Pion Production in Heavy-Ion Collisions

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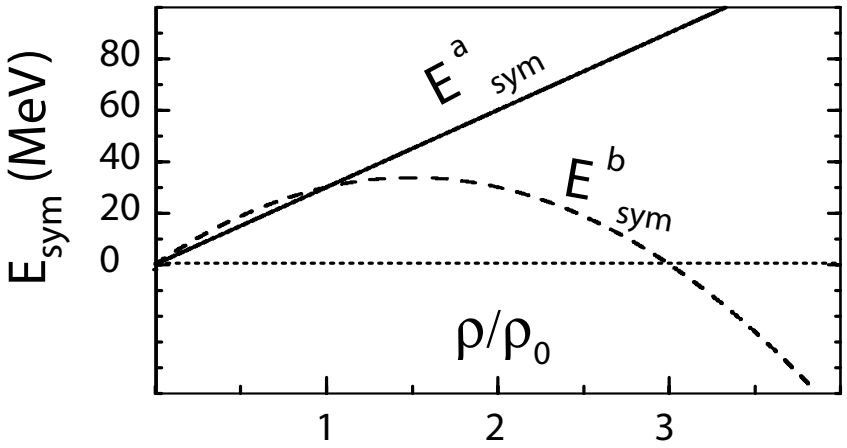
Workshop on Science with SπRIT TPC

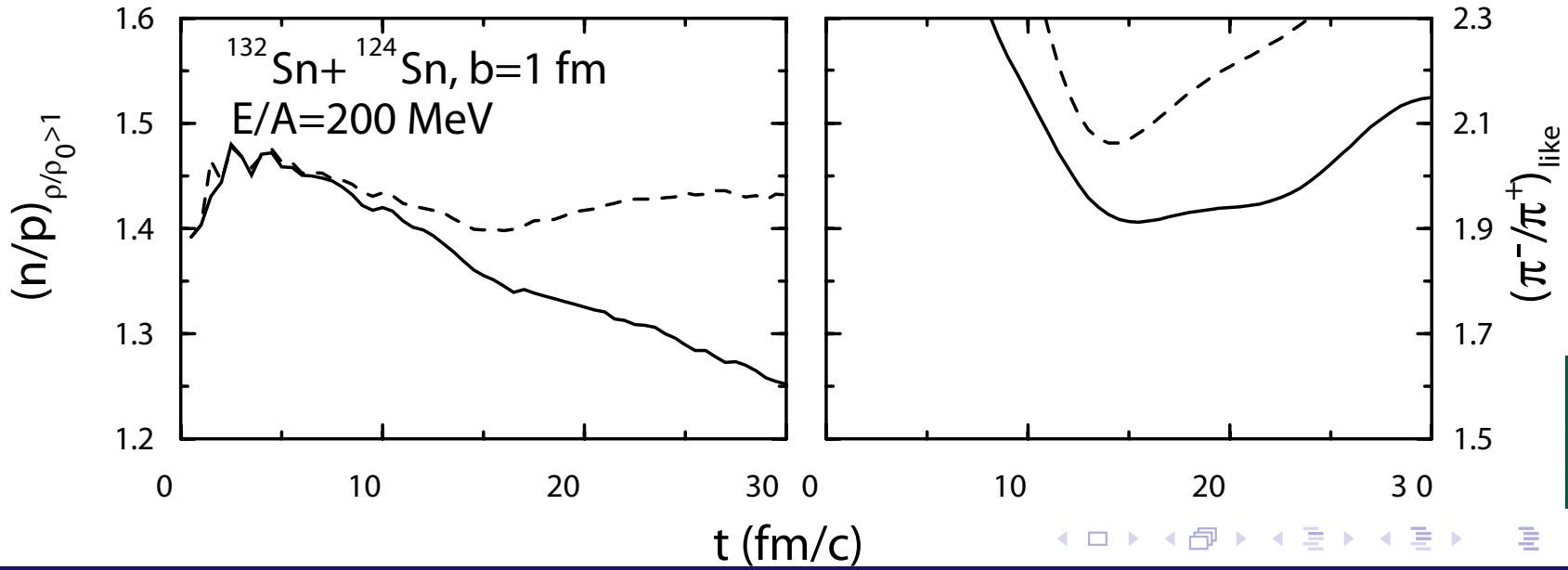
5-6 June, 2015, RIKEN, Wako, Saitama

Interest: π as Probe of High-ρ Symmetry Energy

B-A Li PRL88(02)192701: $S(\rho > \rho_0) \Rightarrow n/p_{\rho>\rho_0} \Rightarrow \pi^-/\pi^+$



Pions originate from high ρ



Simulations of Heavy-Ion Collisions

Separation of time and distance scales:

Short scales reduced to negligible extent with outcomes of events treated probabilistically

Long scales treated explicitly and deterministically

Cut-off scales: $t \sim 1\,\mathrm{fm}/c$, $r \lesssim 1\,\mathrm{fm}$

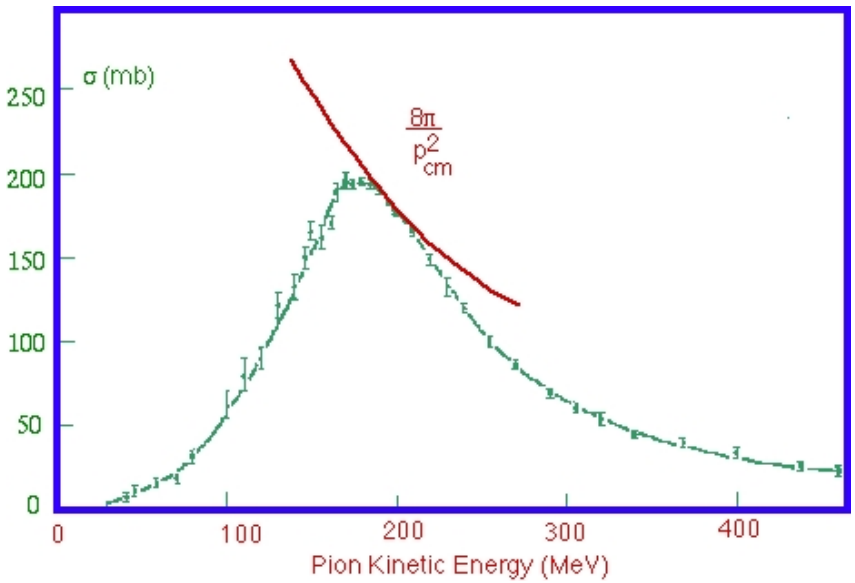
Primarily binary collision processes

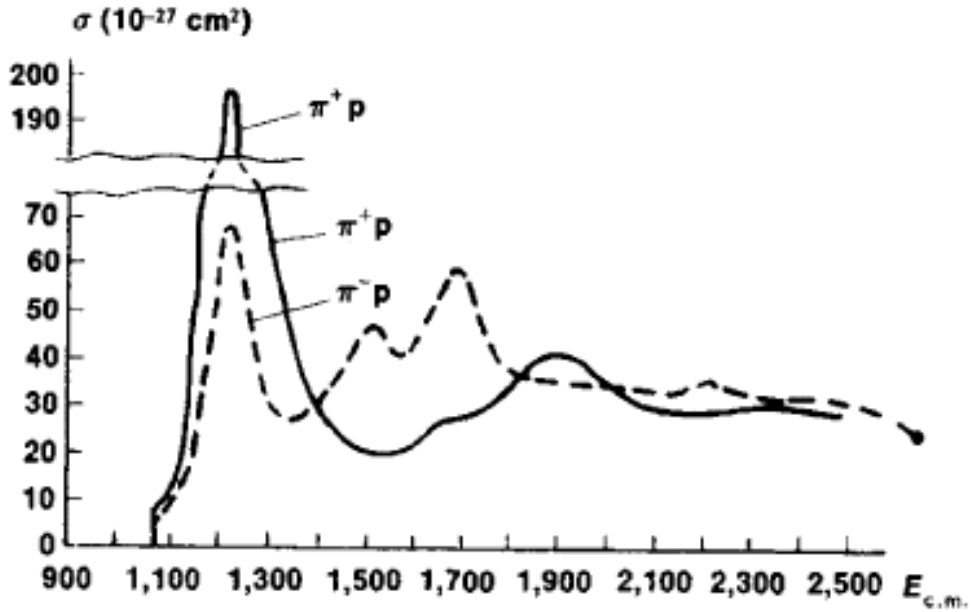
Equation of state: if there is an optical potential affecting a particle, that particle impacts the interaction parts of thermodynamic functions.

Low-E pion production: $N + N \leftrightarrow N + \Delta, \quad \Delta \longleftrightarrow N + \pi$

Δ in π–N Interactions

π–p scattering cross sections





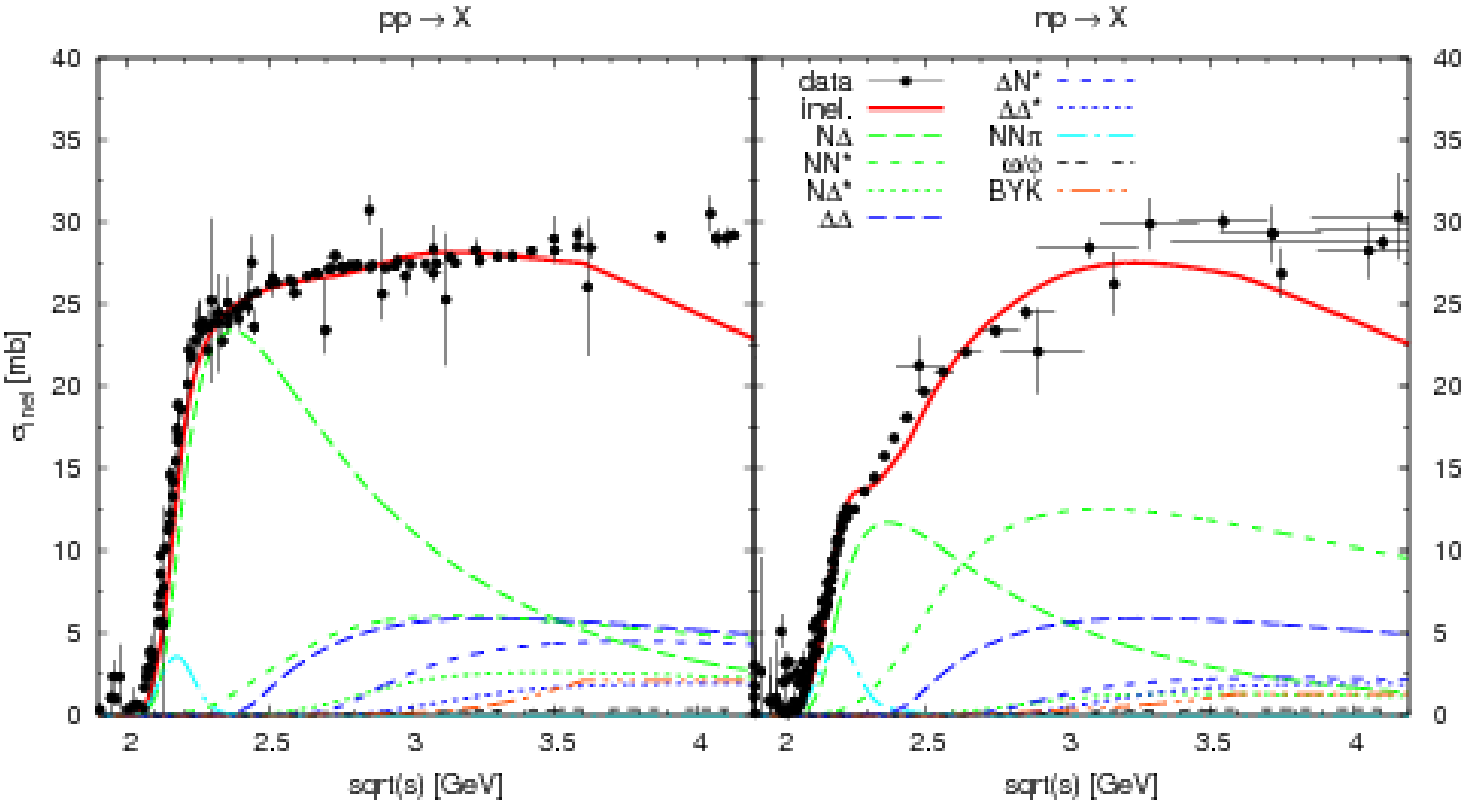
$$\sigma = \frac{4\pi}{p^2}\,\frac{2J+1}{2s+1}\,\frac{\Gamma^2/4}{(E-m_\Delta c^2)^2+\Gamma^2/4}$$

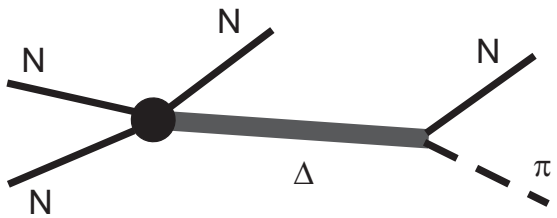
$$J = 3/2,\ m_\Delta = 1232\,MeV/c^2,\ \Gamma(p) \propto p^3$$

Inelastic *NN* Interactions

Decomposition of inelastic *NN* cross section

Weil *et al* EPJA48(12)111

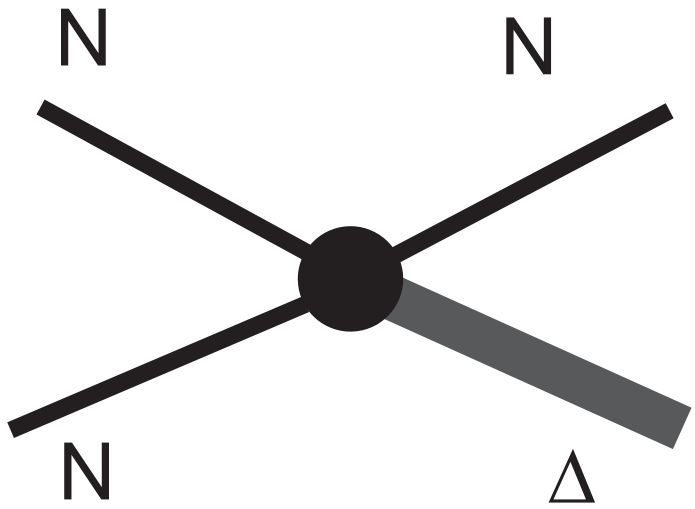




Production and Absorption: Detailed Balance

Time reversal symmetry: same magnitude of mtx element for forward & backward process, $|\mathcal{M}_{NN\to N\Delta}| = |\mathcal{M}_{N\Delta\to NN}|$.

$$\frac{dN_\Delta}{dt} \propto \int d\boldsymbol{p}\, \delta(\boldsymbol{p}_N + \boldsymbol{p}_\Delta - \boldsymbol{p}_N - \boldsymbol{p}_N) \times \delta(\epsilon_N + \epsilon_\Delta - \epsilon_N - \epsilon_N) \times |\mathcal{M}_{NN\to N\Delta}|^2 \left(f_N f_N - f_N f_\Delta\right)$$



in equilibrium: $f = e^{(\mu-\epsilon)/T}$

$$\sigma\, v \propto \int d\boldsymbol{p}\, \delta(E - E)\, |\mathcal{M}|^2$$

Detailed-balance relation: $\sigma_{NN\to N\Delta} \Leftrightarrow \sigma_{N\Delta\to NN}$

Relation nontrivial for Δ due to mass spread.

Balance violated: no thermal distribution, no law of mass action!

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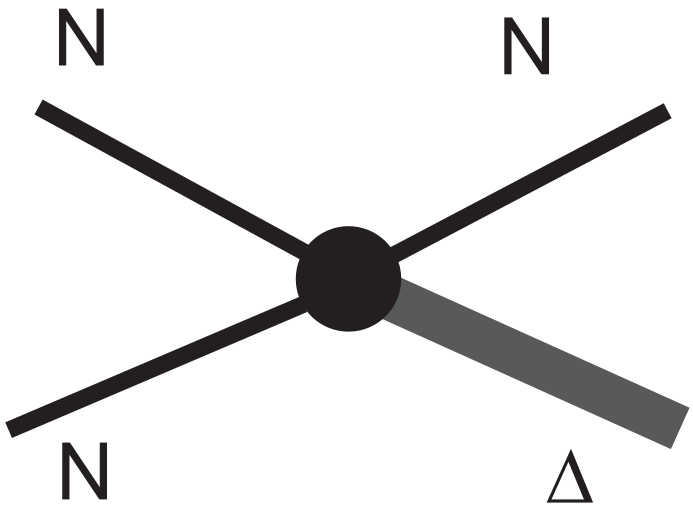

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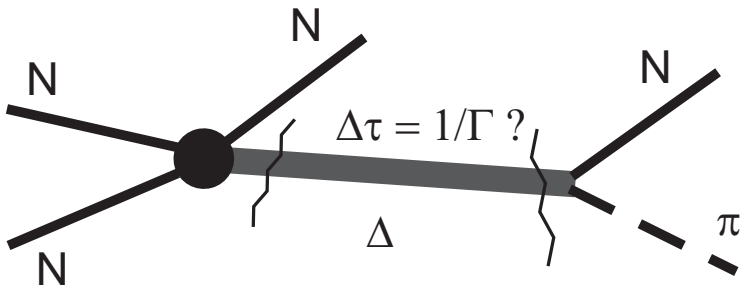
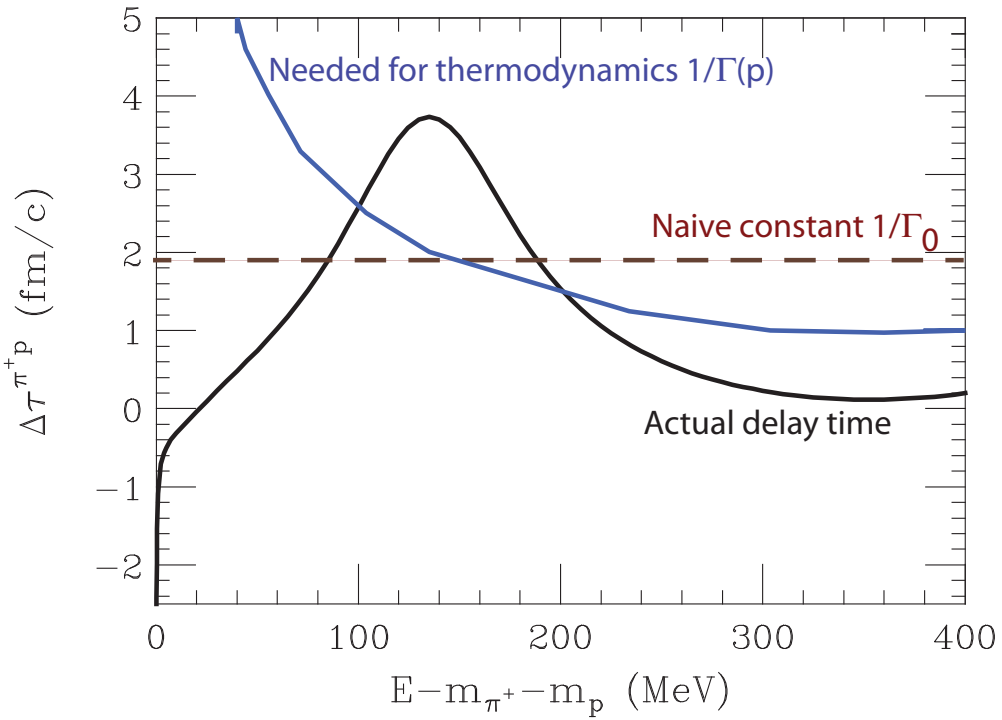
Δ Decay Time

Ambiguity in deciding on time of π production





PD&Pratt PRC53(96)249

Different perspectives yield different Δ lifetimes

$\Delta\tau$ consistent with thermal equilibrium most often used, but it yields unphysically long-lived Δ close to threshold.

$\Rightarrow$ Need to transition to direct 3-ptcle production?

π vs Baryon Optical Potentials

$$\Delta \longleftrightarrow N + \pi \qquad U_\Delta \stackrel{?}{=} U_N + U_\pi$$

'Conservation' of potential consistent with the quark perspective. Also also greatly facilitates calculations of process kinematics as thresholds in kinetic energy stay put.

Ferini *et al* NPA762(05)147: $U_\pi = 0$ & $U_\Delta = U_N$ employed in most models, including IBUU.

However, a strong isospin-dependent potential is needed to explain the existence of pionic atoms!

pBUU: U dependent on conserved quantities, density of baryon number and isospin - π end up with potentials that depend on isospin & symmetry energy

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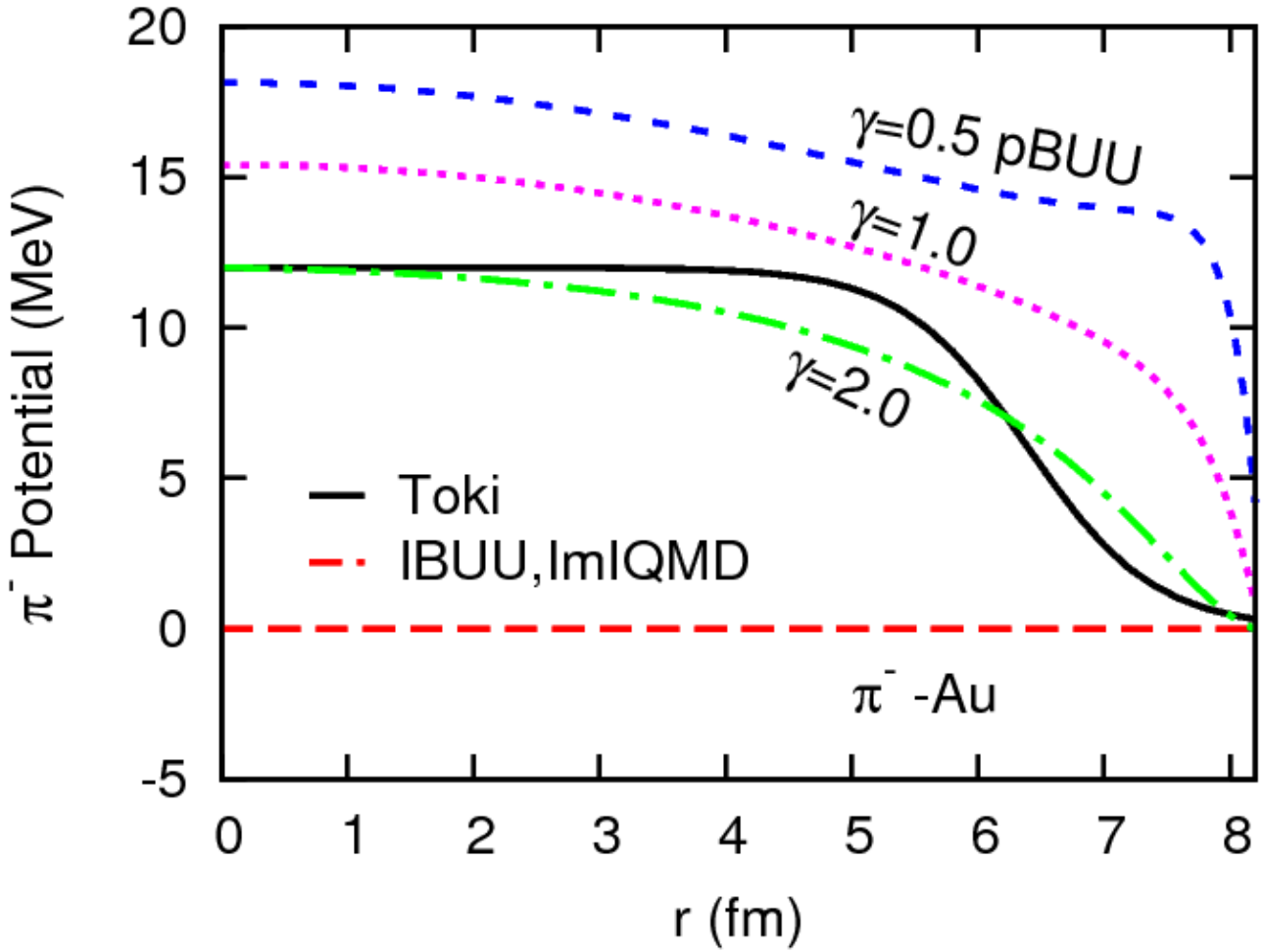
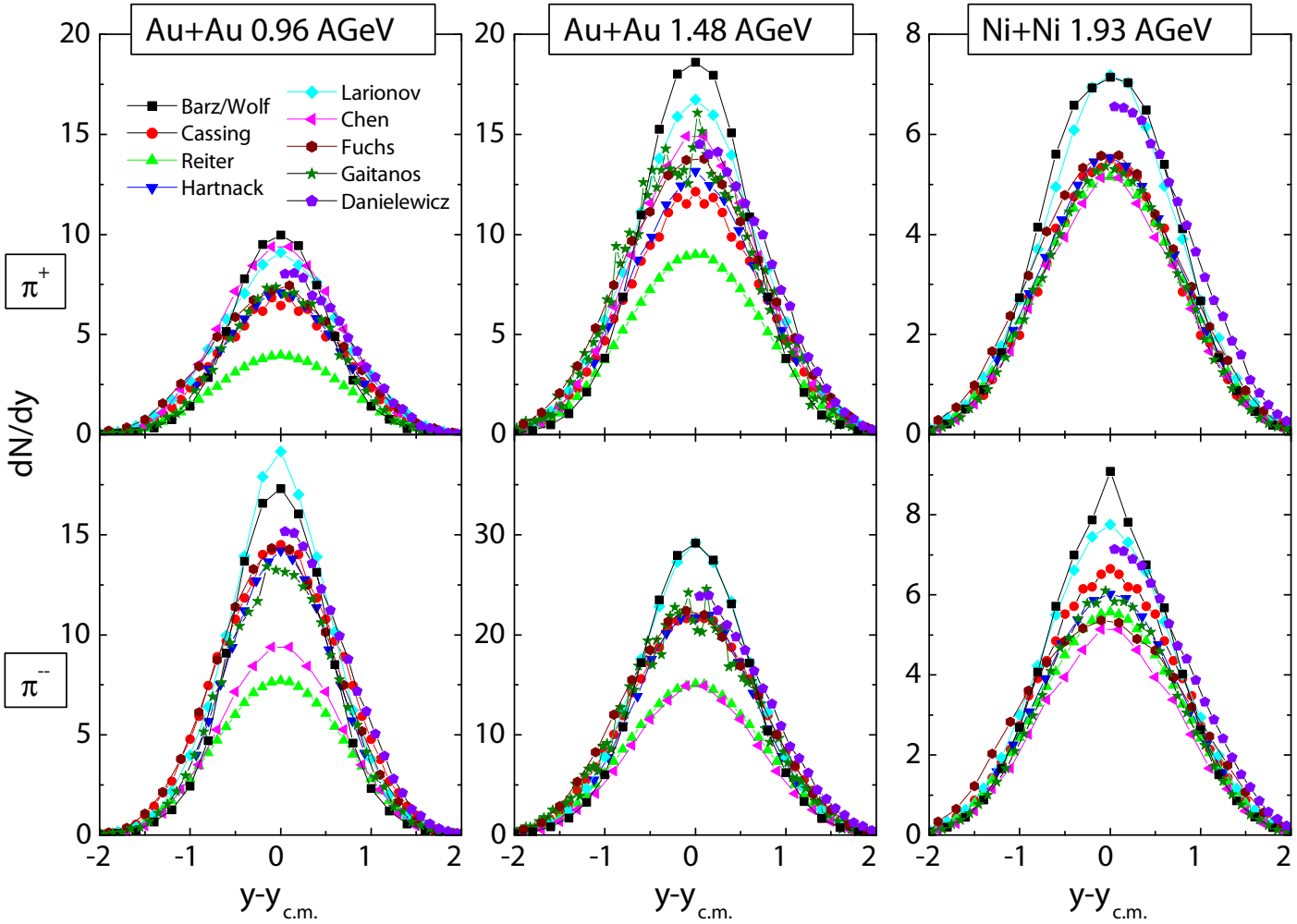
Symmetry-Energy Derived π Potential



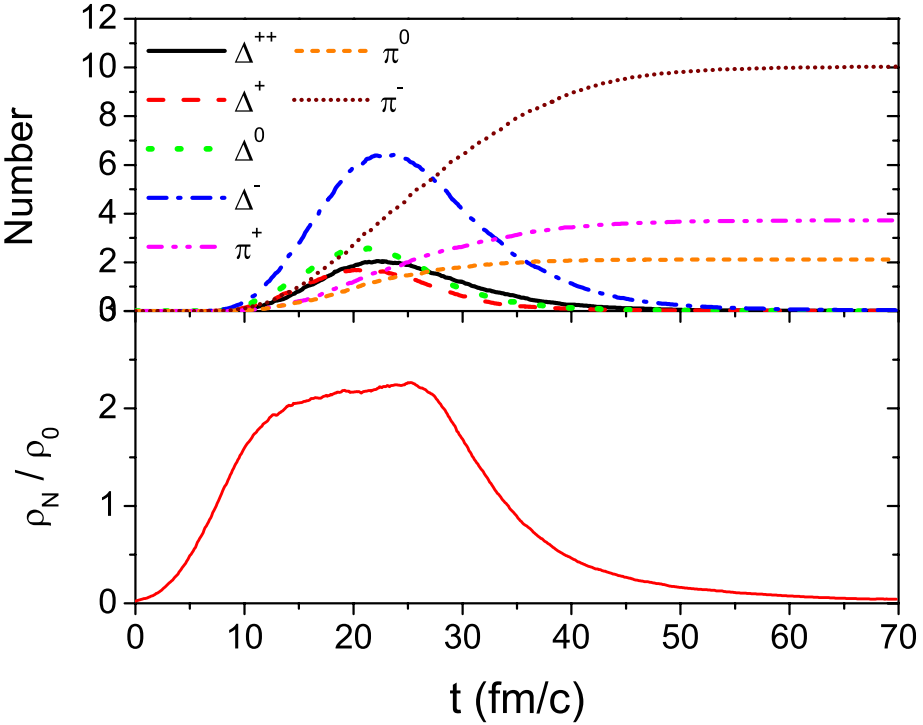
Jun Hong&PD PRC90(14)024605 Nucl density: Thomas-Fermi

Technical Differences between Calculations

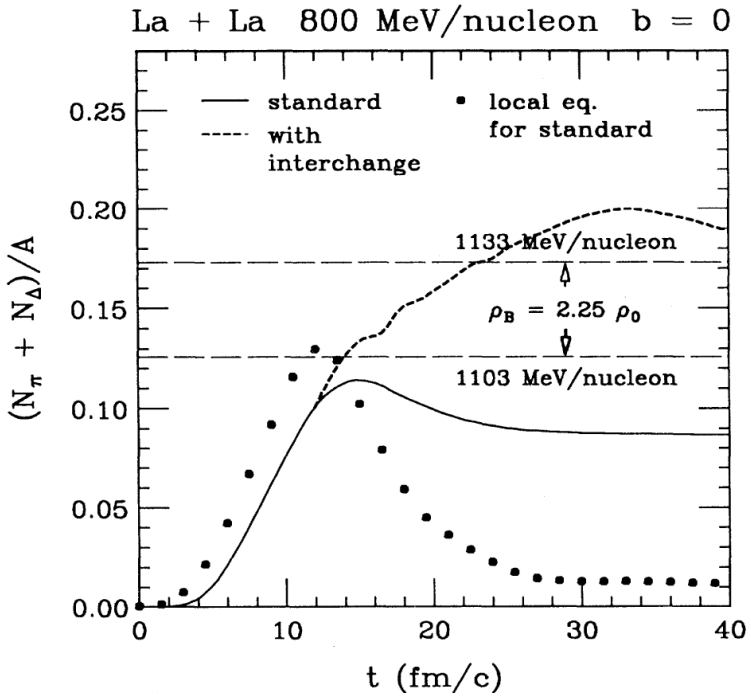


Kolomeitsev *et al* JPG31(05)S741

Pions Probe System at High-ρ!



Song&Ko PRC91(15)014901



PD PRC51(95)716

π test the maximal densities reached and collective motion then

Pions as Probe of High-ρ Symmetry Energy

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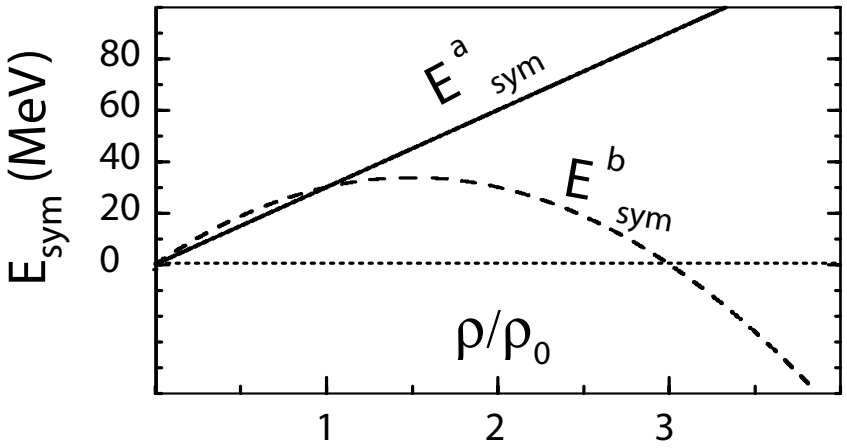

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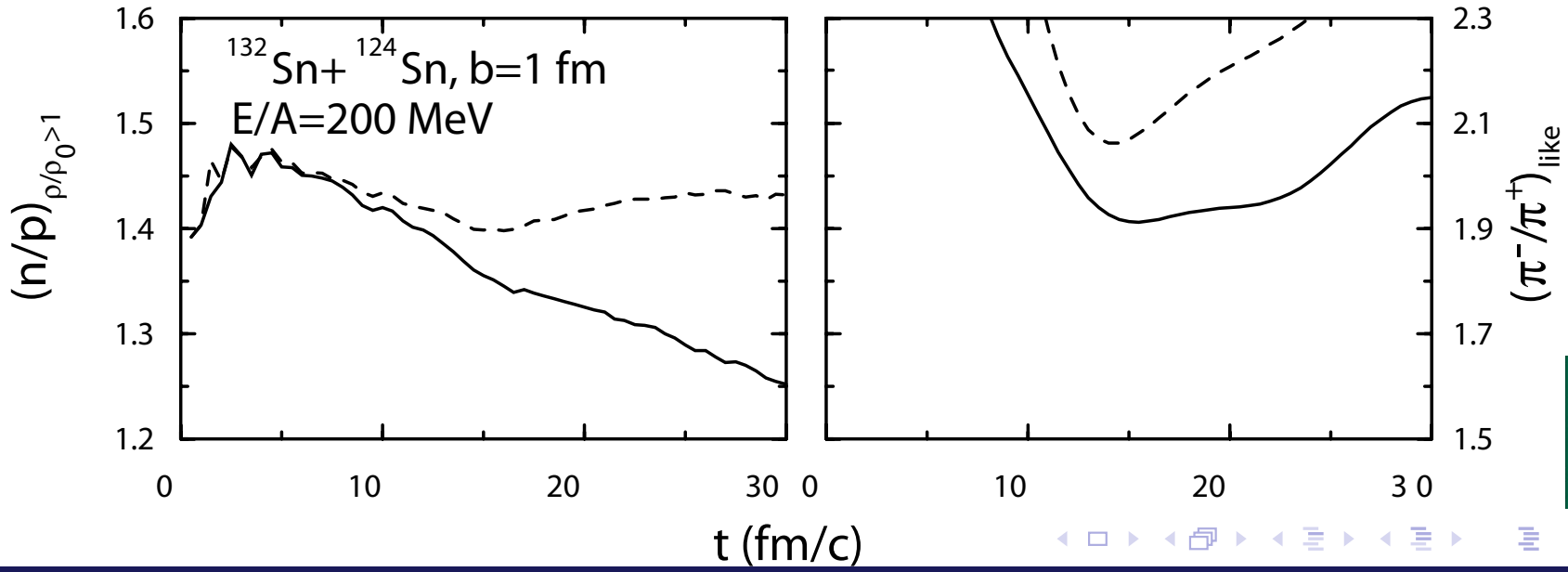
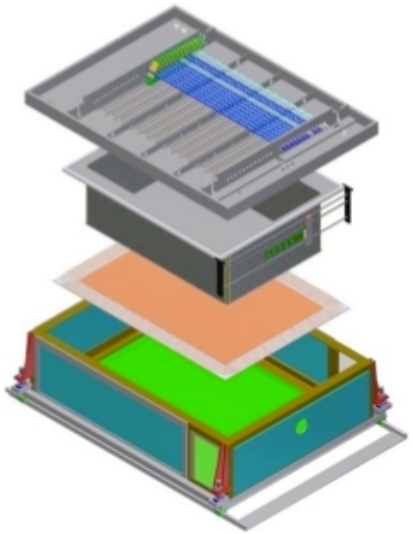


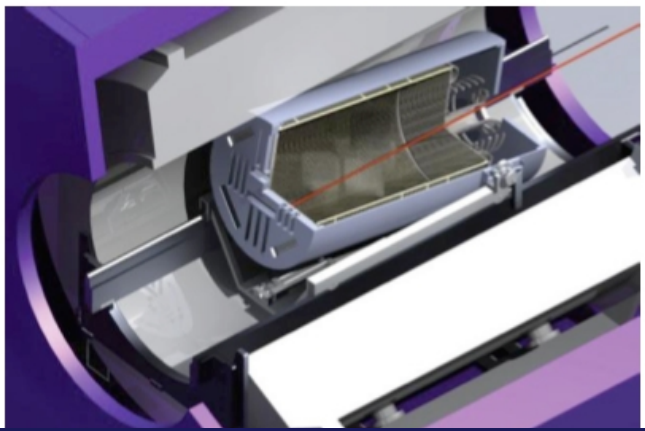
Dedicated Experimental Efforts

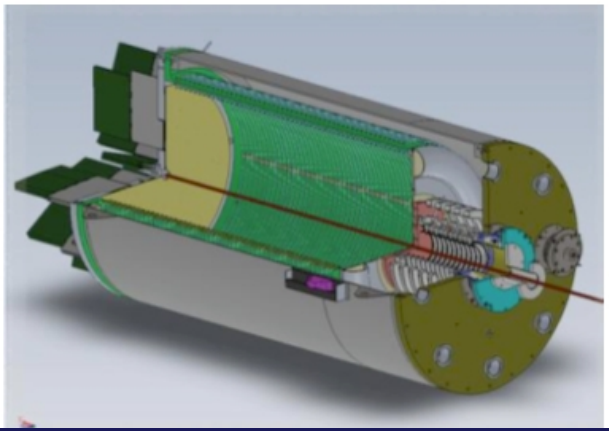
SAMURAI-TPC Collaboration (8 countries and 43 researchers): comparisons of near-threshold π^- and π^+ and also *n*-*p* spectra and flows at RIKEN, Japan.

NSCL/MSU, Texas A&M U
Western Michigan U, U of Notre Dame
GSI, Daresbury Lab, INFN/LNS
U of Budapest, SUBATECH, GANIL
China IAE, Brazil, RIKEN, Rikkyo U
Tohoku U, Kyoto U



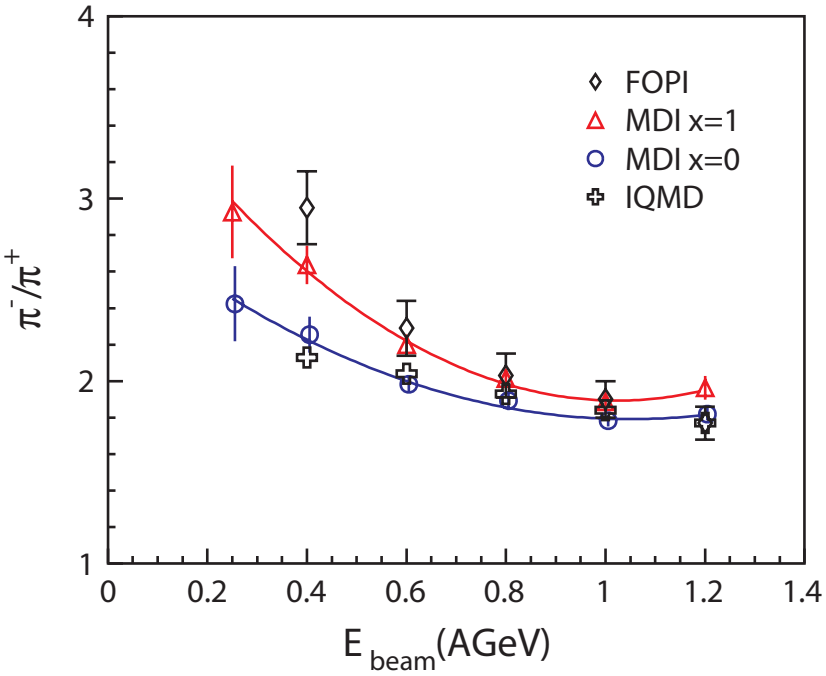
AT-TPC Collaboration (US & France)

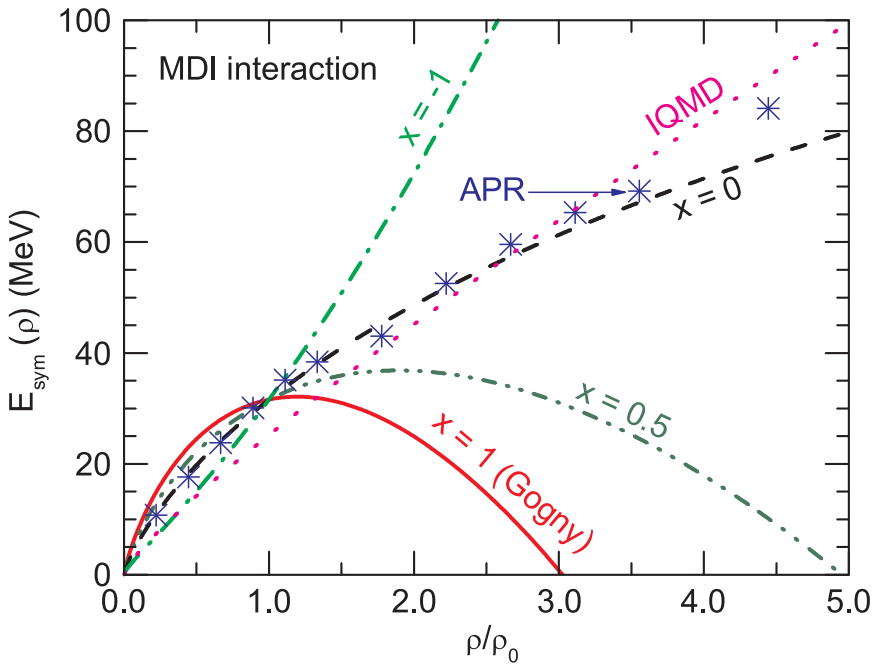




Interpretation of FOPI Data

Reisdorf *et al* NPA781(07)459



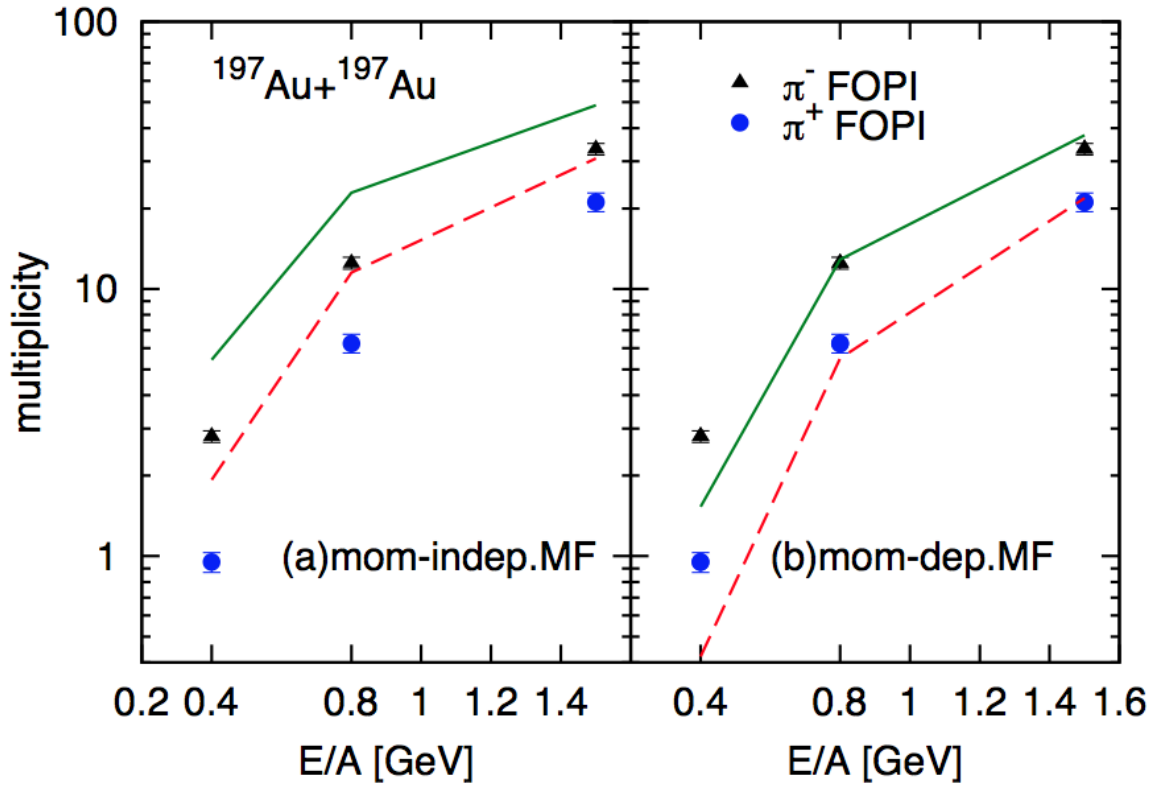


Transport IBUU04 Xiao *et al* PRL102(09)062502

Symmetry energy dropping with ρ, at $\rho > \rho_0$!?

Net π Yields and $U(\rho, p)$ in pBUU

Reisdorf *et al* NPA781(07)459

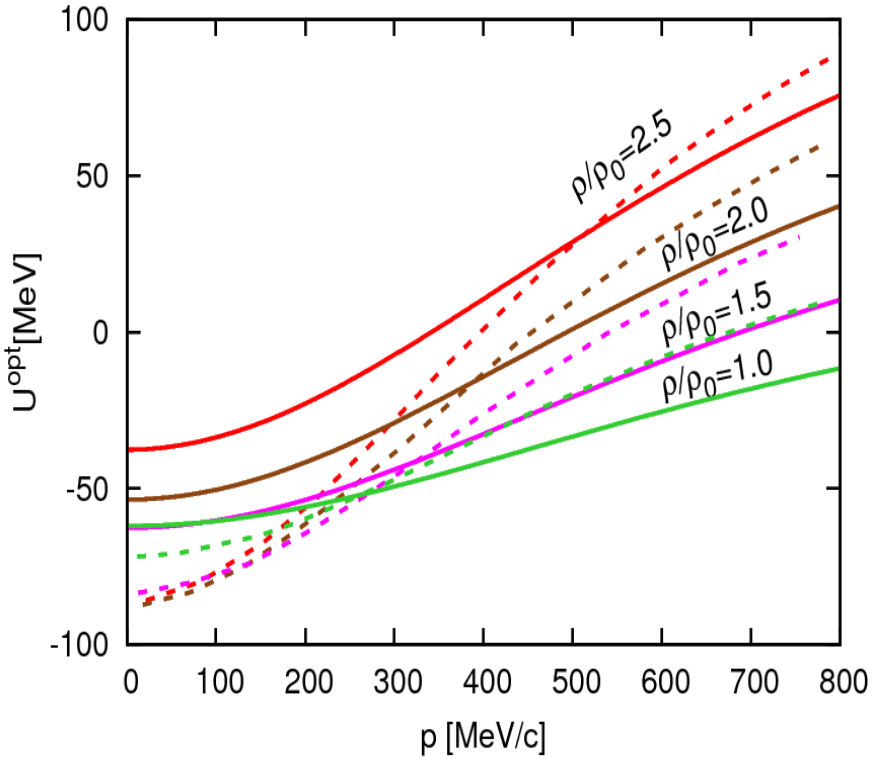


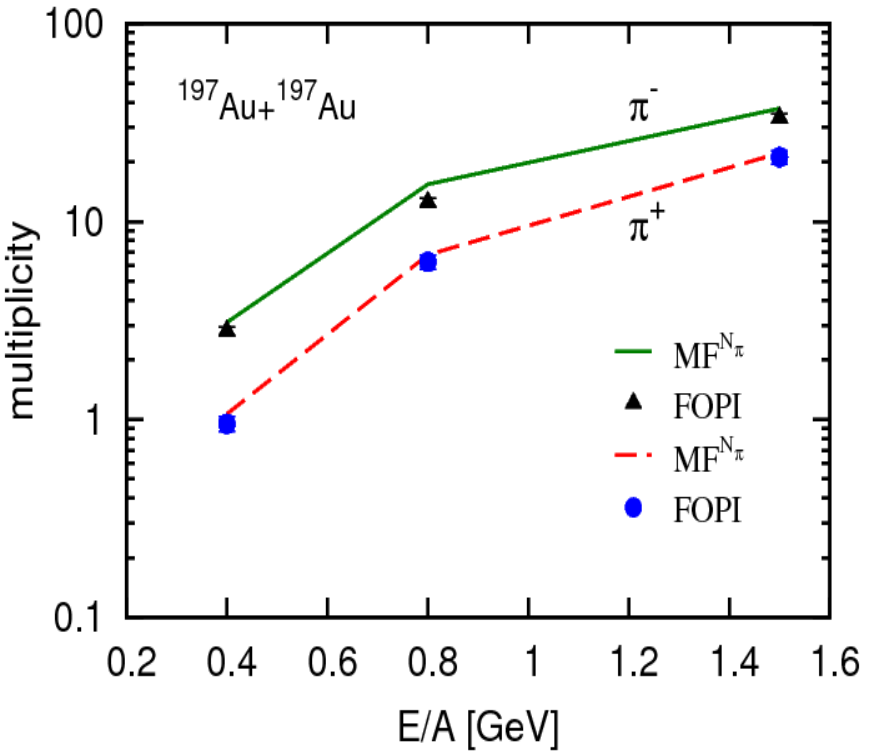
Jun Hong & PD PRC90(14)024605, π^- and π^+

?Imperfect Mom Dependence?? [No sensitivity to π/Δ rates]

affects maximal densities reached

π Yields Reproduced with Softened $U(p)$



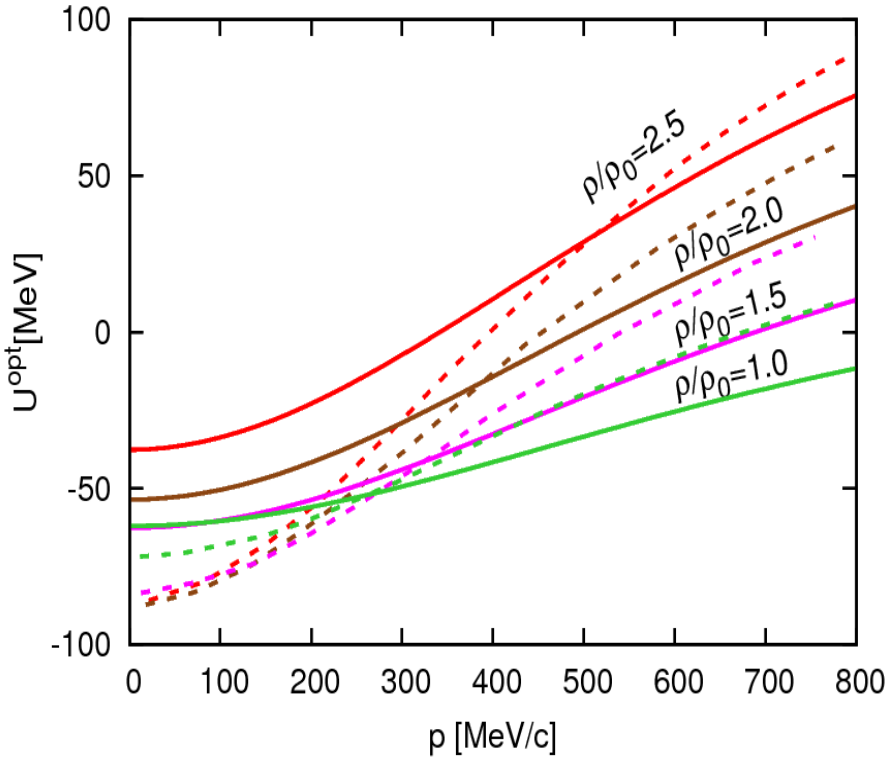


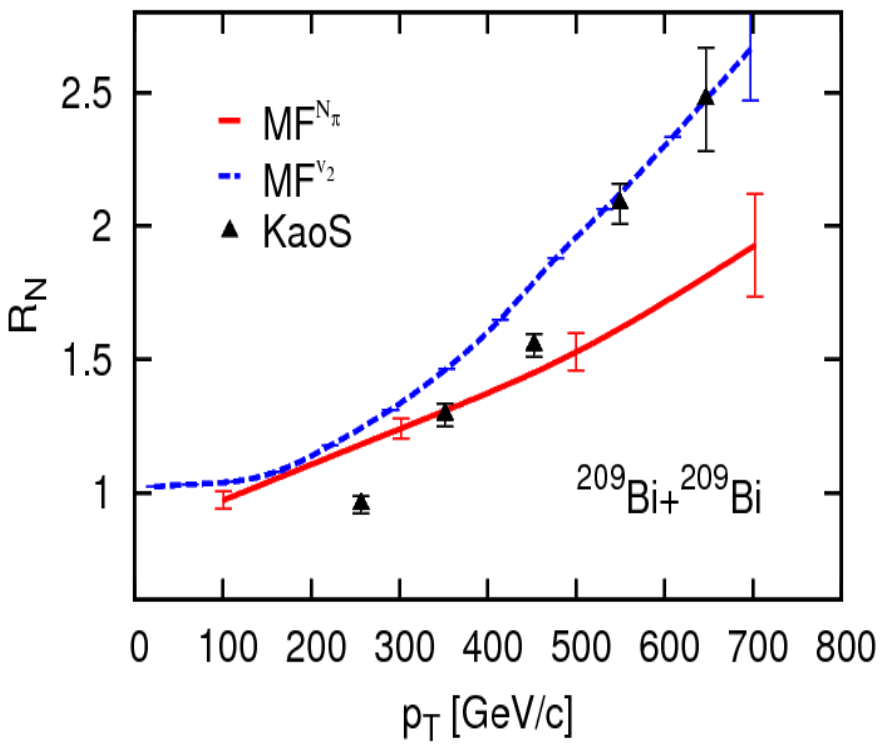
solid: softened $U(p)$

Jun Hong&PD PRC90(14)024605

but then...

Inferior Description of Midrapidity Flow Anisotropy





solid: new $U(p)$, dashed: old $U(p)$

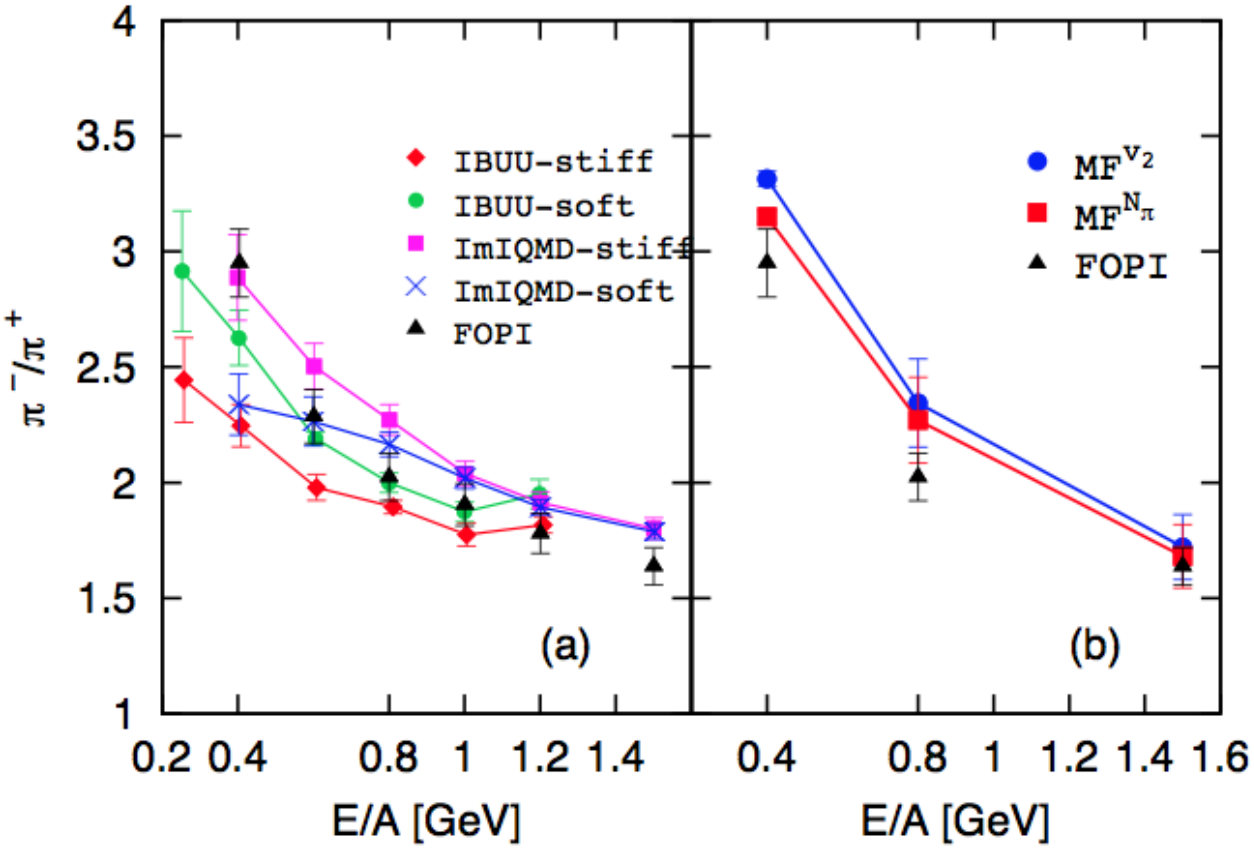
$R_N \leftrightarrow$ elliptic flow

Jun Hong & PD PRC90(14)024605

too weak with new $U(p)$

FOPI π^-/π^+ Reproduced by pBUU

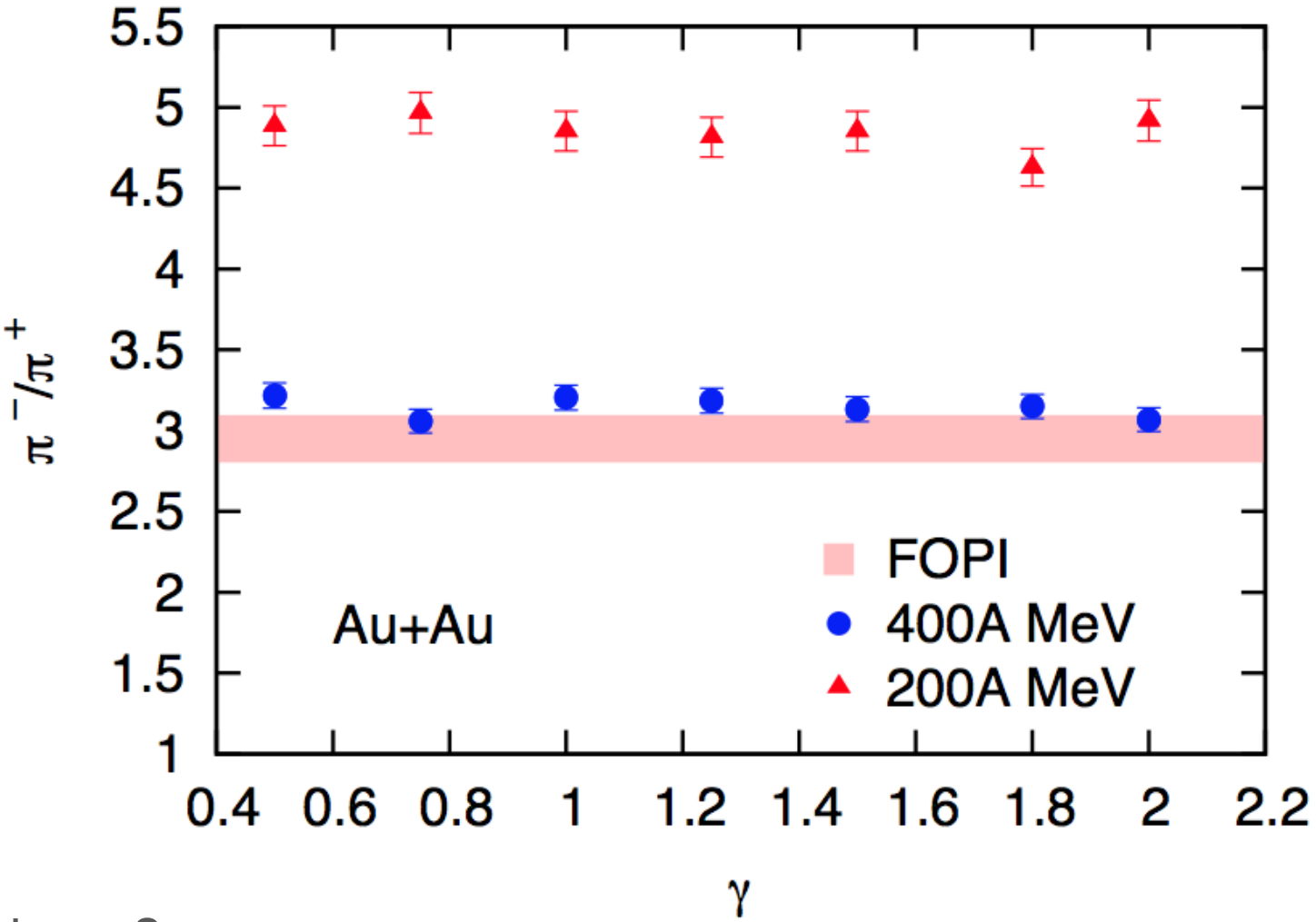
. . . irrespectively of $U(\rho)$, right panel



Left panel: discrepancies in the literature - correlation vs anticorrelation of $S(\rho > \rho_0)$ with π^-/π^+.

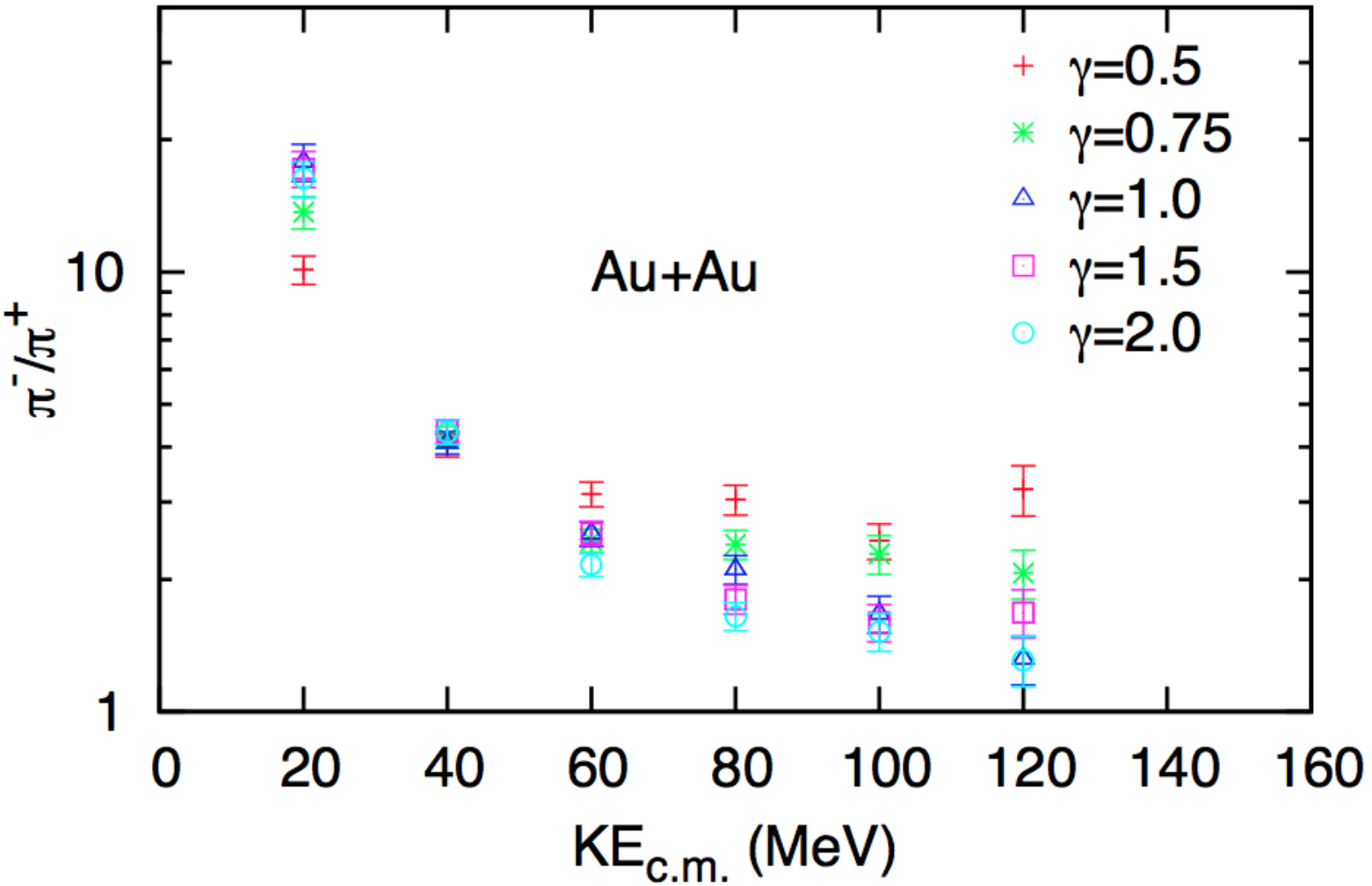
FOPI π^-/π^+ Reproduced by pBUU

. . . irrespectively of $S_{\rm int}(\rho) = S_0\,(\rho/\rho_0)^\gamma$:



?no hope?

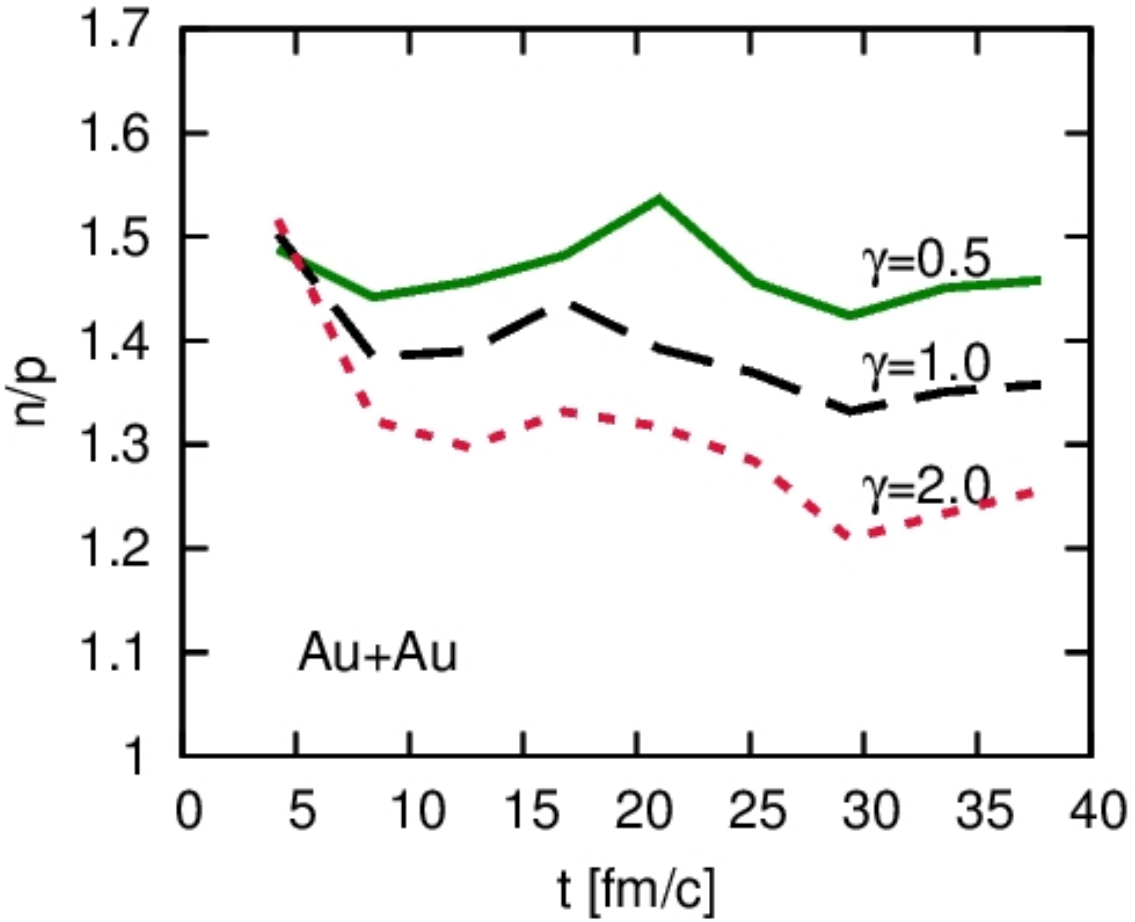
Original Idea Still Correct for High-E π's



$$S_{\text{int}}(\rho) = S_0\,(\rho/\rho_0)^{\gamma}$$

n/p Ratio in pBUU at $\rho > \rho_0$

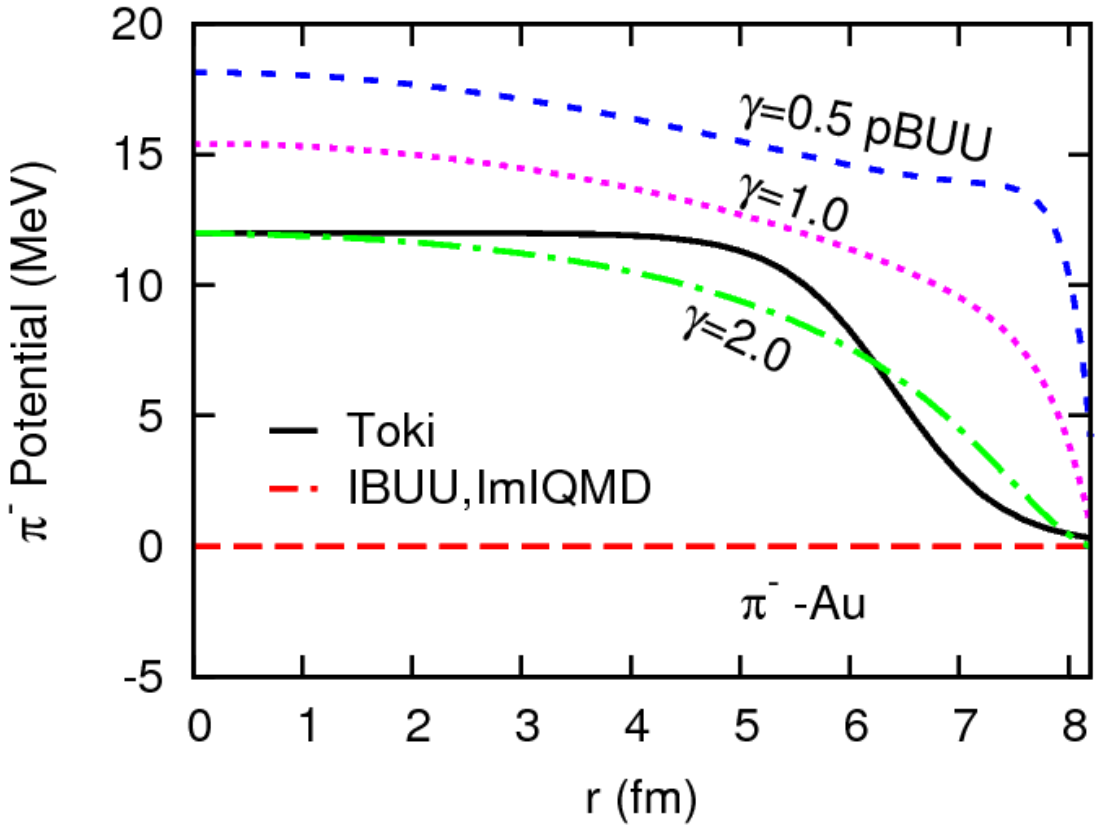
changes with the supranormal symmetry energy:



$$S_{\text{int}}(\rho) = S_0 \left(\rho/\rho_0\right)^{\gamma}$$

Why Differences for Net π Ratios?

In pBUU isospin-driven $\pi^{\pm}$ optical potential



π/Δ rate sensitivities claimed in Larionov&Mosel NPA728(03)135; Prassa *et al* NPA789(07)311 and Song&Ko PRC91(15)014901. Virtually none there in pBUU!

Energy Conservation?

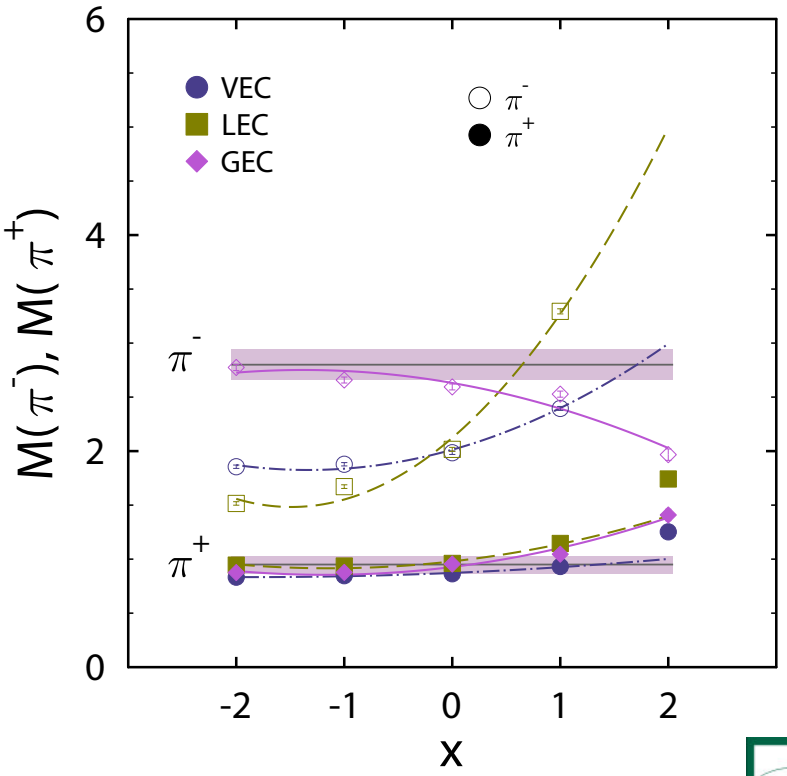
Cozma arXiv:1409.3110 claims that relative π yields are highly sensitive to the manner in which energy conservation is imposed on individual collisions in case of mo-dependent mean fields.

Problem: Detailed balance relations not considered.

$$\sigma\, v \propto \int \mathrm{d}\boldsymbol{p}\, \delta(E - E)\, |\mathcal{M}|^2$$

$$\sigma_{NN\to N\Delta} \overset{?}{\Leftrightarrow} \sigma_{N\Delta\to NN}$$

Relative yields for different energy conservations:



Conclusions

- Pions probe high-ρ matter, net density, n/p-ratio, collective flow there! . . . $U(p)$
- Uncertainties in the near-threshold π production: Δ lifetime, π & Δ optical potentials, in-medium rates.
- pBUU reproduces FOPI π^-/π^+, irrespectively of details in U and S.
- High-energy π^+/π^- ratio more robust than ratio of net yields. Sensitivity to the dependence of effective masses on isospin?
- Azimuthal dependence of π^+/π^- ratio?

Acknowledgement: US Natl Science Foundation

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