What the collective flow excitation function can tell about the quark-gluon plasma

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Quark Matter
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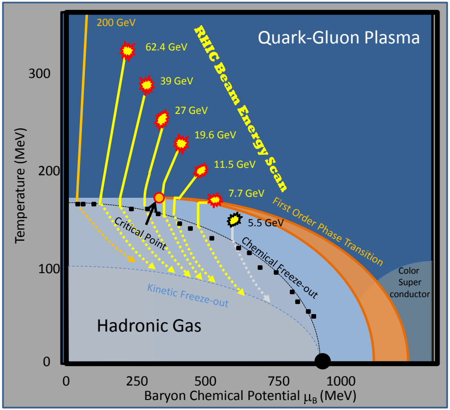
RHIC beam energy scan

Reaching from $\sqrt{s_{NN}} = 200$ GeV down to FAIR energies $\sqrt{s_{NN}} \approx 5$ GeV.

First order phase transition with critical point?

QGP volume and lifetime decreases with decreasing $\sqrt{s_{NN}} \Rightarrow$ signals (jet quenching, collective flow...) should turn off at some point



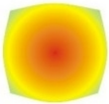
Picture taken from G. Odyniec, Acta Phys. Polon. B 43, 627 (2012).

Transport + hydrodynamics hybrid model

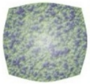
H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stocker, Phys. Rev. C 78, 044901 (2008).

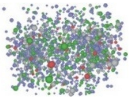
Unified framework for investigating the whole BES energy range, accounting for features emerging at lower collision energies

- Prolonged pre-equilibrium phase: Initial state from UrQMD string/hadronic cascade
  S. A. Bass *et al.*, Prog. Part. Nucl. Phys. 41, 255 (1998), M. Bleicher *et al.*, J. Phys. G 25, 1859 (1999)



- No longitudinal boost-invariance: (3+1)D ideal hydrodynamics using SHASTA 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)
- Nonzero μ_B: Chiral model equation of state with cross-over phase transition
  J. Steinheimer, S. Schramm and H. Stöcker, PRC 84, 045208 (2011)





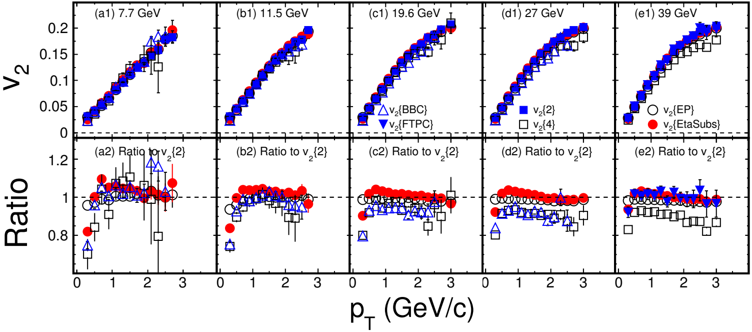
- Transition from hydro back to transport ("particlization") when $\epsilon = 2\epsilon_0 \approx 0.3\ \mathrm{GeV/fm^3}$
  $\rightarrow$ Cornelius hypersurface finder + Cooper-Frye

Pictures: S. A. Bass

P. Huovinen and H. Petersen, Eur. Phys. J. A48, 171 (2012)

RHIC beam energy scan

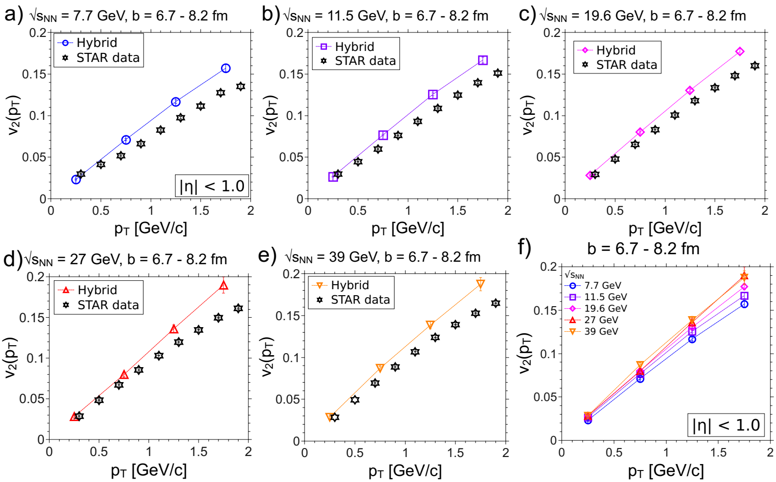
Flow observables v_n imply collective behavior in the system
$\Rightarrow$ considered as one important piece of evidence for QGP formation



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

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

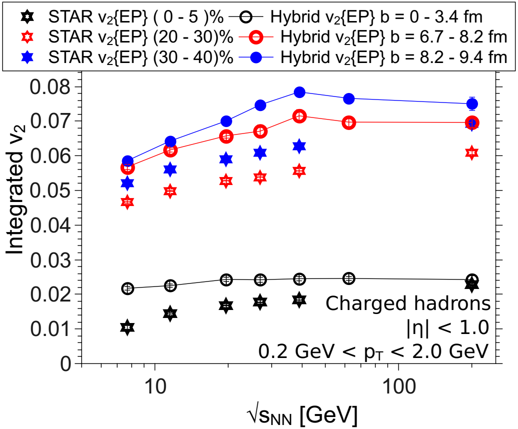
Elliptic flow $v_2\{\mathrm{EP}\}$



$v_2(p_T)$ overestimated at higher p_T; change over $\sqrt{s_{NN}}$ small also in the hybrid model.

J. Auvinen and H. Petersen, PRC **88**, 064908 (2013); STAR Collaboration, PRC **86**, 054908 (2012).

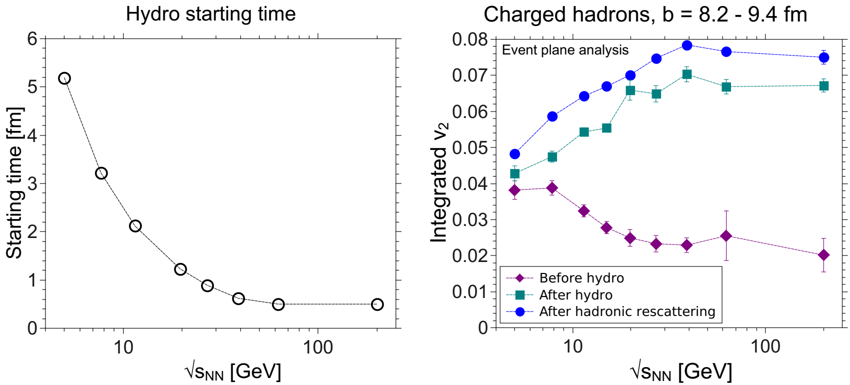
Elliptic flow



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

J. Auvinen and H. Petersen, PRC **88**, 064908 (2013); STAR Collaboration, PRC **86**, 054908 (2012).

Elliptic flow



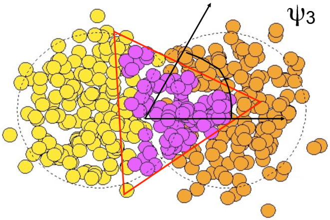
No contribution from hadronic rescatterings in most central collisions; in midcentral collisions $\approx 10\%$ effect.

The role of pre-equilibrium dynamics emphasised at lower energies $\Rightarrow$ compensates for diminishing hydro-produced v_2

J. Auvinen and H. Petersen, PRC 88, 064908 (2013)

Triangular flow

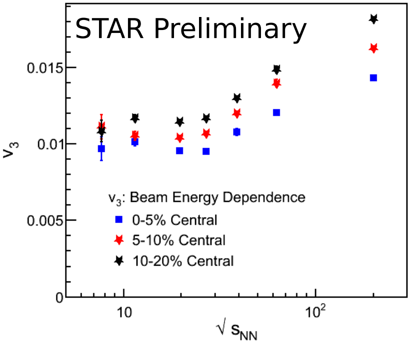
Generated by fluctuations in the spatial configuration of colliding nucleons.



B. Alver and G. Roland, PRC 81, 054905 (2010).

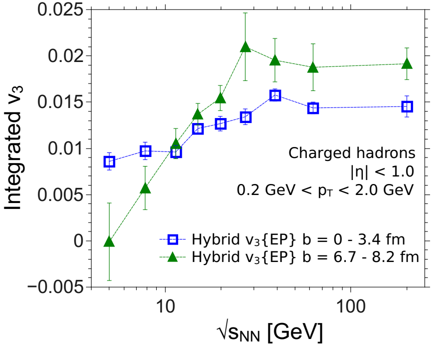
$$v_3\{\mathsf{EP}\} = \frac{\langle\langle\cos[3(\phi_i - \psi_3)]\rangle\rangle}{\langle\cos[3(\psi_3 - \psi_3^{\mathsf{true}})]\rangle}$$

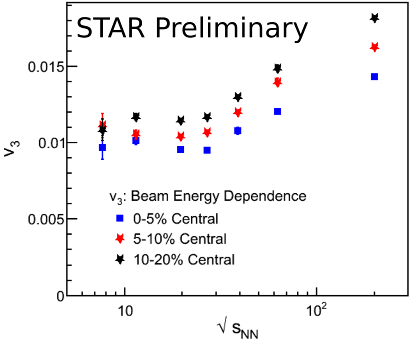
$v_3\{\text{TPC } \eta \text{ Sub}\}$



Y. Pandit [STAR Collaboration], QM2012 talk.

Triangular flow





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

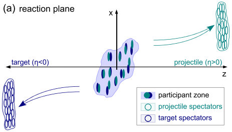
$\Rightarrow$ transport not able to compensate for shortened hydro phase

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

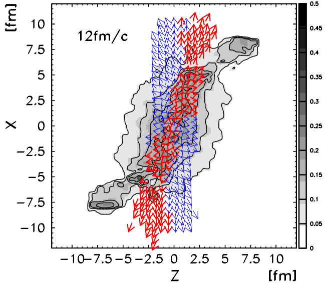
J. Auvinen and H. Petersen, PRC 88, 064908 (2013)

Y. Pandit [STAR Collaboration], QM2012 talk.

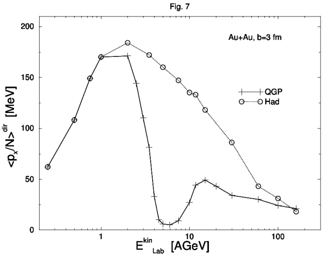
Directed flow



Collective deflection of particles in reaction plane: $v_1(\Delta y)\{\mathrm{RP}\} = \langle \frac{p_x}{p_T} \rangle_{y \in \Delta y}$



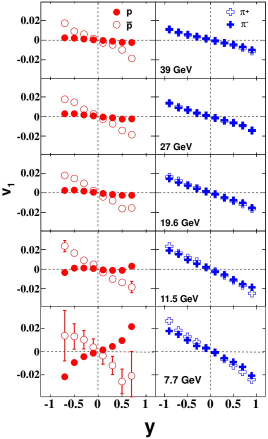
Velocities of midrapidity fluid elements: flow vs. antiflow

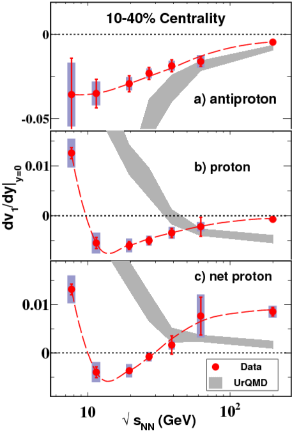


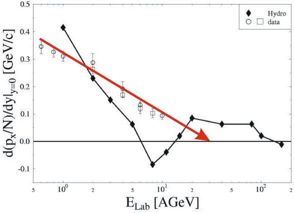
Minimum in the directed flow excitation function
$\Rightarrow$ Phase transition to QGP

Upper left: ALICE Collaboration, PRL 111, 232302 (2013)
Lower left: J. Brachmann *et al.*, Phys. Rev. C 61, 024909 (2000)
Right: D. Rischke *et al.* Heavy Ion Phys. 1, 309 (1995)

Directed flow





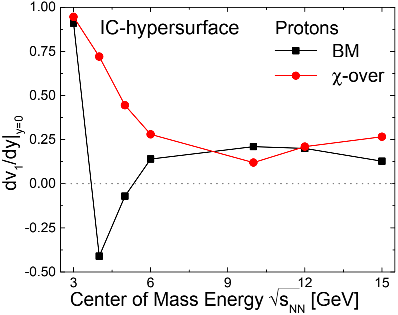


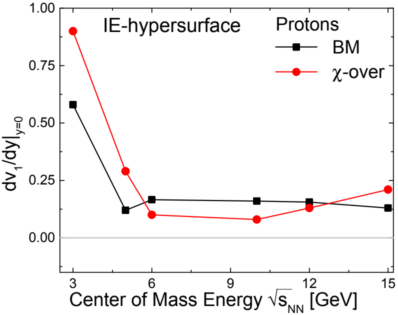
BES: Proton $\frac{dv_1}{dy}|_{y=0}$ has a minimum in interval $\sqrt{s_{NN}}$ =10-20 GeV
$\Rightarrow$ Signal of first-order phase transition?

Left and center: L. Adamczyk *et al.* [STAR Collaboration], arXiv:1401.3043
Right: H. Stöcker, Nucl. Phys. A 750, 121 (2005)

Directed flow (fluid)

Two colliding nuclei described by energy and baryon density distributions of cold nuclear matter; impact parameter $b = 8$ fm



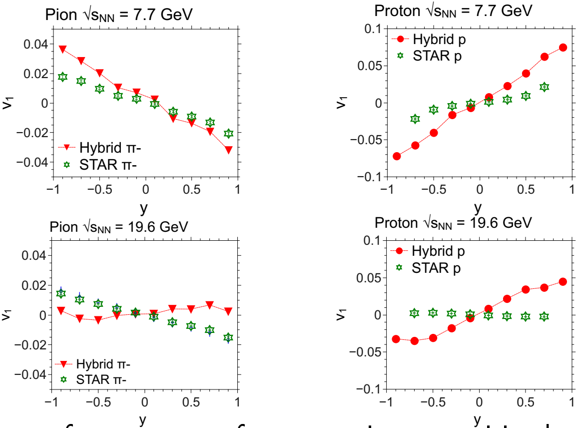


- Stopping hydro evolution at constant time reproduces the early fluid model predictions
- The difference between first-order phase transition and cross-over is considerably smaller when hydro is stopped at constant energy density

J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher and H. Stöcker, arXiv:1402.7236

Directed flow (hybrid)

Hybrid results with $\epsilon_{\text{crit}} = 4\epsilon_0$ and impact parameter $b = 4.6 - 9.4$ fm compared with STAR results in (10-40)% centrality.

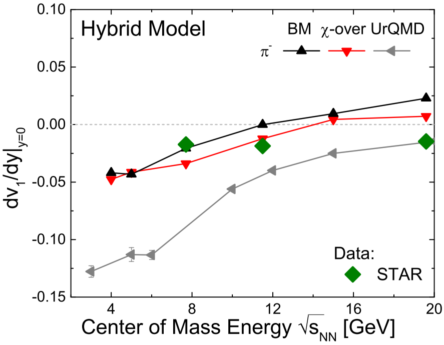


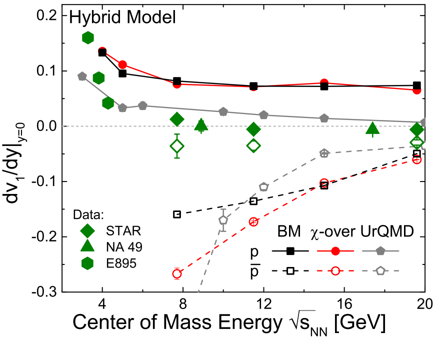
Midrapidity slope of π^- v_1 turns from negative to positive between $\sqrt{s_{NN}} = 7.7$ and 19.6 GeV in the model; proton slopes overestimated.

J. Steinheimer *et al.*, arXiv:1402.7236 L. Adamczyk *et al.* [STAR Collaboration], arXiv:1401.3043

Directed flow (hybrid)

Hybrid results with $\epsilon_{\rm crit} = 4\epsilon_0$ and impact parameter $b = 4.6 - 9.4$ fm compared with STAR results in (10-40)% centrality.
No difference between first-order phase transition and a cross-over.



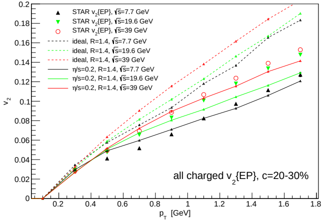


J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher and H. Stöcker, arXiv:1402.7236
L. Adamczyk *et al.* [STAR Collaboration], arXiv:1401.3043
C. Alt *et al.* [NA49 Collaboration], PRC 68, 034903 (2003)
H. Liu *et al.* [E895 Collaboration], PRL 84, 5488 (2000)
For comparison with PHSD transport, see V. P. Konchakovski, W. Cassing, Y. . B. Ivanov and V. D. Toneev, arXiv:1404.2765 [nucl-th]

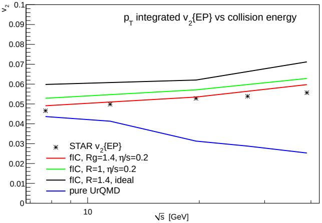
The next step: Viscous (3+1)D hydro + cascade results

See Poster #H-15 by Iurii Karpenko

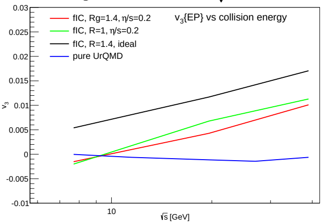
v_2 vs. p_T



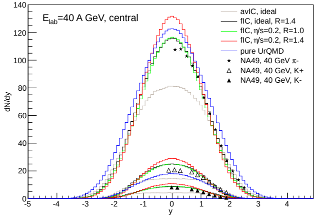
Integrated v_2 vs. $\sqrt{s_{NN}}$



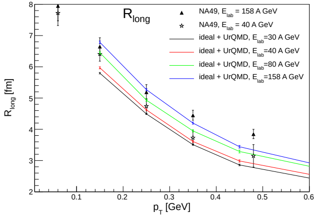
Integrated v_3 vs. $\sqrt{s_{NN}}$



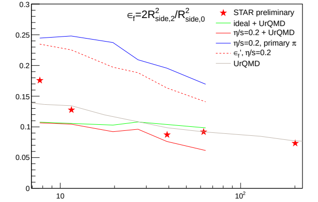
dN/dy for π^-, K^+, K^-



Longitudinal HBT radius vs p_T



Freezeout eccentricity vs. $\sqrt{s_{NN}}$



Summary

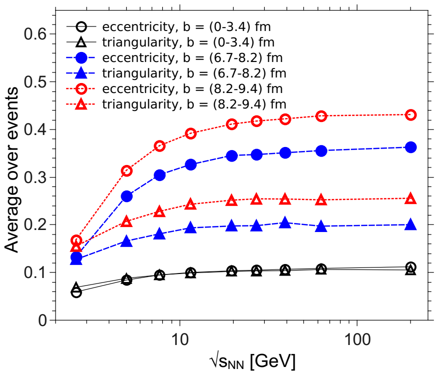
- Elliptic flow v_2 changes relatively slowly as a function of beam energy; transport compensates for diminishing hydrodynamics
  - $v_2(p_T)$ overshoots the data; particlization condition might require adjustment (viscosity?)
  - Hybrid with viscous (3+1)D hydro: Poster #H-15 by Iurii Karpenko
- Triangular flow v_3 has more notable energy dependence, growing from $\approx$ 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
- Directed flow v_1 found insensitive to the order of phase transition; rapidity slopes overestimated compared to data

Extra slides

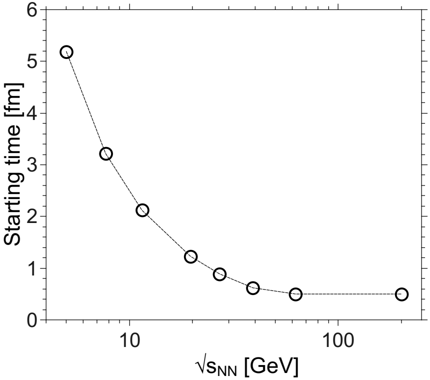
Collision geometry

Eccentricity $\epsilon_2 = \frac{\sqrt{\langle r^2\cos(2\phi)\rangle^2 + \langle r^2\sin(2\phi)\rangle^2}}{\langle r^2\rangle}$

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



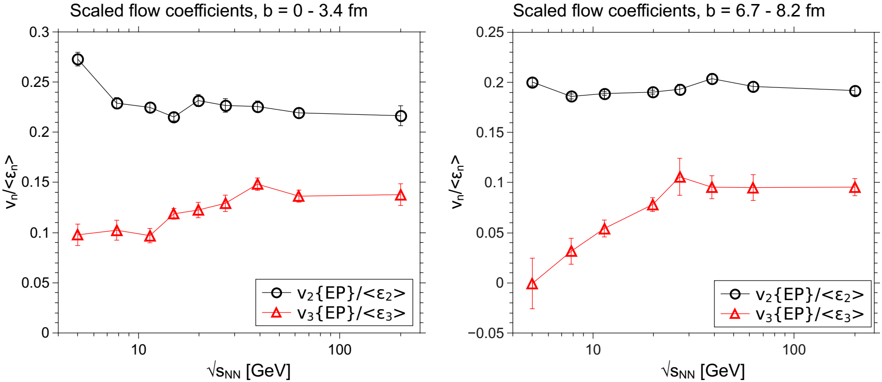
Hydro starting time



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



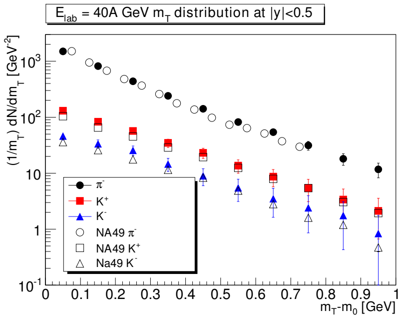
v_2 response to ϵ_2 remains roughly the same in both centrality classes and all energies.

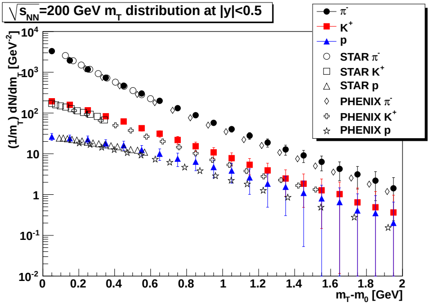
Energy dependence of v_3 persists through scaling.

Particle m_T spectra

(0-7)% centrality.
π^-, K^+, K^- at $\sqrt{s_{NN}} \approx 9$ GeV.

(0-5)% centrality.
π^-, K^+, p at $\sqrt{s_{NN}} = 200$ GeV.

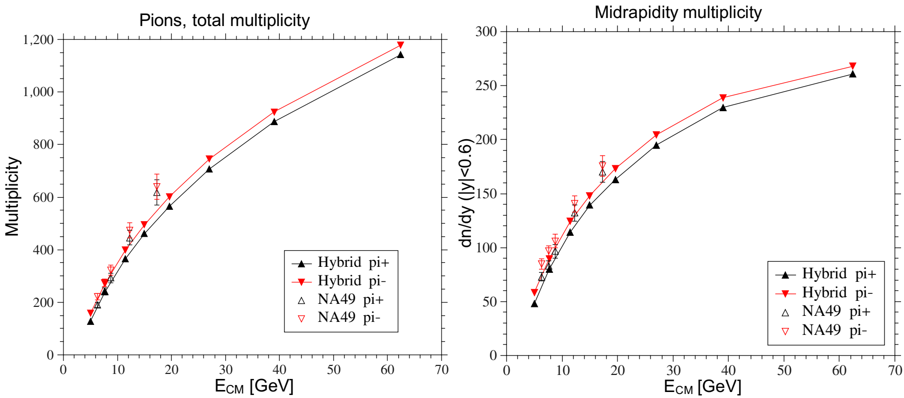




Filled symbols: Hybrid model. Open symbols: Experimental data.

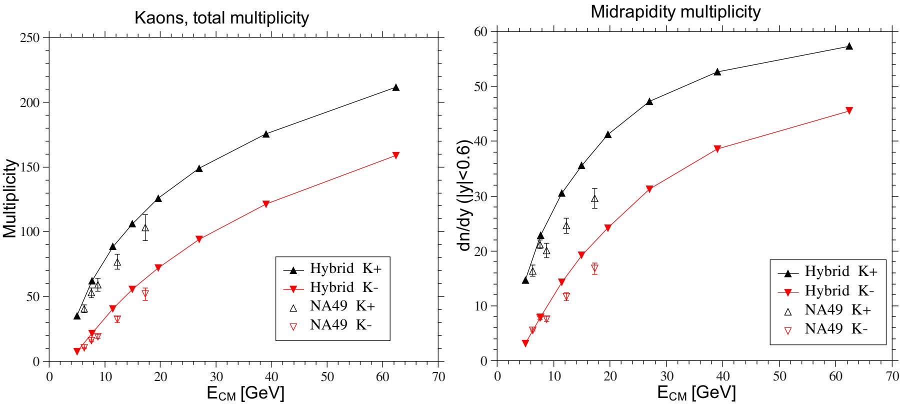
J. Auvinen and H. Petersen, PoS CPOD 2013, 034; PRC **88**, 064908 (2013)
S. V. Afanasiev *et al.* [NA49 Collaboration], PRC **66**, 054902 (2002)
J. Adams *et al.* [STAR Collaboration], PRL **92**, 112301 (2004)
S. S. Adler *et al.* [PHENIX Collaboration], PRC **69**, 034909 (2004)

Particle multiplicity



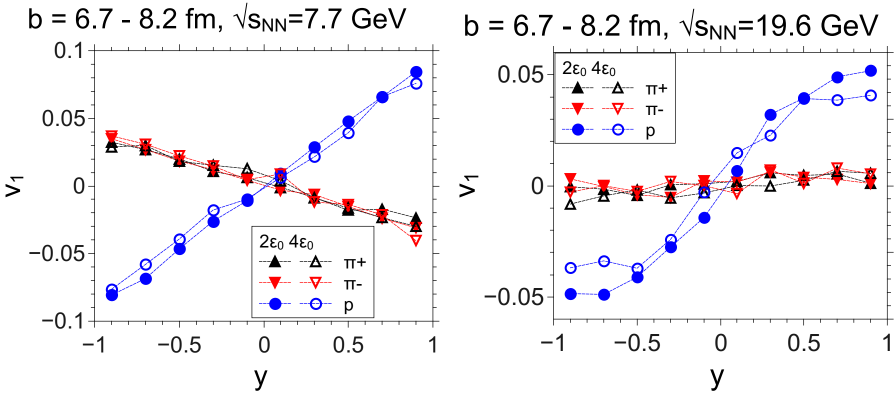
Charged pion multiplicity as a function of $\sqrt{s_{NN}}$.

Particle multiplicity



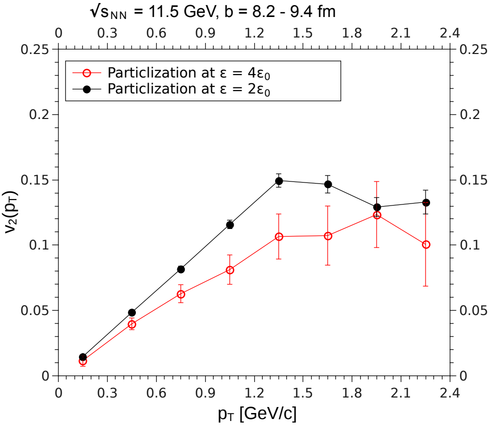
Charged kaon multiplicity as a function of $\sqrt{s_{NN}}$.

Effect of particlization condition on directed flow



$v_1(y)$ has weak sensitivity to hydro-to-transport switching condition.

Effect of particlization condition on elliptic flow



Switching from hydro to transport at higher densities decreases high-p_T v_2.
$\Rightarrow$ Effect on p_T-spectra of particles?