pBUU Description

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Transport 2017: International Workshop
on Transport Simulations for Heavy Ion Collisions
under Controlled Conditions

FRIB-MSU, East Lansing, Michigan, March 27 - 30, 2017

pBUU Features

- Solution of Boltzmann Eq
- 1-Ptcle Energies from Energy Functional
  - Volume (incl Momentum), Gradient, Isospin, Coulomb Terms
- Covariance
  - Covariant: Volume (incl Momentum) Term in Energy, Collisions
  - Noncovariant: Gradient, Isospin, Coulomb Terms in Energy
  - Employed (so far) up to 20 GeV/nucl
- Pions contribute to Symmetry Energy
- Spectral functions of Δ and N^* Resonances in adiabatic approximation
  - Detailed Balance for Broad Resonances
- $A = 2, 3$ Clusters produced in Multinucleon Collisions
  - Cluster Break-Up Data used in describing Production

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pBUU - Technical Aspects

- Initial State from Solving Thomas-Fermi Eqs
- Wigner Functions represented in term of Test Particles
- Lattice Hamiltonian (Lenk & Pandharipande)
  - Profile Functions associated with Lattice Nodes
  - Test-Particle Eqs of Motion from the Lattice Hamiltonian
  - Values of Hamiltonian and Net Momentum Conserved
- Collisions, including Multiparticle, between *Any* Test-Particles within Spatial Cell
- Computational Speed Enhanced processing only Collision No that may be occur within Time-Step
- Occupations f/Pauli Principle: (a) smoothing Test-Particles, *in space but not momentum*, w/same Profile Functions as f/Lattice Hamiltonian, or (b) fitting deformed local Fermi-D
- Coulomb Potential through Relaxation-Method Solution of Poisson Eq

Literature: NPA533(91)712, NPA673(00)375

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Boltzmann Equation

Reaction simulated in terms of a set of semi-phenomenological Boltzmann equations for phase-space distributions f of Ns, πs, Δs, N^*s, ds. . . :

$$\boxed{\frac{\partial f}{\partial t} + \frac{\partial \epsilon_{\mathbf{p}}}{\partial \mathbf{p}} \frac{\partial f}{\partial \mathbf{r}} - \frac{\partial \epsilon_{\mathbf{p}}}{\partial \mathbf{r}} \frac{\partial f}{\partial \mathbf{p}} = I}$$

where the single-particle energies ϵ are given in terms of the net energy functional $E\{f\}$ by,

$$\boxed{\epsilon(\mathbf{p}) = \frac{\delta E}{\delta f(\mathbf{p})}}$$

In the local cm, the mean potential is $U_{opt} = \epsilon - \epsilon_{kin}$ and $\epsilon_{kin} = \sqrt{p^2 + m^2}$.

Energy Functional

The functional: $$\boxed{E = E_{vol} + E_{gr} + E_{iso} + E_{Coul}}$$

where $$E_{gr} = \frac{a_{gr}}{\rho_0} \int d\mathbf{r} \, (\nabla \rho)^2$$

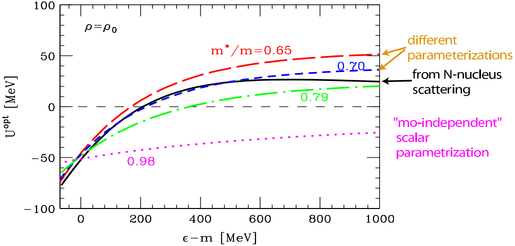
For covariant volume term, ptcle velocities parameterized in local frame:
$$v^*(p, \rho) = \frac{p}{\sqrt{p^2 + m^2 \Big/ \left(1 + c \, \frac{\rho}{\rho_0} \, \frac{1}{(1+\lambda \, p^2/m^2)^2}\right)^2}}$$

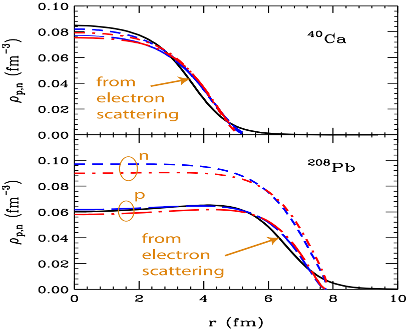
precluding a supraluminal behavior (PD *et al* PRL81(98)2438), with ρ - baryon density. The 1-ptcle energies are then
$$\epsilon(p, \rho) = m + \int_0^p dp' \, v^* + \Delta\epsilon(\rho)$$

Parameters in the velocity varied to yield different optical potentials characterized by values of effective mass, $m^* = p_F/v_F$.

Structure Interface

Potential from p-scattering (Hama *et al* PRC41(90)2737) & parameterizations





Ground-state densities from electron scattering and from functional minimization.
From $E(f) = min$:

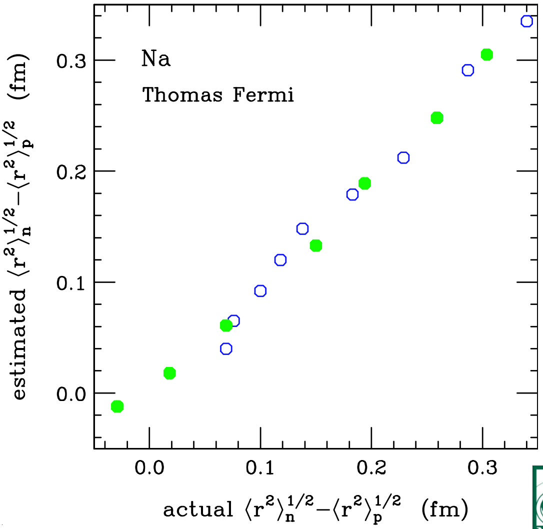
$$0 = \epsilon\left(p^F(\rho)\right) - 2\,a_{gr}\,\nabla^2\left(\frac{\rho}{\rho_0}\right) - \mu$$

$\Rightarrow$ Thomas-Fermi eq.

Finer Details of Thomas-Fermi Solutions

Neutron skin:

macroscopic theory vs Thomas-Fermi w/sym energy variation



Practical Aspects of Dynamics

Pseudoparticle representation for the phase-space distribution

$$f(\mathbf{r},\mathbf{p},t) = \frac{1}{\mathcal{N}} \sum_{i=1}^{A\cdot\mathcal{N}} \delta(\mathbf{r}-\mathbf{r}_i(t))\,\delta(\mathbf{p}-\mathbf{p}_i(t))$$

Space divided in cells of volume ΔV. Lattice hamiltonian (Lenk&Pandharipande PRC39(89)2242) from energy densities at cell nodes μ

$$E = \Delta V \sum_{\nu} e_{\mu}\{f_{\mu}\}$$

where e is energy density and

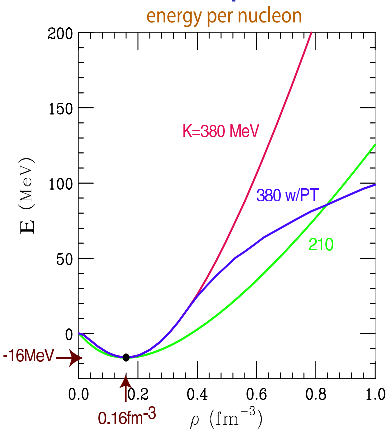
$$f_{\nu} = \frac{1}{\mathcal{N}} \sum_{i} S(\mathbf{r}_{\nu}-\mathbf{r}_i)\,\delta(\mathbf{p}-\mathbf{p}_i(t))$$

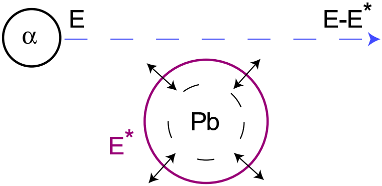
S localized profile function and

$$\dot{\mathbf{r}}_i(t) = \frac{\partial E}{\partial \mathbf{p}_i} \qquad \dot{\mathbf{p}}_i(t) = -\frac{\partial E}{\partial \mathbf{r}_i}$$

integrate the l.h.s. of the Boltzmann eq. (Vlasov).

Incompressibility from Vibrations?





$$E^* = \hbar\Omega = \hbar\sqrt{\frac{K}{m_N\,\langle r^2\rangle_A}}$$

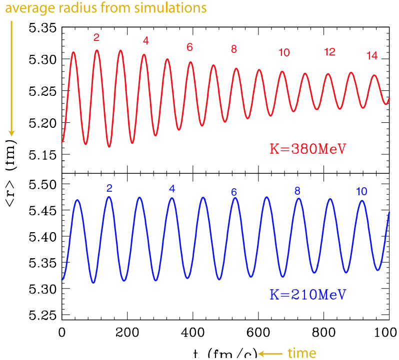
Problem: surface, Coulomb, isospin imbalance

$\Rightarrow$ all that in Boltzmann eq.

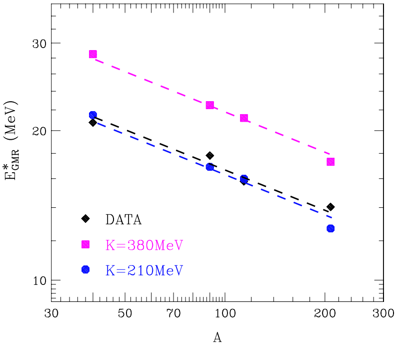
$$K = 9\,\rho_0^2\,\frac{d^2}{d\rho^2}\left(\frac{E}{A}\right) = R^2\,\frac{d^2}{dR^2}\left(\frac{E}{A}\right)$$

Monopole Oscillations

Pb Oscillations



$$E^*_{GMR} = \hbar\Omega$$



data Youngblood, Garg *et al.*

$$\Rightarrow \quad K = (225 - 240)\,\text{MeV}$$

Collision Rates

Collision rate incorporates effects of interactions of different particle numbers:

$$I = I_2 + I_3 + \dots$$

2-body collision rate

$$I_2 = \int |\mathcal{M}_{12\to\dots}|^2 \, \delta(\mathbf{P}' - \mathbf{P}) \, \delta(E' - E) \, f_1 \, f_2 \, (1 - f_1') \cdots$$

3-body collision rate

$$I_3 = \int |\mathcal{M}_{123\to\dots}|^2 \, \delta(\mathbf{P}' - \mathbf{P}) \, \delta(E' - E) \, f_1 \, f_2 \, f_3 \cdots$$

3 nucleons required to form a deuteron, 4 nucleons to form a triton ...

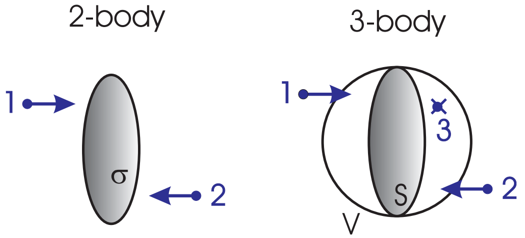
3-Body Collisions

Net 2-body collision rate:

$$\int \mathrm{d}P_f \, |\mathcal{M}_{12\rightarrow\ldots}|^2 \, \delta(\mathbf{P}' - \mathbf{P}) \, \delta(E' - E) = \sigma_{12} \, v_{12}$$

Net 3-body collision rate:

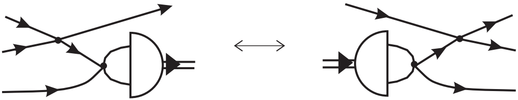
$$\int \mathrm{d}P_f \, |\mathcal{M}_{123\rightarrow\ldots}|^2 \, \delta(\mathbf{P}' - \mathbf{P}) \, \delta(E' - E) = \mathcal{V} \, \mathcal{S} \, v = \mathcal{V}_3 \, \sigma_{12} \, v_{12}$$



Deuteron Production

Detailed balance:

$$\overline{|\mathcal{M}^{npN\to Nd}|^2} = \overline{|\mathcal{M}^{Nd\to Nnp}|^2} \propto \mathrm{d}\sigma^{Nd\to Nnp}$$



Thus, production can be described in terms of breakup.

$$\mathrm{d}\sigma^{Nd\to Nnp} \propto \sigma_{np}\,|\phi_d(p)|^2 \propto \sigma_{np}\,\mathcal{V}_N$$

Modified impulse approximation employed.

(PD&Bertsch NPA533(91)712)

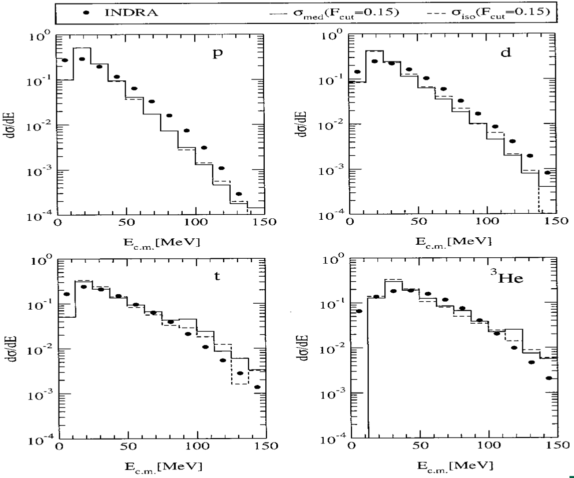
Tritons and helions produced in a similar manner in 4-nucleon collisions.

Low-Energy Comparison to INDRA

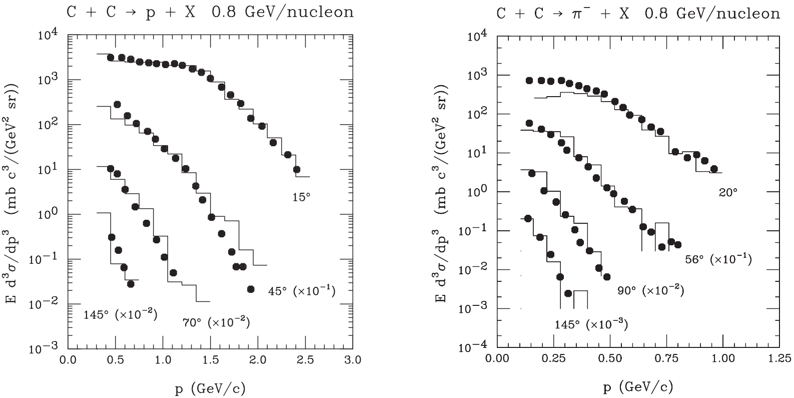
$^{129}Xe+^{119}Sn$ at 50 MeV/nucleon

points - data
Gorio
EPJA7(00)245

histograms - calculations
Kuhrts
PRC63(01)034605



High-Energy Inclusive Data



proton & pion spectra

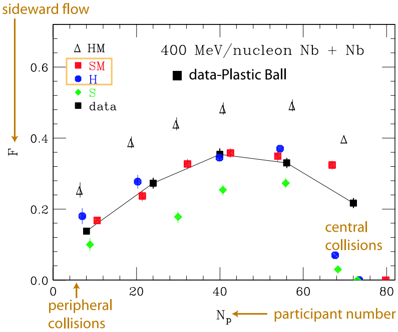
points - data Nagamiya PRC24(81)971
histograms - calculations

Potential Ambiguity in Conclusions

When observables are sensitive to bulk properties, they are usually sensitive to few properties at once.

⇒ For progress, one needs to look for dedicated observables sensitive to one particular observable.

E.g.: Pan&PD PRL70(93)2063

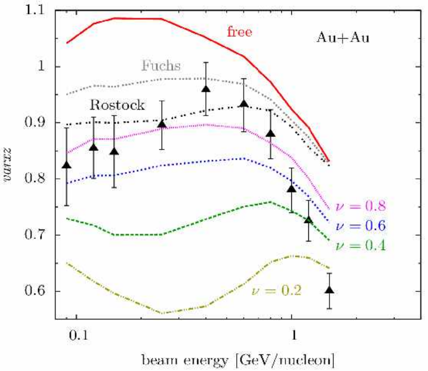


SM - strong dependence of ϵ on p

H - strong dependence of ϵ on ρ

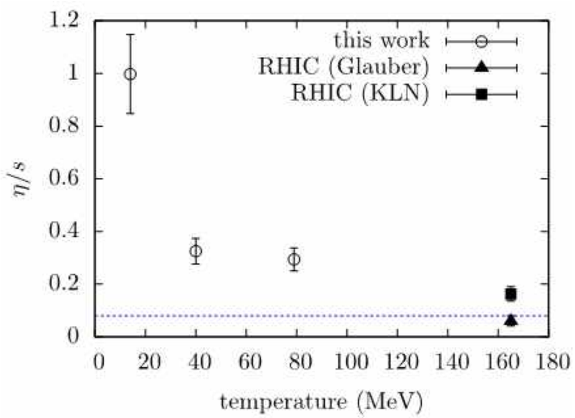
Stopping: σ_{NN} & Viscosity

- Central symmetric collisions from 0.09 to 1.5 GeV/u
- Stopping observables such as
$$varxz = \frac{\Delta y_x}{\Delta y_z}$$
- Free CS overestimates stopping
- Different CS modifications tried
- Tempered CS works best
$$\sigma \lesssim \nu\, \rho^{-2/3}$$
with $\nu \sim 0.7$



Reisdorf *et al* [FOPI]
PRL92(04)232301
NPA848(10)366

Viscosity-to-Entropy Ratio

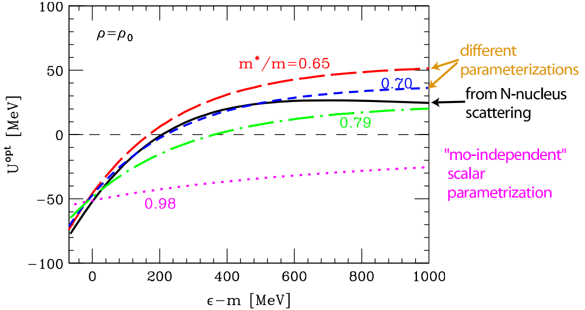


Viscosity from reduced in-medium cross-sections
RHIC: Bernhard *et al* PRC91(15)054910

Momentum Dependence of Mean Field

Nucleon-nucleus scattering gives access to the mean field at densities $\rho \lesssim \rho_0$

Hama *et al* PRC41(90)2737



Evidence for momentum dependence in reactions?
Access to momentum dependence at $\rho > \rho_0$?

$$U^{opt} = \epsilon - \epsilon^{kin} \qquad \boldsymbol{v} = \frac{\partial \epsilon}{\partial \boldsymbol{p}}$$

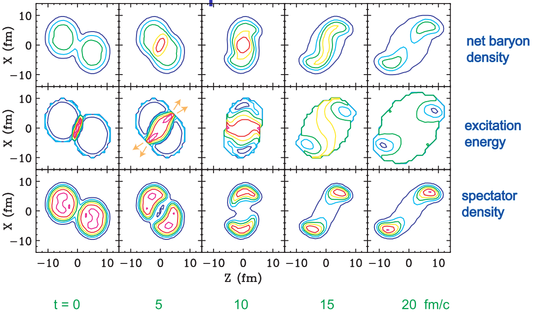
$$v = \frac{\partial \epsilon^{kin}}{\partial p} + \frac{\partial U^{opt}}{\partial p} = v^{kin} + \frac{\partial U^{opt}}{\partial p} > v^{kin}$$

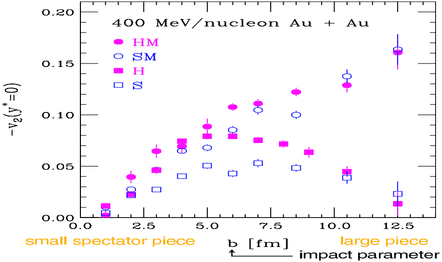
How to assess the in-medium velocities in central reactions??

Anisotropies due to Spectators

Spectator nucleons: weakly affected by reaction, proceed at unaltered velocity

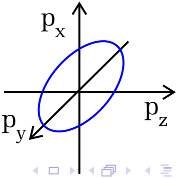
Participants: matter undergoes violent process, compression, excitation & expansion





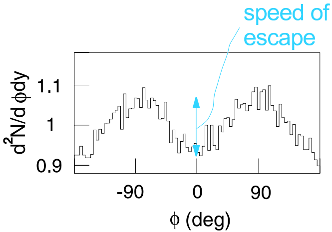
$$v_2 = \langle \cos(2\phi) \rangle$$

ϕ - relative to reaction plane



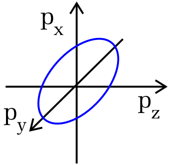
Comparison to Data

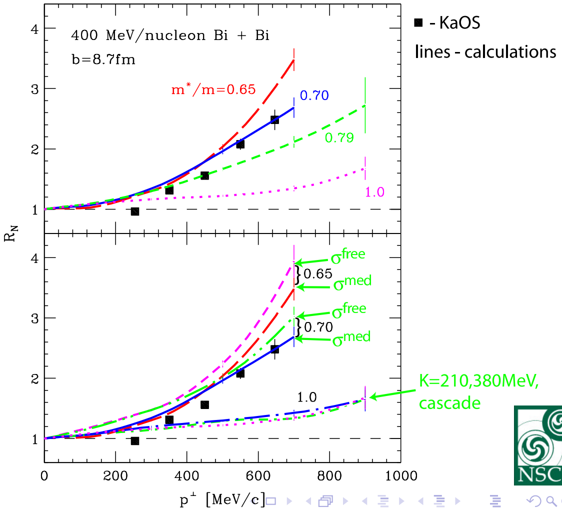
$$R_N = \frac{N(-90^\circ) + N(90^\circ)}{N(0^\circ) + N(180^\circ)}$$



data: KaOS Brill *et al* ZPA355(96)61

More ptcles escape in direction perpendicular to the reaction plane





Supranormal Densities?

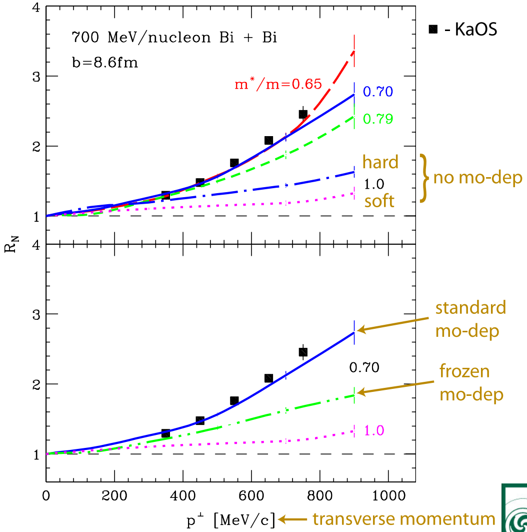
Other beam energies??

Are we just testing the momentum dependence in the vicinity of ρ_0??

Test: Max. ρ in midperipheral collisions at 400, 700 and 1000 MeV/nucleon: $\rho/\rho_0 \approx 1.85$, 2.20 and 2.40, respectively.

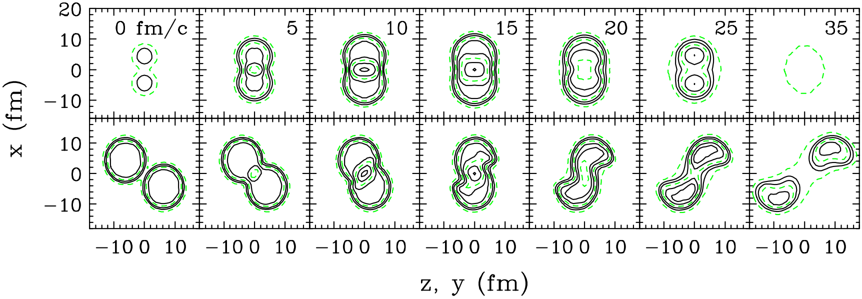
But do they matter??

$\Rightarrow$ Let us make the momentum dependence at $\rho > \rho_0$ follow dependence at ρ_0. MF where velocity ceases to change above ρ_0: $v^*(p, \rho) = v^*(p, \rho_0)$ for $\rho > \rho_0$.



Why Sensitivity to $\rho > \rho_0$ in Transverse Directions??

Contour plots of the density in the reaction plane (bottom) and in the plane $\perp$ to the beam (top) for Bi+Bi at 400MeV/u:

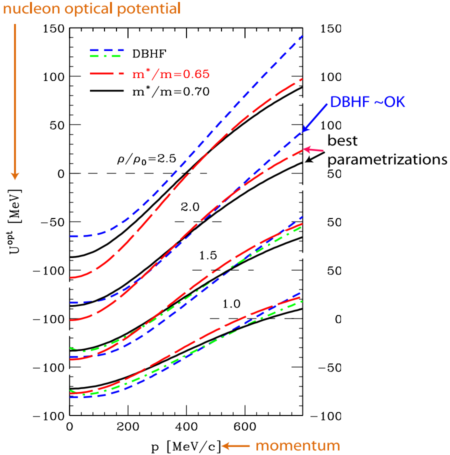


Fast ptcles emitted transversally, around $t \sim 15$ fm/c, directly from high-ρ matter!

PD NPA673(00)375

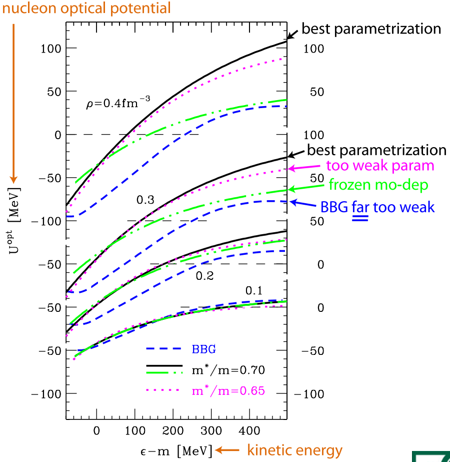
Comparison to Microscopic Calculations

Optical-potential $U = \epsilon - \epsilon_{kin}$ compared to microscopic



Dirac-Brueckner-Hartree-Fock

Machleit *et al.* PRC48(93)2707



Bethe-Brueckner-Goldstone

Lombardo *et al.* PLB334(94)12

Central Reactions

Reaction plane: plane in which the centers of initial nuclei lie.

Spectators: nucleons in the reaction periphery, little disturbed by the reaction.

Participants: nucleons that dive into compressed excited matter.

Nuclear EOS deduced from the features of collective flow in reactions of heavy nuclei.

Collective flow: motion characterized by significant space-momentum correlations, deduced from momentum distributions of particles emitted in the reactions.

Euler eq. in $\vec{v} = 0$ frame:

$$m_N \, \rho \, \frac{\partial}{\partial t} \, \vec{v} = -\vec{\nabla} p$$

EOS and Flow Anisotropies

EOS assessed through reaction plane anisotropies characterizing particle collective motion.

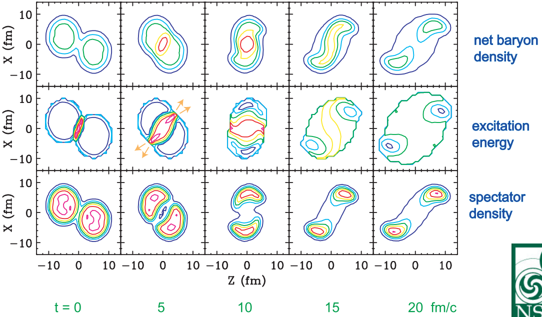
Hydro? Euler eq. in $\vec{v} = 0$ frame: $\boxed{m_N \, \rho \, \frac{\partial}{\partial t} \, \vec{v} = -\vec{\nabla} p}$

where p - pressure. From features of v, knowing Δt, we may learn about p in relation to ρ. Δt fixed by spectator motion.

For high p, expansion rapid and much affected by spectators.

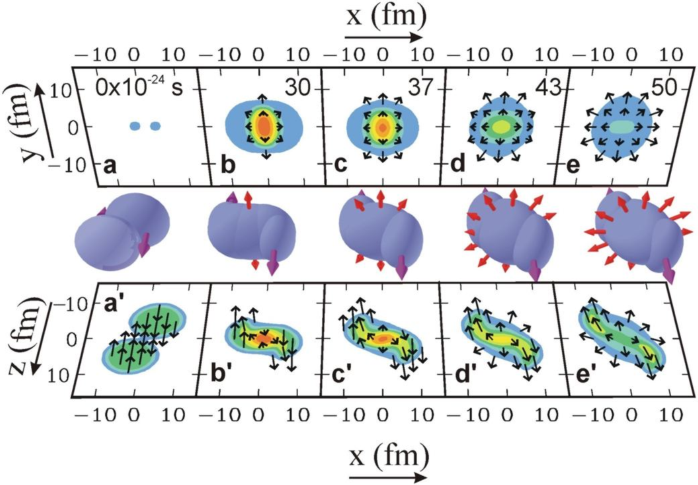
For low p, expansion sluggish and completes after spectators gone.

Simulation by L. Shi



Medium-Energy Collisions of Heavy Nuclei

Thermalized matter at high baryon density! 2 GeV/u Au+Au



Top panels: pressure ⊥ to beam axis (up to 90 MeV/fm^3) + flow

Bottom panels: density (up to $3\rho_0$) in reaction plane + flow

Sideward Flow Systematics

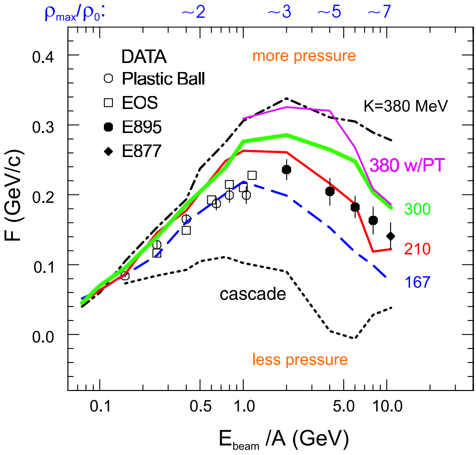
Deflection of forwards and backwards moving particles away from the beam axis, within the reaction plane.

Au + Au Flow
Excitation Function

Note: K used as a label

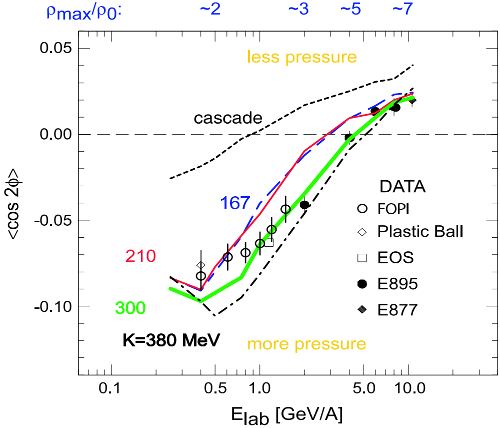
PD, Lacey & Lynch

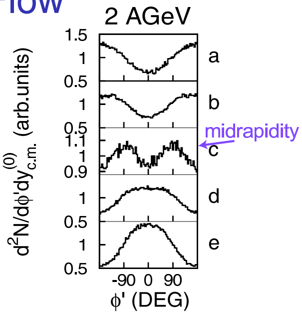
The sideward-flow observable results from dynamics that spans a ρ-range varying with the incident energy.



2^{nd}-Order or Elliptic Flow

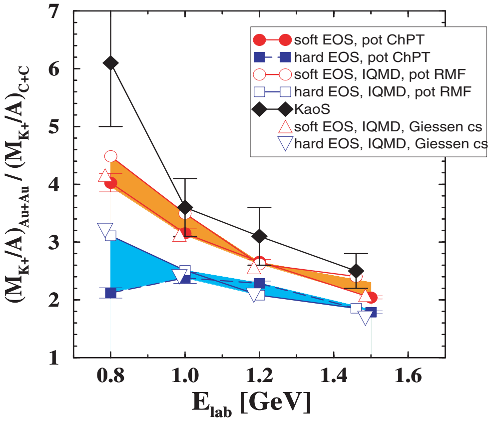
Another anisotropy, studied at midrapidity: $v_2 = \langle \cos 2\phi \rangle$, where ϕ is azimuthal angle relative to reaction plane.





Au+Au v_2
Excitation Function

Subthreshold Meson (K/π) Production



Ratio of kaons per participant nucleon in Au+Au collisions to kaons in C+C collisions vs beam energy

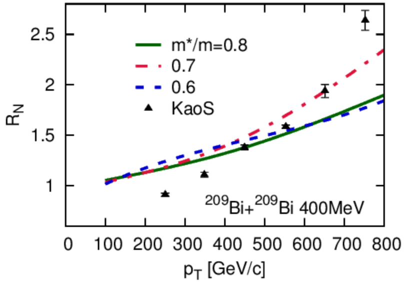
filled diamonds: KaoS data

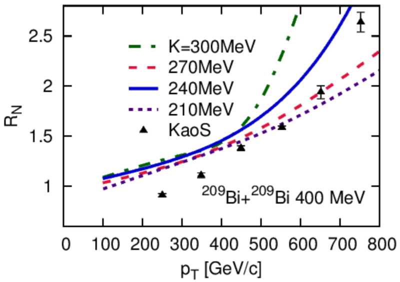
open symbols: theory Fuchs *et al*

Kaon yield sensitive to EOS because multiple interactions needed for production, testing density.

The data suggest a relatively soft EOS.

Sensitivity of Elliptic Flow to m^*/m and K



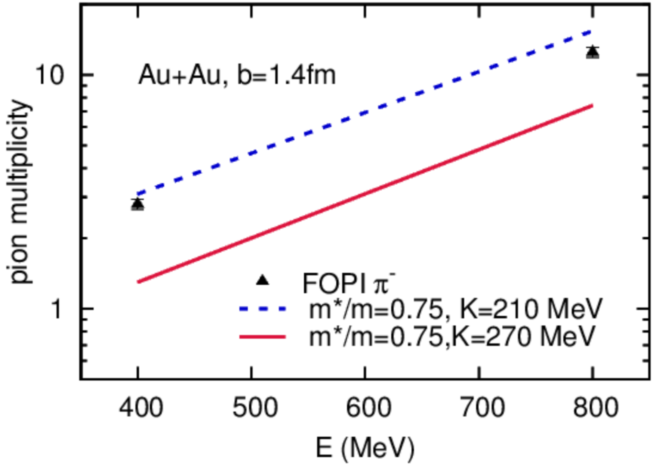


$K = 270\,\mathrm{MeV}$
and changing m^*/m

$m^*/m = 0.7$
and changing K

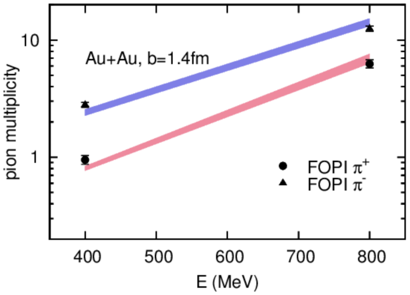
Hysteresis in both cases due to competition between density and momentum dependence

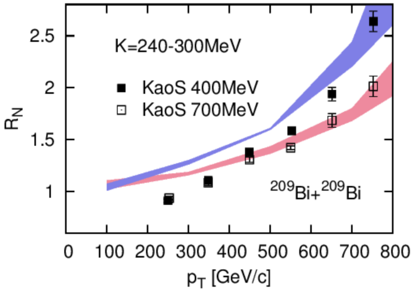
Sensitivity of M_π to Incompressibility K



$m^*/m = 0.75$ and changing K

Raising K Allows to Describe Both M_π and v_2!



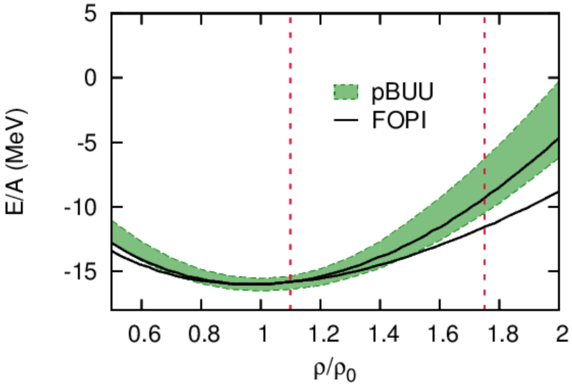


Bands for $K = (240 - 300)$ MeV & optimal m^*/m

$\rightarrow$ Constraints on EOS, at moderately supranormal densities, à la LeFèvre *et al*

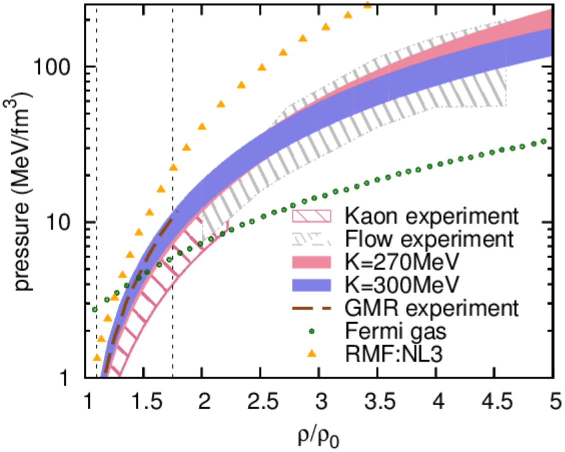
Energy Per Nucleon

Symmetric Matter



Pressure

Symmetric Matter



Principal Features Again

- Solution of Boltzmann Eq
- 1-Ptcle Energies from Energy Functional
  - Volume (incl Momentum), Gradient, Isospin, Coulomb Terms
- Covariance
  - Covariant: Volume (incl Momentum) Term in Energy, Collisions
  - Noncovariant: Gradient, Isospin, Coulomb Terms in Energy
  - Employed (so far) up to 20 GeV/nucl
- Pions contribute to Symmetry Energy
- Spectral functions of Δ and N^* Resonances in adiabatic approximation
  - Detailed Balance for Broad Resonances
- $A = 2, 3$ Clusters produced in Multinucleon Collisions
  - Cluster Break-Up Data used in describing Production

Supported by National Science Foundation under Grant US PHY-1403906