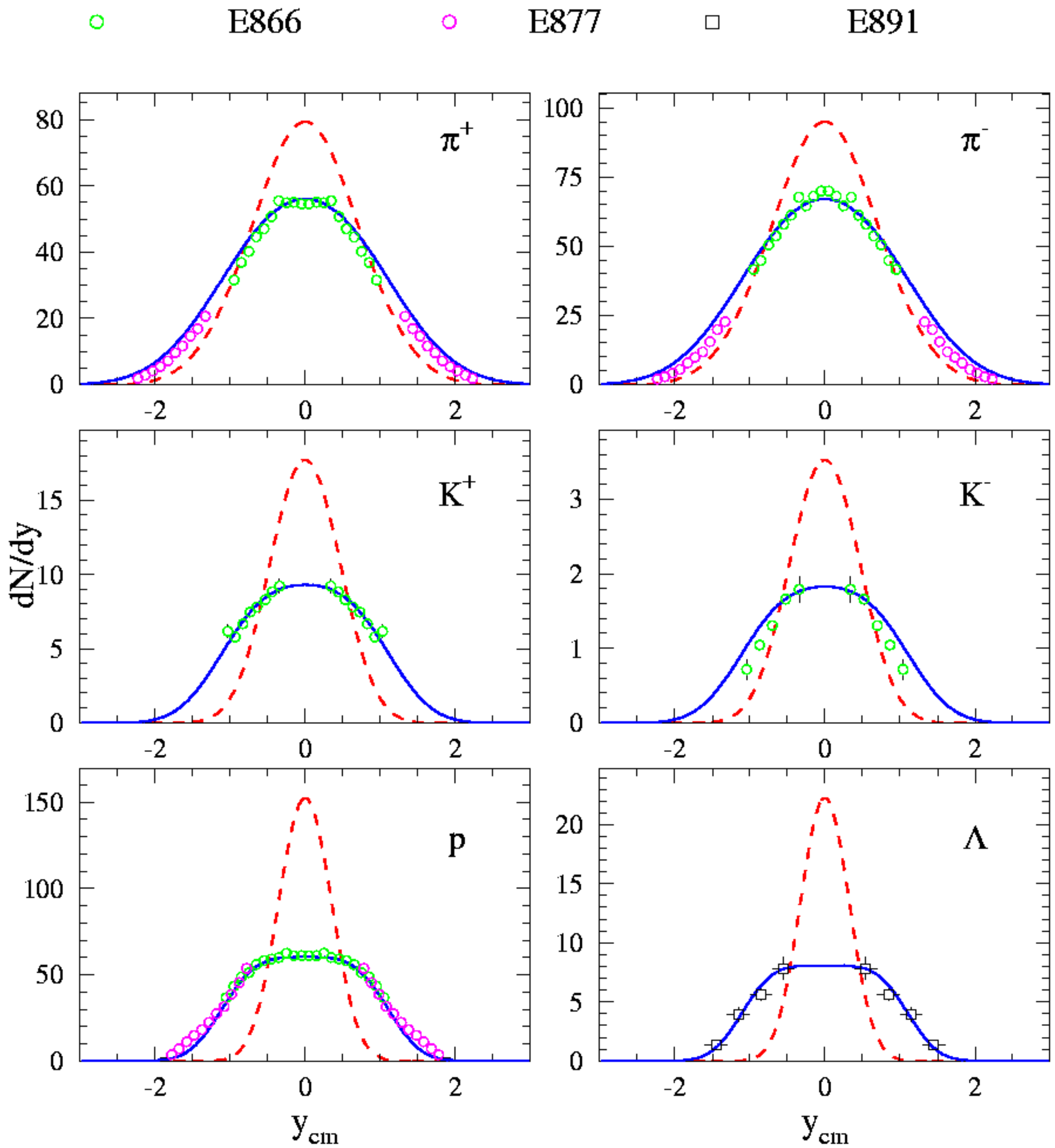
Stopping



AGS: Au + Au @ 10.7 AGeV

Rapidity density distributions Incompatible with isotropic thermal source

↓

Longitudinal expansion.

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

Thermal width of rapidity distribution

Width of isotropic thermal source can be calculated analytically:

$$\frac{dN_{isotropic}}{dy} \propto m^2 T\left(1+2\chi+2\chi^2\right)\exp(-1/\chi),$$

$$\chi = \frac{T}{m\cosh(y)}$$

T can be (has to be) extracted from slopes of thermal spectra at midrapidity.

Measured distributions are at variance with isotropic thermal emission picture.

Possible scenario: longitudinally expanding source(s) with source velocities β_l

$$\langle \beta_l \rangle = \tanh(\langle y' \rangle)$$

$$\frac{dN}{dy} = \int_{-y'_{\max}}^{y'_{\max}} dy' \frac{dN_{iso}(y-y')}{dy'}$$

Stopping

Average rapidity loss:

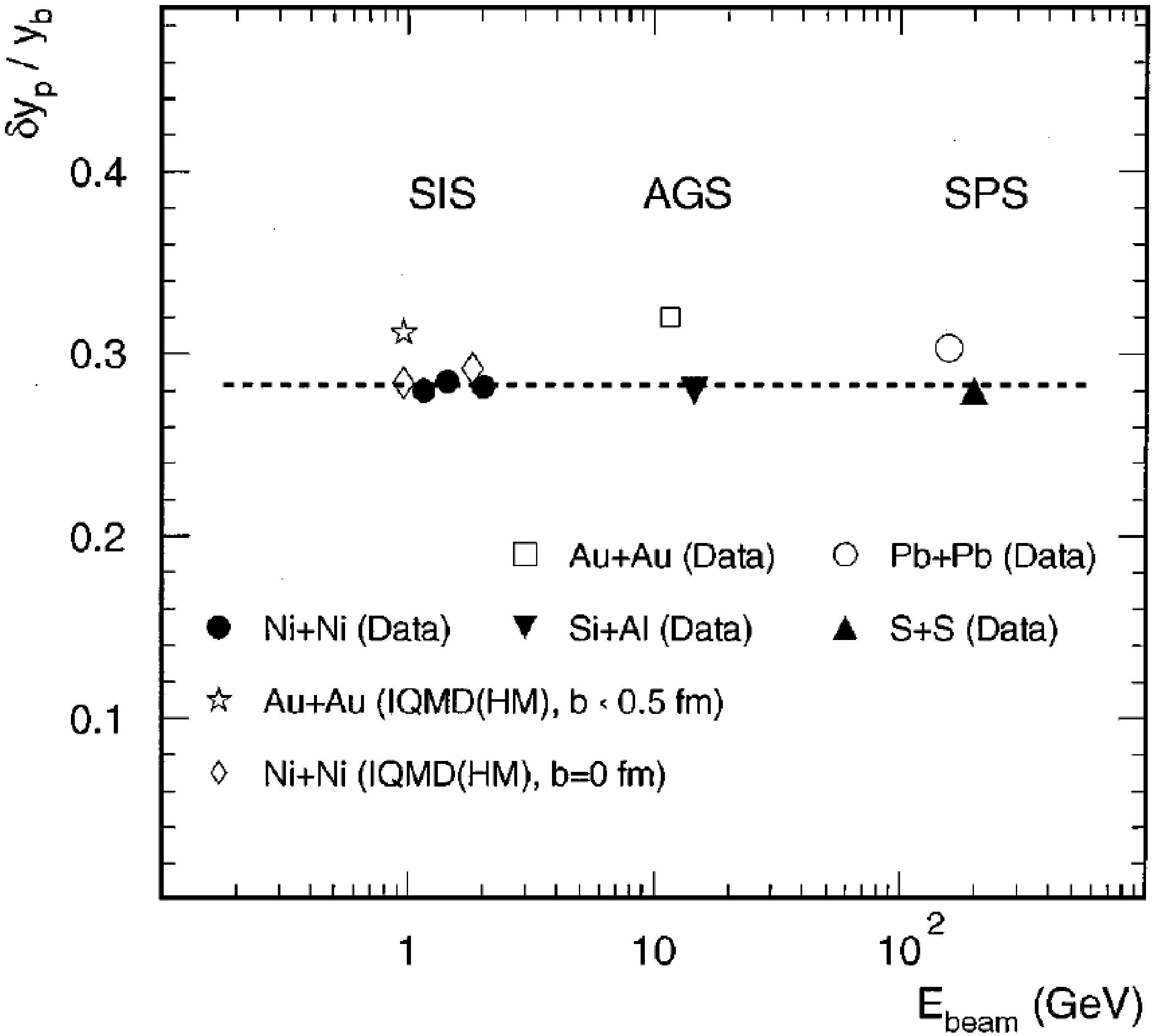
$$\left\langle \delta y_p \right\rangle = y_p - \left\langle y_b \right\rangle$$

$\langle y_p \rangle$ - average net baryon rapidity after the collision

$$\left\langle \delta y_p \right\rangle = \frac{\int_{-\infty}^{0} \left| y_p - y_{t(b)} \right| \left(dN_p / dy \right) dy}{\int_{-\infty}^{\infty} \left(dN_p / dy \right) dy}$$

5.4

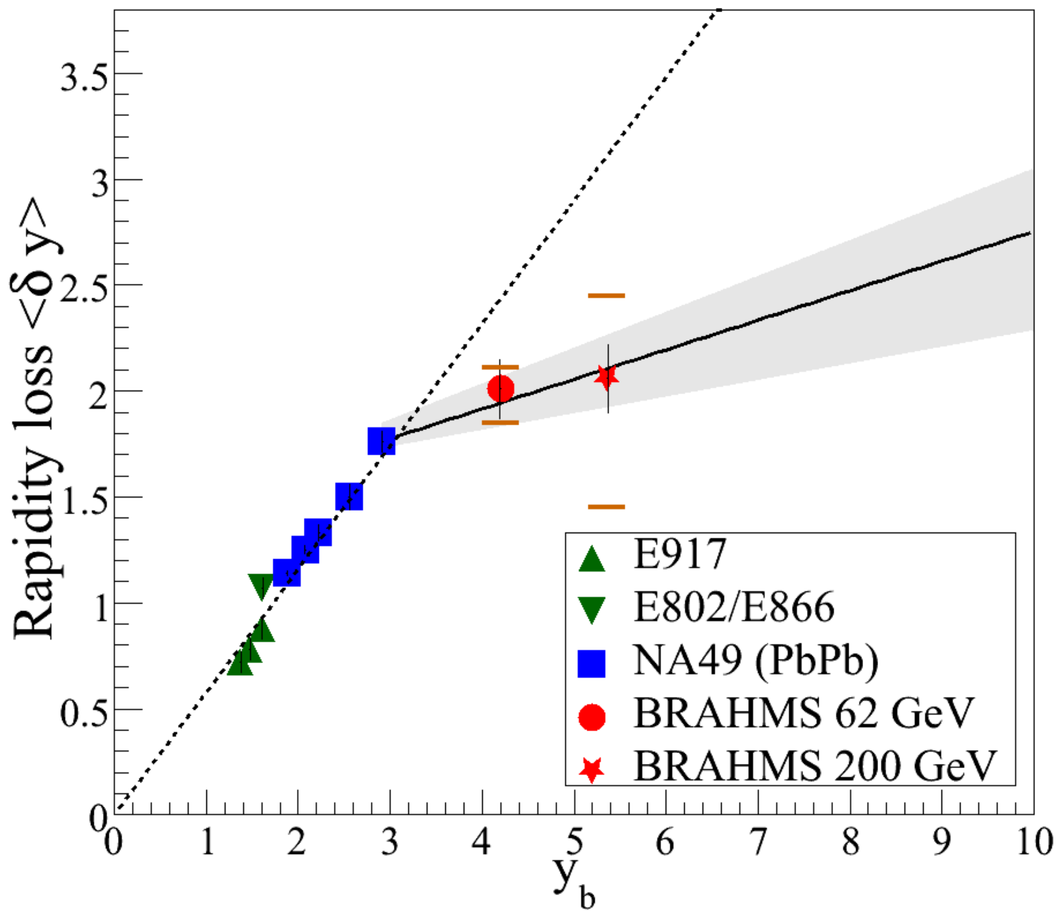
Excitation function of stopping



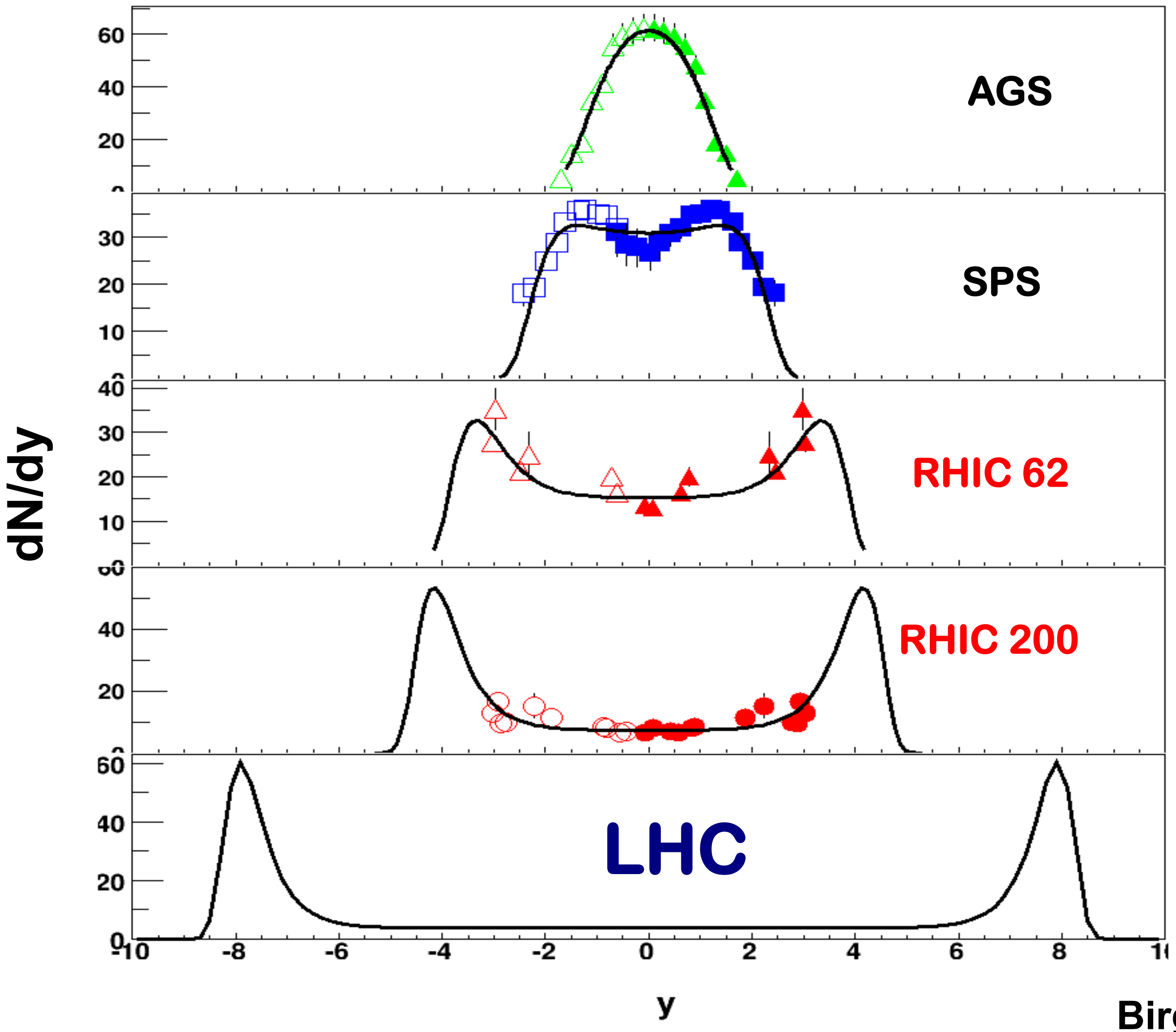
N.Herrmann, J.P. Wessels, T.Wienold, Ann.Rev.Nucl.Part. Sci.49,581 (1999)

5.4

Brahms – rapidity loss



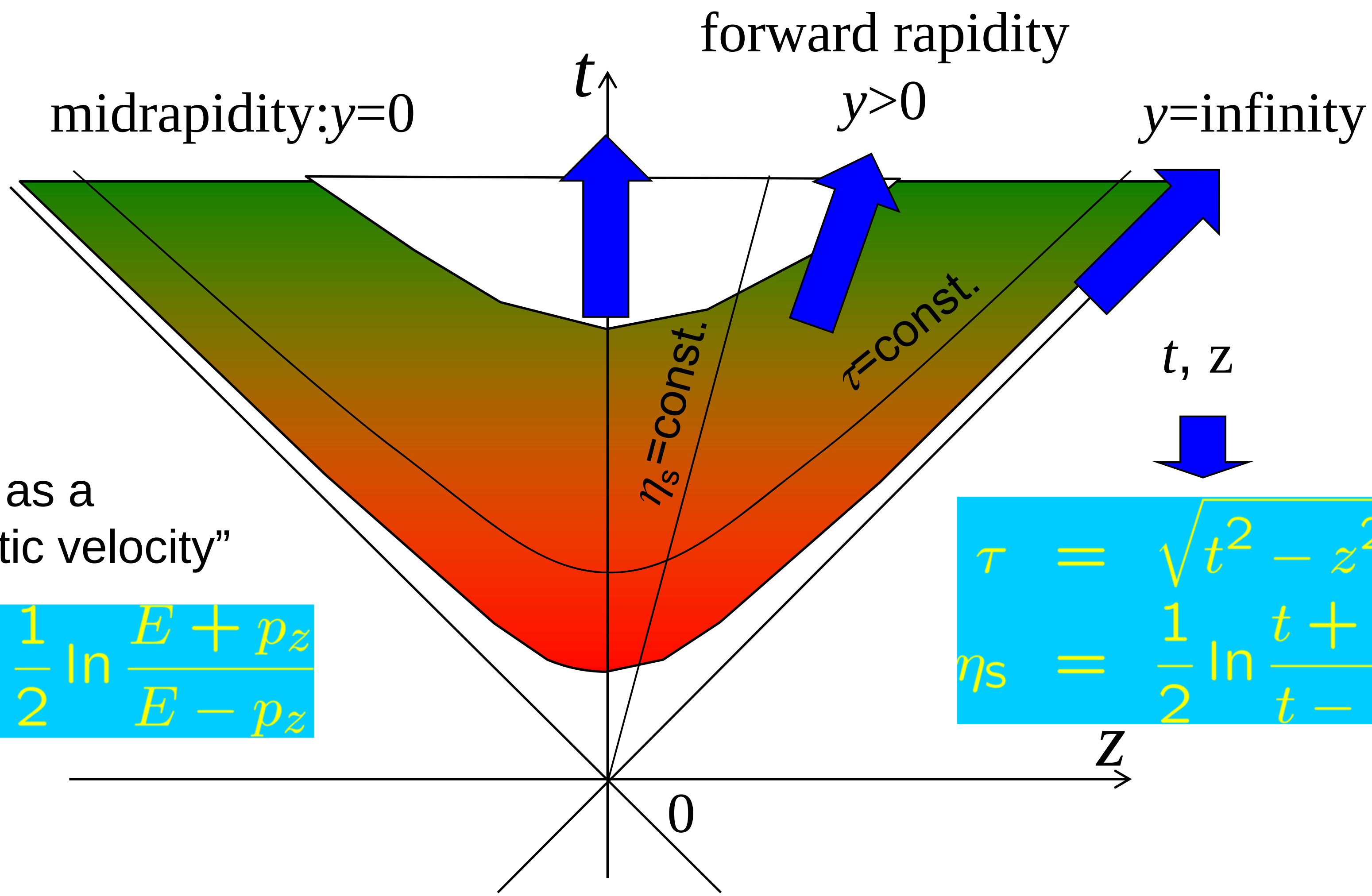
Evolution of rapidity distribution of protons



Birger Back/Phobos

5.2.2

Rapidity and Boost invariant expansion



Rapidity as a "relativistic velocity"

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

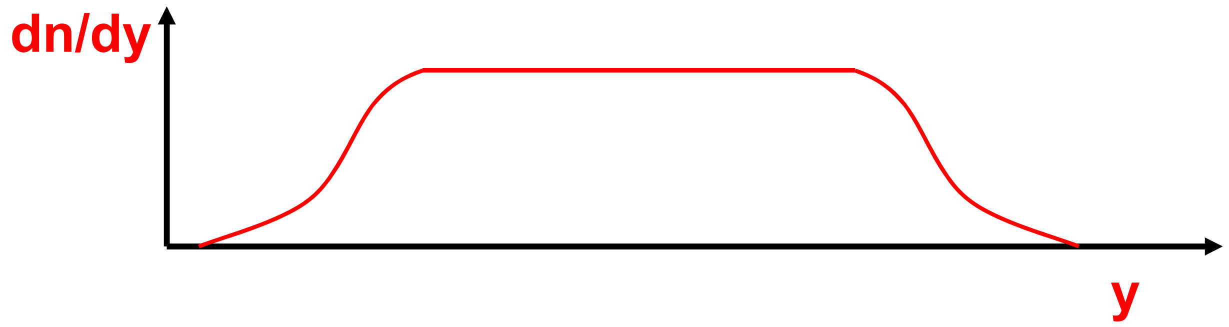
$$\tau = \sqrt{t^2 - z^2}$$
$$\eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$$

Boost invariant ansatz Bjorken ('83)

→ Dynamics depends on τ, not on η_s.

Bjorken Scaling

Bjorken Ansatz: "…… at sufficient high energy there is a 'central-plateau' structure for the particle production as a function of the rapidity variable."



Physics must be invariant under Lorentz-boost:

1) Local thermodynamic quantity must be a function of proper time $\tau = \sqrt{t^2 - z^2}$ only.

2) Longitudinal velocity

$v_z = z/t$ or $y = 0.5 \ln((t+z)/(t-z))$

Bjorken Energy Density

Energy density $\varepsilon = \dfrac{E \times \Delta N}{A \times \Delta z}$

E → average energy per particle
A → transverse area of the collision volume
Δz → longitudinal interval
ΔN → number of particles in Δz interval

$v_z = z/t = \tanh y$; $z = \tau \sinh y$
$\Delta z = \tau \cosh y \, \Delta y$
$E = m_T \cosh y$

$$\varepsilon = \frac{m_T \cosh y \, \Delta N}{A \, \tau \cosh y \, \Delta y} \rightarrow \frac{m_T \, dn/dy}{A\tau}$$

5.2.2

Energy and Baryon density density

Assumption: Bjorken expansion (homologous 1 +1 D expansion)

Estimate of energy density

J.D. Bjorken, PRD 27,140 (1983)

$$\varepsilon = \frac{1}{A_T}\cdot\frac{dE_T}{d\eta}\cdot\frac{d\eta}{dz} = \frac{1}{A_T}\cdot\frac{dE_T}{d\eta}\cdot\frac{1}{\tau_0}$$

$$\rho_B = \frac{1}{A_T}\cdot\frac{dN_B}{dy}\cdot\frac{dy}{dz} = \frac{1}{A_T}\cdot\frac{dN_B}{dy}\cdot\frac{1}{\tau_0}$$

Initial time
τ_0 = 0.2 – 1 fm/c

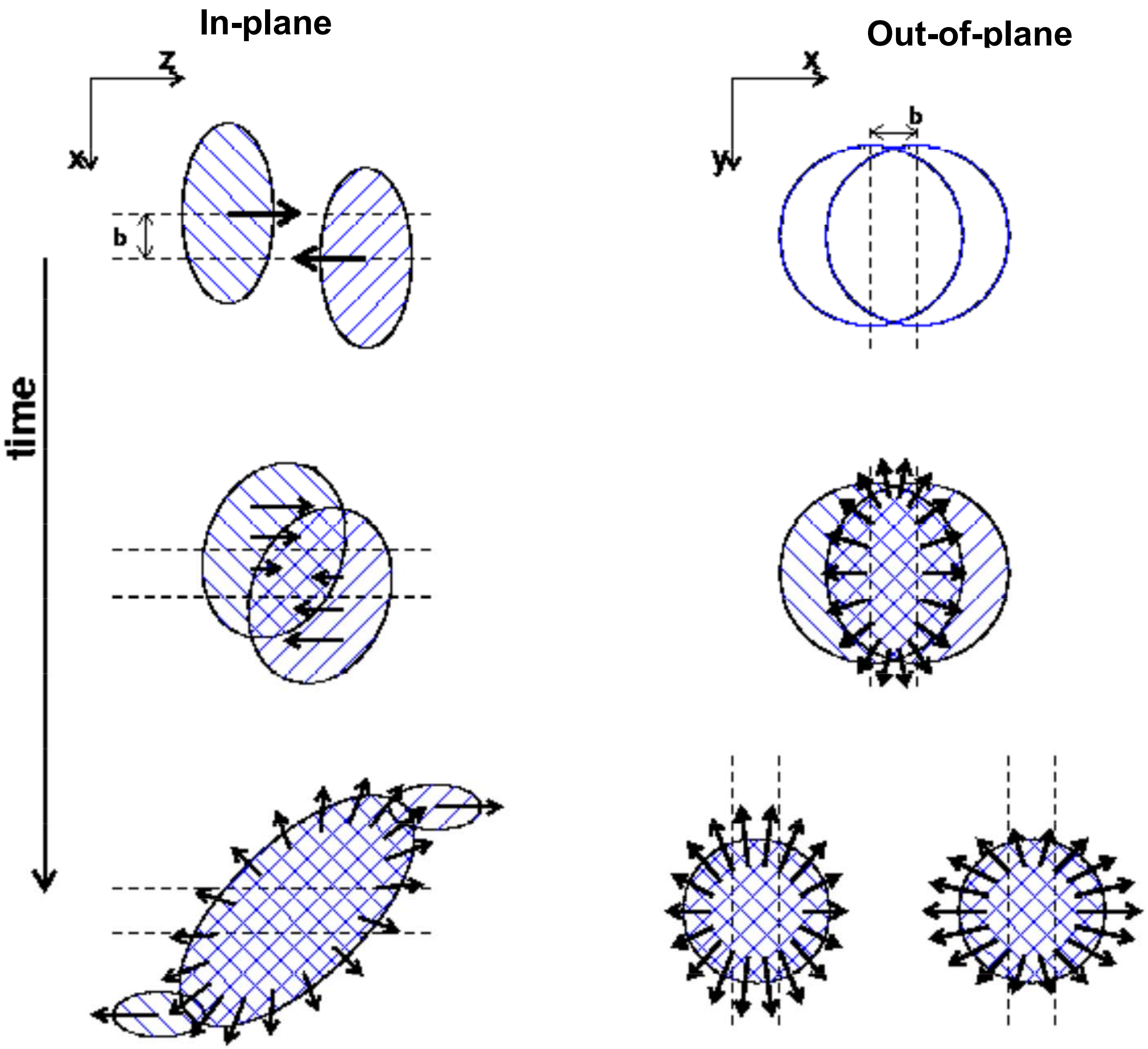
Note:
(from Lattice – QCD)

$$\varepsilon_{crit}^{QGP}\Big|_{\mu_B=0} = 0.8\,\mathrm{GeV/fm^3}$$

Numerical estimates:

	SIS	AGS	SPS
ε(GeV/fm^3)	0.5	1.3	3
ρ(1/fm^3)	0.35	1.1	0.65

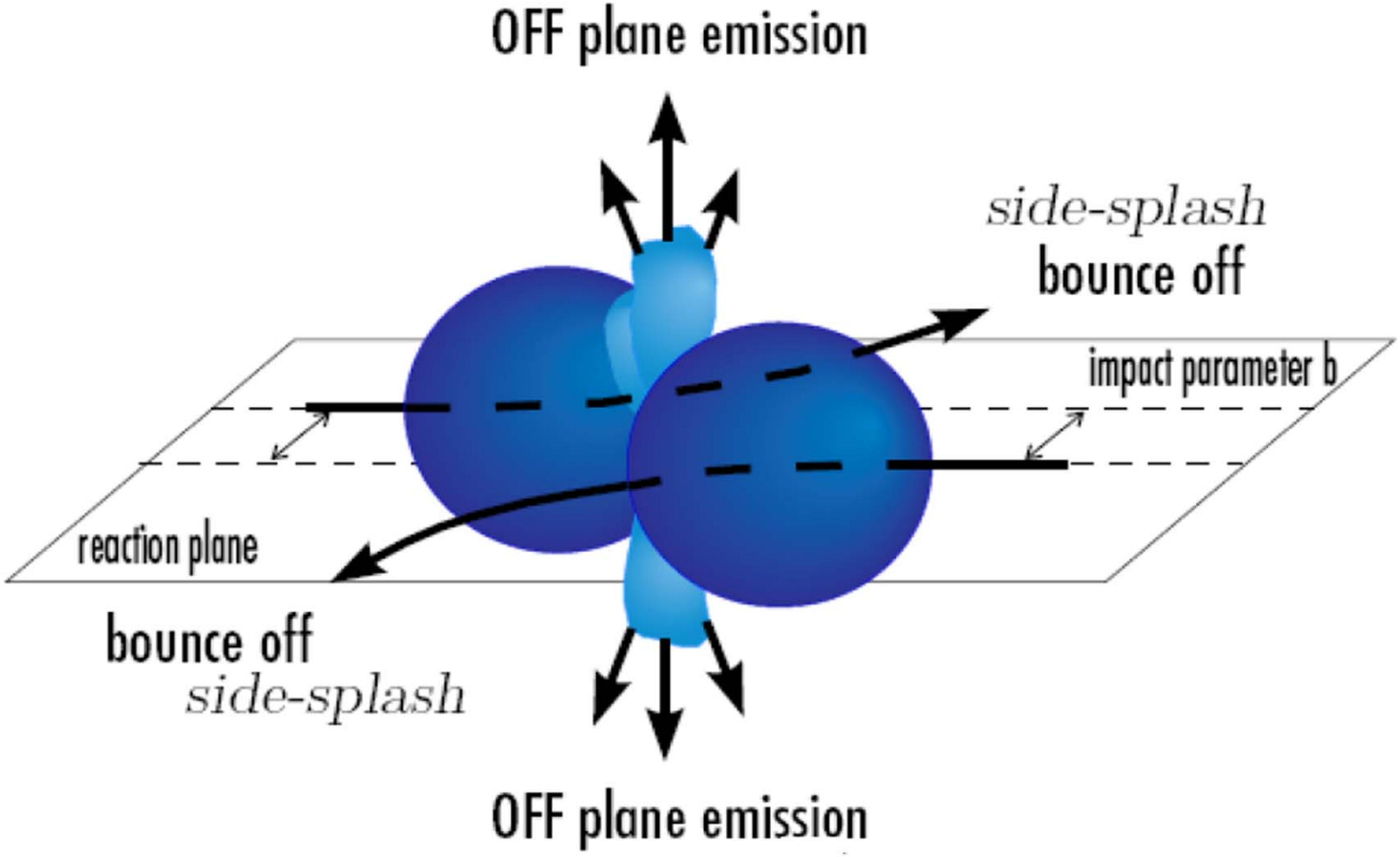
Collective Flow



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

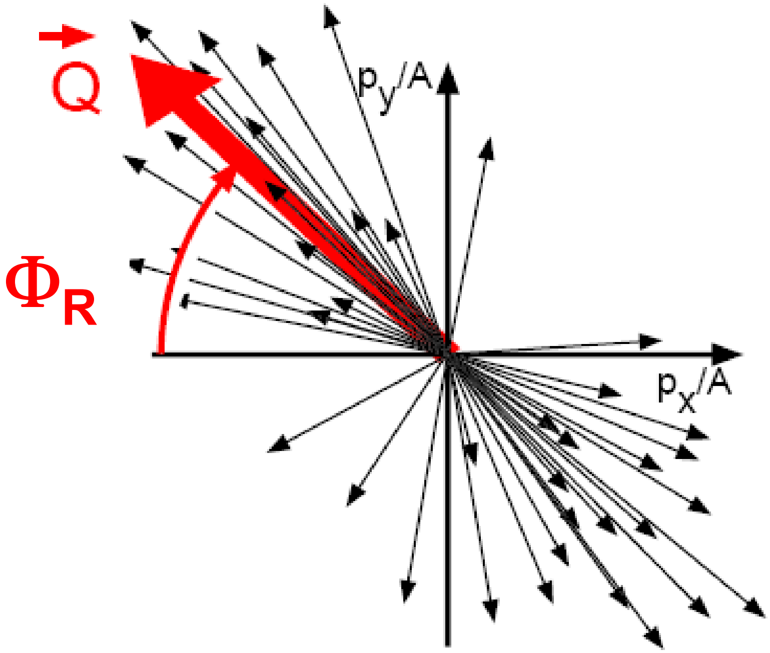
5.2.3

Flow in heavy ion collisions



Reaction Plane

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



$$\vec{Q} = \sum_i \omega(\nu) \cdot \vec{p}_t(\nu),$$

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

Generalisation:

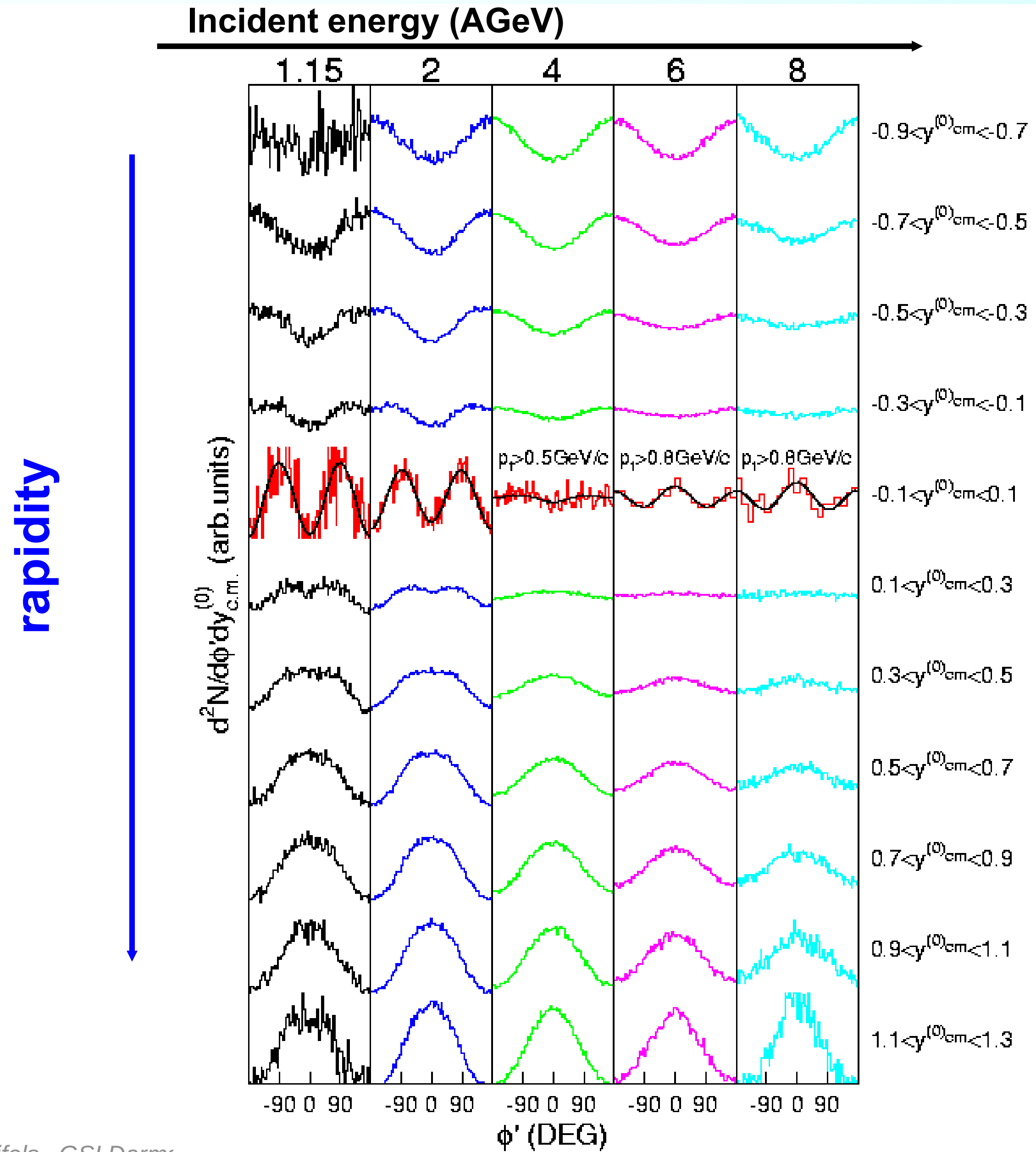
$$\vec{Q}^{(n)} = \sum_i \omega^{(n)} \cdot \left|\vec{p}_t\right| \cdot \begin{pmatrix} \cos(n \cdot \varphi) \\ \sin(n \cdot \varphi) \end{pmatrix}, \qquad n = 1,2,3,\ldots$$

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

Reaction plane angle:

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

Azimuthal distributions

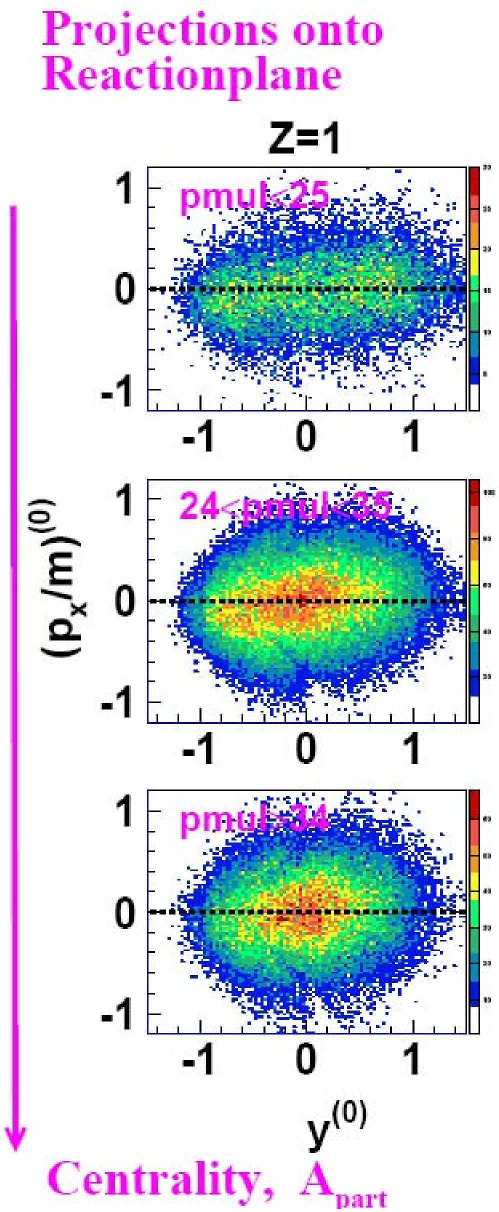


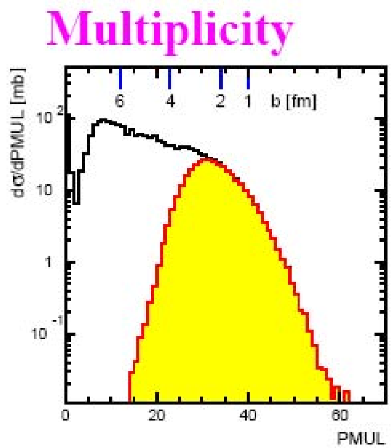
Azimuthal distributions with respect to reaction plane

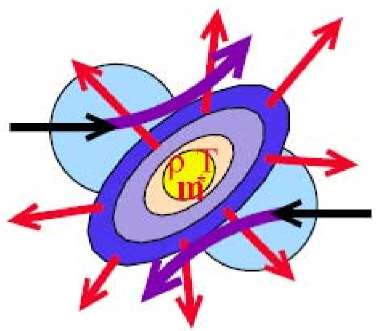
Excitation function of Au+Au reactions

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

Flow observables (history)







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

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

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

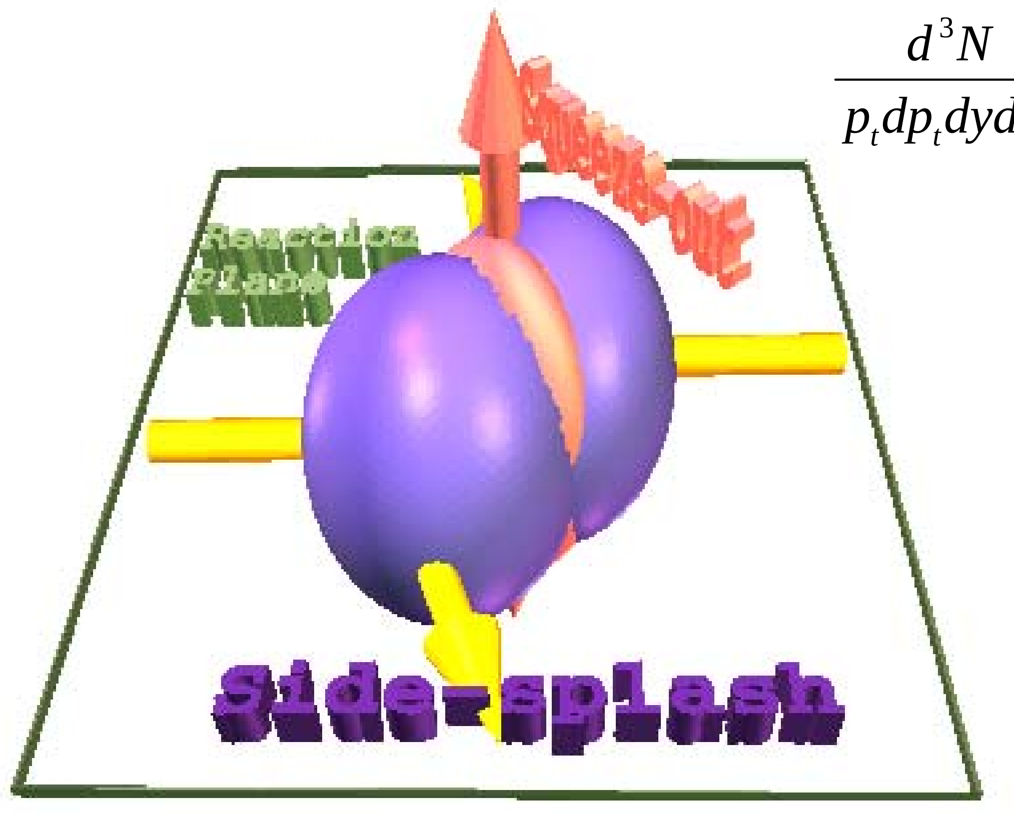
5.2.3

Fourier Expansion of Azimutal Distributions

Phase space distribution with respect to reaction plane Φ_r

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

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



Fourier expansion coefficients

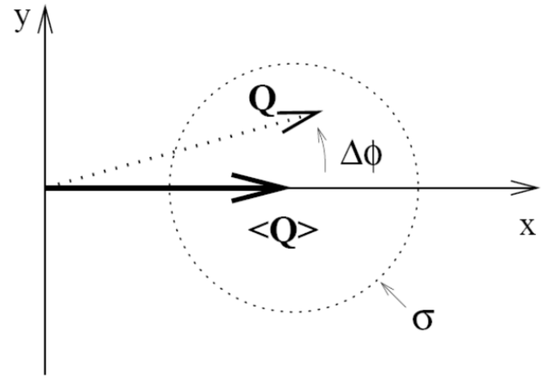
$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle$$ **sideflow**

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

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

Reaction plane 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:

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

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

Ollitrault Formalism

Determination of Fourier coefficients v_i:

1) Fit of azimutal distributions

2) v_i=<cos n $\Delta\phi$>

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

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

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

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]:

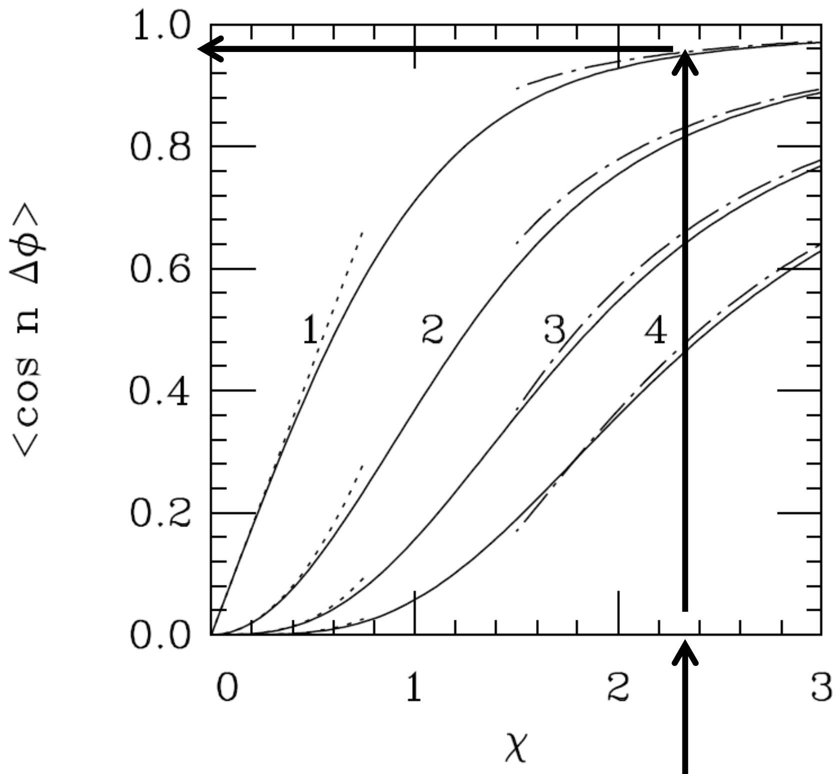
$$\langle\cos n\Delta\phi\rangle = \frac{\sqrt{\pi}}{2}\chi e^{-\chi^2/2}\left[I_{\frac{n-1}{2}}\left(\frac{\chi^2}{2}\right) + I_{\frac{n+1}{2}}\left(\frac{\chi^2}{2}\right)\right] \qquad (8)$$

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

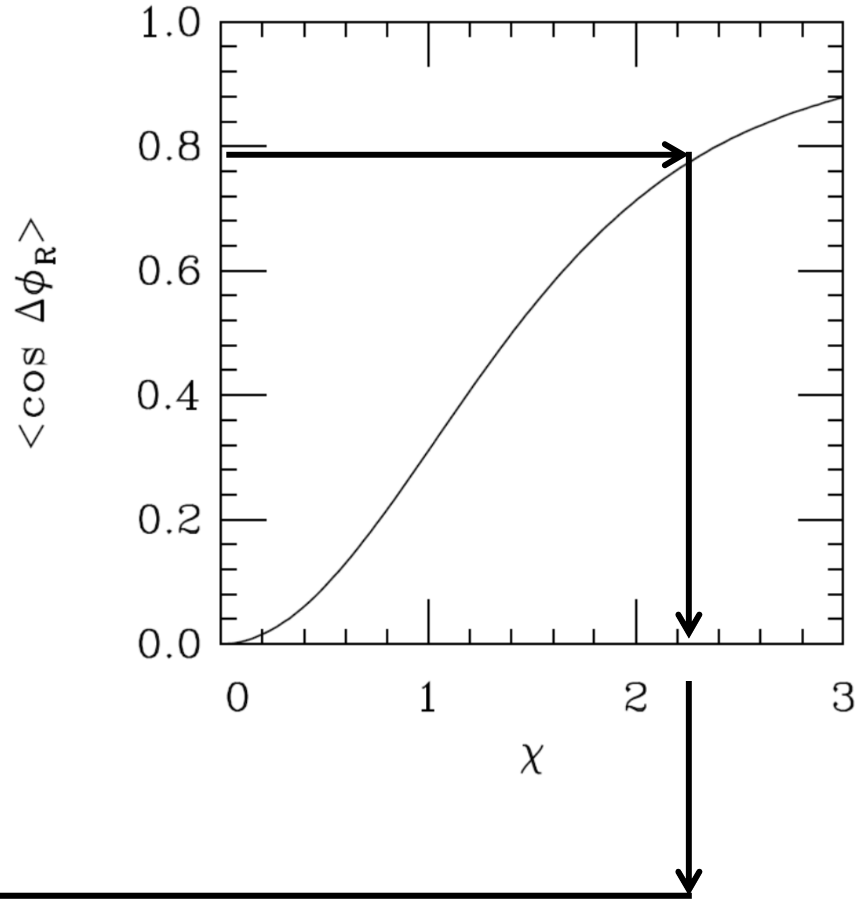
Fourier coefficients v_i can be corrected consistently by evaluating dimensionless parameter χ!

Ollitrault formalism

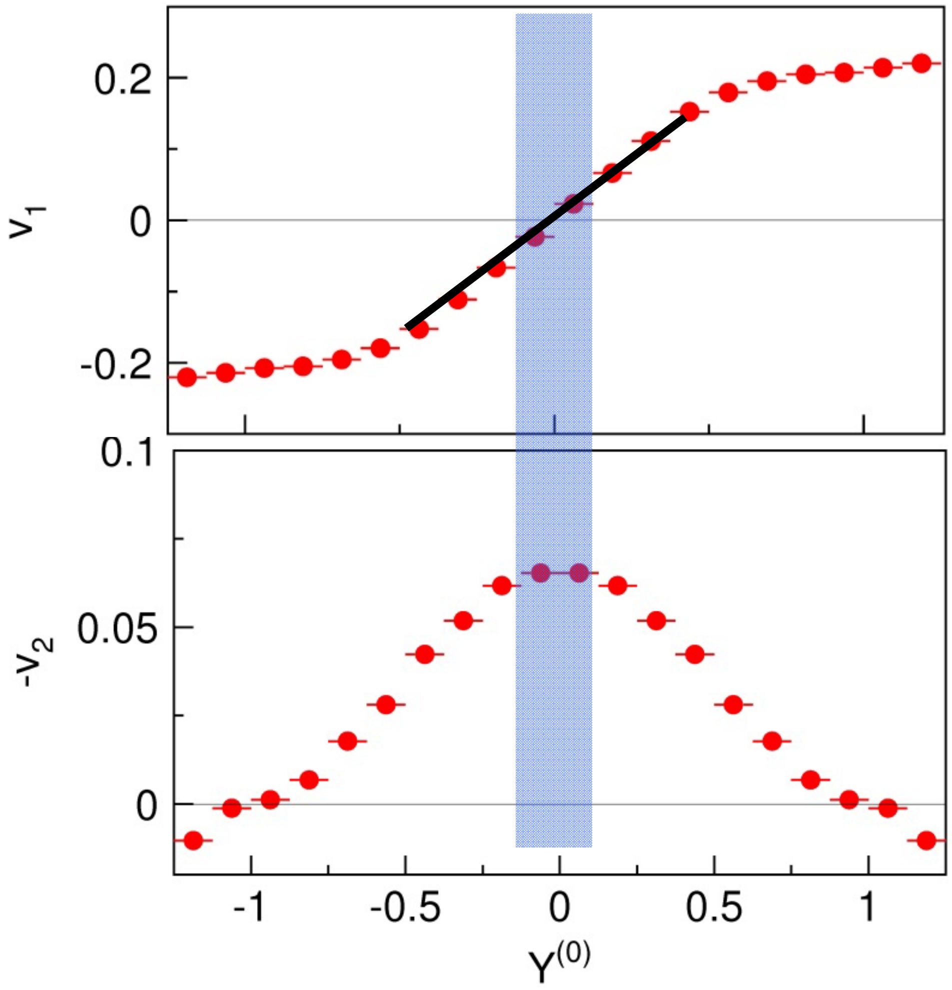
Inverse correction factors



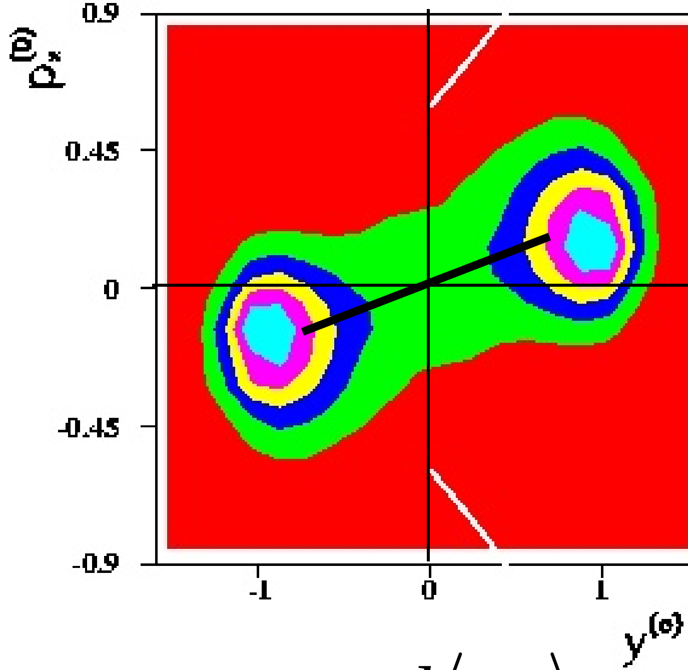
Determination of χ



v1 and v2 as a function of rapidity



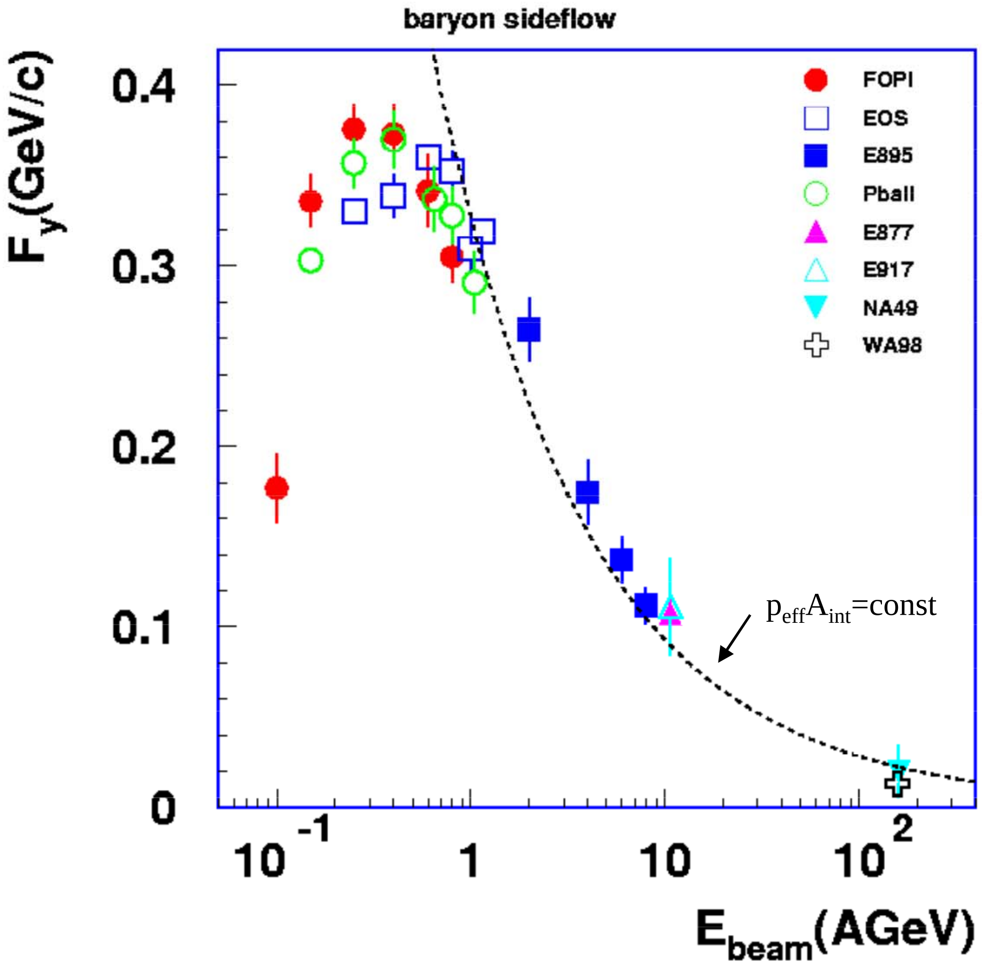
p_x transverse momentum projected onto reaction plane

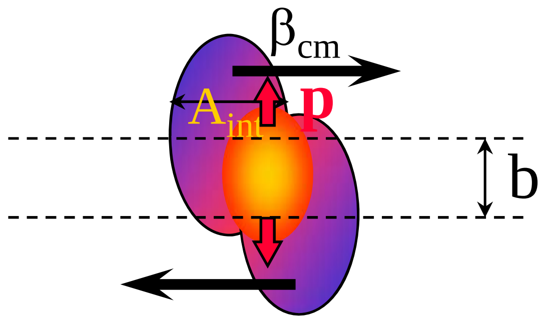


$$F_y = \frac{d\langle p_x \rangle}{dy}$$

~ to slope at v1 at mid-rapidity

Sideflow excitation function



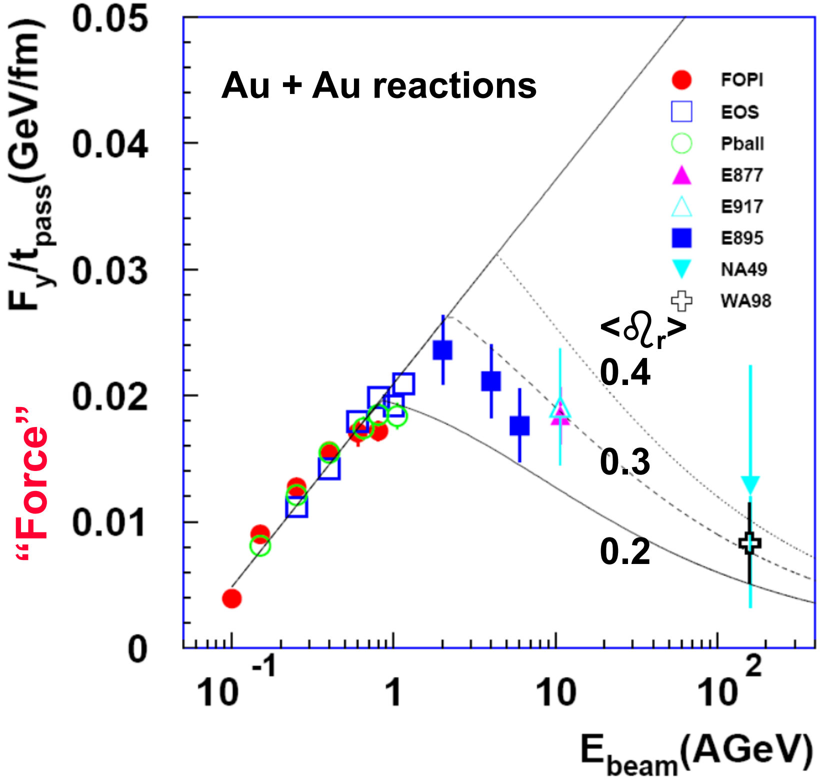


$$F_y \propto \int F dt \approx p_{eff} A_{\text{int}} t_{pass}$$

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

5.2.3

Scaling properties of sideflow

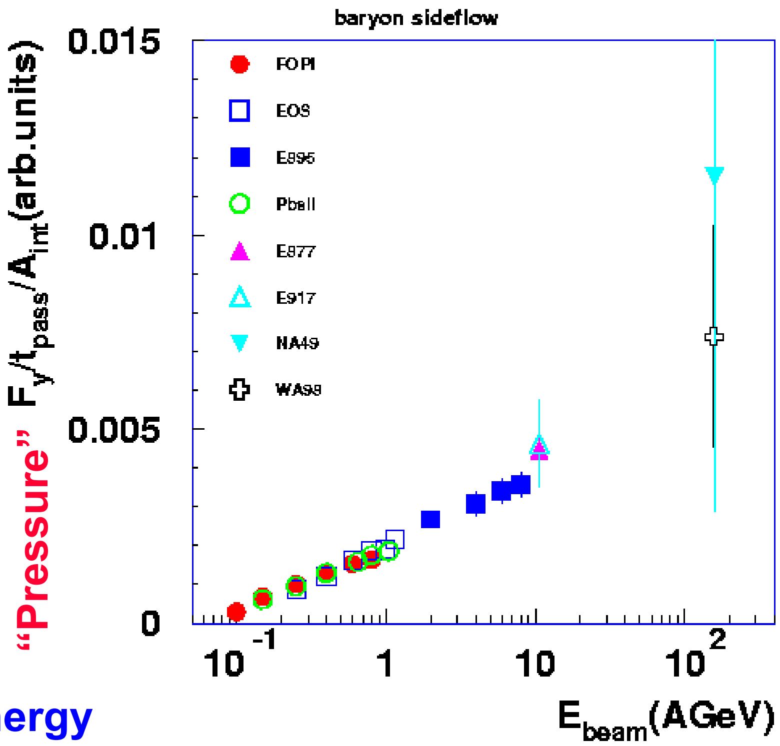


$$F_y \propto \int F dt \approx p_{eff} A_{int} t_{pass}$$

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

$$A_{int} = \frac{A(b)}{\gamma_{CM}}$$

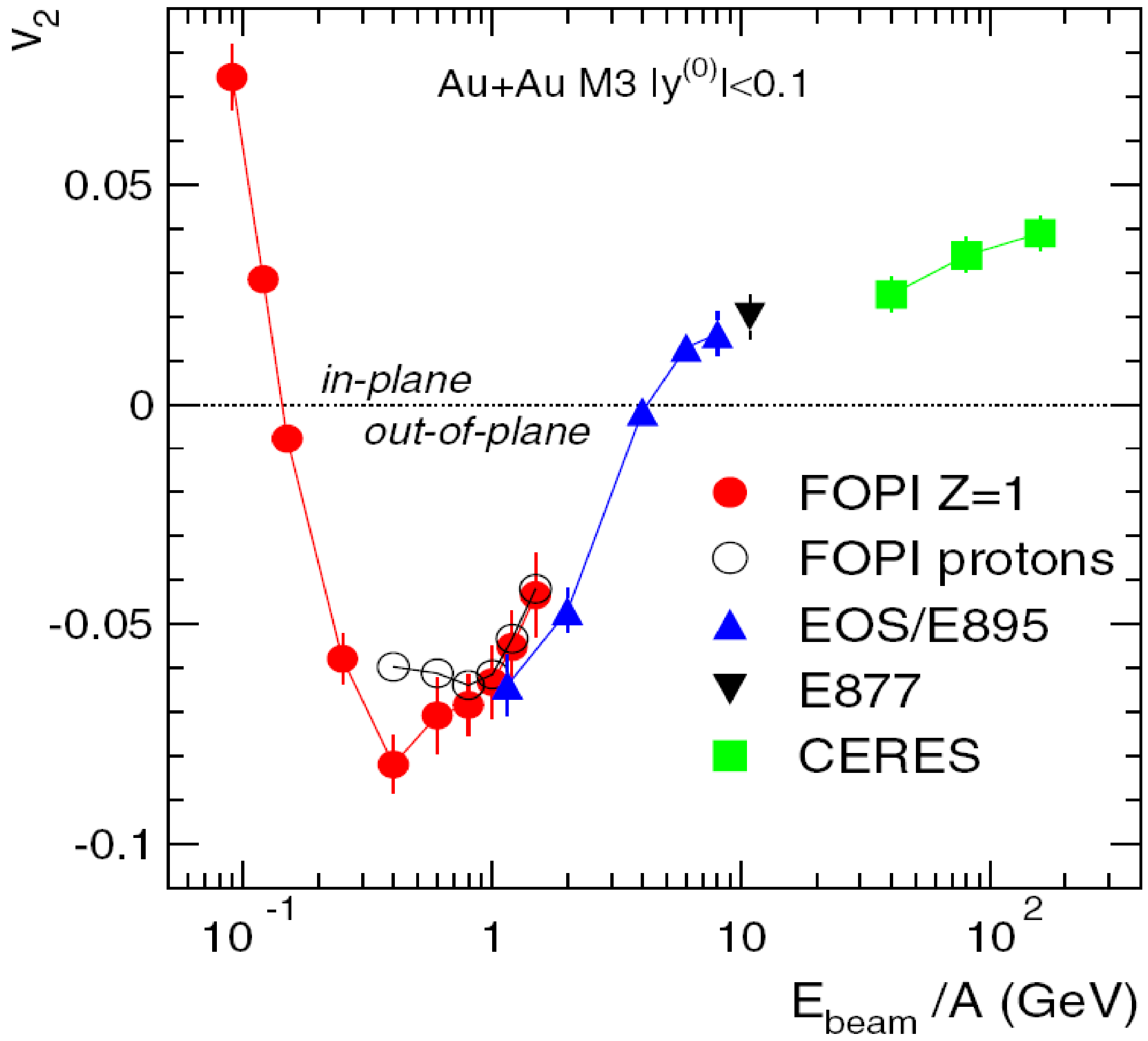
$$p_{eff} \propto \frac{F_y}{A_{int} t_{pass}} = \frac{\gamma_{CM}^2 \beta_{CM}}{A(b) \cdot 2R} \cdot F_y$$



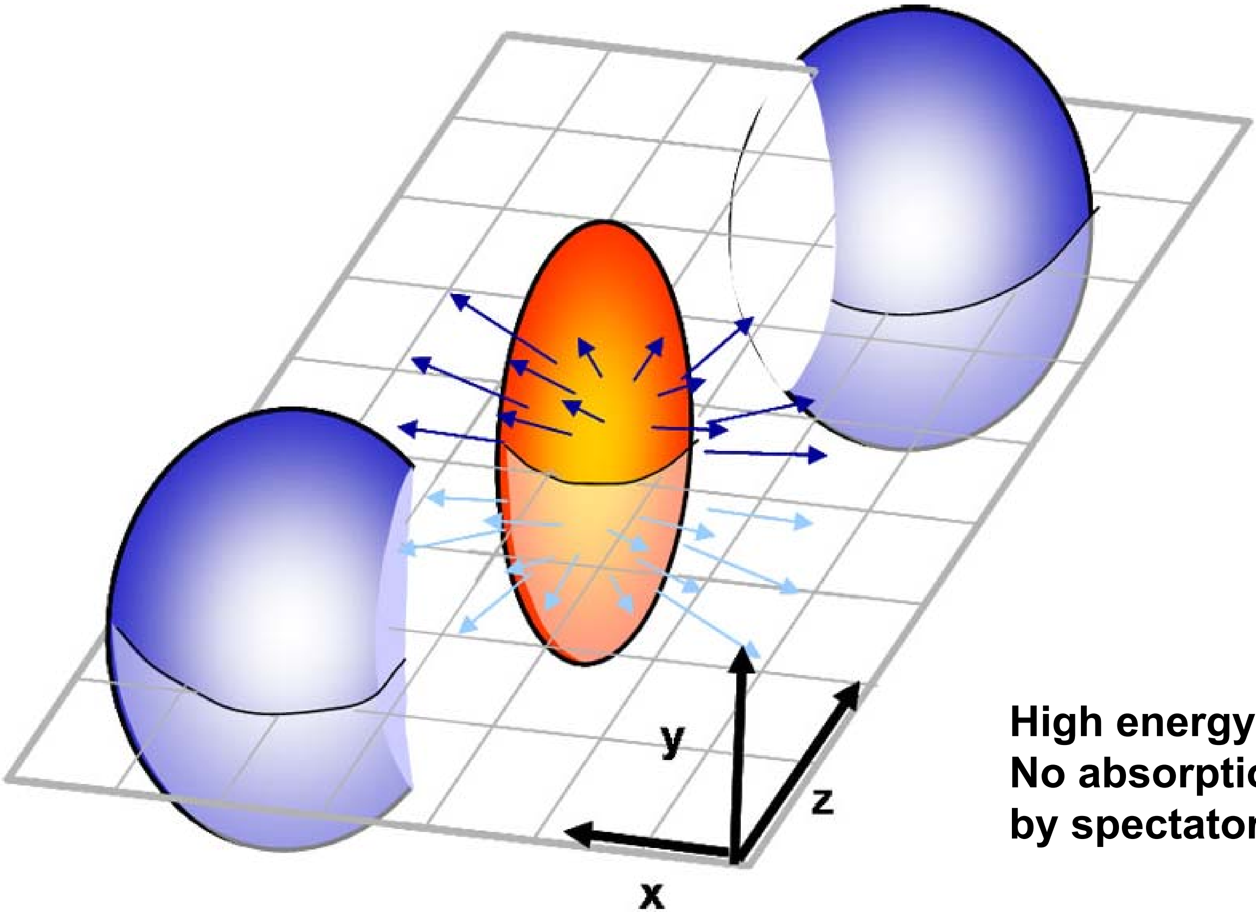
Smooth evolution of pressure with incident energy

Excitation function for elliptic flow

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

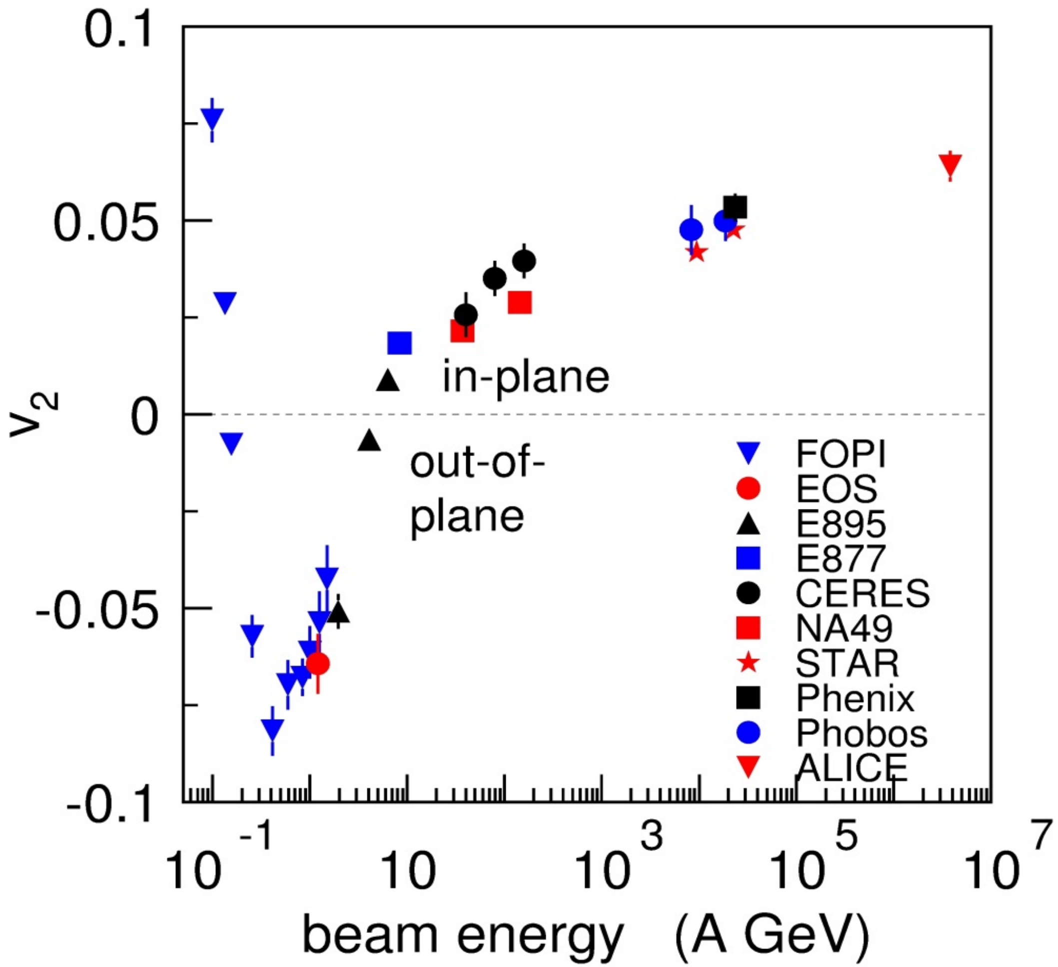


Elliptic in-plane flow

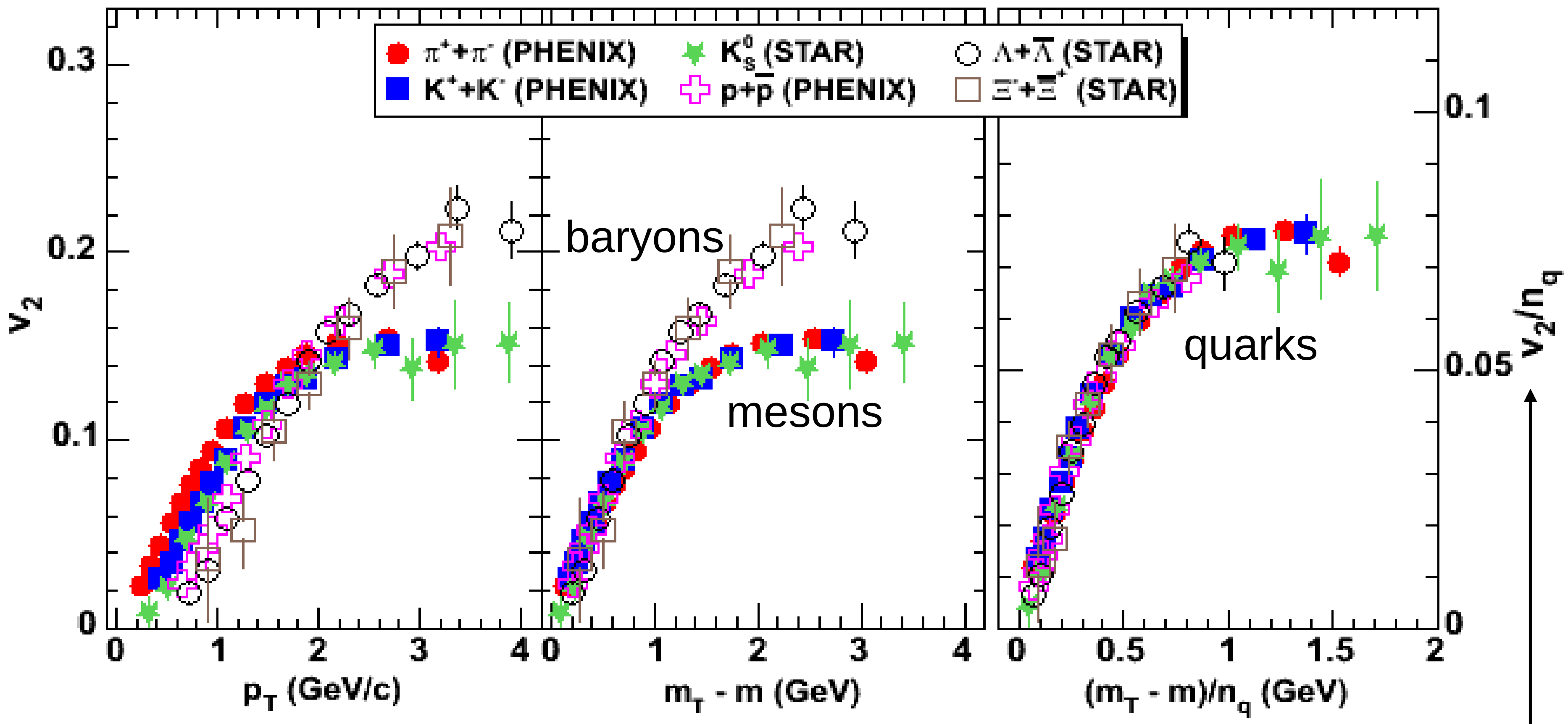


High energy:
No absorption of fireball particles by spectators

Excitation function of elliptic flow



Scaling with Number of Quarks @ 200AGeV



quarks have v_2 before hadronization

both axes scaled by number of constituent quarks

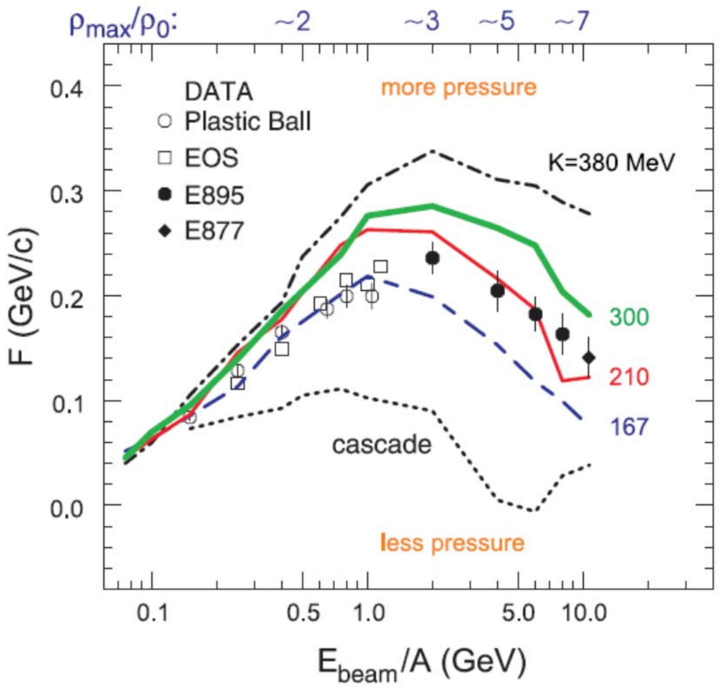
n_q = 2 for mesons
n_q = 3 for baryons

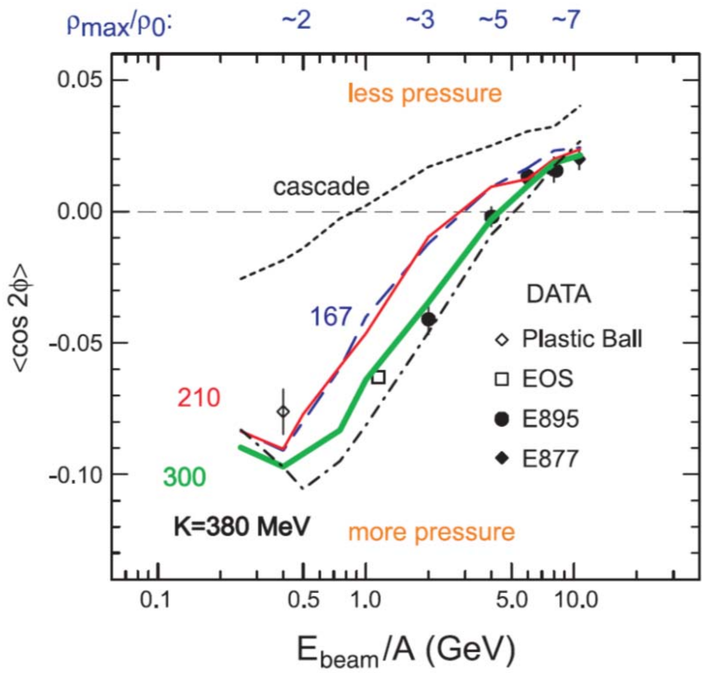
S. Voloshin, QM02, 379c (2003)
STAR, PRL **95**, 122301 (2005)   PHENIX, PRL **98**, 162301 (2007)

Excitation function of flow variables

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

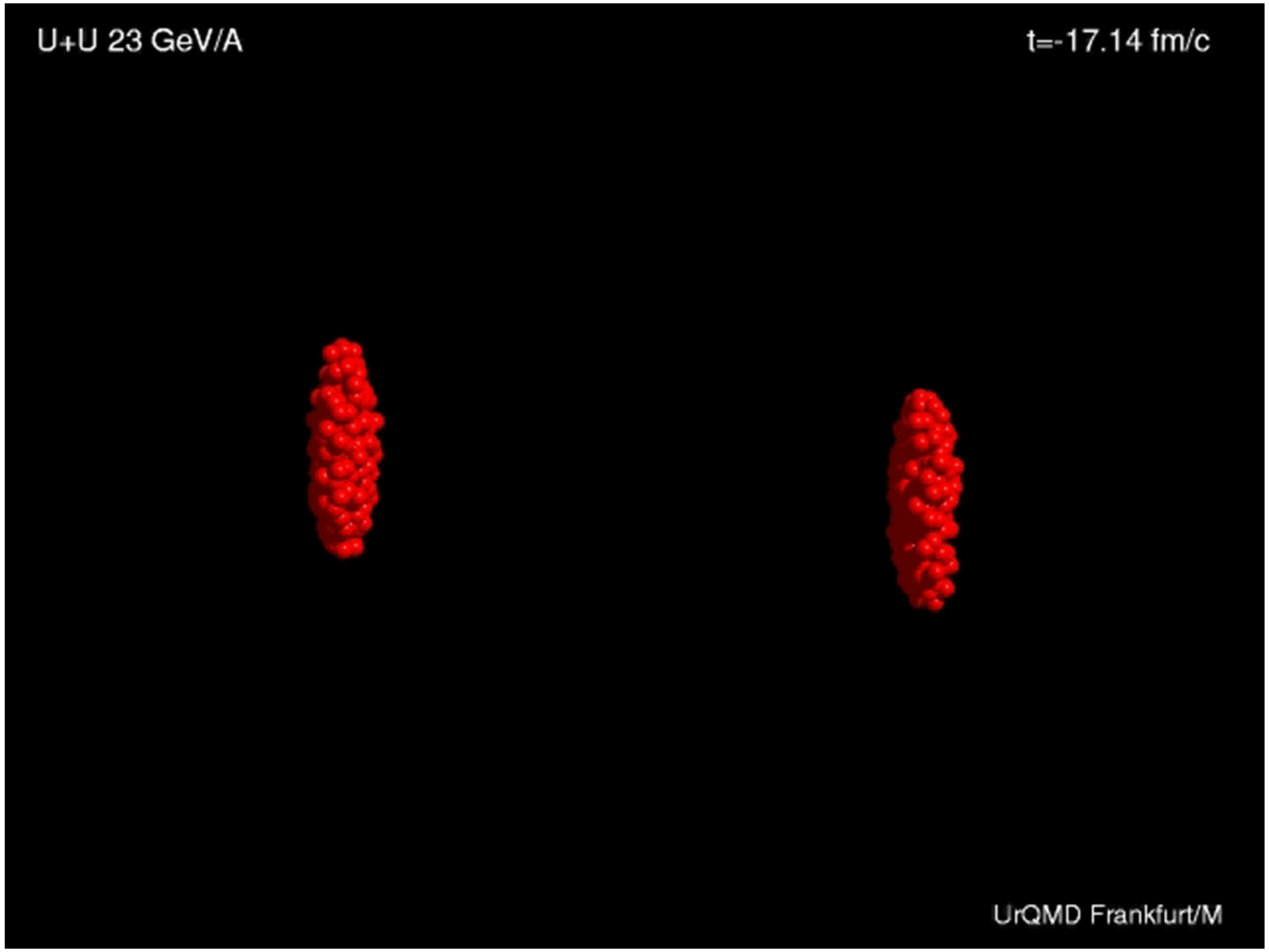
P. Danielewicz et al.
Science 298, 1592 (2002)



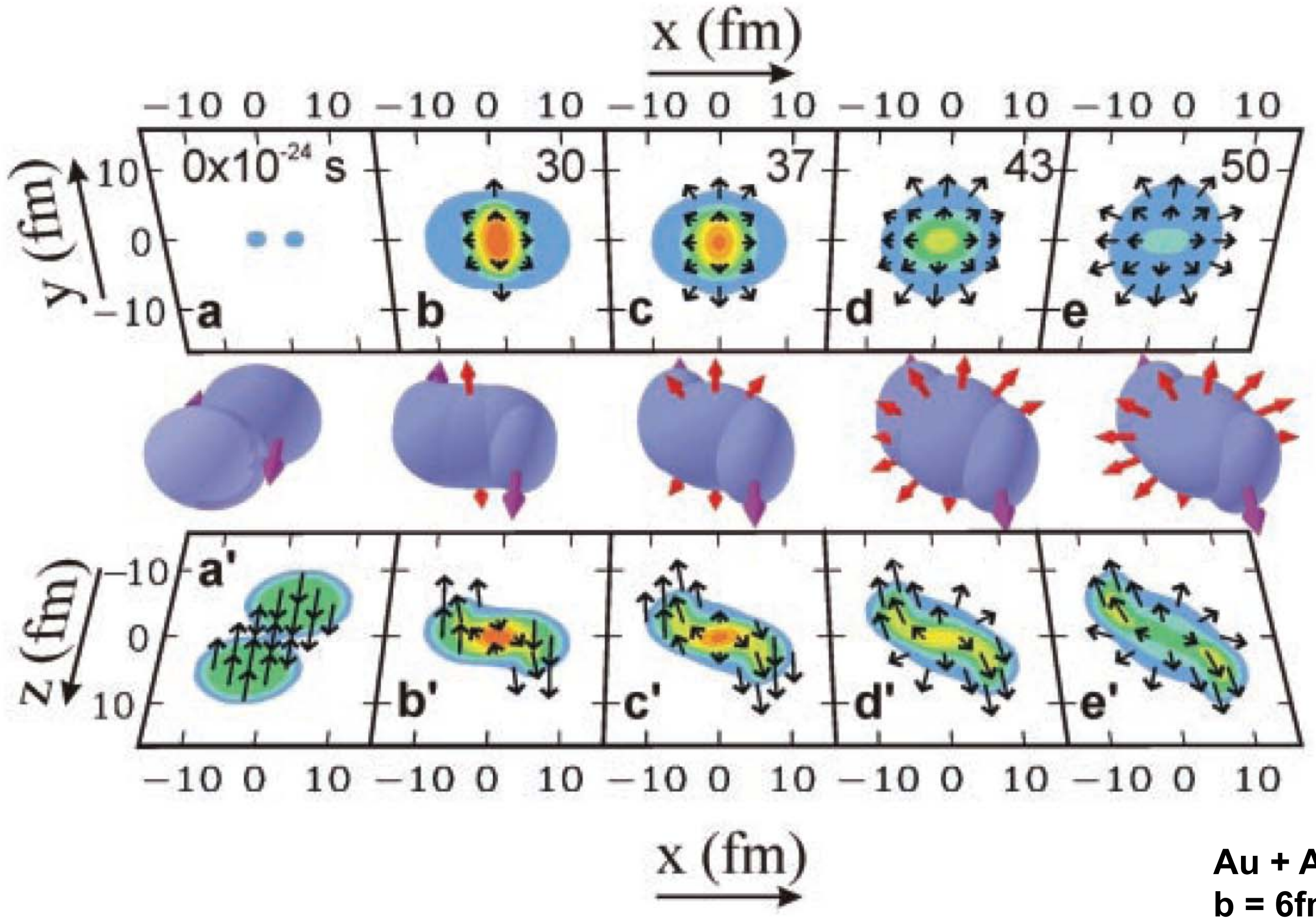


(depending on equation of state)

Movie of a heavy ion collision



Heavy-ion collisions



Au + Au
b = 6fm

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

Models for heavy ion collisions