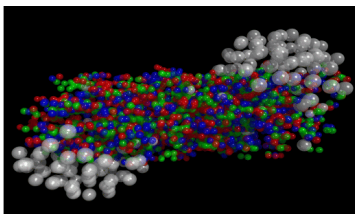


Potential updates in UrQMD

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Outline

- Introduction to the default UrQMD
- The need to update

- Improvements with the new EoS:
 - ✓ In intermediate energy HICs
 - ✓ In high energy HICs

- Conclusions

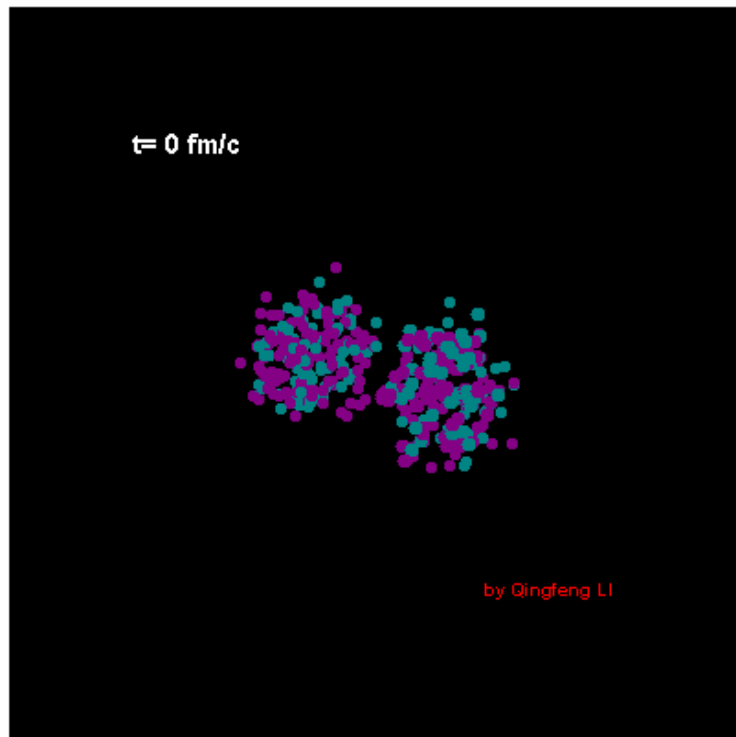
First glance of UrQMD

UrQMD : Ultra-relativistic Quantum Molecular Dynamics,

written mainly by the theoretical group in Frankfurt 10 years ago.

- It is a **non-equilibrium** transport model
- It includes **55** baryon species (with mass up to 2.25GeV) and **32** meson species (with mass up to 1.91GeV) . Hadrons are represented by Gaussian wave packets in phase space
- Particles interact via:
 - Mean Field modification
 - Collisions (with measured and calculated cross sections)
- Particles produce via:
 - Formation and decay of resonance
 - Excitation and fragmentation of string
- It provides full phase-space dynamics of heavy-ion collisions
- It can be used to study HICs at energies from SIS to RHIC
- The current version is v2.3. (<http://th.physik.uni-frankfurt.de/~urqmd/>)

Animations of UrQMD transport

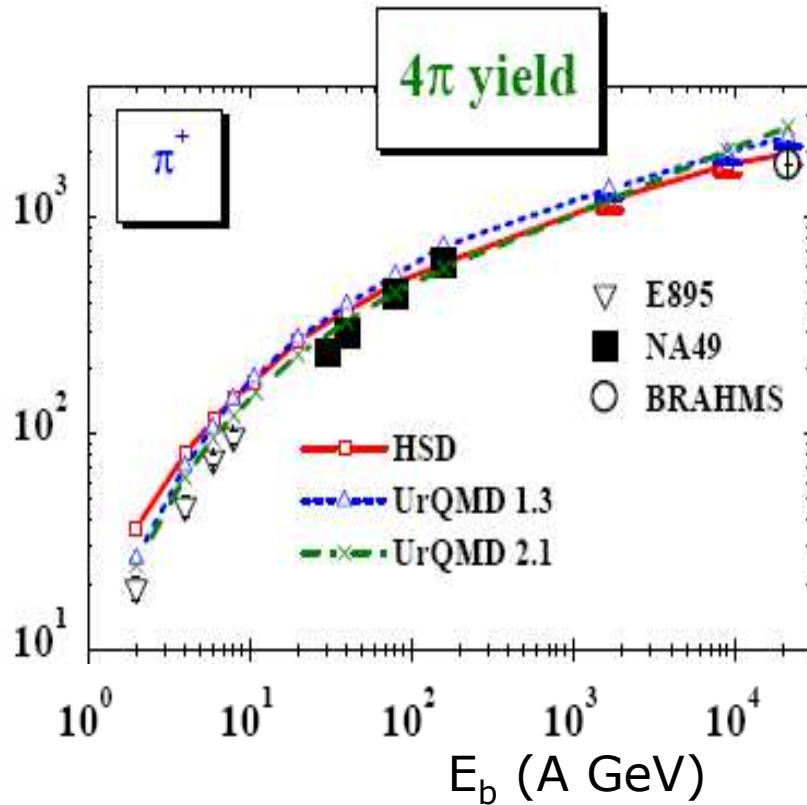


Au+Au $E_b=400A$ MeV $b=0$ fm

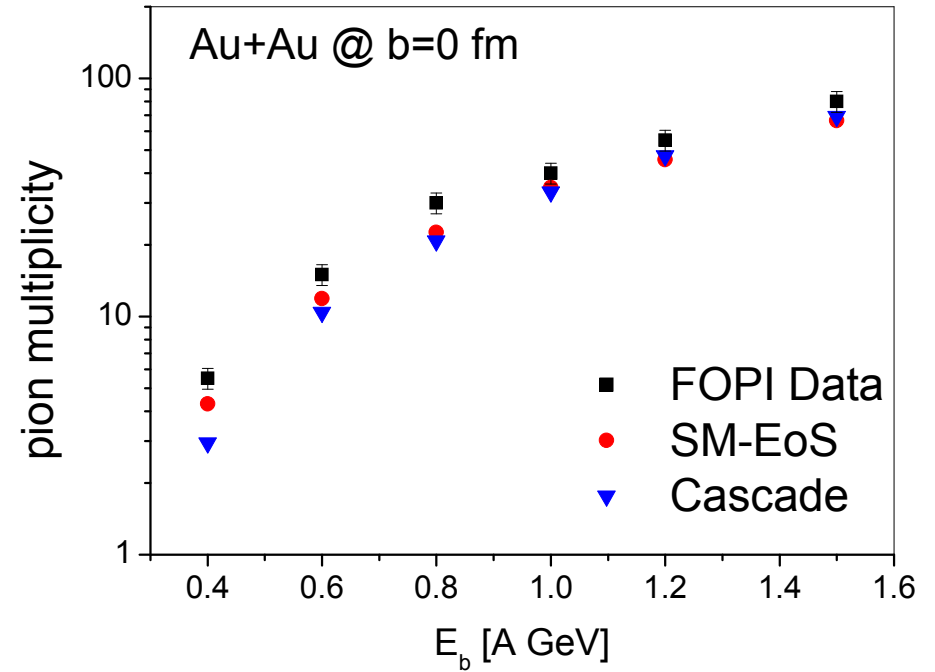


Ca+Ca $E_b=160A$ GeV $b=1$ fm

Second glance of UrQMD

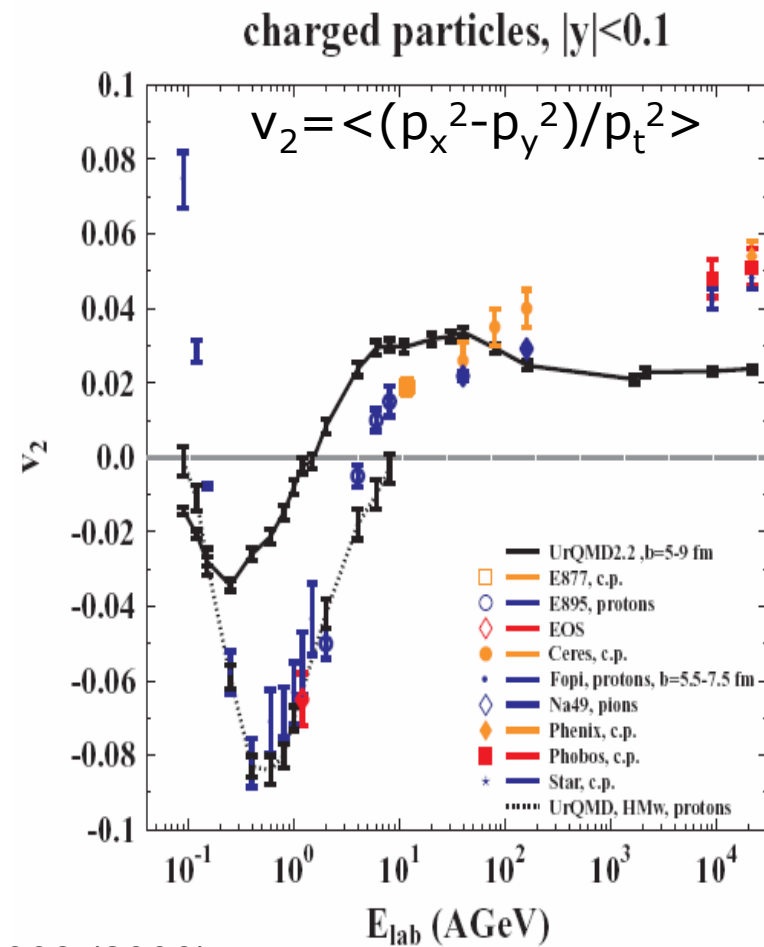
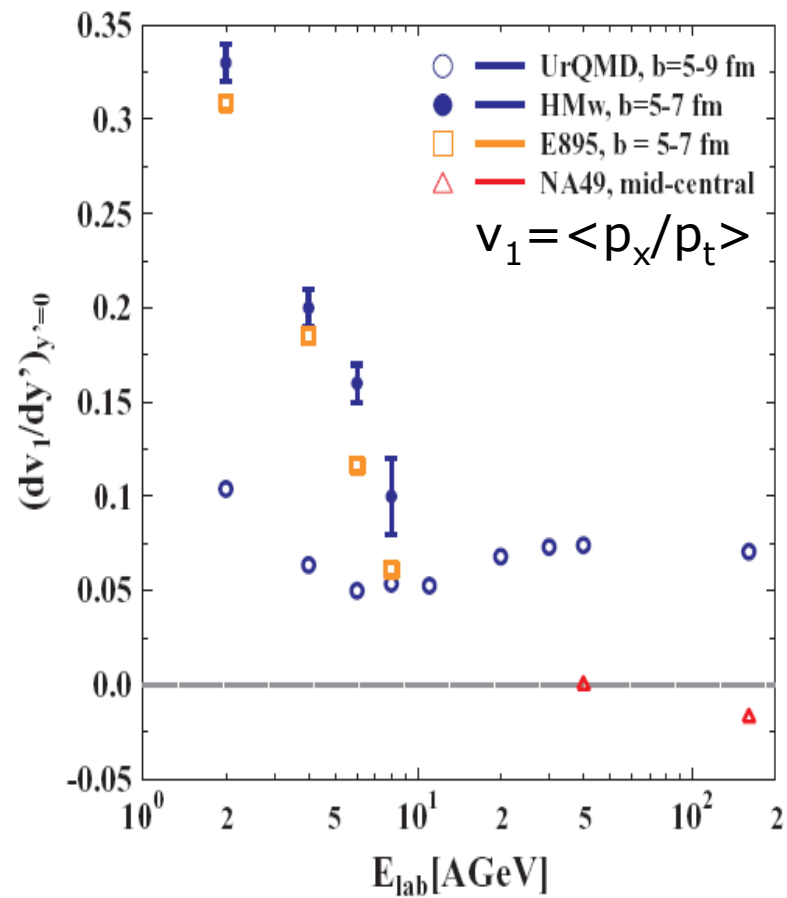


From PRC69, 054907 (2004)



From JPG32, 151 (2006)

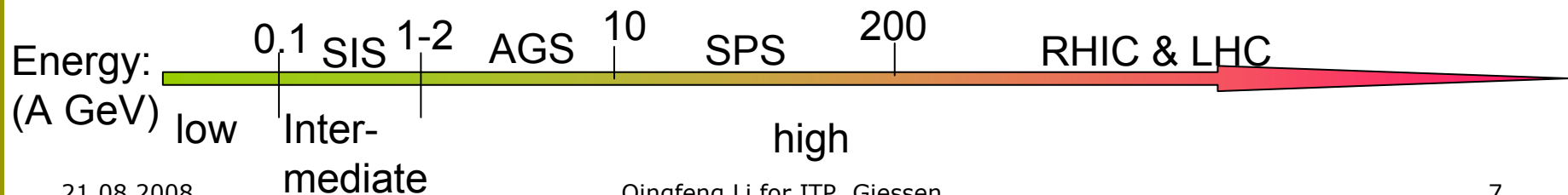
Cont'd



From PRC74, 064908 (2006)

To update the UrQMD

- It originates from two models: QMD (potential updates) and RQMD (collisions of a plenty of particles)
- The original purpose: High energy ICs (from AGS up to RHIC)
- It is possible to have one universal transport model for all ICs with energies spanning from low to high (SIS←AGS-SPS-RHIC→LHC).
- **New physics** can then be investigated in each energy region.





In Intermediate Energy HICs

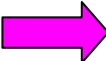
The potential modification

- Hamilton's equation of motion:

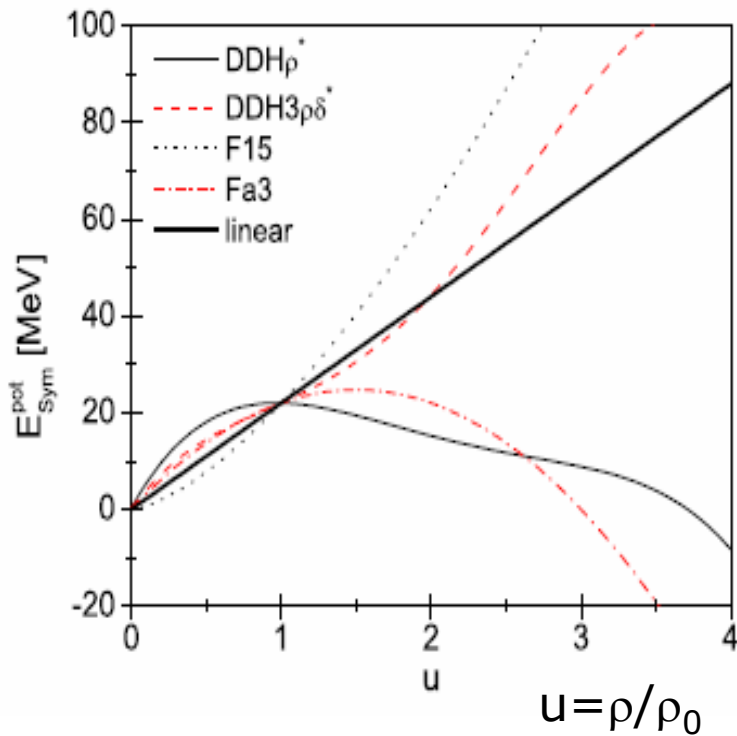
$$\dot{\mathbf{r}}_i = \frac{\partial H}{\partial \mathbf{p}_i} \quad \dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i} \quad H = T + V$$

- Potential energy implements:

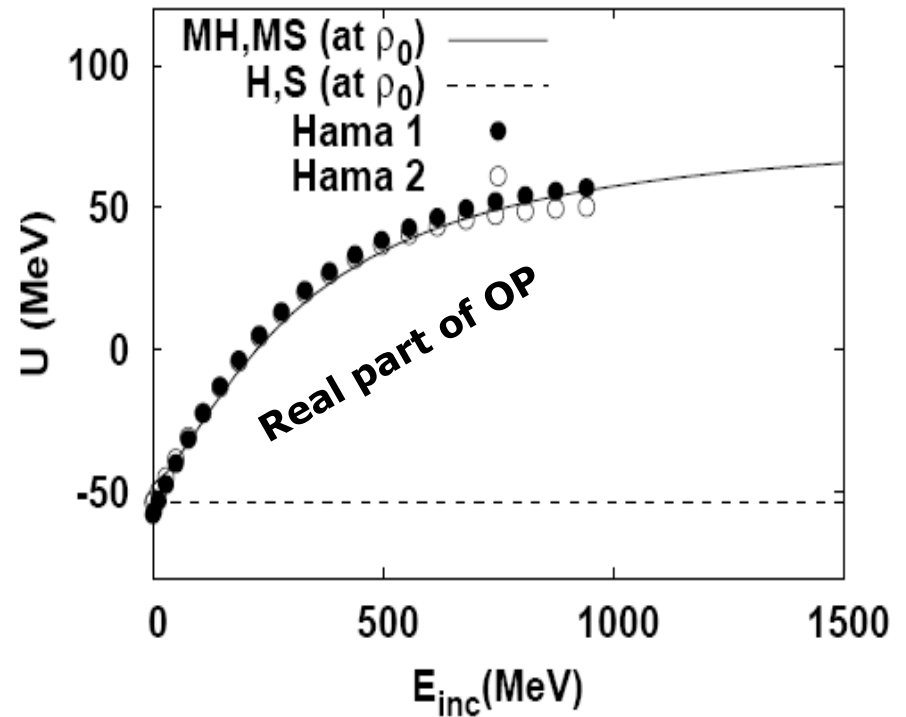
$$V = V_{sky}^{(2)} + V_{sky}^{(3)} + V_{Yuk} + \boxed{V_{Cou}} + V_{Pau}$$

 $+ V_{Sym} + V_{md}$

Sym. & Mom.Dep. terms



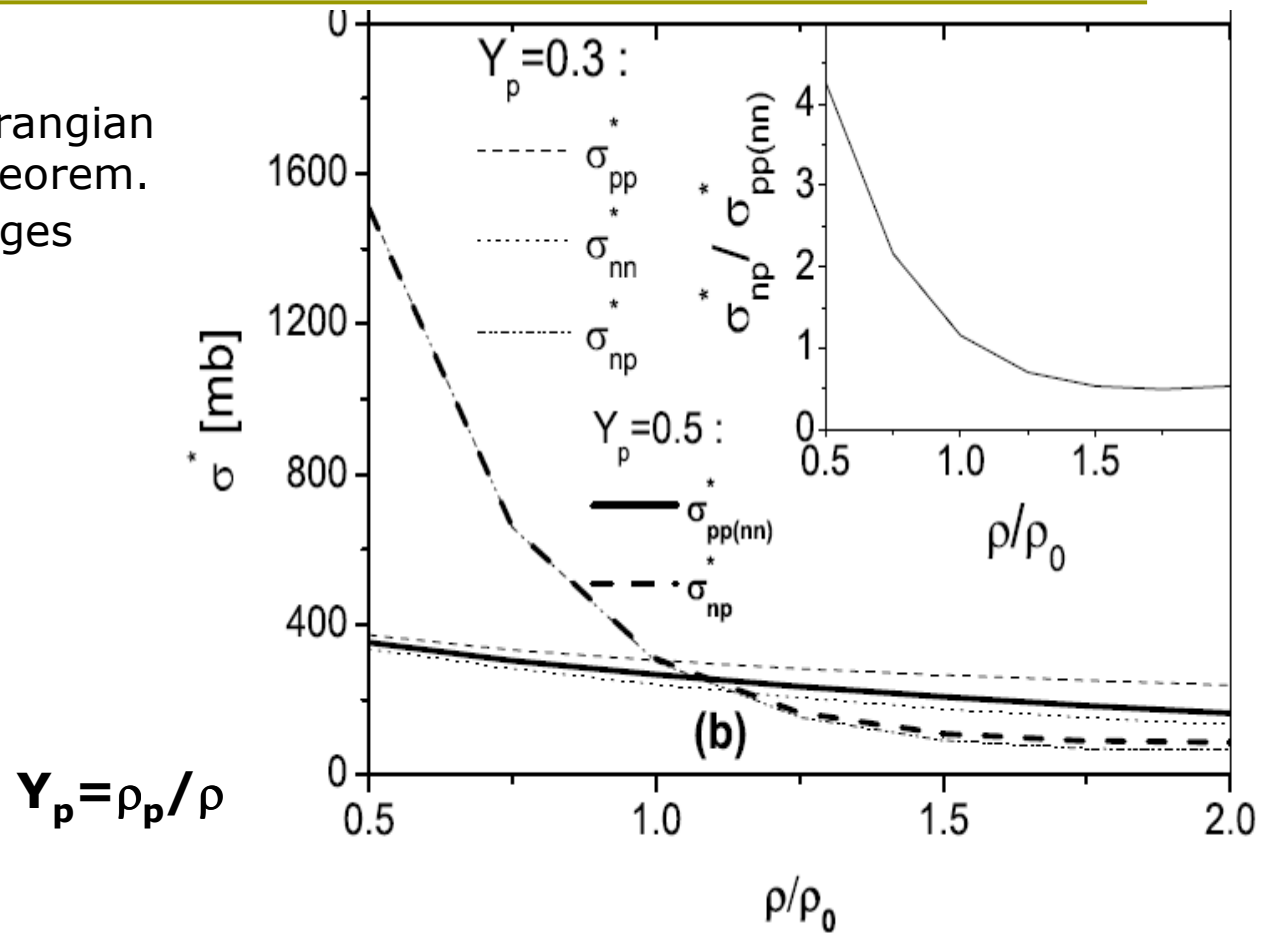
From JPG32, 151 (2006)



From PRC72, 064908(2005)

The medium modifications on N-N elCS

Based on QHD-II type Lagrangian and the RBUU transport theorem.
 (σ, ω) ; (ρ, δ) meson exchanges



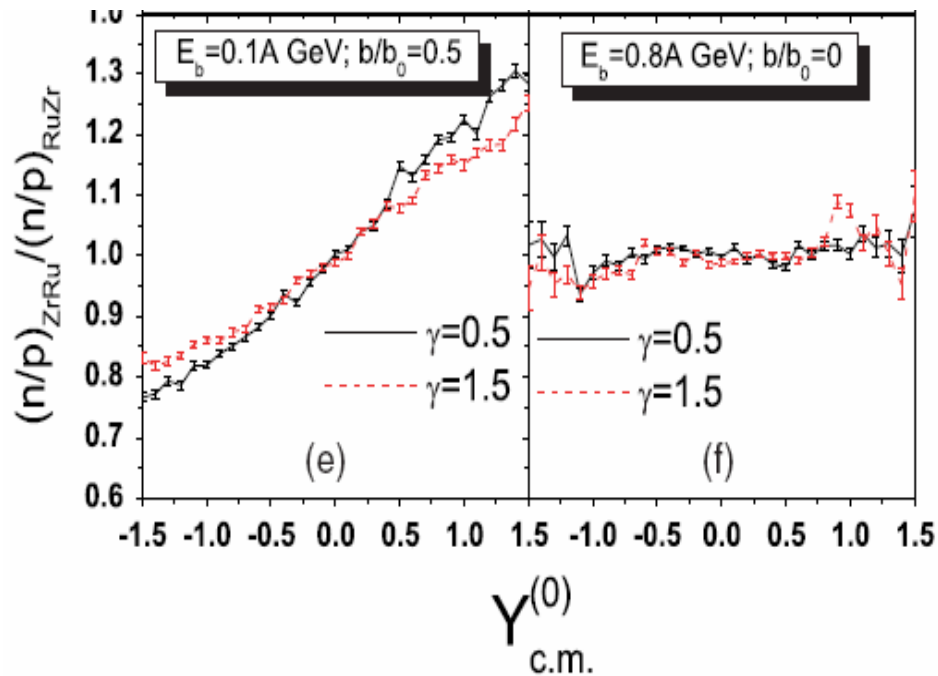
From PRC69, 017601(2004)

One of my interests at intermediate energies

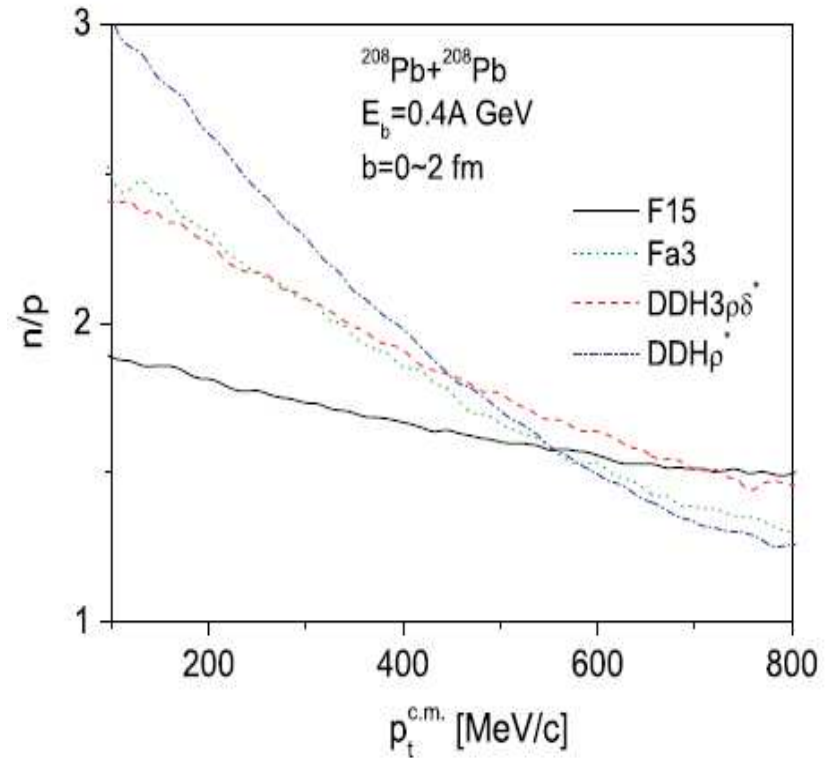
□ Isospin effects in HICs

- The isospin effect is strong and important at SIS energies.
- The density dependent symmetry energy, especially at supranormal densities, is crucial for investigations on the neutron star.
- UrQMD is a favorite model since one can investigate the **observables** with respect to many particles such as free nucleons, resonances, pions, kaons, hyperons...

Examples with nucleons



From PRC 73, 051601 (2006)



PRC72, 034613(2005)

Cont'd

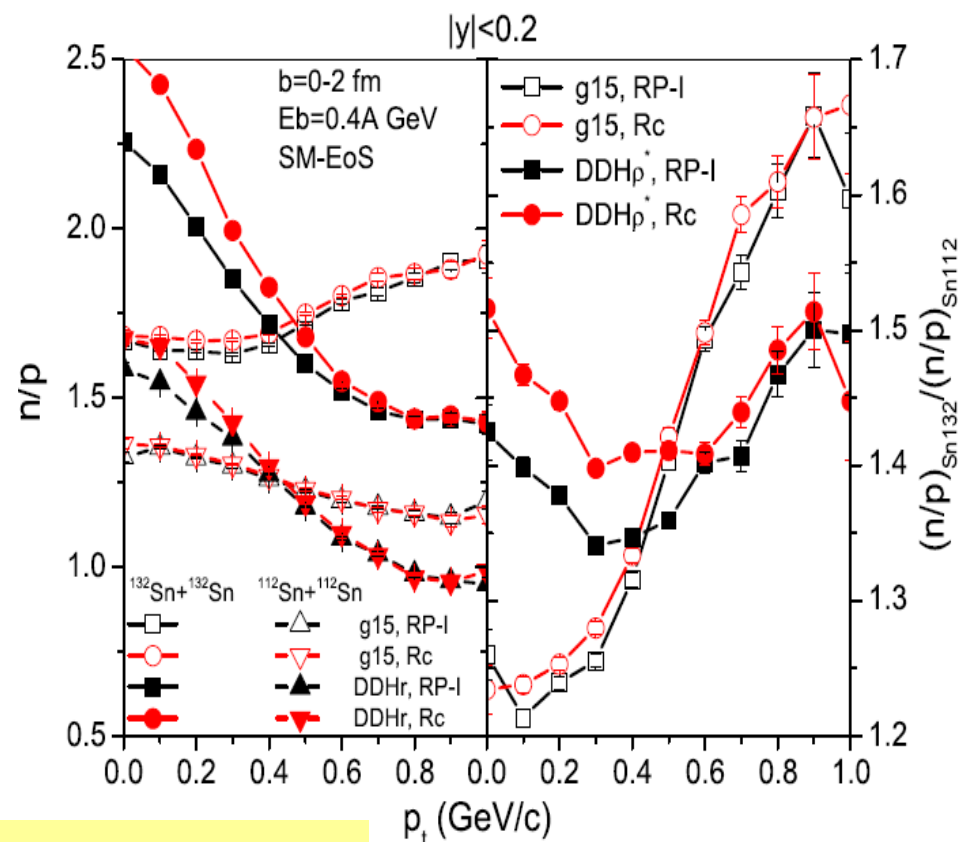
Ways to find free nucleons:

RP-I: coalescence
(in phase space)

Rc: critical density
(in coordinate space)

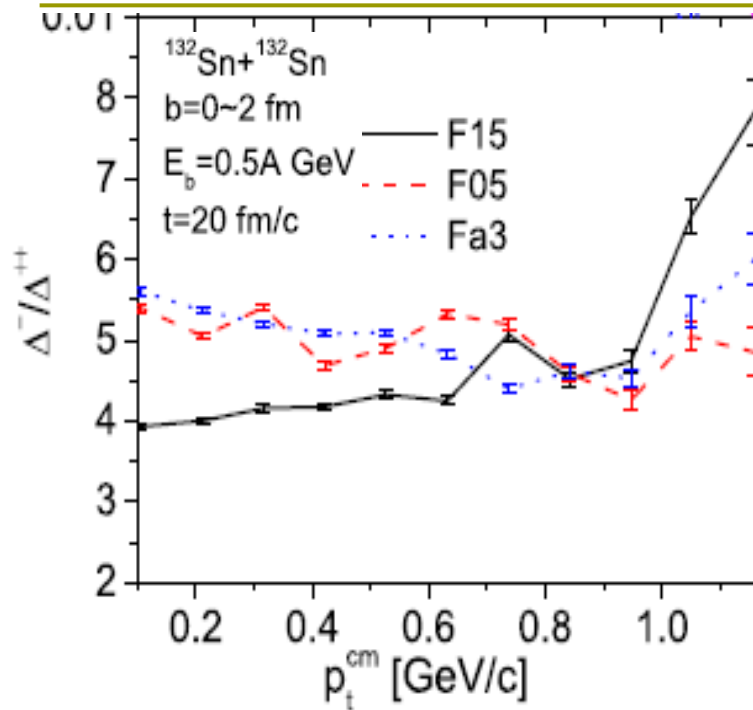
**n/p ratio at large p_t
is insensitive to
construction criteria**

Need to check:
the momentum dependence of the symmetry potential



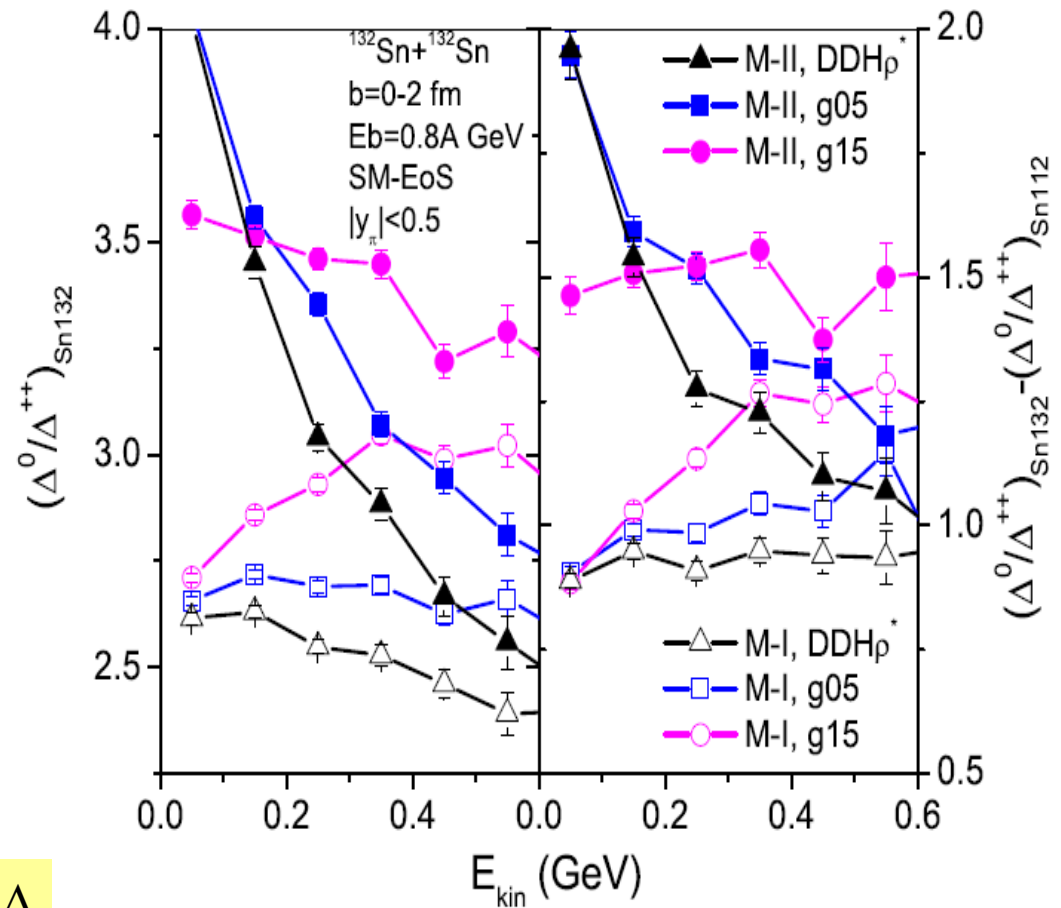
From nucl-th/0808.0624

Examples with Δ s



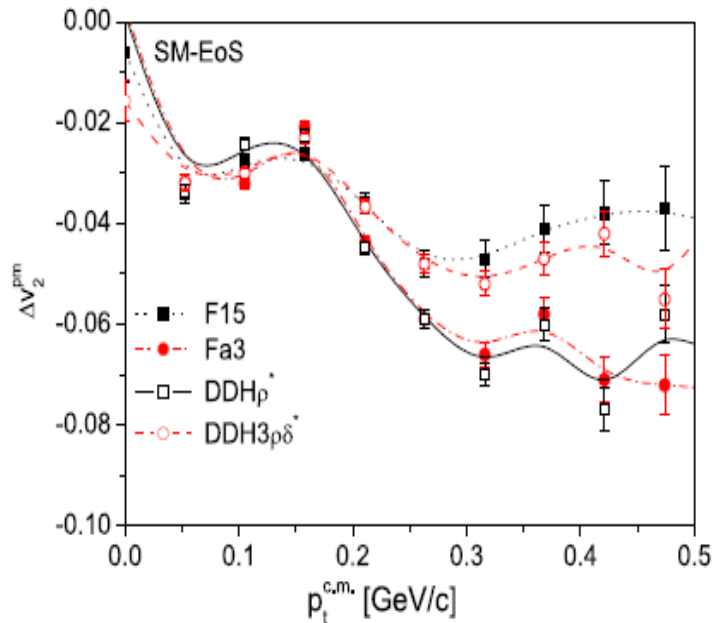
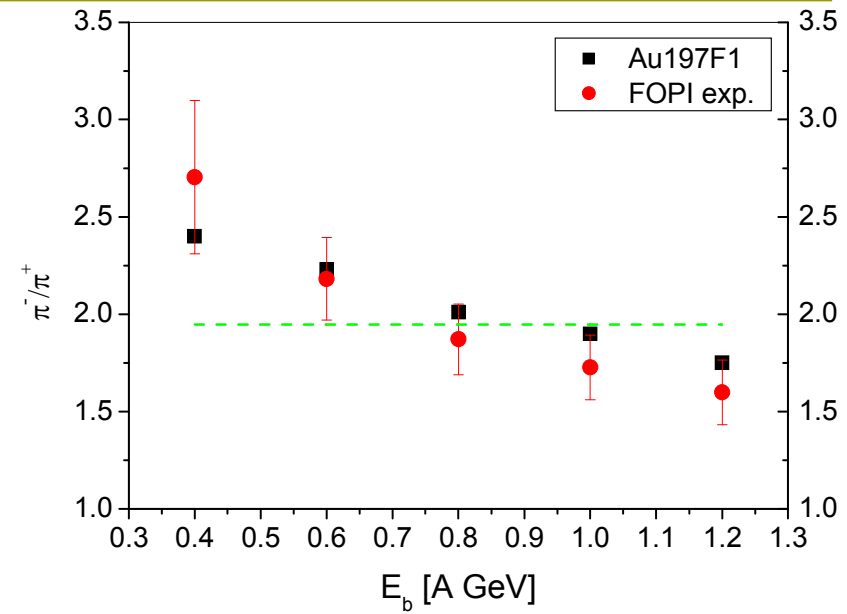
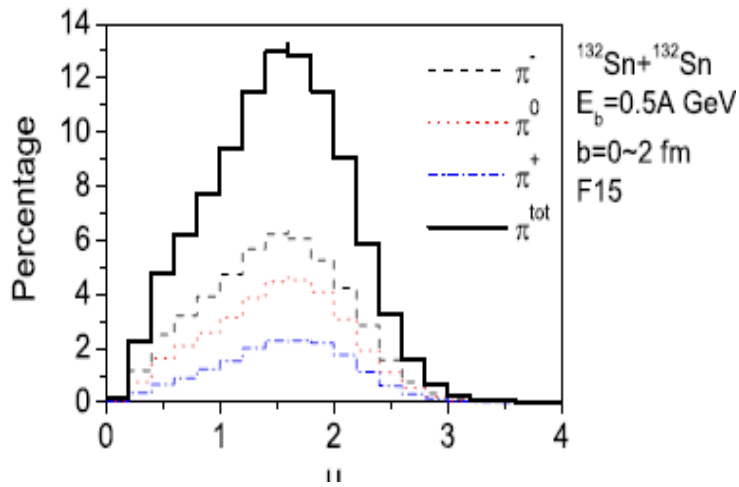
From JPG31, 1359 (2005)

Reconstruction criteria on Δ



From nucl-th/0808.0624

Examples with pions

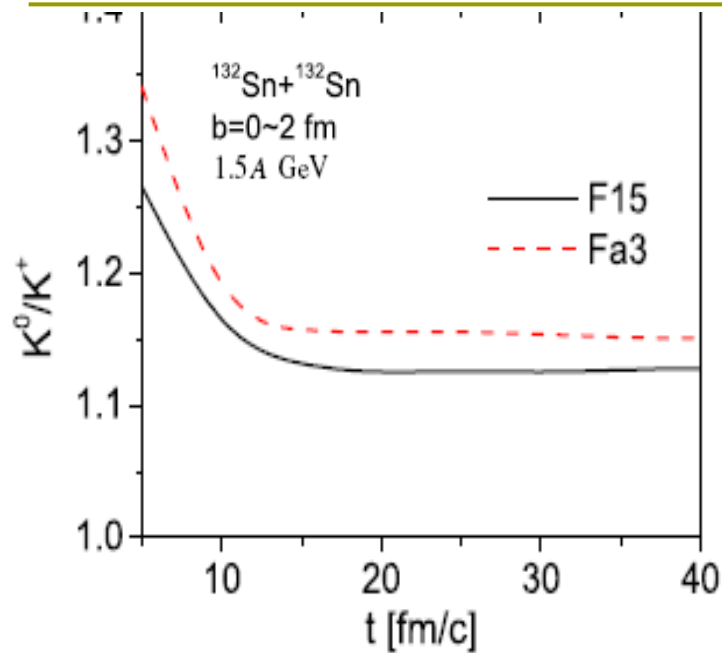


From JPG31, 1359 (2005)

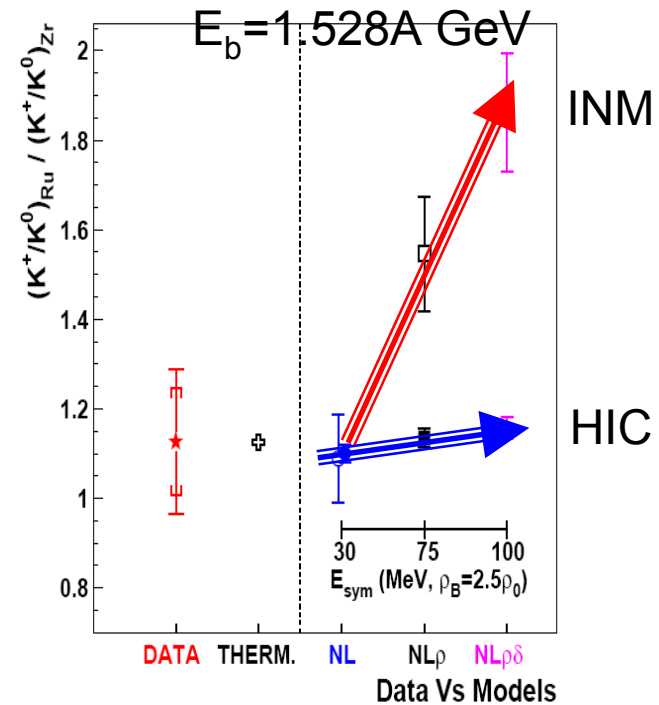
From JPG32, 151 (2005)

Dynamics of Δ resonance

Examples with Kaons



Exp.:

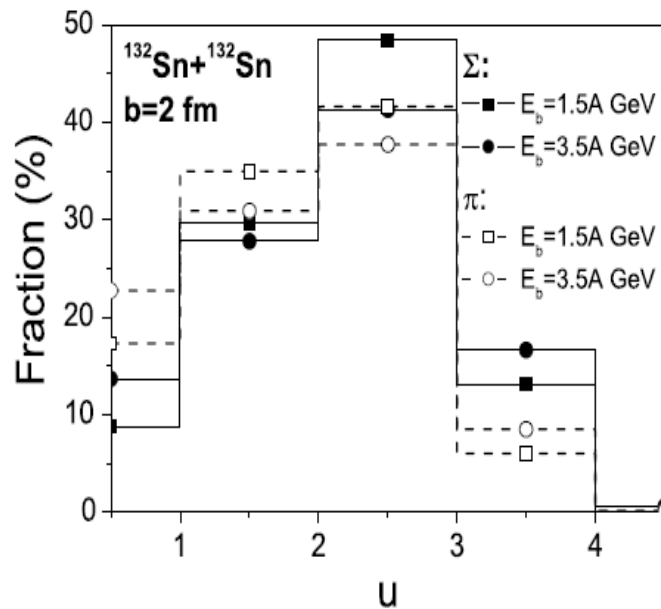


From JPG31, 1359 (2005)

From X. Lopez et al PRC75, 011901(R) (2007)

Kaon production at sub-threshold is better → hard to detect

Examples with Σ s



From PRC71, 054907 (2005)

More uncertainties from hyperson potentials are introduced

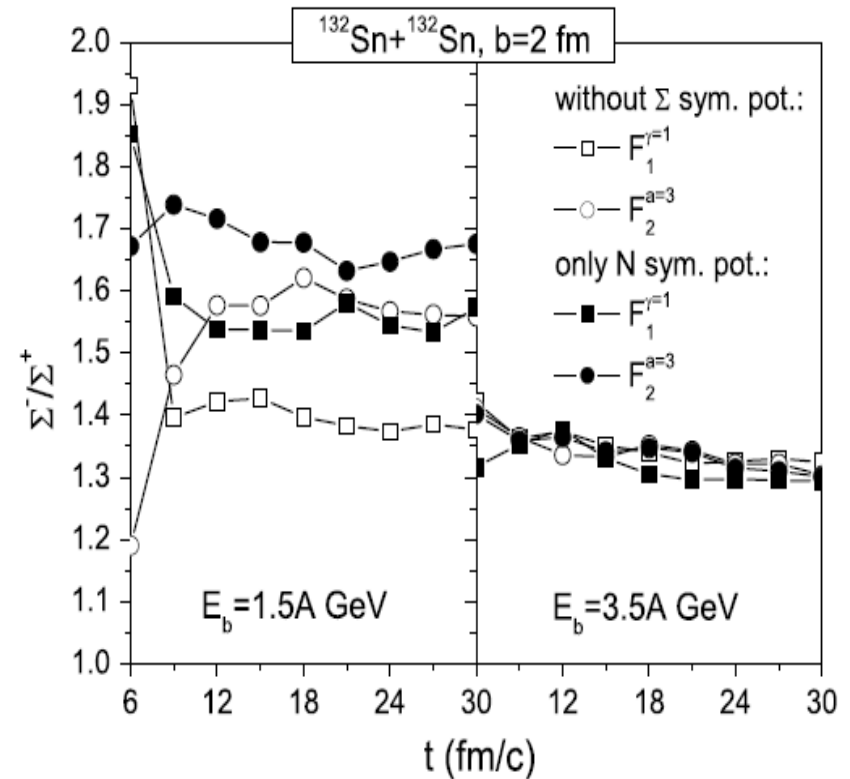
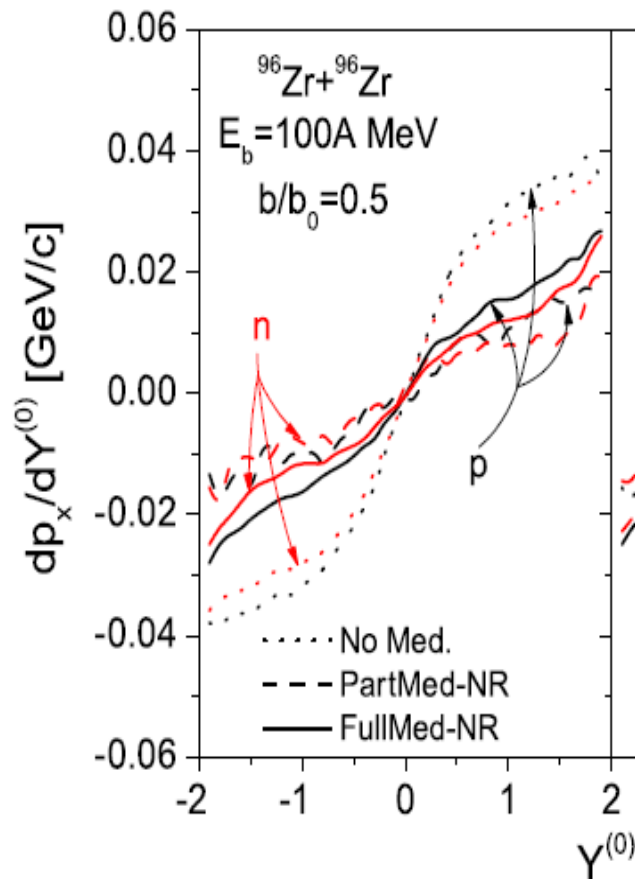


FIG. 8. The ratios Σ^- / Σ^+ for $F_1^{\gamma=1}$ and $F_2^{a=3}$, with the symmetry potentials of different baryons switched on or off.

Medium effects on N-N elastic CS



No Med.: CS in free space
PartMed-NR: isospin-scalar and vector density effects
FullMed-NR: PartMed-NR + momentum constraints

From JPG32, 407 (2006)

A more consistent transport model is awaiting.

Current status

- We focus on the density dependence of the symmetry energy at supranormal densities.
- (The p_t dependence of) the n/p ratio and (the rapidity dependence of) the elliptic flow difference ($v_2^n - v_2^p$) are strongly suggests.
- It becomes possible to check nucleon-related observables by forthcoming experiments at GSI.
- The precision should be much higher (at least 10 times higher than before) .

In cooperation with ALADIN and CHIMERA

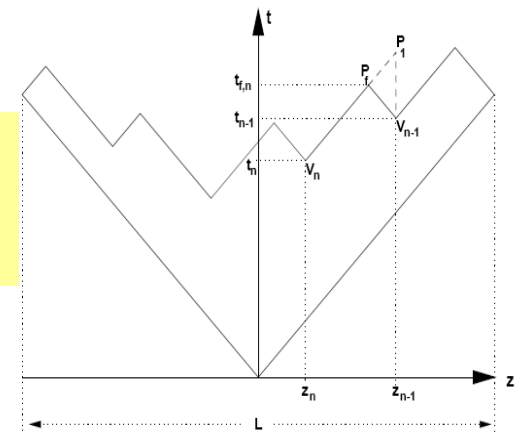


In High Energy HICs

Treatment of the “pre-formed” hadrons before string fragmentation

- At high SPS and RHIC energies, particle production is dominated by the string mechanism.
- The formation time of the hadron is determined by the “yo-yo” mode. During this time, the particles are taken as “pre-formed”. The transport of the “pre-formed” particles is treated to be “free-streaming”.
- The reduced cross sections are only included for leading hadrons.

One thinks that the potentials is not important at high beam energies just because **only the potentials of formed particles are considered!**



Why to consider the potential for “pre-formed” hadrons?

- sQGP tells us that there is a strong coupling between particles at early stage.
- Small elliptic flow at RHIC was predicted by UrQMD.
- The $gg \rightarrow gg$ interaction is believed not enough from Xu and Greiner (PRC71, 064901 (2005)).
- There is no free quarks/gluons in UrQMD.
- Shorter formation time helps to increase the flow but also multiplicities drastically.

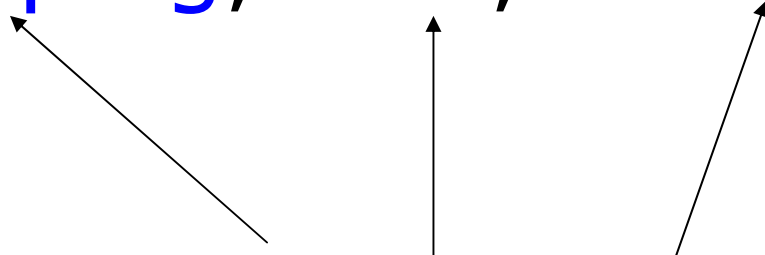
The “pre-formed” hadronic potential

- To modify the interactions at early stage, more collisions (by considering a shorter formation time or larger cross sections for “pre-formed” particles) or a mean-field potential for “pre-formed” hadrons might be taken into account. The former idea has been checked in the AMPT and the HRM models. Here we would like to consider the latter idea.
- As the first step,
 - ① the density dependent term used for formed baryons is used for “pre-formed” particles.
 - ② The “pre-formed” mesons act like “pre-formed” baryons but with a reduction factor ($2/3$) due to the quark-number difference.
 - ③ The potential interaction between formed and “pre-formed” particles is neglected.
 - ④ The “pre-formed” particles also contribute to the hadronic density (for “pre-formed” mesons, the $2/3$ factor is considered).

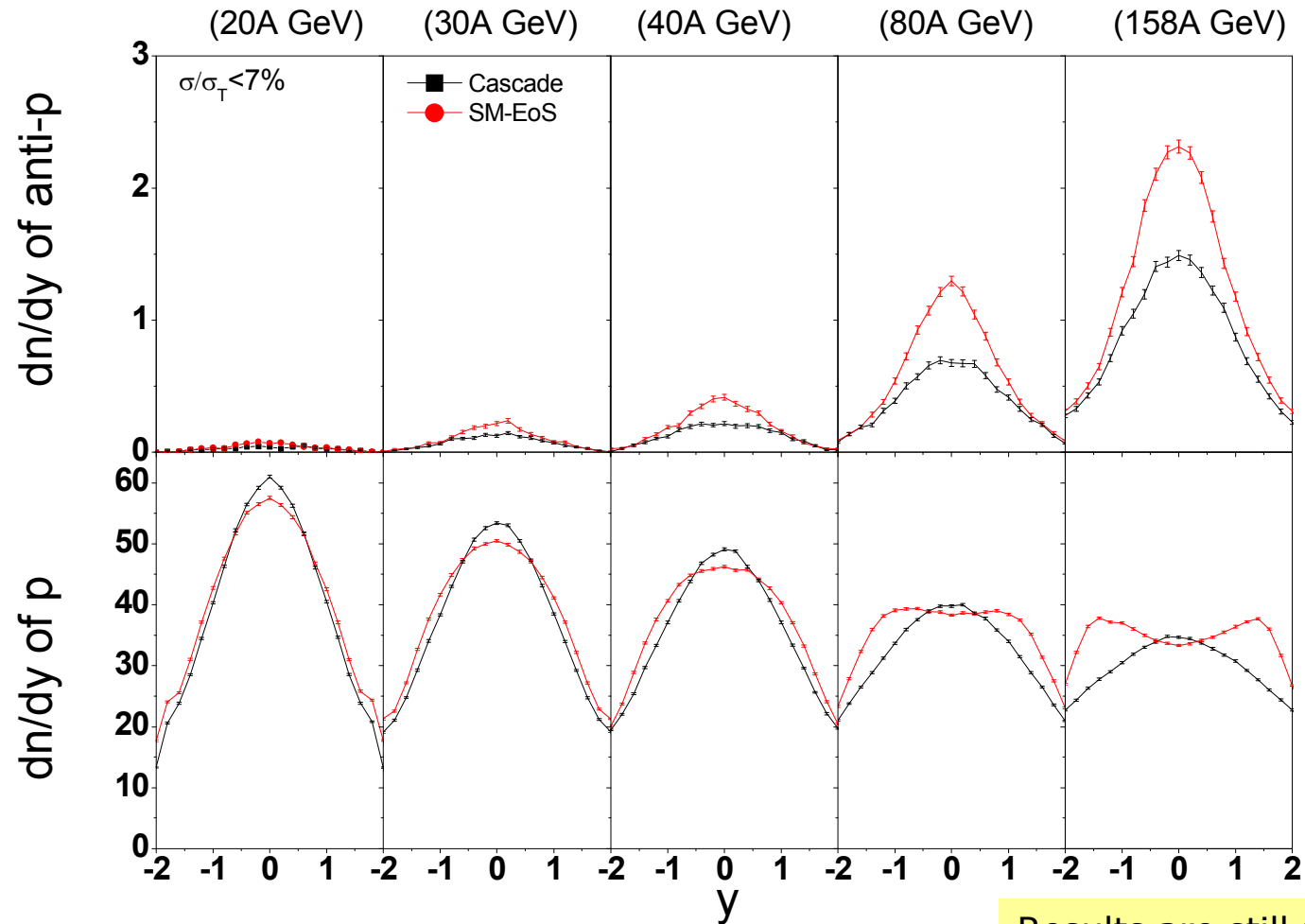
My interests at high energies

- Phase transition from HG to QGP
 - signals: (strangeness enhancement, J/Ψ suppression, energy loss of hard partons);
stopping, **flow**, **HBT correlation**...

Related to soft physics



stopping at SPS energies

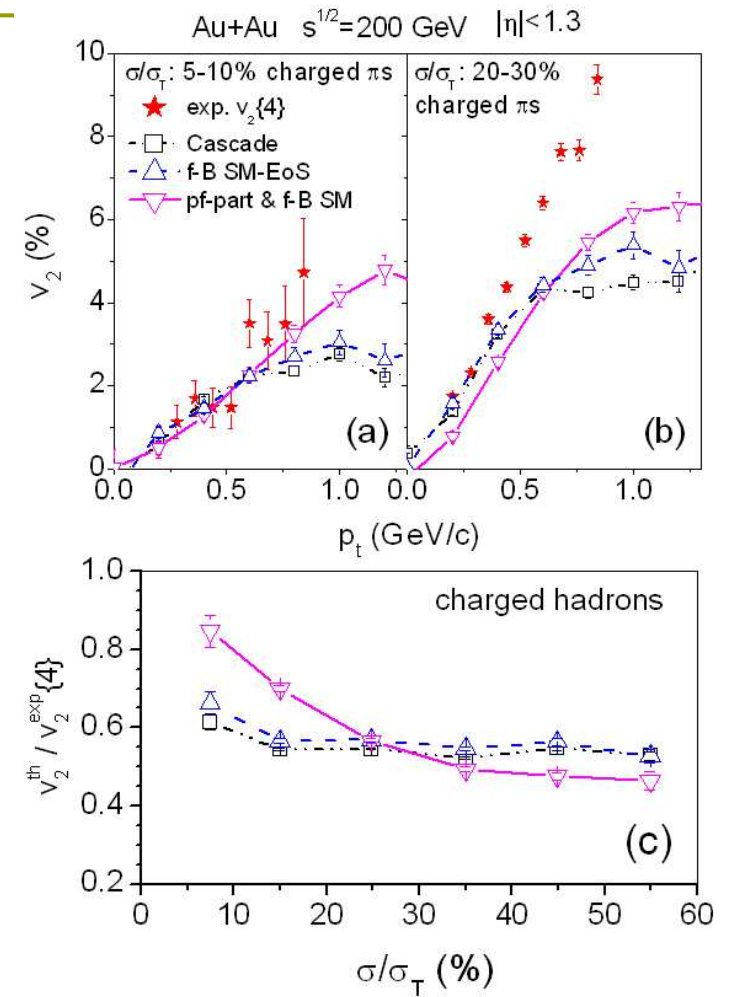
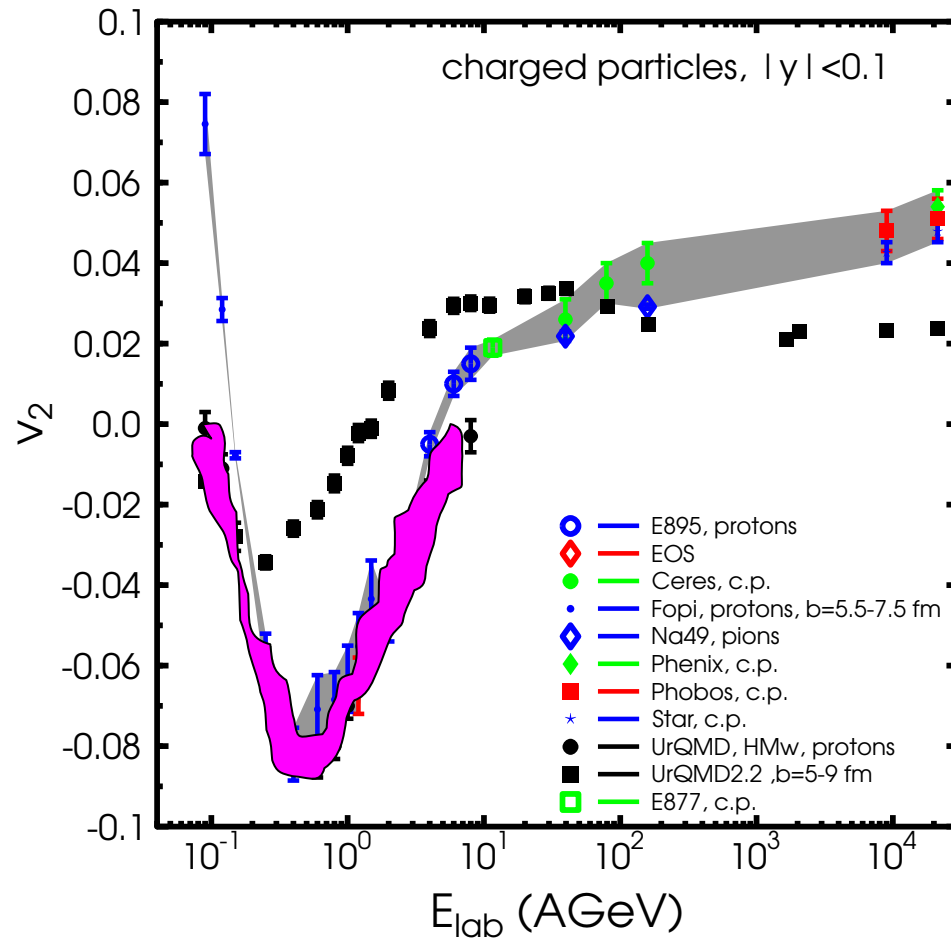


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Results are still preliminary
Proton yield is higher than
data.

Elliptic flow



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Of course, the collision of partons is necessary

From PLB659, 525(2008)

HBT, half century in NP

- **HBT = Robert Hanbury-Brown and Richard Q. Twiss**
 - In 1950's, in order to measure stellar radii through the angle subtended by nearby stars, Robert invited Richard to develop the mathematical theory of intensity interference. They found by astro-observation that two-photons arriving to the correlators behaved as a consequence of **B-E statistics**.
 - In 1959, during the measurements of the ρ^0 resonance (by means of $\rho^0 \rightarrow \pi^-\pi^+$), **Goldhaber** etc (Berkeley) found an angular correlation among identical pions, which were also explained by the B-E. What's more, they parameterized the observed correlation as:

$$C(Q^2) = 1 + \exp(-Q^2 r^2)$$

The subsequential HBT researches in nuclear physics are based on this Gaussian form.

*R. Hanbury Brown and R.Q. Twiss, Philos. Mag. **45**, 663 (1954).

*G. Goldhaber, S. Goldhaber, W. Lee, and A. Pais, Phys. Rev. **120**, 300 (1960)

The HBT correlation and parameterization

The quotient of two-particle and one-particle spectra

Experimentally:

$$C(q, K) = \frac{\frac{d^6 N}{dp_1^3 dp_2^3}}{\frac{d^3 N}{dp_1^3} \frac{d^3 N}{dp_2^3}}$$

$$q = p_1 - p_2$$

$$K = (p_1 + p_2) / 2$$

Theoretically:

$$C(q, K) = \frac{\int dx_1 dx_2 s(x_1, p_1) s(x_2, p_2) |\phi|^2}{\int dx_1 s(x_1, p_1) \int dx_2 s(x_2, p_2)}$$

The two-particle correlator $C(q, K)$ is related to the emission function $\mathbf{s}(\mathbf{x}, \mathbf{K})$, which is the Wigner phase-space density of the particle emitting system and can be viewed as the **probability** that a particle with average momentum K is emitted from the space-time point x in the collision region. ϕ the two-particle relative wave function.

The correlator is constructed with the help of the CRAB program

Cont'd

- CRAB analyzing program:
<http://www.nsl.msui.edu/~pratt/freecodes/crab/home.html>
- Three-dimensional Gaussian parameterization
LCMS is employed in usual calculations
- Coulomb effect in FSI is considered for charged two-kaon correlation with a Bowler-Sinyukov method
- non-Gaussian effect can be discussed under the Edgeworth expansion

$$C(\mathbf{k}, \mathbf{q}) = \frac{\int d^4x_1 d^4x_2 g(x_1, \mathbf{p}_1) g(x_2, \mathbf{p}_2) |\phi(\mathbf{q}, \mathbf{r})|^2}{\int d^4x_1 g(x_1, \mathbf{p}_1) \int d^4x_2 g(x_2, \mathbf{p}_2)}$$

$$C(q_O, q_S, q_L) = 1 + \lambda \exp(-R_O^2 q_O^2 - R_S^2 q_S^2 - R_L^2 q_L^2 - 2R_{OL}^2 q_O q_L)$$

$$C(q_O, q_S, q_L) = (1 - \lambda) + \lambda K_{coul}(q_{inv})(1 + \exp(-R_O^2 q_O^2 - R_S^2 q_S^2 - R_L^2 q_L^2 - 2R_{OL}^2 q_O q_L))$$

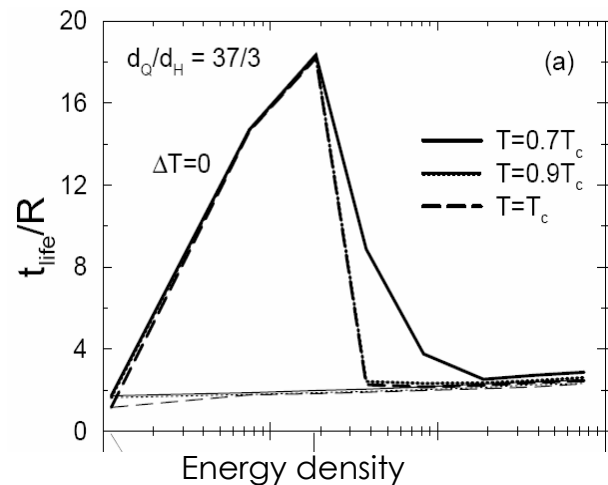
$$C(q_{inv}) = K_{inv} [1 + \lambda_{inv} \exp(-R_{inv}^2 q_{inv}^2)] [1 + \sum_{n=4, \text{even}}^{\infty} \frac{\kappa_{inv, n}}{n! (\sqrt{2})^n} H_n(R_{inv} q_{inv})]$$

$$H_n(z) = (-1)^n e^{z^2} \frac{d^n}{dz^n} e^{-z^2}$$

The fitting work can be done by the ROOT or the ORIGIN software (using χ -squared method)

One task of HBT: to probe the QGP fireball

- A **non-trivial** structure in the excitation function of HBT probes *might* be seen IF there is a (phase) transition.



➤ long life times in the mixed phase?

Predictions by
Rischke, Gyulassy, in
Nucl.Phys.A608:479-512,1996

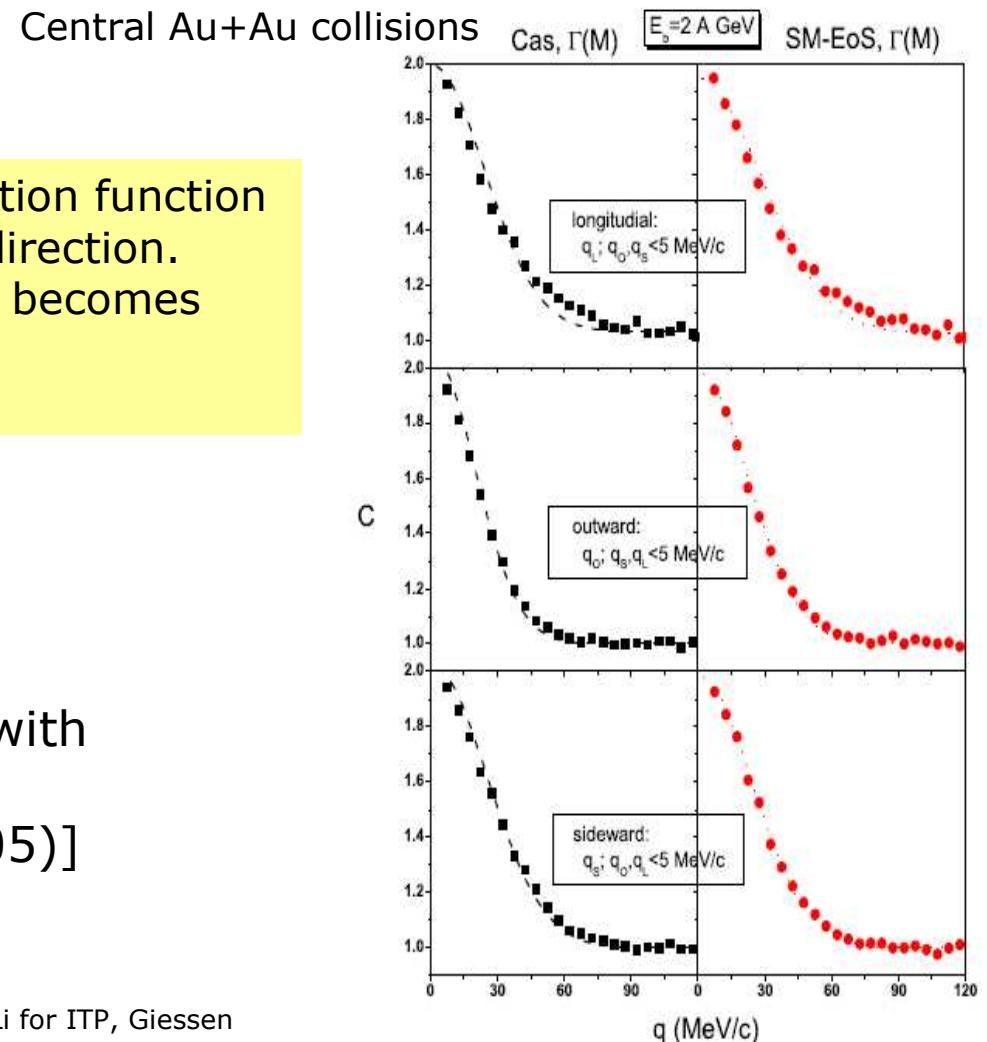
The non-Gaussian effect

The non-Gaussian effect of the correlation function exhibits especially in the longitudinal direction. With SM-EoS, the non-Gaussian effect becomes weaker.

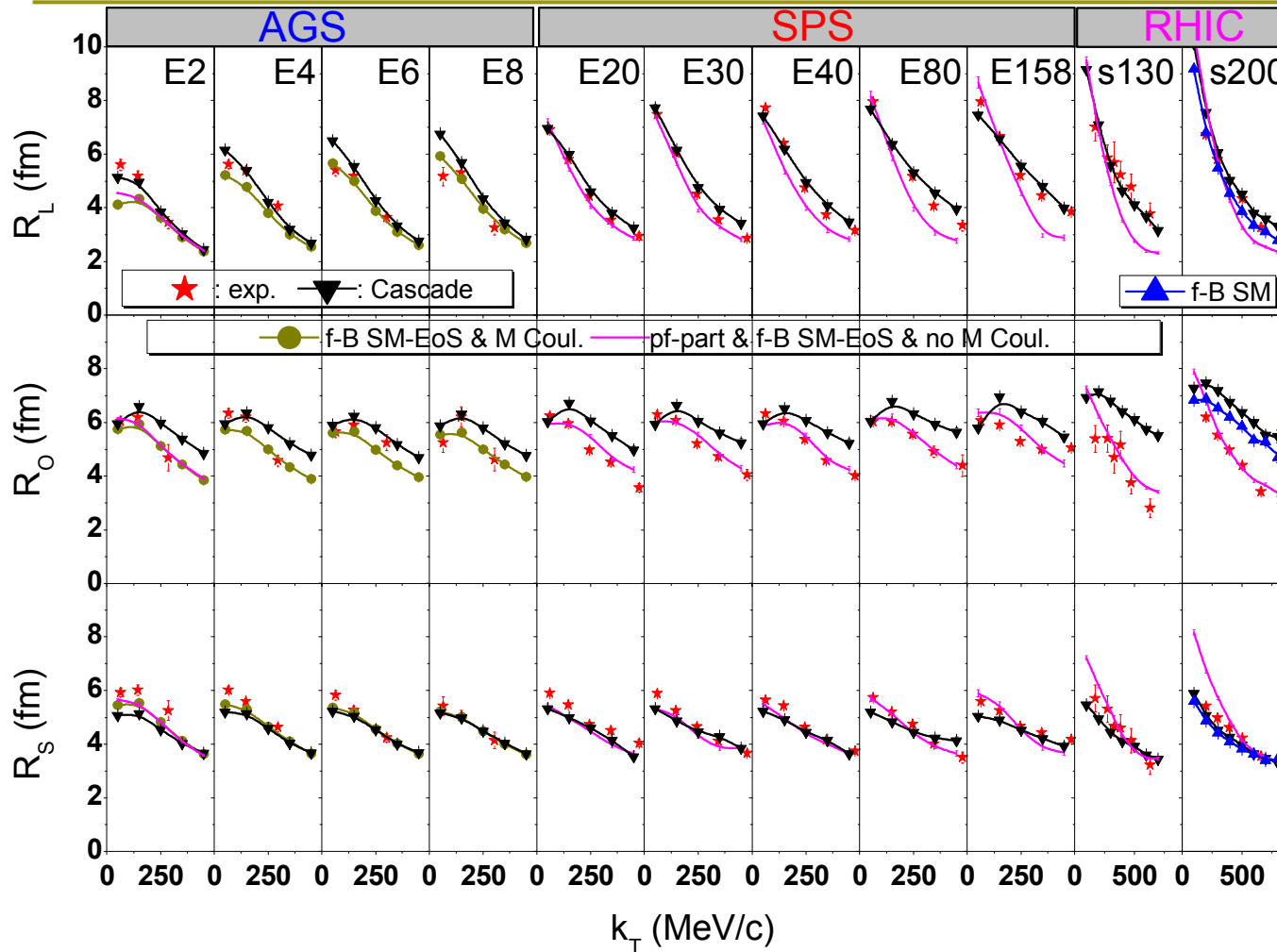
It can be studied more precisely with the imaging method by Danielewicz et al [PLB618,60(2005)]

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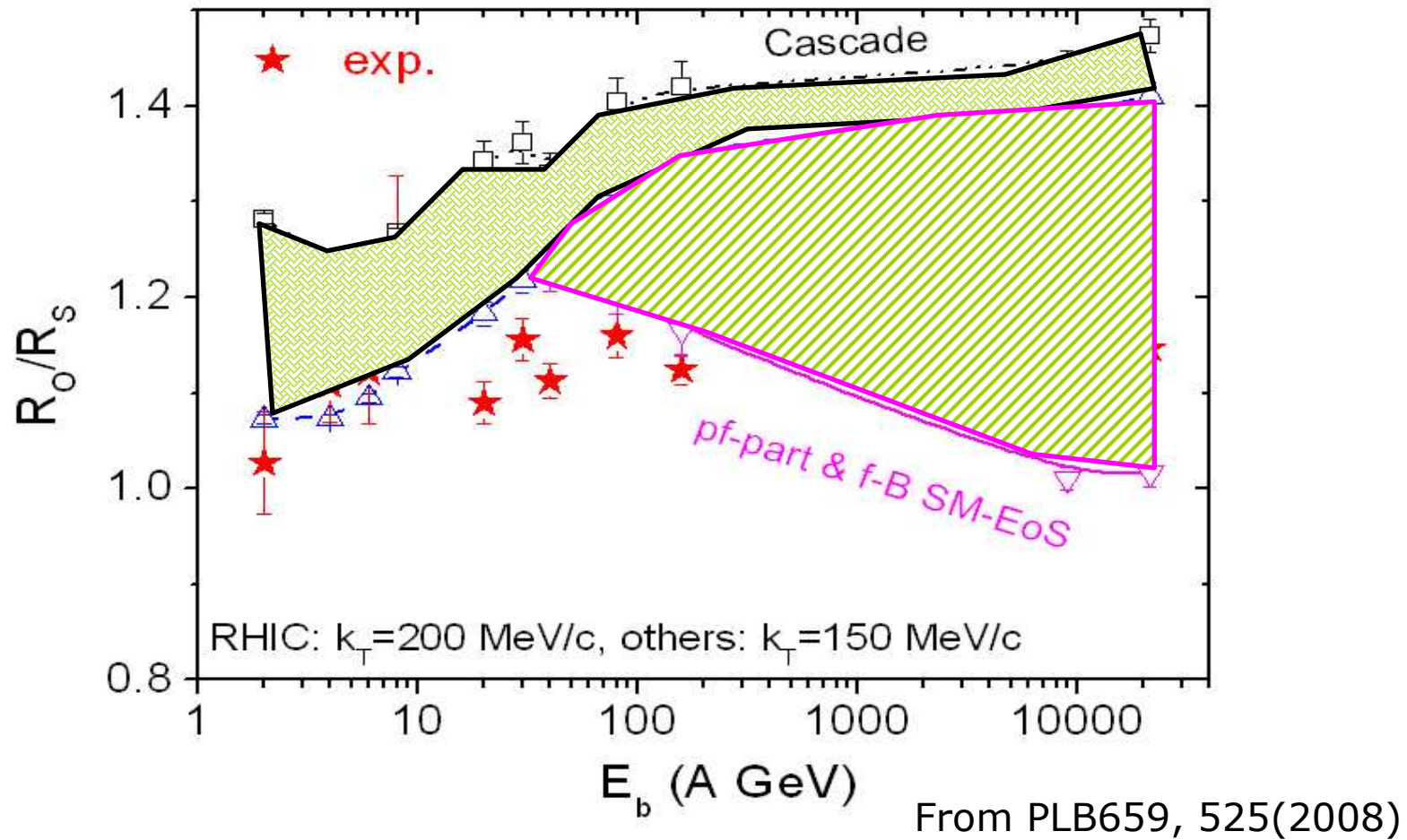


HBT radii from UrQMD



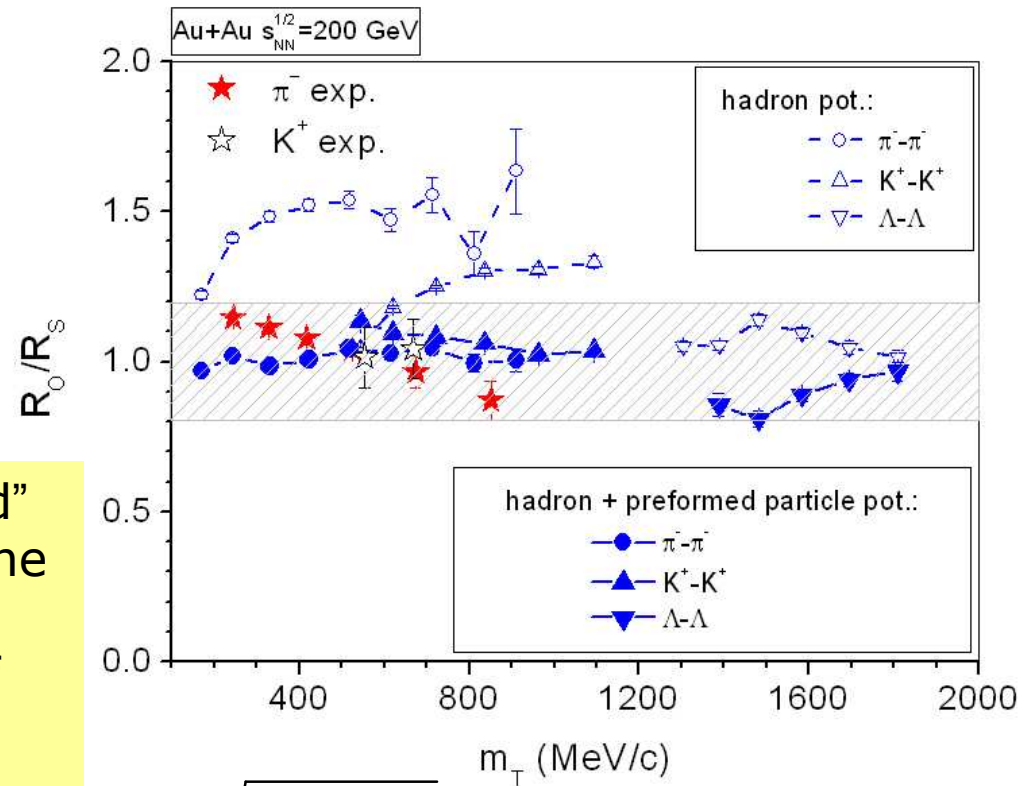
k_T -dep. radii: steeper
 R_O at large k_T : ↓
 R_S at small k_T : ↑

To solve the HBT t-puzzle



Not only for the π source...

The inclusion of “pre-formed” particle interactions cures the deviations and allows for a consistent understanding of the data.



$$m_T = \sqrt{m^2 + k_T^2}$$

From PLB663, 395(2008)

The marked area illustrates the uncertainties from non-Gaussian effect and corrections on FSI

Why so ?

Under the assumptions of thermalization and Gaussian-source shape, the HBT radii can be expressed analytically as

$$R_L^2 = \langle (\tilde{z} - \beta_L \tilde{t})^2 \rangle,$$

$$R_O^2 = \langle (\tilde{x} - \beta_T \tilde{t})^2 \rangle,$$

$$R_S^2 = \langle \tilde{y}^2 \rangle.$$

R_O term can be expanded as:

$$R_O^2 = \langle \tilde{x}^2 \rangle + \langle \beta_T^2 \tilde{t}^2 \rangle - 2 \langle \beta_T \tilde{x} \tilde{t} \rangle.$$

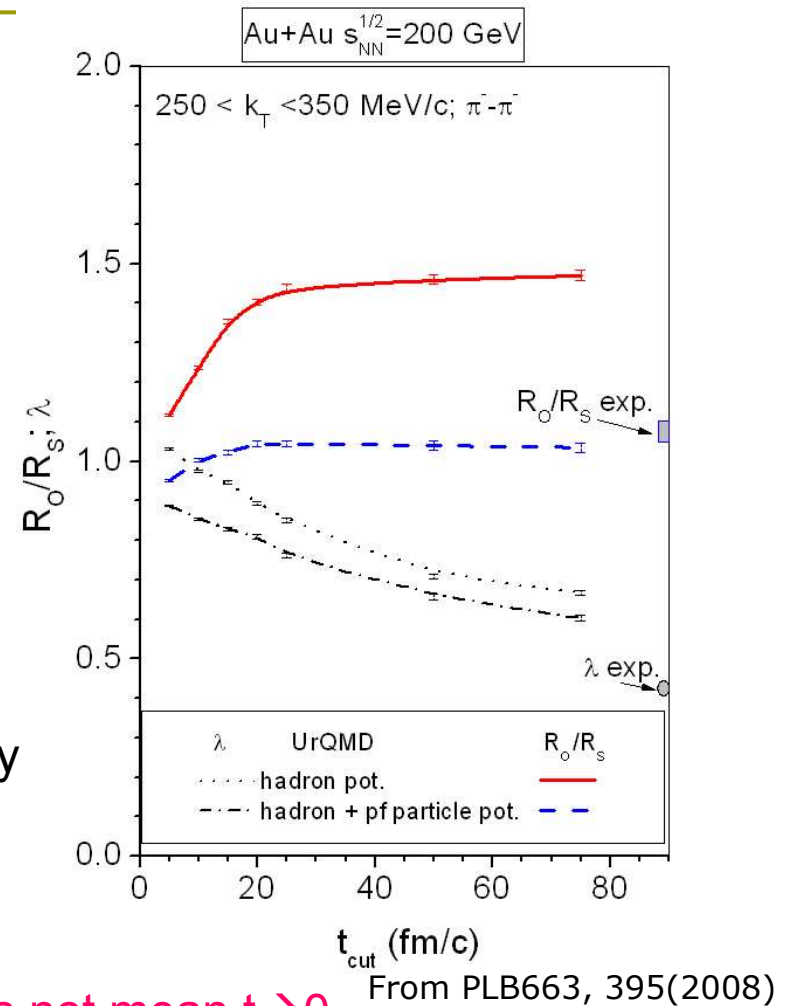
Due to the strong phase-correlation induced by the potentials, the term $-2 \langle \beta_T \tilde{x} \tilde{t} \rangle$ might be comparable to the term $\langle \beta_T^2 \tilde{t}^2 \rangle$.

An important consensus:

Due to the strong x-t correlation, $R_O/R_S \rightarrow 1$ does not mean $t \rightarrow 0$

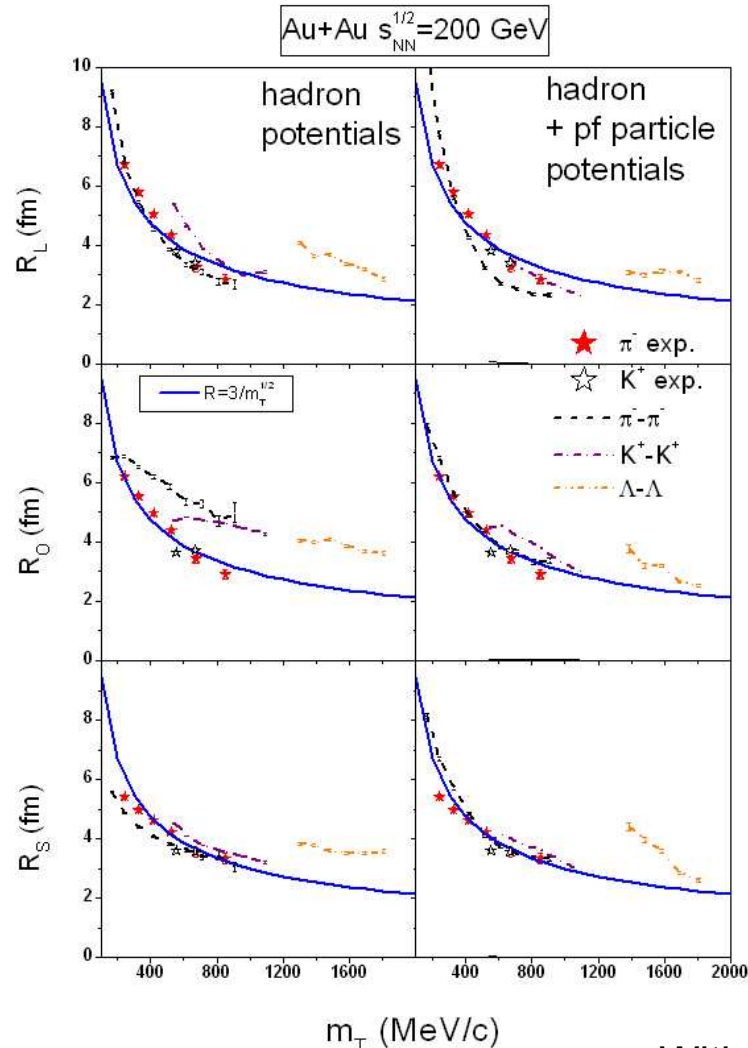
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Improvement to the m_T -scaling



Left Plots:

- Without “pre-formed” hadron potential:
 - R_L : of kaons and Lambdas: Large
 - R_O : of all particles : Large
 - R_S : of Lambdas : Large

Right Plots:

- With “pre-formed” Hadron potential:
 - R_L : of Kaons and Lambda: follow
 - R_O : of all particles : follow
 - R_S : of pions and Kaons : follow the m_T -scaling

T.Csorgo etc, PRC 54, 1390(1996)

From PLB663, 395(2008)
21.08.2008

Without the consideration of the FSI in hydro-dynamics
Qingfeng Li for ITP, Giessen

Conclusions

- ❑ The mean field is very important to HICs not only at low and intermediate energies but also at AGS, SPS, and RHIC energies.
- ❑ In order to pin down the incompressibility of the nuclear medium, a careful comparison of sensitive observables between model predictions and experimental data is a prerequisite.
- ❑ A more consistent version of UrQMD is urgently called for.



Thanks for discussion