Recent results from FOPI - *Isospin signals at SIS energies*

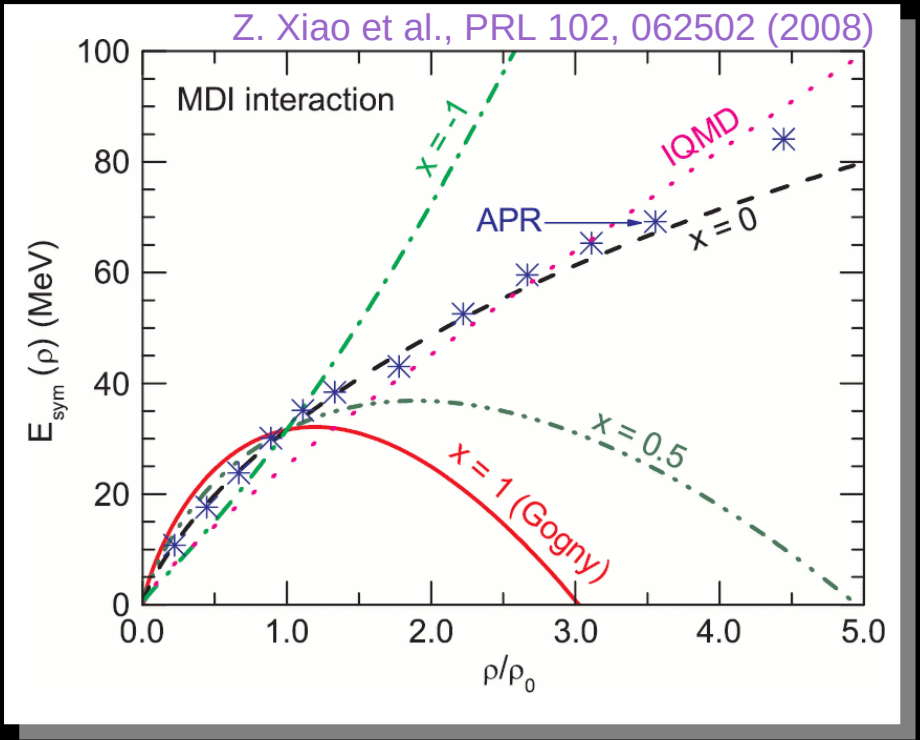
Yvonne Leifels
GSI

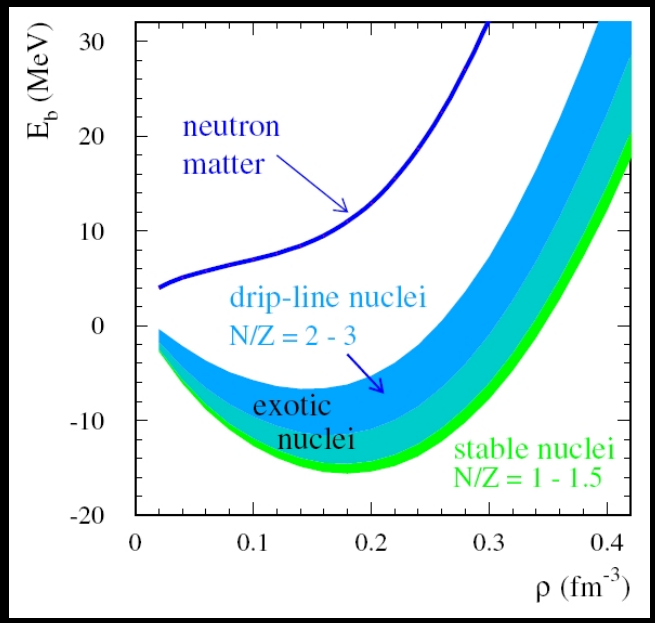
- Motivation
- Experimental set-up
- Observables
  - Cluster production
  - Stopping
  - Flow of isospin pairs
    - n/p
    - t/^{3}He
    - π^+/π^-
- Summary and conclusion

Probing the EOS of asymmetric nuclear matter at supra-normal densities with heavy ion reactions

$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)\ ;$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$



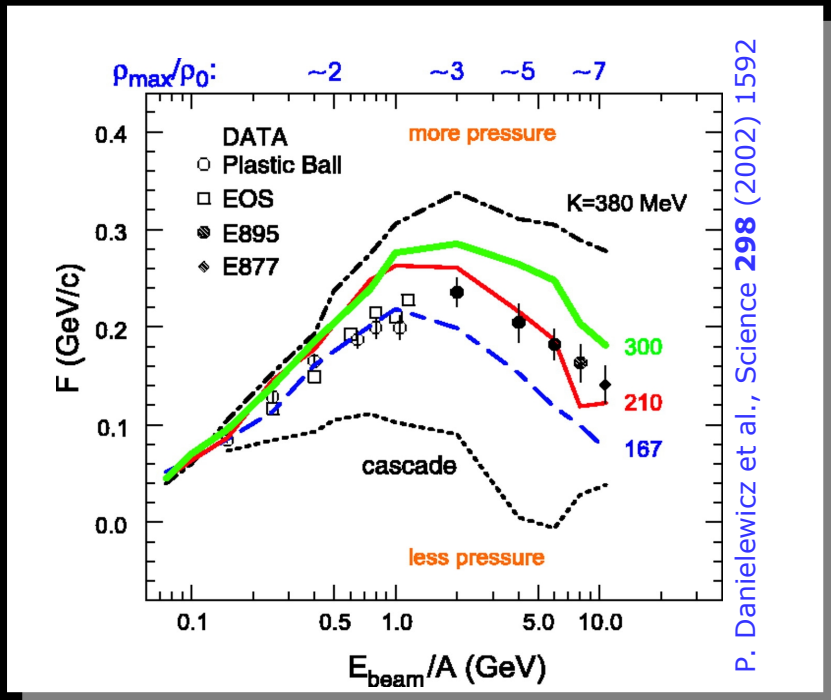


Heavy ion reactions vs astrophysical objects

- density regime
- thermal pressure
- non-equilibrium
- importance of asyEOS

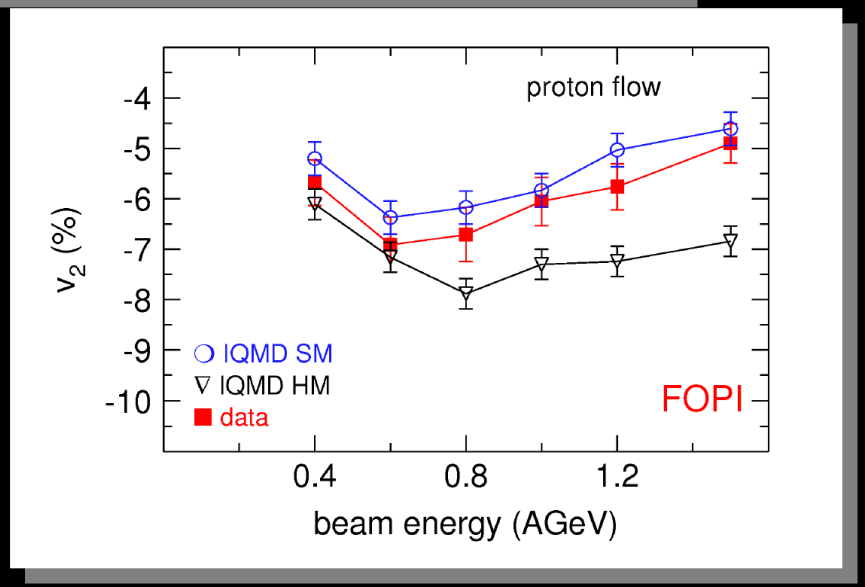
Experiments need models to access the equation of state

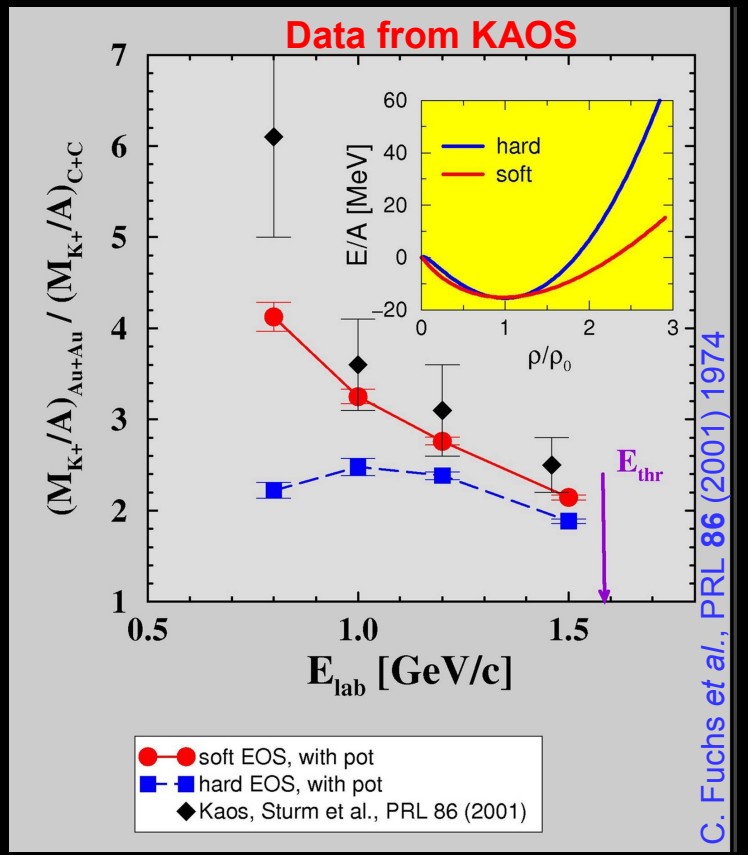
Probing the EOS of asymmetric nuclear matter at supra-normal densities with heavy ion reactions



FOPI's way at high densities ($\rho \approx 2\rho_0$):

- **Spectra and flows of t/^{3}He**
- **Neutrons/Protons**
- **π^+ vs. π^- production, Kaon-production.**





FOPI Detector

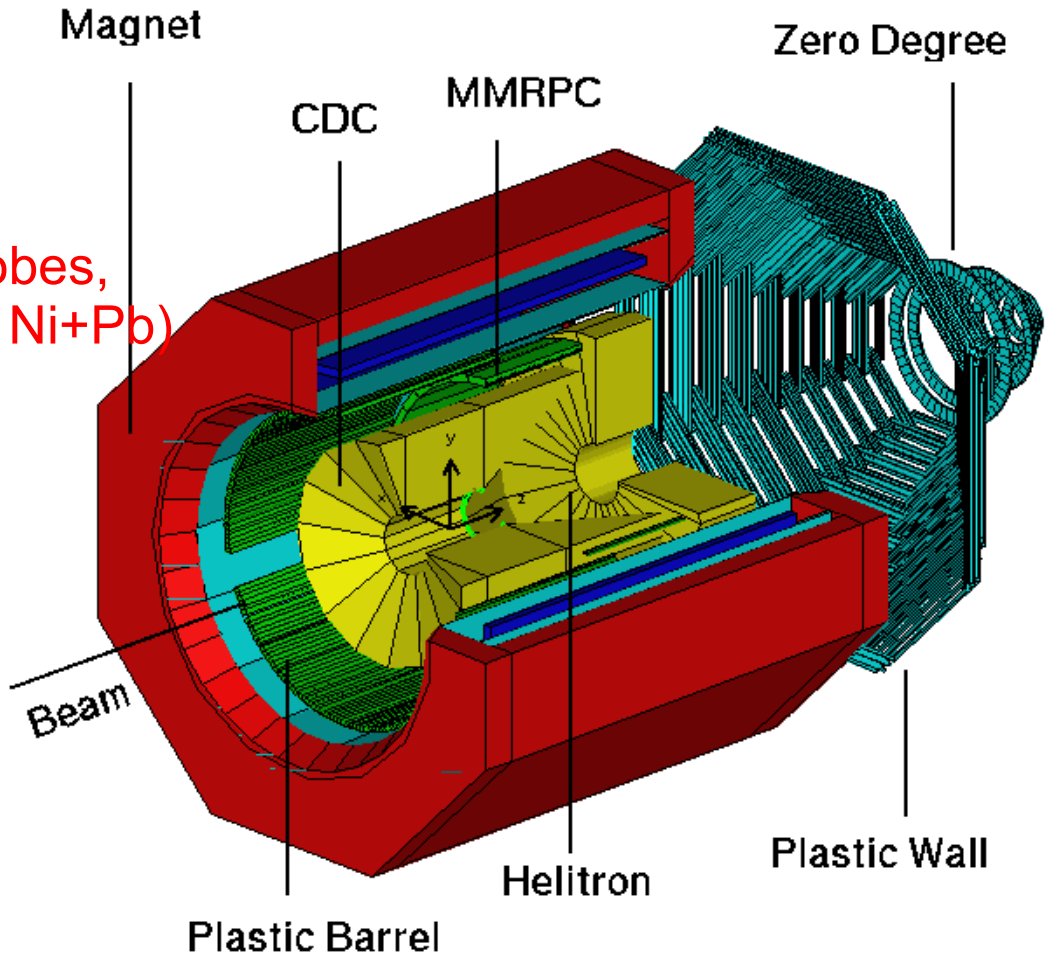
Program:

Dynamics of Heavy Ion Collisions

Stopping, collective flow,
cluster production
Ca+Ca → Au+Au 0.1-2.0 AGeV

Strangeness production

Kaon production and flow, rare probes,
HI collision (Al+Al, Ni+Ni, Ru+Ru, Ni+Pb)
Pion/proton induced reactions



Characteristics:

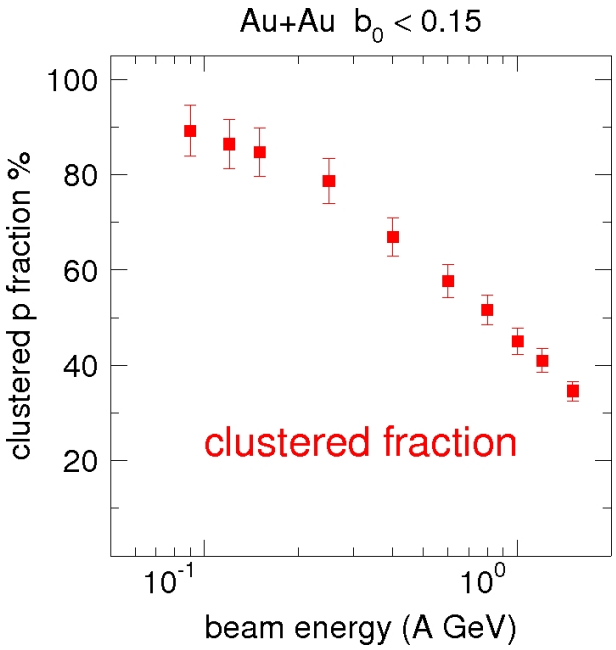
- Homogeneous field 0.6 T
- Charged particle tracking
- Time-of-flight detectors (MMRPC)
- Close to symmetric acceptance in azimuth - π^-, π^+

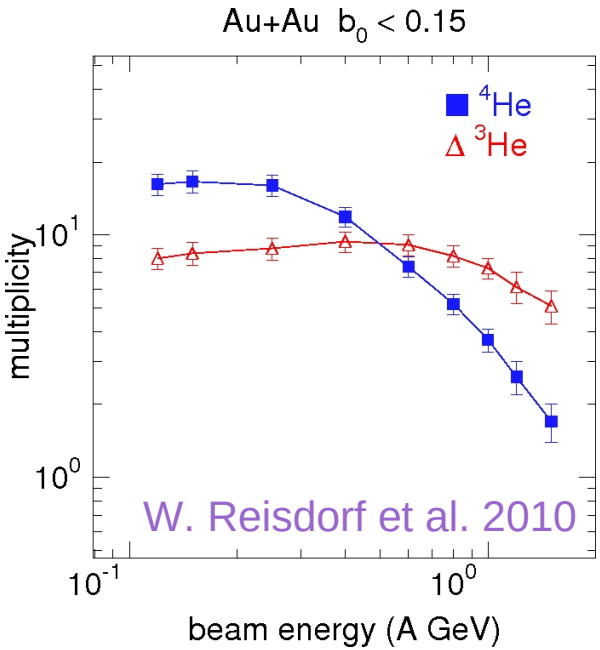
FOPI collaboration

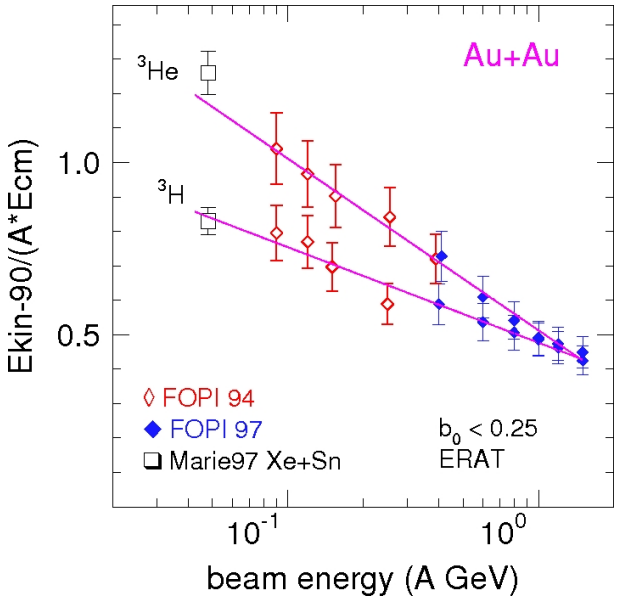
A. Andronic, R. Averbeck, Z. Basrak, N. Bastid, M.L. Benabderramahne, M. Berger, P. Bühler, R. Caplar, M. Cargnelli, M. Ciobanu, P. Crochet, I. Deppner, P. Dupieux, M. Dzelalija, L. Fabbietti, J. Frühauf, F. Fu, P. Gasik, O. Hartmann, N. Herrmann, K.D. Hildenbrand, B. Hong, T.I. Kang, J. Keskemeti, Y.J. Kim, M. Kis, M. Kirejczyk, R. Münzer, P. Koczon, M. Korolija, R. Kotte, A. Lebedev, K.S. Lee, Y. Leifels, A. LeFevre, P. Loizeau, X. Lopez, M. Marquardt, J. Marton, M. Merschmeyer, M. Petrovici, K. Piasecki, F. Rami, V. Ramillien, A. Reischl, W. Reisdorf, M.S. Ryu, A. Schüttauf, Z. Seres, B. Sikora, K.S. Sim, V. Simion, K. Siwek-Wilczynska, K. Suzuki, Z. Tyminski, J. Weinert, K. Wisniewski, Z. Xiao, H.S. Xu, J.T. Yang, I. Yushmanov, V. Zimnyuk, A. Zhilin, Y. Zhang, J. Zmeskal
and
J. Aichelin, E. Bratkovskaya, W. Cassing, C. Hartnack, T.Gaitanos, Q. Li

IPNE Bucharest, Romania
ITEP Moscow, Russia
CRIP/KFKI Budapest, Hungary
Kurchatov Institute Moscow, Russia
LPC Clermont-Ferrand, France
Korea University, Seoul, Korea
GSI Darmstadt, Germany
IReS Strasbourg, France
FZ Rossendorf, Germany
Univ. of Heidelberg, Germany
Univ. of Warsaw, Poland
RBI Zagreb, Croatia
IMP Lanzhou, China
SMI Vienna, Austria
TUM, Munich, Germany
+ P. Kienle (TUM), T.Yamazaki(RIKEN)

Heavy ion collisions at SIS energies - Nucleons and light fragments





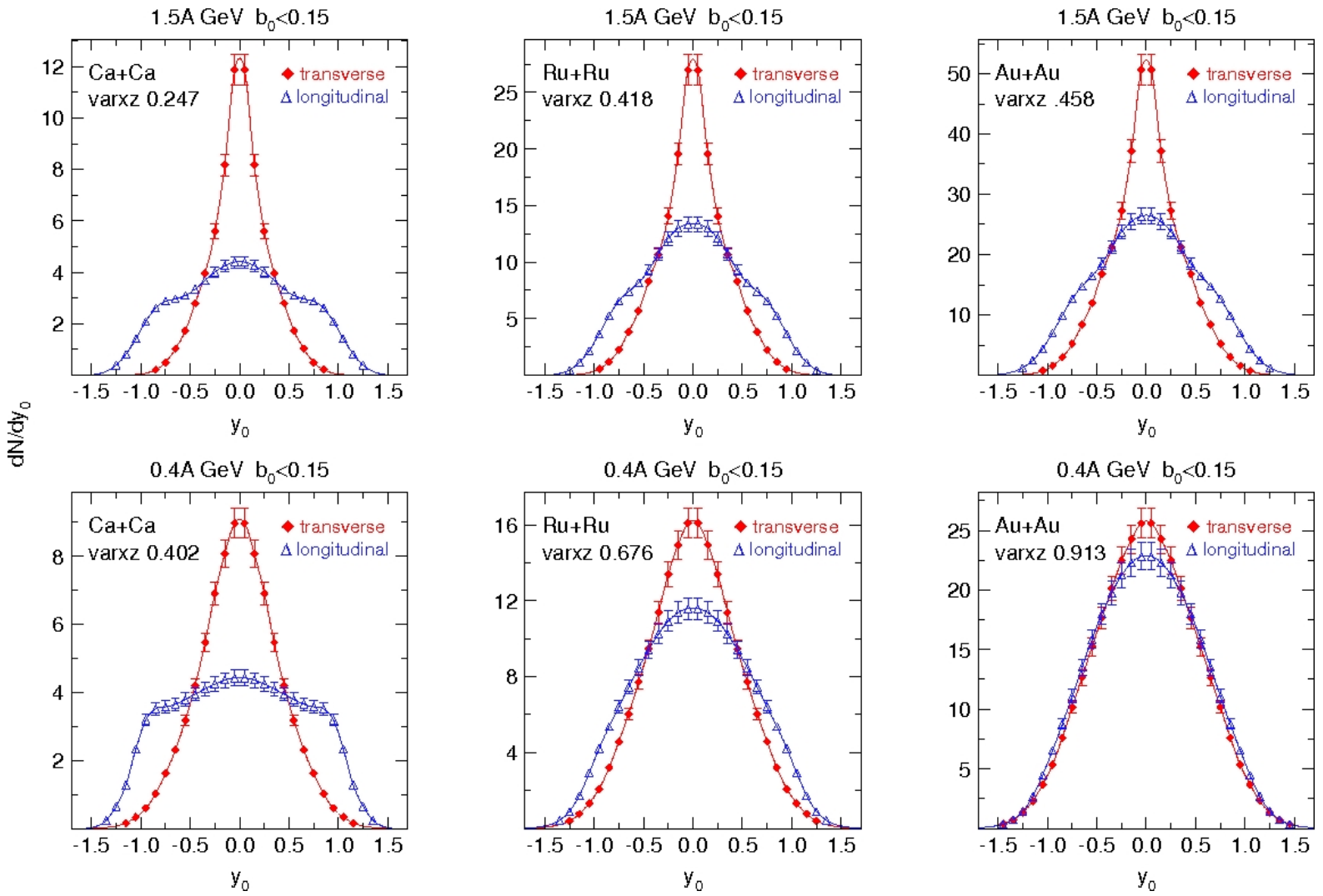


Large amount of nucleons are bound in clusters **Clusterization important!**

Production mechanism for clusters are changing with energy

t/3He anomaly

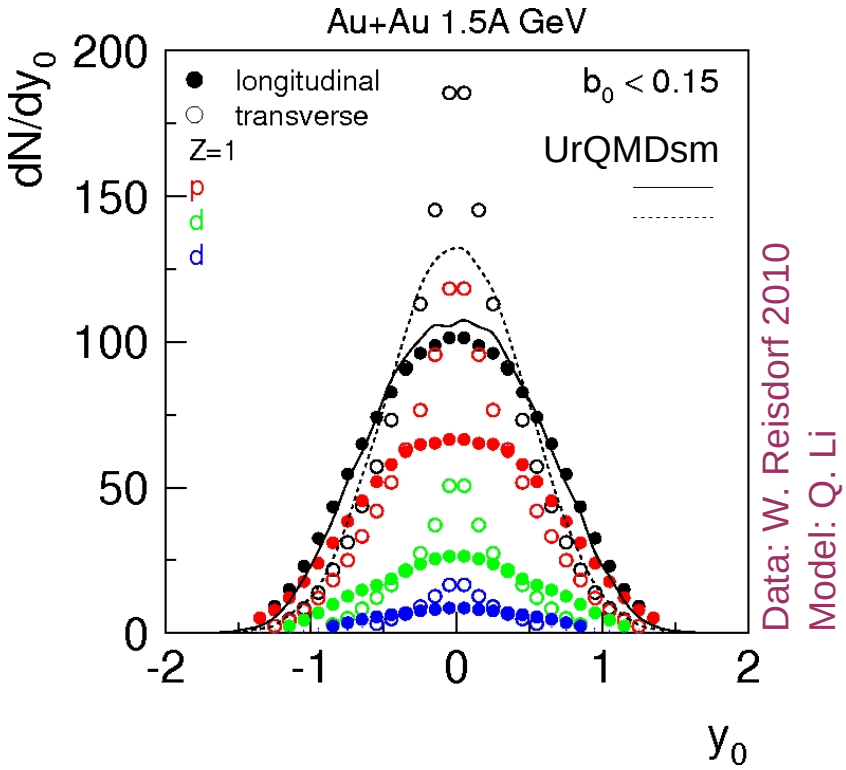
Dynamics of heavy ion collisions - Stopping

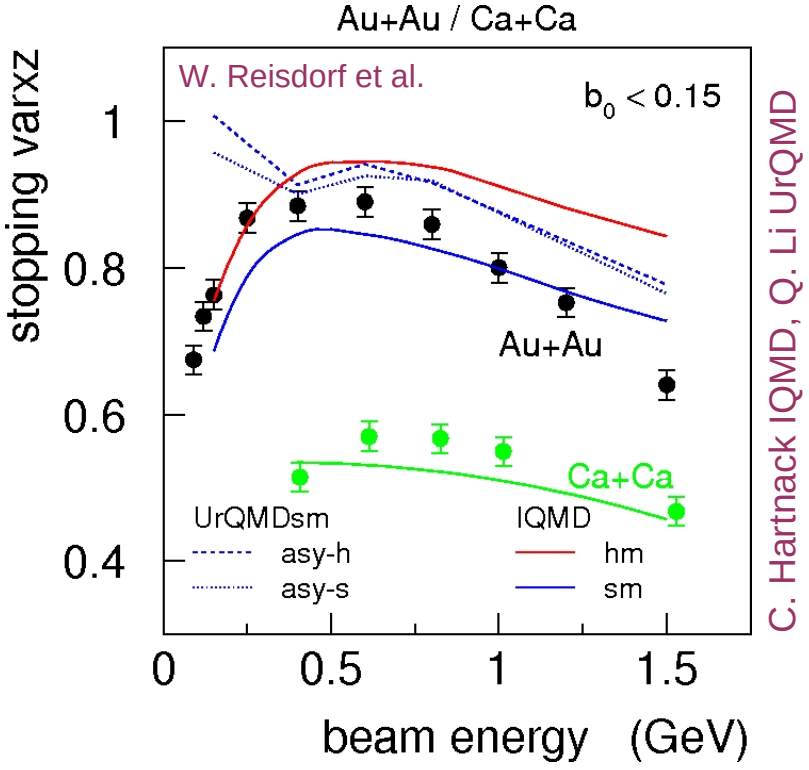


W. Reisdorf et al., nucl-

Y. Leifels, NUSYM 2010

Stopping and its relation to the EOS





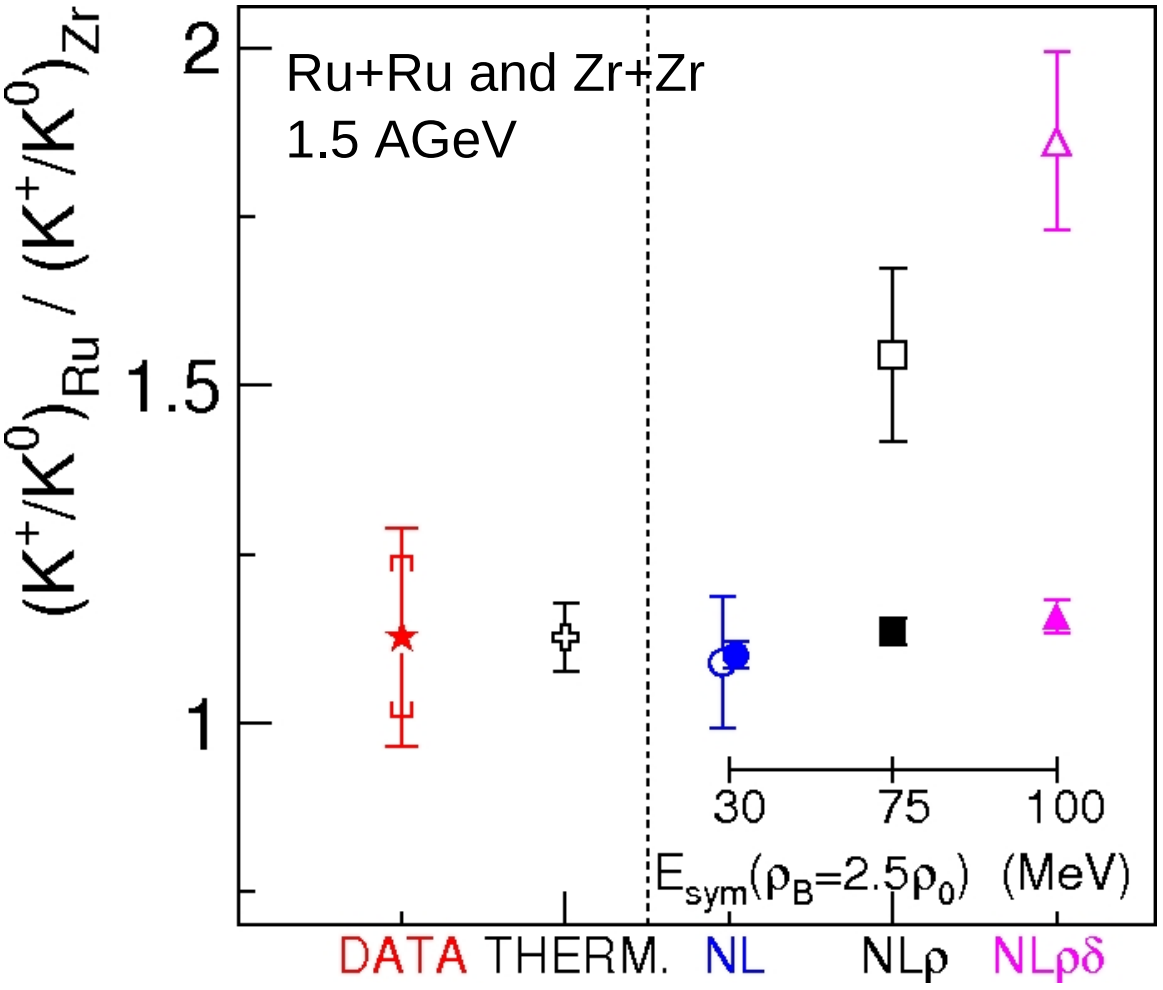
Stopping observable:

$$\text{varxz} = \frac{\sigma^2(y_t)}{\sigma^2(y_l)}$$

- varxz relates transverse and longitudinal expansion
- varxz is sensitive to EOS AND $\sigma_{NN,med}$
- Model ↔ Stopping?

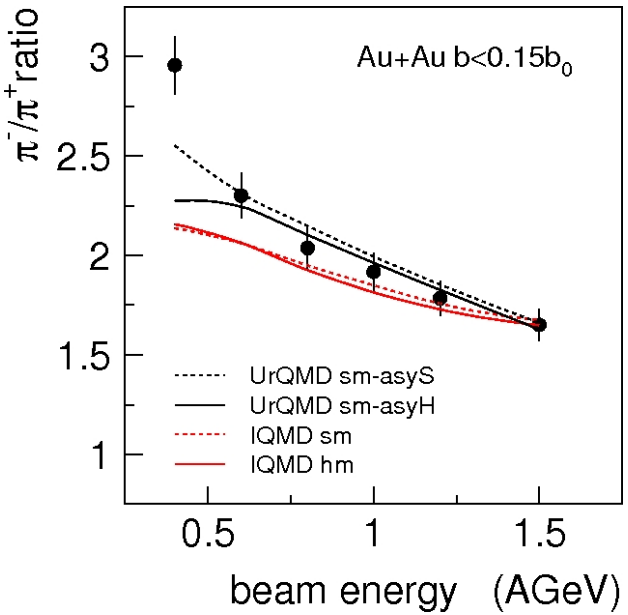
Isospin signals in FOPI
Kaon production as a probe – K^+/K^0 ratio

X. Lopez et al. 2007

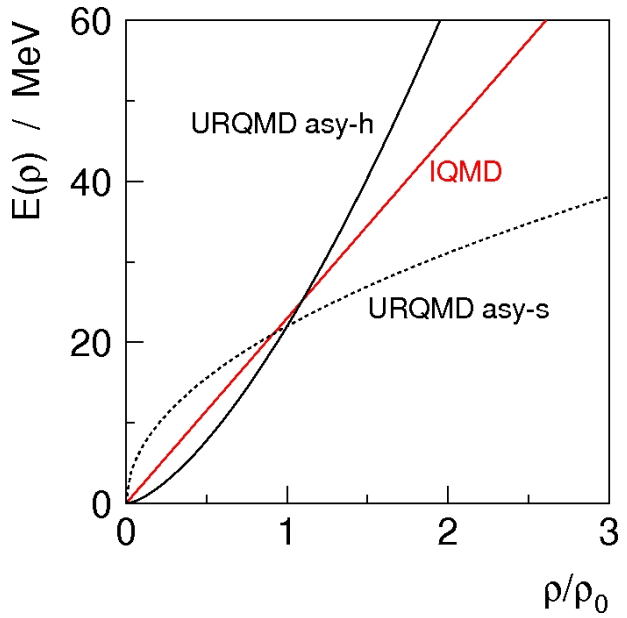


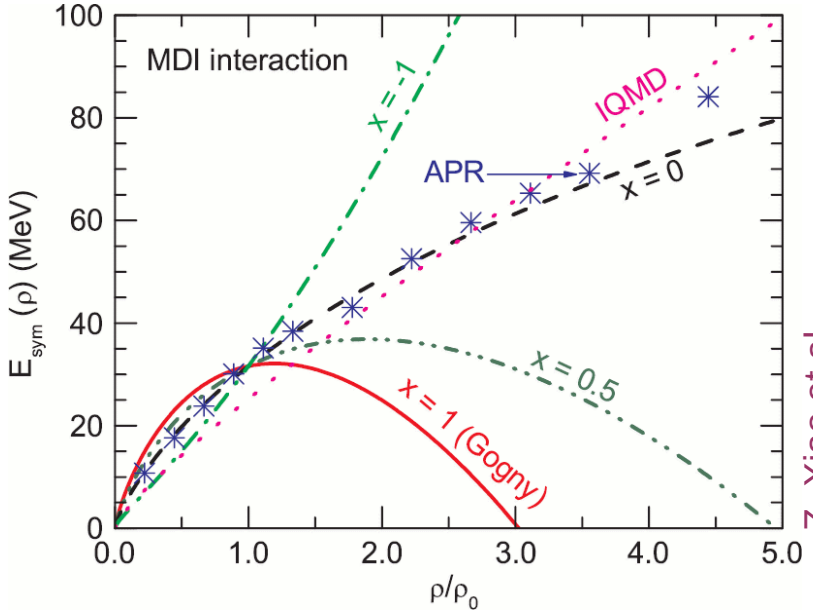
- Double ratio to minimize systemtatic errors
- Result consistent with thermal model prediction
- Larger sensitivity at lower energies close to threshold
- But difficult to measure
- HADES?

Pion production – π-/π+ ratio



W. Reisdorf et al., NPA 781 (2007) 459



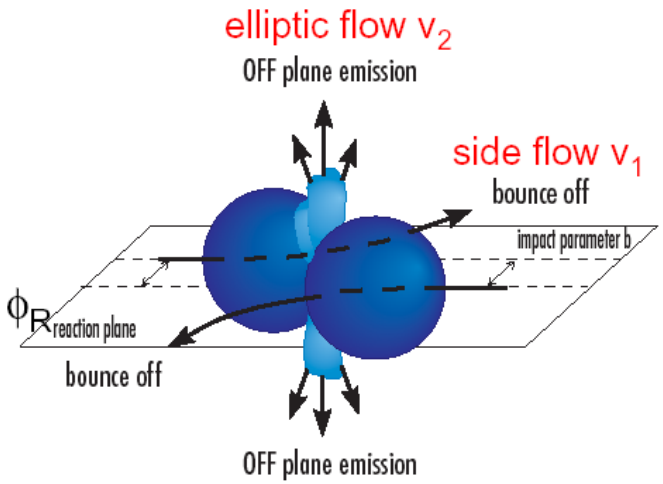


Z. Xiao et al. PRL 102 (2009) 62502

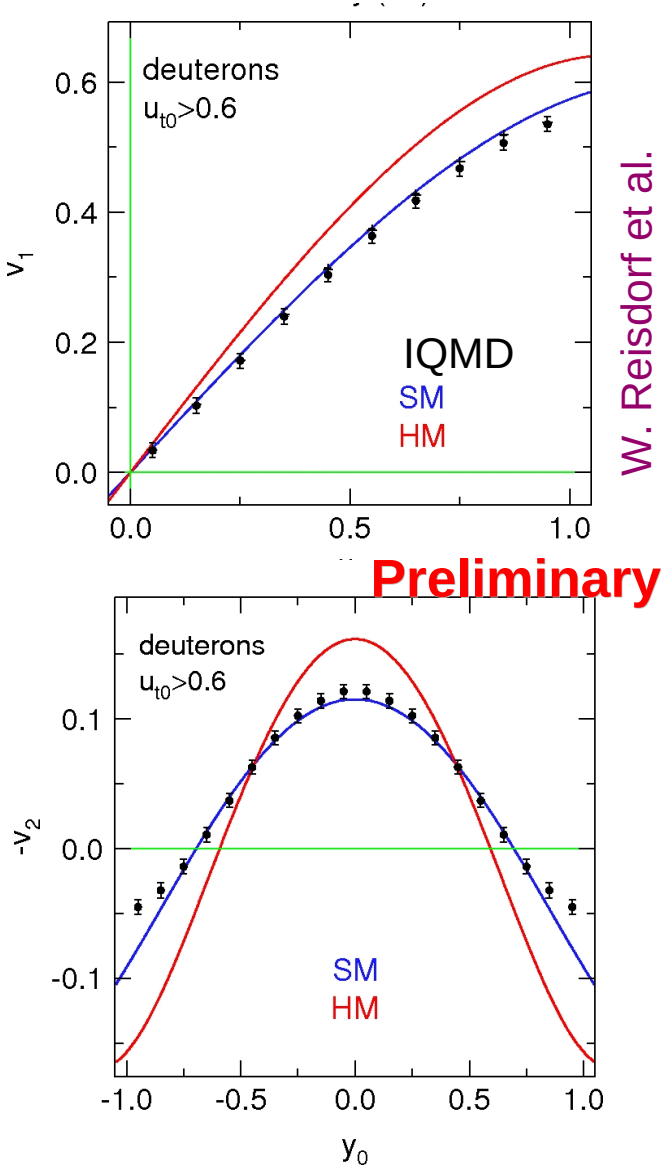
G.Ferini06	RMF	stiffer
Q. Li 06	UrQmd	softer
Z.Q. Feng 09	ImIQMD	stiffer
Z.G. Xiao,B.A. Li 09	IBUU04	softer
J.Aichelin		no influence
A.Bonasera		no influence

Y. Leifels, NUSYM 2010

Collective flow



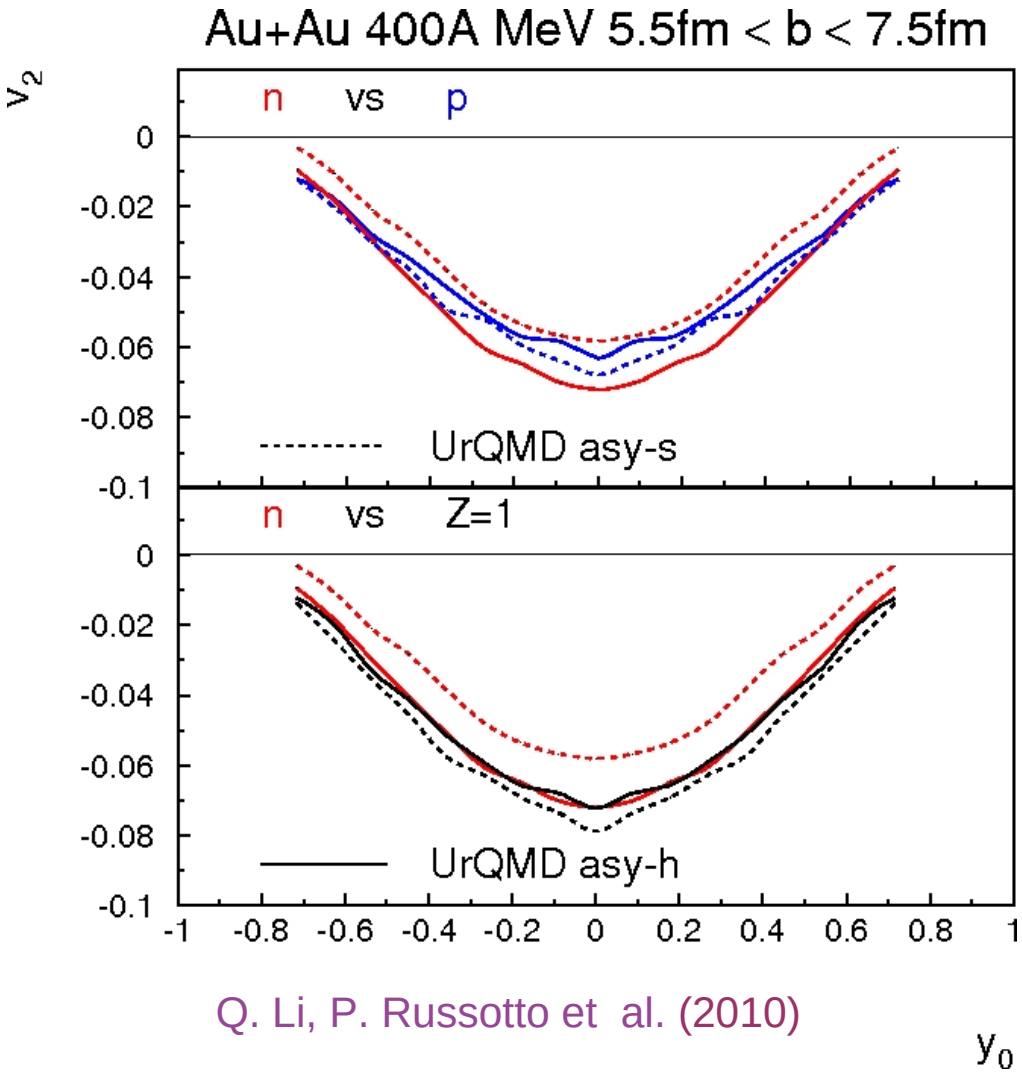
Au + Au 400A MeV $0.25 < b_0 < 0.45$



If the data is correct and the model is correct → soft EOS confirmed
BUT
Stopping and flow correlated
Consistent description required

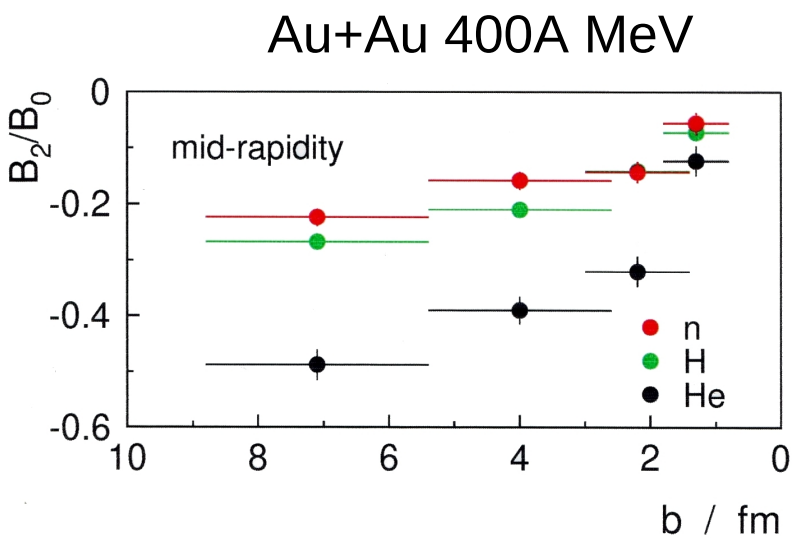
Y. Leifels, NUSYM 2010

Neutron elliptic flow and the AsyEOS



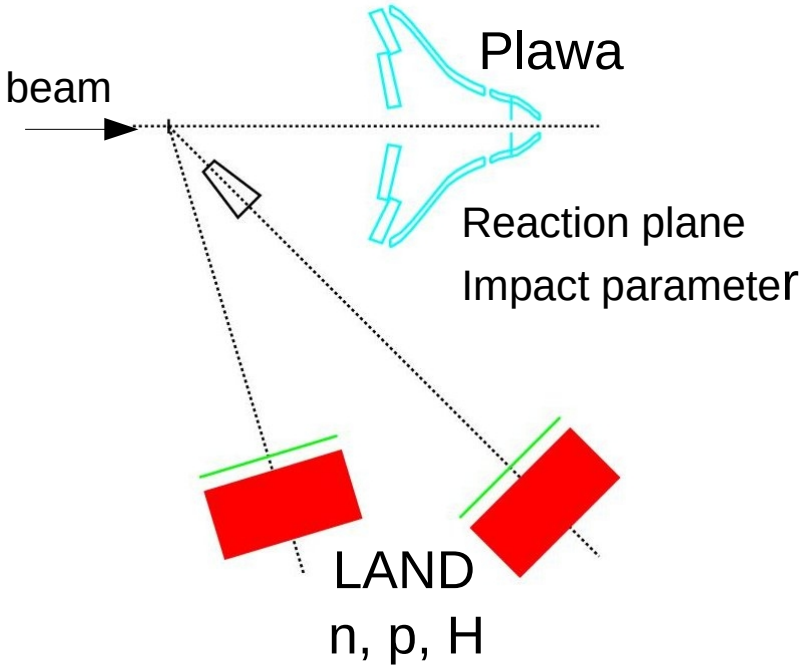
Q. Li, P. Russotto et al. (2010)

- Protons slightly changed
- Neutrons influenced
- Neutron elliptic flow compatible to Z=1 flow for asy-h
- Influence of ASY-EOS most strong at large p_t

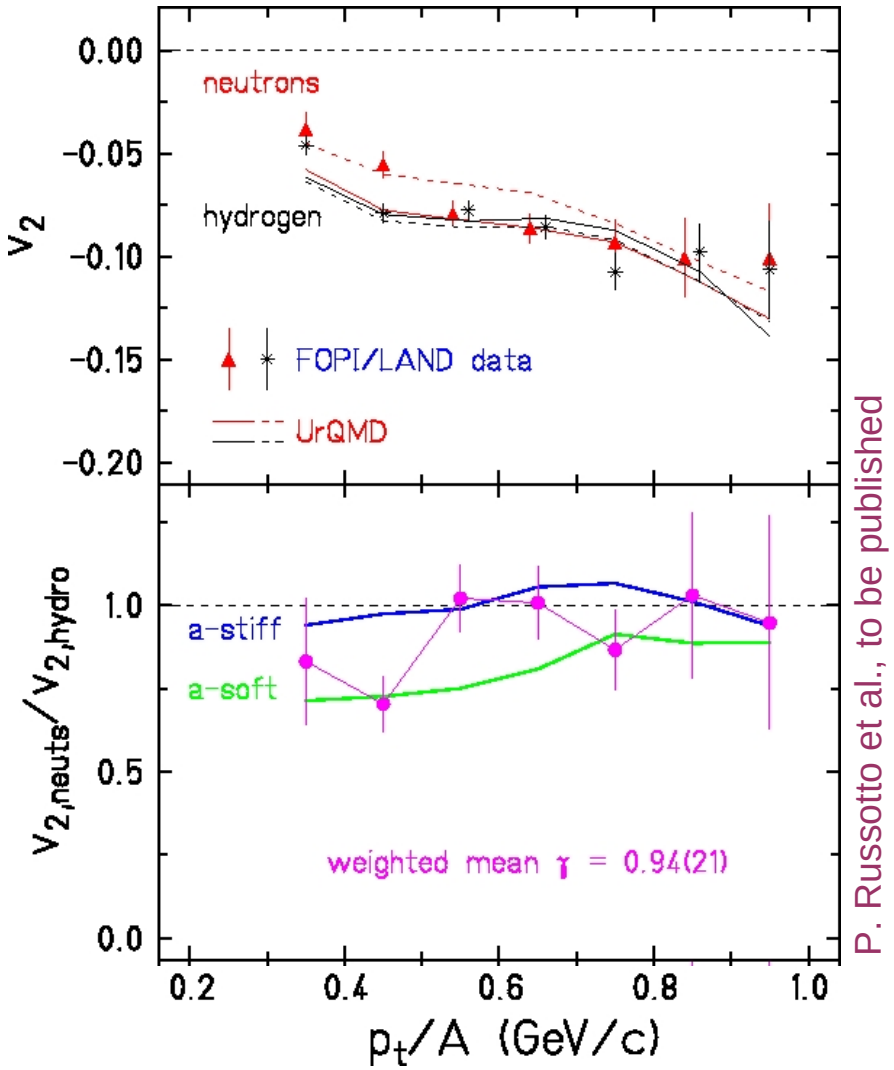


Y. Leifels et al., PRL 71:963-966(1993)

Elliptic flow of neutrons and hydrogen isotopes LAND and FOPI

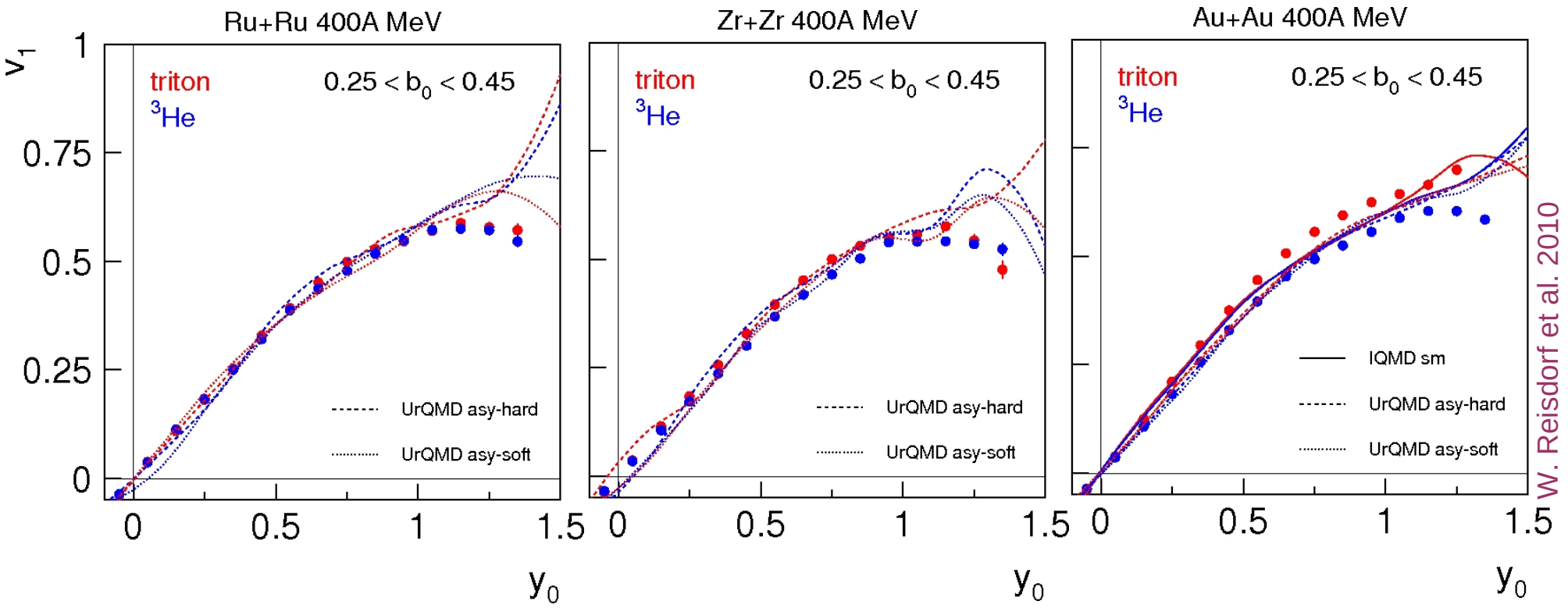


- Result $\gamma \approx 0.94(21)$
- Reproduction of hydrogen isotope yields by the models crucial
- Protons cleaner probe
- Lacking statistics
- New experiment
- ASY-EOS @ GSI



Y. Leifels, NUSYM 2010

Sideward flow of t and ^{3}He

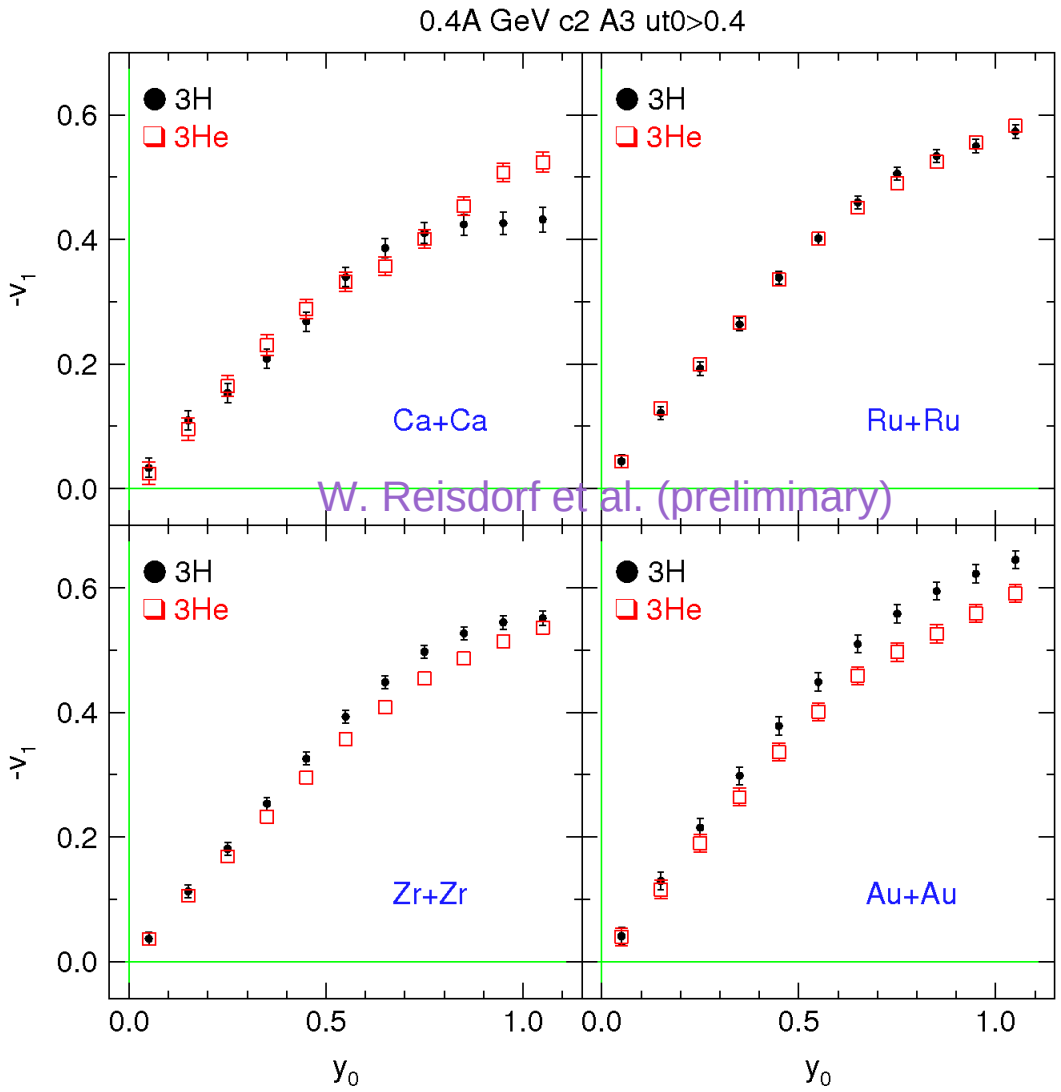


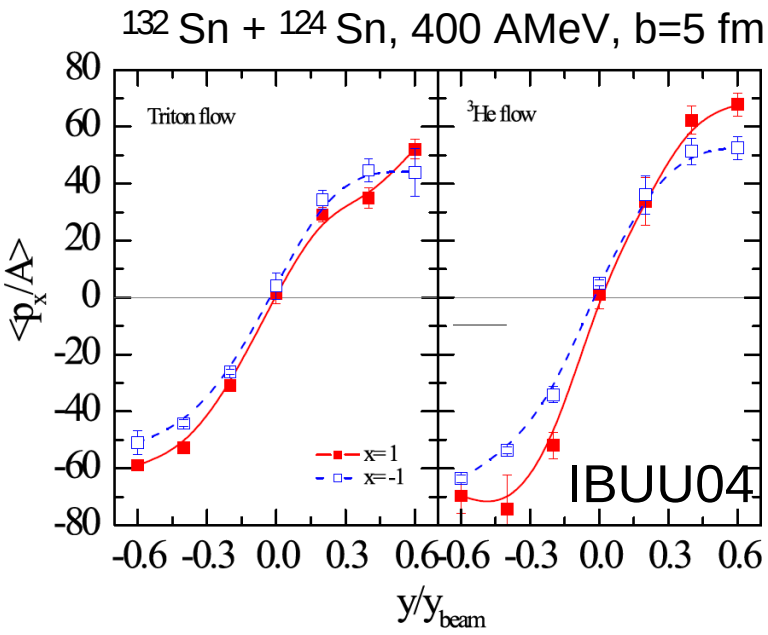
W. Reisdorf et al. 2010

- Difference between t and ^{3}He rising with N/Z
- Good overal description of the experimental data
- Neither IQMD nor UrQMD account for the difference of t and ^{3}He flow
- Other models in literature predicting an influence of the symmetry energy on the flow of t and ^{3}He

Y. Leifels, NUSYM 2010

t vs 3He flow
Constraining the ASY-EOS at $\rho > \rho_0$?



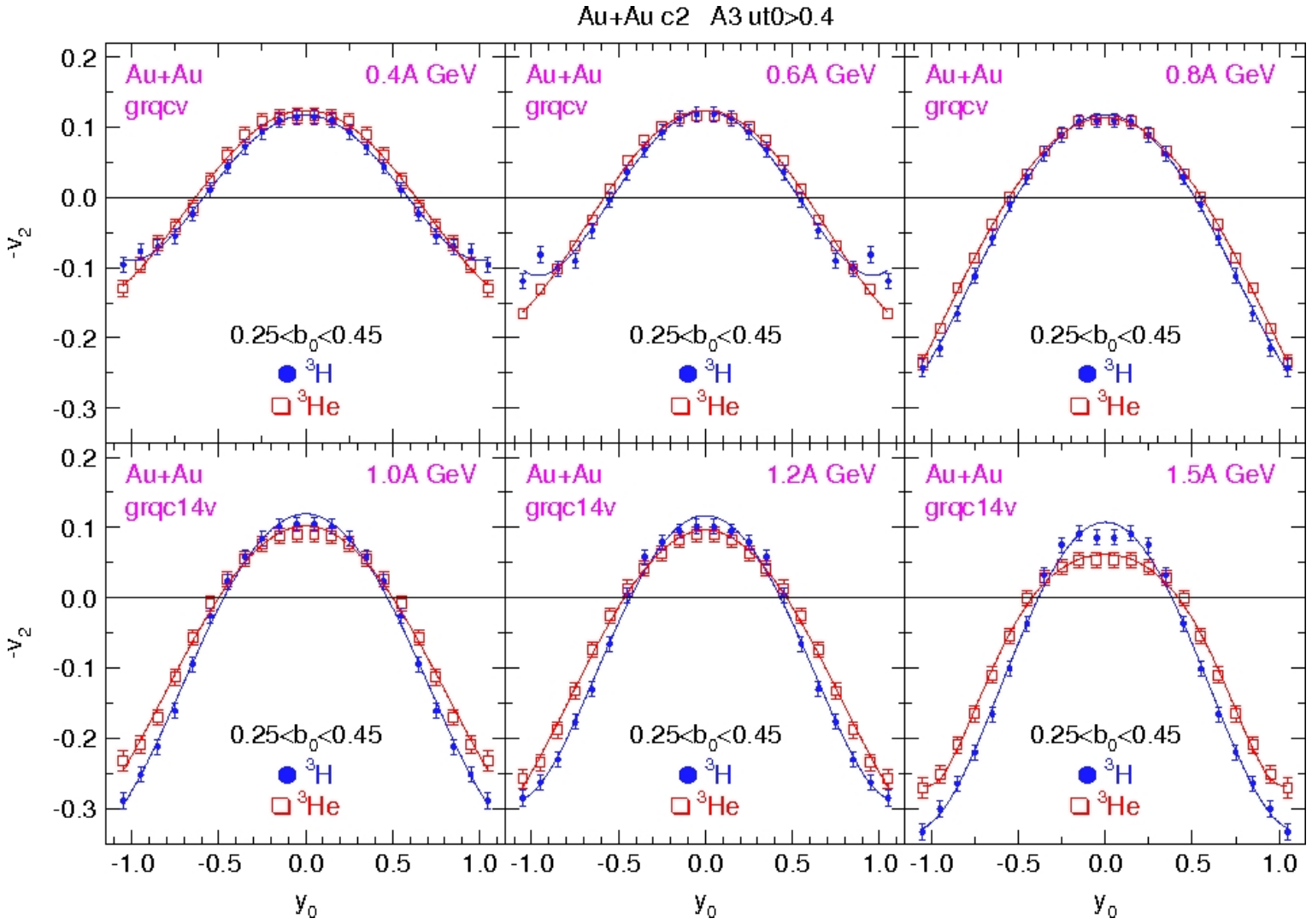


Gao-Chan Yong et al., nucl-the:0906.0939

Larger difference between t and 3He for systems with larger N/Z

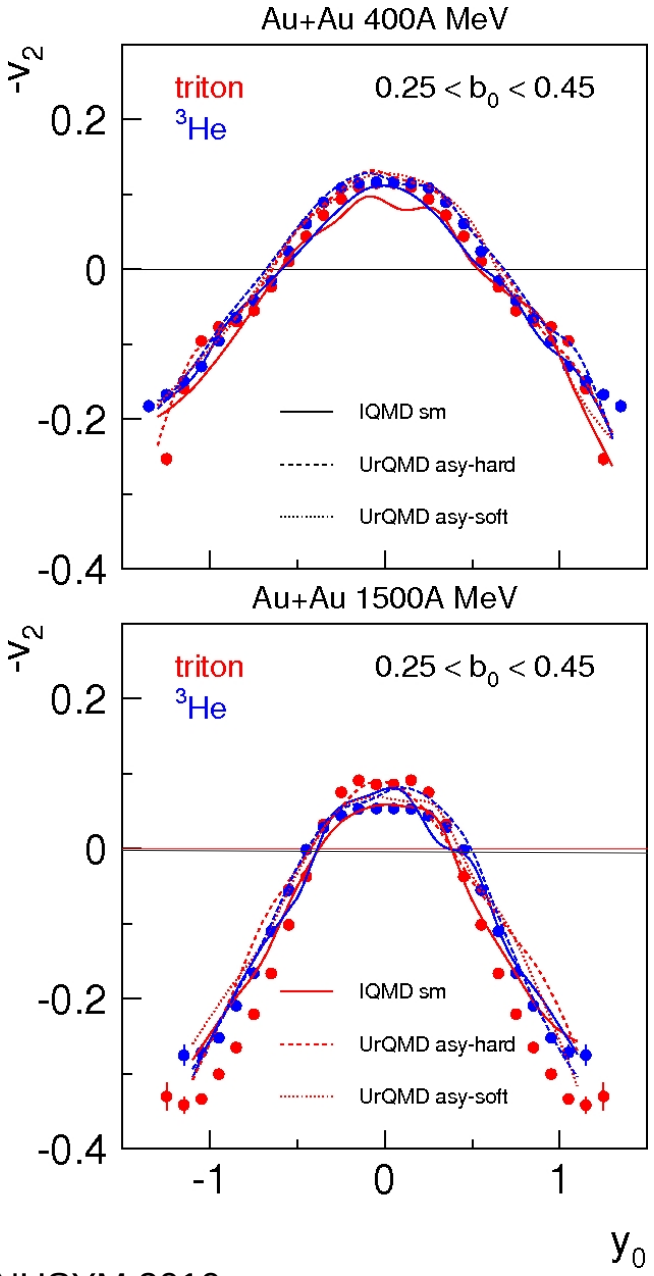
Y. Leifels, NUSYM 2010

Elliptic flow of t and ^{3}He



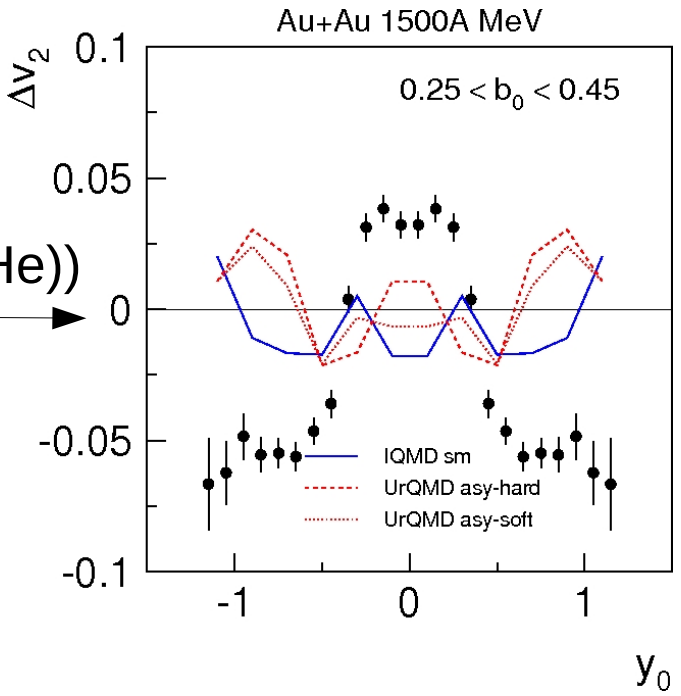
Y. Leifels, NUSYM 2010

Elliptic flow of t and ^{3}He



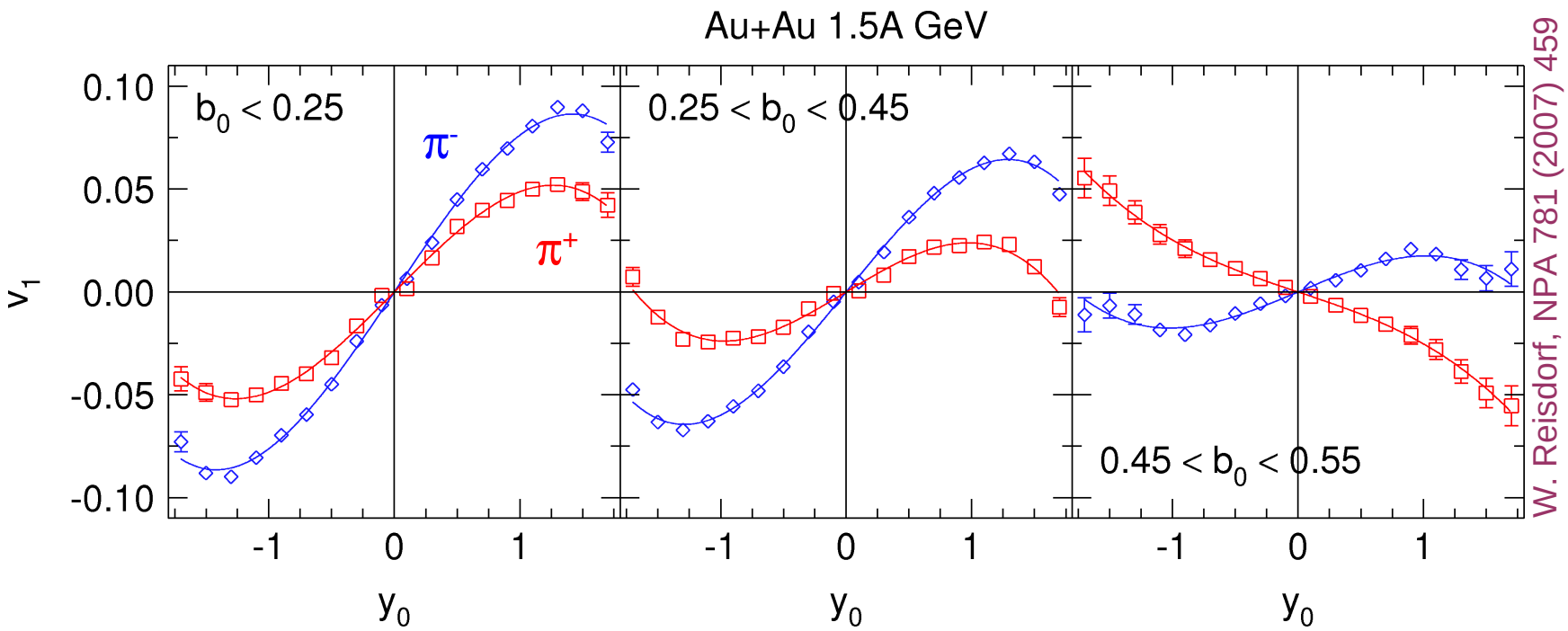
- Difference at higher energies
- Triton elliptic flow larger
- Neither IQMD nor UrQMD describe the observations at higher energies

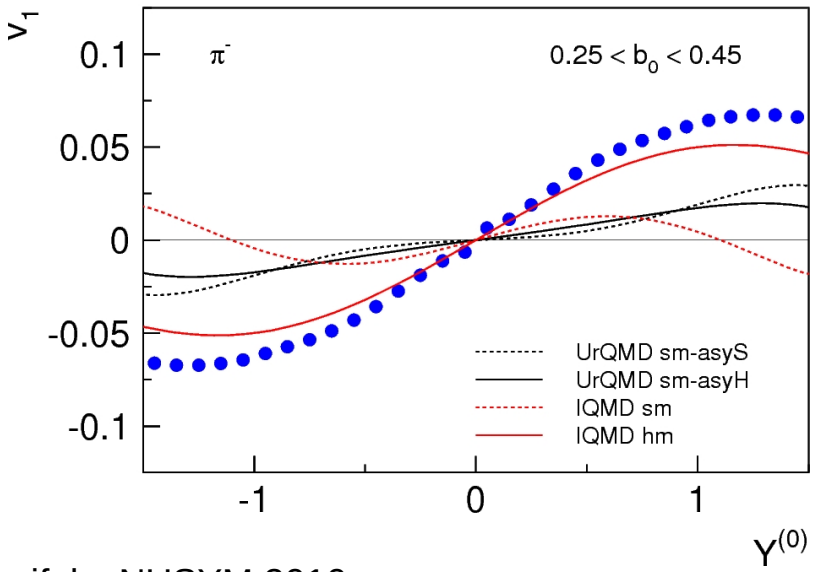
$-v_2(t) - (-v_2(^3He))$



Y. Leifels, NUSYM 2010

Sideward flow of π^- and π^+





- Hard EOS is better describing the data (IQMD and UQMD are consistent)
- Description of π^+ worse
- According to UrQMD no significant sensitivity to the asymmetry term

Y. Leifels, NUSYM 2010

Summary and Conclusions

Completed systematics on charged particle production in symmetric systems

- Flow of isospin pairs: effects/different flows not reproduced by models
- Ratio π^-/π^+ : consistent description still lacking
- Neutron and Z=1 elliptic flow: $\gamma = 0.94(21)$ with UrQMD
- t/^{3}He production yields and spectra (not discussed)

→ **No consistent description**

To be done

- Systematic comparison to model predictions

To conclude

- Clusterization important → models
- Effects of asymmetry energy small
- Constraining asymmetry energy at supra normal densities requires detectors with excellent particle identification properties, high efficiency, and large acceptance
- Pion and Kaon identification and isotope separation (ASY-EOS @ SIS18 as an exploratory experiment concentrating on neutron squeeze-out and fragment flow, aDet @ FAIR?)