Observable consequences of titled initial state

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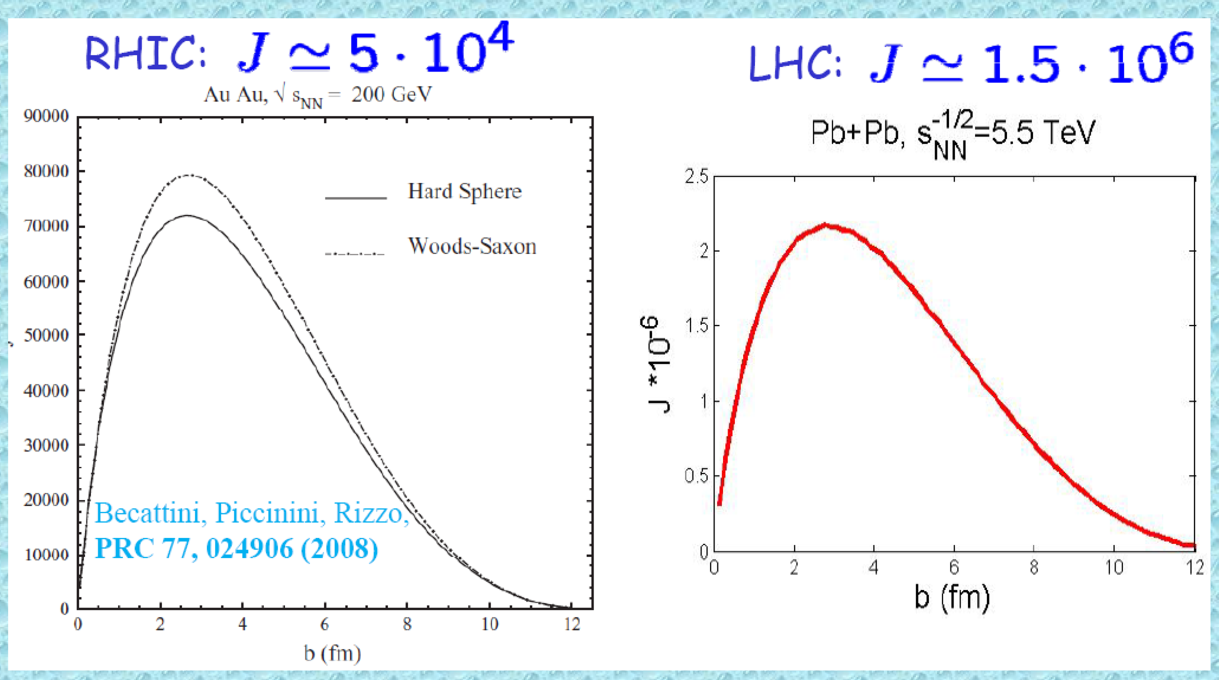
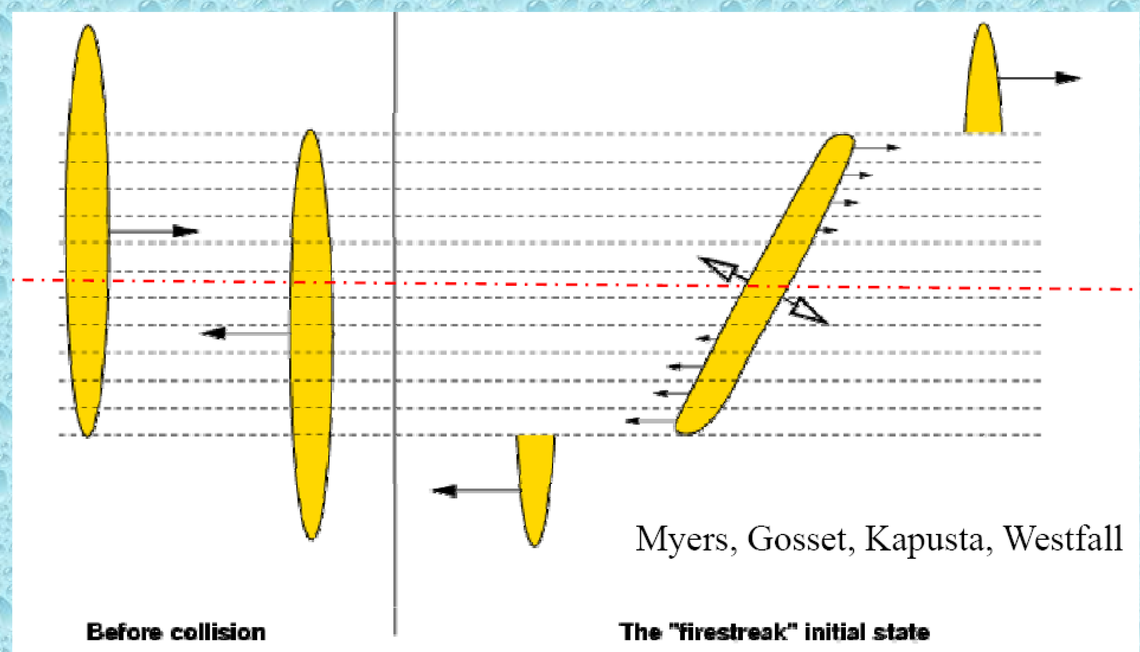
Nuclei colliding at relativistic energies with nonzero impact parameter have a large initial angular momentum, which is usually ignored in the initial conditions assumed for hydro calculations

RHIC: $J \simeq 5 \cdot 10^4$ LHC: $J \simeq 1.5 \cdot 10^6$

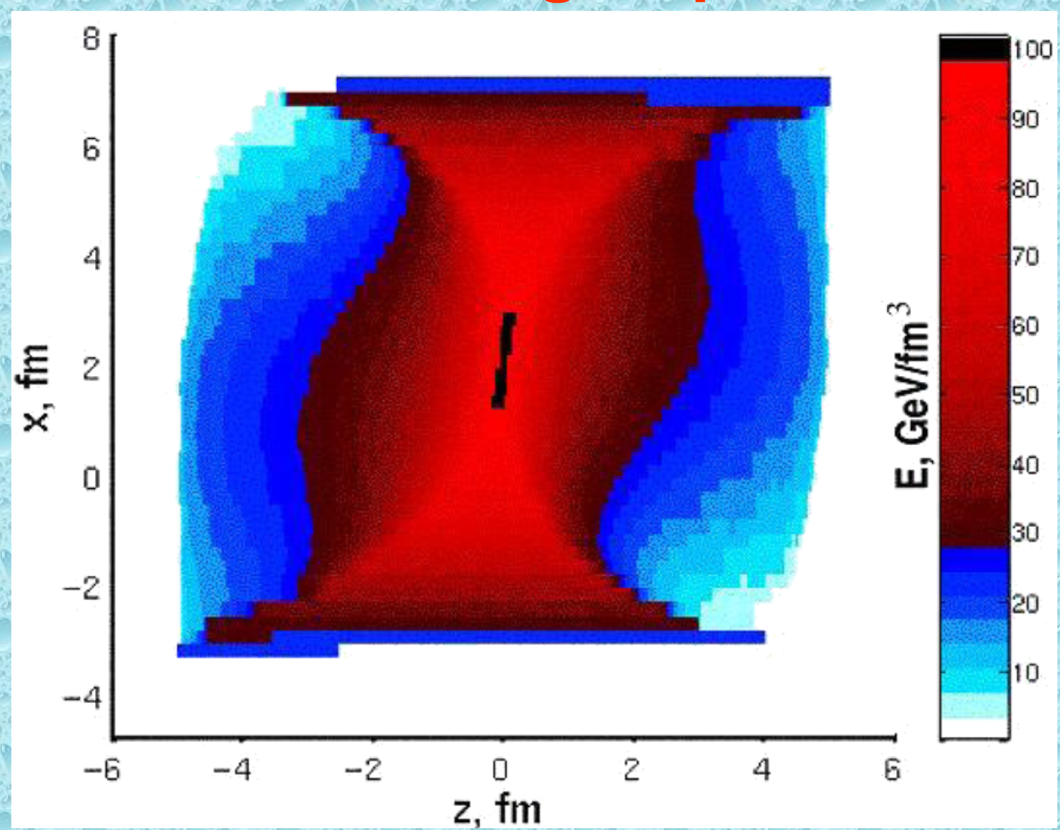


Qualitative model of the initial state



Tilted!

Initial state from Effective String Rope Model



Au+Au at 100+100 GeV/nucl, b=0.25*2R

Magas, Csernai, Strottman, Phys. Rev. C64 (2001) 014901, Nucl. Phys. A712 (2002) 167

Which potential output such a tilted initial state may have?

- Directed flow, v_1
- Elliptic flow, v_2
- HBT
- Vorticity ⇒ particle polarization

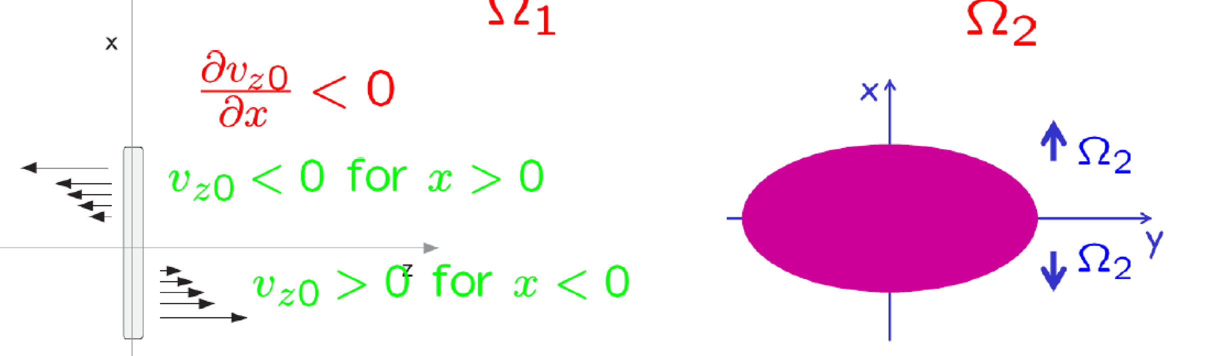
Elliptic flow from rotating initial state: toy model calculations

Euler equation

$$(e+P)(\mathbf{u}\cdot\partial)\mathbf{u}^\mu = \mathbf{g}^{\mu\nu}\partial_\nu \mathbf{P} - (\mathbf{u}\cdot\partial\mathbf{P})\mathbf{u}^\mu$$

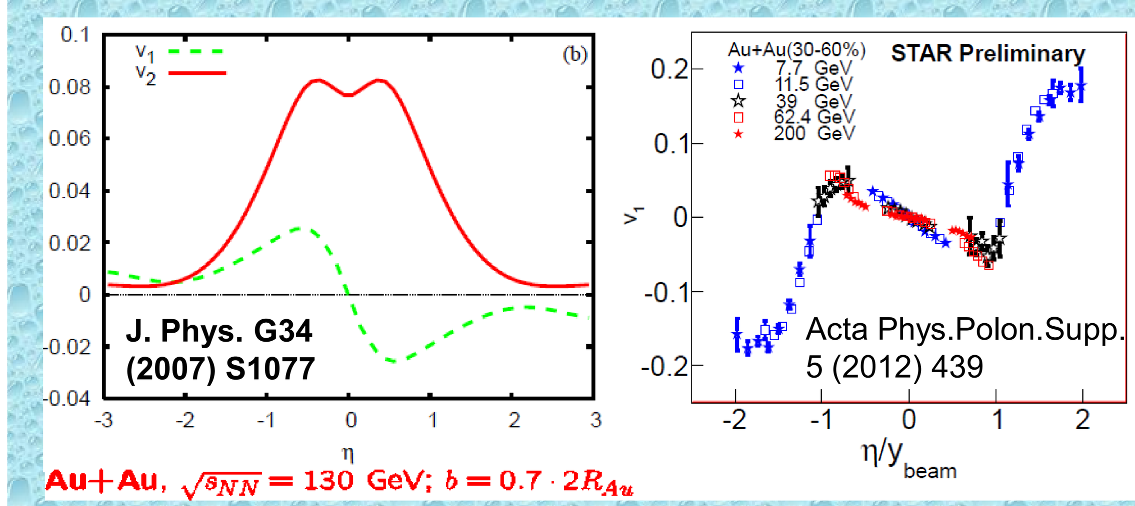
$t=0:\ v_x = v_y = 0,\ \gamma_0^2 = 1/(1-v_{z0}^2);\ P = e/3$

$$e_0\gamma_0^3 \frac{\partial u_i}{\partial t}\Big|_{t=0} = \underbrace{-\frac{1}{4}\frac{\partial e\gamma^2}{\partial x_i}\Big|_{t=0}}_{\Omega_1} + \underbrace{\frac{1}{4} 2 e_0 \gamma_0^4 v_{z0}\frac{\partial v_{z0}}{\partial x_i}\Big|_{t=0}}_{\Omega_2}$$



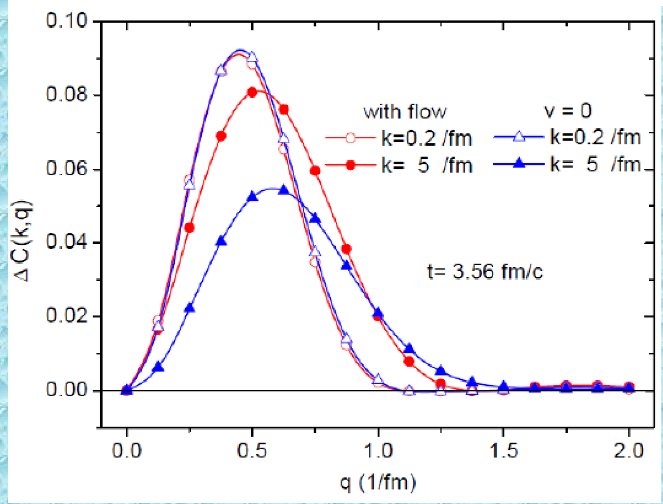
Ω_2 helps to produce elliptic flow!

Strong antiflow in v_1 is predicted and indeed observed at RHIC



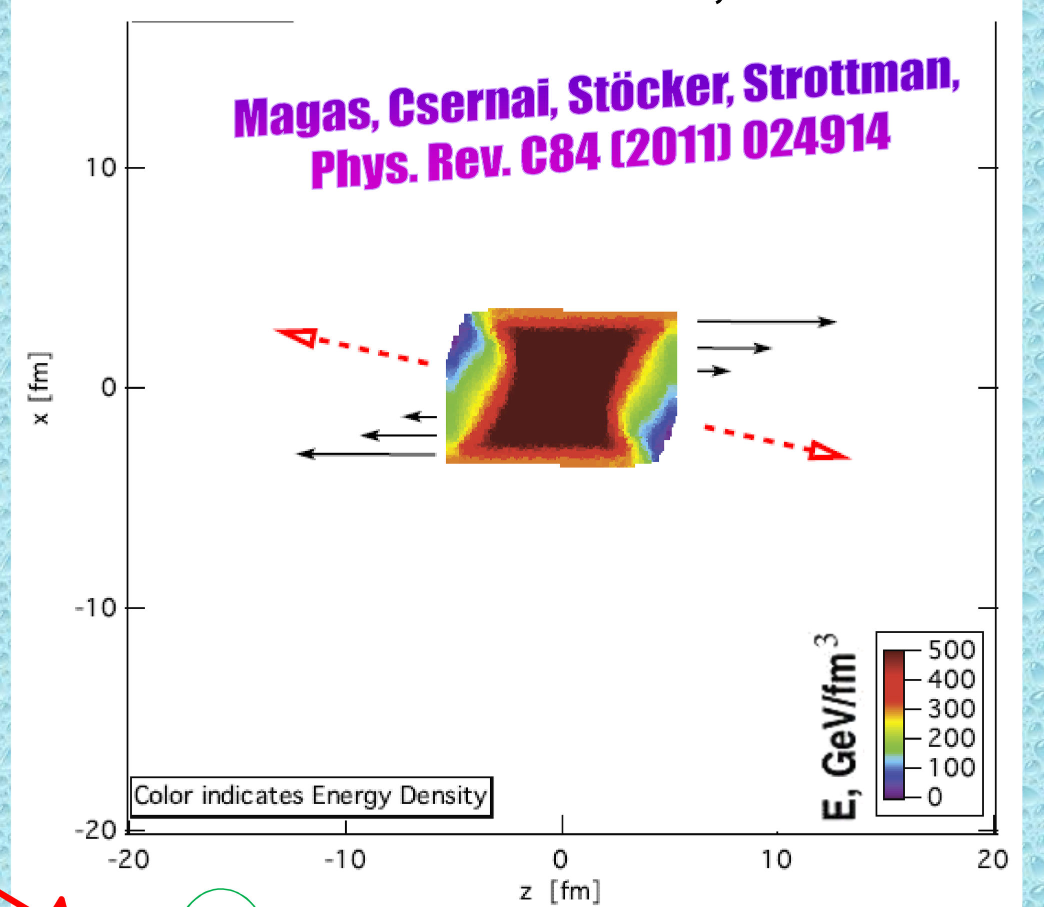
Detecting initial rotation: Differential HBT

$$\Delta C(k_\pm, q_{out}) \equiv C(k_+, q_{out}) - C(k_-, q_{out}) = \frac{4\exp(-R^2q^2)\,\epsilon\sinh\left(\frac{2u_zbk}{T_s}\right)(1-\epsilon^2)\left[1-\cosh\left(\frac{u_zbq}{T_s}\right)\cos(aqd_z)\right]}{\left[(1+\epsilon^2)\cosh\left(\frac{2u_zbk}{T_s}\right)+(1-\epsilon^2)\right]^2 - 4\epsilon^2\sinh^2\left(\frac{2u_zbk}{T_s}\right)}$$



Csernai, Velle , arXive:1305.0385 [nucl-th]; Csernai, Velle, Wang, arXive:1305.0396 [nucl-th]

Pb+Pb at 1.38 + 1.38TeV/nucl, b = 0.5*2R

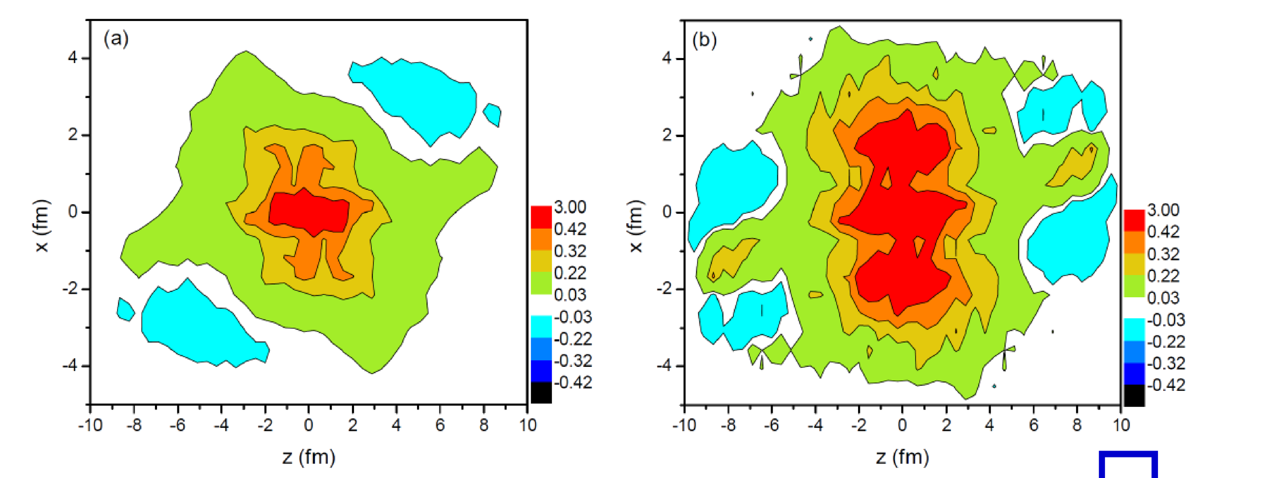


Flow Vorticity

Classical: $\omega \equiv \frac{1}{2}\text{rot } v = \frac{1}{2}\nabla \times v$

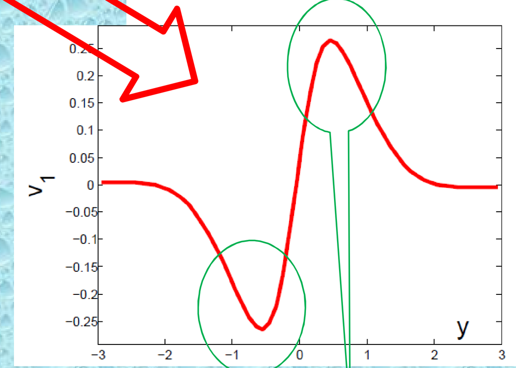
$\Omega_{zx} \equiv w(z,x)\ \omega_{zx}$ — energy density weighted vorticity

Relativistic: $\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$

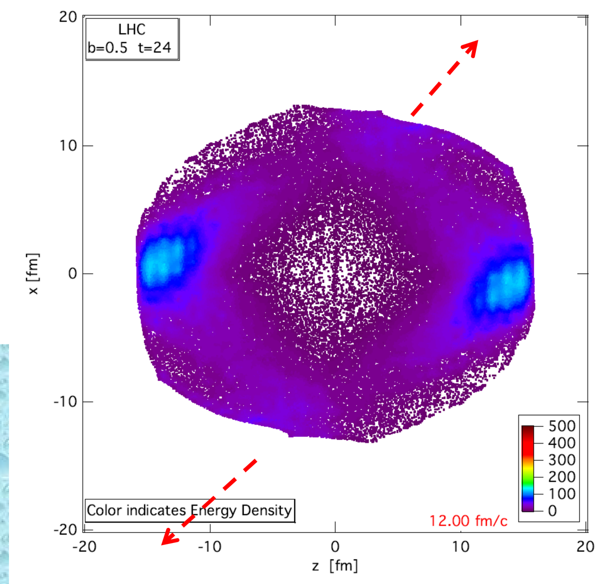


Csernai, Magas,Wang, **PRC 87 (2013) 034906**

At LHC energies "tilted" initial state = "rotating" initial state



Peaks are in the opposite directions!

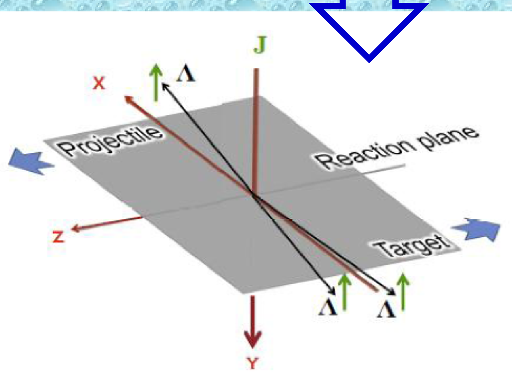


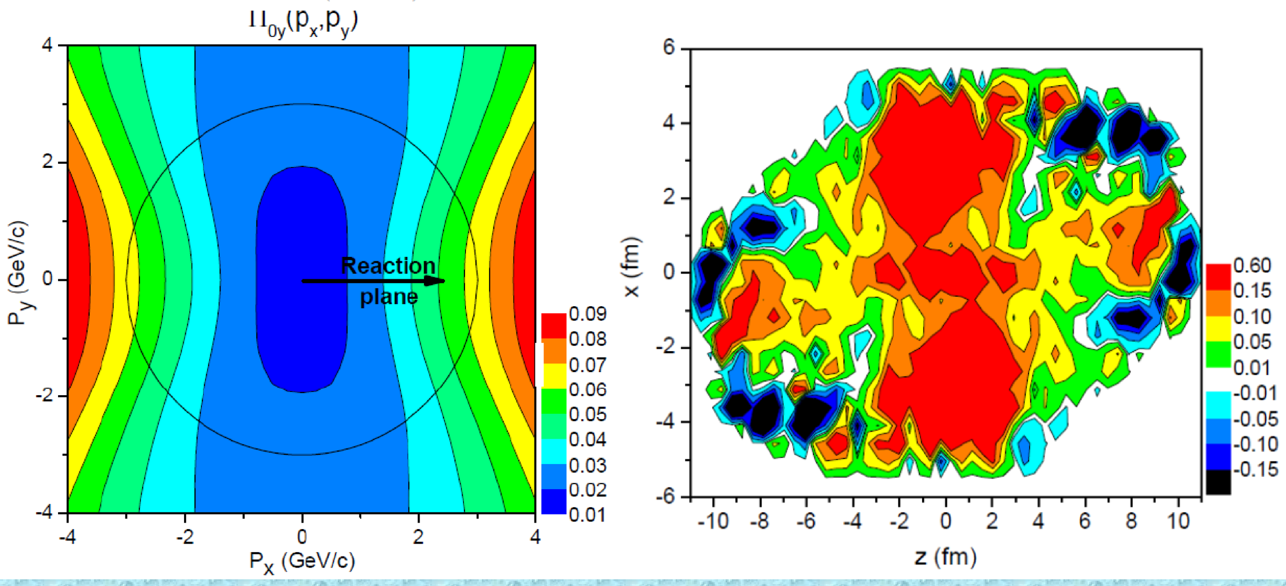
Detecting rotation: Lambda polarization

$$\Pi(p) = \frac{\hbar\varepsilon}{8m}\frac{\int dV\, n_F\,(\nabla\times\beta)}{\int dV\, n_F}$$

$\beta^\mu(x) = (1/T(x))u^\mu(x)$ ← from hydro

$$\Pi_0(p) = \Pi(p) - \frac{\mathbf{p}}{\varepsilon(\varepsilon+m)}\Pi(p)\cdot\mathbf{p}$$

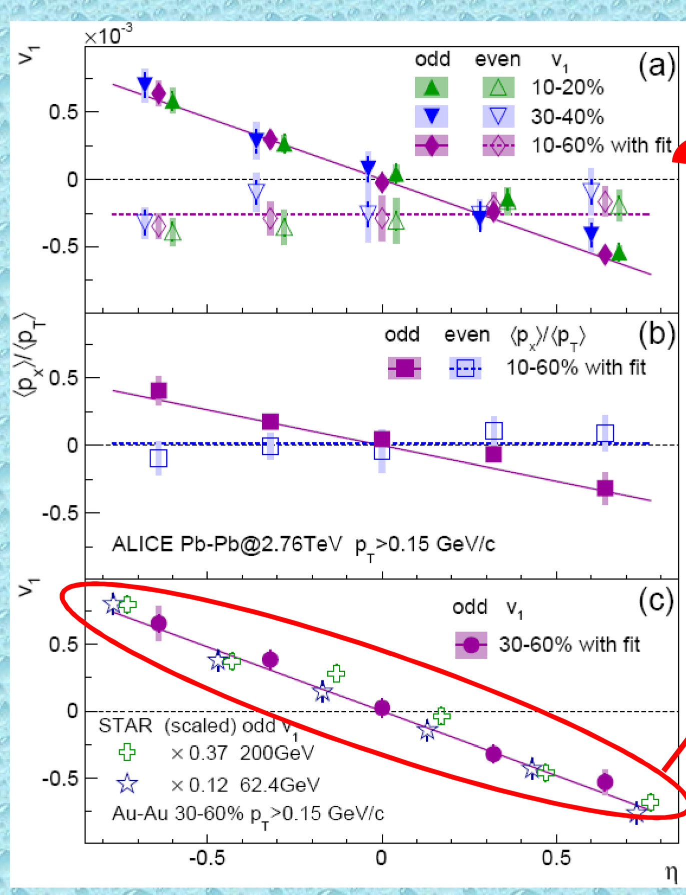




Becattini, Csernai, Wang, **PRC88 (2013) 034905**

Current experimental status

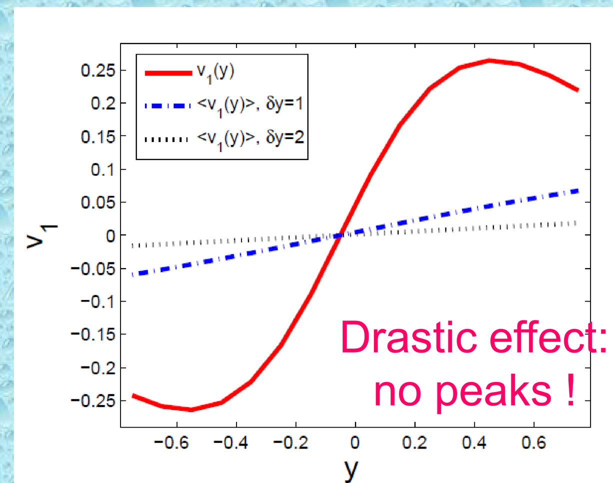
ALICE Coll., **PRL 111 (2013) 232302**



V_1 at LHC can have an important contribution from the fluctuations

V_1 at LHC has the same negative slope as at RHIC, but smaller magnitude

V_1 is extremely sensitive to the initial state fluctuations



Can we correct for the fluctuations?

Csernai, Eyyubova, Magas, **PR C86 (2012) 024912**