Topics in Heavy Ion Collisions
McGill University
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Anisotropy of flow and hydrodynamics —What have we learned

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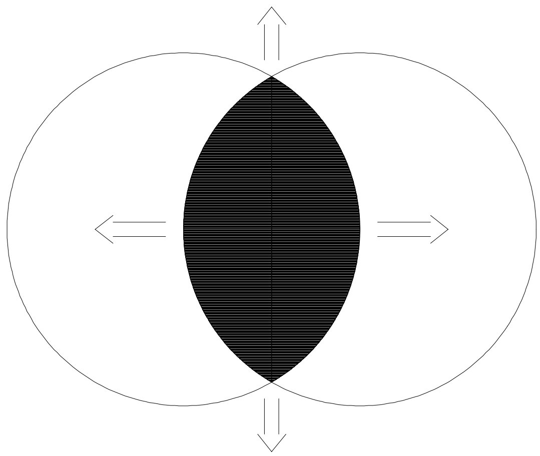
Anisotropic particle distribution

Non-central collision:



Anisotropy in configuration space

$\Downarrow$

Anisotropy in particle distributions
i.e. in momentum space

Characterized by Fourier coefficients:

$$E\frac{dN}{d^3p} = \frac{dN}{2\pi p_t dp_t dy} \times [1 + 2v_1(p_t)\cos(\phi) + 2v_2(p_t)\cos(2\phi) \ + \cdots]$$

or as averaged over p_t:

$$\frac{dN}{dyd\phi} = \frac{dN}{2\pi dy} \times [1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \cdots]$$

Hydrodynamical description

assumes

- local kinetic equilibrium
- local chemical equilibrium
- no dissipation

Basic quantity is the energy-momentum tensor

$$
\begin{aligned}
T^{\mu\nu} &= \int \frac{d^3\mathbf{p}}{(2\pi)^3 E} p^\mu p^\nu f(x,\mathbf{p}) \\
&= (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu}
\end{aligned}
$$

where the lower equation holds for non-viscous matter.

- relativistic viscous hydro is possible in principle but very complicated to implement (Muronga: nucl-th/0104064)

Space-time evolution is given by

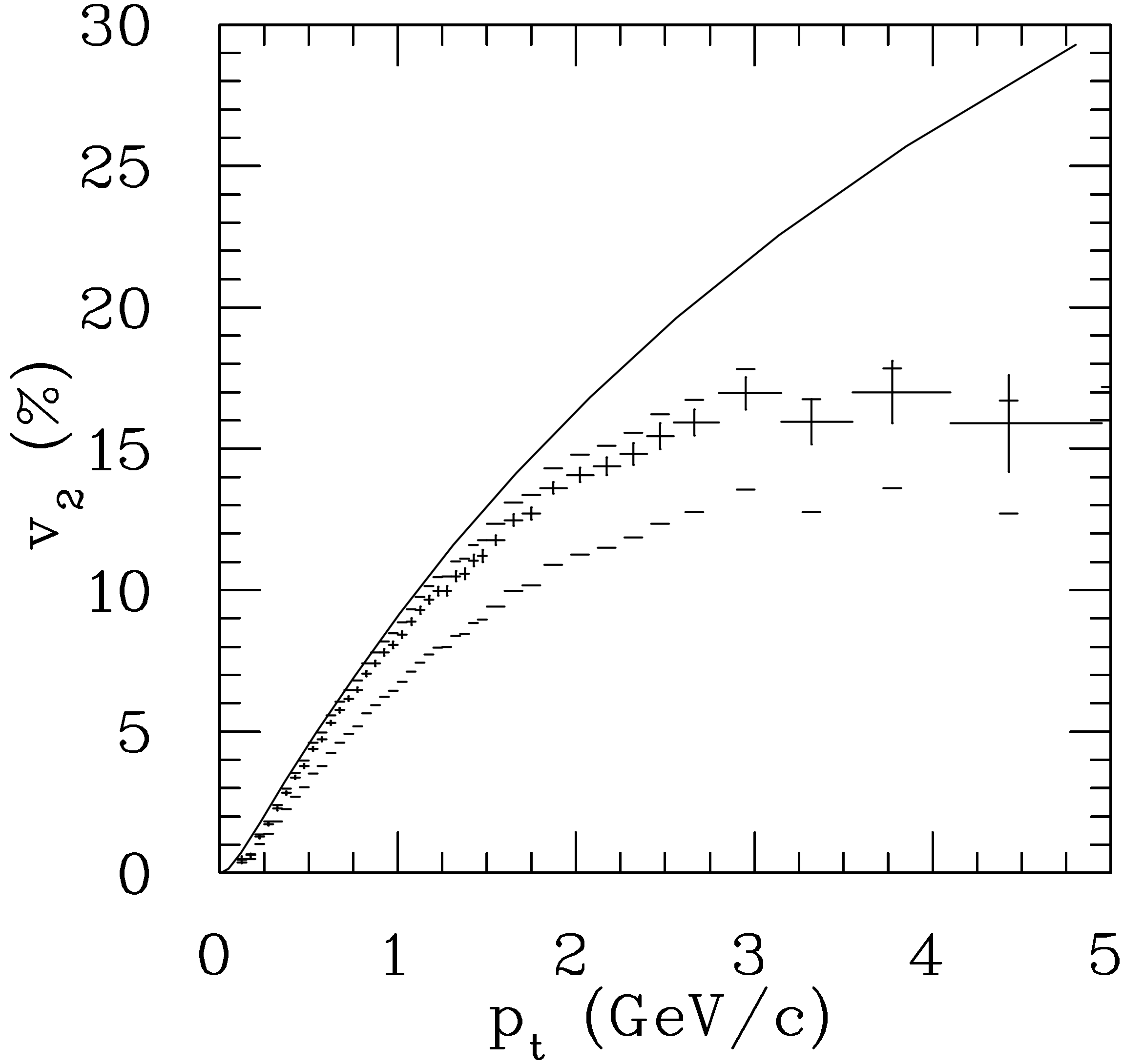
$$\partial_\mu T^{\mu\nu} = 0 \qquad \text{and} \qquad \partial_\mu j^\mu = 0$$

These equations express local conservation of 4-momentum and baryon number

By nature hydrodynamics describes bulk phenomena,
i.e. low p_t particles, not high p_t

$v_2(p_t)$, minimum bias

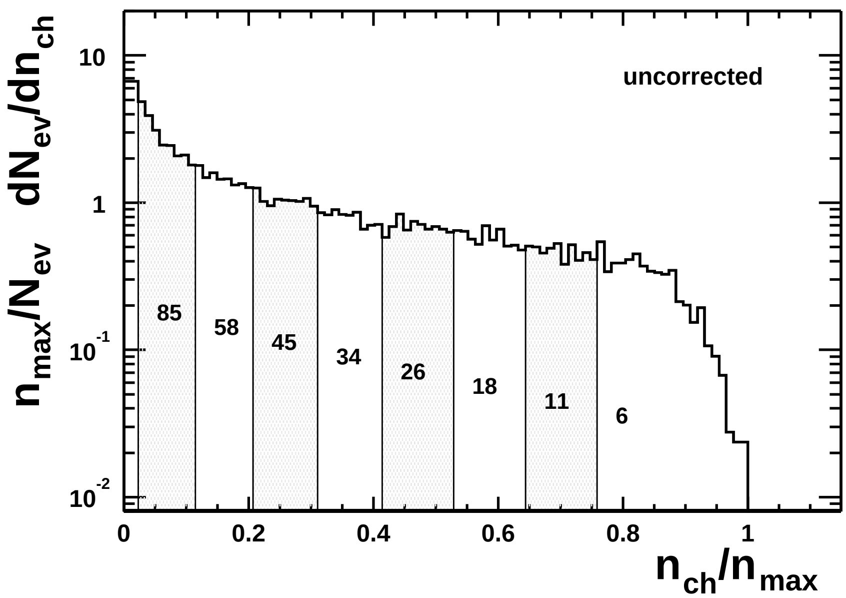
Negative hadrons



Data: STAR, Phys. Rev. Lett. **90**, 032301 (2003)

Centrality selection

STAR centrality cuts:

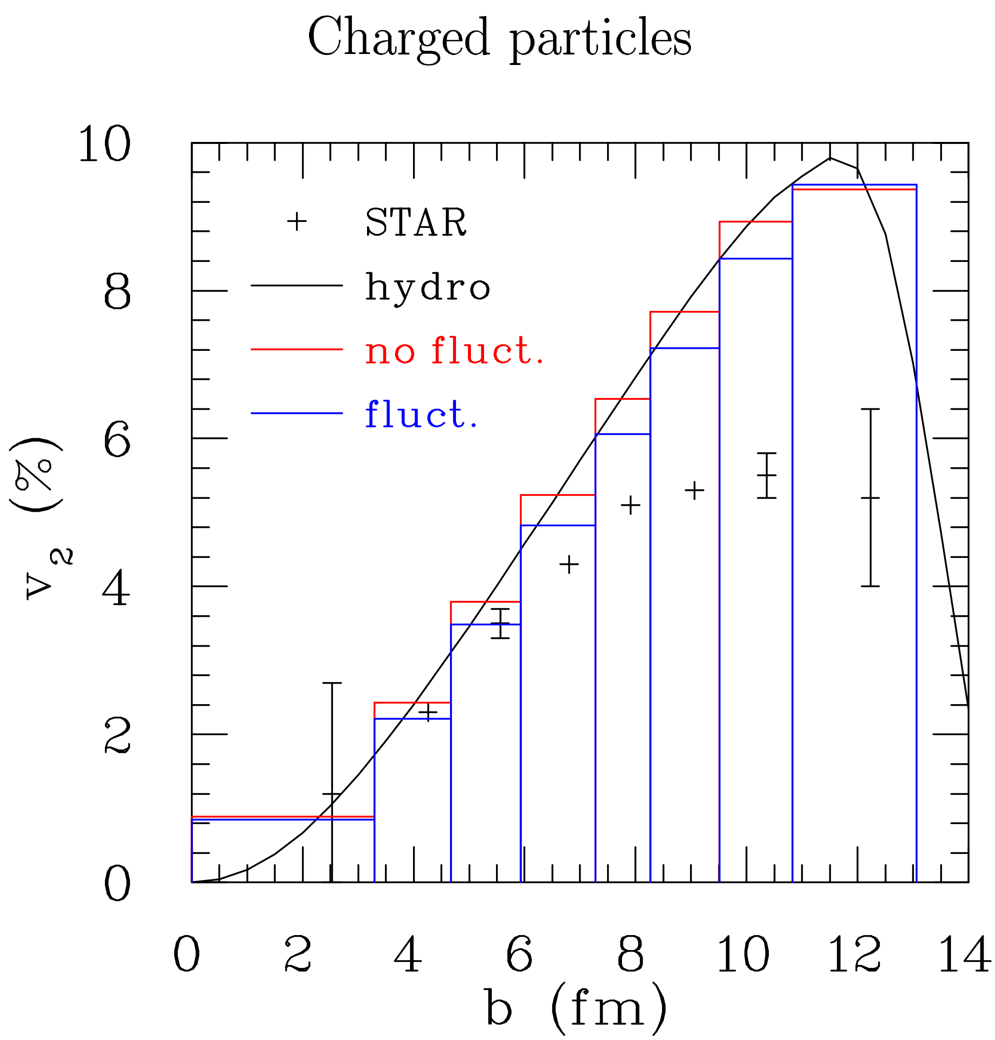


- Multiplicity at fixed b fluctuates $\rightarrow$ contributions from wide range of b in each bin.
- In hydro no fluctuations.
- Assume thermal fluctuations: $\langle \Delta N^2 \rangle = N$:

$$\mathcal{N}_{\rm events}(\mathcal{N}_{\rm ch}, \lfloor) \lceil \mathcal{N}_{\rm ch} \lceil \lfloor$$
$$\propto \frac{d\sigma}{db} \frac{1}{\sqrt{2\pi \langle N(b) \rangle}} \exp\left(-\frac{(\langle N(b) \rangle - N_{\rm ch})^2}{2\langle N \rangle} \right) dN_{\rm ch}\, db$$

- Cross section either from black disc ($R_{\rm max} = 14.7$ fm) or optical Glauber (difference negligible)

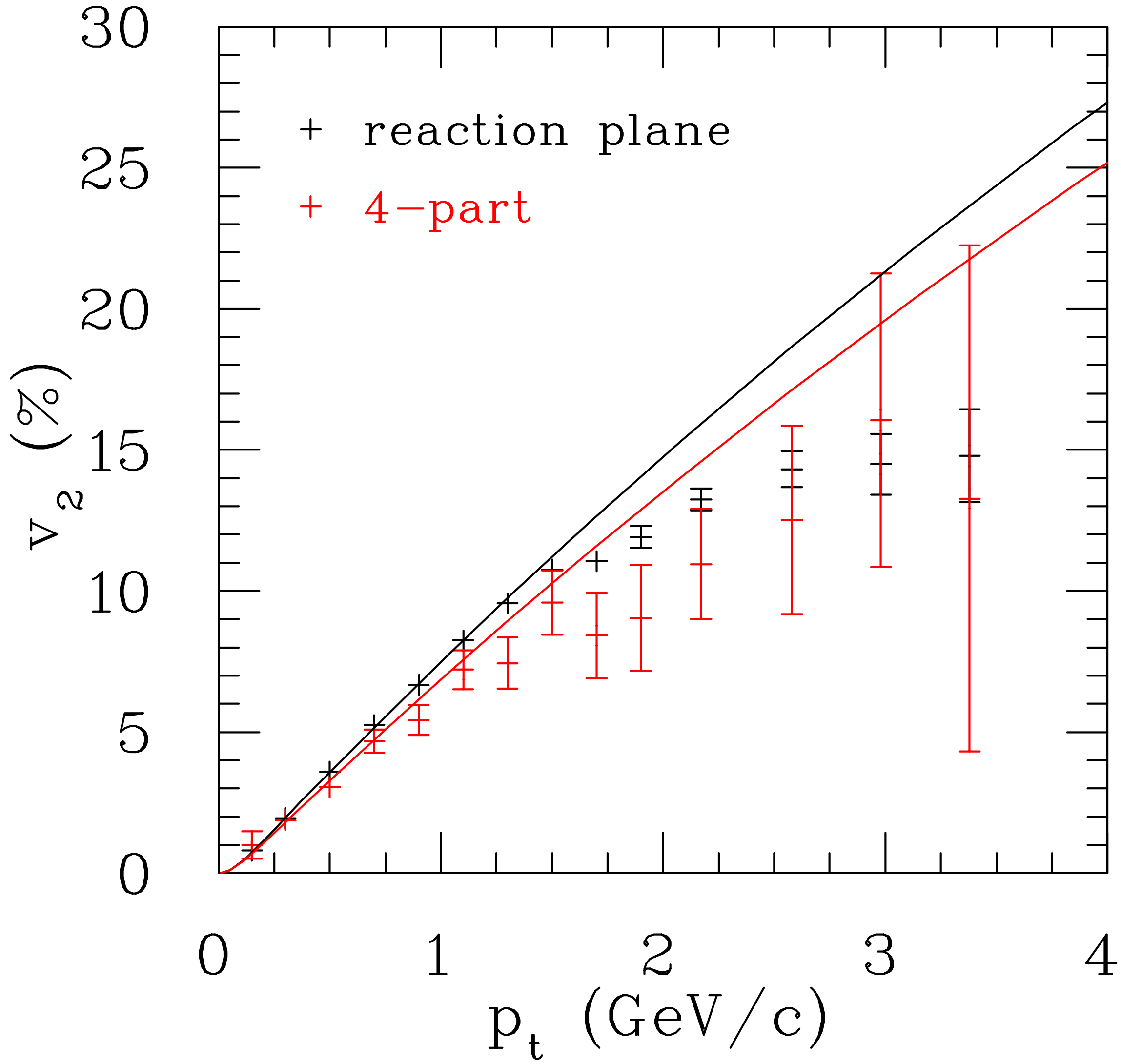
Elliptic anisotropy v_2 as function of centrality



Data: STAR, Phys. Rev. C **66**, 034904 (2002)

Charged hadrons, $v_2(p_t)$

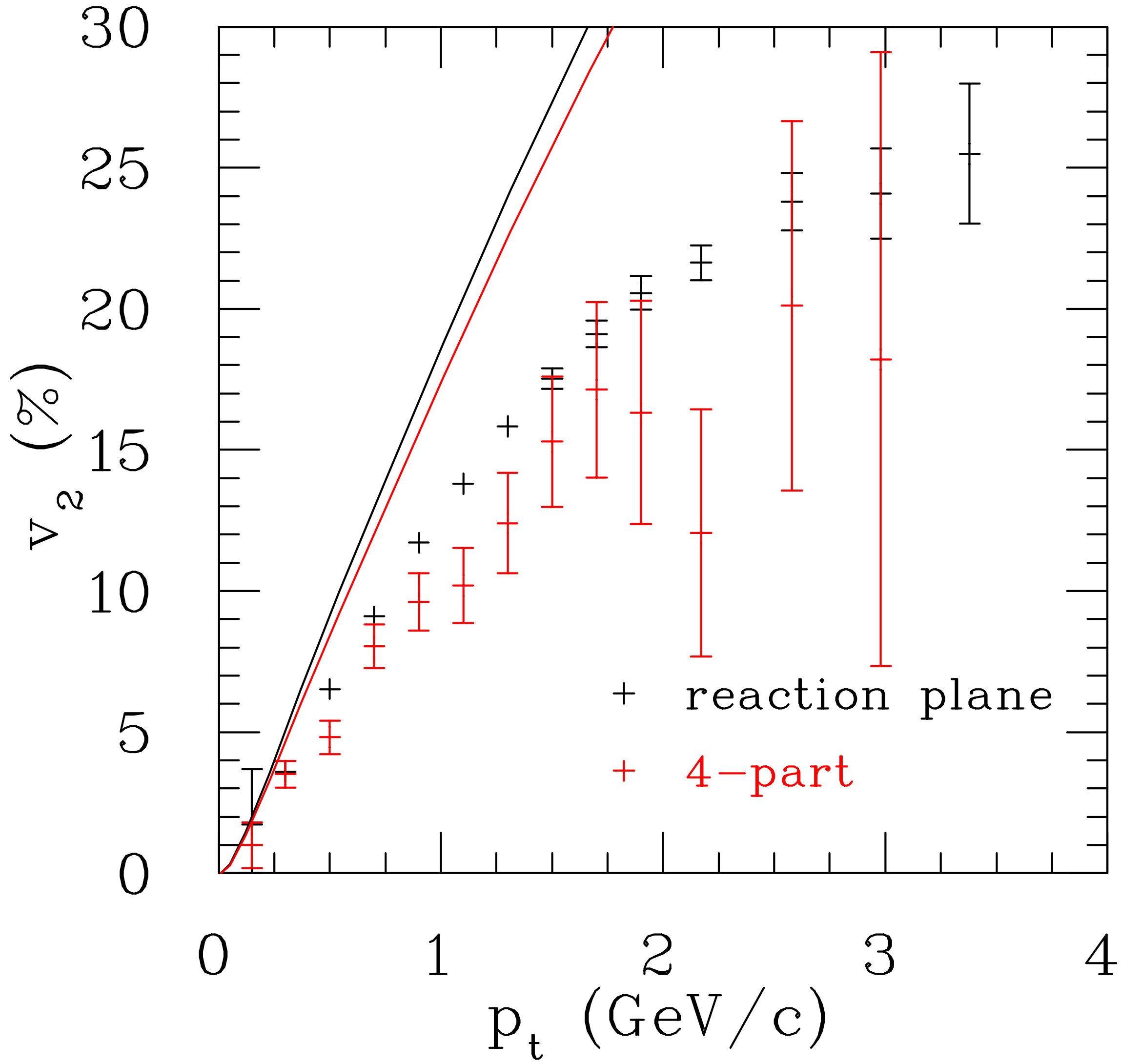
10%–16% centrality, $4.7 < b < 5.9$ fm



Data: STAR, Phys. Rev. C **66**, 034904 (2002)

Charged hadrons, $v_2(p_t)$

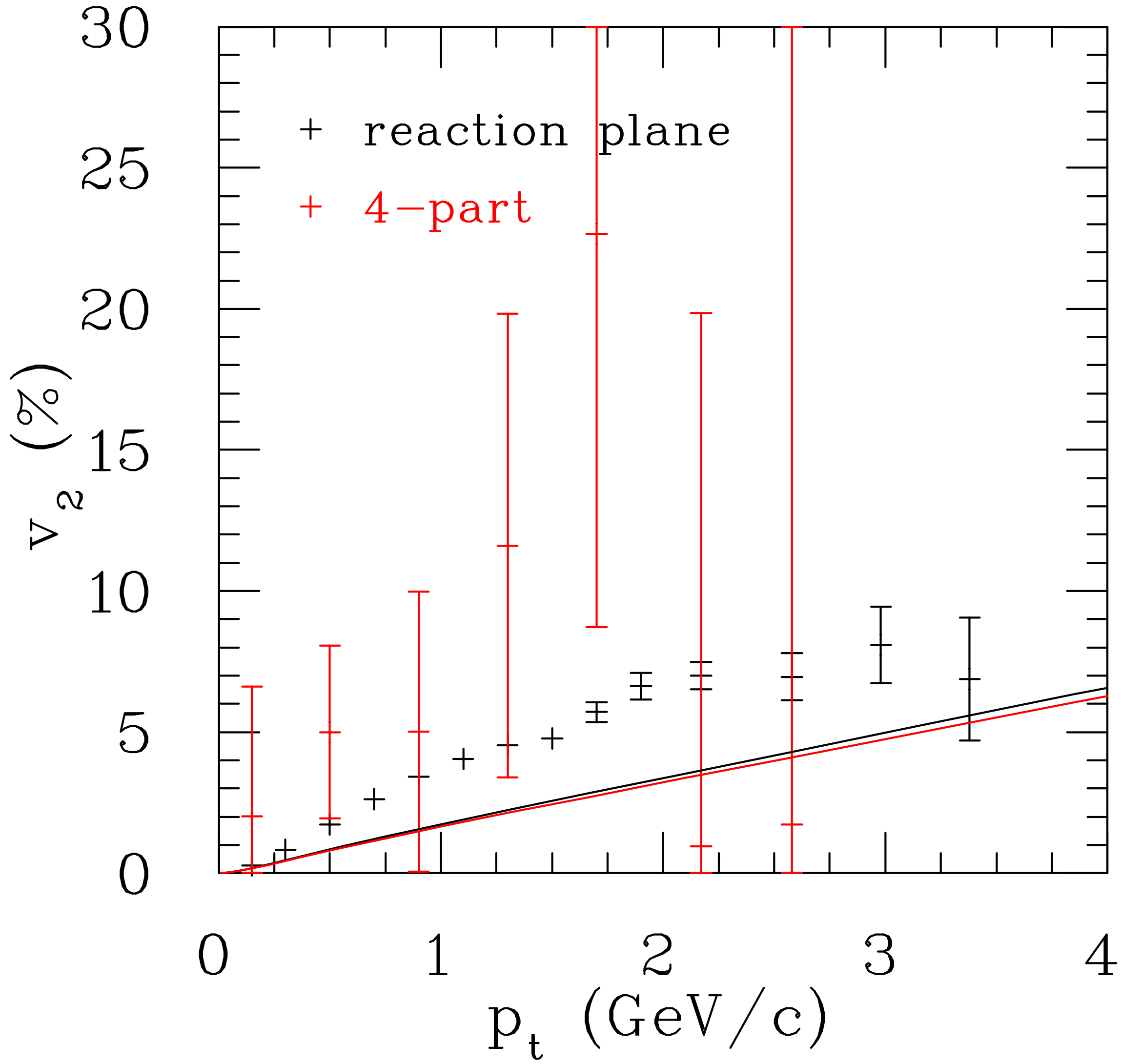
41%–53% centrality, $9.5 < b < 10.8$ fm



Data: STAR, Phys. Rev. C **66**, 034904 (2002)

Charged hadrons, $v_2(p_t)$

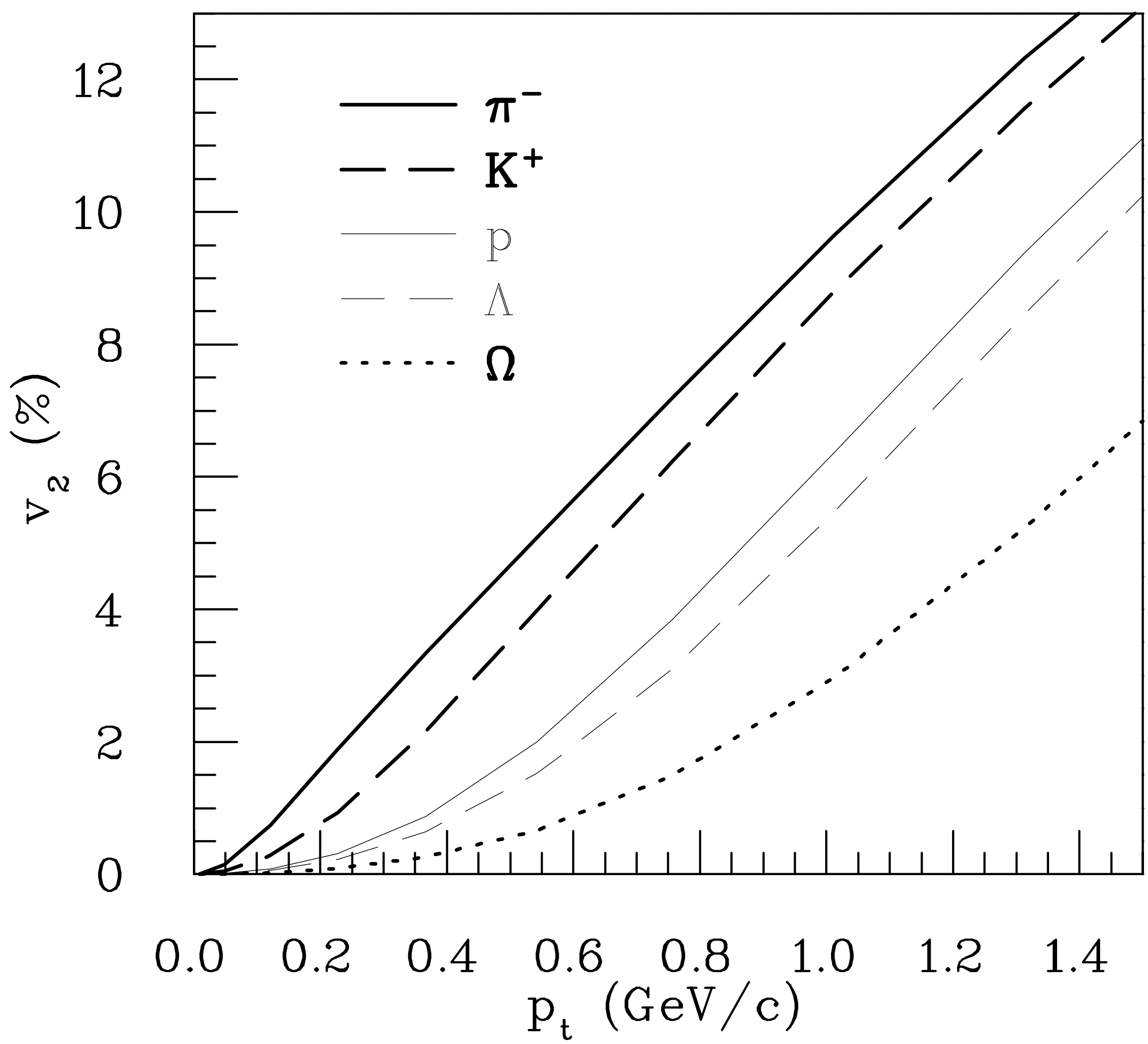
0%–5% centrality, $0 < b < 3.3$ fm



Data: STAR, Phys. Rev. C **66**, 034904 (2002)

Identified particle, $v_2(p_t)$

minimum bias

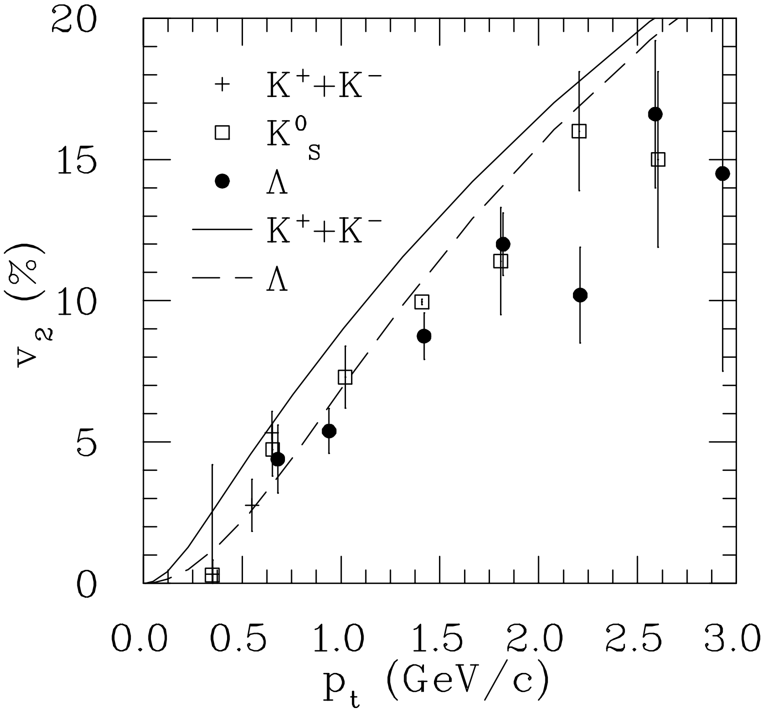


- Hydrodynamical prediction at low p_T:

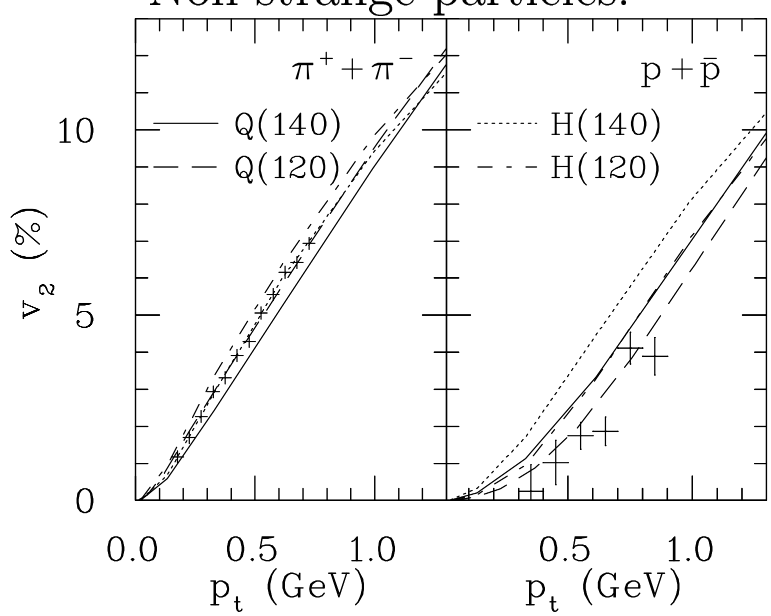
$$m_1 < m_2 \rightarrow v_2(p_T, m_1) > v_2(p_T, m_2)$$

Identified particle, $v_2(p_t)$

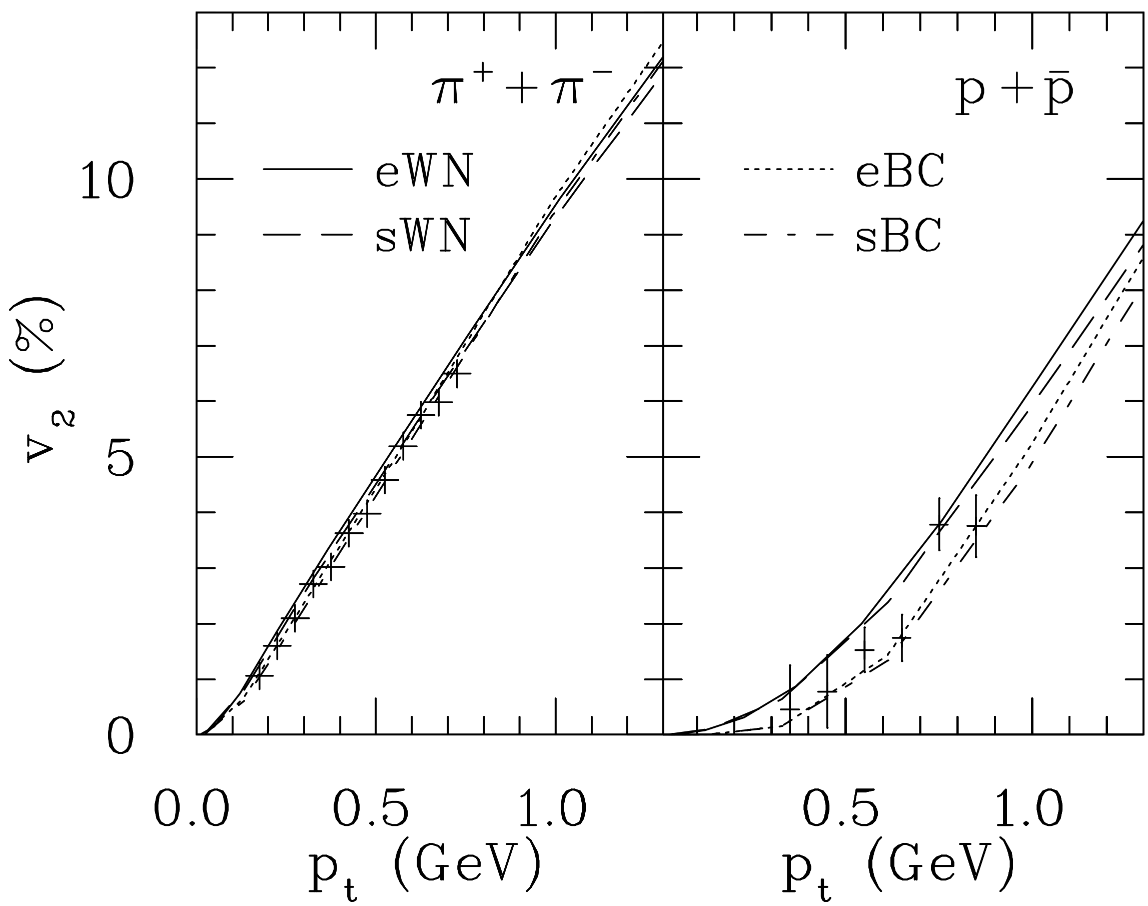
Strange particles:



Non-strange particles:



Effect of initial shape on identified particle v_2

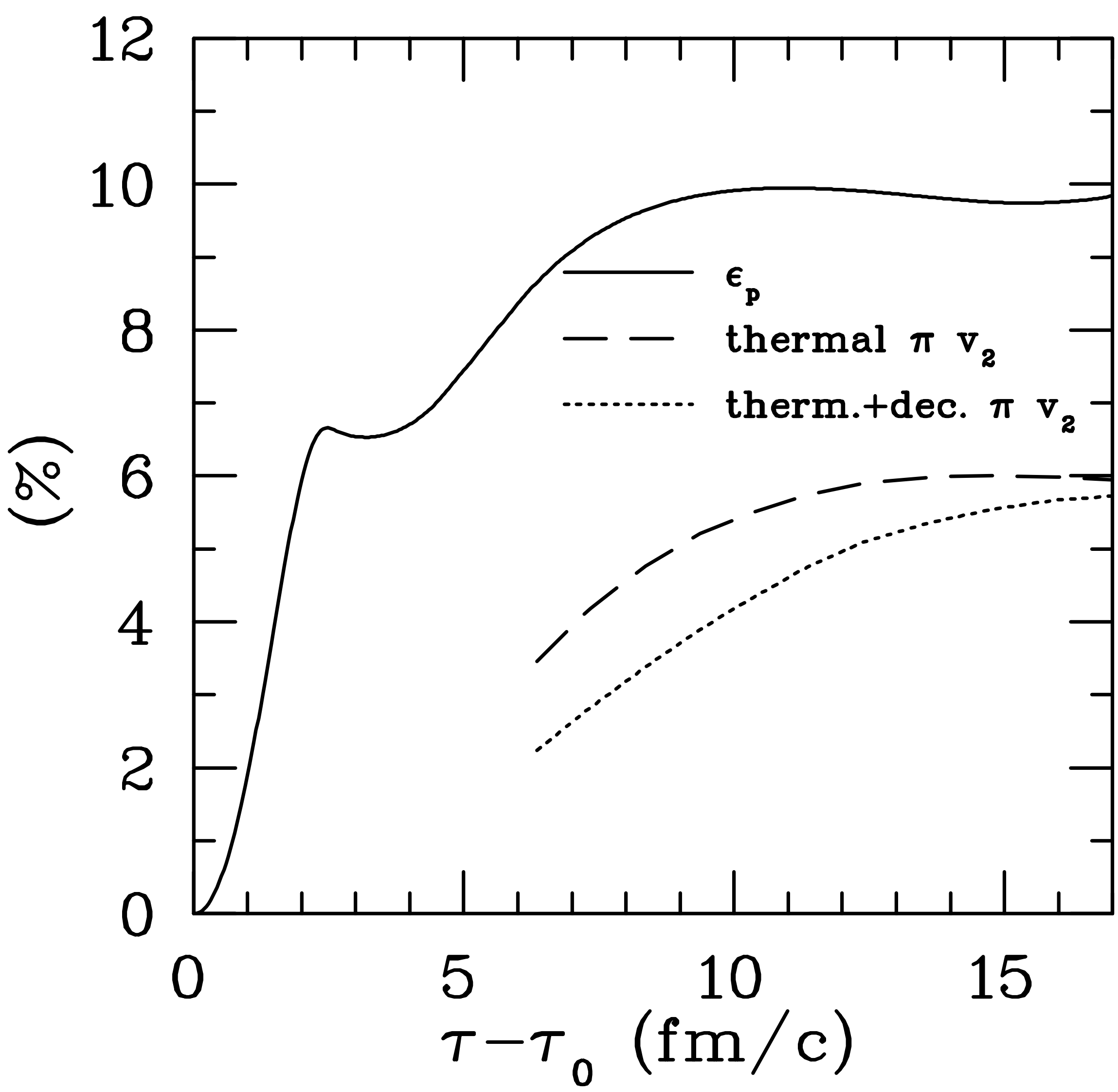


- Additional constraints from p_T spectra.
- Careful comparison not done yet.

When is v_2 built up?

- Sorge (PRL78,2309) and Kolb *et* al. (PRC62,054909): "Elliptic flow is a sign of early pressure"
- Momentum anisotropy

$$\varepsilon_p = \frac{T^{xx} - T^{yy}}{T^{xx} + T^{yy}}$$



Summary

- What works:
  - $v_2(p_T)$ of charged particles
  - Mass dependence of $v_2(p_T)$ of identified particles $\rightarrow$ Collision system behaves as thermal system at $b < 6$ fm.
- What needs to be done:
  - Short $\tau_0 < 1$ fm difficult to prove
  - Constraints for EoS still elusive
  - And HBT is also a puzzle...