FOPI flow

References

- FOPI publications on reaction plane related flow

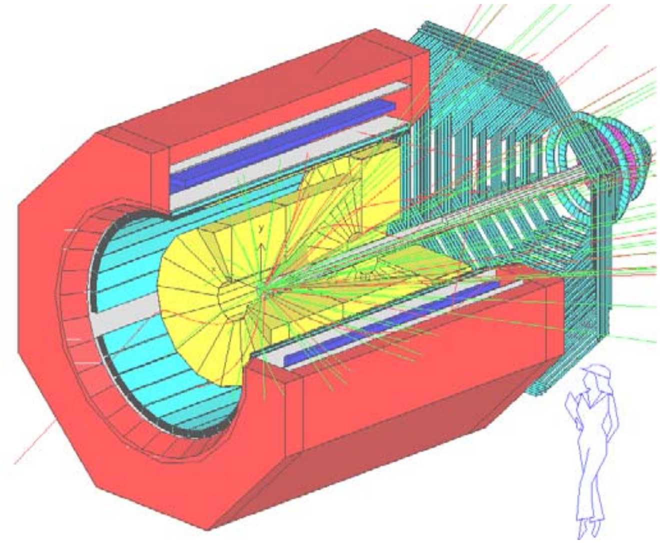
Technicalities

- Reaction plane estimation
- Fourier expansion of azimuthal distributions
- Flow determination without reaction plane
- Quadrant method

Selected results

- EOS from IQMD comparison
- Charged kaon flow

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 – Literature on Collective Flow

1) Systematics of azimuthal asymmetries in heavy ion collisions in the 1 A GeV regime.
By FOPI Collaboration (W. Reisdorf *et al.*). Dec 2011. 70pp.
Published in Nucl.Phys.A876:1-60,2012, e-Print: arXiv:1112.3180 [nucl-ex]

11) Systematics of pion emission in heavy ion collisions in the 1A- GeV regime.
By FOPI Collaboration (W. Reisdorf *et al.*). Oct 2006. 56pp.
Published in Nucl.Phys.A781:459-508,2007, e-Print: nucl-ex/061002

12) First analysis of anisotropic flow with Lee-Yang zeroes.
By FOPI Collaboration (N. Bastid *et al.*). Apr 2005. 5pp.
Published in Phys.Rev.C72:011901,2005, e-Print: nucl-ex/0504002

14) Excitation function of elliptic flow in Au+Au collisions and the nuclear matter equation of state.
By FOPI Collaboration (A. Andronic *et al.*). Nov 2004. 10pp.
Published in Phys.Lett.B612:173-180,2005, e-Print: nucl-ex/0411024

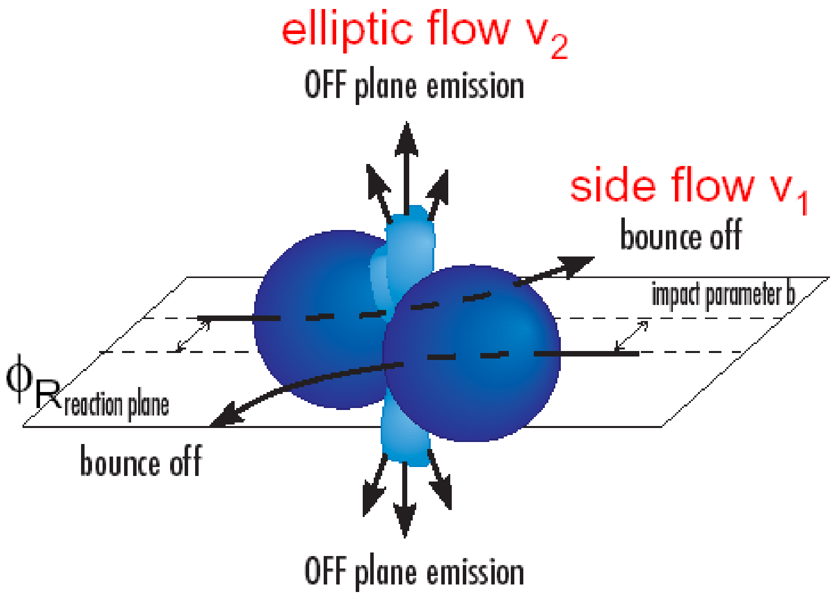
17) Nuclear stopping from 0.09-A-GeV to 1.93-A-GeV and its correlation to flow.
By FOPI Collaboration (W. Reisdorf *et al.*). Apr 2004. 4pp.
Published in Phys.Rev.Lett.92:232301,2004, e-Print: nucl-ex/0404037

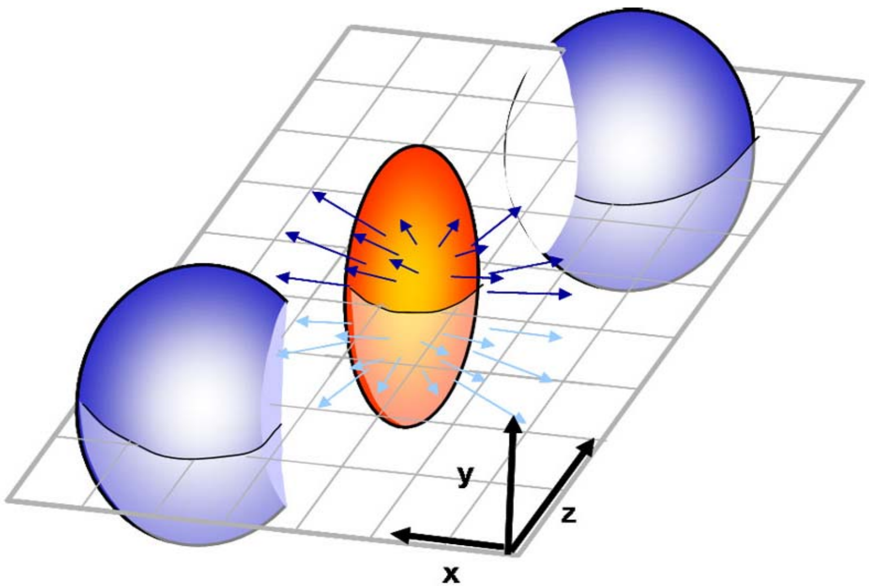
18) Azimuthal dependence of collective expansion for symmetric heavy ion collisions.
By FOPI Collaboration (G. Stoicea *et al.*). Jan 2004. 4pp.
Published in Phys.Rev.Lett.92:072303,2004, e-Print: nucl-ex/0401041

20) Directed flow in Au + Au, Xe + CsI and Ni + Ni collisions and the nuclear equation of state.
By FOPI Collaboration (A. Andronic *et al.*). Jan 2003. 20pp.
Published in Phys.Rev.C67:034907,2003, e-Print: nucl-ex/0301009

22) Differential directed flow in Au+Au collisions.
By FOPI Collaboration (A. Andronic *et al.*). Aug 2001. 5pp.
Published in Phys.Rev.C64:041604,2001, e-Print: nucl-ex/0108014

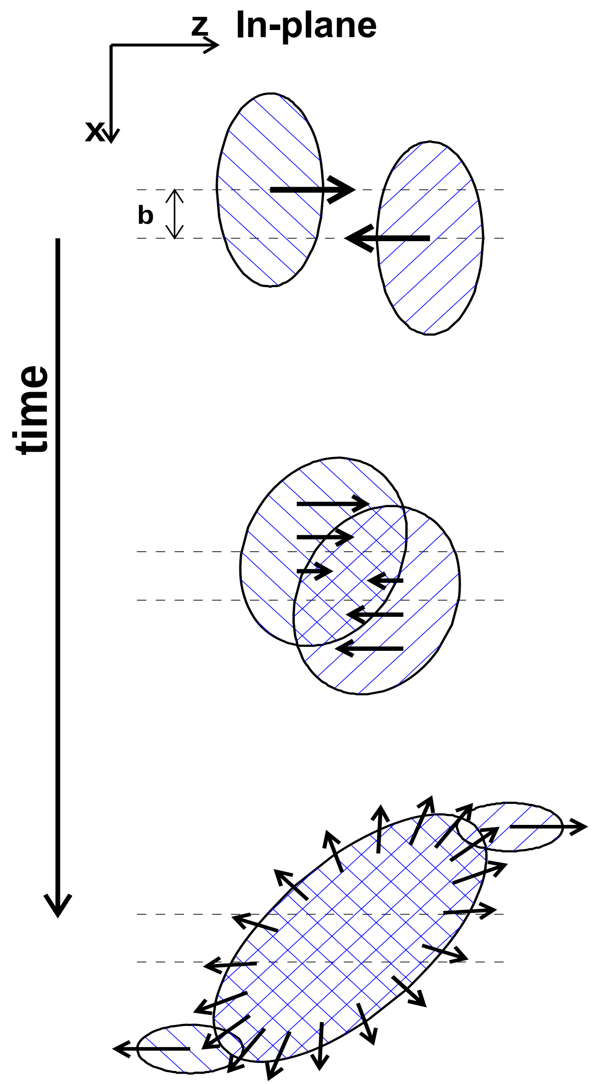
Collective flow



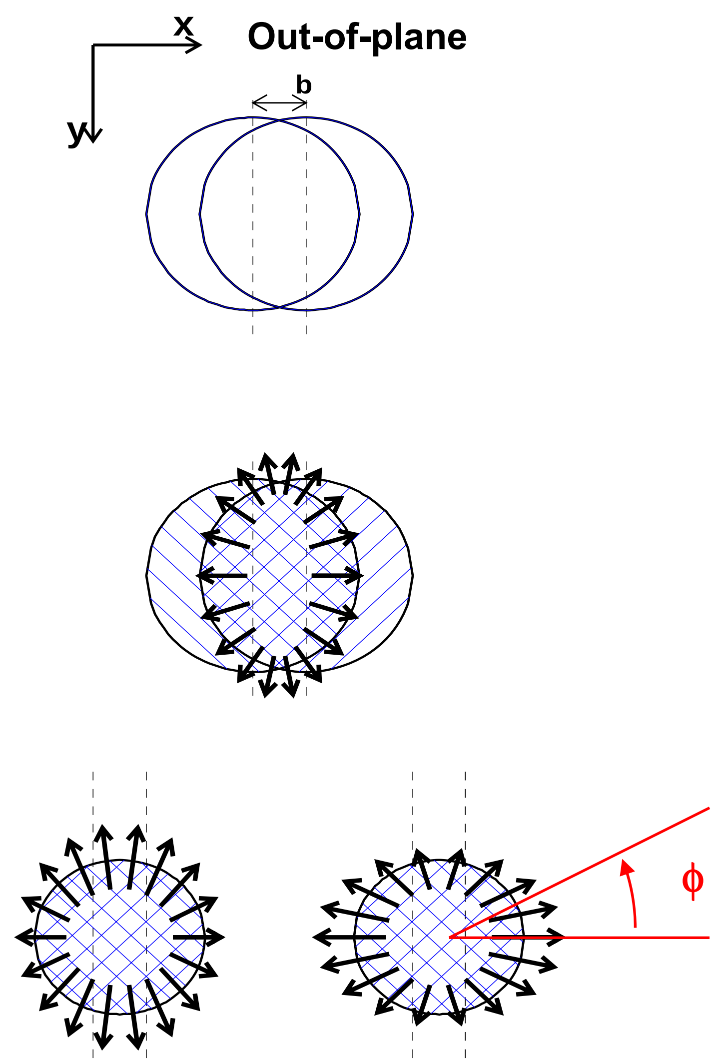


Collective Flow

In – plane



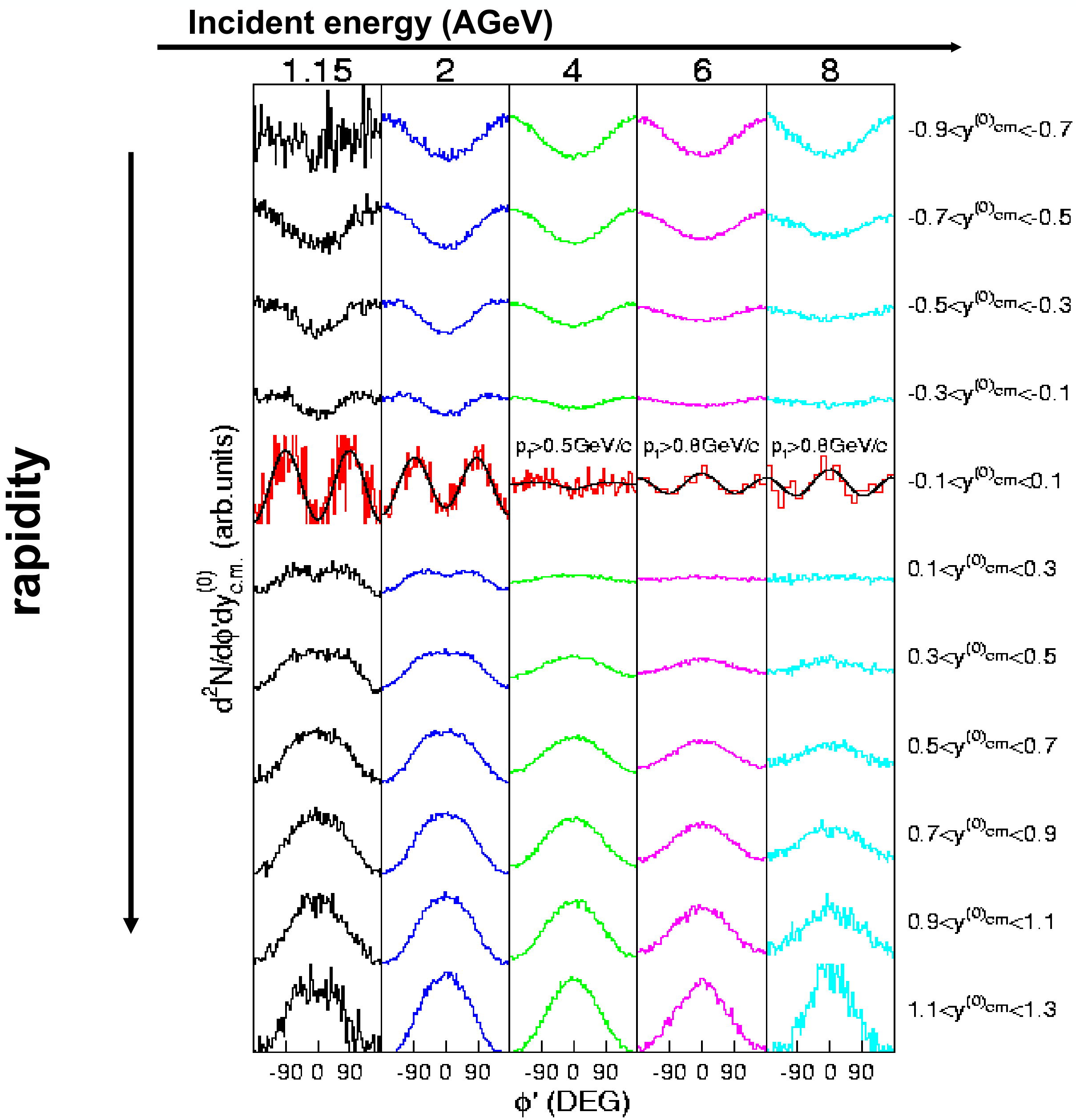
Transverse plane in CMS



with **without ‘spectators’**

N.Herrmann,
J.P. Wessels,
T.Wienold,
Ann.Rev.Nucl.Part.
Sci.49,581 (1999)

Azimuthal distributions



Azimutal Distributions with respect to reactionplane

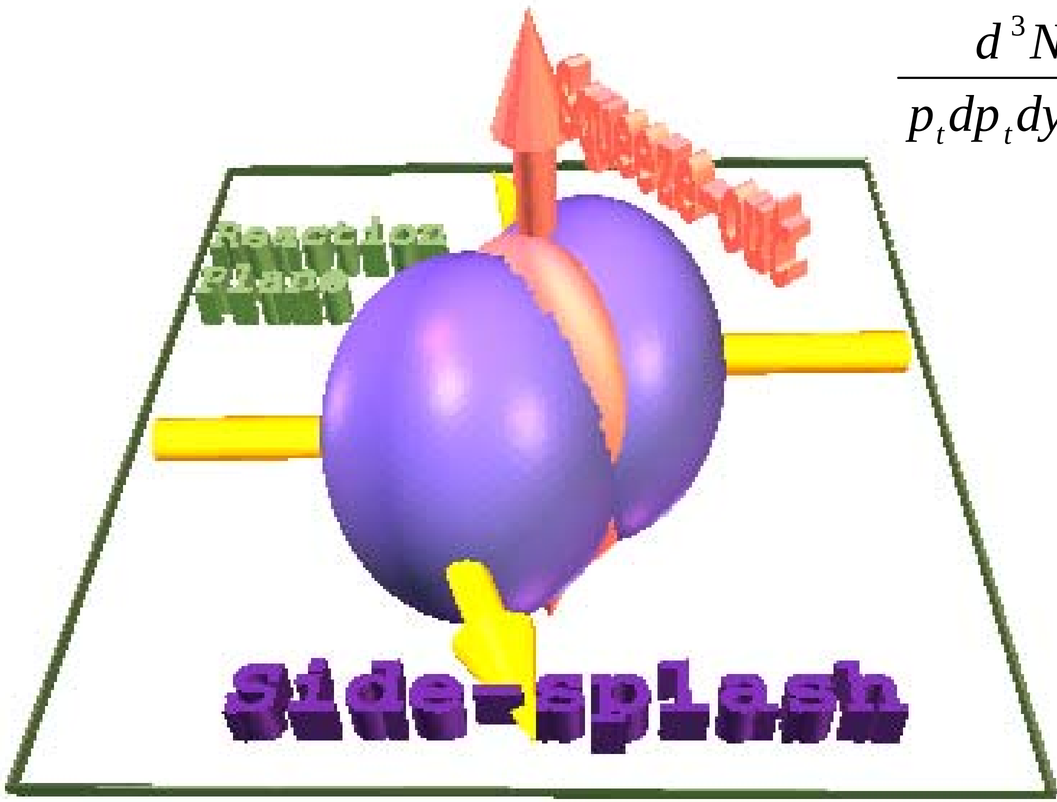
C.Pinkenburg et al., (E895), Phys.Rev.Lett. 83 (1999) 1295
nucl-ex/9903010

Reaction: Au + Au

Centrality: 0.5 < Mul < 0.75 Mul_{max}
(5 fm < b < 7fm)

Fourier Expansion of Azimutal Distributions

Phase space distribution with respect to reaction plane Φ_R



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

$$\frac{d^3N}{p_t dp_t dy d\varphi'} \propto (1 + 2\mathrm{v}_1 \cos(\varphi') + 2\mathrm{v}_2 \cos(2\varphi') + \ldots)$$

Fourier expansion coefficients

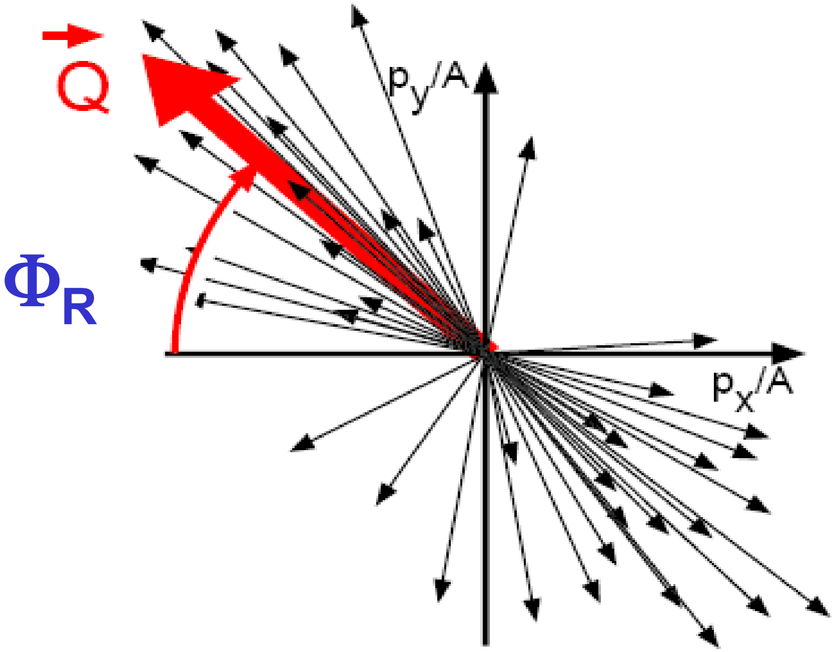
$$\mathrm{v}_1 = \left\langle \frac{p_x}{p_t} \right\rangle$$ **sideflow**

$$\mathrm{v}_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$ **elliptic flow**

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

Reaction Plane

Transverse momentum method: P. Danielewicz, G. Odyniec, *Phys. Lett.* 157B, 146 (1985)



$$\vec{Q}^{(n)} = \sum_{\nu} \omega(\nu) \cdot \vec{p}_t(\nu),$$

$$\omega(\nu) = \begin{cases} 1 & y(\nu) > y_{CM} + \delta y \\ -1 & y(\nu) < y_{CM} - \delta y \end{cases}$$

Generalisation:

$$\vec{Q}^{(n)} = \sum_{\nu} \omega^{(n)} \cdot \left|\vec{p}_t\right| \cdot \begin{pmatrix} \cos(n \cdot \varphi) \\ \sin(n \cdot \varphi) \end{pmatrix}, \qquad n = 1,2,3,...$$

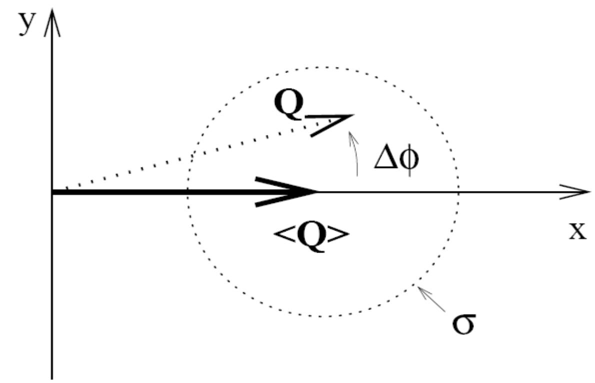
ω(n) has different sign in forward/backward hemisphere for odd values of n.

Reaction plane angle:

$$\Phi_R^{(n)} = \arctan\left(Q_y^{(n)}, Q_x^{(n)}\right)/n$$

Reaction plane resolution

Reconstructed reaction plane is fluctuating around true reaction plane
=> measured v_i are smaller than true v_i.



Subevent method:

$$\left\langle \cos\left(n\left(\Phi_A^{(n)} - \Phi_B^{(n)}\right)\right)\right\rangle = \left\langle \cos\left(n\left(\Phi_A^{(n)} - \Phi_R\right)\right)\right\rangle \cdot \left\langle \cos\left(n\left(\Phi_B^{(n)} - \Phi_R\right)\right)\right\rangle$$

Estimate for correction factors of Fourier expansion coefficients:

$$\mathrm{v}_m = \mathrm{v}_m^{obs} / \sqrt{\left\langle \cos\left(n\left(\Phi_A^{(n)} - \Phi_B^{(n)}\right)\right)\right\rangle}$$

Ollitrault formalism

J.Y. Ollitrault, arXiv:nucl-ex/9711003

Eq.(6) can be easily integrated over Q [21] to yield the distribution of $\Delta\phi$:

$$\frac{dN}{\Delta\phi} = \frac{1}{\pi}\exp(-\chi^2)\left\{1 + z\sqrt{\pi}\,[1+\mathrm{erf}(z)]\exp(z^2)\right\}. \quad (7)$$

where $z = \chi\cos\Delta\phi$ and $\mathrm{erf}(x)$ is the error function. This distribution depends on $\bar{Q}$ and σ only through the dimensionless parameter $\chi \equiv \bar{Q}/\sigma$. The Fourier coefficients are most easily calculated by integrating Eq.(6) first over $\Delta\phi$ and then over Q [14]:

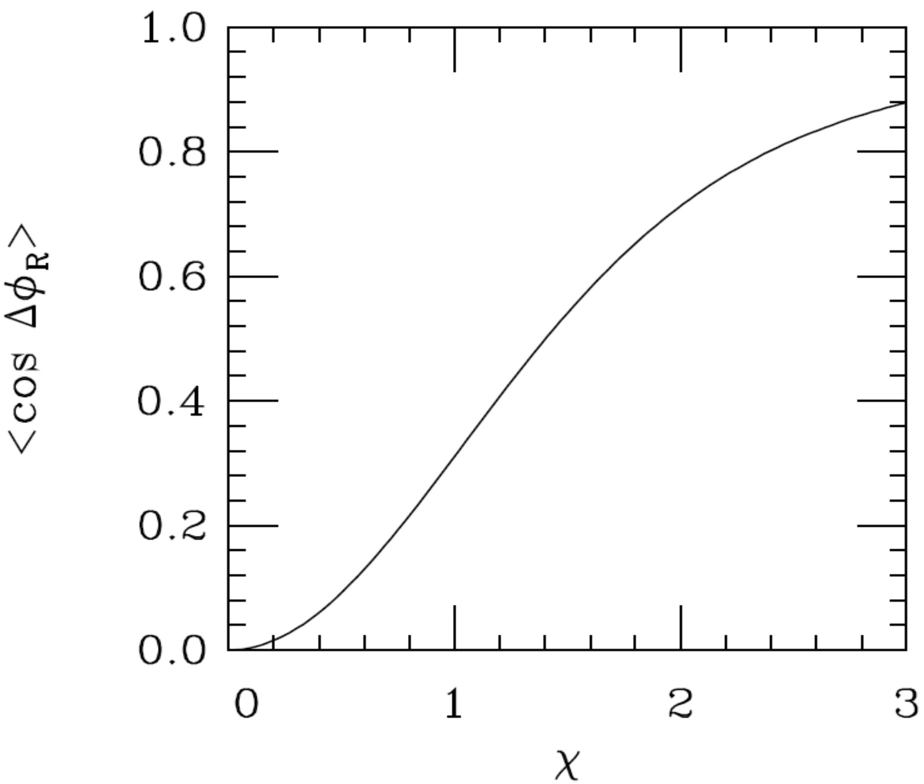
$$\langle\cos n\Delta\phi\rangle = \frac{\sqrt{\pi}}{2}\chi e^{-\chi^2/2}\left[I_{\frac{n-1}{2}}\left(\frac{\chi^2}{2}\right) + I_{\frac{n+1}{2}}\left(\frac{\chi^2}{2}\right)\right] \quad (8)$$

where I_k is the modified Bessel function of order k. The variations of the first coefficients

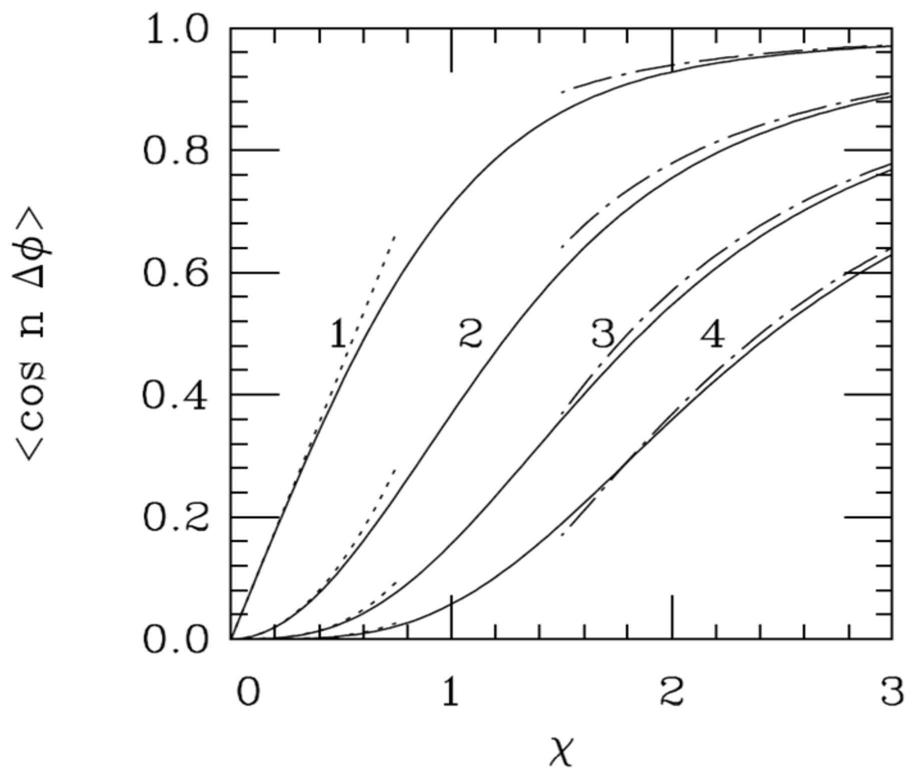
Fourier coefficients v_i can be corrected consistently by evaluating dimensionless parameter χ!

Ollitrault formalism

Determination of χ



Inverse correction factors



Test of formalism with Monte Carlo

Andronic 2003

TABLE I. The geometric impact parameters intervals Δb_{geo} and the correction factors for the reaction plane resolution, $1/\langle\cos\Delta\phi\rangle$, for three centrality bins of Au+Au collisions at the incident energy of 400A MeV.

Centrality bin	M3	M4	M5
Δb_{geo} (fm)	6.1-7.6	1.9-6.1	0-1.9
$1/\langle\cos\Delta\phi\rangle$	1.05	1.04	1.17

TABLE II. The geometric impact parameters intervals Δb_{geo}, the reduced impact parameters $\langle b_{geo}\rangle/b_{geo}^{max}$ and the correction factors for the reaction plane resolution, $1/\langle\cos\Delta\phi\rangle$, for the three systems at the incident energy of 250A MeV, M4 centrality bin.

System	Au+Au	Xe+CsI	Ni+Ni
Δb_{geo} (fm)	1.9-6.1	1.7-4.8	1.5-3.4
$\langle b_{geo}\rangle/b_{geo}^{max}$	0.31	0.29	0.27
$1/\langle\cos\Delta\phi\rangle$	1.05	1.09	1.27

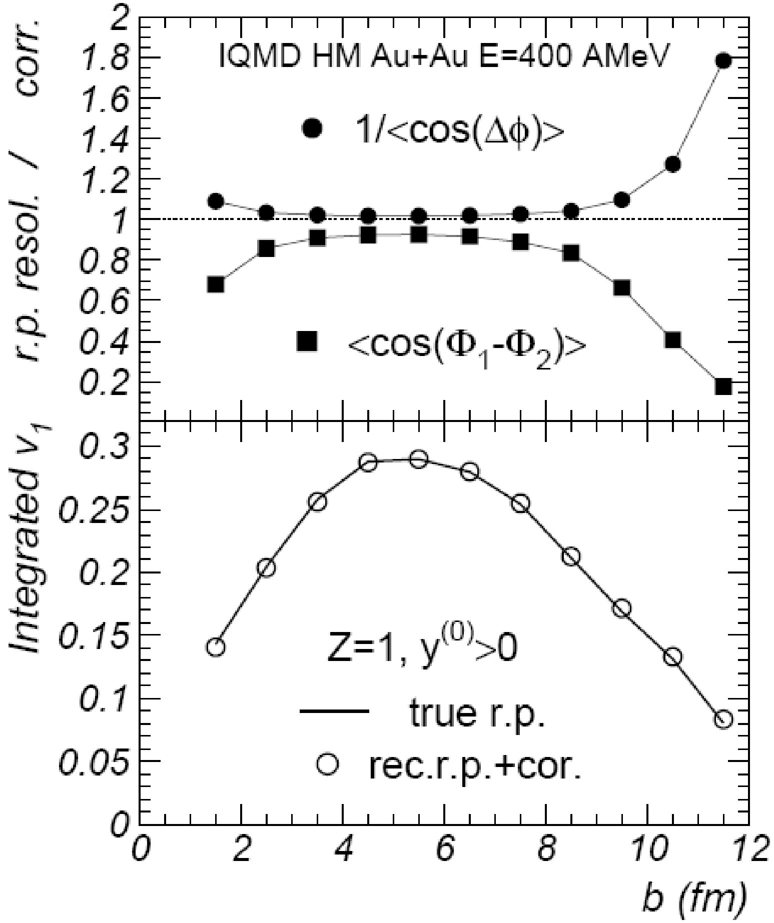
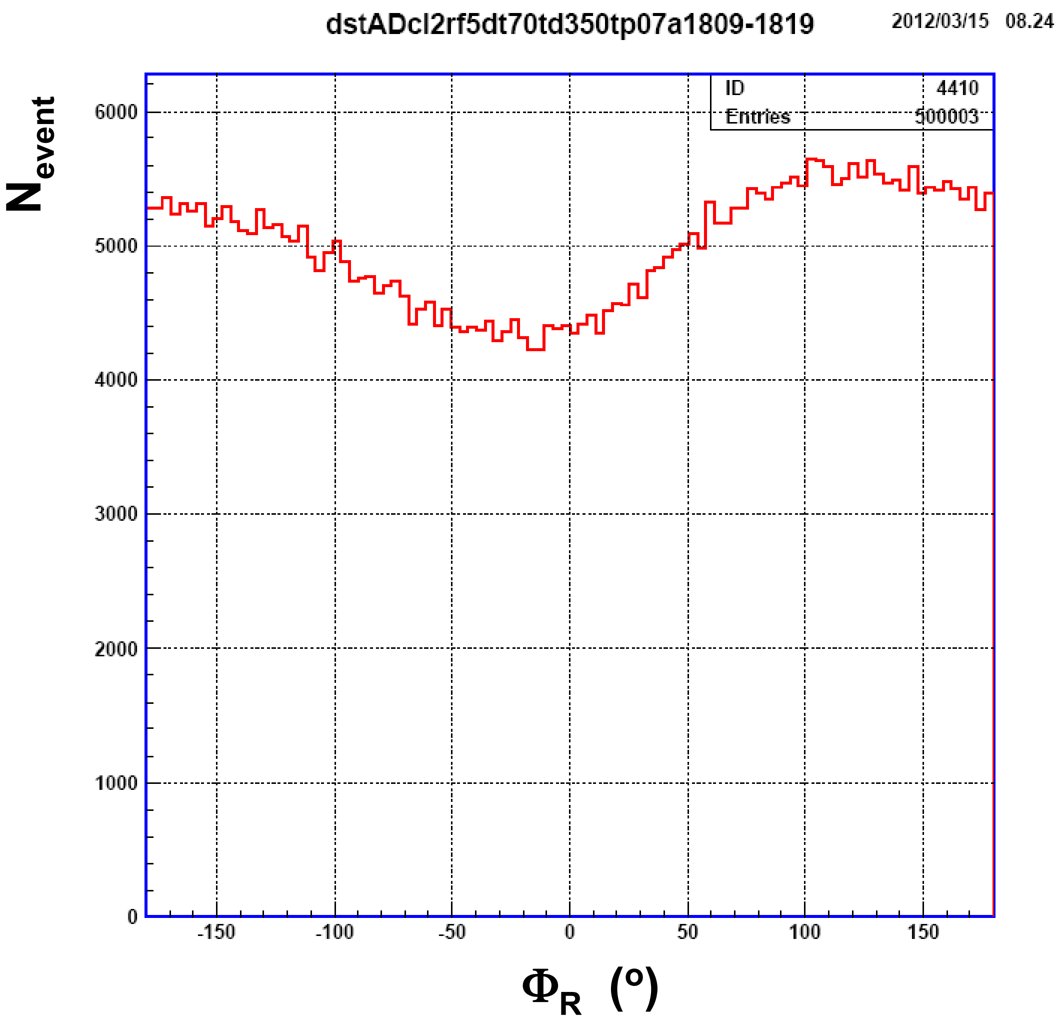


FIG. 2. Upper panel: the resolution of the reconstructed reaction plane (squares) and the corresponding correction factors (dots). Lower panel: v_1 values for the true (continuous line) and reconstructed and corrected (dashed line) reaction plane. IQMD HM events were used for these studies.

Uniformity of the reaction plane distribution

Ex.: Ni + Ni @ 1.92 AGeV (S325e)



Reaction plane from FOPI PLA forward wall

No corrections

Asymmetry ~ 20%

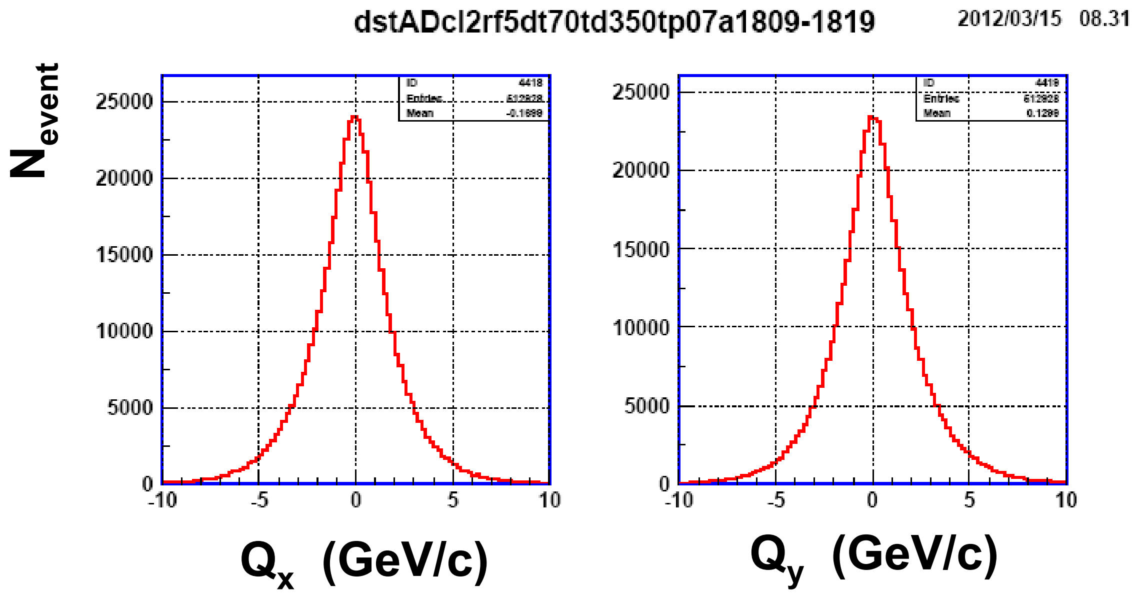
$$Q_x = \sum_i \omega_i p_{x,i}$$

$$Q_y = \sum_i \omega_i p_{y,i}$$

$$\Phi_R = \arctan 2\left(Q_y, Q_x\right)$$

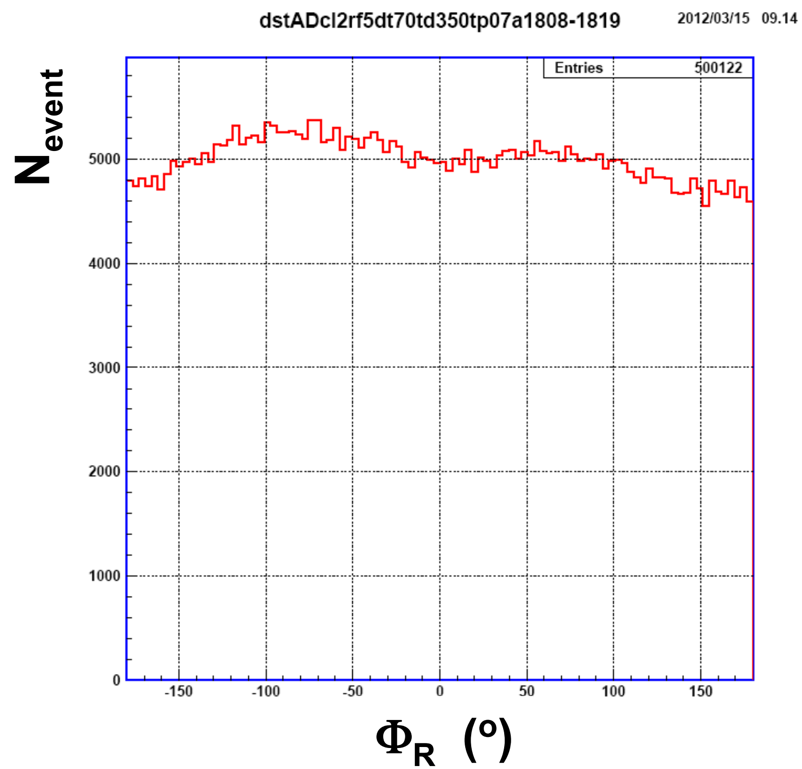
Uniformity of the reaction plane distribution

Ex.: Ni + Ni @ 1.92 AGeV (S325e)



Reaction plane from FOPI PLA forward wall

"Recentering"



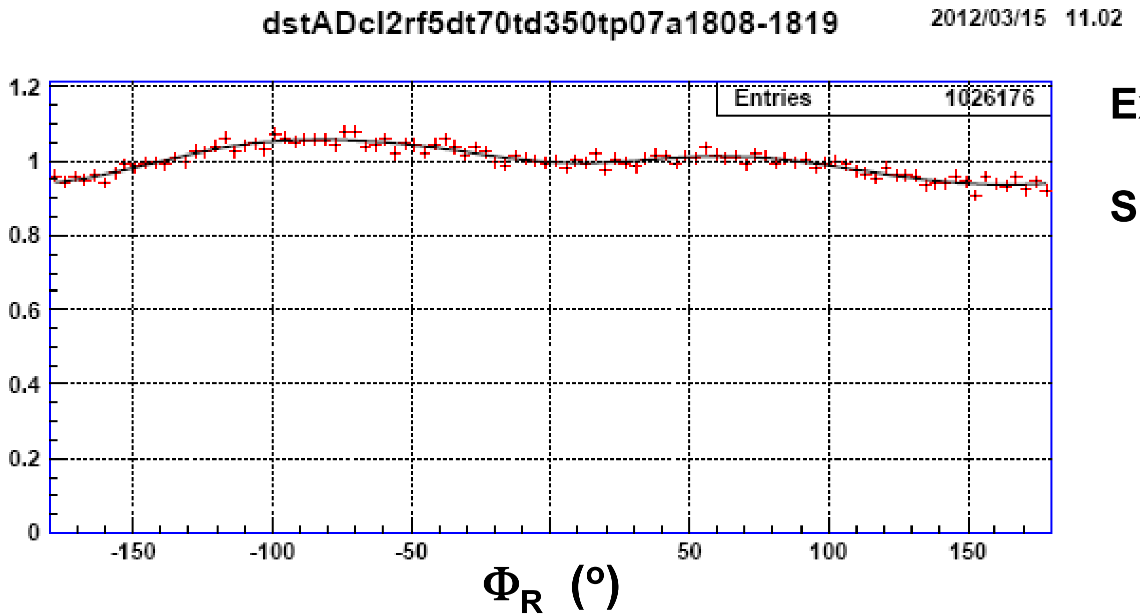
$$Q_x = \sum_i \omega_i p_{x,i} - \langle Q_x \rangle$$

$$Q_y = \sum_i \omega_i p_{y,i} - \langle Q_y \rangle$$

$$\Phi_R = \arctan 2(Q_y, Q_x)$$

Average over event sample

Reaction plane flattening



J. Barrette et al. (E877), PRC 56, 3254 (1997)

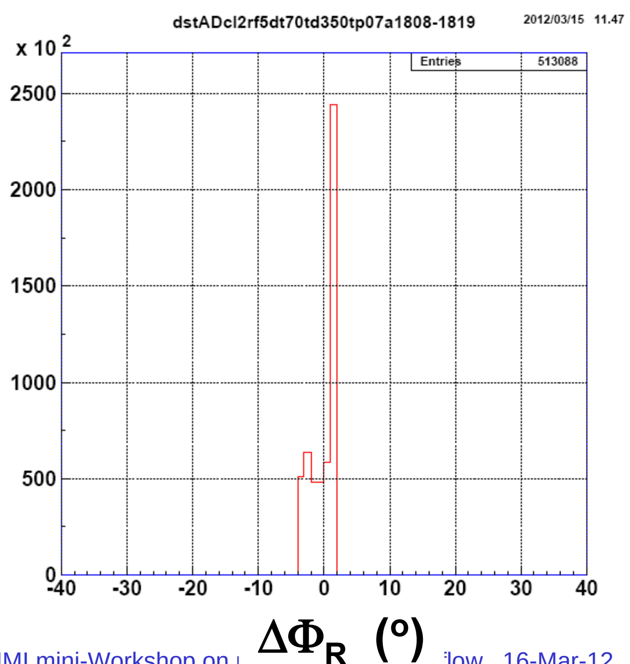
Extraction of average fourier components

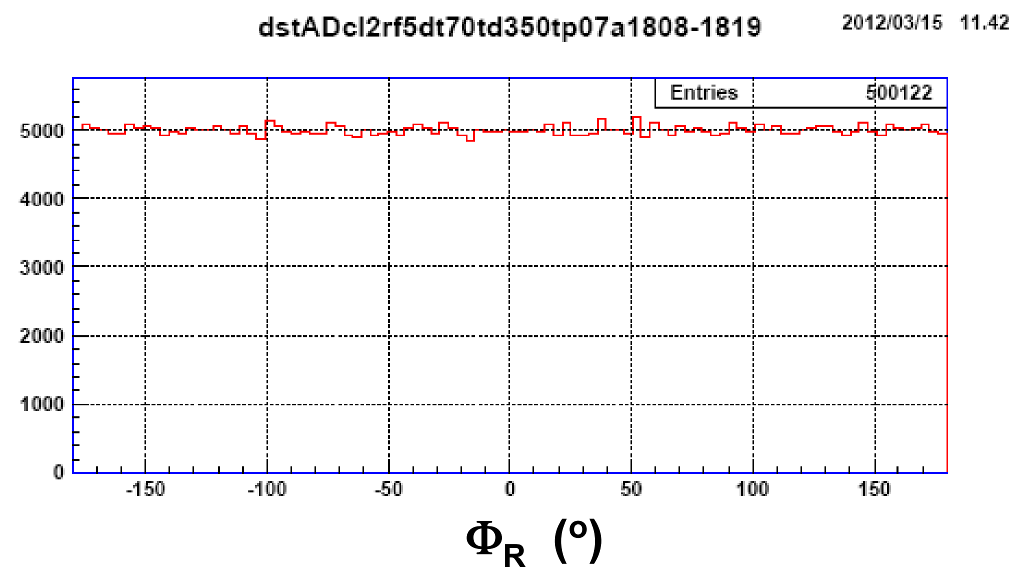
Shift of reaction plane by

$$\Delta\Phi_R = \sum_n \left[A_n \cos(n\Phi_R) + B_n \sin(n\Phi_R)\right]$$

$$A_n = -\frac{2}{n}\langle \sin(n\Phi_R)\rangle$$

$$B_n = \frac{2}{n}\langle \cos(n\Phi_R)\rangle$$

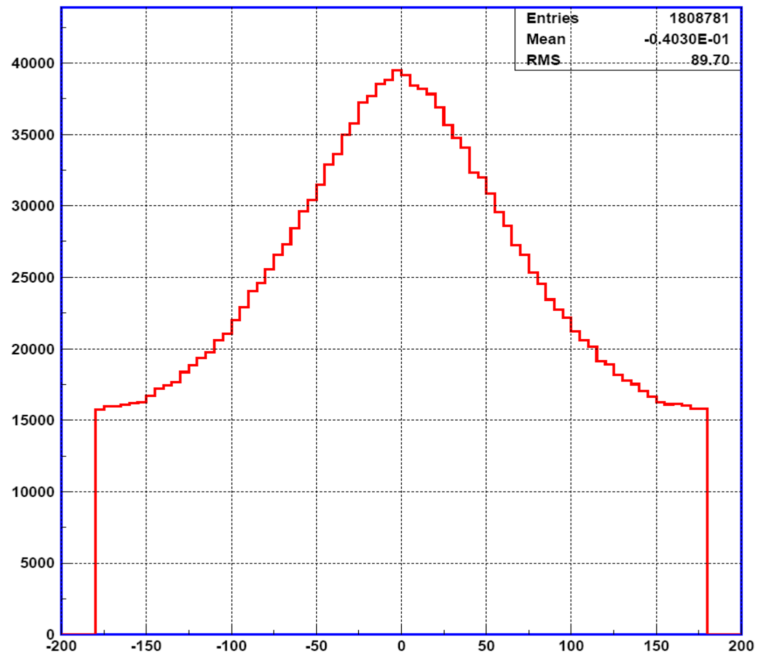




Reaction plane resolution

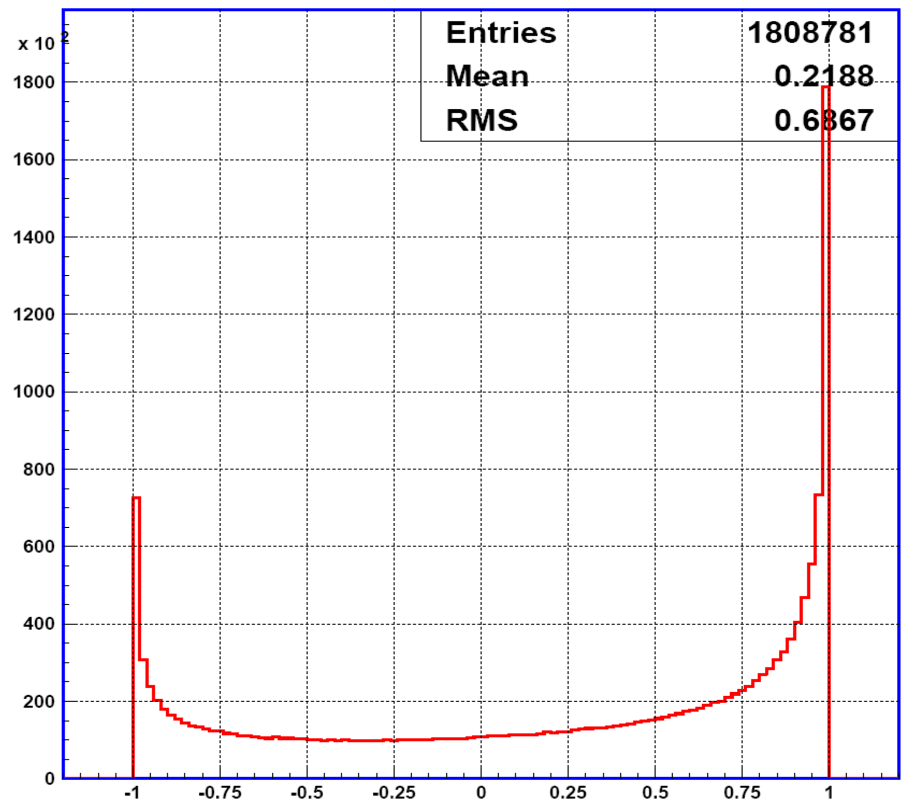
FOPI: Ni + Ni @ 1.91 AGeV (S325e)

Random subevents



$\Delta\Phi_{Rsub}$

$$RMS(\Delta\Phi_R) = 89.7^0$$
$$\cos(\Delta\Phi_R) = 0.219$$
$$C_{v_1} = 1.62$$
$$C_{v_2} = 3.78$$



cos $(\Delta\Phi_{Rsub})$

Example for Reaction Plane Resolution

Ni + Ni @ 1.91 AGeV (S325e)

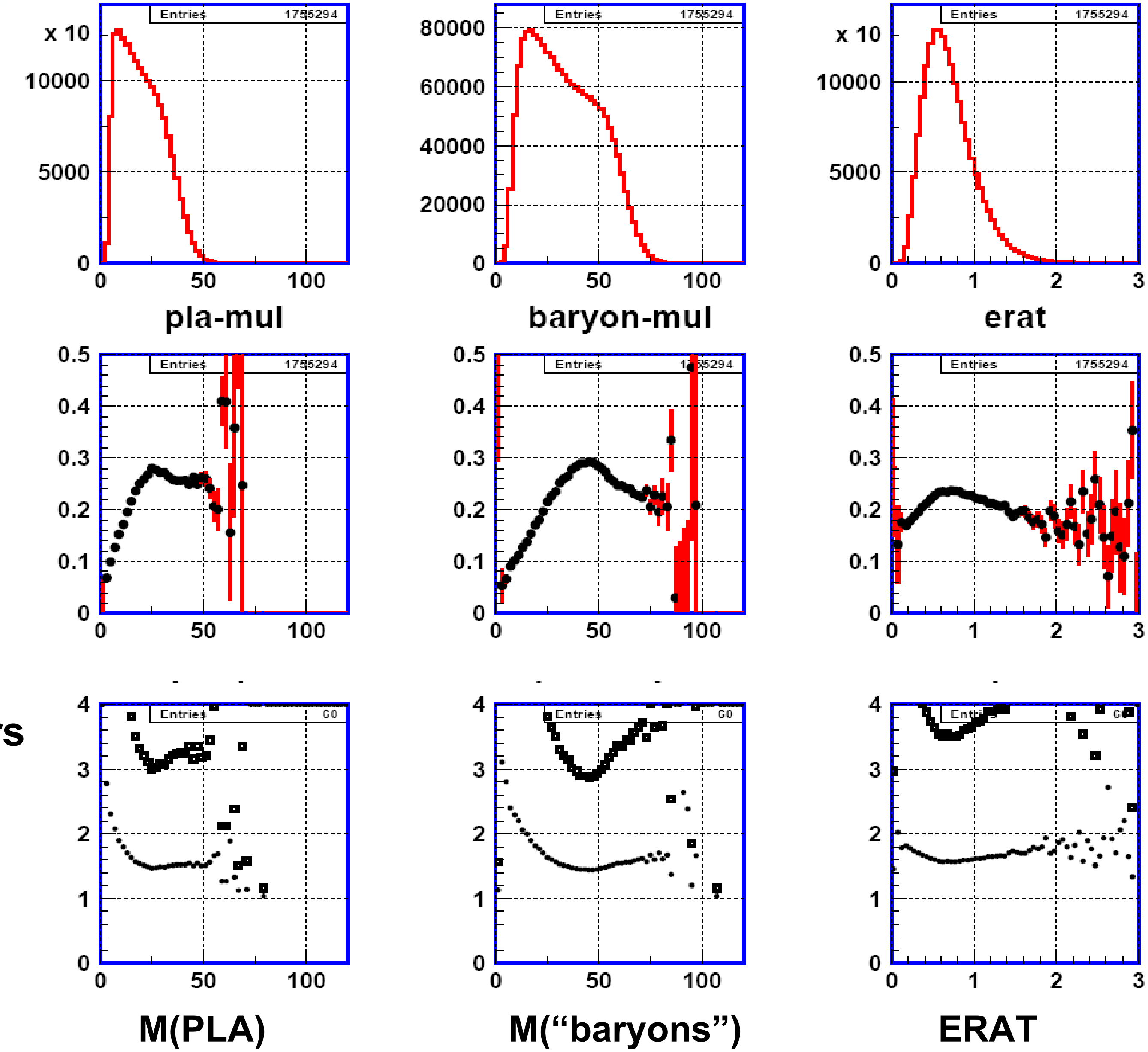
N_{events}

$<\cos(\Delta\Phi_R)>$

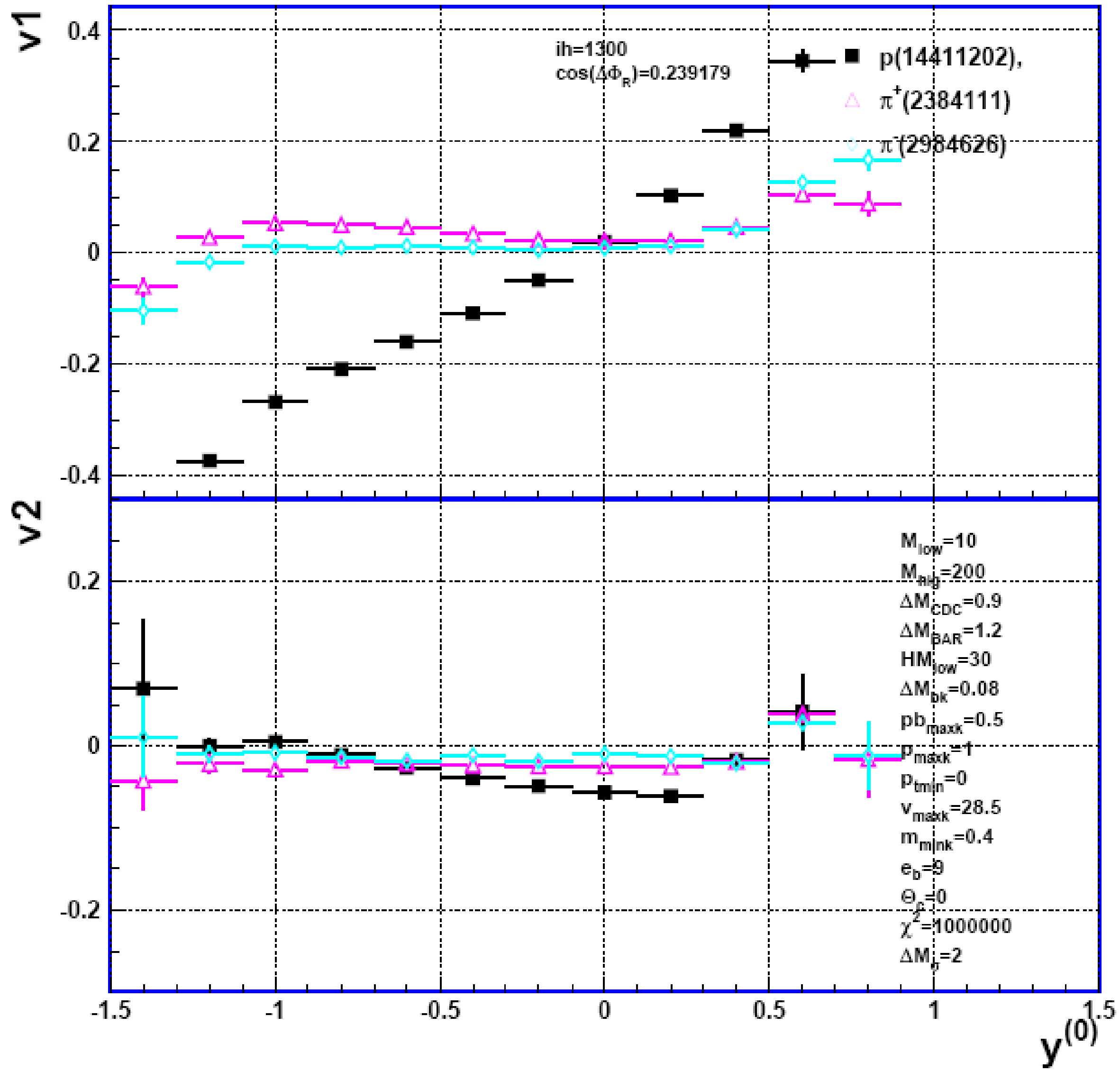
Correction factors

v_2,

v_1



Ni + Ni @ 1.91 AGeV (S325e)



Autocorrelation removed

$$Q_x^{(j)} = \sum_{i \neq j} \omega_i p_{x,i} = Q_x - \omega_j p_{x,j}$$

$$Q_y^{(j)} = \sum_{i \neq j} \omega_i p_{y,i} = Q_y - \omega_j p_{y,j}$$

$$Q_R^{(j)} = \arctan 2\left(Q_y^{(j)}, Q_x^{(j)}\right)$$

Symmetry requirement:

$$\mathrm{v}_1\left(y^{(0)} = 0\right) = 0$$

$$\mathrm{v}_1^{\exp} \neq 0$$

$$\mathrm{v}_1^{\exp} = \mathrm{v}_1^{\exp}\left(A_{sys}, \mathrm{Centrality}, m_0\right)$$

Note: recoil effect negligible for Integrated flow

$$|\omega_j| \rightarrow \left(1 - \frac{m_j}{m_{tot}}\right)|\omega_j|$$

Differential $v_{1/2}$ - distributions

Andronic 2001

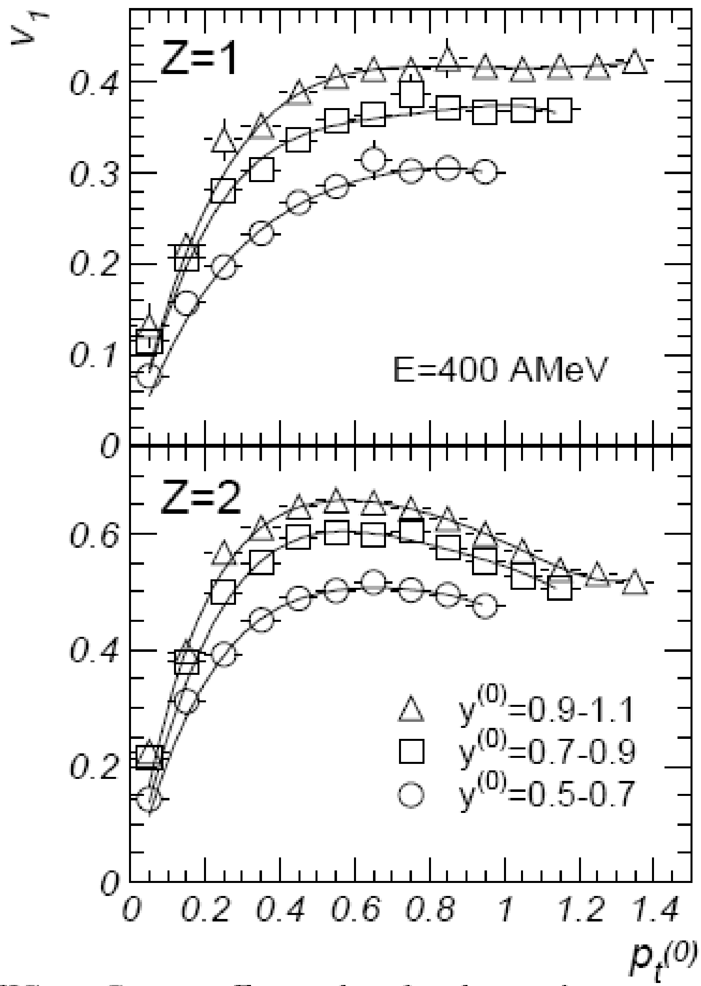


FIG. 5. Same as Fig. 4, but for the incident energy of 400-A MeV.

Au + Au @ 400 AMeV

Autocorrelation removed.

$$Q_x^{(j)} = \sum_{i \neq j} \omega_i p_{x,i}$$

$$Q_y^{(j)} = \sum_{i \neq j} \omega_i p_{y,i}$$

$$Q_R^{(j)} = \arctan 2\left(Q_y^{(j)}, Q_x^{(j)}\right)$$

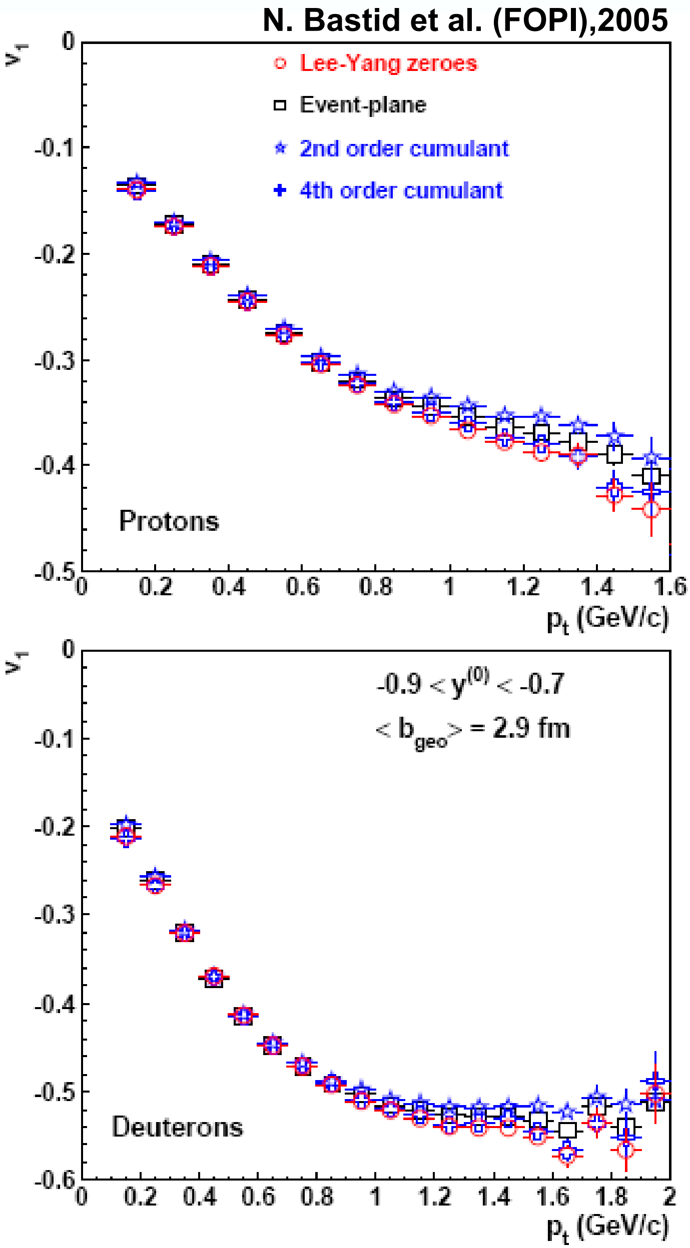
Result:

complex pattern

no simple scaling law

need transport models for interpretation

Alternative methods without reaction plane



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.

Integral flow observables

Integral sideflow

$$p_x^{dir} = \sum_{\nu} \omega \cdot \vec{p}_t(\nu) \cdot \vec{Q} / \left| \vec{Q} \right|$$

(Classical) 'Sideflow'
(slope of mean p_x at midrapidity)

$$F_y = \frac{d \langle p_x \rangle / A}{dy}$$

Transverse momentum tensor

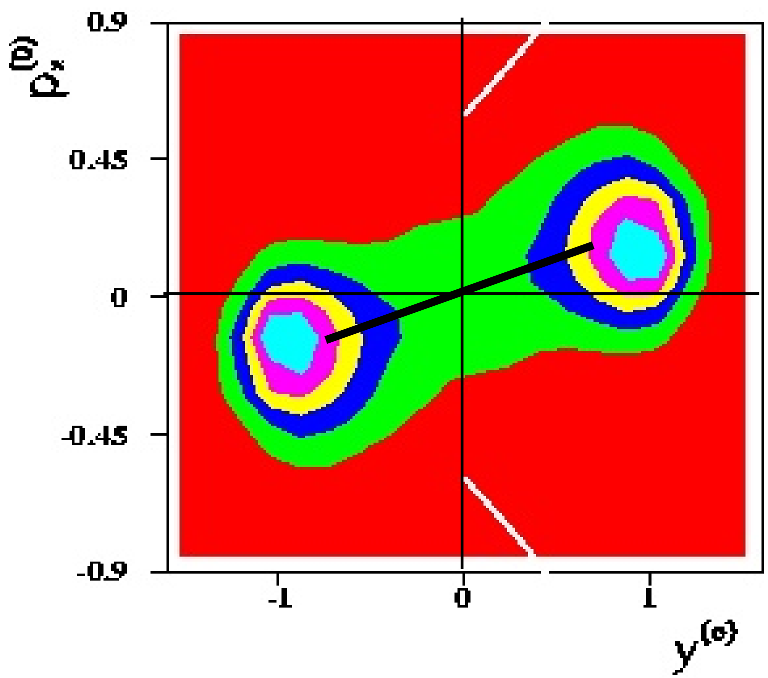
$$F_{ij} = \sum_{\nu} p_i(\nu) p_j(\nu) / 2m_\nu ,$$

$$i, j = x, y, z$$

Sideflow

Au+Au @ 0.4AGeV, Li-fragments

P.Crochet et al., (FOPI), NPA624, 755 (1997)



$$F_y = \frac{d\langle p_x \rangle}{dy}$$

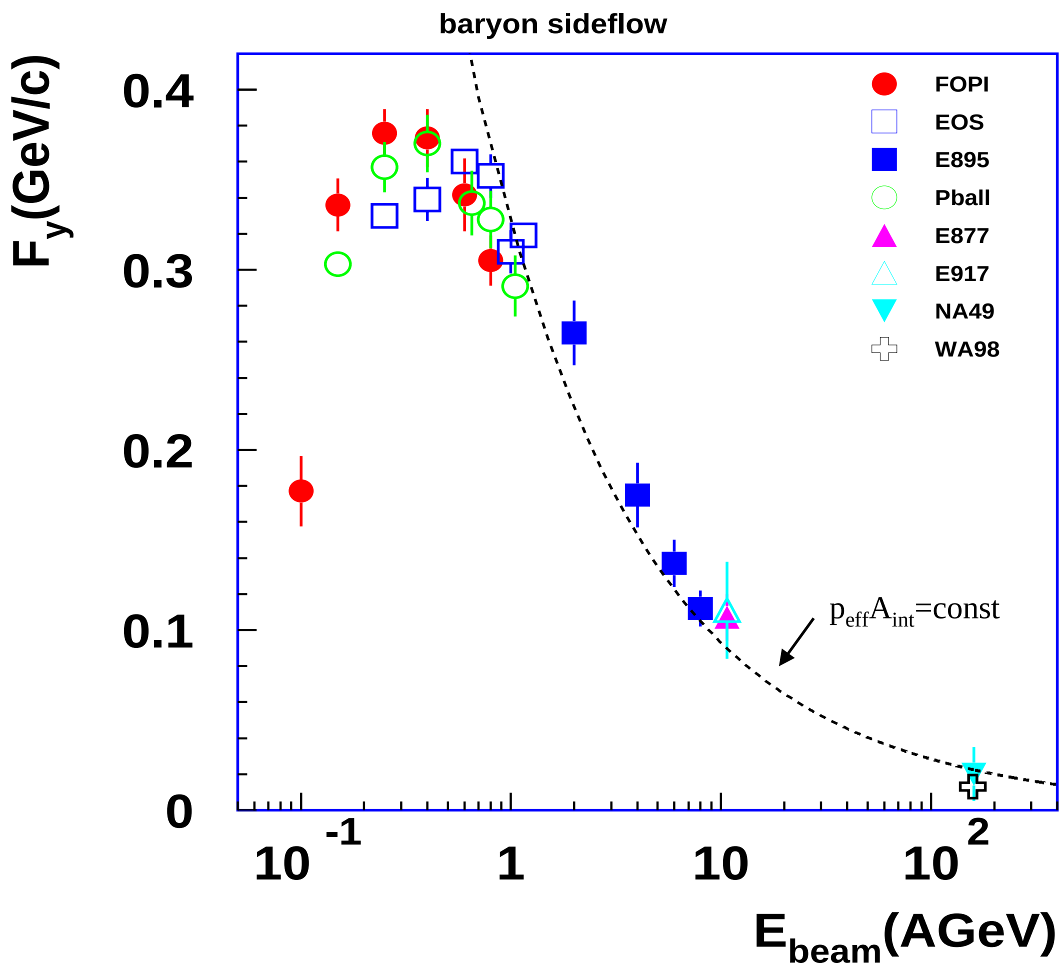
Slope at midrapidity

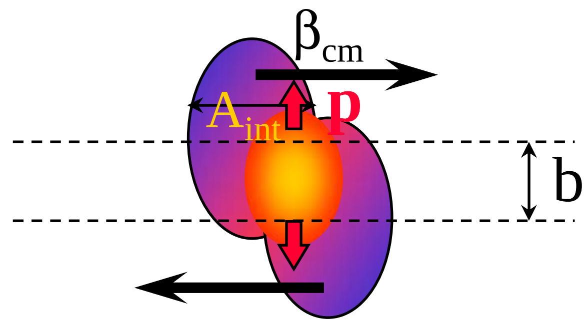
Hydrodynamically scale invariant

W.Reisdorf, H.G.Ritter, Ann.Rev.Nucl.Part.Sci.47,663(1997)

Autocorrelation with reaction plane has to be removed

Sideflow excitation function

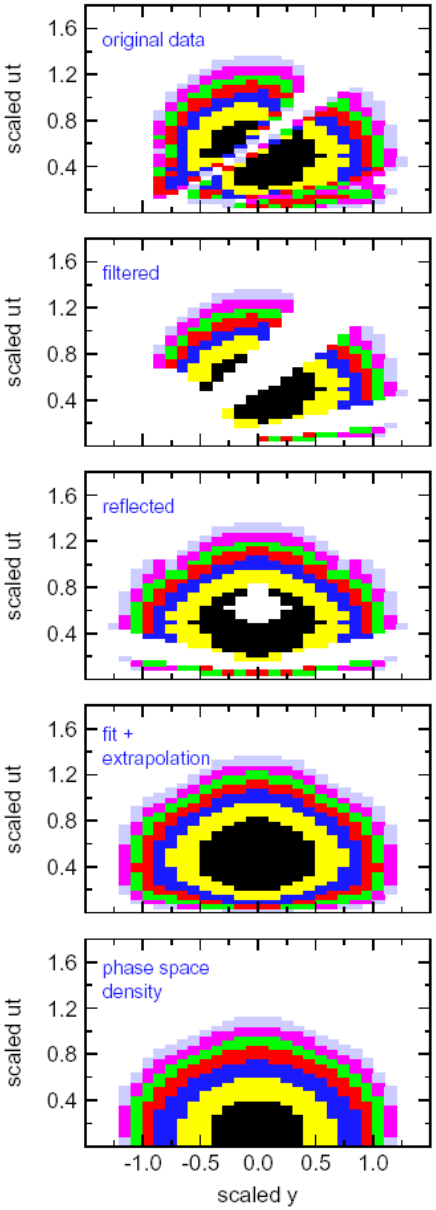




$$F_y \propto \int F dt \approx p_{eff} A_{int} t_{pass}$$

$$t_{pass} = \frac{2R}{\gamma_{CM}} \cdot \frac{1}{\beta_{CM}}$$

Correlation of stopping & flow



original data

filtered

reflected

2-dim fit

phase space density

Stopping

$b/b_{max}<0.15$

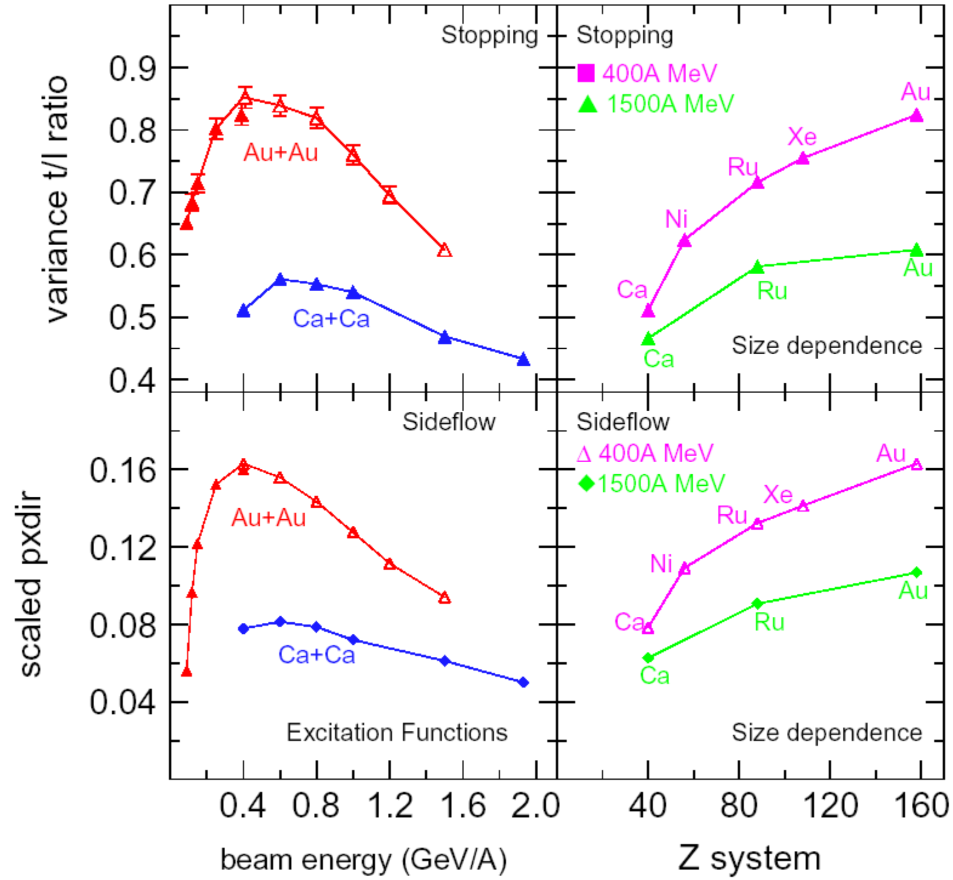
$$\frac{\sigma^2(y_t)}{\sigma^2(y_z)}$$

Sideflow

$b/b_{max}\approx 0.4$

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

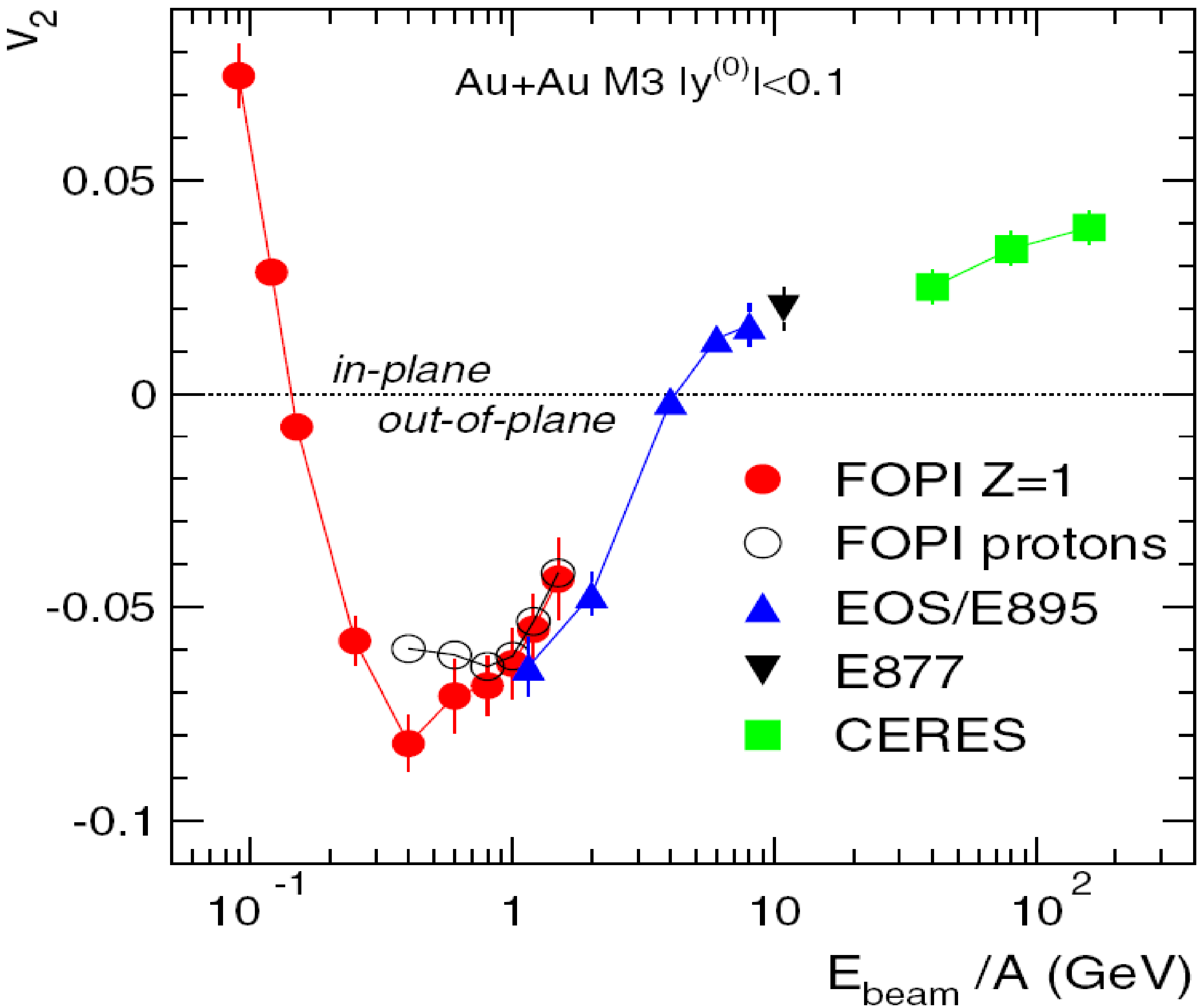
W.Reisdorf et al. (FOPI) PRL 92. 232301 (2004)



Pressure correlates with energy density -> EOS
System size dependence does not show a plateau.

Excitation function for elliptic flow

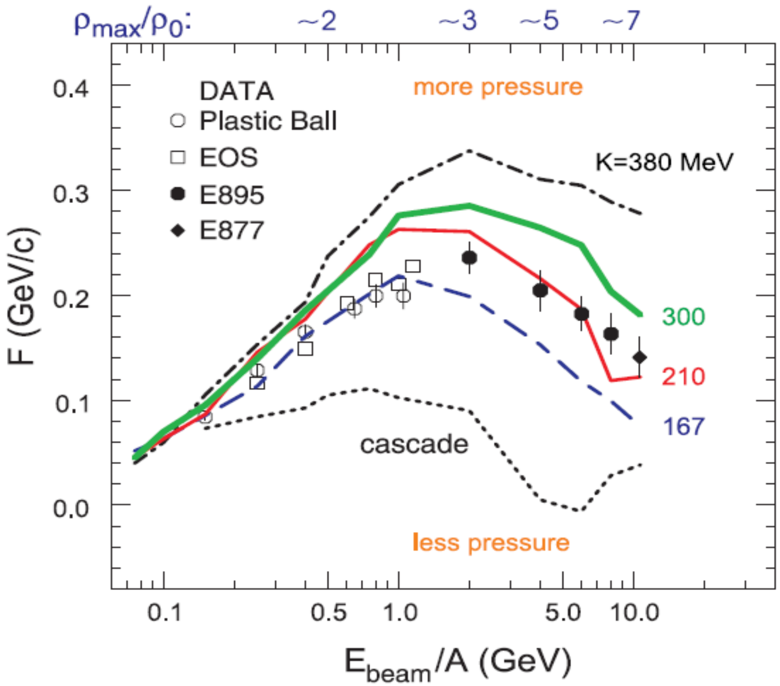
A.Andronic et al. (FOPI), PLB 612, 173 (2005)

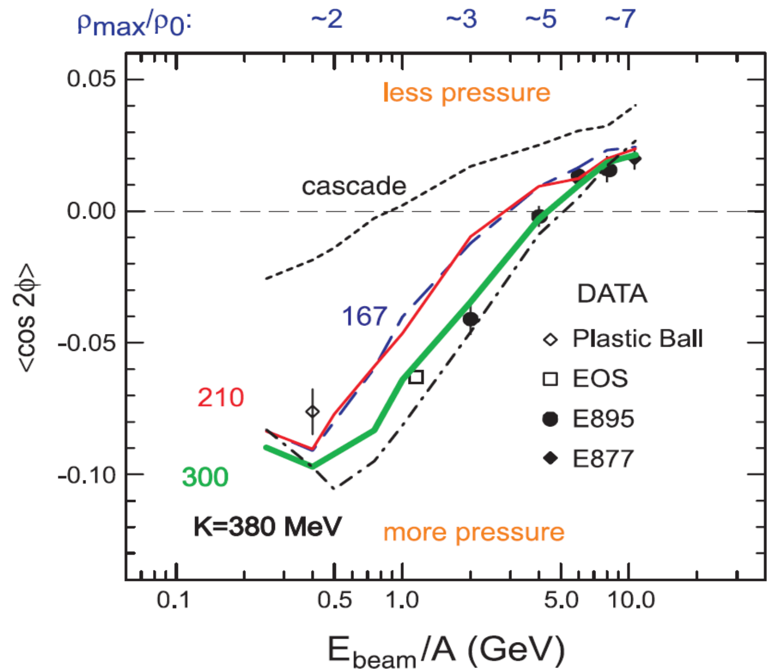


Excitation function of flow variables

$$F = \frac{d\langle p_x / A\rangle}{d(y/y_{cm})}$$

P. Danielewicz et al.
Science 298, 1592 (2002)



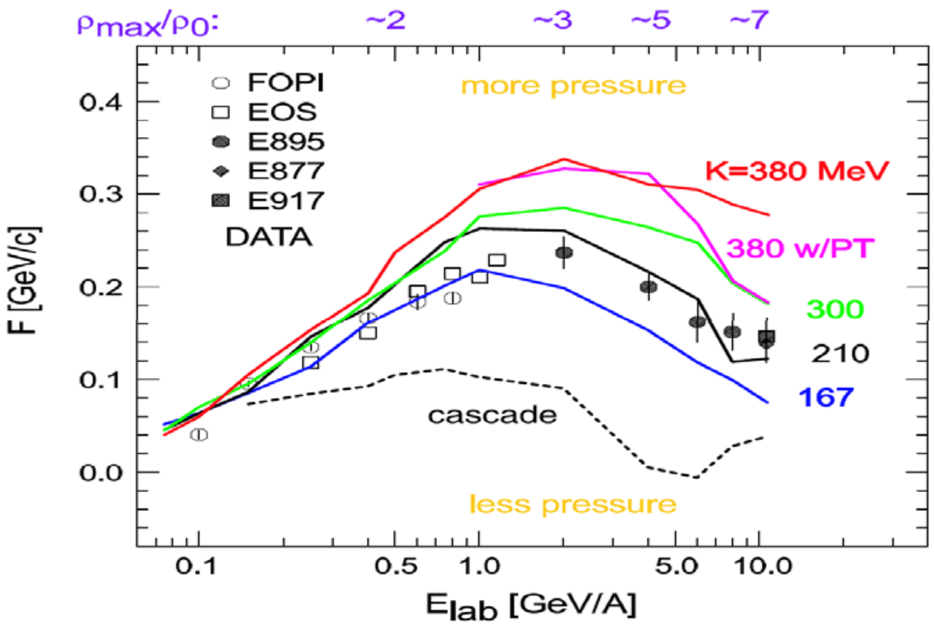


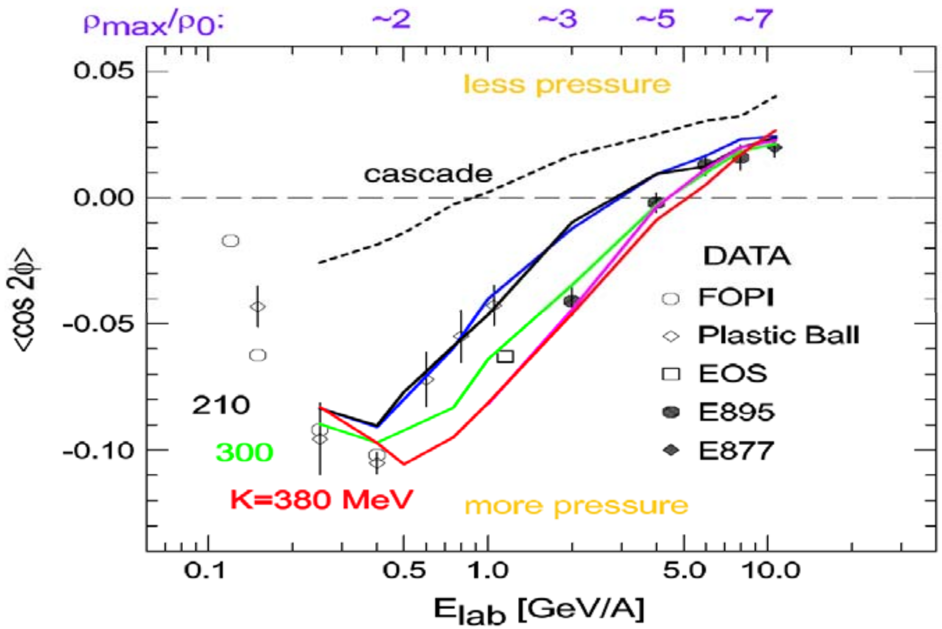
incomplete selection of data

Excitation function of flow variables

P. Danielewicz et al.
nucl-th/0112006 (2001)

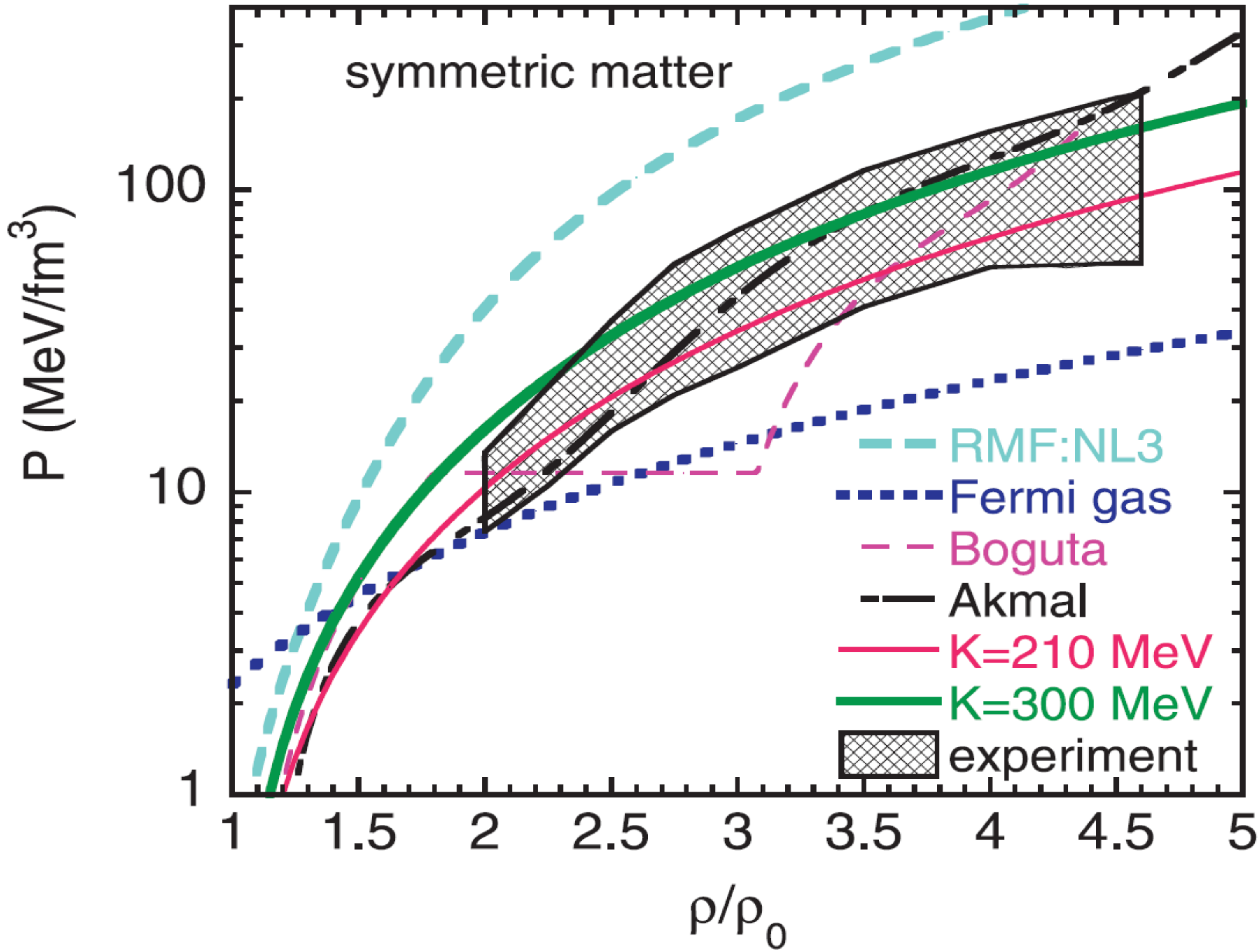
$$F = \frac{d\langle p_x / A\rangle}{d(y/y_{cm})}$$





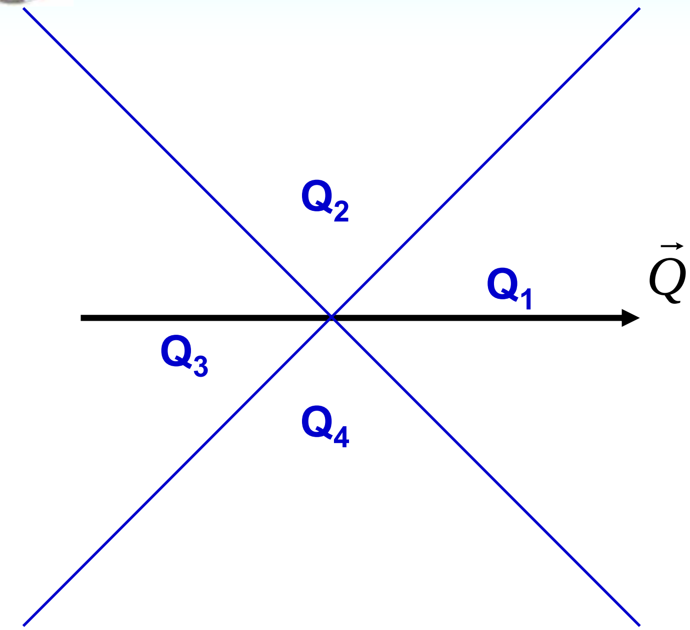
- **Mean field effects clearly visible by difference to 'cascade' calculations.**
- **None of the model calculations describes all the available data.**

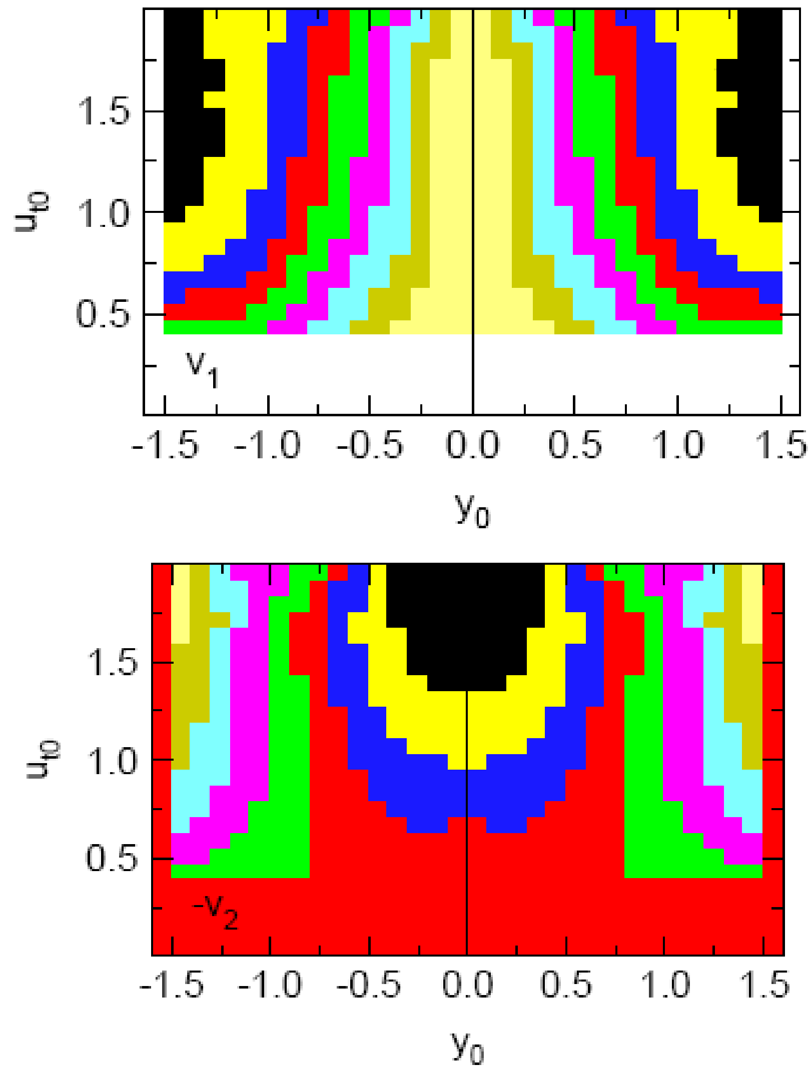
EOS from HI – collisions



Quadrant method

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





Symmetry

Definitions

$$Q_2 = Q_4$$

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

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

Relation to Fourier coefficients

$$\frac{Q_1 - Q_3}{Q_0} = \frac{2\sqrt{2}}{\pi} v_1$$

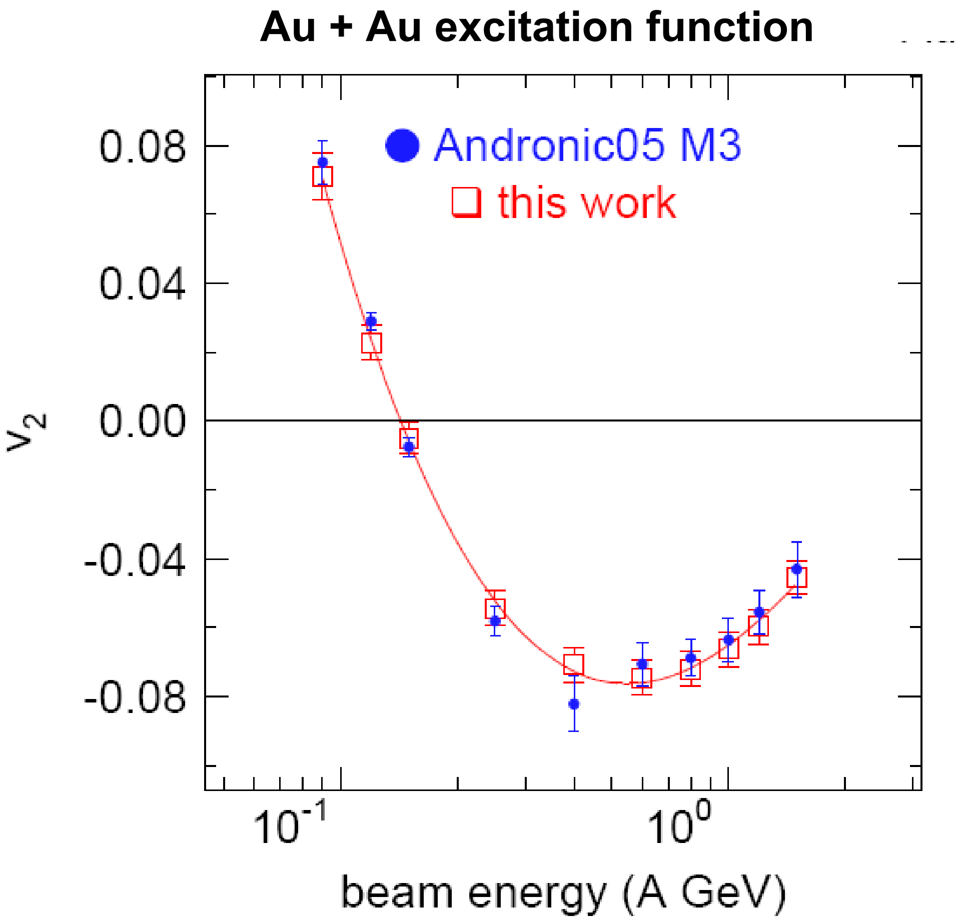
$$\frac{Q_{24}}{Q_0} - \frac{1}{2} = -\frac{2}{\pi} v_2$$

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

$_0$- normalisation to CMS quantities

Quadrant method

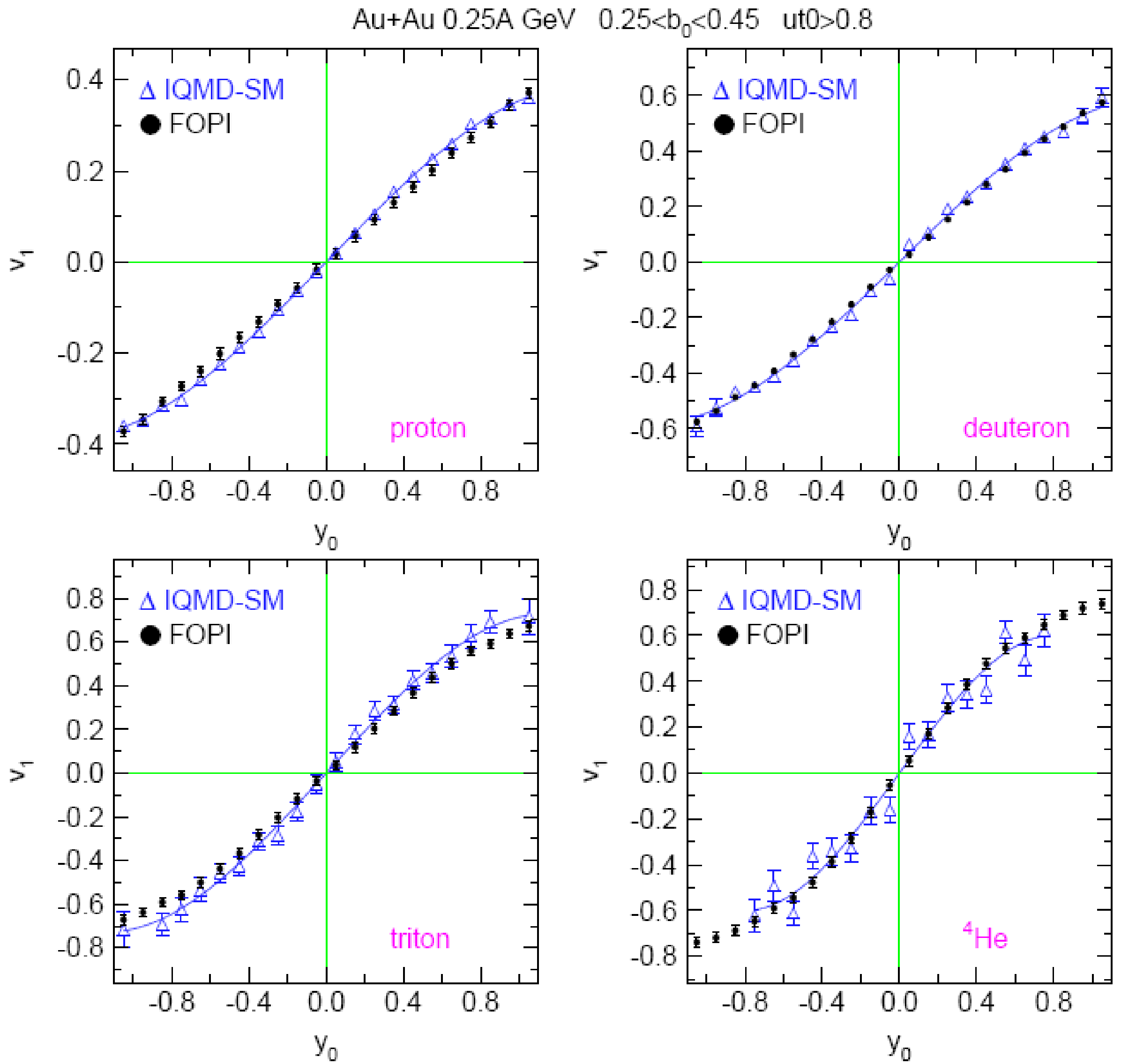
W. Reisdorf et al. (FOPI), NPA, 2012



Analyzed data:

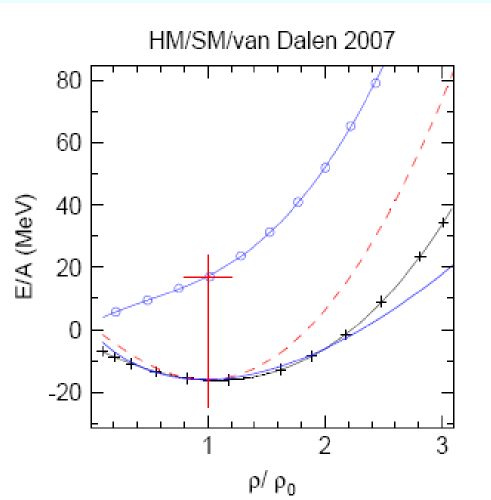
System	Energies (AGeV)
^{40}Ca+^{40}Ca	0.4, 0.,6 0.8,1.0, 1.5, 1.93
^{58}Ni+^{58}Ni	0.15,0.25
^{129}Xe+CsI	0.15, 0.25
^{96}Ru+^{96}Ru	0.4, 1.0, 1.5
^{96}Zr+^{96}Zr	0.4, 1.5
^{197}Au+^{197}Au	0.09, 0.12, 0.15, 0.25, 0.4, 0.6, 0.8, 1.0, 1.2, 1.5

Comparison to IQMD at 0.25 AGeV

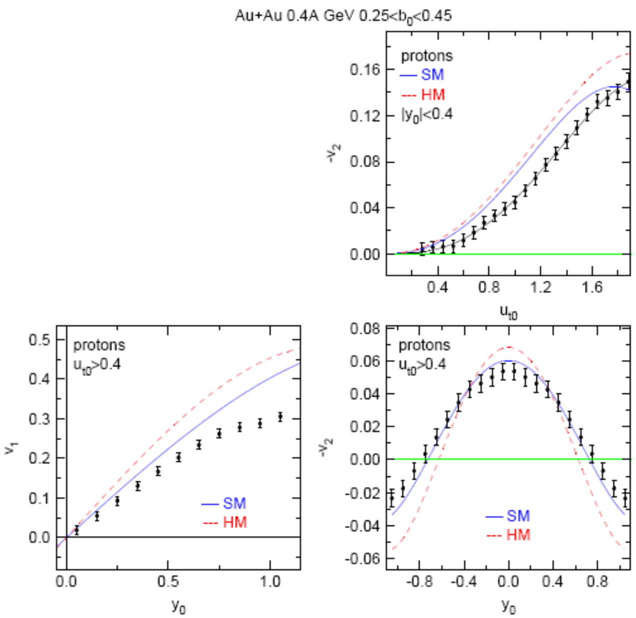


Comparison to IQMD at 0.4 AGeV

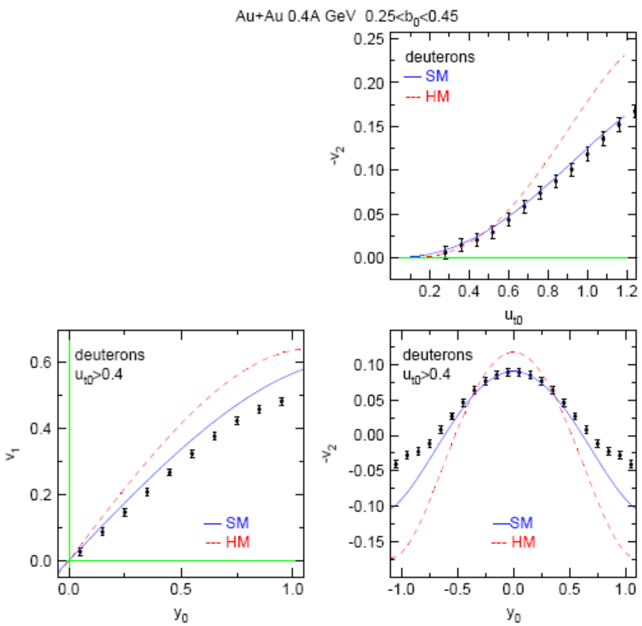
Equation – of – state



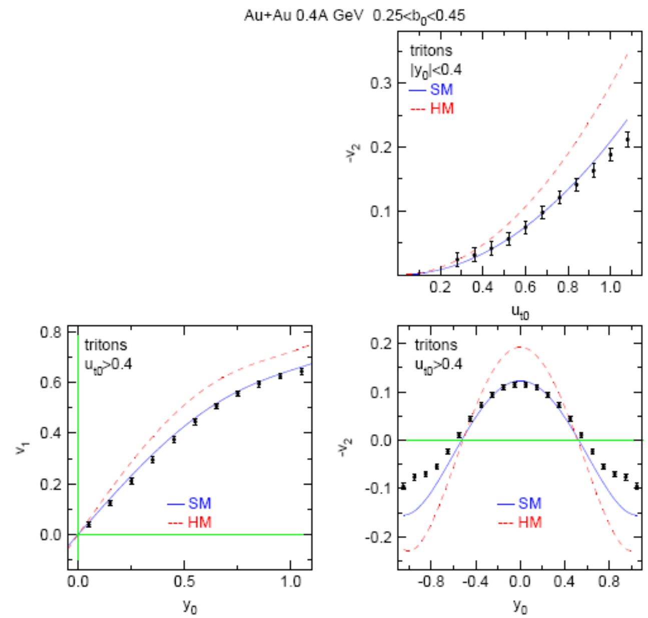
protons



deuterons

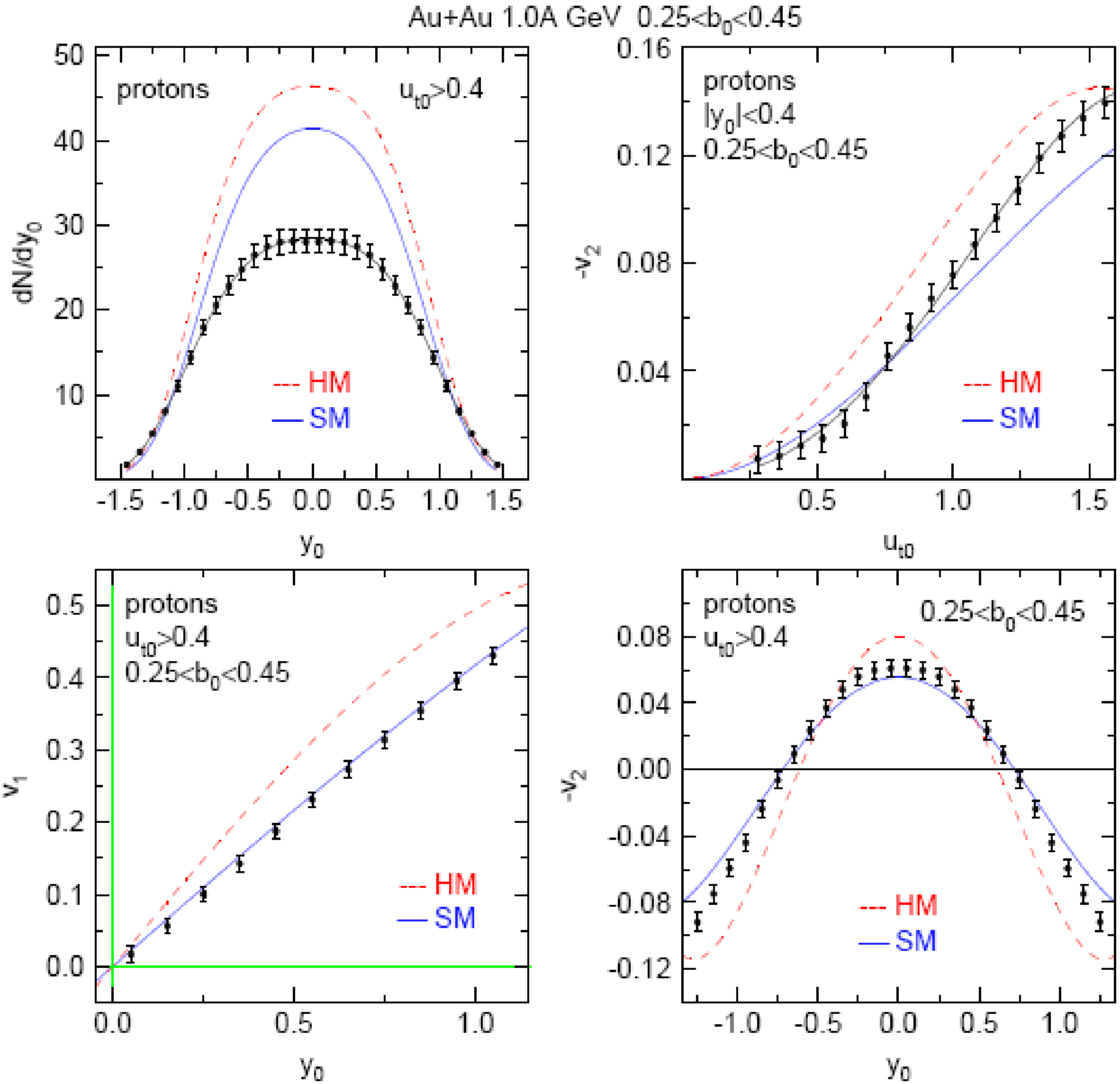


tritons



Model comparison at 1 AGeV

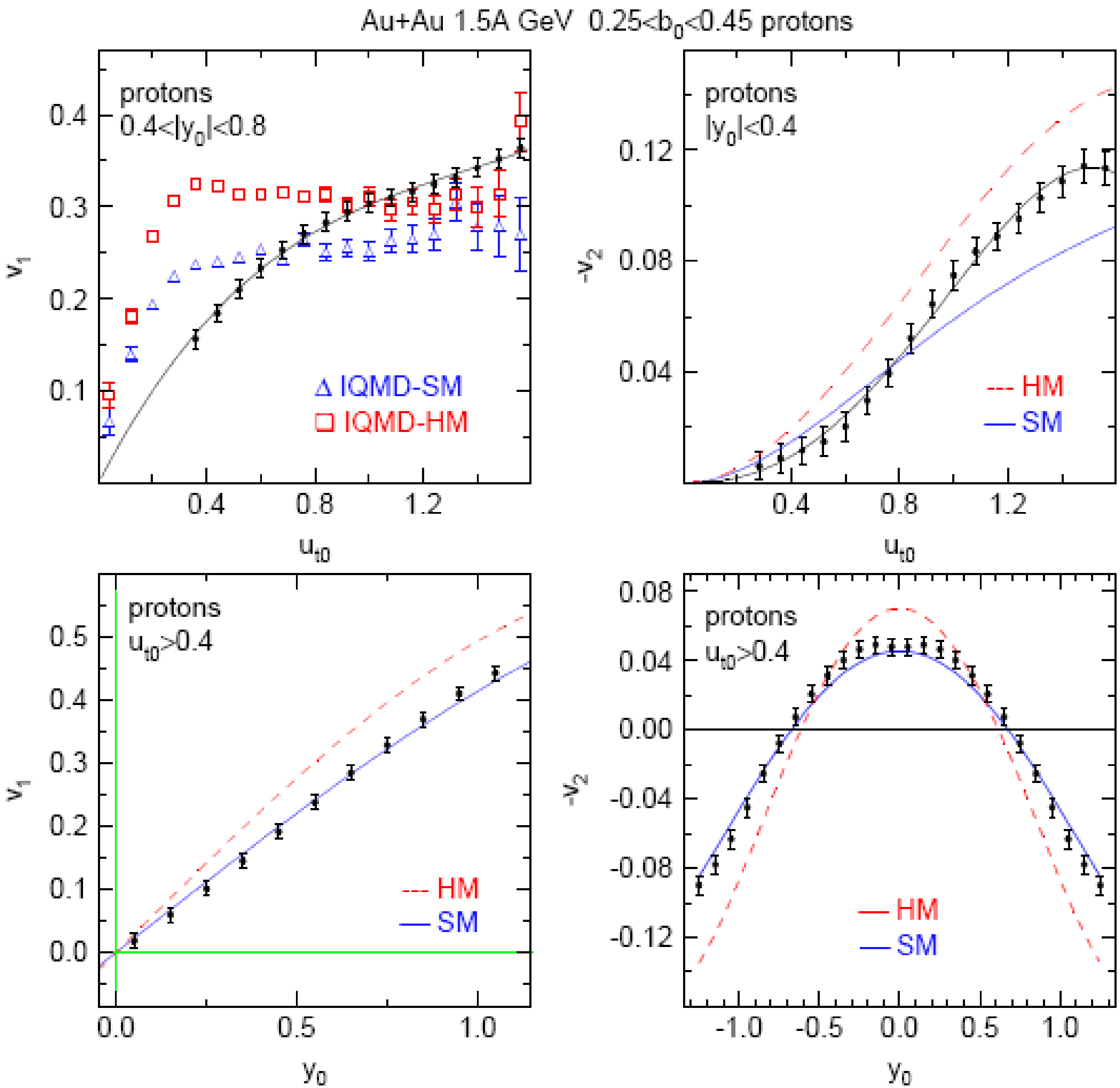
W. Reisdorf et al. (FOPI), NPA, 2012



Proton yield overestimated,

Preference for EOS with SM

Model comparison at 1.5 AGeV



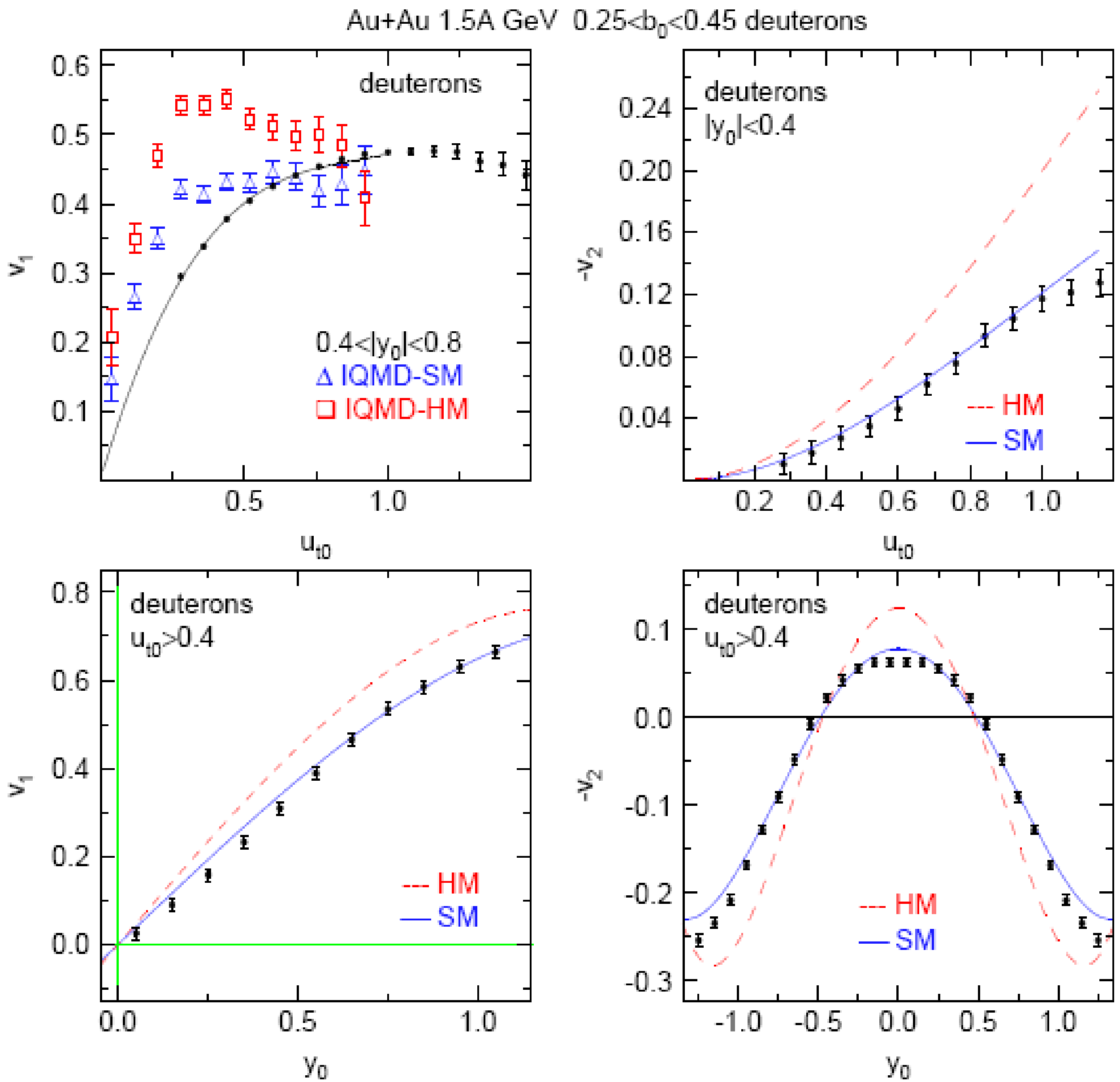
W. Reisdorf et al. (FOPI), 2012

No perfect agreement,

preference for EOS with SM

Model comparison at 1.5 AGeV

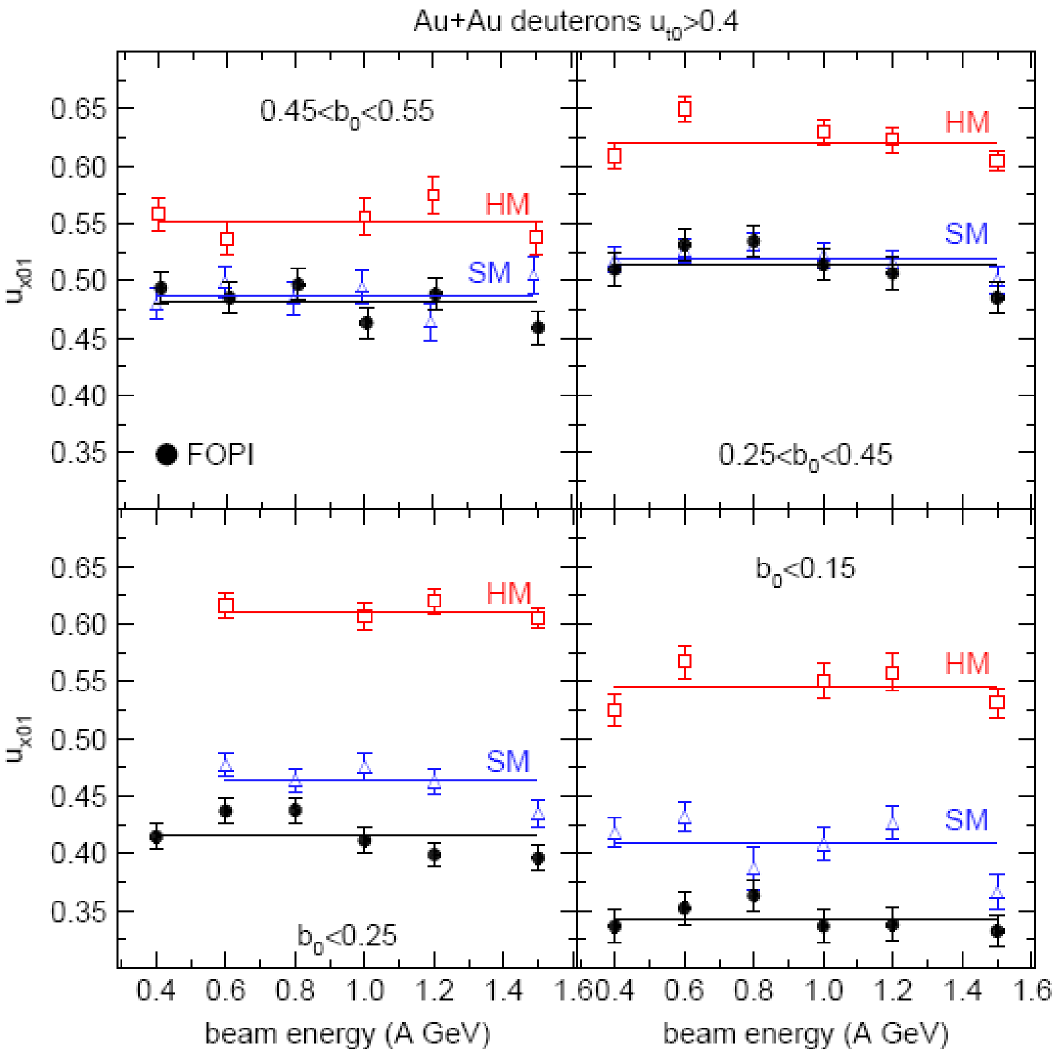
W. Reisdorf et al. (FOPI), 2012



No perfect agreement,

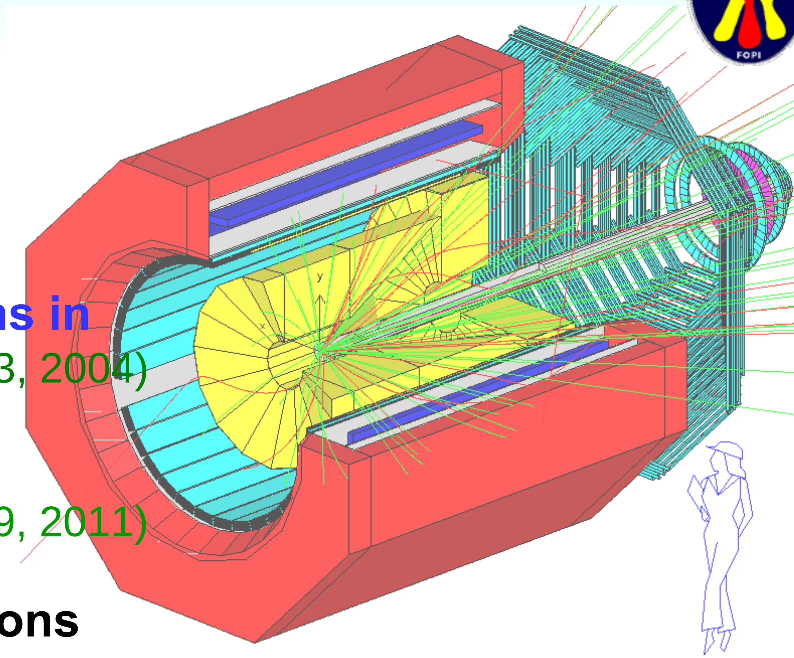
preference for EOS with SM

IQMD - model comparison of midrapidity slopes



Preference for EOS with SM

Experimental strangeness program of FOPI @ SIS18



Reference data from elementary reactions

K^0 , Λ production and phase space distributions in

π^- + C, Al, Cu, Sn, Pb @ 1.15 GeV/c, (S273, 2004)

K^0 , K^+, K^-, ϕ, Λ production in

π^- + LH_2, C, Pb @ 1.7 GeV/c, (S339, 2011)

Systematics of strangeness data from heavy-ion reactions

K^0 , K^+, K^-, ϕ, K^*, Λ, $\Sigma^*(1385)$ production and kaon flow

Search for kaonic bound states

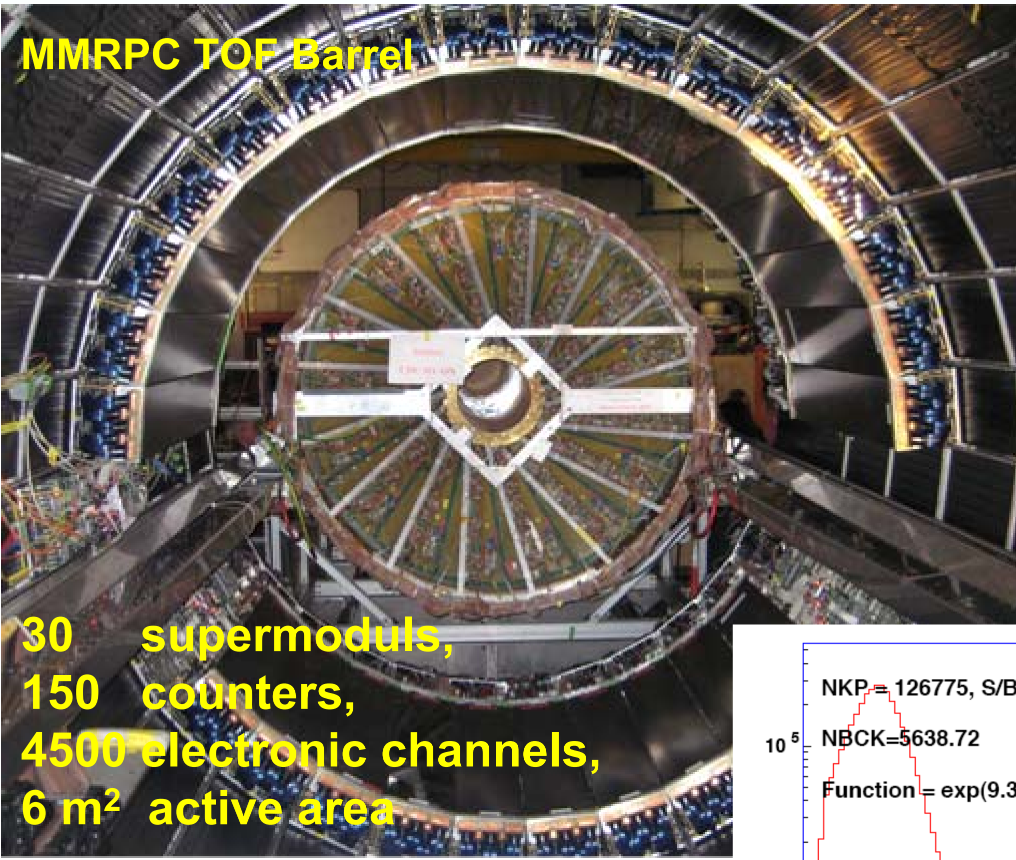
System	beam energy	events	(proposal, year)
Ni + Ni	1.93 AGeV,	100M	(S261, 2003)
Al + Al	1.91 AGeV,	200M	(S297, 2005)
Ni + Ni	1.91 AGeV,	80M	(S325, 2008)
Ni + Pb	1.91 AGeV,	100M	(S338, 2009)
Ru+ Ru	1.7 AGeV,	210M	(S338, 2009)

Search for exotica in elementary reaction

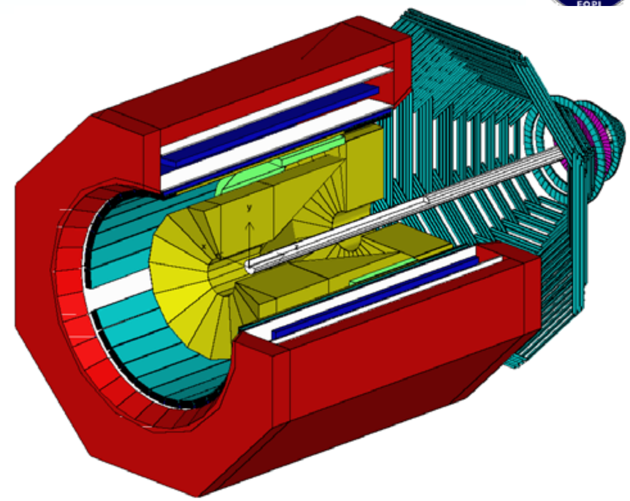
existence of ppK^- - bound state

p + p	3 GeV,	80M	(S349, 2009)

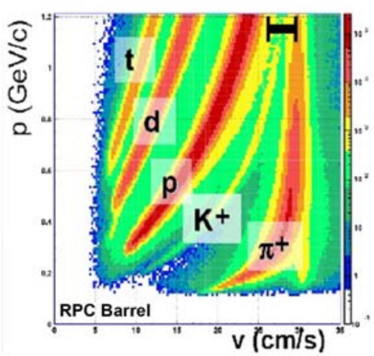
FOPI III (2007 – 2010) with improved PID

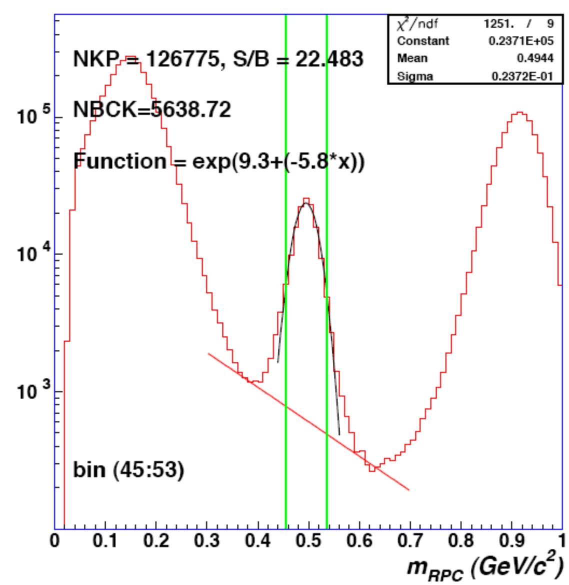


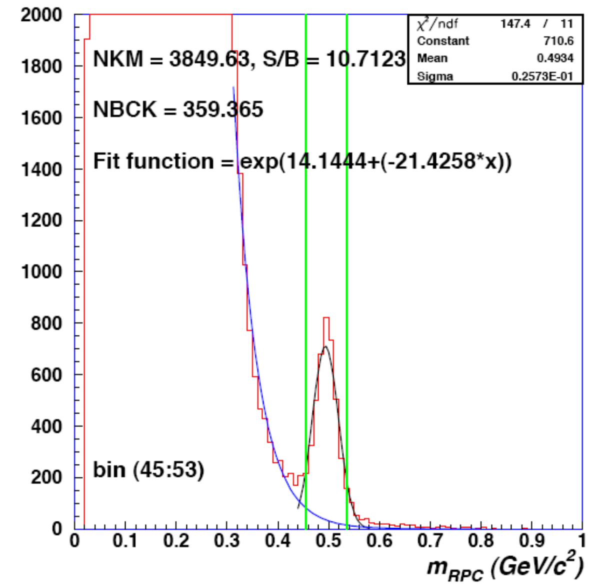
Performance:
σ_{system} ~ 88 ps
σ_{RPC} ~ 67 ps



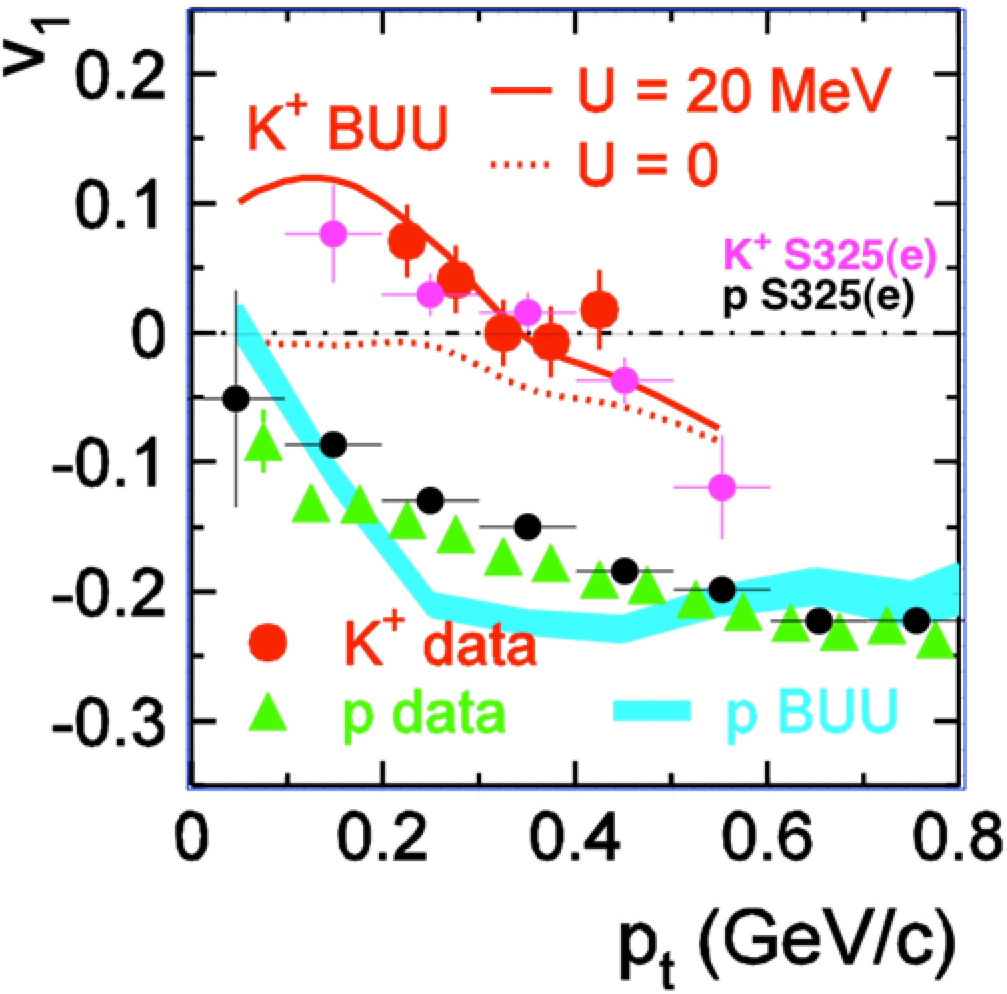
kaon identification







Differential sideflow of K^+ in central collisions



New data are consistent with earlier data in range $-1.2 < y^{(0)} < -0.65$, σ_{geo}=200mb

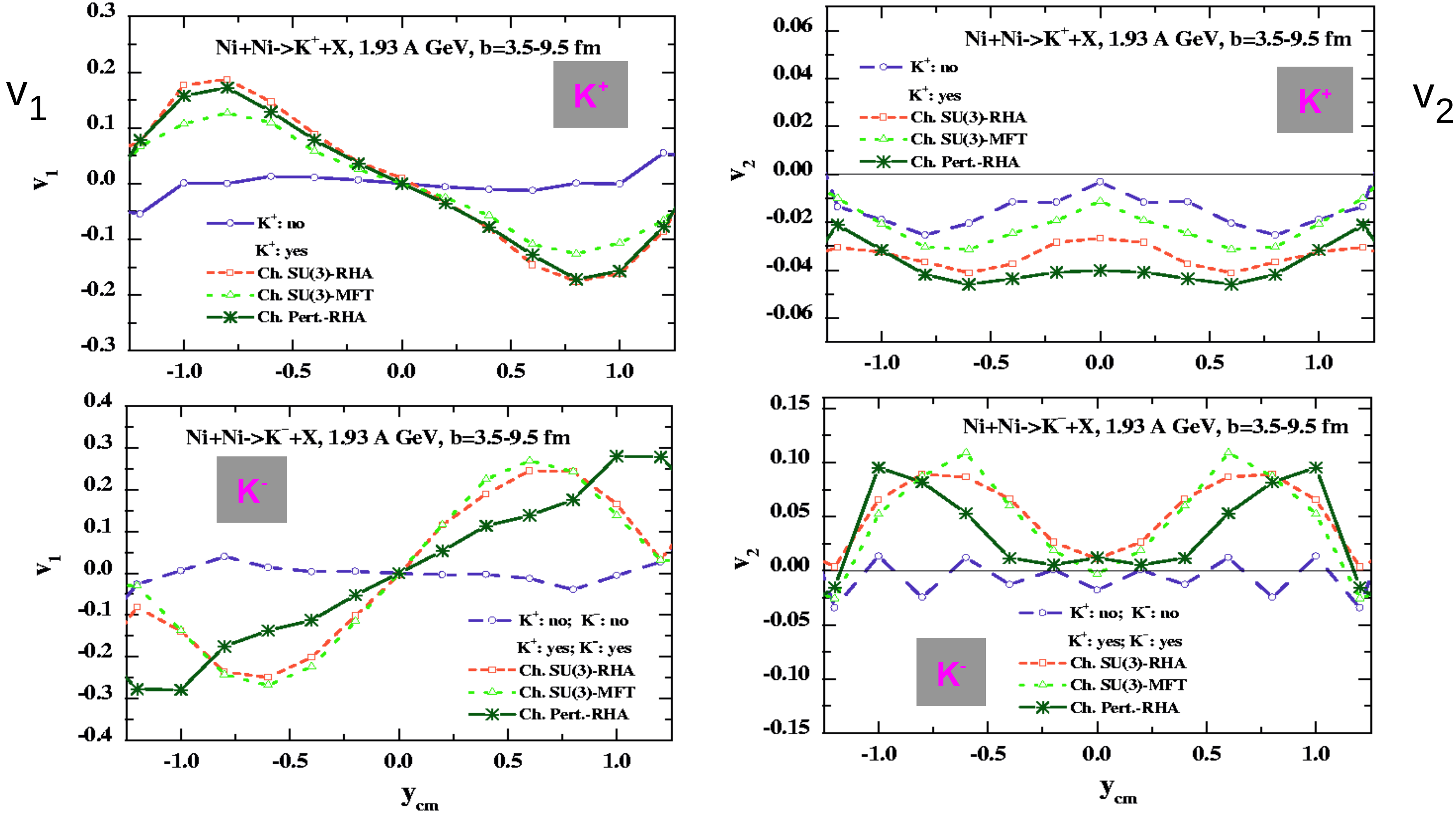
P.Crochet et al., PLB 486, 6 (2000)

Conclusion:

Data favor the presence of repulsive potential $U(\rho=\rho_0)$ = 20 MeV

Predictions of transport model

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



Large asymmetries are predicted for semi-peripheral collisions …

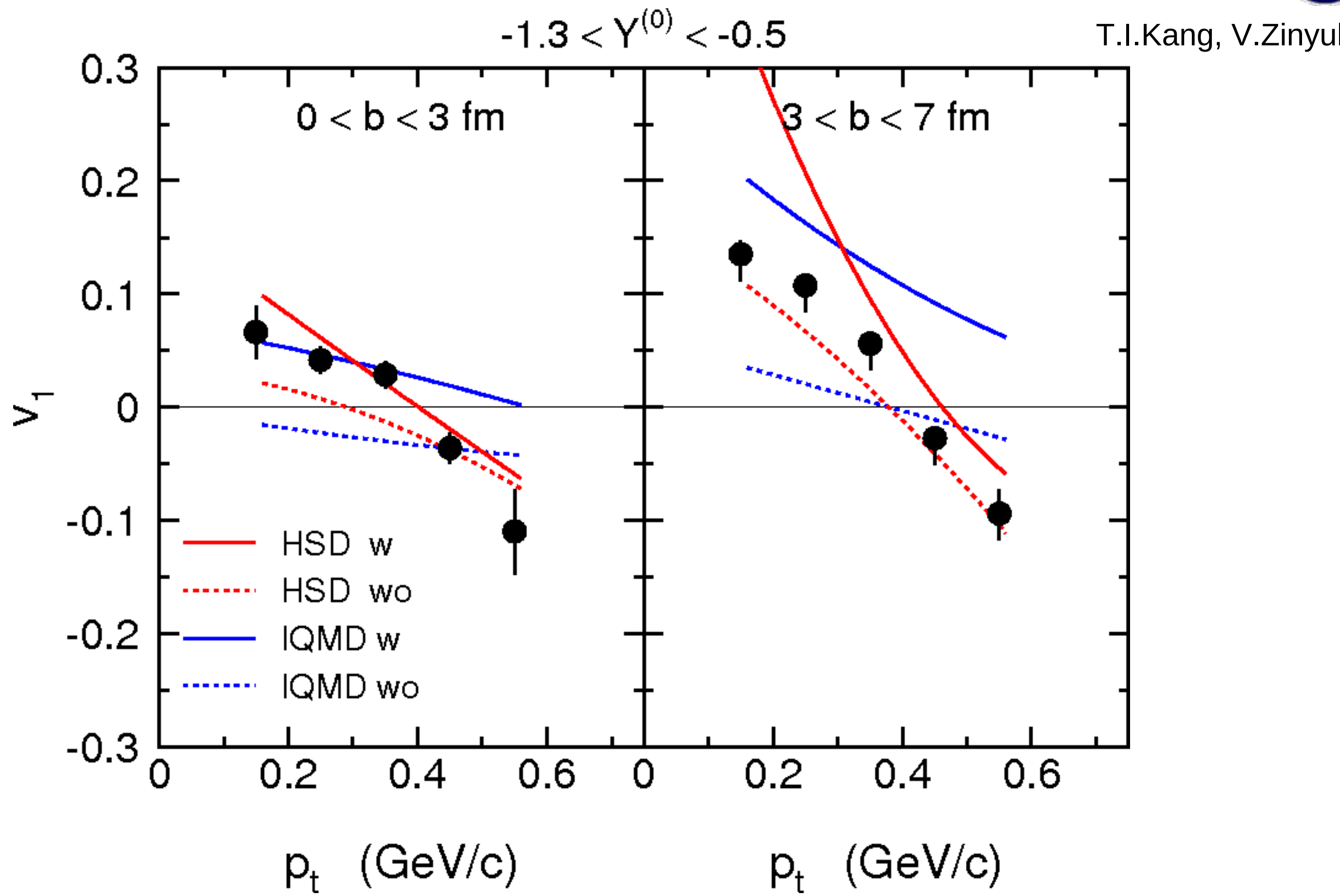
Differential flow of K^+ - mesons

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.

Flow of charged kaons

T.I.Kang, V.Zinyuk

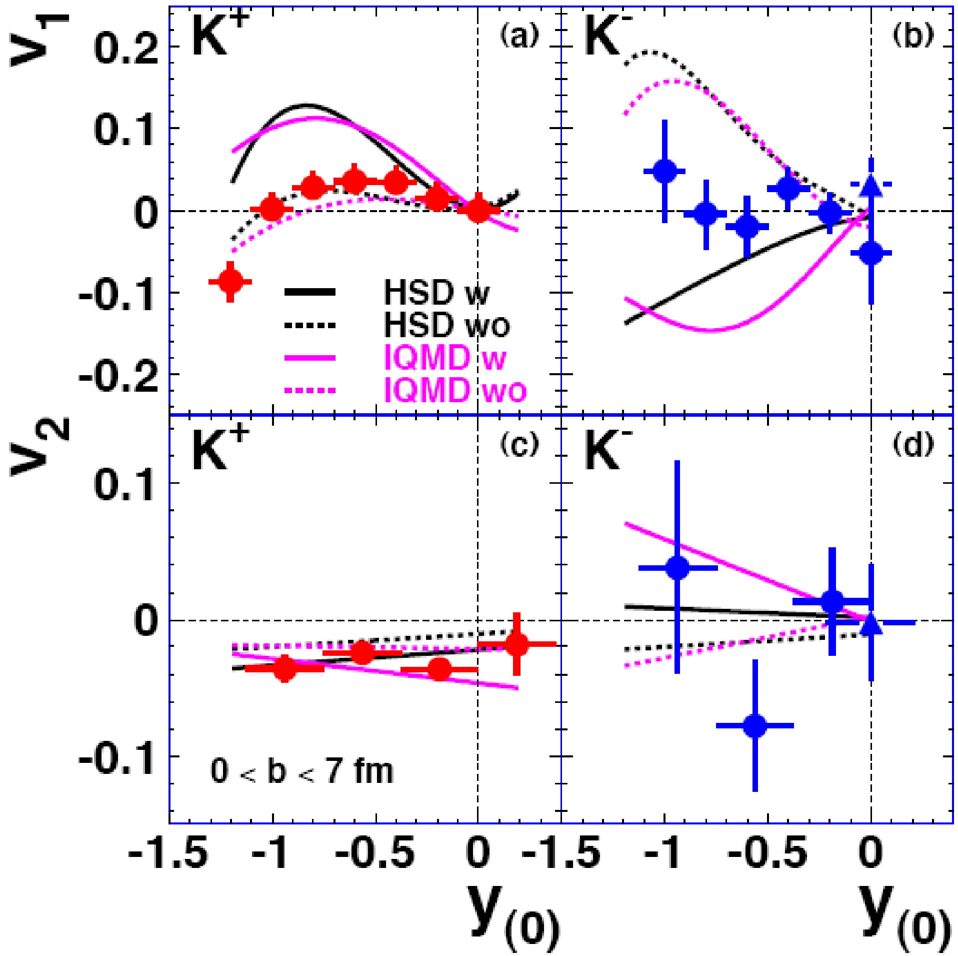
Ni+Ni at 1.91 AGeV
(S325 + S325e data)
σ = 1.5 b
b_{geo}= 7 fm

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^+ sideflow much smaller than expectation from model calculations.
K^- sideflow compatible with zero, in variance with model expectiations.
K^+ - elliptic flow negativ $\longrightarrow$ out of plane emission.
K^- - elliptic flow consistent with zero.

Summary / Conclusion

Collective flow is sensitive to pressure,
Necessary ingredient to extract equation-of-state and in-medium potentials.

Errors dominated by systematic uncertainties.

Large dataset exists for baryon and pion flow
that awaits description by theoretical transport model.

Comparison to IQMD model calculations shows preference for soft EOS (SM).

Current analysis status of ‘flow’ of strange particles.

- **First measurement of K^- - sideflow,**
  first measurement of K^+ - flow for semi peripheral reactions,

  Results are in variance with theoretical expectations.

Systematic measurements (system size and incident energy dependence)
and consistent analysis are needed to extract the underlying physics!

bmb+f - Förderschwerpunkt
Hadronen - und Kernphysik
Großgeräte der physikalischen Grundlagenforschung