Evolution of elliptic and triangular flow as a function of beam energy in a hybrid model

Jussi Auvinen
in collaboration with Hannah Petersen

Frankfurt Institute for Advanced Studies
Germany

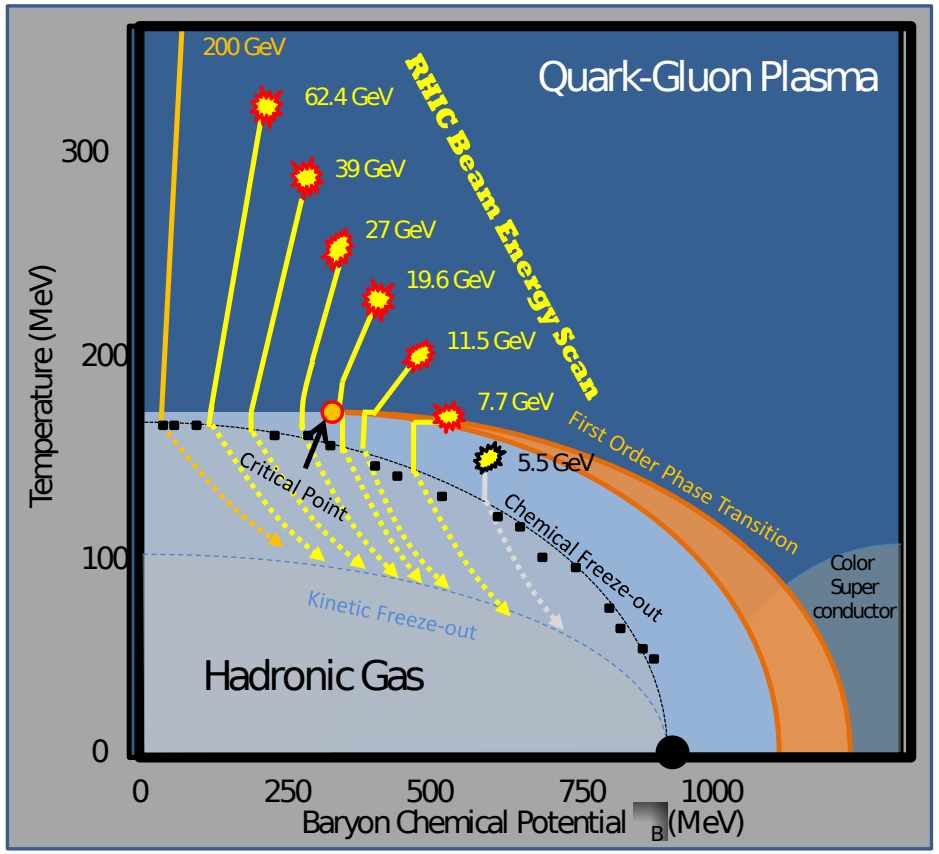
FAIRNESS 2013
September 19, 2013

Outline

Beam energy scan

First order phase transition with critical point?

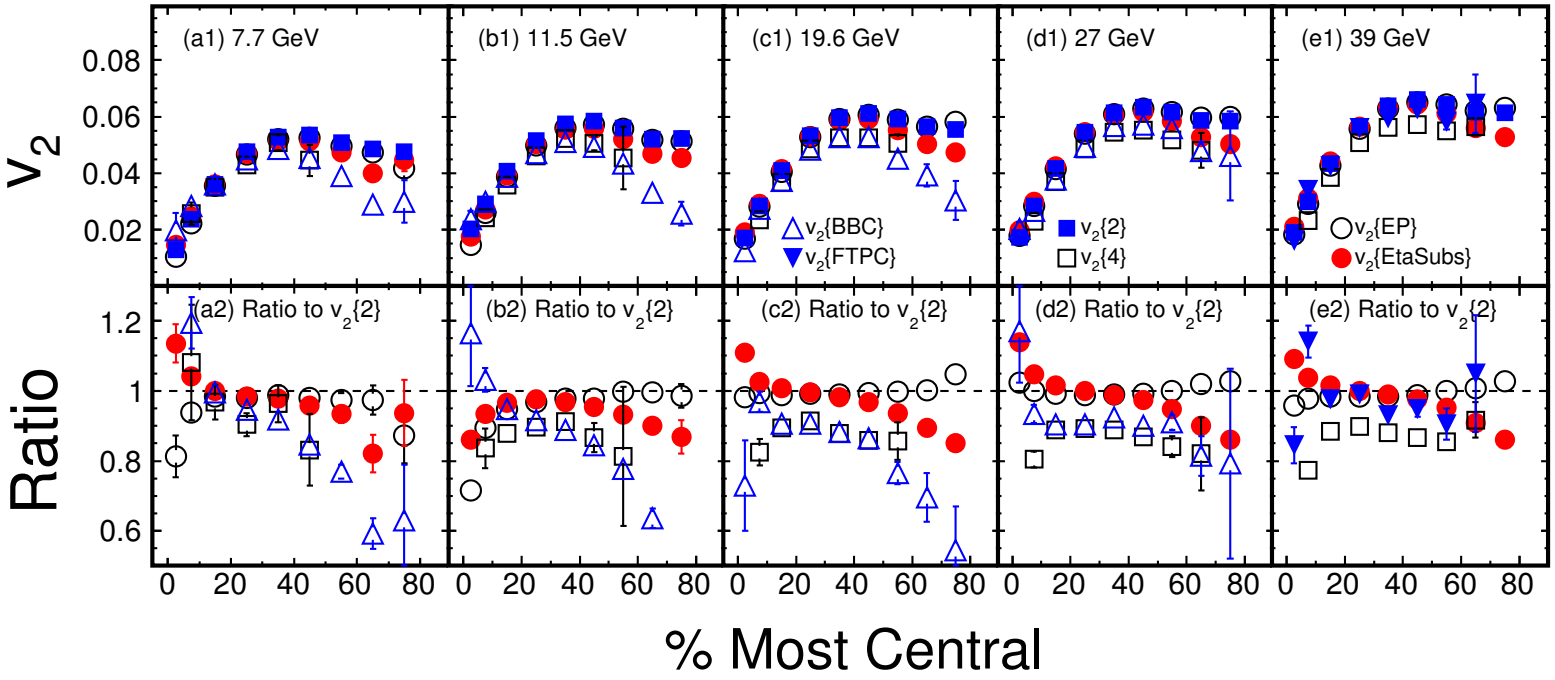
QGP volume and lifetime decreases with decreasing $\sqrt{s_{NN}}$ $\Rightarrow$ completely vanishes at some point? Any QGP at FAIR?



Picture taken from G. Odyniec, Acta Phys. Polon. B 43, 627 (2012).

Beam energy scan

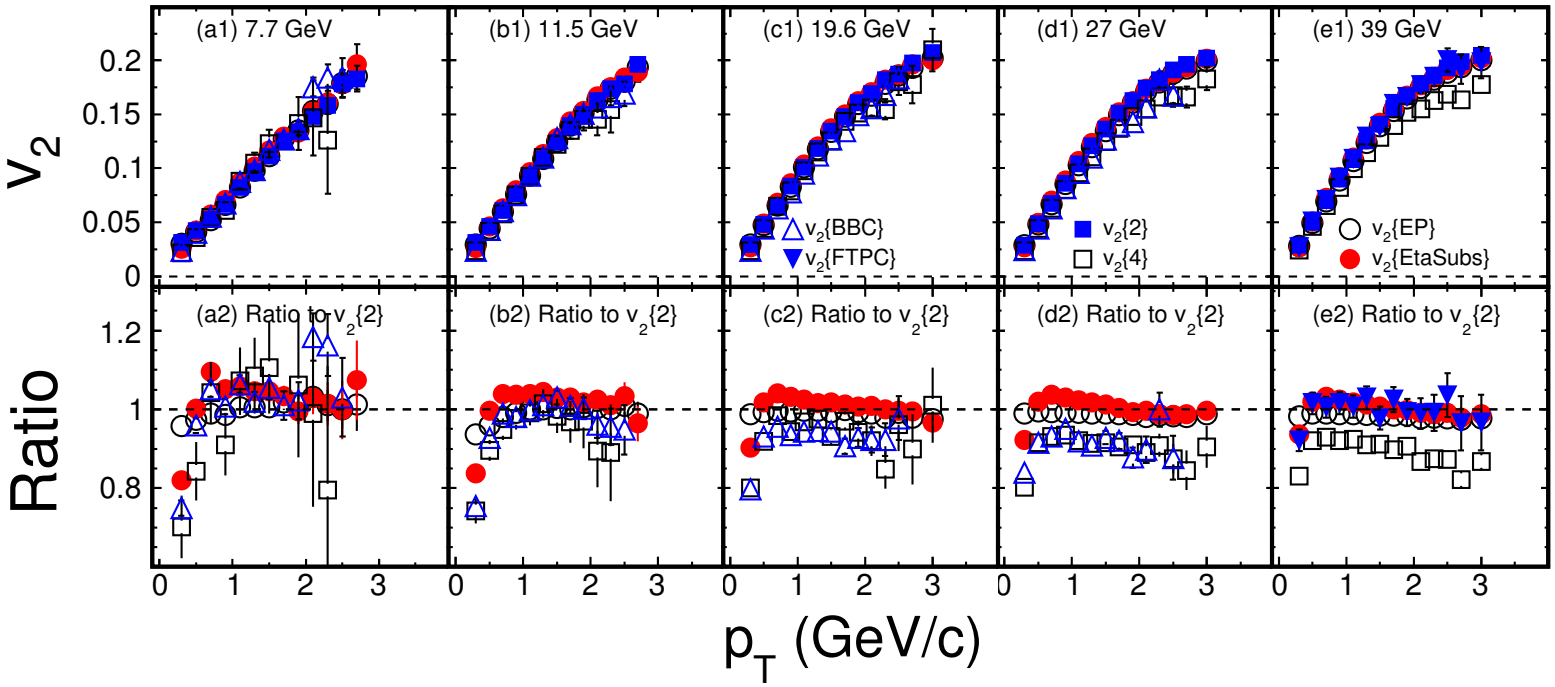
Flow observables v_n imply collective behavior in the system $\Rightarrow$ considered as evidence of QGP



Charged hadron v_2, however, shows only weak collision energy dependence (no turn-off seen on this signal!).

L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. C **86**, 054908 (2012).

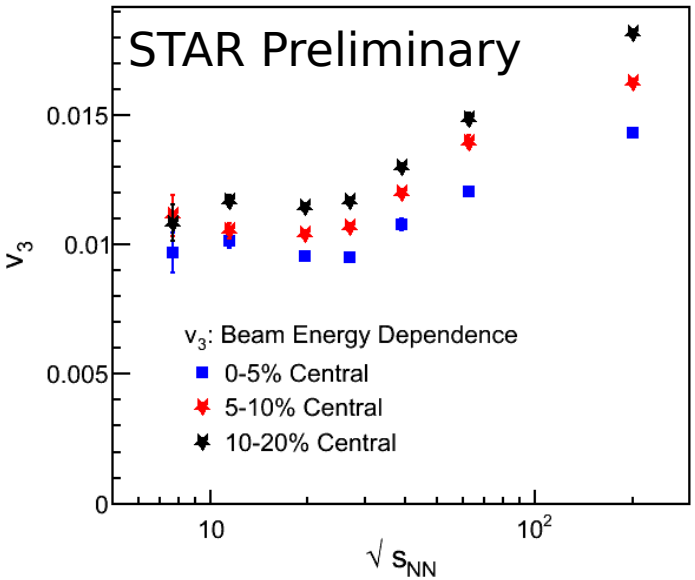
Beam energy scan

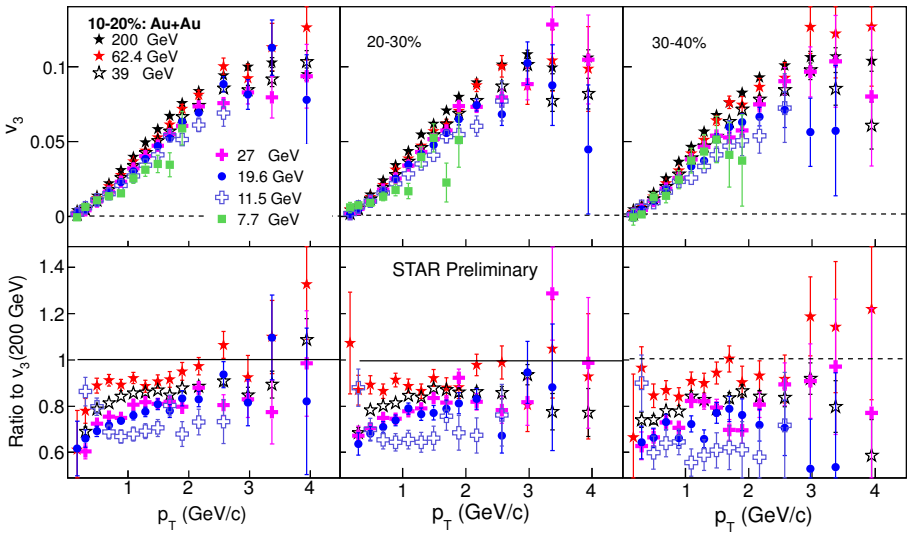


Differential v_2 almost identical for all $\sqrt{s_{NN}}$.

L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. C 86, 054908 (2012).

Beam energy scan





Y. Pandit [STAR Collaboration], QM2012 talk; arXiv:1210.5315.

v_3 more sensitive to beam energy? Generated solely by event-by-event fluctuations of the initial state, while v_2 is strongly affected also by collision geometry.

Can these dependencies be reproduced using a hybrid model?

Transport + hydrodynamics hybrid model

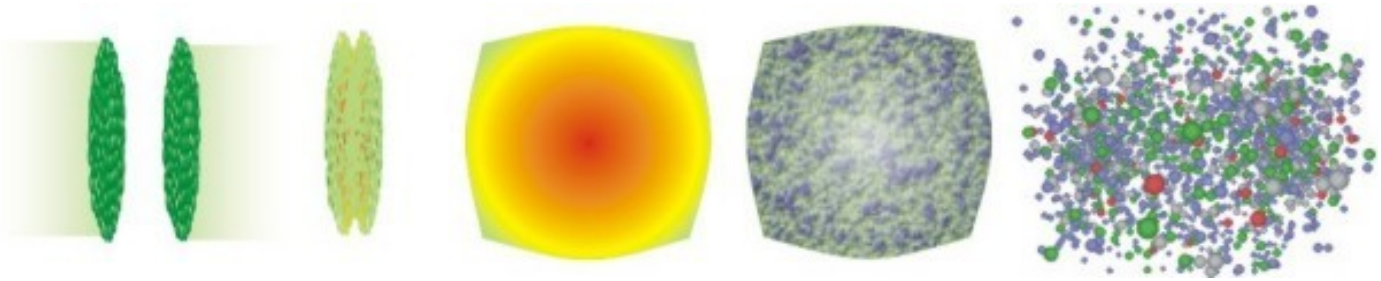


Image source: Duke University

Transport

- Microscopic description of the whole phase-space distribution
- Non-equilibrium evolution based on the Boltzmann equation

$$p^\mu \partial_\mu f_i(x,p) = C_i$$

- Partonic or hadronic degrees of freedom
- Phase transition?

Hydrodynamics

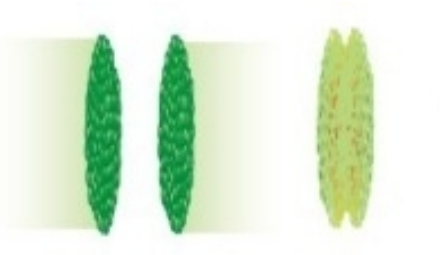
- Macroscopic description
- Local equilibrium is assumed
- System evolves according to conservation laws

$$\partial_\mu T^{\mu\nu} = 0,\ \partial_\mu N^\mu = 0$$

- Equation of state provides the phase transition
- Before and after: Initial conditions? Freeze-out?

Transport + hydrodynamics hybrid model

H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stocker, Phys. Rev. C 78, 044901 (2008).



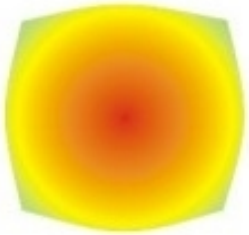
Initial State from UrQMD[1] string/hadronic cascade

- Start the hydrodynamical evolution when nuclei have passed through each other: $t_{\text{start}} = \max\{\frac{2R_{\text{nucleus}}}{\sqrt{\gamma_{CM}^2-1}}, 0.5 \text{ fm}\}$.
- Energy-, momentum- and baryon number densities (3D Gaussians) are mapped onto the hydro grid
- Event-by-event fluctuations are taken into account (width of Gaussians $\sigma = 1.0$ fm)
- Spectators are propagated separately in the cascade

[1] S. A. Bass *et al.*, Prog. Part. Nucl. Phys. 41, 255 (1998), M. Bleicher *et al.*, J. Phys. G 25, 1859 (1999).

Transport + hydrodynamics hybrid model

H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stocker. Phys. Rev. C **78**, 044901 (2008).



Hydrodynamical evolution

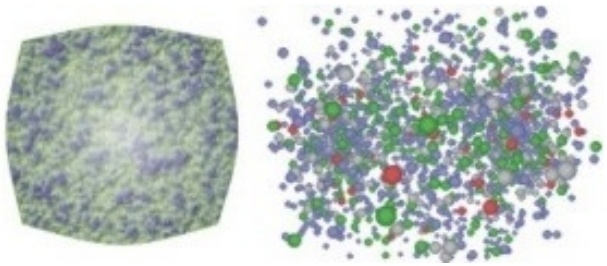
- (3+1)D ideal hydrodynamics using SHASTA[2]
- Equation of state[3]:
  - Chiral model coupled to Polyakov loop to include the deconfinement phase transition
  - Qualitative agreement with lattice QCD data at $\mu_B = 0$
  - Applicable also at finite baryon densities
  - Has the same degrees of freedom as UrQMD in hadronic phase

[2] D. H. Rischke, S. Bernard and J. A. Maruhn, Nucl. Phys. A **595**, 346 (1995), D. H. Rischke, Y. Pursun and J. A. Maruhn, Nucl. Phys. A **595**, 383 (1995).

[3] J. Steinheimer, S. Schramm and H. Stocker, J. Phys. G **38**, 035001 (2011).

Transport + hydrodynamics hybrid model

H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stocker, Phys. Rev. C 78, 044901 (2008).



Freeze-out Procedure

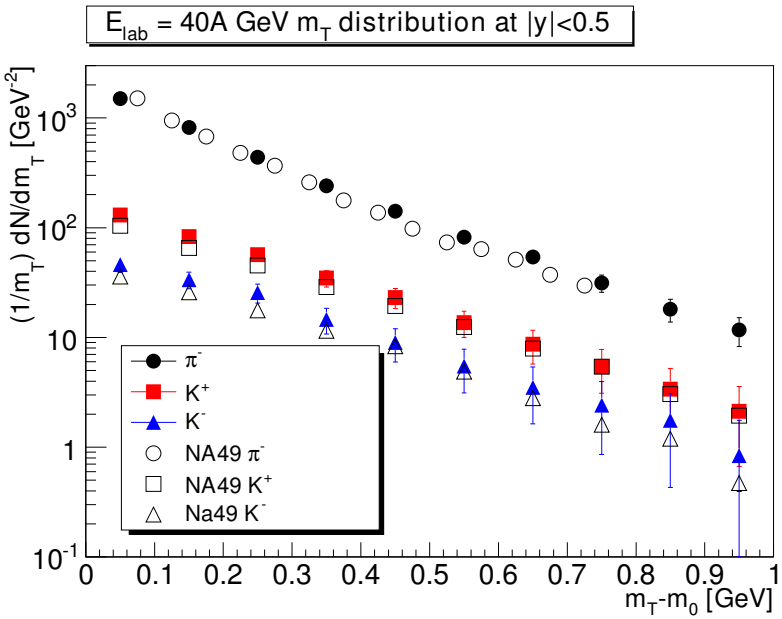
- Transition from hydro to transport ("particlization") when energy density ϵ is smaller than critical value $x\epsilon_0$, where $\epsilon_0 = 146$ MeV/fm^3 represents the nuclear ground state and $x \geq 1$.[4]
- Cornelius hypersurface finding algorithm

  P. Huovinen and H. Petersen, arXiv:1206.3371.
- Particle distributions are generated according to the Cooper-Frye formula
- Rescatterings and final decays calculated via hadronic cascade (UrQMD)

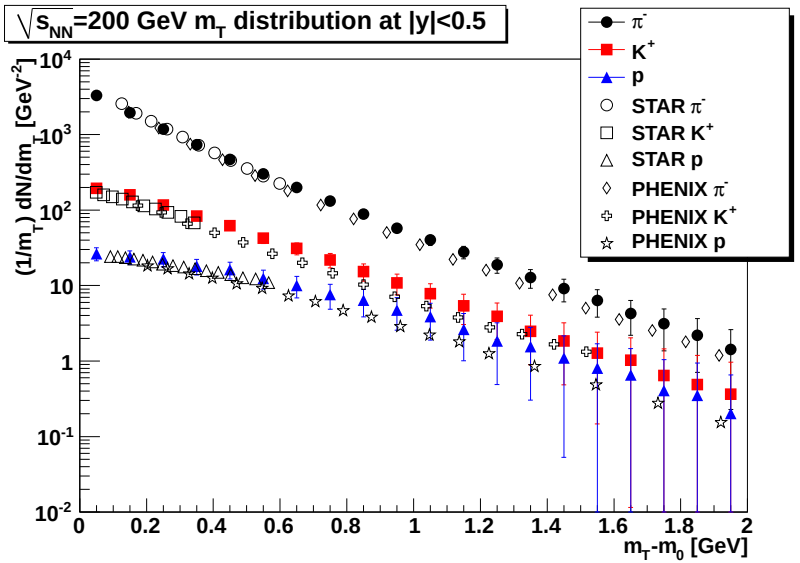
[4] In this study $x = 2$, corresponding to temperature $T \approx 154$ MeV.

Particle m_T spectra

(0-7)% centrality.



(0-5)% centrality.



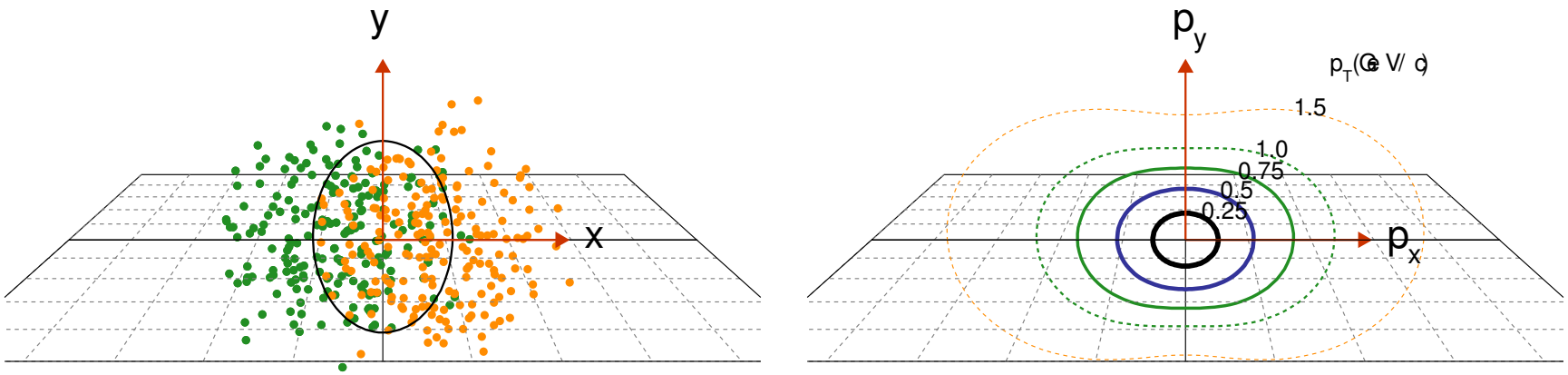
Left: π^-, K^+, K^- at $\sqrt{s_{NN}} \approx 9$ GeV.
Right: π^-, K^+, p at $\sqrt{s_{NN}} = 200$ GeV.

S. V. Afanasiev *et al.* [NA49 Collaboration], Phys. Rev. C **66**, 054902 (2002).
J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **92**, 112301 (2004),

S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. C **69**, 034909 (2004).

Elliptic flow

Generated by pressure gradients due to spatial anisotropy of initial state.

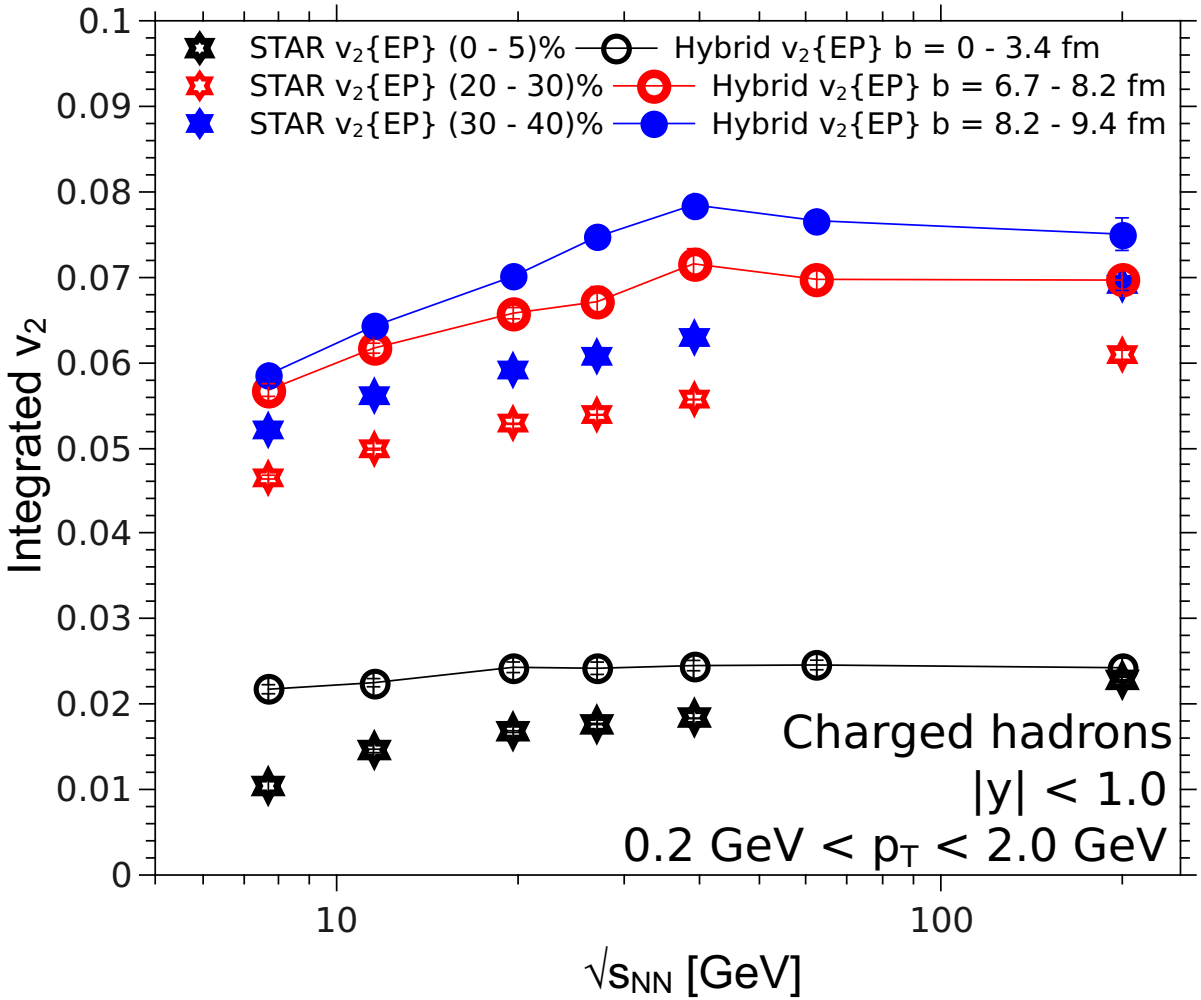


P. Sorensen, arXiv:0905.0174 [nucl-ex].

Initial spatial anisotropy: eccentricity $\epsilon_2 = \frac{\sqrt{\langle r^2 \cos(2\phi)\rangle^2 + \langle r^2 \sin(2\phi)\rangle^2}}{\langle r^2 \rangle}$.

Final momentum anisotropy: $v_2\{\text{EP}\} = \frac{v_2\{\text{observed}\}}{R_2} = \frac{\langle\langle \cos[2(\phi_i - \psi_2)]\rangle\rangle}{\langle \cos[2(\psi_2 - \psi_2^{\text{true}})]\rangle}$

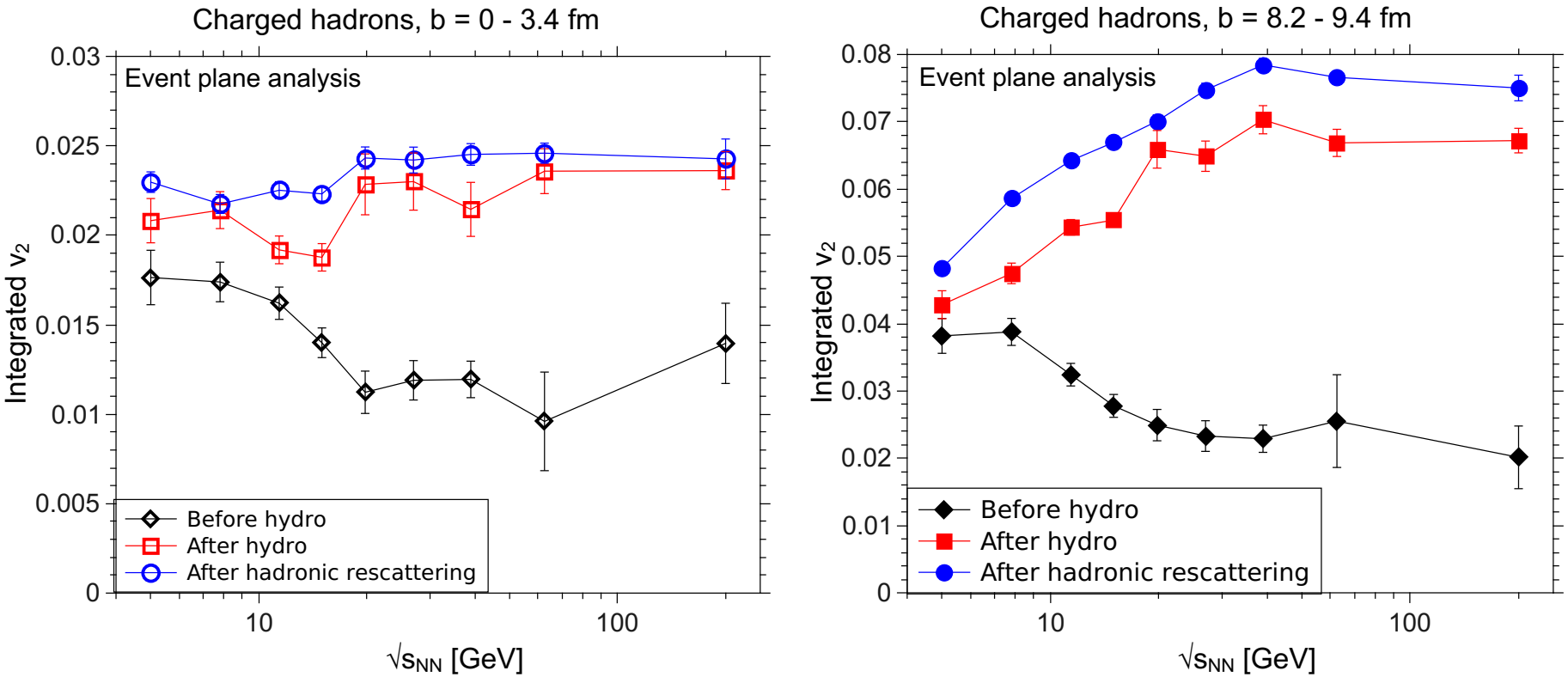
Elliptic flow



Rising slope in 0-5% centrality not reproduced; qualitative agreement at midcentrality.

L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. C 86, 054908 (2012).

Elliptic flow

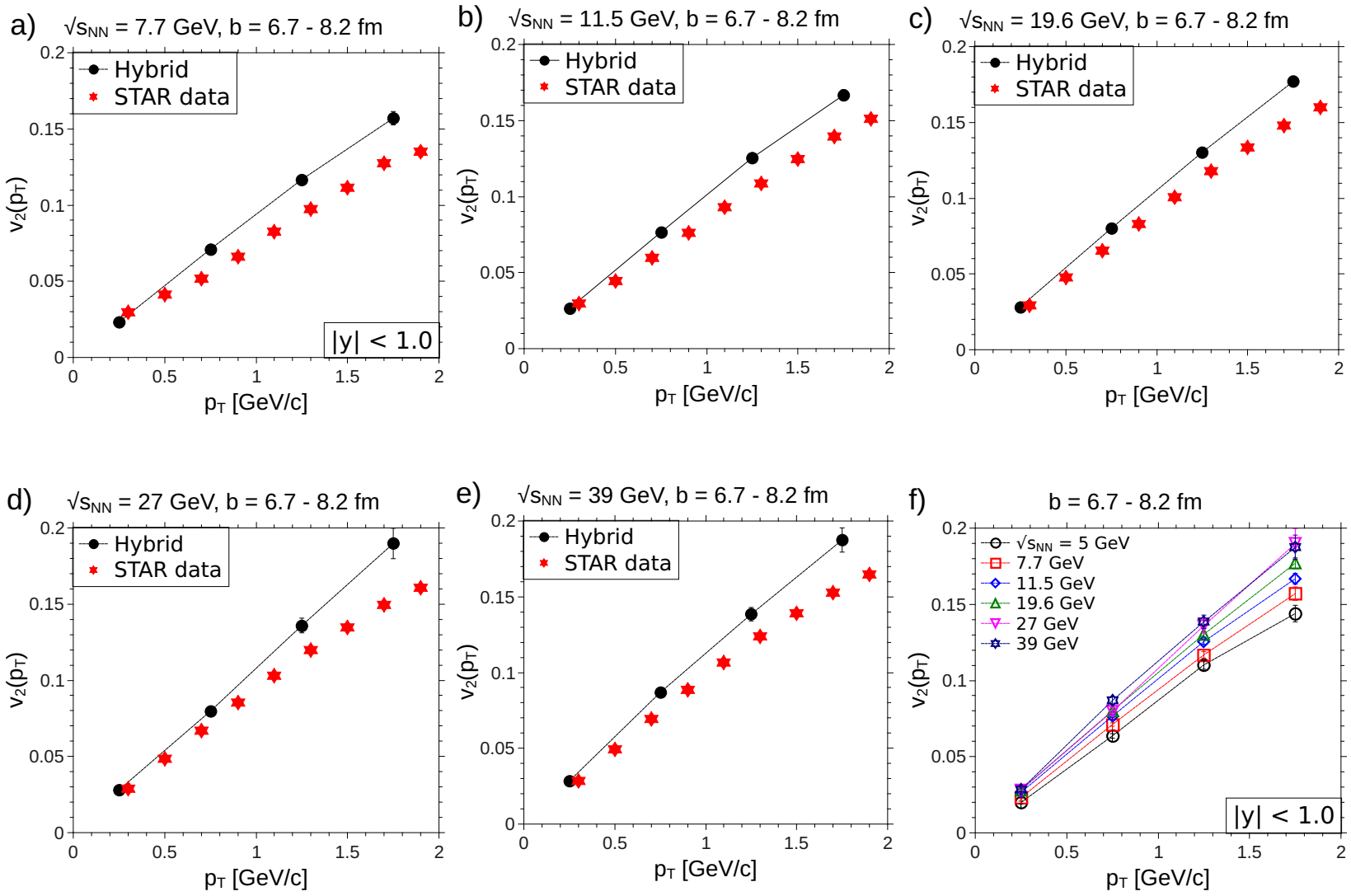


No contribution from hadronic rescattering in most central collisions. In midcentral collisions $\approx 10\%$ effect.

Pre-equilibrium dynamics more important at lower energies.

Hydro contribution vanishes at $\sqrt{s_{NN}} = 5$ GeV.

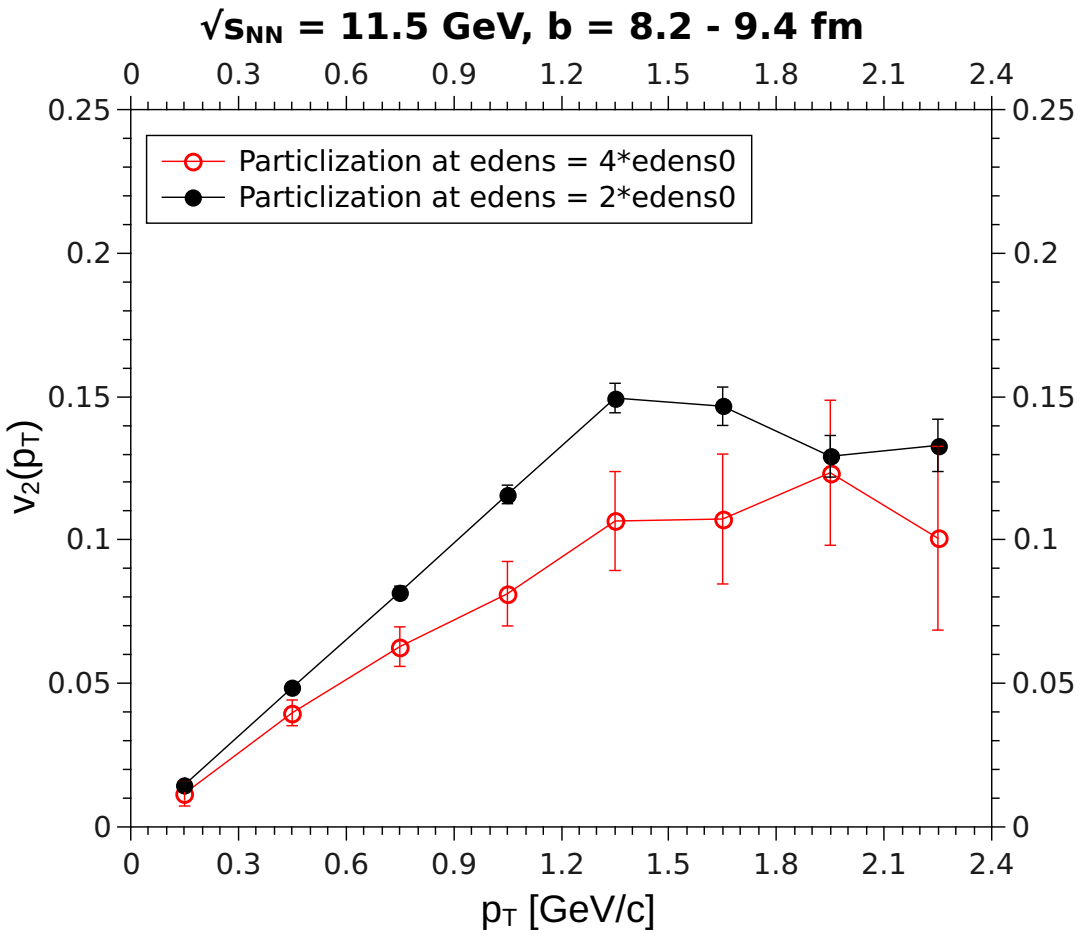
Elliptic flow



$v_2(p_T)$ overestimated at higher p_T. Add viscosity? Particlization condition?

L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. C **86**, 054908 (2012).

Effect of particlization condition on elliptic flow



The earlier end of the hydrodynamical evolution flattens the p_T-slope.

Triangular flow

Originates from the event-by-event fluctuations in the spatial nucleon configuration of the initial state.

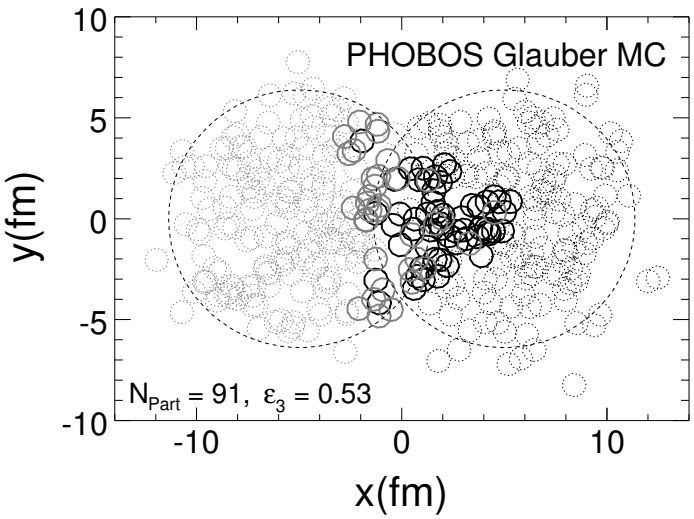


FIG. 3: Distribution of nucleons on the transverse plane for a $\sqrt{s_{NN}}$ = 200 GeV Au+Au collision event with ε_3=0.53 from Glauber Monte Carlo. The nucleons in the two nuclei are shown in gray and black. Wounded nucleons (participants) are indicated as solid circles, while spectators are dotted circles.

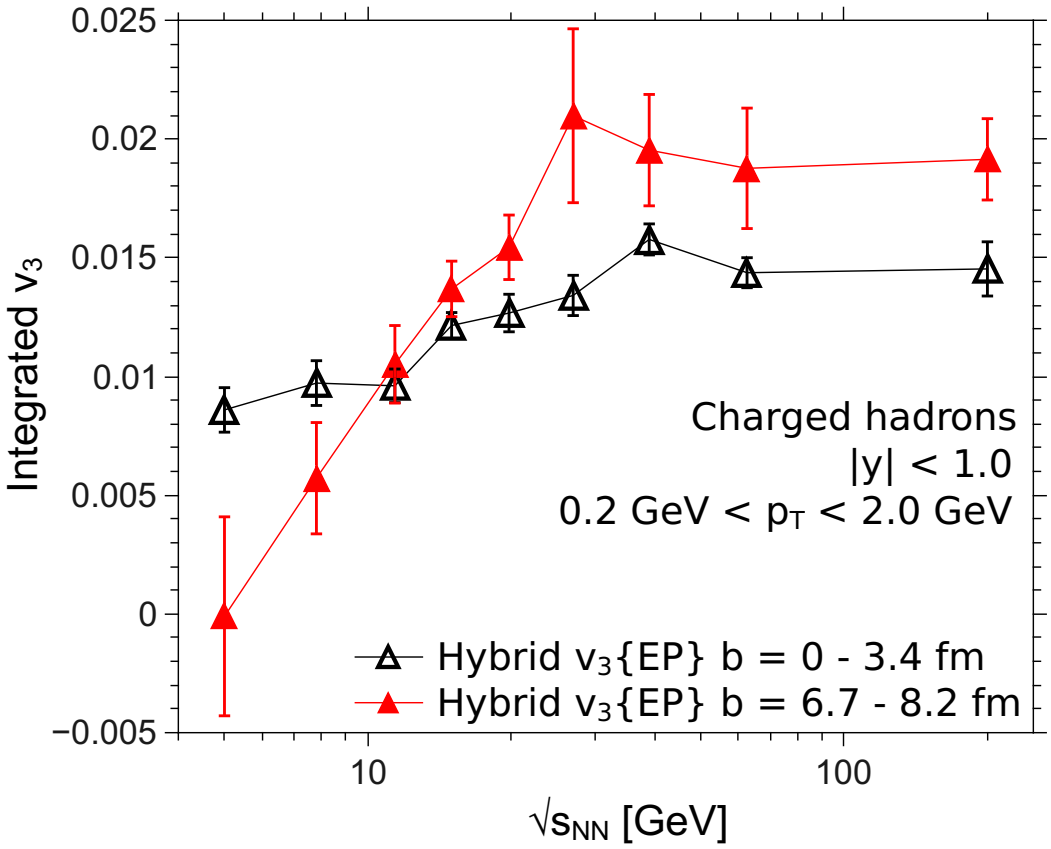
Triangularity:

$$\epsilon_3 = \frac{\sqrt{\langle r^3 \cos(3\phi)\rangle^2 + \langle r^3 \sin(3\phi)\rangle^2}}{\langle r^3 \rangle}$$

$$v_3\{\mathrm{EP}\} = \frac{\langle\langle \cos[3(\phi_i - \psi_3)]\rangle\rangle}{\langle \cos[3(\psi_3 - \psi_3^{\mathrm{true}})]\rangle}$$

B. Alver and G. Roland, Phys. Rev. C 81, 054905 (2010), [arXiv:1003.0194].

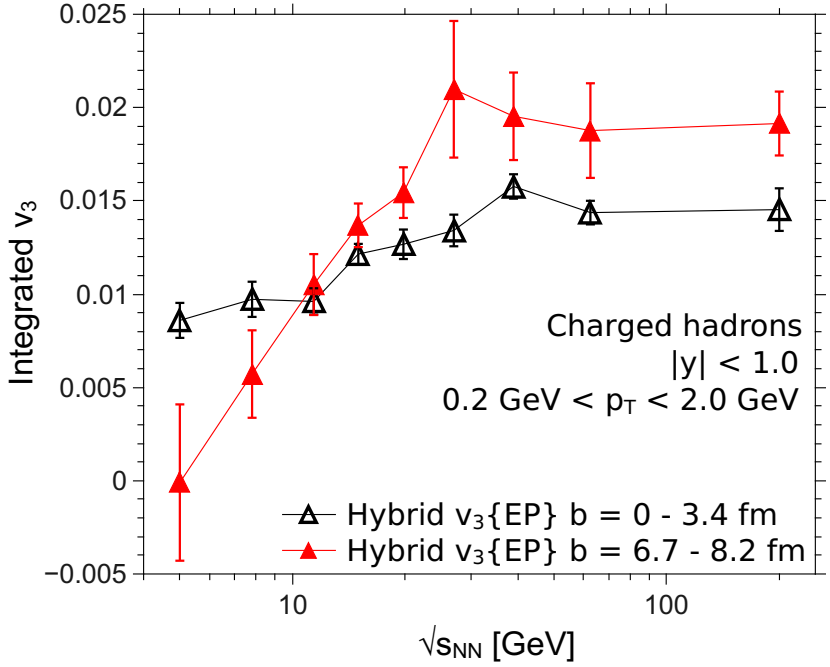
Triangular flow

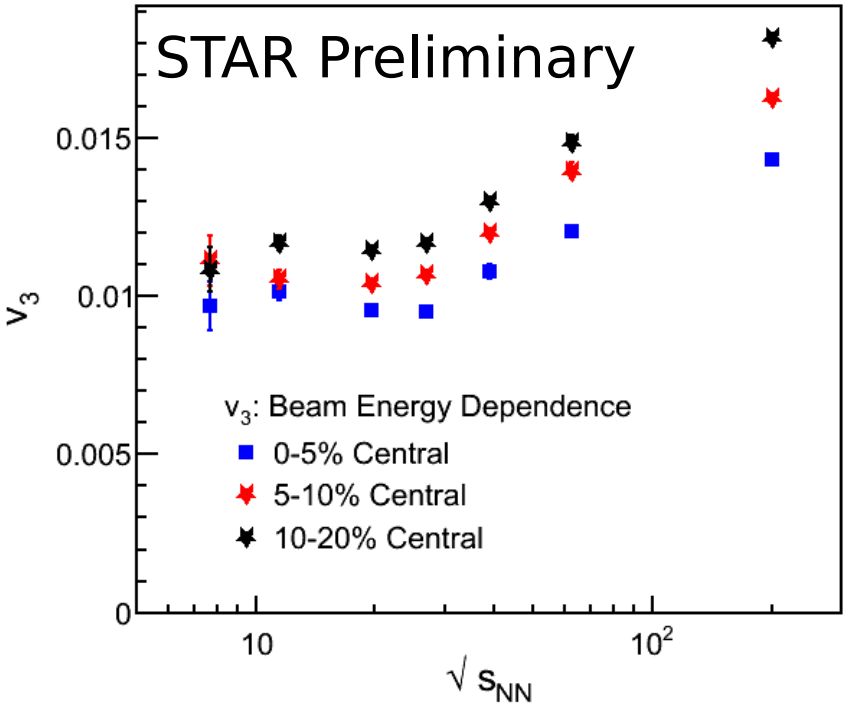


Clear energy dependence from $\sqrt{s_{NN}}$ =5 to 27 GeV!

Total v_3 vanishes at $\sqrt{s_{NN}} = 5$ GeV (no compensation from transport)

Triangular flow

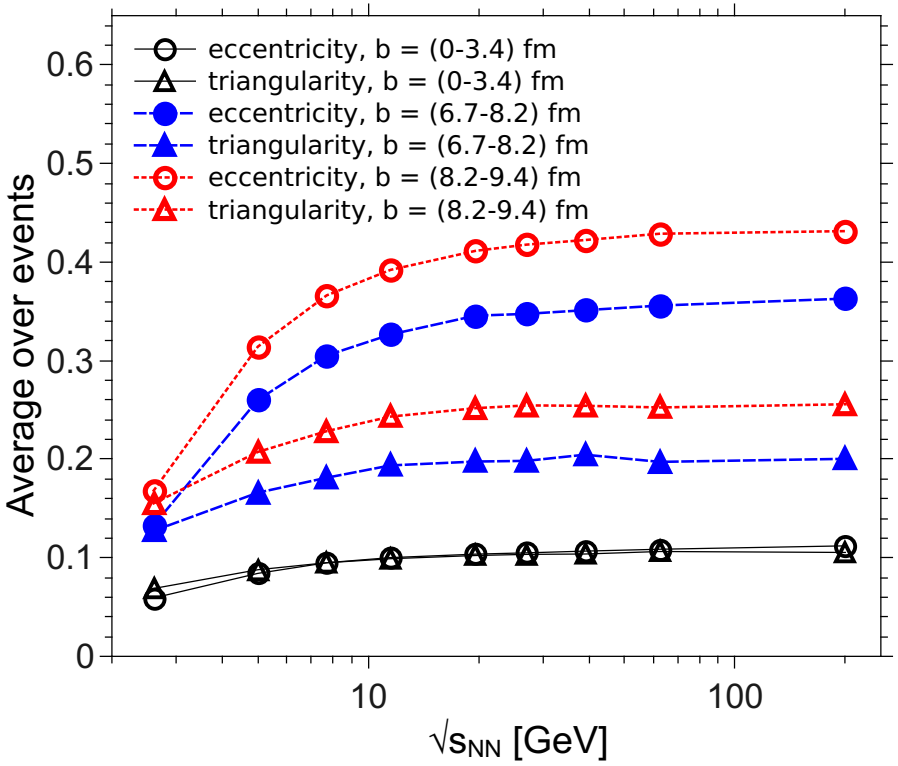


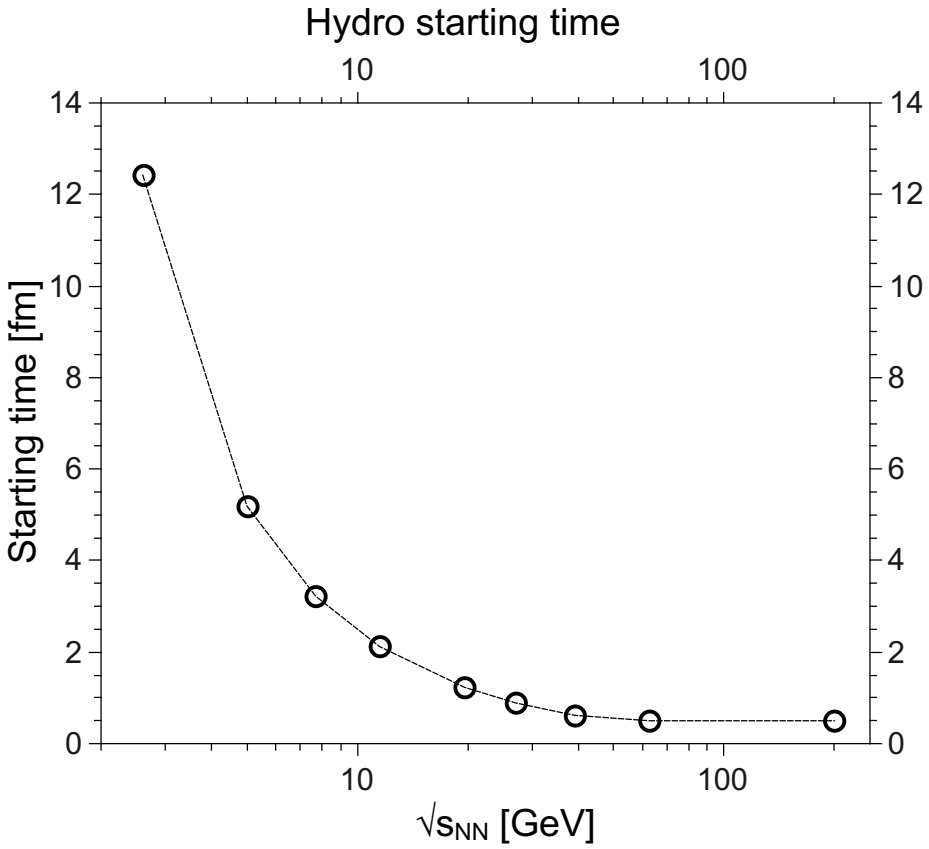


Preliminary data shows a somewhat different energy evolution.
Agreement on the magnitude in central collisions.

Y. Pandit [STAR Collaboration], QM2012 talk.

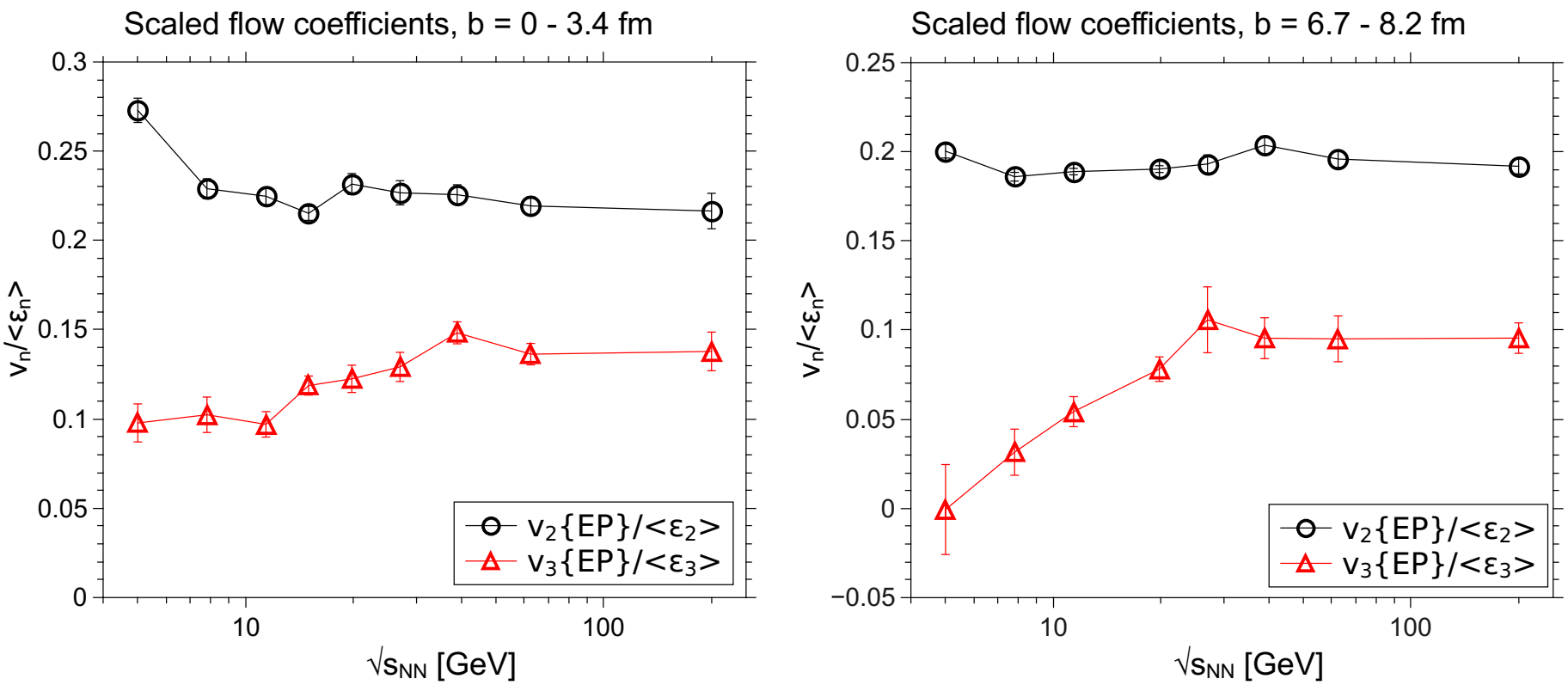
Collision geometry





ϵ_2 more sensitive than ϵ_3 to changes on b and $\sqrt{s_{NN}}$.
$\sqrt{s_{NN}}$-dependence mainly due to the longer initial transport evolution.

Scaled flow coefficients

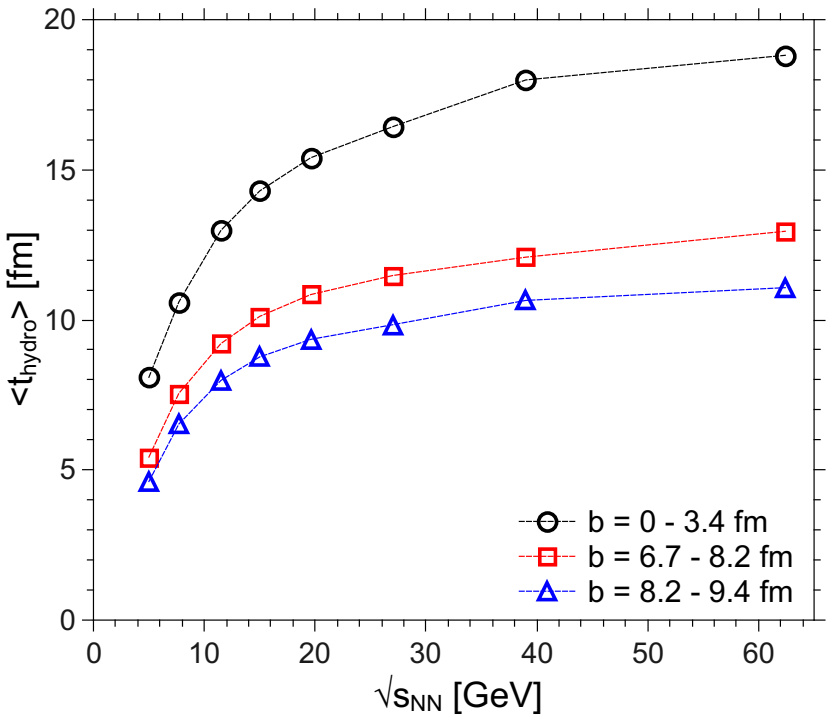


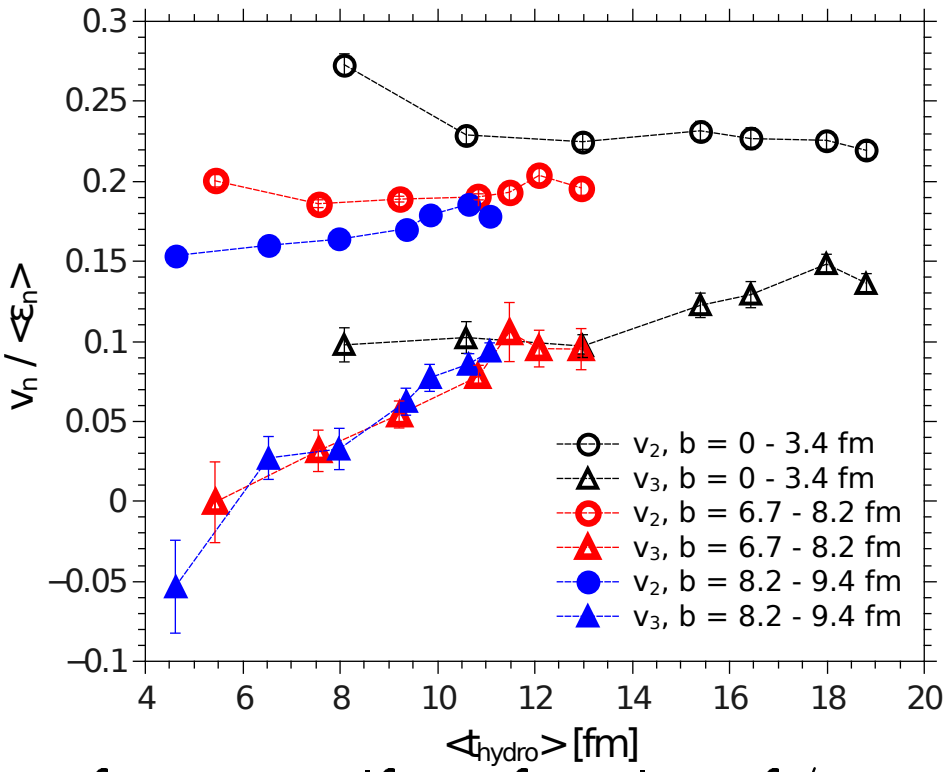
v_2 response to ϵ_2 remains roughly the same in both centrality classes and all energies.

Energy dependence of v_3 persists through scaling.

Scaled flow coefficients

$\langle t_{\rm hydro} \rangle$ = average total duration of hydrodynamical phase in the simulation





v_3 generated purely by hydro $\Rightarrow$ points form an uniform function of $\langle t_{\rm hydro} \rangle$

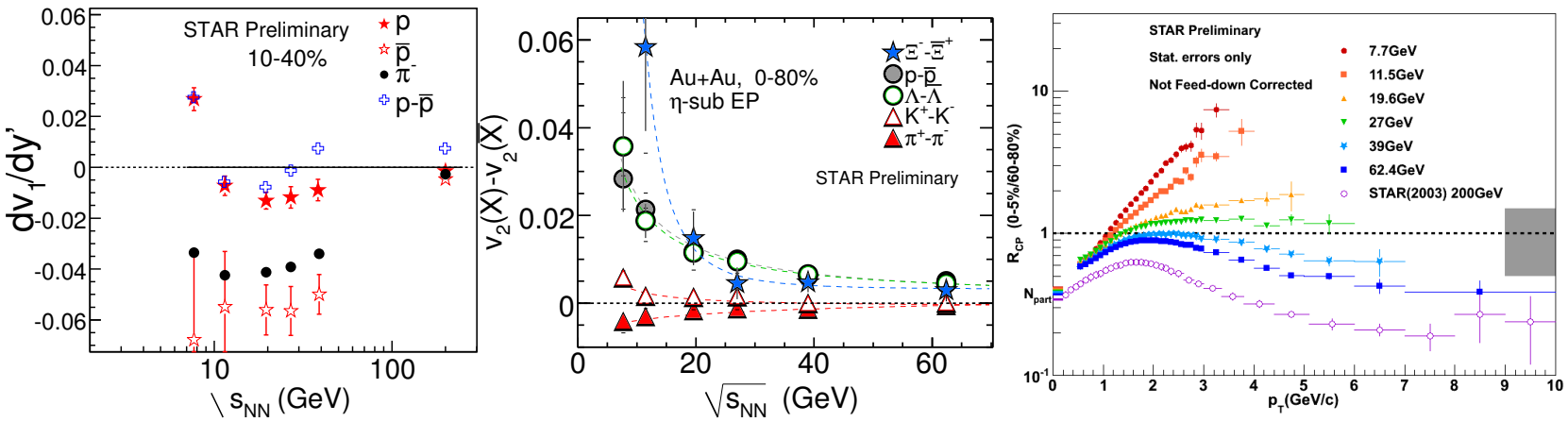
v_2 generated by hydro + transport $\Rightarrow$ non-uniform behavior as a function of $\langle t_{\rm hydro} \rangle$

Summary

- Elliptic flow v_2 changes little as a function of beam energy; transport compensates for diminishing hydrodynamics.
- $v_2(p_T)$ overshoots the data; particlization condition might require adjustment (viscosity?)
- Triangular flow v_3 has much more notable energy dependence, growing from ≈ 0 at $\sqrt{s_{NN}} = 5$ GeV to 0.02 at $\sqrt{s_{NN}} = 27$ GeV in midcentral collisions.
- Preliminary STAR data shows a different energy evolution, agreement on the magnitude of the central collision v_3 at $\sqrt{s_{NN}} = 7.7$ GeV.
- v_3 is the better indicator of the presence of low-viscous fluid – challenging to measure at low energies though...
- Hydrodynamically behaving matter might still be produced in the most central heavy ion collisions at highest FAIR energies!

Extra slides

Beam energy scan



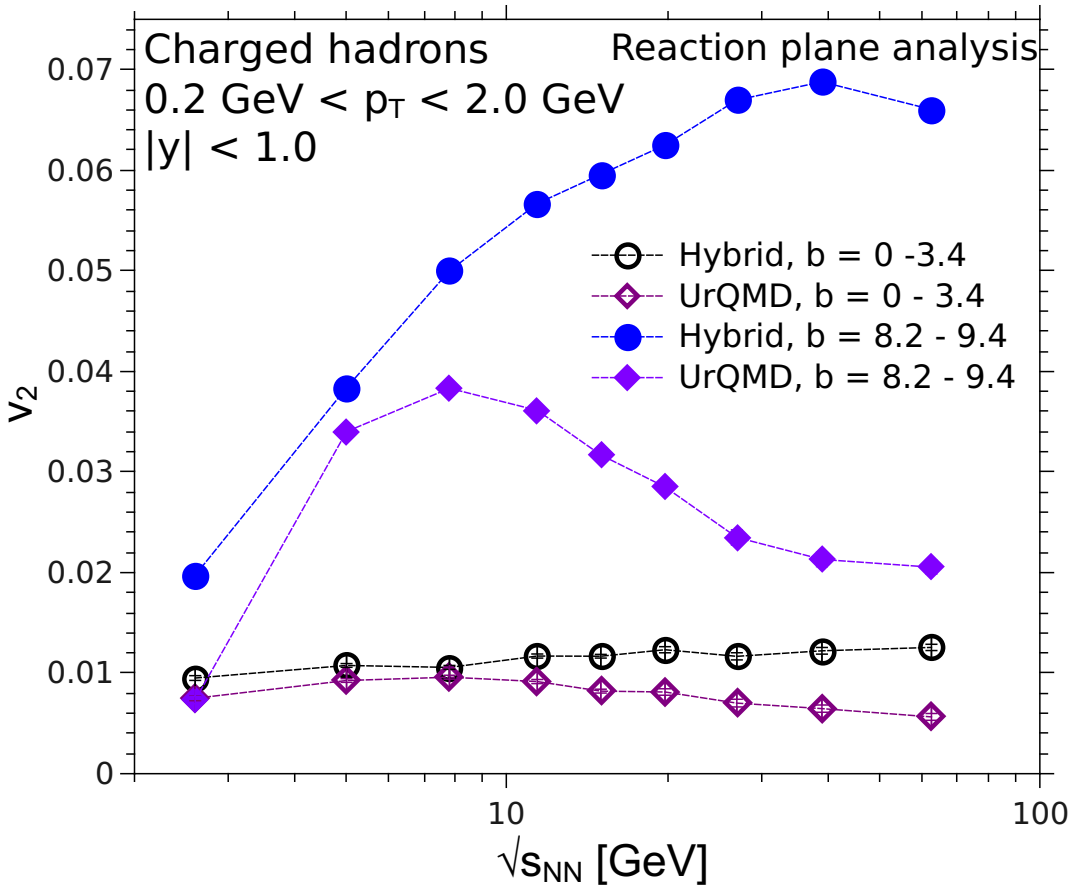
Some interesting findings:

- Non-monotonic $\sqrt{s_{NN}}$ dependence of net-proton v_1
- Difference in particle and antiparticle v_2 at lower energies
- R_{CP} suppression turns to enhancement between $\sqrt{s_{NN}} = 39$ and 27 GeV

v_1 and v_2 figures from L. Kumar [STAR Collaboration], arXiv:1211.1350 [nucl-ex],

R_{CP} from Hot Quarks 2012 talk by S. Horvat.

Elliptic flow



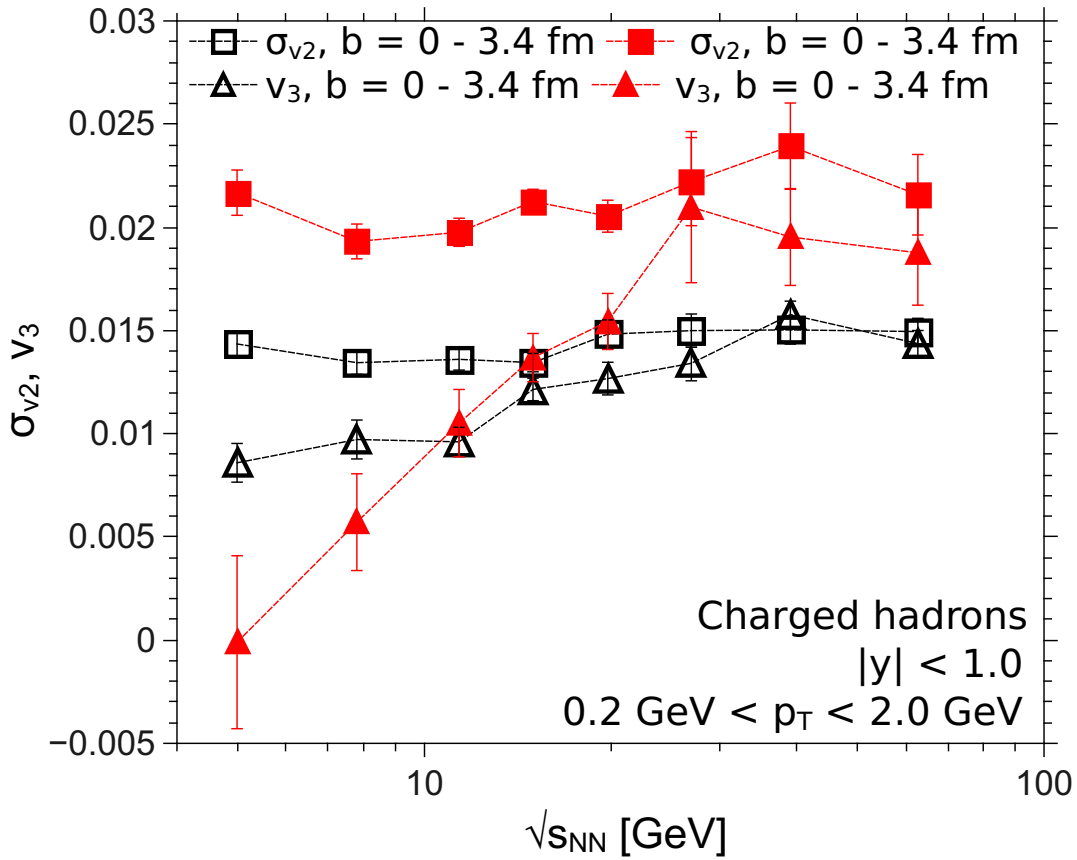
Reaction plane analysis suggests increased flow contribution from hydrodynamics at lower energies!

– Applicability of ideal hydro at $E_{\rm lab} = 2$ GeV?

Triangular flow

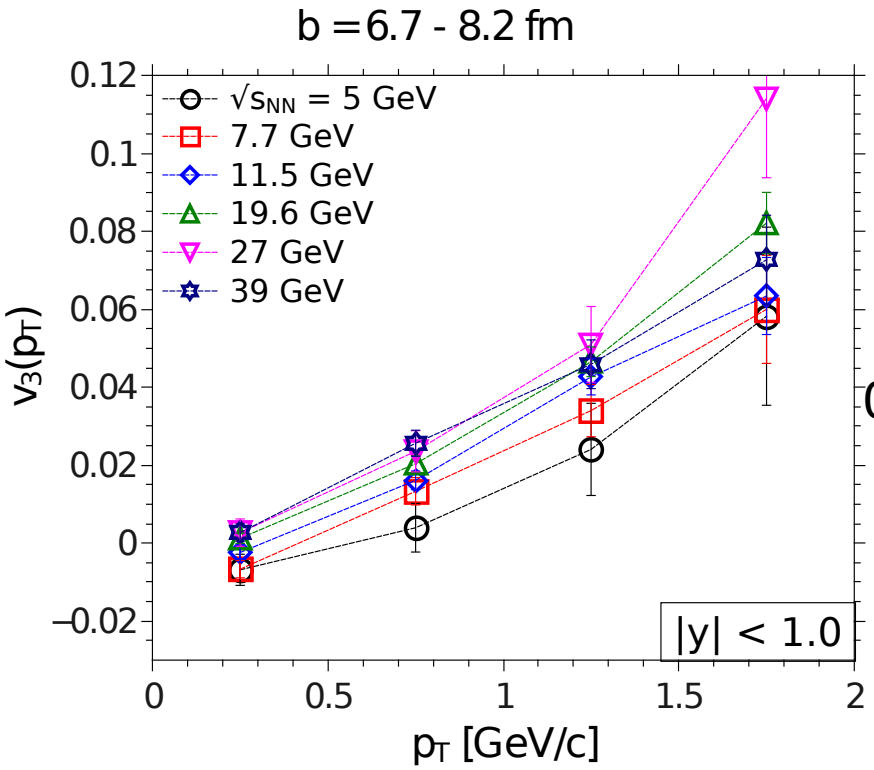
Contribution of initial state fluctuations to event plane v_2:

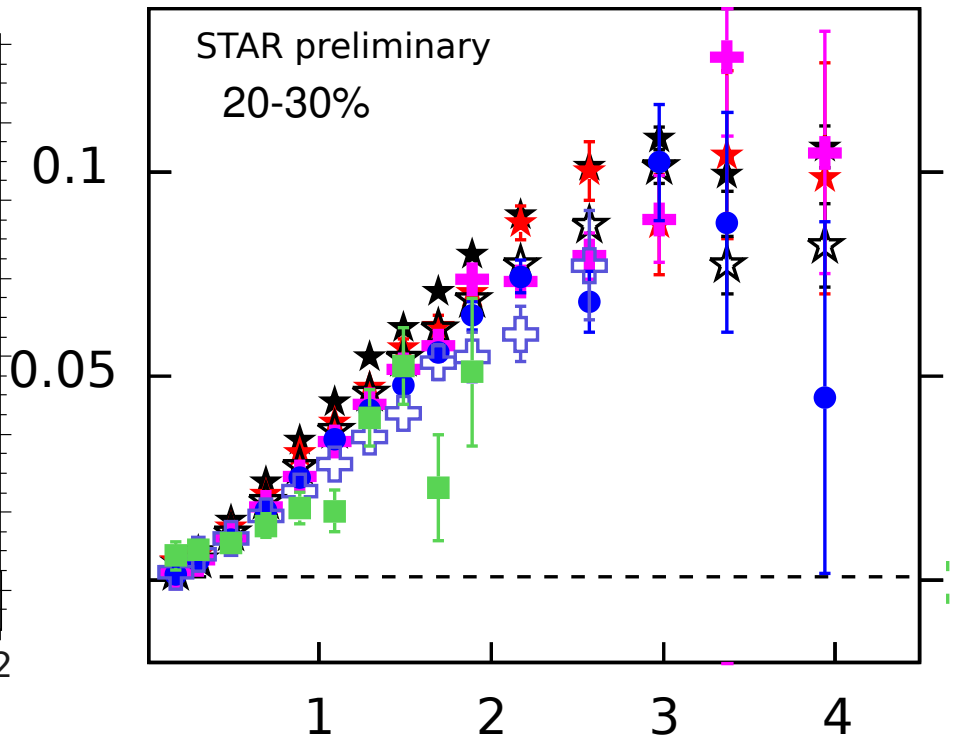
$$\sigma_{v2} = \sqrt{\frac{1}{2}(v_2\{\mathrm{EP}\}^2 - v_2\{\mathrm{RP}\}^2)}$$



$v_3 \approx \sigma_{v2}$ at high energies.

Triangular flow

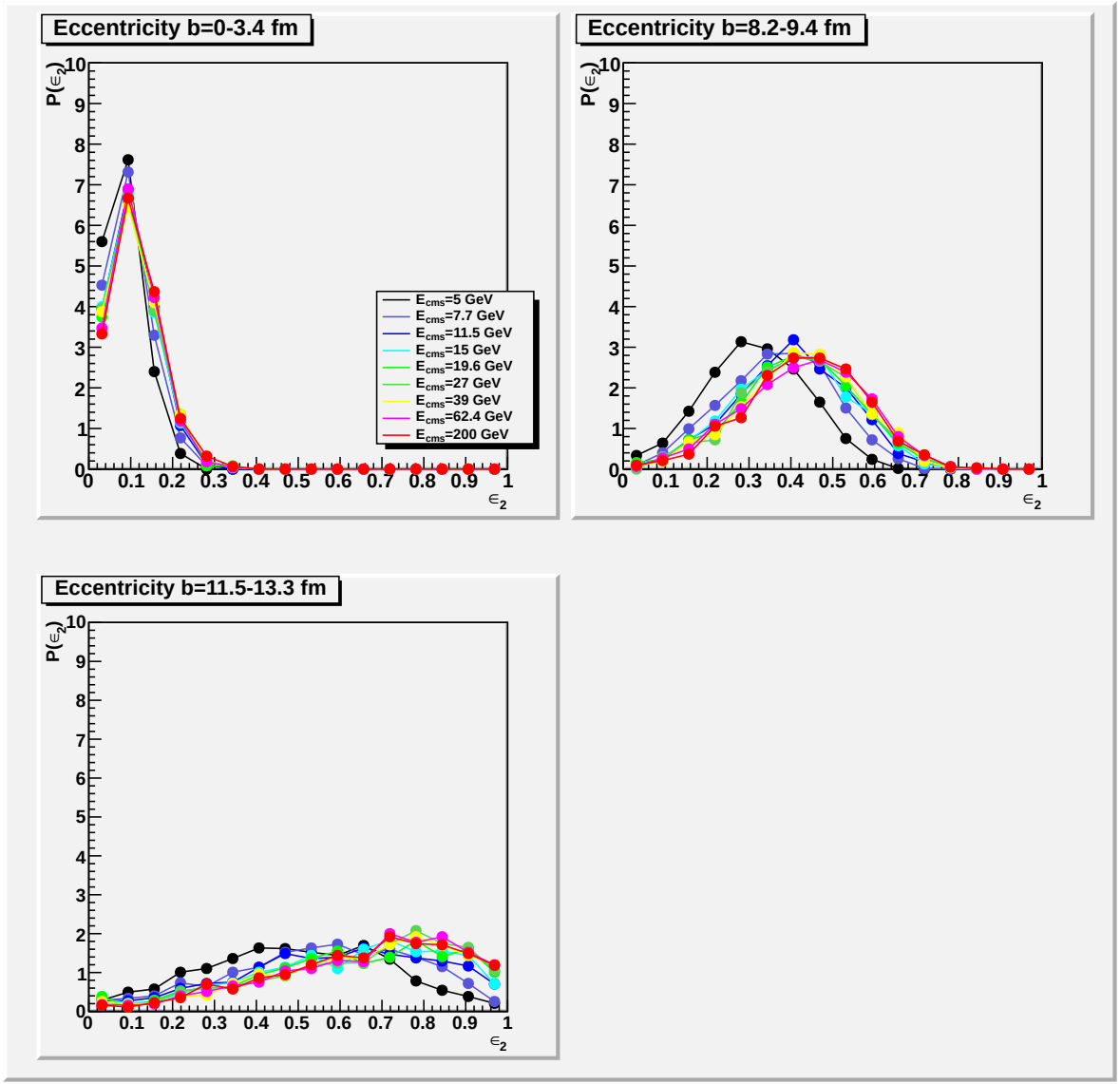




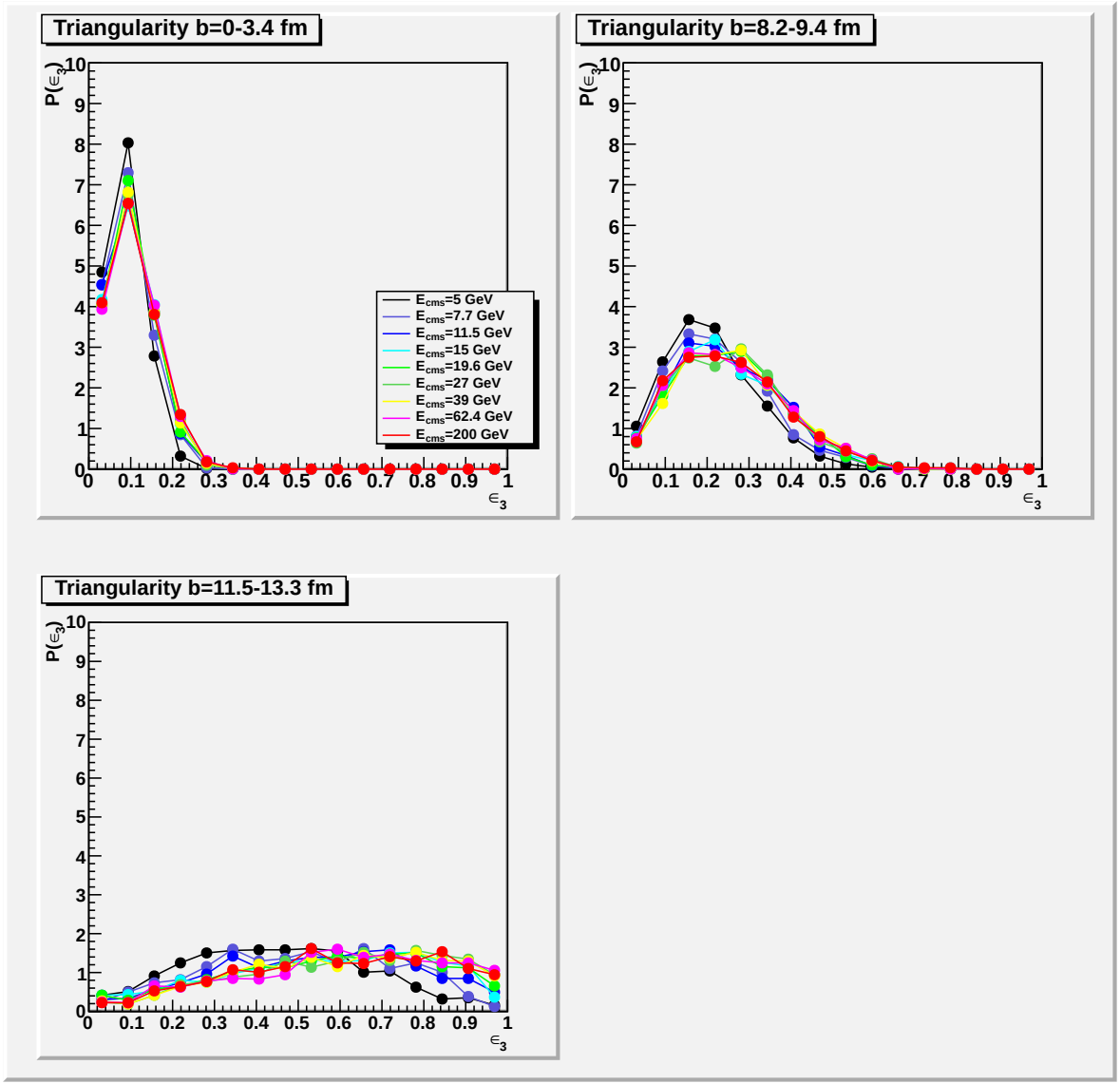
Differential v_3 challenging to interpret due to small magnitudes.

Y. Pandit [STAR Collaboration], arXiv:1210.5315.

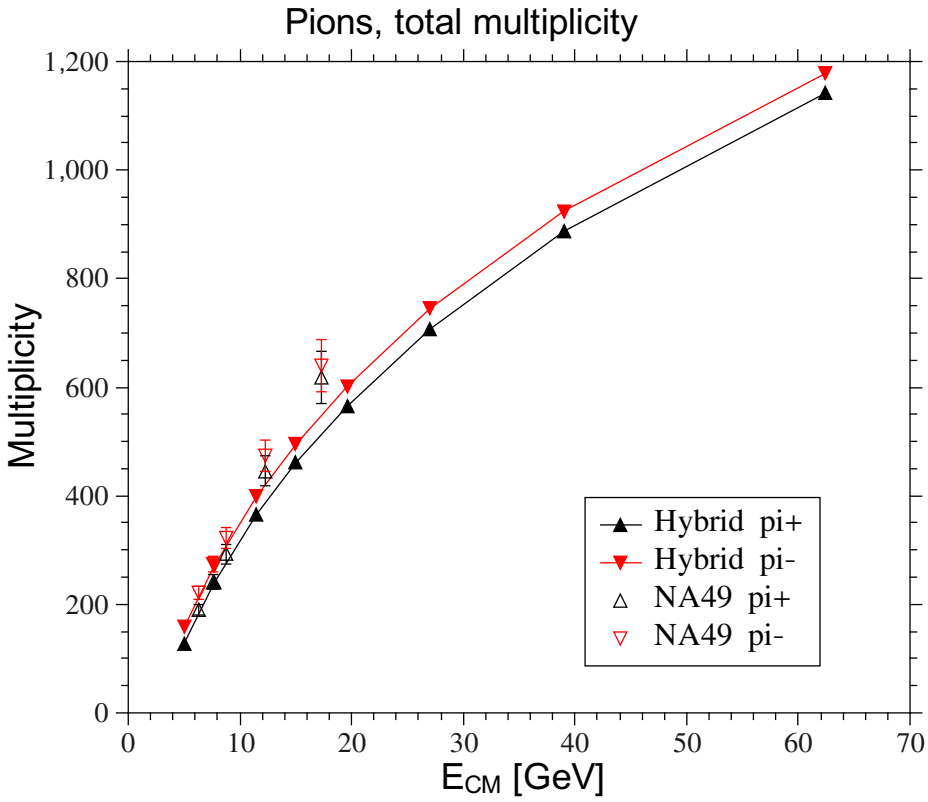
Eccentricity probability distributions

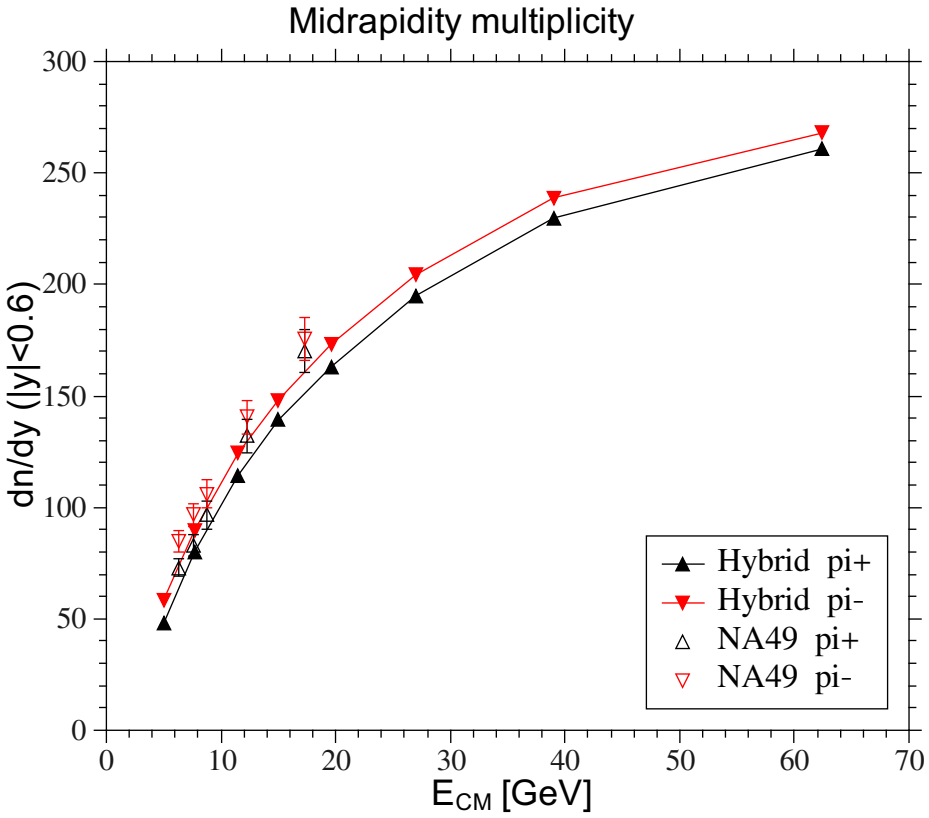


Triangularity probability distributions



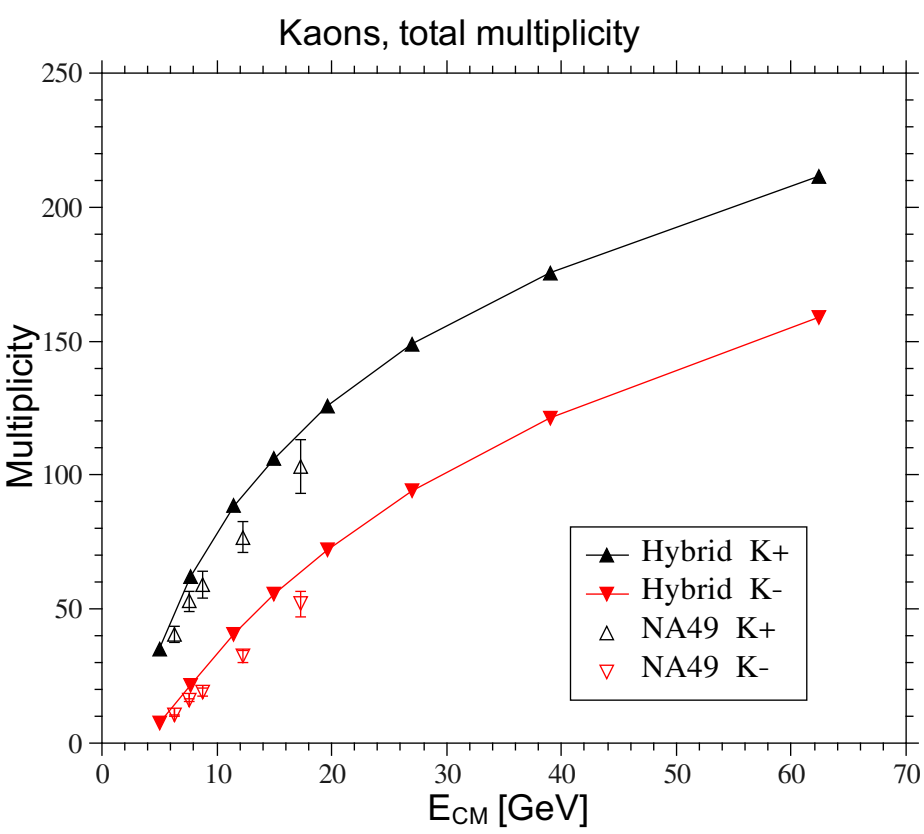
Particle multiplicity

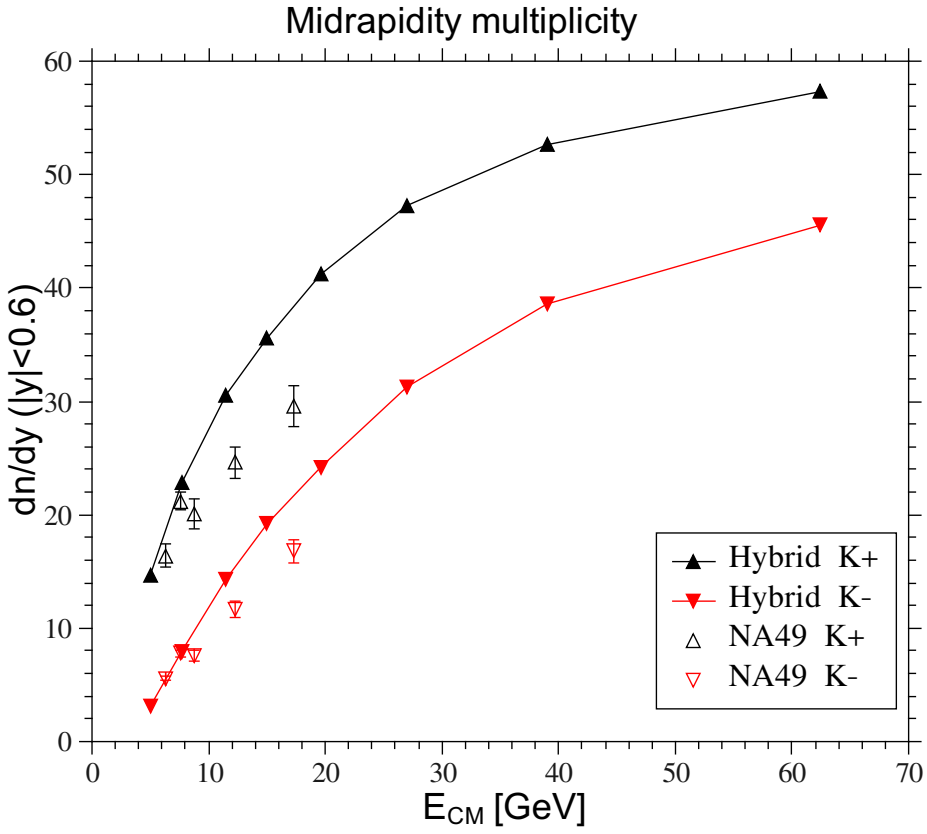




Charged pion multiplicity as a function of $\sqrt{s_{NN}}$.

Particle multiplicity





Charged kaon multiplicity as a function of $\sqrt{s_{NN}}$.