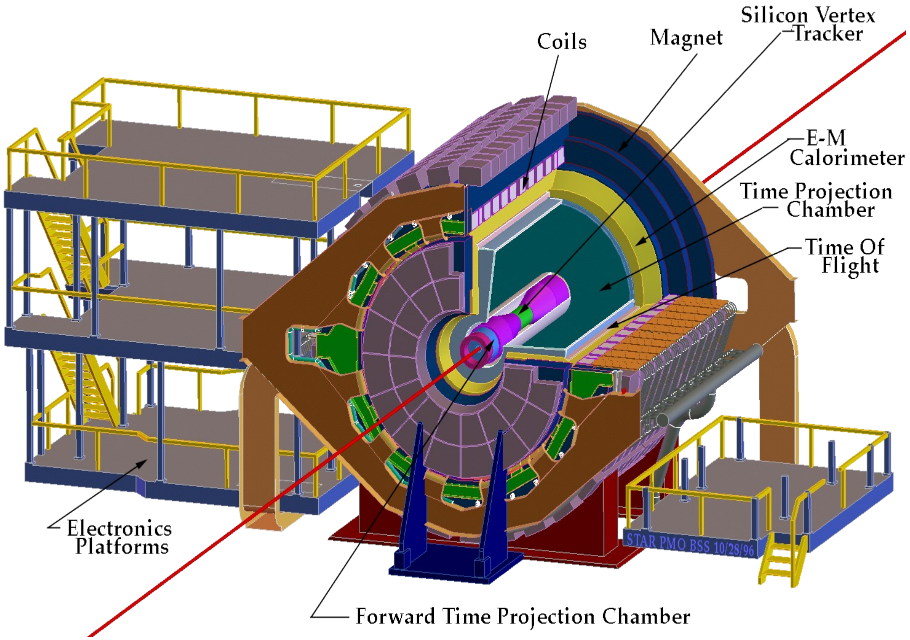
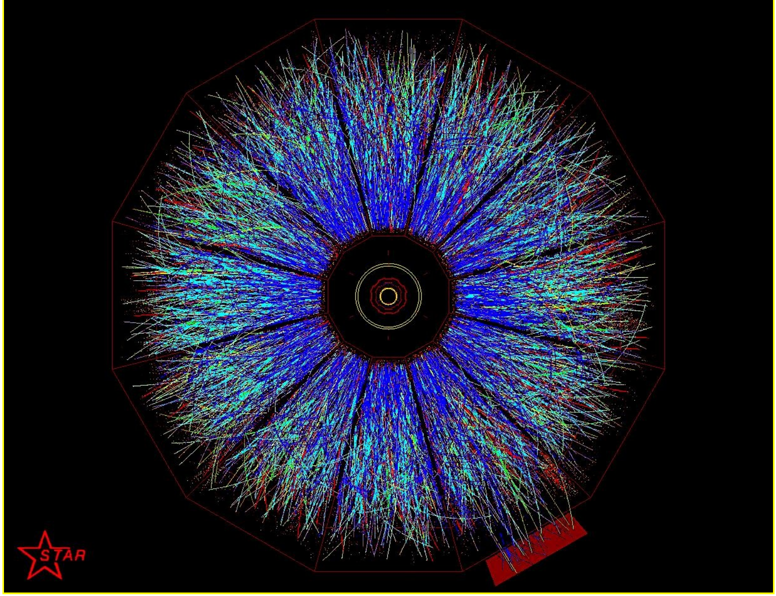




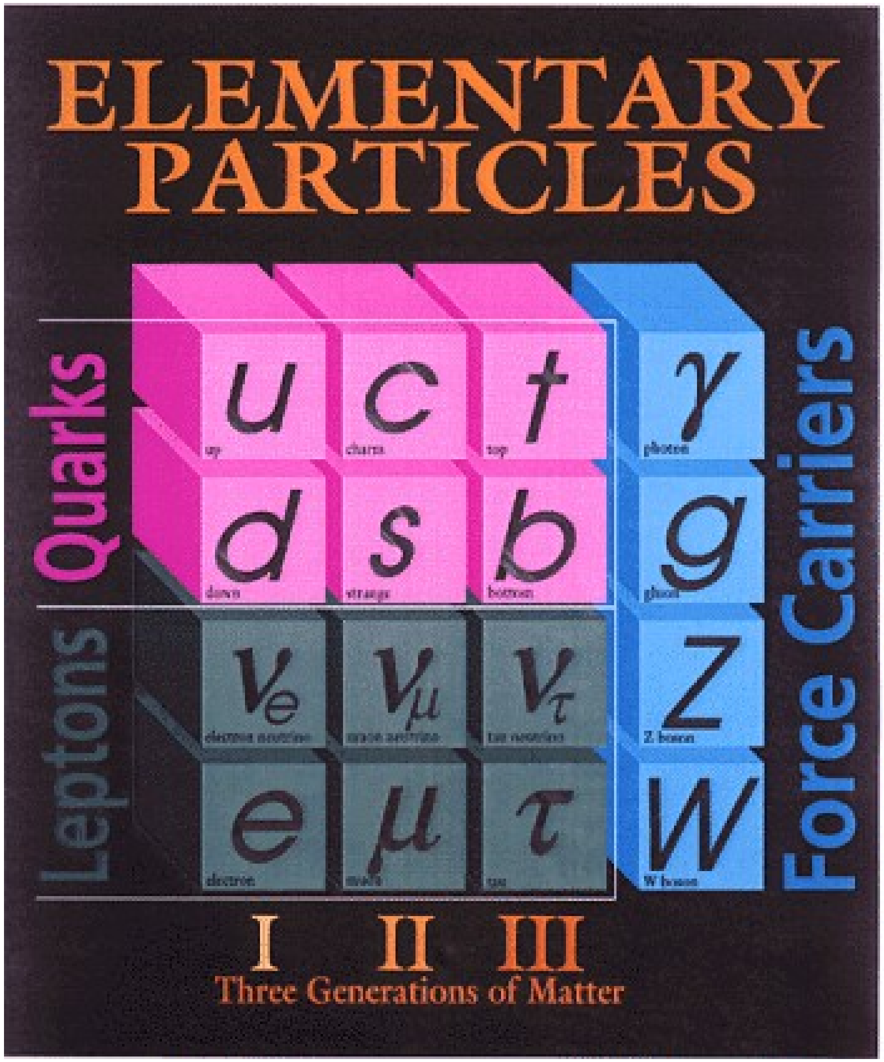
Zderzenia ciężkich jonów obserwowane w eksperymencie STAR

Hanna Paulina Zbroszczyk

Politechnika Warszawska
Wydział Fizyki

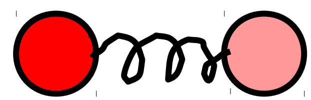
Warszawa, 18.12.2009

Basics on Quantum Chromodynamics

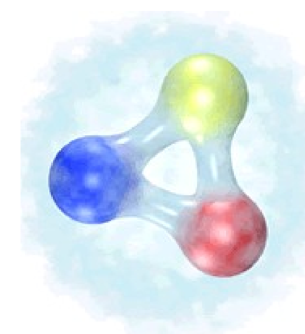


1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.
2) Gluons hold quarks together to from hadrons:

meson



baryon

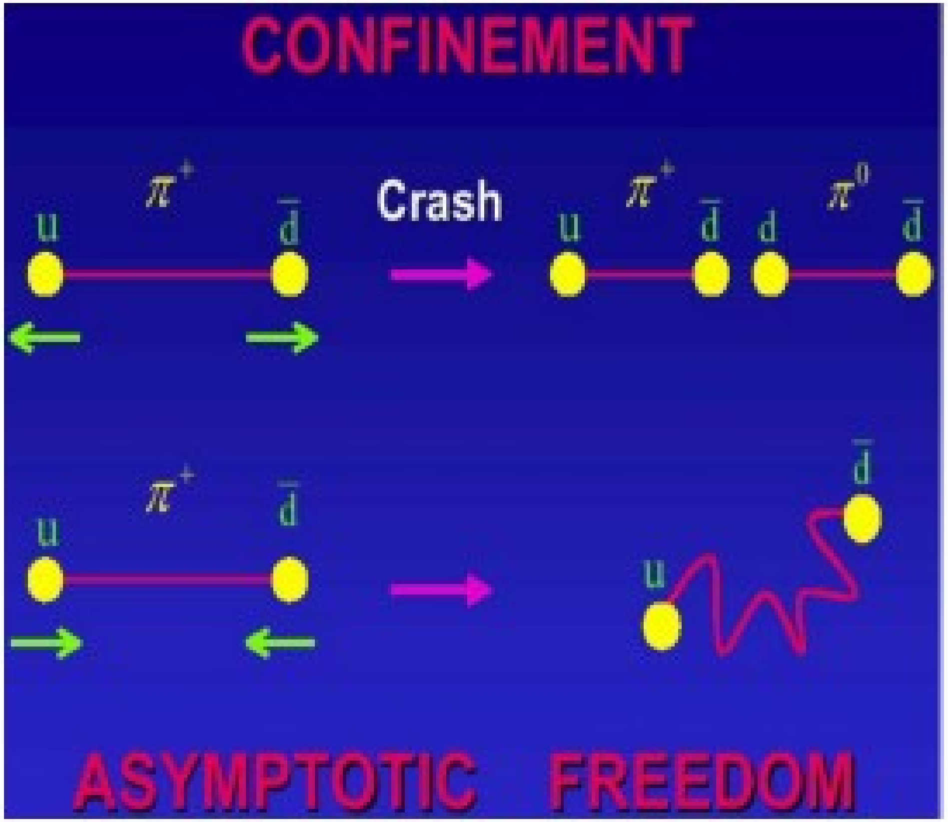


1) Gluons and quarks, or partons, typically exist in a color singlet state: ***confinement.***

Quark gluon plasma (QGP)

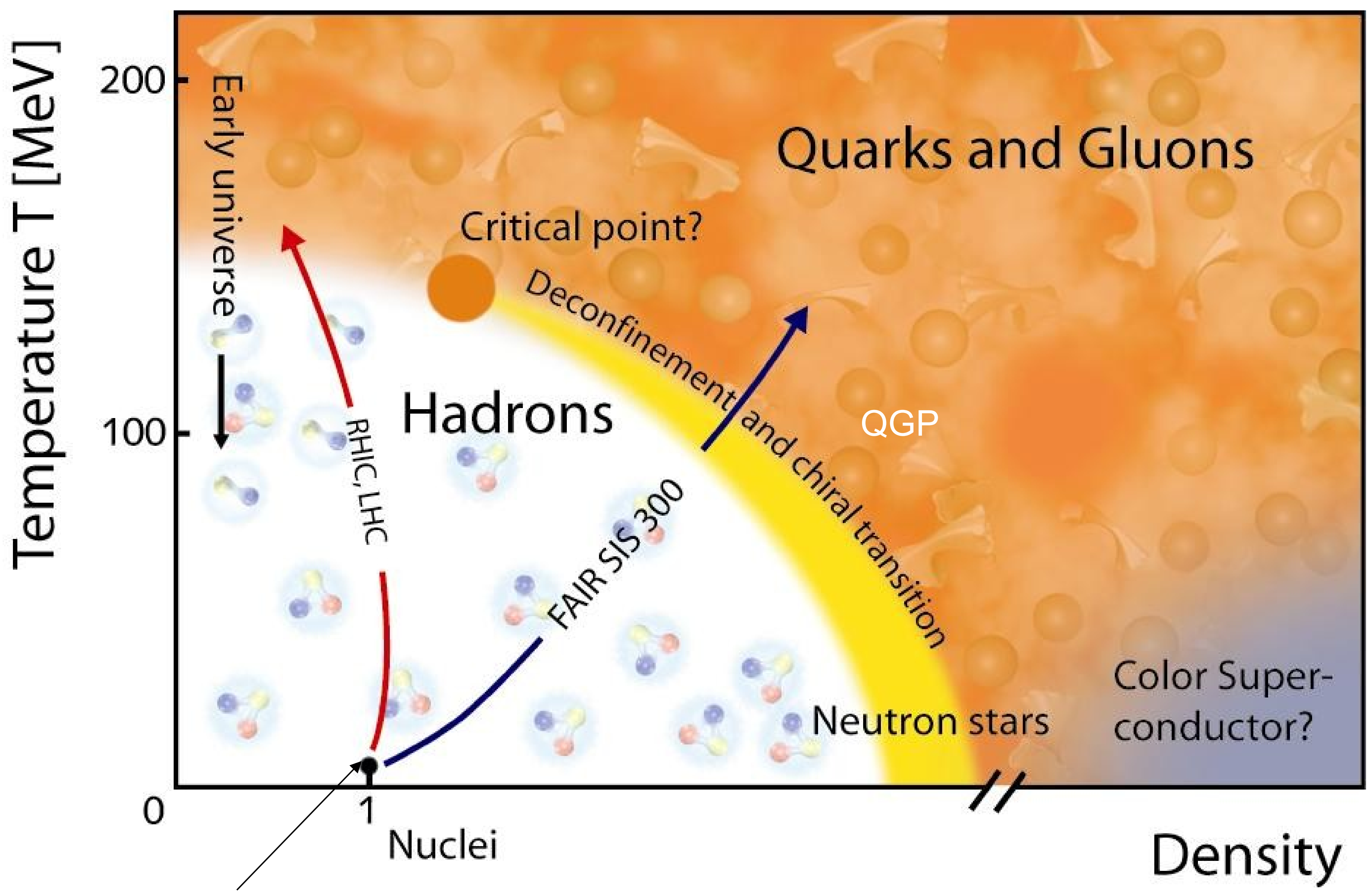
Asymptotic freedom is the property of some gauge theories in which the interaction between the particles, such as quarks, becomes arbitrarily weak at ever shorter distances, i.e. length scales that asymptotically converge to zero.

Confinement is the physics phenomenon that color charged particles (such as quarks) cannot be isolated. The quarks are confined with other quarks by the strong interaction to form pairs or triplets so that the net color is neutral, to obey the Pauli exclusion principle. Quarks in mesons must be of a color and the corresponding anti-color to achieve color neutralism; in baryons a red-green-blue mixture (or its anti-color equivalent in an antiparticle) must be achieved.

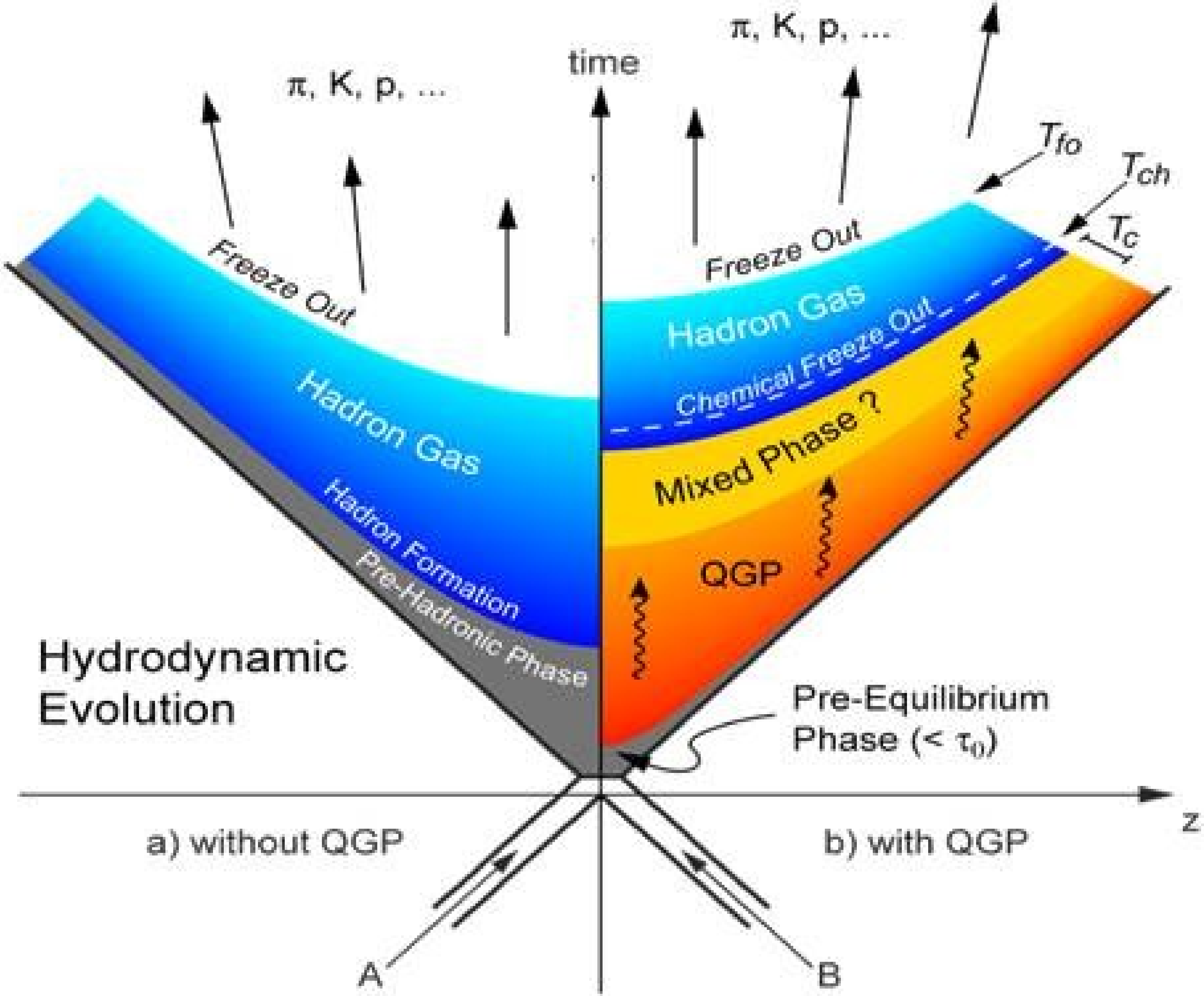


Quark-gluon plasma (QGP) is a phase of quantum chromodynamics (QCD) which exists at extremely high temperature and/or density.
This phase consists of (almost) free quarks and gluons which are the basic building blocks of matter.

Phase Diagram

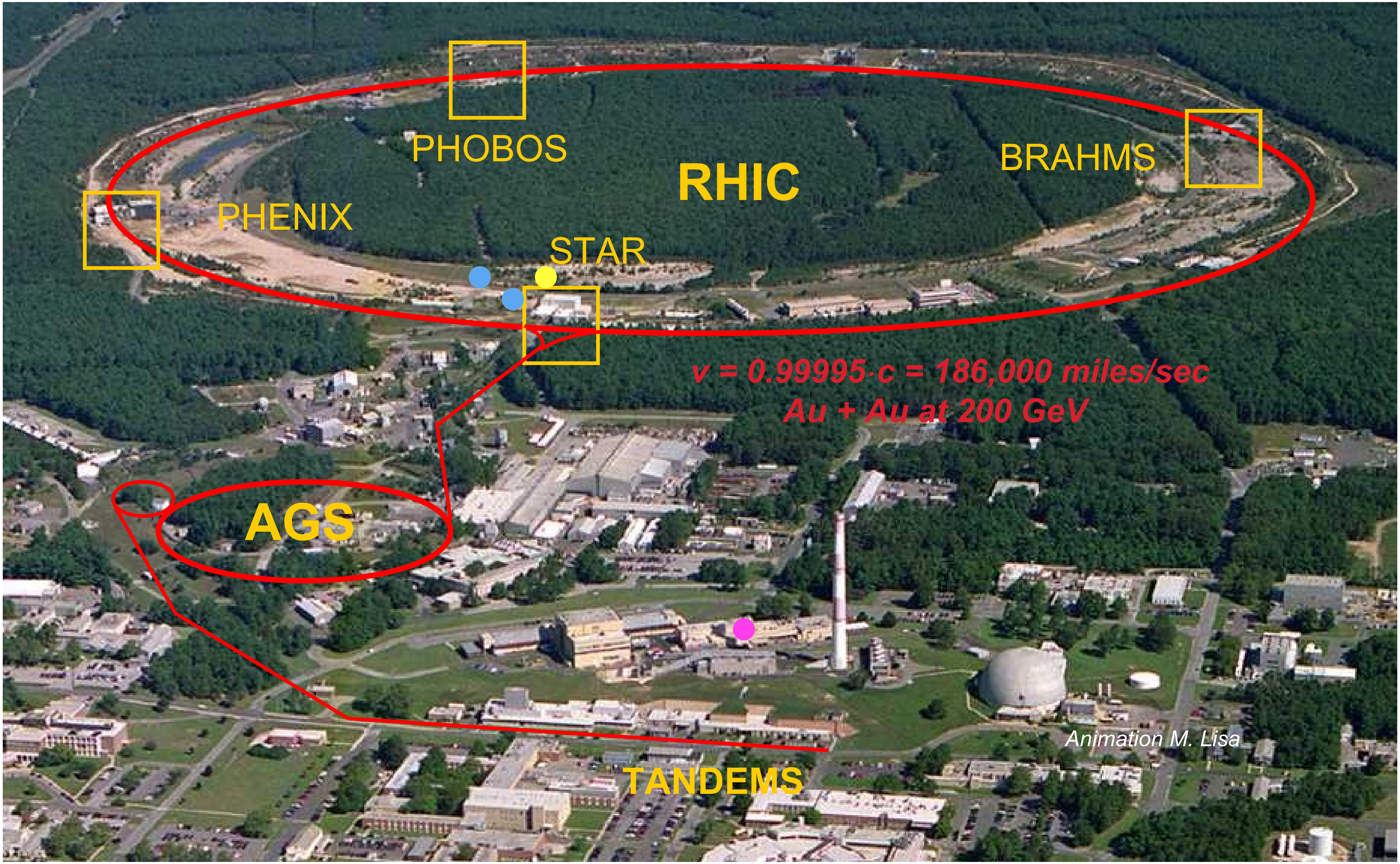


Hadronization – two scenarios..



Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY



Where are we?

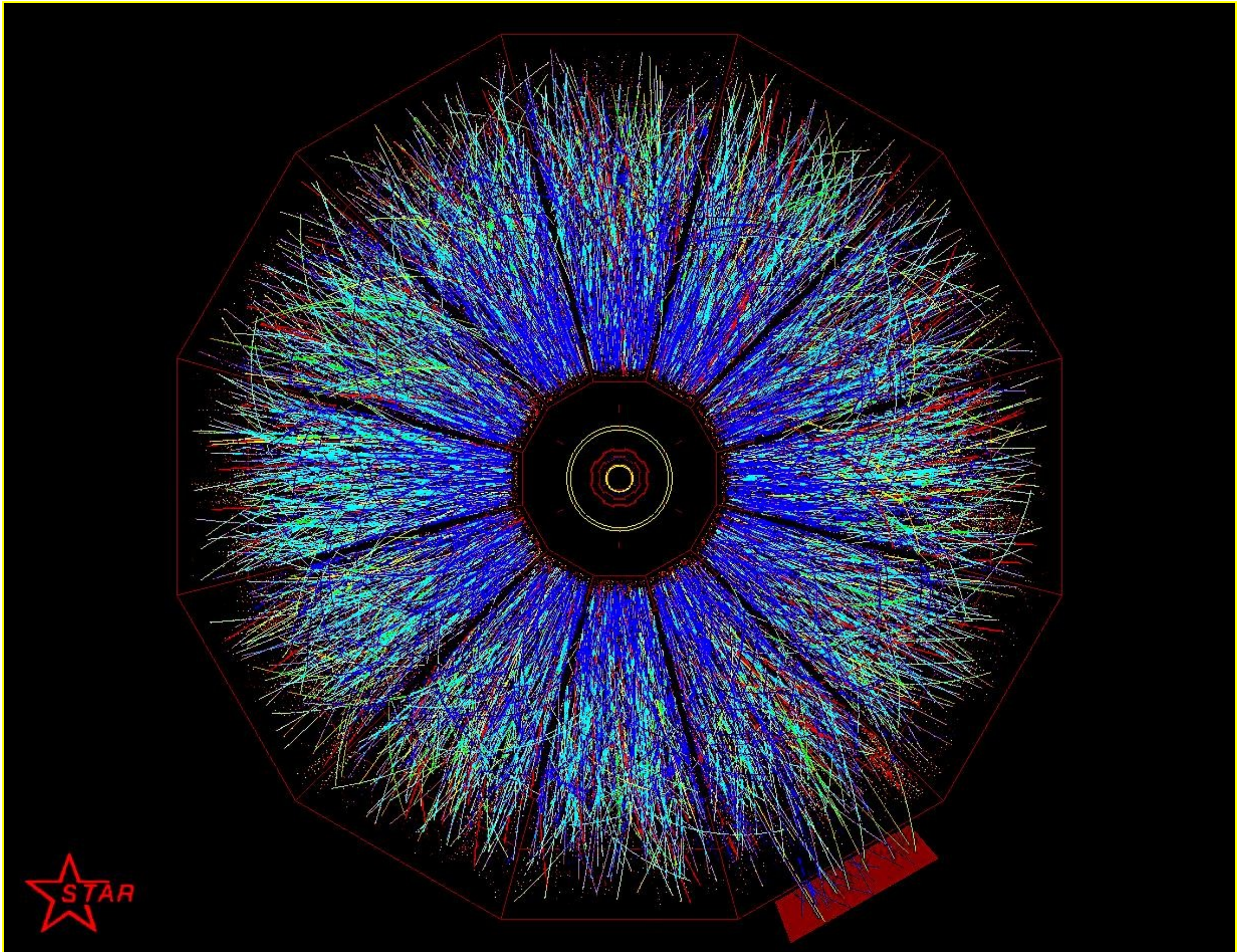
Goal of the RHIC Heavy Ion Program:

- search the QGP and measure its properties
- map the QCD phase diagram

What have we learned so far?

STAR NPA 757 (2005) 102

Strongly interacting, hot, dense matter with partonic collectivity



Outline: Recent STAR results

Investigation on the initial state in high energy A+A collisions

1) Systematic studies on the bulk properties (soft physics)

- More precision data on identified particle v_2
- Hydro limit reached?
- Strangeness production
- Observation of the anti-hypertriton
- ρ^0 observable
- Search for local strong parity violation in QCD
- *Femtoscopic measurements (identical, nonidentical, baryon particle combinations)*

2) Using calibrated probes to learn medium properties (hard physics)

- Hard probes of the initial state (Upsilon in d+Au)
- Hard probes of the final state/medium (J/Psi at high p_T in Cu+Cu; Jet flavor conversion, Ridge characteristics)

3) Beam Energy Scan (BES)

- measurements at 9 GeV
- future plans

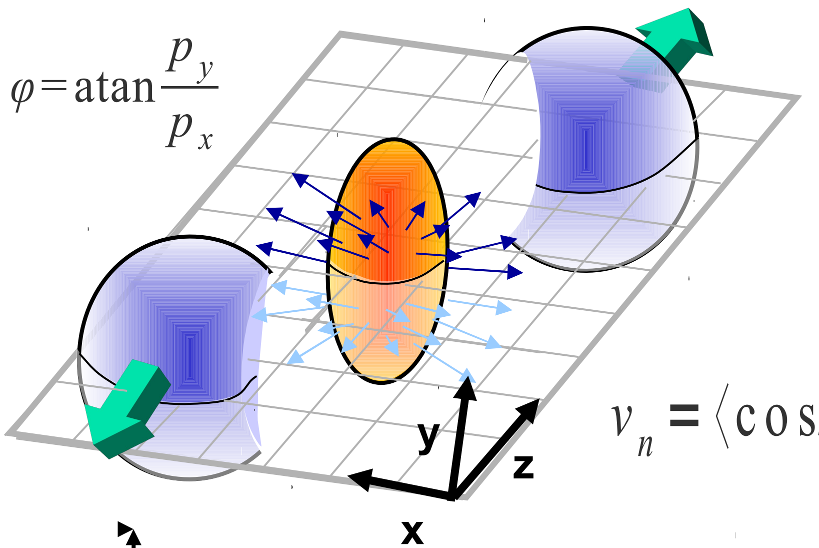
3') LHC predictions

soft physics

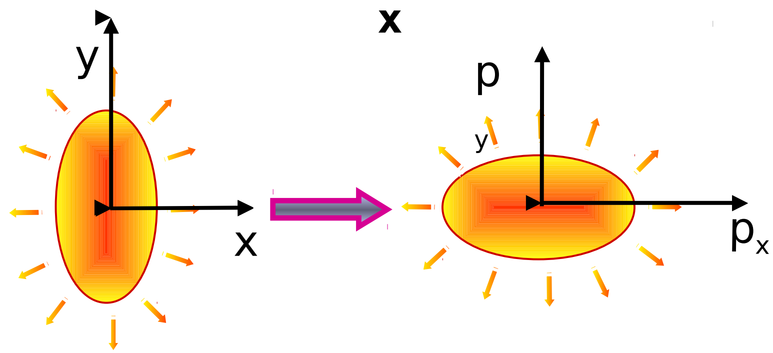
1) v_2; limit of hydrodynamics;
2) strangeness production; anti-hypertriton;
3) ρ^0 observable;
4) local strong parity violation;
5) *femtoscopy*

(1) Anisotropic Flow

$$\varphi = \operatorname{atan}\frac{p_y}{p_x}$$



$$v_n = \langle \cos n \cdot \varphi \rangle$$



$$dN/d\phi \;\propto\; 1 + \sum_n 2 v_n \cos n\,(\phi - \Psi_{RP})$$

- Look at peripheral collisions
- Overlap region is not symmetric in coordinate space
- Almond shaped overlap region
  - Larger pressure gradient in x-z plane than in y-direction

Spatial anisotropy → Momentum anisotropy

- **Interactions among constituents transform the initial spatial anisotropy into an (observed) momentum anisotropy**
- **Process quenches itself → sensitive to early times in the evolution of the system**
- **sensitive to the equation of state**

- **Fourier decomposition of the momentum space particle distributions in the x-y plane**
  - **v_n is the n-th harmonic Fourier coefficient of the distribution of particles with respect to the reaction plane**
    - **v_1: "directed flow"**
    - **v_2: "elliptic flow"**

The first STAR publication

Elliptic Flow in Au+Au Collisions at sqrt(s_m) = 130 GeV

Submitted September 12, 2000, published January 18, 2001

Phys. Rev. Lett. **86** (2001) 402

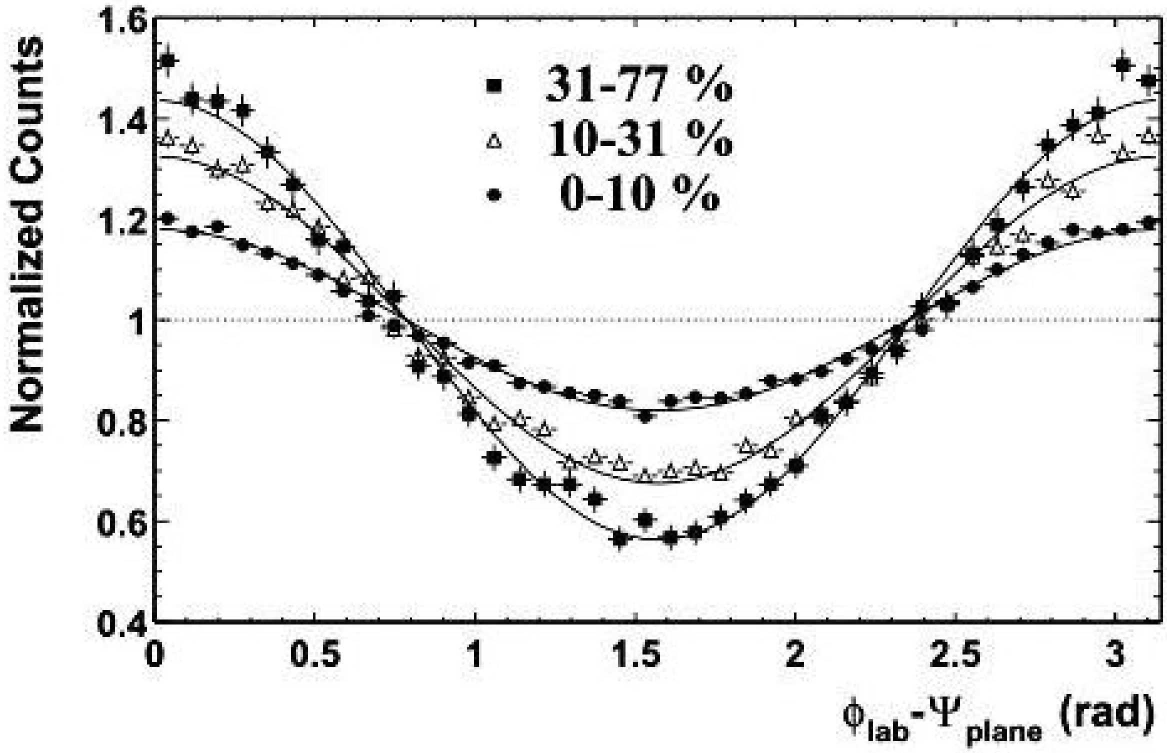


FIG. 10 Distribution of particle momentum relative to the reaction plane for events of three different centrality measured by STAR (10).

The first STAR publication

Elliptic Flow in Au+Au Collisions at sqrt(s_m) = 130 GeV

Submitted September 12, 2000, *published January 18, 2001*

Phys. Rev. Lett. **86** (2001) 402

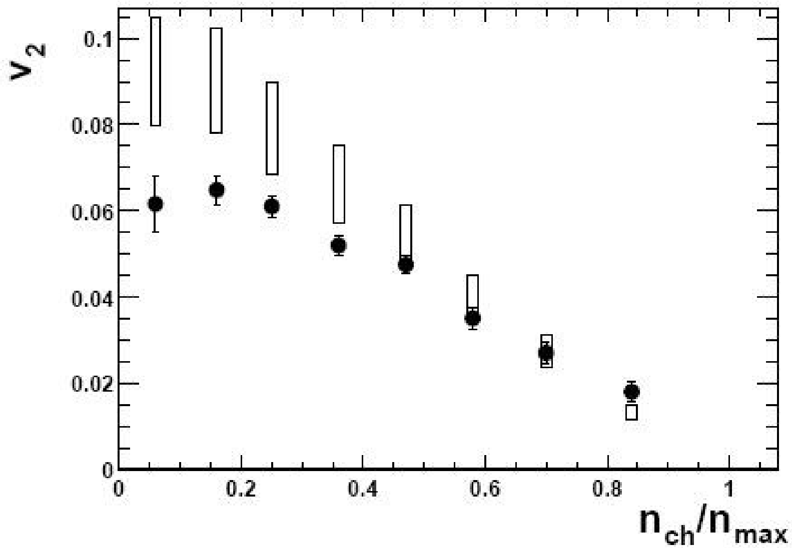


FIG. 3. Elliptic flow (solid points) as a function of centrality defined as n_{ch}/n_{max}. The open rectangles show a range of values expected for v_2 in the hydrodynamic limit, scaled from ϵ, the initial space eccentricity of the overlap region. The lower edges correspond to ϵ multiplied by 0.19 and the upper edges to ϵ multiplied by 0.25.

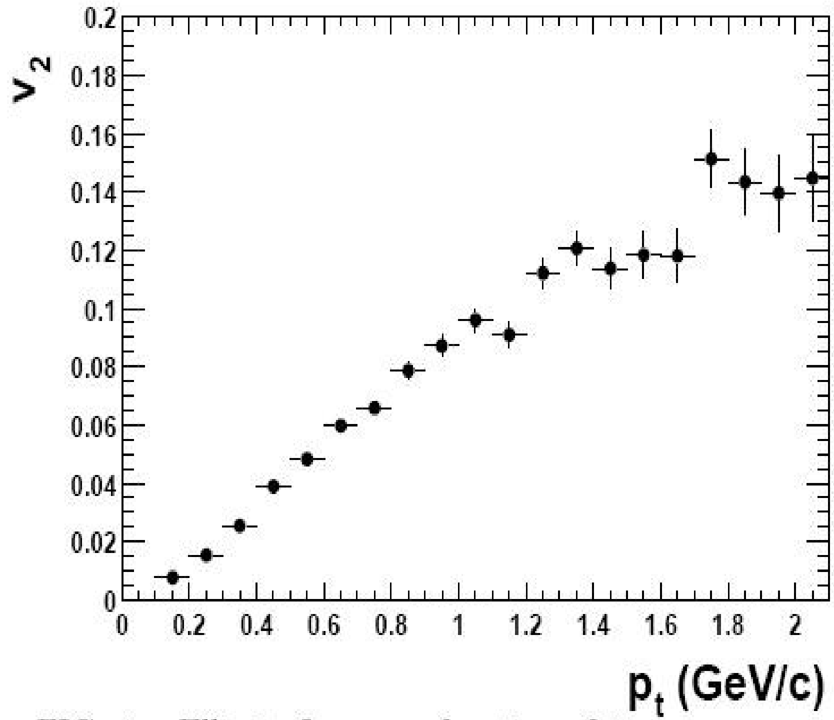


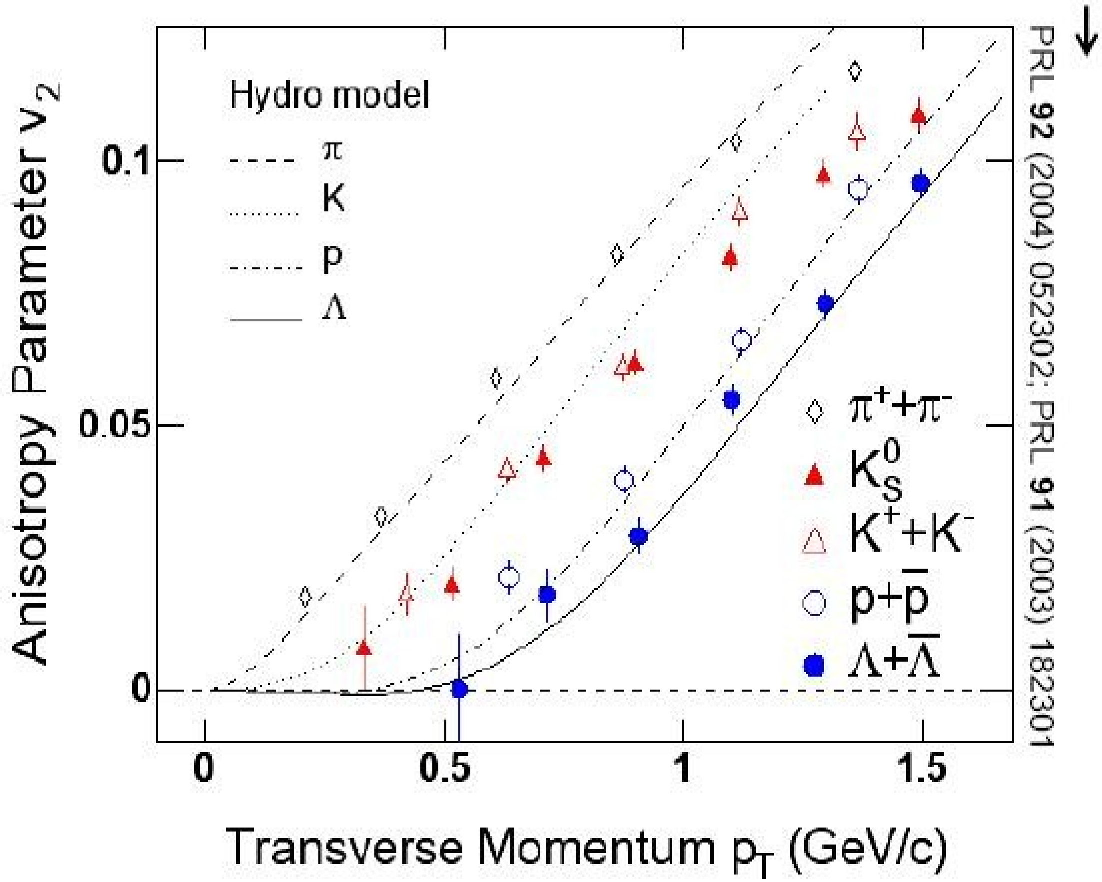
FIG. 4. Elliptic flow as a function of transverse momentum for minimum bias events.

Phys. Rev. Lett. **86** (2001) 402

Hydrodynamics

Hydrodynamics - the mean free path for interaction of the constituents represented by the fluid cells is very small compared with the region of nuclear overlap

Does pressure convert spatial anisotropy to momentum anisotropy according to the equations of ideal hydrodynamics?



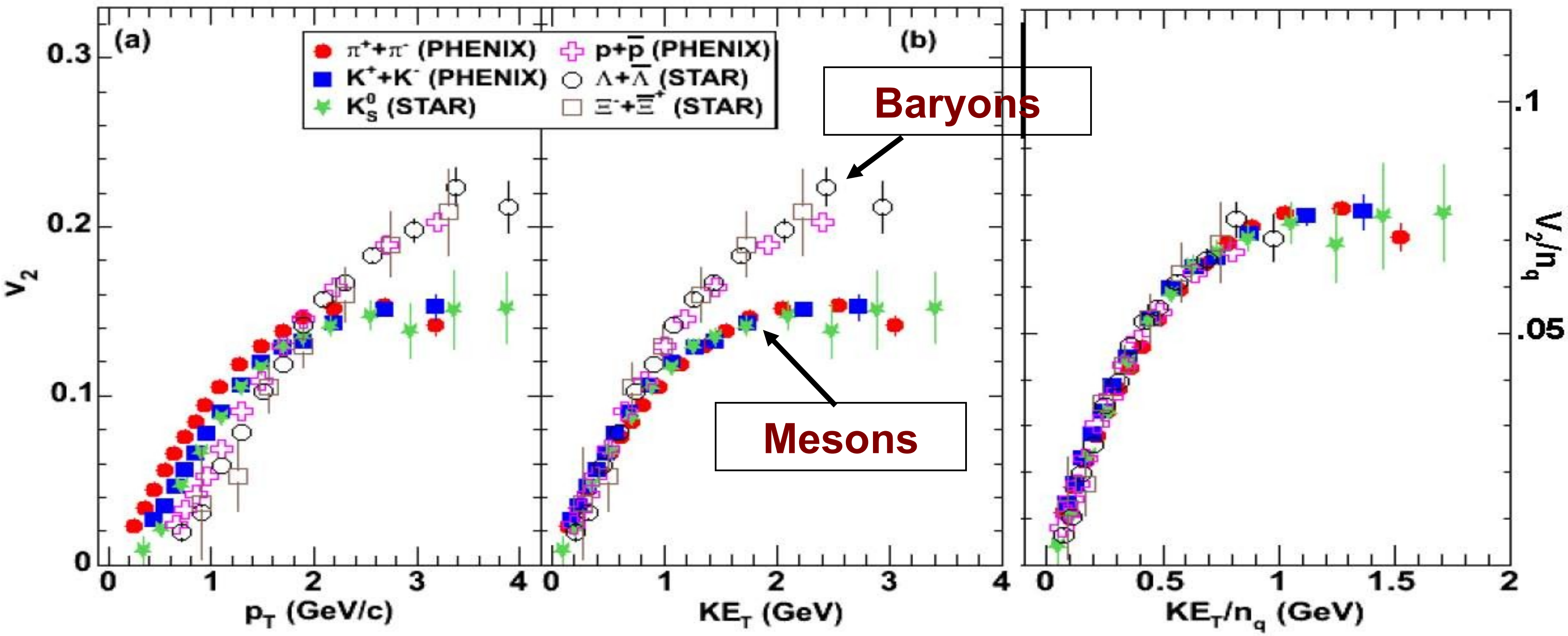
Mass ordering for soft particles indicative of a common velocity.

Calculations are sensitive to the equation-of-state.

Consistent with the formation of locally equilibrated matter.

KE_T – CQN Scaling

Transverse kinetic energy: $KE_T \approx m_T - m$, where $m_T^2 = p_T^2 + m^2$



Quark-Like Degrees of Freedom Evident

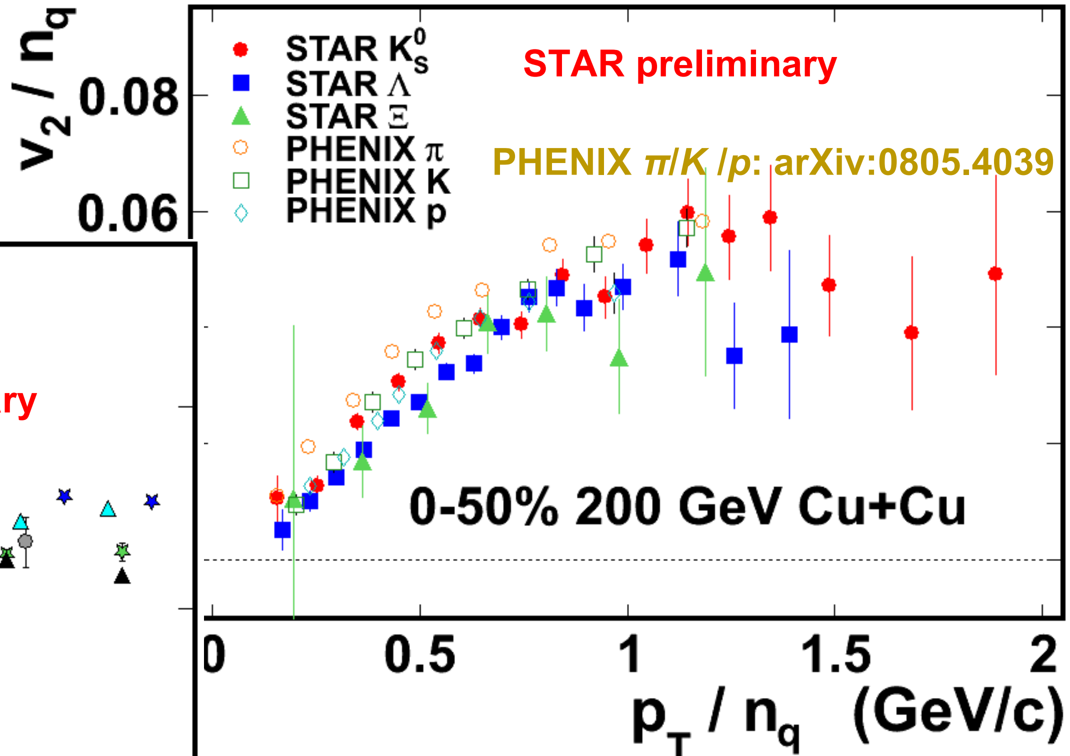
As well as an Indication for strong coupling?

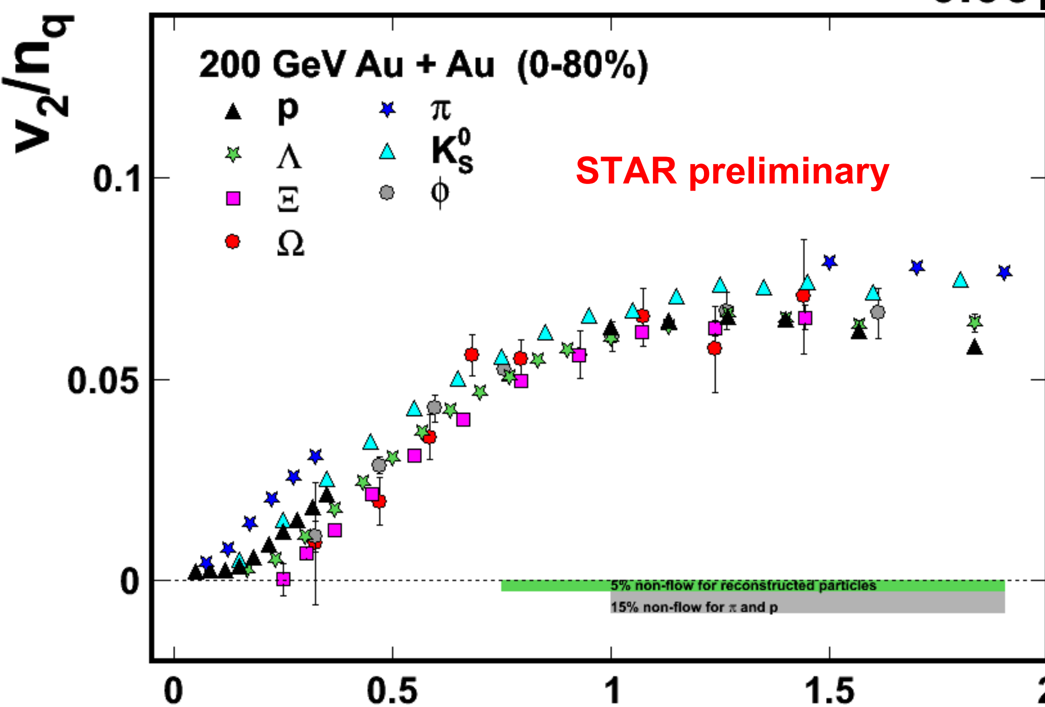
Roy A. Lacey, Stony Brook; Quark Matter 09, Knoxville, TN March 30 - April 4, 2009

v_2: NQ scaling

The observation of NQ scaling in Au+Au provides empirical evidence for coalescence/recombination scheme for hadronization of bulk partonic matter.

NQ scaling works with available data in Cu+Cu collisions.





Different collision system

Different p_T region

Different n_q other than 2 or 3: ρ^0?

D. Molnar and S. Voloshin, PR**L91**, 092301 (2003)
R. J. Fries et. al., PR**C68**, 044902 (2003)
V. Greco et. al, PR**C68**, 034904 (2003)
J. Jia and C. Zhang, PR**C75**, 031901(R) (2007)...

Collectivity and deconfinement at RHIC

- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

At RHIC:

➪ **n_q-scaling**
novel hadronization process

➪ **Partonic flow**
De-confinement

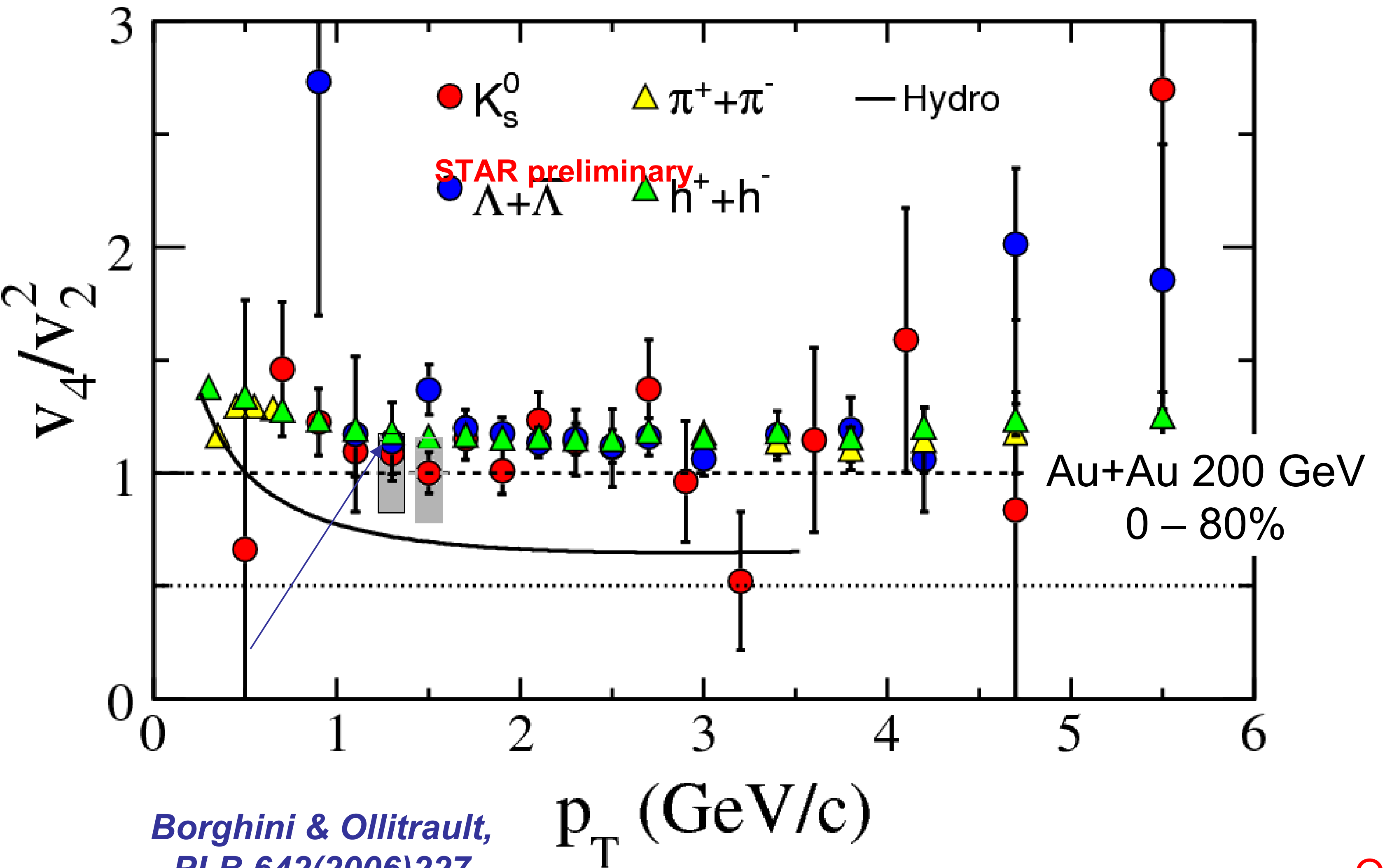
In the hadronic case, absence of n_q-scaling and the value of v_2 of ϕ will be small or zero.

Low p_T(≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks ordering***

=> Collectivity developed at partonic stage!
=> De-confinement in Au+Au collisions at RHIC!

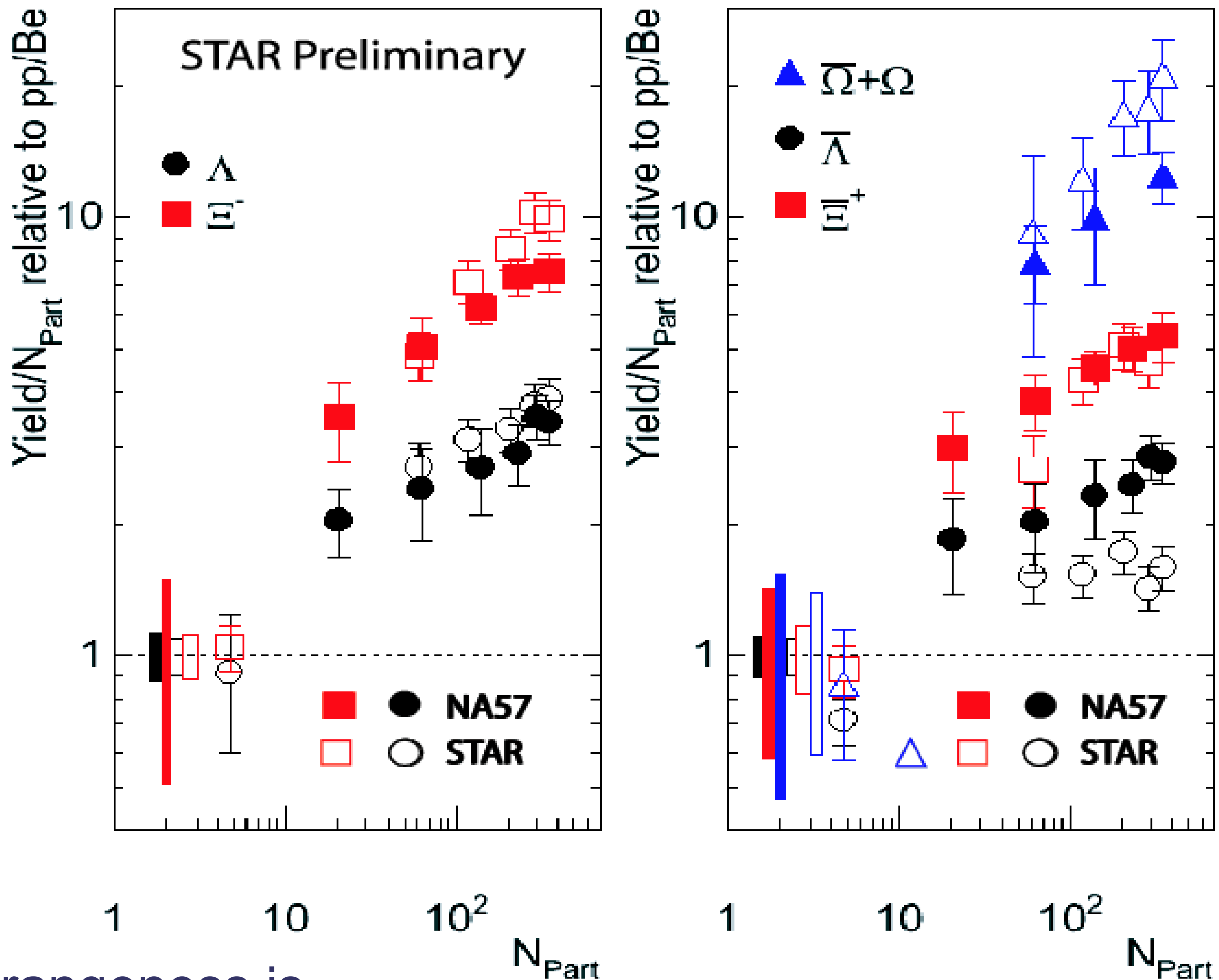
Ideal hydrodynamic limit

- v_4/v_2^2 results suggest that ideal hydro limit is not reached
- Need to study η/s to see how far away we are from ideal hydro limit



Borghini & Ollitrault, PLB 642(2006)227

2) Strangeness enhancement

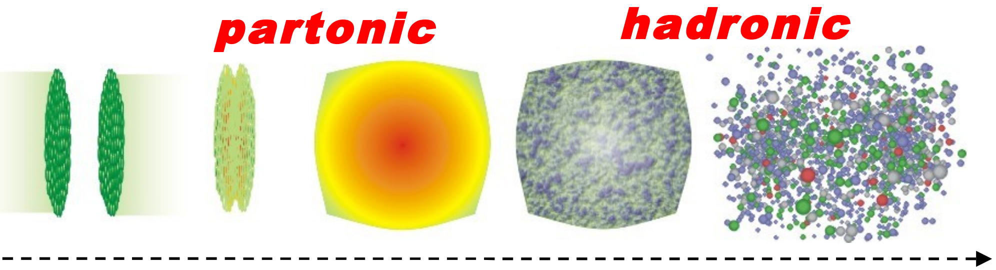


In QGP production of strangeness is expected to enhance due to increased production mechanisms:

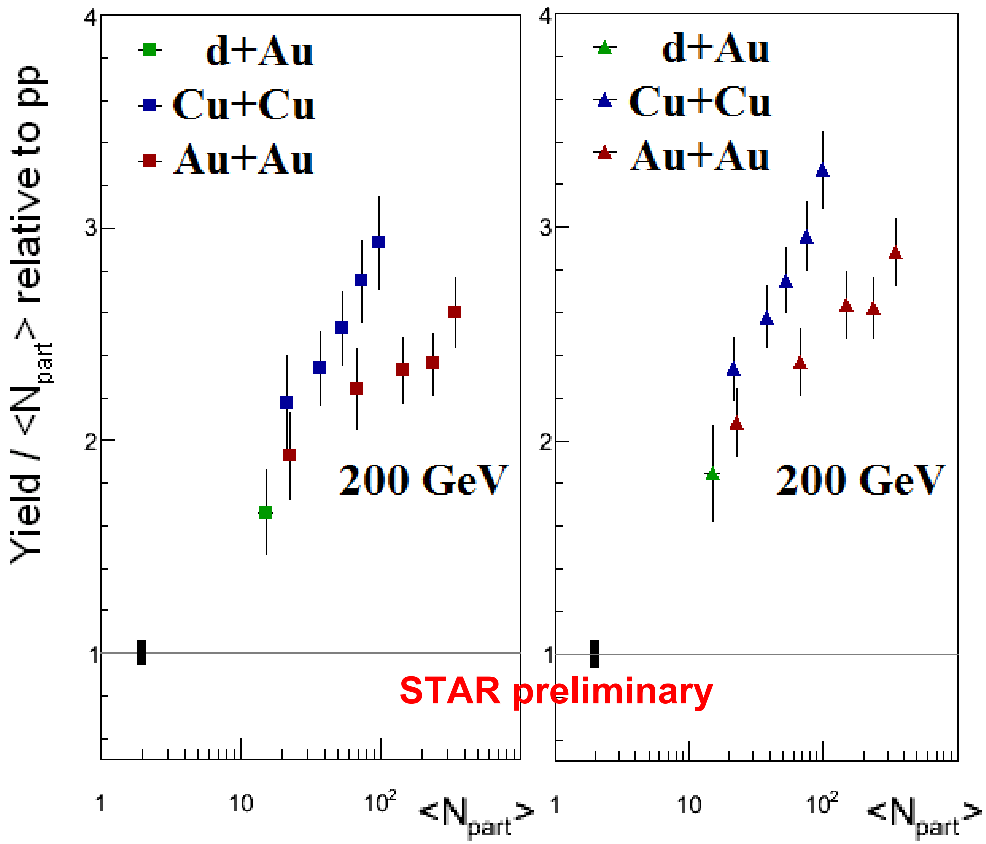
g+g → s+ (anti) s

q+(anti) q → s+ (anti) s

Strangeness production: low p_T



ϕ, Ω, Ξ, Λ, K_S^0

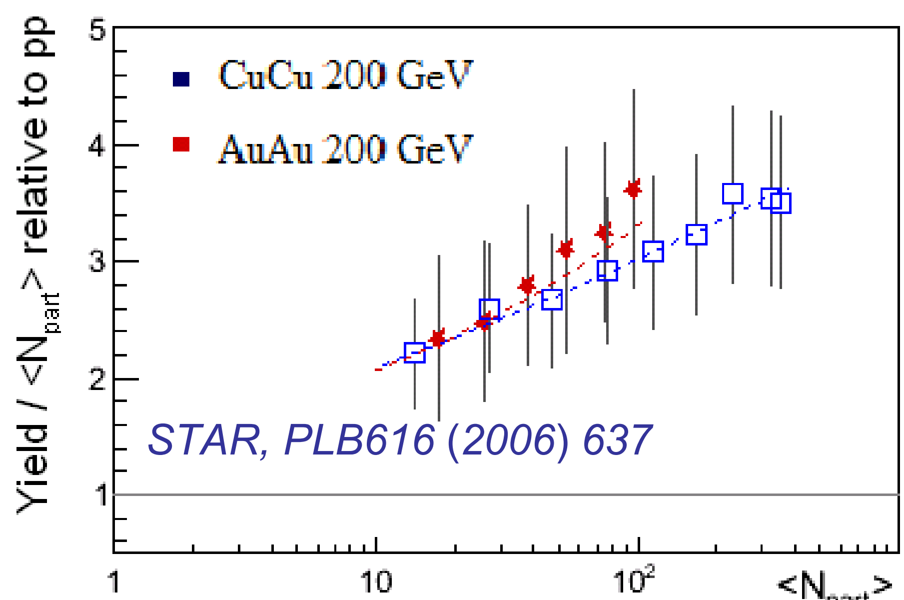


Rich set of strange particle measurements at STAR. Strange hadrons are less sensitive to hadronic rescattering.

- ➔ Produced in the collision
- ➔ Messengers from the phase boundary

Strangeness enhancement measured in Cu+Cu, Au+Au and d+Au.

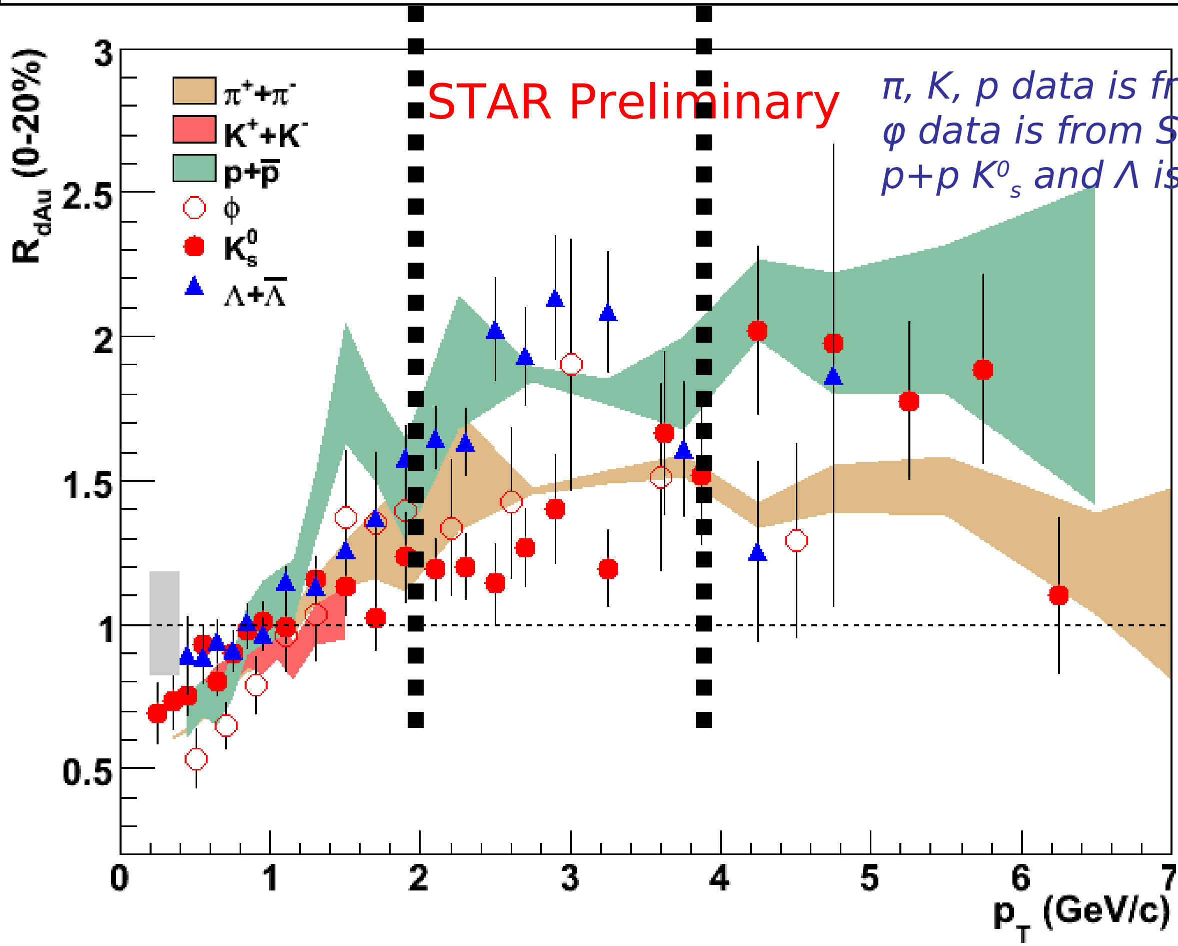
Quark Matter 2009



Strangeness production: mid p_T

Baryon/meson separation at $2 < p_T < 4$ GeV/c observed in the strangeness sector

- K^0_s R_{dAu} agrees with that of π
- Λ agrees with proton
- φ meson R_{dAu} also falls into the meson band.

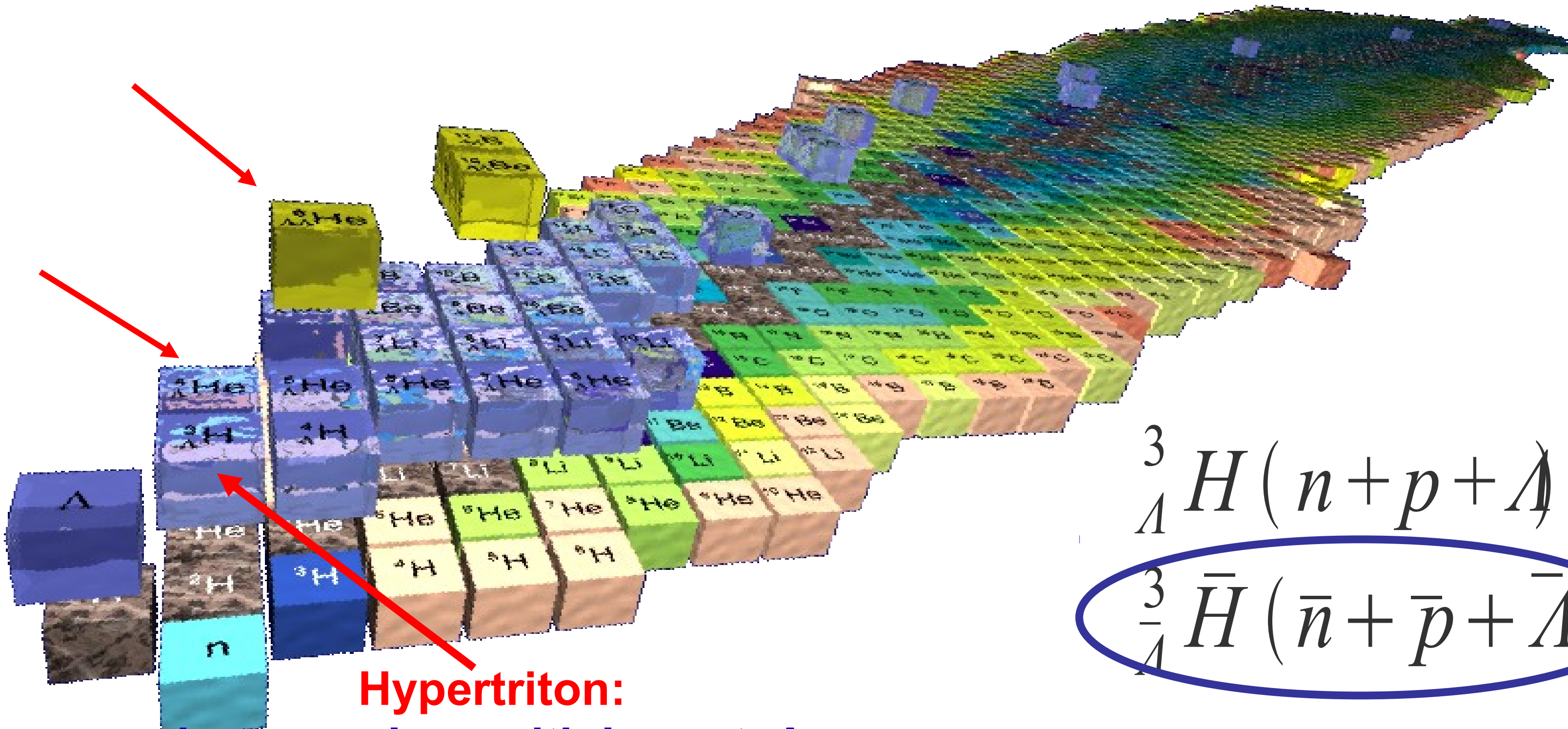


π, K, p data is from STAR, PLB616, 637, statistical error only
φ data is from STAR arXiv:0809.4737
p+p K^0_s and Λ is from STAR PRC75

Quark Matter 2009

In addition to strange hadrons, we are also interested in hypernuclei

Observation of ${}^{3}_{\Lambda}H$ and ${}^{3}_{\bar{\Lambda}}\bar{H}$ @ RHIC



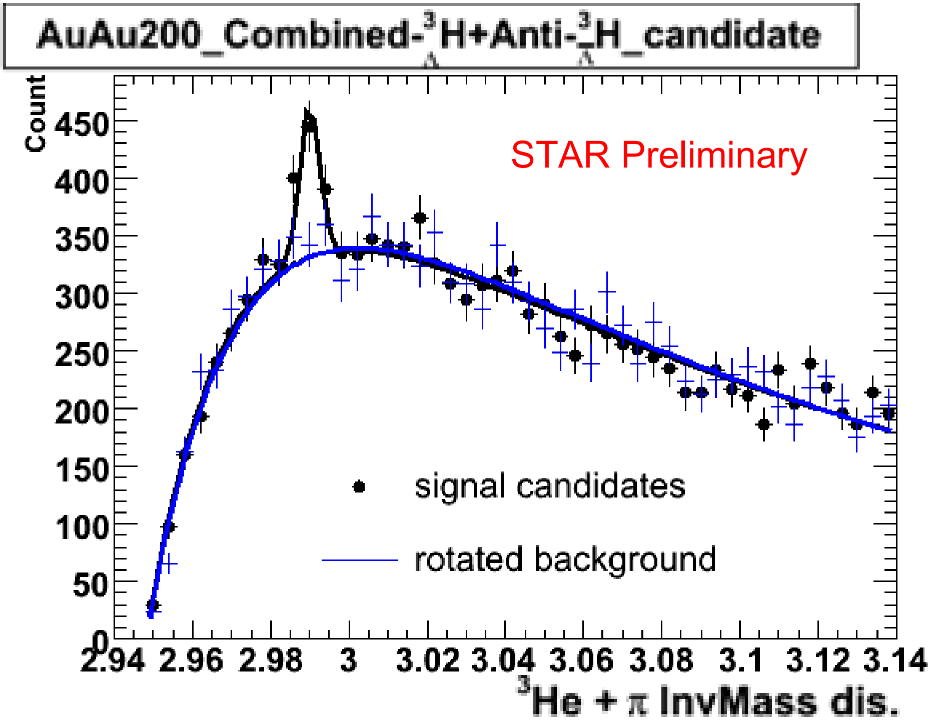
$${}^{3}_{\Lambda}H\left(n+p+\Lambda\right)$$

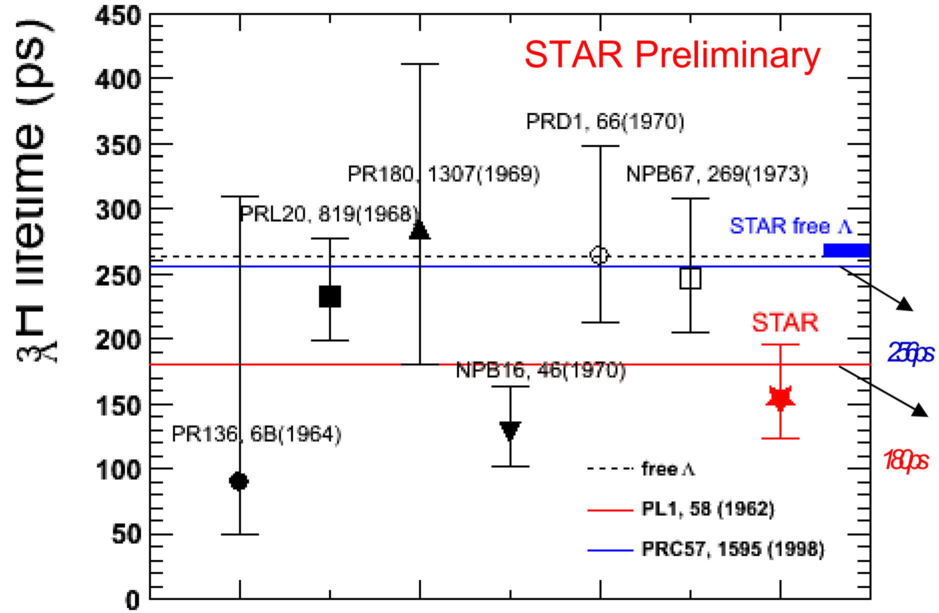
$${}^{3}_{\bar{\Lambda}}\bar{H}\left(\bar{n}+\bar{p}+\bar{\Lambda}\right)$$

Never observed before

- Y-N interaction: a good window to understand the baryon potential
- **Study the strange sector of baryon-baryon interaction**
- **Interesting for astrophysics objects, like neutron star**

Observation of $^{3}_{\Lambda}H$ and $^{3}_{\bar{\Lambda}}\bar{H}$ @ RHIC





World data

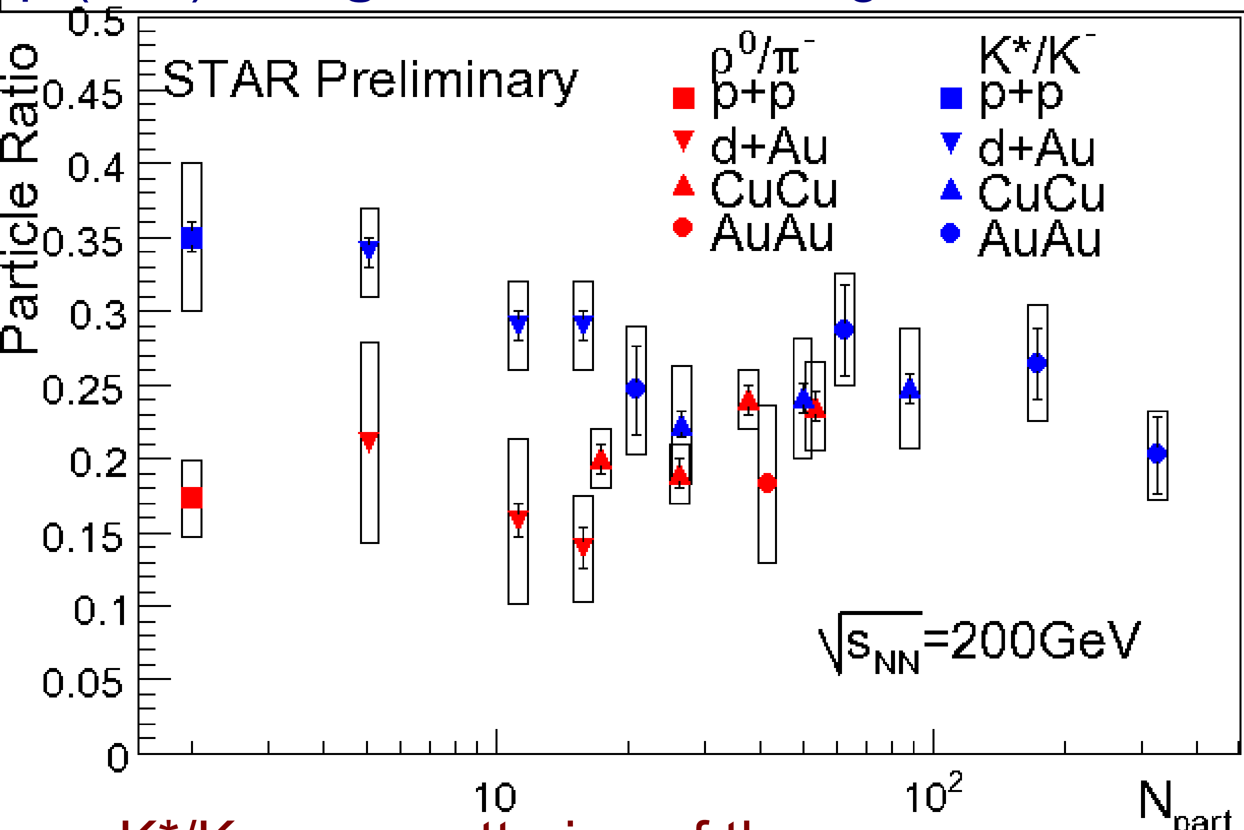
- First ever observation **of an anti-hypernucleus** (4σ signal of $^{3}_{\bar{\Lambda}}\bar{H}$)
- The hypertriton and anti-hypertriton signal : 244±35
- The hypertriton and anti-hypertriton lifetime: $\tau = 153 \pm^{43}_{30}\ ps$

[1] R. H. Dalitz, *Nuclear Interactions of the Hyperons* (1965).
[2] R.H. Dalitz and G. Rajasekharan, Phys. Letts. 1, 58 (1962).
[3] H. Kamada, W. Glockle at al., Phys. Rev. C 57, 1595(1998).

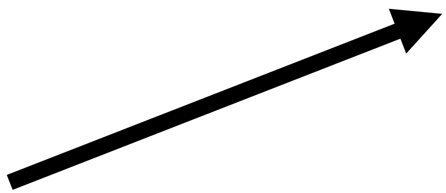
3) A special probe: ρ^0

$\rho^0(770) \Rightarrow$ hadronic decay channel $\Rightarrow$ between chemical and kinetic freeze-out

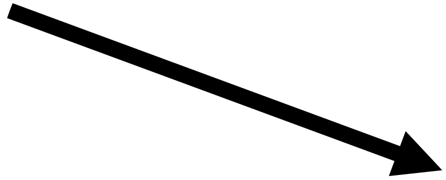
$\rho^0(770) \Rightarrow$ **regeneration** vs. daughter **rescattering**



Regeneration:



Rescattering:



$\sigma(K\pi) < \sigma(\pi\pi)$

- $K^*/K^- \Rightarrow$ rescattering of the daughters.
- $\rho^0/\pi^- \Rightarrow$ regeneration compensating for rescattering of the daughters.

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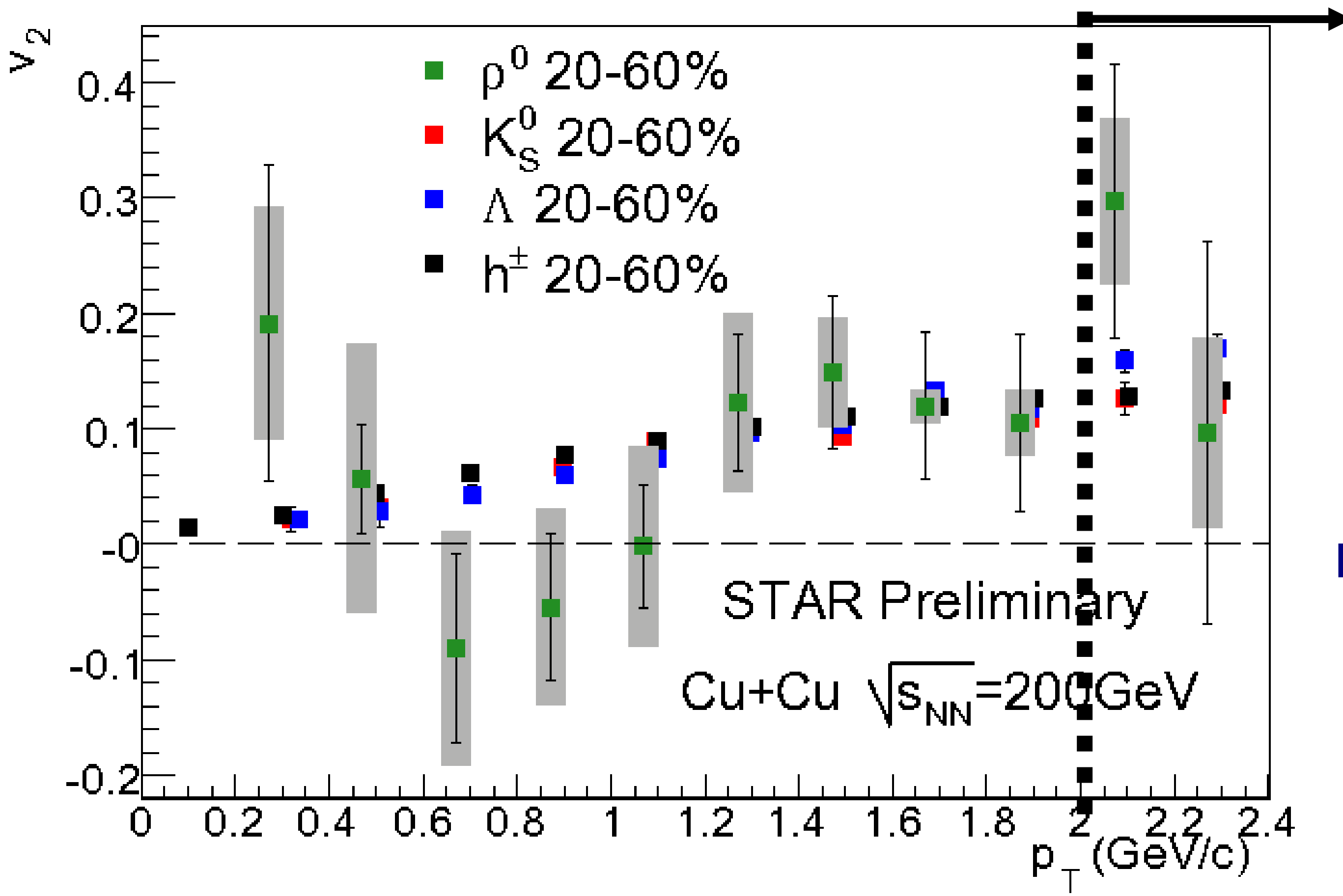
ρ^0 v_2

- Significant ρ^0 v_2 measured for p_T > 1.2 GeV/c (13% ± 4%).
- p_T range covered not sufficient for conclusive statement on the resonance production mechanism: *hadronization* or *hadron regeneration*?



Coalesence region

Different NQ scaling

Hadronization:

n_q = 2

Hadron regeneration:

n_q = 4

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4) Search for local strong *P*-violation

Looking into a mirror,
you see not quite yourself…
It's a ***parity violation?***!

<u>**Parity transformation**</u>:

A spatial inversion of the coordinates.

$$\vec{x} \rightarrow -\vec{x}$$

Origins of parity violation:

0. <u>Fake</u> parity violation

(The mirror is broken there… Doesn't count!)

- <u>Explicit</u> parity violation

Occurs in weak interactions

  - Confirmed

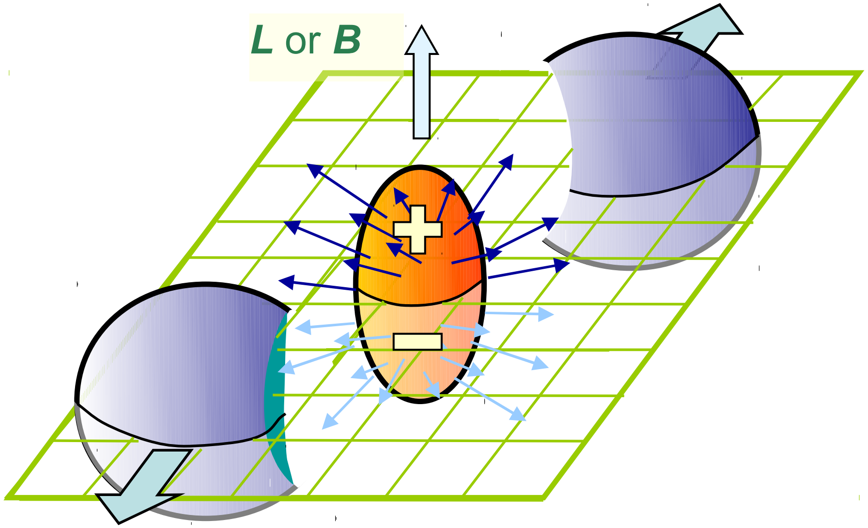
- <u>Spontaneous</u> parity violation

Predicted in strong interactions

  - Not yet confirmed (we are working on it…)

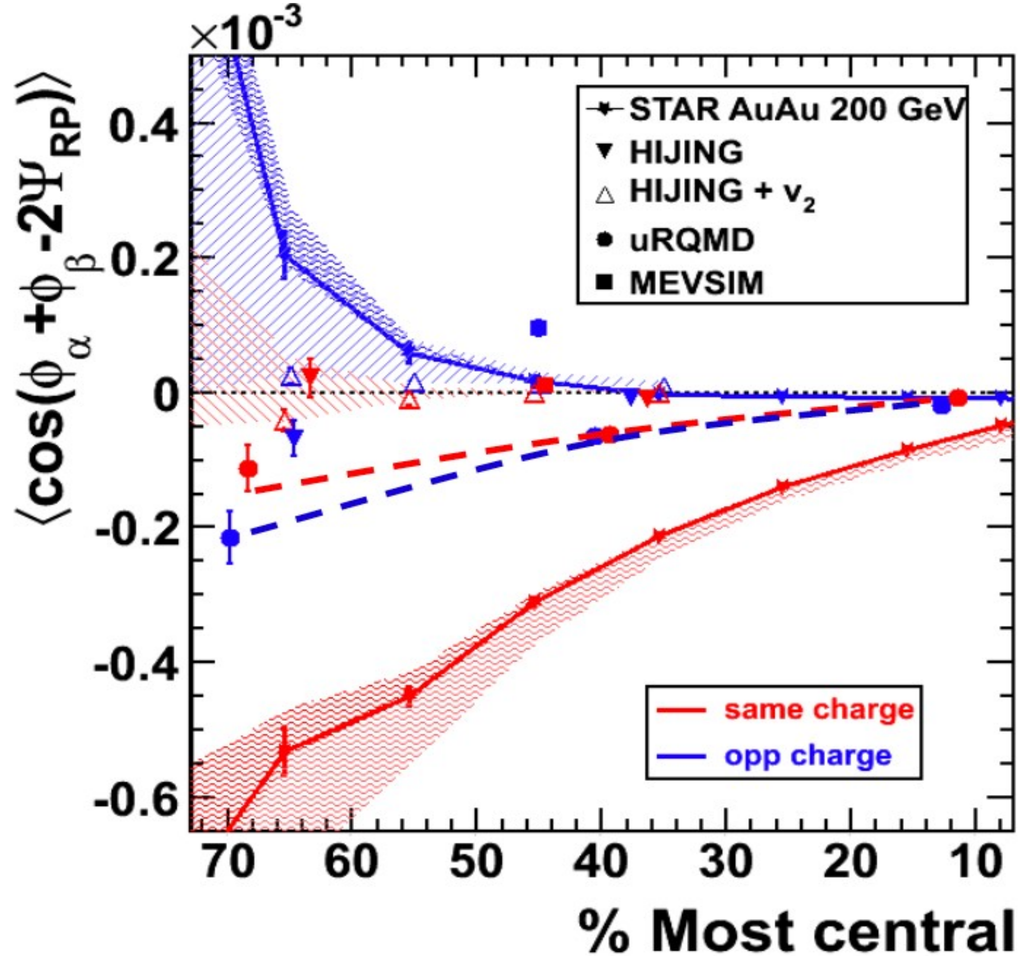
Kharzeev, PLB 633 260 (2006) [hep-ph/0406125]
Kharzeev, Zhitnitsky, NPA 797 67 (2007)
Kharzeev, McLerran, Warringa, NPA 803 227 (2008)
Fukushima, Kharzeev, Waringa, PRD 78, 074033

Search for local strong *P*-violation



In heavy ion collisions:
Quark charge separation along ***L***.
D. Kharzeev, PLB 633 (2006) 260
- Deconfinement
- Chiral symmetry restoration

Correlation Technique: P-even



The data is generally in agreement with theoretical expectations for parity violation in heavy ion collisions!

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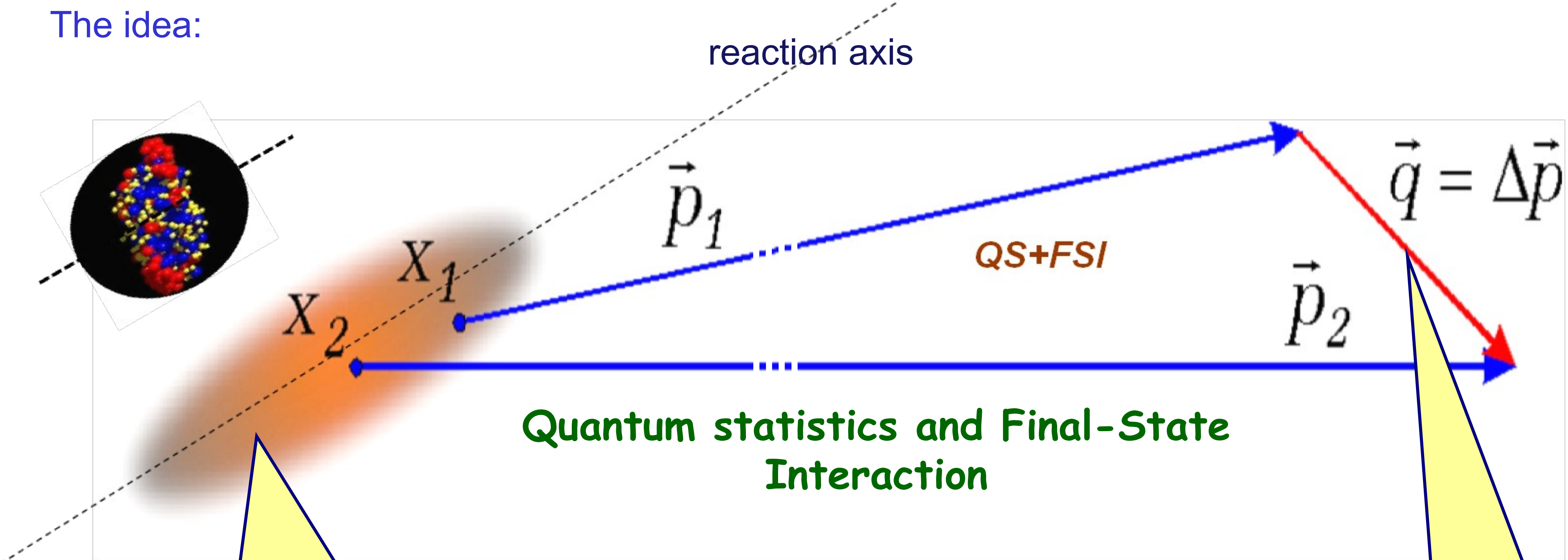
5) FEMTOSCOPY (HBT)

Particle correlations as a tool to explore the space-time geometry and dynamics

The idea:



Space-time sizes and dynamics (10^{-15} m, 10^{-23} s)
(cannot be measured directly)
☹

close velocity correlations

momentum Difference (20-200) MeV/c
(can be measured)
☺

Few words about femtoscopy

Single- and two- particle distributions

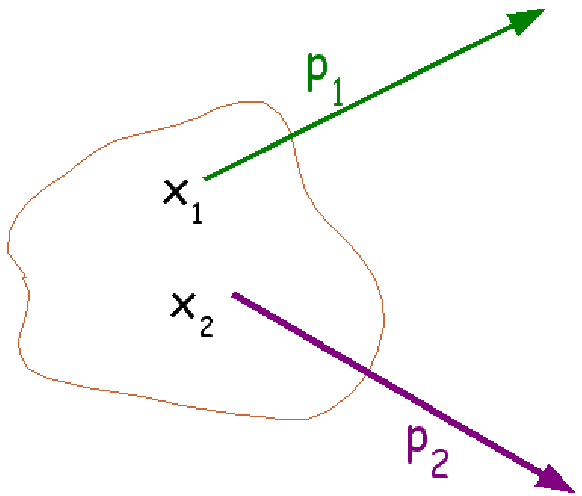
$$P_1(p) = E\frac{dN}{d^3p} = \int d^4x S(x,p)$$

S(x,p) – emission function: the distribution of source density probability of finding particle with x and p

$$P_2(p_1,p_2) = E_1 E_2 \frac{dN}{d_1^3p\, d_2^3p} = \int d^4x_1 S(x_1,p_1) d^4x_2 S(x_2,p_2) \Phi(x_2,p_2|x_1,p_1)$$

The correlation function

$$C(p_1,p_2) = \frac{P_2(p_1,p_2)}{P_1(p_1) P_1(p_2)}$$



Gaussian Parameterization

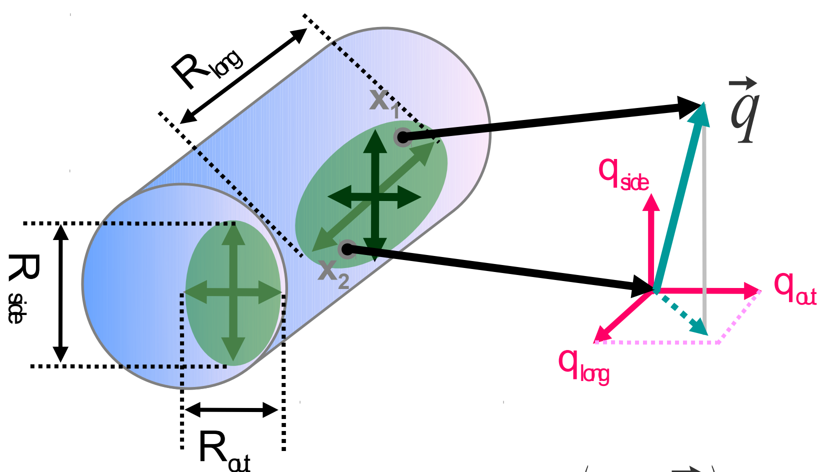
$$C(\vec{q},\vec{k}) = 1 + \lambda(\vec{k})\exp\left(-\sum_{i,j=o,s,l} R_{ij}^2(\vec{k})\, q_i q_j\right)$$

If source is approximated as

a Gaussian →

3D Cartesian Pratt-Berstch parameterization:

λ takes non BE correlations into account (0 ‹ λ ‹ 1)



- for an azimuthally symmetric collision
- in the LCMS frame at midrapidity

$$C(\vec{q},\vec{k}) = 1 + \lambda(\vec{k})\exp\left(-R_o^2(\vec{k})q_o^2 - R_s^2(\vec{k})q_s^2 - R_l^2(\vec{k})q_l^2\right)$$

$$\vec{q} = \vec{p}_2 - \vec{p}_1$$

$$\vec{k} = \frac{1}{2}\left(\vec{p}_2 + \vec{p}_1\right)$$

First STAR paper on HBT

Pion interferometry of s(NN)(1/2) = 130-GeV Au+Au collisions at RHIC.**
By STAR Collaboration (C. Adler *et al.*). Jul 2001. 6pp.
Published in **Phys.Rev.Lett.87:082301,2001**.

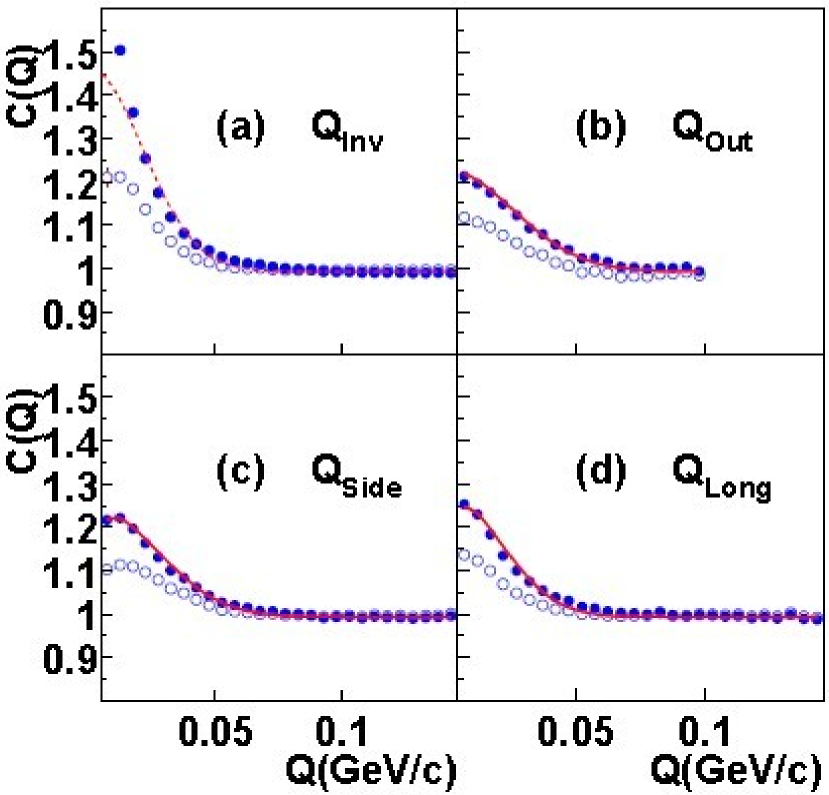
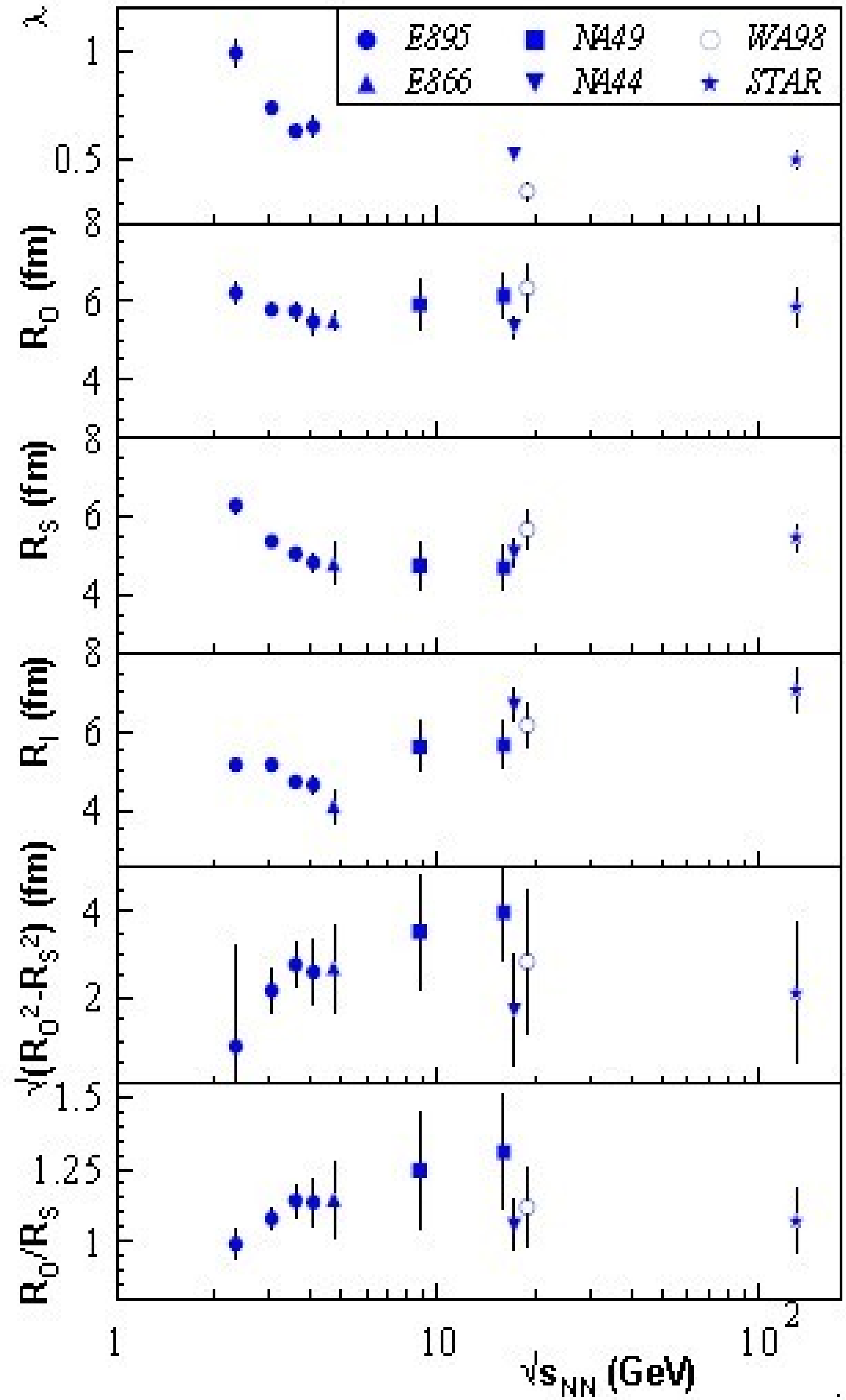


FIG. 1. Coulomb-corrected (full dots) and uncorrected (circles) correlation functions for low-p_T π^- emitted at midrapidity from central collisions. Shown in panel (a) is the Q_{inv} correlation function, and in panels (b-d) projections of the 3-dimensional correlation function onto the q_o, q_s, and q_l axes. To project onto one q-component, the others are integrated over the range 0-35 MeV/c. Fits to Coulomb-corrected correlations are shown by curves.



Dependence of transverse mass and the energy $\sqrt{s_{NN}}$

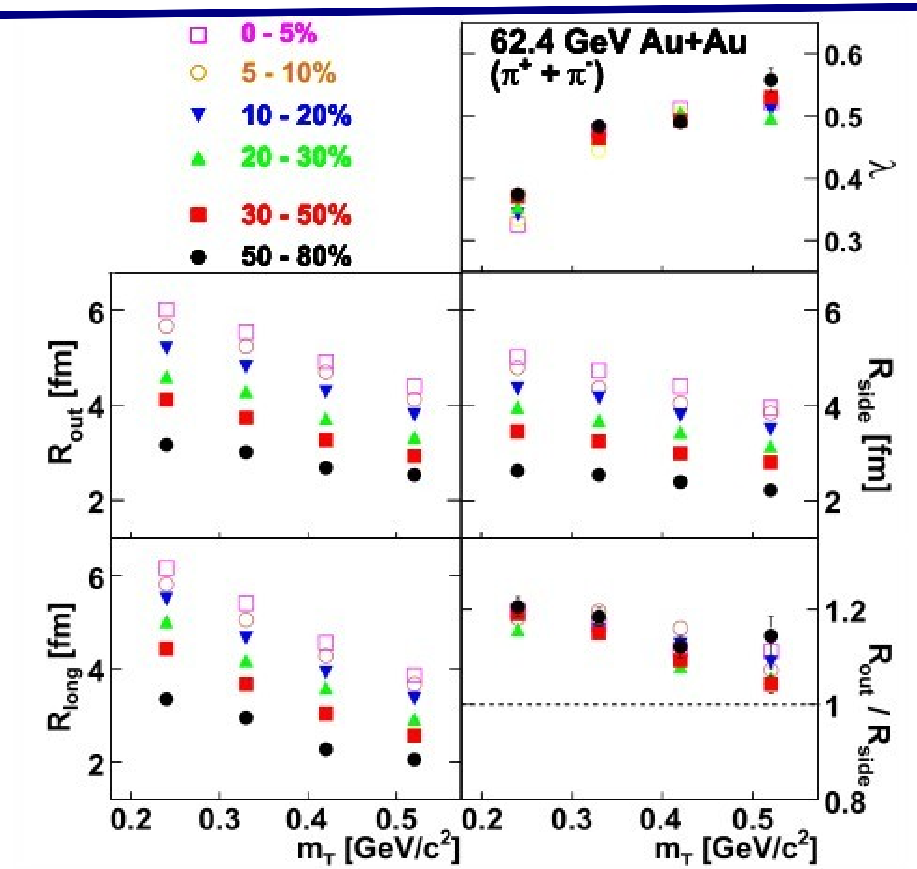
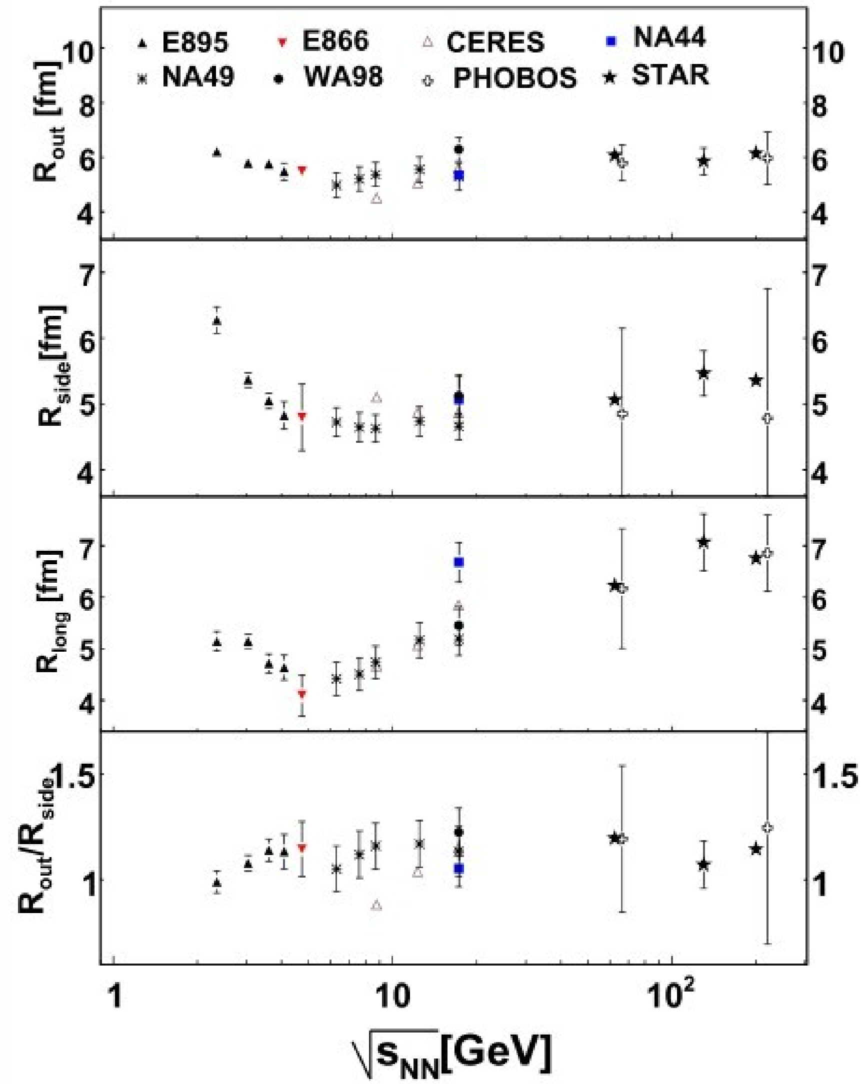


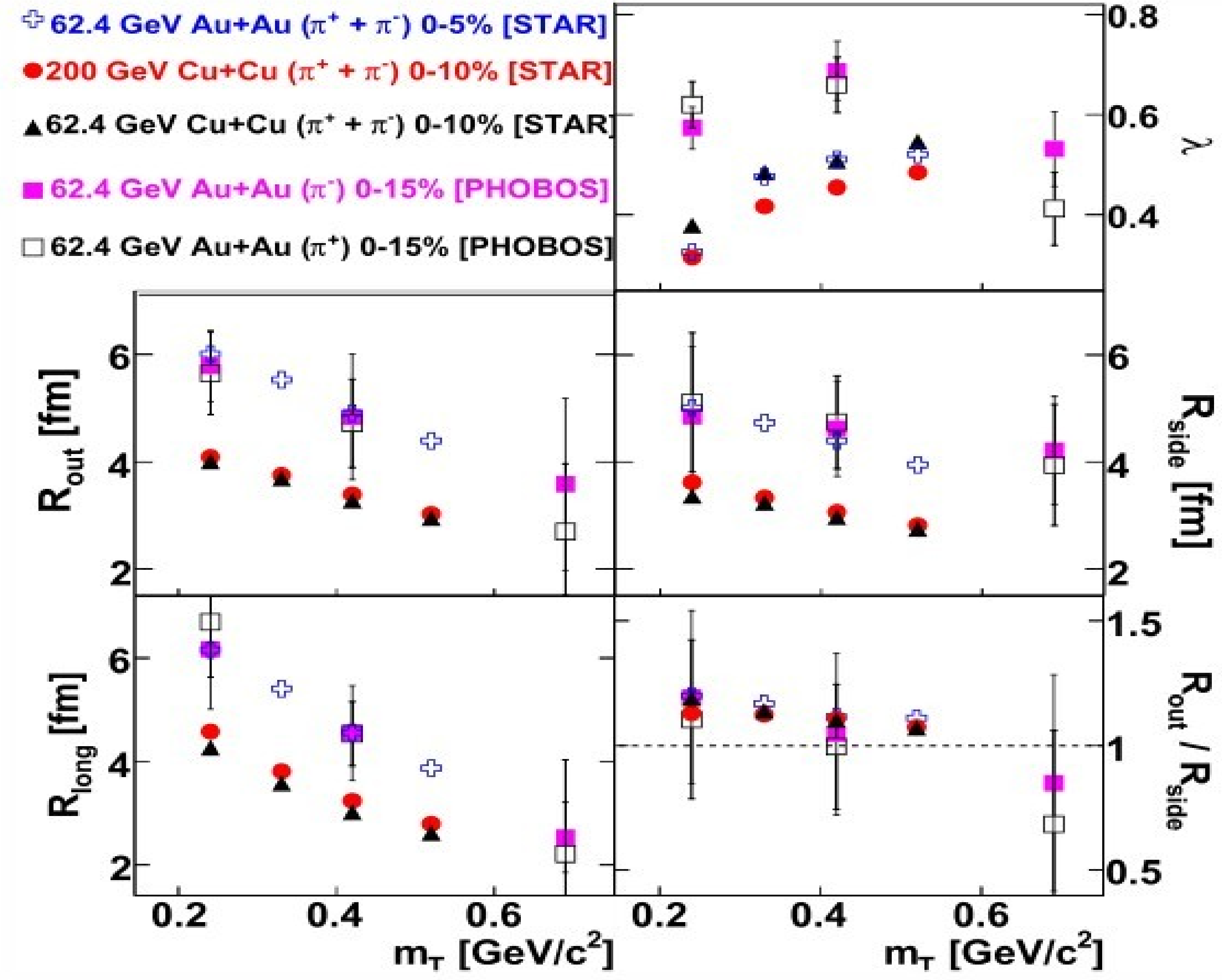
FIG. 1: (Color Online) The femtoscopic parameters vs. m_T for 6 different centralities for Au+Au collisions at $\sqrt{s_{NN}}$ = 62.4 GeV. Only statistical errors are shown. The estimated systematic errors are less than 10% for R_{out}, R_{side}, R_{long}, λ in all centrality and k_T bins.



$$m_T = \sqrt{k_T^2 + m_\pi^2}$$

arXiv:0903.1296 [nucl-ex]

Comparison of STAR and PHOBOS results



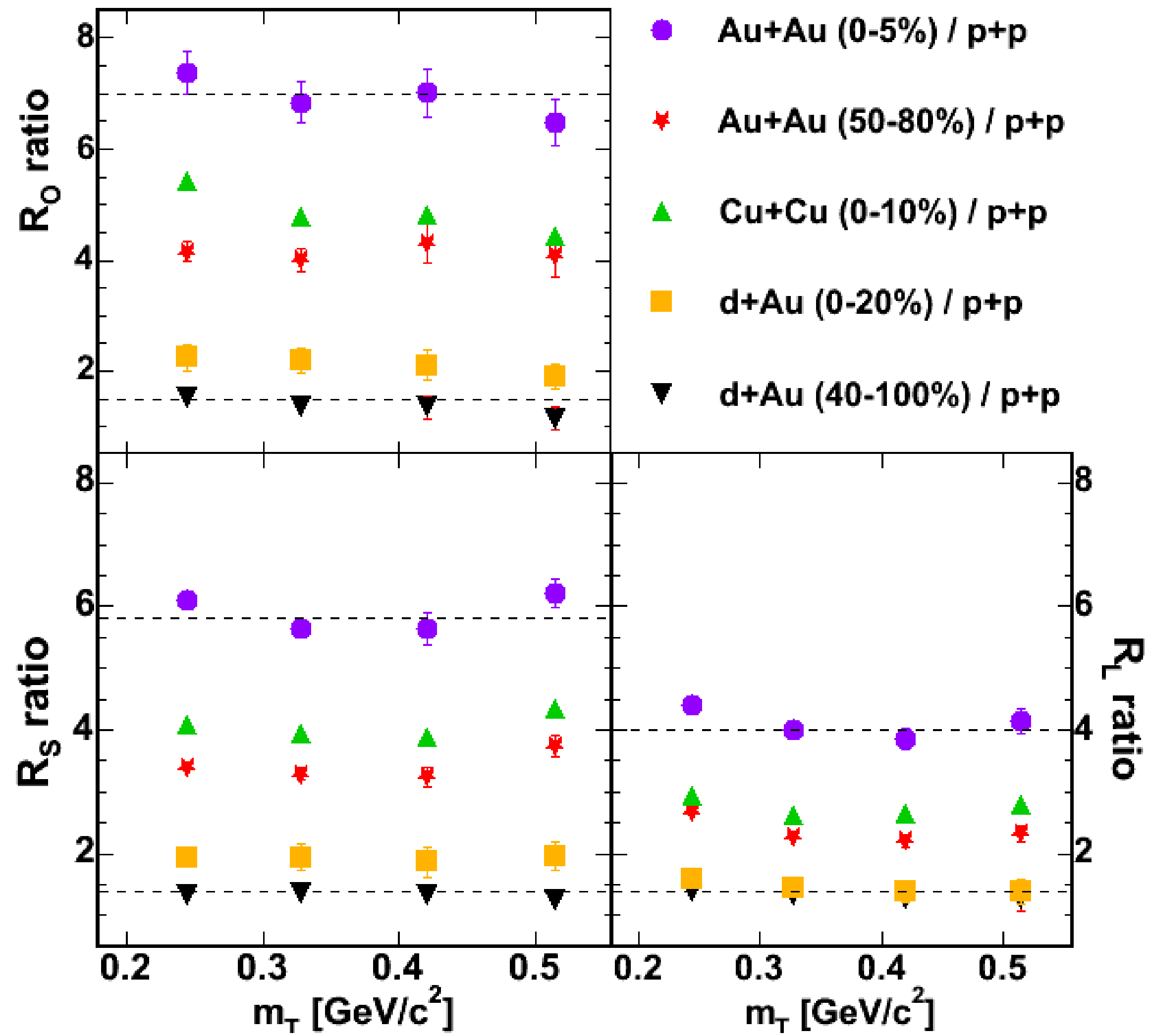
Surprising scaling

- All $p_T(m_T)$ dependences of HBT radii observed by STAR scale with pp although it's expected that different origins drive these dependences

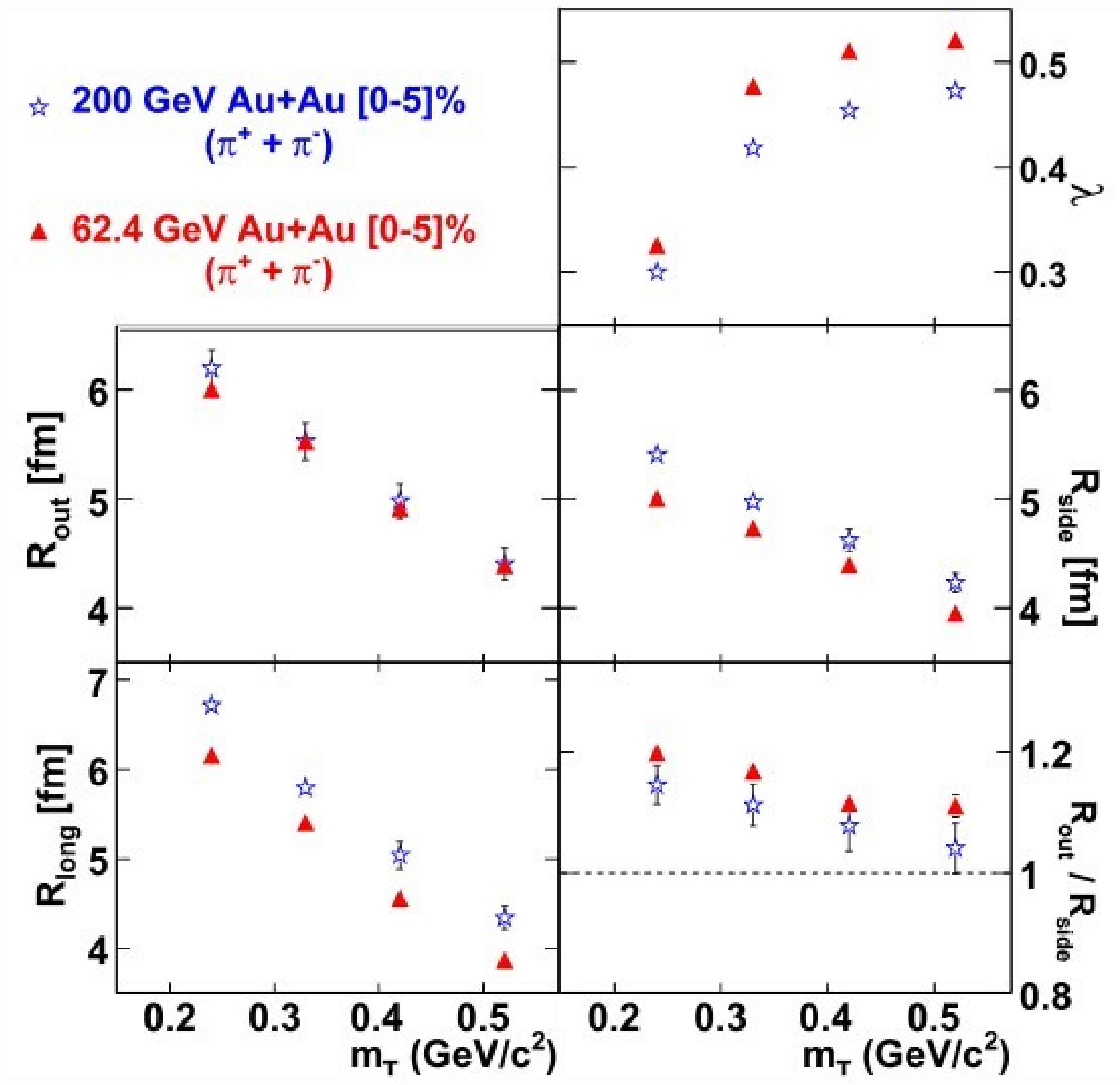
HBT radii scale with pp

Scary coincidence or something deeper?

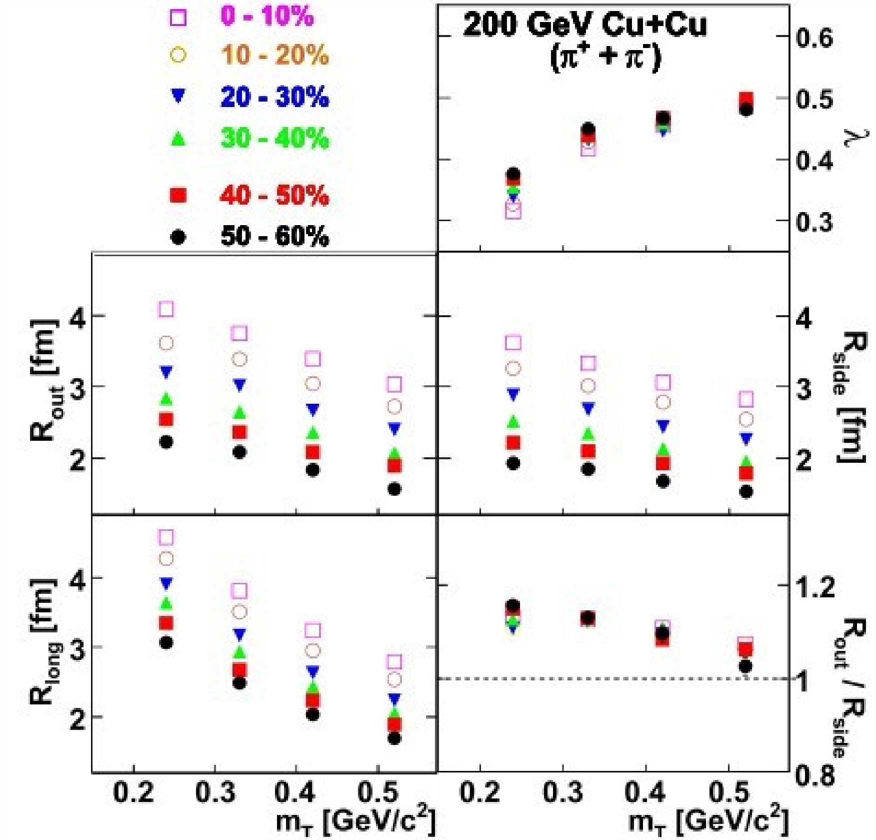
Ratio of (AuAu, CuCu, dAu) HBT radii by pp

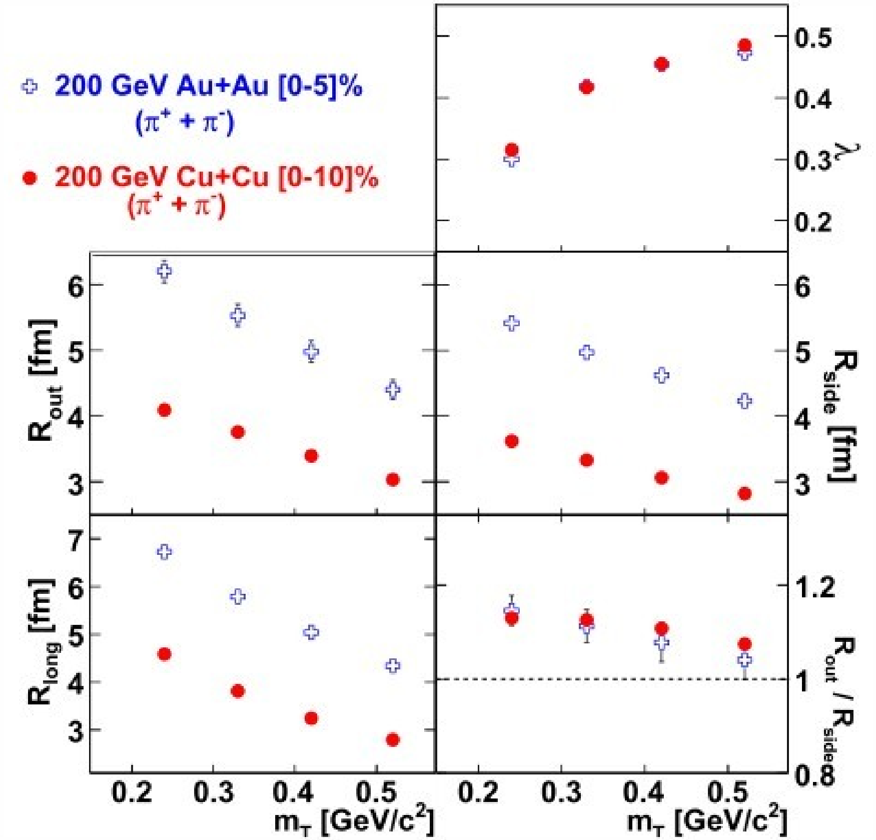


Two different collision energies



Two different collision reactions





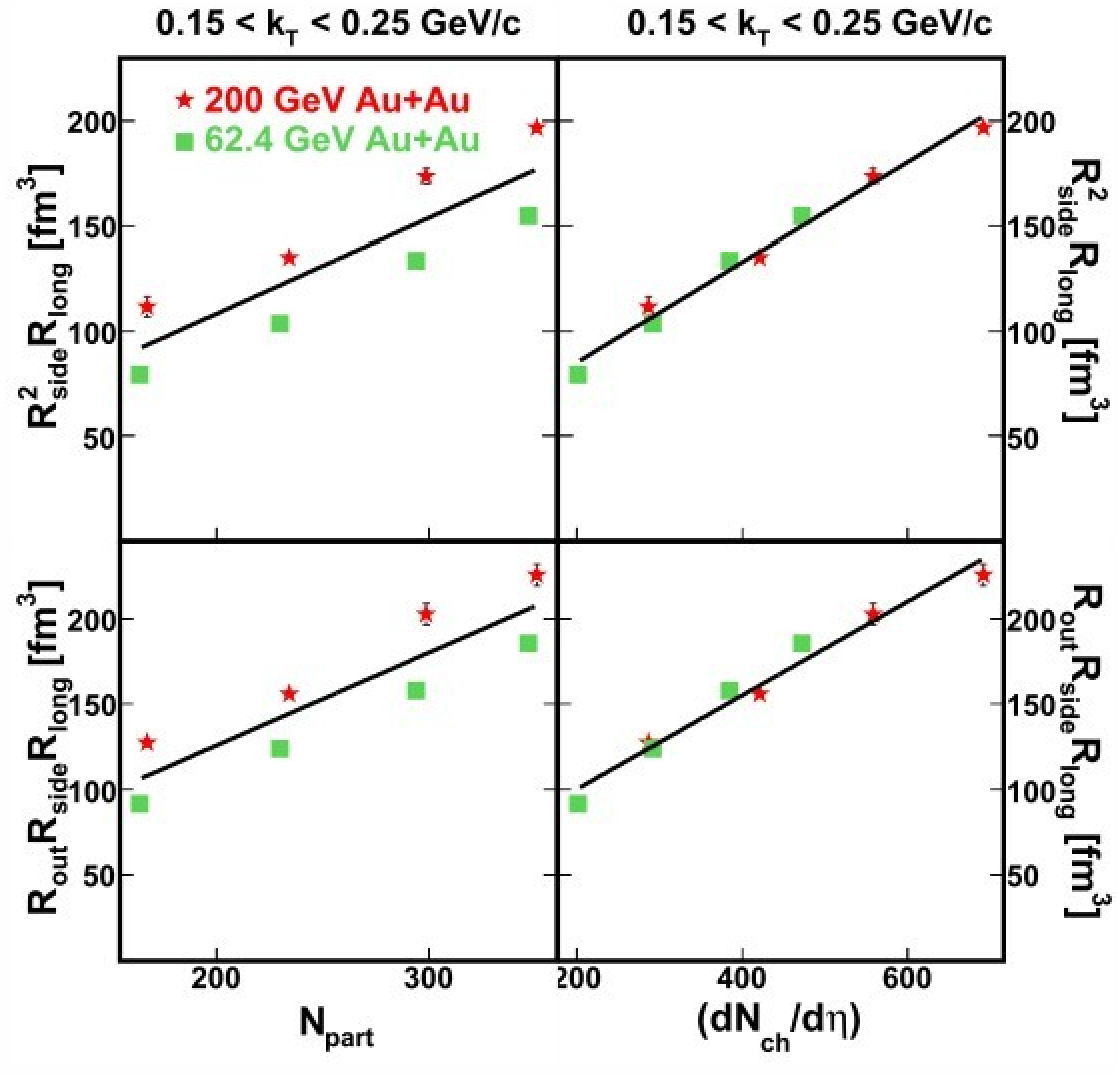
Dependence of freezeout volume

$$V_f \propto R_{\rm out} R_{\rm side} R_{\rm long}.$$

Mean free path

$$\lambda_f = \frac{1}{\rho_f \sigma} = \frac{V_f}{N\sigma}$$

Universal value of mean free at freezeout time



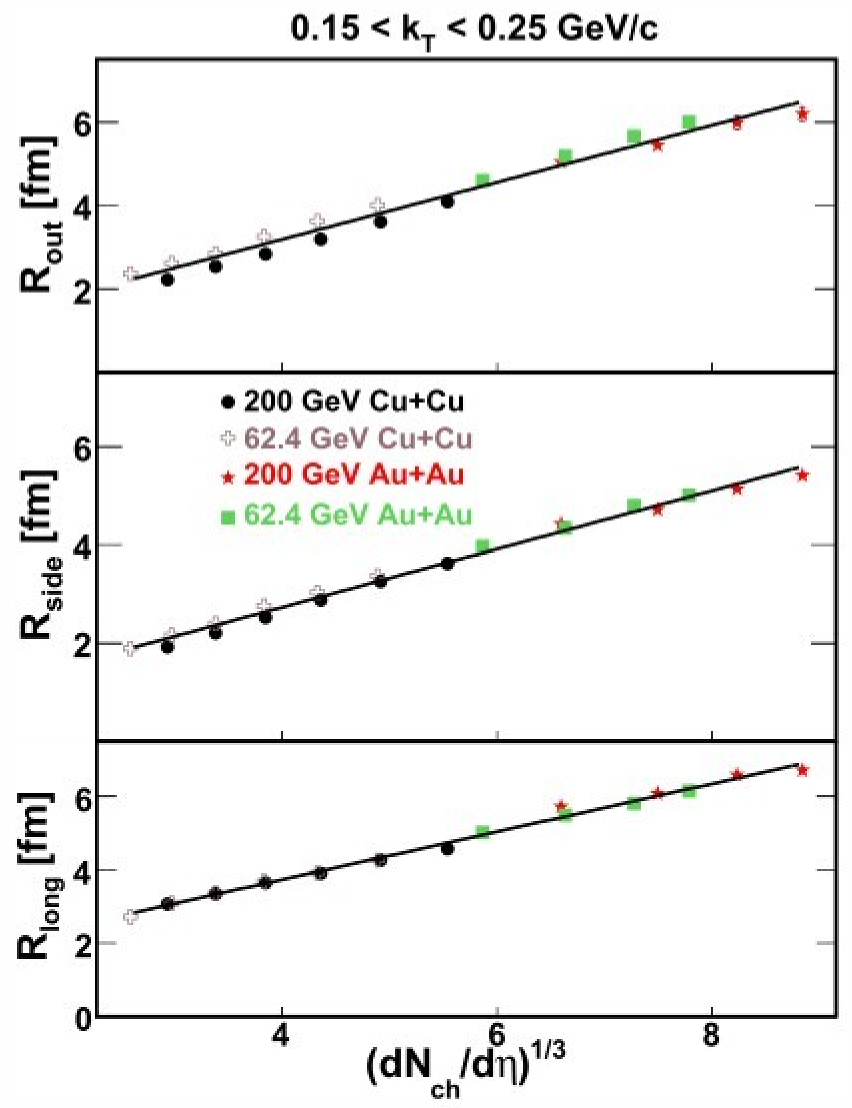
Dependence of freezeout volume

Constant mean free path length of pions at freezeout

$$\lambda_f = \frac{1}{\rho_f \sigma} = \frac{V_f}{N\sigma}$$

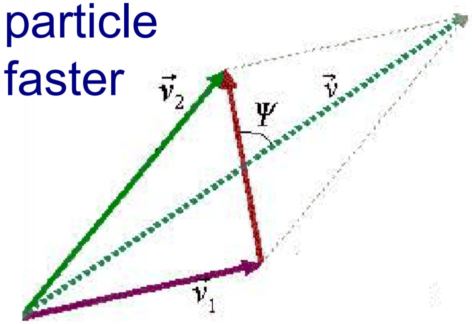
in Eq. (4). The denominator, $N\sigma$, can be expanded as the sum of the pion-pion and pion-nucleon contributions. At AGS energies the pion-nucleon term dominates since the pion-nucleon cross-section is larger than the pion-pion cross-section. Also, the number of nucleons at these lower energies at mid-rapidity exceeds the number of pions. Hence, a decrease in the number of mid-rapidity nucleons leads to a decrease in the observed freeze-out volume (V_f) as a function of $\sqrt{s_{\rm NN}}$. At SPS and RHIC energies the pion-pion term dominates the denominator in Eq. (4) due to copious pion production leading to an increase in the observed V_f.

Dependence of HBT radii on multiplicity

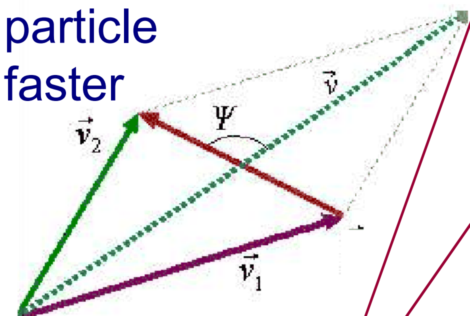


The asymmetry analysis

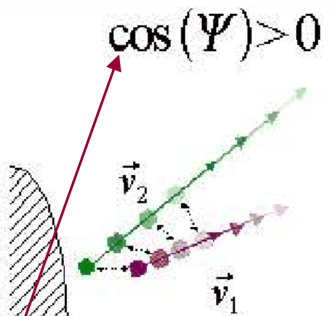
Second type particle faster

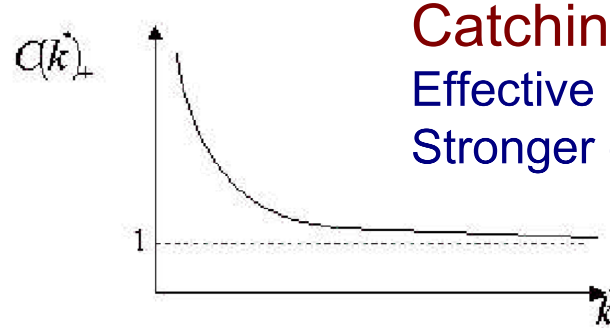


First type particle faster



From here we conclude about asymmetry

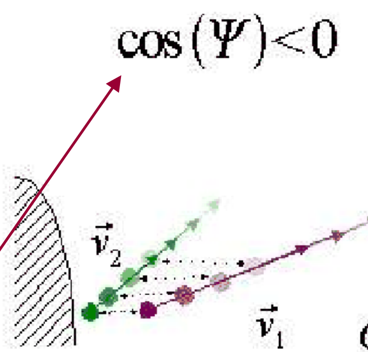


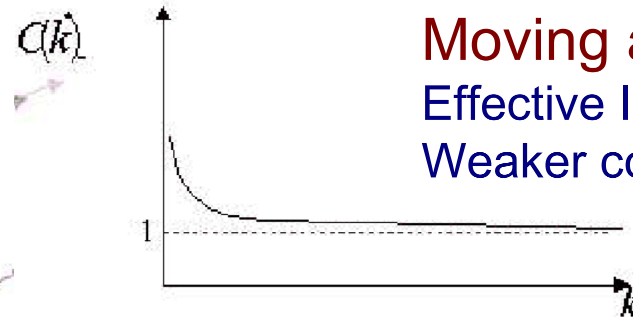


Catching up

Effective interaction time larger

Stronger correlation

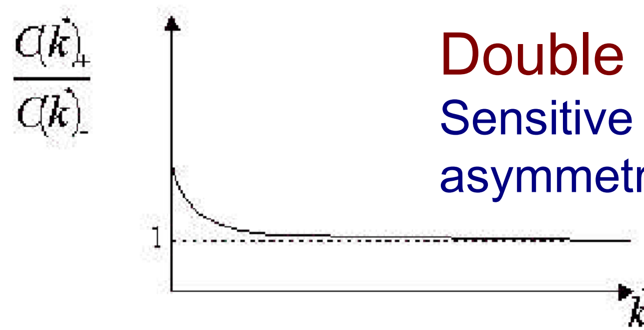




Moving away

Effective Interaction time smaller

Weaker correlation



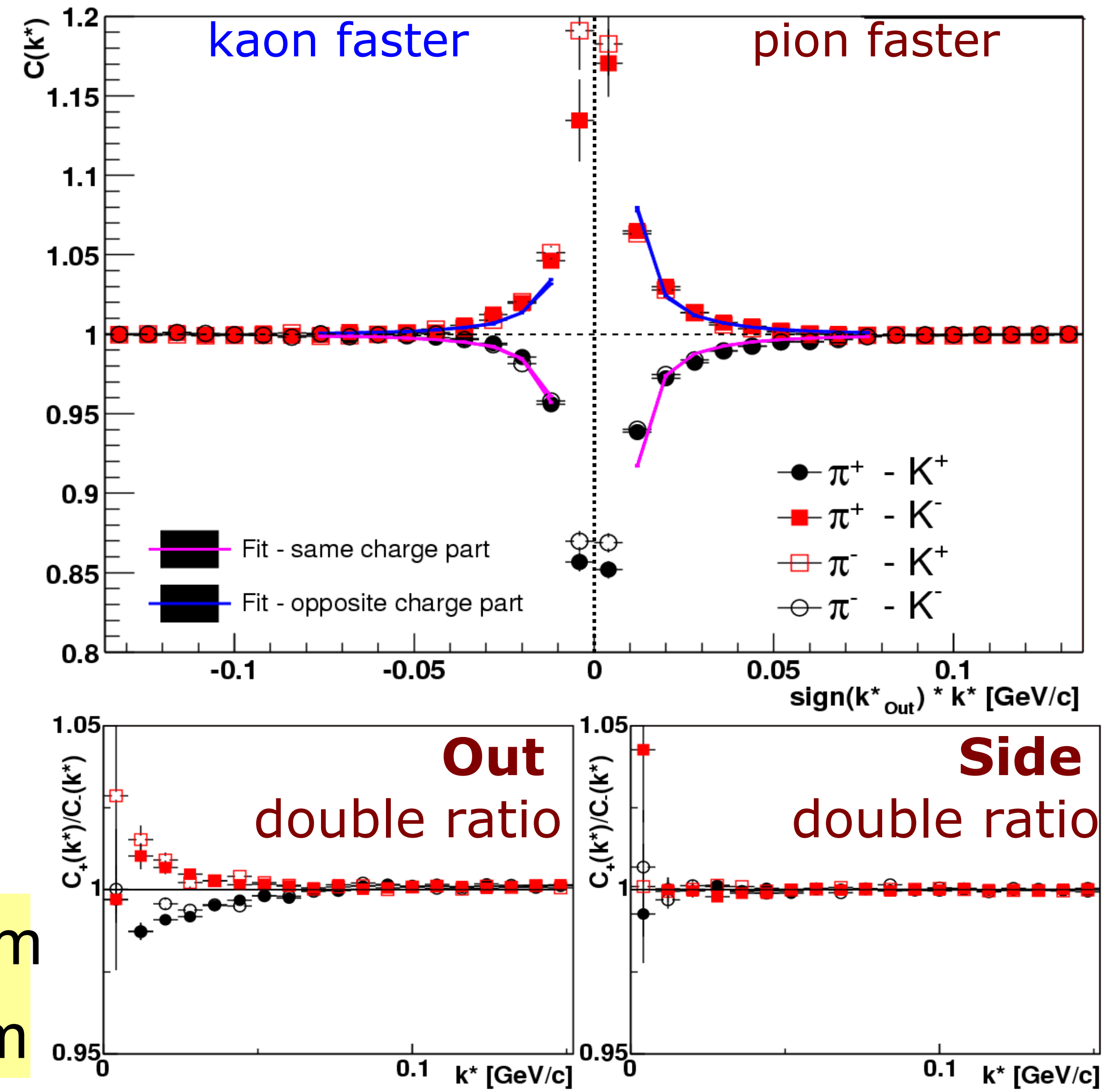
Double ratio

Sensitive to the space-time asymmetry in the emission process

R.Lednicky, V. L.Lyuboshitz, B.Erazmus, D.Nouais, Phys.Lett. B373 (1996) 30.

Pion-Kaon at 200 AGeV

- **Good agreement for same-charge combinations**
- **Clear emission asymmetry signal**

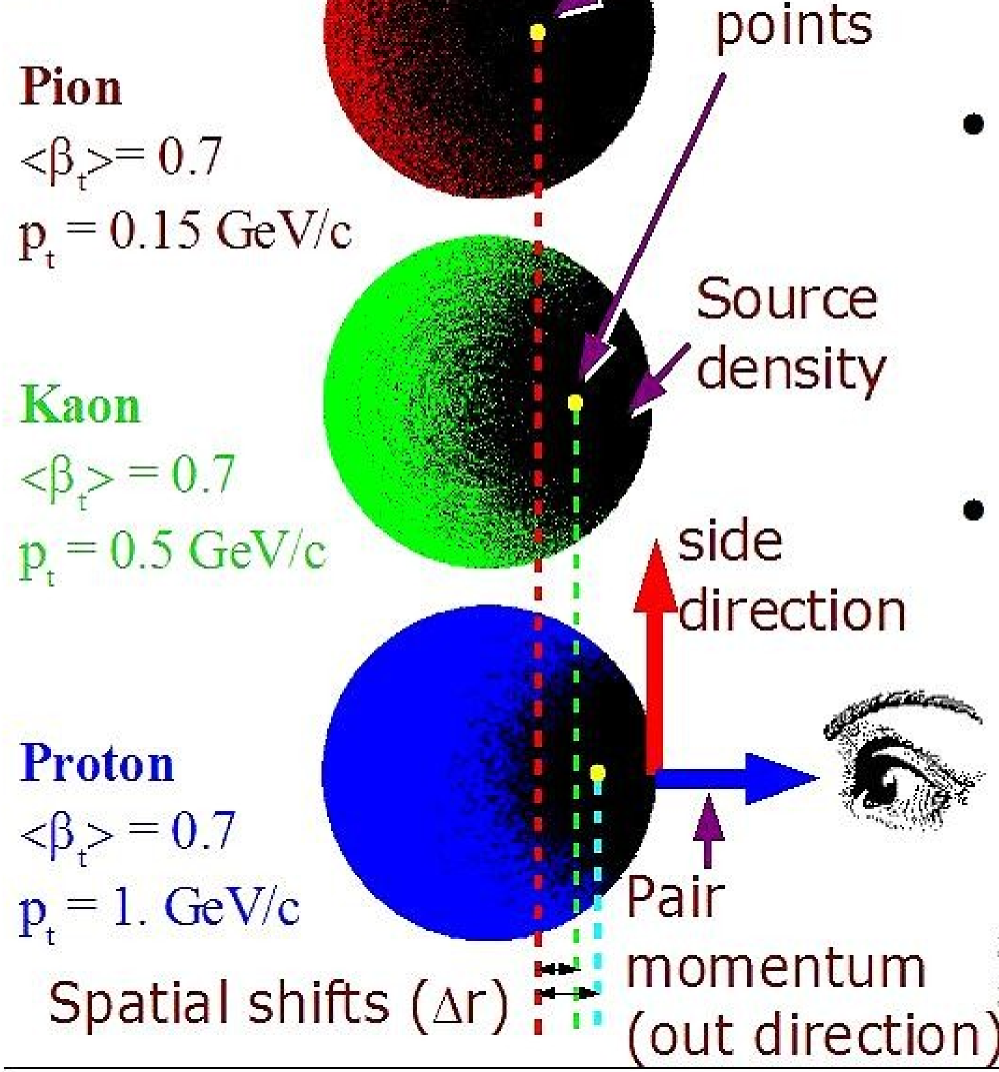


Sigma: $\mathbf{17.3 \pm 0.8}\,^{+\,0.9\text{ syst.}}_{-\,1.6\text{ syst.}}$ fm

Mean: $\mathbf{-7.0 \pm 1.2}\,^{+\,6.1\text{ syst.}}_{-\,4.0\text{ syst.}}$ fm

Flow in the transverse plane

nucl-th/0312024
F. Retiere,
M. Lisa



- Flow produces emission asymmetries in space Δr
- Observed asymmetry r* can come from emission time difference Δt too

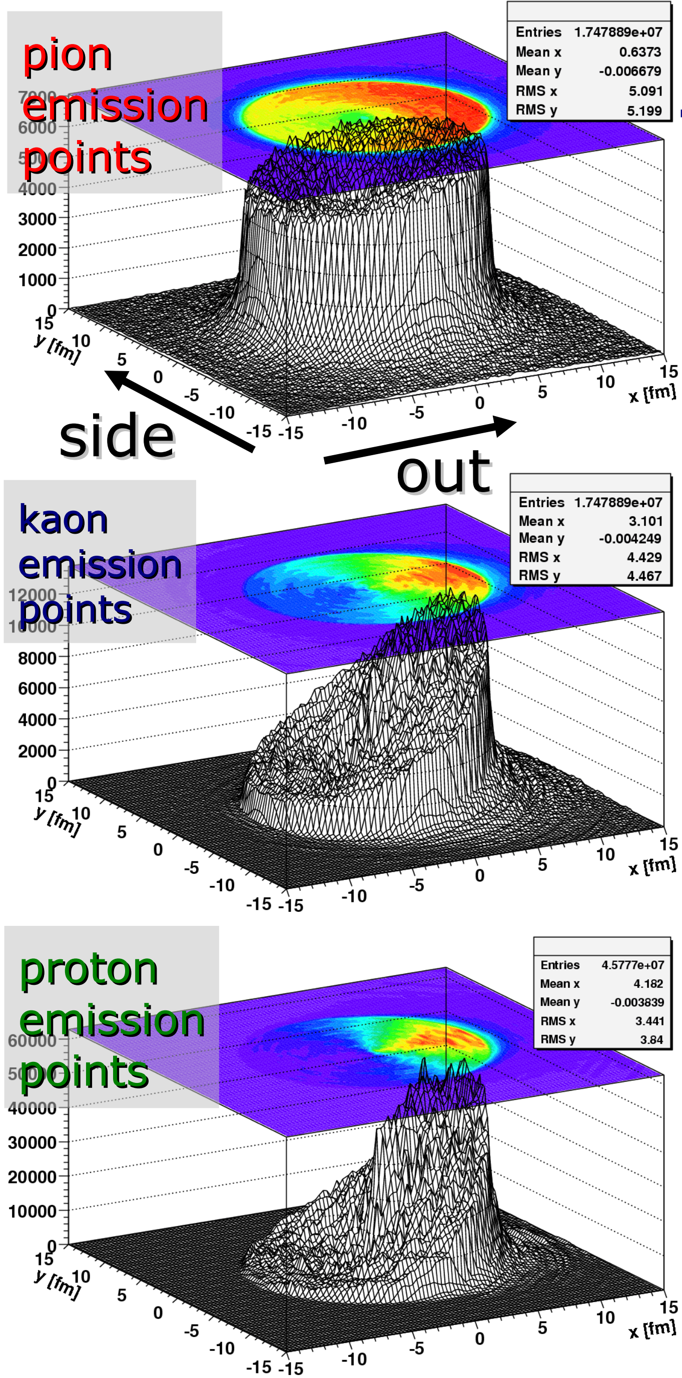
$$\langle r^* \rangle = \gamma(\langle \Delta r \rangle - \beta_T \langle \Delta t \rangle)$$

- We expect asymmetry in "out" direction, but not in "side", due to symmetry

S.Voloshin, R.Lednicky, S. Panitkin, N.Xu, Phys.Rev.Lett.**79**(1997)30

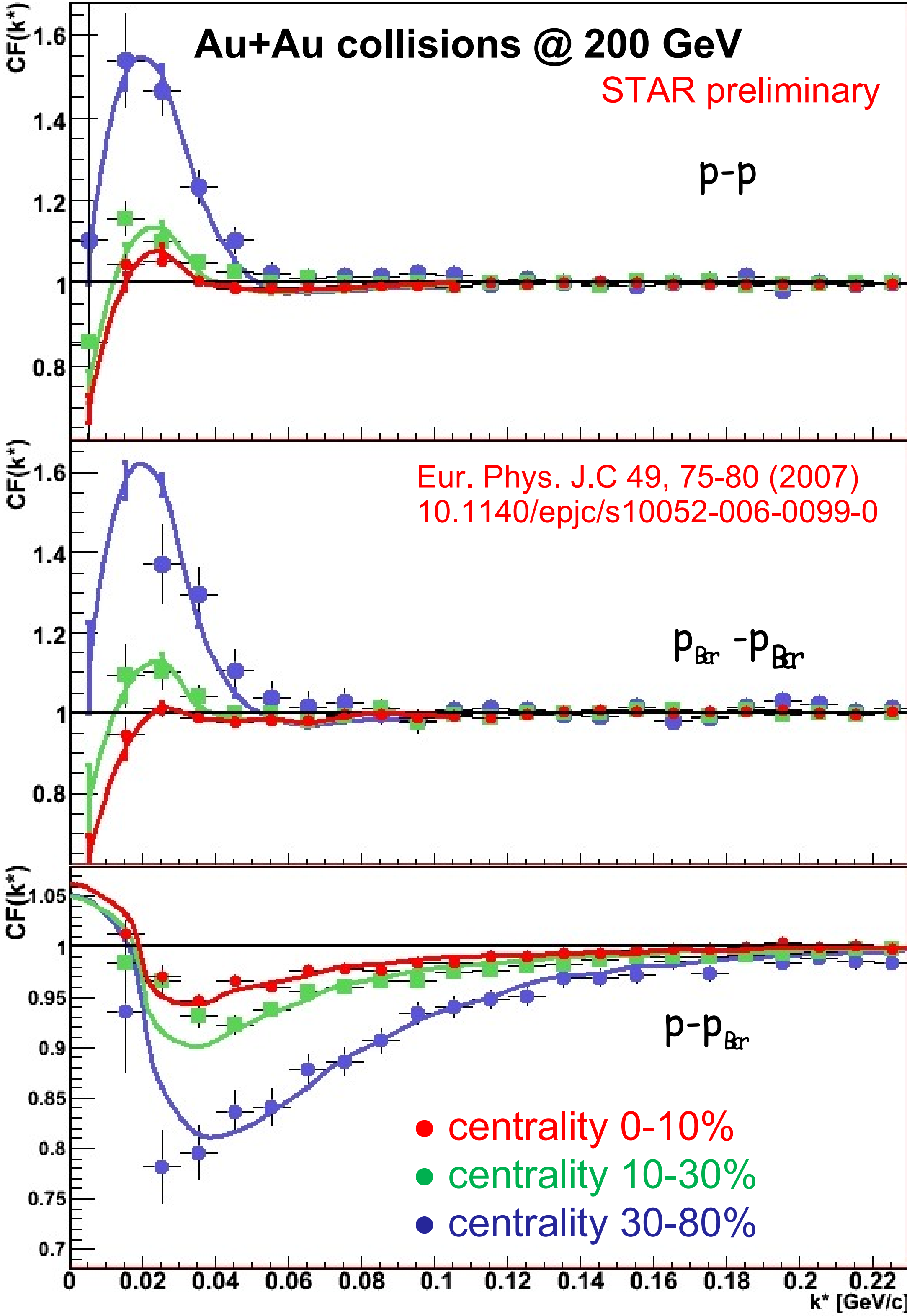
R. Lednicky, nucl-th/0305027

Space asymmetry from flow



THERMINATOR calculation

- Transverse momentum of particles is composed of the thermal (randomly distributed) and flow (directed "outwards") components
- With no flow average emission point is at center of the source and the length of homogeneity is the whole source
- Flow makes the source smaller **("size"-p correlation)** AND shifted in outwards direction **(x-p correlation)**
- For particles with large mass thermal motion matters less – they are shifted more in "out" direction. The difference is measured as emission asymmetry.



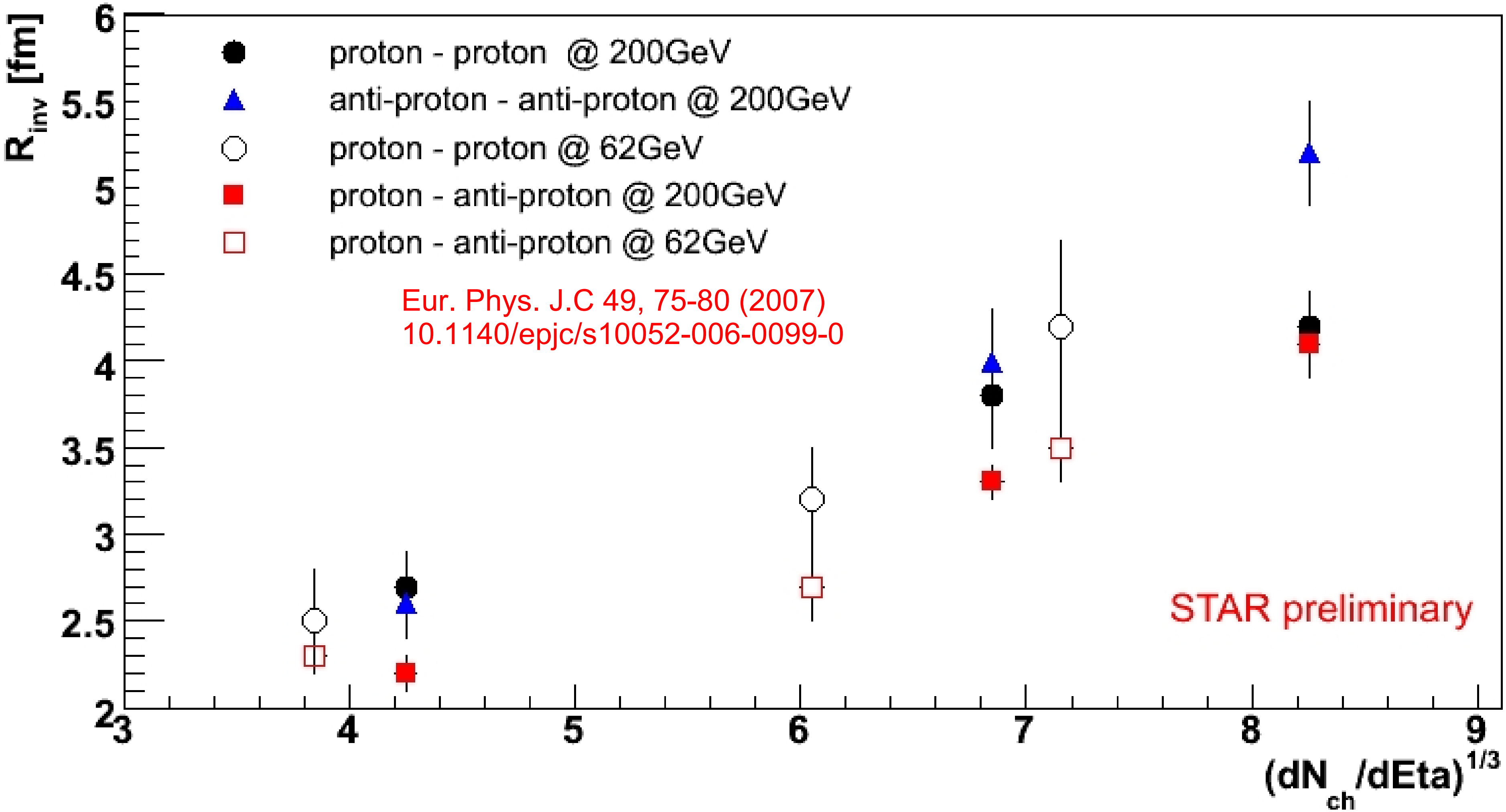
Proton femtoscopy

- 10 millions of minimum-bias data analyzed
- Applied corrections: purity, resolution smearing, residual correlations
- Centrality dependence is shown
- Gaussian source distribution assumed (the same source size in each direction)
- Agreement of experimental data and fits is very good

For the first time:

- The analysis of two-baryon correlations for all proton and antiproton systems (in the same experimental conditions)
- The sizes of antiproton emission region measured
- Data corrected for the residual correlations

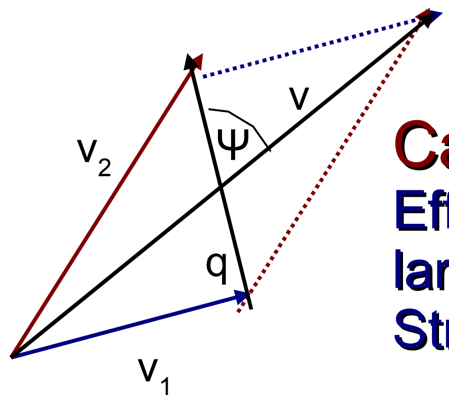
Proton-proton, antiproton-antiproton, proton- antiproton



Results for collision energy $\sqrt{s_{NN}}$ =62 and 200 GeV

The collision dynamics, asymmetry analysis

Antiproton faster

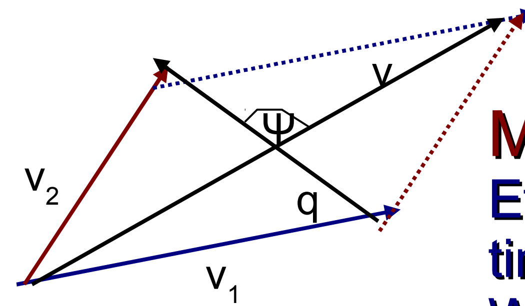


Catching up

Effective interaction time larger

Stronger correlation

Proton faster



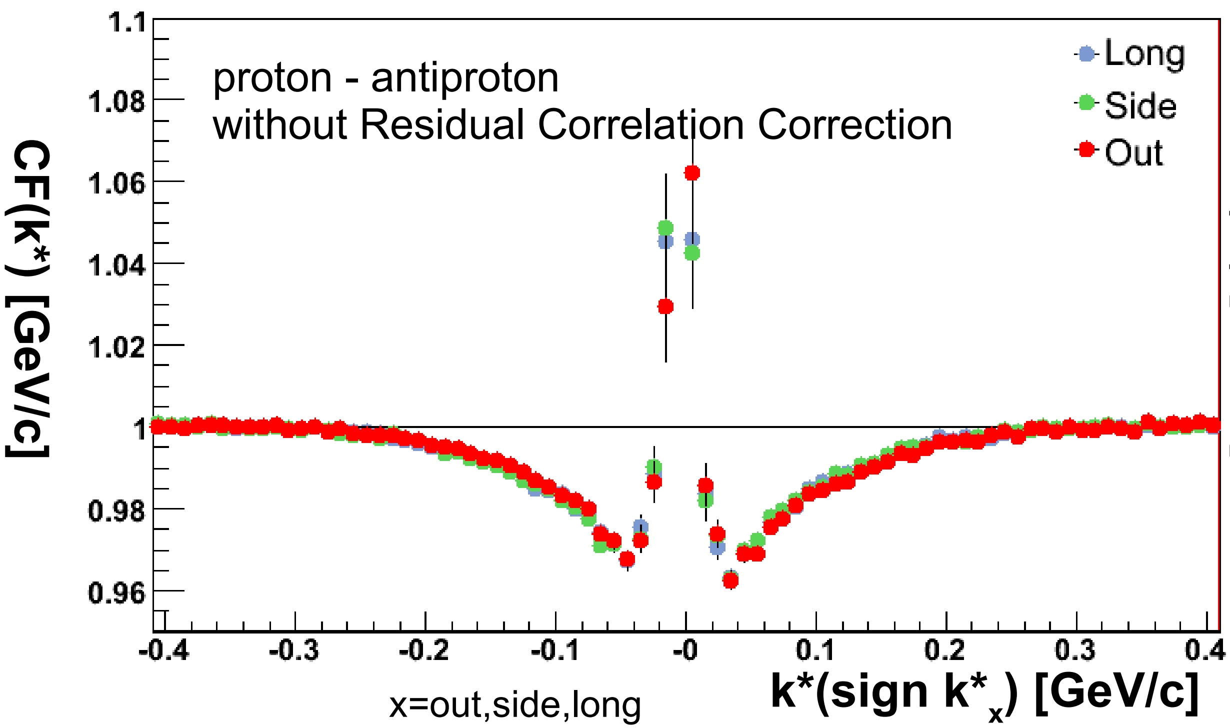
Moving away

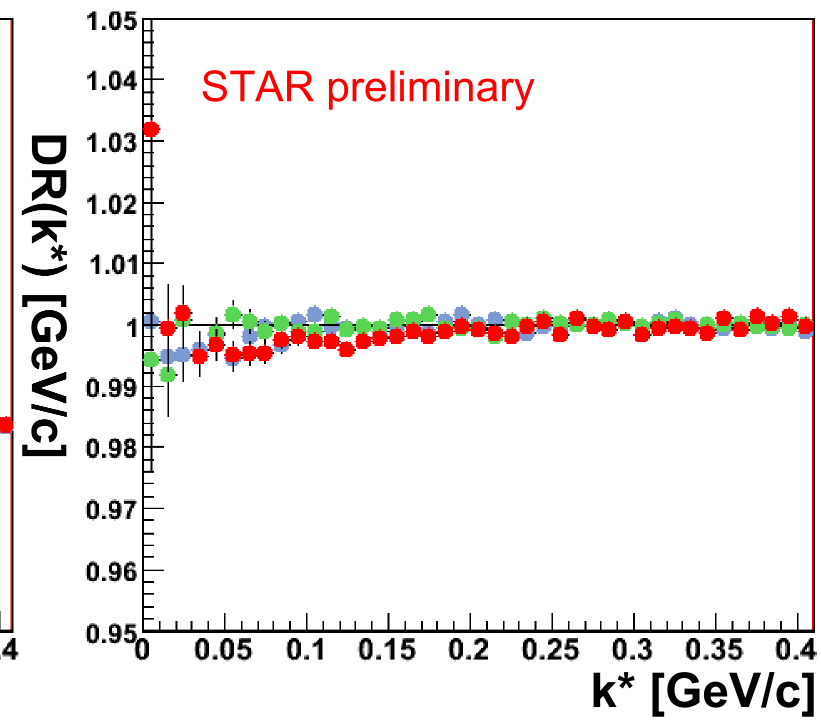
Effective Interaction time smaller

Weaker correlation

Let's assume, that proton is emitted earlier

R.Lednicky, V. L.Lyuboshitz, B.Erazmus, D.Nouais, Phys.Lett. B373 (1996) 30.





Summary

Investigation on initial state of high energy nucleus

More precision measurements on medium bulk properties

- precision PID v_2, NCQ test
- ideal hydro limit not reached
- strangeness production
- first observation of anti-hypernucleus
- ρ^0 meaurements
- parity P-violation
- femtoscopy observables

More knowledge on jet-medium interaction mechanisms

- Ridge characteristics
- Probe jet flavor conversion

Heavy flavor program is underway

- J/psi R_{CuCu} consistent with unity at high p_T
- Upsilon N_{bin} scaling in d+Au

Beam Energy Scan to map the QCD phase diagram

- 9.2 measurements demonstrate the STAR readiness

We are looking forward to new data from heavy-ion program at LHC!

Where are we?

Goal of the RHIC Heavy Ion Program:

- search the QGP and measure its properties
- map the QCD phase diagram

What have we learned so far?

STAR NPA 757 (2005) 102

Strongly interacting, hot, dense matter with partonic collectivity

What do we do next?

Investigate the medium properties:

- thermalization degree / EoS
- search for chiral symmetry restoration

Search for QCD critical point and phase boundary

Wait for LHC!

Thank you!