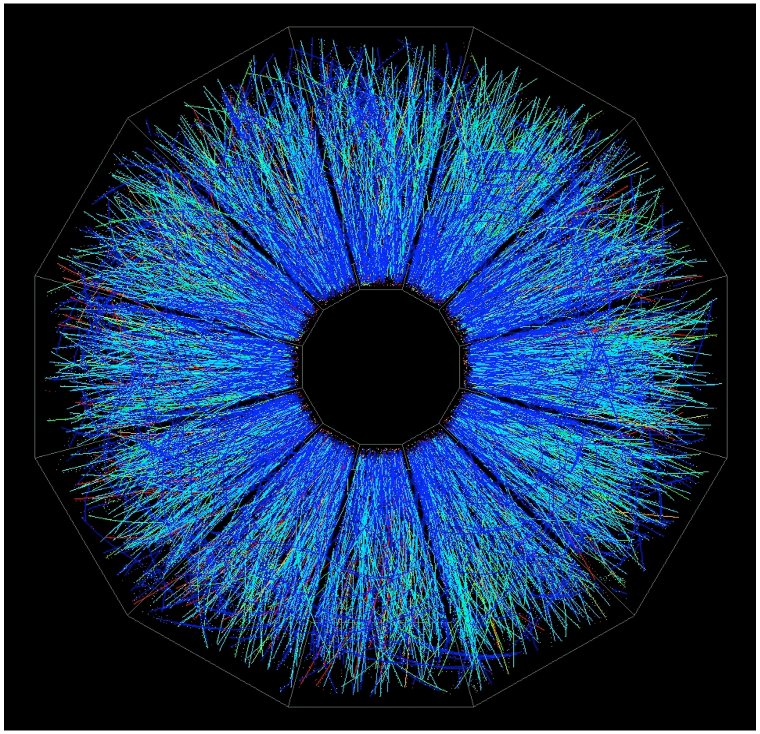
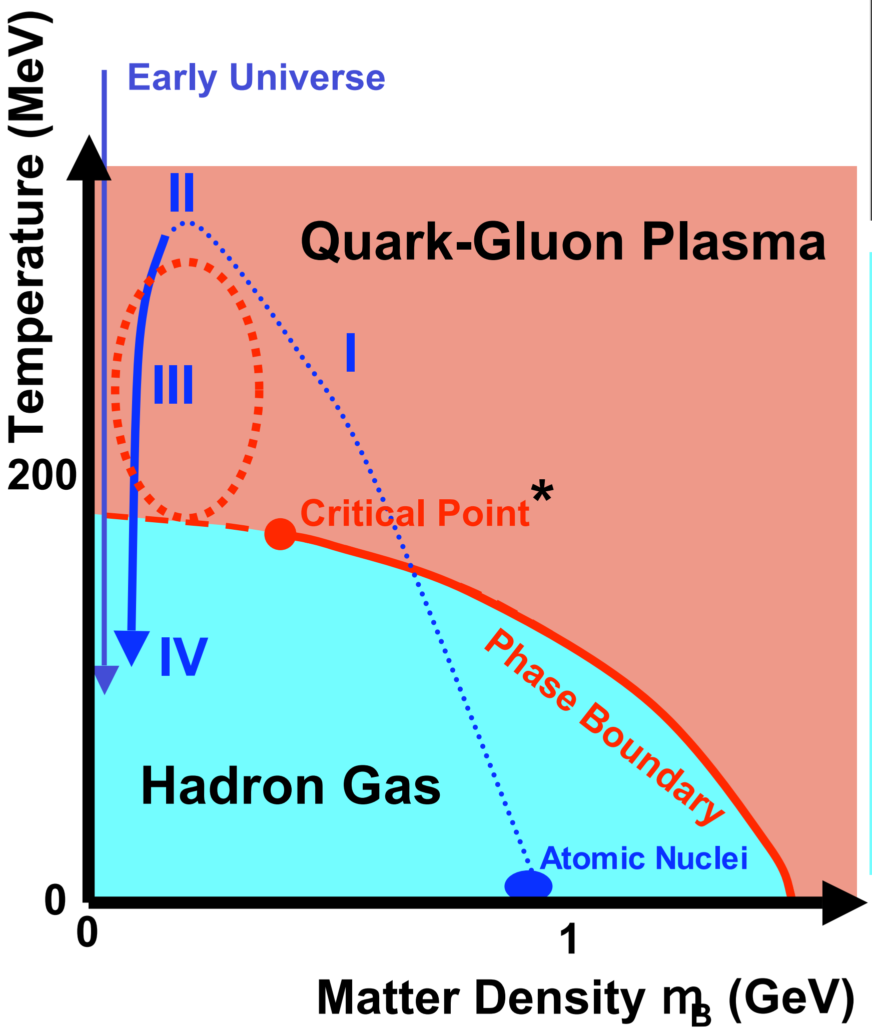
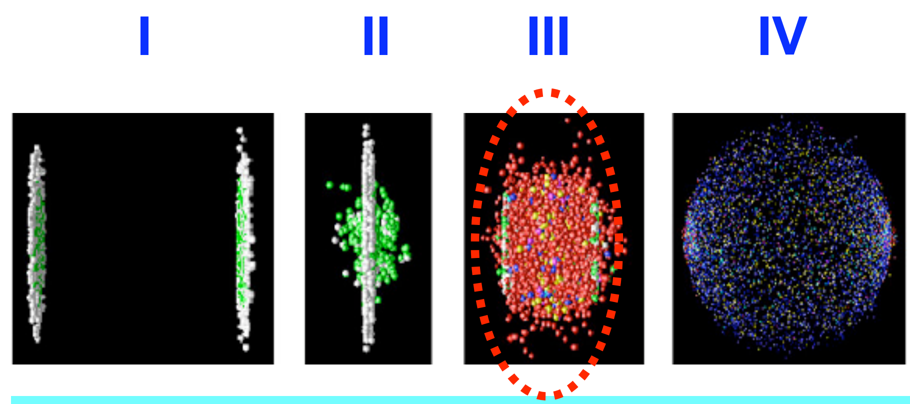
RHIC: Physics Results



Gunther Roland - MIT

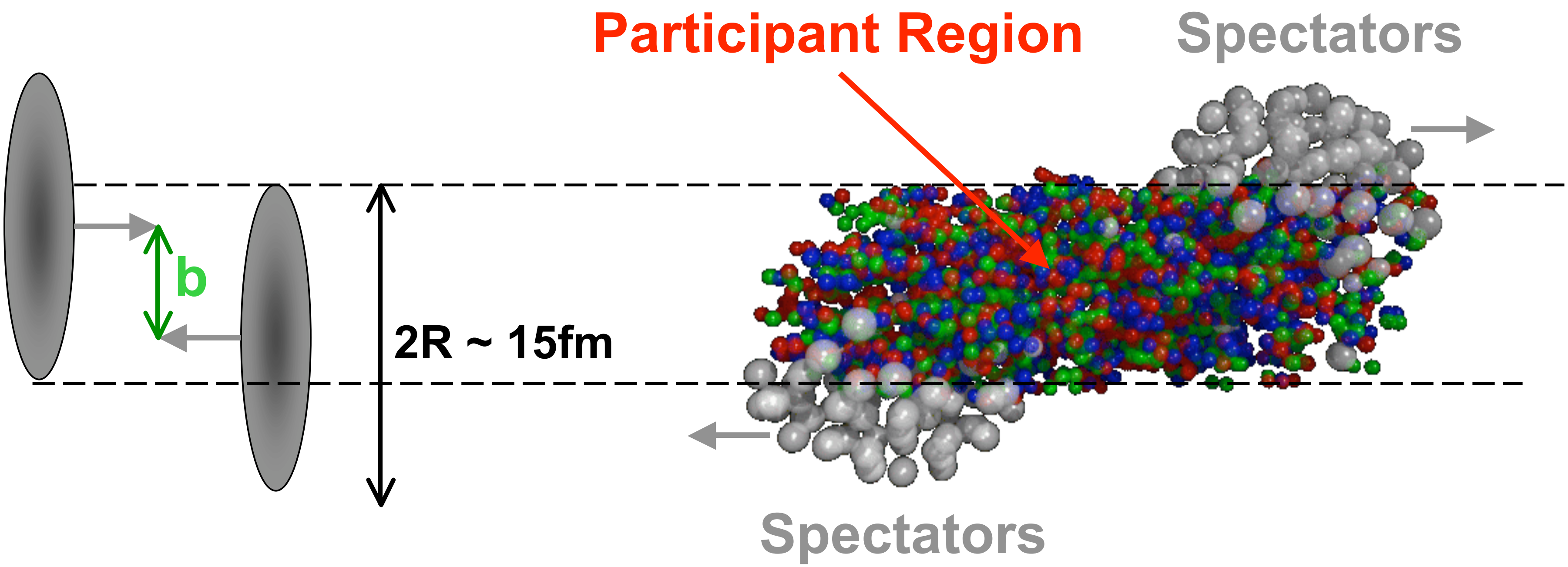
Exploring QCD with Heavy Ions





1. Structure of Relativistic Nuclei
2. Mechanism of Entropy Production
3. QCD phase diagram
4. Properties of QGP

Interlude: Collision Geometry



Smaller Impact Parameter b

↕

More Participants (N_{part})

↕

Bigger Collision System ⟶ More Produced Particles!

Relativistic Heavy Ion Collider

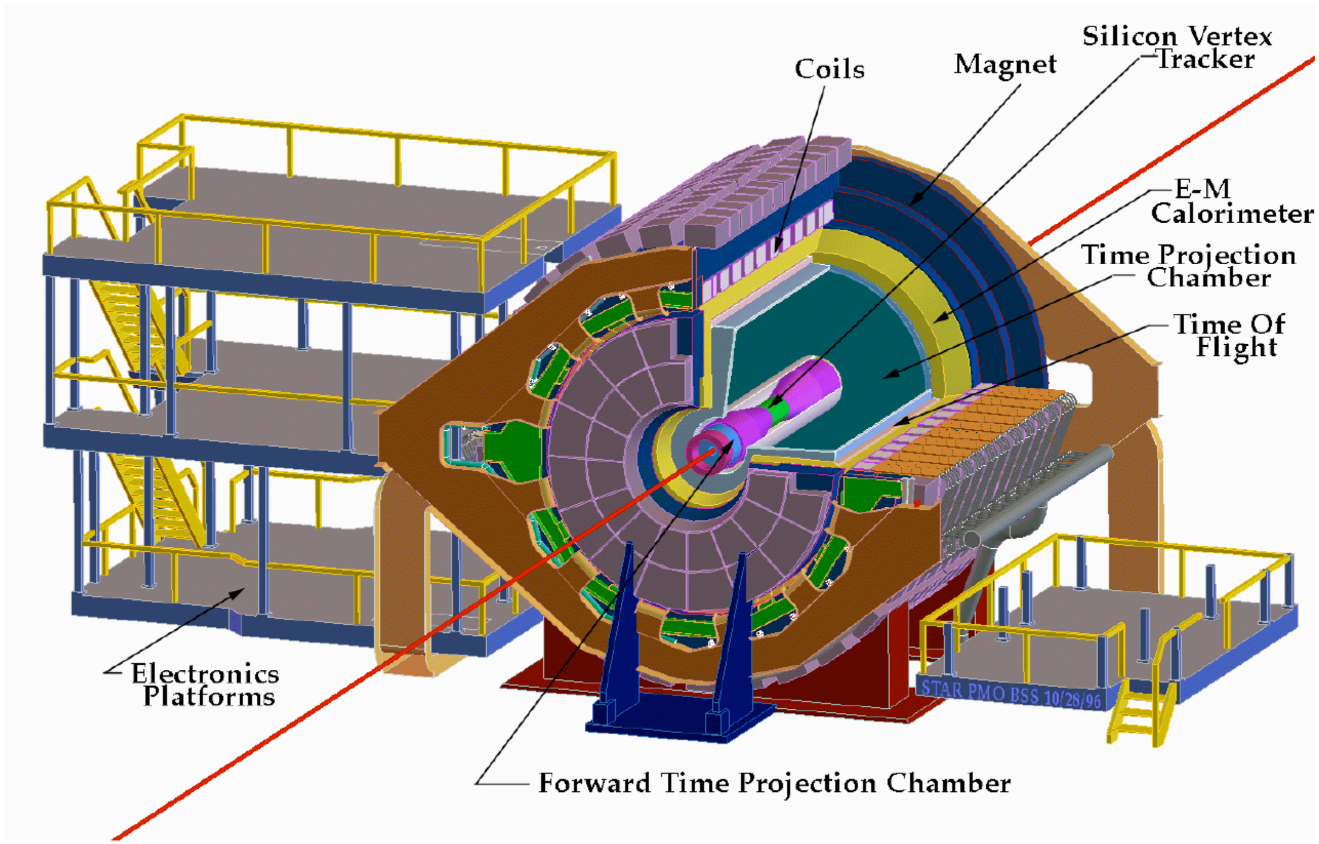
First Physics in '00

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

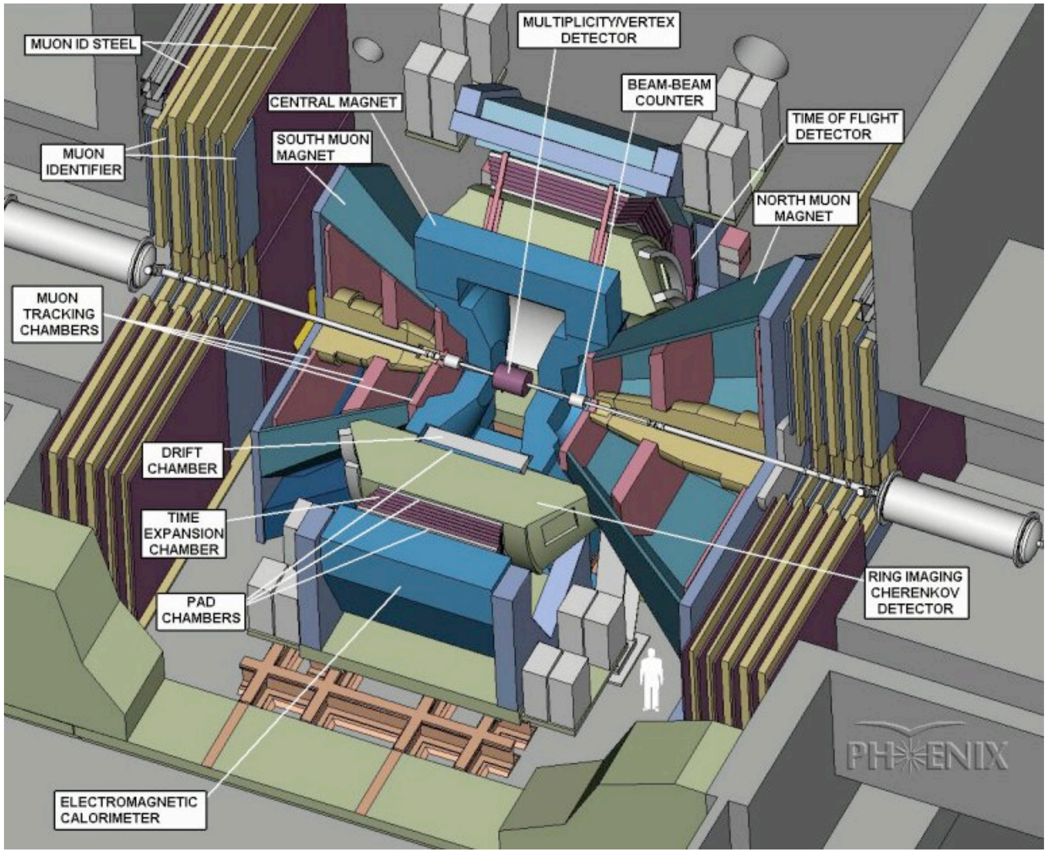
- 4 Experiments
  - 2 big
  - 2 small
- Complementary capabilities

STAR



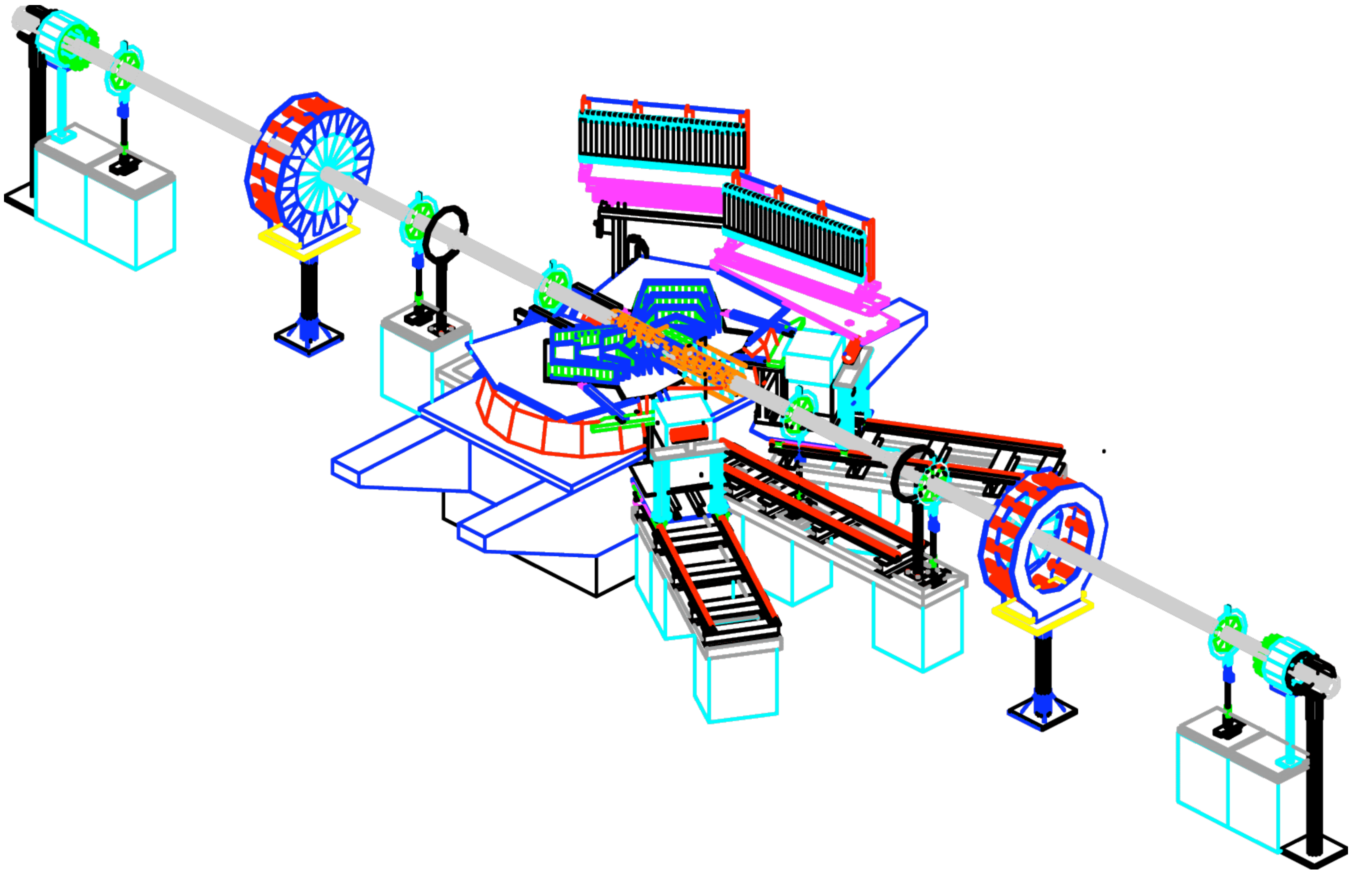
- Large acceptance tracking detector
- Mass, charge and momentum for 2000 hadrons per event

PHENIX



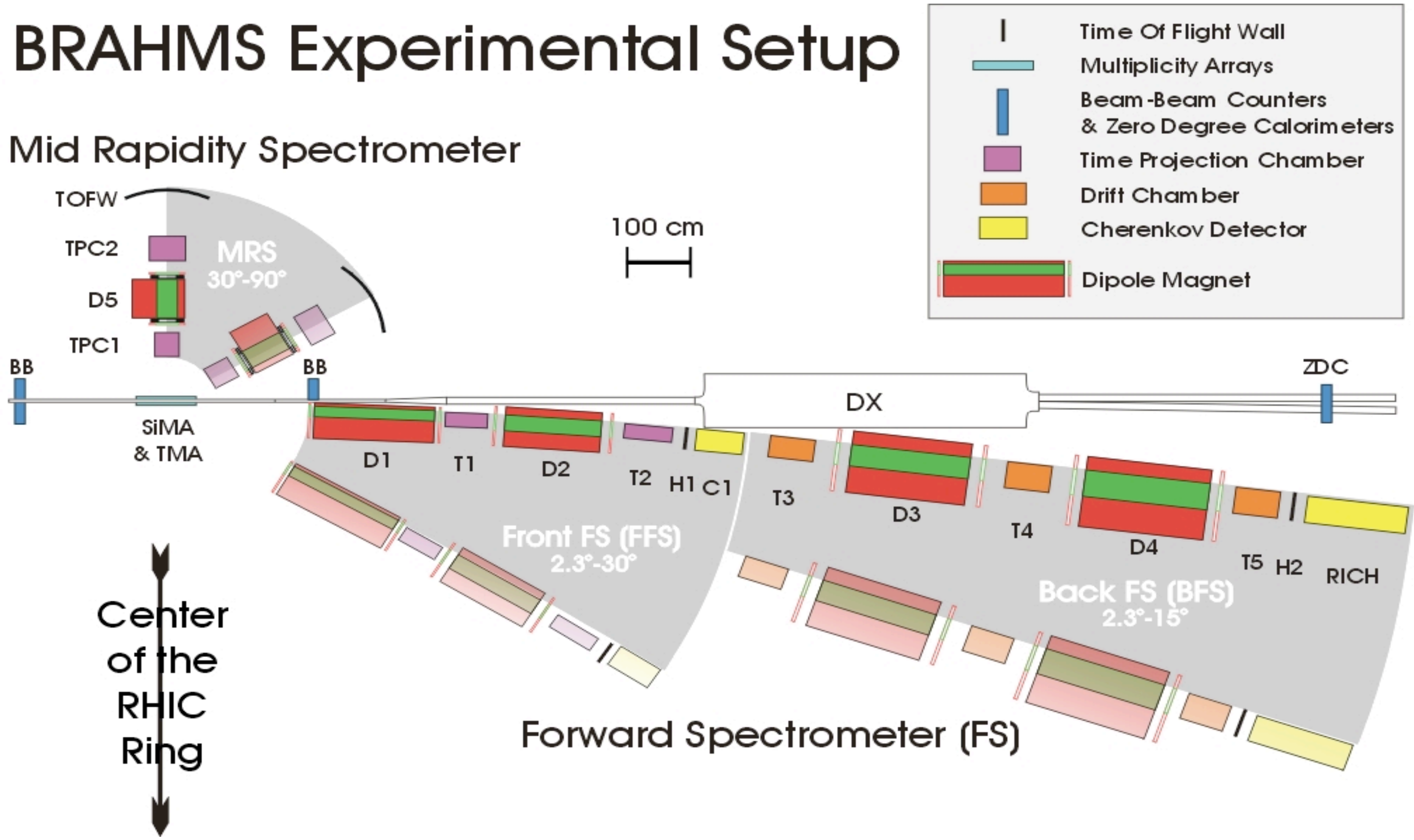
- High Rate, Particle ID, Triggering
- Rare particles: Leptons, High p_T

PHOBOS



- Full Acceptance Multiplicity Detector
- High precision spectrometer near y=0

BRAHMS



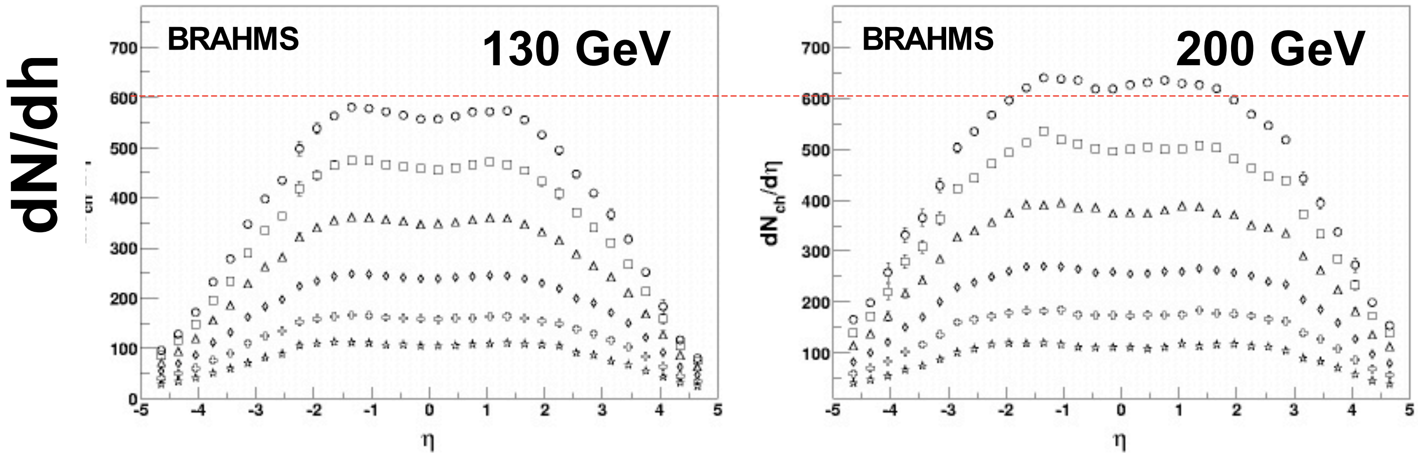
- Particle Production at small angles
- High resolution spectrometer & good particle ID

Bulk Particle Production @ RHIC

1. Initial Conditions/Energy Density
2. Thermalization
3. Hadro-Chemistry
4. Expansion Dynamics

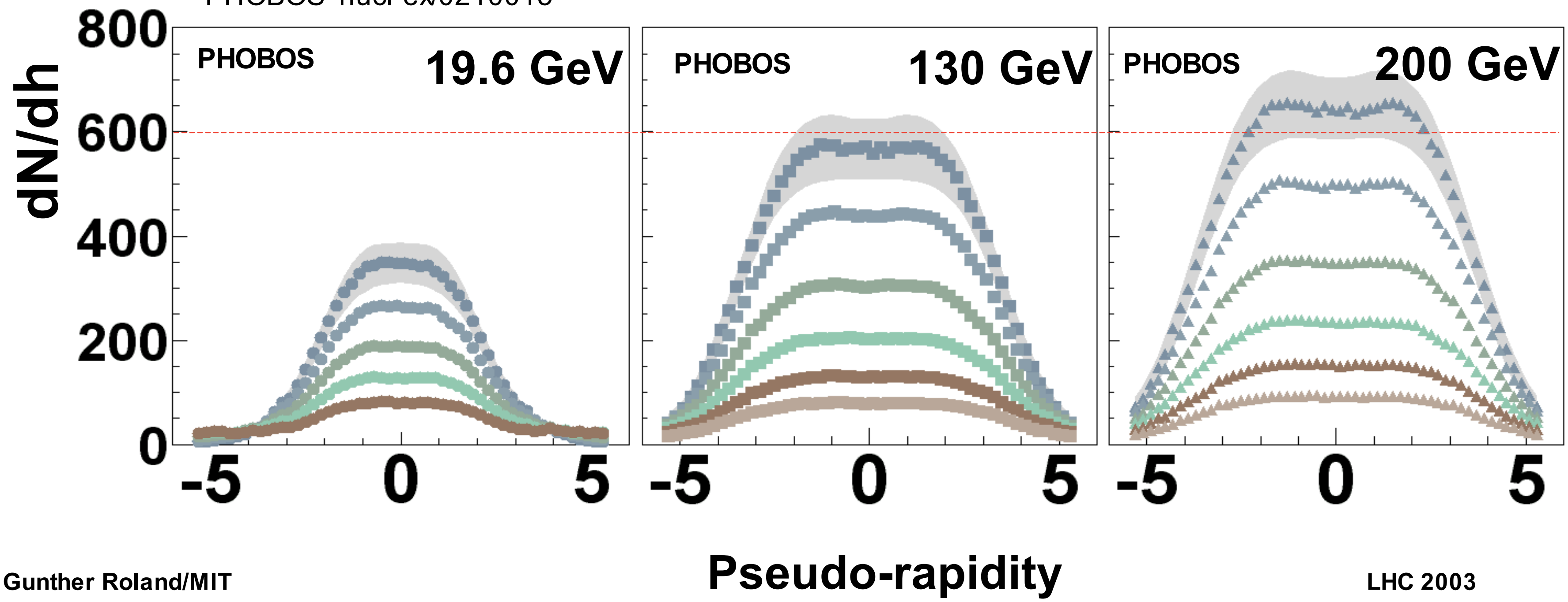
4-p Multiplicity at RHIC

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



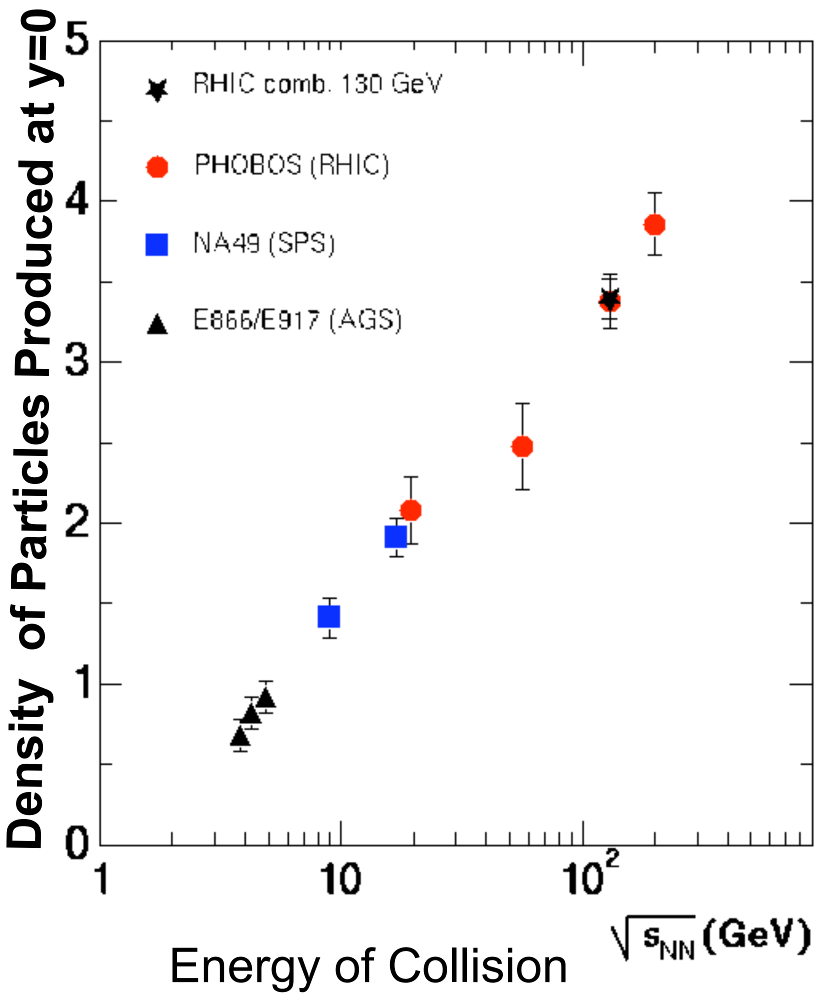
Excellent agreement!

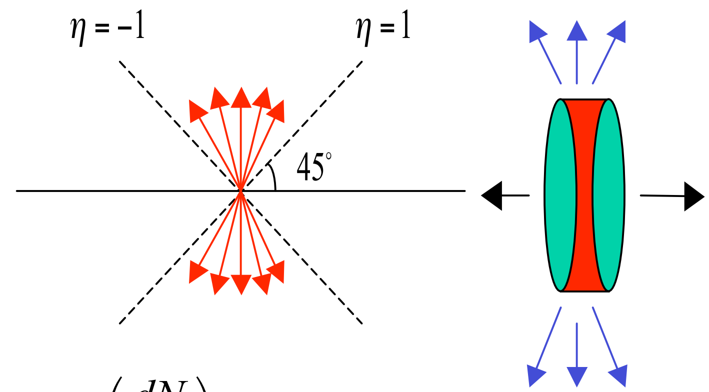
PHOBOS nucl-ex/0210015



Energy Density

W. Busza, Moriond '03





$$\left(\frac{dN}{d\eta}\right)_{all} \sim 1000$$

$$\langle E \rangle \sim 1 GeV$$

Total energy released ~2000GeV

Max. initial overlap volume

$\sim \pi R^2 (1\,fm) \sim 200\,fm^3$

Initially released energy density

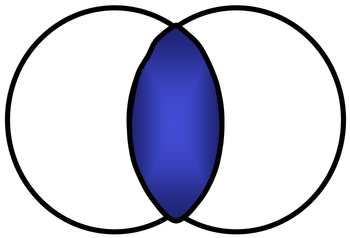
~ 5GeV/fm^3

Note: energy density inside proton ≈ 0. 5GeV/fm^3

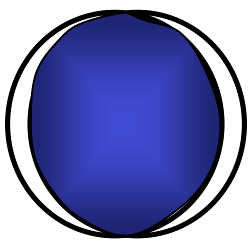
Azimuthal Anisotropy

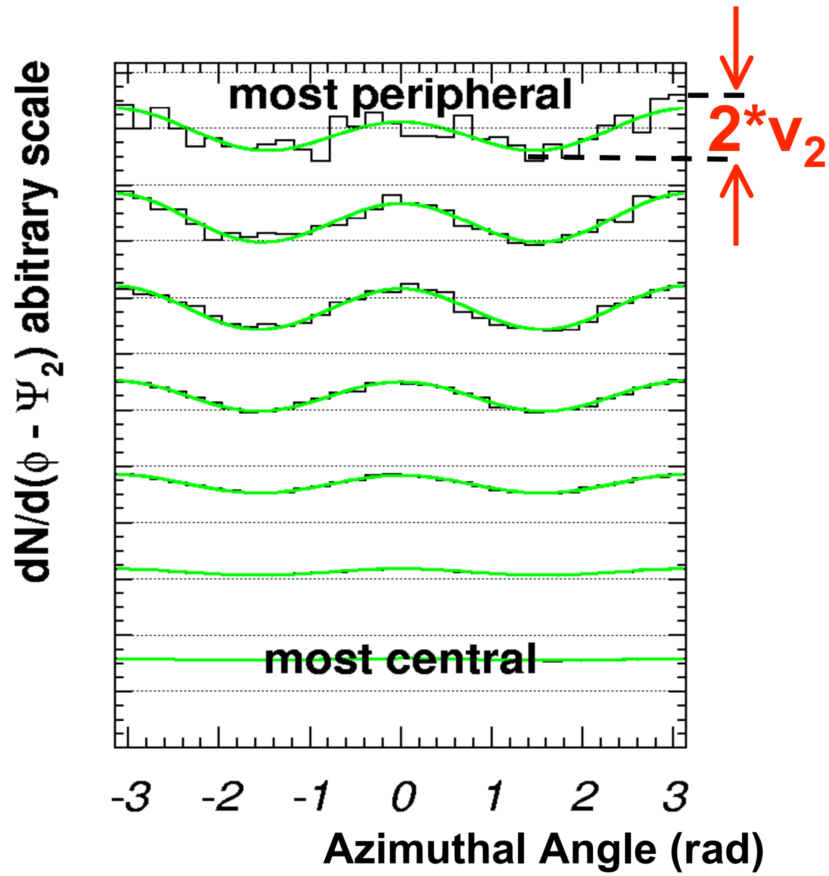
“Head on” view of colliding nuclei

Peripheral



Central



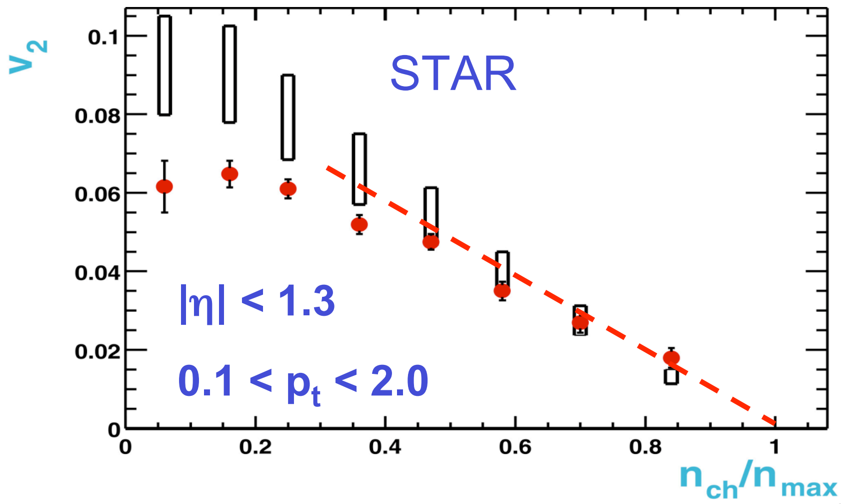


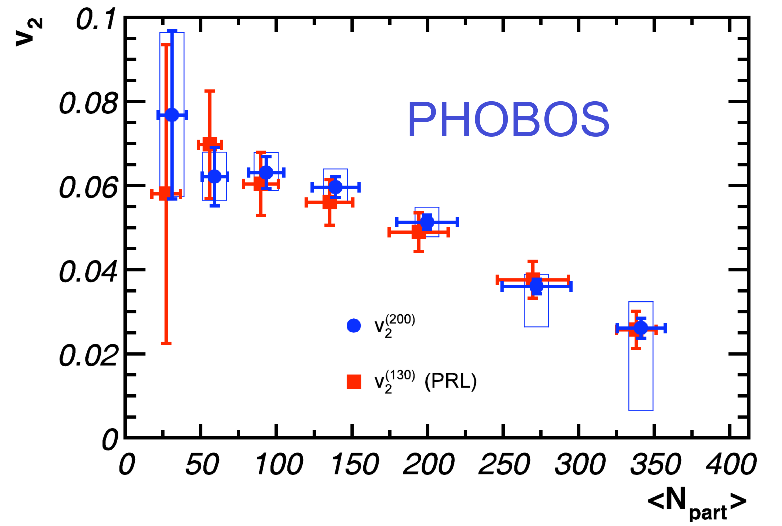
Initial State Anisotropy
Coordinate Space

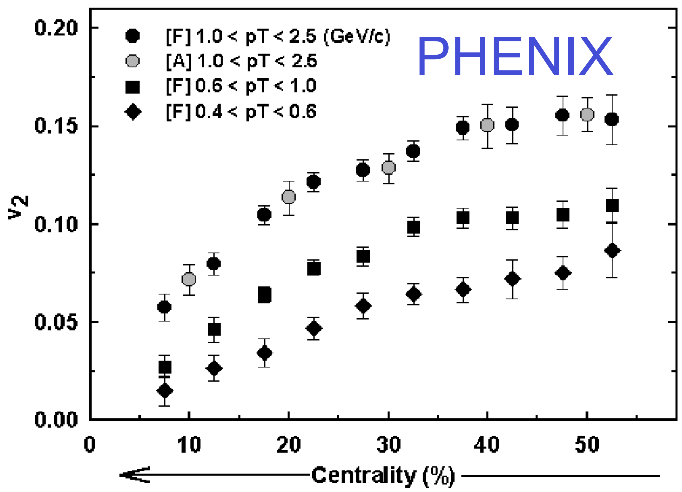
Interaction! →

Final State Anisotropy
Momentum Space

Anisotropy v_2 vs Centrality







Consistent results

Hydro-limit reached for mid-central collisions

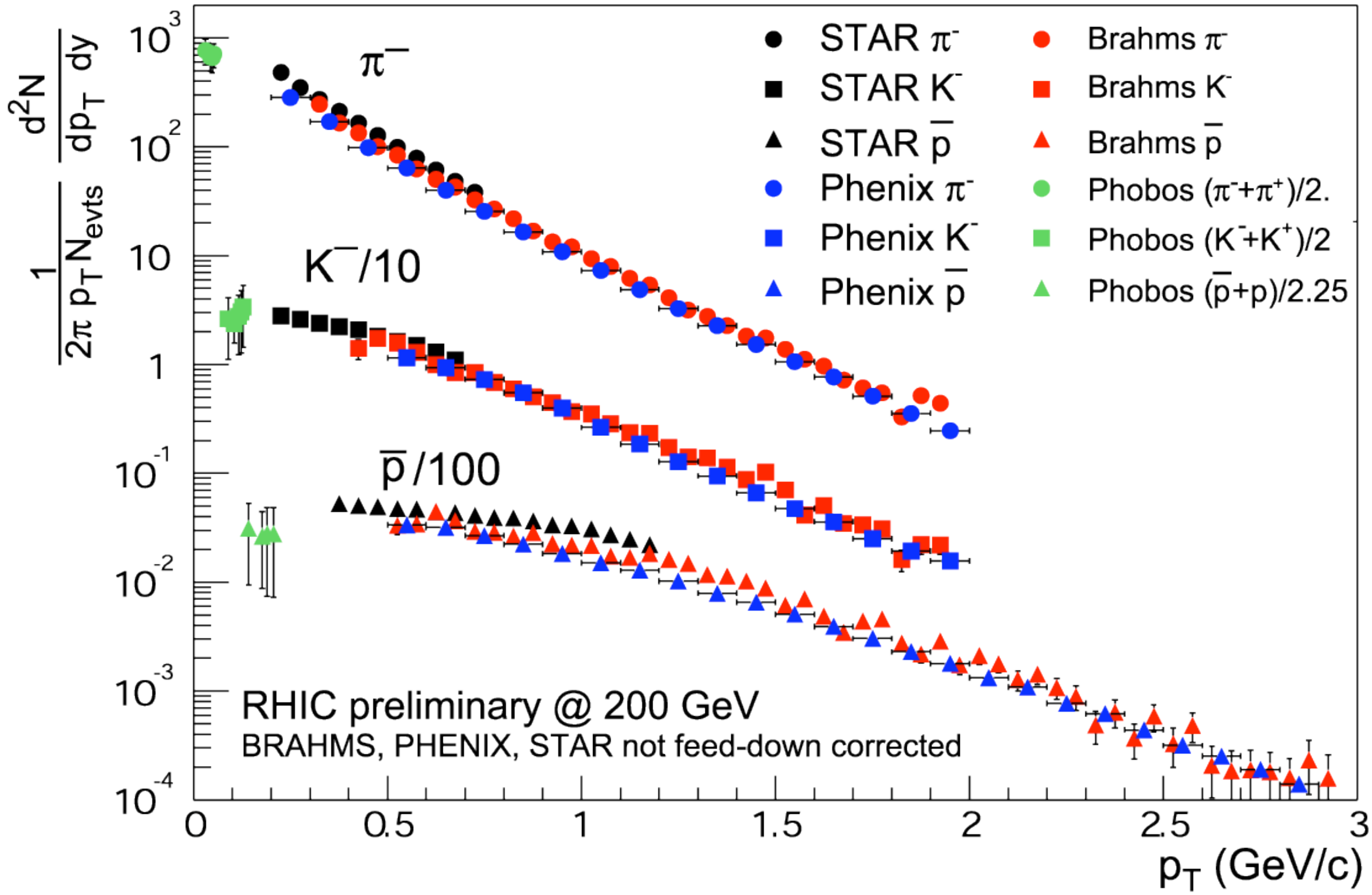
from R. Snellings

Bulk Particle Production @ RHIC

1. Initial Conditions/Energy Density: > 5 GeV/fm^3
2. Thermalization: ✓
3. Hadro-Chemistry
4. Expansion Dynamics

Charged Particle Spectra

Th. Ullrich QM'02

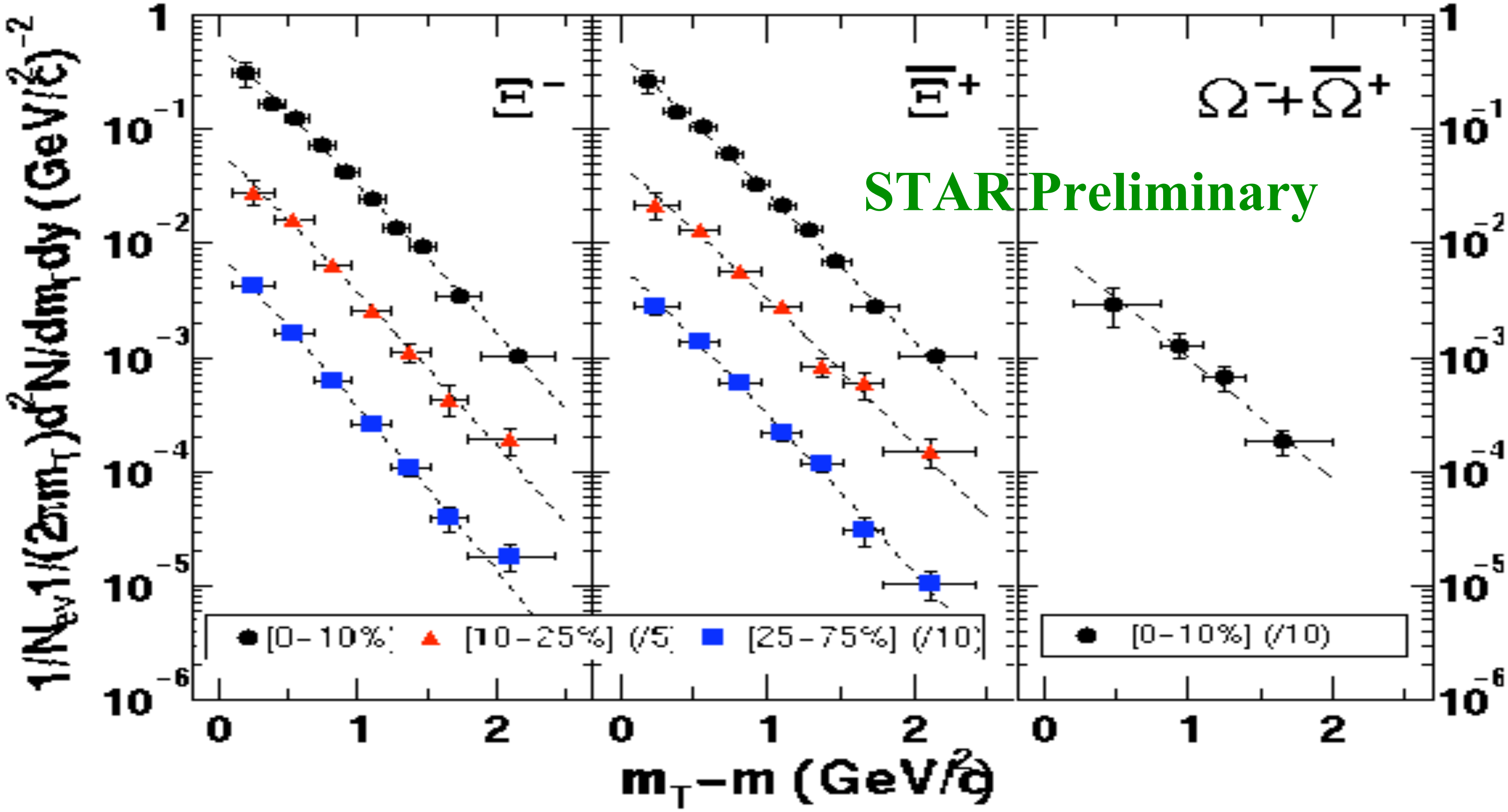


Results (largely) consistent

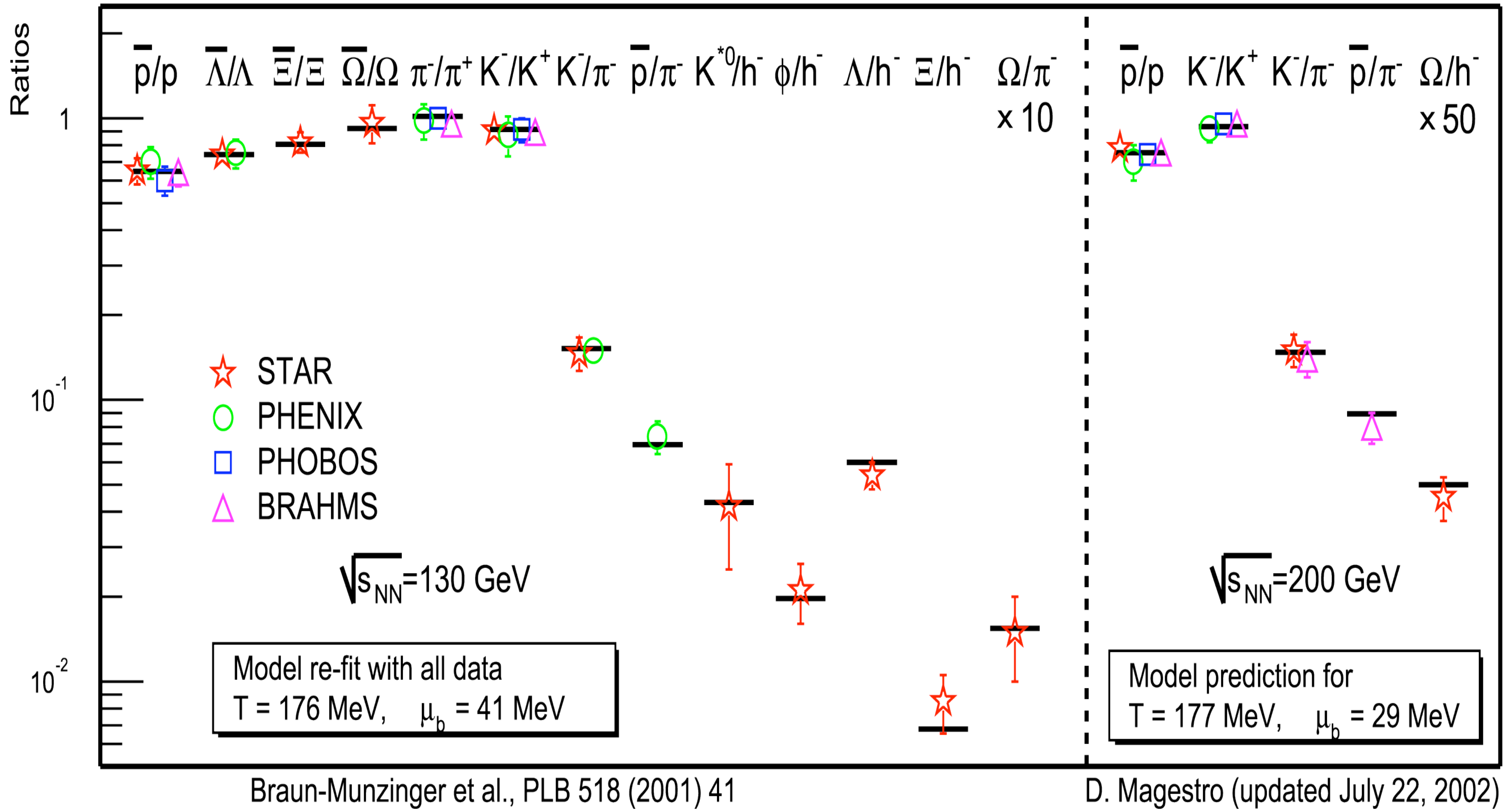
Clear Mass Hierarchy of Slopes

Multi-Strange Particles

J. Castillo SQM'03



Statistical Model Fit

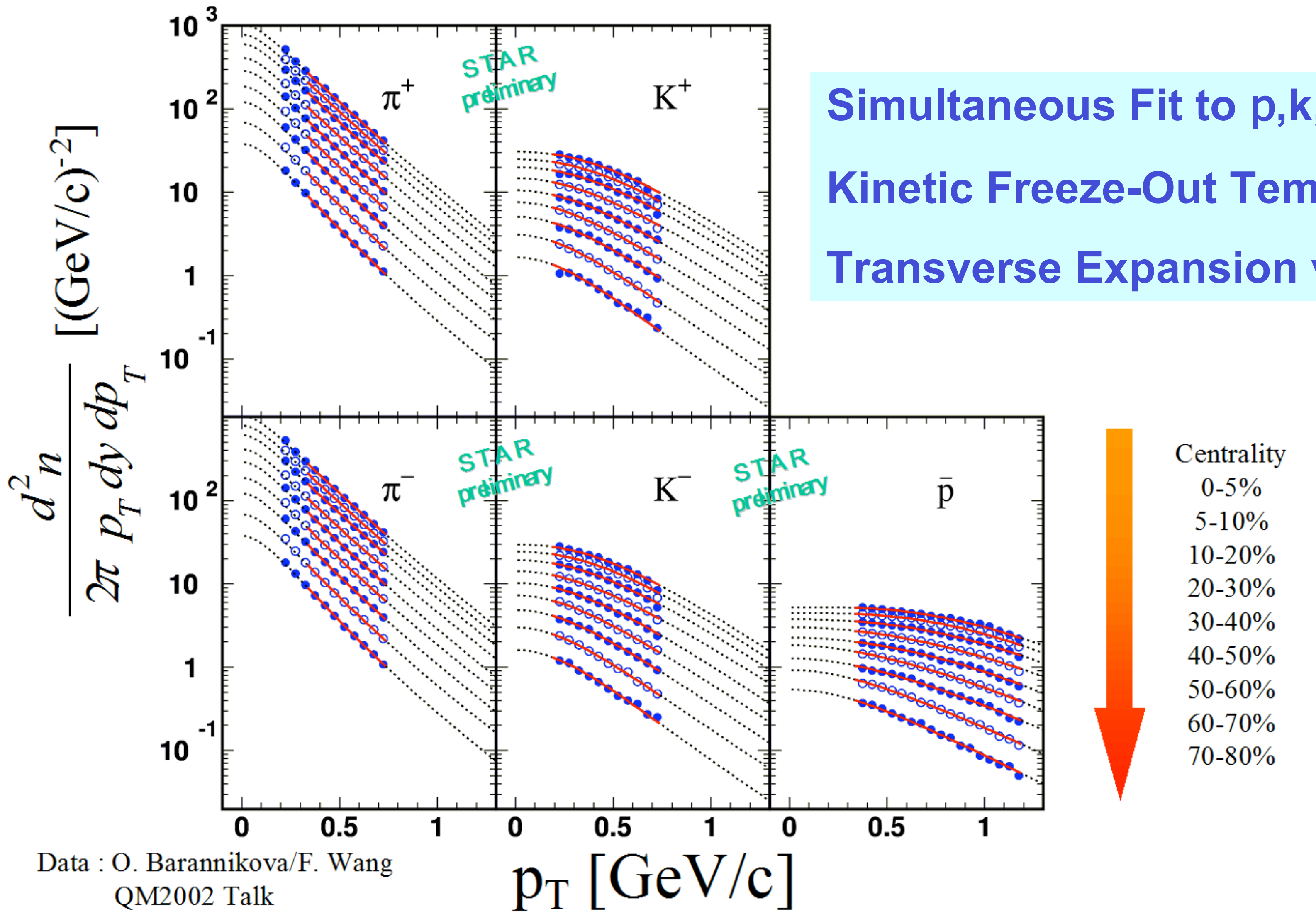


Relative Abundance: Two Parameters !

Bulk Particle Production @ RHIC

1. Initial Conditions/Energy Density: > 5 GeV/fm^3
2. Thermalization: ✓
3. Hadro-Chemistry: T_{ch} ~ 180 MeV, m_B~25MeV
4. Expansion Dynamics

'Hydro' Fits to Spectra

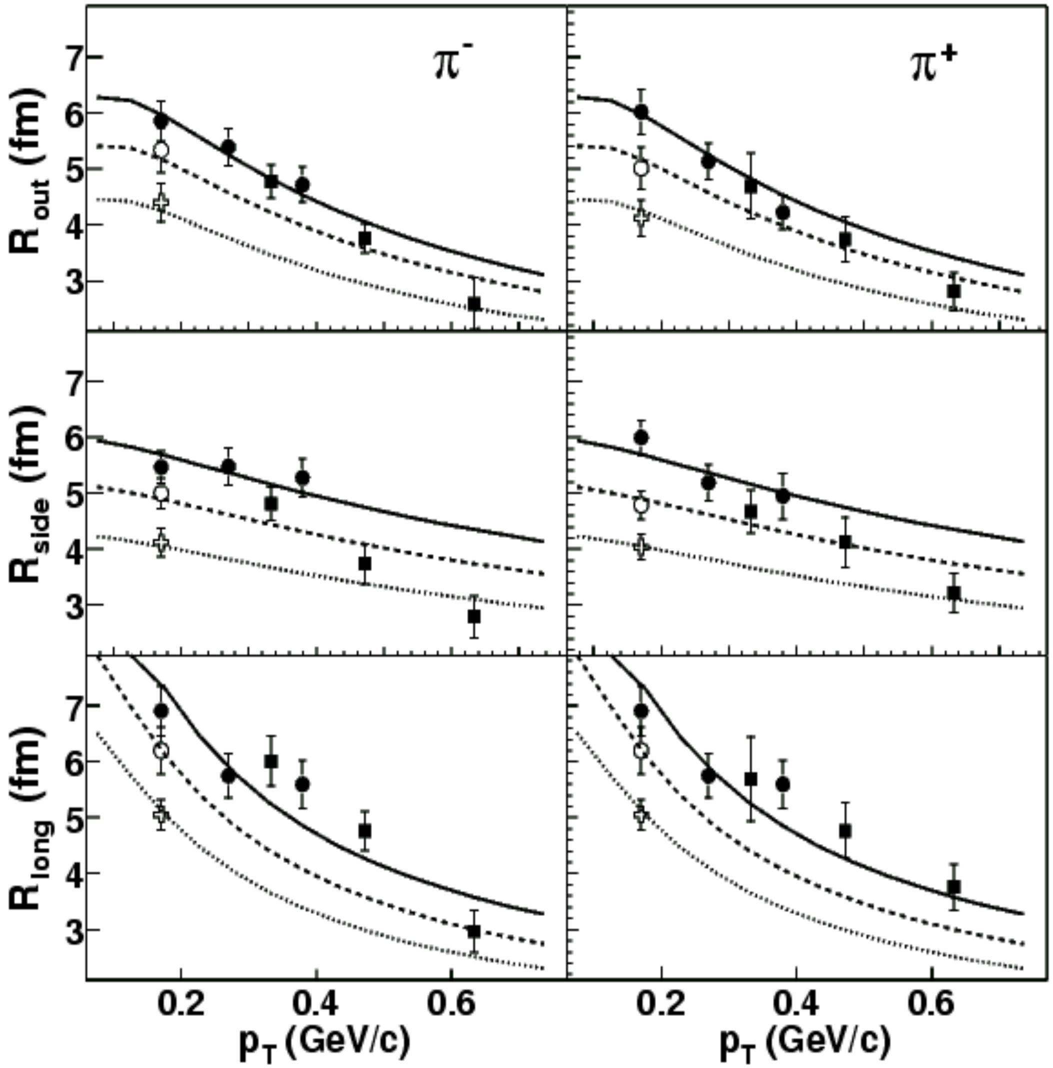


Simultaneous Fit to p,k,p gives

Kinetic Freeze-Out Temperature,

Transverse Expansion velocity

‘Hydro’ 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**

Bulk Particle Production @ RHIC

1. Initial Conditions/Energy Density: > 5 GeV/fm^3
2. Thermalization: ✓
3. Hadrochemistry: T_{ch} ~ 180 MeV, m_B~25MeV
4. Expansion Dynamics: T_{th} ~ 110 MeV, <b_T> ~ 0.6c

   <t_{fo}>~ 10 fm/c, Dt_{fo}~ 0-3 fm/c

Bulk Particle Production @ RHIC

1. Initial Conditions/Energy Density: $> 5\ GeV/fm^3$
2. Thermalization: ✓
3. Hadrochemistry: T_{ch} ~ 180 MeV, m_B~25MeV
4. Expansion Dynamics: T_{th} ~ 110 MeV, $<b_T>$ ~ 0.6c

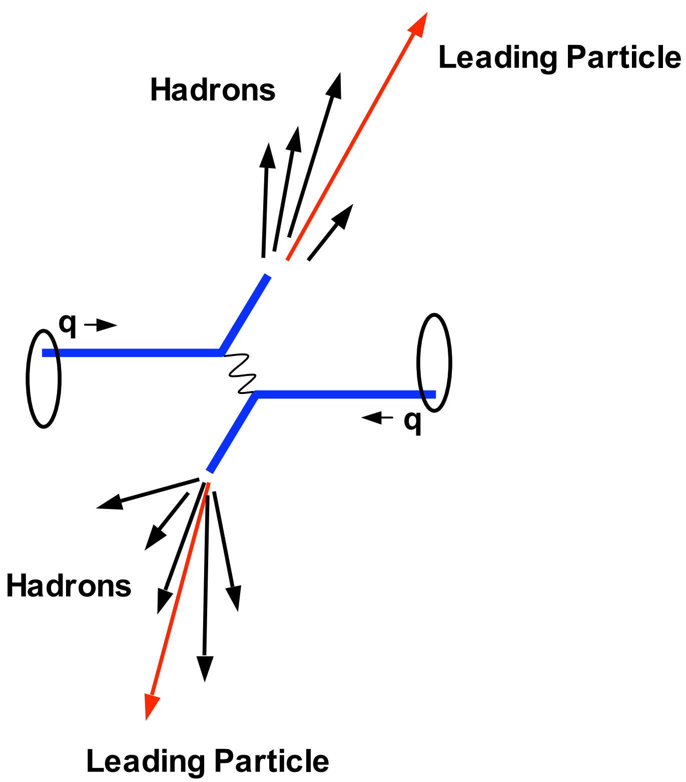
   $<t_{fo}>$~ 10 fm/c, Dt_{fo}~ 0-3 fm/c

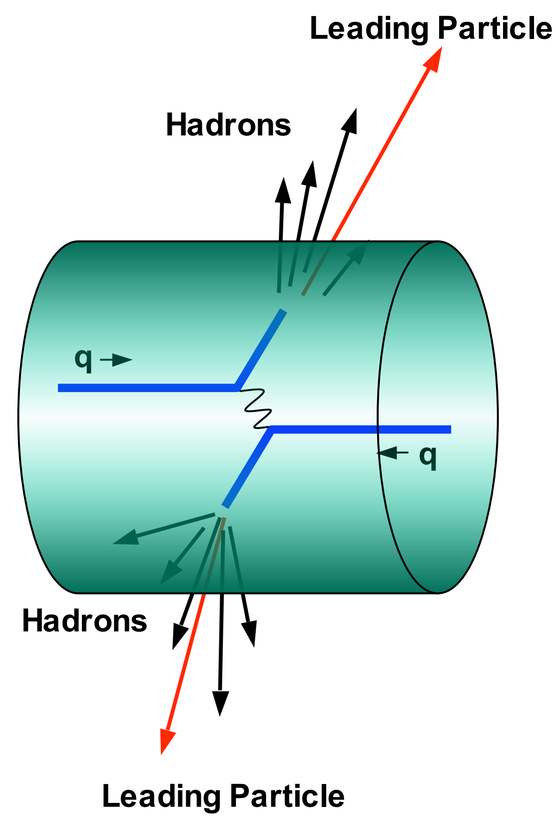
Consistent *Description* of Final State

But we're missing a picture of *Dynamical Evolution*

Dense Matter Diagnostics

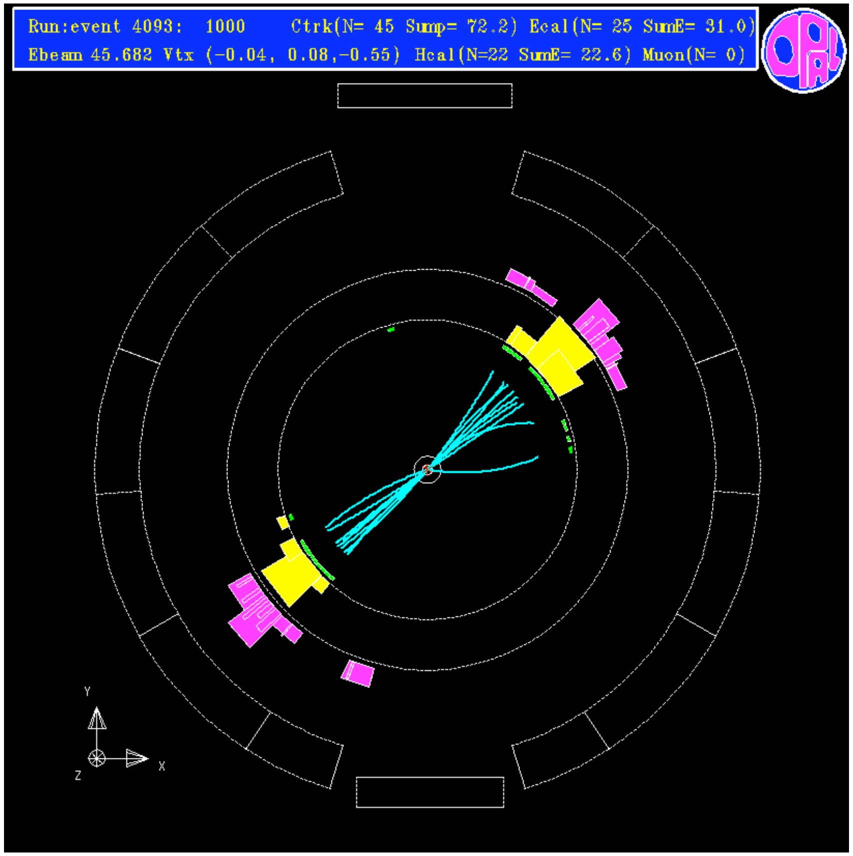
Jet cross-section calculable in QCD → **Study fate of jets in dense matter in Au+Au**



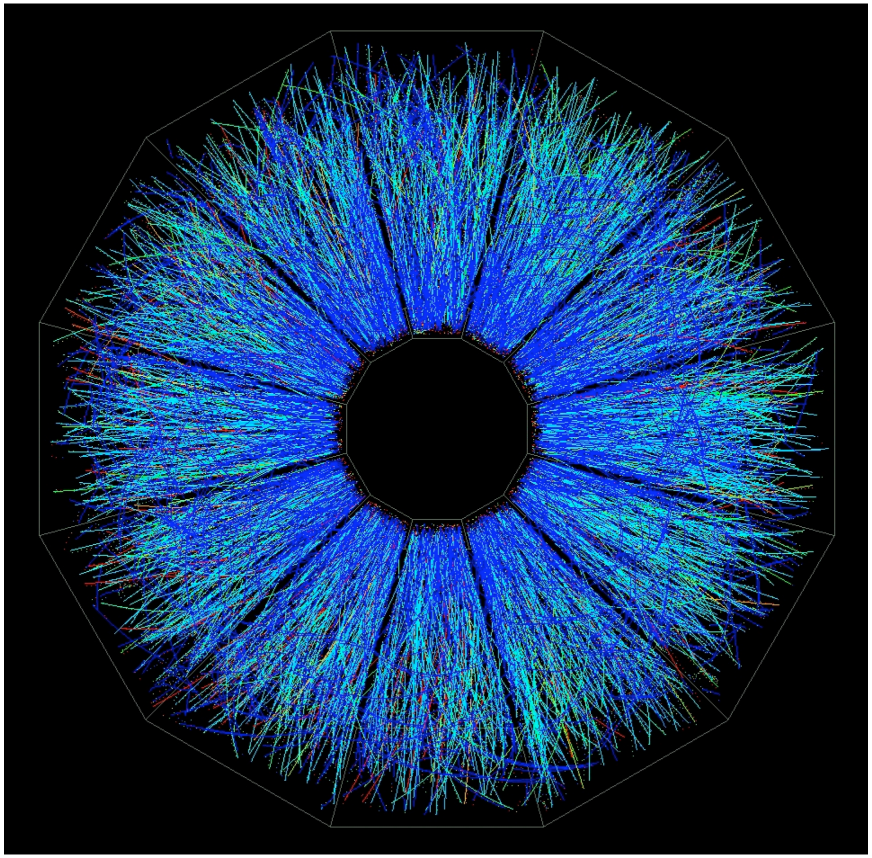


Look for "Leading Particle" (carries most of Jet momentum)

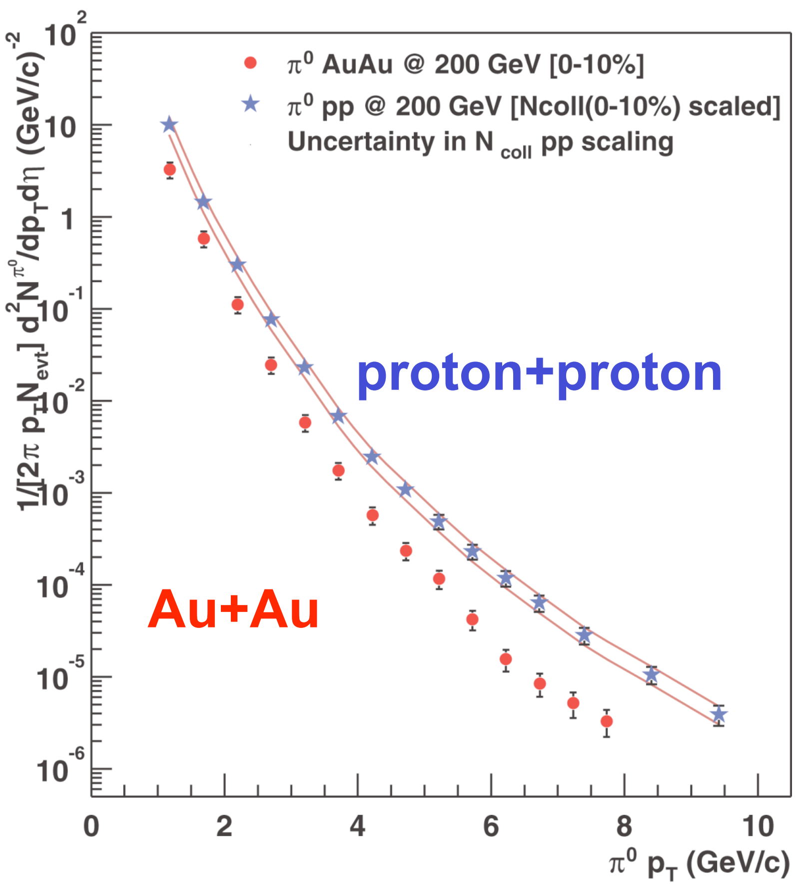
Opal e^+e^-

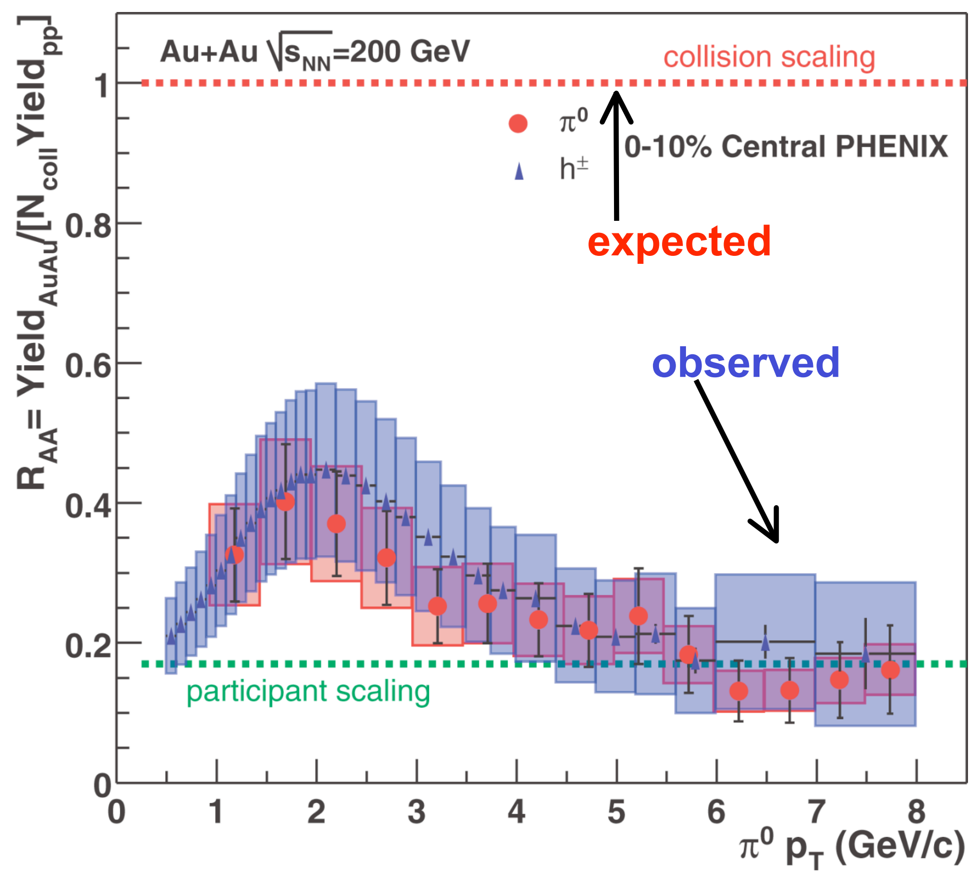


STAR Au+Au



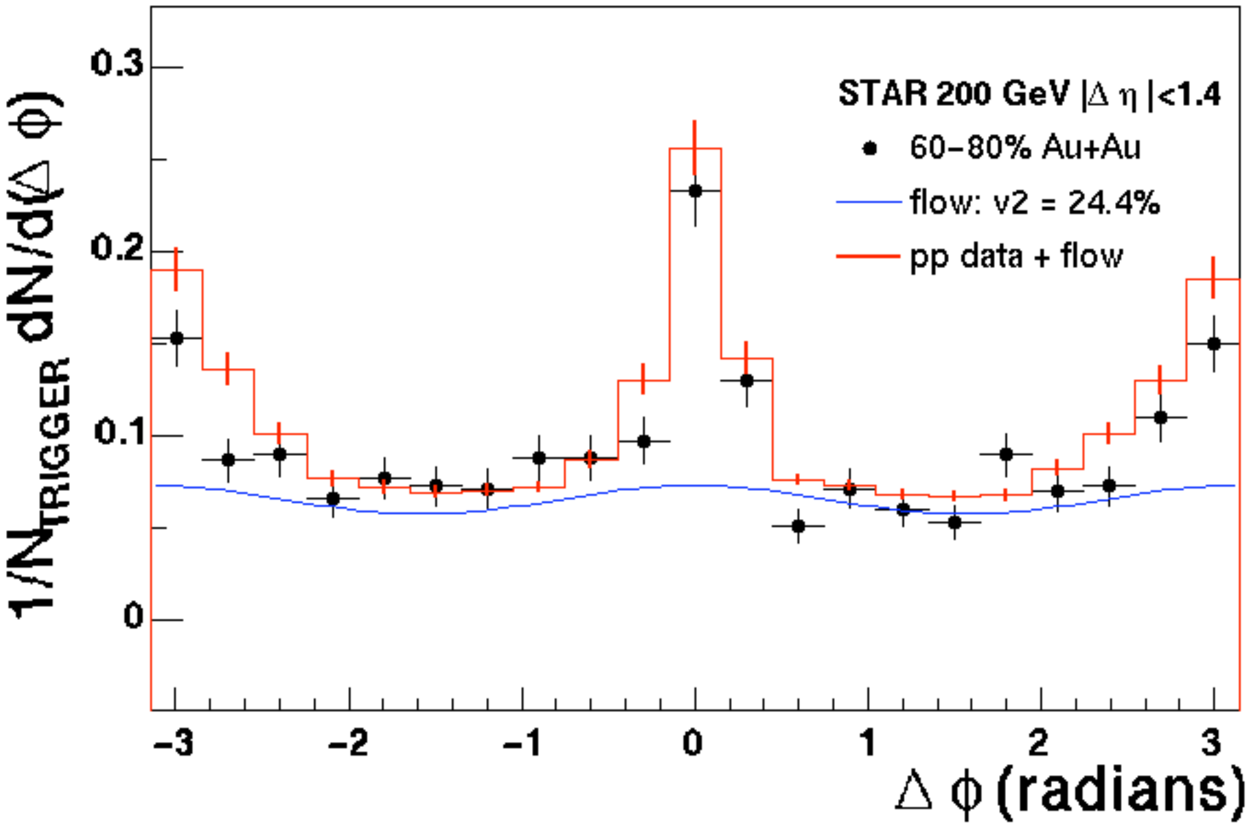
"Jet Quenching" at High p_T





Yield at high p_T only 20% of <N_{coll}> scaling expectation

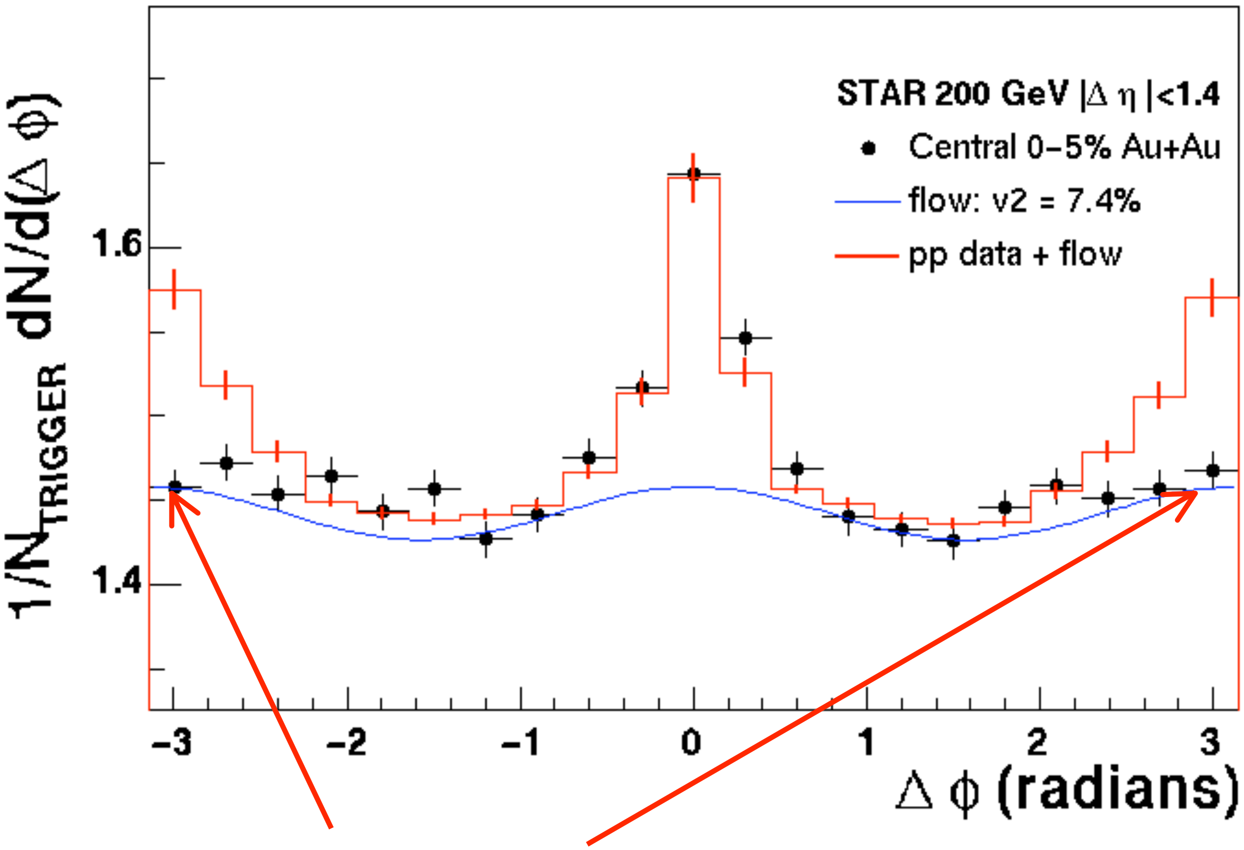
Peripheral Au+Au data



D. Hardtke
QM '02

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

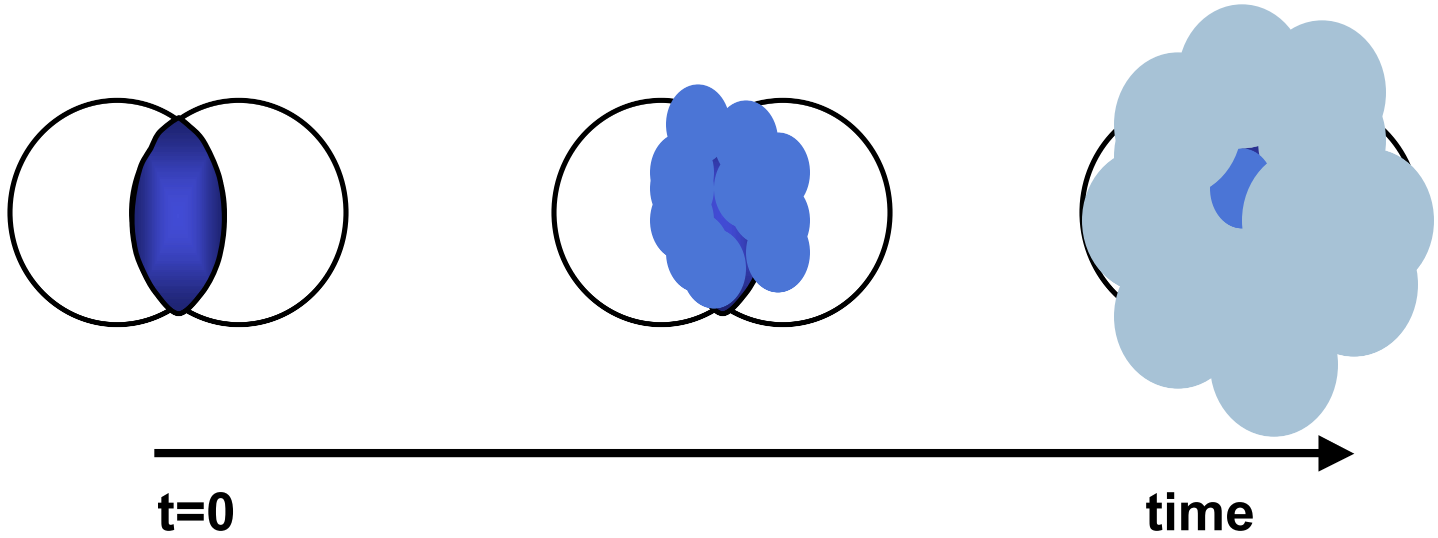
Central Au+Au data



D. Hardtke
QM '02

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

Thermalization timescale

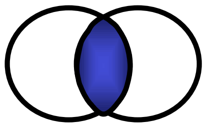


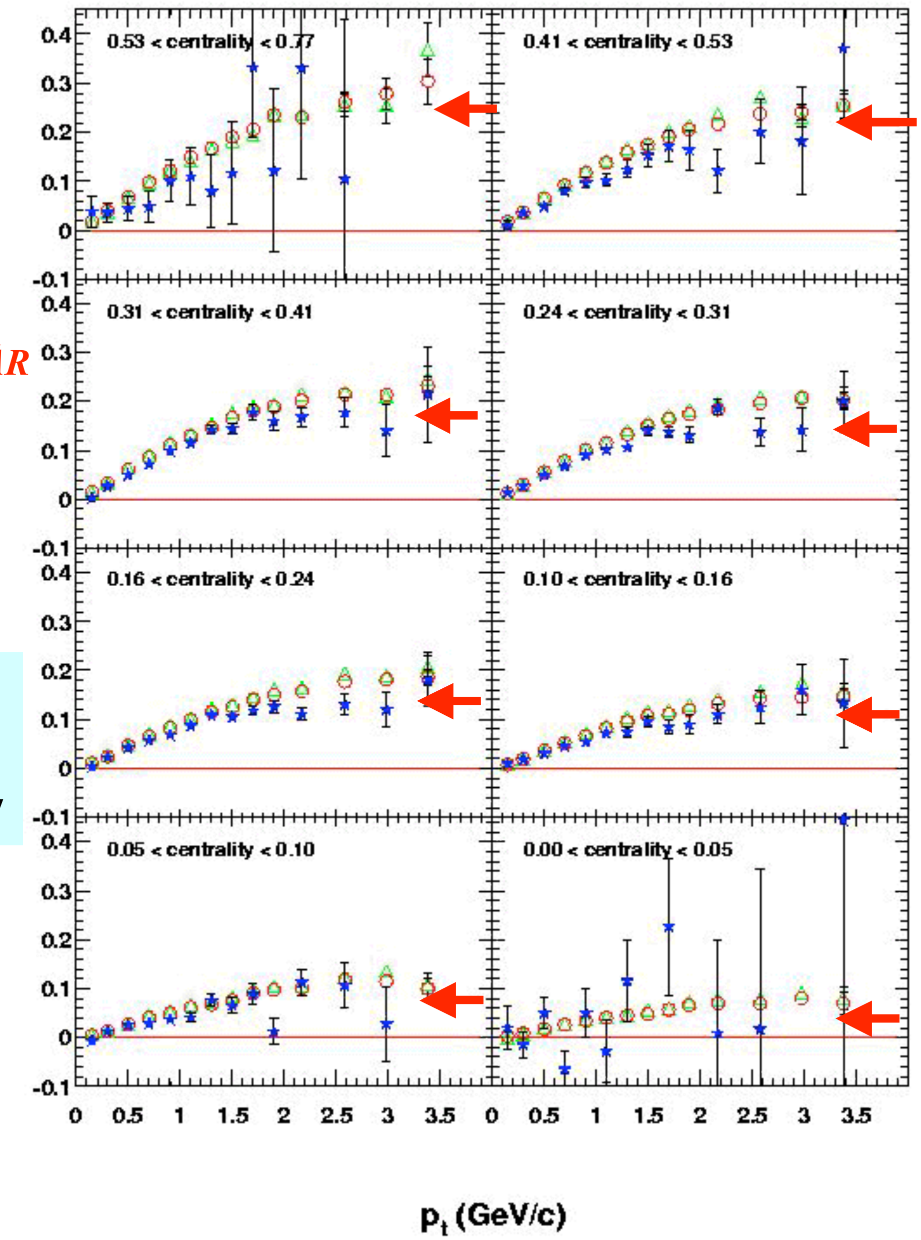
- To fully preserve anisotropy:
  - Instant formation of dense system (l_{mfp} small)
- Why "instant"? Once washed out, anisotropy can't be recovered!

“Instant” Thermalization?

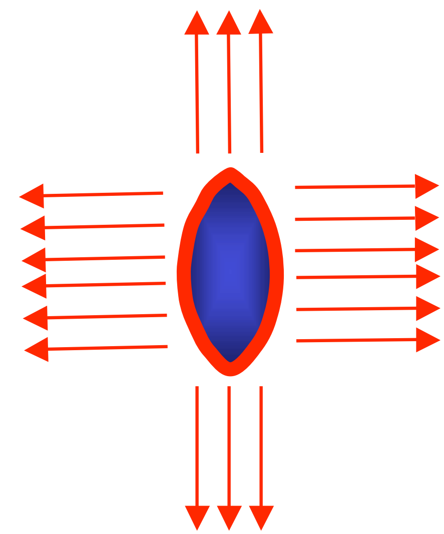
E. Shuryak,
nucl-th/0112042

Peripheral

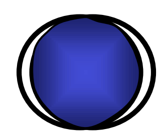




Limit ($l_{mfp} = 0$)

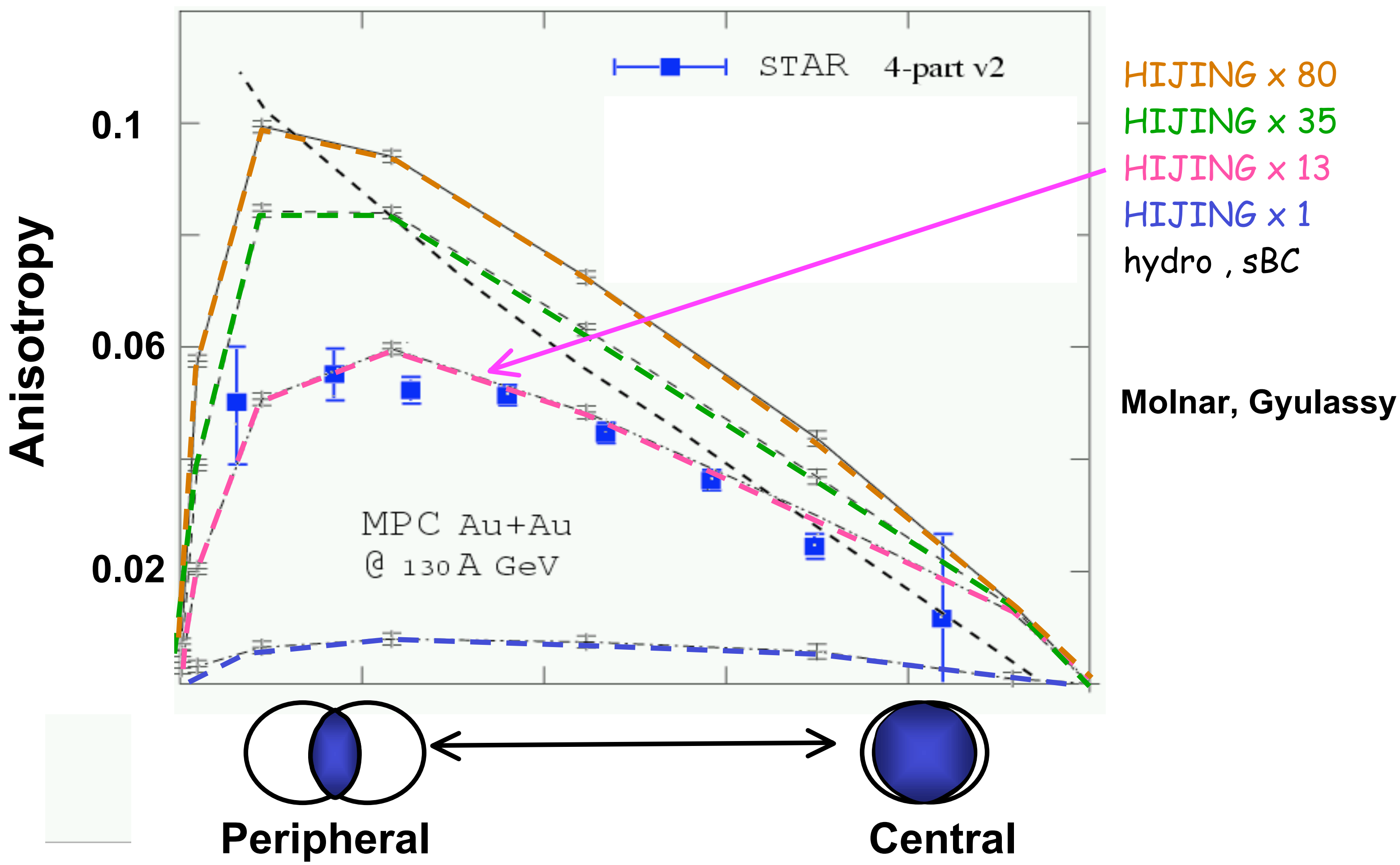


High p_T particles produced early: Biggest anisotropy



Central

Anisotropy in Parton Cascade



Parton cascade can describe data…

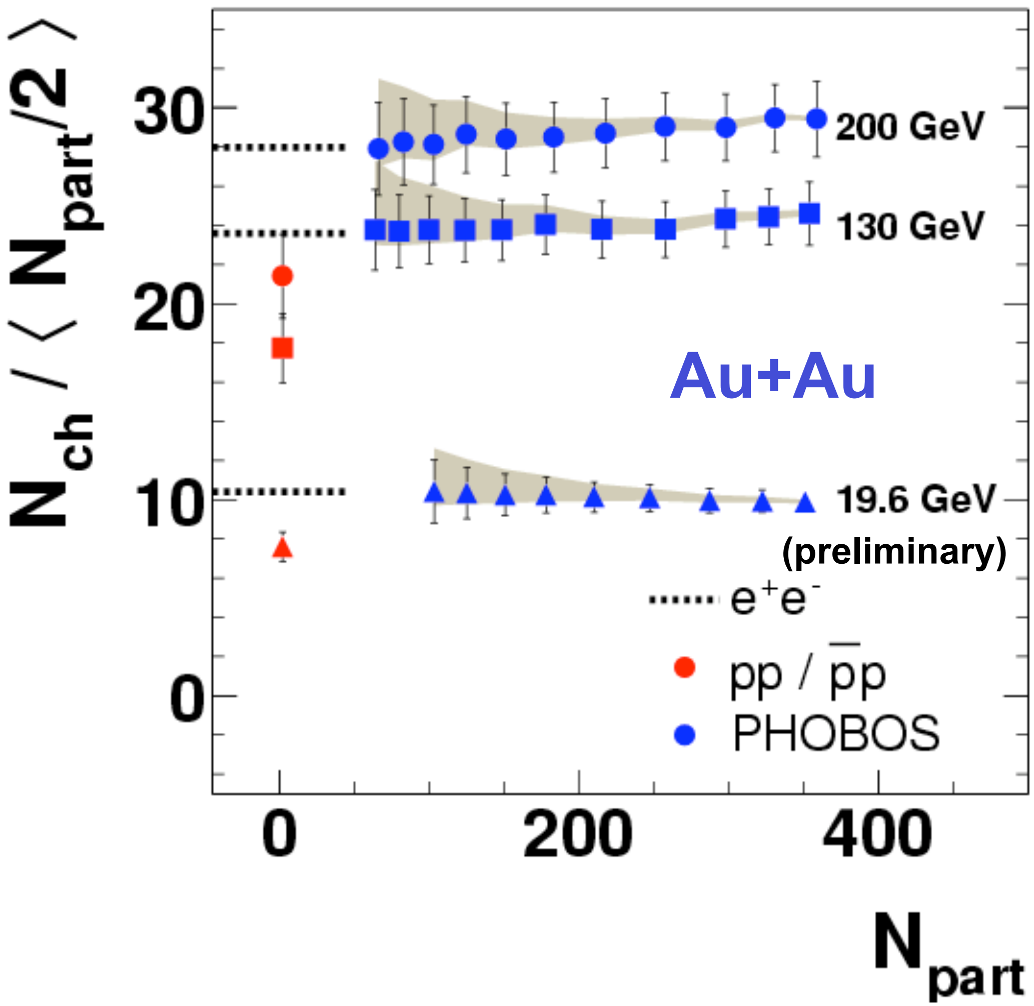
…if cross-sections are multiplied by 13!

Opaque Matter

- Flow measurements indicate early formation of dense matter
- Trend seen in parton cascade, but strength not as big as in data
- How can we study properties of this matter?

II. RHIC in Context

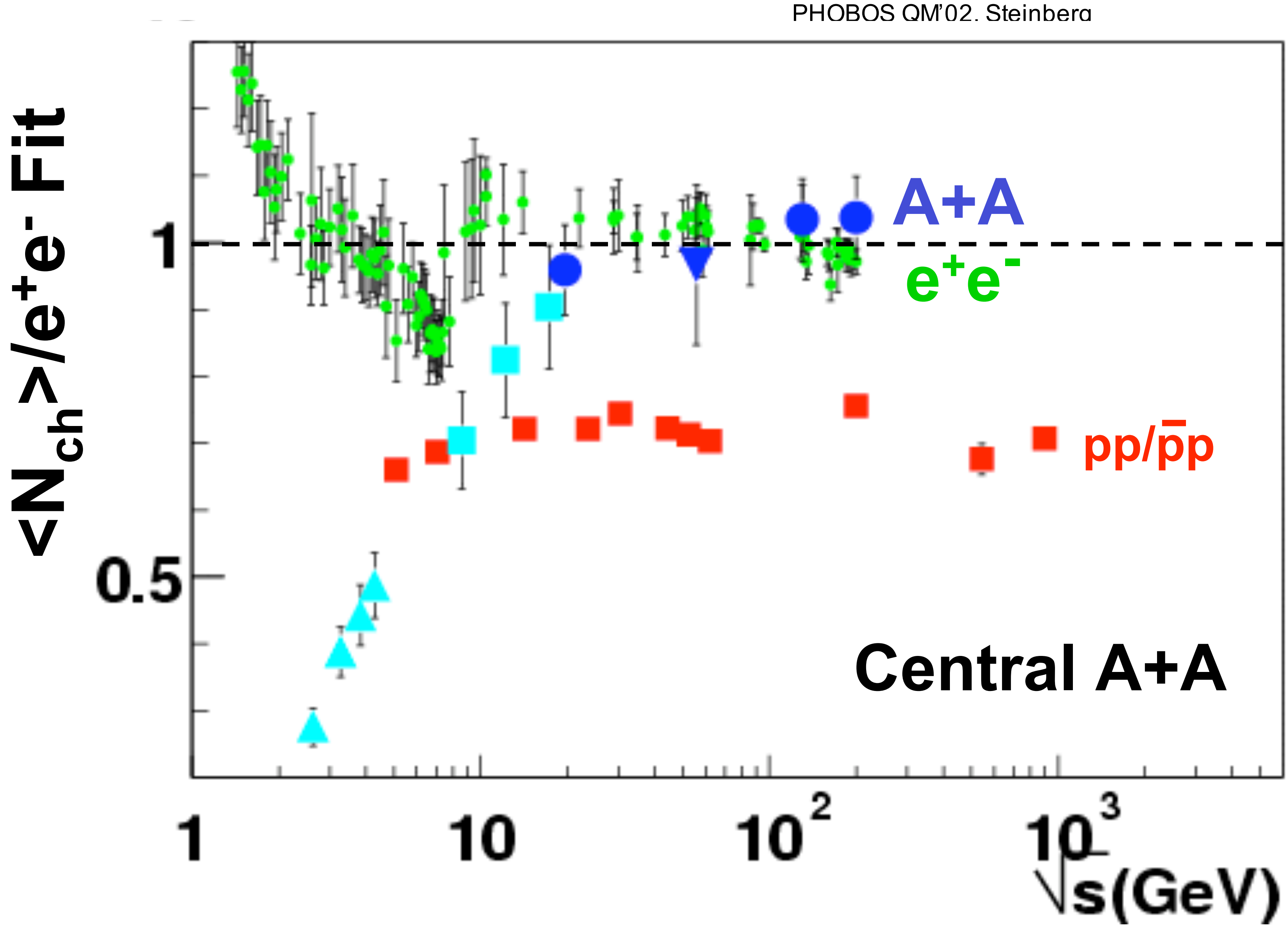
Total Multiplicity vs N_{part}



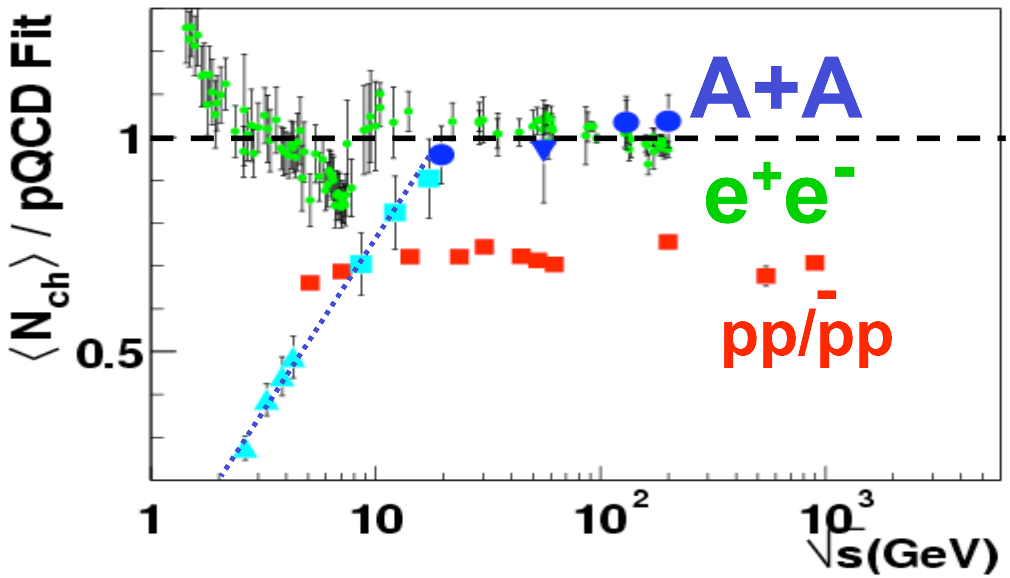
Error bands due to high-h extrapolation

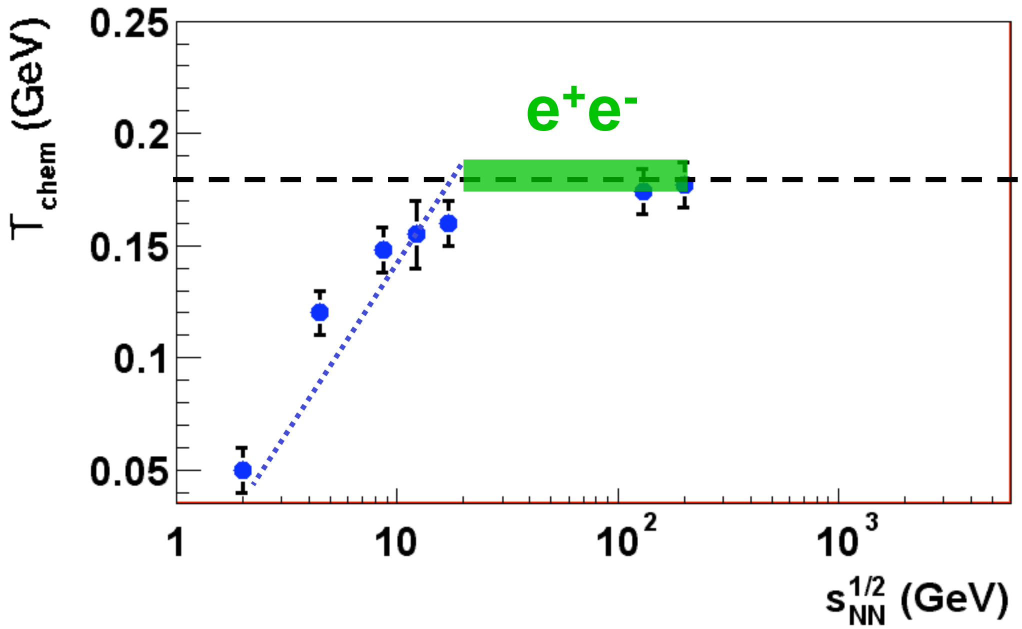
Total charged particle production ~ N_{part}

Total Multiplicity vs. Beam Energy



Asymptotic region at RHIC?





Universality?

Energy

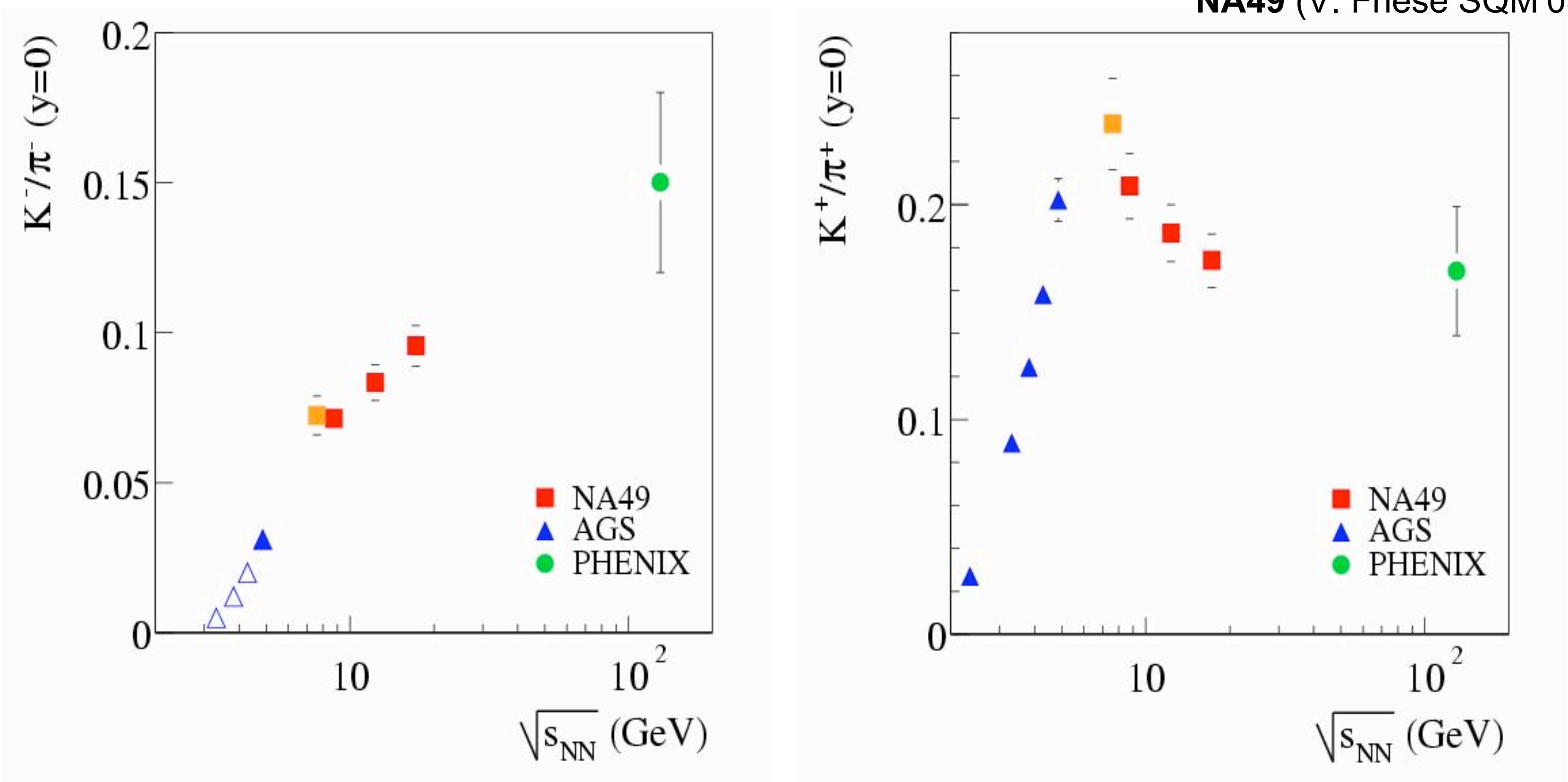
↓

Hadrons

What about strangeness?

Mid-Rapidity K/π

NA49 (V. Friese SQM'03)



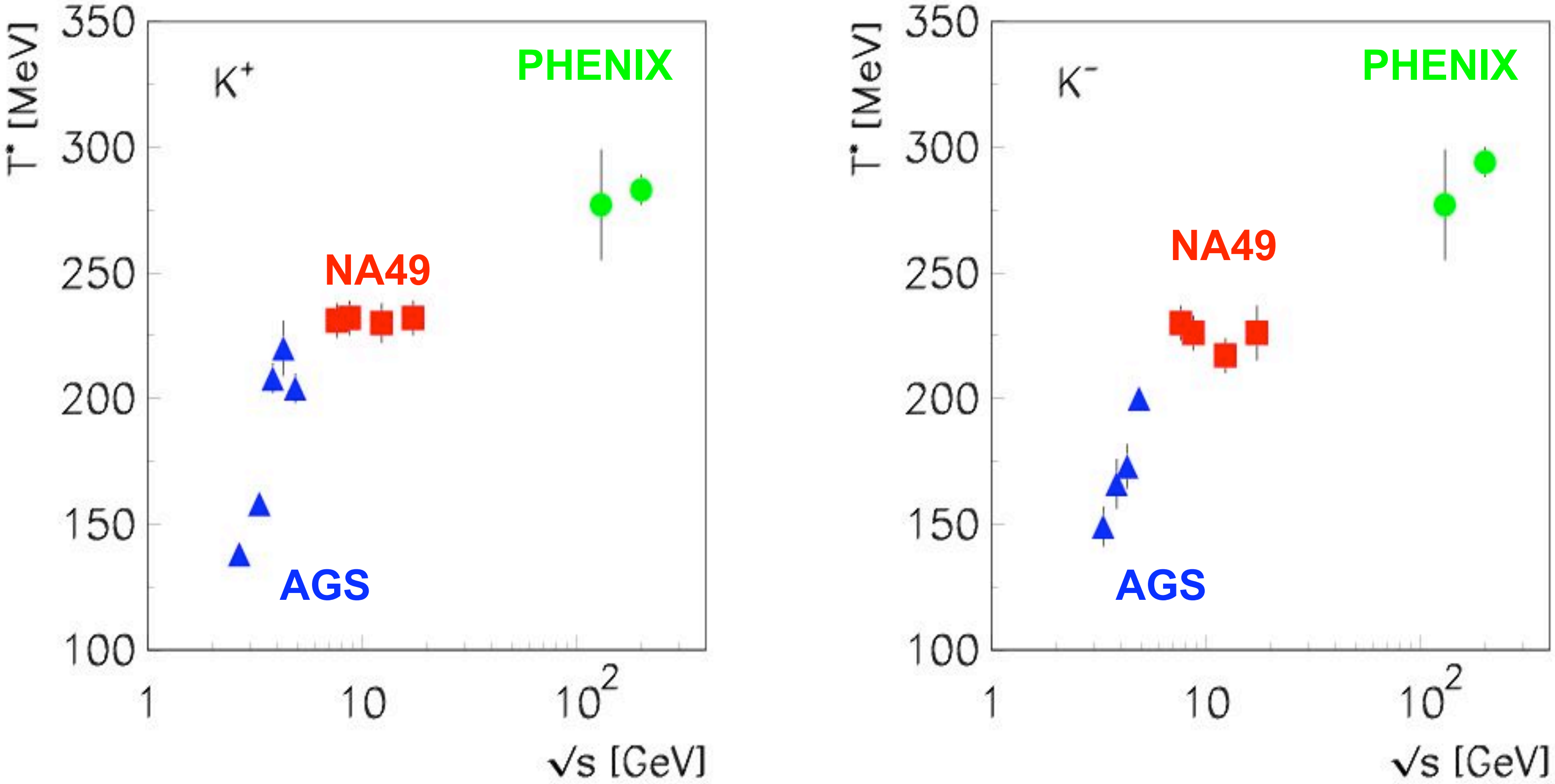
Non-monotonic Evolution!

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

Too kinky!

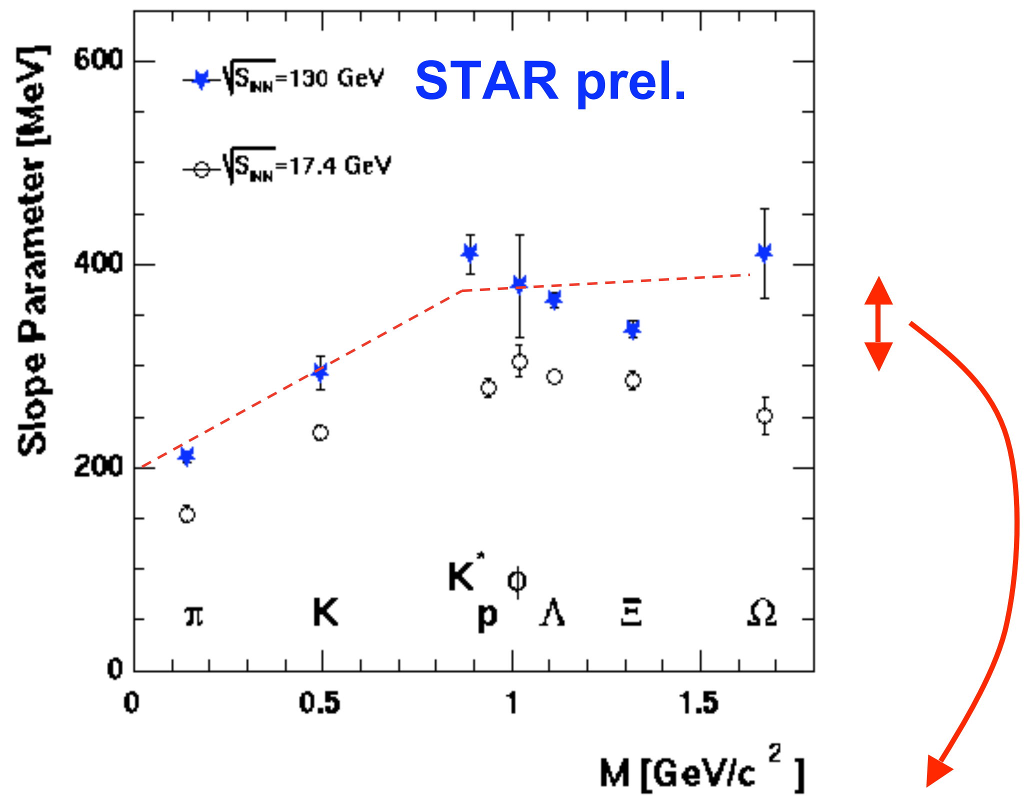
Kaon Slope Parameters

NA49 (V. Friese SQM'03)



‘T’ vs mass, sqrt(s)

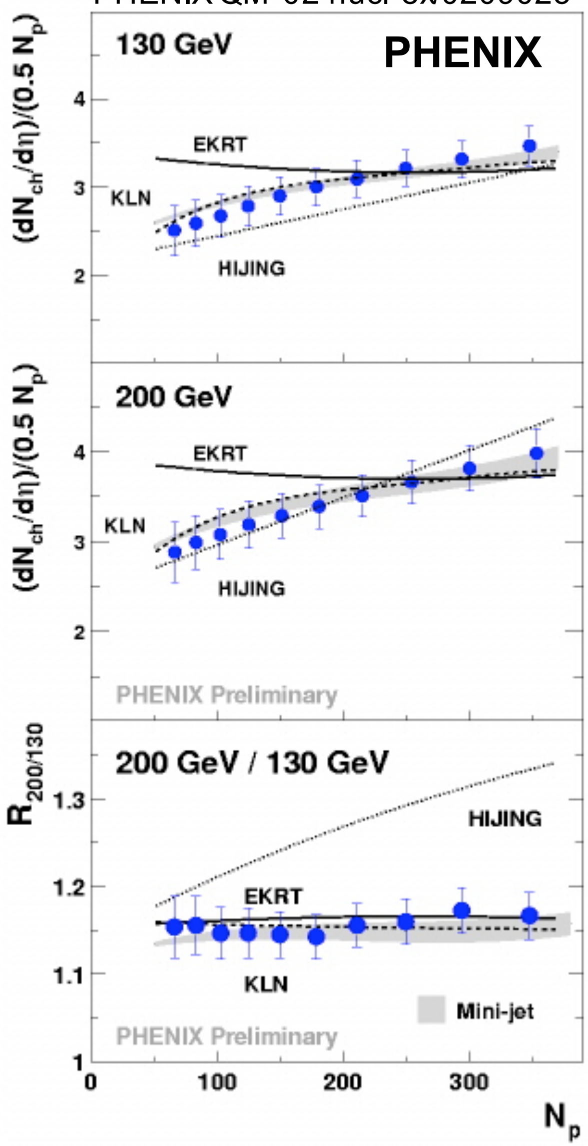
Data: J. Castillo SQM’03



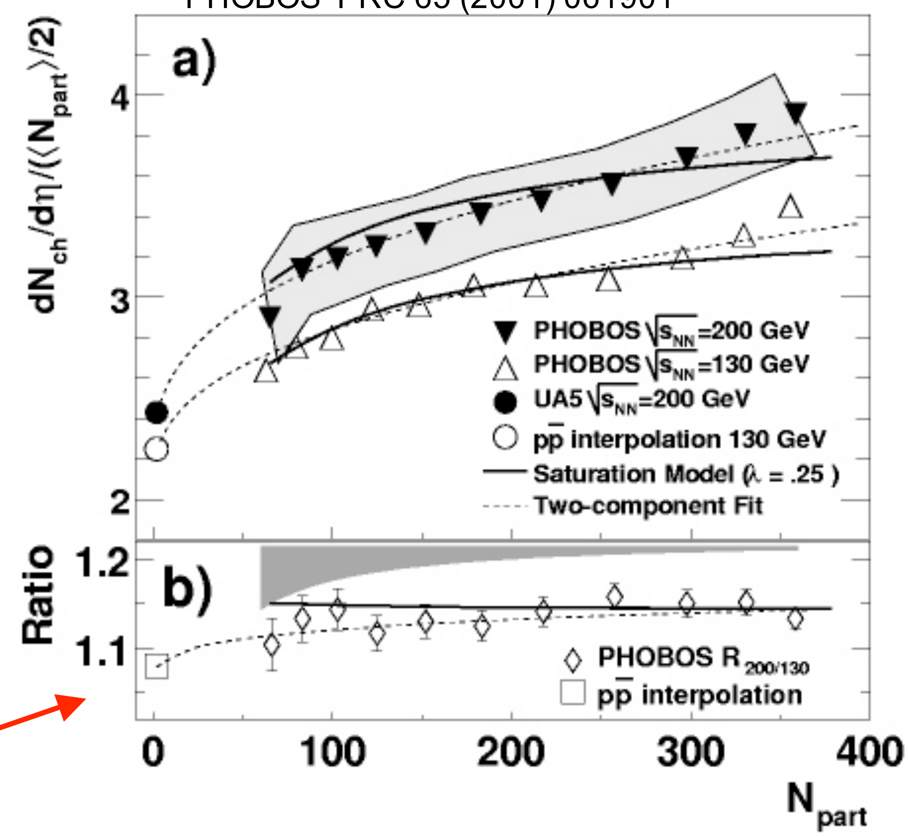
Significant increase in <p_T> from SPS to RHIC

Centrality Dependence at |h| < 1

PHENIX QM '02 nucl-ex/0209025



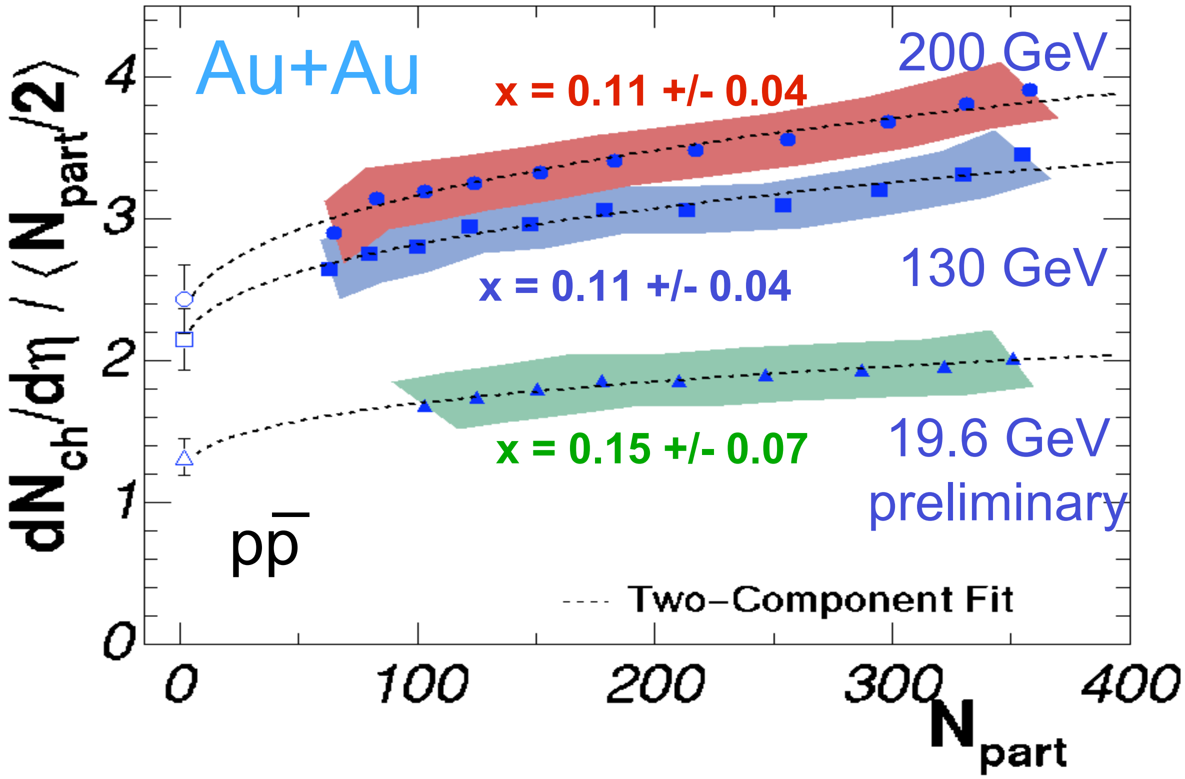
PHOBOS PRC 65 (2001) 061901



Agreement on flatness of $R_{200/130}$!

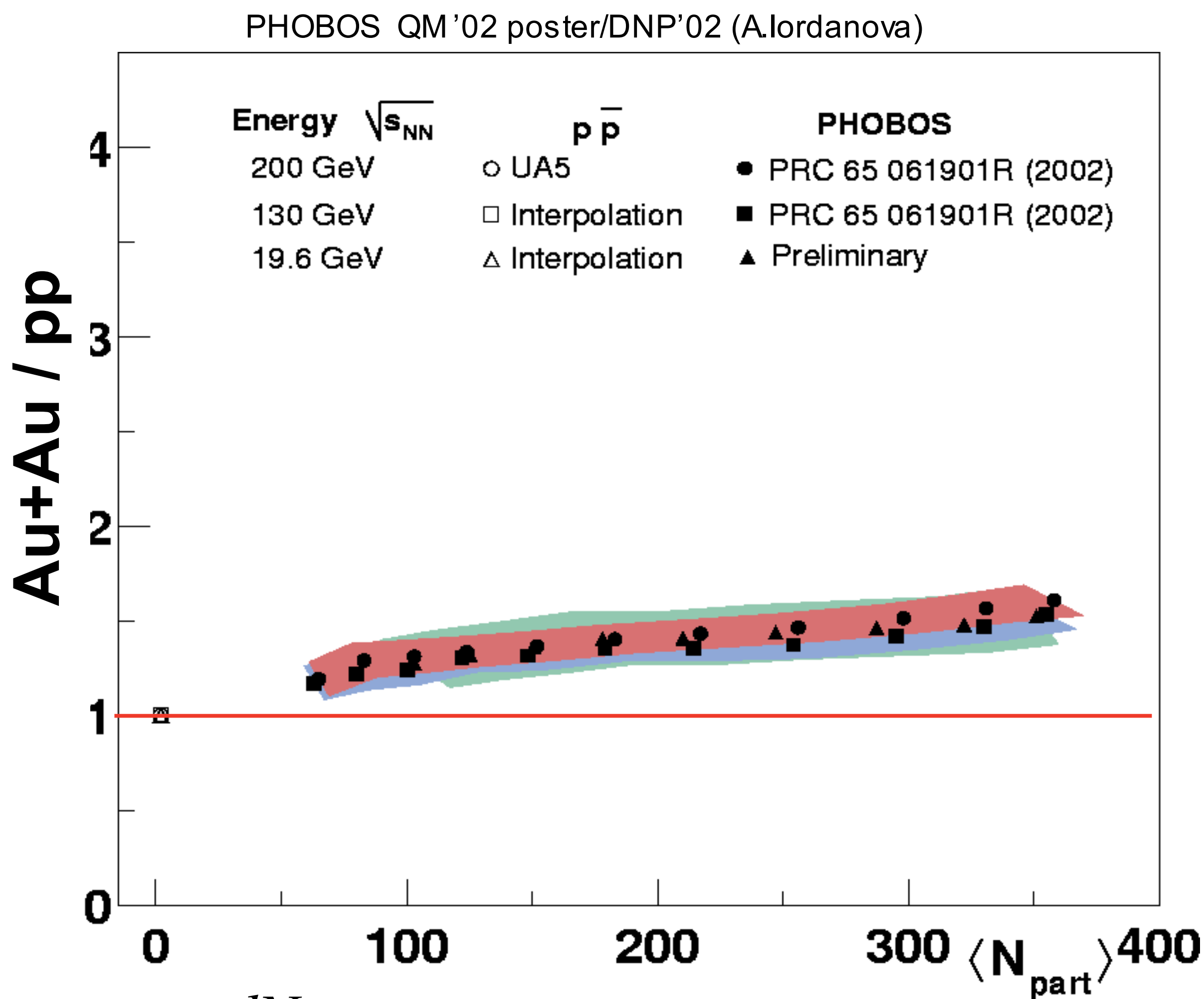
Centrality Dependence at |h| < 1

PHOBOS QM'02 poster/DNP'02 (A.Iordanova)



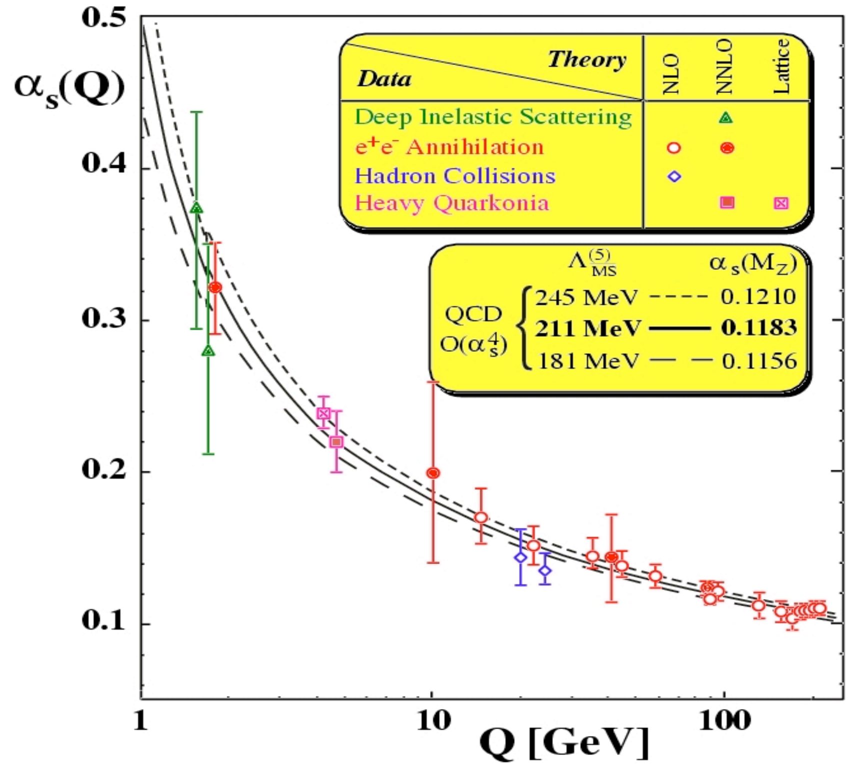
$$\frac{dN}{d\eta} = (1-x) n_{pp} N_{\frac{part}{2}} + x n_{pp} N_{coll}$$

Centrality Dependence at |h| < 1



$$\frac{dN}{d\eta} = (1-x)n_{pp}\frac{N_{part}}{2} + xn_{pp}N_{coll}$$

Soft vs Hard Particle Production

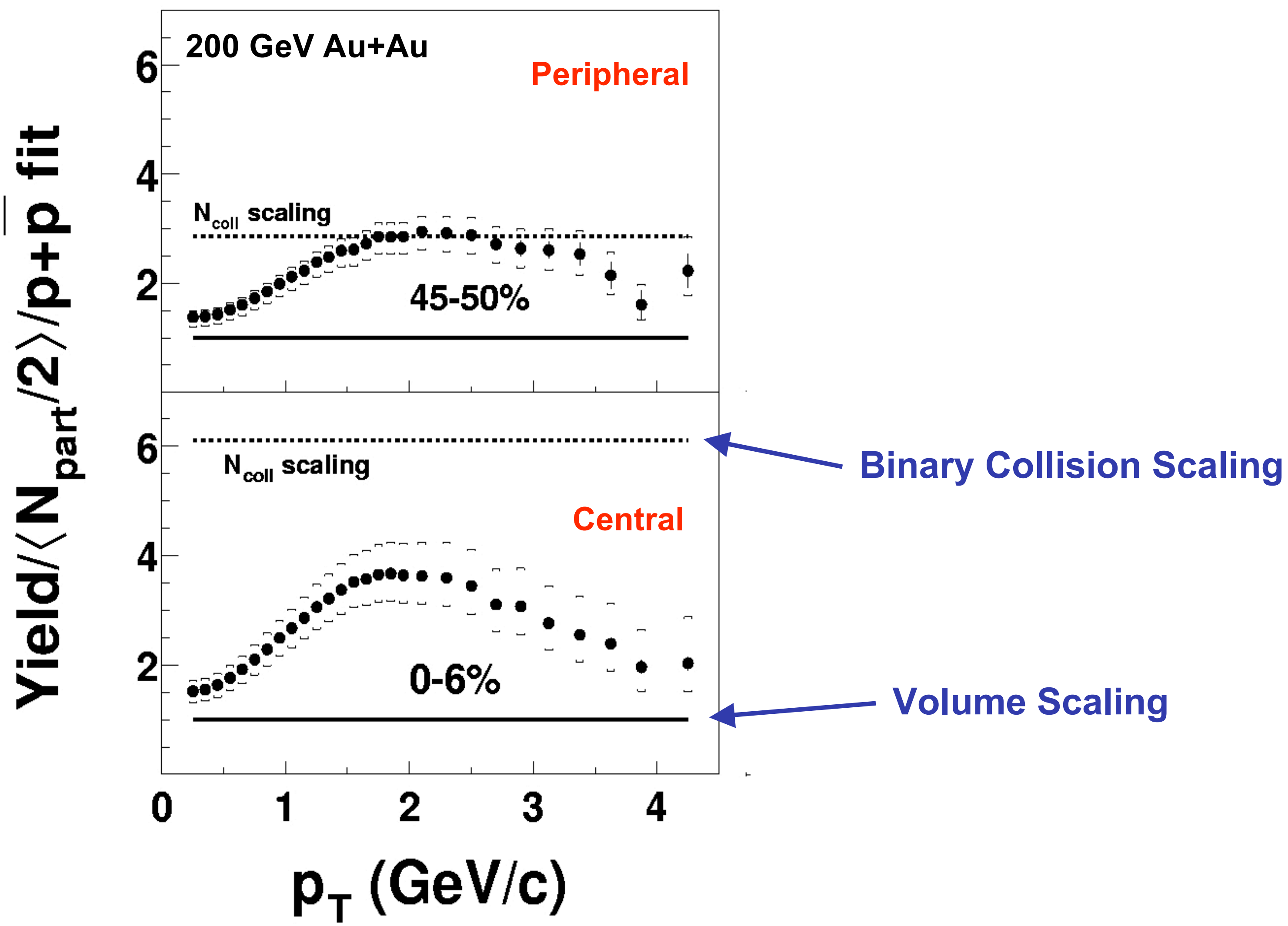


Running Coupling Constant

1. Soft Physics
2. Bulk particle production
3. Scaling ~ Volume
4. Hydrodynamics

1. Hard Scattering
2. Rare Processes
3. Scaling: Point-like
4. Perturbation Theory

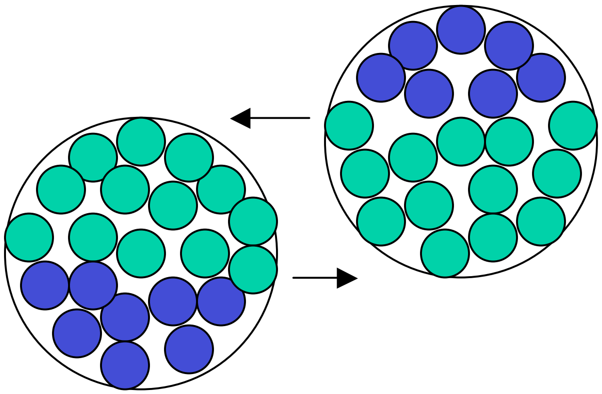
Soft vs Hard Particle Production



Summary

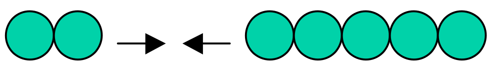
- Extensive and Consistent Data Set
  - BRAHMS, PHENIX, PHOBOS, STAR
  - AGS, SPS, RHIC
- Consistent and Concise description of Final State
- Puzzles
  - Short time scales
  - Strangeness evolution
  - Universality
- Challenge: ***Consistent Dynamical Scenario***
  - Energy Dependence
  - Soft vs Hard particle Production

What Are the Correct Variables?



Spectator Nucleons

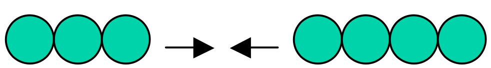
Participating Nucleons



N_{part}= 7

$N_{coll.}$= 10

Will the following be equivalent to the above?



$N_{quarks\ +gluons}$ = ?

$N_{inelastic}$= 1

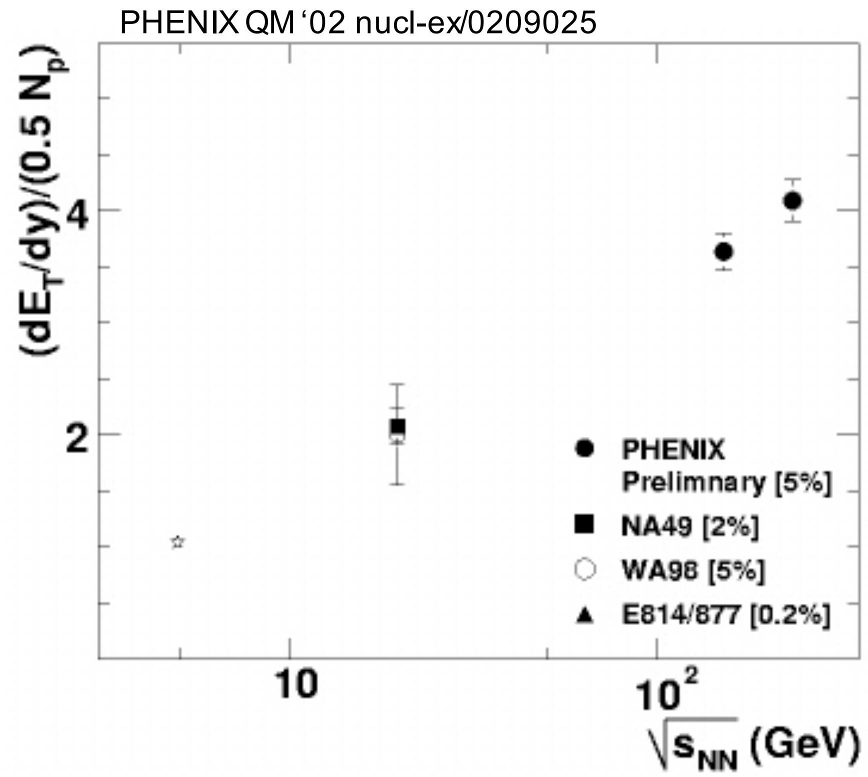
$$\sigma_{inel} \sim (R_1+R_2)^2 \sim (A_1^{1/3} + A_2^{1/3})^2 \sim A^{2/3}$$

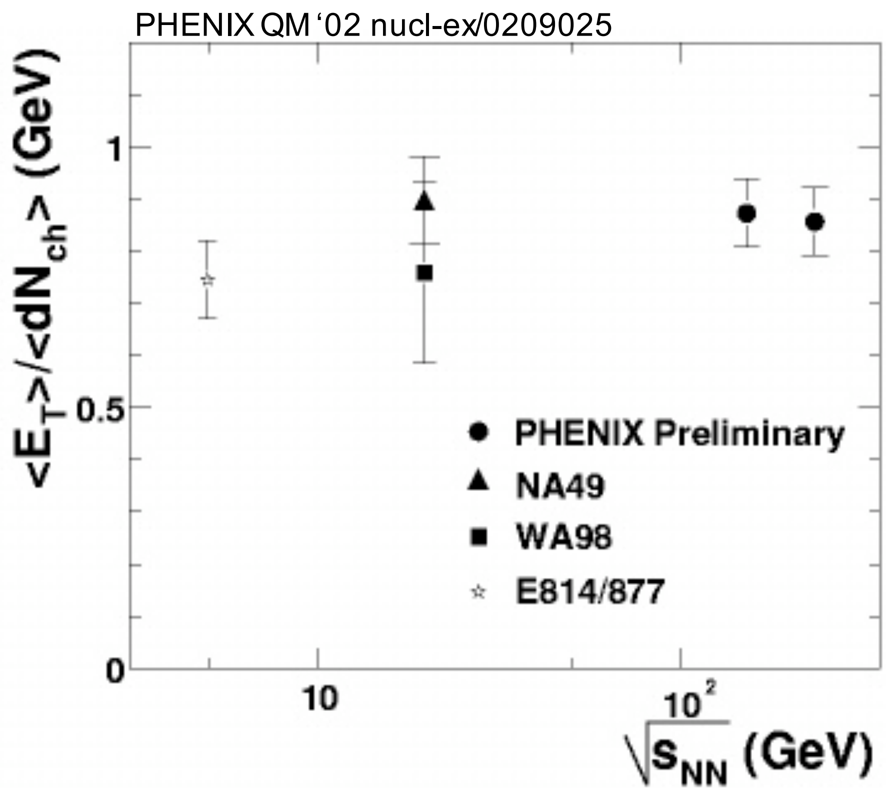
$$N_{part} \sim A^{2/3}(A_1^{1/3}+ A_2^{1/3}) \sim A$$

$$N_{coll} \sim A^{2/3}(A_1^{1/3} * A_2^{1/3}) \sim A^{4/3}$$

In calculating N_{part} or N_{coll} σ taken to be nucleon-nucleon inelastic cross-section. A priori no reason for this choice other than that it seems to give a useful parameterization.

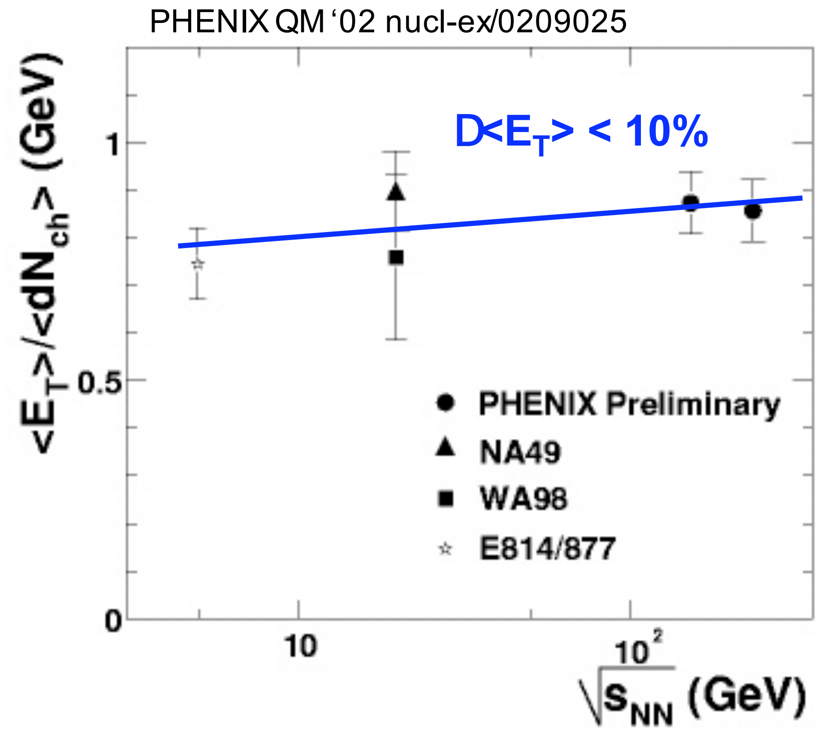
Transverse Energy near h=0

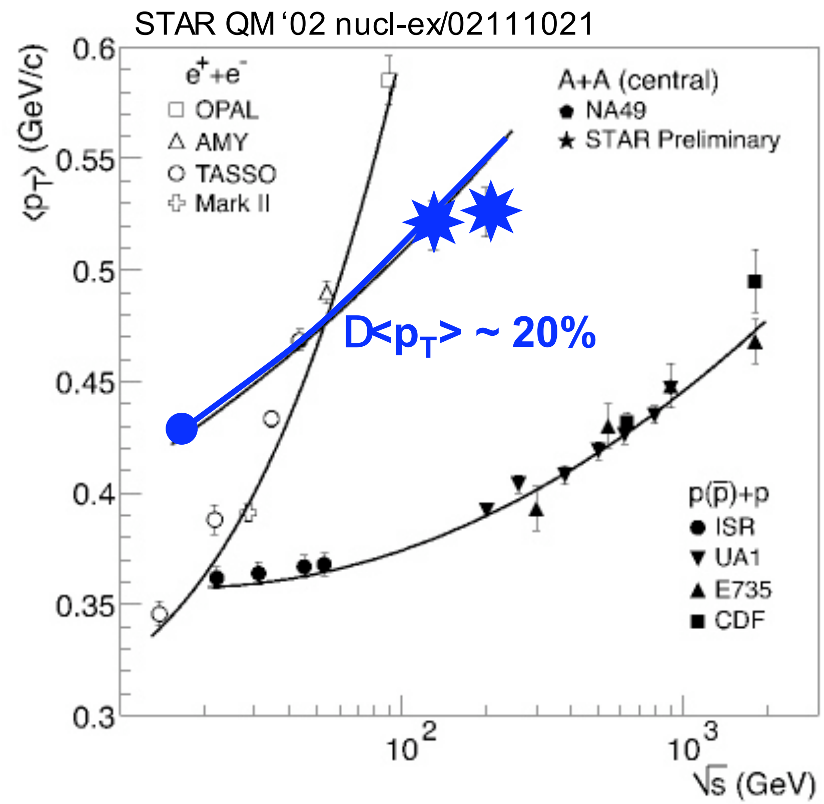




- dE_T/dh exhibits smooth rise vs sqrt(s)
- Surprisingly, $\langle E_T \rangle$ per particle at h=0 constant
  - even though p+p spectra get much harder with sqrt(s)

Transverse Energy near h=0



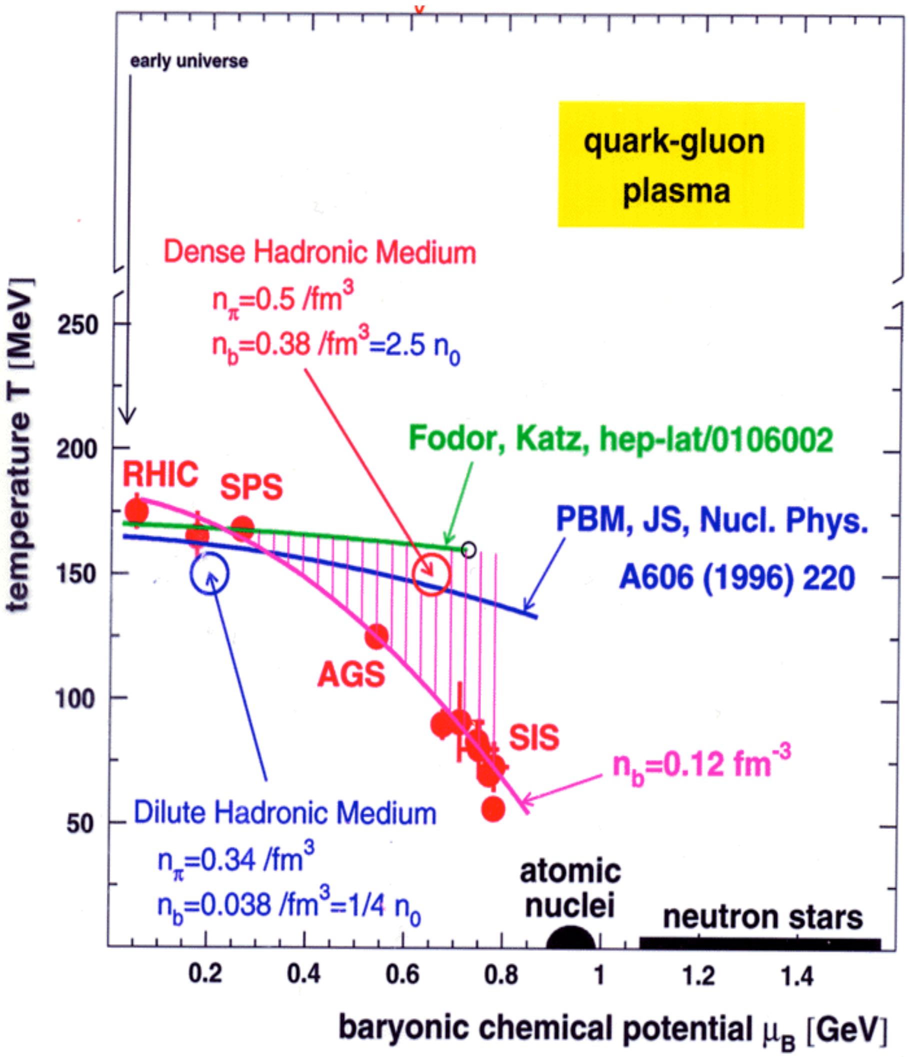


If $<E_T>$ is constant…. **…and $<p_T>$ goes up**

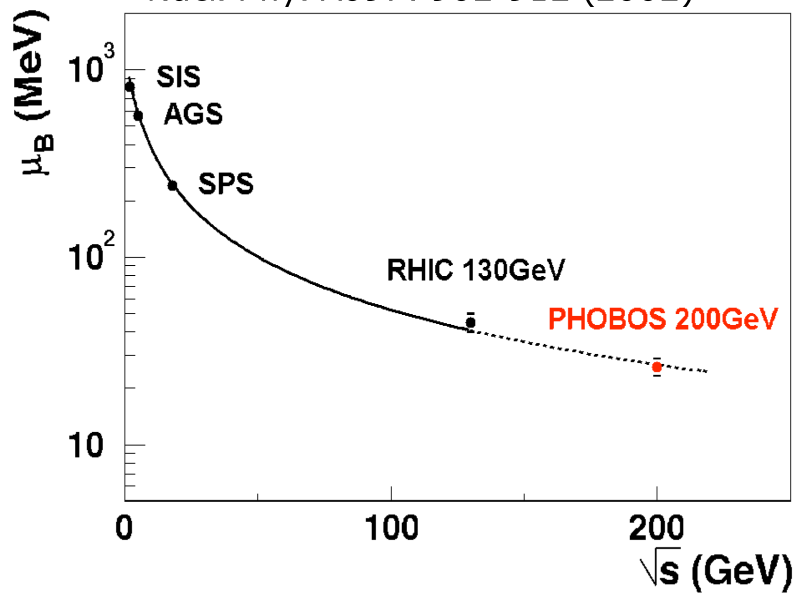
…does <M> go down?

Ullrich, nucl-ex/0211004

Chemistry vs sqrt(s)

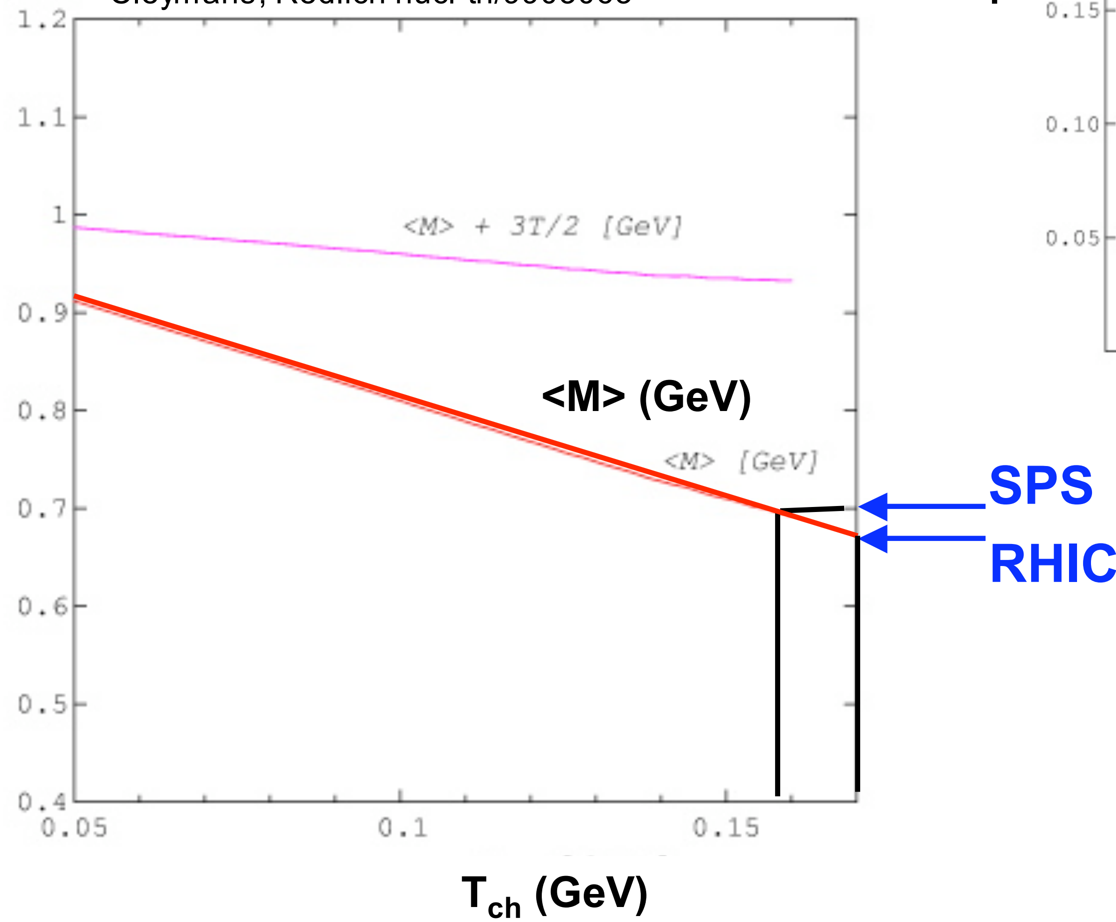


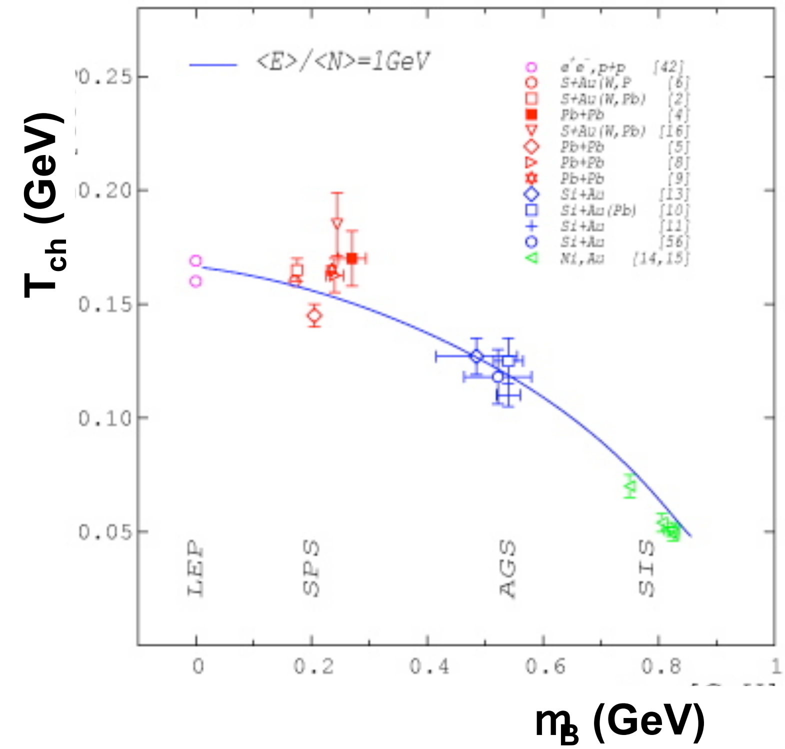
Nucl. Phy. A697: 902-912 (2002)



Energy in thermal model

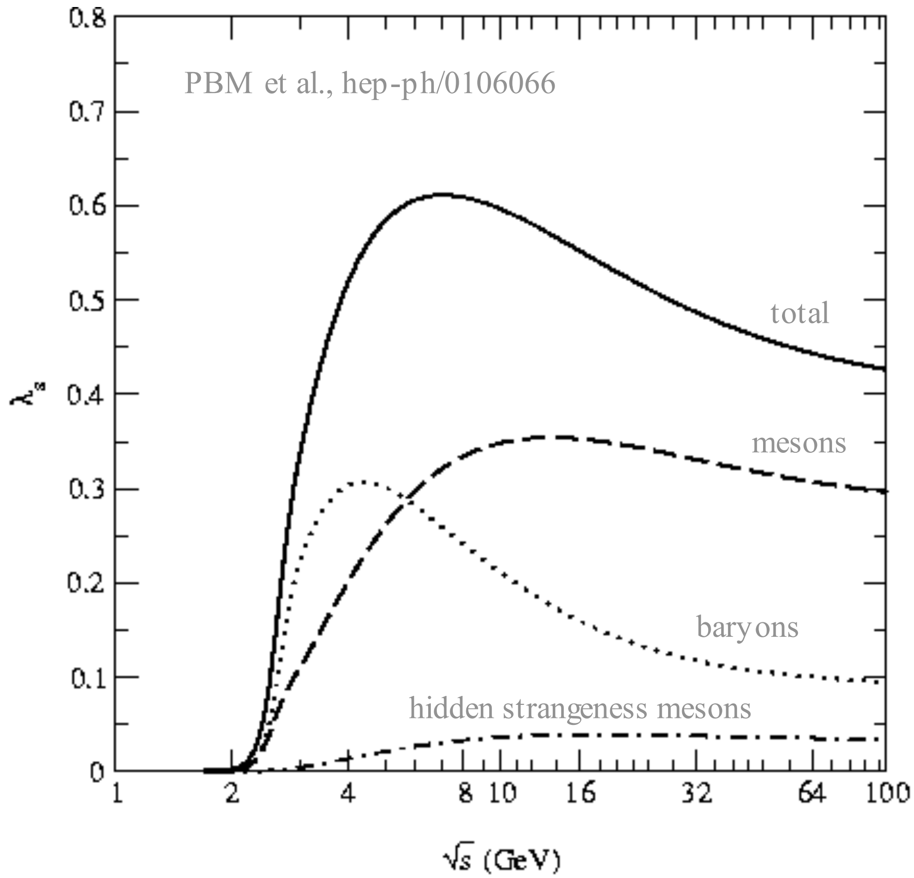
Cleymans, Redlich nucl-th/9903063





maybe….

Strangeness production vs sqrt(s)



Statistical model 'prediction'