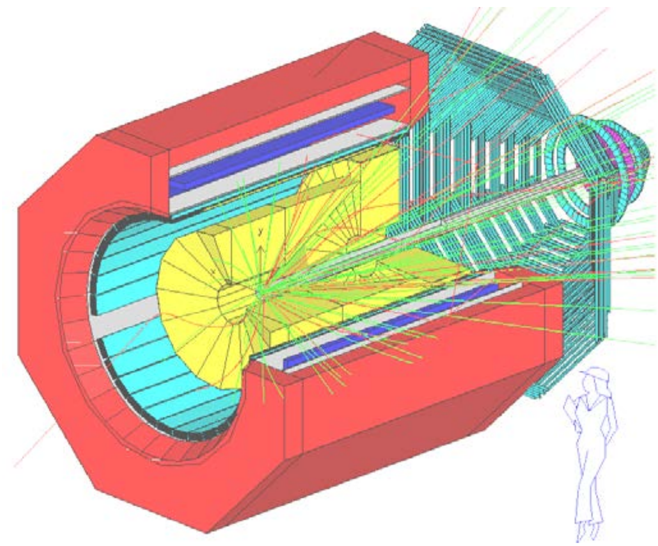
Extracting the nuclear matter EOS from FOPI data
- Status and Problems

Experimental setup & dataset
- FOPI history
- Observables sensitive to EOS

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

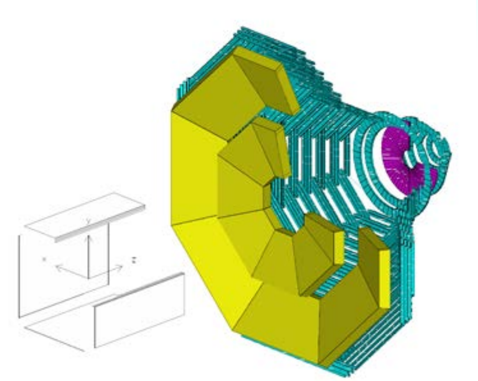
Selected results
- Global features
- Stopping
- Collective flow of charged baryons
- Pion flow
- Flow of charged kaons

Conclusions



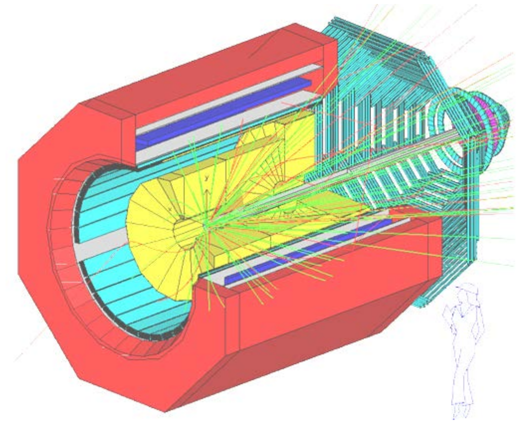
IPNE Bucharest, Romania
CRIP/KFKI Budapest, Hungary
LPC Clermont-Ferrand, France
GSI Darmstadt, Germany
FZ Rossendorf, Germany
Univ. of Warsaw, Poland
IMP Lanzhou, China
SMI, Vienna, Austria
ITEP Moscow, Russia
Kurchatov Institute Moscow, Russia
Korea University, Seoul, Korea
IReS Strasbourg, France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

FOPI data sets



Phase I — **1990 – 1992**

Setup: no magnetic field, forward wall & ionisation chambers
Main physics: radial expansion, fragment formation
Systems: Au+Au
Beam energy: 0.1 – 0.4 AGeV

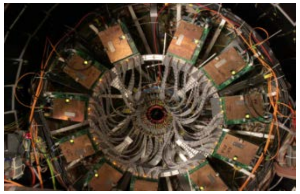


Phase II — **1993 – 1998**

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

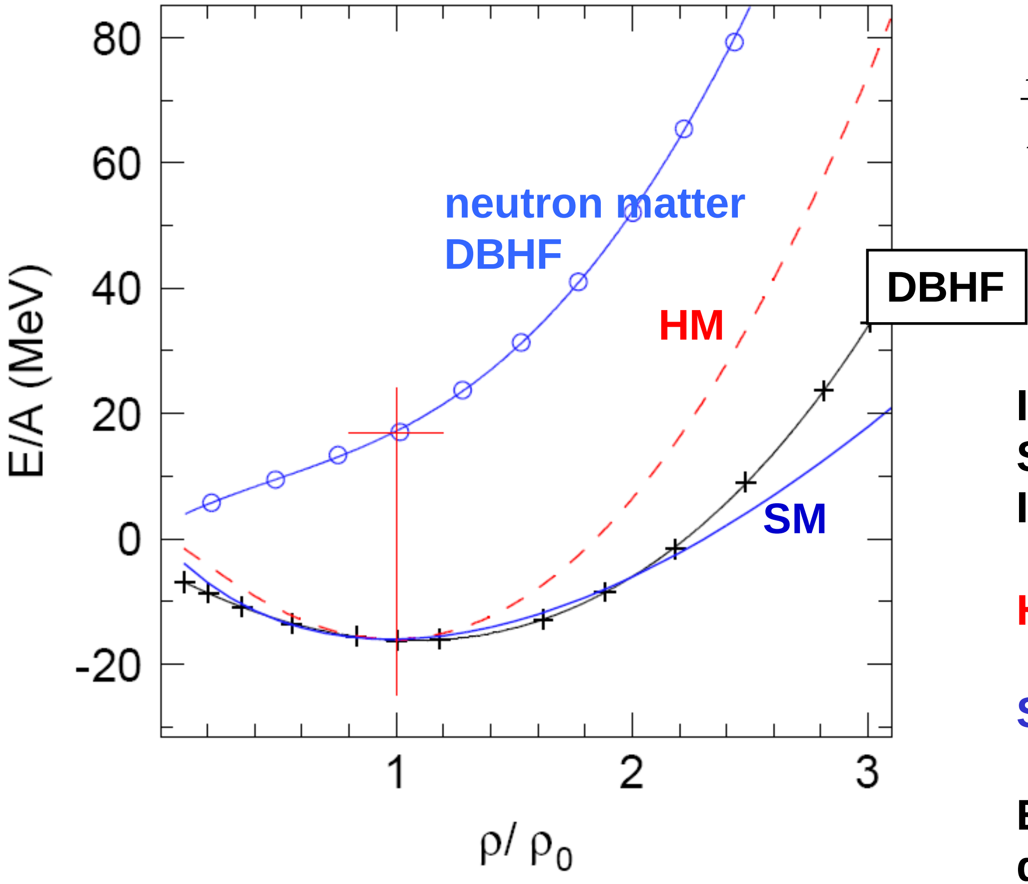
Phase III — **since 2001**

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



Equation – of – State

DBHF: E. N. E. van Dalen, C. Fuchs, A. Faessler, Eur. Phys. J. A 31 (2007) 29



$$\frac{E}{A}(\rho) = \frac{E}{A}(\rho_o) + \frac{1}{18} K \left(\frac{\rho - \rho_o}{\rho_o} \right)^2$$

In transport models EOS implemented by Skyrme potentials U(ρ) tuned to reproduce Incompressibility K:

HM: K=380 MeV

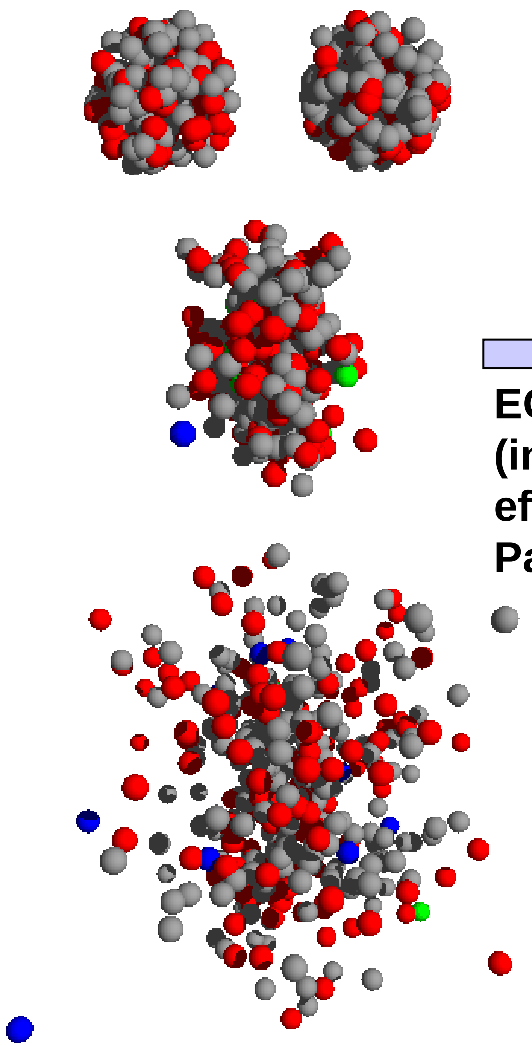
SM: K=200 MeV

EOS does not have to have a quadratic density dependence!

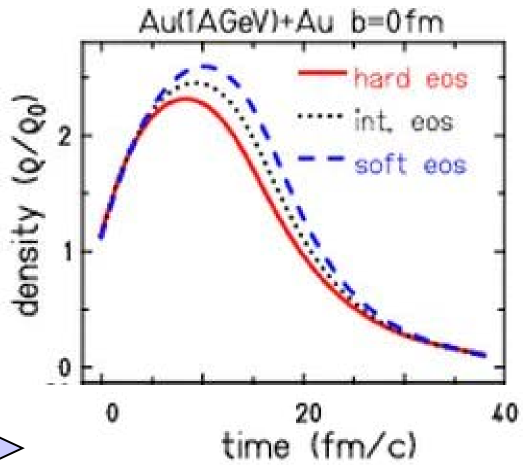
In HI – reactions
n-p asymmetries are small with respect to neutron matter (neutron stars).

Transport models

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

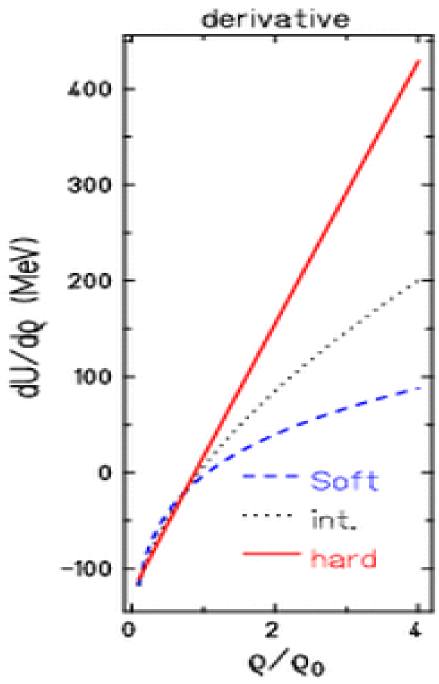


EOS
(in-medium) cross sections
effective masses
Pauli - blocking



Density

(in medium) particle production



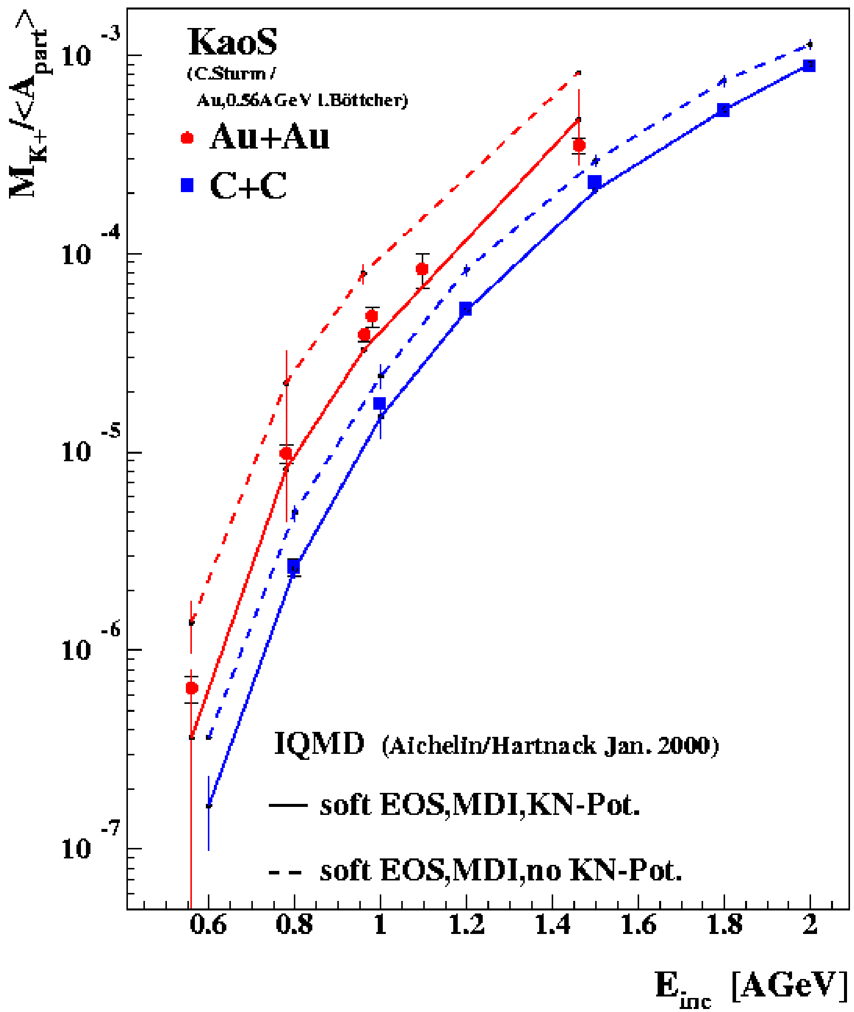
Pressure

(in medium) particle propagation

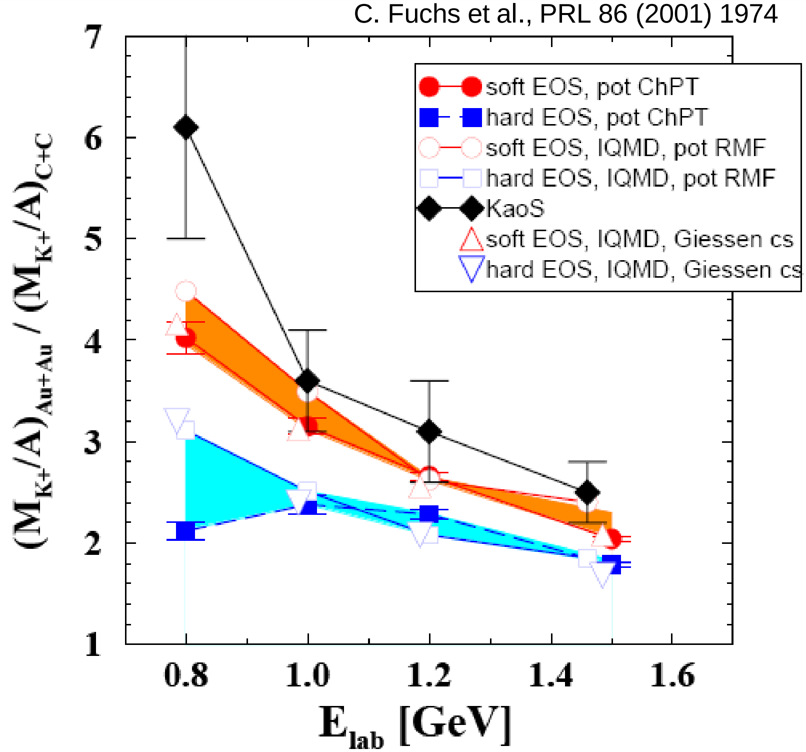
collective flow

EOS from Subthreshold Kaon Yields

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



C. Fuchs et al., PRL 86 (2001) 1974



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

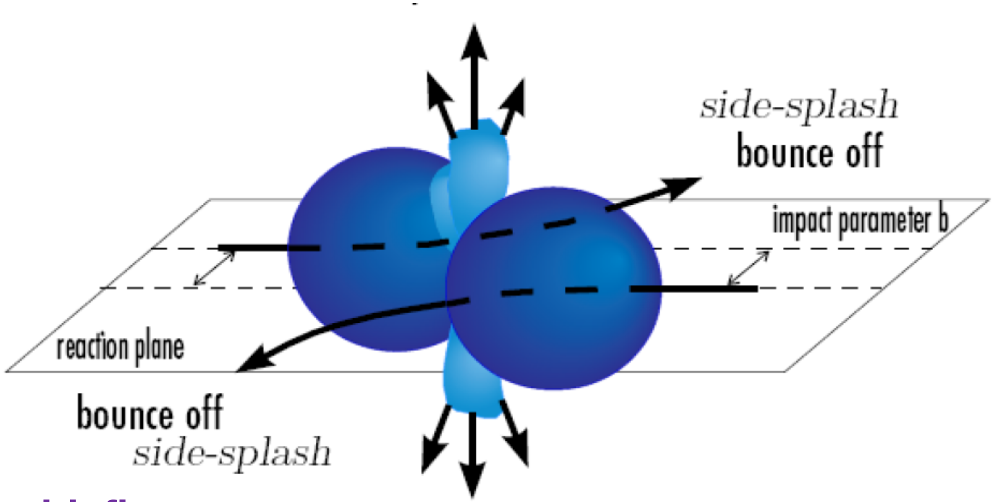
Strong sensitivity to EOS due to multistep production (formation of nucleon resonances, e.g. Δ)
-> soft EOS (K=200)

Isospin dependence of **[N/Z(Au) = 1.49]**
EOS,
in-medium potentials??

Collective flow

Elliptic flow v_2

Squeeze – out



sideflow v_1

Discovery: Bevalac

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

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

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

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

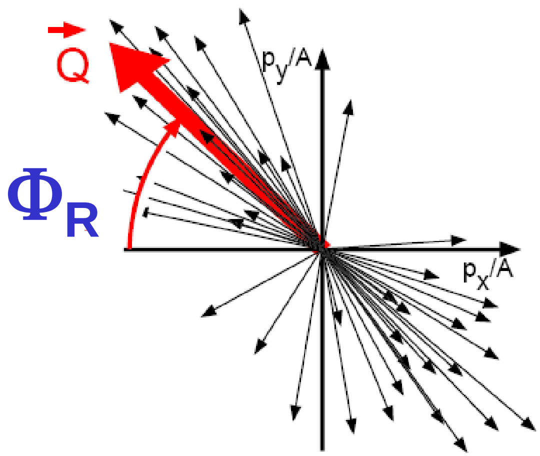
Quantitatively correctable for finite number fluctuations !

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

Reaction plane related flow

Transverse momentum method

P. Danielewicz, G. Odyniec, *Phys. Lett.* 157B, 146 (1985)

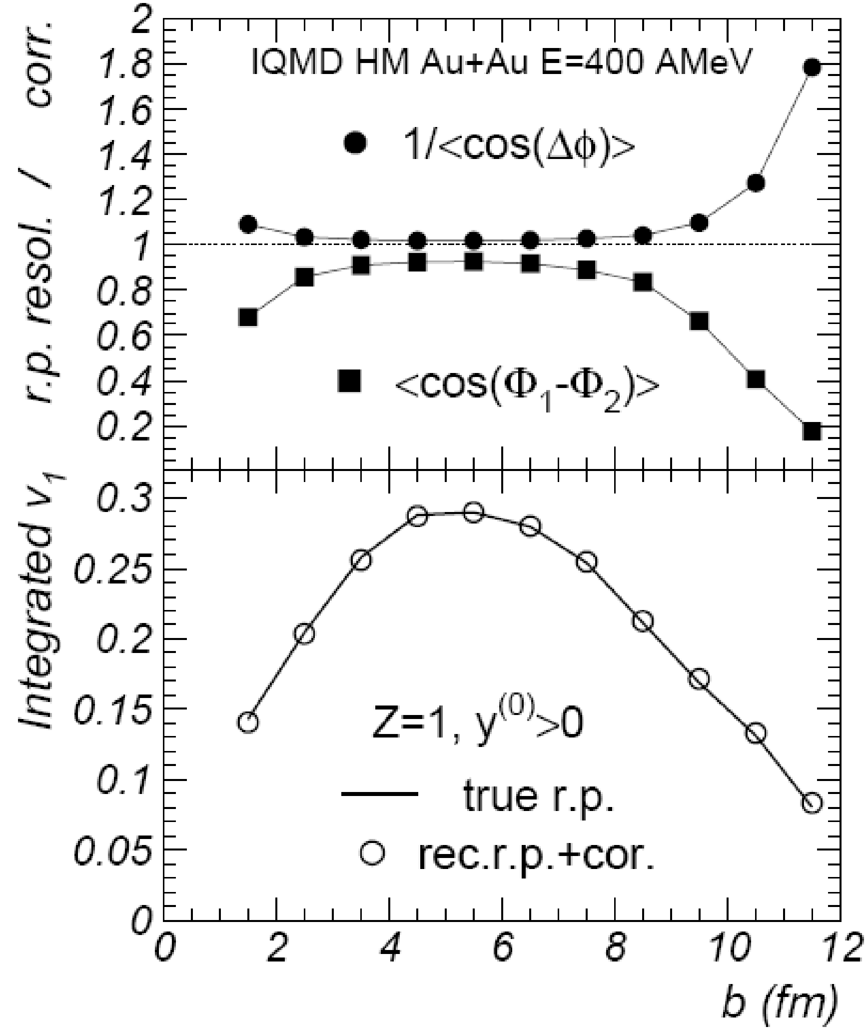


$$\vec{Q} = \sum_i \omega_i \cdot \vec{p}_t\,(i),$$

$$\omega_i = \begin{cases} 1 & y_i > y_{CM} + \delta y \\ -1 & y_i < y_{CM} - \delta y \end{cases}$$

Resolution of flow measurement

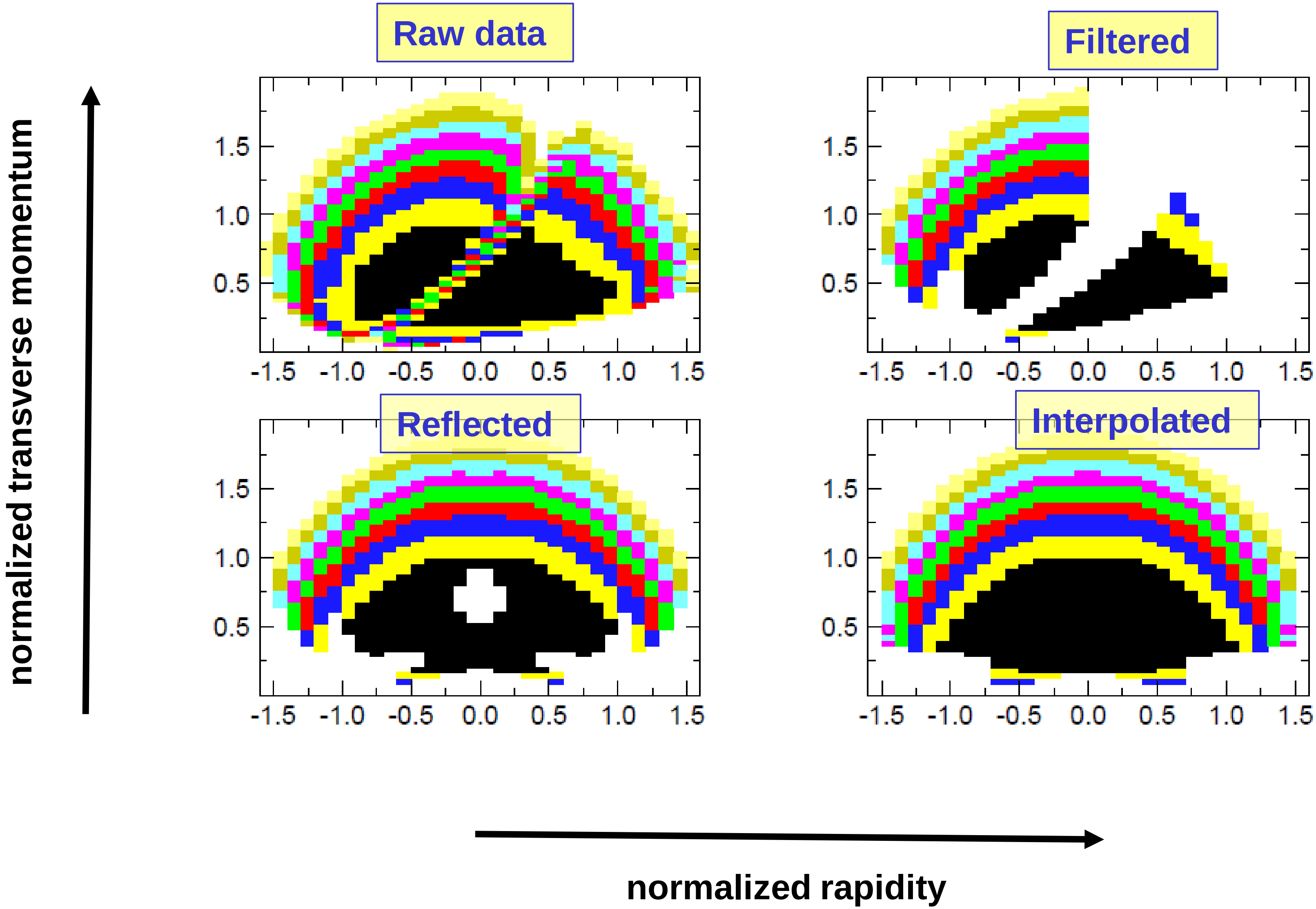
A. Andronic et al. (FOPI), PRC67, 034907 (2003)



FOPI acceptance and data analysis

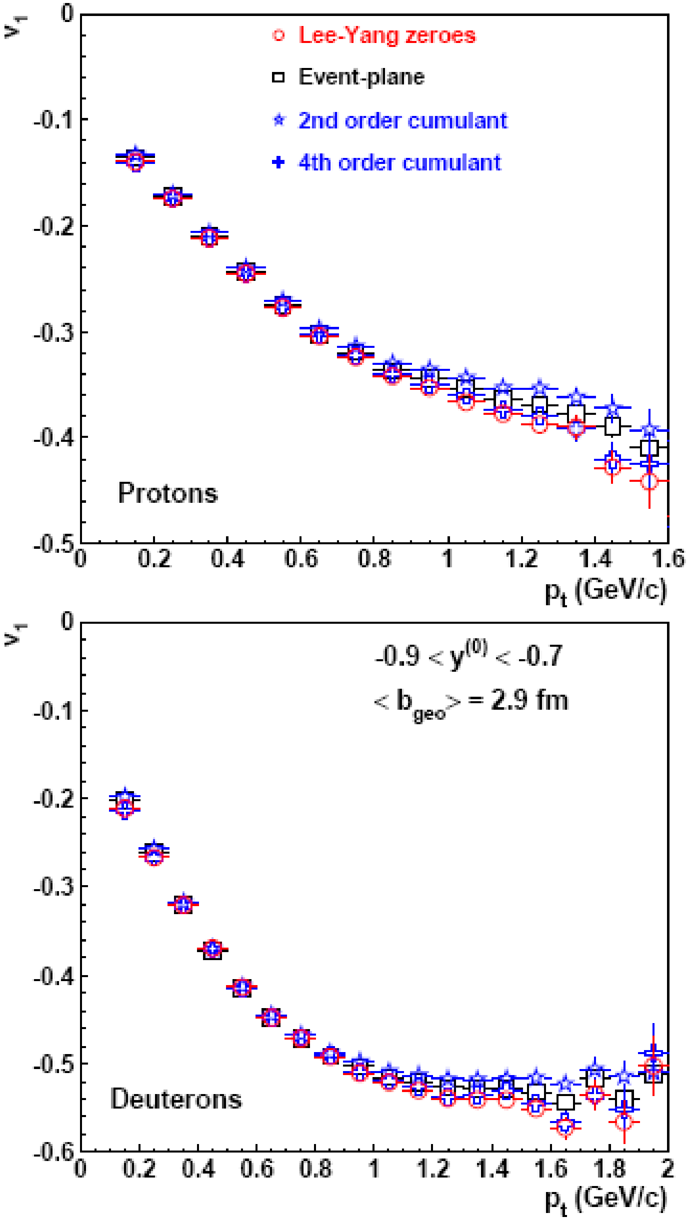
Proton – phase space distribution for Au+Au at 1 AGeV

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



Alternative methods without reaction plane

N. Bastid et al. (FOPI), PRC72, 011901 (2005)



Cumulant method:
N. Borghini, P.M. Dinh, and J.-Y. Ollitrault, Phys. Rev.C 64, 054901 (2001).

Lee-Yang zeroes:
R.S. Bhalerao, N. Borghini, and J.-Y.Ollitrault, Nucl. Phys. A 727, 373 (2003).

Reaction Ru + Ru @ 1.69 AGeV

Small systematic differences at high transverse momenta.

Differences of event-plane (EP) to 2nd order cumulant due to recoil corrections done for EP – method.

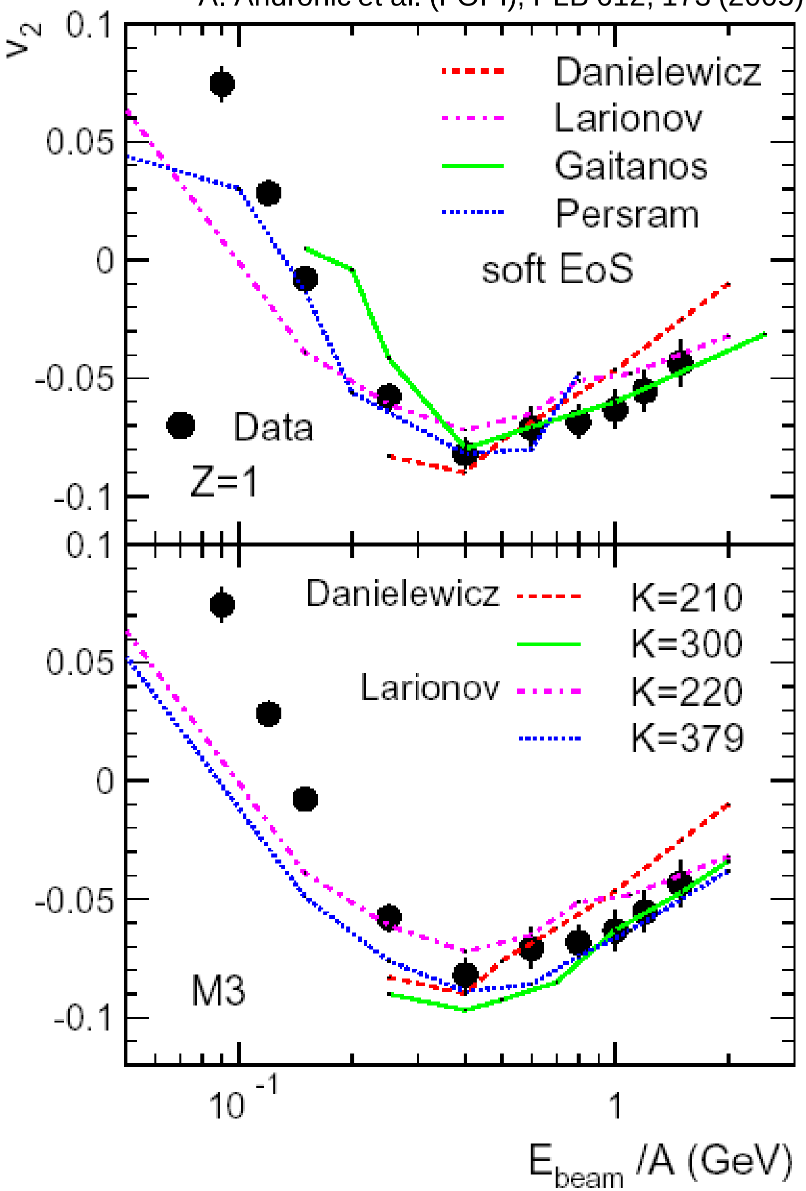
Differences 2nd order – 4th order cumulant most likely due to momentum conservation missed by 2nd order cumulant.

Lee-Yang zeroes follows 4th order cumulant.

No significant contribution of non-flow contributions.

EOS from model comparison of flow

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

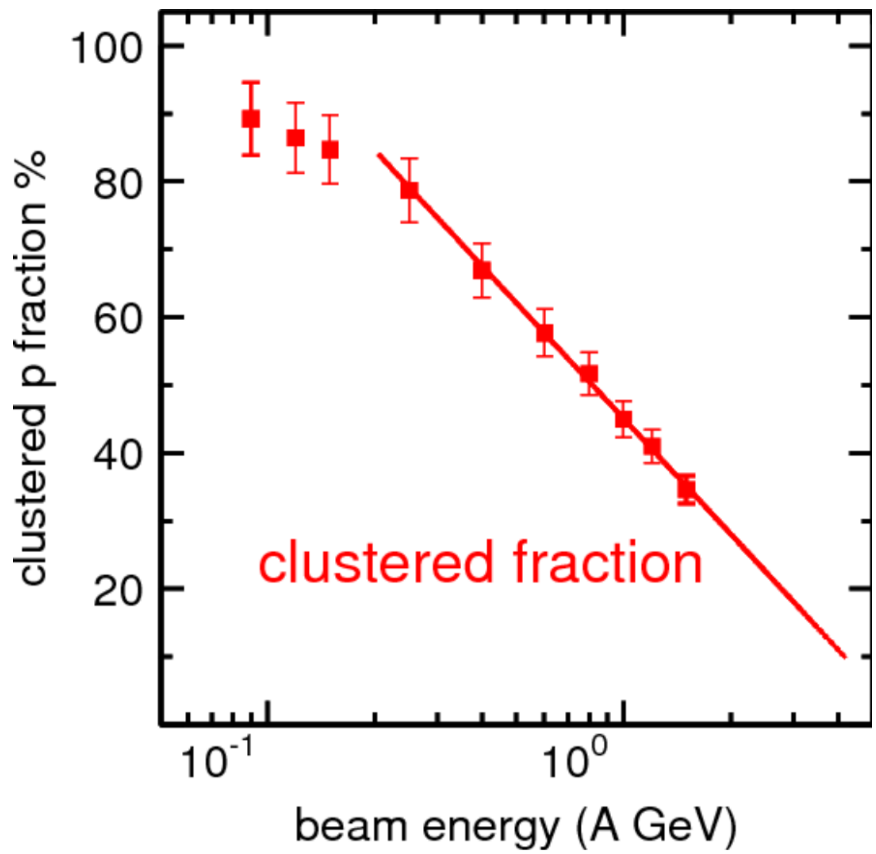
Global features of HI reactions from 0.1 – 2 AGeV

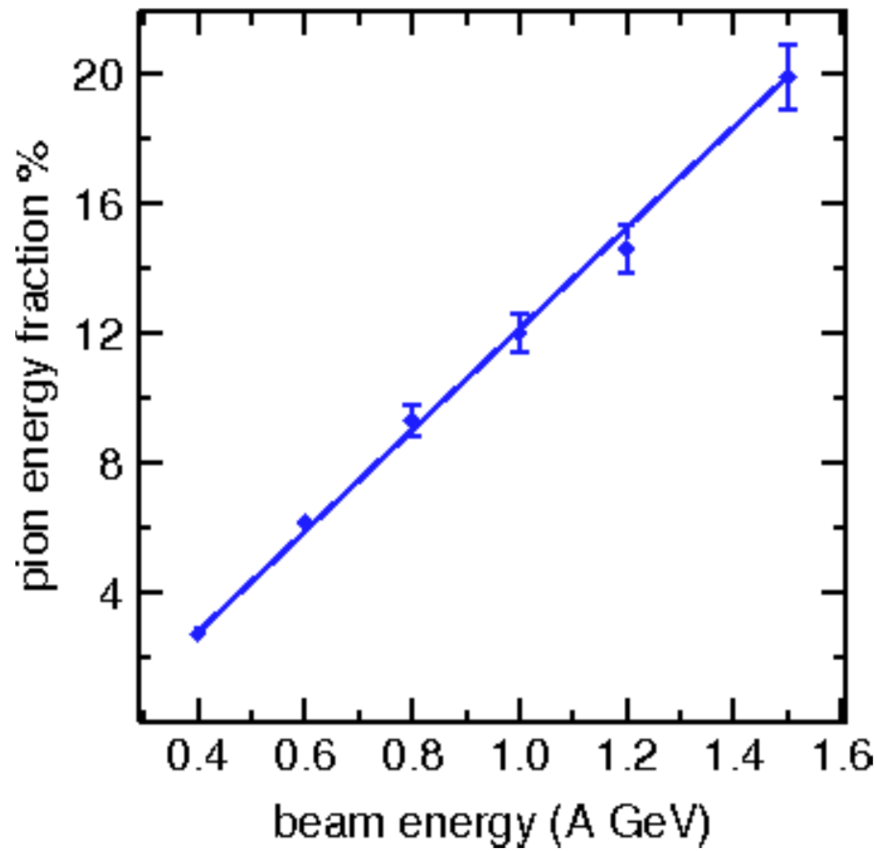
W. Reisdorf et al. (FOPI), NPA 848, 366 (2010)

Clusterisation

Pion production

Au + Au $b_0 < 0.15$





Correlation of stopping & flow

W.Reisdorf et al. (FOPI) PRL 92, 232301 (2004)

Stopping

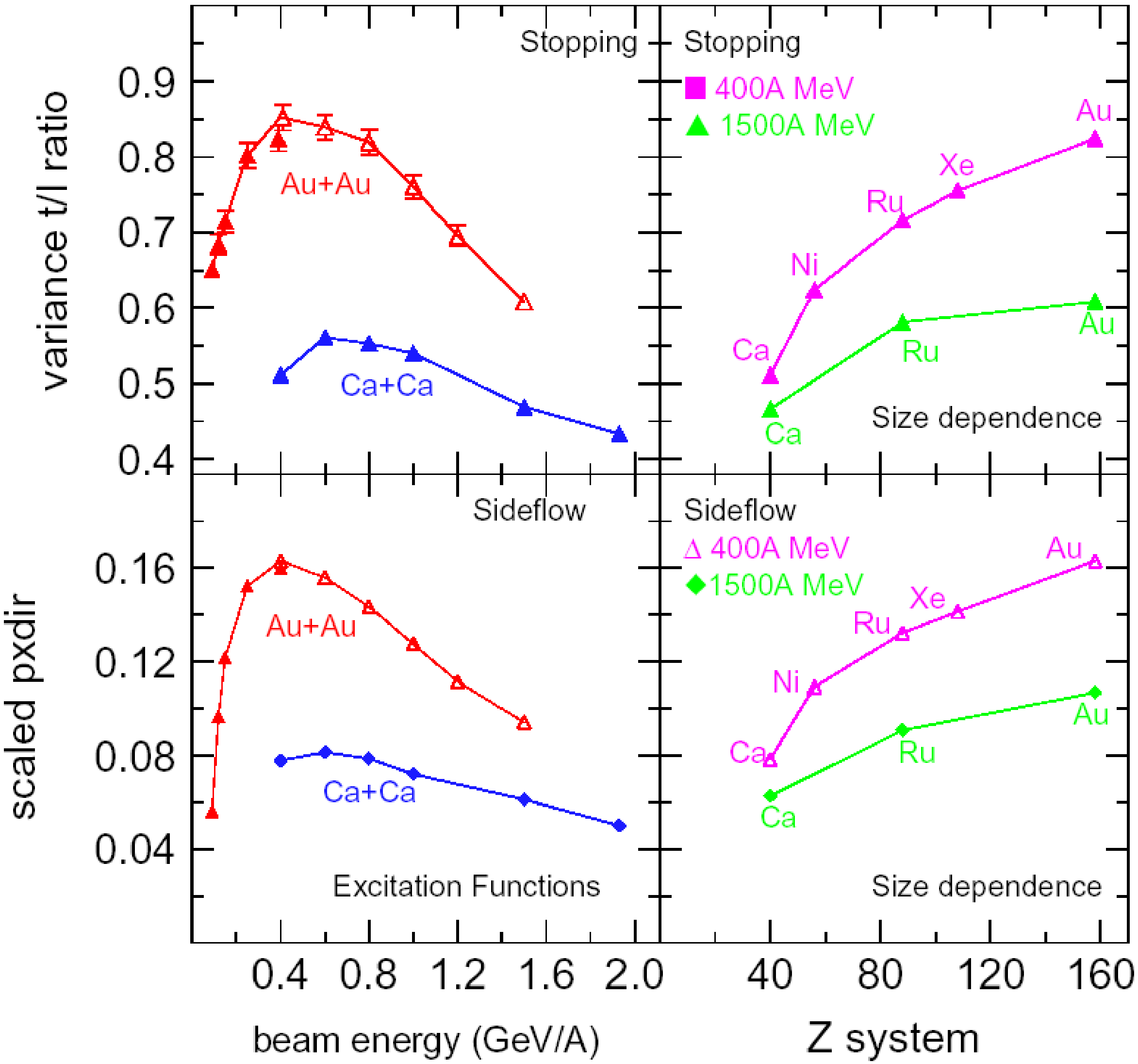
$b/b_{max}<0.15$

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

Sideflow

$b/b_{max}\approx 0.4$

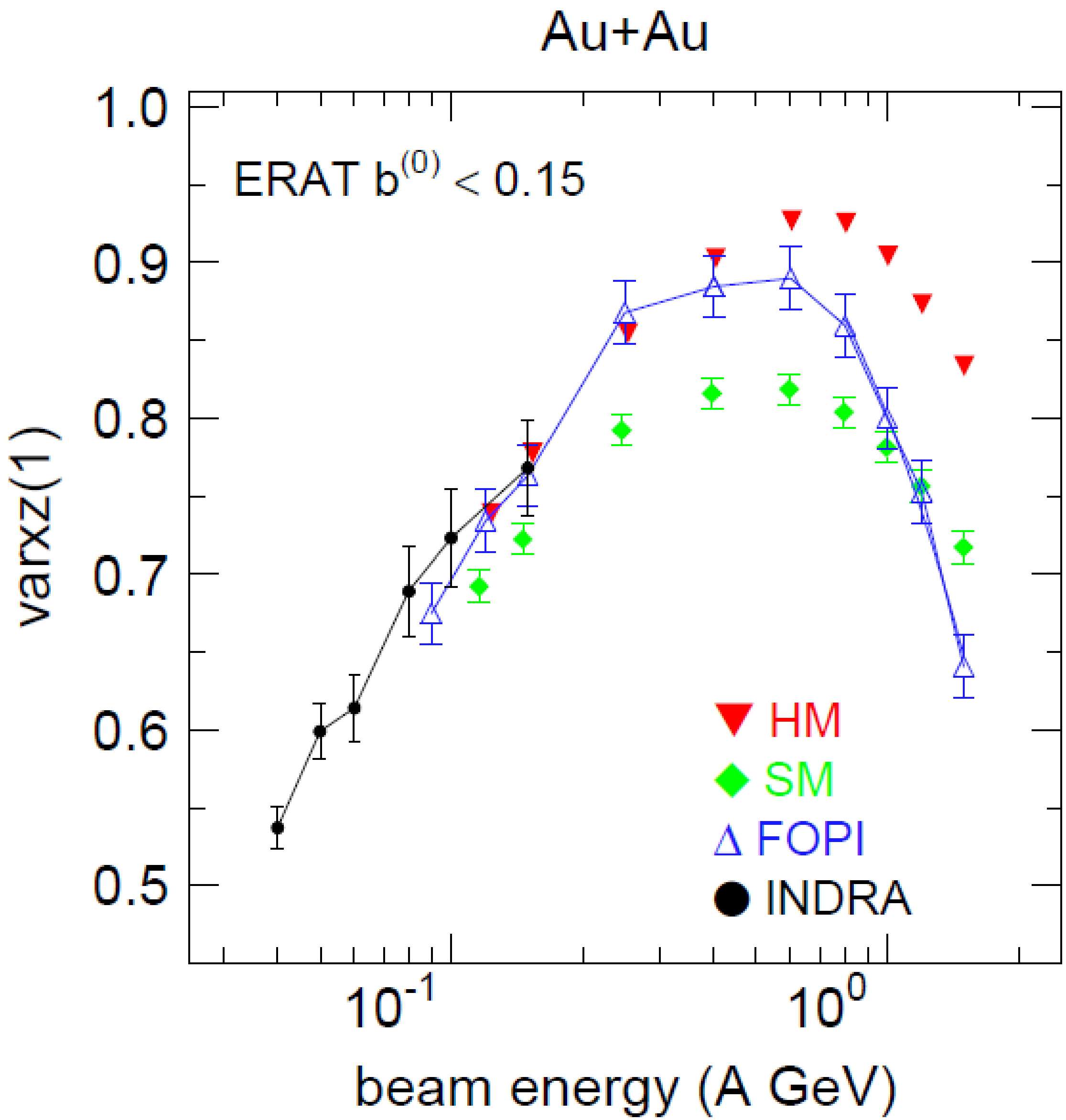
$$p_x^{dir} = \frac{\sum_i sign(y_i) Z_i u_{xi}}{\sum_i Z_i}$$



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

Stopping

W. Reisdorf et al. (FOPI), NPA 848, 366 (2010)

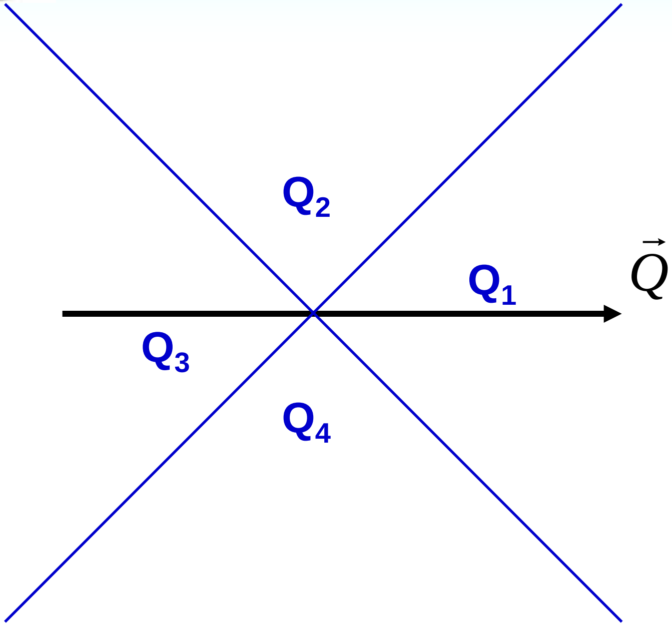


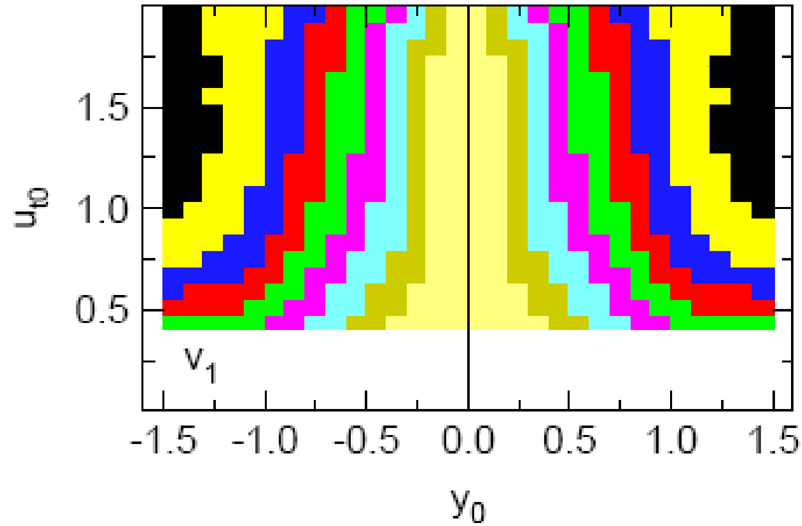
Width of rapidity distributions in FOPI consistent with INDRA,

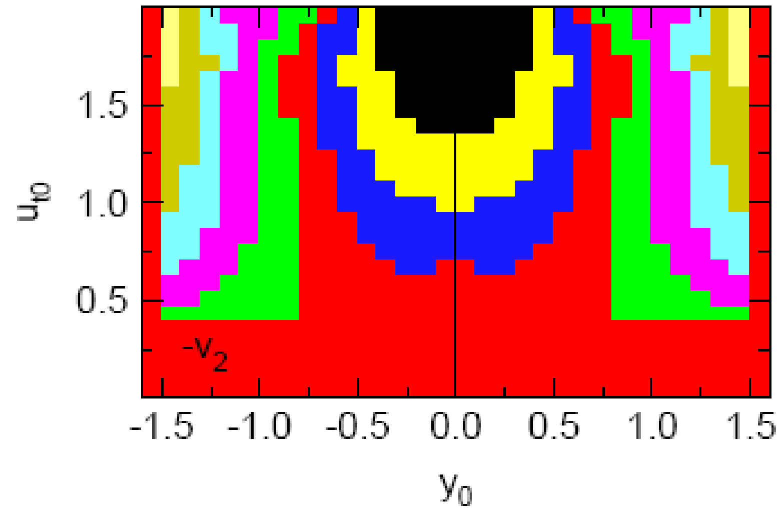
Sensitivity to EOS in central collisions,

Up to 400 AMeV stopping favors stiff EOS (IQMD).

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







Symmetry

$$Q_2 = Q_4$$

Definitions

$$Q_0 = Q_1 + Q_2 + Q_3 + Q_4$$

$$Q_{24} = Q_2 + Q_4$$

Relation to Fourier coefficients

$$\frac{Q_1 - Q_3}{Q_0} = \frac{2\sqrt{2}}{\pi} \mathrm{v}_1$$

$$\frac{Q_{24}}{Q_0} - \frac{1}{2} = -\frac{2}{\pi} \mathrm{v}_2$$

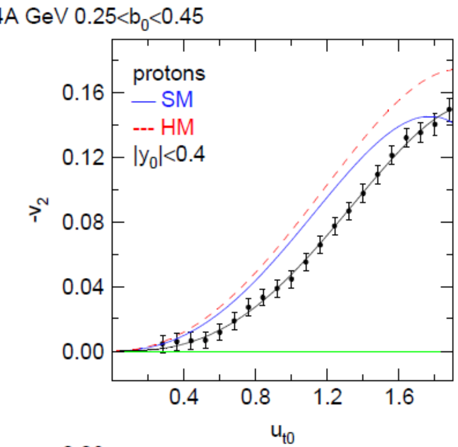
$$u_{t0} = (\beta_t \gamma)_0 = \left(\frac{p_t}{m}\right)_0$$

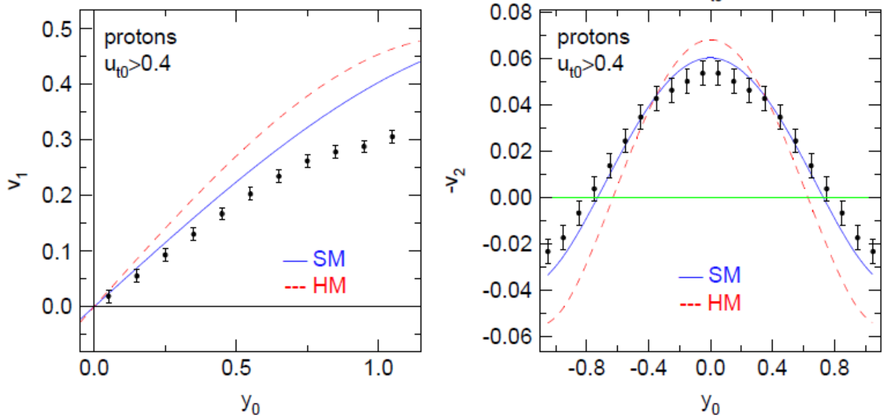
'$_0$'- normalisation to CMS quantities

Comparison to IQMD at 0.4 AGeV

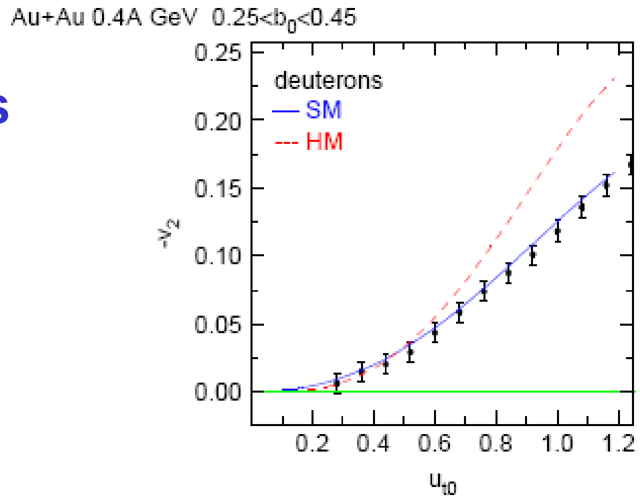
W. Reisdorf et al. (FOPI), NPA 876, 1 (2012)

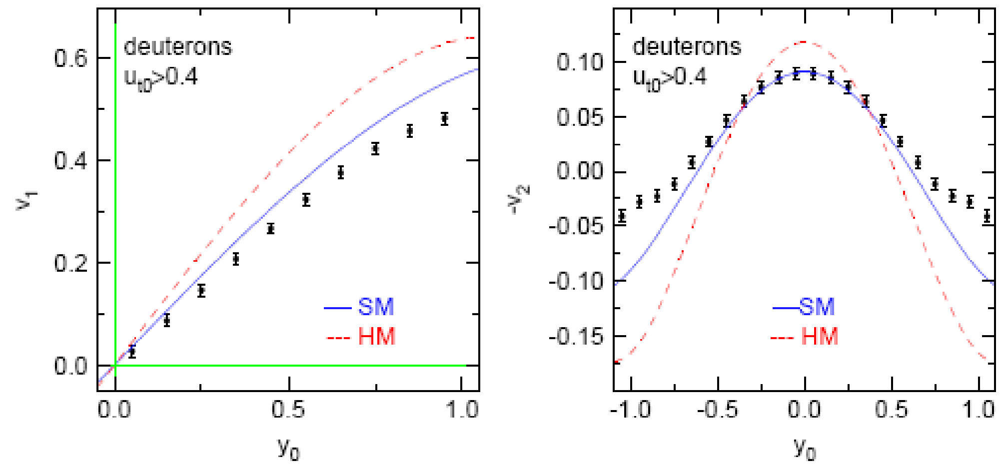
protons





deuterons





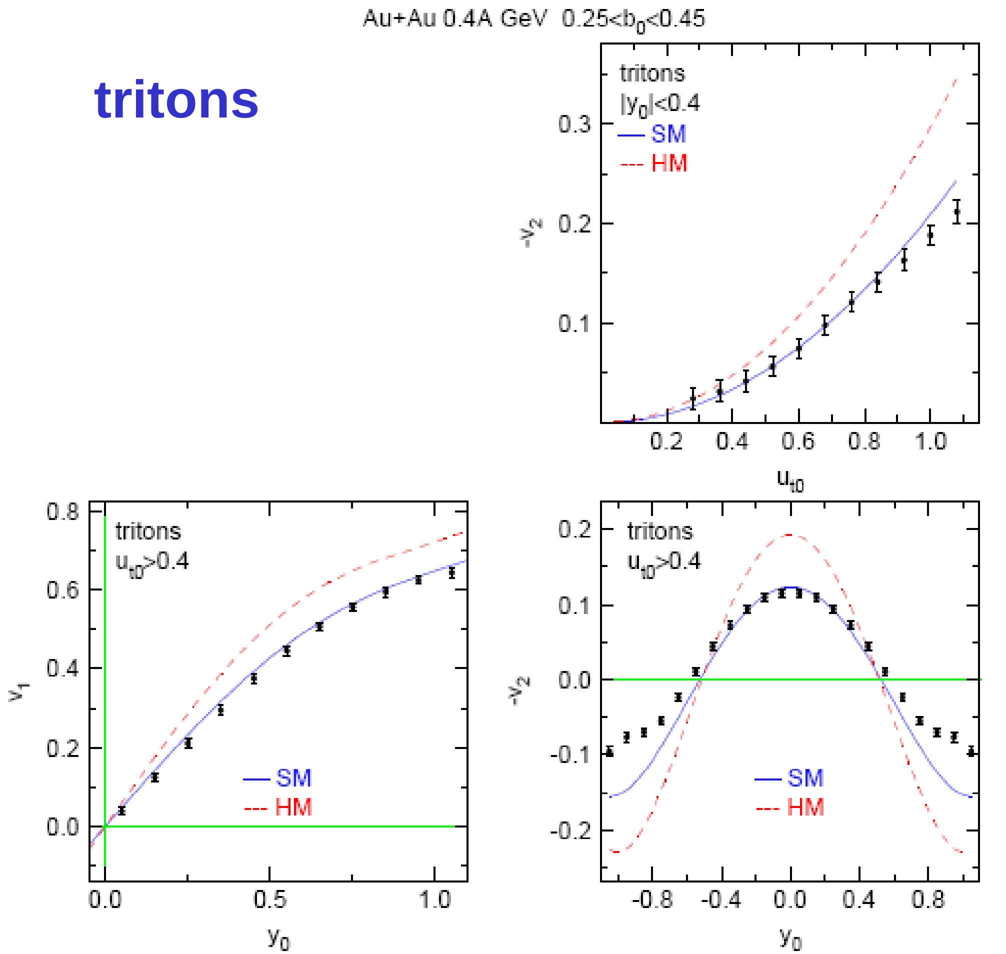
EOS impacts whole phase space asymmetries,

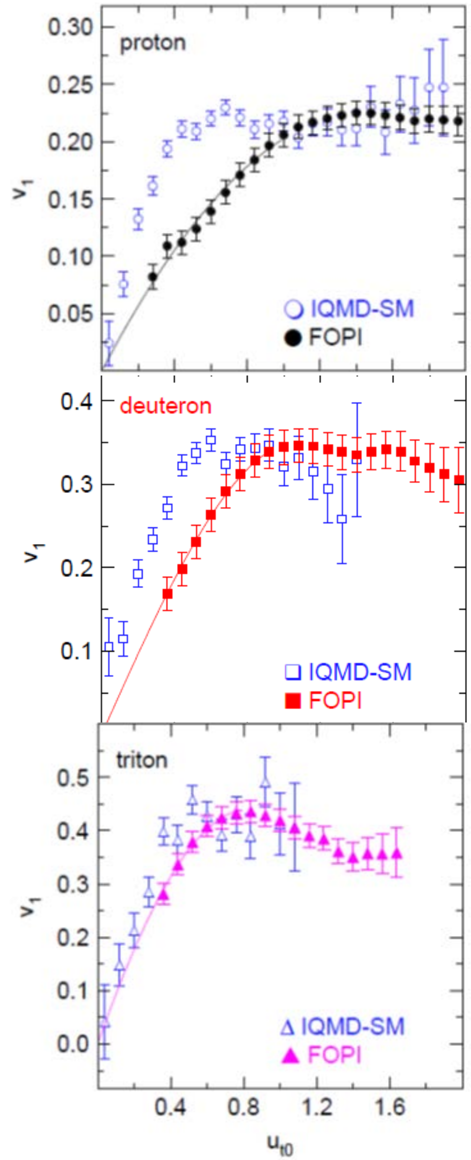
heavier clusters (d) are less influenced by thermal noise,

Proton and deuteron distributions favor a soft EOS (IQMD).

Flow and clusterisation at 0.4 AGeV

tritons



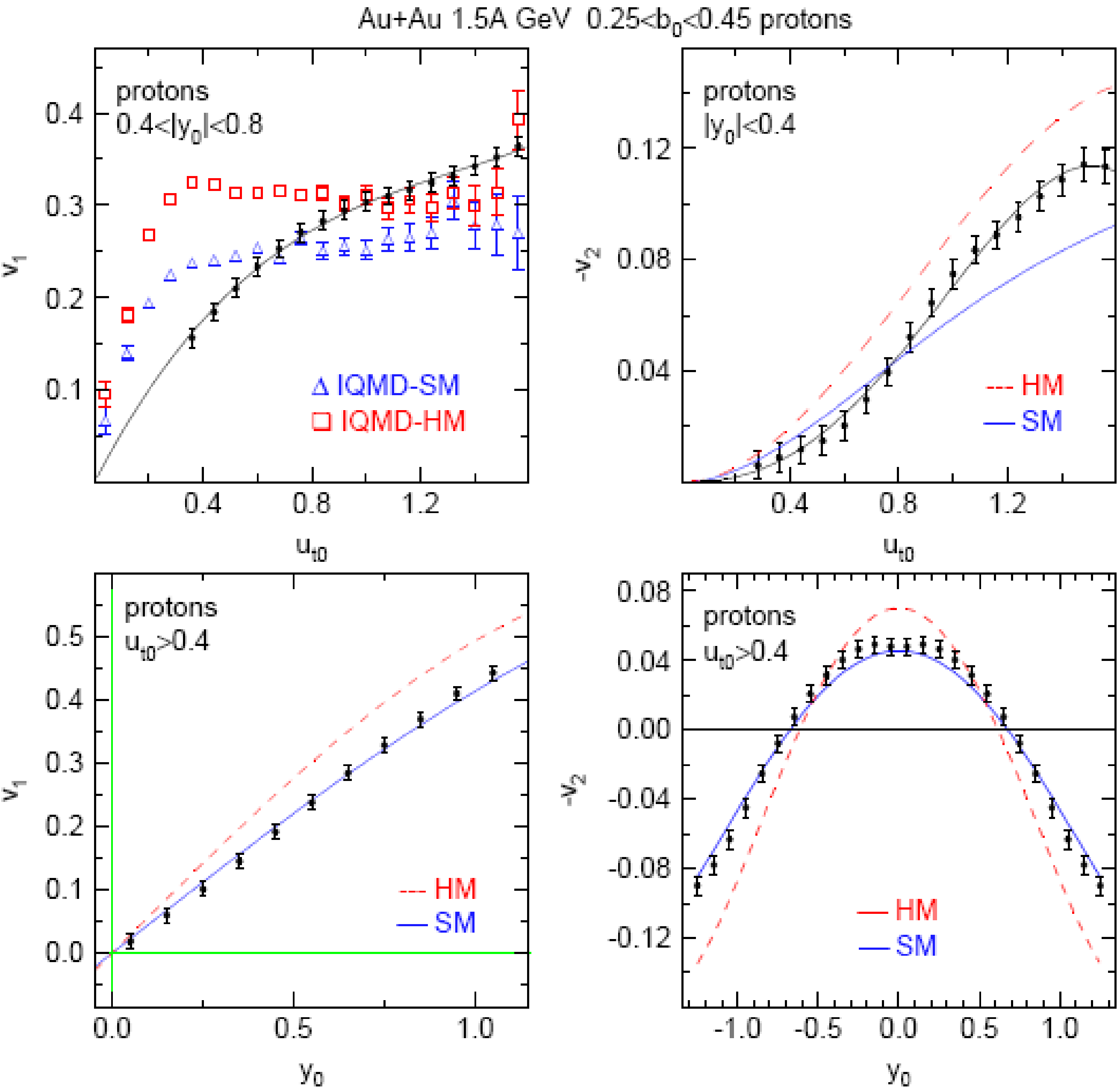


differential sideflow: $0.3<|y_0|<0.7$

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.

Model comparison at 1.5 AGeV (protons)



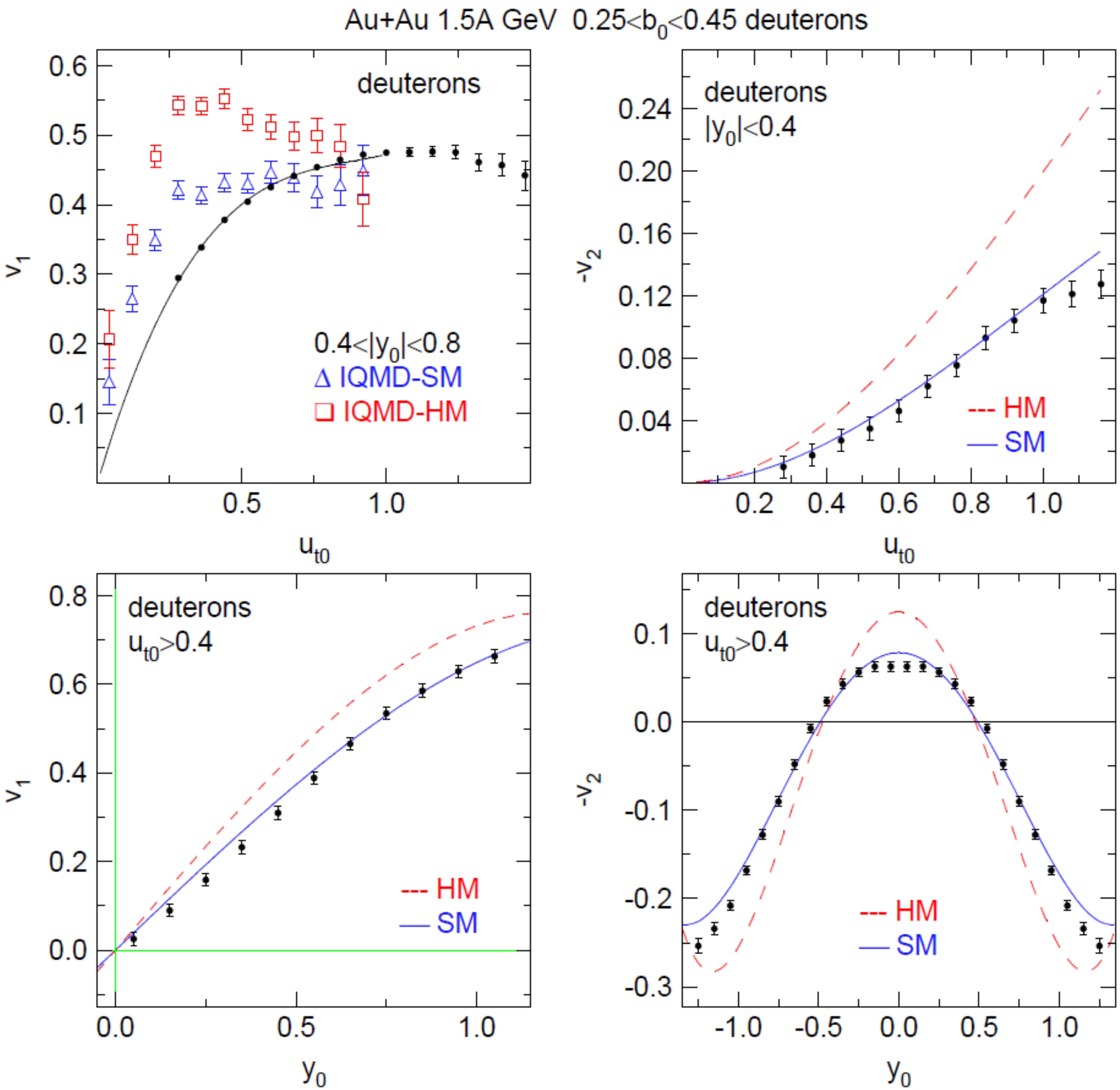
W. Reisdorf et al. (FOPI), NPA 876, 1 (2012)

No perfect agreement,

preference for EOS with SM

Model comparison at 1.5 AGeV (deuterons)

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

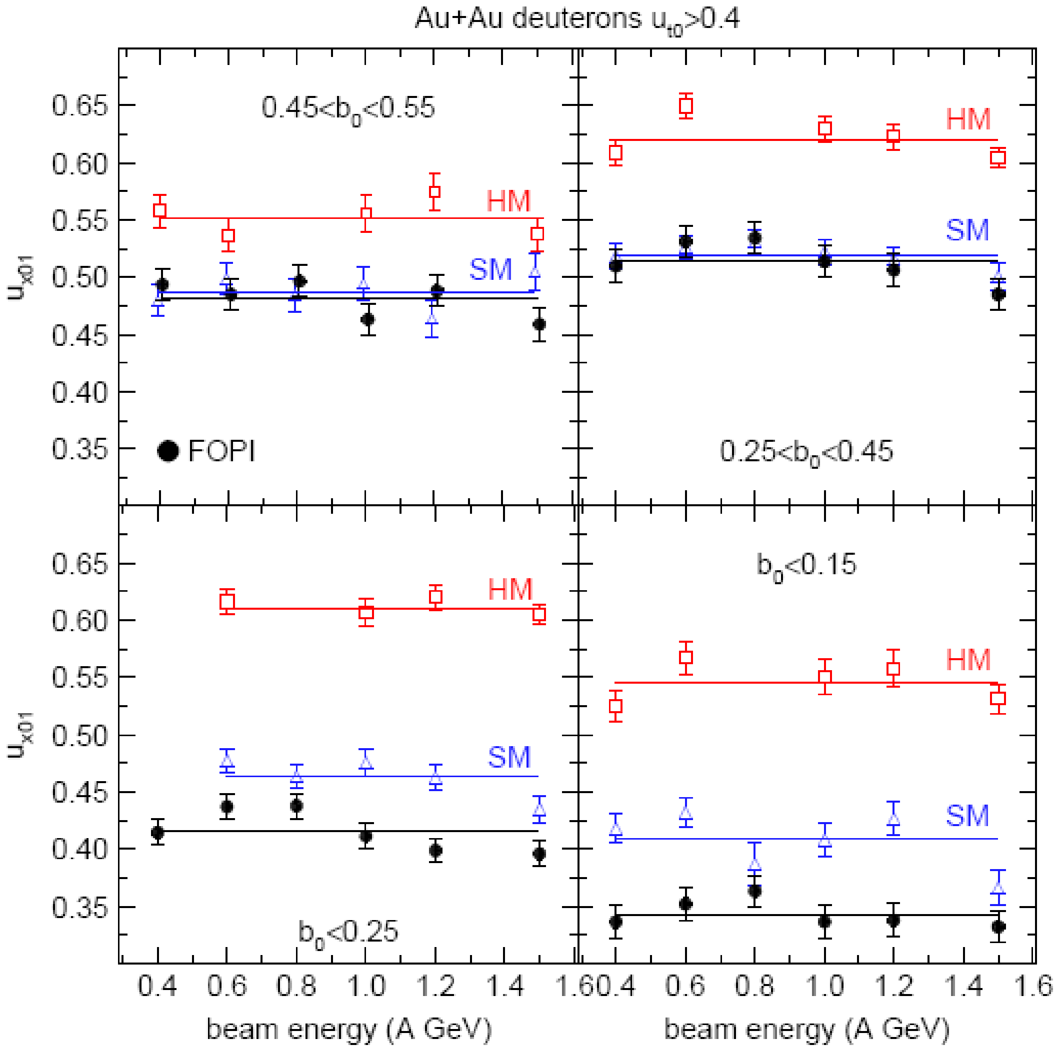


preference for EOS with SM

IQMD - model comparison of midrapidity slopes

Excitation function:

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



Measure of collective flow:

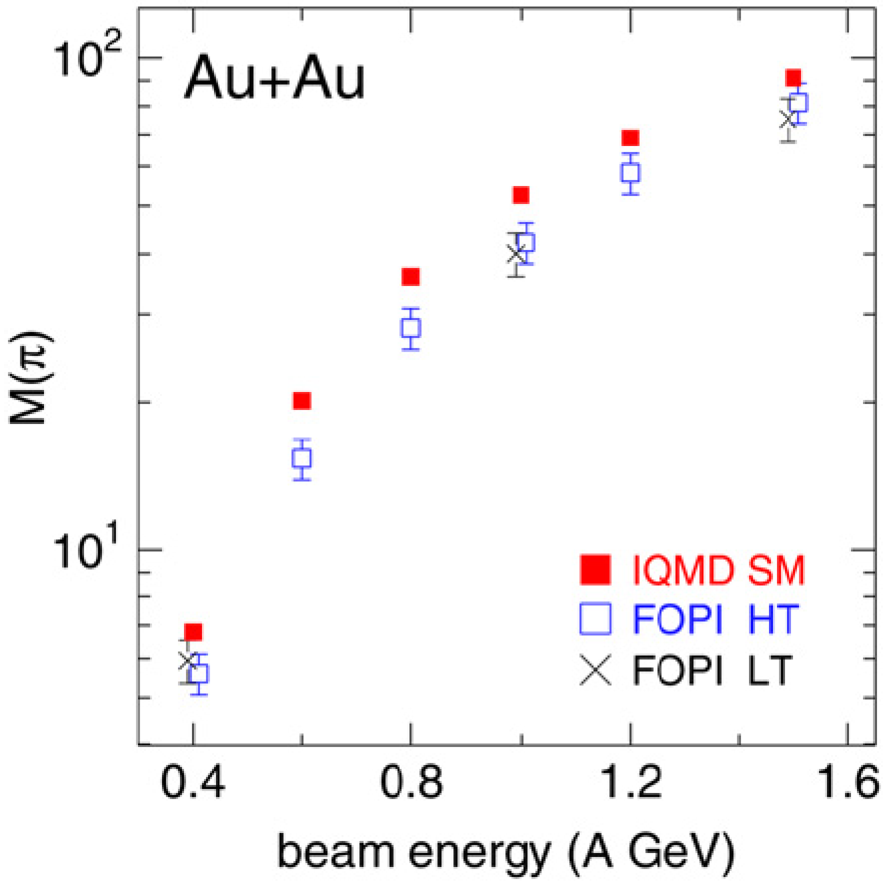
$$u_{x01} \equiv \frac{d\langle v_1 \cdot u_{t0} \rangle}{dy_0}$$

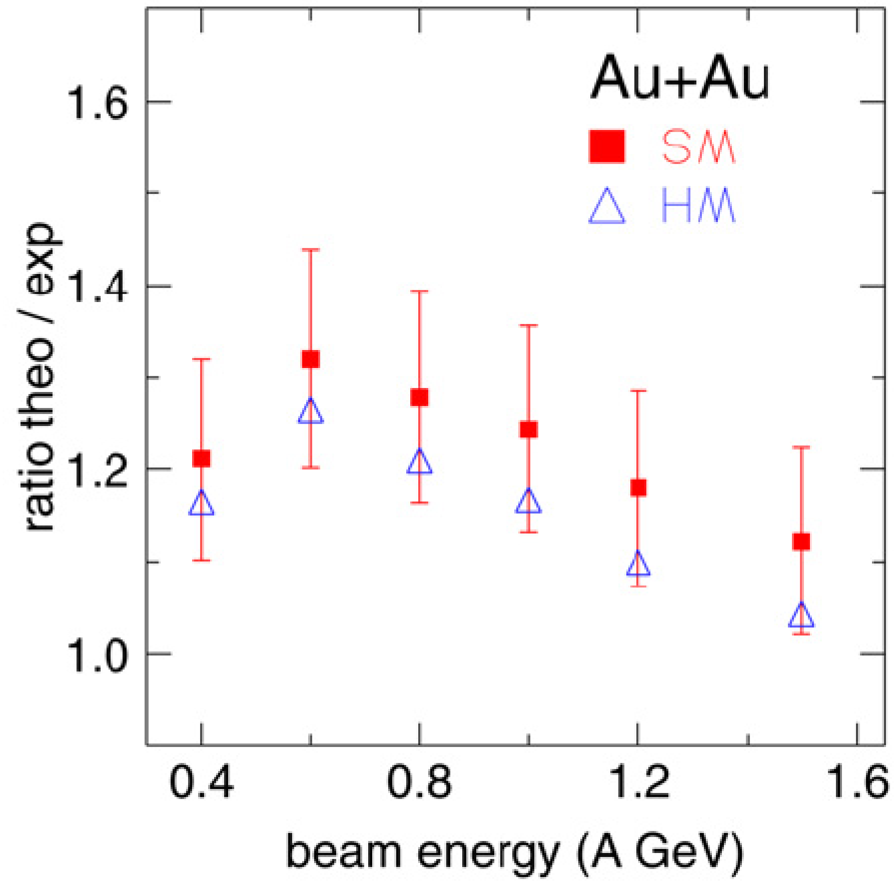
Why deuterons?
- **not distorted by decays (evaporation, weak decays),**
- **small influence of thermal noise.**

Preference for soft EOS (SM, IQMD) for all centralities.

Centrality dependence (significant within error bars) needs to be understood.

Pion multiplicities



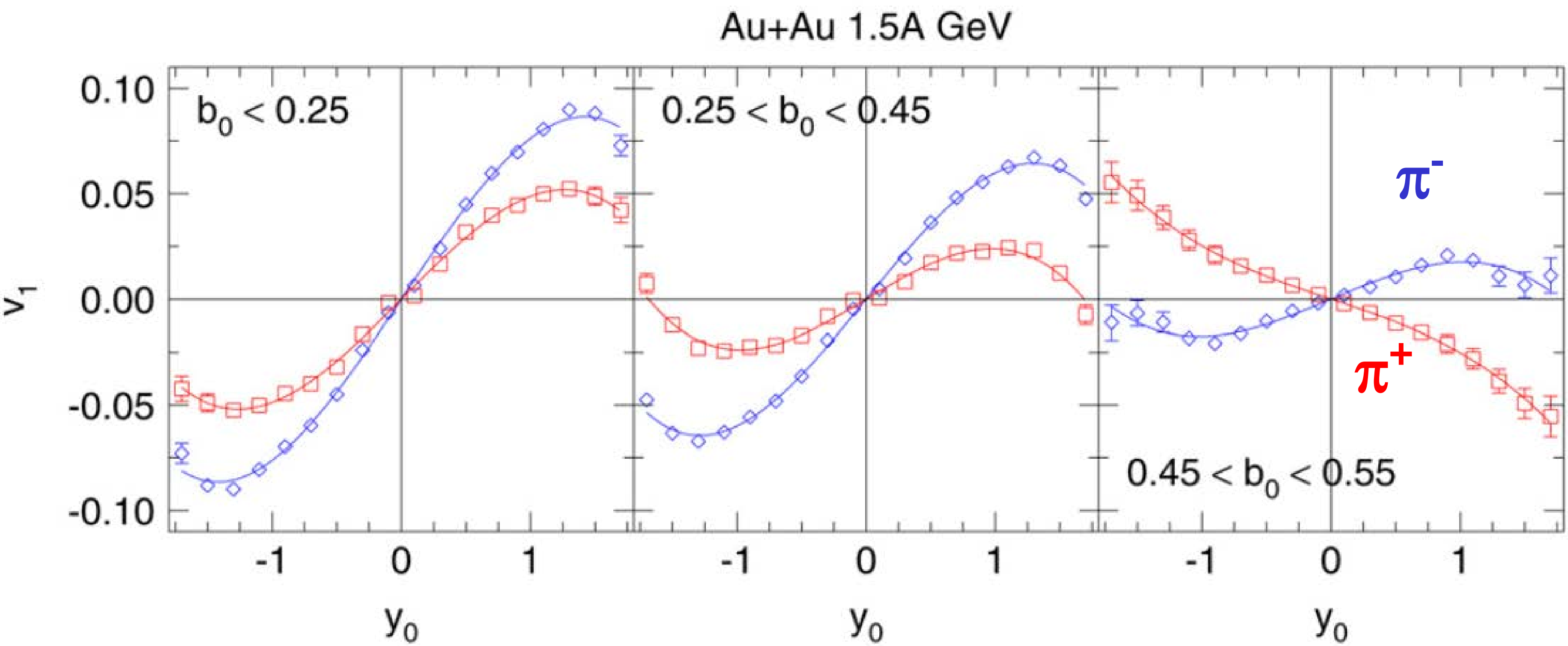


Pion multiplicities are over-predicted in IQMD.

Pion flow

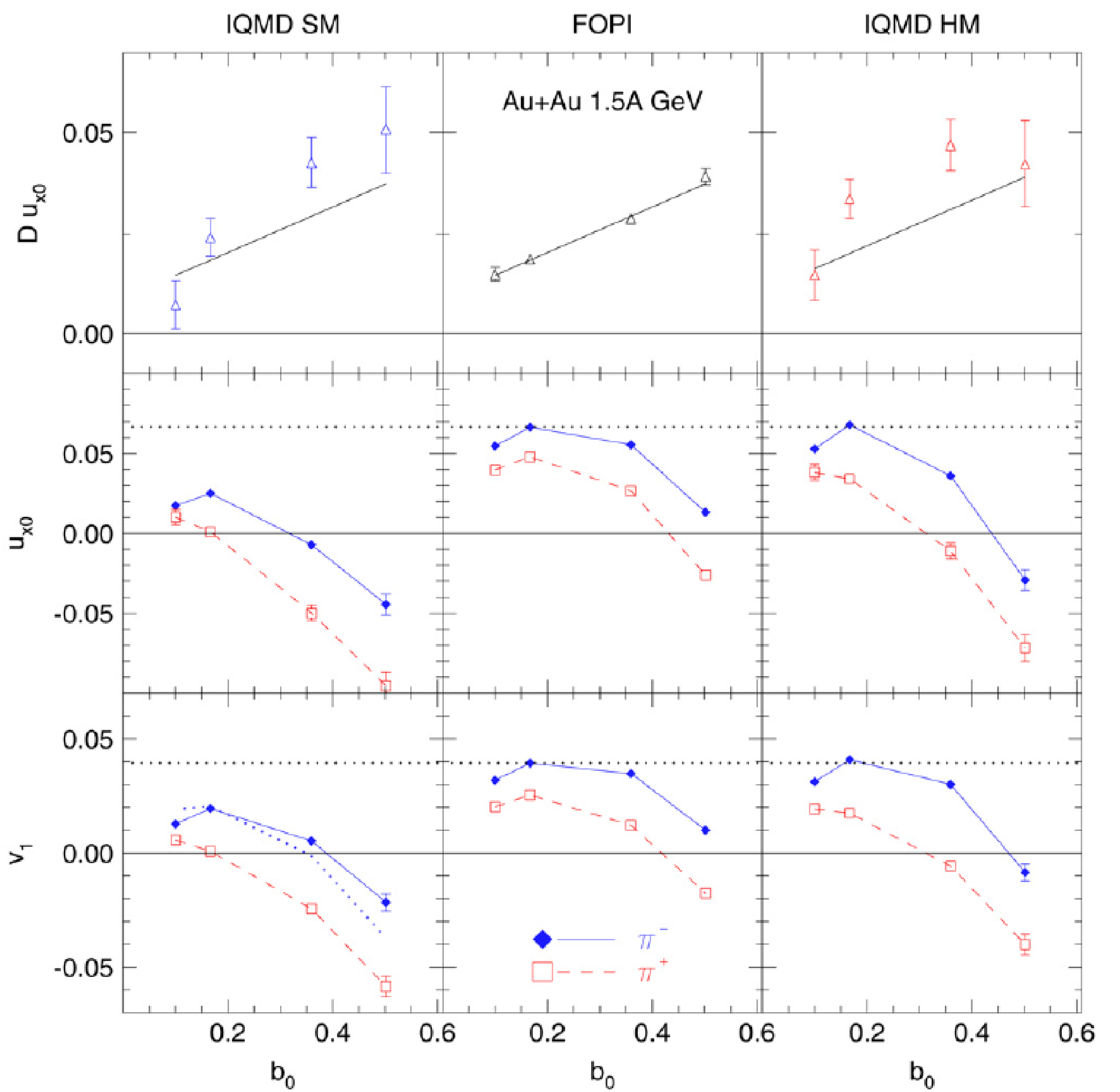
W. Reisdorf et al. (FOPI), NPA 781, 459 (2007)

Integration interval: $1.0 < u_{t0} < 4.2$.



Pions exhibit distinct flow pattern as function of centrality
(FOPI results are partially inconsistent with EOS @ Bevalac: J.C. Kintner, et al., PRL 78, 4165 (1997))

Pion Flow



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

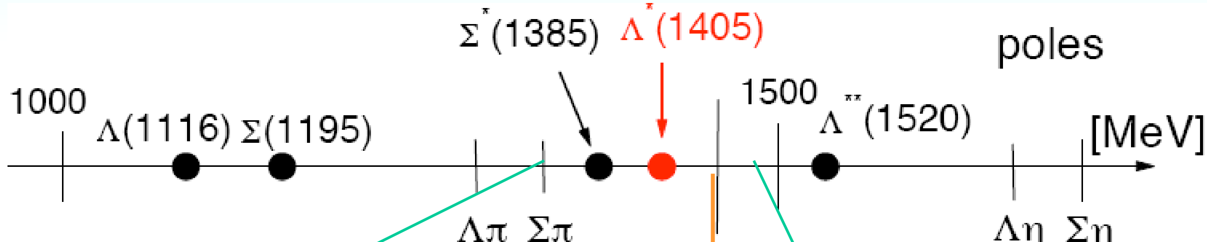
slope difference π^- - π^+

slope at midrapidity

Integral v_1

Pion flow favors HM (IQMD),
- **Δ – lifetime,**
- **in – medium cross sections.**

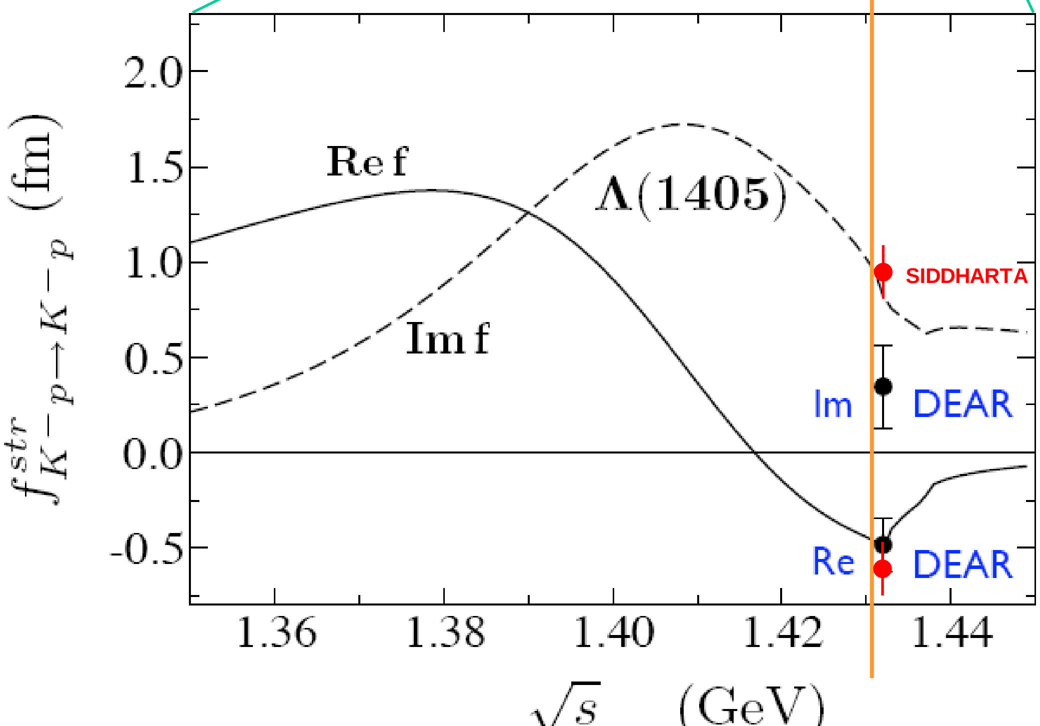
K̄N – interaction



$$\sqrt{s} = \omega + m_N$$

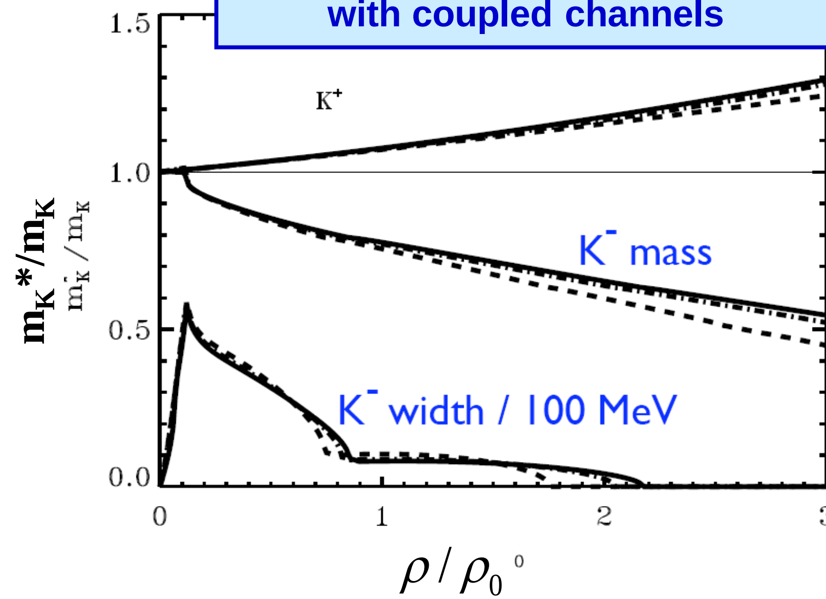
↑ K̄ – energy

Scattering amplitude f



W.Weise et al.: PLB 379, 34 (1996), PRL 94, 213401 (2005)
Y.Ikeda et al. arXiV:1109:3005

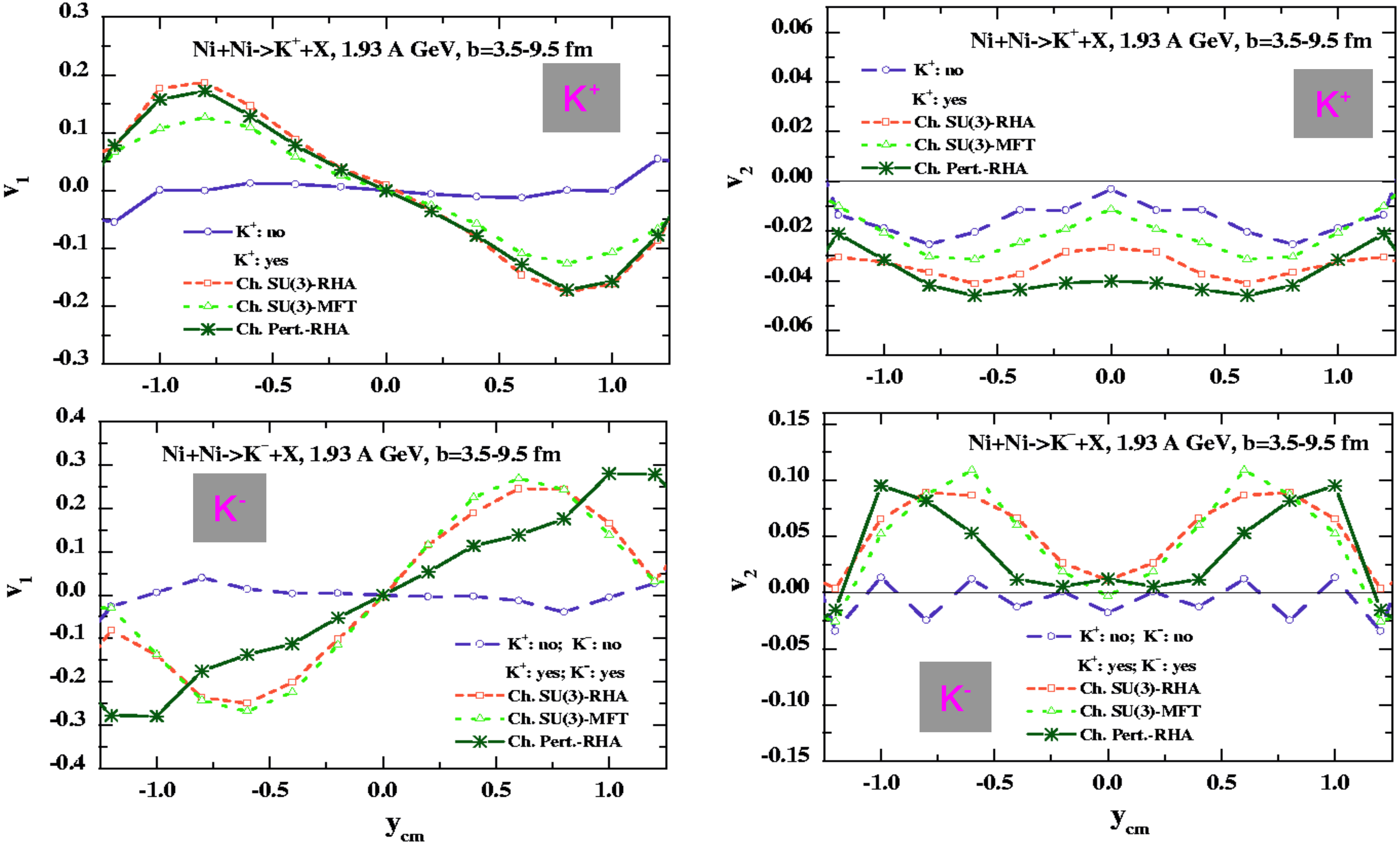
due to presence of resonances
↓
non – perturbative problem
↓
chiral SU(3) effective field theory with coupled channels



K̄N – interaction is attractive at finite densities, but strength (depth of potential) is unclear
Experimental signatures: flow of kaons
bound baryonic states

Predictions of kaon flow transport model

v_1 **v_2** A. Mishra *et al.* PRC 70(2004) 044904



Large asymmetries are predicted for semi-peripheral collisions …

Flow of charged kaons

V.Zinyuk, T.I. Kang

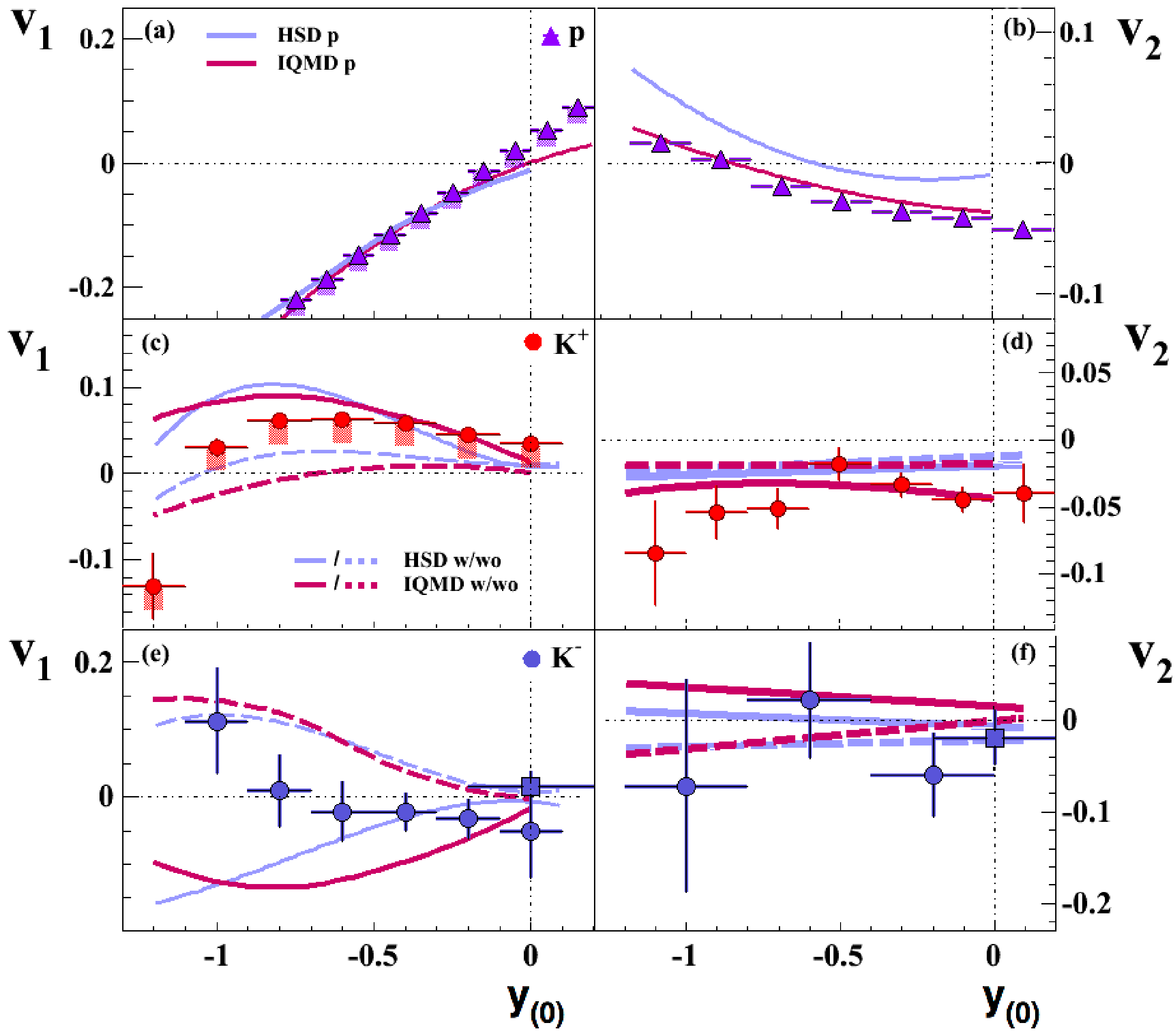
Ni+Ni at 1.91 AGeV
(S325 + S325e data)
σ = 1.5 b

Models with FOPI acceptance filter

Potentials with linear density dependence.

At $\rho=\rho_0$:

$U_{HSD}(K^+)$	20 MeV
$U_{IQMD}(K^+)$	40 MeV
$U_{HSD}(K^-)$	50 MeV
$U_{IQMD}(K^-)$	90 MeV



K^+ and K^- sideflow in variance with model expectations.

Differential flow of K^+ - mesons

T.I.Kang, V.Zinyuk

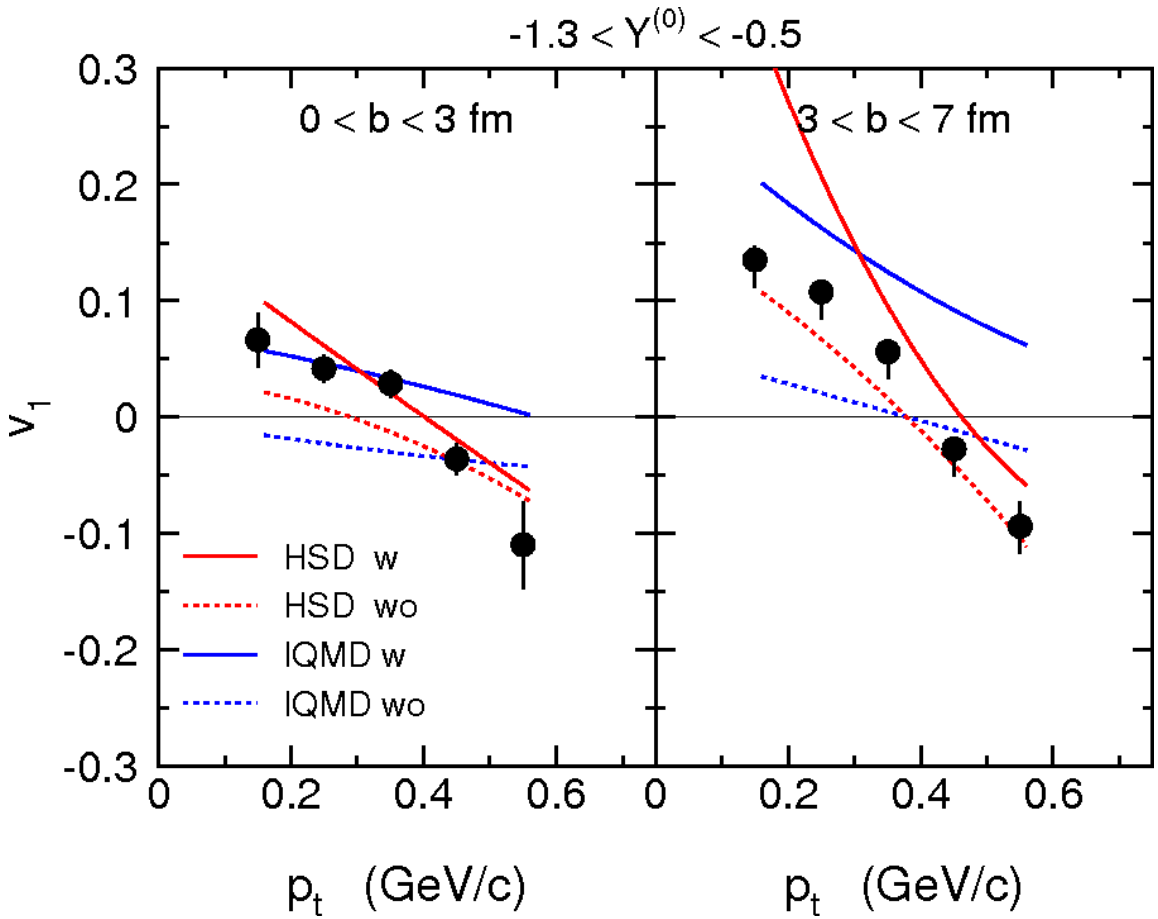
Ni+Ni at 1.91 AGeV (S325 + S325e data)

Models with FOPI acceptance filter

Potentials with linear density dependence.

At $\rho=\rho_0$:

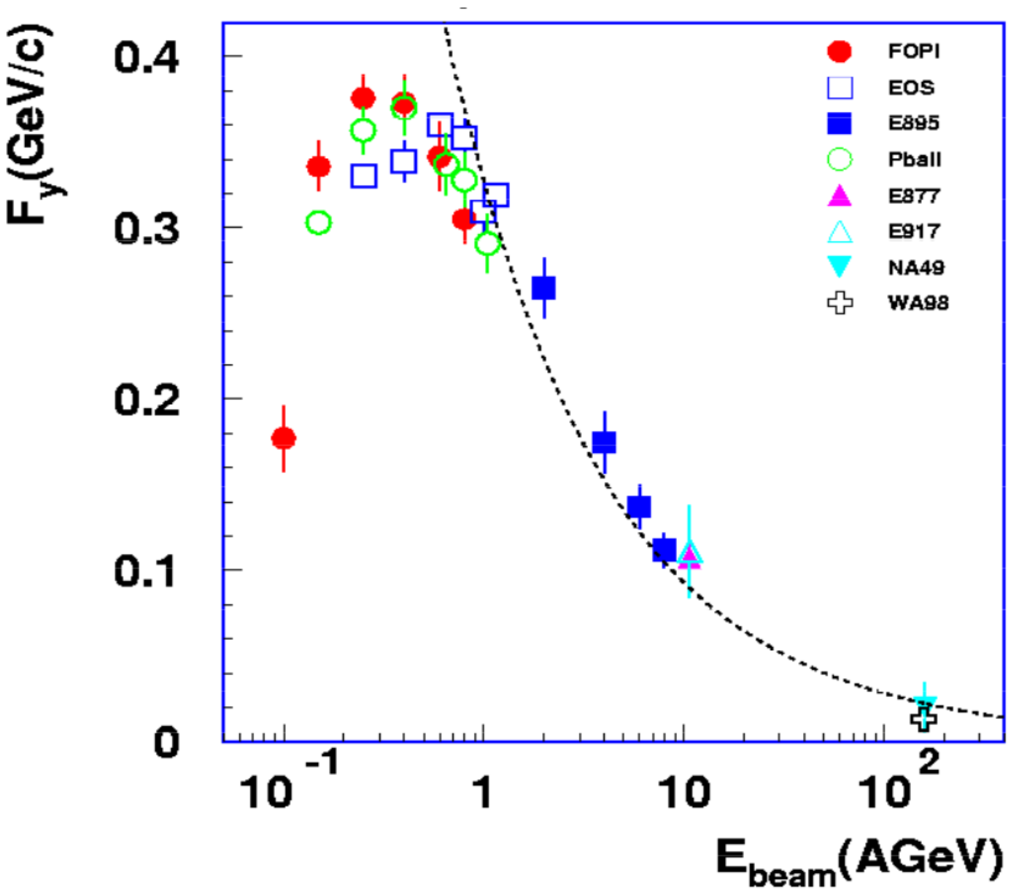
$U_{HSD}(K^+)$	**20 MeV**
$U_{IQMD}(K^+)$	**40 MeV**



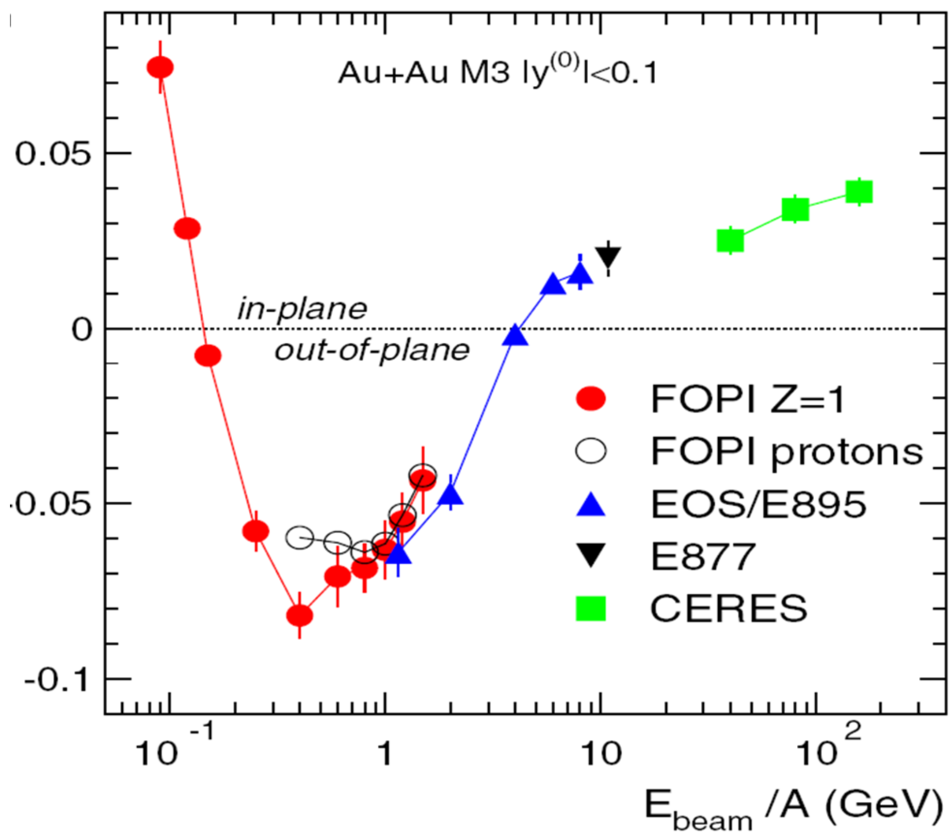
Differential sideflow in central collisions compatible with HSD & potential.

Models fail to describe the centrality dependence.

Excitation functions



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



CBM @ SIS100

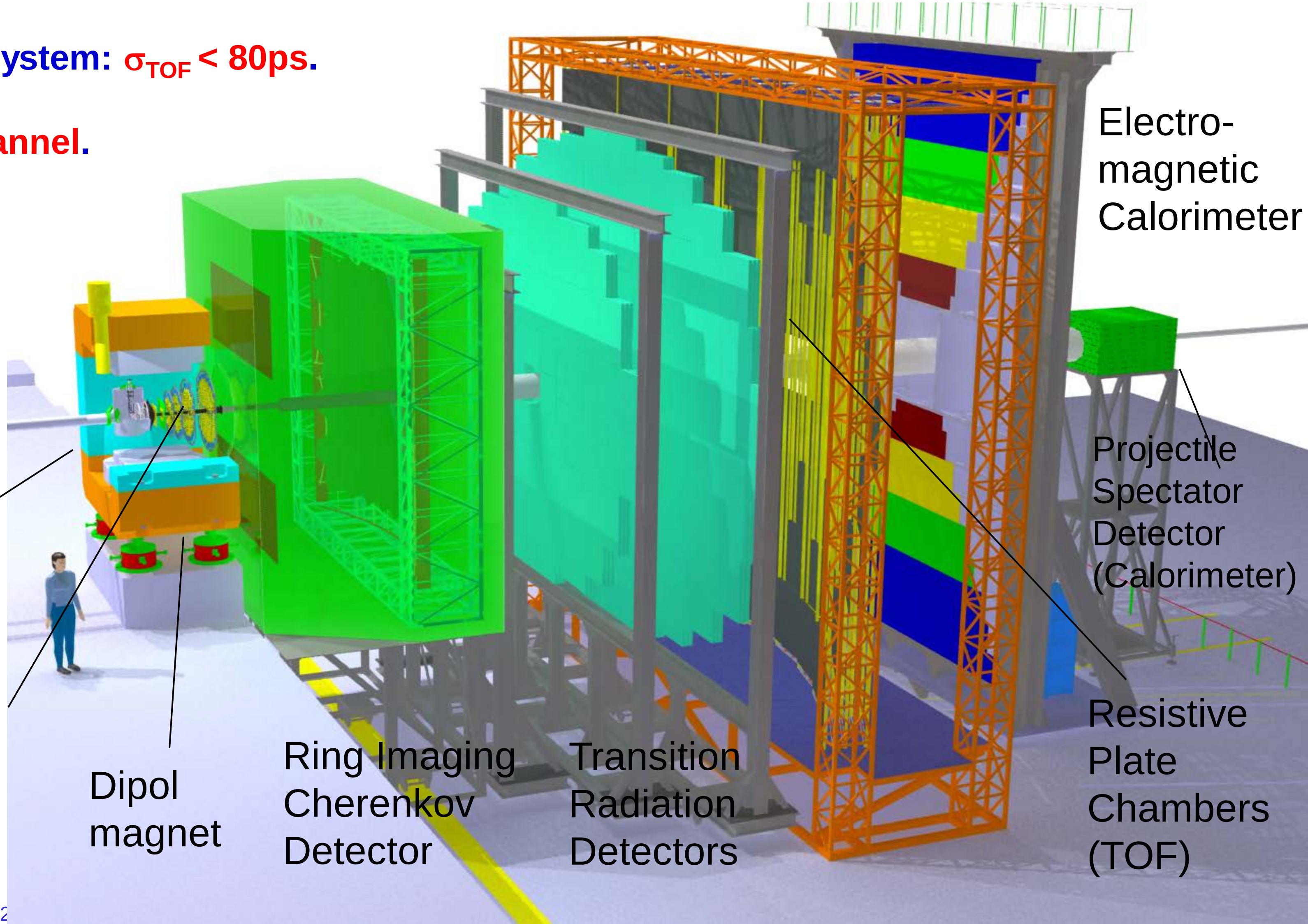
All components designed to run without trigger at 10 MHz interaction rate (free streaming readout).

RPCs at small angles are exposed to rates R=20 kHz/cm^2.

Requirement for TOF system: σ_{TOF} < 80ps.

Granularity: 70.000 channel.

Area: 120 m^2



Collaborators

(FOPI)
A. Andronic, R. Averbeck, Z. Basrak, N. Bastid,
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Conclusions

- **systematic measurements of collective baryon flow and stopping observables in beam energy range 0.1 – 2 AGeV flow published,**
- **from baryon flow data, preference for soft EOS with momentum dependent interaction (SM, IQMD) found,**
- **description of clusterisation indispensible for quantitative understanding,**
- **pion flow not yet understood,**
- **antikaon flow indicative of shallow anti-kaon potential.**

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