INT program Interfaces between structure and reactions for rare isotopes and nuclear astrophysics

Seattle, August 8 - September 2, 2011

Exploring the isovector equation of state at high densities with HIC

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Outline

First questions to be answered:
Why is the Symmetry Energy so important?

- At *low densities*: Nuclear structure (neutron skins, pigmy resonances), Nuclear Reactions (neutron distillation in fragmentation, charge equilibration), and Astrophysics, (neutron star formation, and crust),
- At *high densities*: Relativistic Heavy ion collisions (isospin flows, particle production), Compact stars (neutron star structure), and for fundamental properties of strong interacting systems (transition to new phases of the matter).

Why HIC?

- Probing the in-medium nuclear interaction in regions away from saturation.
- Reaction observables sensitive to the symmetry term of the nuclear equation of state.
- High density symmetry term probed from isospin effects on heavy ion reactions at relativistic energies.

In this talk:

- HIC at intermediate energies $400AMeV$-$2AGeV$.
- Investigation of particle ratios: Probes for the symmetry energy density dependence. In-medium effects in inelastic cross sections & Kaon potential choices.

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Equation of State (EOS)

The nuclear matter thermodynamical properties are described by an equation of state.

The nuclear EOS gives the **binding energy E/A** or the **pressure P** of the system per nucleon, as a function of the **baryon density** or the **temperature**.

$$E(\rho, T) = E_{th}(\rho, T) + E_c(\rho, T = 0) + E_0$$

$E_{th}(\rho, T)$: thermic energy, consists of a kinetic and a dynamic term.
$E_c(\rho, T = 0)$: compression energy at $T = 0$.
E_0: binding energy at $T = 0$ and ρ_0.

Incompressibility: $K = 9\rho_0^2(\frac{\partial^2 E}{\partial \rho_B^2})|_{\rho_B=\rho_0}$

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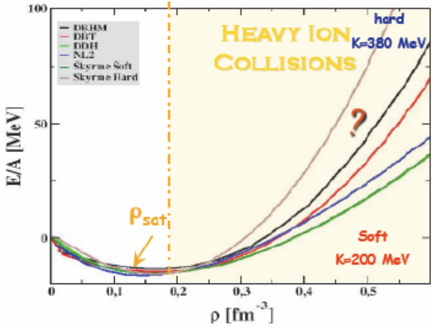

At ρ_{sat}: well defined by studies on stable nuclei.

High ρ_B: is predicted by the theoretical models and is adjusted to fit the HIC data.

Constraints from HIC:
Multiplicities and Flows of n and p .

Symmetry Energy

The EOS depends on the asymmetry parameter $\alpha = \frac{N-Z}{N+Z}$:

$$E(\rho_B, \alpha) \equiv \frac{\epsilon(\rho_B, \alpha)}{\rho_B} = E(\rho_B, 0) + E_{sym}(\rho_B)\alpha^2$$

Thus, it gives a definition of the symmetry energy:

$$E_{sym} \equiv \frac{1}{2}\frac{\partial^2 E(\rho_B, \alpha)}{\partial \alpha^2}|_{\alpha=0} = \frac{1}{2}\rho_B \frac{\partial^2 \epsilon}{\partial \rho_{B3}^2}|_{\rho_{B3}=0}$$

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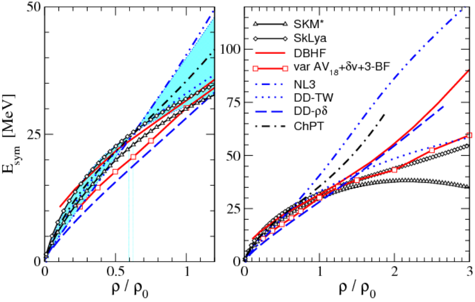
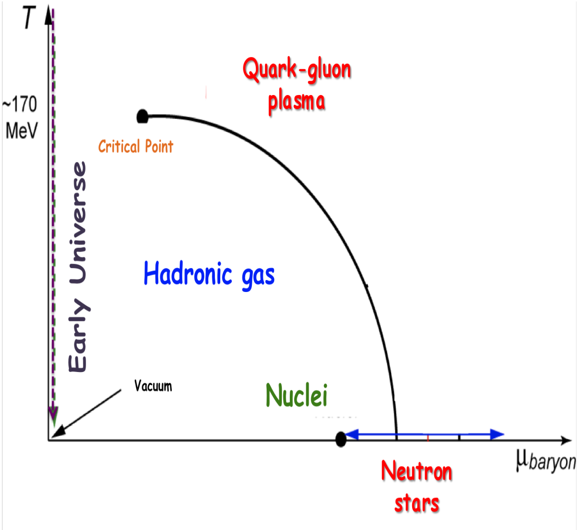
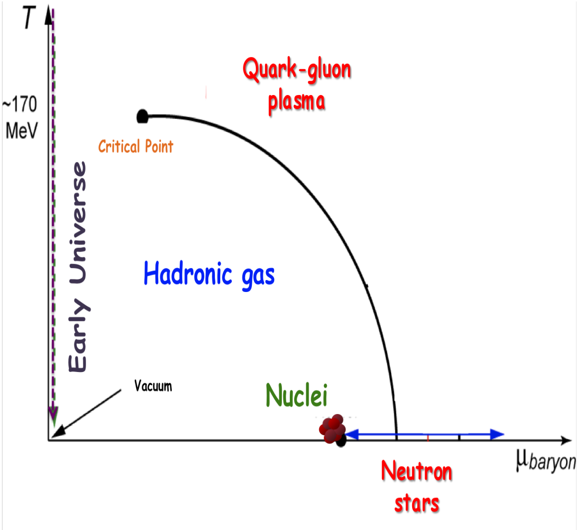


Different behavior even at saturation point.

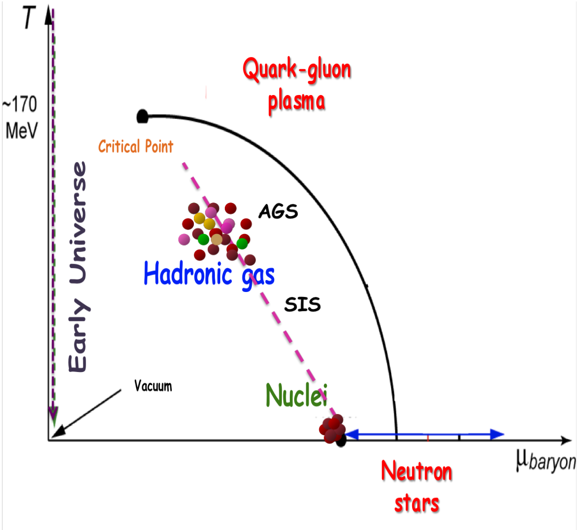
High ρ_B, discrepancies between the models increases.

Constraints from HIC:
Multiplicities and Differential flows of n and p.
Pion flows and **Isospin ratios** π^-/π^+, K^0/K^+ .

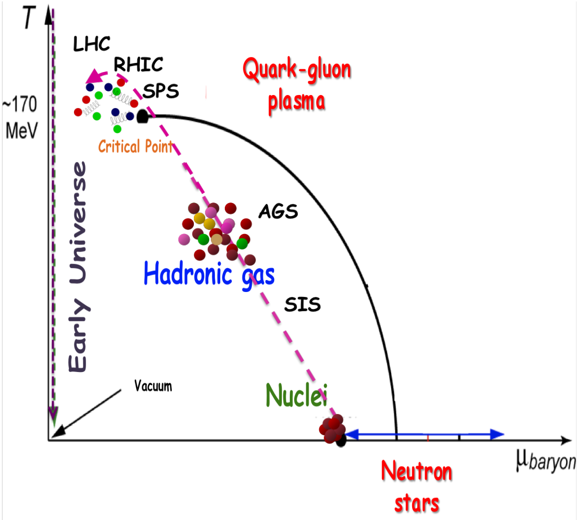

T
~170
MeV
Quark-gluon
plasma
Critical Point
Early Universe
Hadronic gas
Vacuum
Nuclei
Neutron
stars
μbaryon



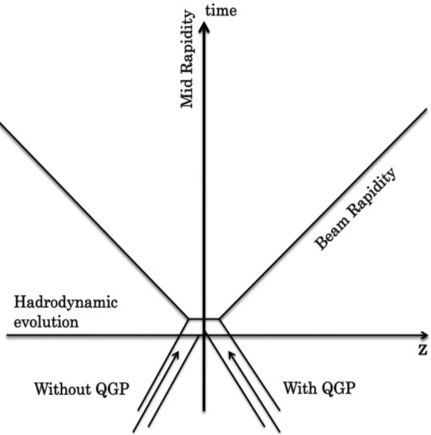
- **Liquid phase:**
  $T \approx 10 MeV$.

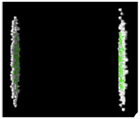


- **Gas phase:** RHIC
  $T \approx 10 - 100 MeV$.
- **Liquid phase:**
  $T \approx 10 MeV$.

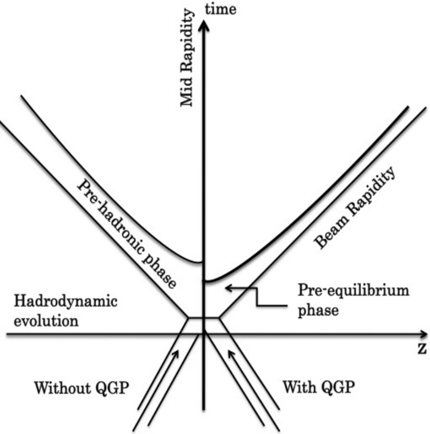


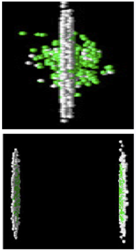
- **Quark-gluon plasma:** Ultra RHIC $T > 100 MeV$
- **Gas phase:** RHIC $T \approx 10 - 100 MeV$.
- **Liquid phase:** $T \approx 10 MeV$.





- **Initial stage.** Nuclei at ground state. $P = 0$, $T = 0, \rho = \rho_0$.





- **Compression.** Sequential N-N binary collisions. Incoming matter of the target & the projectile is **mixed** & **compressed** forming a short-lived stage of nuclear matter of high ρ_B that depends on the EOS. $E = 1AGeV$, $T \approx 30 - 60MeV$, $\rho_B \approx 2 - 3\rho_0$.
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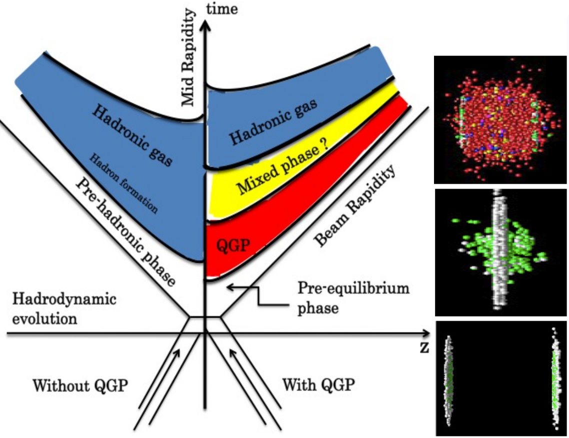

- **Expansion.** Expansion of the density energy. $T, \rho \Downarrow$. Hot matter interacts with the cold matter of the spectator. $E_{beam} > 10AGeV \Rightarrow QGP_{limit}$, P lower than $P_{hadronic \quad phase}$.
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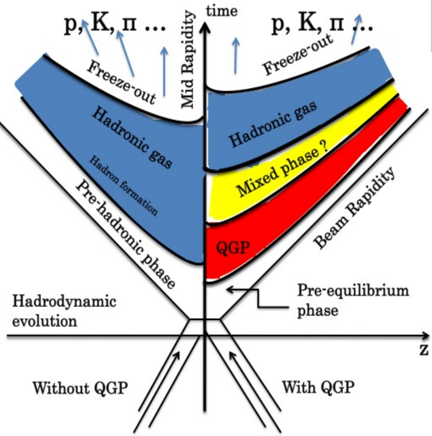

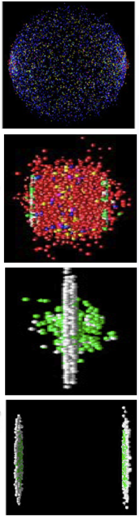

- **Freeze-out.** Low $\rho_B \Rightarrow$ no further interaction.
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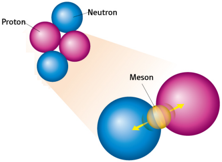

The NN Interaction is described by the exchange of **mesons**.
SCALAR (attraction): σ, δ (isospin dependence).
VECTOR (repulsion): ω, ρ (isospin dependence).

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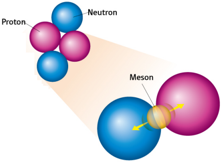


Lagrangian density

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi + \frac{1}{2}\partial_{\mu}\sigma\partial^{\mu}\sigma - U(\sigma) + \frac{1}{2}m_{\omega}^2\omega_{\mu}\omega^{\mu} - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu}$$
$$+ \frac{1}{2}m_{\rho}^2\vec{\rho}_{\mu}\cdot\vec{\rho^{\mu}} - \frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}(\partial_{\mu}\vec{\delta}\cdot\partial^{\mu}\vec{\delta} - m_{\delta}^2\vec{\delta}^2)$$
$$+ \bar{\psi}(-g_{\omega}\omega_{\mu} - g_{\rho}\gamma\vec{\tau}\cdot\vec{\rho}_{\mu} + g_{\sigma}\sigma + g_{\delta}\vec{\tau}\cdot\vec{\delta})\psi$$

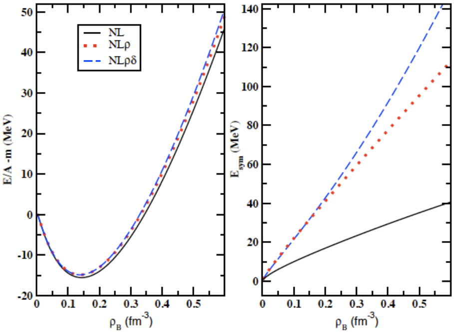
Lagrangian density of: the **free nucleons**, the σ **meson** with $U(\sigma) = \frac{1}{2}m_{\sigma}^2\sigma^2 + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4$, the ω **meson** with the field tensor $\Omega_{\mu\nu} \equiv \partial_{\mu}\omega_{\nu} - \partial_{\nu}\omega_{\mu}$, the ρ **meson** with the field tensor $\vec{R}_{\mu\nu} \equiv \partial_{\mu}\vec{\rho_{\nu}} - \partial_{\nu}\vec{\rho_{\mu}}$, the δ **meson** and of their **interaction**.

The *nuclear EOS* for asymmetric nuclear matter in the QHD picture:

$$\mathcal{E} = \sum_{i=n,p} 2 \int \frac{\mathrm{d}^3 k}{(2\pi)^3} E_i^\star(k) + U(\Phi) + \frac{1}{2} f_V \rho_B^2 + \frac{1}{2} f_\rho \rho_{B3}^2 + \frac{1}{2} f_\delta \rho_{S3}^2$$

The nuclear *Symmetry energy* in the QHD picture :

$$E_{sym} = \frac{1}{6} \frac{k_F^2}{E_F^*} + \frac{1}{2} \left[f_\rho - f_\delta \left(\frac{m^*}{E_F^*} \right)^2 \right] \rho_B$$



Relativistic transport equation

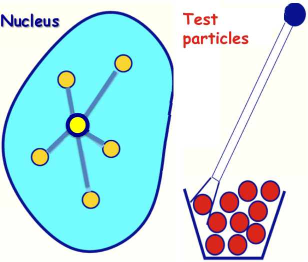
Relativistic Boltzmann-Uehling-Uhlenbeck (RBUU)

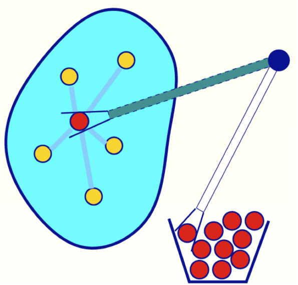
$$[p^*_{\mu i}\partial^\mu_x + \left(g_\omega p^*_{\nu i} F^{\mu\nu}_i + m^*_i (\partial^\mu_x m^*_i)\right)\partial^{p^*}_\mu] f_i(x,p^*) =$$
$$\frac{g}{(2\pi)^3}\int \frac{d^3p_2^*}{p_2^{*0}}\frac{d^3p_3^*}{p_3^{*0}}\frac{d^3p_4^*}{p_4^{*0}} W(p^*,p_2^*,p_3^*,p_4^*)$$
$$\{f_3 f_4[1-f][1-f_2] - f f_2[1-f_3][1-f_4]\}$$

- **Vlasov term**. Temporal evolution of the system, which is described by the phase-space distribution function $f(x,p^*)$, under the influence of a mean field (m_i^*, p_i^*).
- **Collision term.** Transition rate W, is expressed by the differential cross section $\left(\frac{d\sigma}{d\Omega(s,\Theta)}\right)$,

$$W(p^*,p_2^*,p_3^*,p_4^*) = (p^*+p_2^*)^2\frac{d\sigma}{d\Omega}\delta^4(p^*+p_2^*-p_3^*-p_4^*)$$

where Θ is the scattering angle in the cms frame and s the square of the total energy, $s=(p^*+p_2^*)^2$.





Test particle method

Representation of the phase-space distribution function by a number of test particles.

Gaussian test particles

$$g\left(p^* - p_i^*(\tau)\right) = \alpha_p \; e^{(p^* - p_i^*(\tau))^2/\sigma_p^2} \delta\left[p^*_\mu p_i^{*\mu}(\tau) - m_i^{*2}\right]$$

Distribution function

$$f(x, p^*) = \frac{1}{N(\pi\sigma\sigma_p)} \sum_{i=1}^{A\cdot N} \int_{-\infty}^{+\infty} d\tau \; e^{R_{i\mu}(x) R_i^\mu(x)/\sigma^2} e^{(p^* - p_i^*(\tau))^2/\sigma_p^2} \times \delta[(x_\mu - x_{i\mu}(\tau)) u_i^\mu(\tau)] \delta\left[p^*_\mu p_i^{*\mu}(\tau) - m_i^{*2}\right]$$

Test particles equations of motions

$$\frac{d}{d\tau} x_i^\mu = \frac{p_i^*(\tau)}{m_i^*(x_i)},$$

$$\frac{d}{d\tau} p_i^{*\mu} = \frac{p_{i\nu}^*(\tau)}{m_i^*(x_i)} F_i^{\mu\nu}\left(x_i(\tau)\right) + \partial^\mu m_i^*(x_i)$$

Collision term

$$\mathcal{I}_c = \frac{g}{(2\pi)^3}\int \frac{d^3p_2^*}{p_2^{*0}}\frac{d^3p_3^*}{p_3^{*0}}\frac{d^3p_4^*}{p_4^{*0}} W(p^*, p_2^*, p_3^*, p_4^*)$$
$$\{f(x,p_3^*)f(x,p_4^*)[1-f(x,p^*)][1-f(x,p_2^*)] -$$
$$f(x,p^*)f(x,p_2^*)[1-f(x,p_3^*)][1-f(x,p_4^*)]\}$$

- Factors $(1-f_i)$, $(f_i = f(x,p_i^*))$, Pauli principle.
- **Transition rate**: $W = (2\pi)^4\delta^4(k+k_2-k_3-k_4)(m^*)^4|T|^2$.
- Two particles collide if: $d < d_0 = \sqrt{\frac{\sigma_{tot}}{\pi}}$.

Elastic channels

1. $NN \Longleftrightarrow NN$
2. $N\Delta \Longleftrightarrow N\Delta$
3. $\Delta\Delta \Longleftrightarrow \Delta\Delta$

Inelastic channels

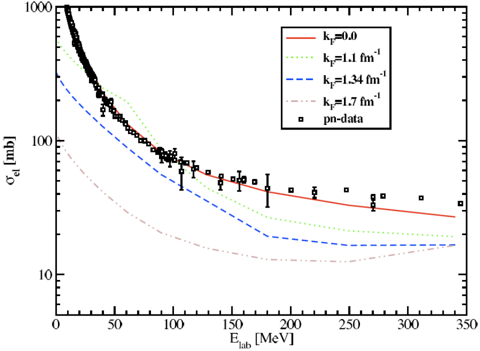
Ingoing channel	Outgoing Channel	Isospin coefficients
nn	$p\Delta^-$	1
	$n\Delta^0$	2/3
np	$p\Delta^0$	1/3
	$n\Delta^+$	2/3
pp	$p\Delta^+$	1/3
	$n\Delta^{++}$	1

Decay width:

$$\Gamma(q) = \tilde{\Gamma}\,\frac{q^3R^2}{1+q^2R^2}\,z(q), \quad z(q) = \frac{q_r^2+\delta^2}{q^2+\delta^2}$$

Resonance decay probability P,

$$P = 1 - \exp\left[-\frac{\Gamma(M)\Delta t}{\gamma\hbar c}\right]$$



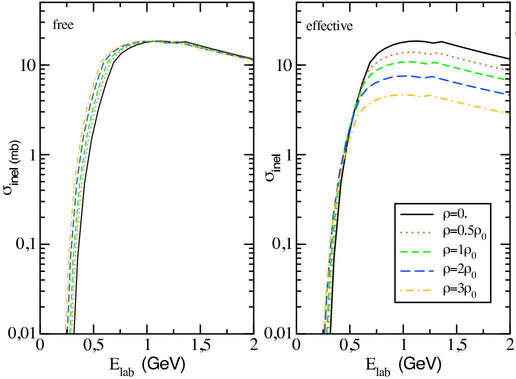
Elastic Baryon-Baryon collisions

In-medium effects: Dirac-Brueckner.

Suppression of cross sections at $E_{beam} < 300 AMeV$ and high ρ_B.

At high $E_{\rm lab}$, the σ_{eff} approaches asymptotically σ_{free}

Fuchs et al. Phys. Rev. C64 (2001), 024003.



Inelastic Baryon-Baryon collisions

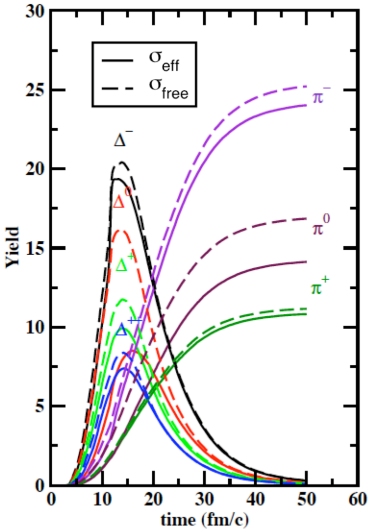
In-medium effects: DBHF.
Ter Haar and Malfliet, Phys.Rev.C36, 4 (1987)

$$\sigma^{inel}_{eff} = f(\rho)\sigma^{inel}_{free}(E_{\rm lab})$$

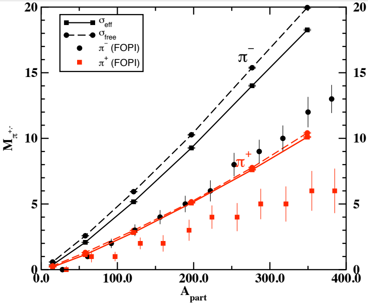
$f(\rho) = 1 + a_0(\rho_B/\rho_0) + a_1(\rho_B/\rho_0)^2 + a_2(\rho_B/\rho_0)^3$.

Inverse channel:

$$\sigma_{N\Delta\to NN} = \frac{(2S_N+1)(2S_N+1)}{(2S_N+1)(2S_\Delta+1)}\frac{q_f^2}{q_i^2}\sigma_{NN\to N\Delta}.$$



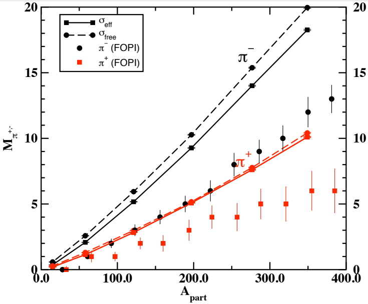
State	I_3	Decay channel	Weights
Δ^-	$-3/2$	$n\pi^-$	1
Δ^0	$-1/2$	$p\pi^-$	1/3
		$n\pi^0$	2/3
Δ^+	$+1/2$	$p\ \pi^0$	2/3
		$n\ \pi^+$	1/3
Δ^{++}	$+3/2$	$p\ \pi^+$	1



Centrality dependence

$Au + Au$ collision at $1AGeV$.
A_{part}: number of participants in a collision.

Overestimation of data.



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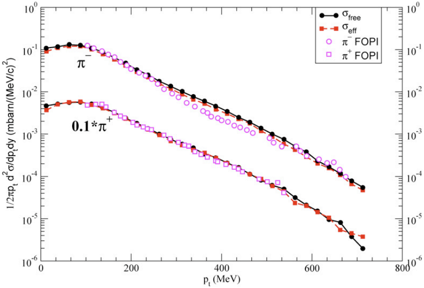


Transverse momentum spectra

$Au + Au$ collision at $1AGeV$, at mid-rapidity ($-0.2 < y^0 < 0.2$).

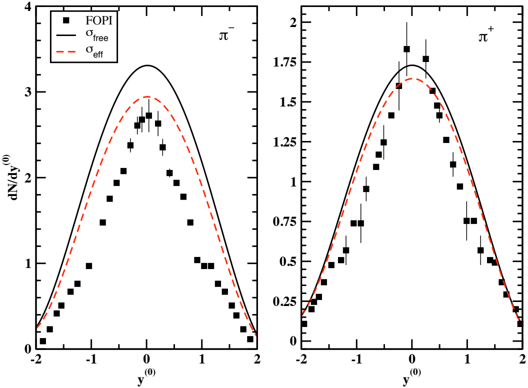
Very good agreement with data.

Pion rapidity distribution

$Au + Au$ collision at $E_{\text{beam}} = 1\ AGeV$, with $p_t > 0.1\ GeV/c$.

Mid rapidity region: good agreement.

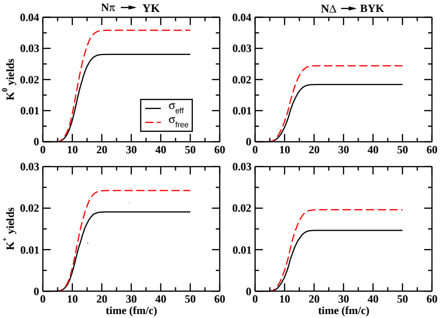
Spectator region: overestimation.



Kaon production

1. $\pi B \longrightarrow YK$
2. $BB \longrightarrow BYK$

$Au + Au$ central collision at $1AGeV$.



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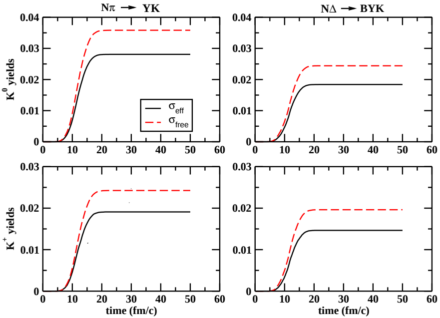
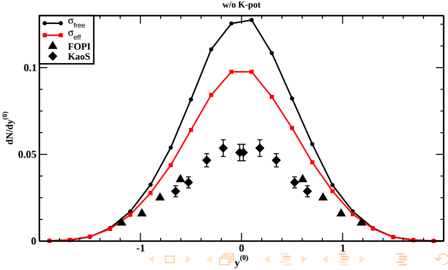


Rapidity distribution of K^+

$Ni + Ni$ collision at $1.93AGeV$.

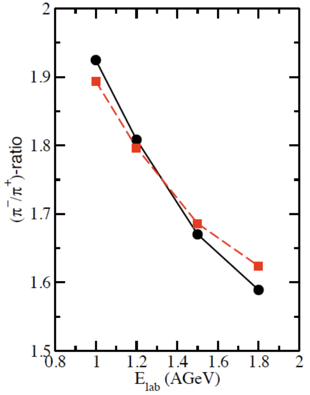
σ_{eff}: **reduction of $K^+ \Longrightarrow$ towards a better agreement with data.**

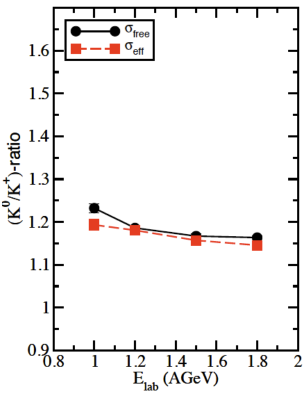


Yield ratios: **Determination** of the E_{sym} behavior.

π^-/π^+: partially affected from the in-medium cross sections.
K^0/K^+: appears **robust** against the in-medium cross sections.

V. Prassa et al, Nucl.Phys. A789, 311-333 (2007)





Kaons equation of motion

$$\left[(\partial^\mu + iV_\mu)^2 + m_K^{*2}\right]\phi_K(x) = 0$$

Kaon in-medium energy

$$E_K(\mathbf{k}) = k_0 = \sqrt{\mathbf{k}^2 + m_K^{*2}} + V_0$$

Chiral perturbation theory potential

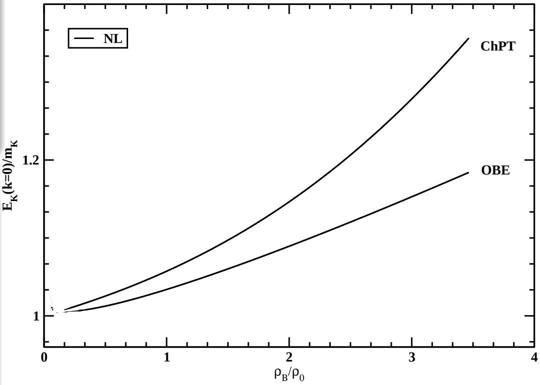
$$V_\mu = \frac{3}{8f_\pi^{*2}} j_\mu$$

$$m_K^* = \sqrt{m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2}\rho_s + V_\mu V^\mu}$$

One boson exchange model potential

$$V^\mu = \frac{1}{3} f_\omega^* j^\mu$$

$$m_K^* = \sqrt{m_K^2 + \frac{m_K}{3} g_{\sigma N}\sigma}$$



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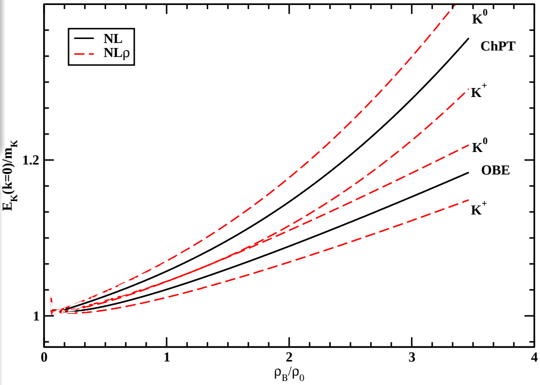
upper sign K^+



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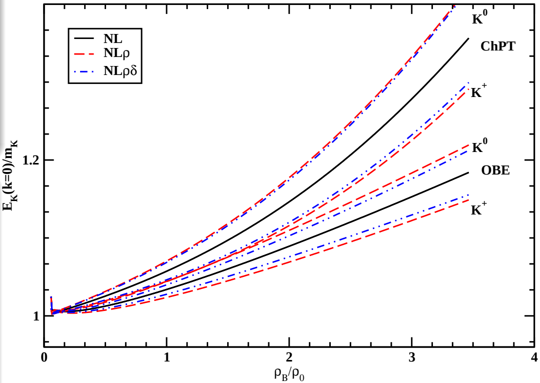
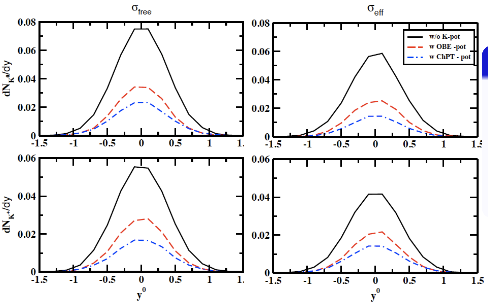
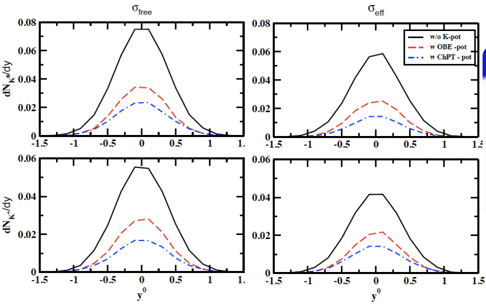




Rapidity distribution: Dependence on the V_K

Central $Au + Au@1AGeV$.
Reduction in the whole rapidity region.
OBE: *less stopping*.

Combination of V_K and σ_{eff}: further reduction.



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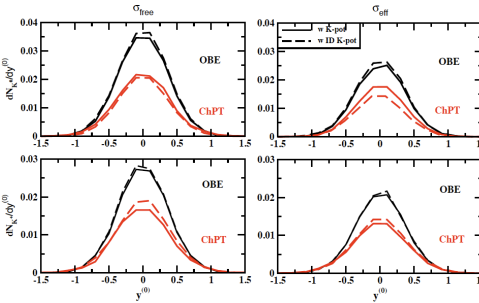
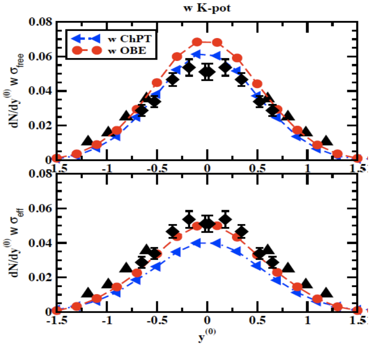


Rapidity distribution: Isospin dependent-V_K

Central $Au + Au@1AGeV$.

Rapidity distributions *not* affected.
Main contribution: *mid-rapidity* region.

Combination V_K and σ_{eff}: further reduction.



Rapidity distributions of K^+

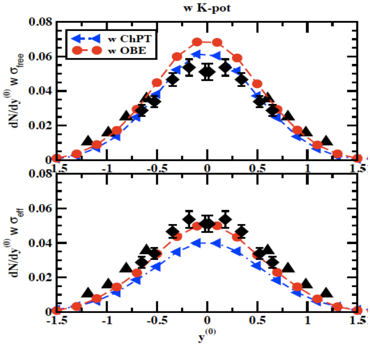
$Ni + Ni@1.93AGeV \;\; b < 4fm.$

ChPT: σ_{free} good agreement with exp. data.

σ_{eff}: underestimation of the exp. data.

OBE: σ_{free} good agreement with exp. data.

σ_{eff}: on the exp. data.



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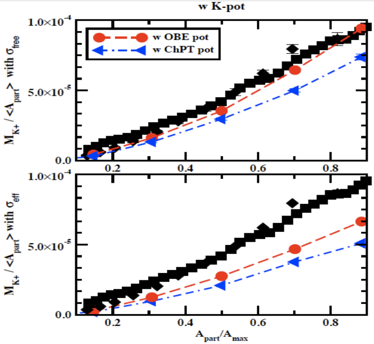


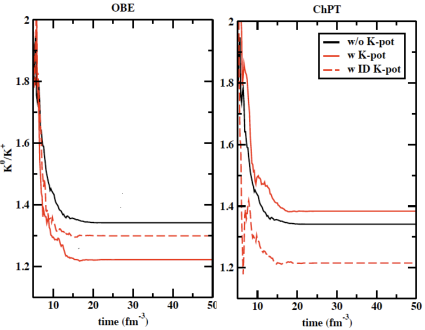
Centrality dependence K^+

$Au + Au@1AGeV$ collision.

Underestimation of the experimental data.

OBE: closer to the exp.data.

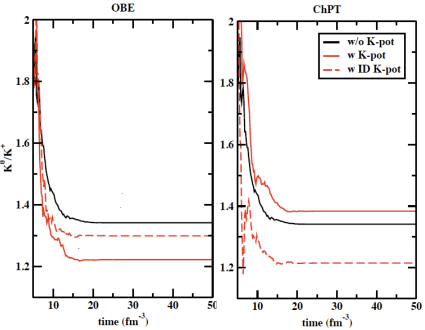
V. Prassa et al, Nucl.Phys. **A832** *88-99 (2010)*



Temporal evolution of K^0/K^+

Central $Au + Au@1AGeV$.
OBE: reduction K^0/K^+. Favors K^+ production.
ChPT: raise. Favors K^0 production.

IOBE: raise K^0/K^+.
IChPT: sharp drop.



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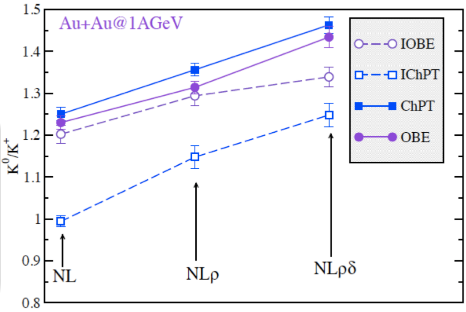
K^0/K^+ dependence on the EOS

Central $Au + Au@1AGeV$.

IChPT: reduction $\approx 20\%$.

IOBE: $NL\rho \approx 3\%$, while $NL\rho\delta \approx 5\%$.



Summary

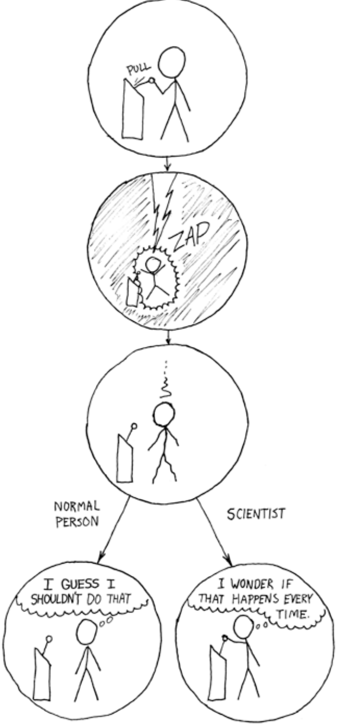
- **Effective N-N cross sections**:

  Dirac Brueckner Hartree Fock.
  - Pions: reduction of production. At mid-rapidity good agreement with the data.
  - π^-/π^+: depends on the effective inelastic cross sections.
  - Kaons: more affected ($\approx 30\%$).
  - K^0/K^+ almost unchanged (large mean free path).
- **Kaon-nucleon potential**
  1. Chiral Perturbation Theory, ChPT.
  2. One-Boson-Exchange, OBE.
     - Reduction of kaon production.
     - Good agreement with the data (particularly with OBE).
     - ChPT: K^0/K^+ depends on the parametrization of the EOS.
     - OBE: K^0/K^+ more robust against the EOS parametrization.

Outlook

- Inclusion of momentum dependence.

  T. Gaitanos, et al. Nucl.Phys. A828, 9-28 (2009).
- Improvement of NN-interactions.



THANK YOU FOR YOUR ATTENTION

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