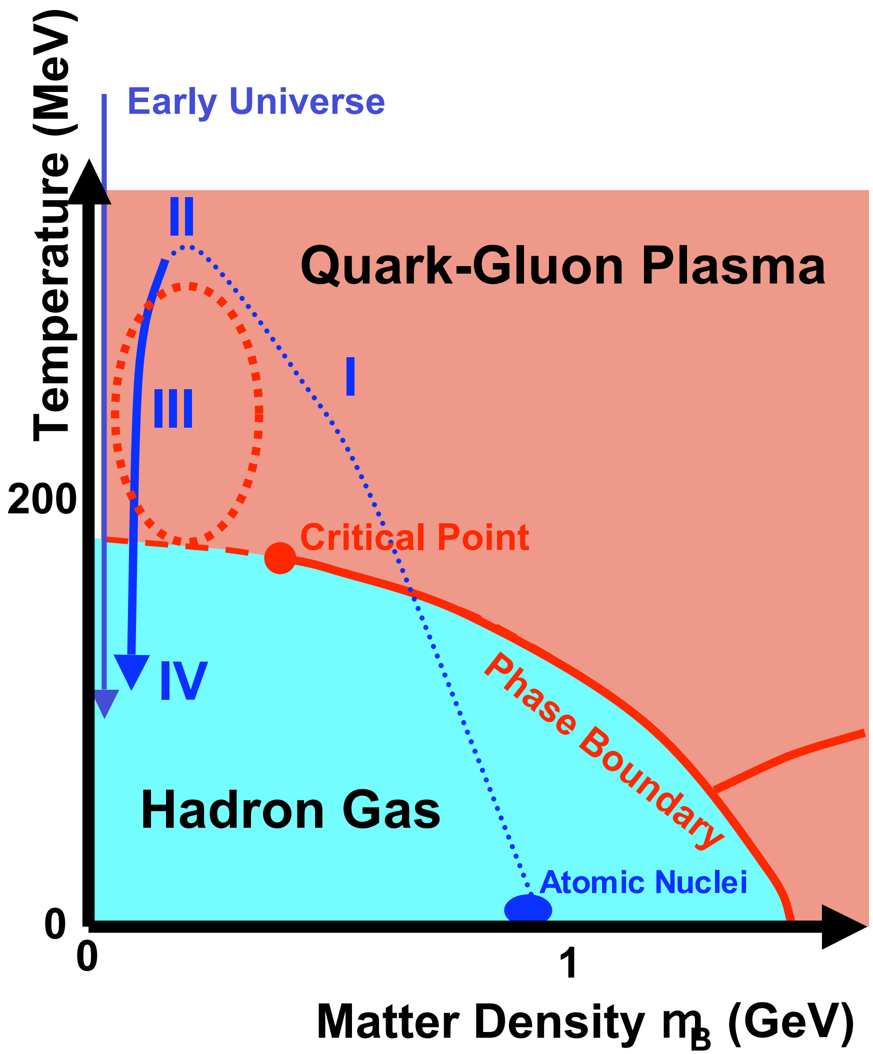


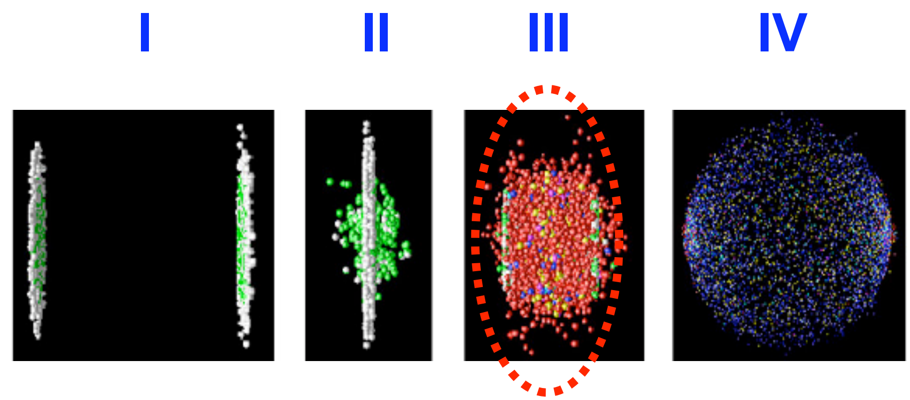
Gunther Roland

XLIII Cracow School of Theoretical Physics

Zakopane 5/30-6/7 2003

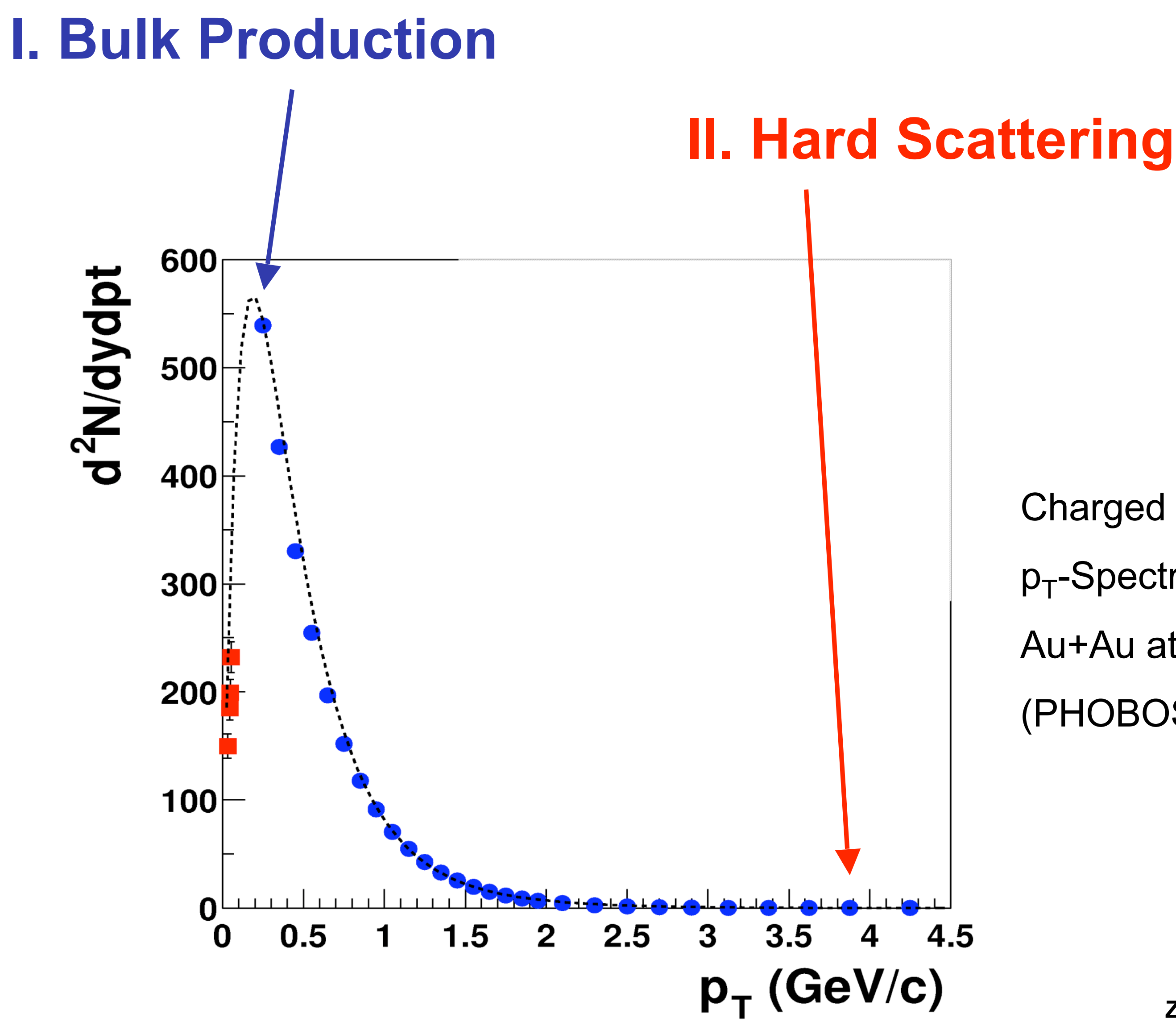
Exploring QCD with Heavy Ions





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

Two Lectures

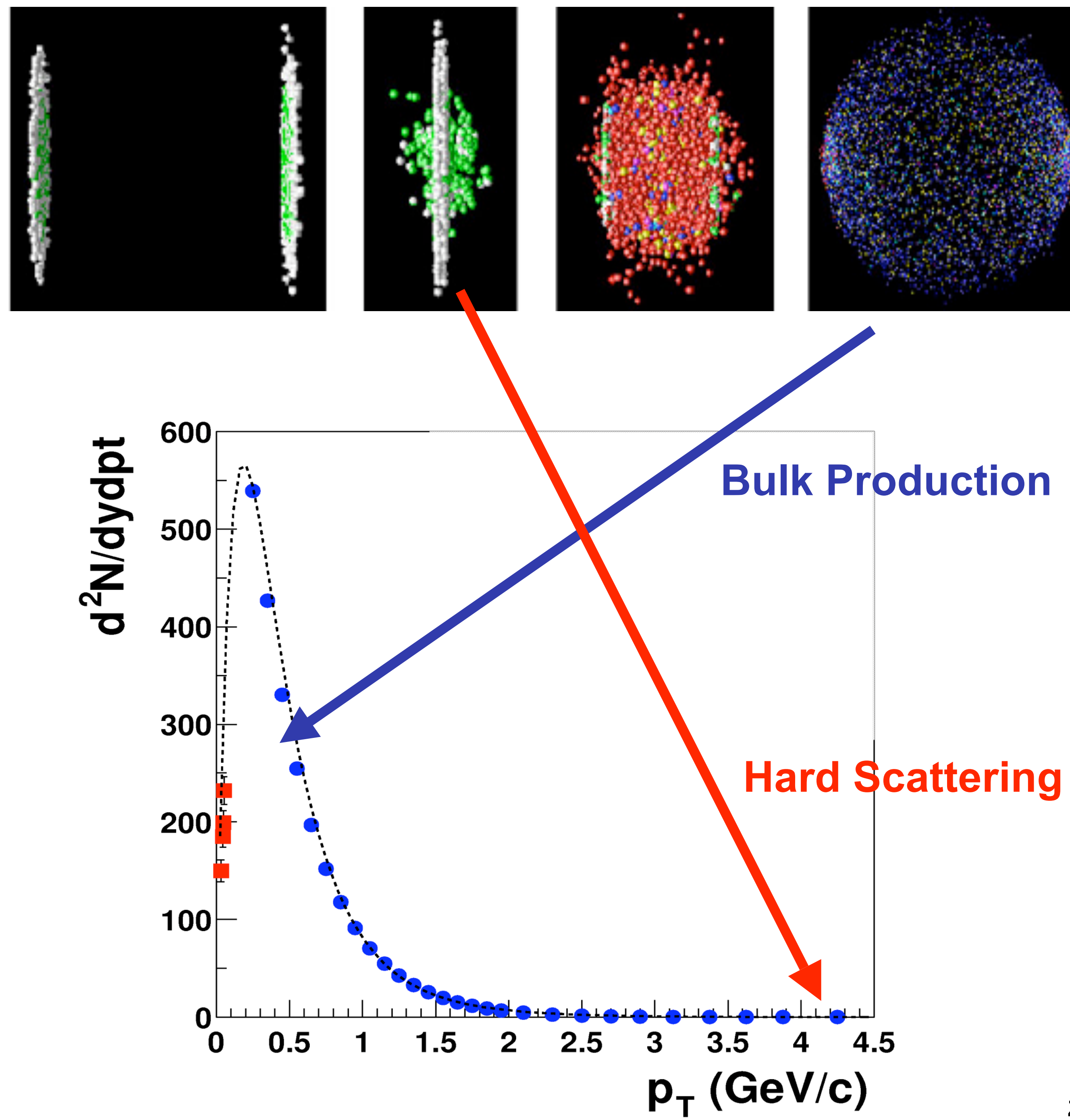


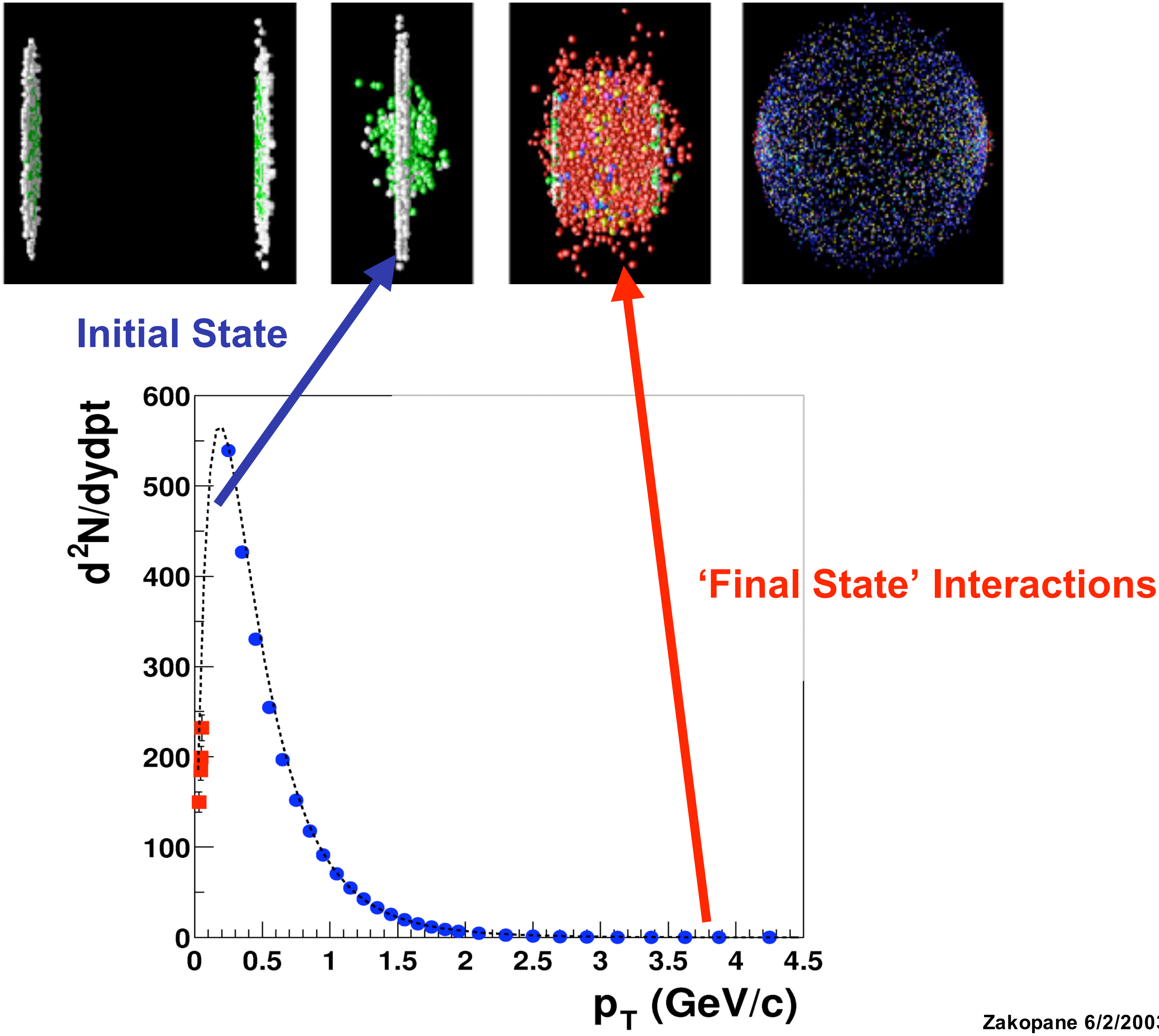
Charged Hadron

p_T-Spectrum in

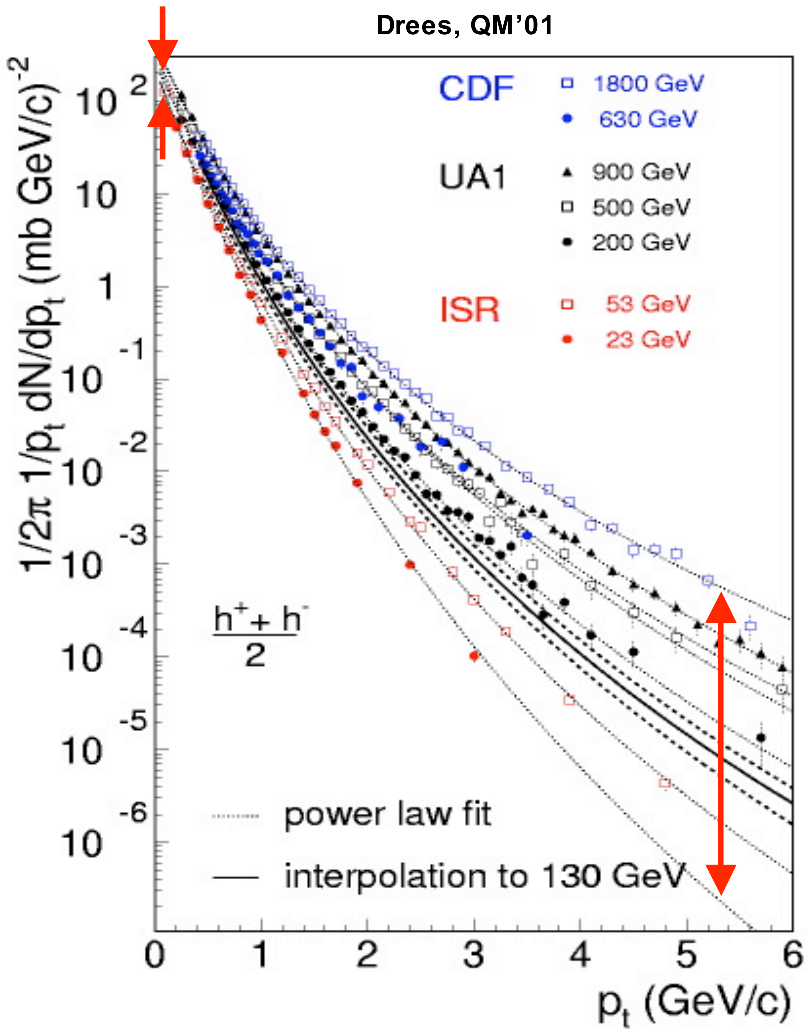
Au+Au at RHIC

(PHOBOS)


Bulk Production
Hard Scattering
d²N/dydpt
600
500
400
300
200
100
0
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5
p_T (GeV/c)

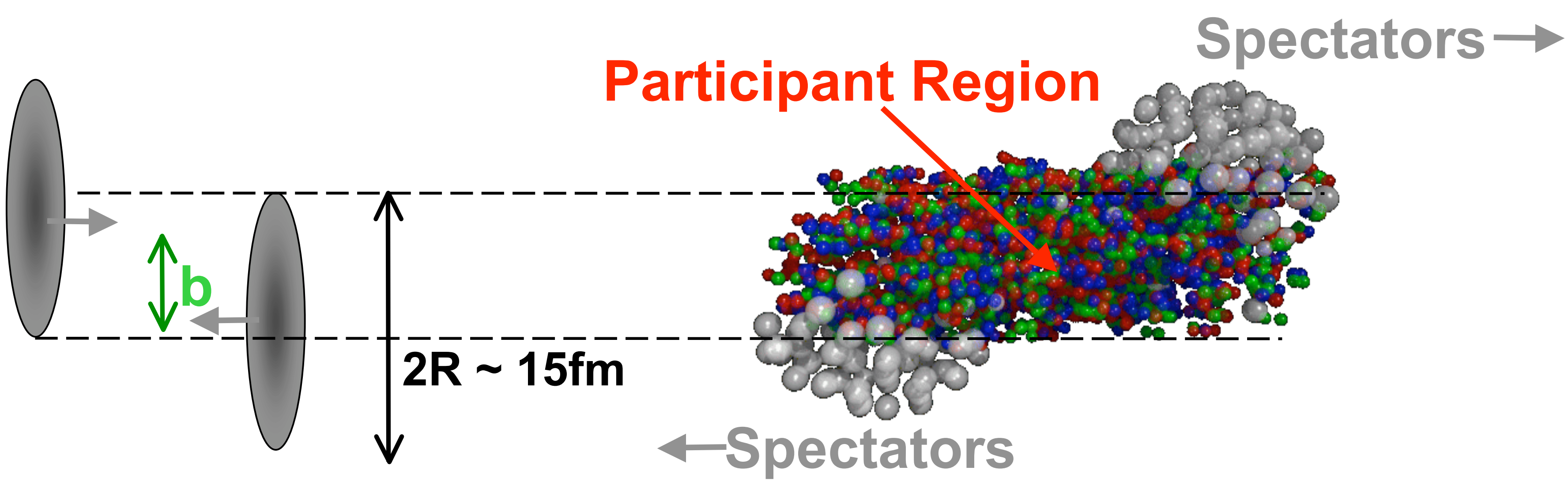

Initial State
'Final State' Interactions
600
500
400
300
200
100
0
d²N/dydpt
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
p_T (GeV/c)

Control Parameters: sqrt(s)



Different sqrt(s) dependence of 'soft' vs 'hard' processes

Control Parameters: Centrality



Smaller Impact Parameter b

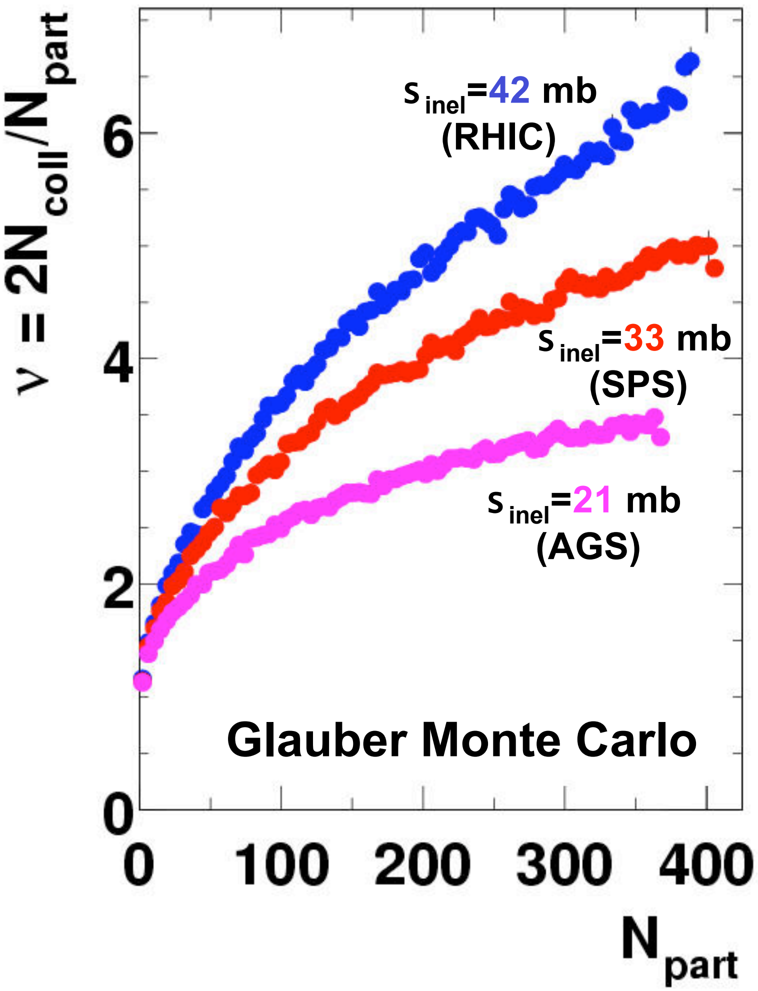
⬍

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

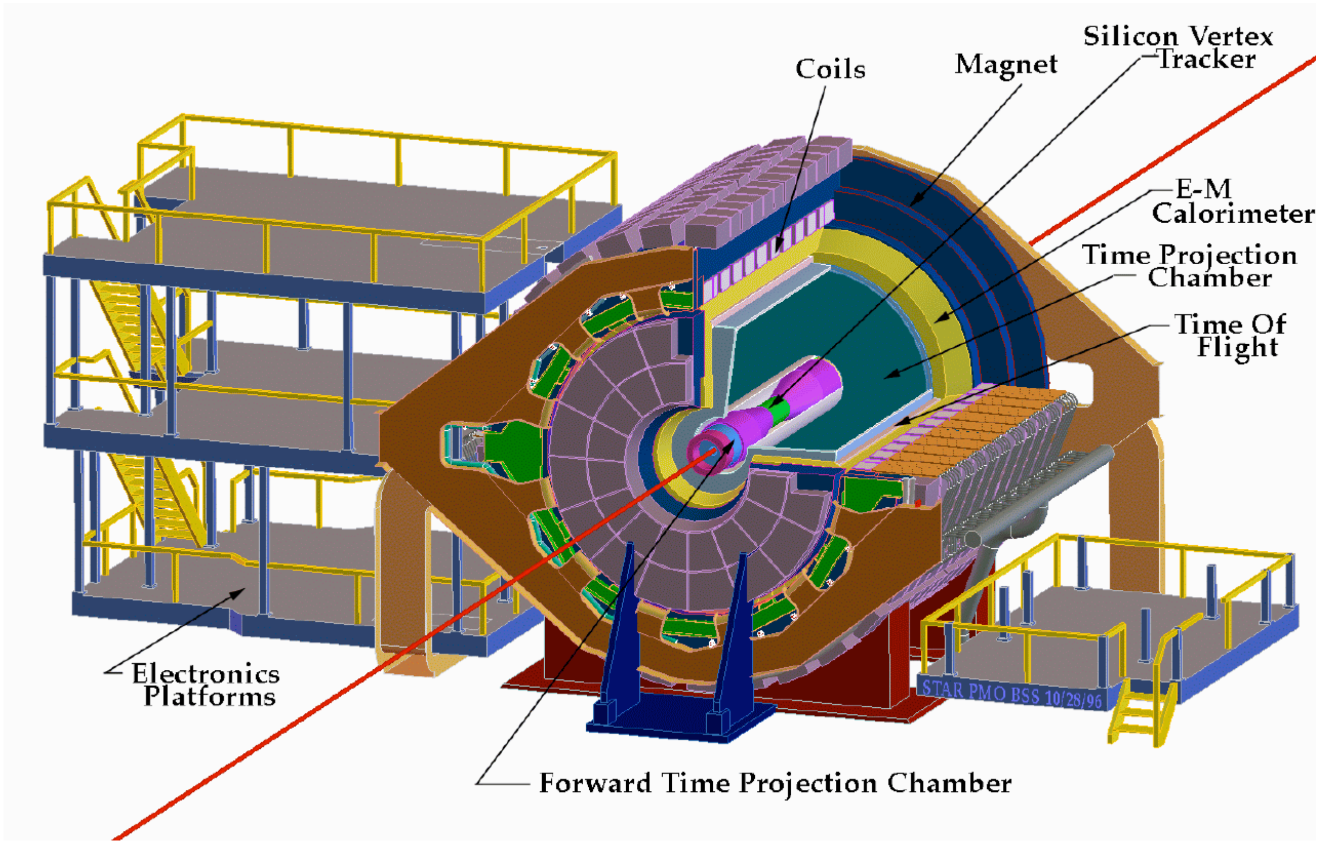
First Physics in ‘00

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

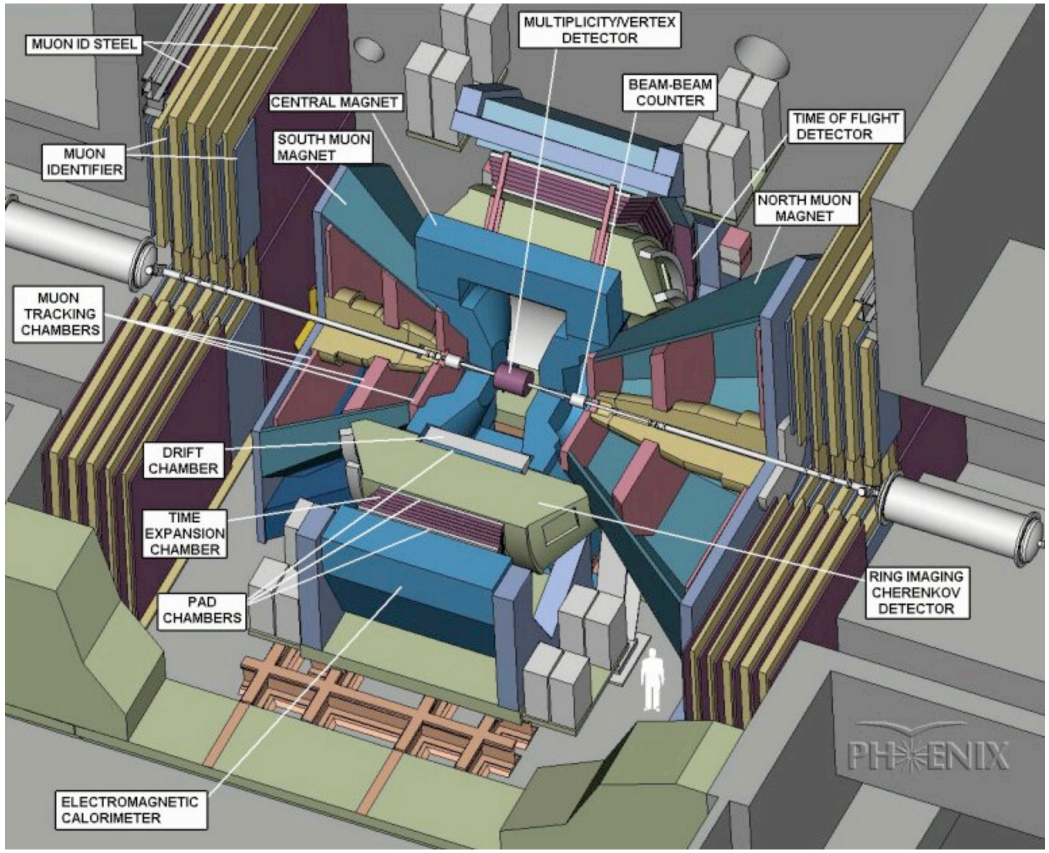
- 4 Experiments
  - 2 big
  - 2 small
- Complementary capabilities

STAR



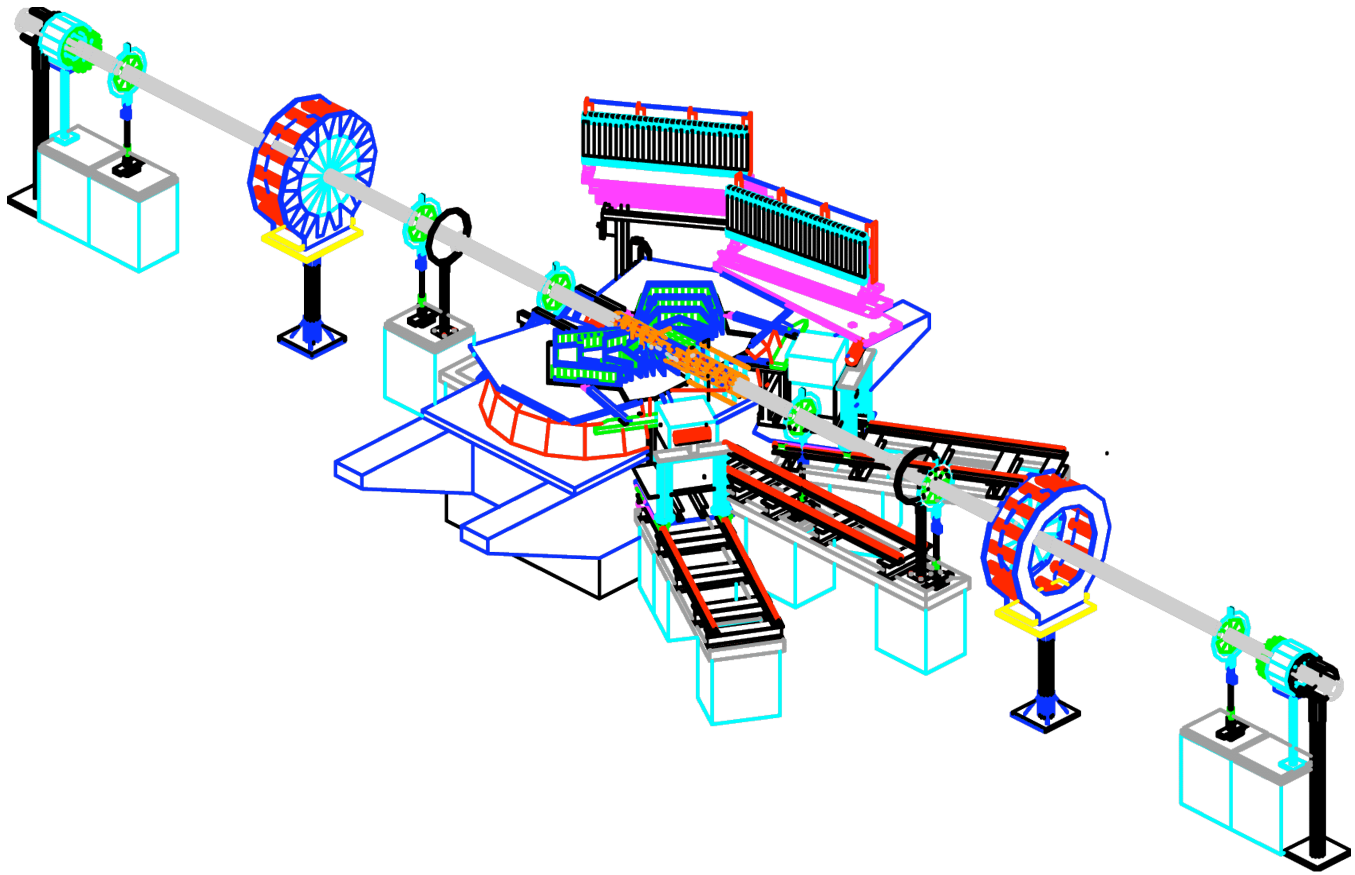
- Large acceptance tracking detector
- Mass, charge and momentum for >1000 hadrons per event

PHENIX



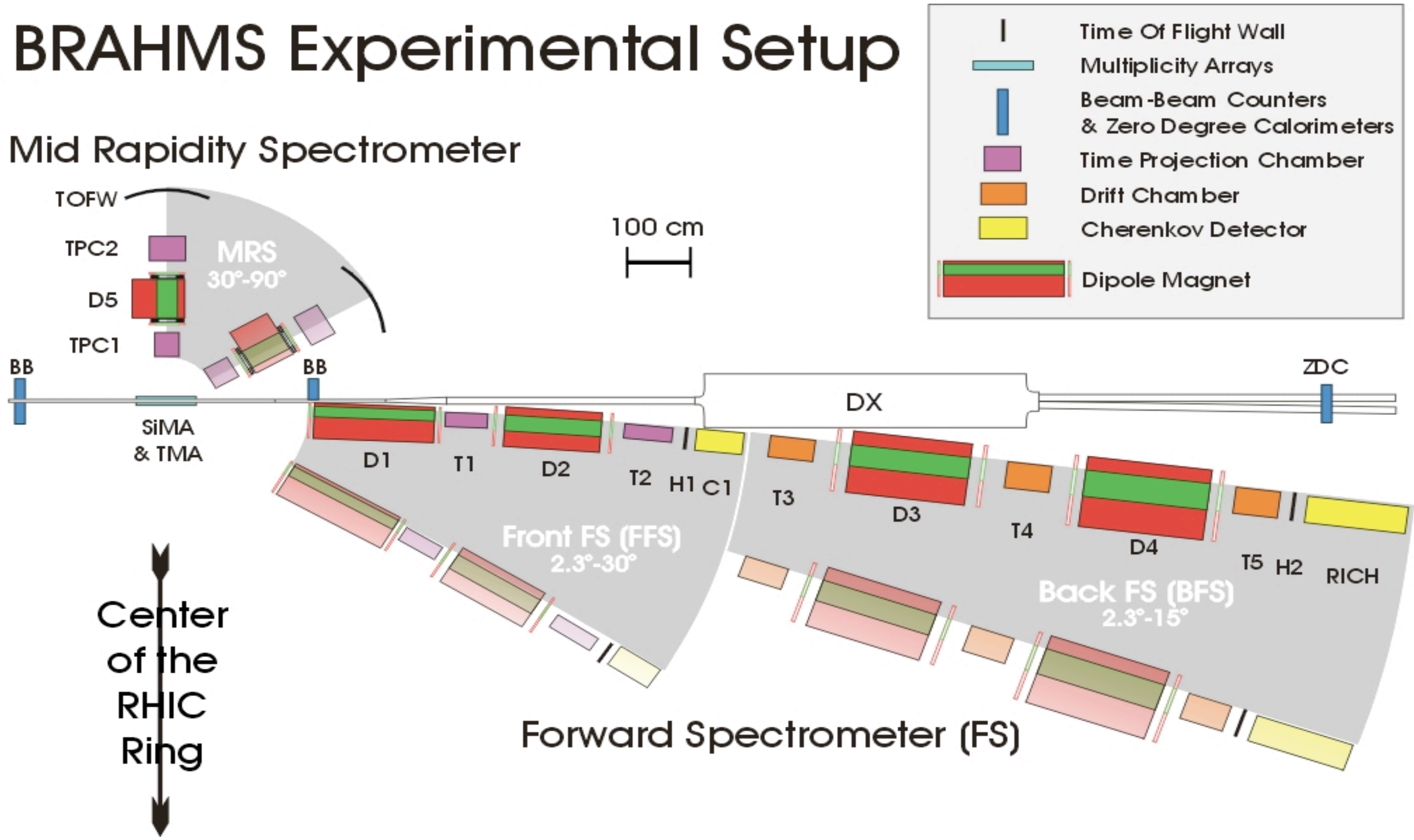
- High Rate, Particle ID, Triggering
- Rare particles: Leptons, High p_T

PHOBOS



- Full Acceptance Multiplicity Detector
- High precision spectrometer near y=0 (low p_T)

BRAHMS



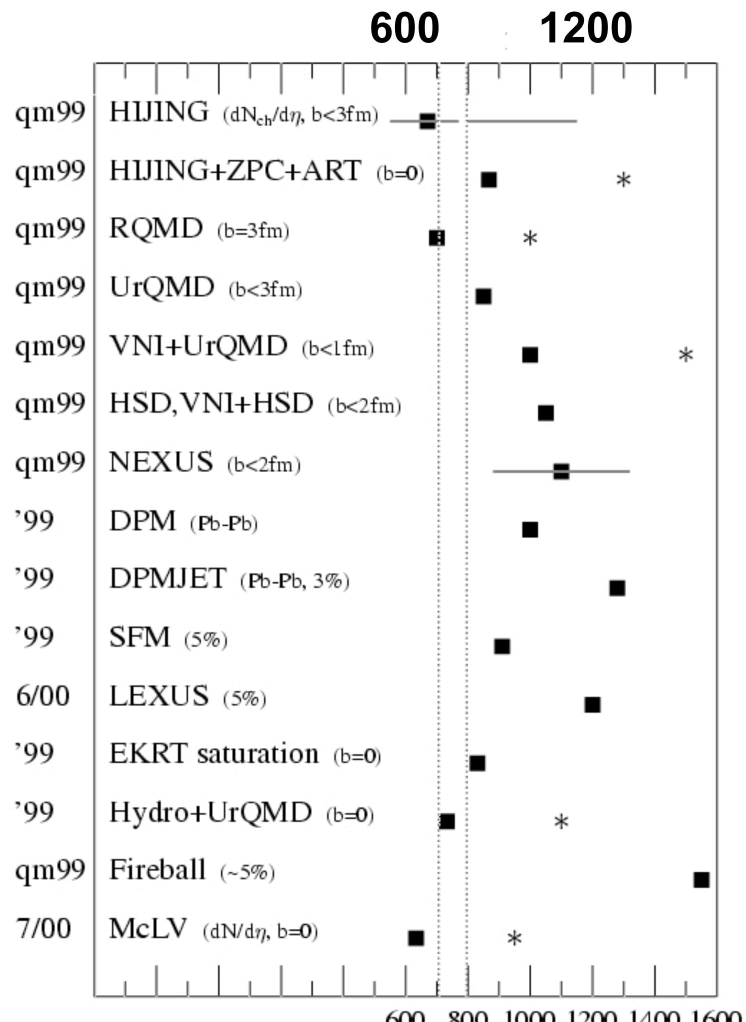
- **Particle Production at small angles**
- **High resolution spectrometer & good particle ID**

Part I: Bulk Particle Production

Predicted Multiplicity for RHIC

- Extrapolate
  - A+A at 20 GeV
  - p+$\bar{p}$ at 200 GeV

Central Au+Au (200 GeV)

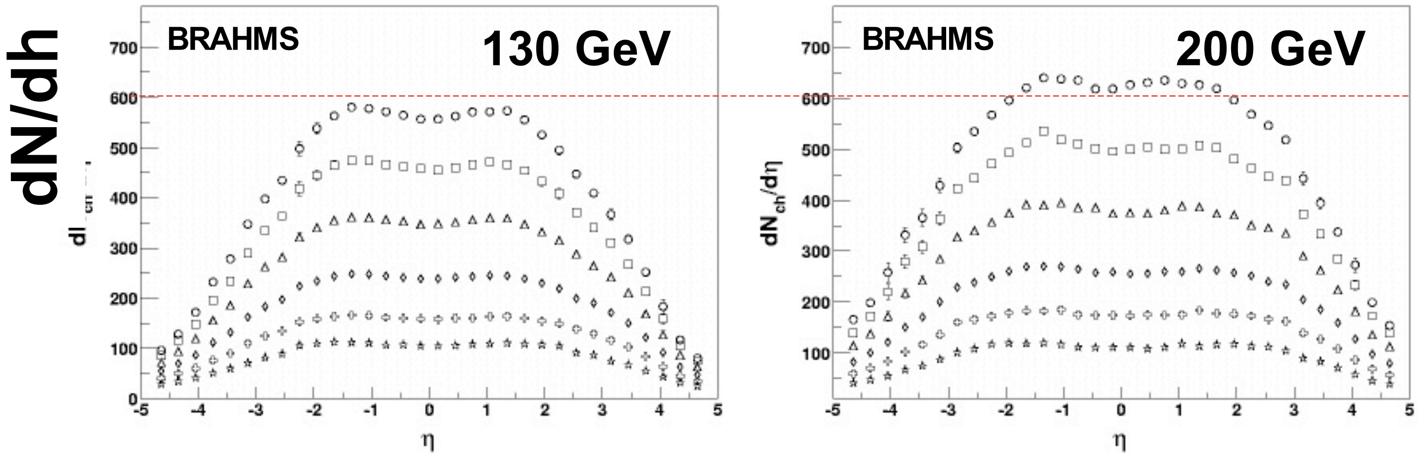


Compilation by K. Eskola

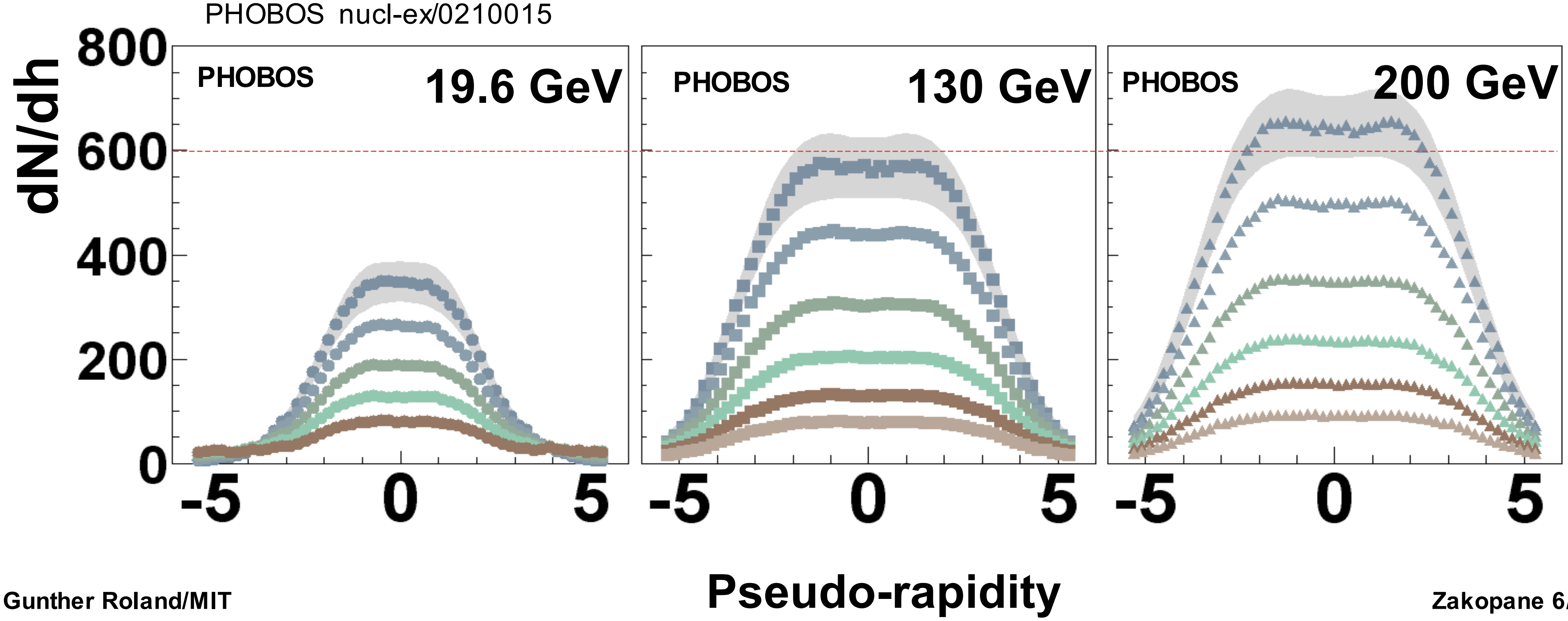
Rapidity Density

4-p Multiplicity at RHIC

BRAHMS PLB 523 (2001) 227, PRL 88 (2002) 202301

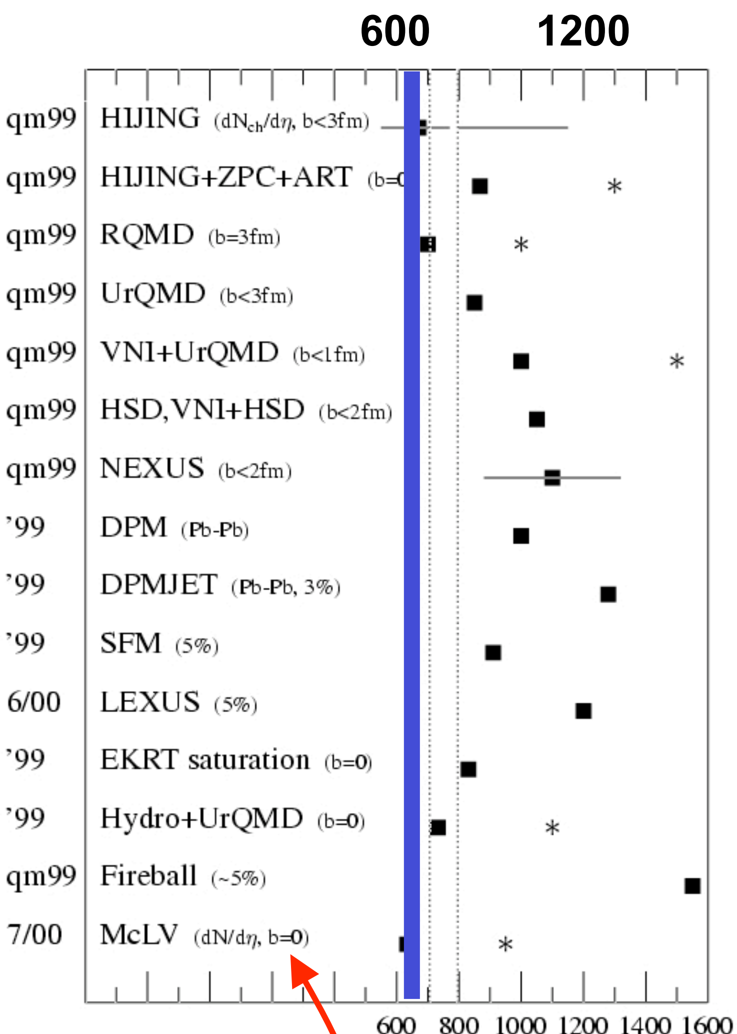


PHOBOS nucl-ex/0210015



Result vs Predictions

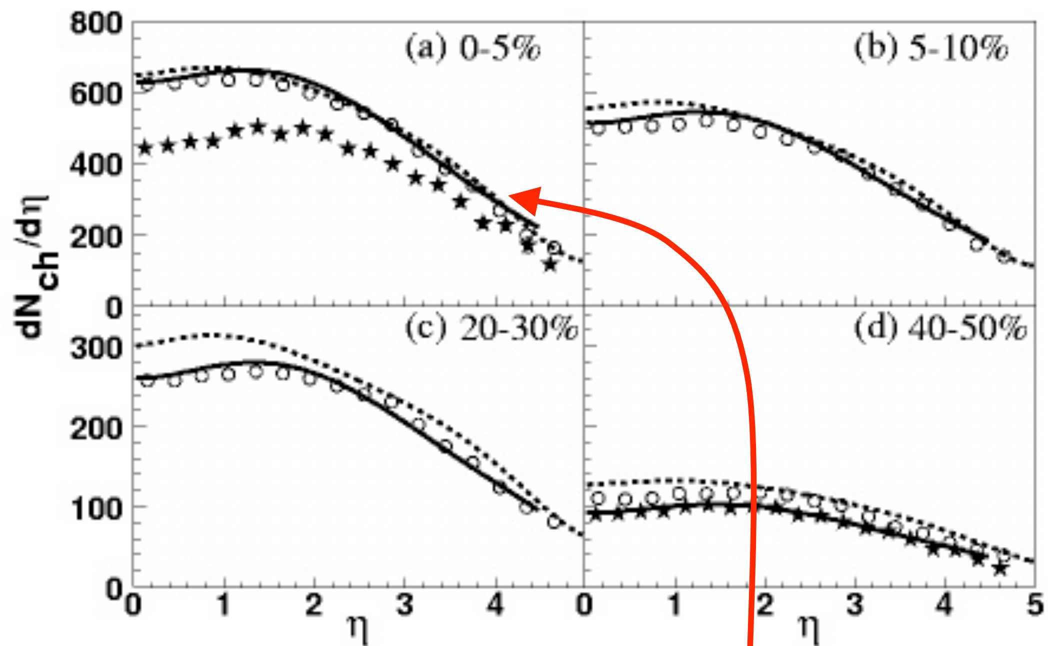
Central Au+Au (200 GeV)



Color Glass

Rapidity Density

- Multiplicity at low end of range
- Most models didn't do so well

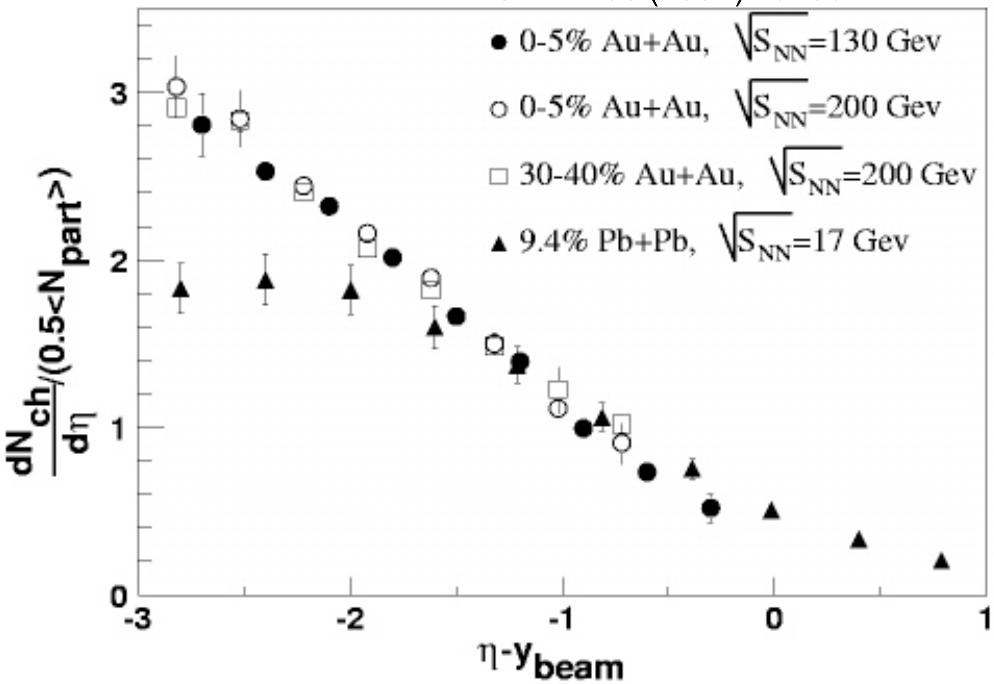


Parton Saturation
Kharzeev, Levin

Limiting Fragmentation

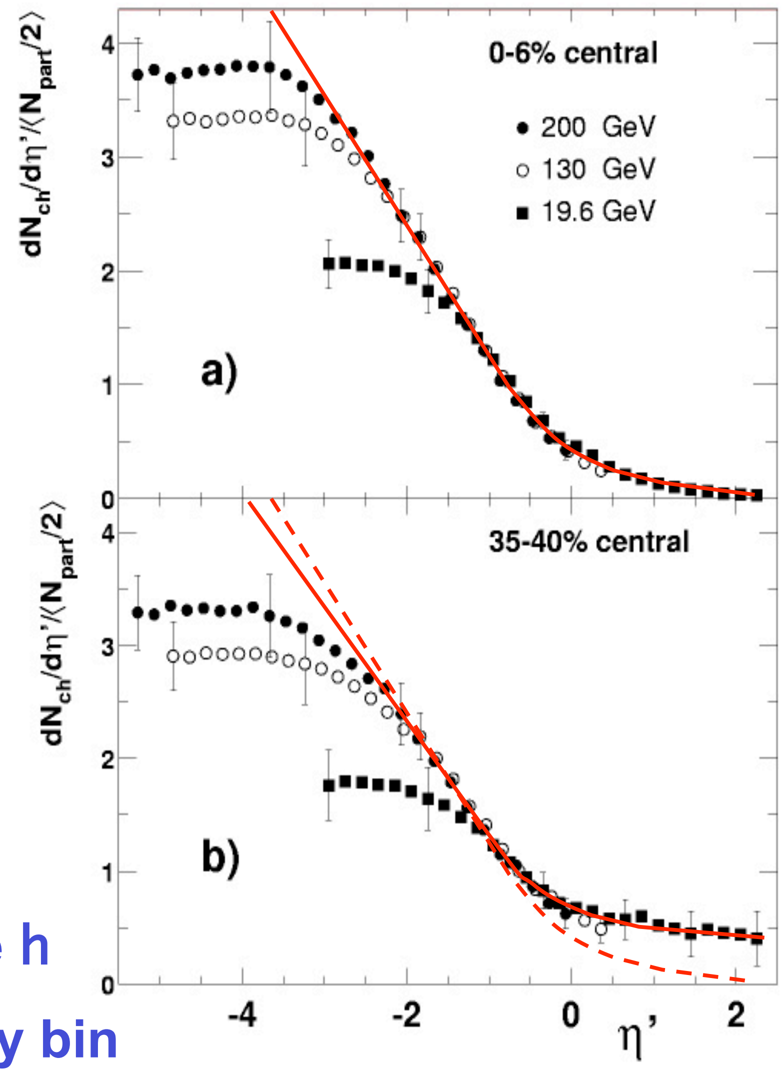
BRAHMS

BRAHMS PRL 88 (2002) 202301



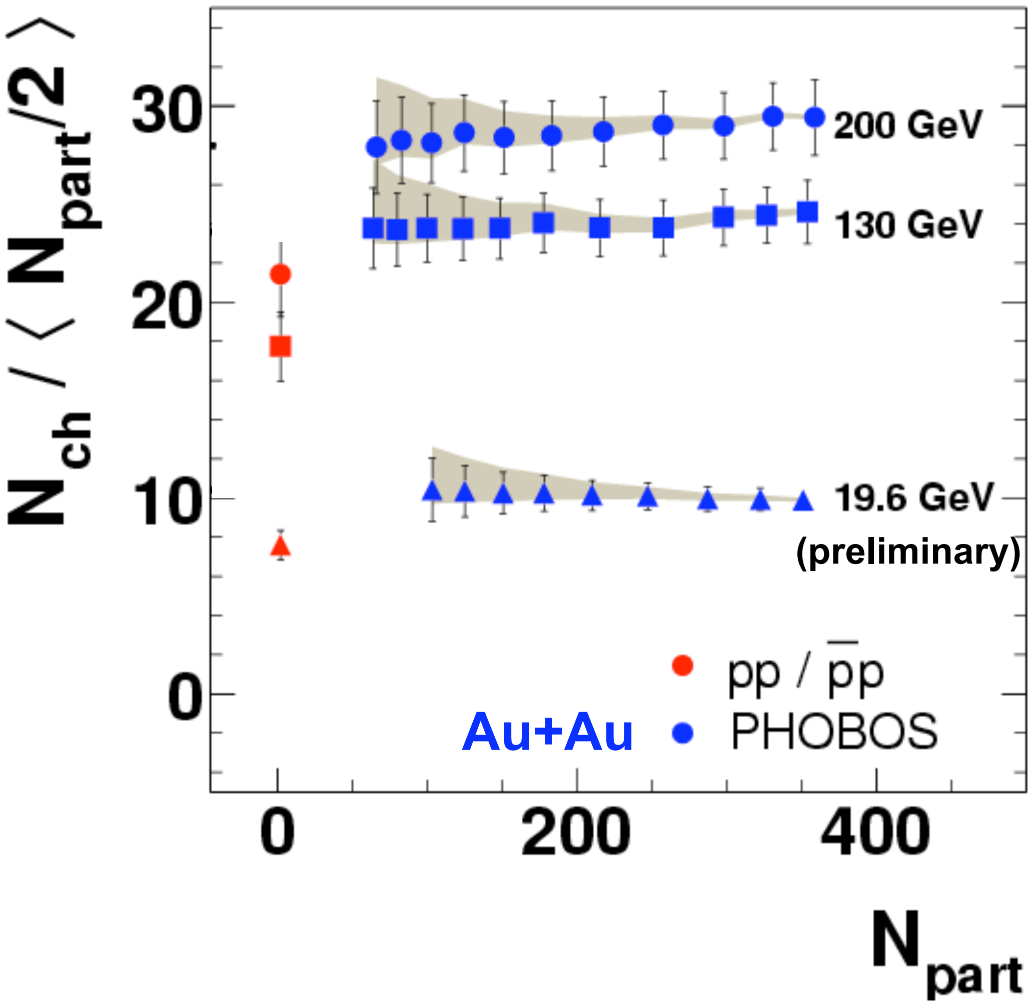
PHOBOS

PHOBOS nucl-ex/0210015



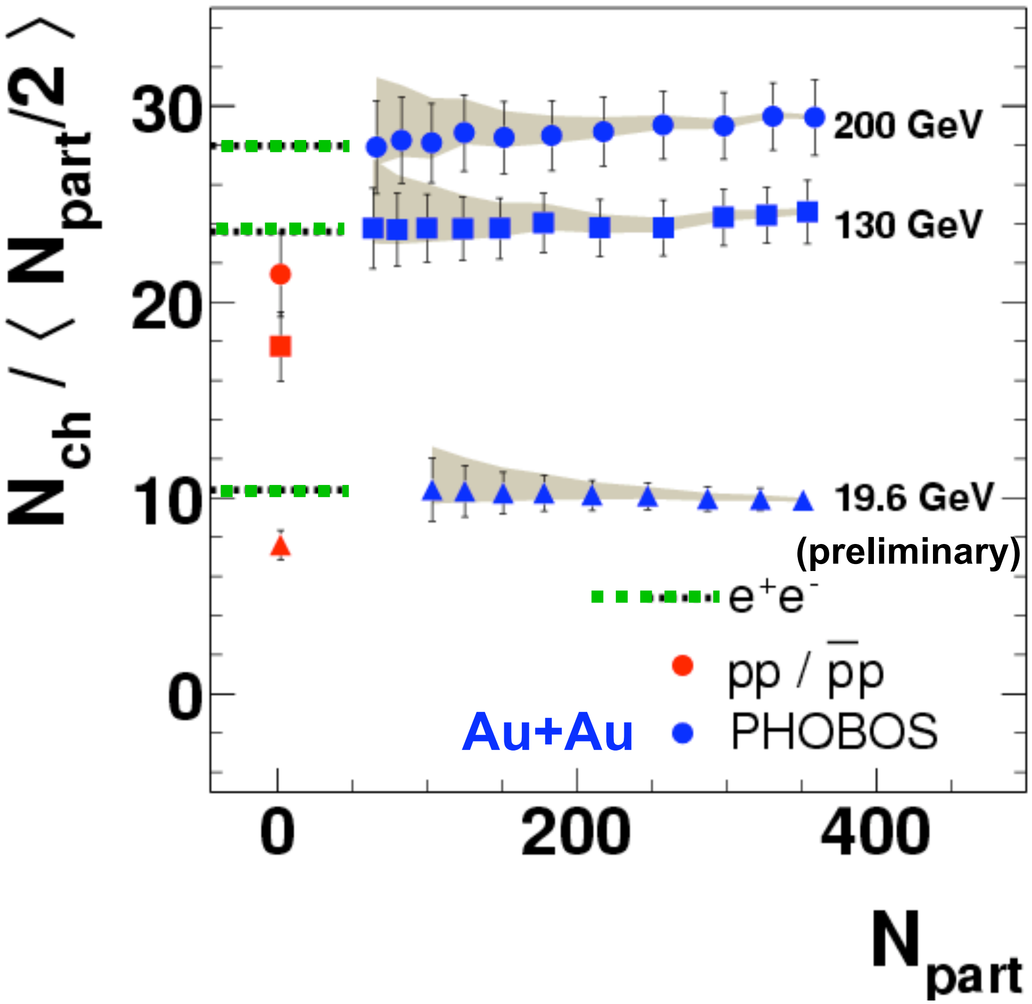
- Study shape in rest-frame of one nucleus
- Distributions fall on limiting curve at large h
- Limiting curve is unique for each centrality bin

$\langle N_{ch} \rangle$ scaling vs N_{part}



N_{ch} proportional to N_{part}

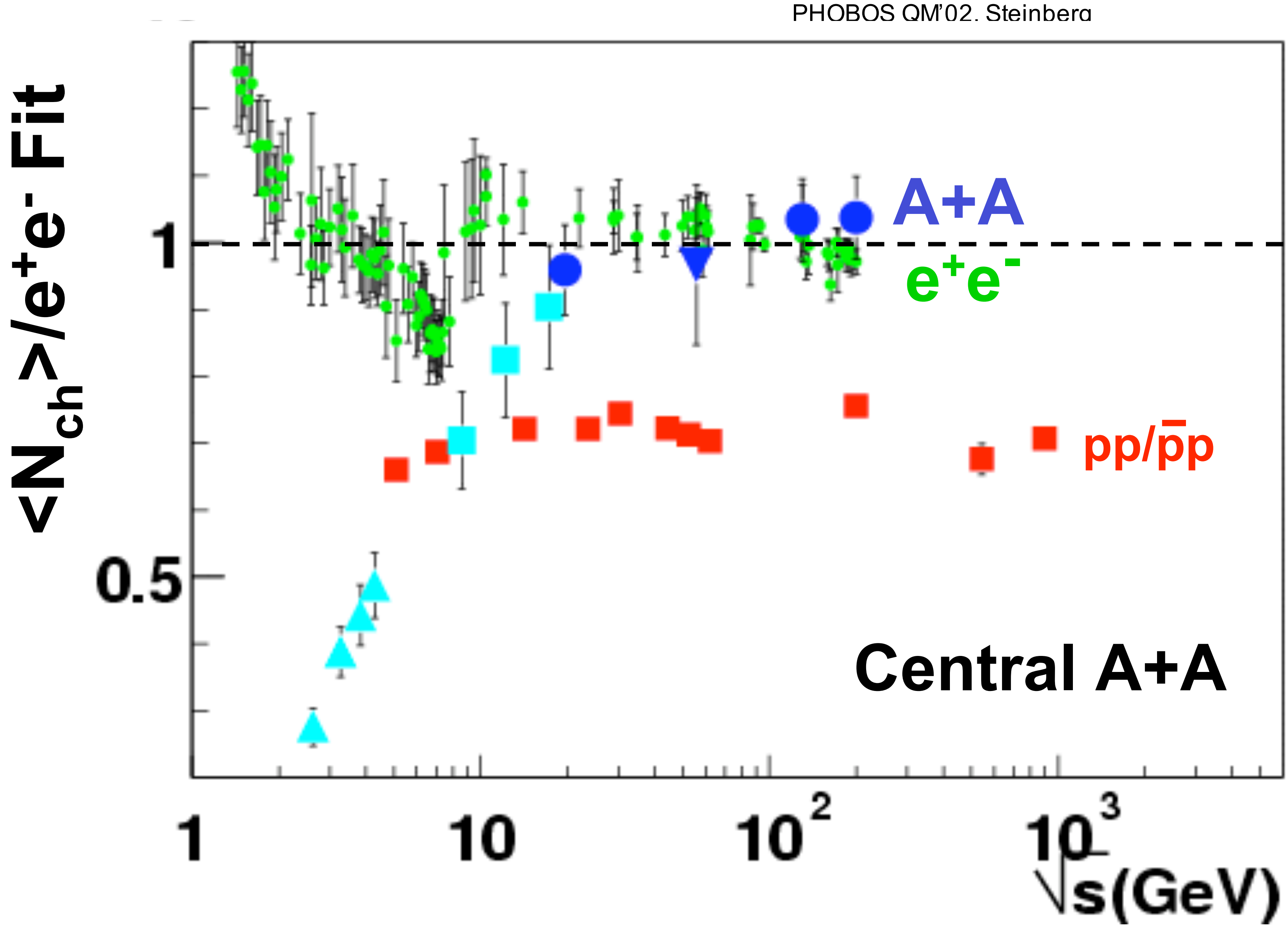
$\langle N_{ch} \rangle$ scaling vs N_{part}



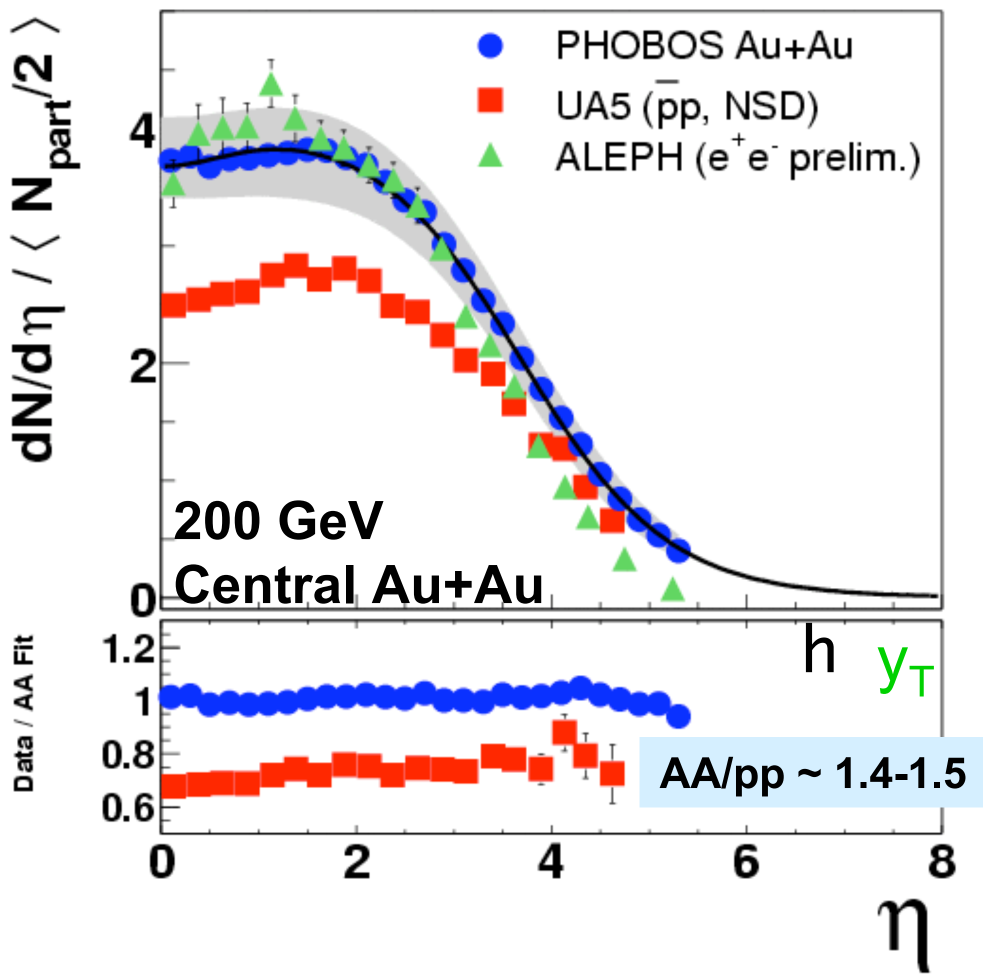
N_{ch} proportional to N_{part}

Constant of proportionality = N_{ch} in e^+e^- at same sqrt(s)

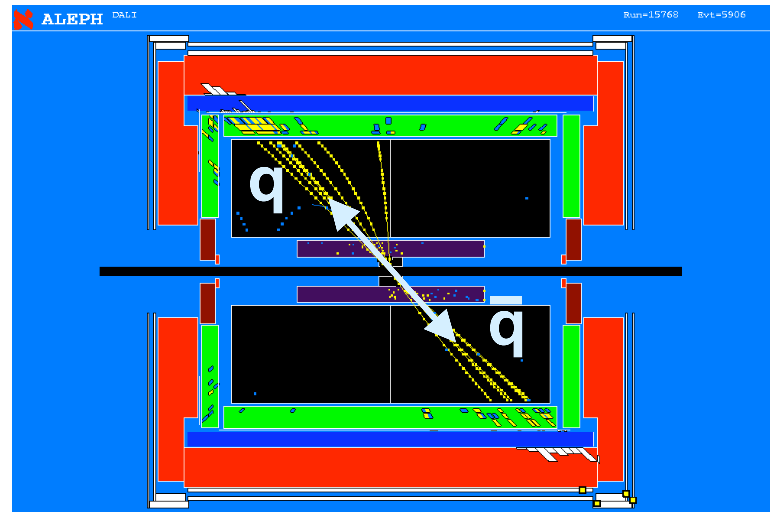
Total Multiplicity vs. Beam Energy



Rapidity Distributions at 200 GeV



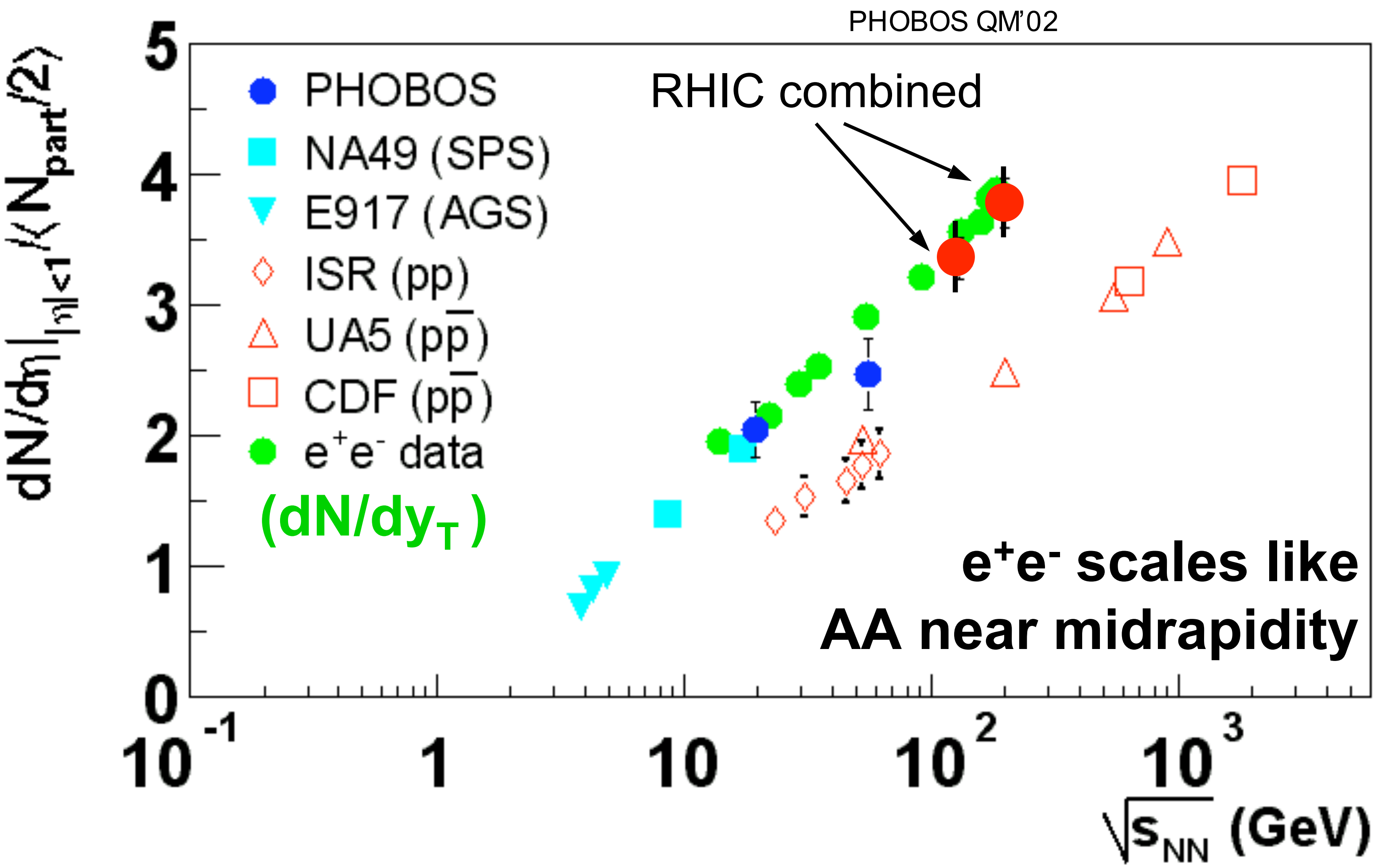
PHOBOS QM'02, Steinberg



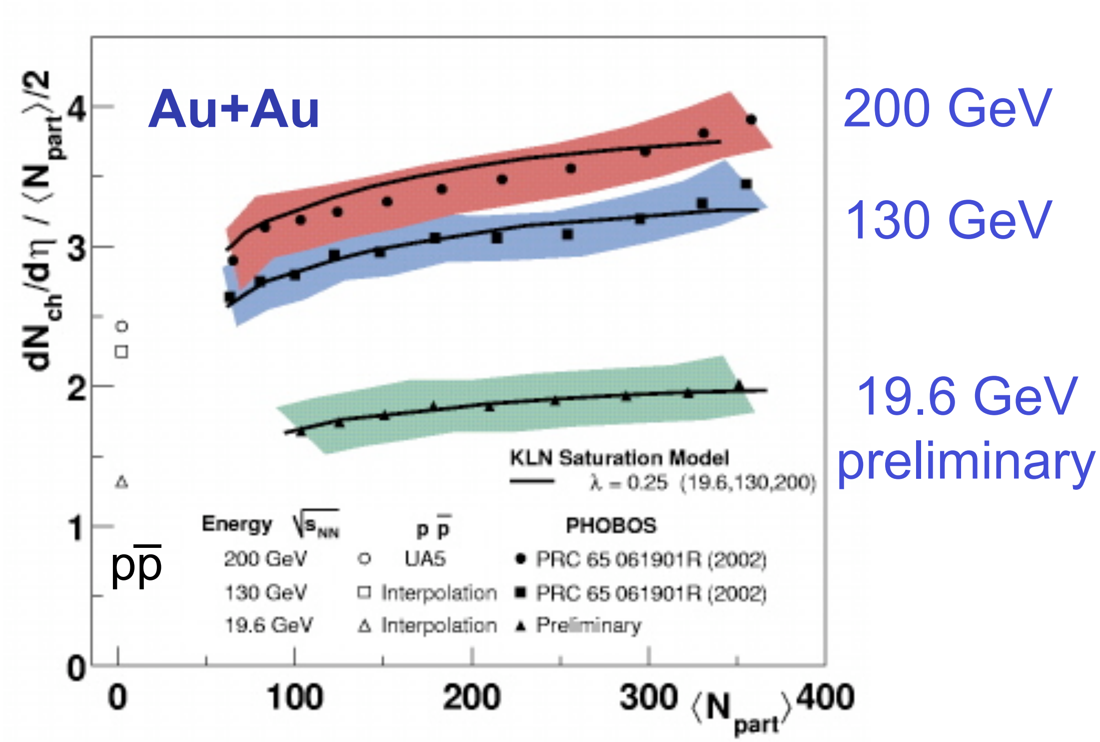
e^+e^- measures dN/dy_T (rapidity relative to "thrust" axis)

Surprising agreement in shape between AA/e^+e^-/pp

Particle density near midrapidity



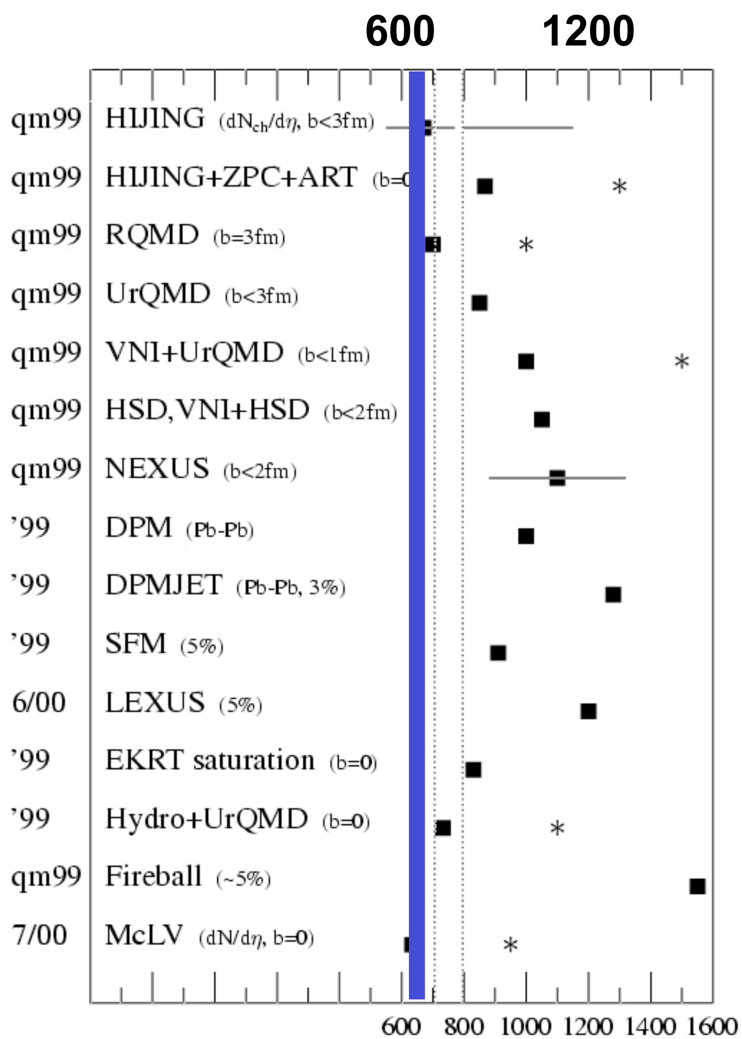
Centrality Dependence at |h| < 1



Saturation model works from 20 to 200 GeV

What is the Energy Density?

Central Au+Au (200 GeV)



Rapidity Density

$e = 650 * 1\,\mathrm{GeV}/(p\, R^2 * 1\,\mathrm{fm/c}) = 4\,\mathrm{GeV/fm^3}$

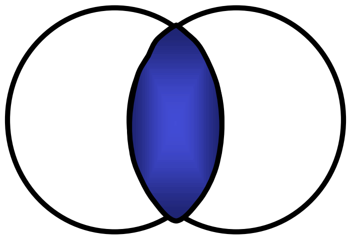
Much bigger than e_{crit}…

…*if* we have
fast thermalization!

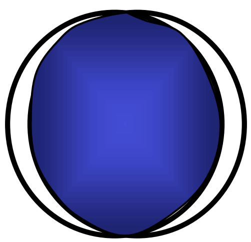
Azimuthal Anisotropy

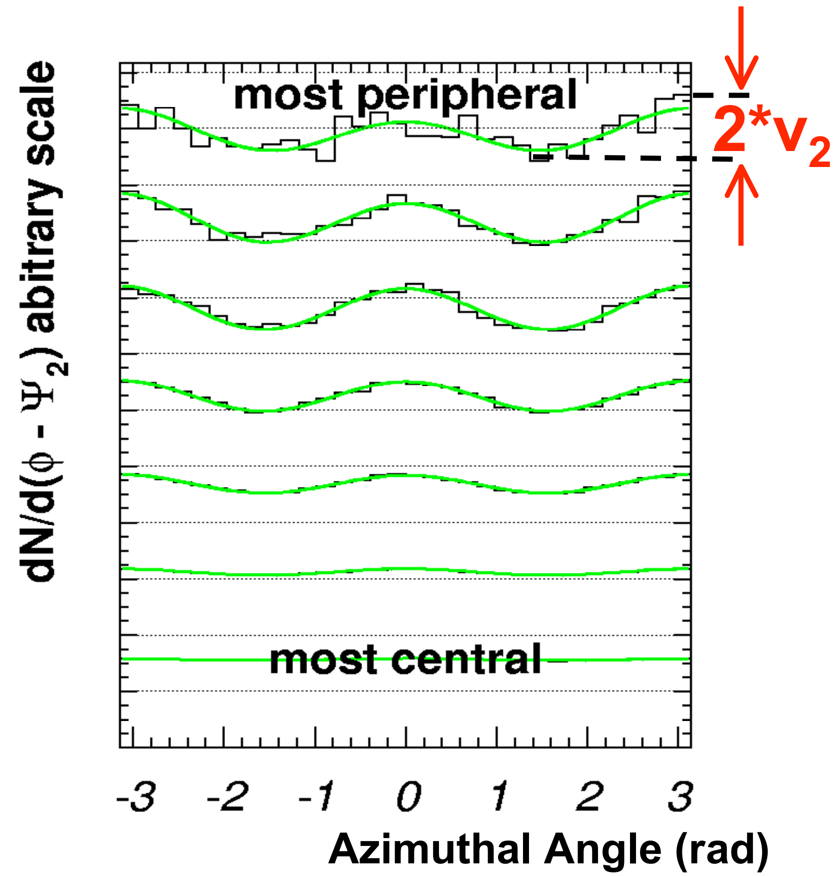
“Head on” view of colliding nuclei

Peripheral



Central



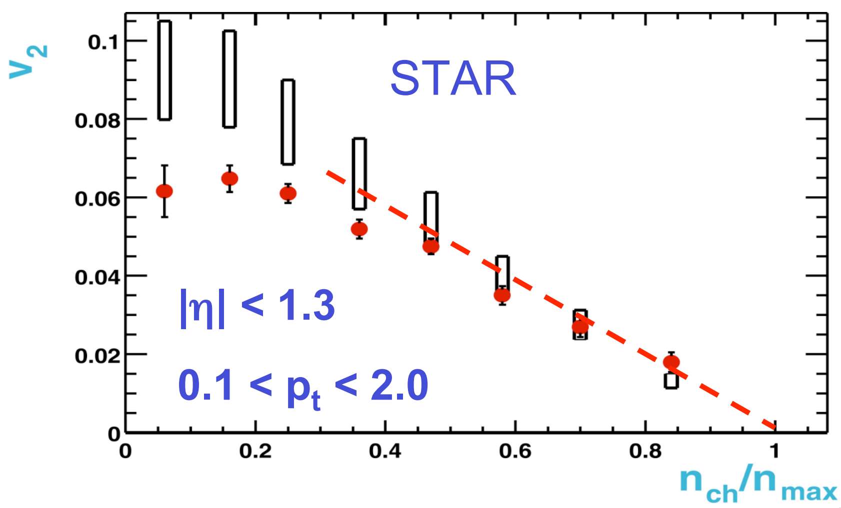


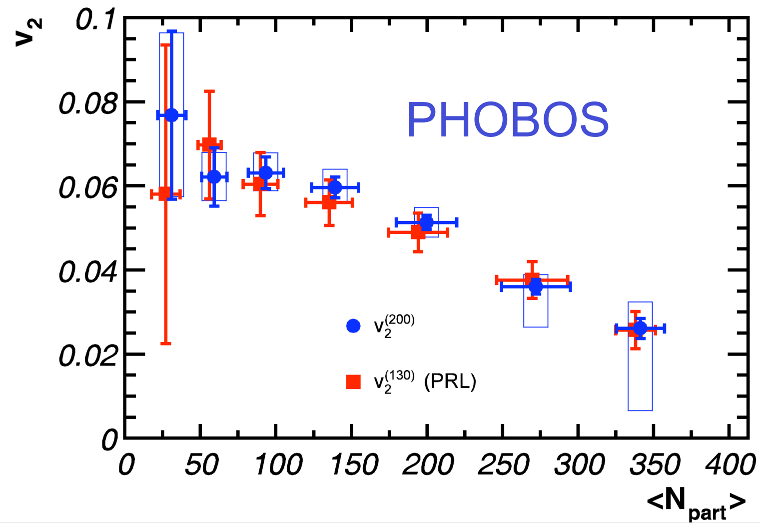
Initial State Anisotropy
Coordinate Space

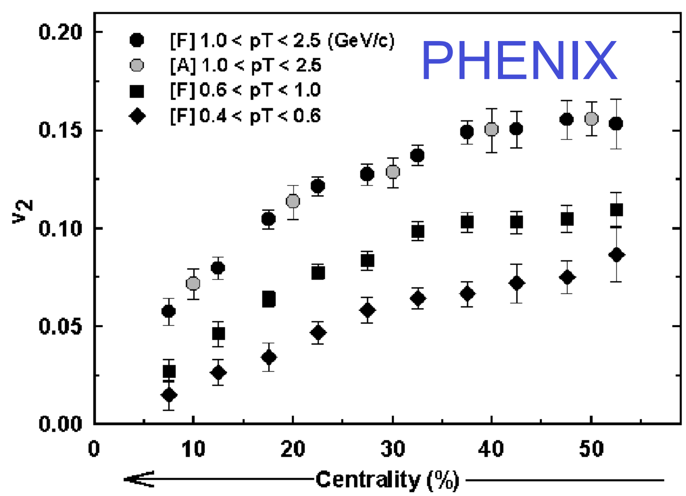
Interaction! →

Final State Anisotropy
Momentum Space

Anisotropy v_2 vs Centrality



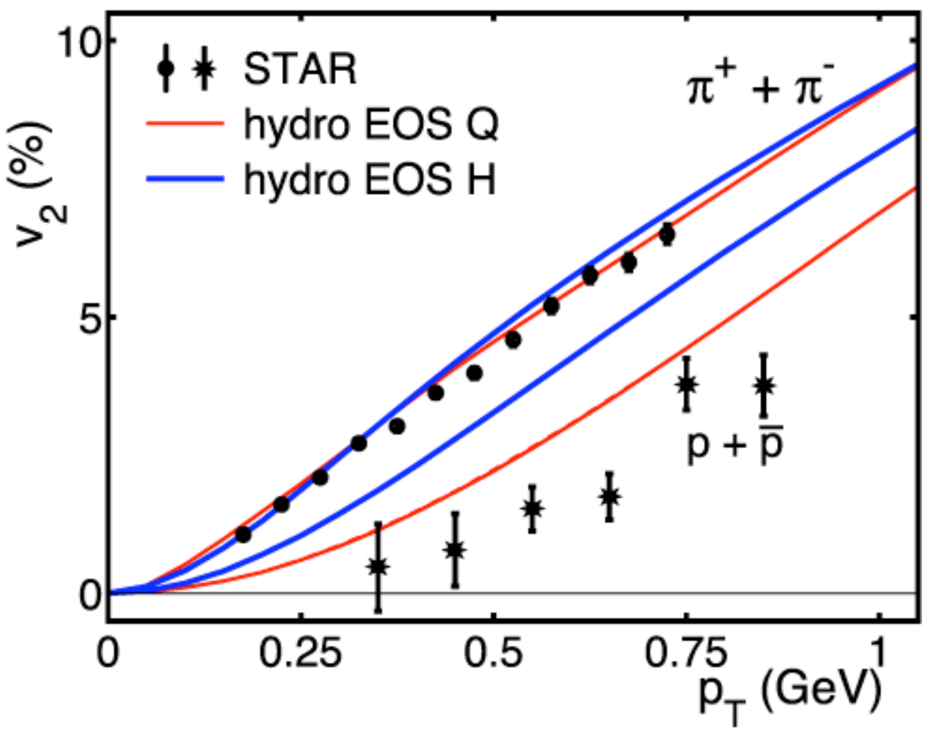




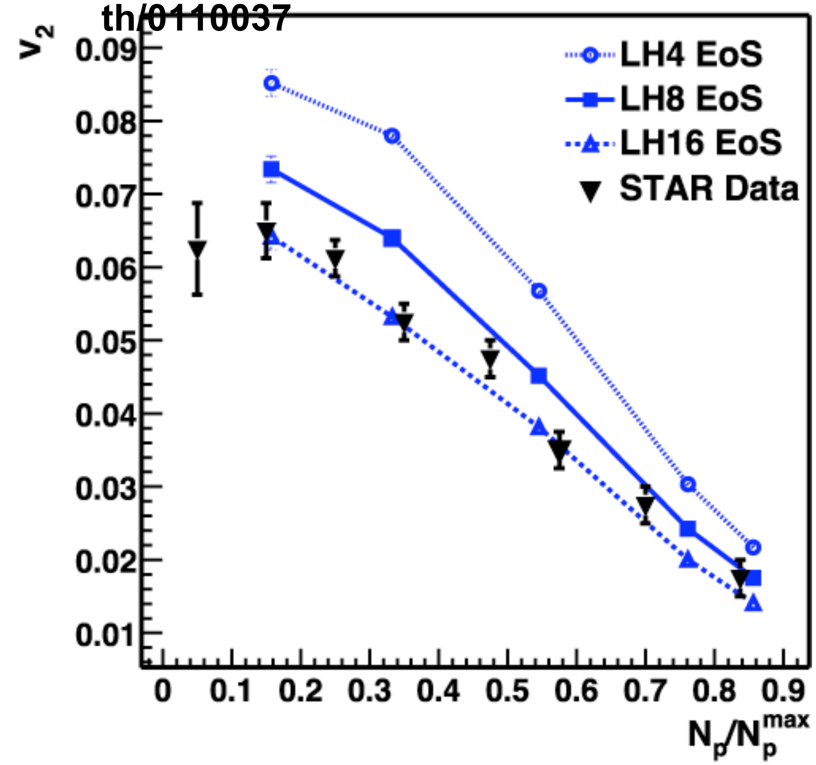
Up to mid-central collisions, v_2 reaches hydro limit

Hydrodynamics and v_2

Kolb, Heinz, nucl-ex/0204061



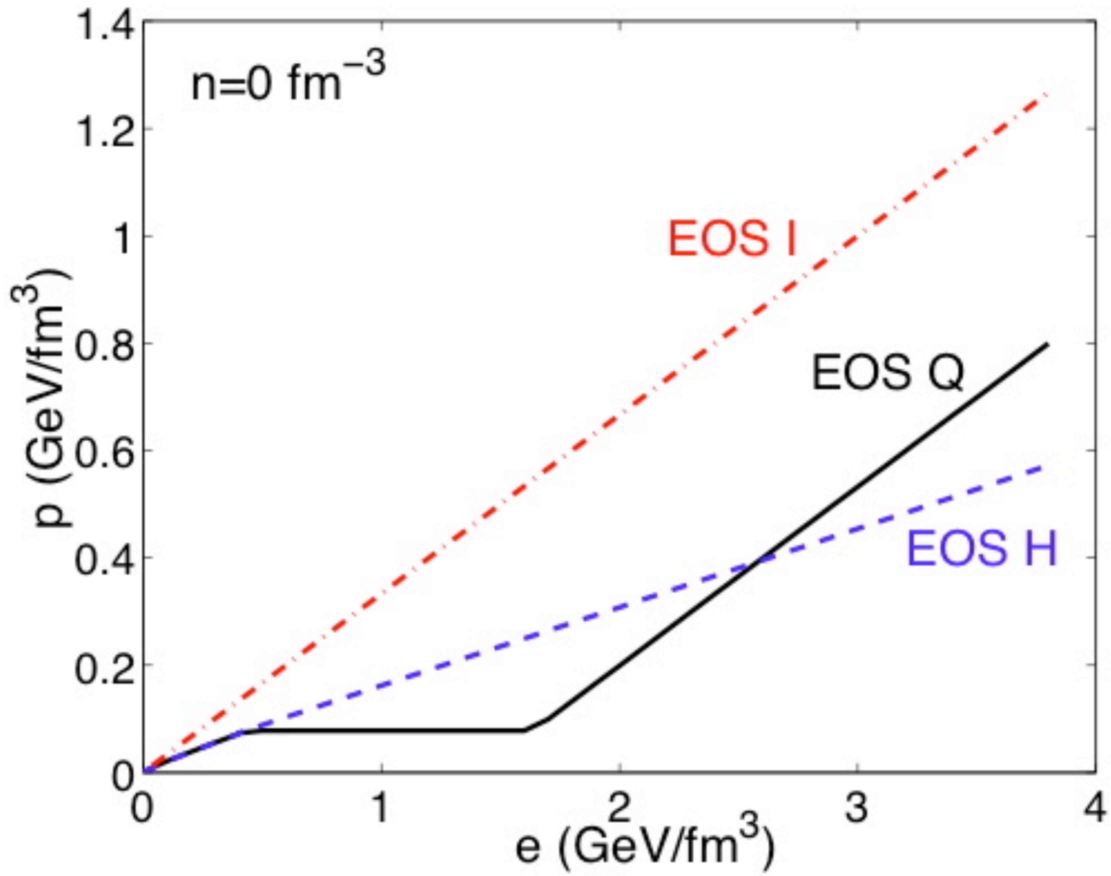
Teaney, Lauret, Shuryak, nucl-th/0110037



- Data consistent with hydro calculations
- Sensitivity to EoS

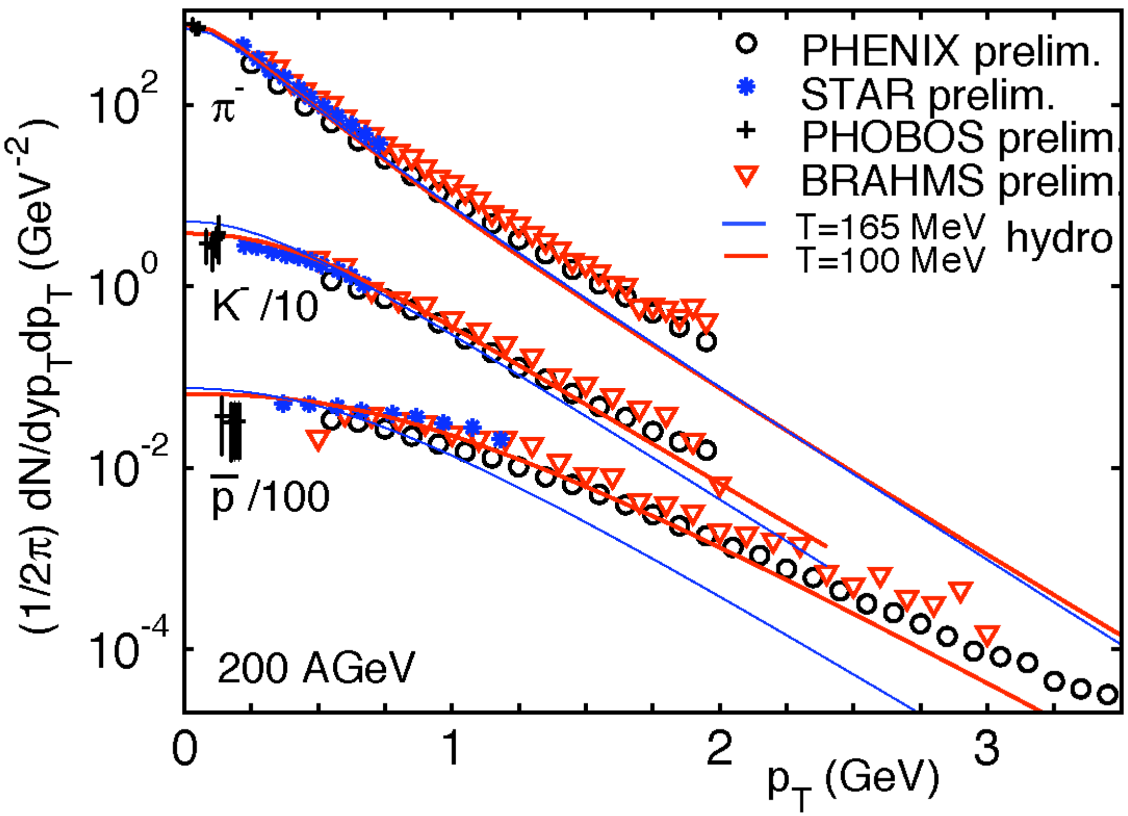
Hydro Equation of State

Kolb, Heinz, nucl-ex/0305084



Hydrodynamics and Spectra

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



Parameters:

τ_0 = 0.6 fm/c

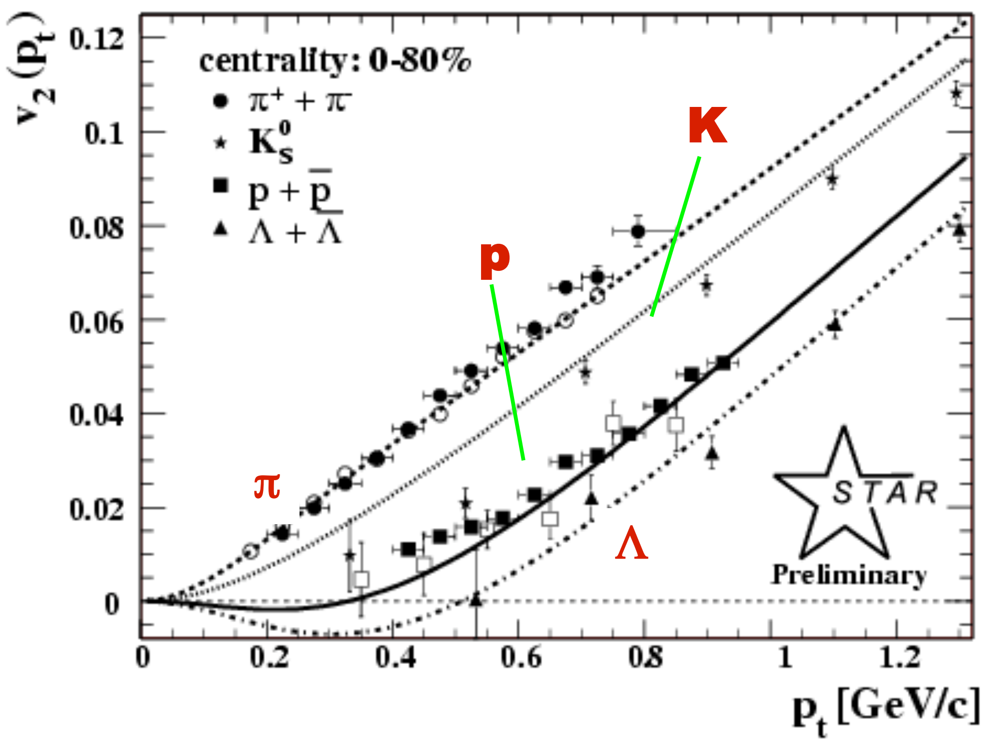
s_0 = 110 fm^{-3}

s_0/n_0 = 250

T_{crit}=T_{chem}=165 MeV

T_{dec}=100 MeV

Blast wave fit

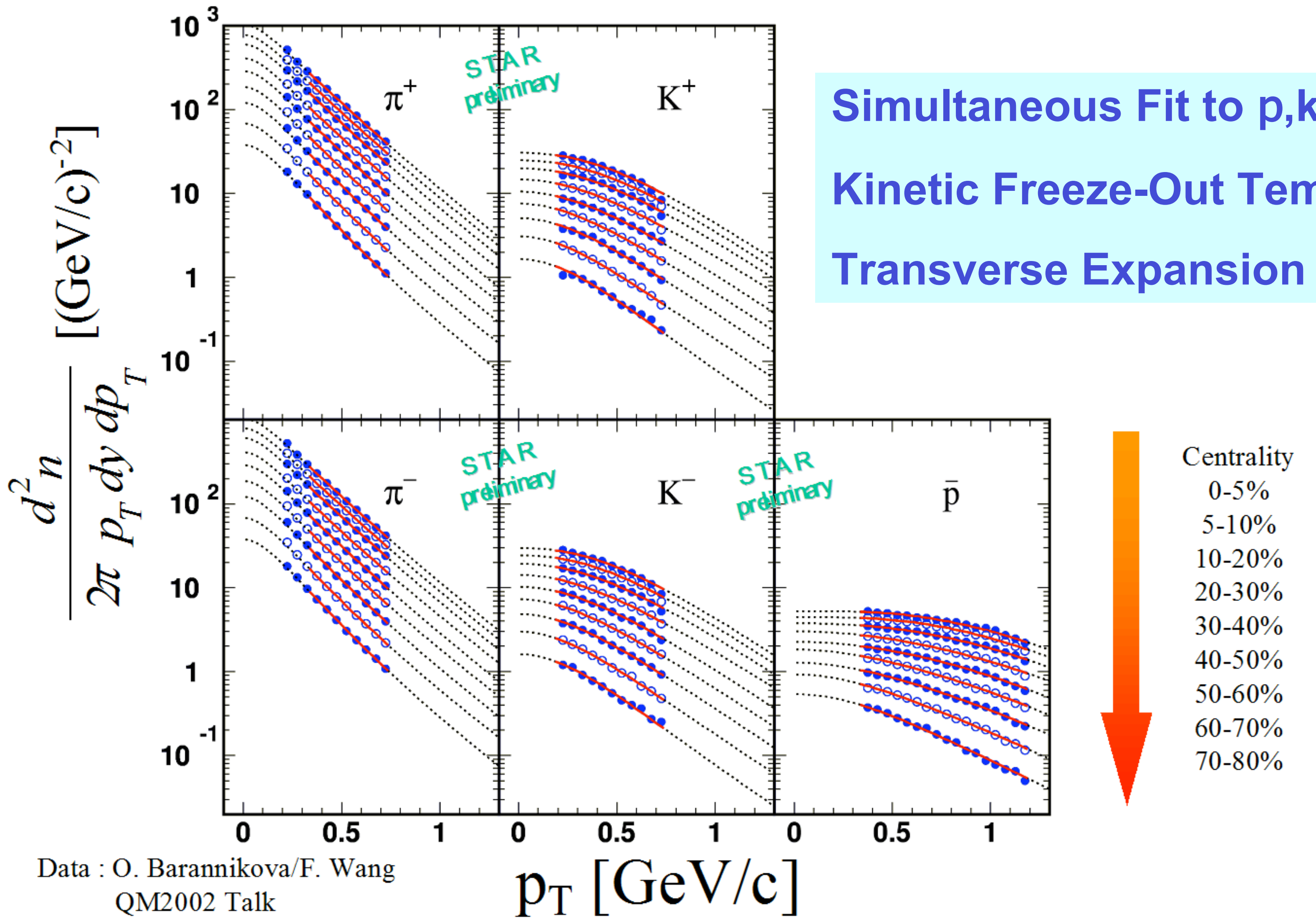


Blast wave:

- "Hydro-inspired" Fit
- Parametrize Final State
  - Local thermal equilibrium (T)
  - Linear radial flow profile $r_{x,y}(r) = r_{0,x,y} * r$
  - Geometrical size r_x and r_y
  - Freeze-out time t_o and duration Dt_o

Even better than the real thing…

Blast wave Fits to Spectra

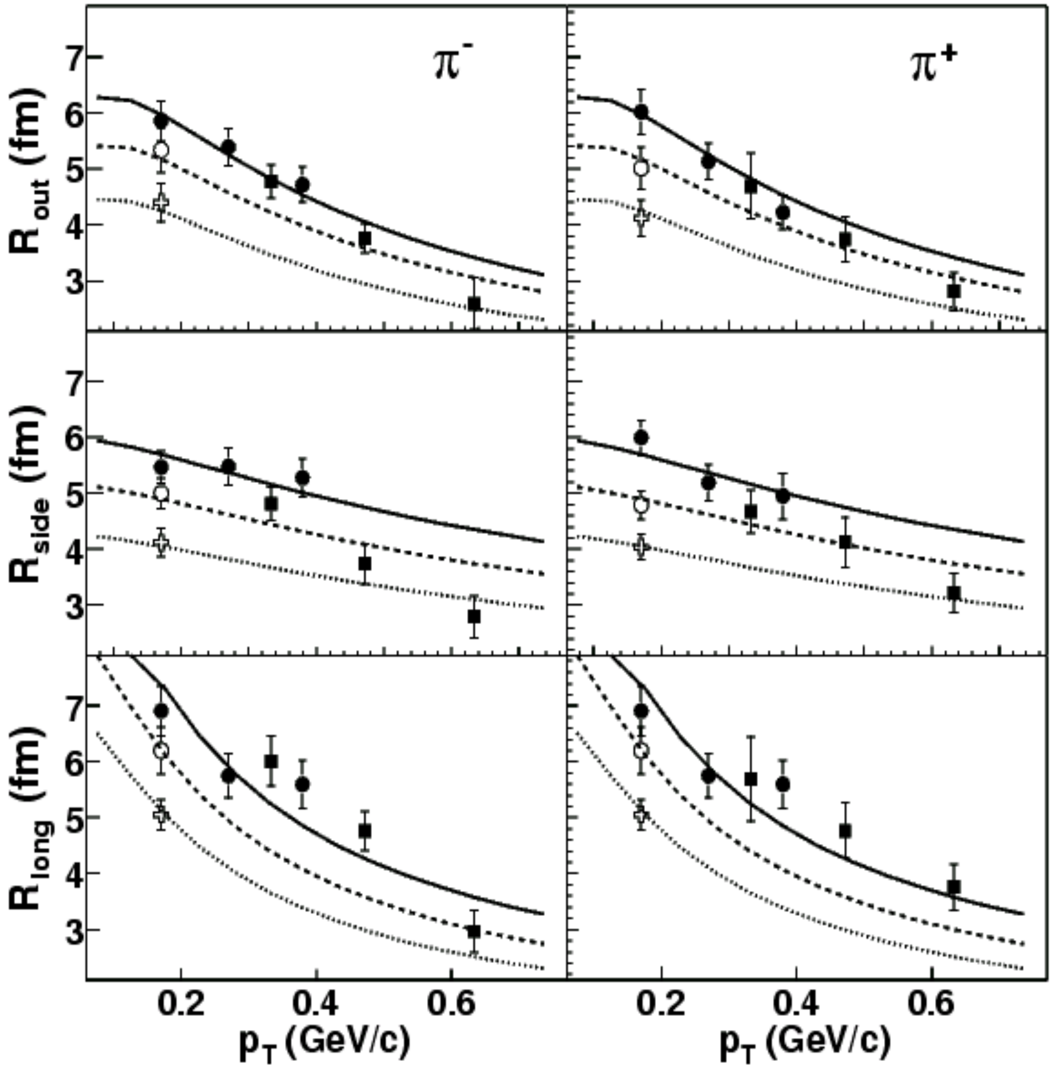


Simultaneous Fit to p,k,p gives

Kinetic Freeze-Out Temperature,

Transverse Expansion velocity

Blast wave Fit to Correlation Data



Fabrice Retiere SQM '03, Mike Lisa

Consistent Data from

STAR, PHENIX, PHOBOS

Also

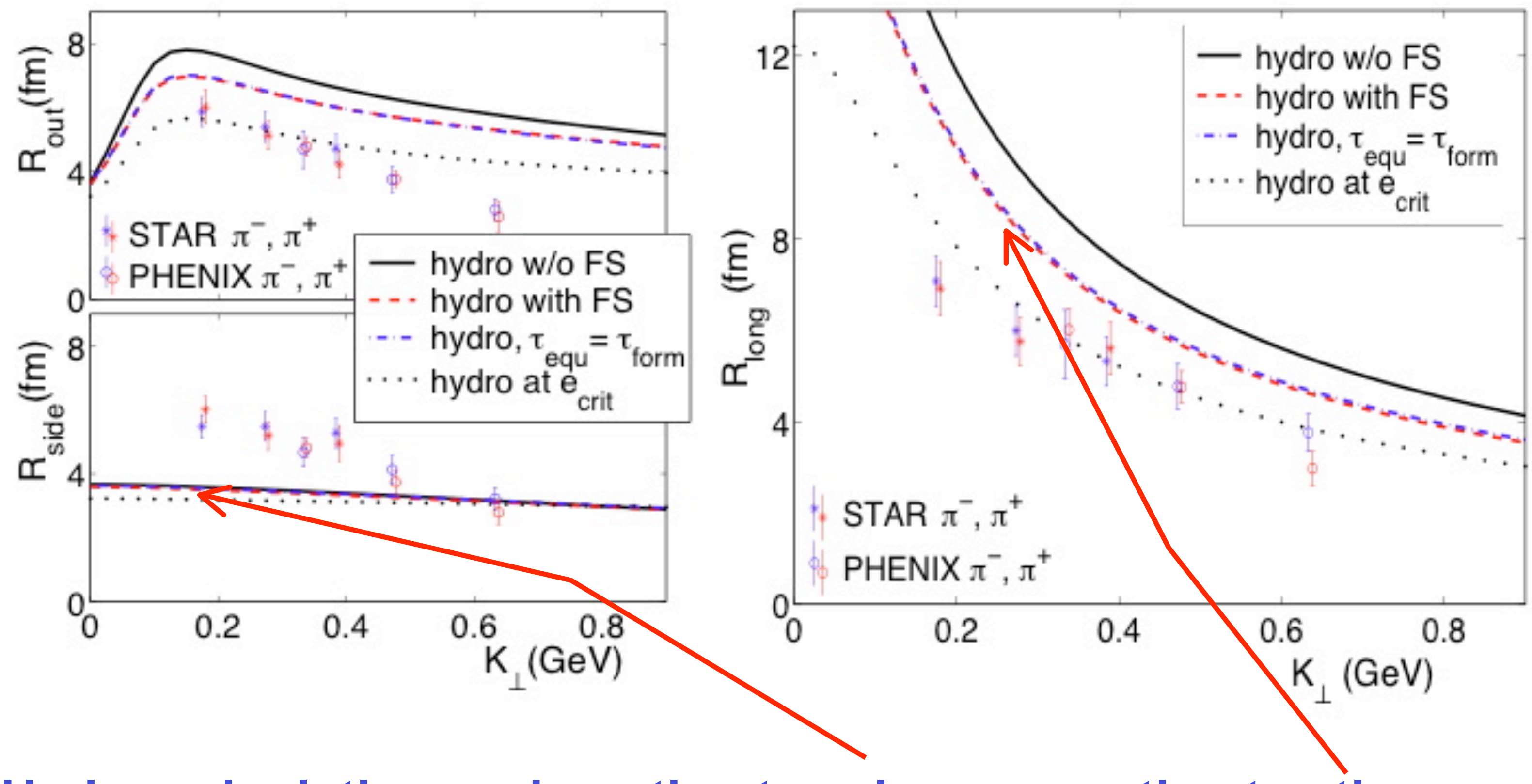
- HBT vs reaction plane
- Unlike particles
- Balance Functions
- Short-lived Resonances

Consistent Results

- Lifetime ~ 10 fm/c
- Particle emission over few fm/c

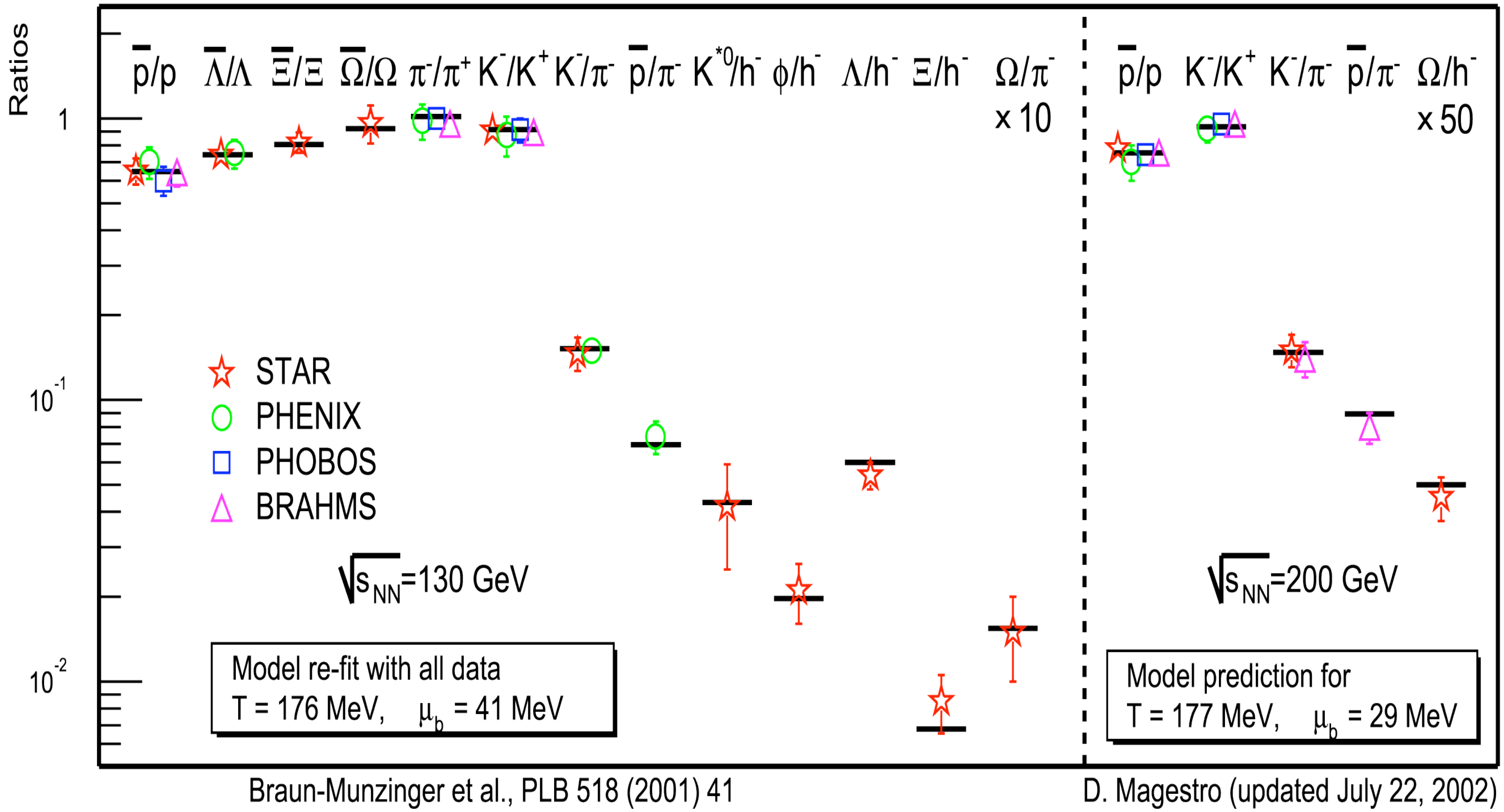
Hydro and Correlation Data

Kolb, Heinz nuclt-th/0305084



Hydro calculation underestimates size, overestimates time

Statistical Model Fit

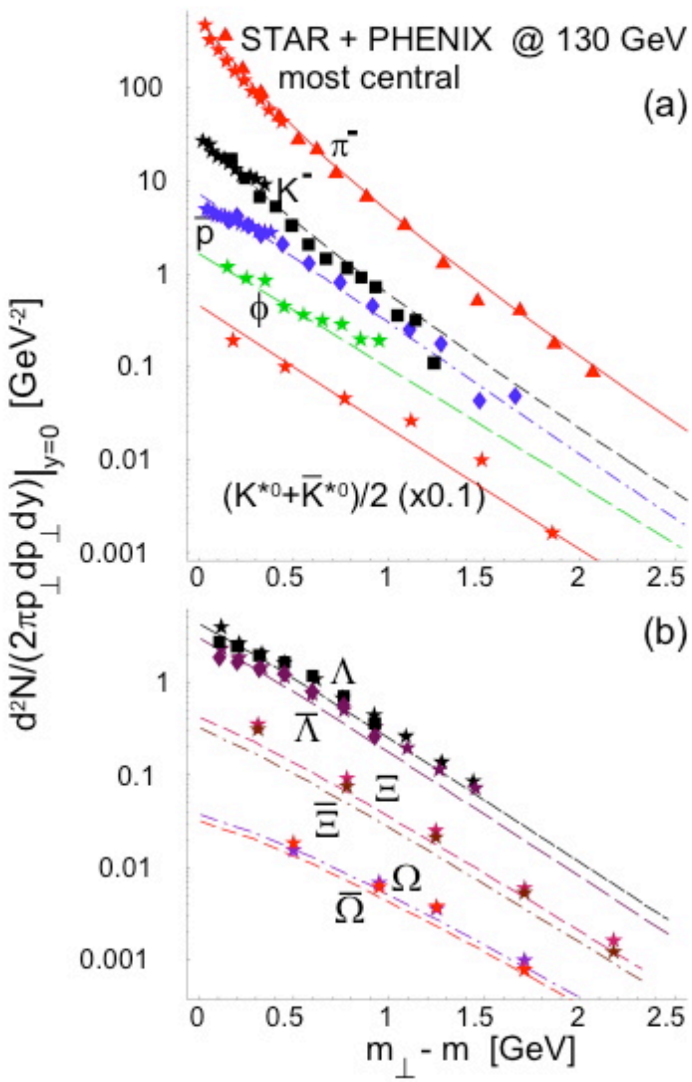


Relative Abundances: Two Parameters (or three or four) !

Caveat: Resonances, Phase-space over/under population

T_{chem} vs T_{kin}

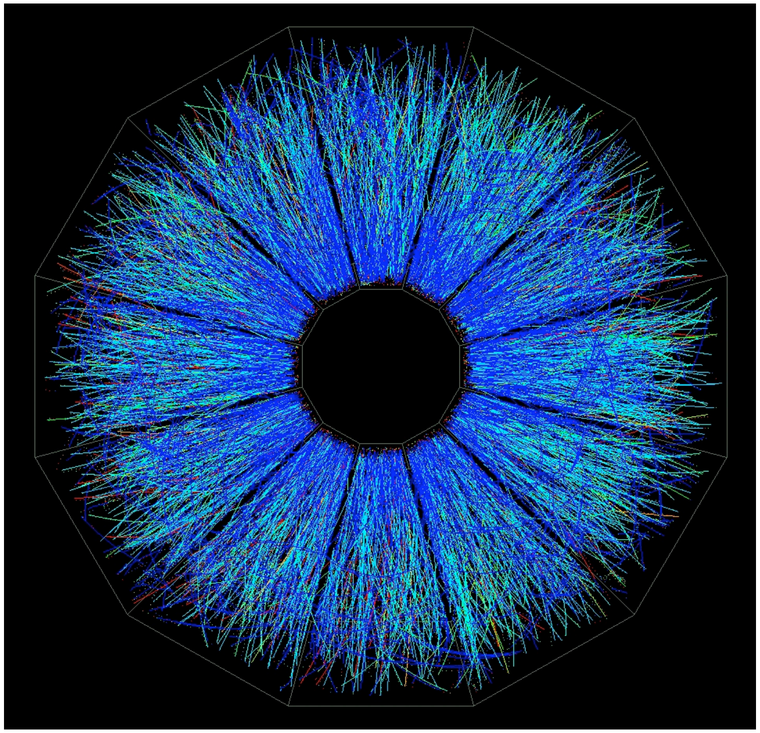
Florkowski, Broniowski, nucl-th/0212052



Addition of resonances may allow freezeout with $T_{chem} = T_{kin}$

c.f. Torrieri, Rafelski, nucl-th/030507

Physics Results from RHIC: Lecture II



Gunther Roland

XLIII Cracow School of
Theoretical Physics

Zakopane 5/30-6/7 2003

Memento: Bulk Particle Production @ RHIC

– Saturation consistent w/ multiplicity systematics

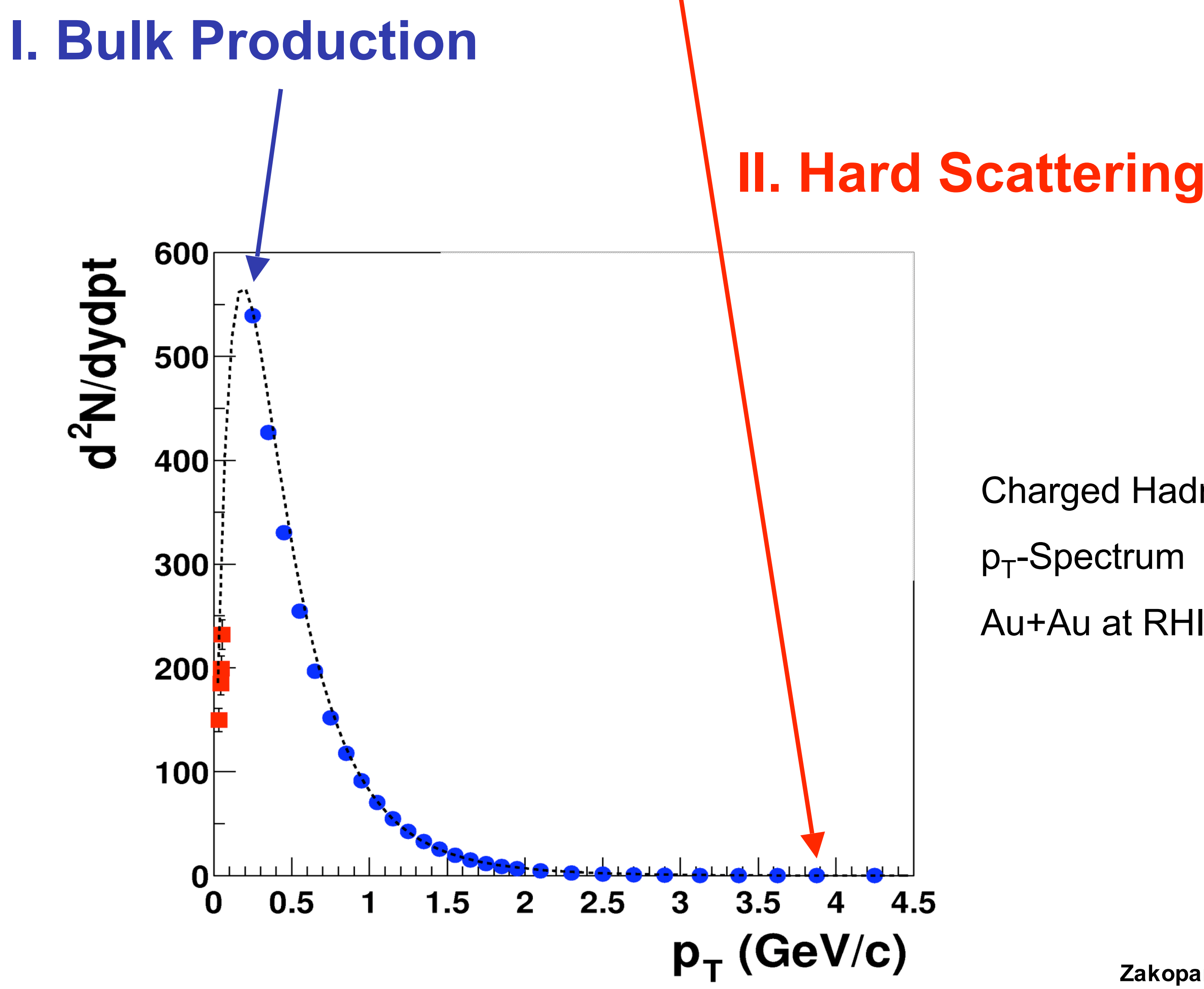
– Final state anisotropy indicates “Thermalization”
  Energy Density: > 5 GeV/fm^3

– Momentum distributions and correlations are hydro-like, with a large radial flow field

– Hydrodynamic calculations show sensitivity of results to EoS; many qualitative features

– Timescales are very short: Thermalization, Expansion, Freeze-out

2nd Lecture



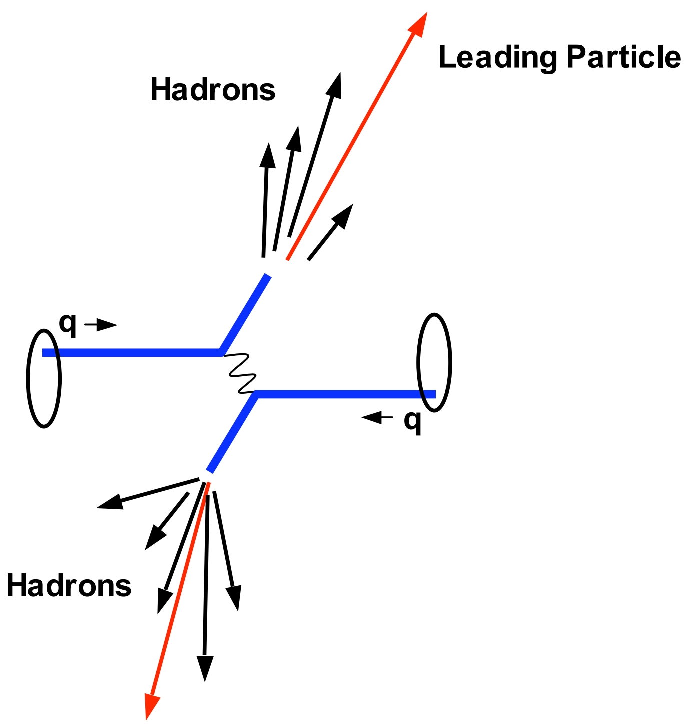
Charged Hadron

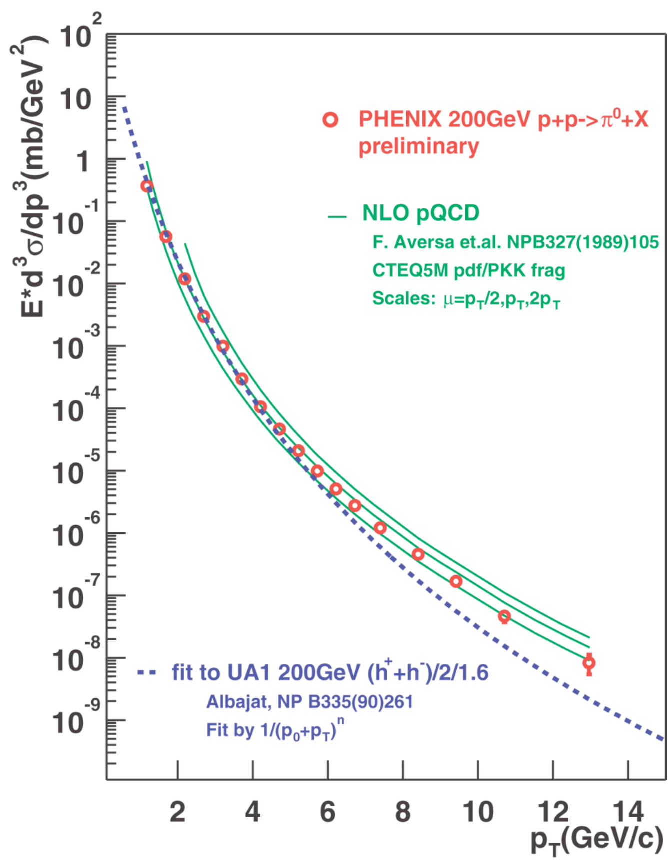
p_T-Spectrum in

Au+Au at RHIC

Dense Matter Diagnostics

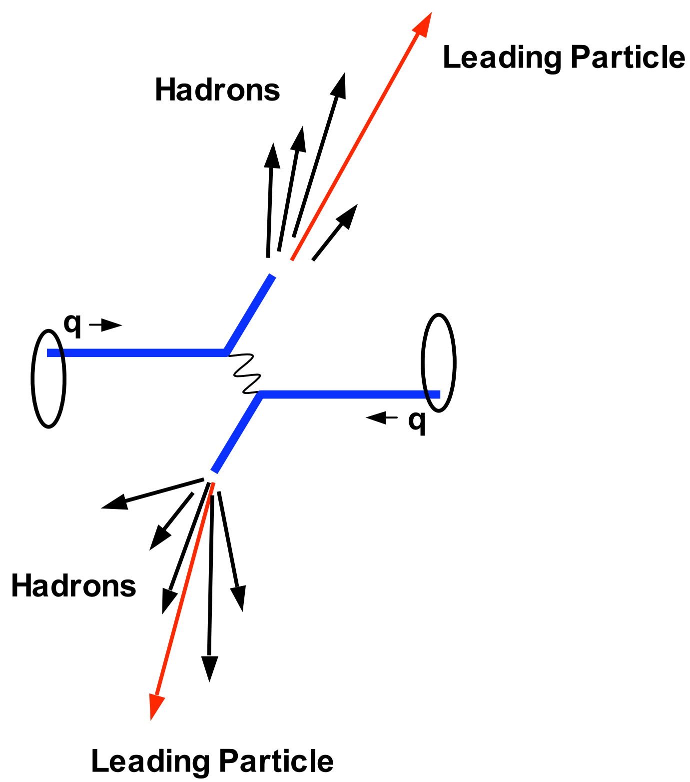
Jet cross-section calculable in QCD

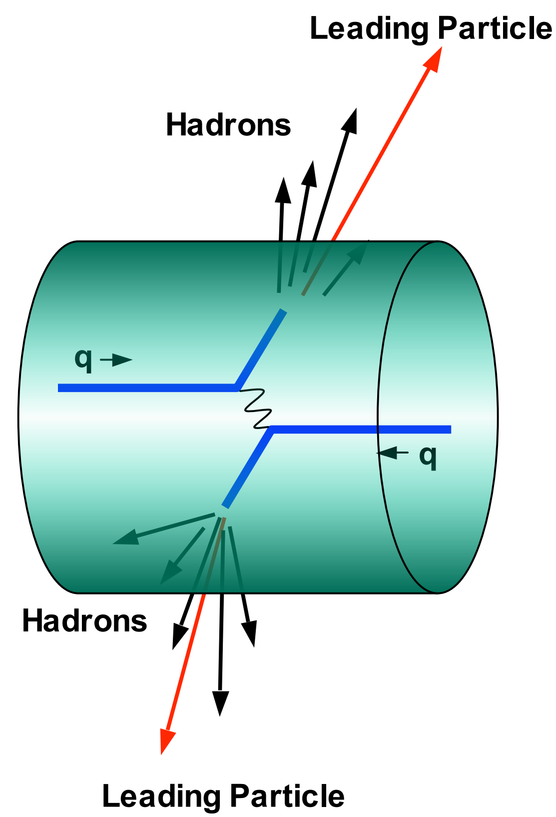




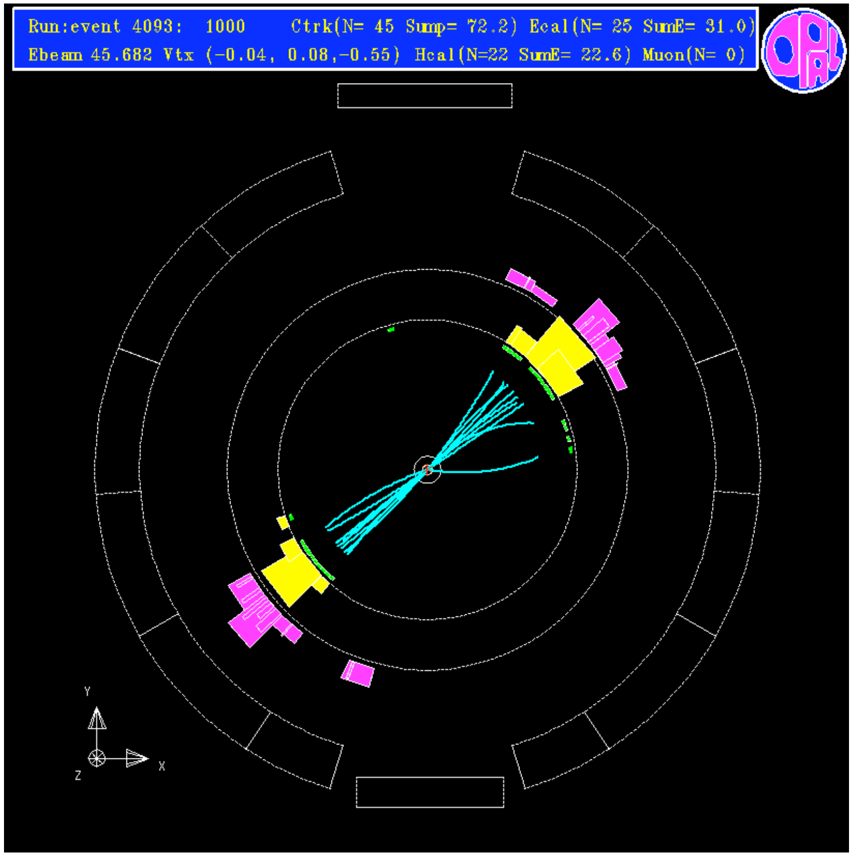
Dense Matter Diagnostics

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

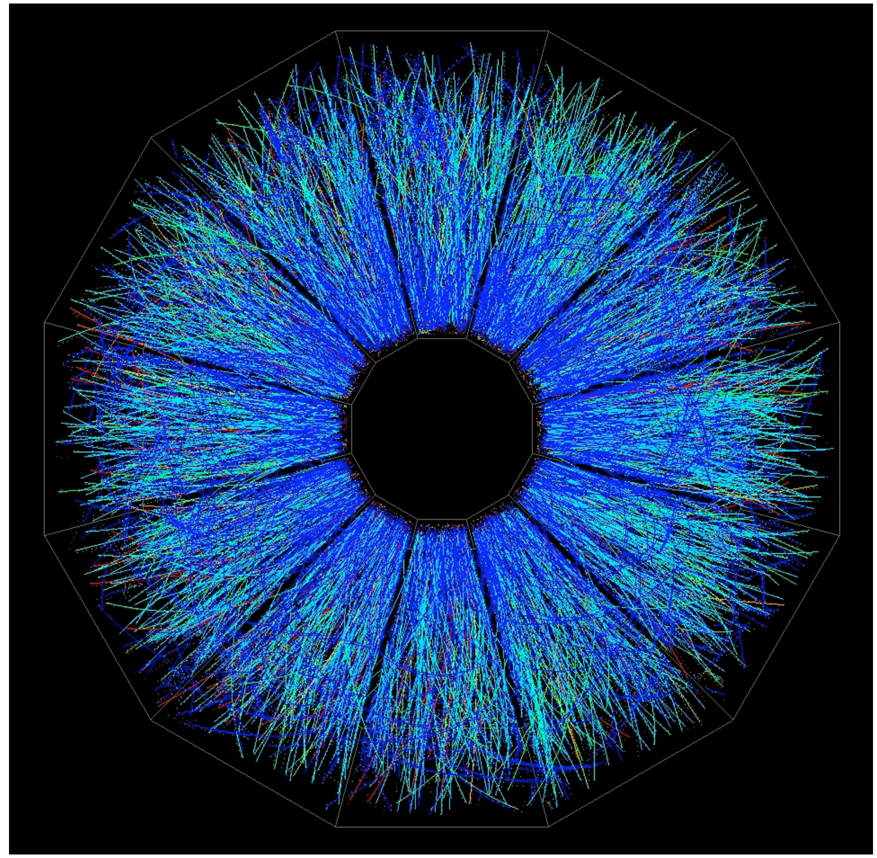




Opal e^+e^-

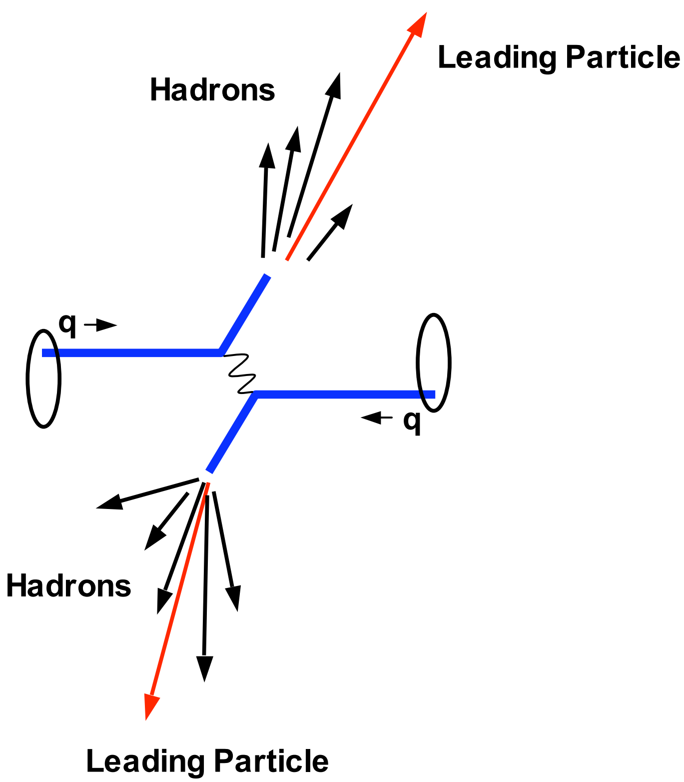


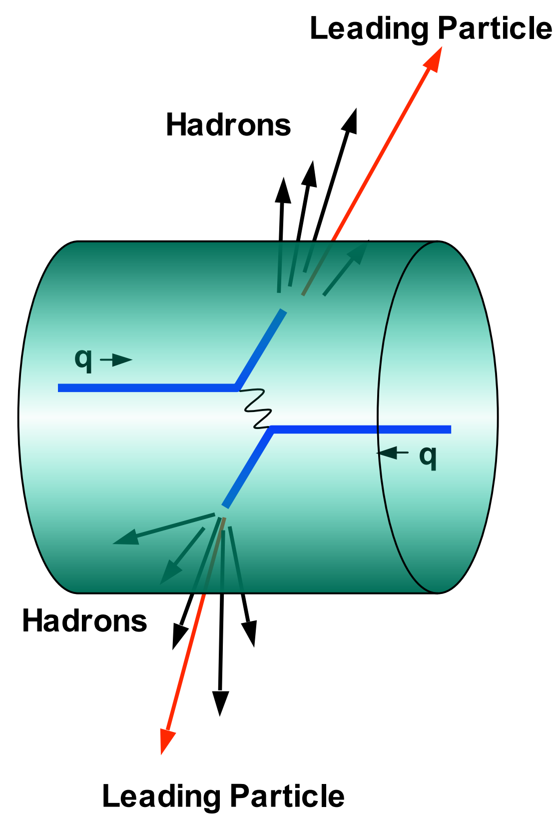
STAR Au+Au



Dense Matter Diagnostics

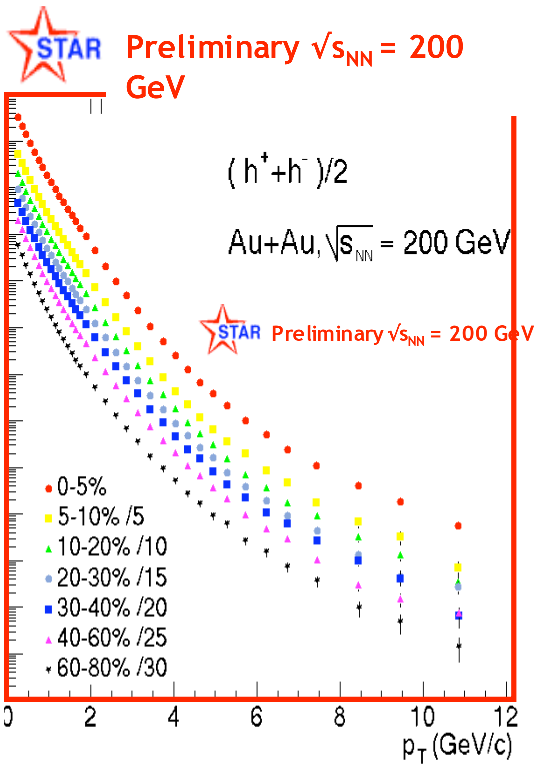
Jet cross-section calculable in QCD → Study fate of jets in dense matter in Au+Au

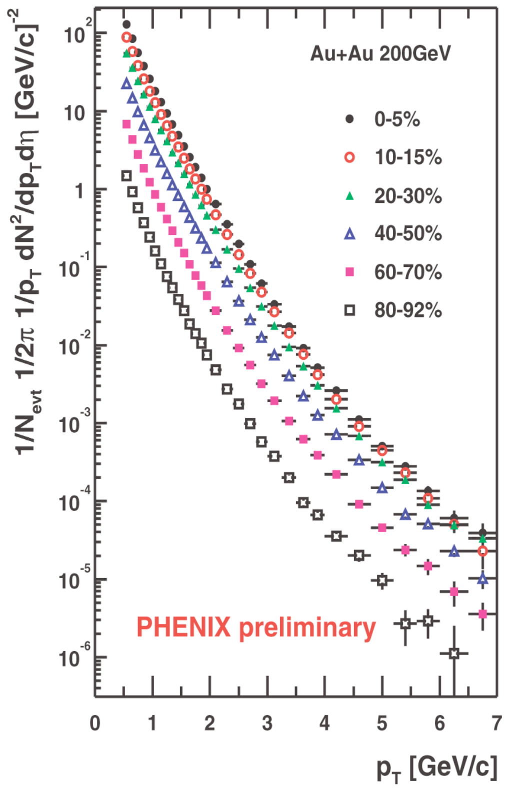


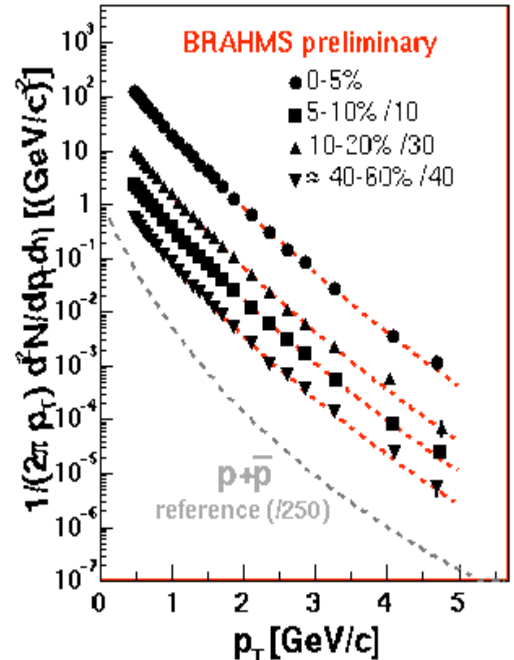


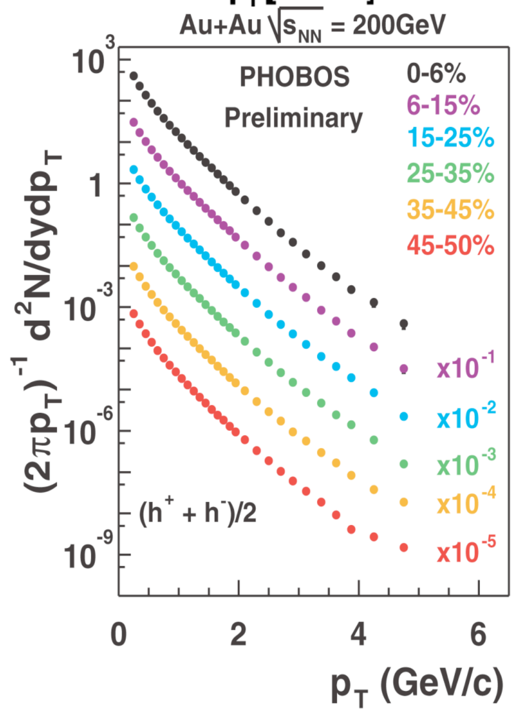
Poor man's jet: Leading Particles

Charged Hadron Spectra



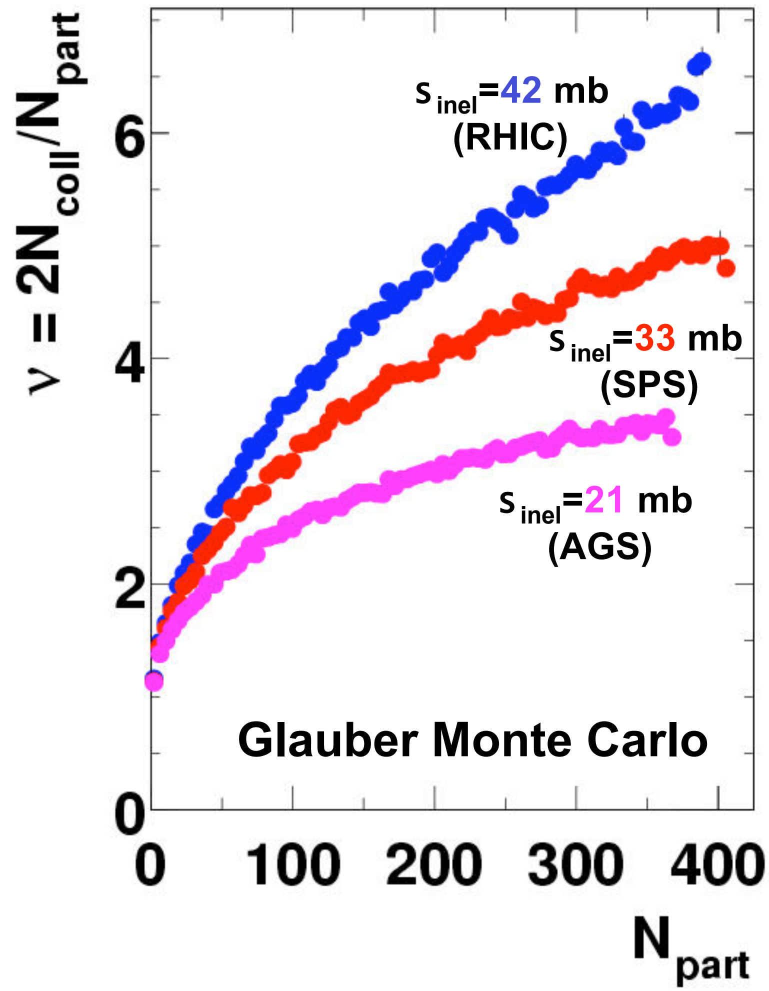






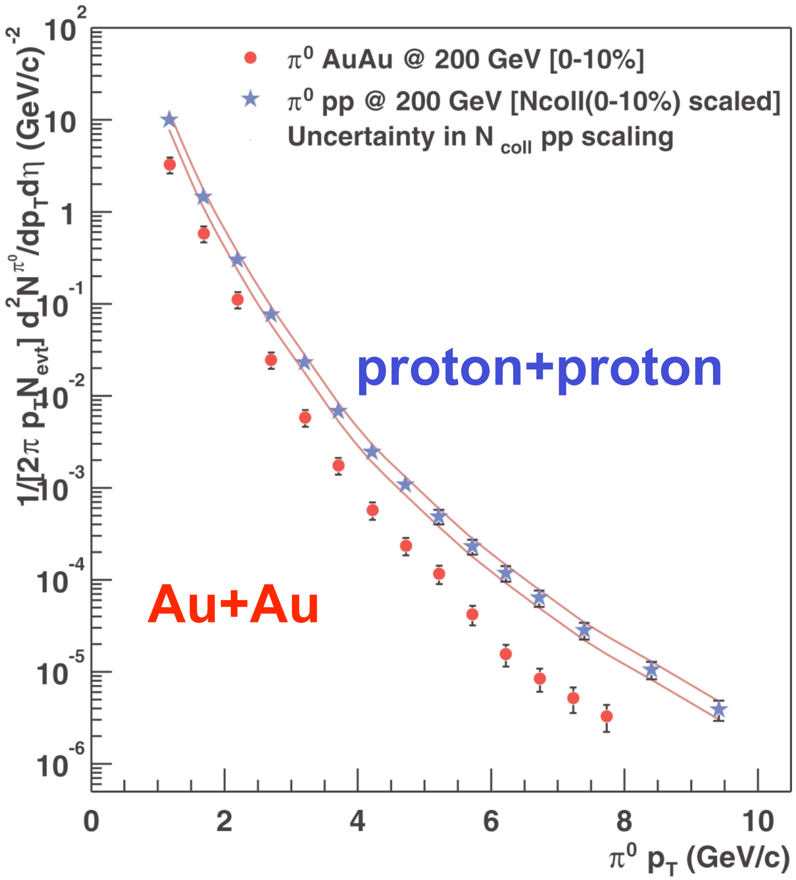
Results from all RHIC experiments!

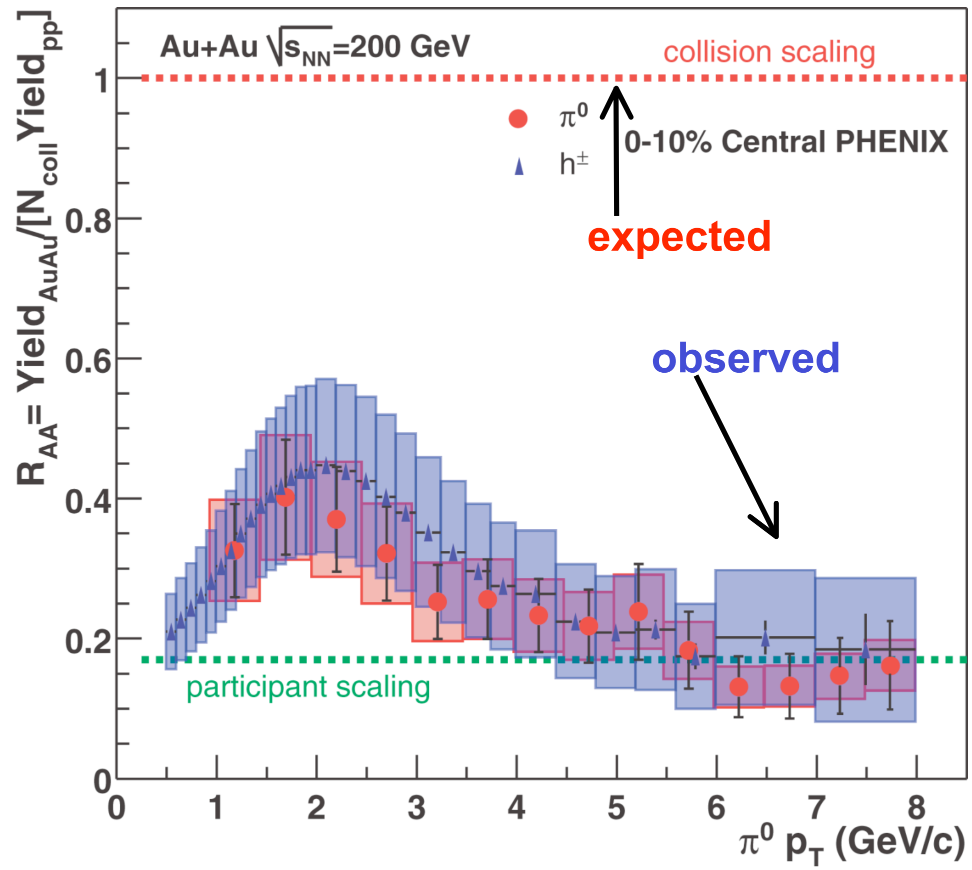
Control Parameters: Centrality



- Total yield scales with N_{part}
  - Volume-scaling <-> Coherence
- Expect N_{coll} scaling for hard (point-like) processes
  - Incoherent production

“Jet Quenching” at High p_T





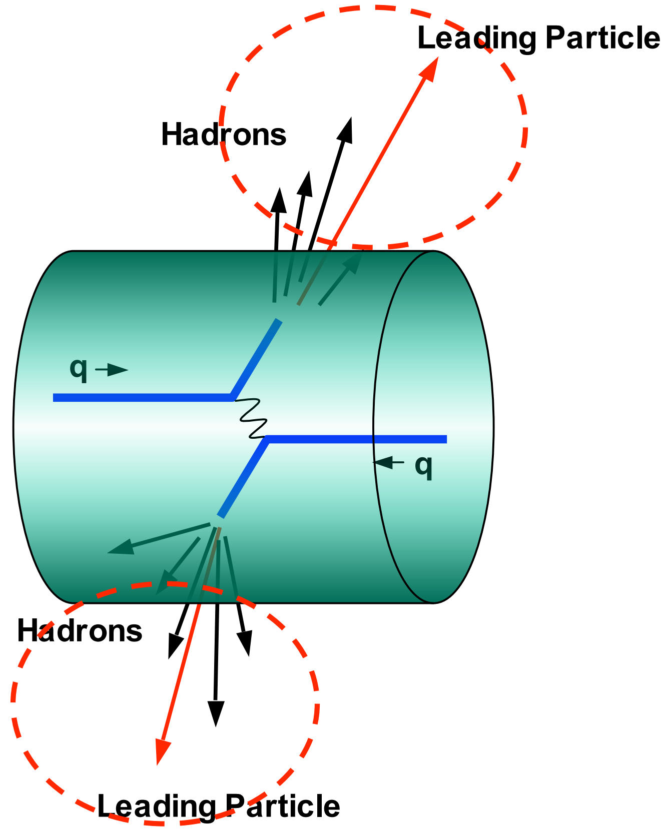
Yield at high p_T in AA is 6 times smaller than expected

Jets in Dense Matter

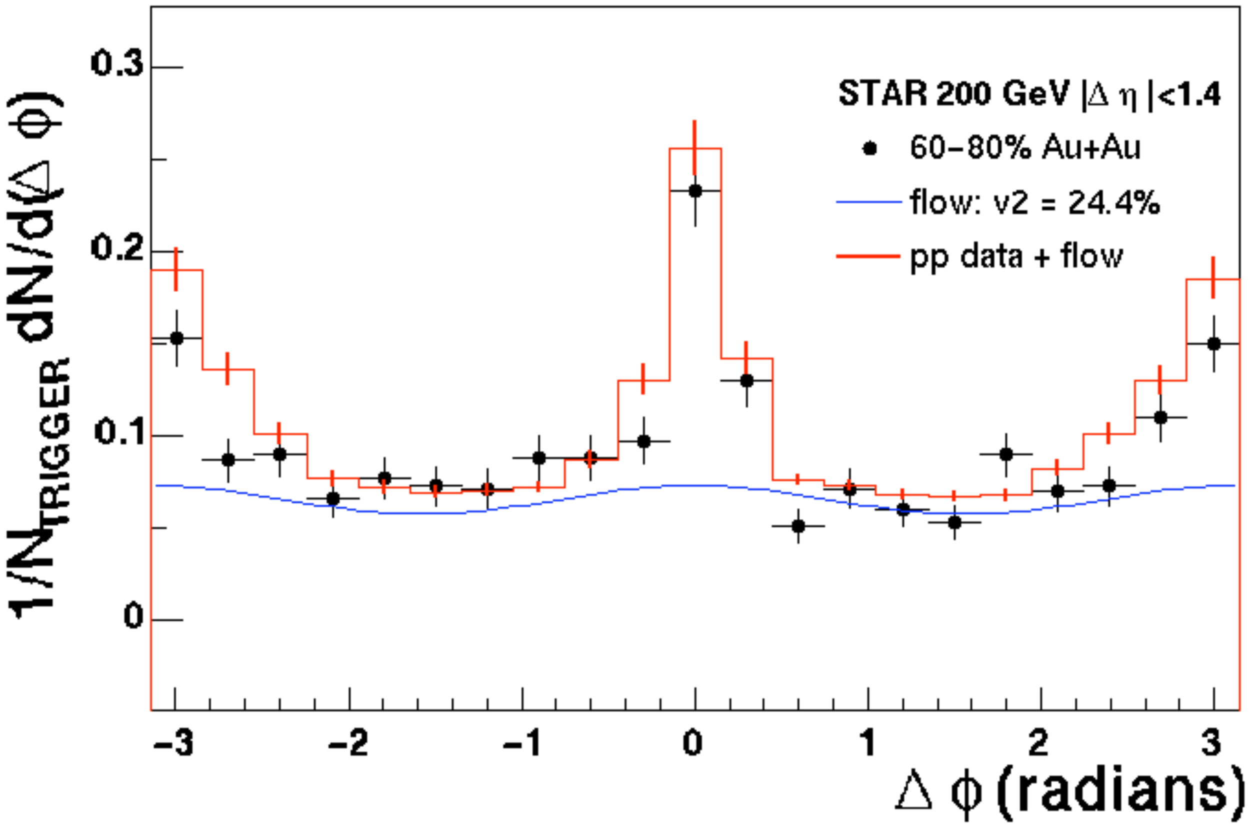
Are we really looking at jets?

- Look for jet structure by measuring
  - small angle correlations
  - back-to-back correlations

  relative to high p_T leading particle



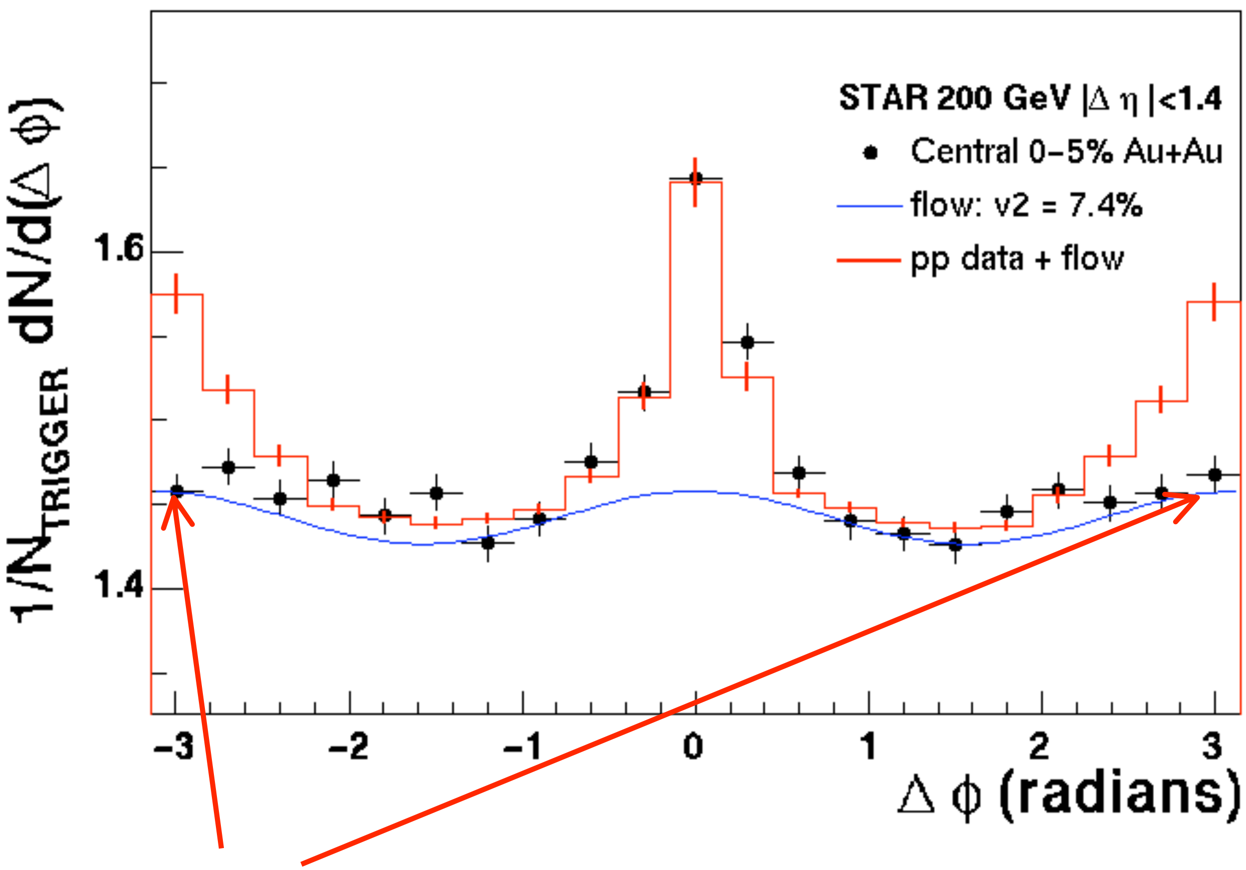
Peripheral Au+Au data



D. Hardtke
QM '02

- Jets seen in peripheral Au+Au and p+p
- Azimuthal correlations
  - Small angle (Df ~ 0)
  - Back-to-Back (Df ~ p)

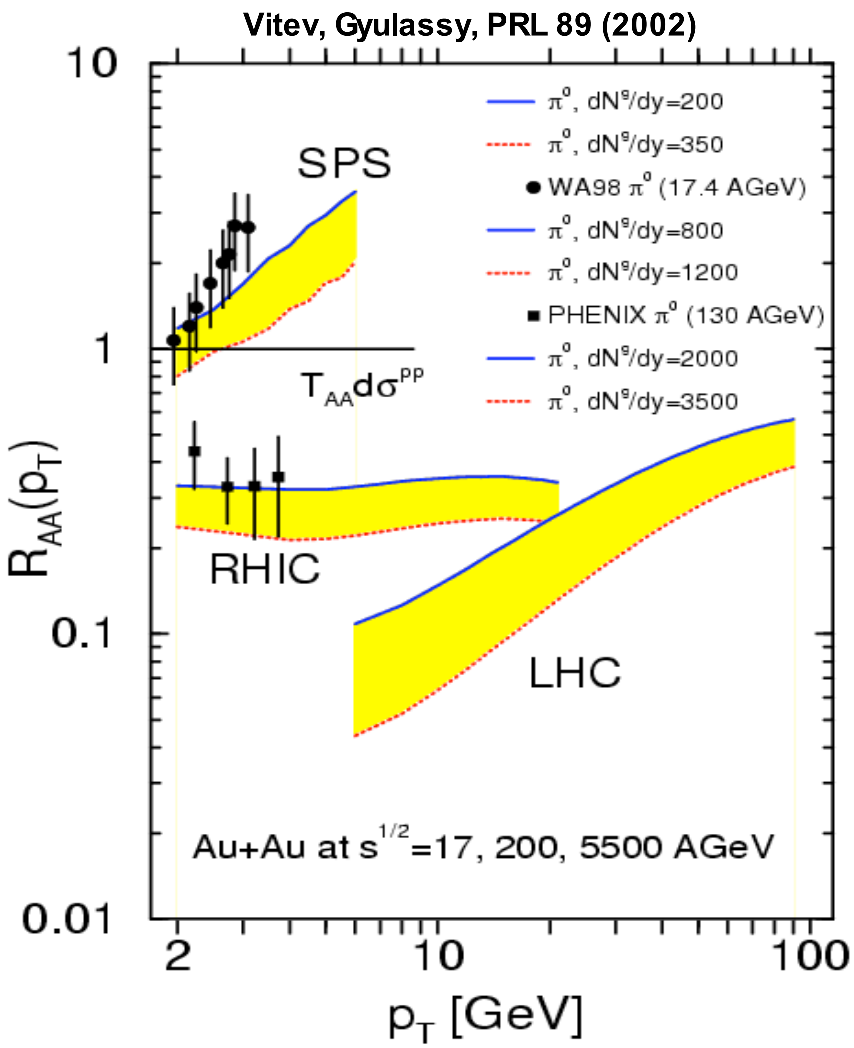
Central Au+Au data



D. Hardtke
QM ‘02

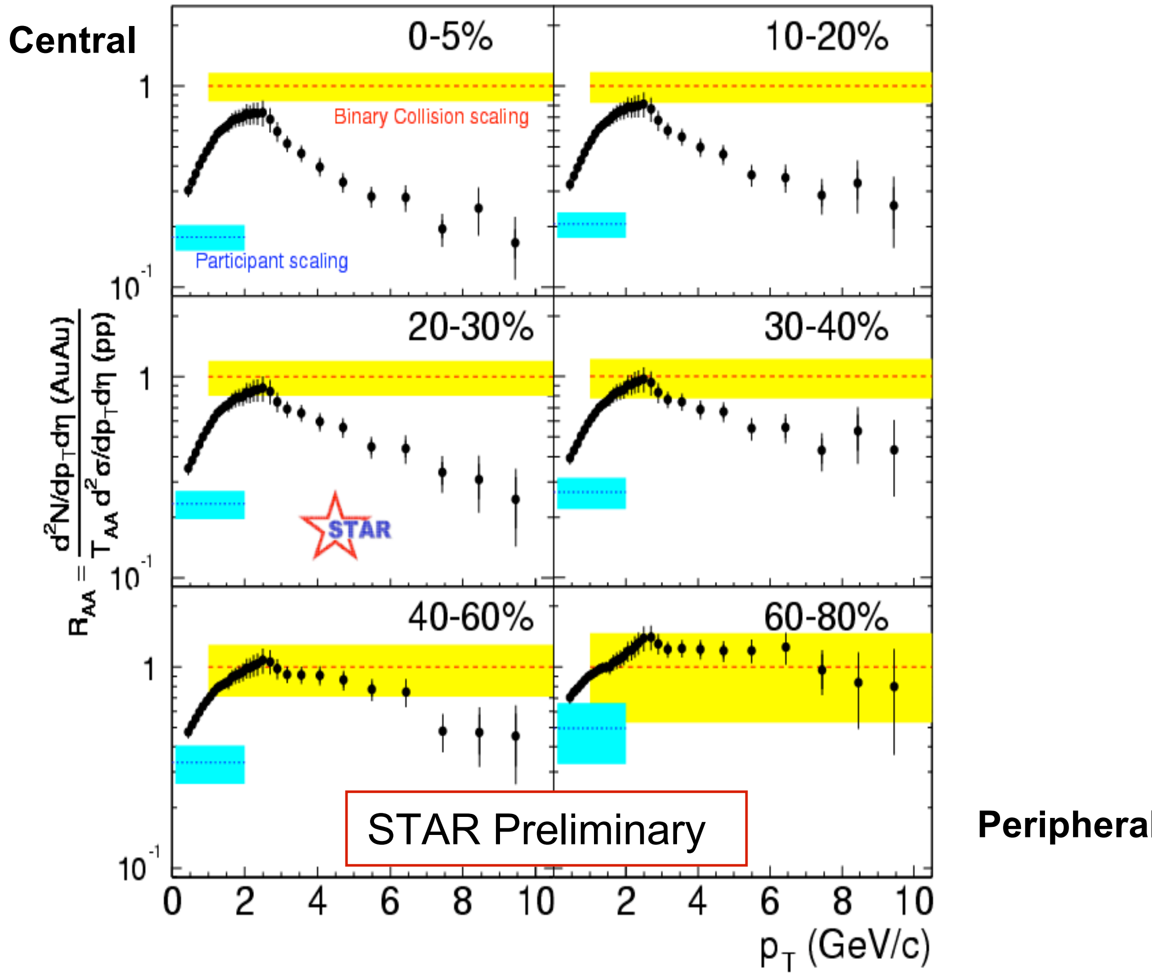
- Disappearance of back-to-back correlations in central Au+Au
- Away-side particles absorbed or scattered in medium

Jet suppression via Energy Loss

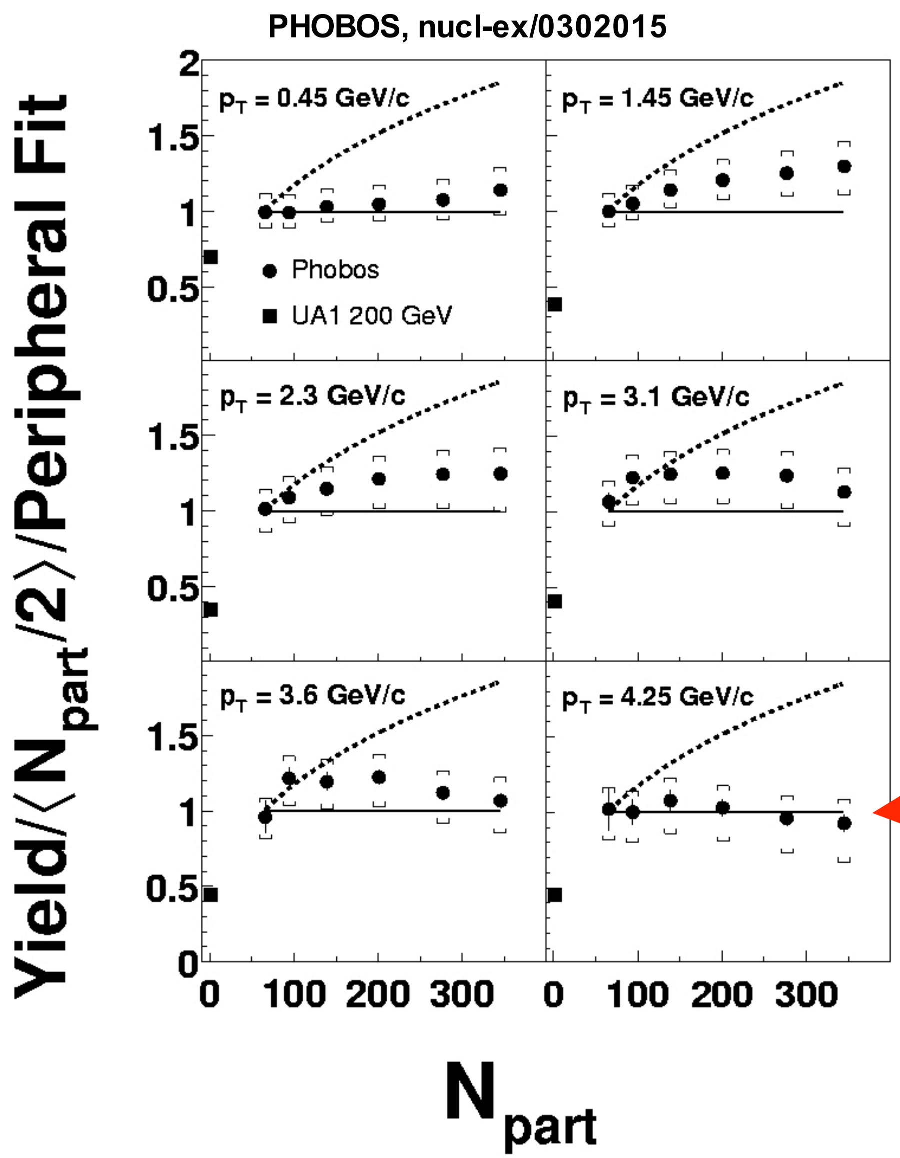


Suppression due to the energy loss of fast partons in plasma via induced gluon radiation

Centrality Dependence of Suppression

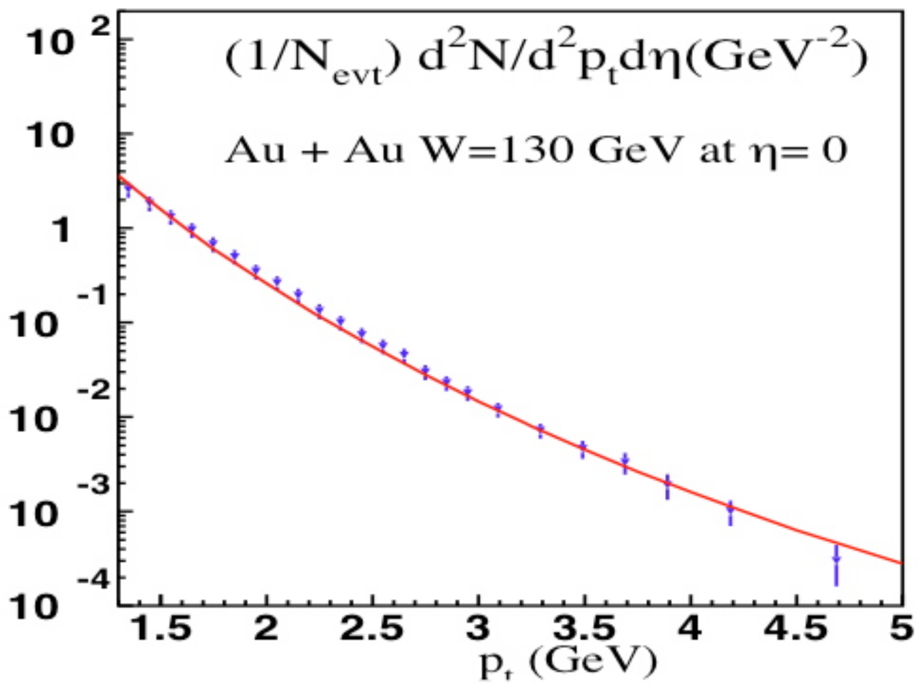


Another Look at Centrality Dependence

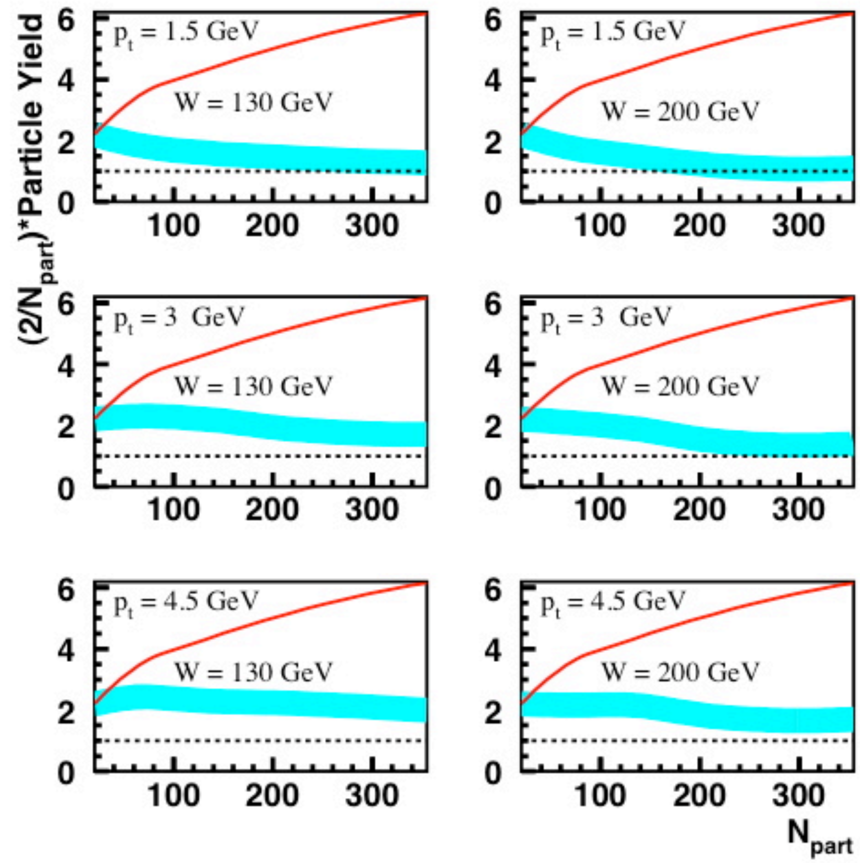


approximate N_{part}-scaling at "intermediate" p_T !?

N_{part} Scaling in Saturation Model

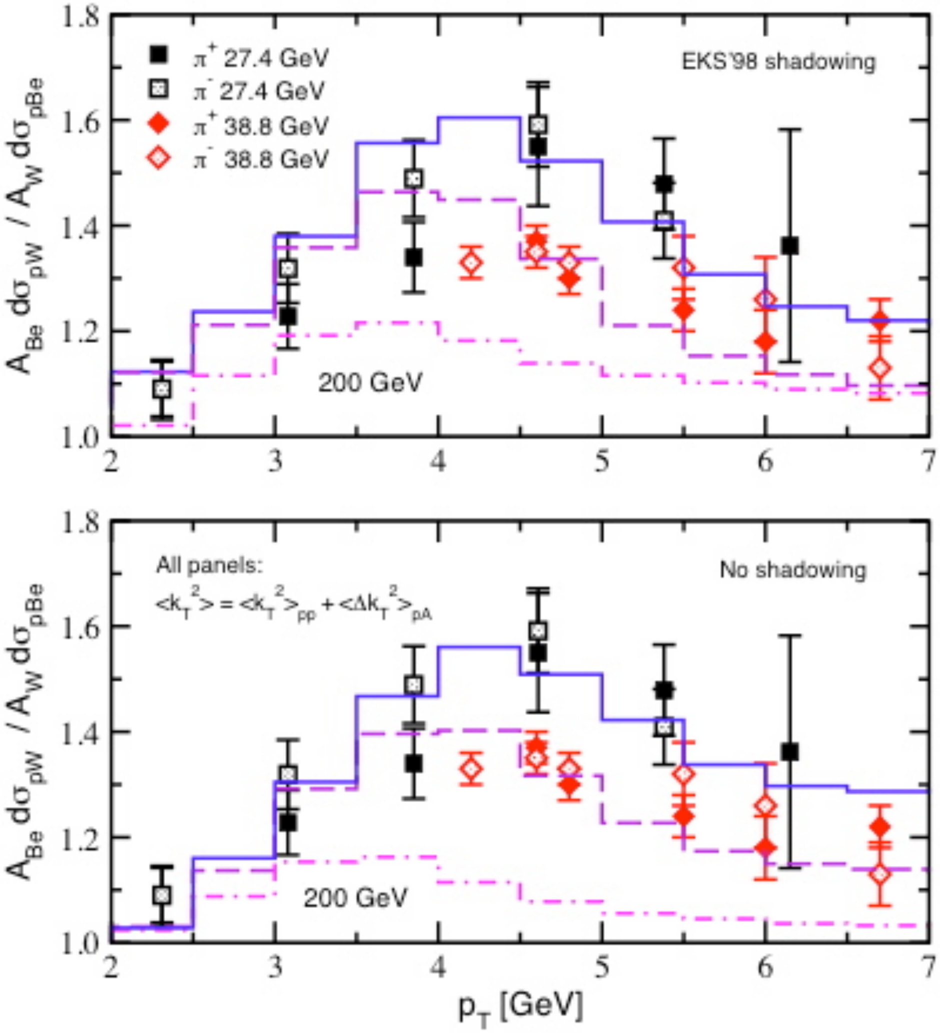


Kharzeev, Levin, McLerran, hep-ph/021332



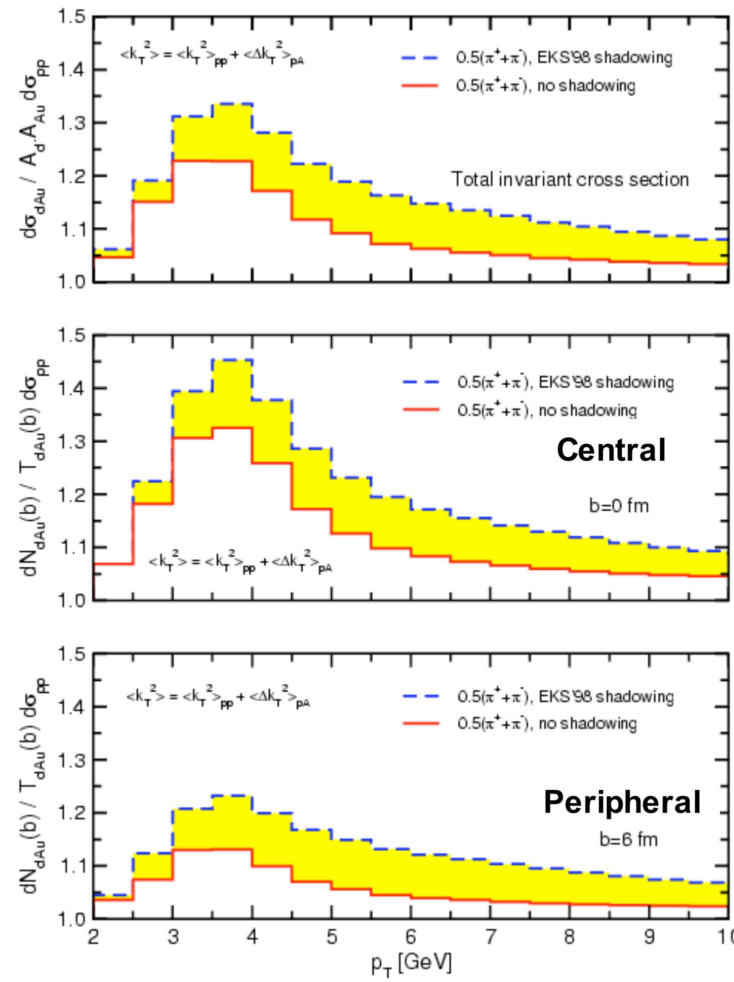
High p_T suppression as an initial state effect:
Parton saturation breaks incoherence

Experimental Test: d+Au



Fixed target p+A data

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



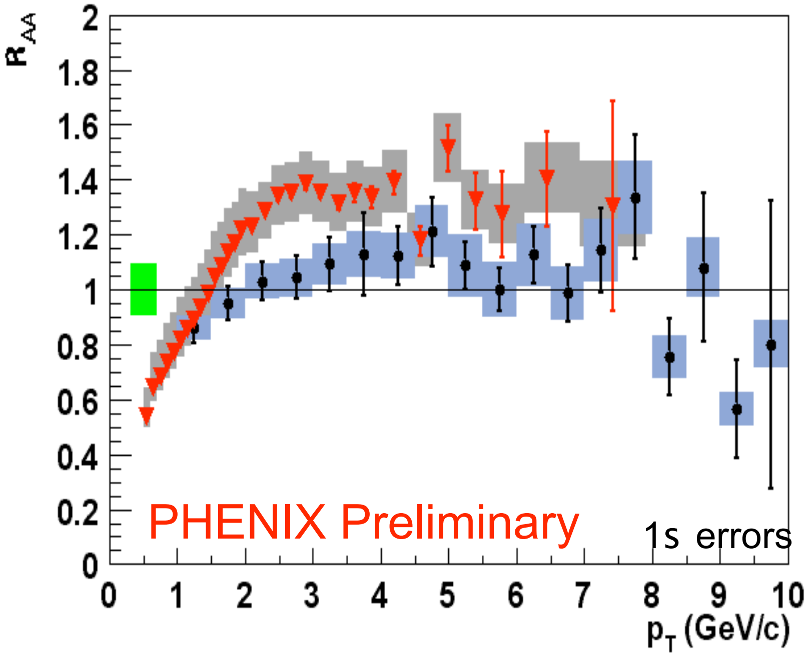
Prediction for RHIC

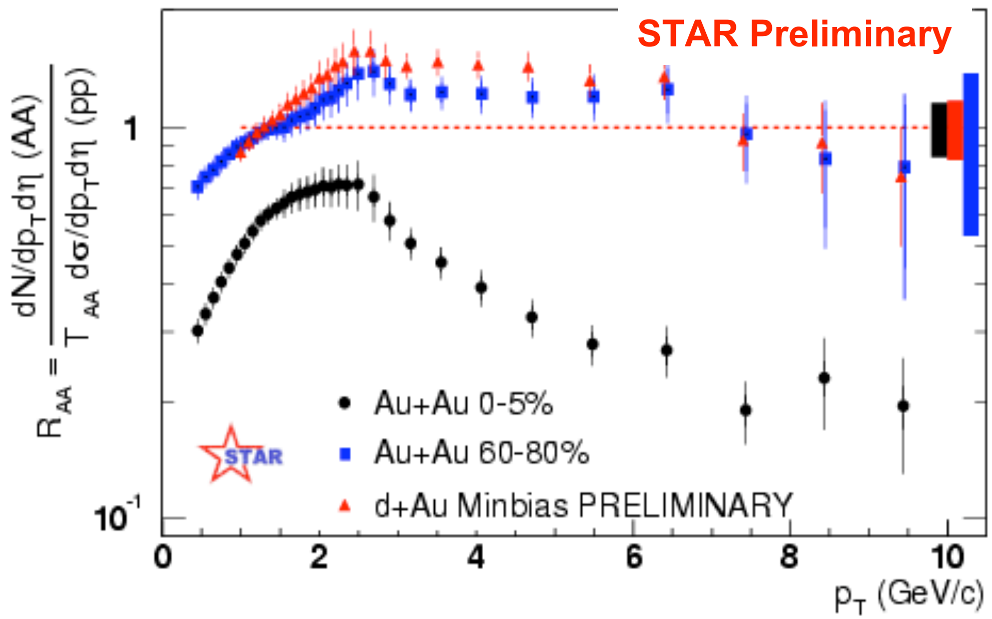
Experimental Test: d+Au

We expect the saturation effects to set in around $N_{part}^{Au} \simeq 6$, corresponding to the impact parameter of dAu collision $b = 5 \div 6$ fm [53]. We thus predict that around $N_{part}^{Au} \simeq 6$ the yields of high p_t particles would begin to deviate from the scaling with the number of collisions $N_{coll} \sim N_{part}^{Au}$; the yield per participant will start to decrease as $(N_{part}^{Au})^{-1/2}$. In 15% most central dAu events, where $N_{part}^{Au} \simeq 12$ [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†.

Kharzeev, Levin, McLerran, hep-ph/021332

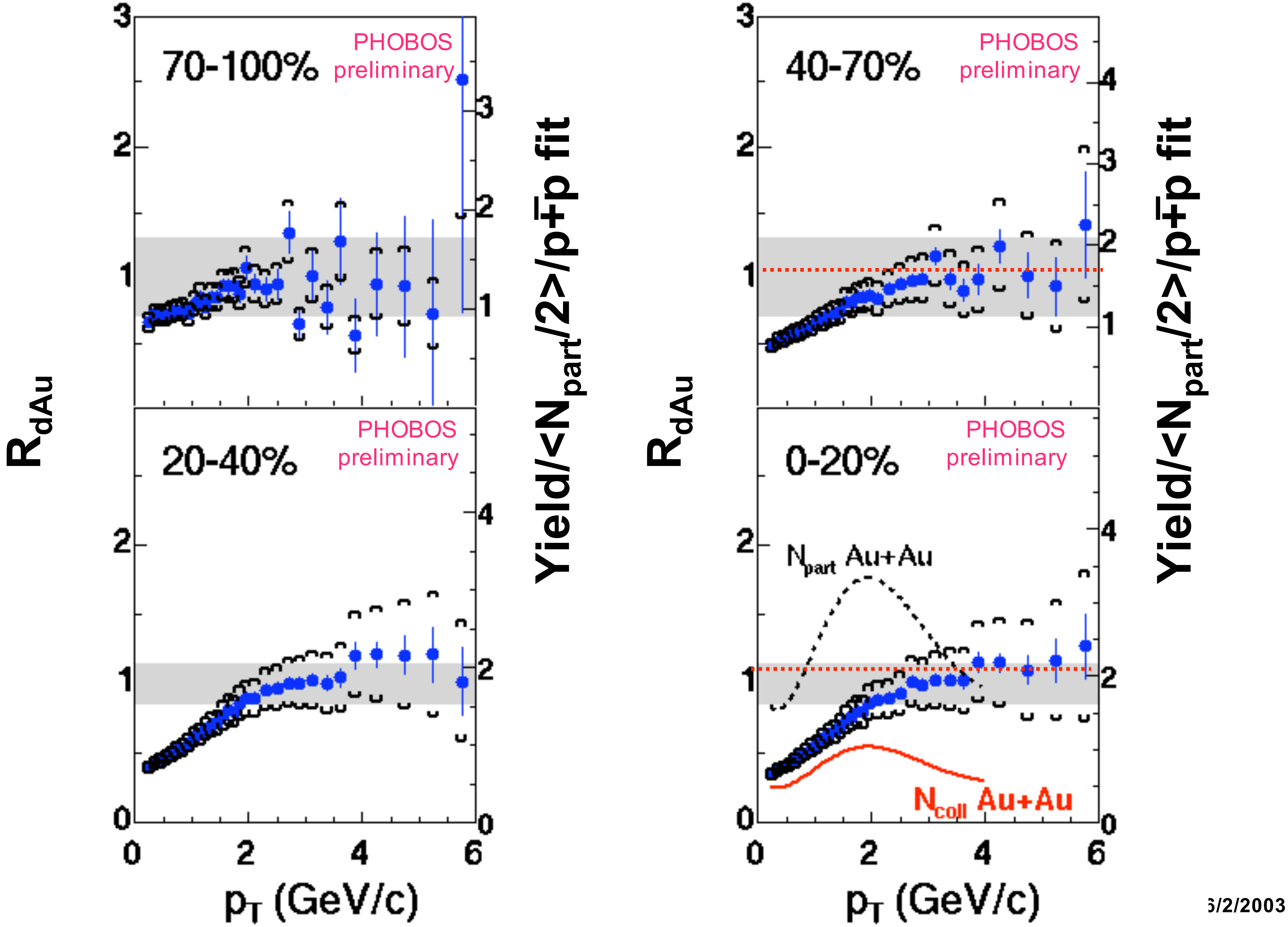
Preliminary Results for d+Au



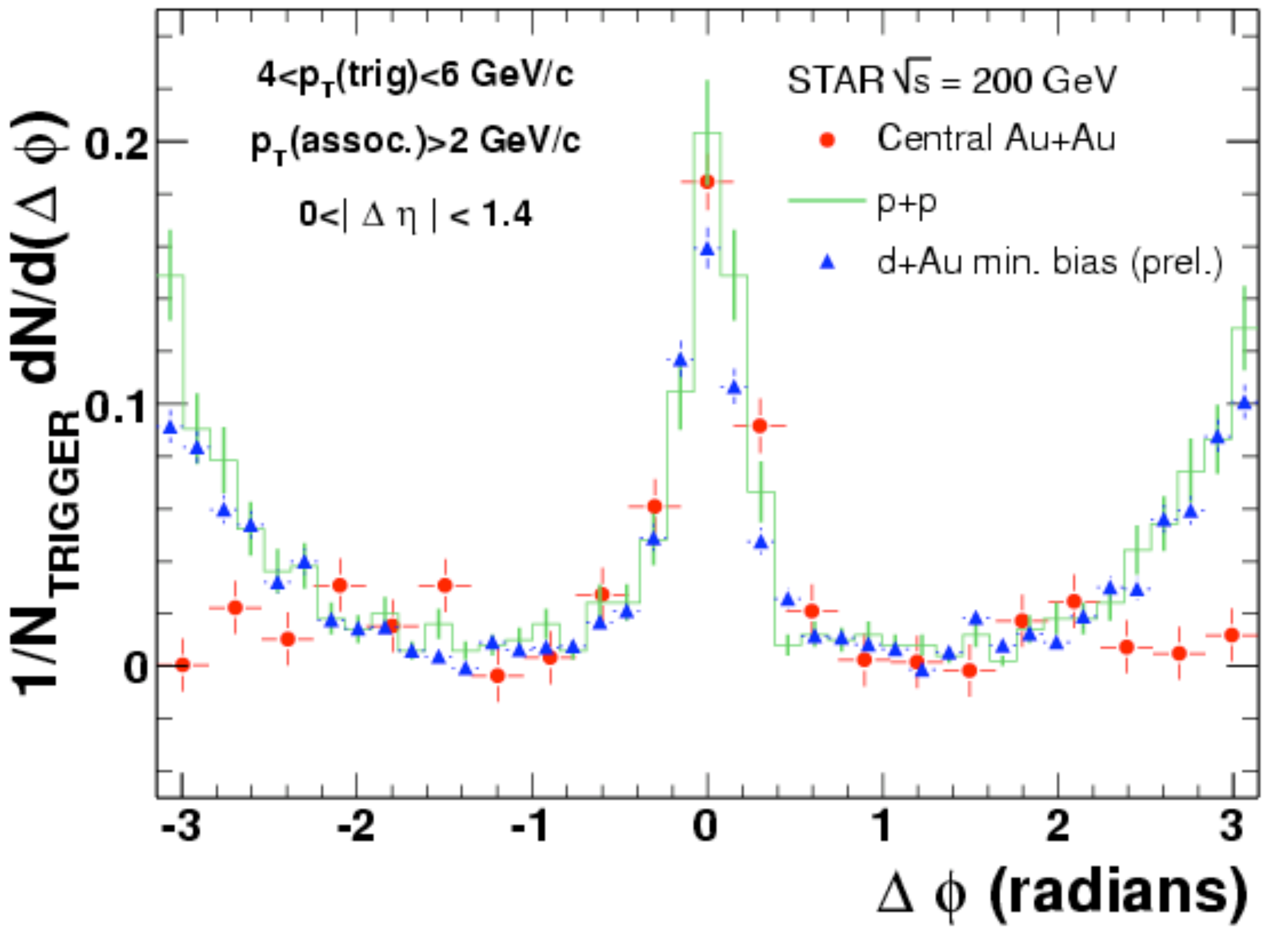


- Min-bias d+Au data from PHENIX/STAR, relative to p+p
  - Similar to low-energy data (Cronin effect)
  - No suppression

Centrality dependence of R_{dAu}



Back-to-back 'Jets' in d+Au



d+Au

Au+Au

Preliminary Lesson from d+Au

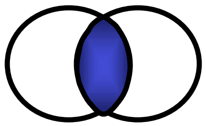
- Back-to-Back Jets are observed
- Data compatible with extrapolation of Cronin-effect to RHIC
- No suppression effects seen
- If data holds: "Jet quenching" indicative of light parton energy loss (2-3 GeV) in a dense medium

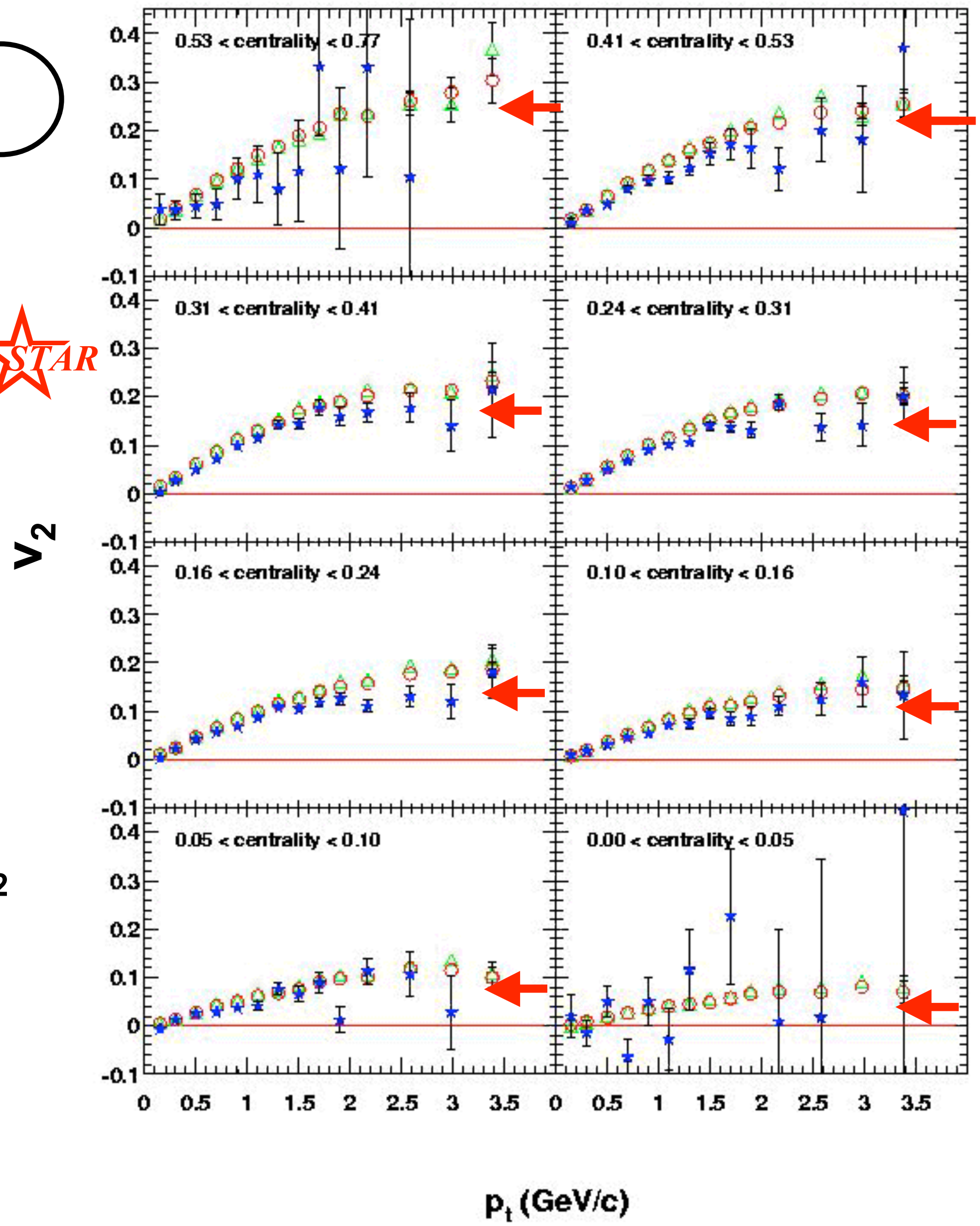
Some high-p_T "puzzles" remain ->

“Instant” Thermalization

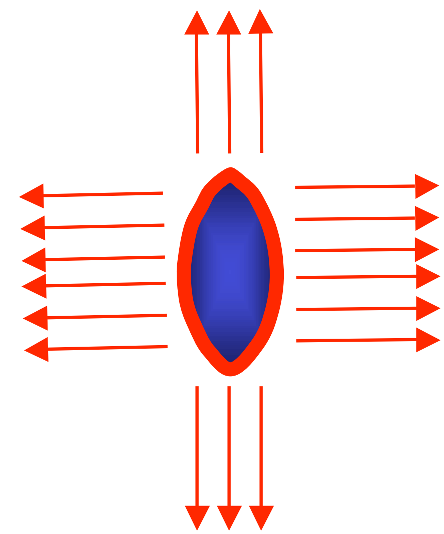
E. Shuryak, nucl-th/0112042

Peripheral

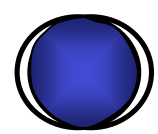




Limit (l_{mfp} = 0)

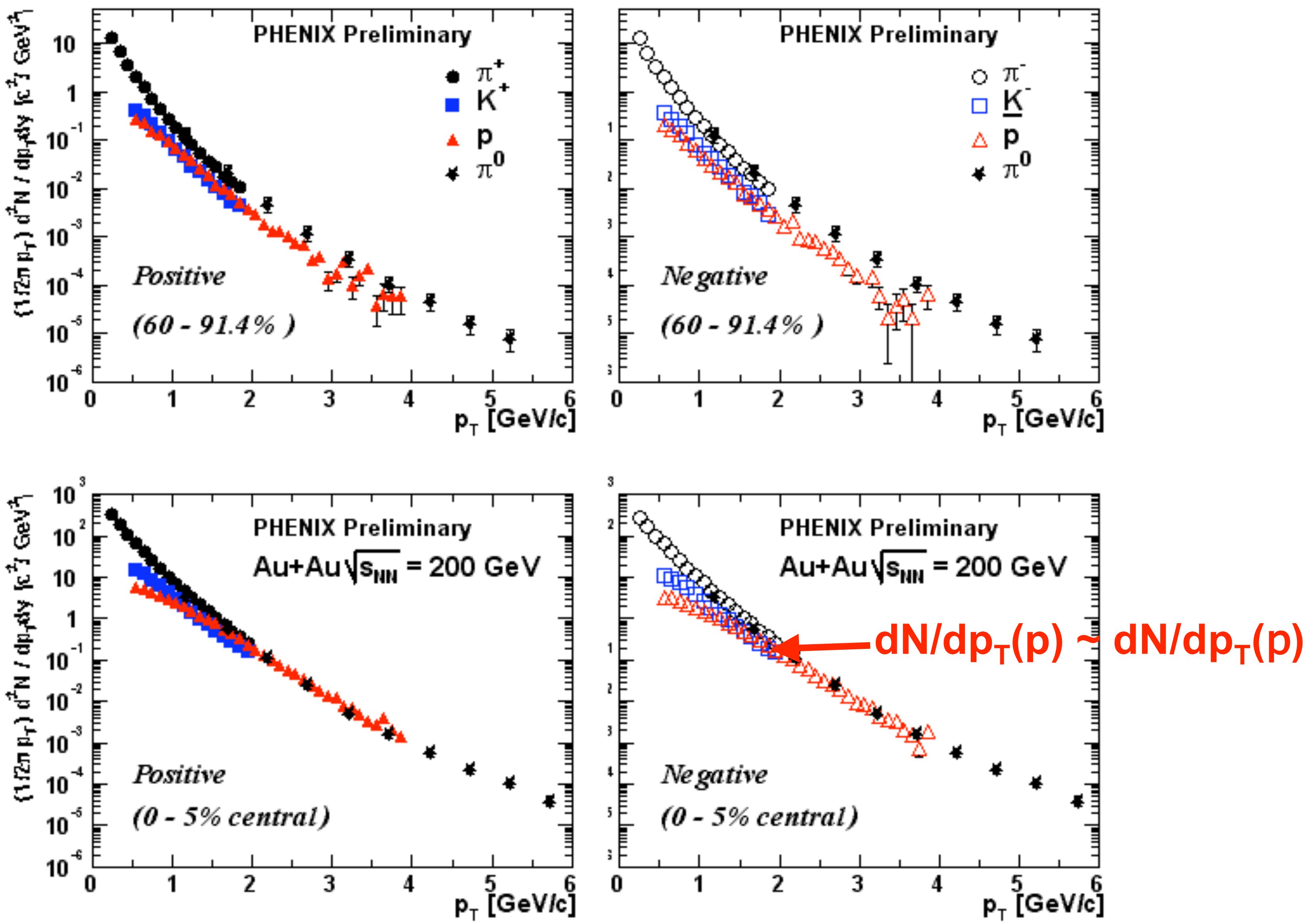


S. Voloshin, QM’02

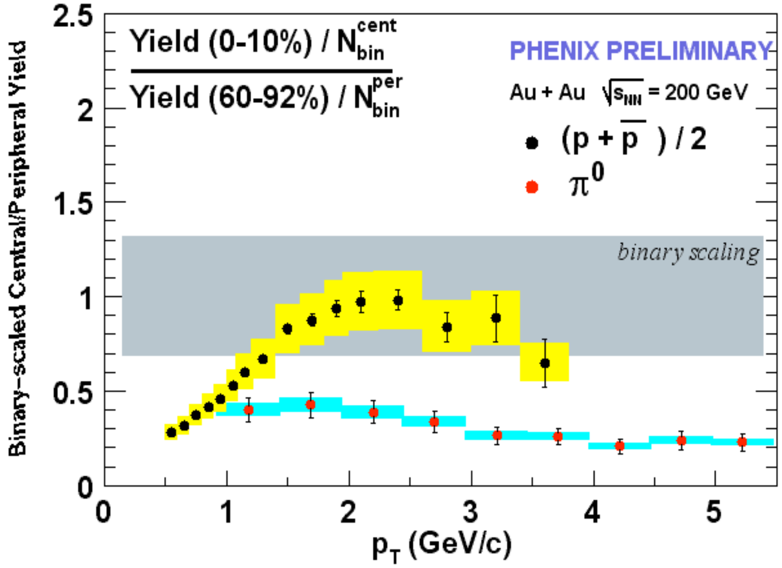


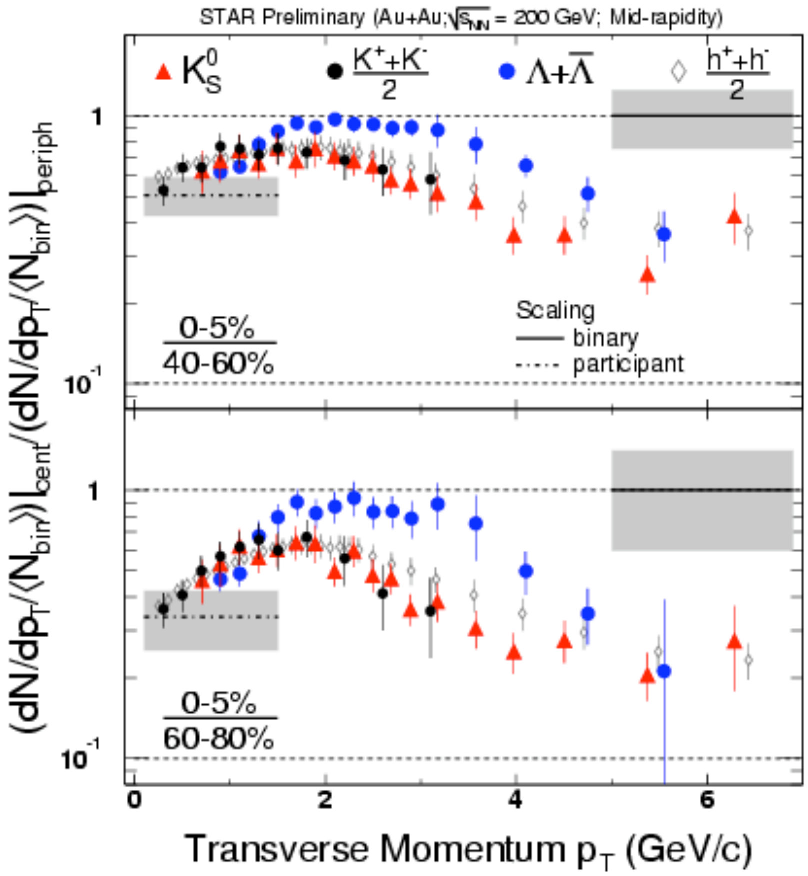
Central

"Proton puzzle"



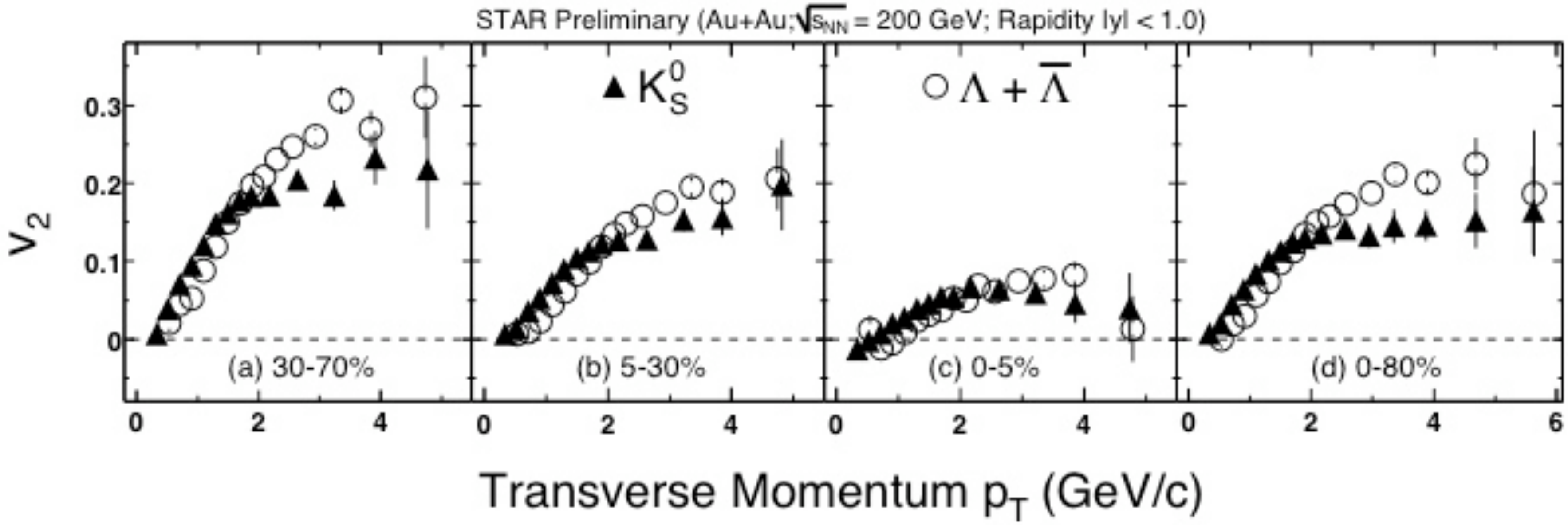
"Suppression" for light/heavy hadrons





- High-p_T hadrons from fragmentation of fast partons:
  - Suppression/energy loss should effect all hadrons
  - But: No suppression for baryons at $2 < p_T < 4$ GeV/c

Baryon v_2



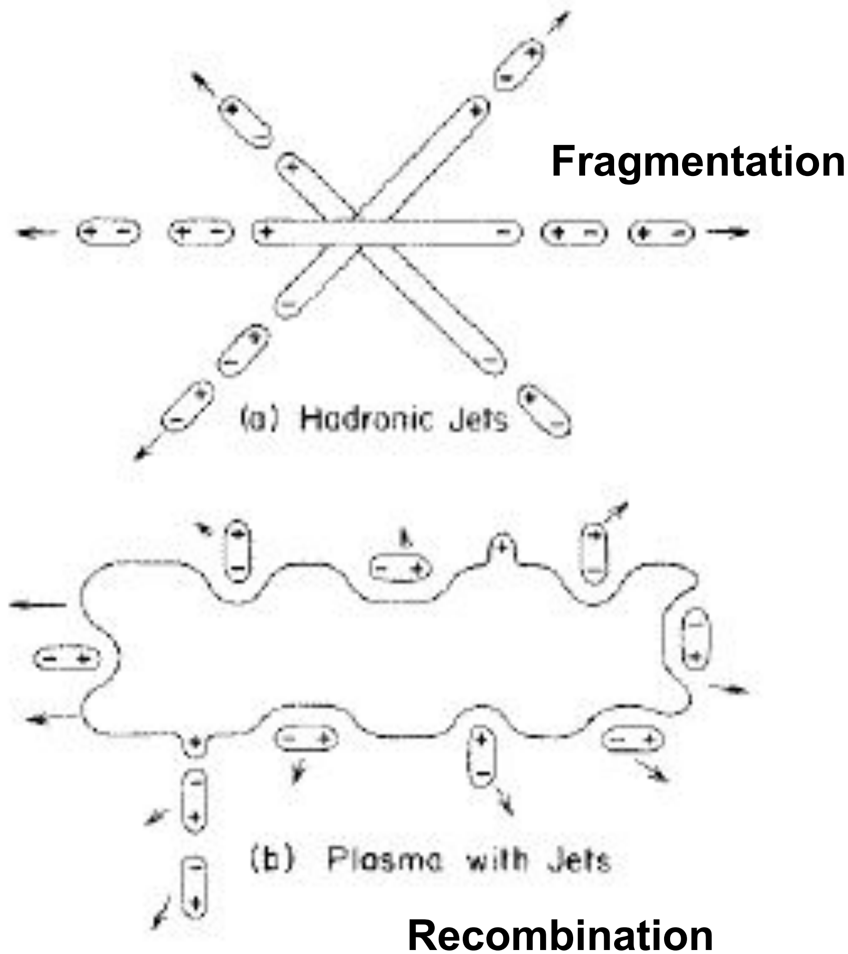
- **At high-p_T**
  - **Baryon anisotropy exceeds that for mesons**
  - **Also seen for p vs p**

New (old) Idea: Recombination

Fries, Mueller, Nonaka, Bass, nucl-th/0301087
Greco, Ko, Levai, nucl-th/0301093
Molnar, Voloshin, nucl-th/0302014]

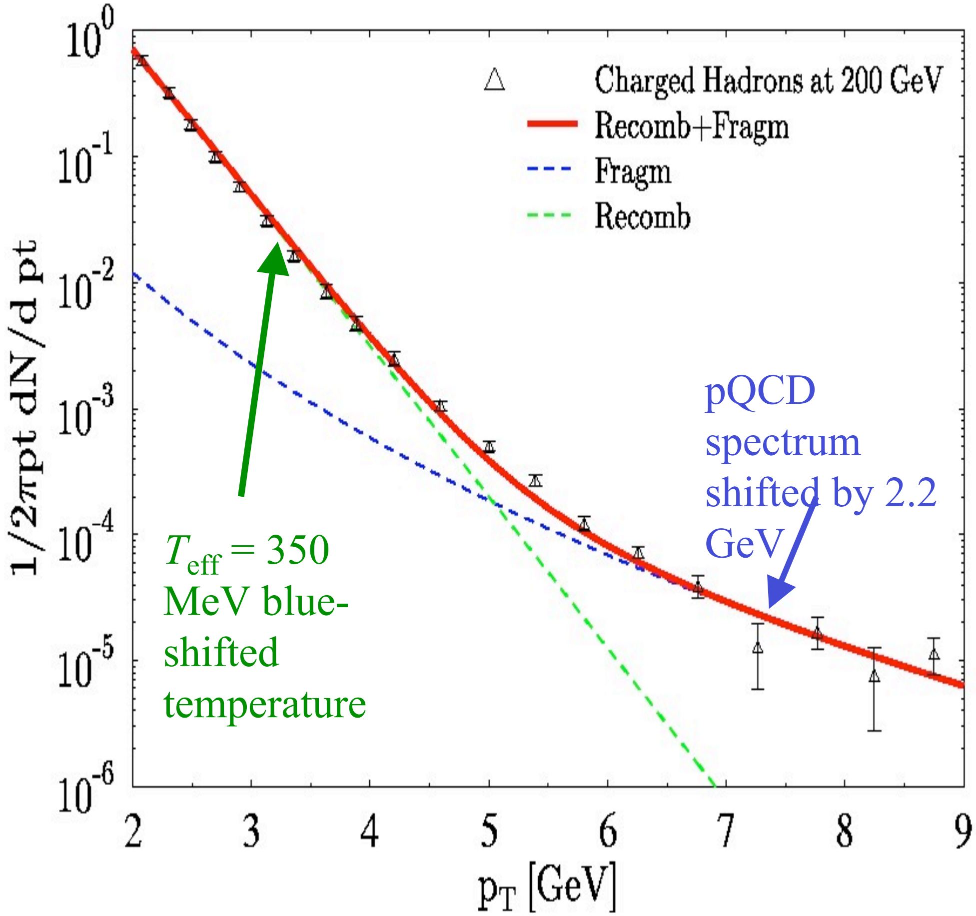
Lopez, Parikh, Siemens, PRL 53 (1984) 1216

- Dense partonic medium
  - Hadron production by quark recombination (coalescence)
  - Fries et al: Favorable relative to fragmentation for thermal parton momentum distribution

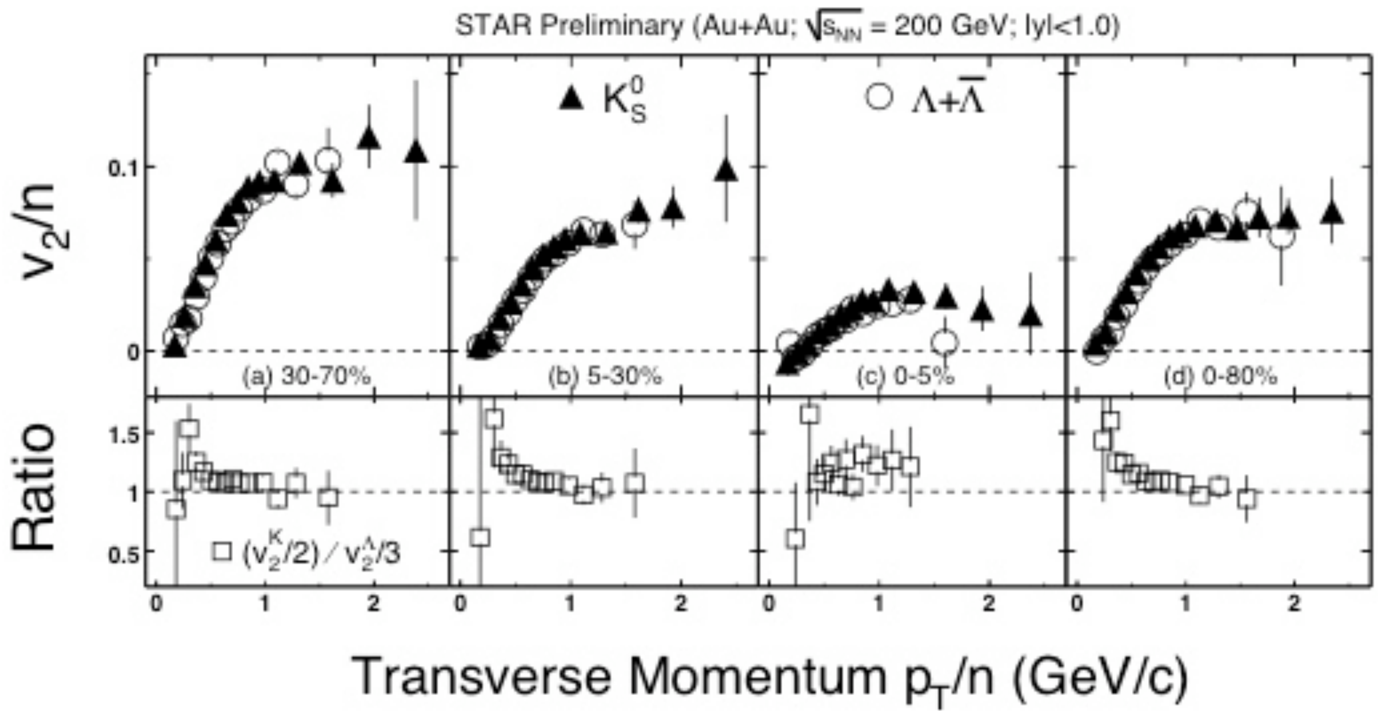


Recombination/Fragmentation

Fries, Mueller, Nonaka,Bass nucl-th/0301087



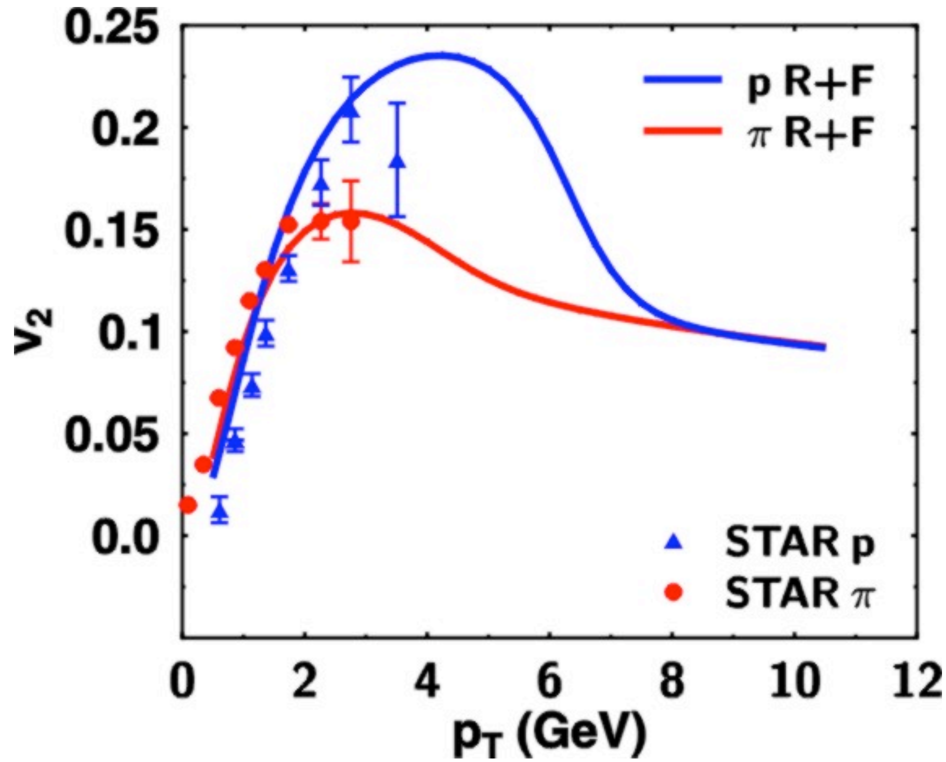
Recombination and v_2



- **Looking "per quark":**
  - **Common behavior for Baryons/Mesons**
  - **Do we see partonic flow?**
  - **Gluons? Entropy?**

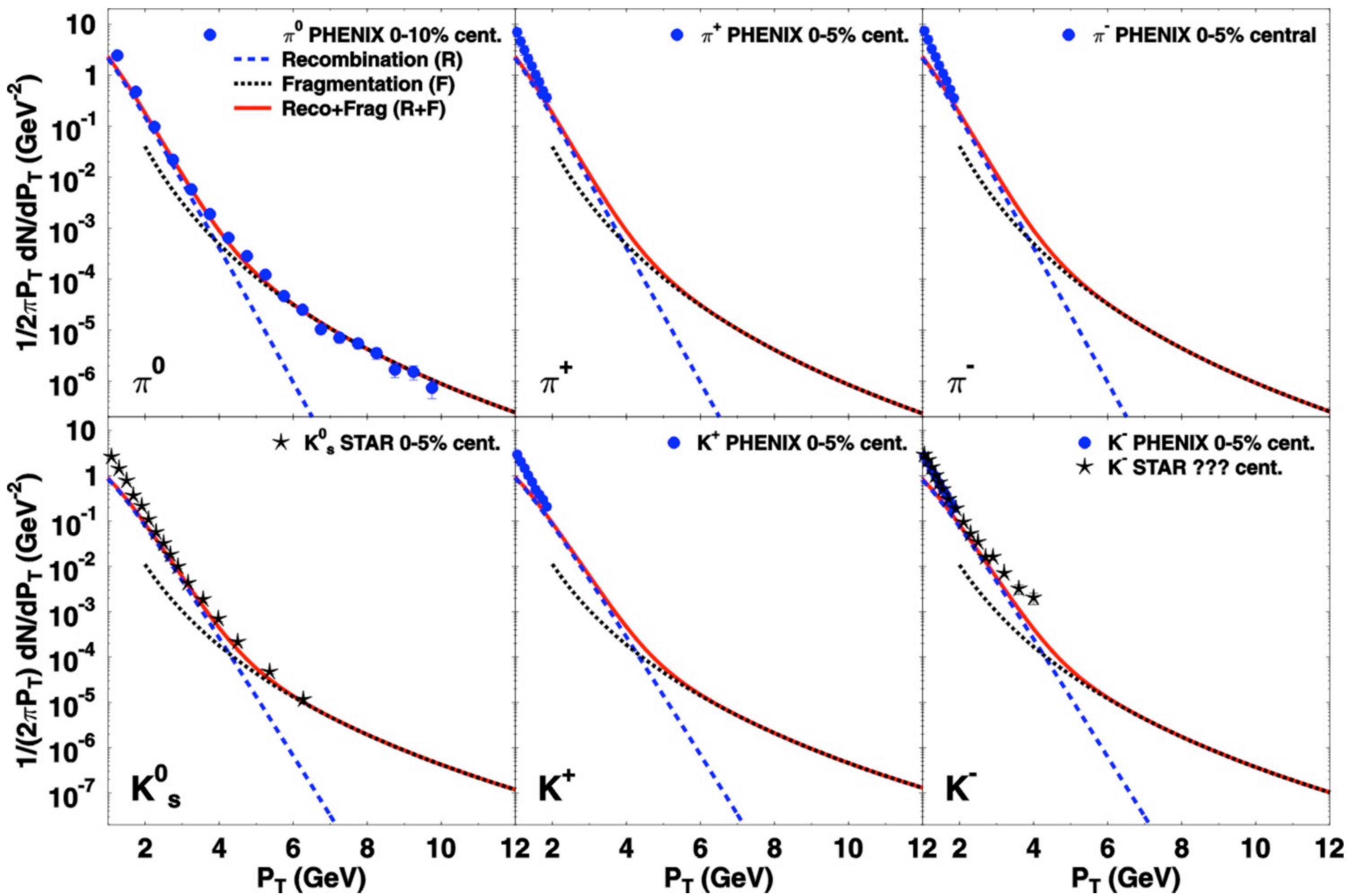
Recombination/Fragmentation and v_2

Bass, CIPANP '03



Recombination/Fragmentation and Spectra

Bass, CIPANP '03



Summary Lecture II

- Extensive data sets for intermediate/high p_T
- Observation of several unique effects
  - Violation of collision scaling
  - Large elliptic flow (Baryons vs Mesons)
  - Proton puzzle
- New data (d+Au) and new ideas (recombination)
  - Suggest we're looking at:
    - Energy loss of fast partons in dense partonic matter
    - Collective flow of partonic matter