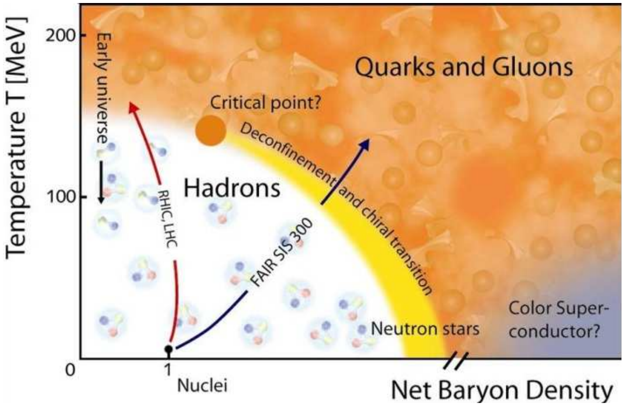
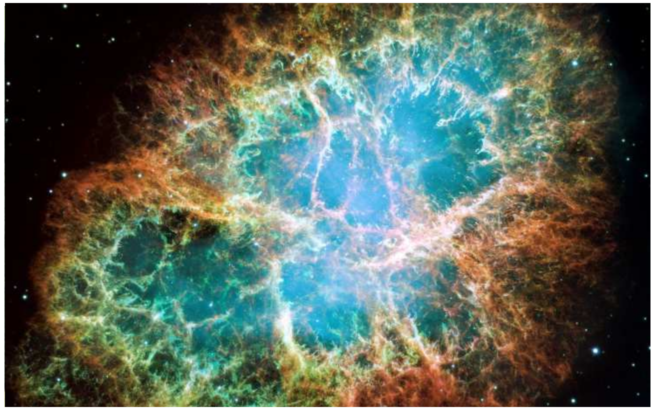




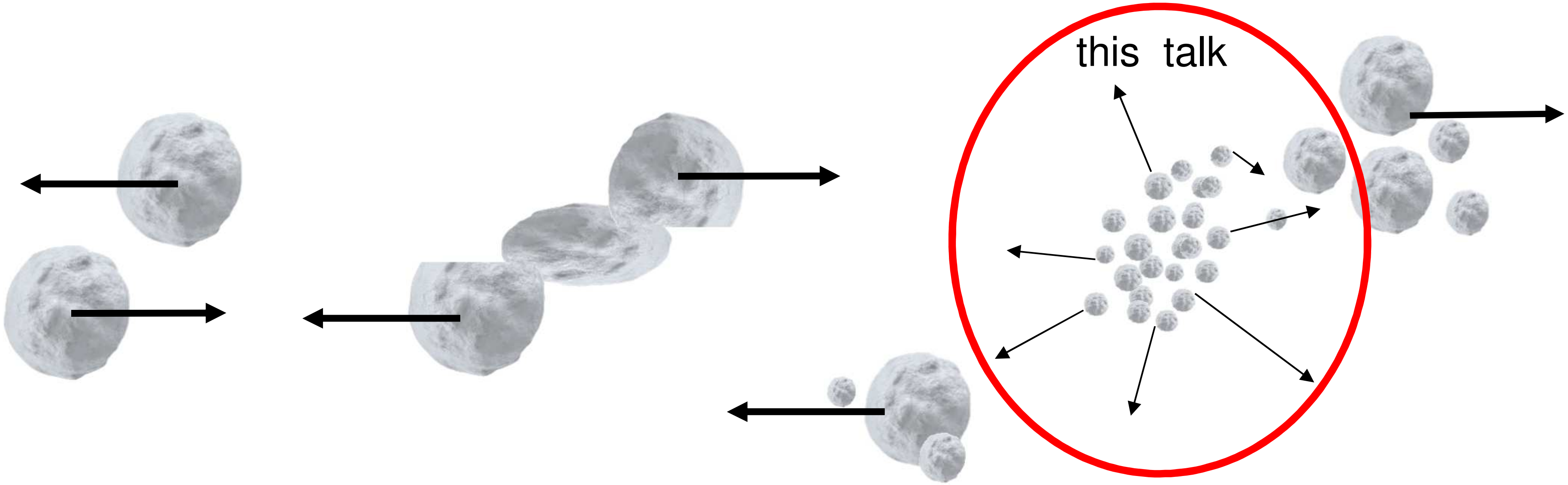
Light nuclei formation at SIS energies

Y. Leifels for the FOPI collaboration
and with FOPI data
GSI Helmholtzzentrum für
Schwerionenforschung, Darmstadt

EMMI Workshop
11.02.-13.02.2019
GSI

FAIR GSI

Formation of light nuclei in heavy ion collisions

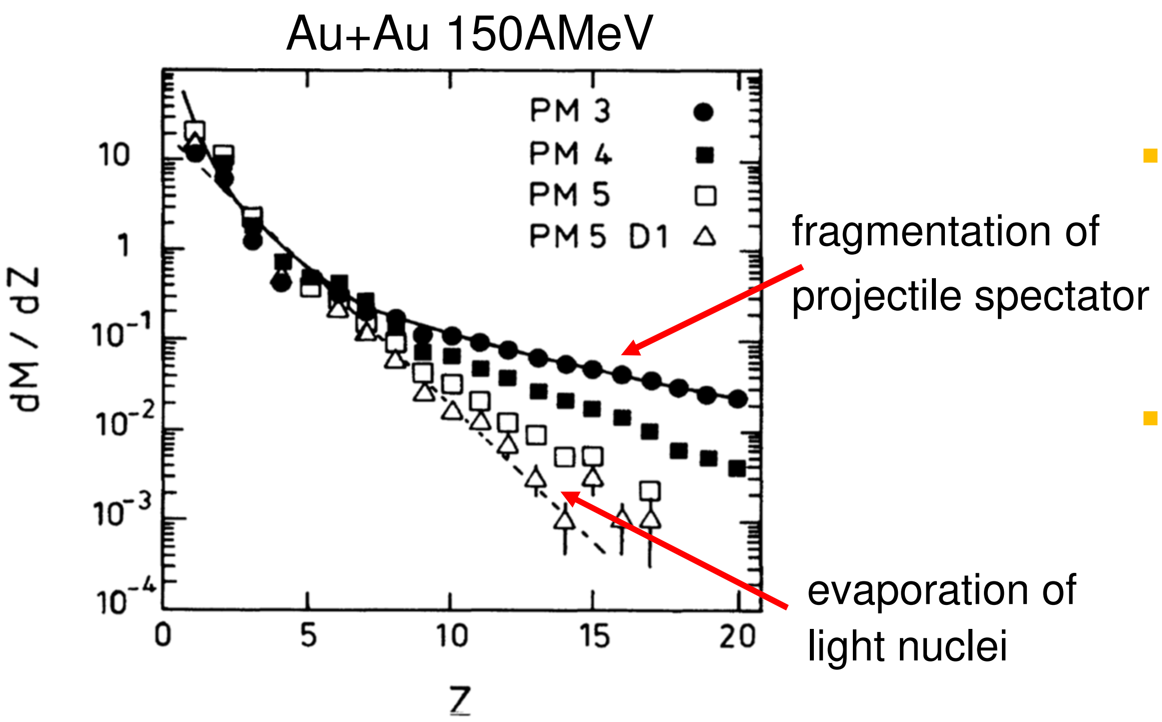


- source at mid-rapidity
- observed best in central collisions
- no clear separation between projectile/target spectators and participants
- complete dynamical description needed

Formation of light nuclei in heavy ion collisions

- centrality dependence

$1<\theta_{lab}<30^o$



C. Kuhn et al., PRC 48, 1232 (1993)

- exponential behaviour of Z distributions observed in most central collisions
  - evaporation mechanism
- in peripheral collisions flattening of the shape
  - multi-fragmentation

Outline

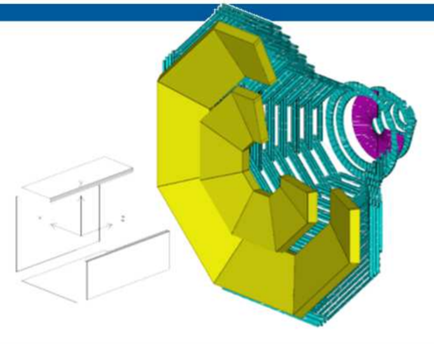
Experimental setup & dataset
- FOPI history

Analysis technique
- Reaction plane determination
- Fourier expansion of azimuthal distributions
- Quadrant method

Selected results
- Global features
- Stopping
- Collective flow of charged baryons

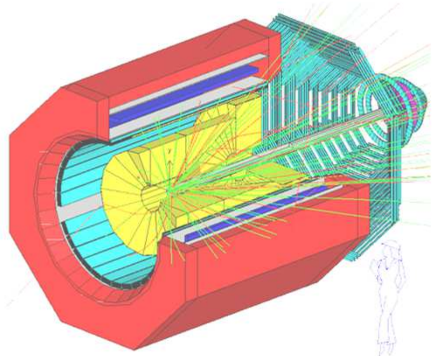
Conclusions

FOPI data sets



Phase I 1990 – 1992

Setup: no magnetic field, forward wall & ionisation chambers
Main physics: radial expansion, fragment formation
Systems: Au+Au, Xe+CsJ
Beam energy: 0.1 – 0.8 AGeV

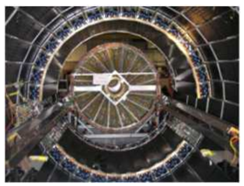


Phase II 1993 – 1998

Setup: tracking in solenoid, forward wall
Main physics: stopping, EOS
Systems: Ca+Ca, Ru/Zr + Ru/Zr, Au+Au
Beam energy; 0.4 – 1.5 AGeV

Phase III 2001 – 2012

Setup upgrades: DAQ (2001), TOF (2007), Λ – trigger (2008), Gem-TPC (2010)
Main physics: strangeness in dense medium
Systems: Ni+Ni, Al + Al, Ni+Pb, Ru+Ru
π^- + C,Cu,Pb
Beam energy: 1.6 – 1.9 AGeV



Motivation: Equation of state of nuclear matter

Nuclear matter equation of state

- infinite symmetric nuclear matter N=Z
- ground state properties: ρ_0 = 0.16 N/fm^3 and $E(\rho_0)$ = -16 MeV
- expansion in density:

$$E(\rho, T=0, \delta=0) = E_0 + \frac{K}{18\rho^2}(\rho-\rho_0)^2 + \dots$$

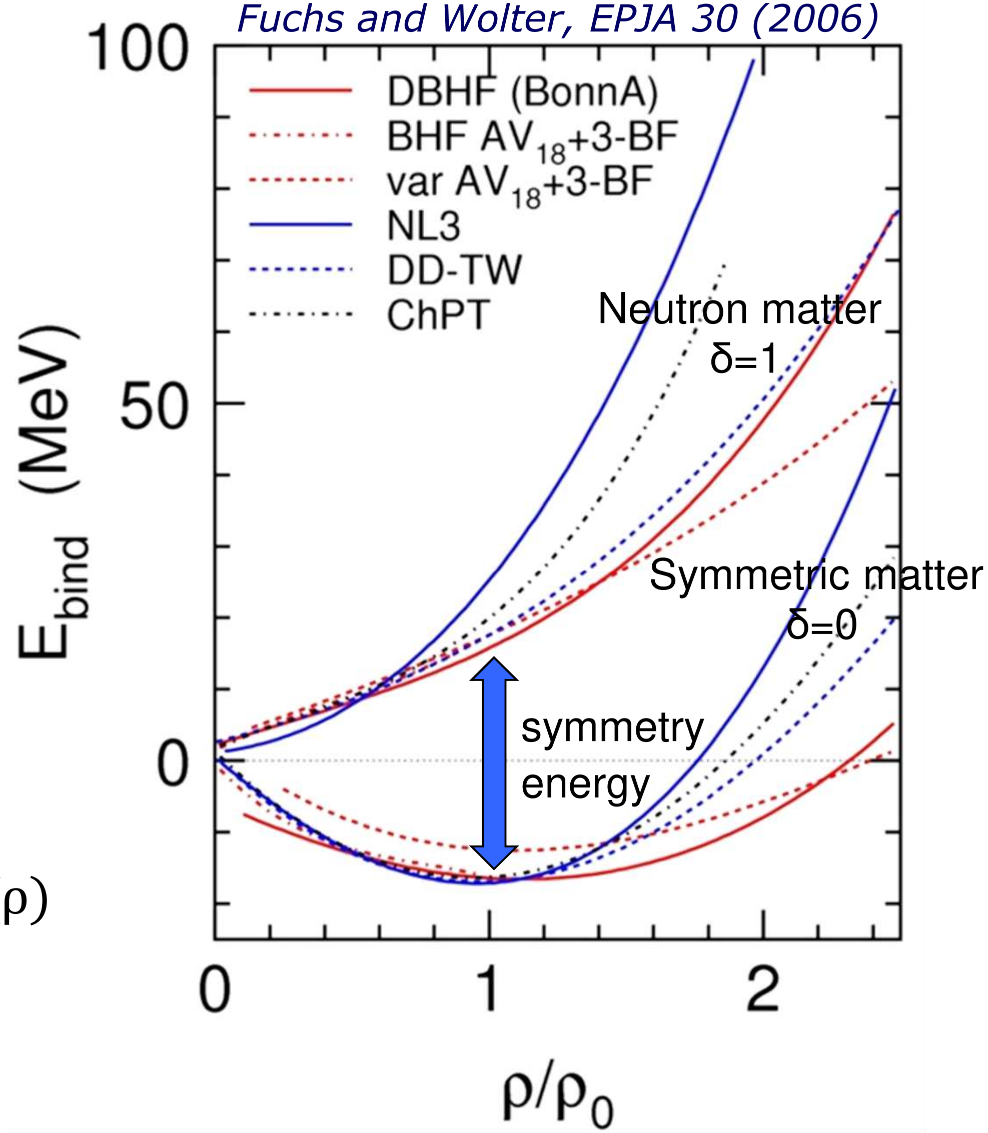
From symmetric nuclear matter to neutron matter:

$$\delta = \frac{\rho_n - \rho_p}{\rho}$$

$$E(\rho,\delta) = E_{SNM}(\rho, \delta=0) + \delta^2 E_{sym}(\rho)$$

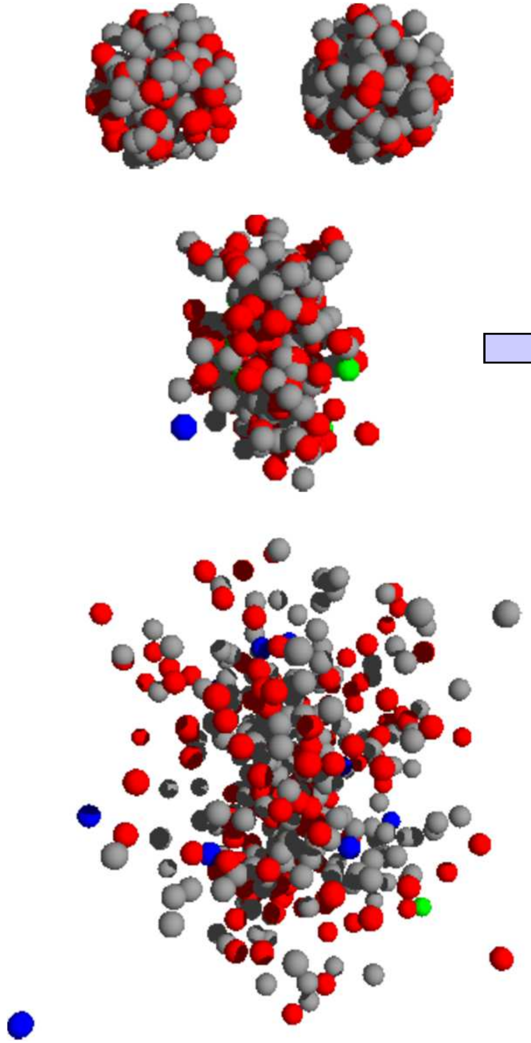
In heavy ion reactions n-p asymmetries are small with respect to neutron stars

Fuchs and Wolter, EPJA 30 (2006)

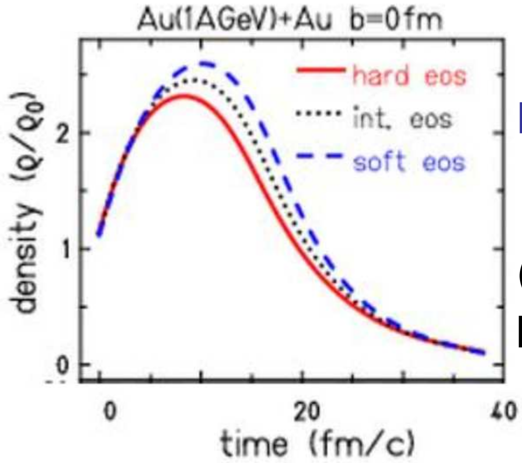


Nuclear EOS and heavy ion collisions

IQMD: C. Hartnack, EPJ 1, 151 (1997)

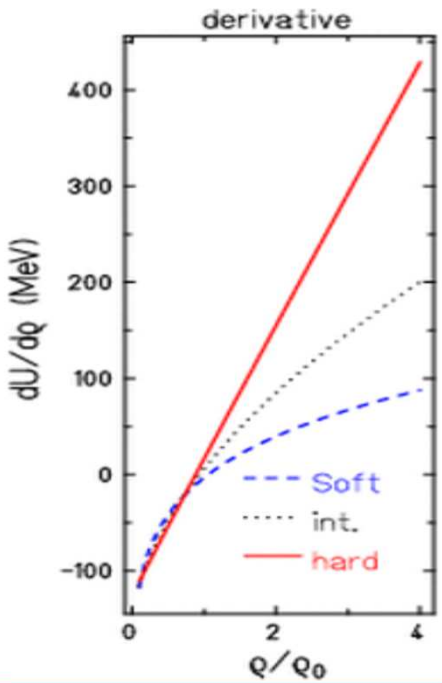


EOS
(in-medium)
cross sections
effective masses
Pauli - blocking



Density

(in medium)
particle production



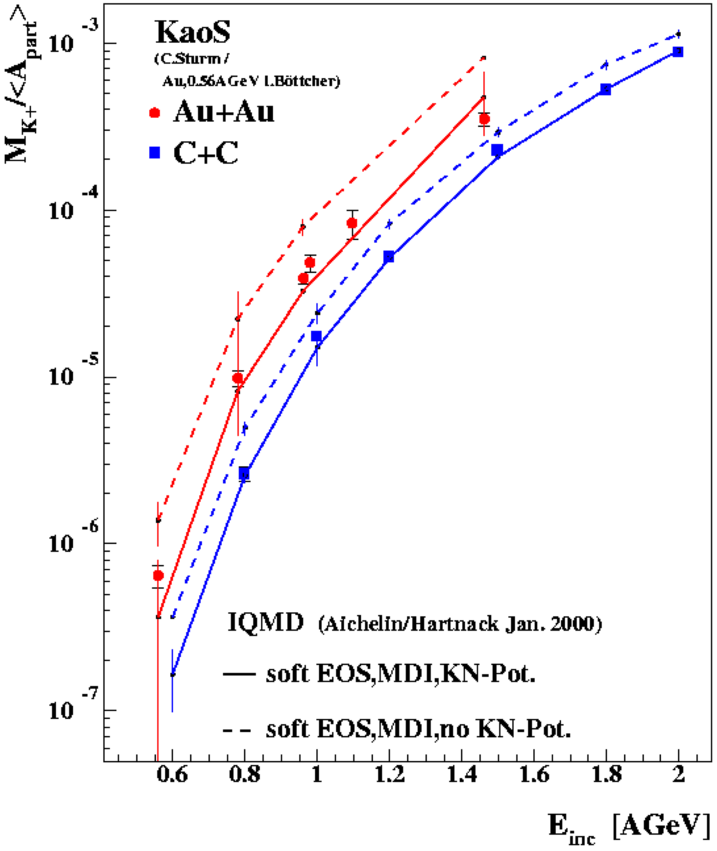
Pressure

(in medium)
particle propagation

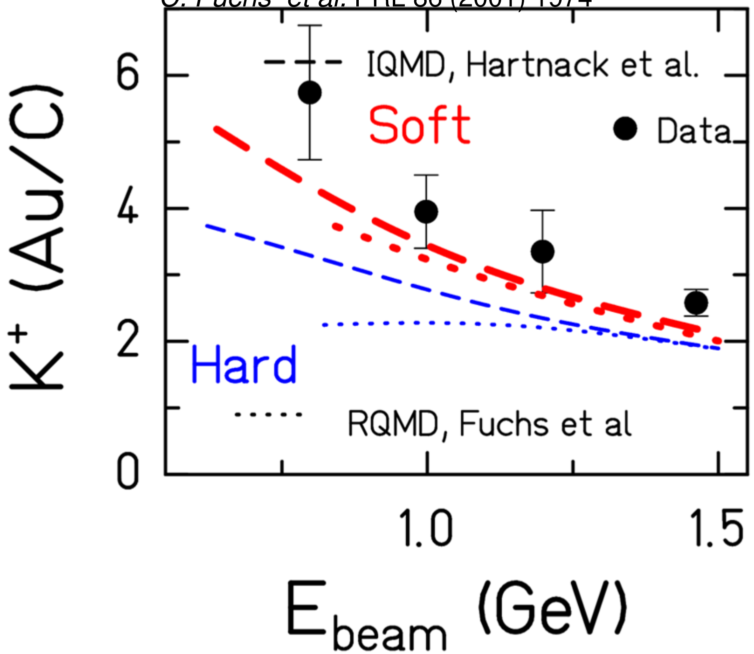
collective flow

Probing the EOS with Kaon production

C.Sturm et al. (KaoS), PRL 86 (2001) 39



C. Sturm et al., PRL 86 (01) 39
Ch. Hartnack et al., PRL 96 (2006) 01230
C. Fuchs et al. PRL 86 (2001) 1974

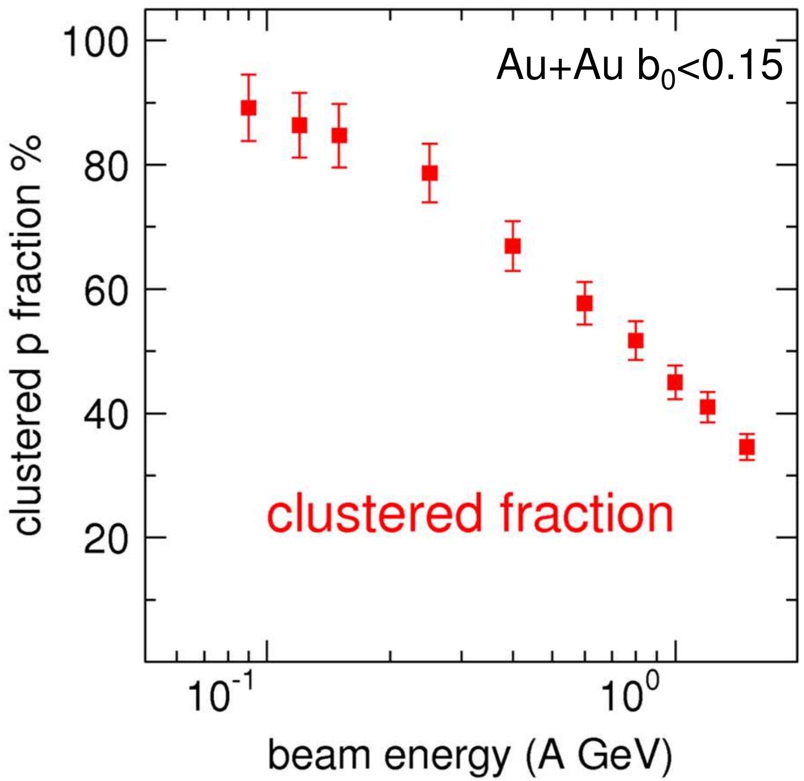


Ratio of yields stable against variation of
K^+ production cross section

Strong sensitivity to EOS due to multistep production (formation of nucleon resonances, e.g. Δ)
-> soft EOS (K=200)

Isospin dependence of EOS [N/Z(Au) = 1.49]

Formation of light nuclei in heavy ion collisions

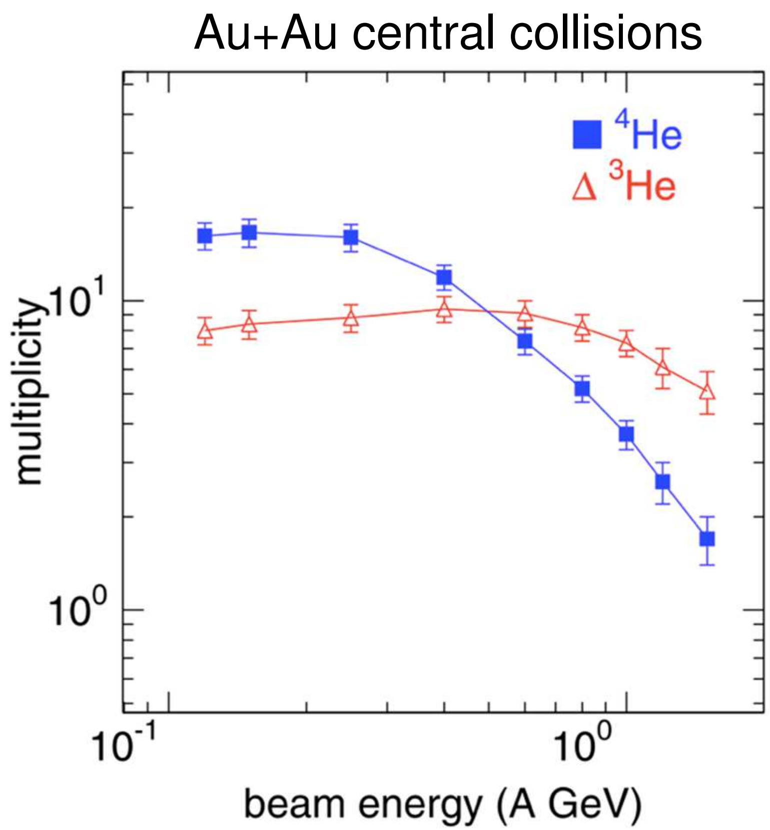


- high degree of cluster formation even in most central collisions
- cluster production influences phase space distributions of all particles
- clusters are less disturbed by „thermal noise“
  - stronger flow patterns than protons
  - generally: higher mass, stronger flow

Statistical/thermal models (QSM, WIX/FRESCO)

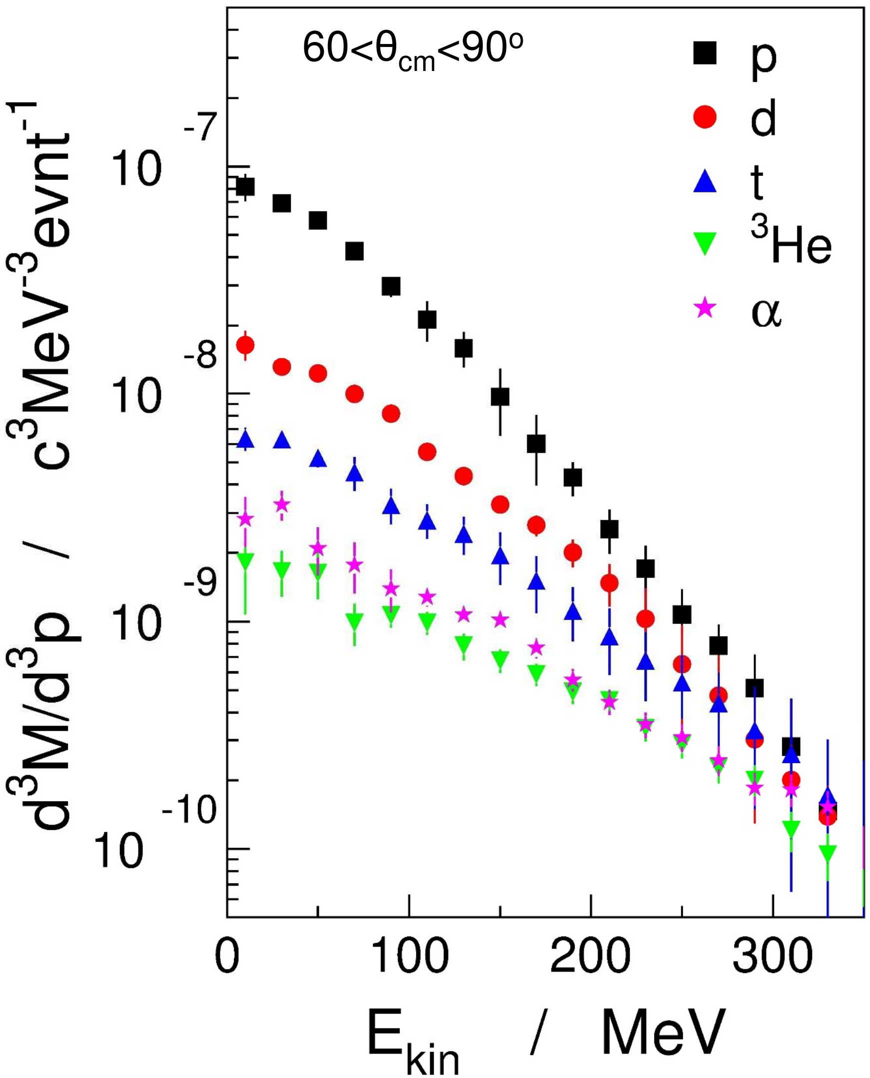
- does not lead to consistent results (yields vs spectra, *Poggi et al 1993*)

Light nuclei are not formed by coalescence



- light nuclei are formed in a multitude of processes
  - primordial
    - e.g. ^{3}He
  - primordial with subsequent capture of neutrons or other particles
    - e.g. ^{4}He
  - secondary after the decay of heavier fragments
    - e.g. ^{4}He, t
- but NOT generally by coalescence
  - only at high energies (>1.5AGeV) or in light systems where cluster production can be treated perturbatively

Light nuclei formation at 250 MeV



Au+Au 250 MeV b<3.5 fm

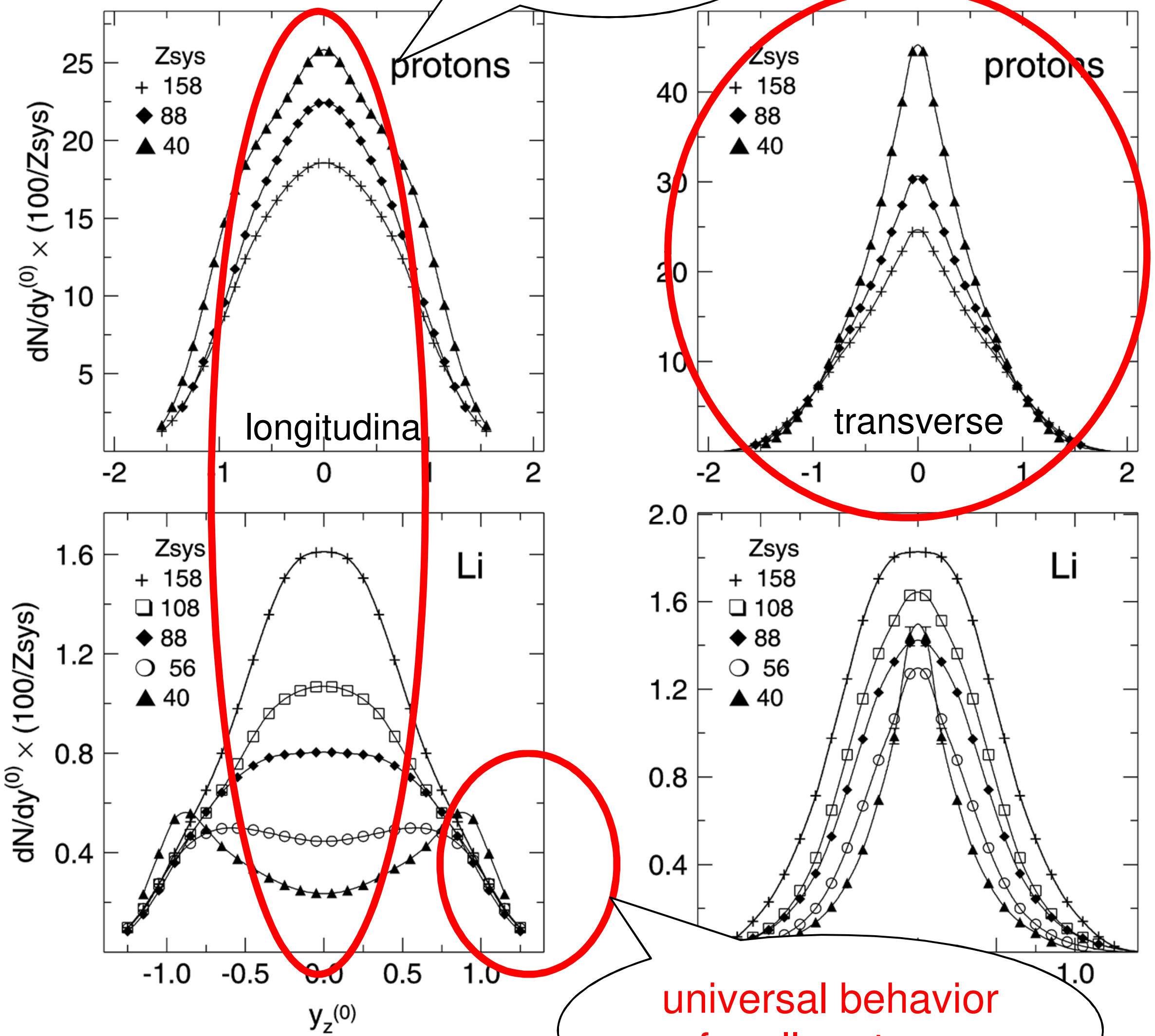
G. Poggi et al. NPA 586 (1995) 755

^{3}H and ^{3}He yields

- at low kinetic energies large differences
- spectra converging at high kinetic energies
- ^{3}He shows larger inverse slope parameter than ^{3}H
  - larger than the difference in Coulomb energies
  - difference diminishes with energy, vanished at 600 AMeV Au+Au
  - secondary decay of heavier clusters contributes more to the ^{3}H spectrum
  - n capture on ^{3}He

Formation of l… lei in heavy ion collisions

- system size depe… AMeV (Au+Au, Xe+CsJ, Zr+Zr, Ca+Ca)



- unbound protons ↔ bound light nuclei
- more fragments in heavier systems
  - radial flow larger in heavy systems
  - correlation between cluster multiplicities and collective radial flow
- normalized transverse rapidity distributions similar at high rapidities

W. Reisdorf et al., PLB 595,118 (2004)

W. Reisdorf et al., NUPA 848, 366 (2010)

Radial flow of light nuclei

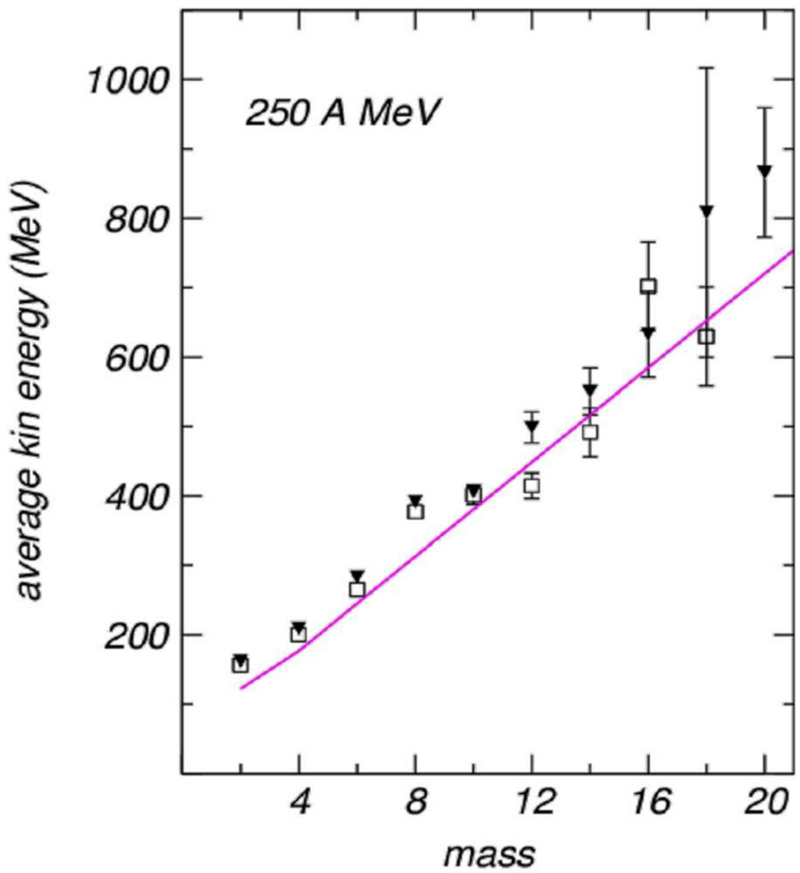
- Generally defined (in experimental papers) as an azimuthally symmetric collective expansion of the emitting source
- Predicted by Hydrodynamical model
  - Bondorf et.al. NPA296(1978)320, Siemmens &
  - Rasmussen PRL 42(1979) 880
  - (Stoecker & Greiner, Phys. Rep. 137 (1986) 227)
- Observed for the first time in central Au+Au collisions at 150AMeV (FOPI@GSI) *S.G. Jeong et al (FOPI), PRL 72 (1994) 3468*

→ Large fraction of the initial KE (~30%) is converted into the collective expansion
→ Implications on collision dynamics and underlying reaction mechanisms

Described by:

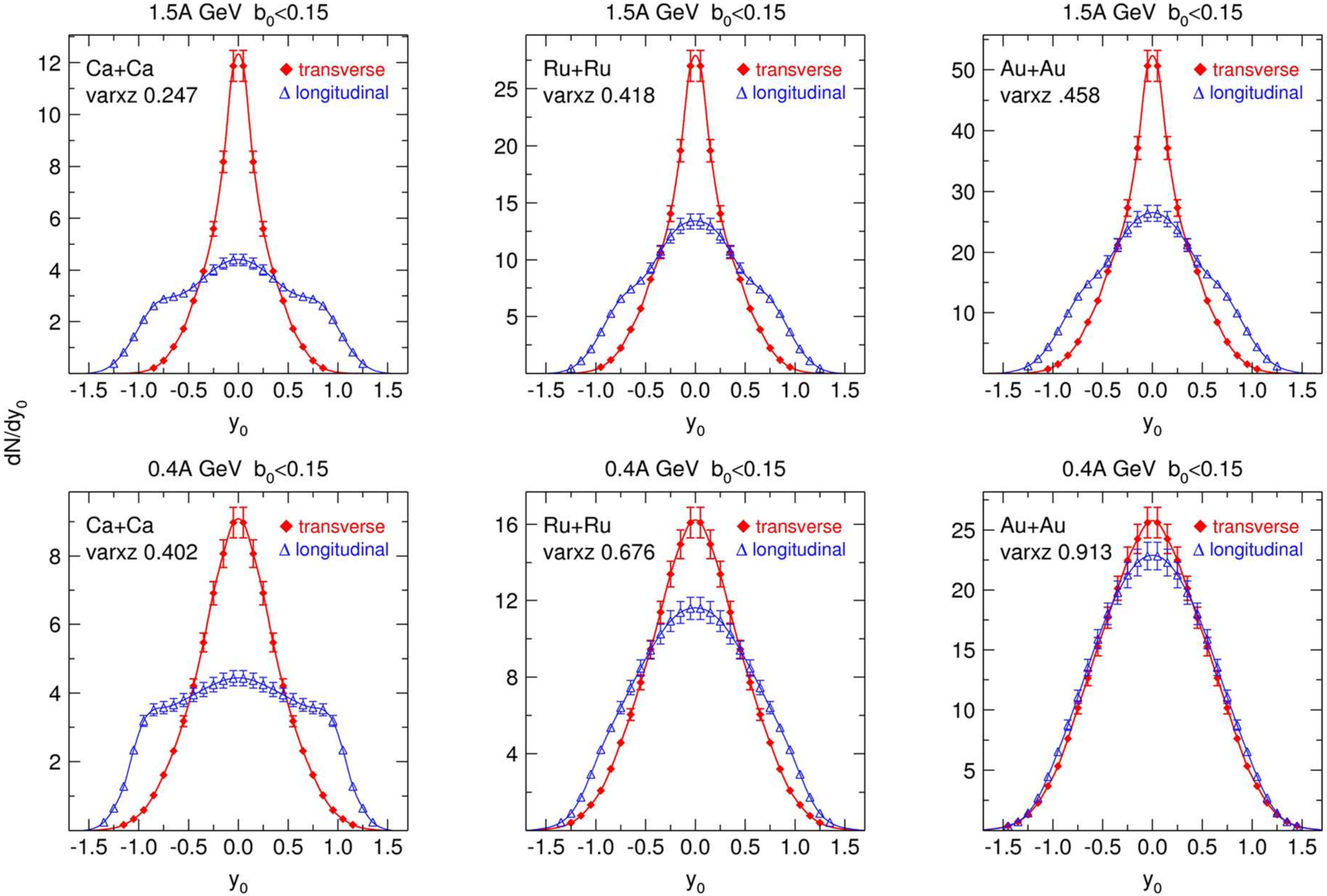
$$E_{kin} = \left(\gamma_{flow} - 1\right) \cdot m_N \cdot A + E_0$$

W.Reisdorf et al (FOPI), NPA612(97)493



Rapidity distributions of light nuclei

deuterons



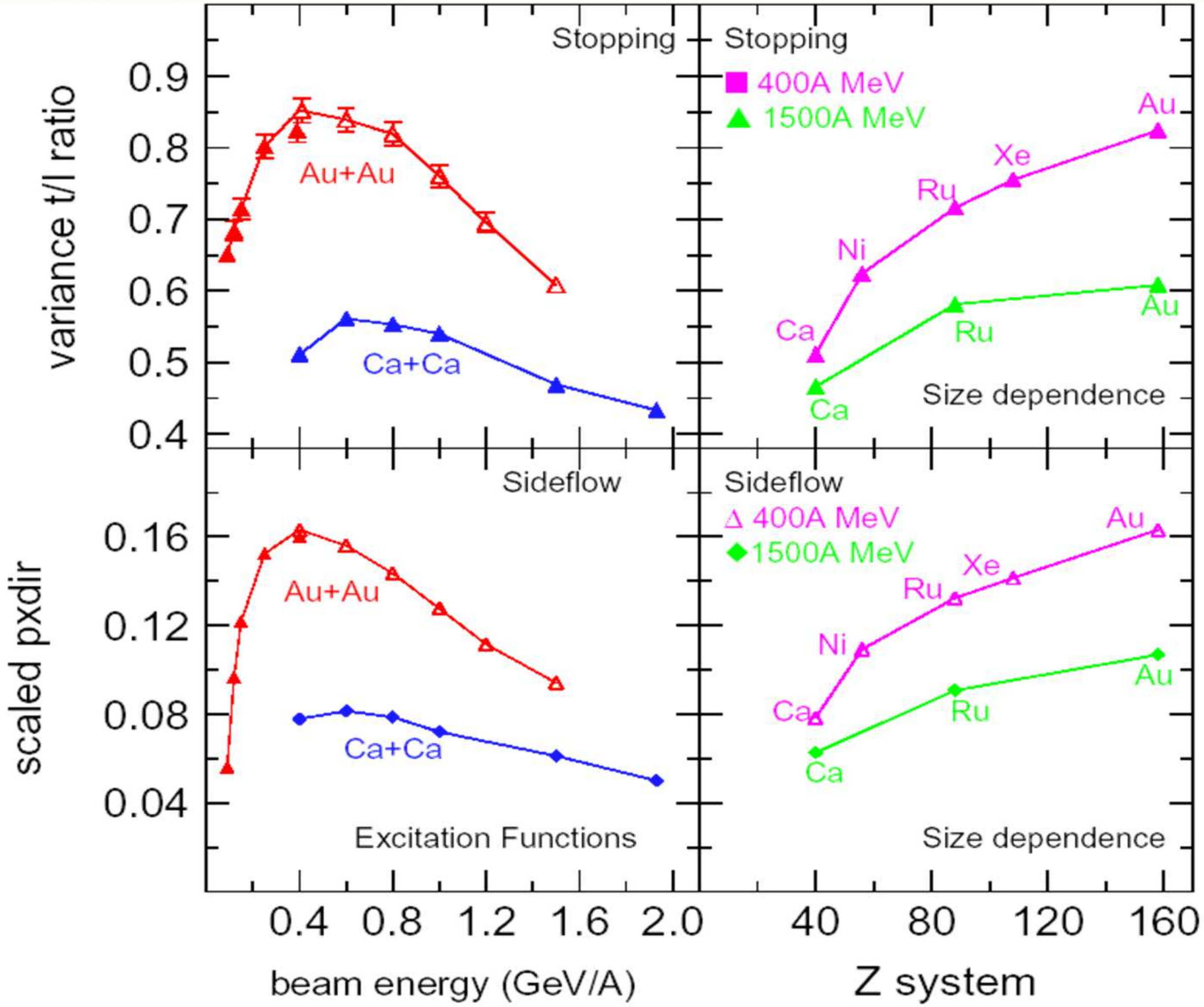
Correlation between stopping and directed flow

Stopping
$b/b_{max}<0.15$

$$\frac{\sigma^2(y_t)}{\sigma^2(y_z)}$$

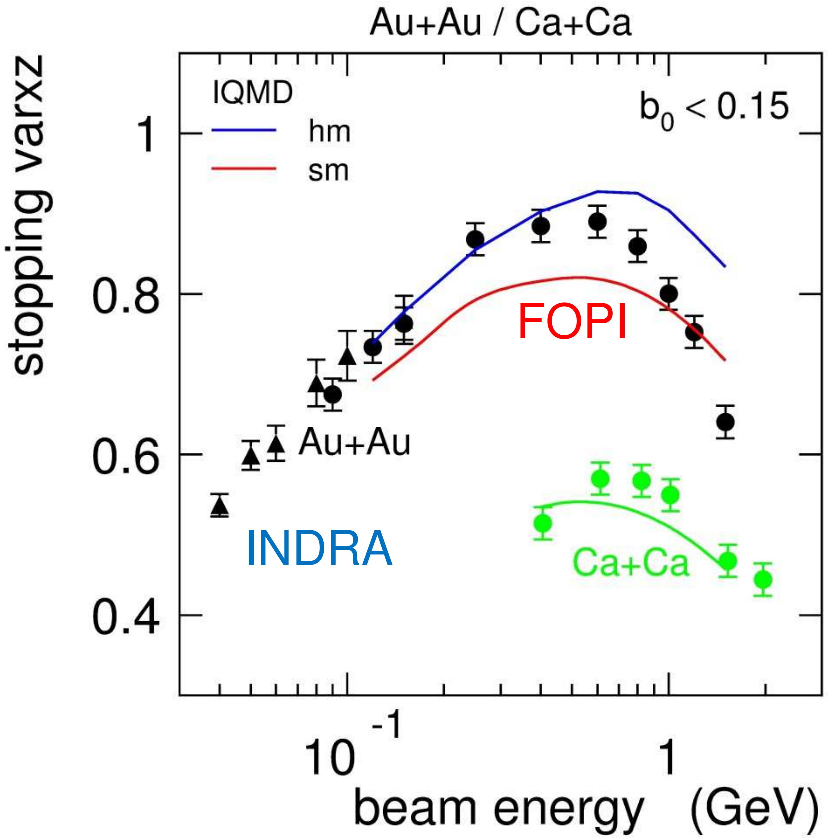
Sideflow
$b/b_{max}\approx 0.4$

$$p_x^{dir} = \frac{\sum_i sign(y_i) Z_i u_{xi}}{\sum_i Z_i}$$



Pressure (flow) correlates with energy density (stopping) => EOS accessible,
System size dependence does not show a plateau => transport models necessary.

Stopping in heavy ion collisions (Z<5)



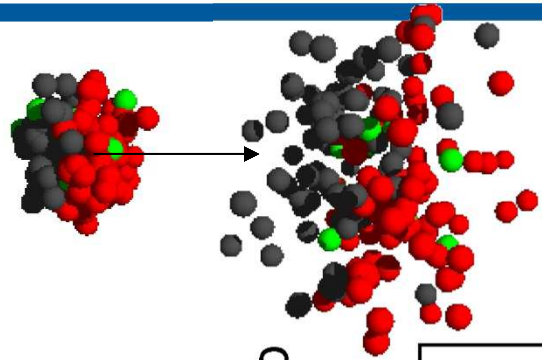
Data: FOPI+Indra, A.Andronic et al.
Eur.Phys. J.30 (2006) 31-46
IQMD, C. Hartnack et al. EPJ A1 (1997) 151

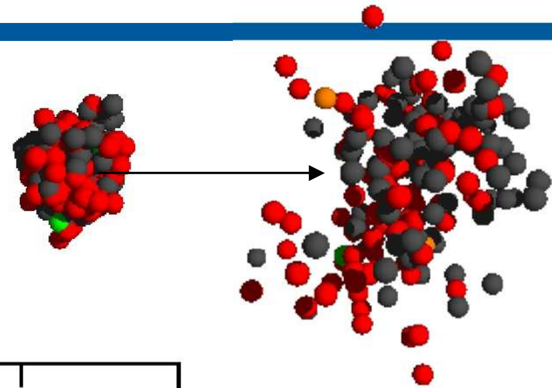
- Stopping deduced from phase space distributions

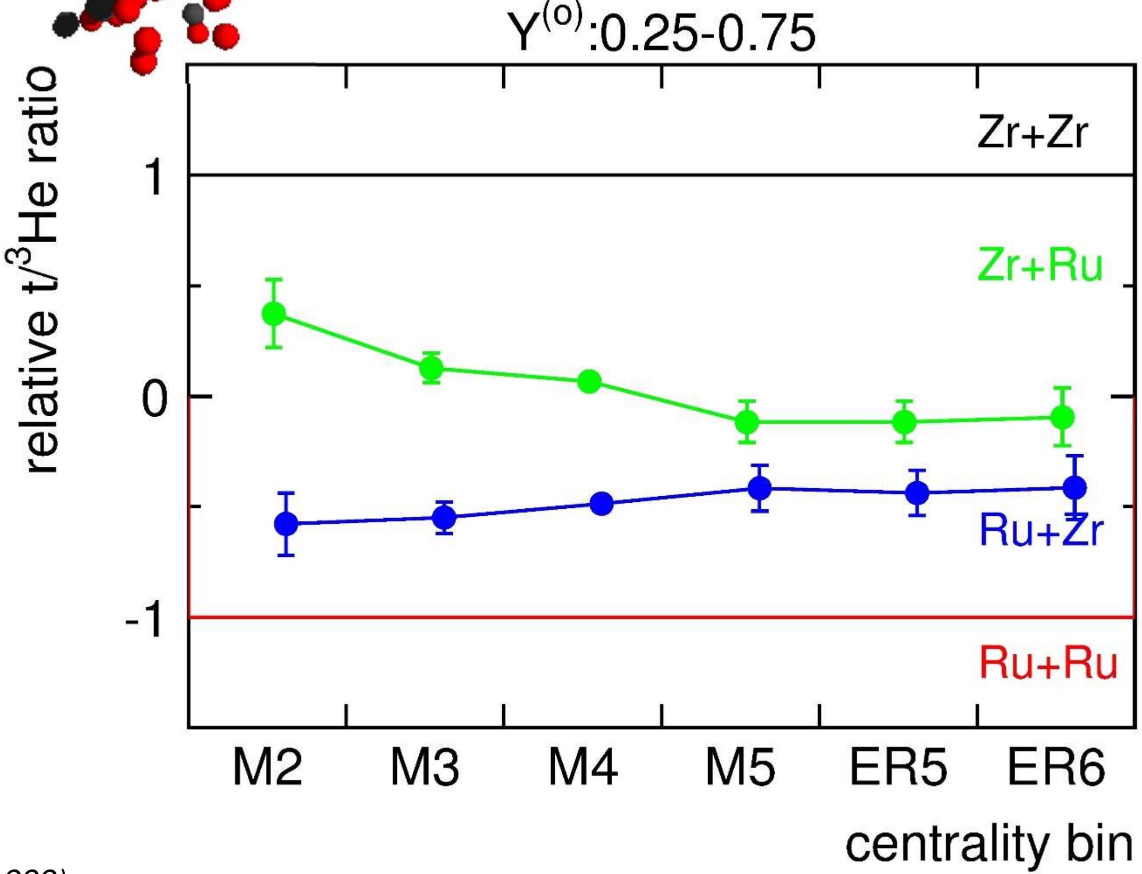
$$\text{var xz} = \frac{\sigma^2_{y_x}}{\sigma^2_{y_z}}$$

- microscopic models reproduce the stopping reasonably well
- sensitive to in-medium modifications of NN cross sections and polar angle distributions of NN scattering

Testing stopping and equilibration with t and 3He







400 AMeV

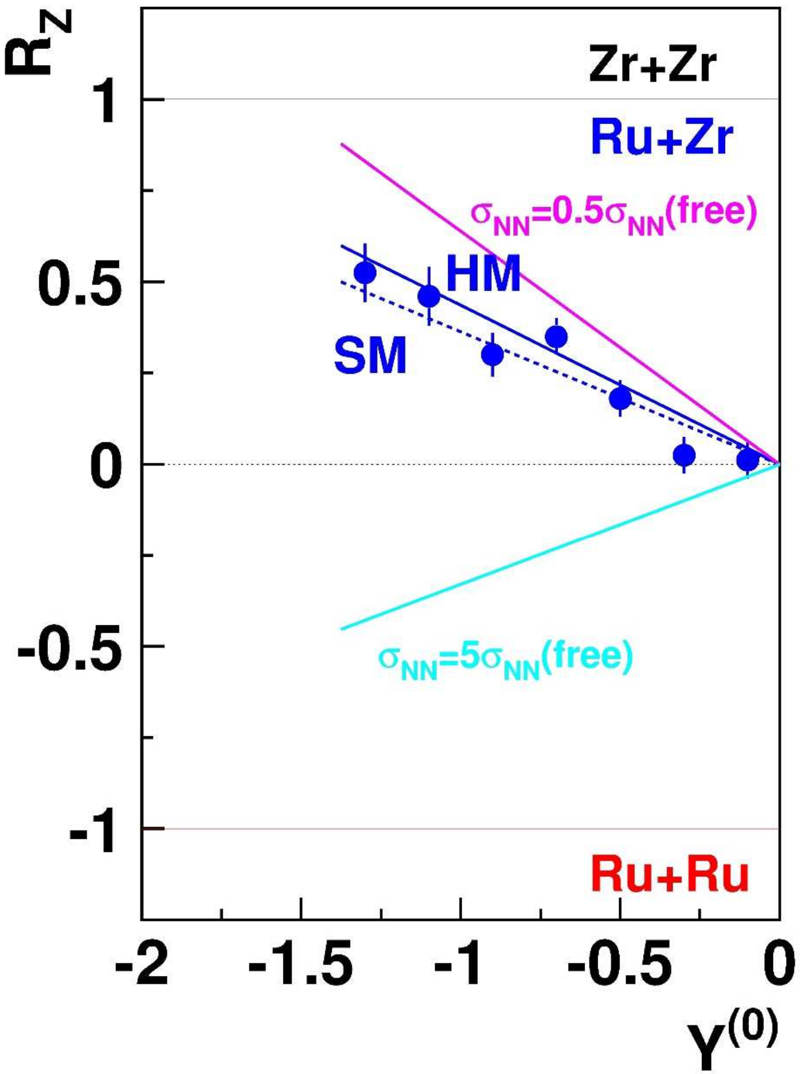
Masse 96

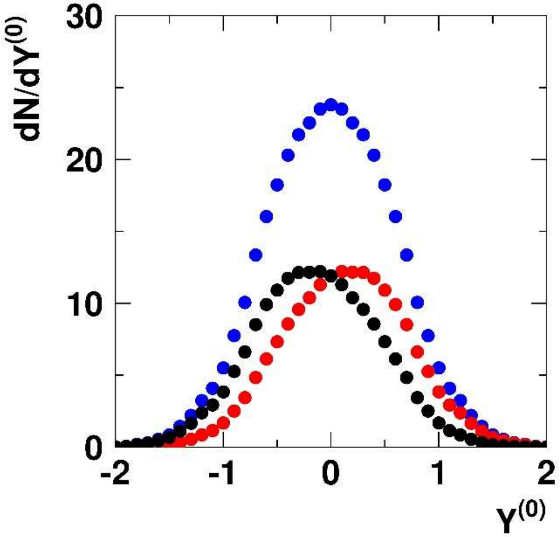
Z(Zr) = 40

Z(Ru) = 44

F. Rami et al., PRL (1999)

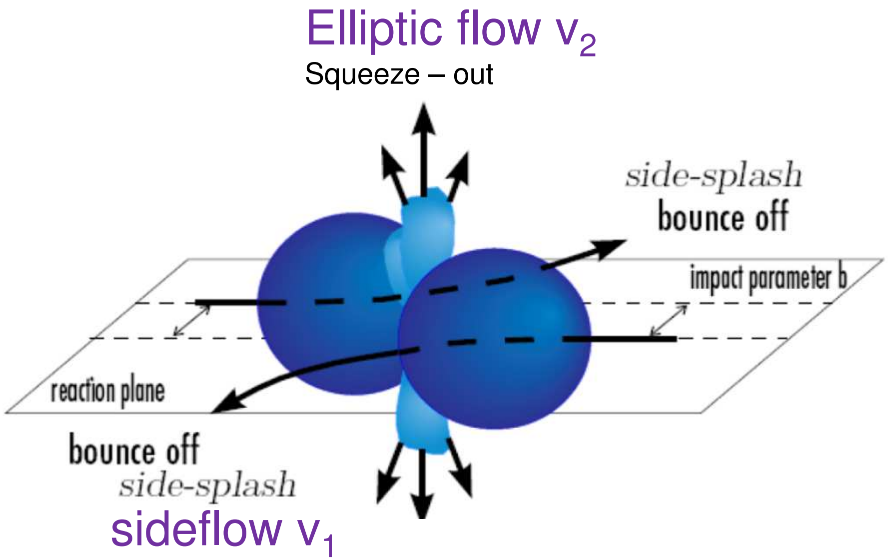
Testing stopping and equilibration mit Z=1 nuclei





- with measured rapidity distribution deconvolution of target and projectile contributions
- smooth linear evolution of all observables
  - not completely stopped, not mixed
  - not equilibrated
  - dynamically evolving
- at 1.5 AGeV a more mixed source is observed!!

Collective flow



Phase space distribution
with respect to reaction plane Φ_R

$$\varphi' := \varphi - \Phi_R$$

$$\frac{d^3N}{p_t dp_t dy d\varphi'} \propto (1 + 2v_1 \cos(\varphi') + 2v_2 \cos(2\varphi') + \ldots)$$

Fourier expansion coefficients

$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle = \langle \cos \varphi' \rangle$$ sideflow

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos 2\varphi' \rangle$$ elliptic flow

Discovery: Bevalac

H.A. Gustafsson, et al., Phys. Rev. Lett. 52 (1984) 1590.
R.E. Renfordt, et al., Phys. Rev. Lett. 53 (1984) 763.

Quantitatively correctable for finite number fluctuations !

S. Voloshin, Y. Zhang, hep-ph/9407082
J.Y. Ollitrault, nucl-ex/9711003

Flow of light nuclei

- fragments much more sensitive to dynamical effects
- clusters formation is omnipresent in HIC, important for analysis (observables depend on degree of cluster formation)

cluster production in models

statistical (grand) canonical ensemble

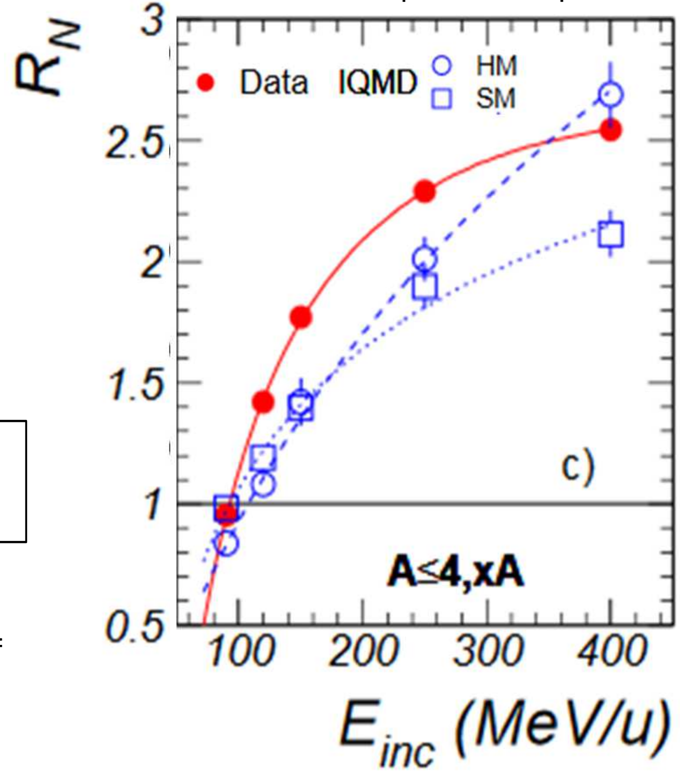
- often successful

dynamical evolution of the reaction

- few body correlations, treat clusters as explicit degrees of freedom (AMD, pBUU)
- fluctuations and/or mean field (..BUU, ..MD) + coalescence or MST or SACA/FRIGA

Elliptic flow

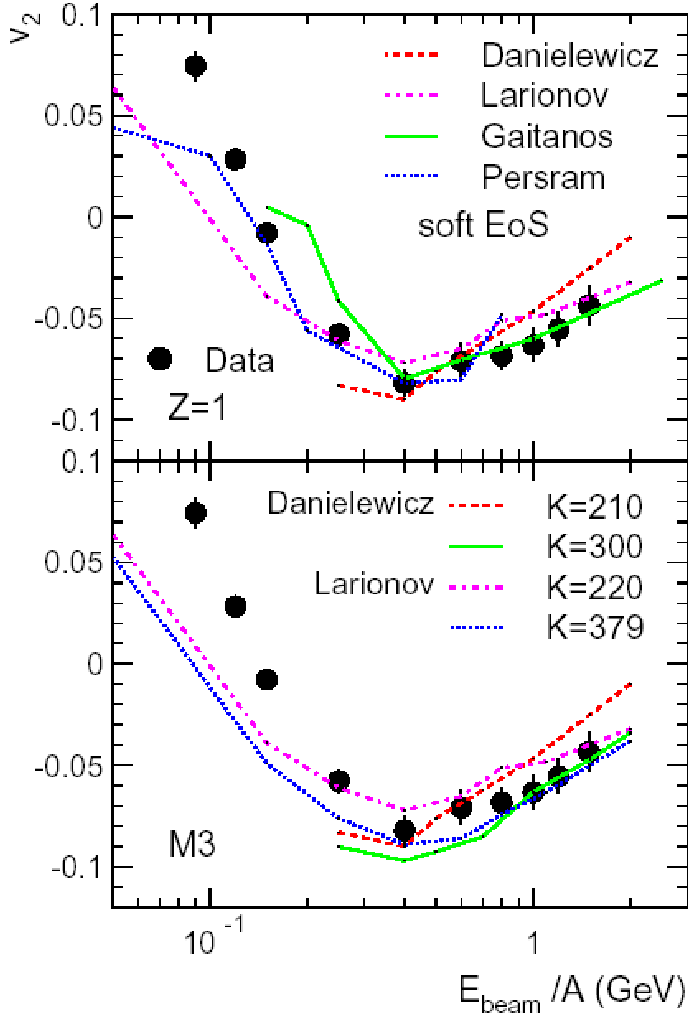
Ratio out-of plane to in-plane



FOPI: Stoicea et al. (1996)

Elliptic flow in comparison to models

A. Andronic et al. (FOPI), PLB 612, 173 (2005)

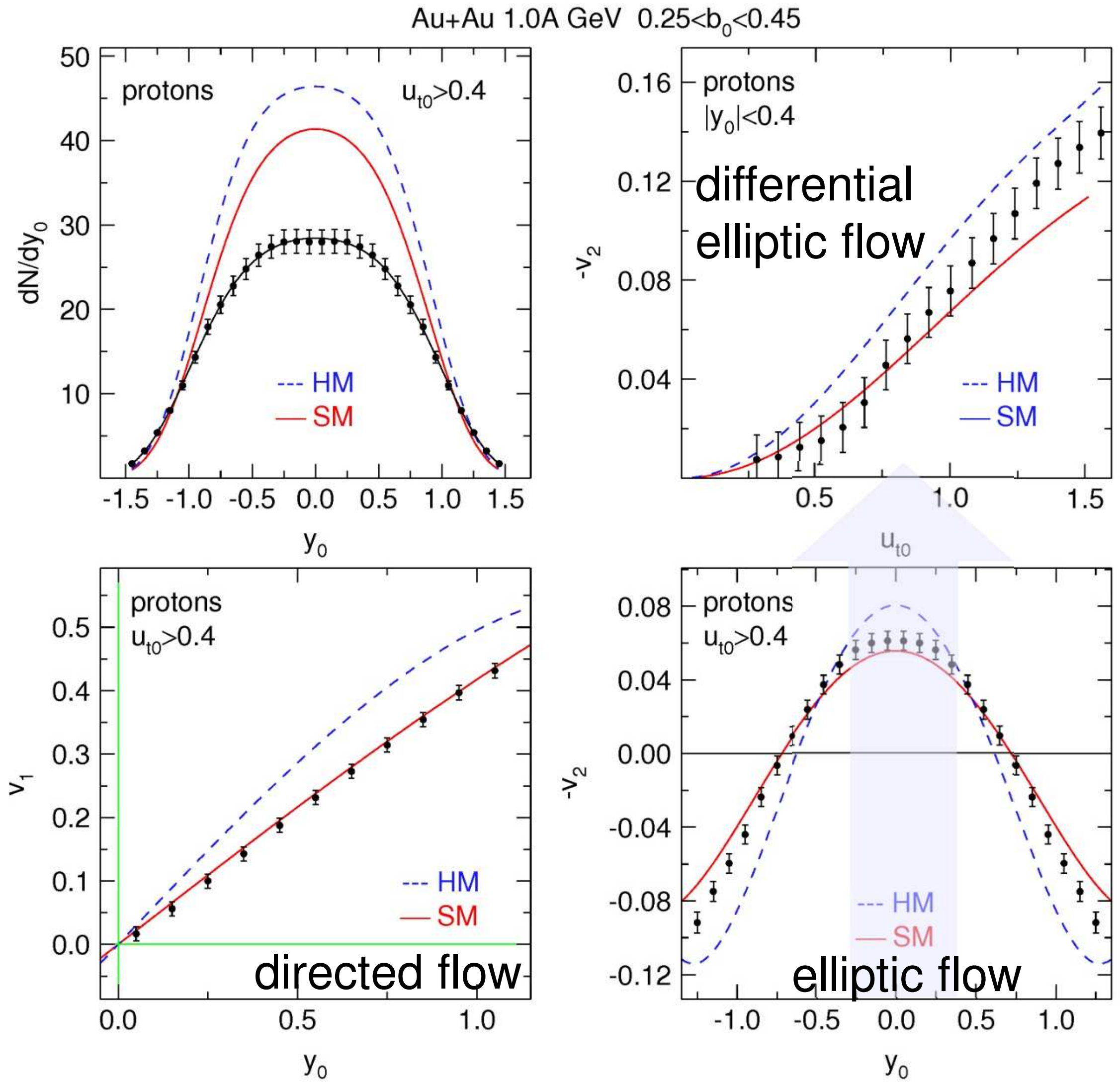


Ambiguities in the interpretation.
Imperfections in event selection
‘Z=1’, ‘M3’

Single observable is not sufficient to disentangle
EOS
(in-medium) cross section
momentum dependent interaction

Strategy:
use one model as reference -> IQMD
compare other models to IQMD

Collective flows in Au+Au collisions at 1.0A GeV

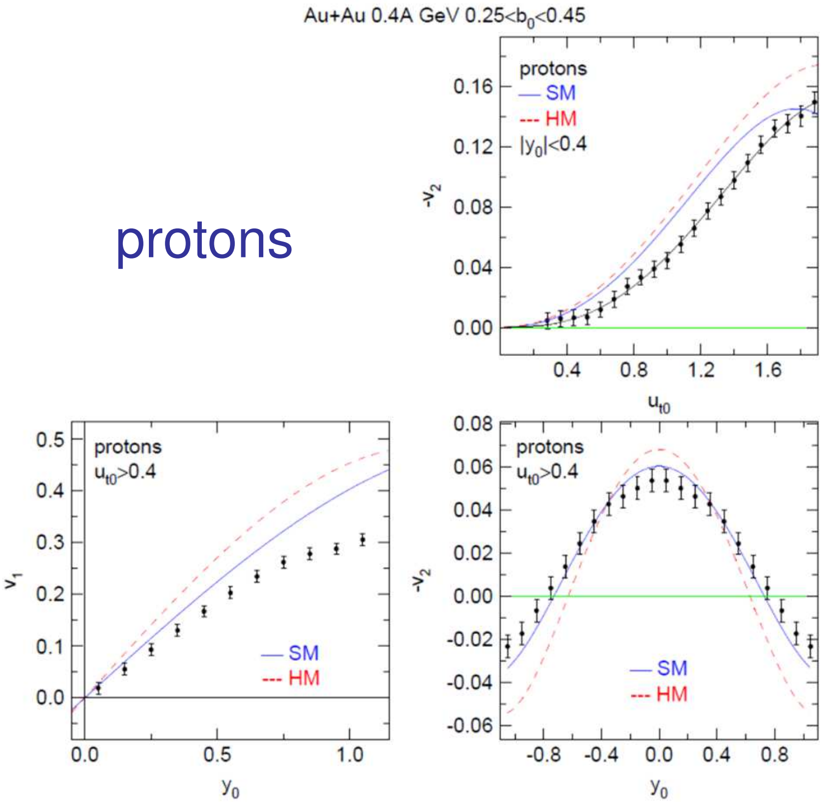


W. Reisdorf et al, Nucl. Phys. A 876 (2012) 1

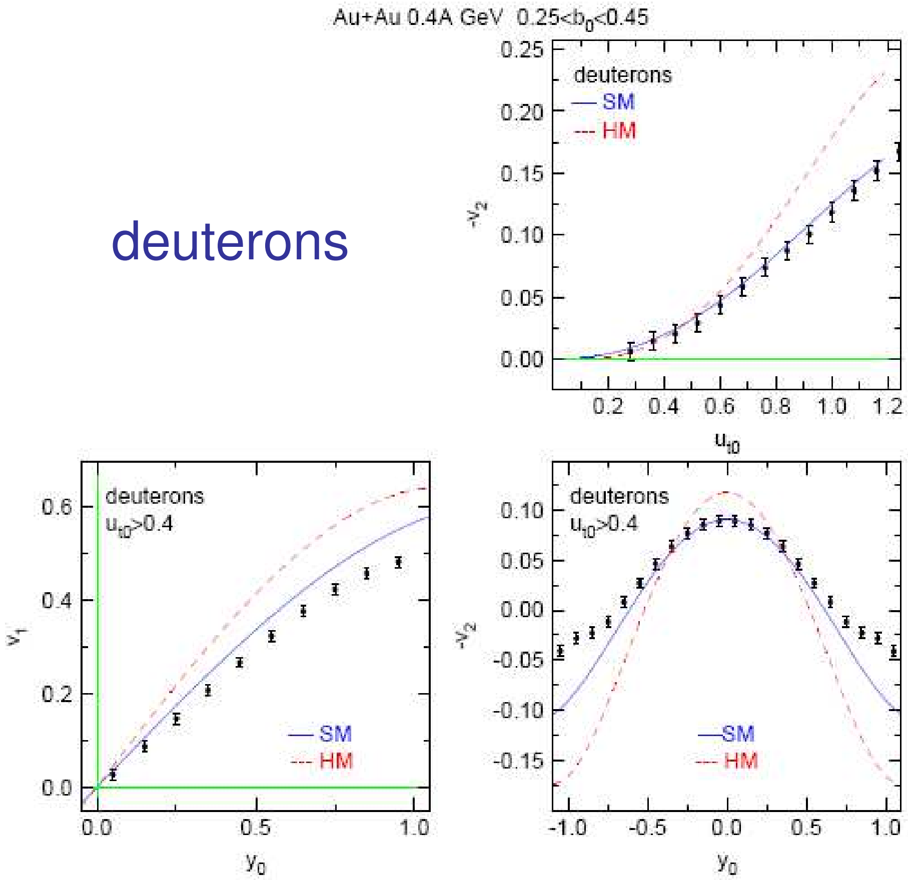
Flow of light nuclei in Au+Au at 0.4AGeV

W. Reisdorf et al. (FOPI), NPA 876, 1 (2012)

protons



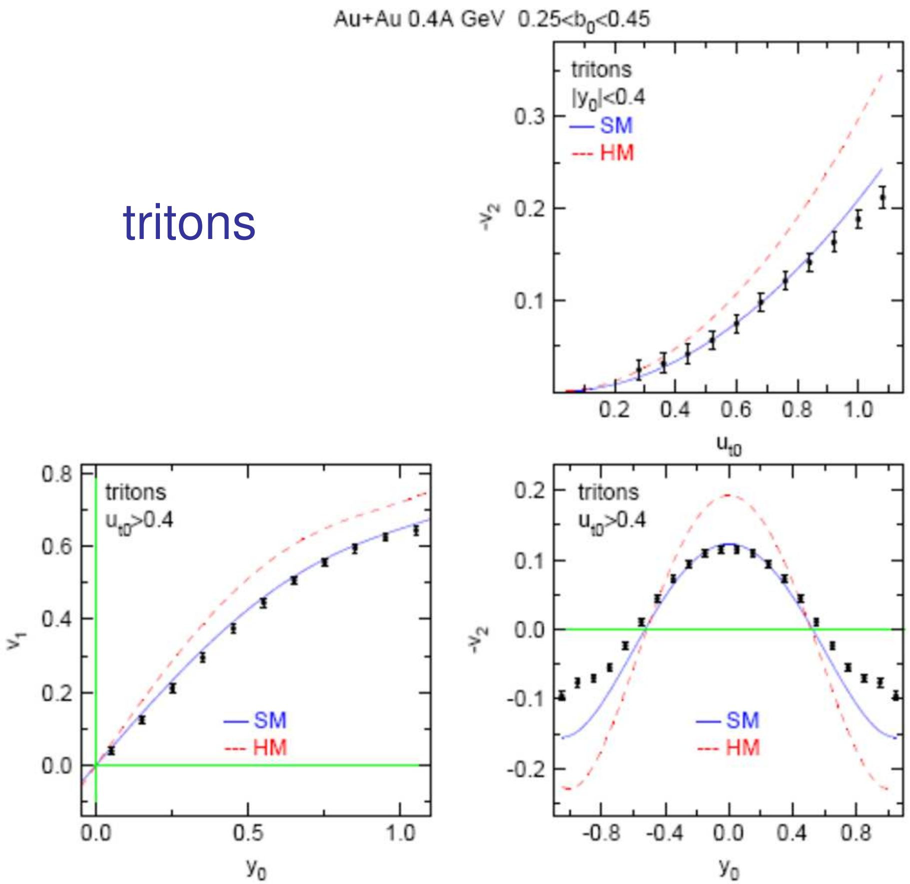
deuterons



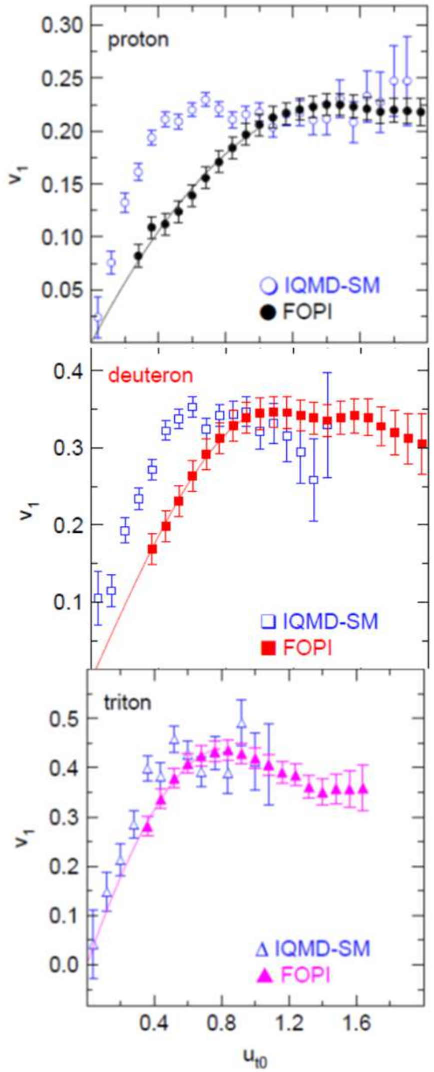
- heavier clusters (d) are less influenced by thermal noise → stronger flow
- no mass scaling observed
- EOS impacts the whole phase space distribution
- Proton and deuteron distributions favor a soft EOS (IQMD).

Flow of light nuclei in Au+Au collisions at 0.4 AGeV

tritons

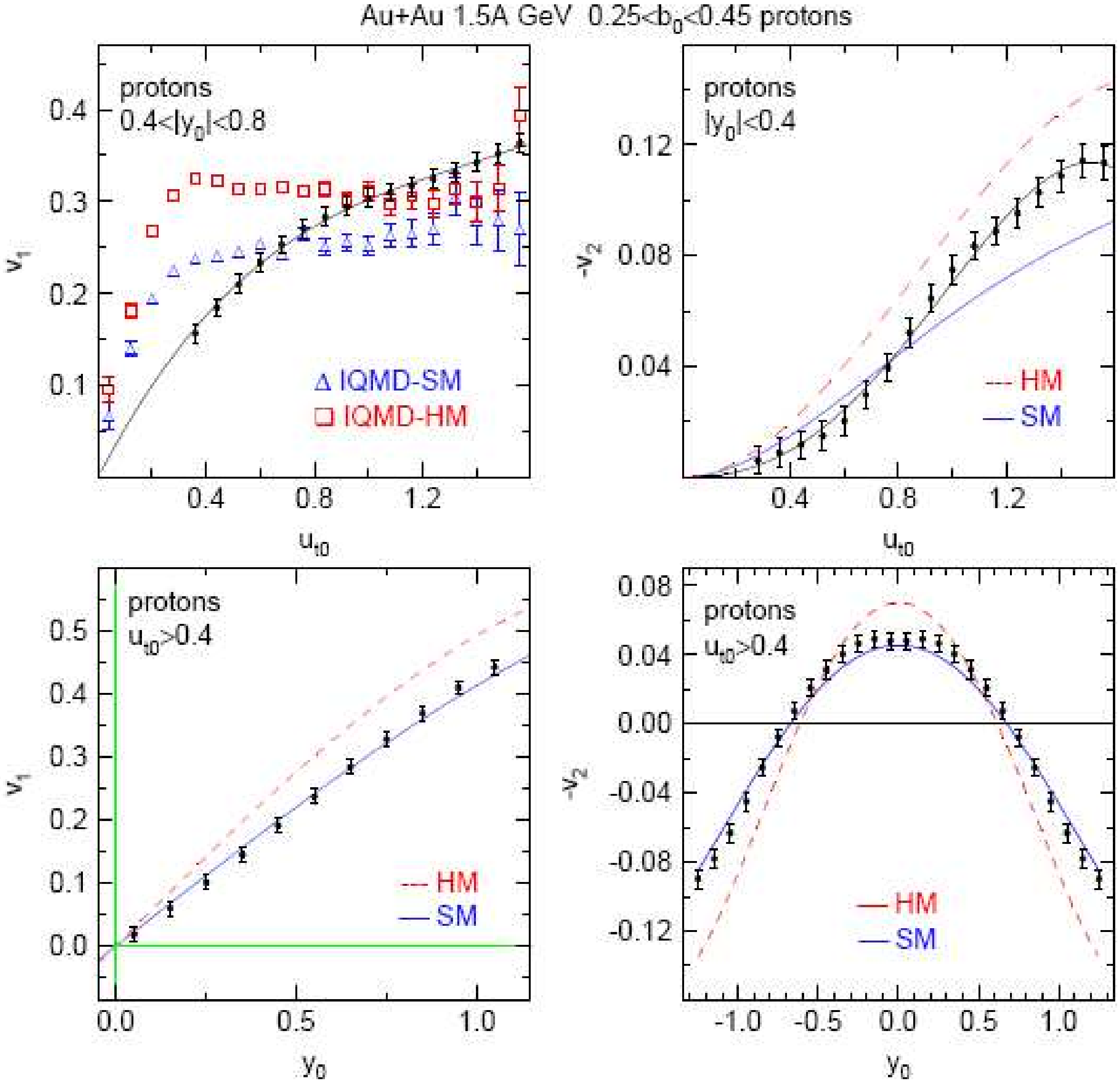


differential sideflow:
$0.3<|y_0|<0.7$



- Flow pattern of heavy clusters is described by SM despite the mismatch in the overall yield.
- Mismatch in differential sideflow point to insufficient description of clusterisation.

Flows of protons at higher energies

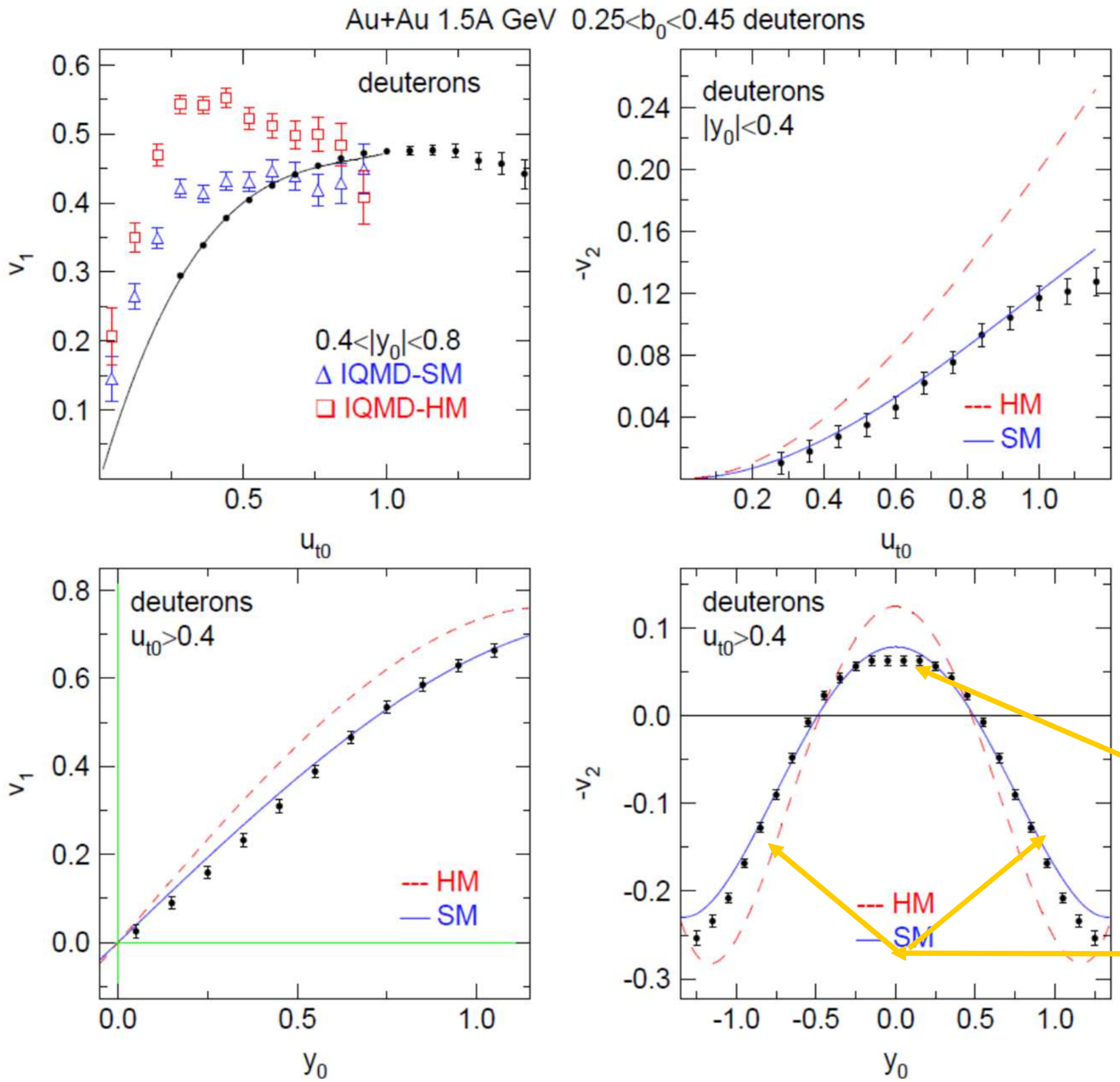


W. Reisdorf et al. (FOPI), NPA 876, 1 (2012)

No perfect agreement,

preference for EOS with SM

Flows of deuterons at higher energies



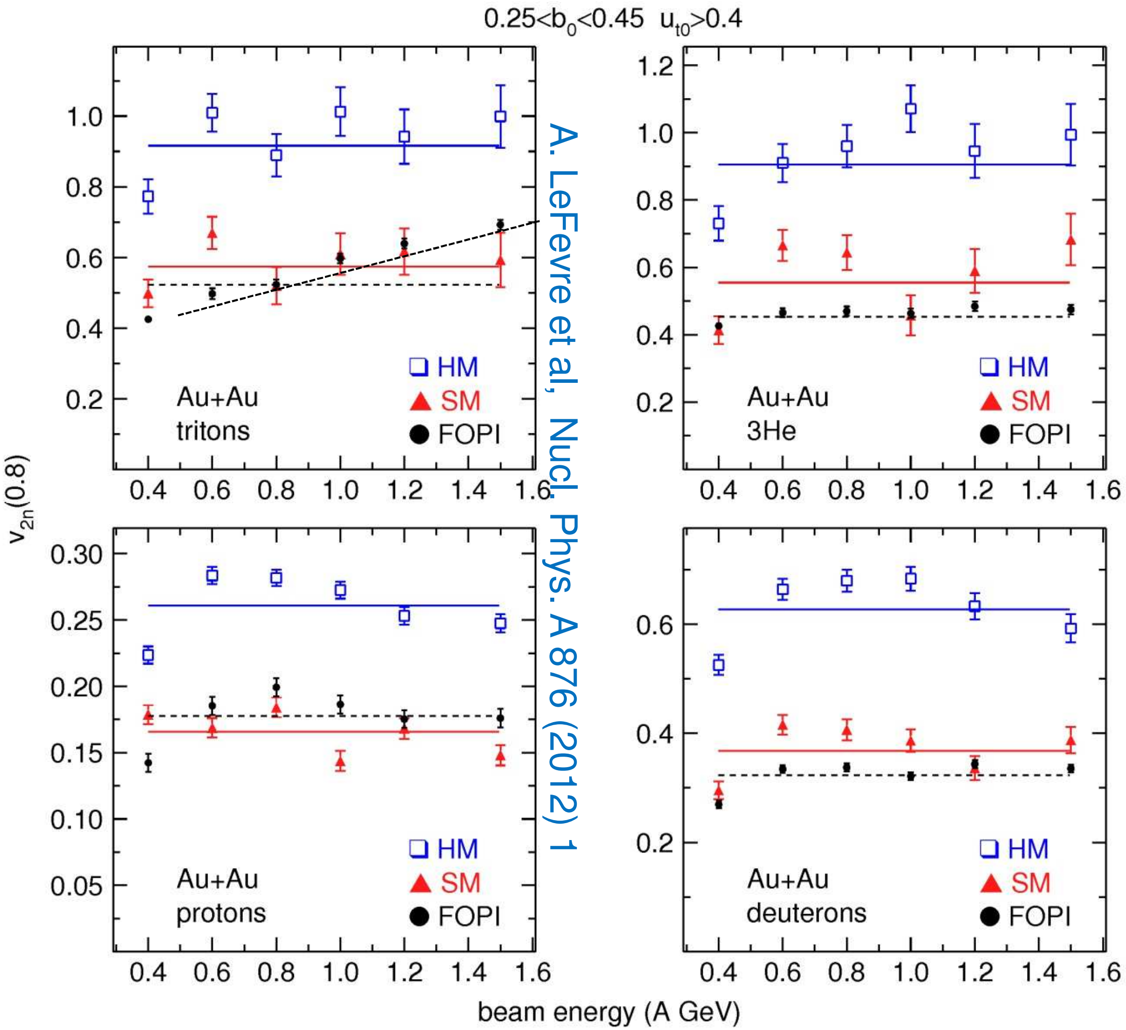
W. Reisdorf et al. (FOPI), NPA 876, 1 (2012)

- composite particles are less influenced by thermal noise, larger flows
- flow pattern of clusters described by IQMD SM despite mismatch in the overall yields
- mismatch in the region of target/projectile rapidity point to insufficient description of clusterization

$$v_2(Y^{(0)}) = v_{20} + v_{22} \cdot Y^{(0)2}$$

$$v_{2n} = |\, v_{20}\,| + |\, v_{22}\,|$$

Elliptic flow of light charged clusters



- influence of clusterisation is partially removed by using this observable
- isotopically resolved elliptic flow is described by IQMD employing an SM EOS
- huge difference for the two types of EOS (SM and HM), much larger than the experimental error bars
- promising observable to constrain the symmetry energy

Summary

- light nuclei are copiously formed in heavy ion reactions
  - primordial
  - after secondary decays
  - ....
- their formation cannot be described consistently in thermal models
  - for yields rather low temperatures are required
- phase space distributions of light nuclei are less disturbed by thermal noise
  - radial flow
  - side/elliptic flows
- they formation cannot be described easily
  - no coalescence
  - MST‘s often used, need a lot of tuning
  - more advanced models describing the complete dynamics are needed
    - our solution FRIGA (see Arnaud‘s talk, work in progress, needs benchmarking with data)
    - other solutions: AMD….

Thank you for your attention

Special thanks to
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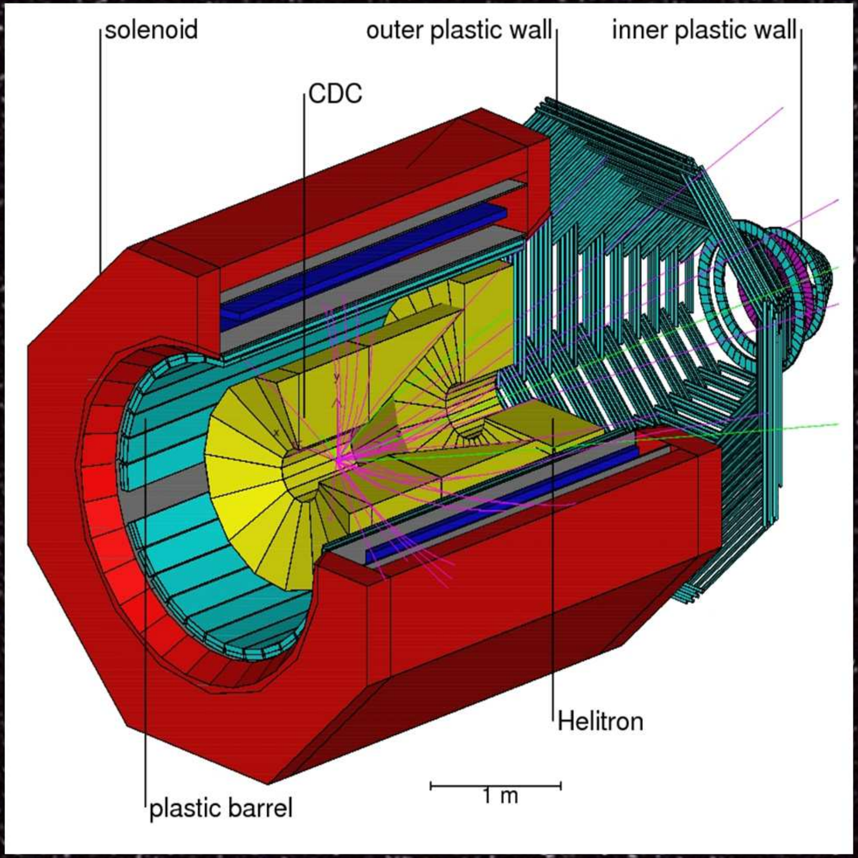
A. Andronic, R. Averbeck, Z. Basrak, N. Bastid, M.L. Benabderramahne, M. Berger, P. Bühler, R. Caplar, M. Cargnelli, M. Ciobanu, P. Crochet, I. Deppner, P. Dupieux, M. Dzelalija, L. Fabbietti, J. Frühauf, F. Fu, P. Gasik, O. Hartmann, N. Herrmann, K.D. Hildenbrand, B. Hong, T.I. Kang, J. Keskemeti, Y.J. 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



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, T.Yamazaki(RIKEN)