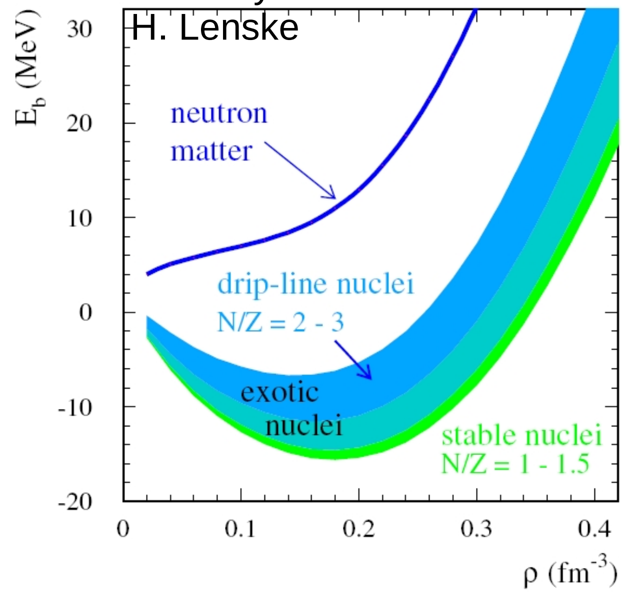
Constraining the symmetry energy at supra – saturation densities with heavy ion reactions

Yvonne Leifels
GSI, FOPI collaboration

courtesy T. Aumann
H. Lenske



An experimentalists overview

Introduction
Will be skipped

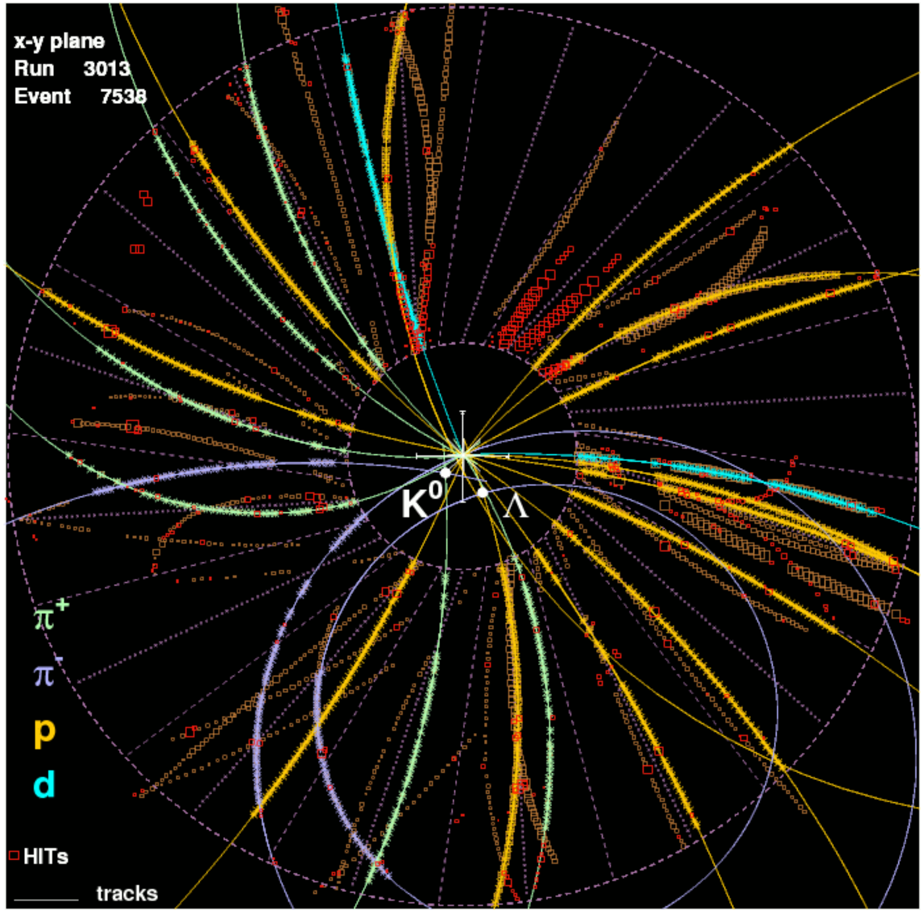
~~**Detectors for HICs at 90-600 AMeV**~~
~~New detectors~~
~~Existing detectors~~

Characteristics of Heavy Ion collisions
Some...

Models
H. Wolter → Friday

Probes - Current status
π-/π+
n/p
t/3He
Strangeness

Summary/Conclusions

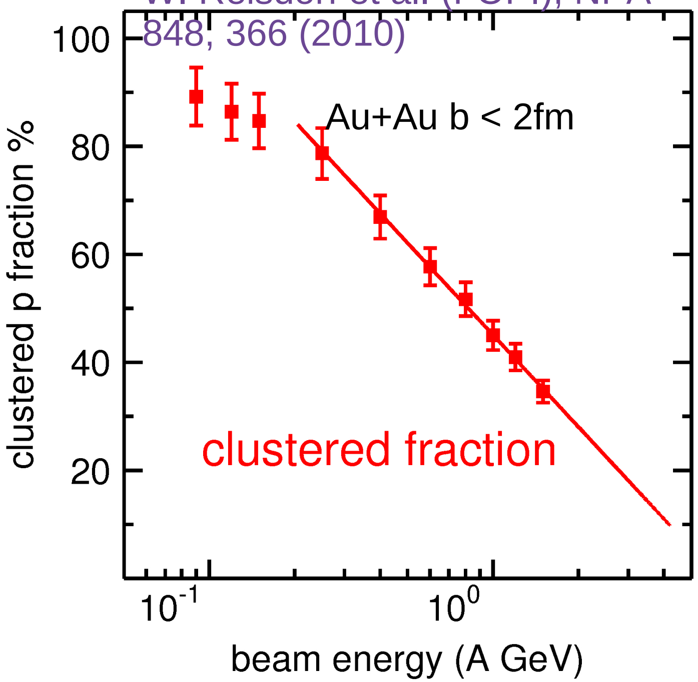


FOPI xy – view, Ni+Ni 1.93 AGeV

Some characteristics of Heavy ion collisions at beam energies > 100A MeV

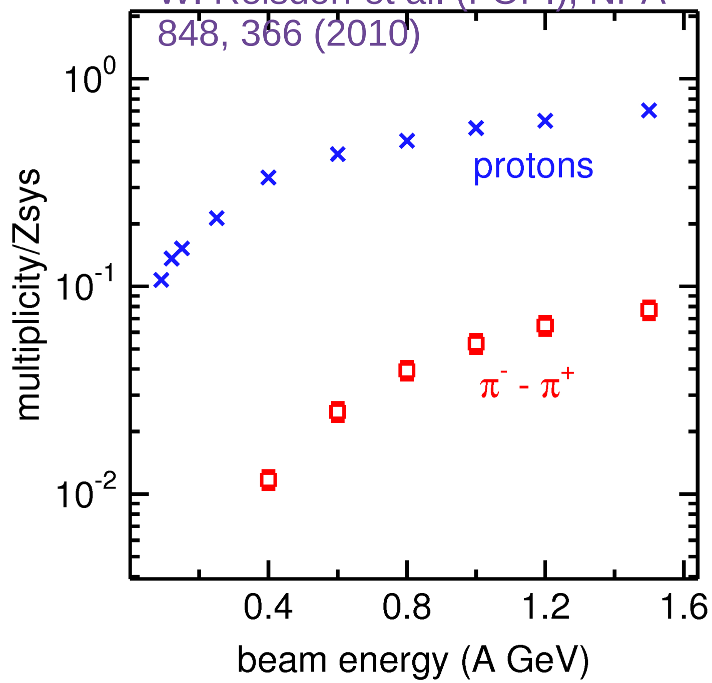
Heavy ion reactions at SIS18 enegies

Clusterization



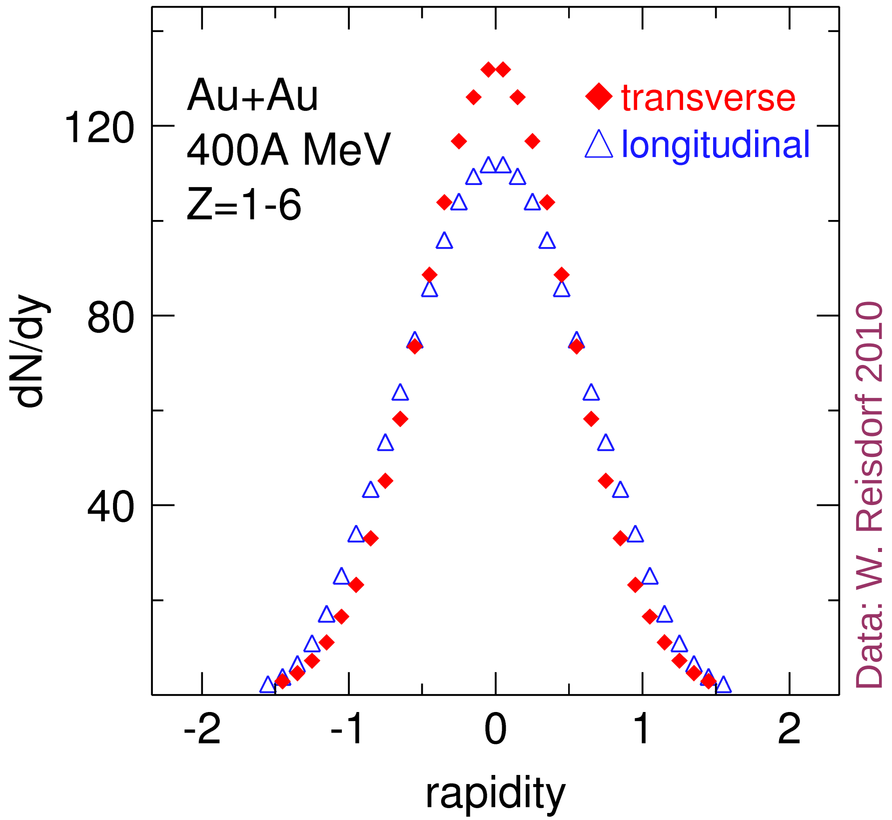
- Large amount of nucleons are bound in clusters (deuteron...)
- Clusterization non-perturbative
- Coalescence picture not valid in general → clusters may be formed early

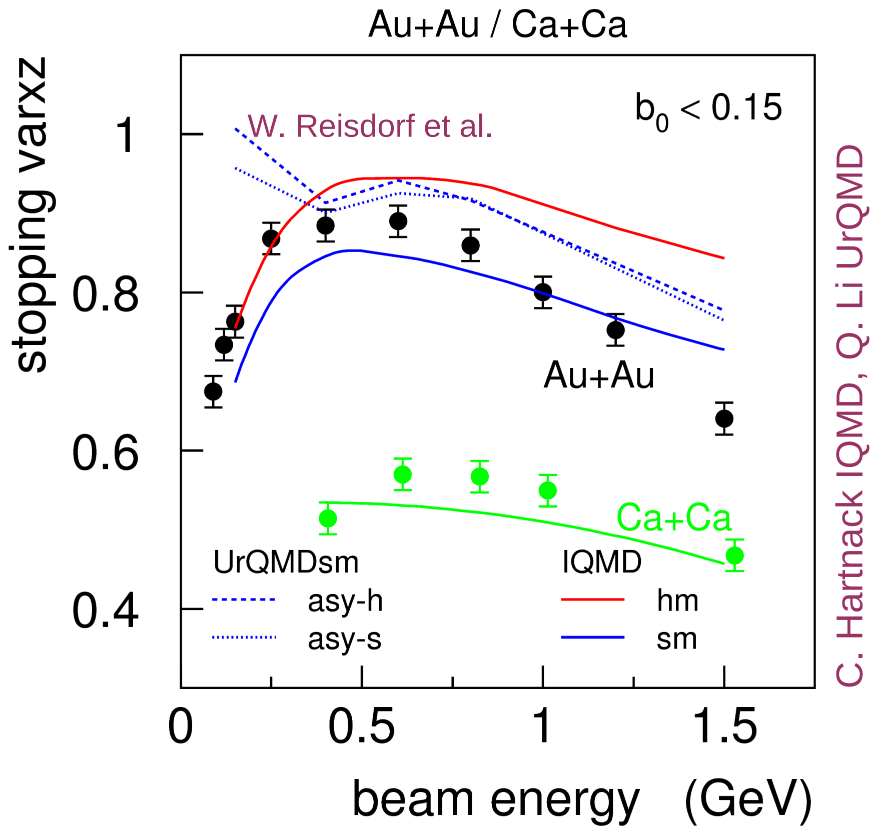
Particle production



- Onset of particle production
- Pion threshold $E_{lab,NN}$ = 290 MeV
- $K^{+/0}$ threshold $E_{lab,NN}$ = 1.6 GeV
- η threshold $E_{lab,NN}$ = 1.25 GeV

Stopping in HICs at SIS18





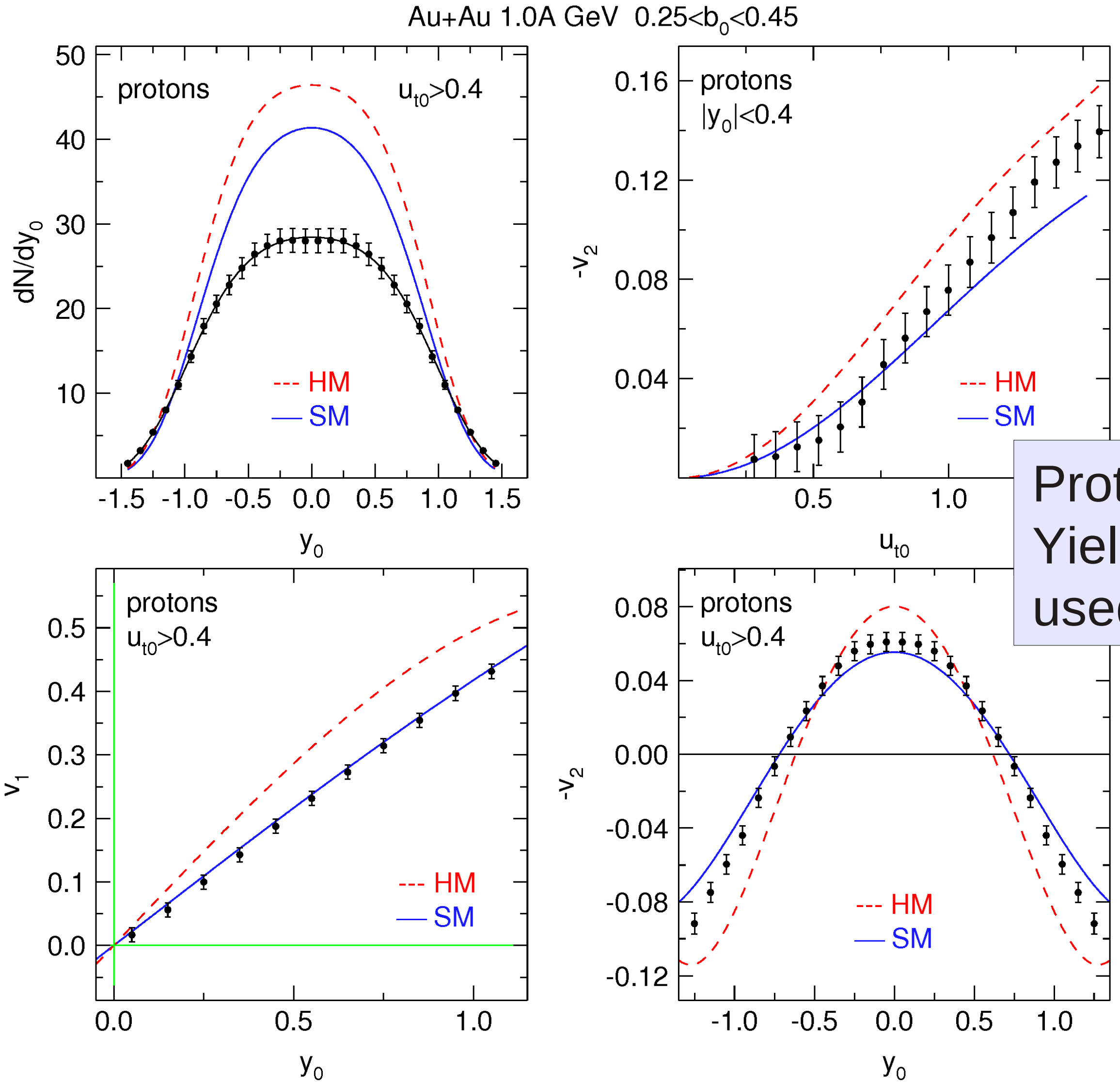
Stopping observable:

$$varxz = \frac{\sigma^2(y_{t,x})}{\sigma^2(y_{l,z})}$$

- Stopping reaches a maximum at ~400-500A MeV
- As do
  - directed flow
  - elliptic flow

Comparison FOPI data to IQMD

Yields, direct and elliptic flow v_2



Proton yield overestimated, Yields depending potential used in model

$$
\begin{aligned}
V^{ij} &= G^{ij} + V^{ij}_{\text{Coul}} \\
&= V^{ij}_{\text{Skyrme}} + V^{ij}_{\text{Yuk}} + V^{ij}_{\text{mdi}} + V^{ij}_{\text{Coul}} + V^{ij}_{sym} \\
&= t_1\delta(\vec{x}_i - \vec{x}_j) + t_2\delta(\vec{x}_i - \vec{x}_j)\rho^{\gamma-1}(\vec{x}_i) + t_3\frac{\exp\{-|\vec{x}_i - \vec{x}_j|/\mu\}}{|\vec{x}_i - \vec{x}_j|/\mu} + \\
&\quad t_4 \ln^2(1 + t_5(\vec{p}_i - \vec{p}_j)^2)\delta(\vec{x}_i - \vec{x}_j) + \frac{Z_i Z_j e^2}{|\vec{x}_i - \vec{x}_j|} + \\
&\quad t_6 \frac{1}{\varrho_0} T_3^i T_3^j \delta(\vec{r}_i - \vec{r}_j)
\end{aligned}
$$

2 and 3 body interactions (no equilibrium required)

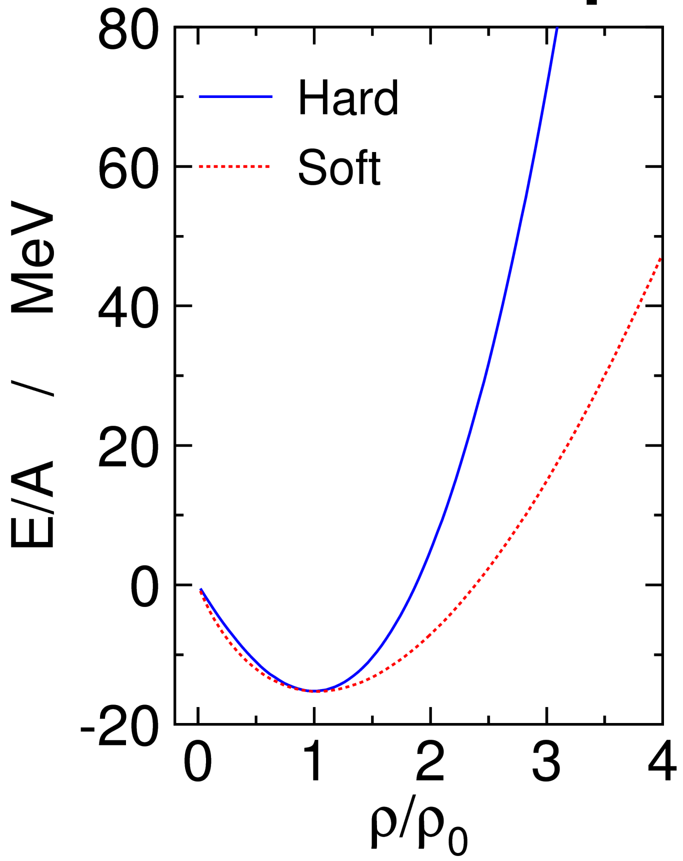
Bethe Weizsaecker –mass formula:

Volume term (with eos) **+Surface term** **+Coulomb term** **+symmetry term**

(+pairing term not included)

Inside IQMD...

after the convolution of the Skyrme type potentials supplemented by momentum dependent interactions (mdi) for infinite saturated nuclear matter at equilibrium



$$U_{skyrme} = \alpha \cdot \left(\frac{\rho}{\rho_0}\right) + \beta \cdot \left(\frac{\rho}{\rho_0}\right)^{\gamma} + \delta \ln^2\left(\epsilon \left(\Delta \vec{p}\right)^2 + 1\right) \cdot \left(\frac{\rho}{\rho_0}\right)$$

IQMD	α MeV	β MeV	γ	δ MeV	ε c^2/GeV^2	κ MeV
S	-356	303	1.17	-	-	200
SM	-390	320	1.14	1.57	500	200
H	-124	71	2.00	-	-	376
HM	-130	59	2.09	1.57	500	376

Models → Talk of Hermann Wolter

Probes

Probes

- Pions

  What a mess?

- n/p

  Difficult

- t/3He

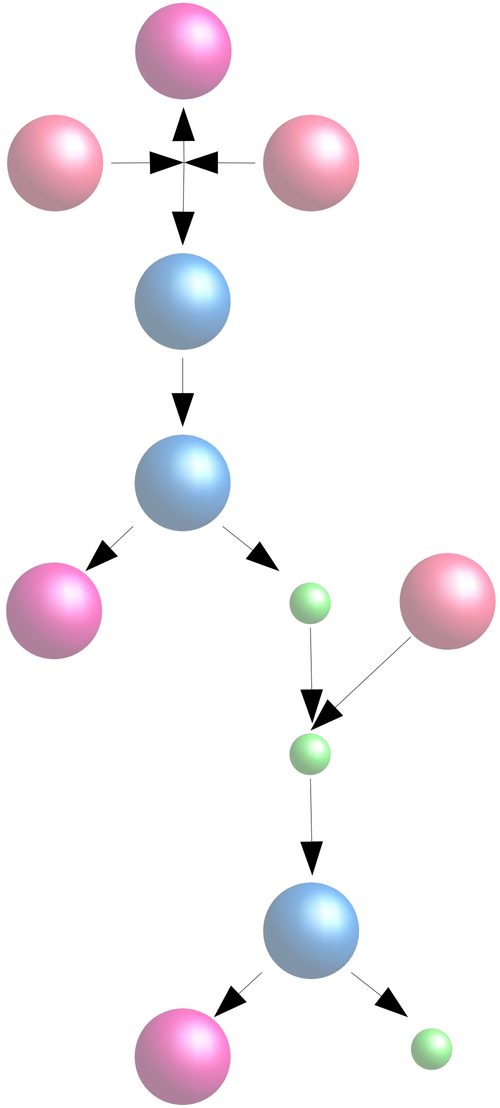
  hmm...

- Strangeness

  Challenging

Pion production

Inelastic cross sections



- pion production most dominant channel
- threshold energy in fixed target pp collisions 0.29 GeV
- pp and np cross sections differ
- production via resonances (Δ, N*)
- pion production sensitive to N/Z
- in case predominantly via Δ

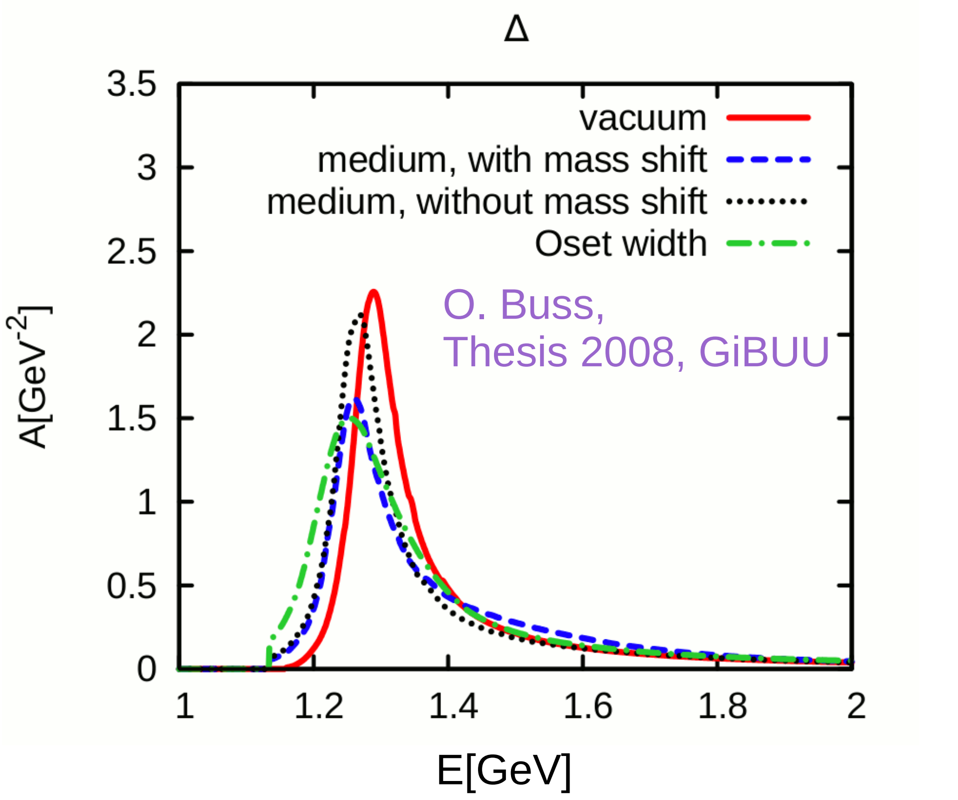
$$\frac{\pi^-}{\pi^+} = \frac{5N^2 + NZ}{5Z^2 + NZ} \approx \left(\frac{N}{Z}\right)^2$$

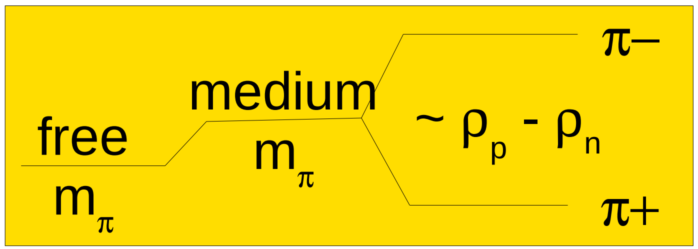
- pion recreation cycle

$$NN \rightarrow NN \qquad NN \rightarrow N\Delta$$
$$N\Delta \rightarrow NN \qquad \Delta \rightarrow N\pi$$
$$N\pi \rightarrow \Delta$$

Pion production "en-detail"

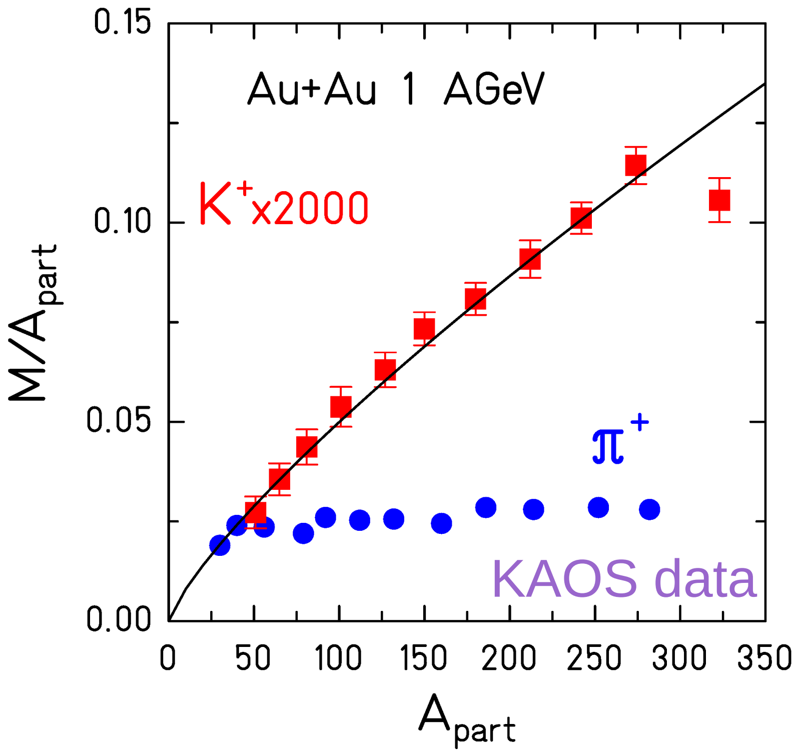
- Relevant isospin dependent cross sections
- Detailed balance
- N
  - Momentum-dependent potential
  - Pauli-blocking
- Δ
  - Pauli-blocking of final states
  - Collisional broadening of width, new decay channels in medium
  - Momentum-dependent potential, U_{opt} ~ -30 MeV (Ericson-Weise, "Pions and nuclei")
  - Off – shell propagation
- π
  - Potential derived from self energy
  - Pauli – blocking of states if π is absorbed



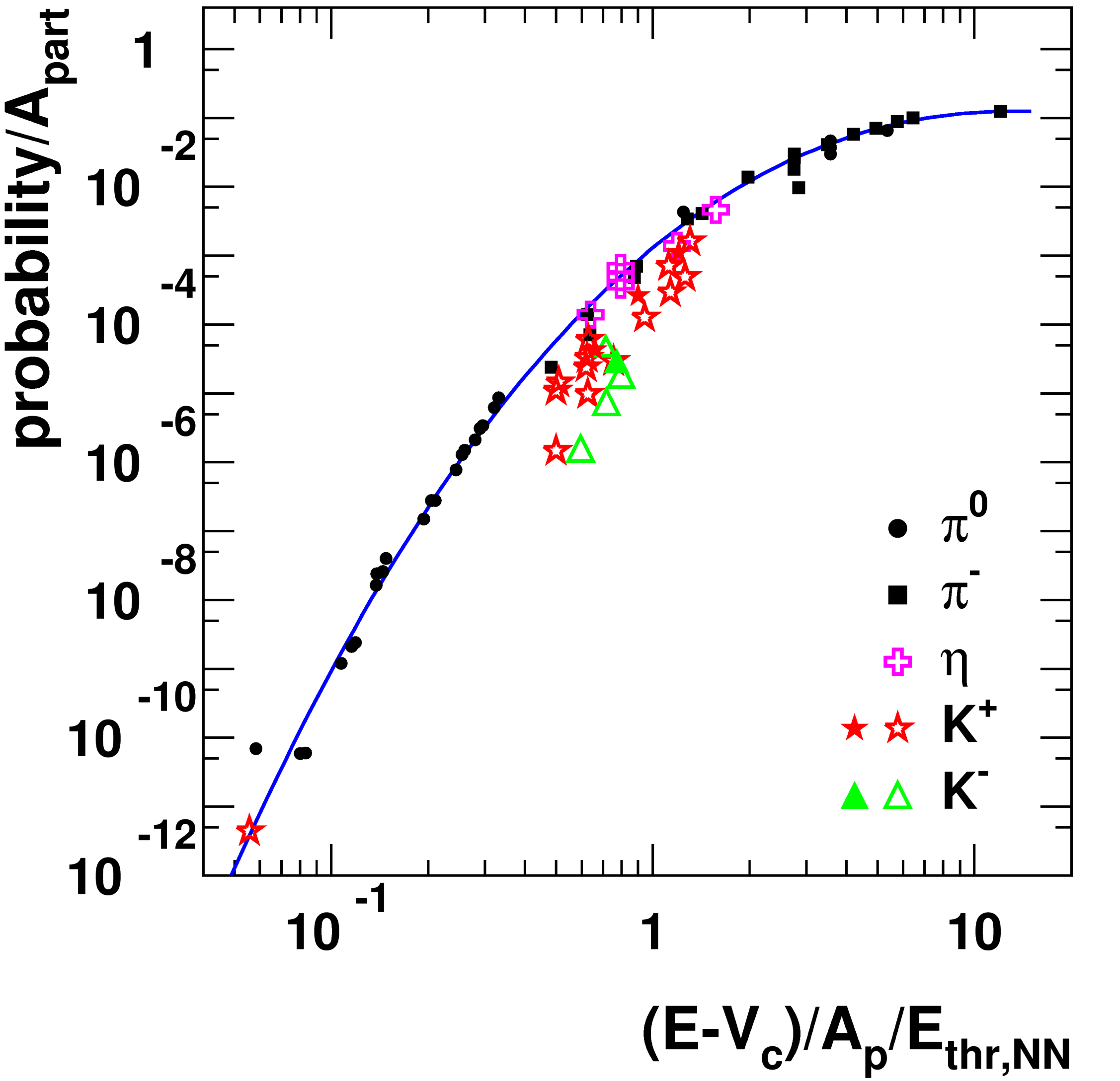


Sub-threshold pion production

- Pion production measured far below threshold in HICs
- M/A_{part} of π independent of A_{part}

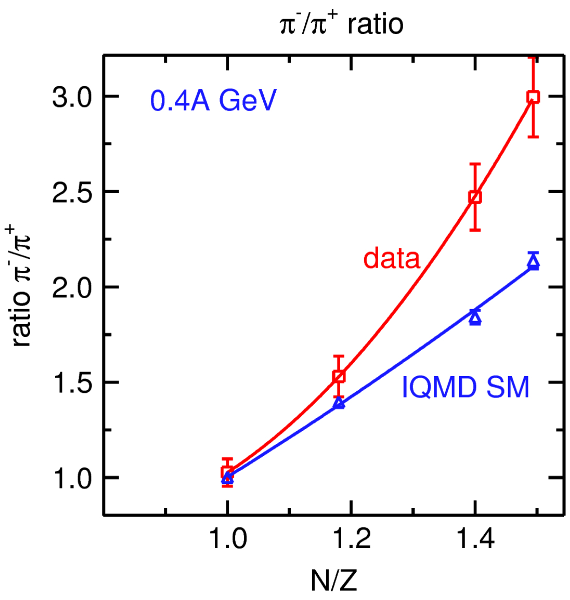


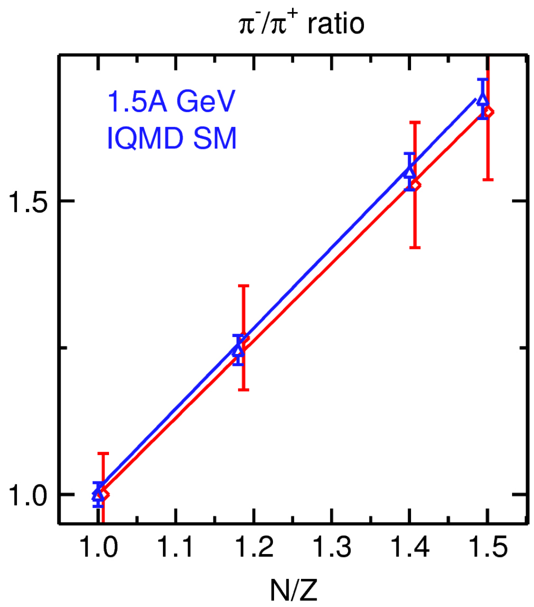
meson-production probability (V.Metag)

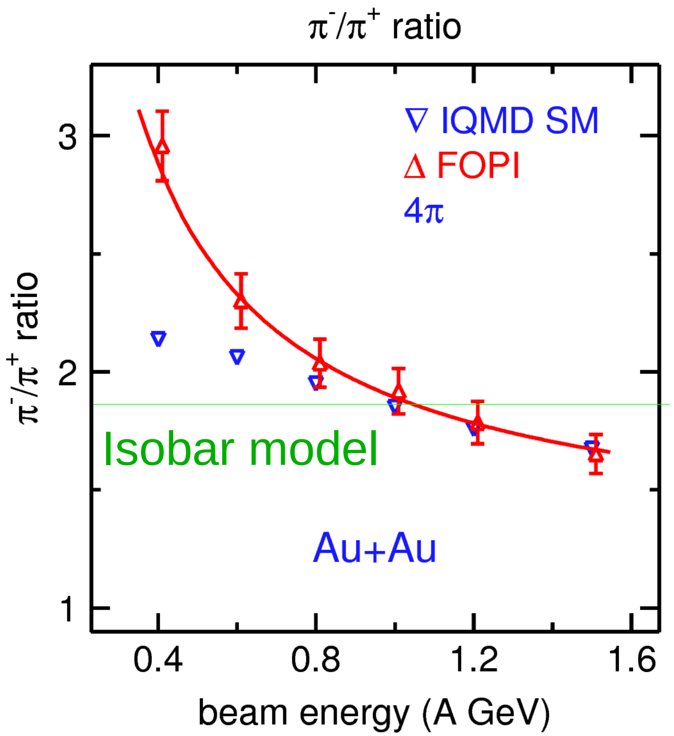


Experimental data at 400A MeV

W. Reisdorf et FOPI
Nucl.Phys.A781:459-508,2007







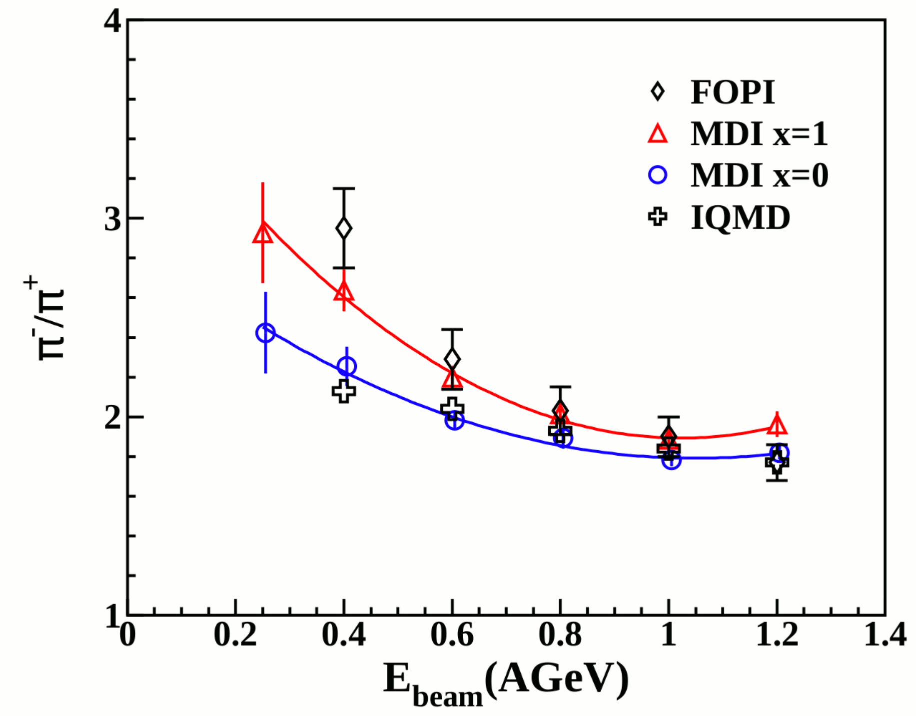
low(er) E/A: perturbative
~ $(N/Z)^2$
predicted by isobar model

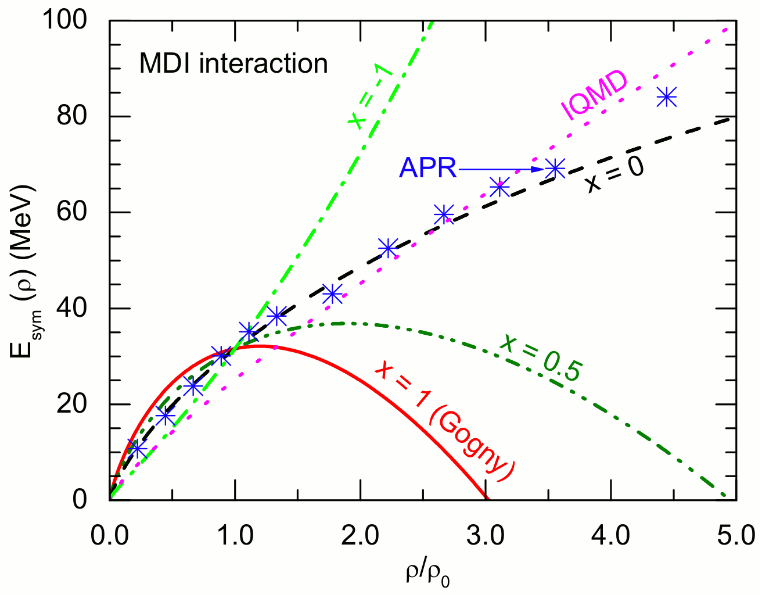
high(er) E/A: back-flow
~ (N/Z)
measure π^-/π^+ and n/p

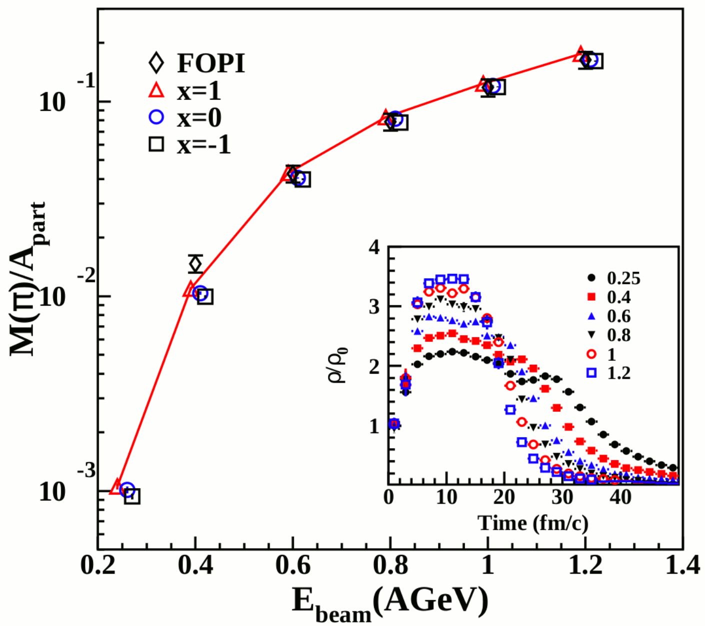
$(N/Z)_{final} < (N/Z)_{init}$

Isobar model value ~ 1A GeV
Value at high energies → 1

Confrontation with models

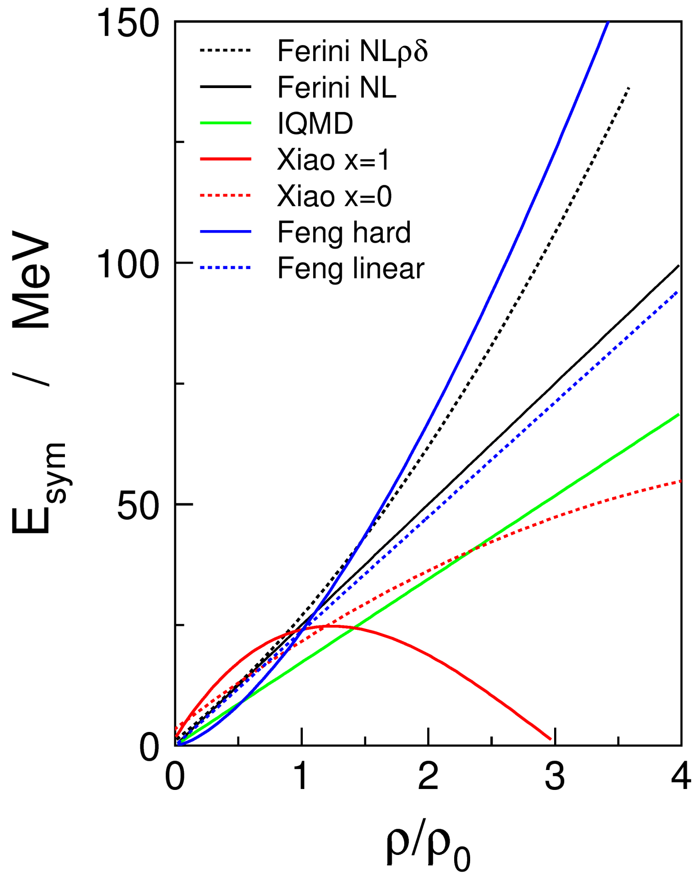


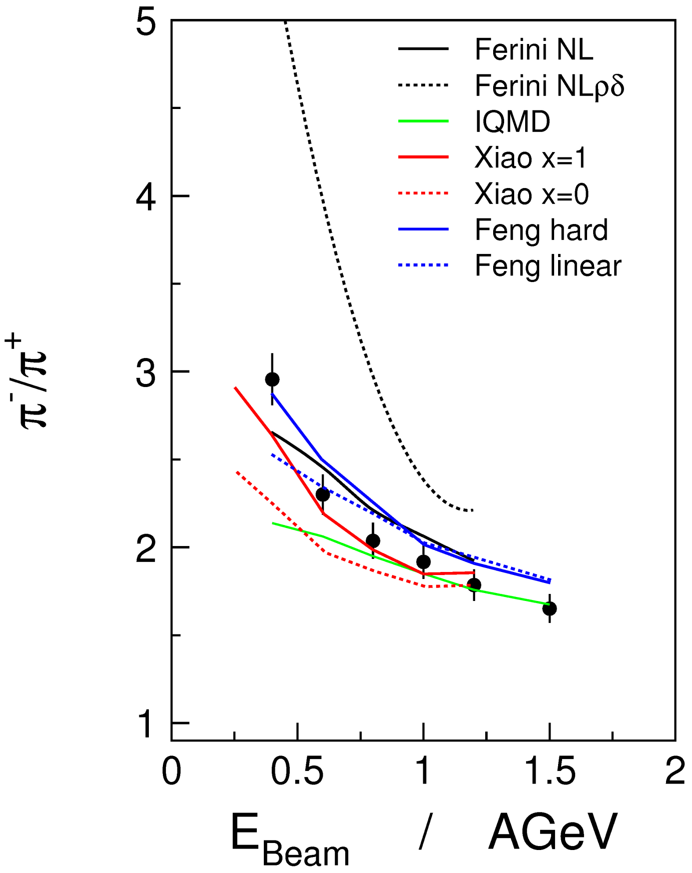




- Ratio vs beam energy described by very soft SE
- Ratio vs N/Z descreibed
- Measured multiplicities reproduced independent of SE

World could have been so nice...





Z. Xiao et al. PRL 102 (2009) 625
J. Xie et al, PLB 718 (2013)
J. Xu et al., nucl-the 1305.0099
G. Ferini et al. PRL 97 (2006) 202301
Feng et al, nucl-th 0907.2990
C. Hartnack, J. Aichelin (2013)
J. Hong, P. Danielewicz (2013)

This status lasts now for 4 years...

Attempts to explain differences:
M. Di Toro et al., arXiv:1003.2957

- symmetry energy → n/p ratio, number of nn, np, pp collisions

$$\text{asy stiff} \quad \frac{n}{p}\downarrow \Rightarrow \frac{Y(\Delta^{0,-})}{Y(\Delta^{+,++})}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$$

- medium → effective masses (N, π, Δ), cross sections
  → thresholds

$$\text{asy stiff} \quad \Rightarrow \frac{\pi^-}{\pi^+}\uparrow$$

Model comparison:
Transport at low energies Trento 2009 → H. Wolter
IBUU04 vs UrQMD → Models give different results with respect to N/Z ratios, time evolution of N/Z etc. (W.M. Guo et al. arxiv:1306.4873v1)

→ **Common effort needed**

Comparison of models

Model	Type	SE	U_{NN}	N mass	Δ	Δ Pot.	det. Bal.	π mass	σ in med
IQMD	QMD-Nantes	Exponent, no kinetic term	Skyrme with momentum	free	phase shift from Randrup	2/3 U_{NN}	yes	free	free, isospin dependent
IBUU04	BUU								
LQMD									
ImQMD									
..									
..									
..									
..									
..									

Probes

- Pions

  What a mess?

- n/p

  Difficult

- t/3He

  hmm...

- Strangeness

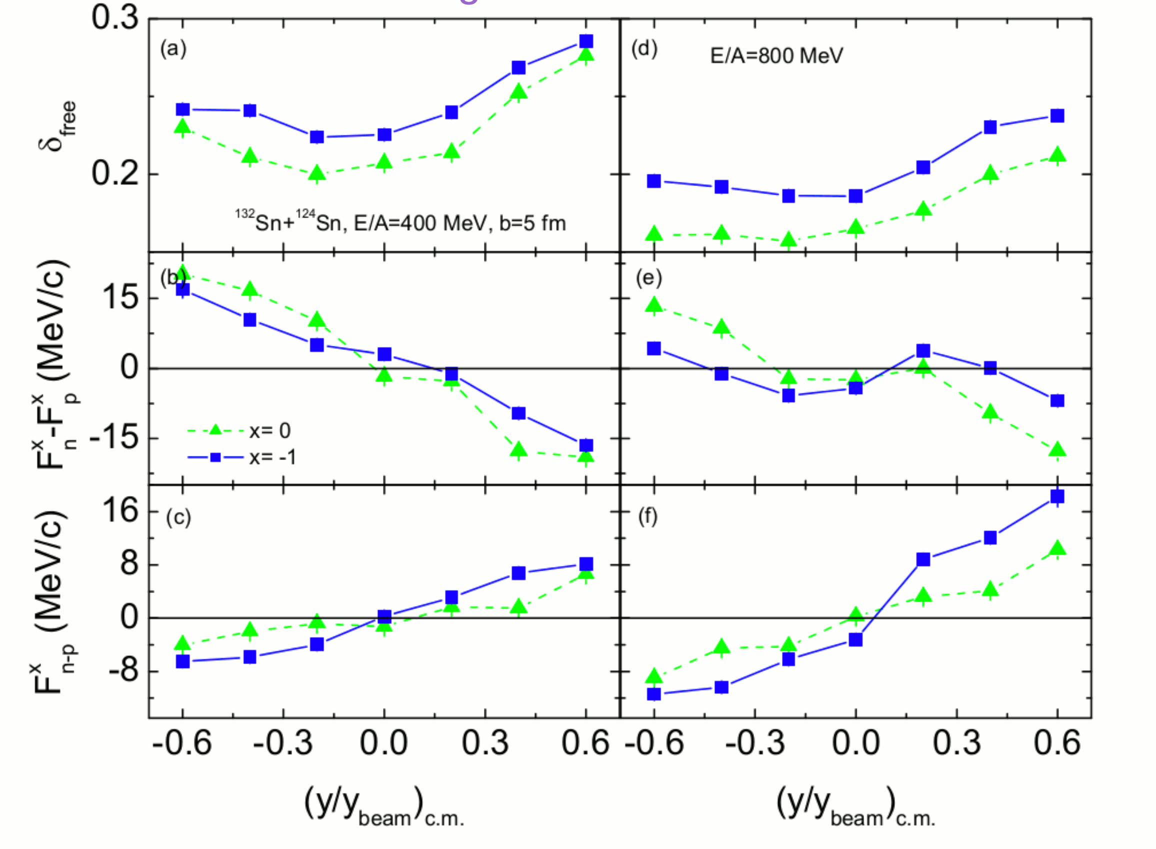
  Challenging

Predictions

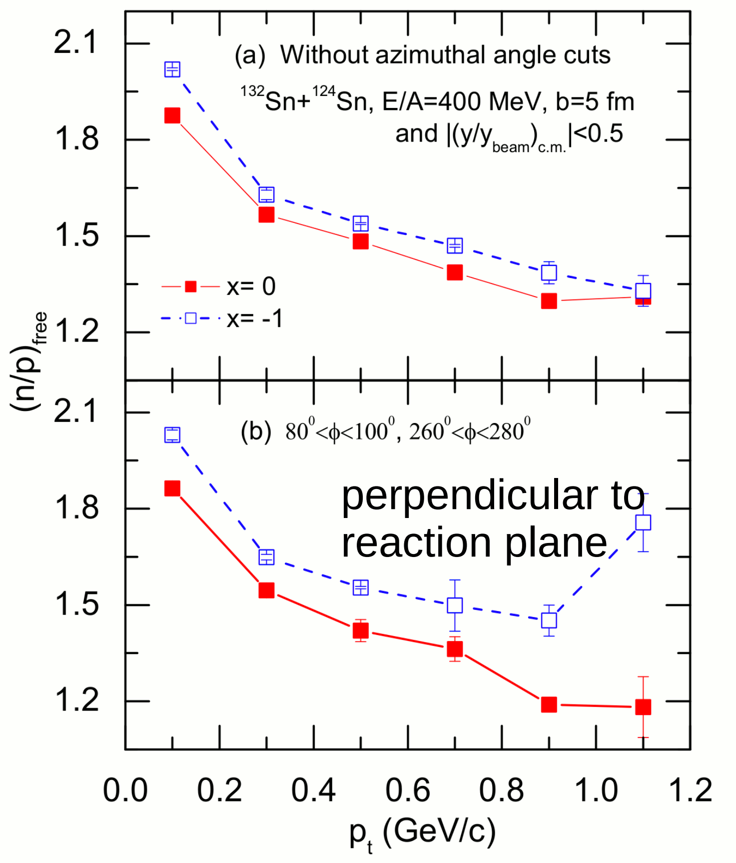
Predicted observables

- n/p ratios
- n/p differential direct flow
- n/p differential elliptic flow

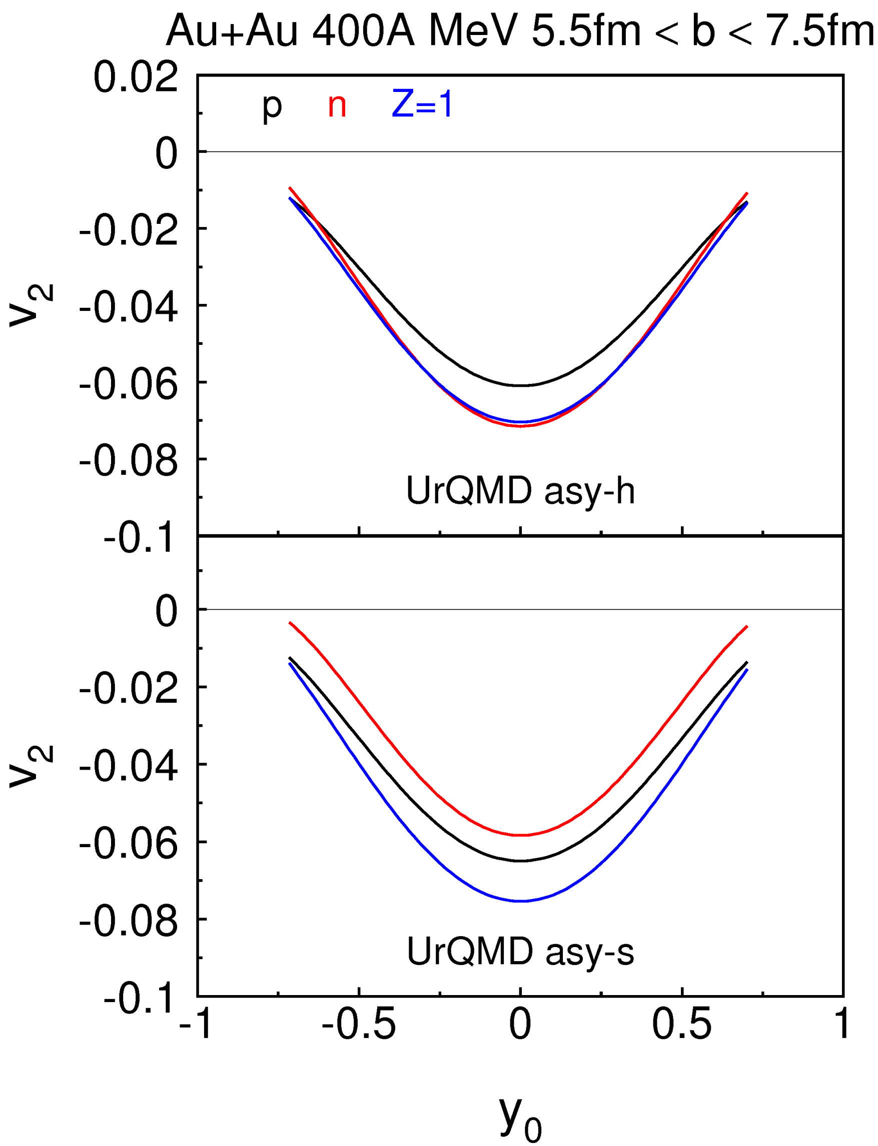
G. Young et al. nucl-the0606003



G. Young et al. nucl-the0703042



Elliptic neutron/proton flow



UrQMD predictions
P. Russotto et al.
PLB 697 (2011) 471

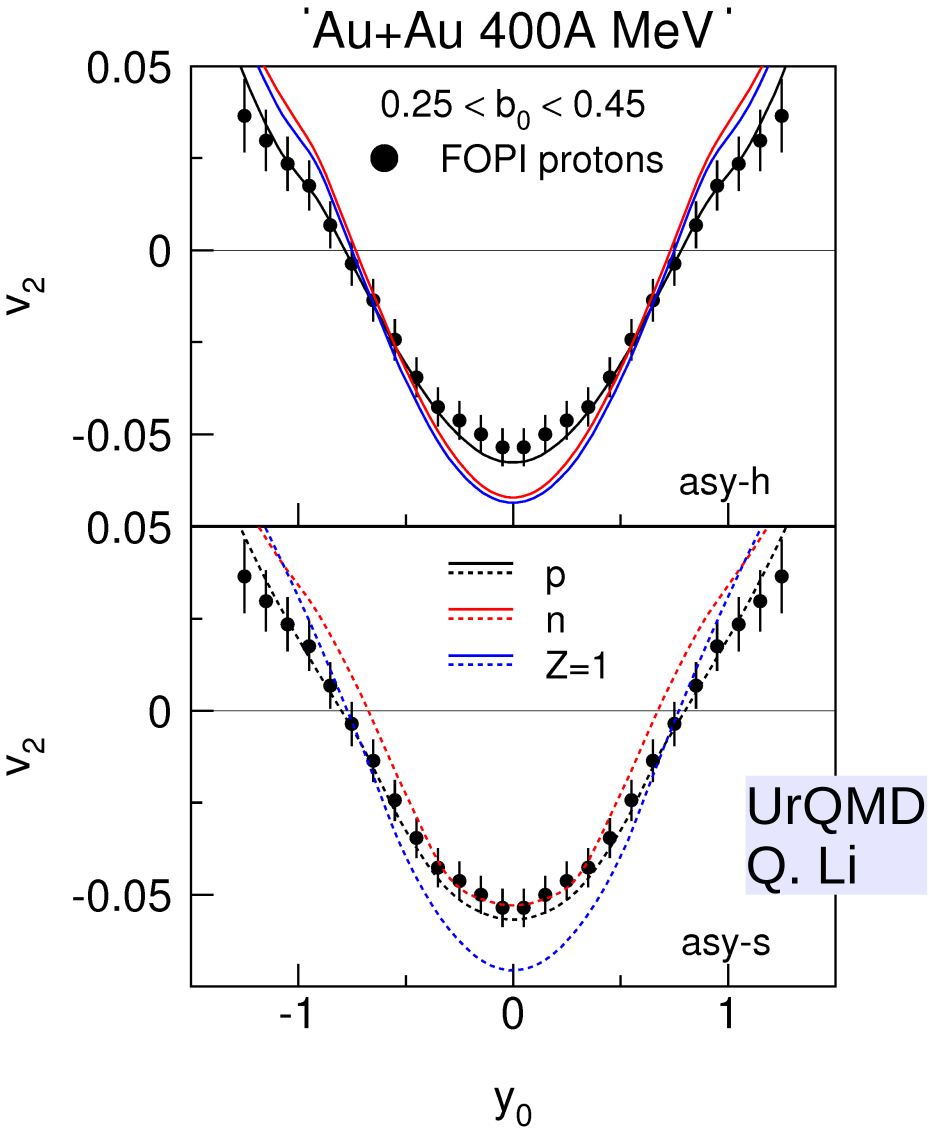
Asy-hard
Neutron elliptic flow as large as Z=1

Asy-soft
Neutron elliptic flow smaller than proton flow

Elliptic neutron/proton flow

Cutted to FOPI acceptance:

- Elliptic flow of protons described by the model predictions
- Elliptic flow of Z=1 not a sensitive observable any more
- Measure neutrons **and** charged particles



Published results

Comparison to UrQMD predictions:

$$E_{sym} = 22\left(\frac{\rho}{\rho_0}\right)^{\gamma} + 12\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

Diffent parametrization for in-medium cross sections

neutron/hydrogen

FP1: γ = 1.01 ± 0.21

FP2: γ = 0.98 ± 0.35

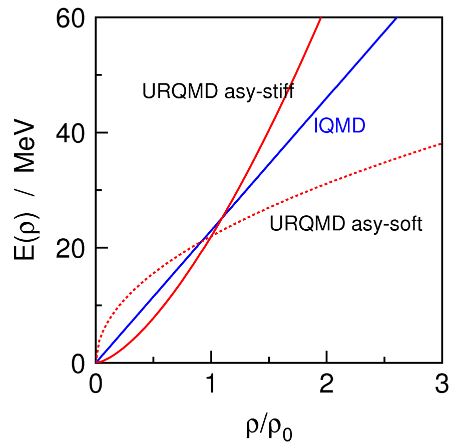
neutron/proton

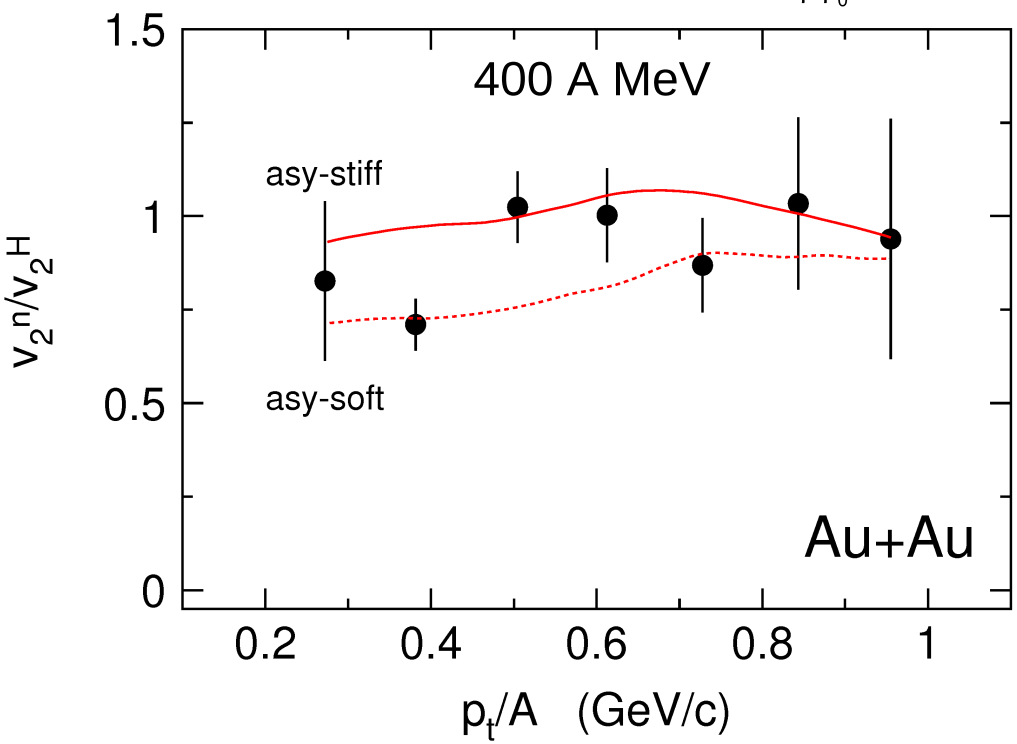
FP1: γ = 0.99 ± 0.28

FP2: γ = 0.85 ± 0.47

adopted: γ = 0.9 ± 0.4

P. Russotto et al., PLB 267(2010)



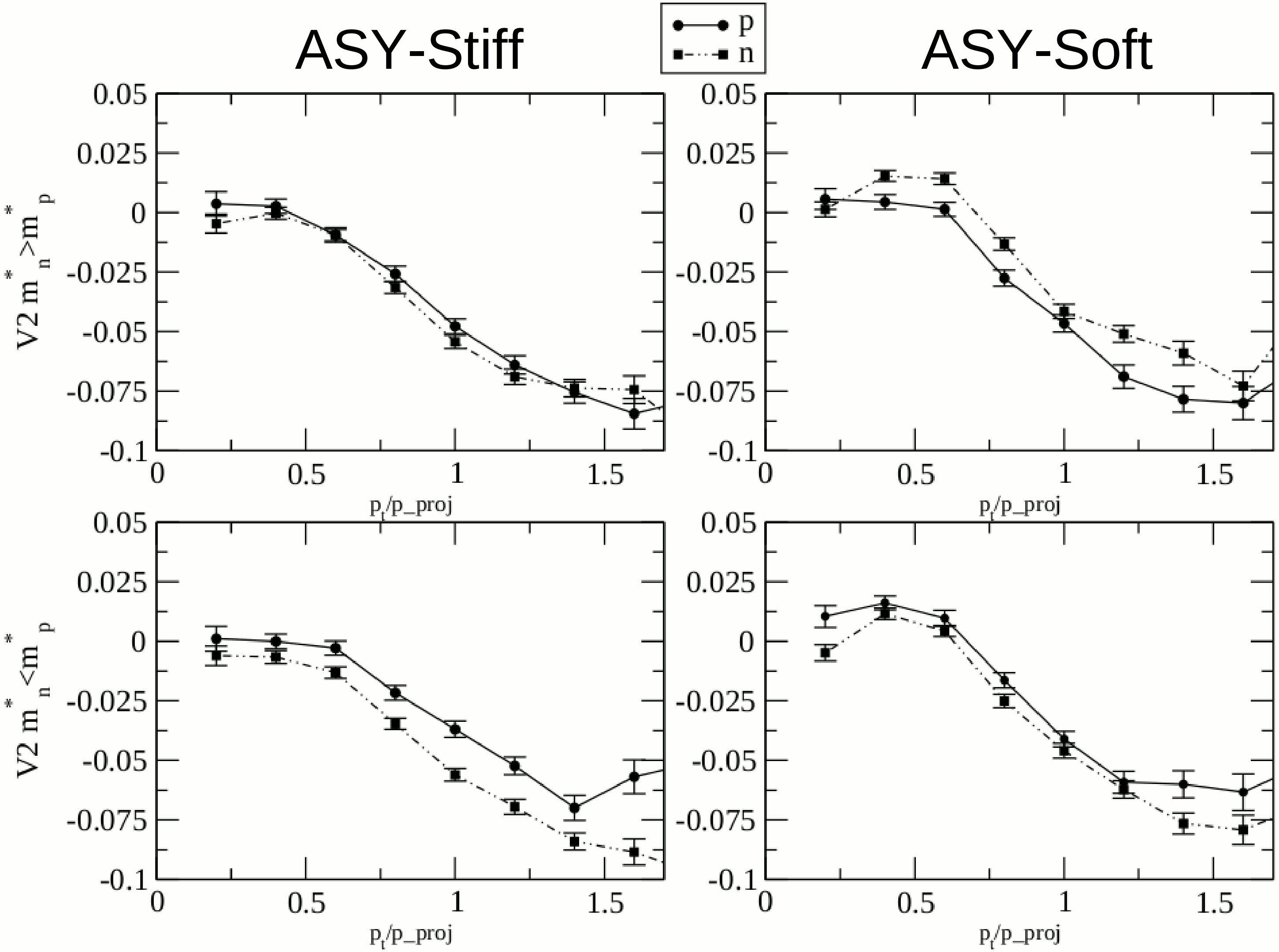


FP1/FP2 different parametrizations for in medium elastic cross sections
→ J. Lukasik

Effective masses still unresoved!

$m_n^{eff} > m_p^{eff}$

$m_p^{eff} > m_n^{eff}$



Di Toro et al., arXiv-nucl-the:1003.2957

Probes

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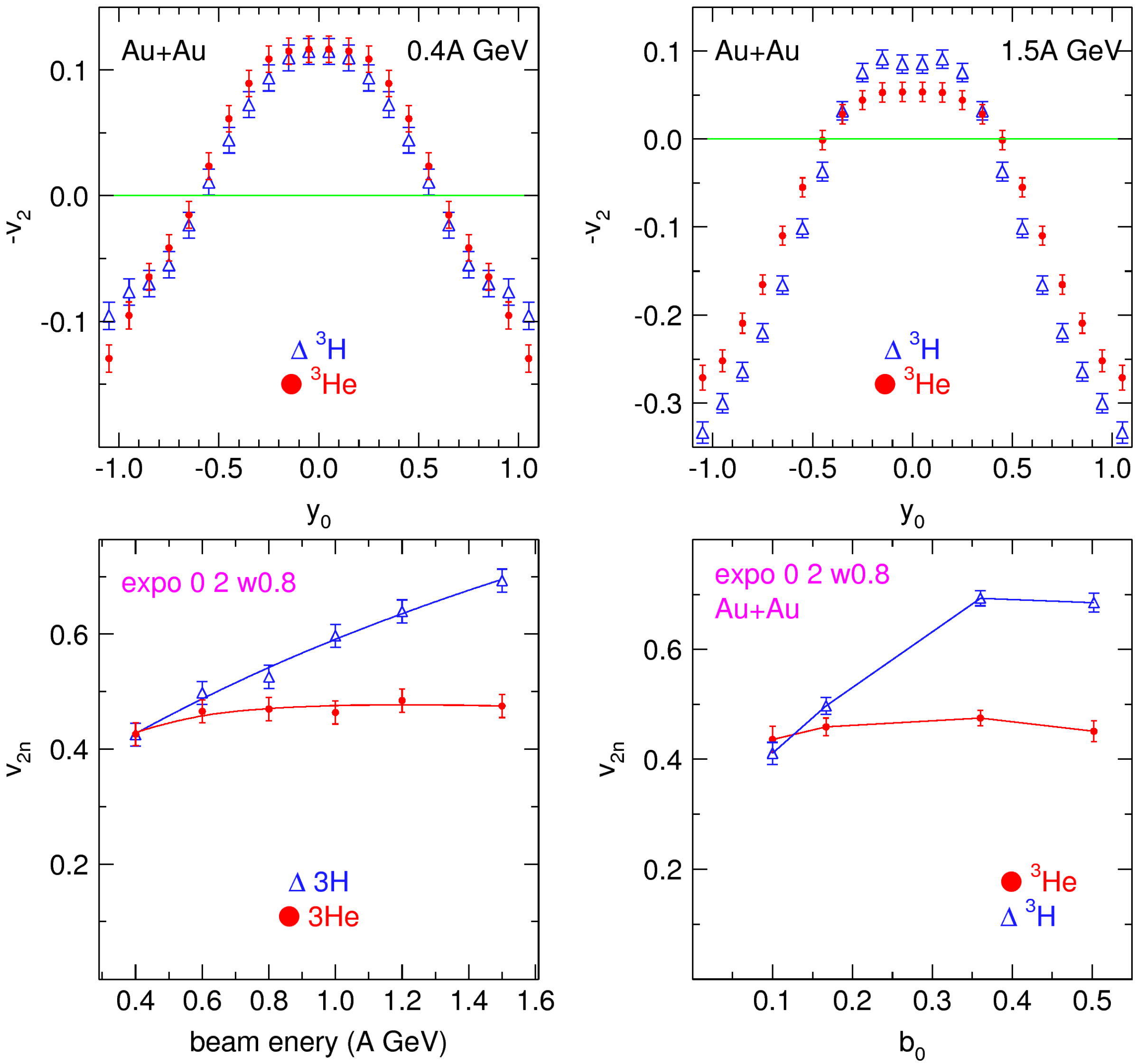
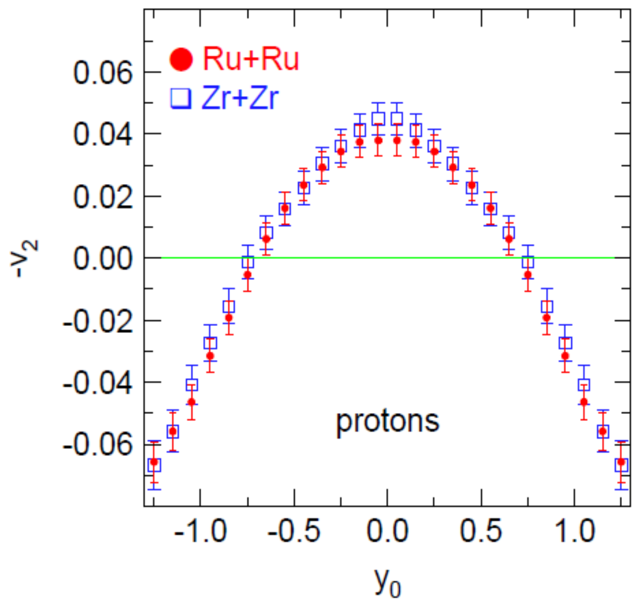
t/3He data

Au+Au ut0>0.4

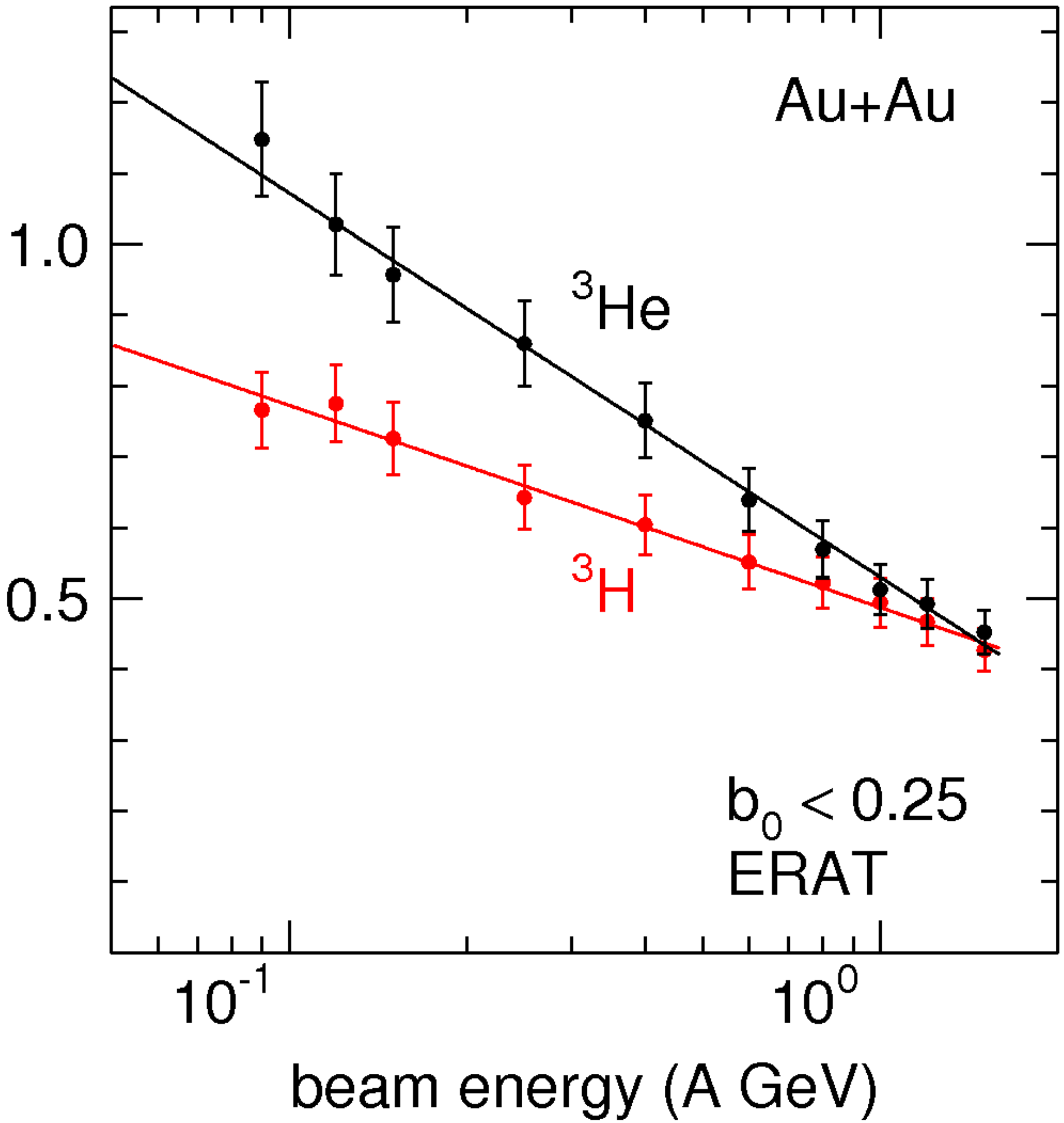




Increasing effects
- beam energy
- impact parameter
- system mass

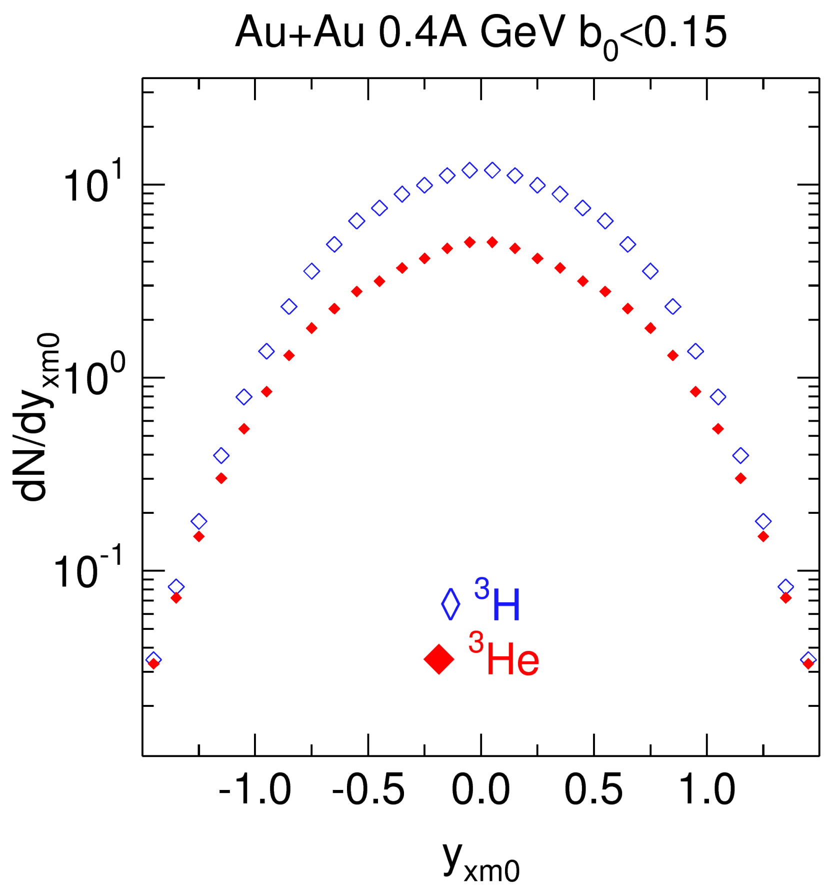
→ Talk of J. Lukasik

The t/3He puzzle

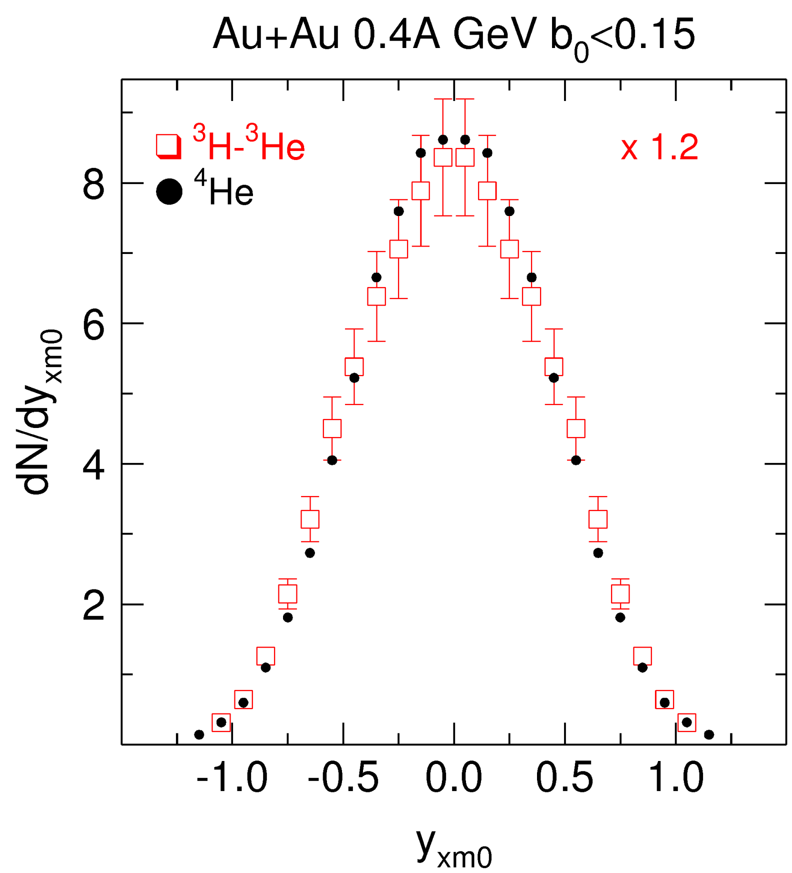


Difference
beyond expectations
for Coulomb at low
energies

Where are all the 3He gone?



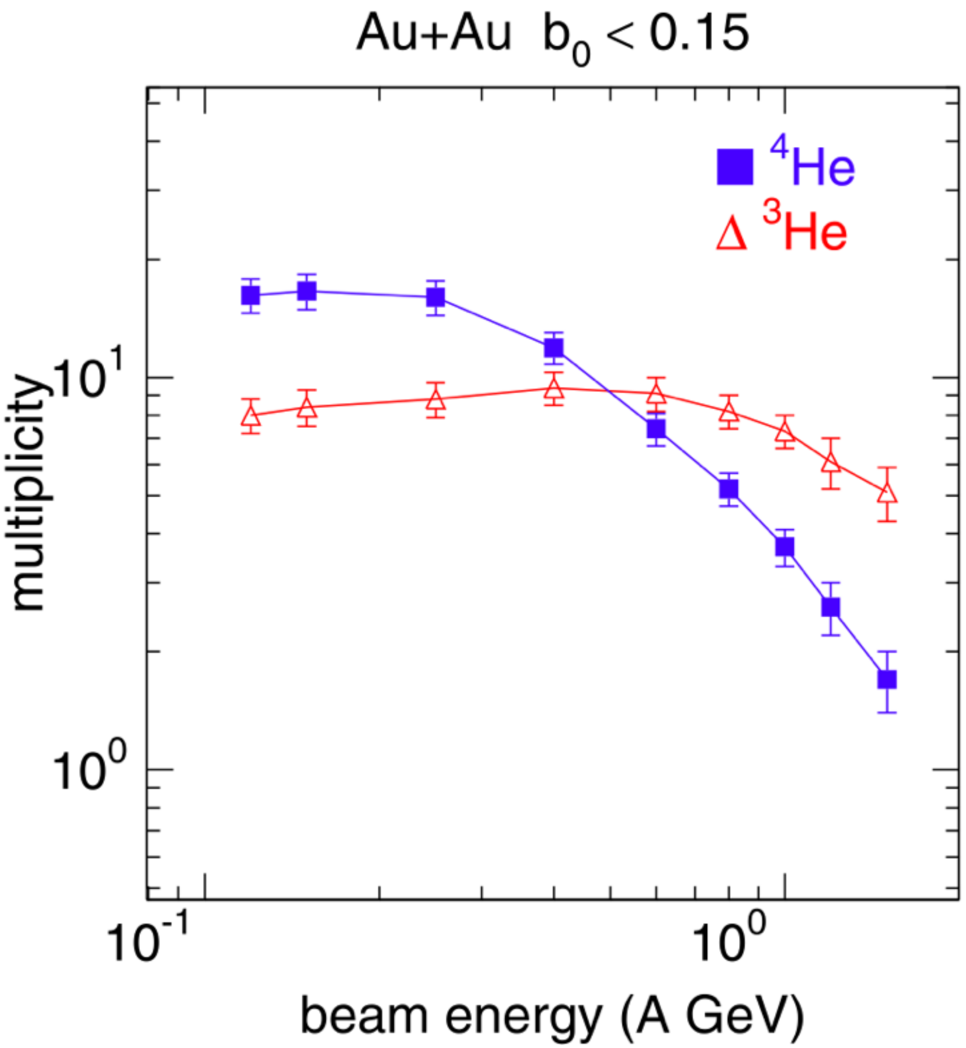
Transverse rapidity spectrum
At high transverse rapidities t and ^{3}He spectra match



→ substracted spectrum matches the ^{4}He spectrum

→ Poster by M. Young

How are all the t's and 3He's made?



What are the underlying mechanisms?
Can one describe that?

Experimentalists approach to clusterization

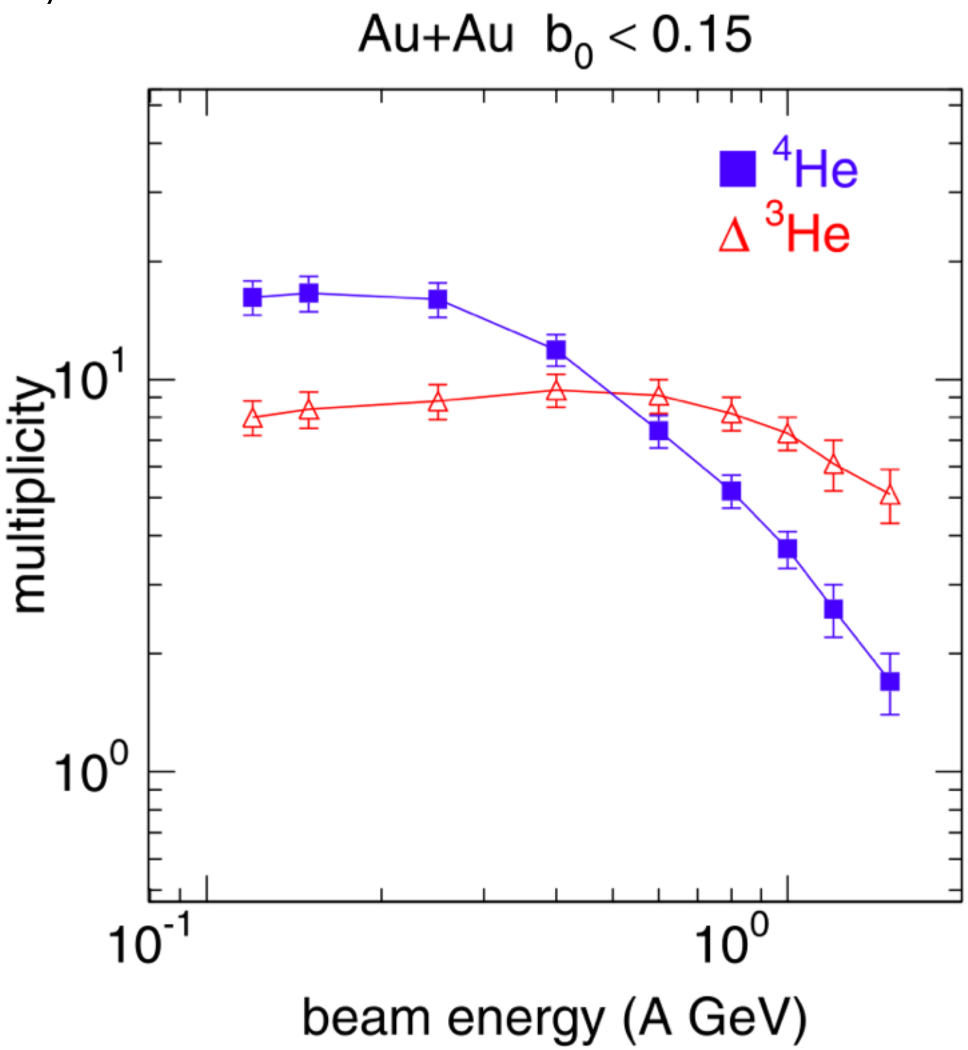
A. LeFevre, C. Hartnack, Y. Leifels, J. Aichelin,

- Good description of flow data
- Z yields can be accounted for
- Isotopic yields difficult
- Influence of cluster formation on flow
- Various studies on the way

Problem with most approaches
start at relatively late times
but
pre-fragments are formed early

Our approach

- Simple algorithm
- Applicable to any transport model
- Using potentials of the transport model
- Starting formation of clusters early
- Propagation in Coulomb field
- Eventually deexcitation by evaporation



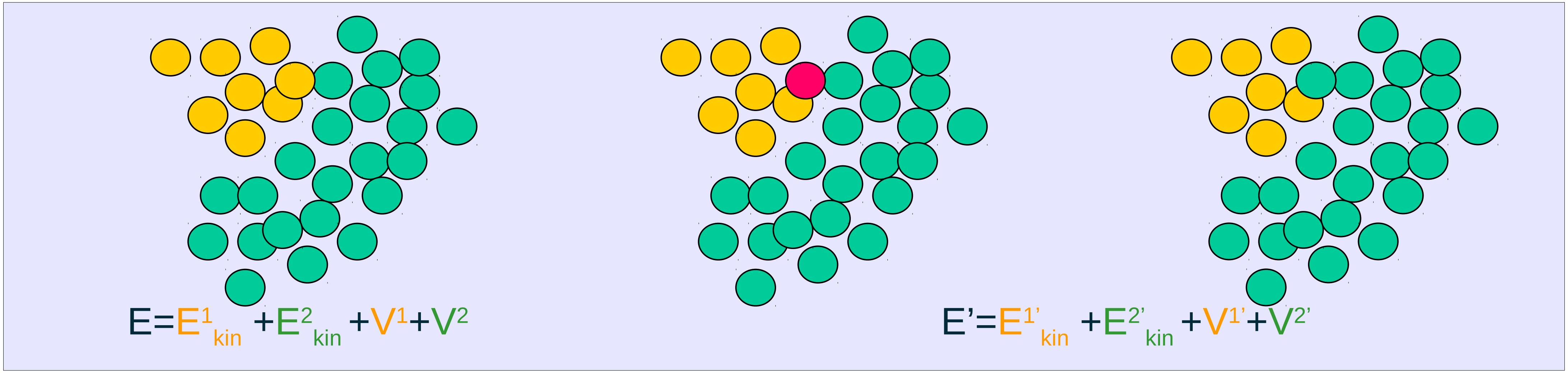
SACA

Simulated annealing cluster algorithm

A. Lefevre, C. Hartnack, J. Aichelin, Y. Leifels

Dorso et al. (Phys.Lett.B301:328,1993)

1. Take randomly 1 nucleon out of pre-seleceted fragment
2. Add it randomly to another fragment

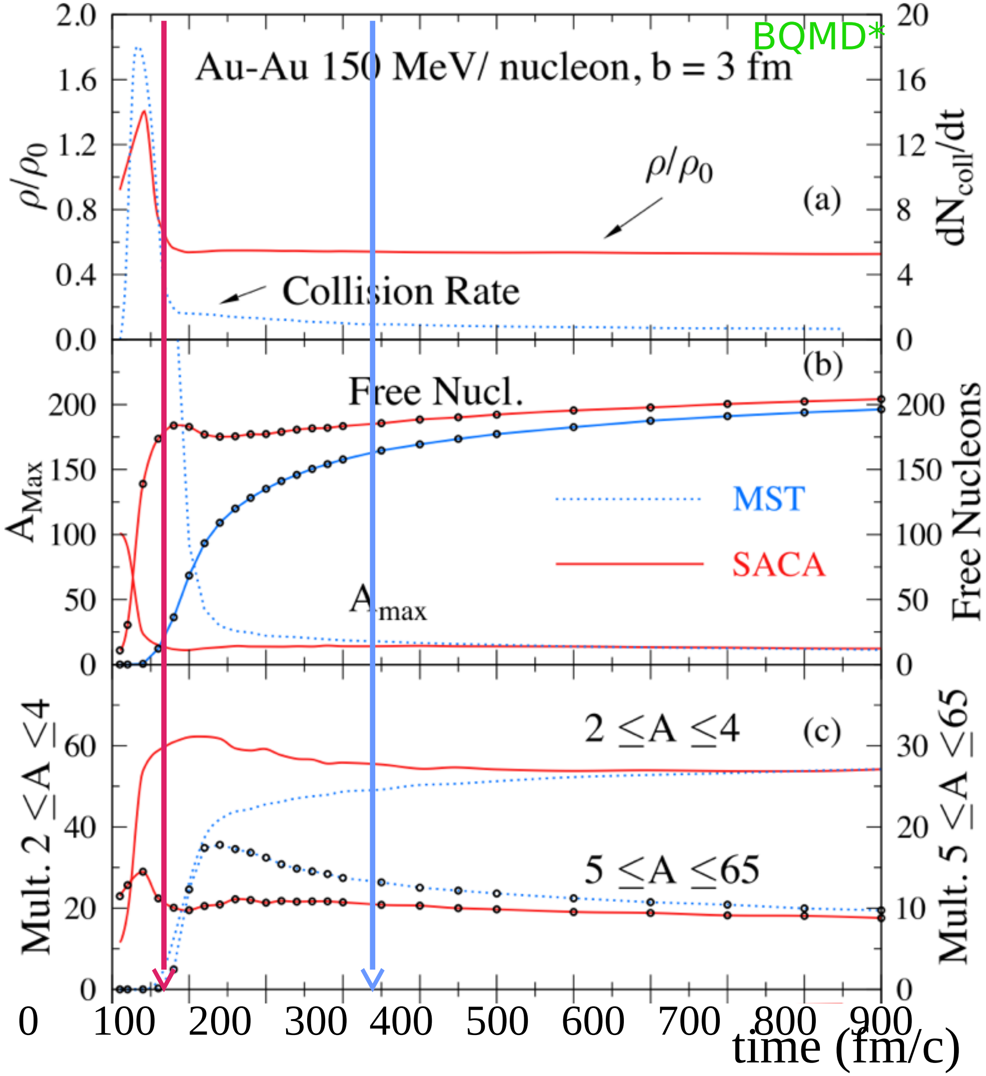


<u>E' < E</u> → new configuration
<u>E' > E</u> → old configuration with a probability depending on E'-E
Repeat this procedure very many times...
→ leads to the most bound configuration
(Metropolis algorithm)

SACA

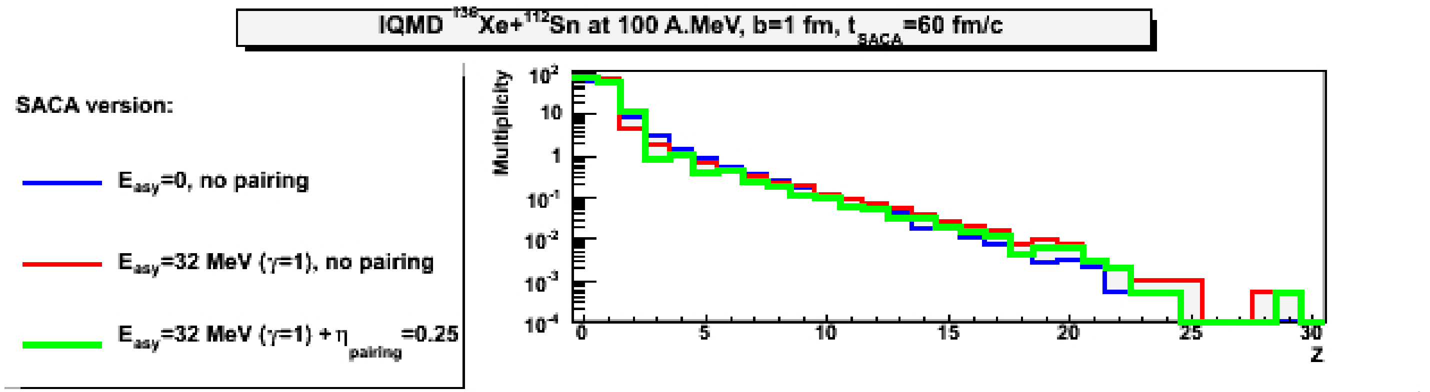
SACA produces stable fragment yiels relativly early

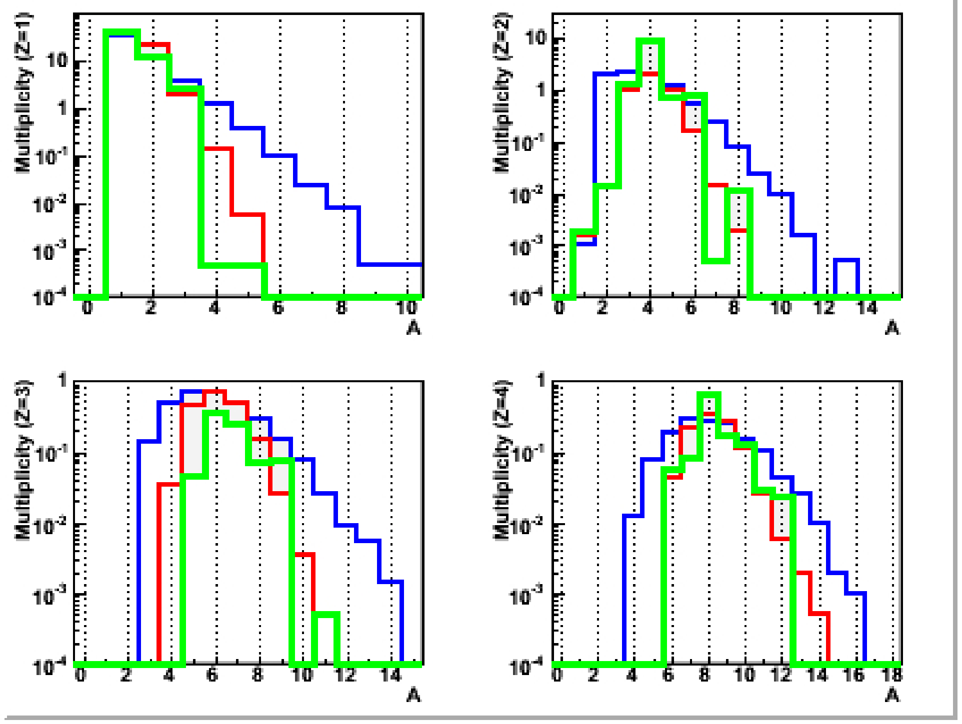
- ➔ MSTs yield stable fragment distributions at later times (150-400 fm/c), where the dynamical conditions are no longer the same.
- ➔ Advantage of SACA: the fragment partitions can reflect the early dynamical conditions (Coulomb, density, flow details, strangeness...).



* P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390

SACA with pairing





$\Delta B_{pairing}(N,Z,\rho_B)$ =

$\Delta B_{pairing}(N,Z,\rho_0) * f_\eta(N,Z,\rho_B)$

correction function $f_\eta(N,Z,\rho)$ following the approach by E. Khan et al., NPA 789 (2007) 94

$$V_{pairing} = V_0\left(1-\eta\frac{\rho(r)}{\rho_0(r)}\right)\delta(\vec{r}_1-\vec{r}_2)$$

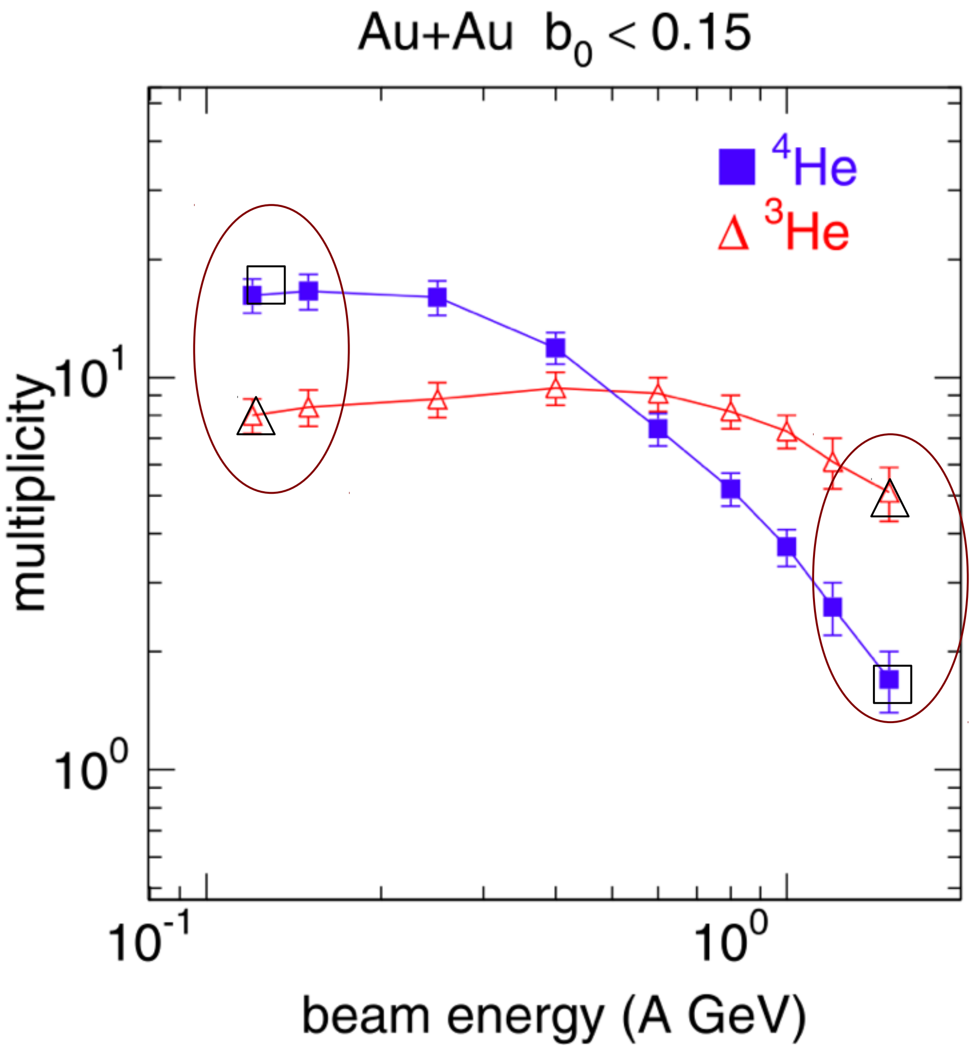
η chosen to fit experimental data (Indra at 150A MeV

And?

W. Reisdorf and the FOPI Collaboration
Nuclear Physics A 848 (2010) 366–427

IQMD + SACA reproduces the low and the high energy yields of t/^{3}He

→ with asymmetry term and pairing at low energies
→ without at the high energy



And?

W. Reisdorf and the FOPI Collaboration
Nuclear Physics A 848 (2010) 366–427

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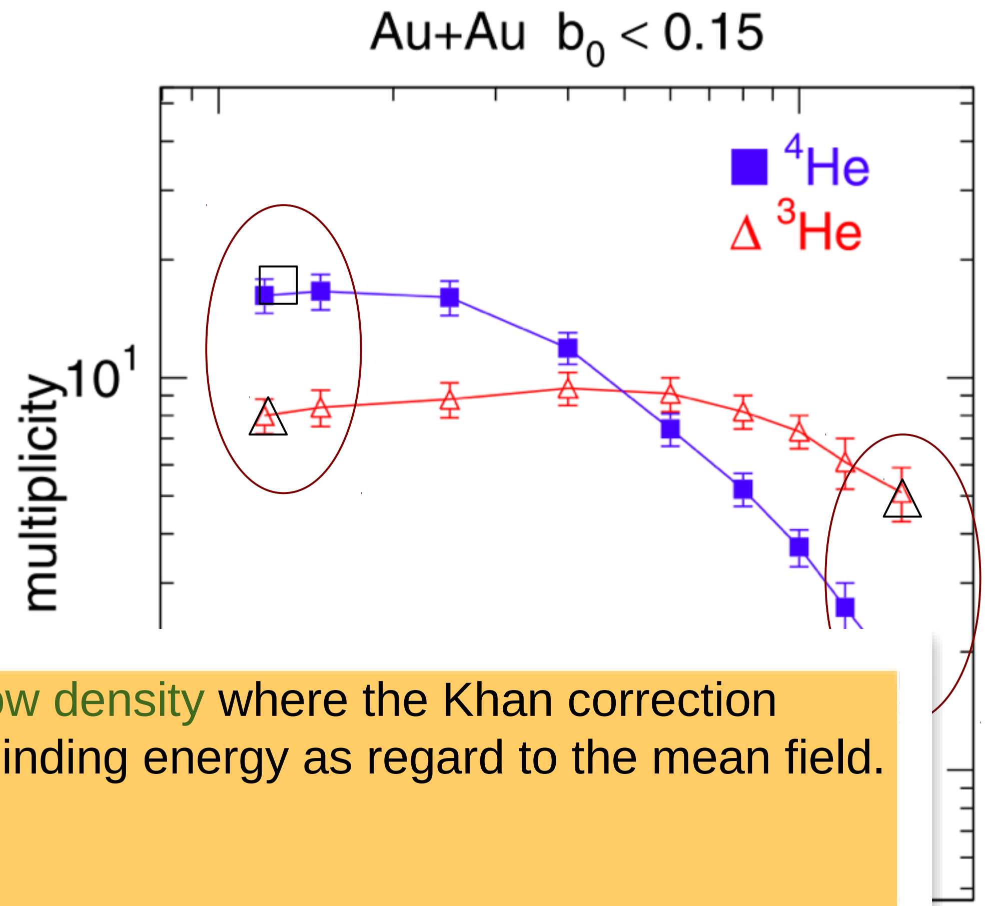
→ with asymmetry term and pairing



Primary clusters are mostly created at a rather low density where the Khan correction factor strongly over-emphasizes the “structure” binding energy as regard to the mean field.
➡ Forces to use an artificial linear dependence.
➡ The Khan approach is not valid in-medium.
➡Use instead a scaling dependence of the “structure” binding energy with regards to the total binding energy :

$$\Delta B_{pairing}(N,Z,\rho_B) = \Delta B_{pairing}(N,Z,\rho_0) \,/\, B_{exp.\ wo\ Coulomb\ BW}(N,Z,\rho_0) \text{ x } B_{mean\ field+Yuk.+asym.}(N,Z,\rho_B)$$

Probes

- Pions

  What a mess?
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  Difficult
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  hmm...
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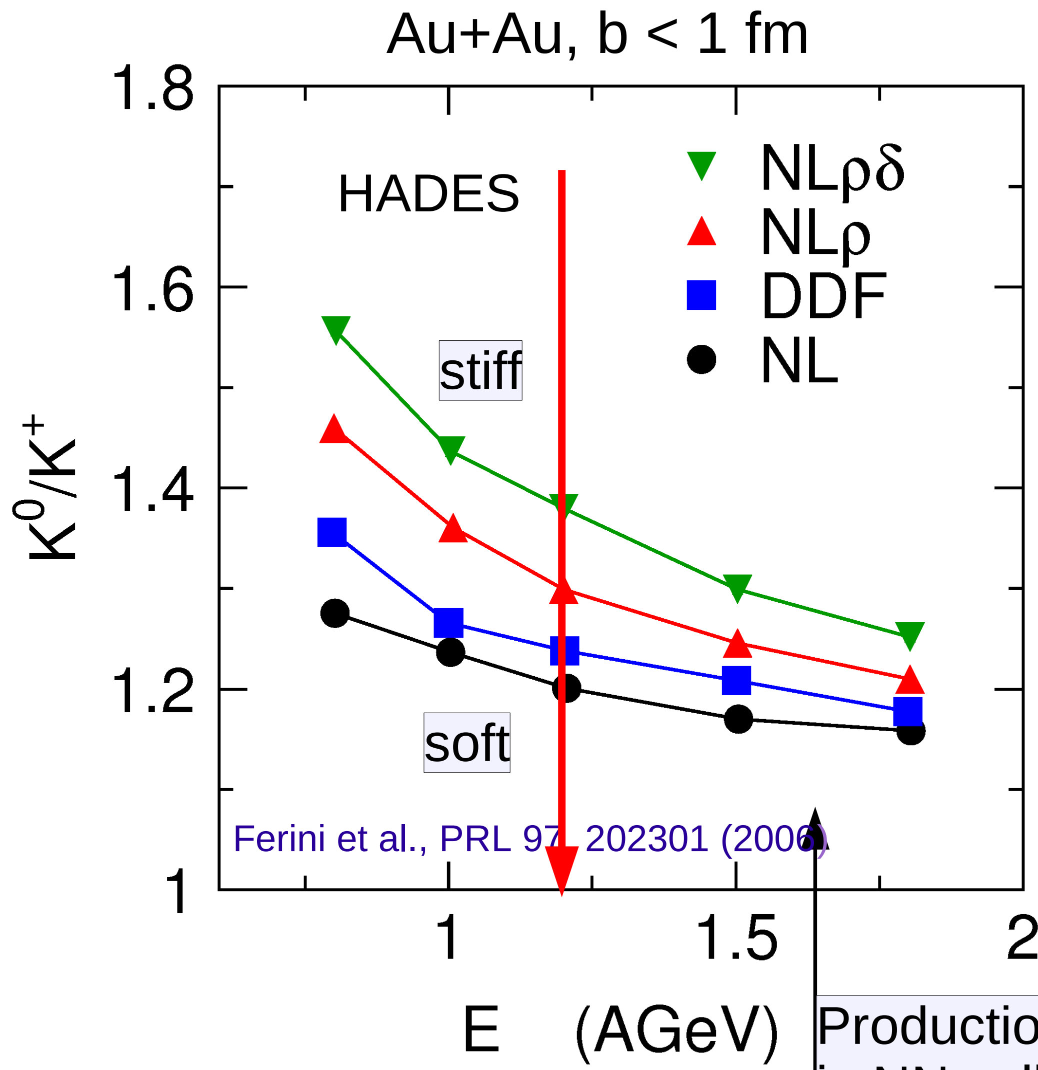
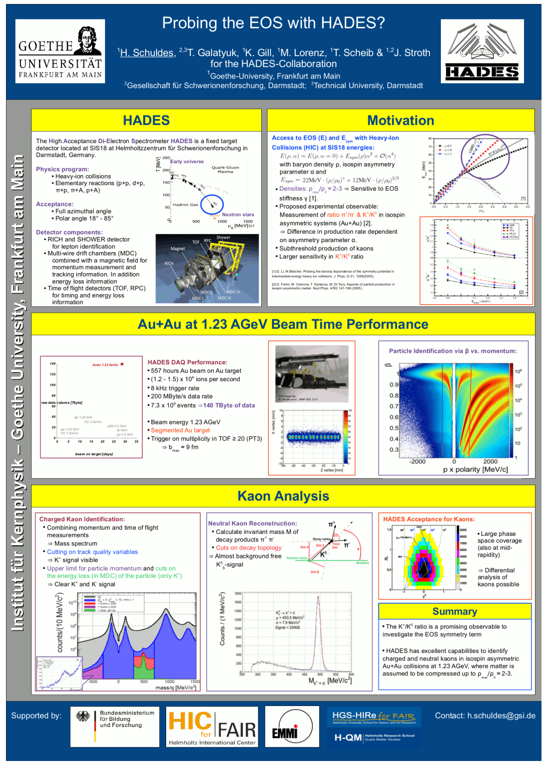
Strangeness as a



- higher sensitivity at lower energies
- requires excellent kaon identification and long beam times
- **needs more independent model predictions**
- **pions need to be described**

Production threshold in NN collision



Some numbers from the HADES beam time

Total number of recorded events:	7.3 x 109 events in ~4 Weeks
Number of reconstructed K0s:	26,000
Number of reconstructed K0s / event:	1/280,000
Number of reconstructed K0s in acceptance of K+:	13,000 (guessed)
Number of K+:	at least five times higher
Statistical error in this run (K0 only):	< 1%
E_{beam}/E_{thr}	0.75
Deep subthreshold energy	800A MeV
E_{beam}/E_{thr}	0.5
Metag systematics	~ Yield lower by a factor of 10
Statistical error at 800 MeV assuming same conditions:	< 3 %

The other strange particle

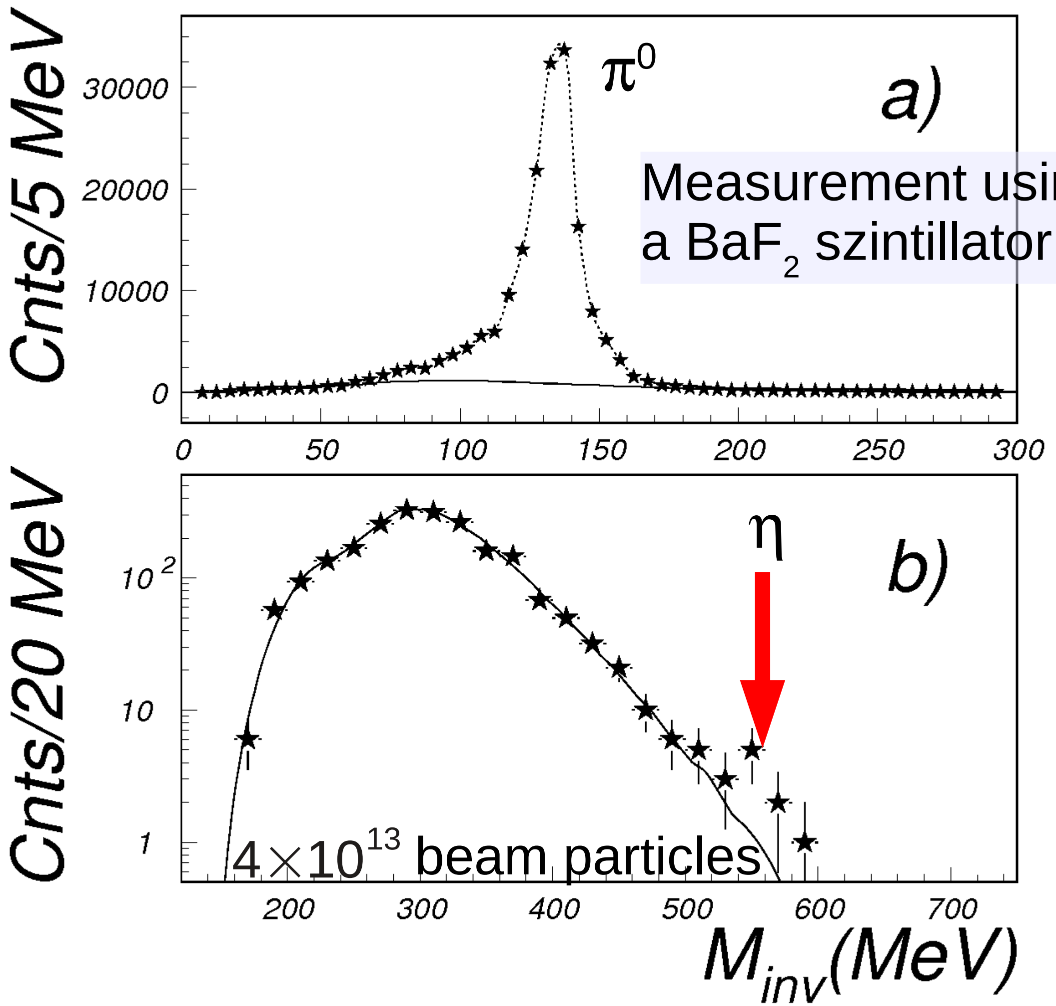
Ar+KCl 180A MeV

$\eta \rightarrow \gamma\gamma$ (38 %)

$\rightarrow \pi^+\pi^-\pi^0$

$\rightarrow 3\pi^0$

2γ easily accessible



Measurement using a BaF_2 szintillator array

4×10^{13} beam particles

η production much lower than expected

G. Martinez et al., arXiv-ex:9912011v1

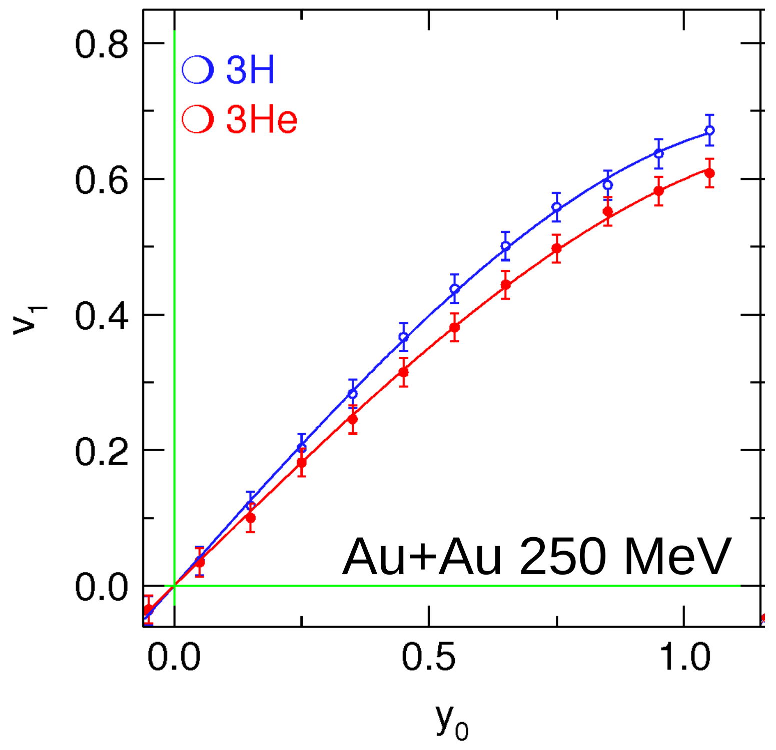
Summary – Observables sensitive to SE

π+/π– measurements in Au+Au – Ca+Ca at 400 – 1.5 (2.0)A GeV

- ratio in Au+Au consistent with the isobar model at around 1 AGeV
- drops at higher energies → 1
- rises at low energies
- strong rise is supportend by $(N/Z)^2$ dependence of ratio at 400A MeV
- potentially sensitive to SE but conclusions model dependent

t/3He measured in Au+Au – Ca+Ca at 400 – 1.5A GeV

- side flow tiny differences t v1 sligthly larger than ^{3}He
- elliptic flow differences at higher beam energies and peripheral collisions (momentum dep.)
- flow described by IQMD and UrQMD (wo accounting differences between t and ^{3}He)



n/p elliptic flow measured at 400A MeV Au+Au

- UrQMD describes data with moderatly hard SE
- More data taken → Analyses ongoing

Generally, flow, stopping, pion production described by IQMD (and UrQMD), with exception of pion flow and cluster production

Summary

Strangeness

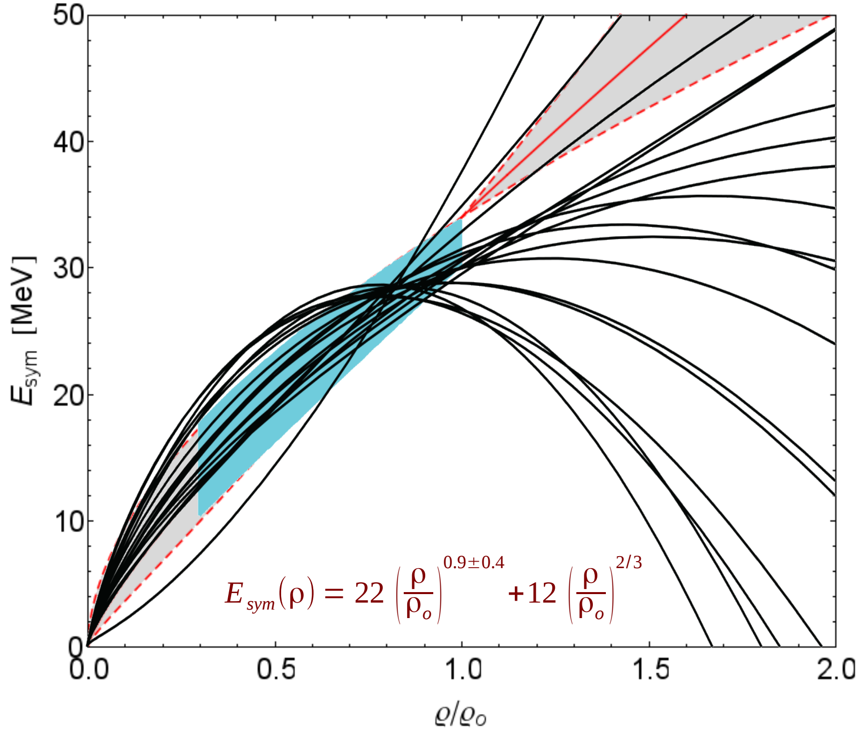
- K0/K+ ratio may be extracted in high statistics run of HADES
  – Au+Au 1.23AGeV
- 800 MeV seems feasible...

Models

No consistent description of isospin observables (except n/p...)

New experiments

More data with new projects at radioactive beam facilities



P. Russotto et al. PLB 697 (2011) 471
M.B. Tsang et al., PRC 86(2012)015803

What did I learn from using transport codes!

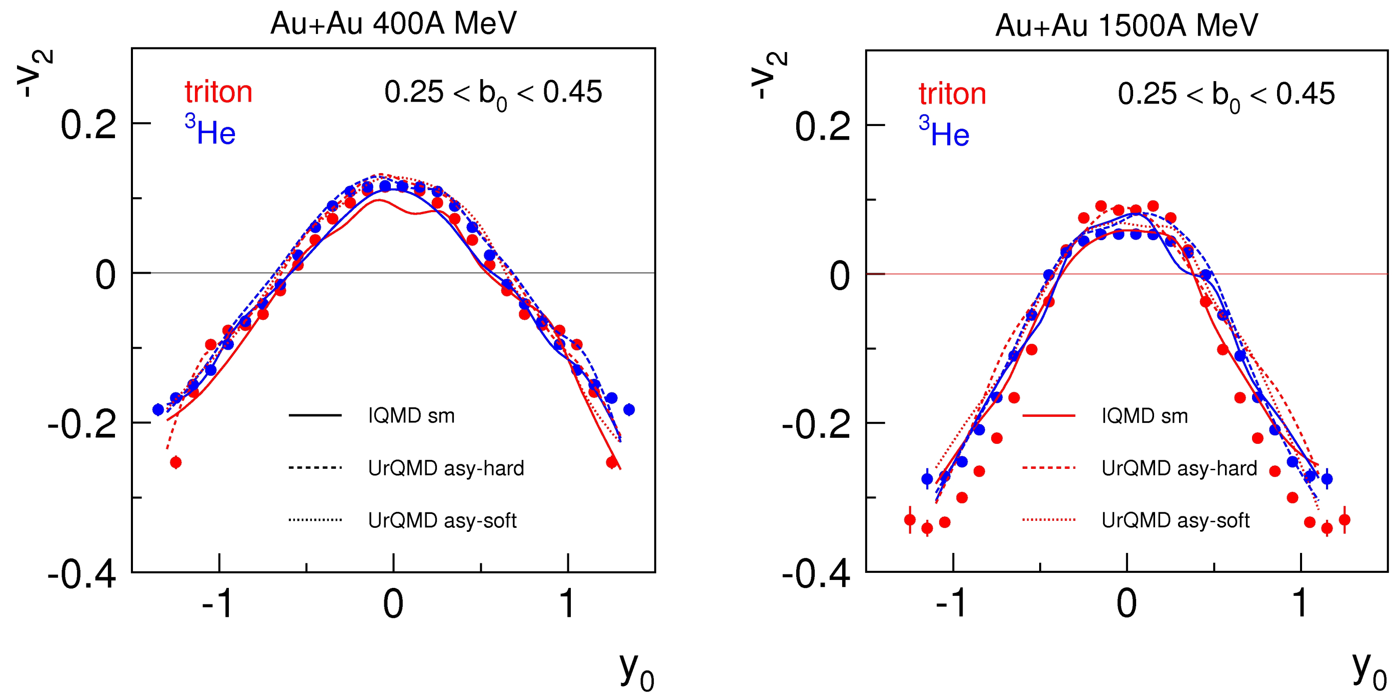
- Code version
  - code version system (svn or something similar)
  - use version numbers for code (also in publications)
- Any version must be documented
  - reference plots for verification
  - source files
  - input files
  - executable
- One common output format
  - format for freeze-out configuration
  - format for time steps
- No compromises (all processes/effects which are established must be included)
- Parameters must be read in (and not buried somewhere in the code)
- Input data (cross sections, potentials) should be stored in external files
- **Distribute your code to experimentalists**

What esle?

- **Data base for HI collisions and relevant elementary data**
  - experimental data
  - for bench mark testing
  - cover certain range in energy and system sizes
  - impact parameter selection must be described
  - simple observables

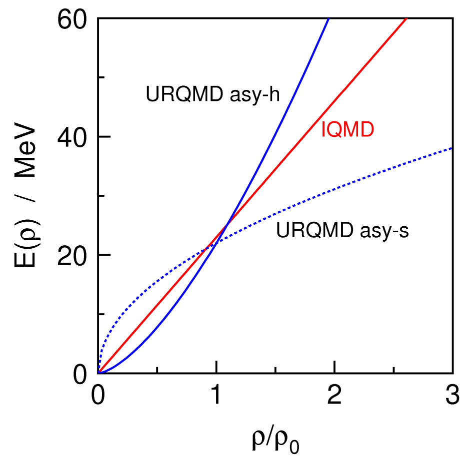
UrQMD vs IQMD

t/^{3}He elliptic flow compared to IQMD/UrQMD

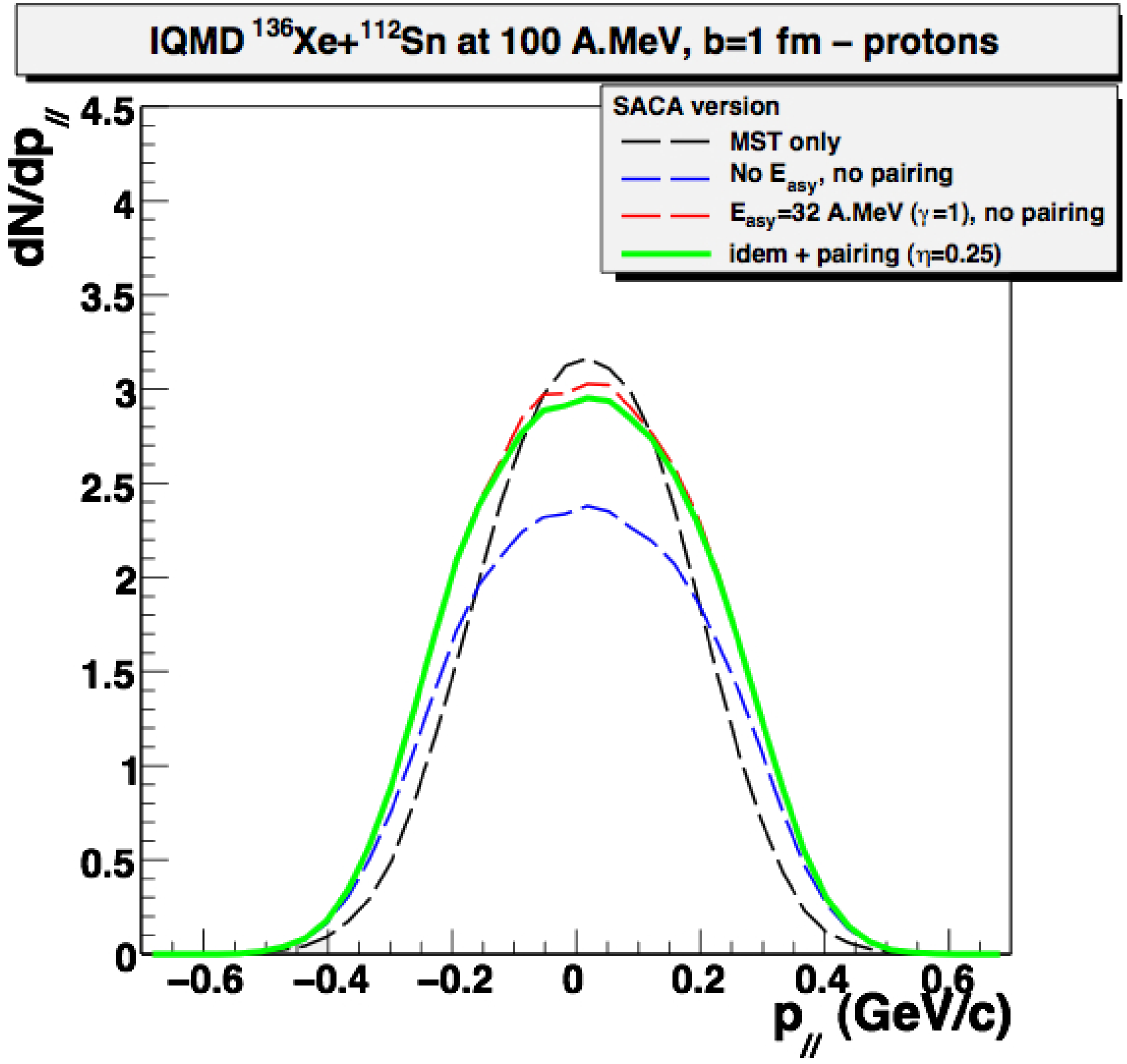


FOPI,
W. Reisdorf et al.
IQMD,
C. Hartnack
UrQMD,
Q. Li

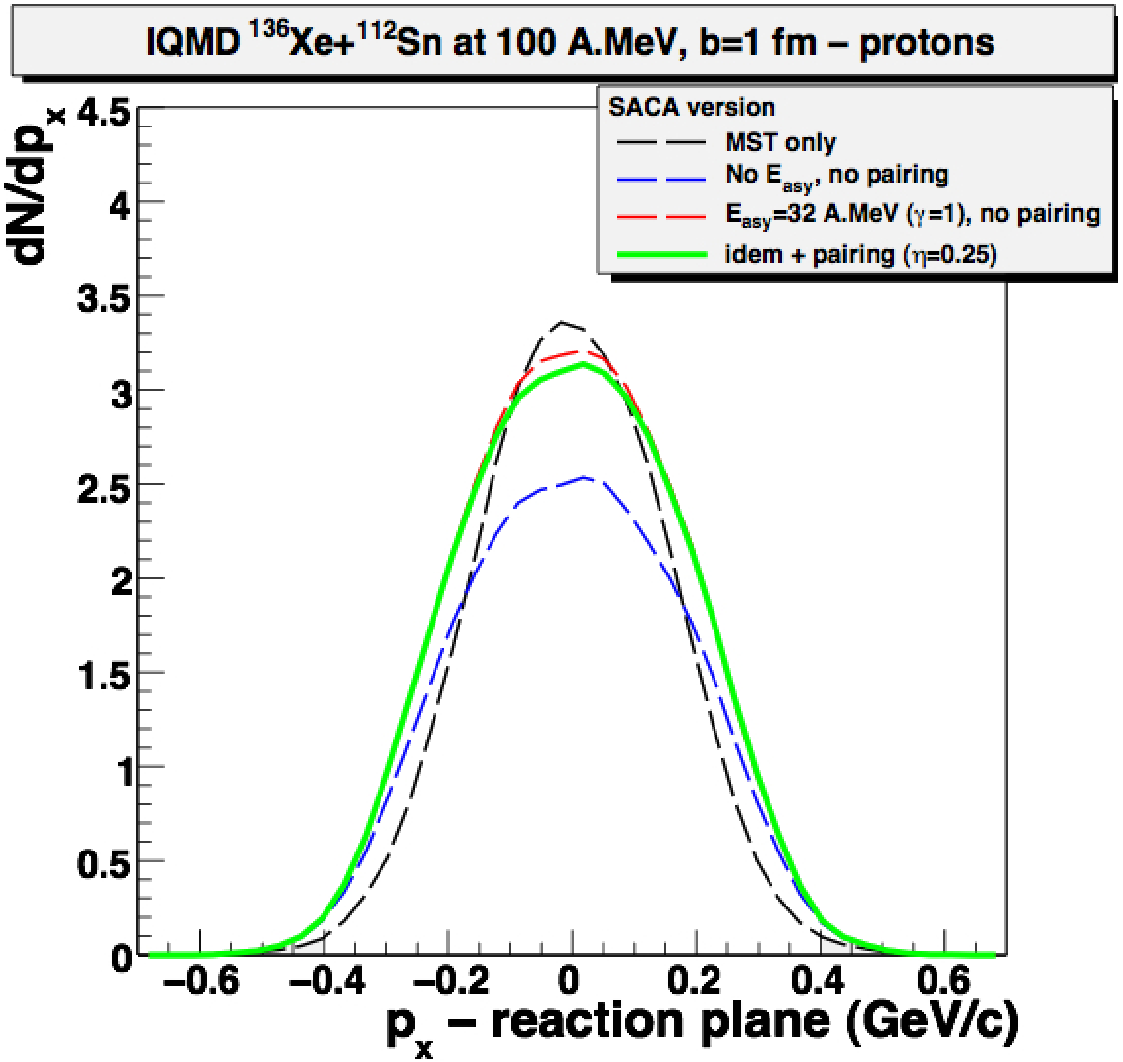
- Difference at highest energies
- Triton elliptic flow larger
- Neither IQMD nor UrQMD describe the observations at higher energies
- Momentum dependence of SE?



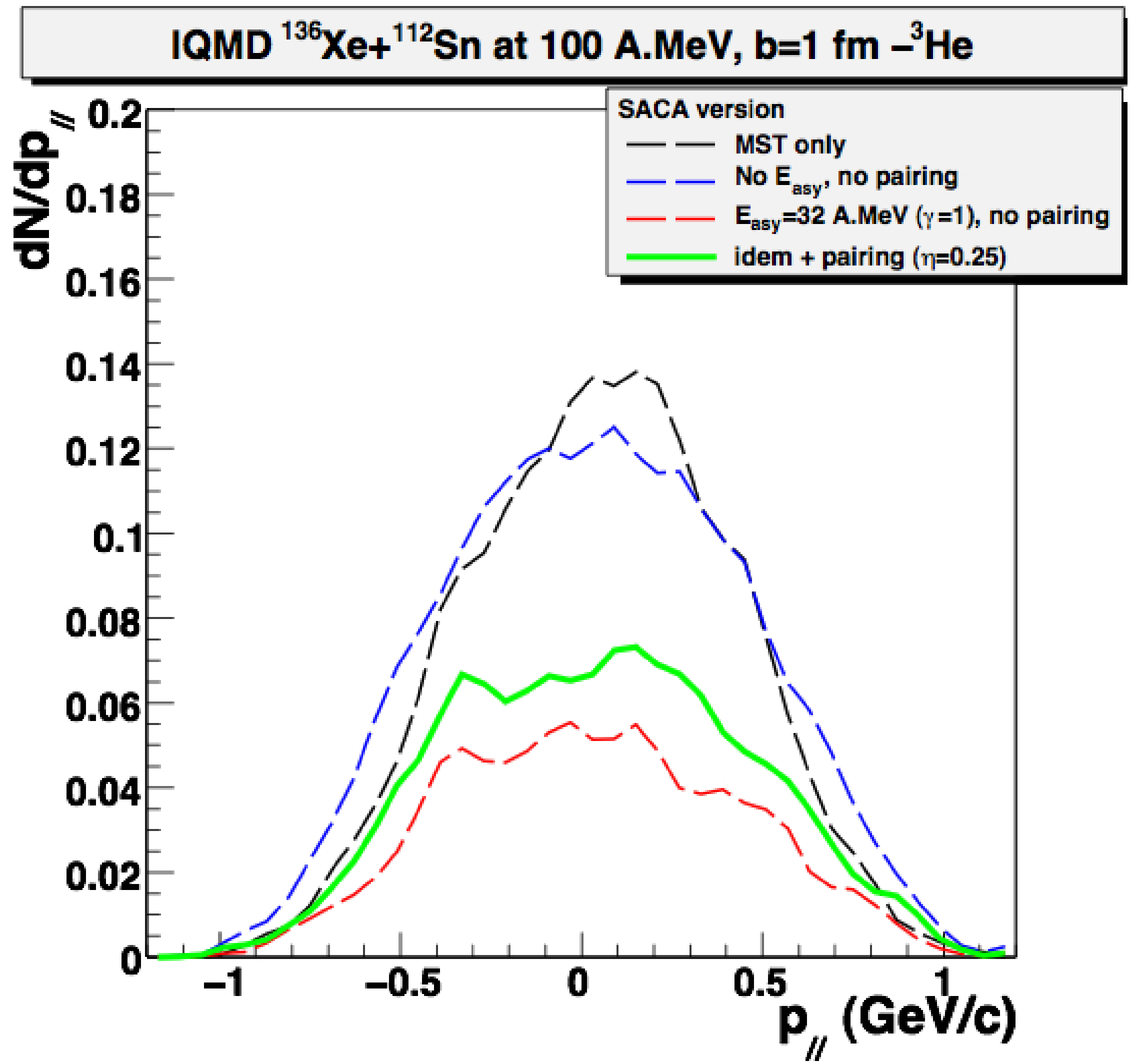
SACA
Influence on phase space distributions



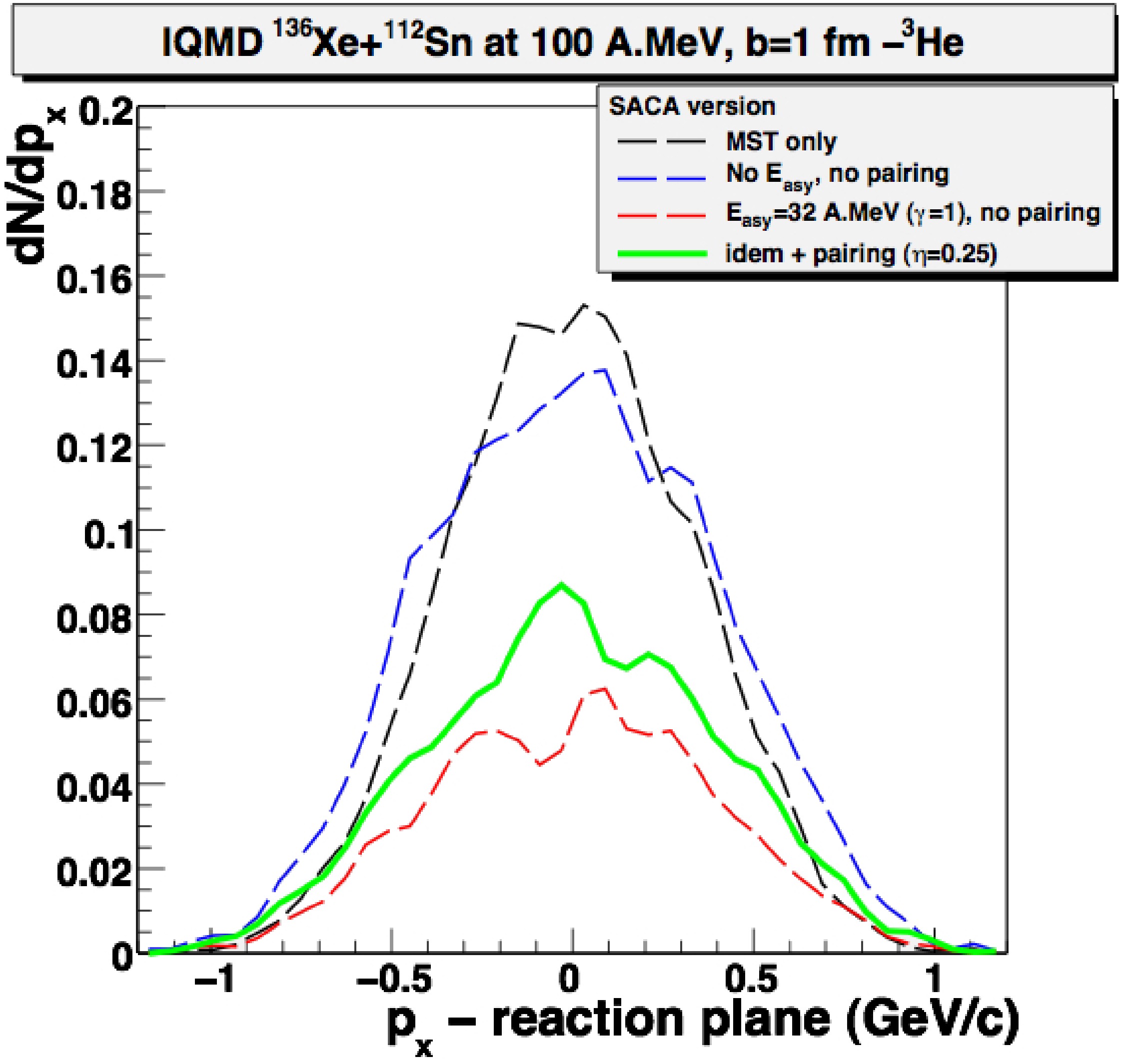
SACA
Influence on phase space distributions



SACA
Influence on phase space distributions



SACA
Influence on phase space distributions



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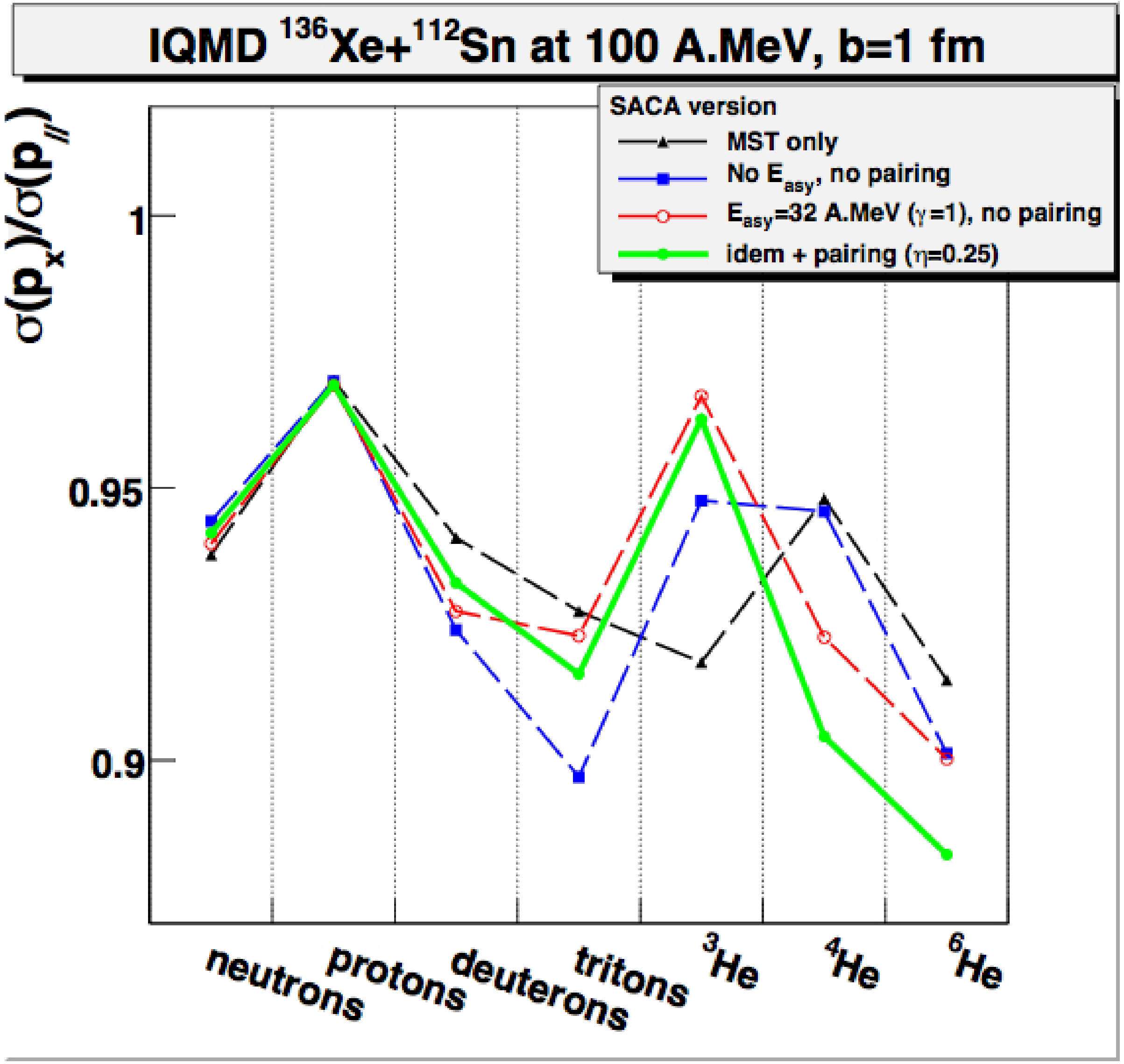
Influence on phase space distributions



Phase space distributions influenced by

- Method
- Contributions to potential