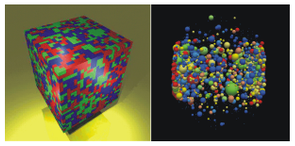
Beam Energy Scan: Observables and the Equation of State

Hannah Petersen

6.12.17, Zimanyi School, Budapest, Hungary



SFB-TR-211
Strong-interaction matter under extreme conditions

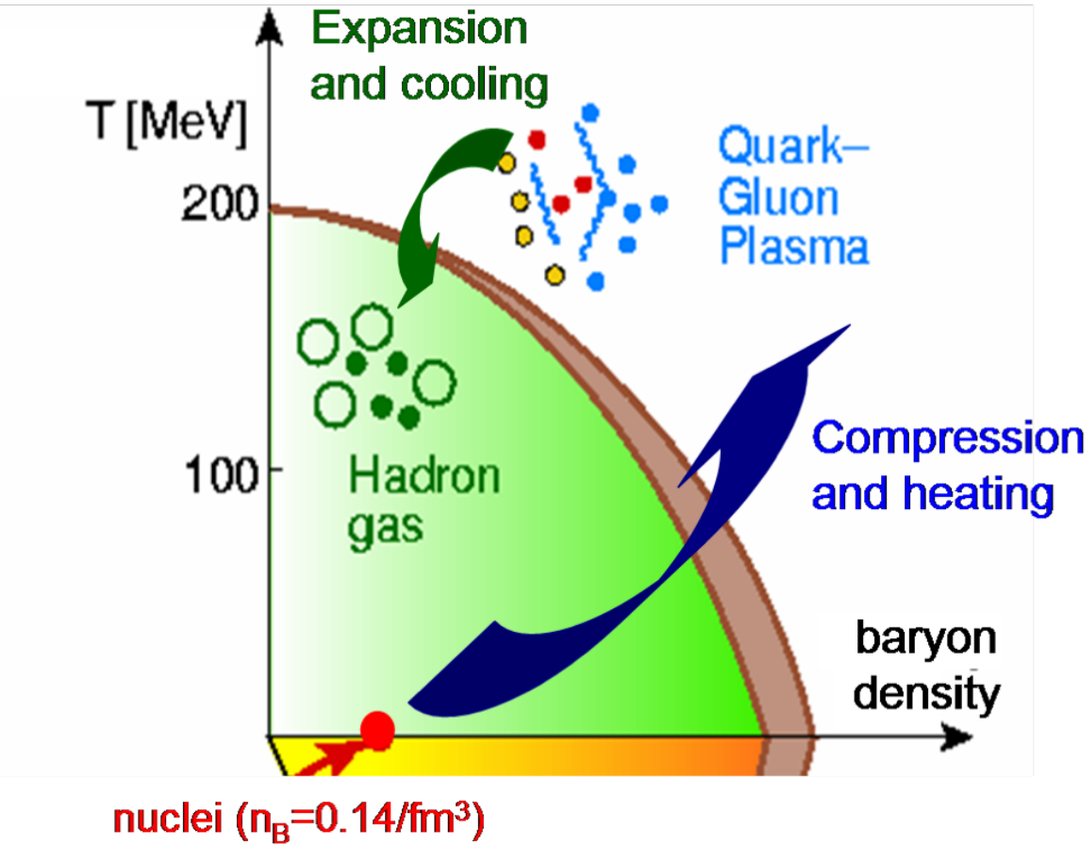
Deutsche Forschungsgemeinschaft

HIC for FAIR
Helmholtz International Center

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

The QCD Phase Diagram

- Main goals of the **beam energy scan** program:

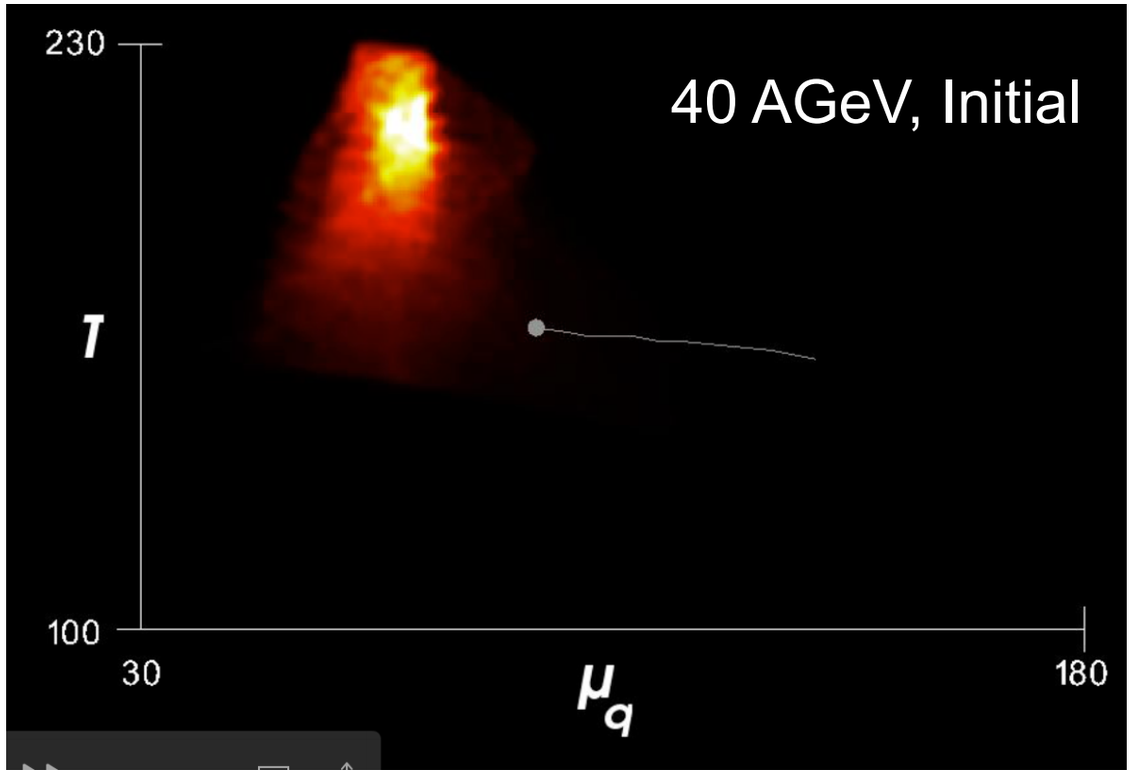


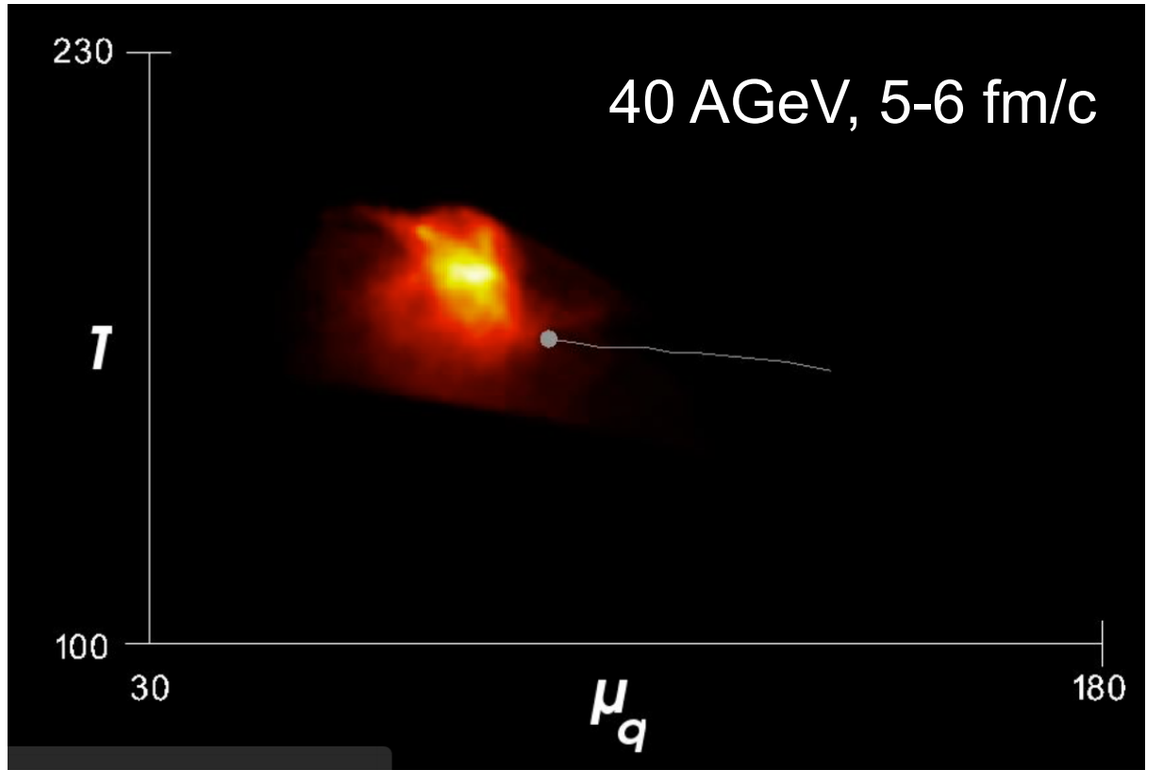
- **Questions** to be answered:
  - What is the temperature and the density? What are the relevant degrees of freedom?
  - Phase transition, critical point?
  - What are the transport properties? $(\eta/s)(T,\mu_B)$ and $(\zeta/s)(T,\mu_B)$

- **The** chance to learn about QCD thermodynamics that is not (yet) accessible by lattice techniques
- What is necessary to establish **definitive links** between observables and structures in the QCD phase diagram?

The Remaining Challenge

- **Spread of the system** in temperature and baryo-chemical potential has consequences on observables



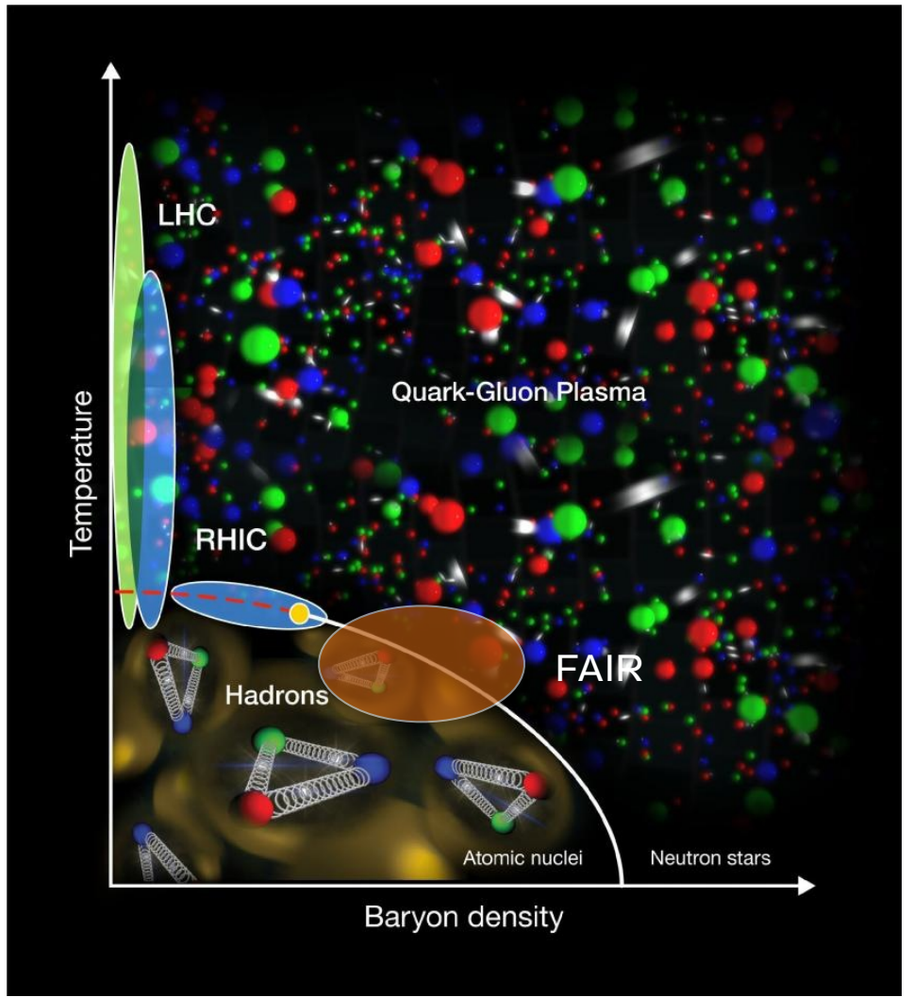


S. Bass et al, arXiv:1202.0076, CPOD 2011

- Detailed dynamical modeling is required:
  - EoS and transport coefficients in the whole phase diagram
  - Non-equilibrium dynamics at the phase transition

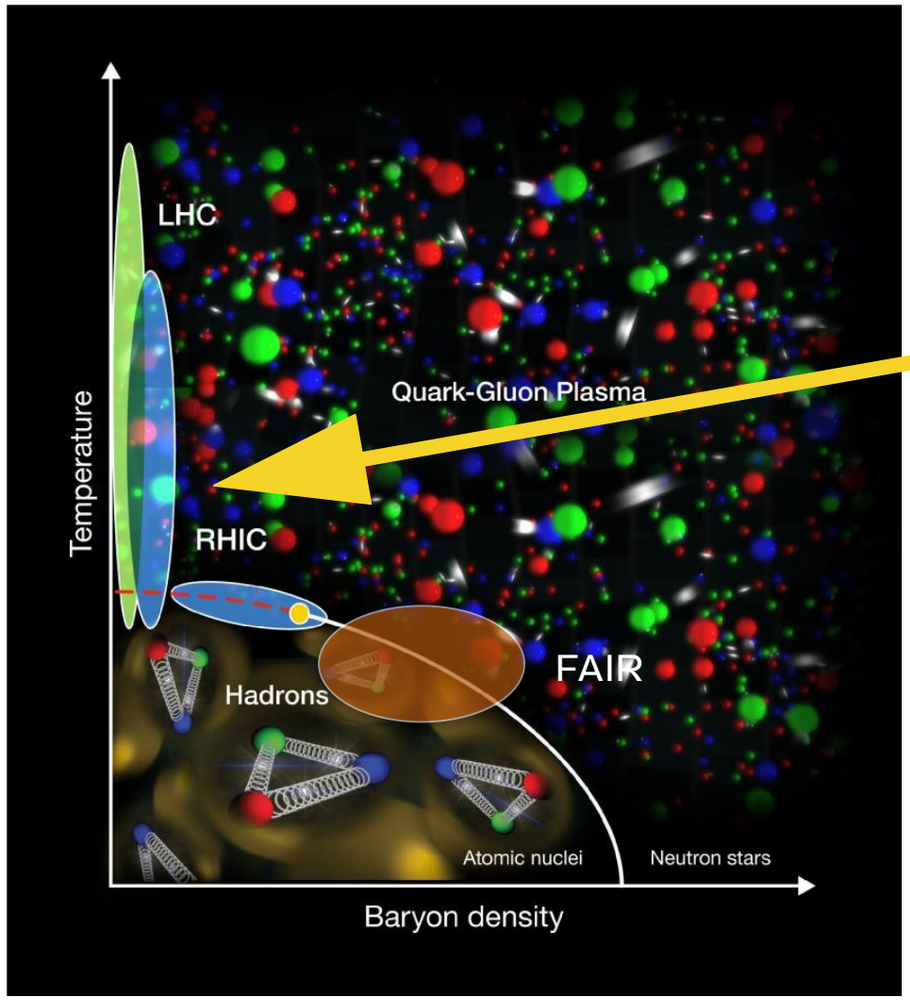
Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



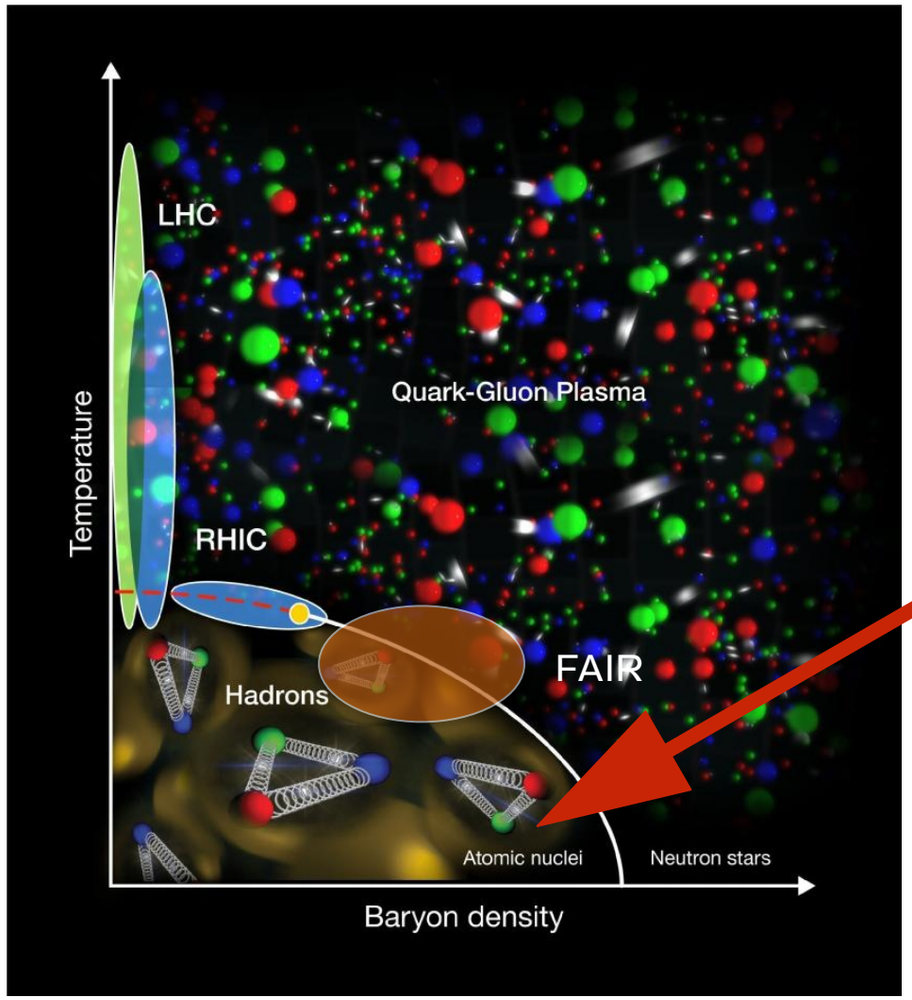
‚Standard model' at high energies ($\sqrt{s_{\mathrm{NN}}}$ = 39 GeV-5.5 TeV+):

- Non-equilibrium initial evolution
- Viscous hydrodynamics
- Hadronic transport

—> Refinement and Bayesian multi-parameter analysis

Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



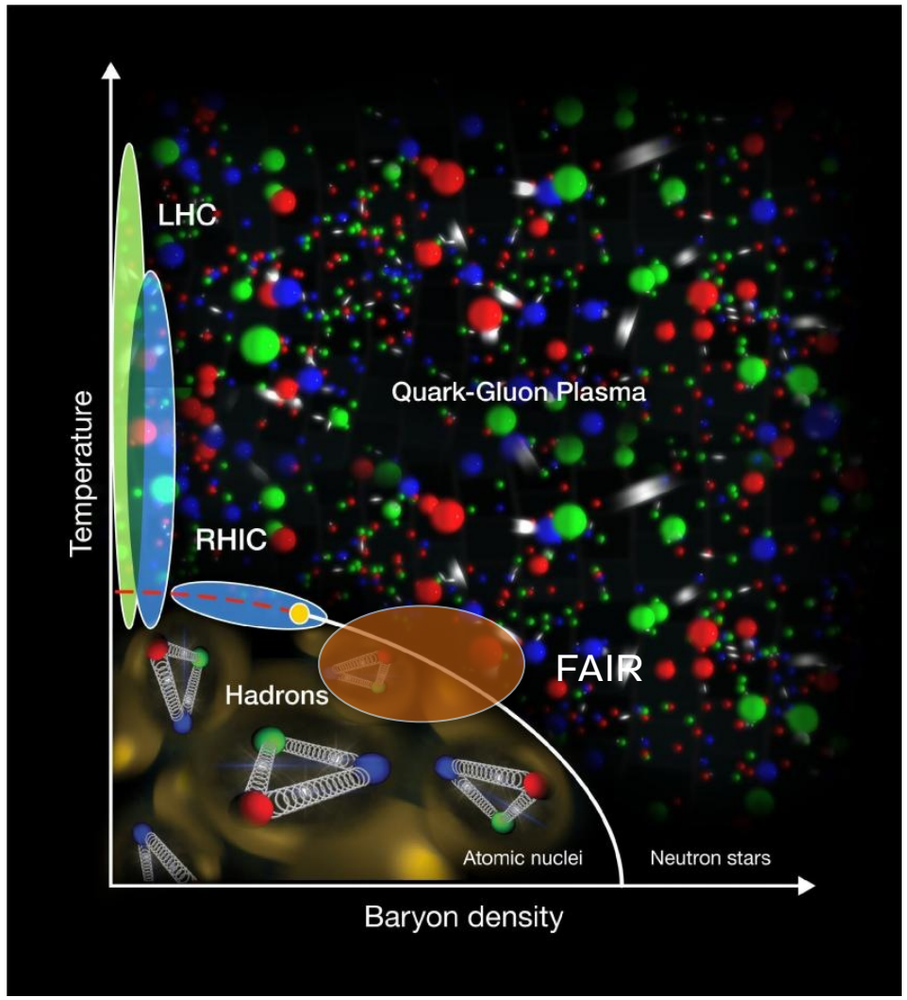
At very low beam energies ($\sqrt{s_{\mathrm{NN}}}$ < 3 GeV):

- **Hadronic** transport approaches
- Resonance dynamics
- Nuclear potentials

—> High density phase?
Multi-particle interactions?

Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



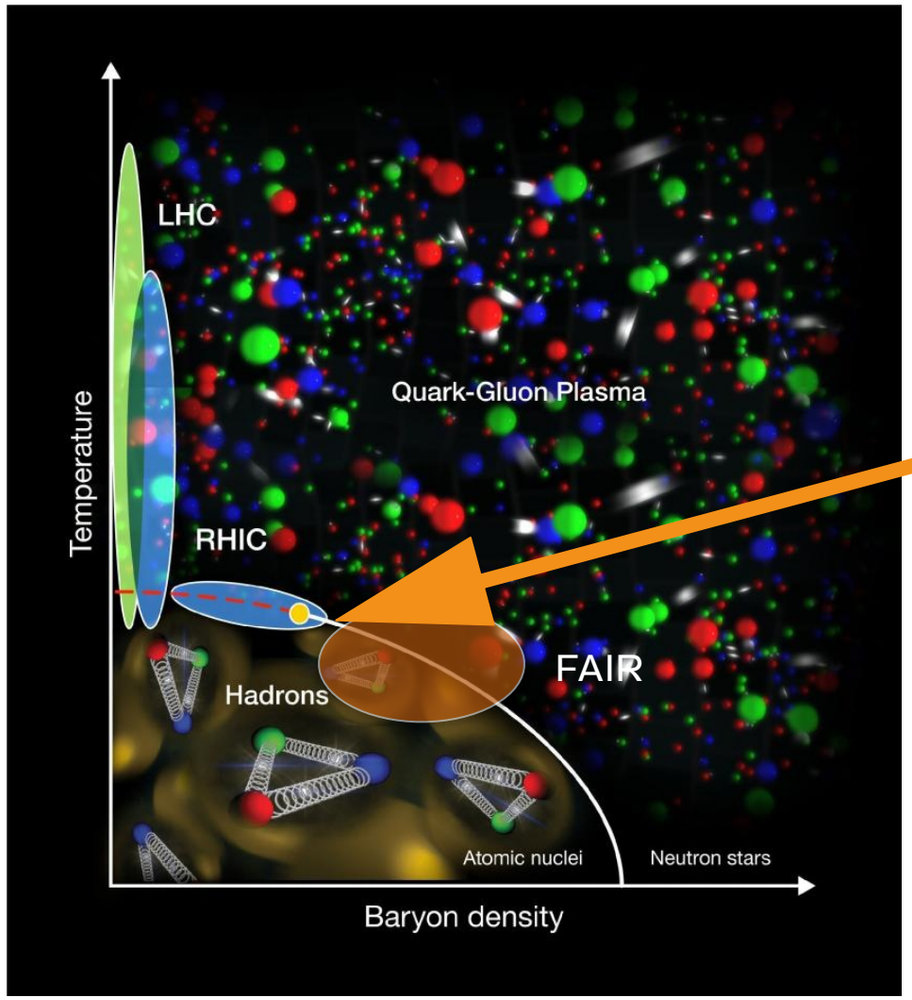
‚**Standard model**' at high energies ($\sqrt{s_{\mathrm{NN}}}$ = 39 GeV-5.5 TeV+)

Hadron transport at very low beam energies ($\sqrt{s_{\mathrm{NN}}}$ < 3 GeV)

- How to **interpolate** between the two? Transport with hydro bubbles? Hydro with transport corona?
- How to model the phase transition/critical point?

Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches

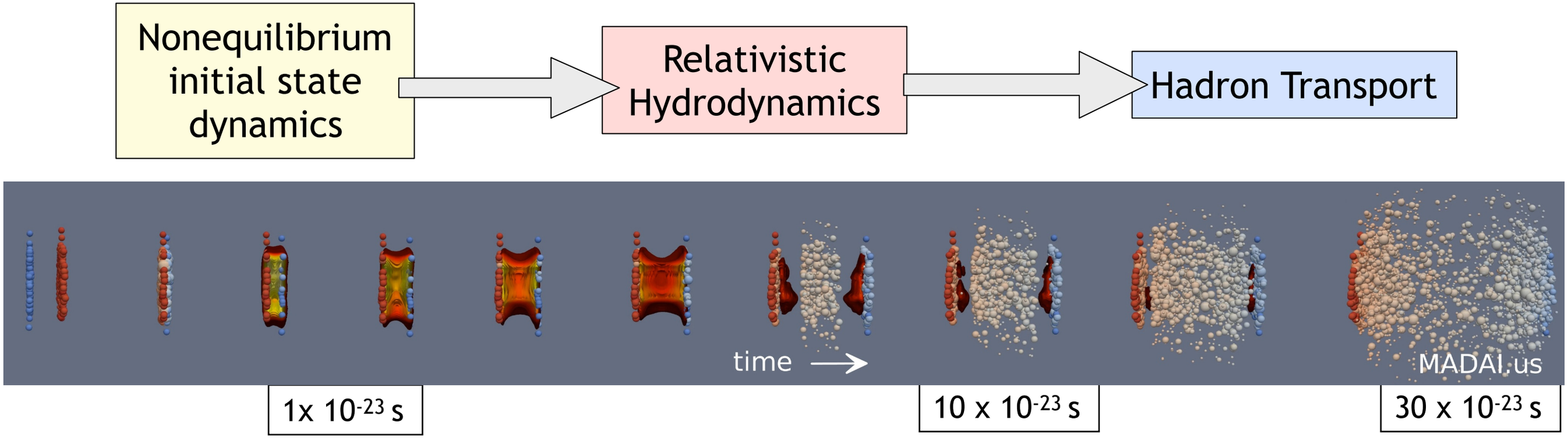


Low beam energies:
($\sqrt{s_{\mathrm{NN}}}$ = 3-39 GeV):

THIS TALK

- Disclaimer:
  Personally biased selection of observables and results

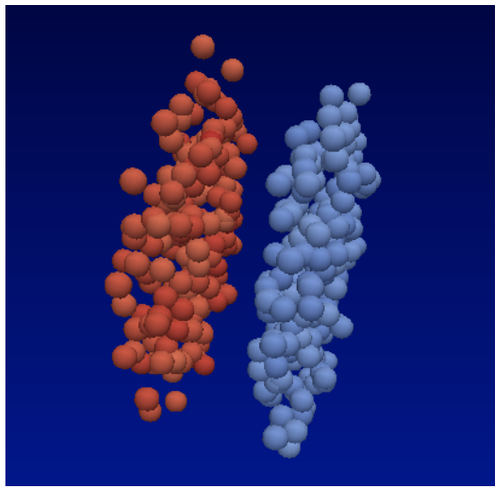
‚Standard Model' at High Energies

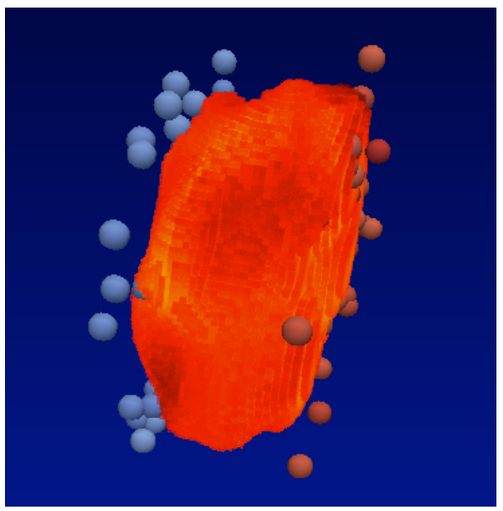


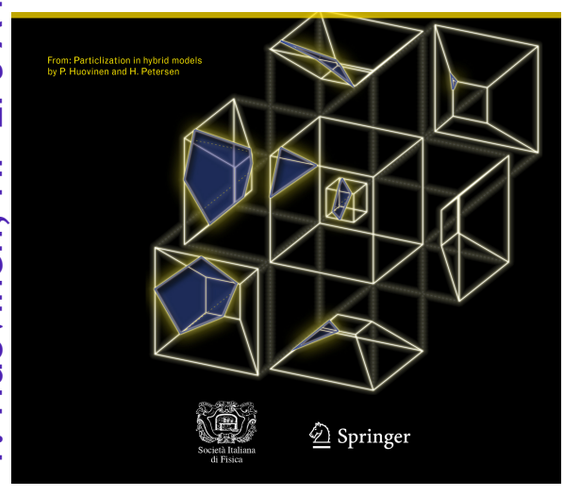
- Challenges at lower beam energies:
  - Finite **net-baryon density** (as conserved current and in EoS)
  - Dissipative effects/hadronic interactions gain importance
  - Non-equilibrium dynamics with a probably **first order** phase transition

Hybrid Approach

HP, arXiv:1404.1763 (special issue)
J. Phys. G: Nucl. Part. Phys. 41 (2014) 124005







P. Huovinen, HP EPJ A48 (2012) 171

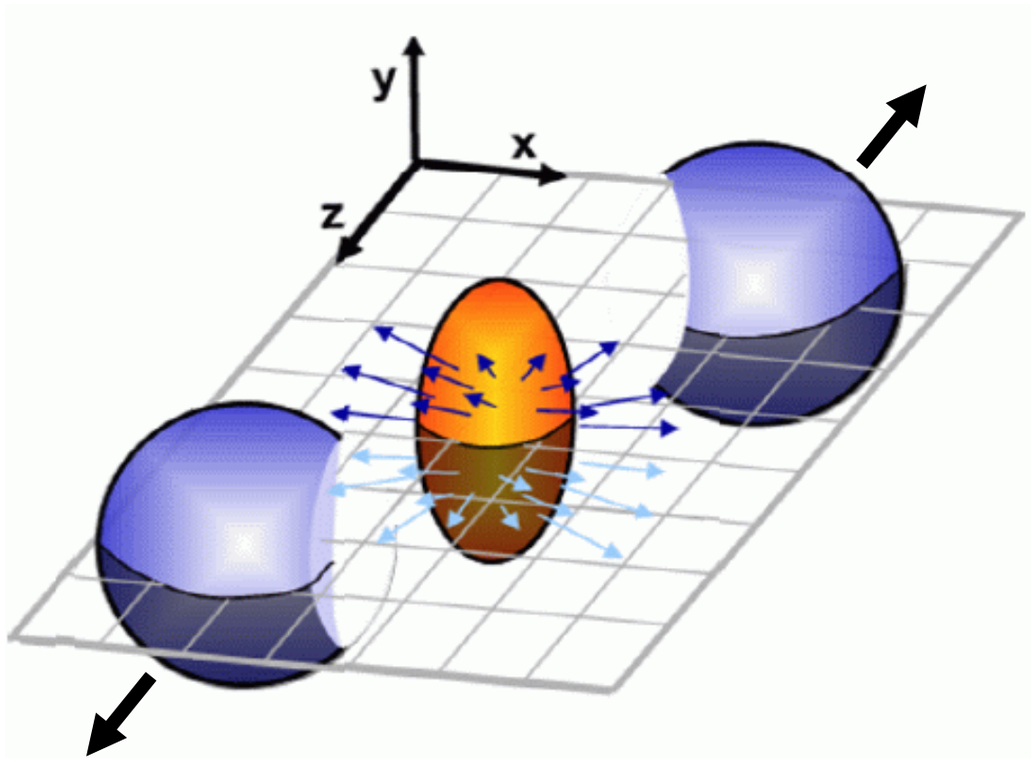
- Initial State:
  - Initialization of two nuclei
  - Non-equilibrium hadron-string dynamics
  - Initial state fluctuations are included naturally
- 3+1d Hydro +EoS:
  - **SHASTA** ideal relativistic fluid dynamics
  - Net baryon density is explicitly propagated
  - Equation of state at finite μ_B
  - Karpenko et al: 3+1d viscous hydrodynamics
- Final State:
  - Hypersurface at constant energy density
  - Hadronic rescattering and resonance decays within hadron transport

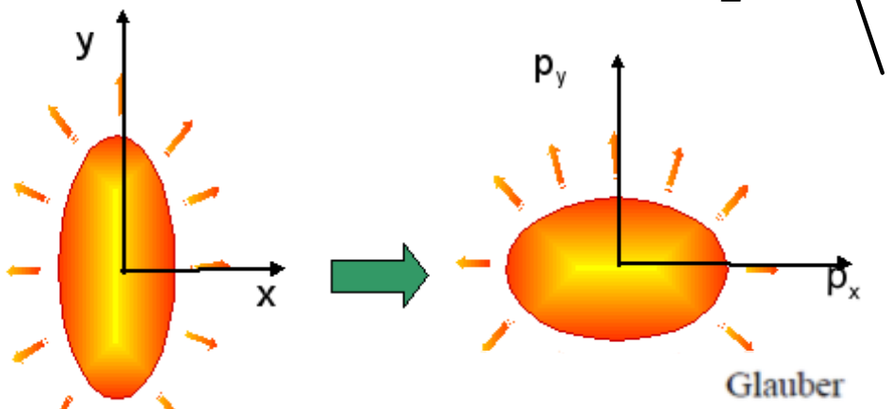
HP et al, PRC78 (2008) 044901, G. Gräf, J. Steinheimer and M. Bleicher, UrQMD-3.4 (urqmd.org)

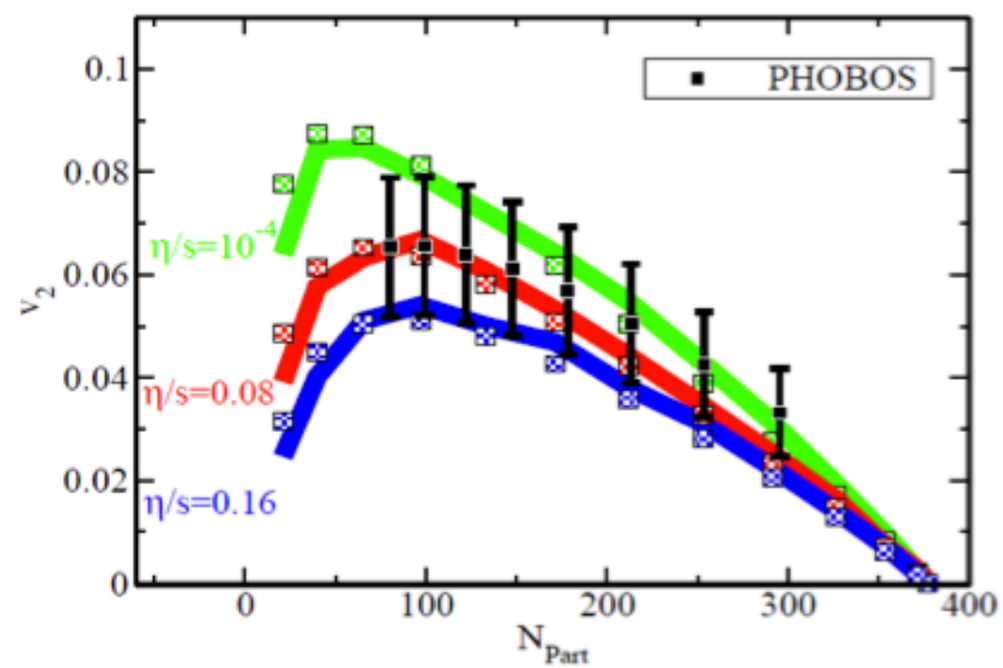
Elliptic Flow

Second coefficient of the Fourier expansion of the azimuthal particle distribution:

$$v_2 = \left\langle \left(\frac{p_x^2 - p_y^2}{p_T^2} \right) \right\rangle$$







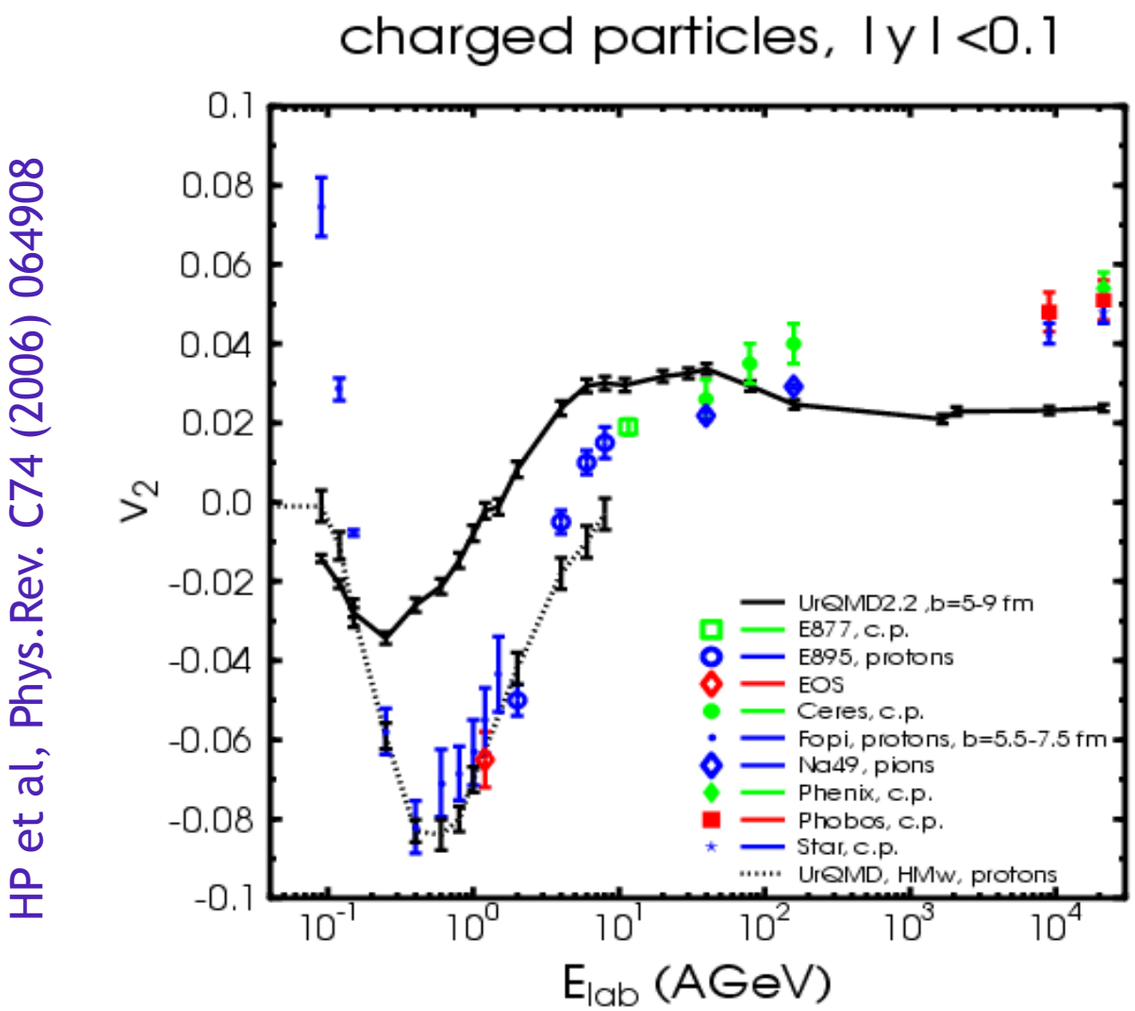
M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915

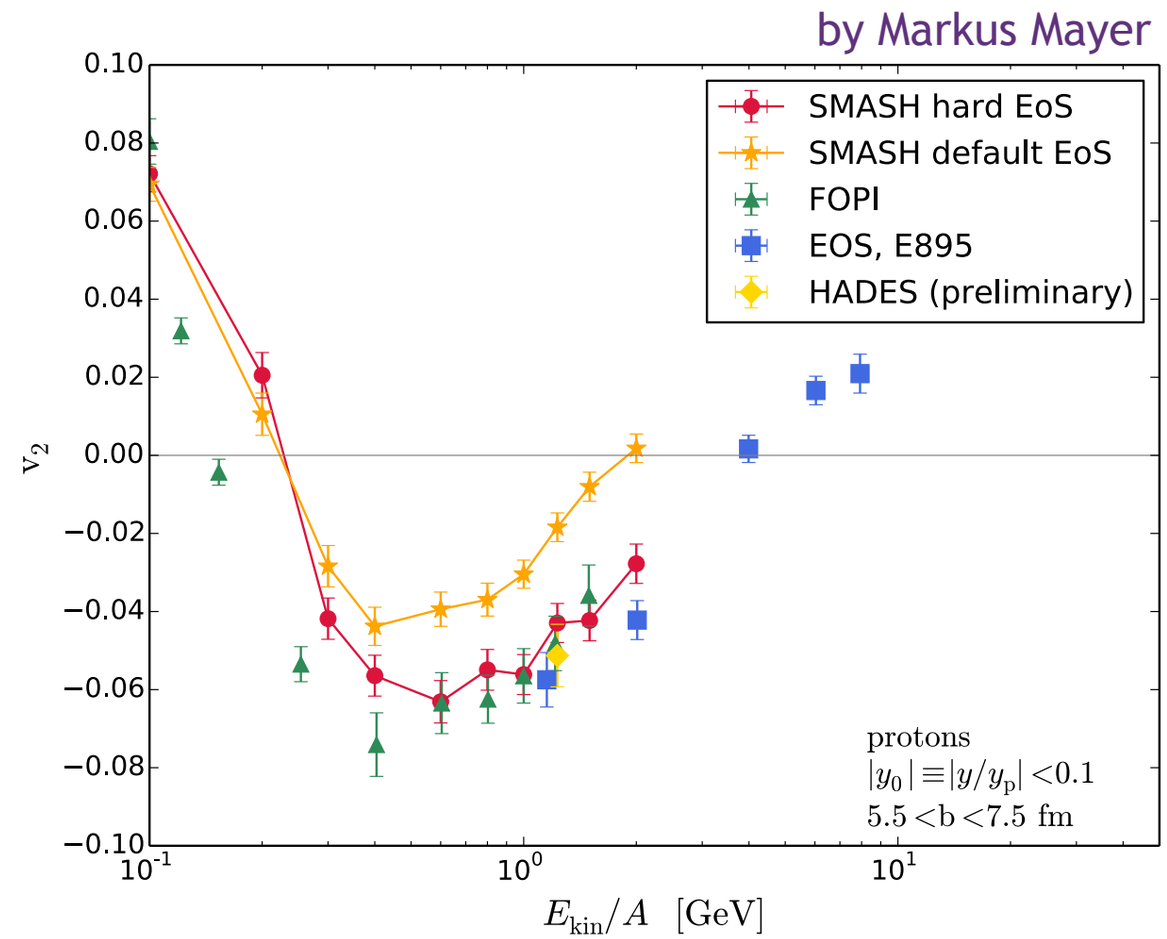
Coordinate space asymmetry
→ momentum space **anisotropy**

Relativistic fluid dynamics with very **low viscosity** describes elliptic flow at RHIC (and LHC)

v_2 Excitation Function

- Transition from squeeze-out at low energies to in-plane flow at high energies-> hadron transport underestimates flow

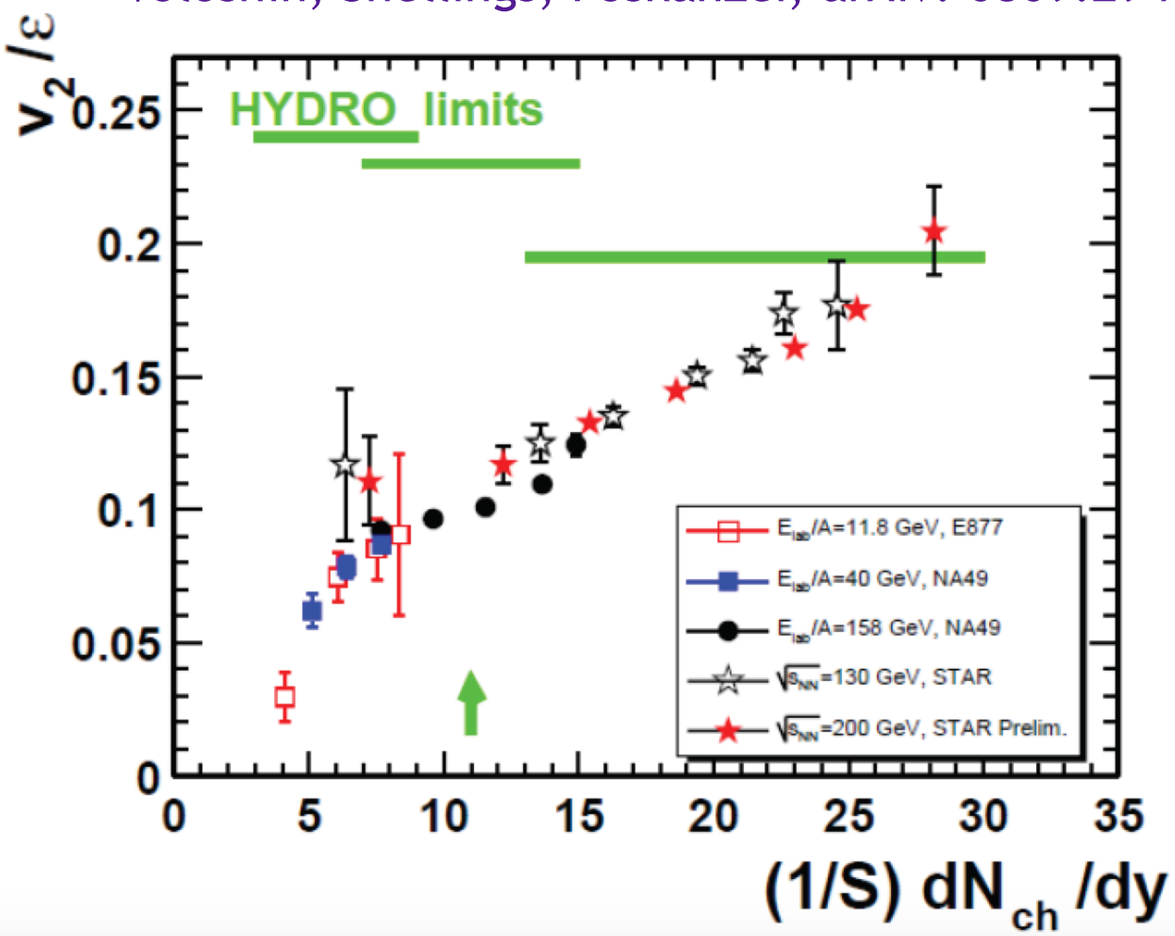




- Sensitive to equation of state of nuclear matter, here in terms of a mean field between nucleons

Ideal Hydrodynamics at RHIC

Voloshin, Snellings, Poskanzer, arXiv: 0809.2949

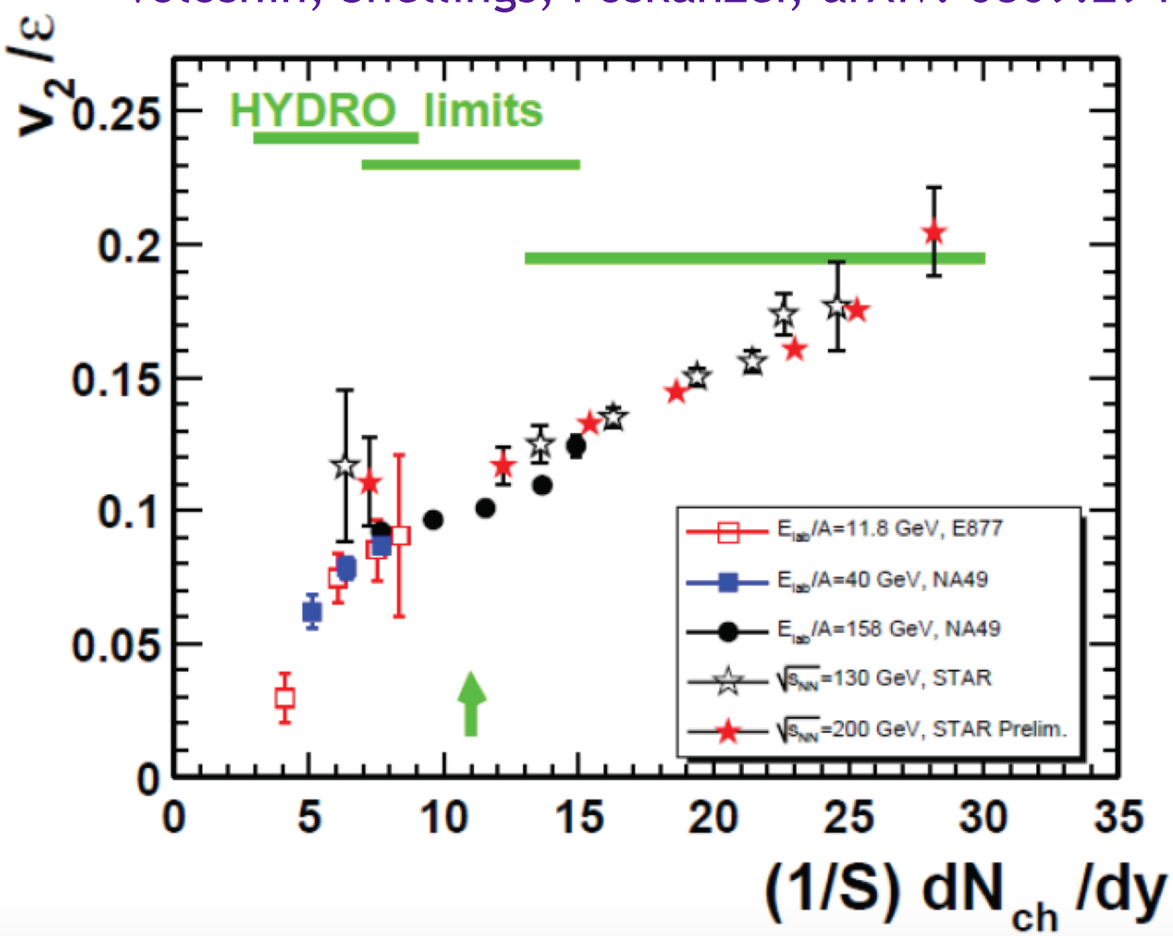


Elliptic flow scaled by the initial eccentricity vs. density in the overlap region allows to compare different centralities and energies

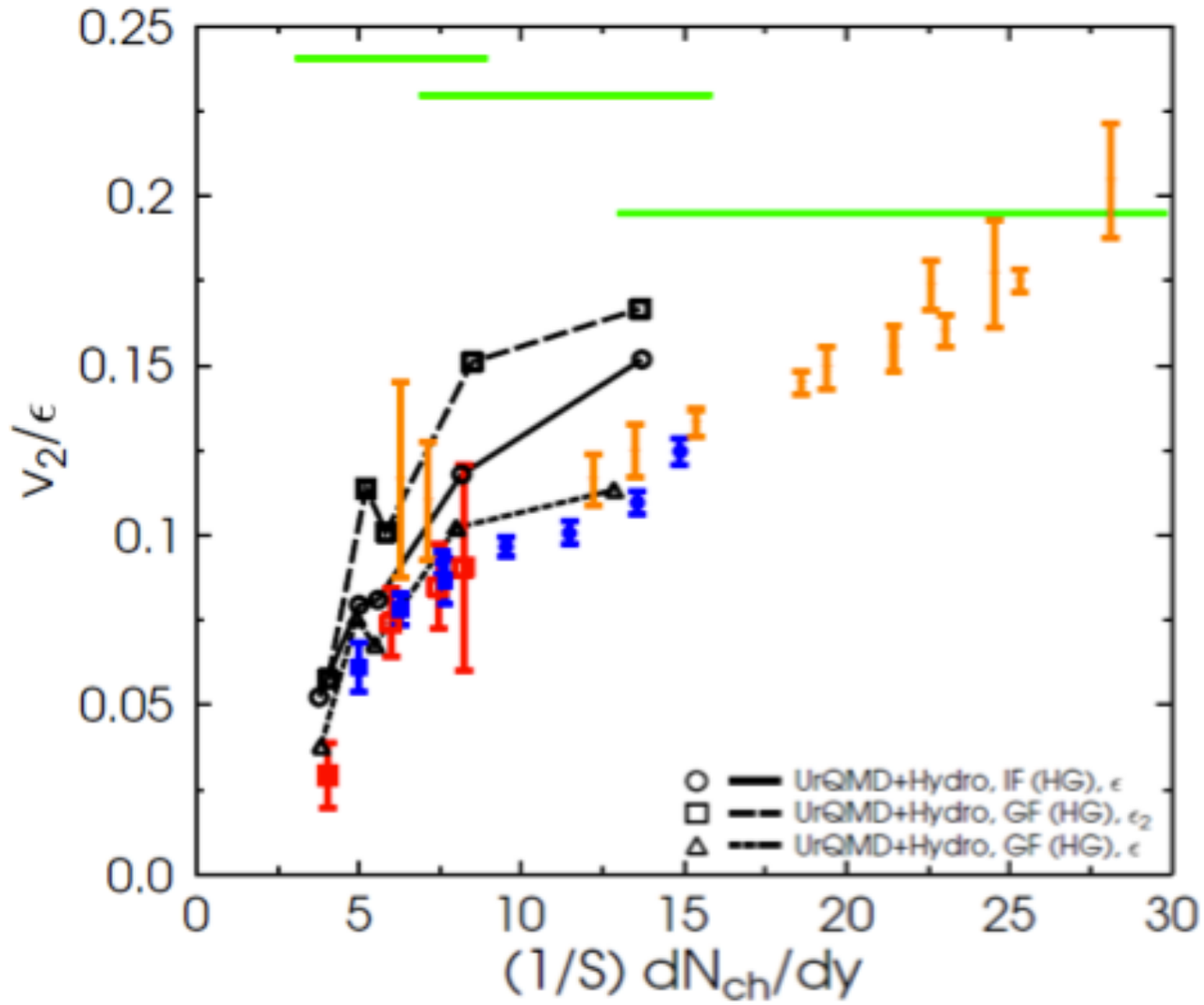
→ Ideal hydro limit reached at highest RHIC energies

Ideal Hydrodynamics at RHIC

Voloshin, Snellings, Poskanzer, arXiv: 0809.2949



HP et al, Phys.Rev. C79 (2009) 054904



Elliptic flow scaled by the initial eccentricity vs. density in the overlap region allows to compare different centralities and energies

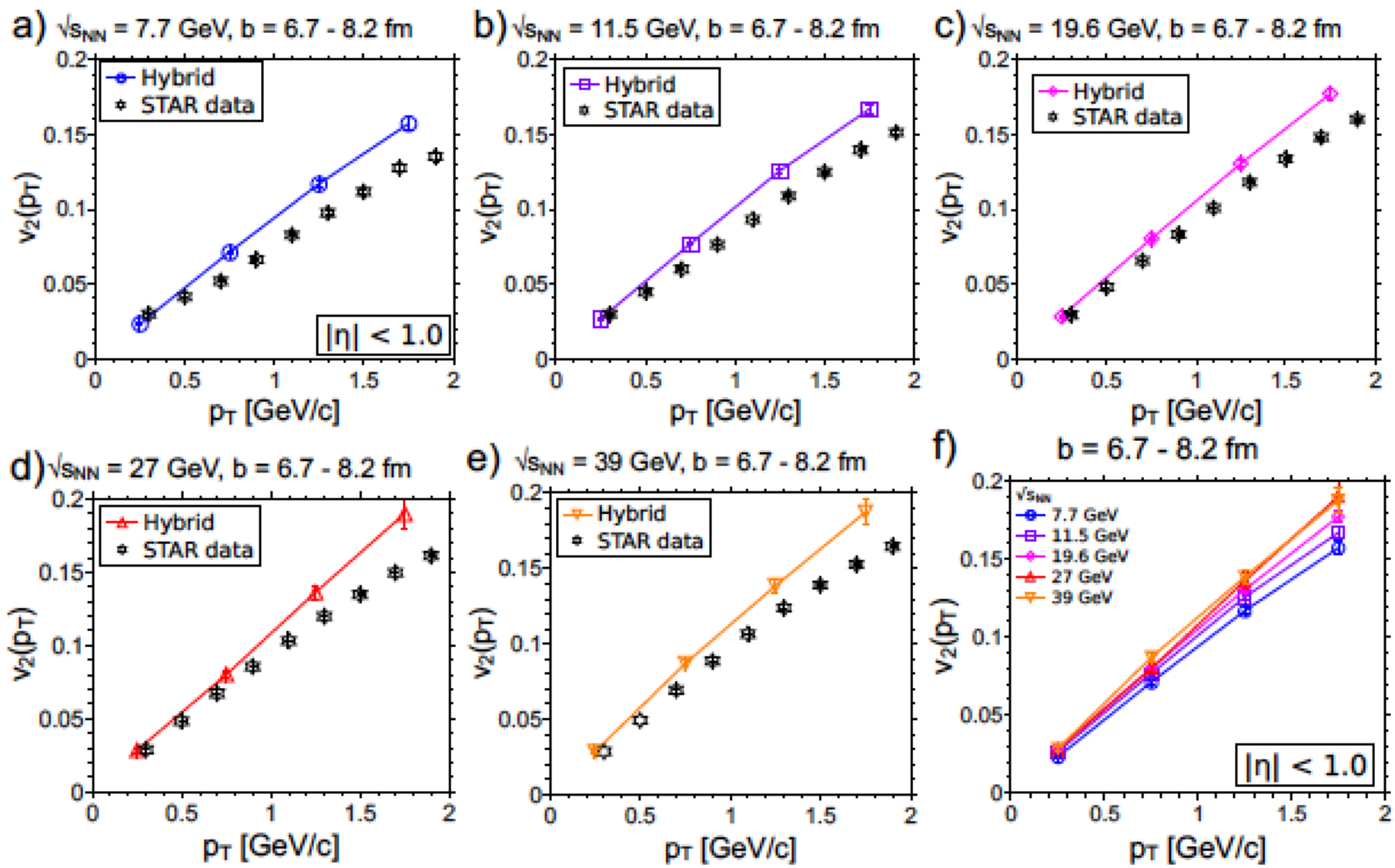
→ Ideal hydro limit reached at highest RHIC energies

Qualitative behaviour nicely reproduced in 3+1d transport+hydro approach

→ Uncertainty due to **eccentricity** calculation

Elliptic Flow

- Flow observables considered as evidence for QGP



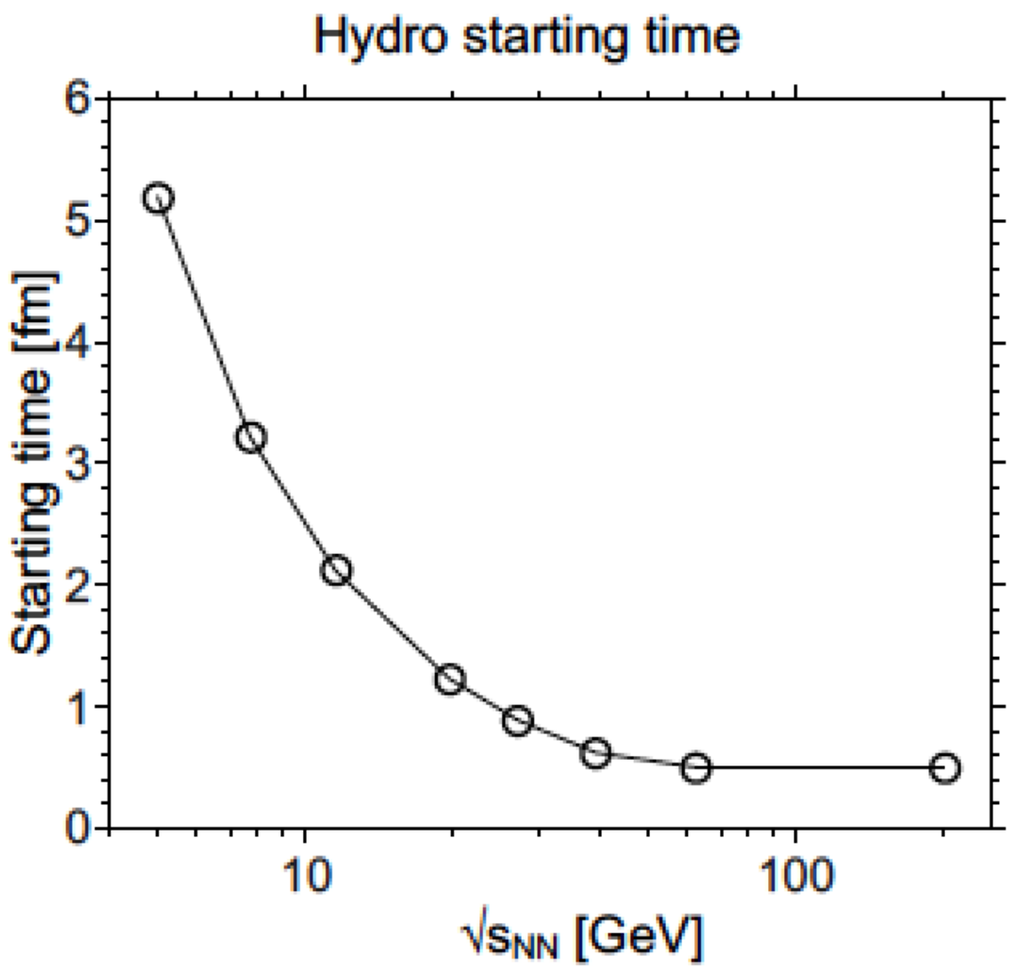
- $v_2(p_T)$ almost identical at all beam energies

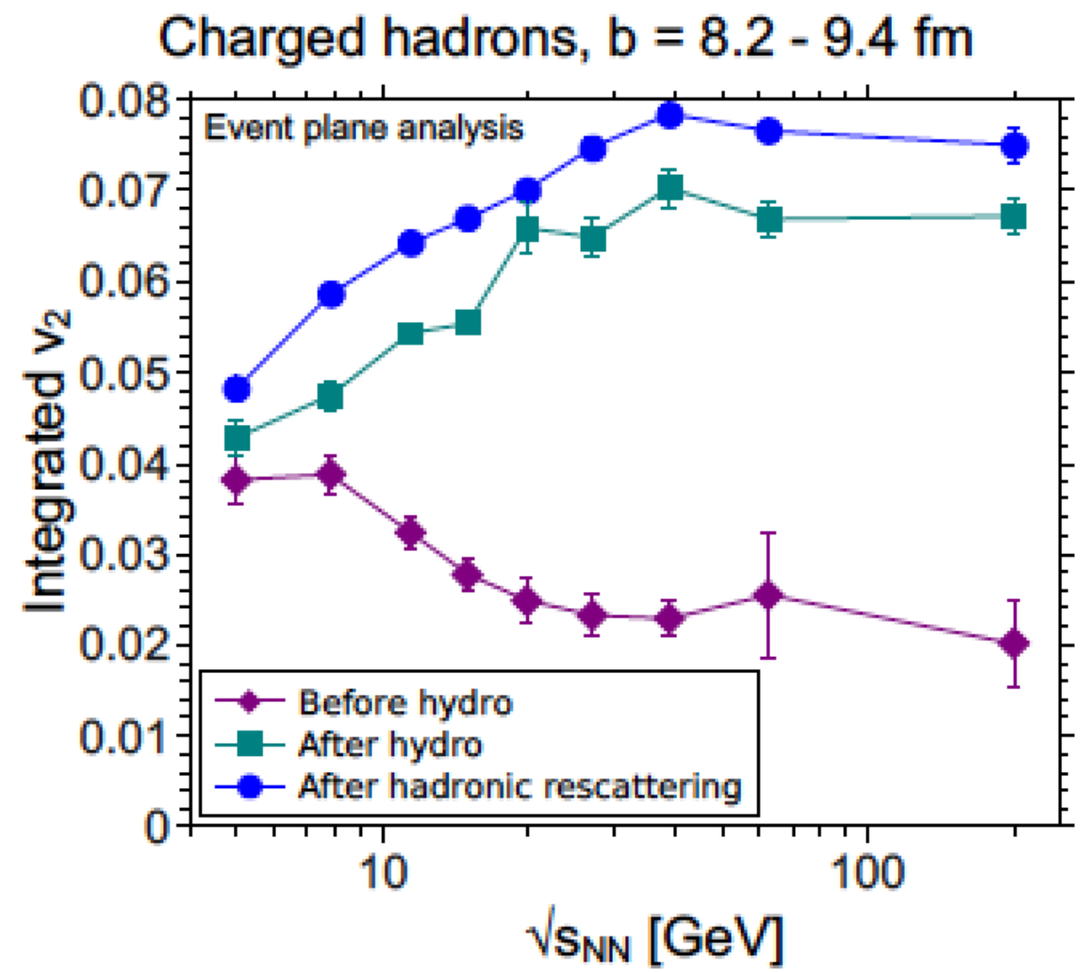
STAR, PRC 86 (2012) 054908

- Small energy dependence is reproduced by hybrid approach

J. Auvinen and HP, Phys.Rev. C88 (2013) 064908

Interplay of Hydro + Transport





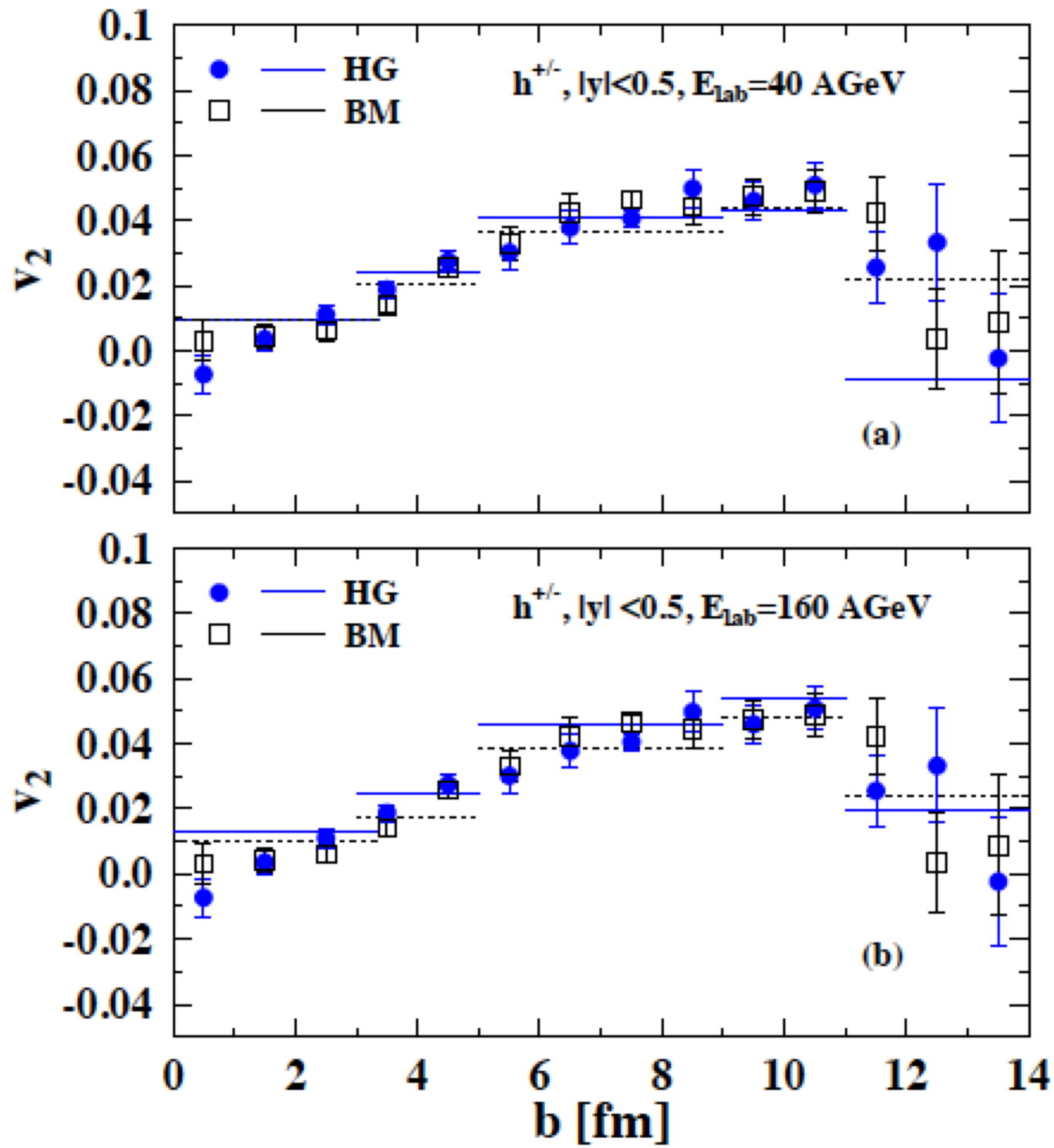
- Initial non-equilibrium evolution compensates for diminished hydrodynamic stage at lower beam energies
- Contribution of late stage hadronic rescattering ~10%

J. Auvinen and HP, Phys.Rev. C88 (2013) 064908

Equation of State and IC Fluctuations

- Symbols: Event-by-event calculations
- Horizontal lines: Averaged results
- Blue: Hadron Gas EoS
- Black: Bag Model EoS with first order phase transition

- **NO** difference visible in the centrality dependence of elliptic flow



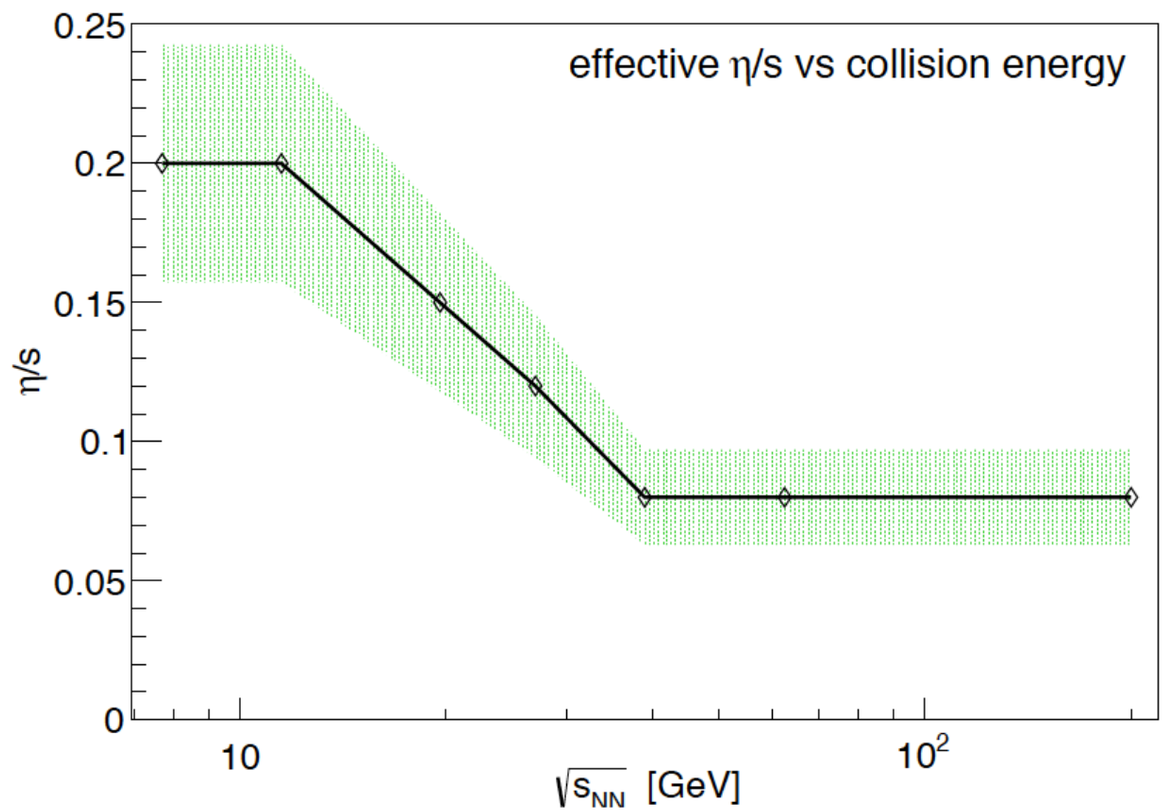
HP et al, Phys.Rev. C81 (2010) 044906

η/s Energy Dependence

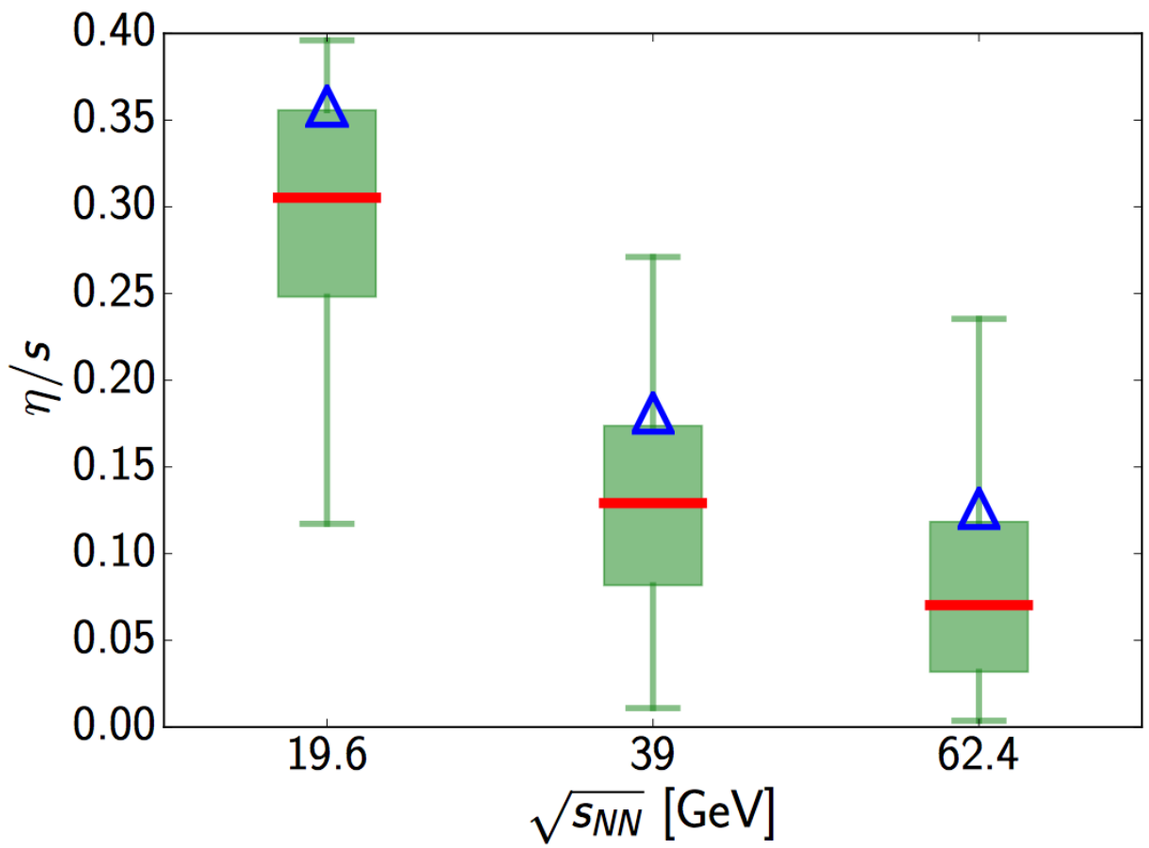
- Viscous UrQMD hybrid fitted to beam energy scan and SPS data allows to extract **effective** shear viscosity of the hydrodynamic stage

Y. Karpenko et al, Phys.Rev. C91 (2015)

Analysis „by eye“



Bayesian framework



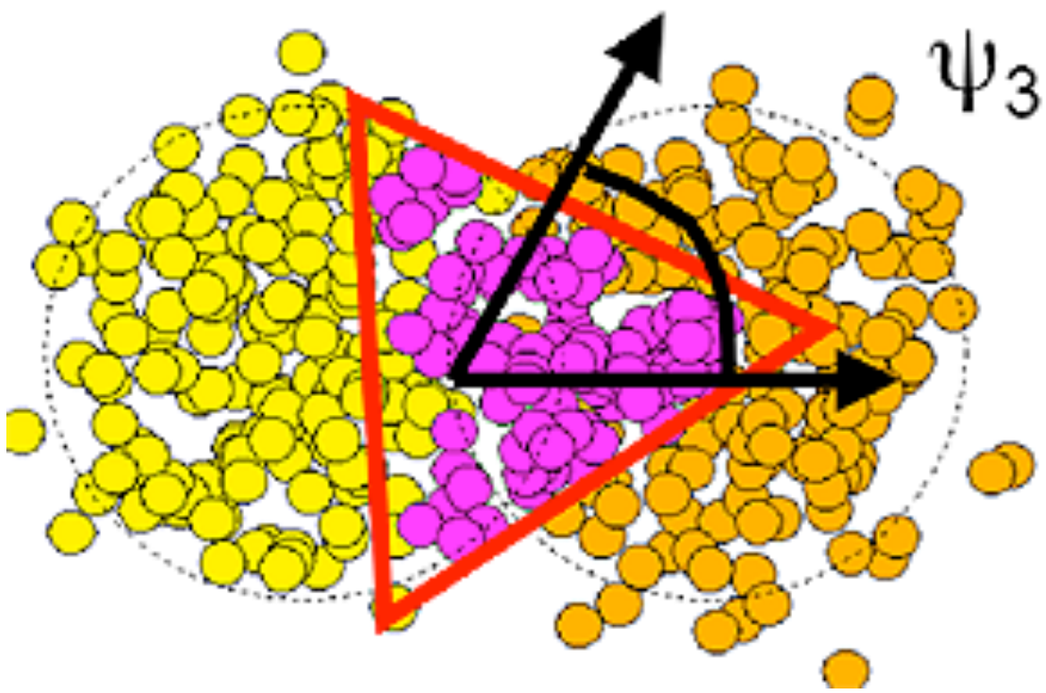
Auvinen et al., arXiv:1610.00590

- More insights on transport coefficients especially at **finite μ_B** from non-perturbative methods are needed

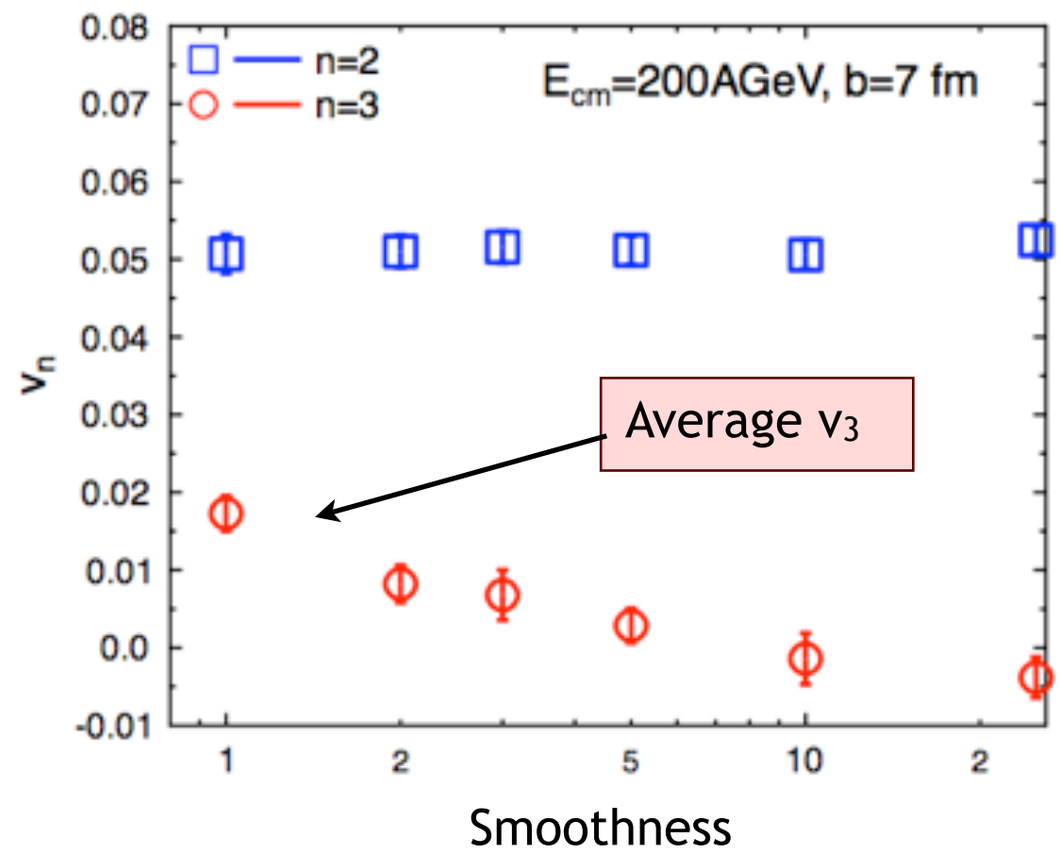
see e.g. holographic approaches: R. Rougemont et al, Phys. Rev. Lett. 115, 202301 and JHEP 04 (2016) 102

Triangular Flow

Initial State Fluctuations



Third Harmonic Coefficient



HP et al, JPG G39 (2012)

- Fluctuations introduce **higher order flow coefficients** that have been observed at the RHIC and LHC experiments
- A chance to disentangle initial state fluctuations from other e-by-e fluctuations related to phase transition?

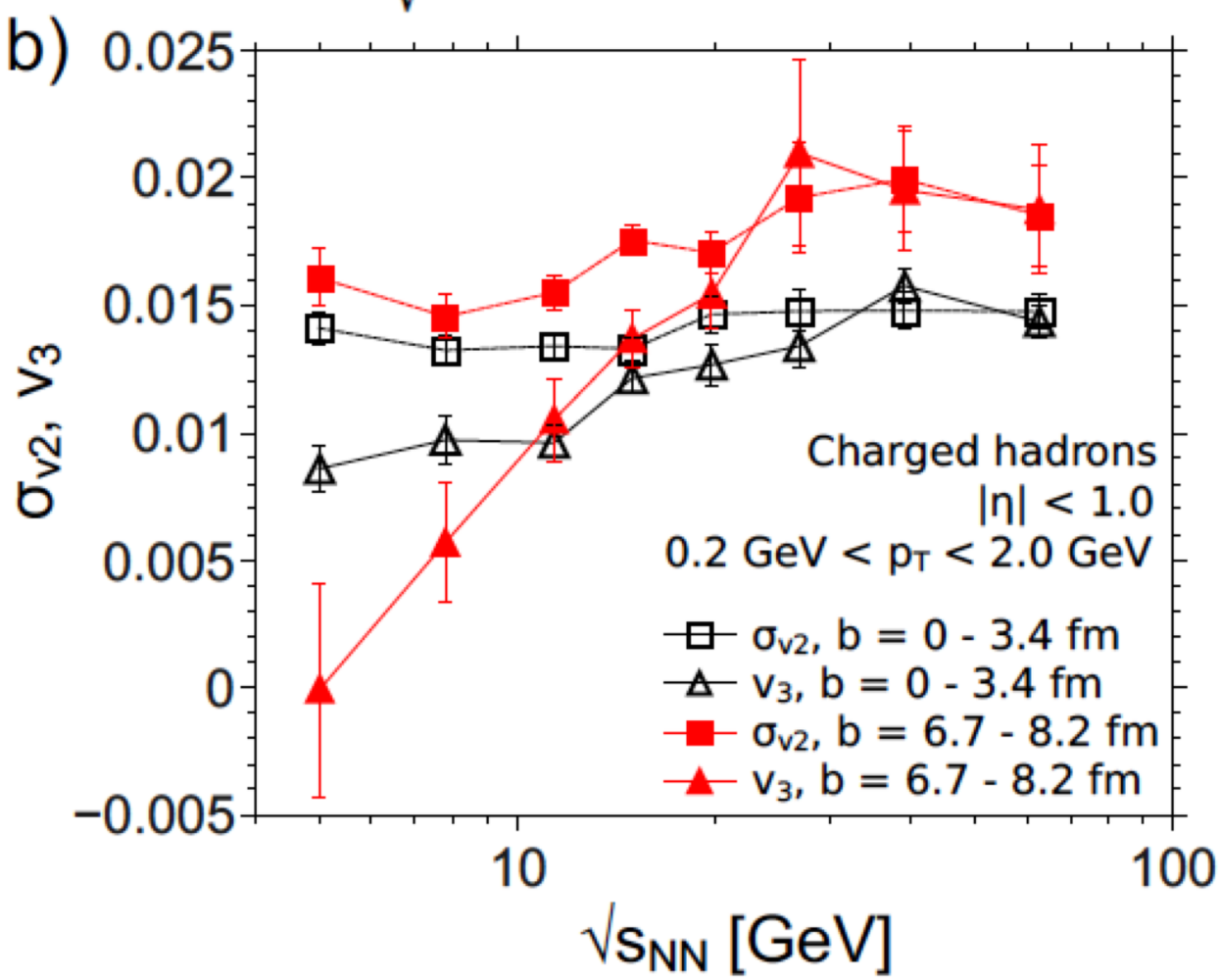
B. Alver and G. Roland, PRC 2010; Workshop summary: A. Adare, M. Luzum, HP, Phys.Scripta 87 (2013);

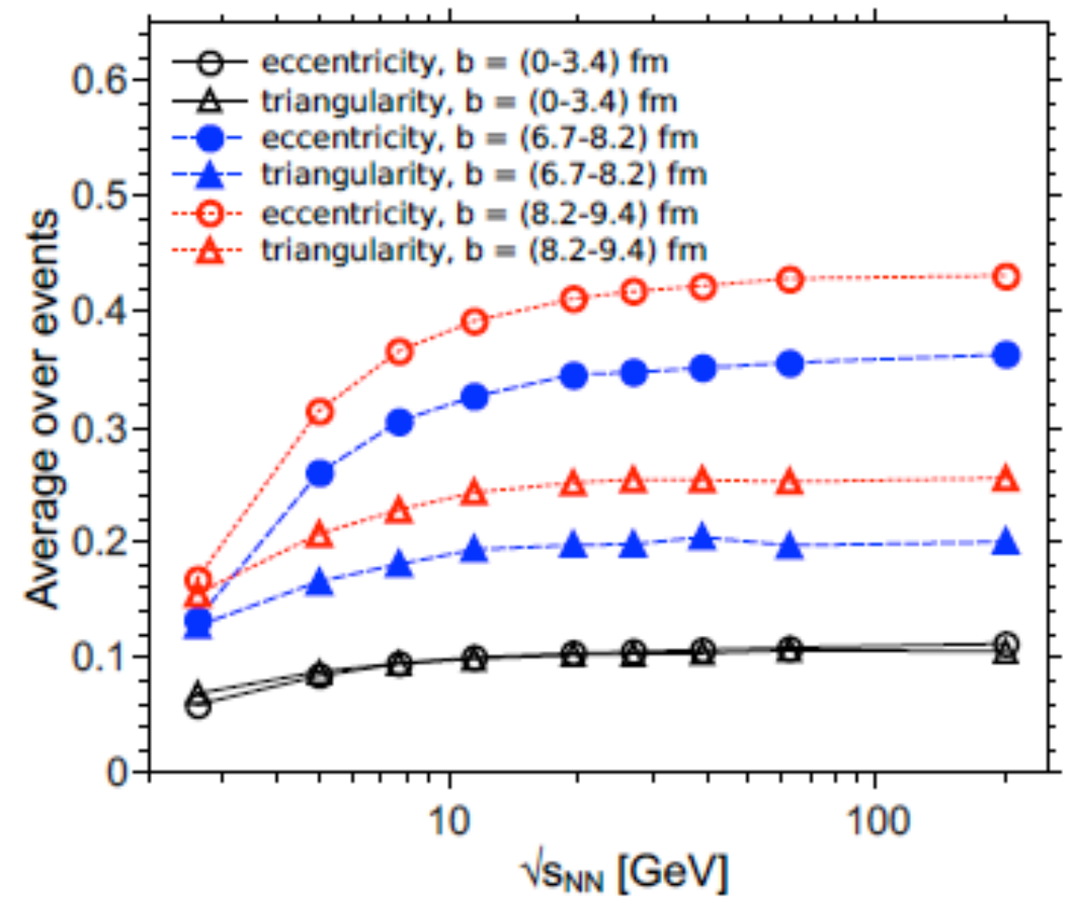
Topical Review: M. Luzum, HP, J.Phys. G41 (2014) 063102

Measuring Fluctuations

- At high energies:
  - v_3 is equal to σ_{v2}
- At lower energies v_3 vanishes

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





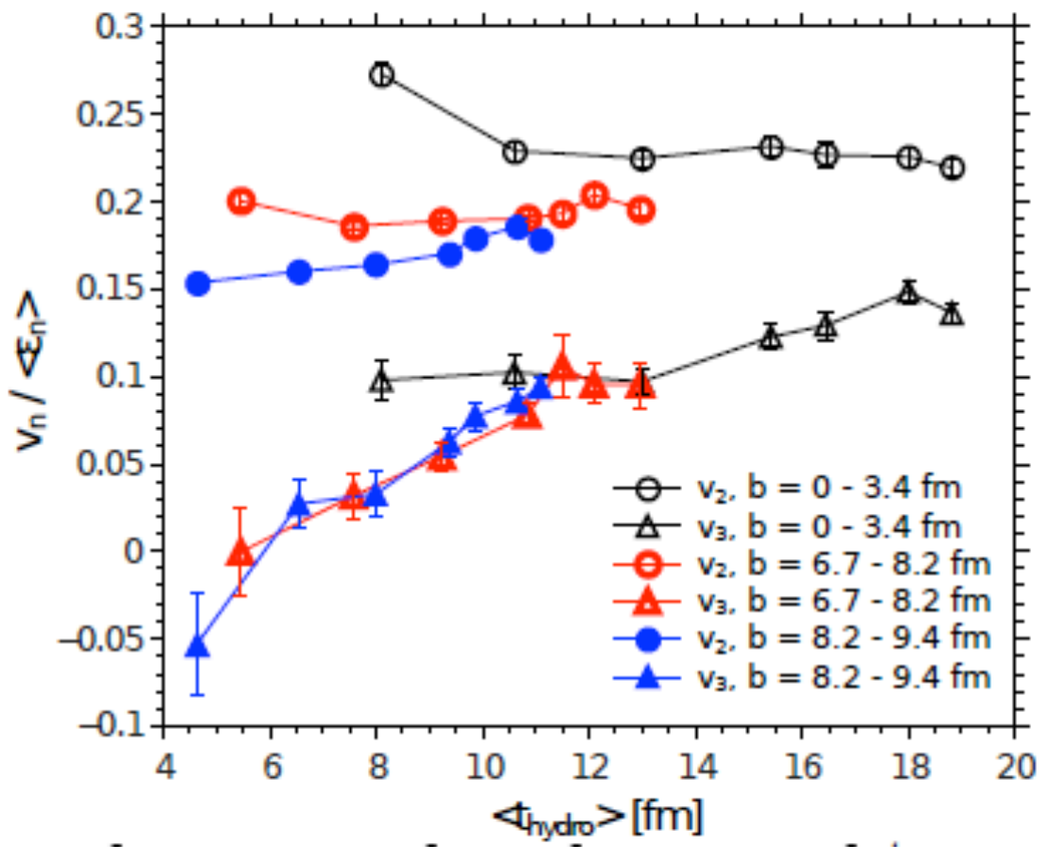
- Initial state geometry and fluctuations rather independent of beam energy

J. Auvinen and HP, Phys.Rev. C88 (2013) 064908

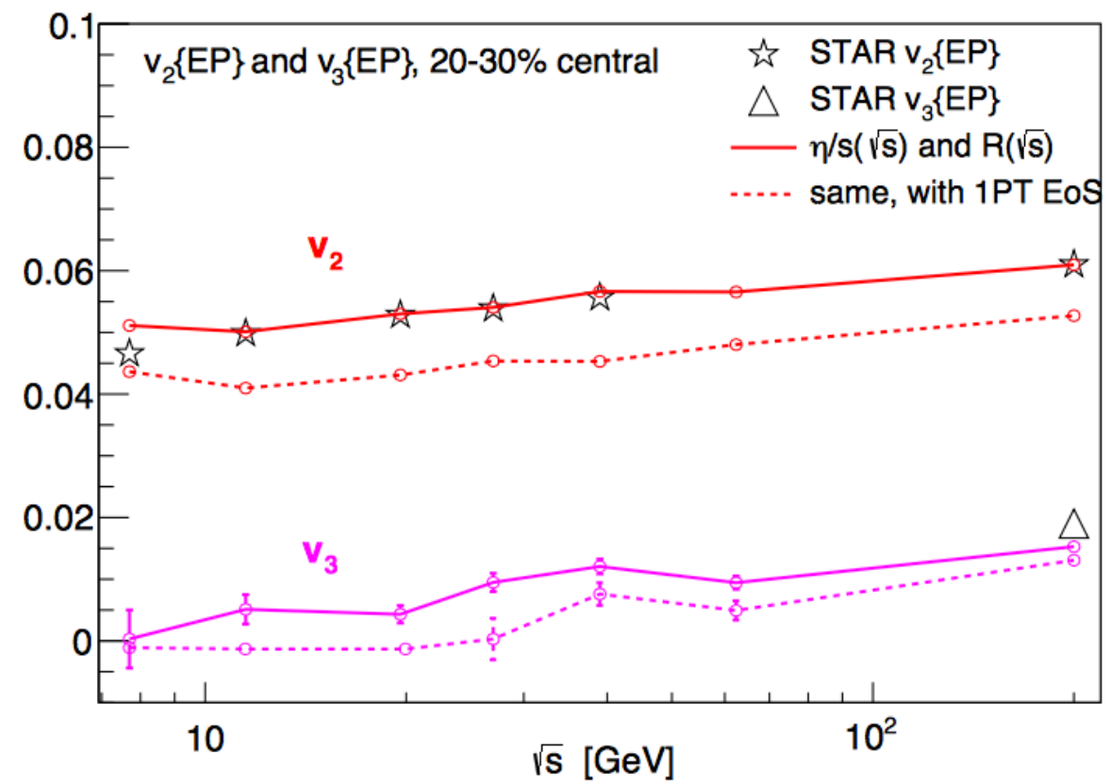
Summary: Elliptic and Triangular Flow

Hydrodynamic response in ideal UrQMD hybrid approach

J. Auvinen and HP, Phys.Rev. C88 (2013) 064908



Prediction of triangular flow in Karpenko viscous hybrid approach



see also, CERES, arXiv:1604.07469; STAR, Phys. Rev. Lett. 116

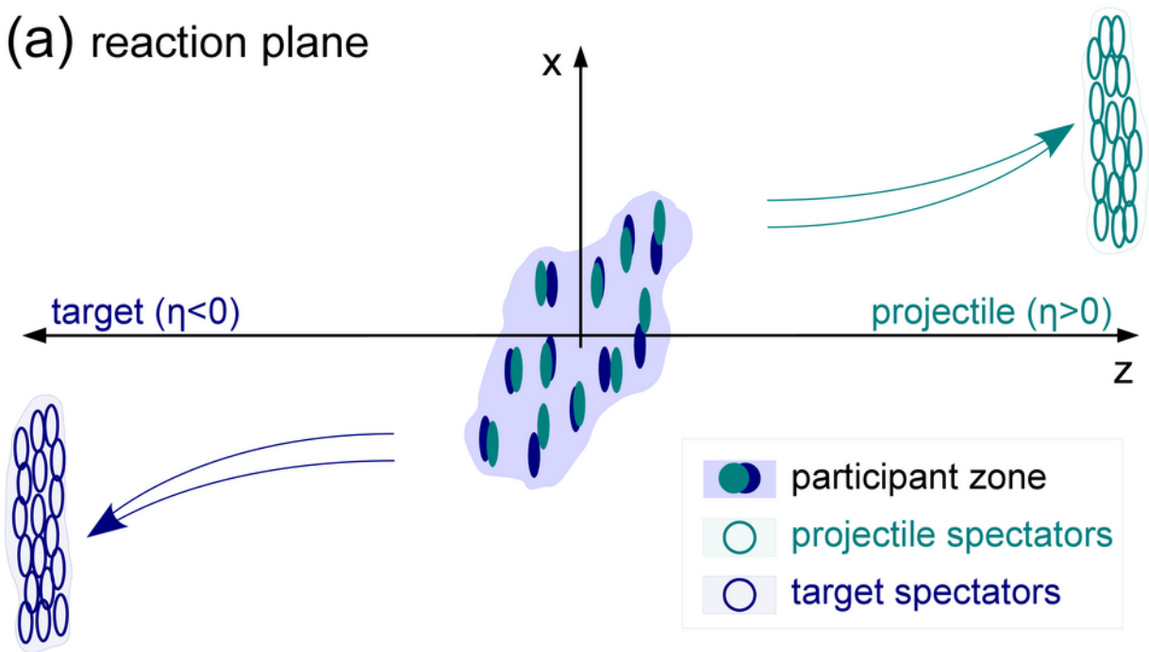
Y. Karpenko et al, Nucl.Phys. A956

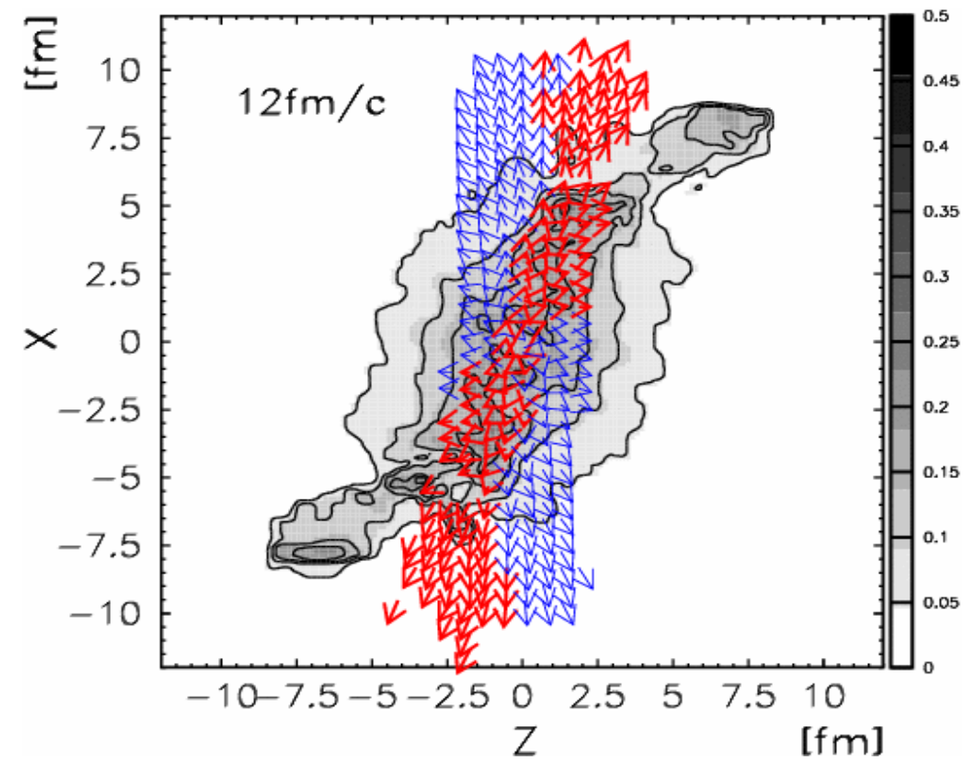
- Elliptic flow also builds up in hadronic transport approach
- v_3 is more sensitive to the viscosity
- **Disappearance of v_3** as a signal of the disappearance of the quark-gluon plasma?

Directed Flow

- Collective deflection of particles in reaction plane

sketch from ALICE, Phys. Rev. Lett. 111





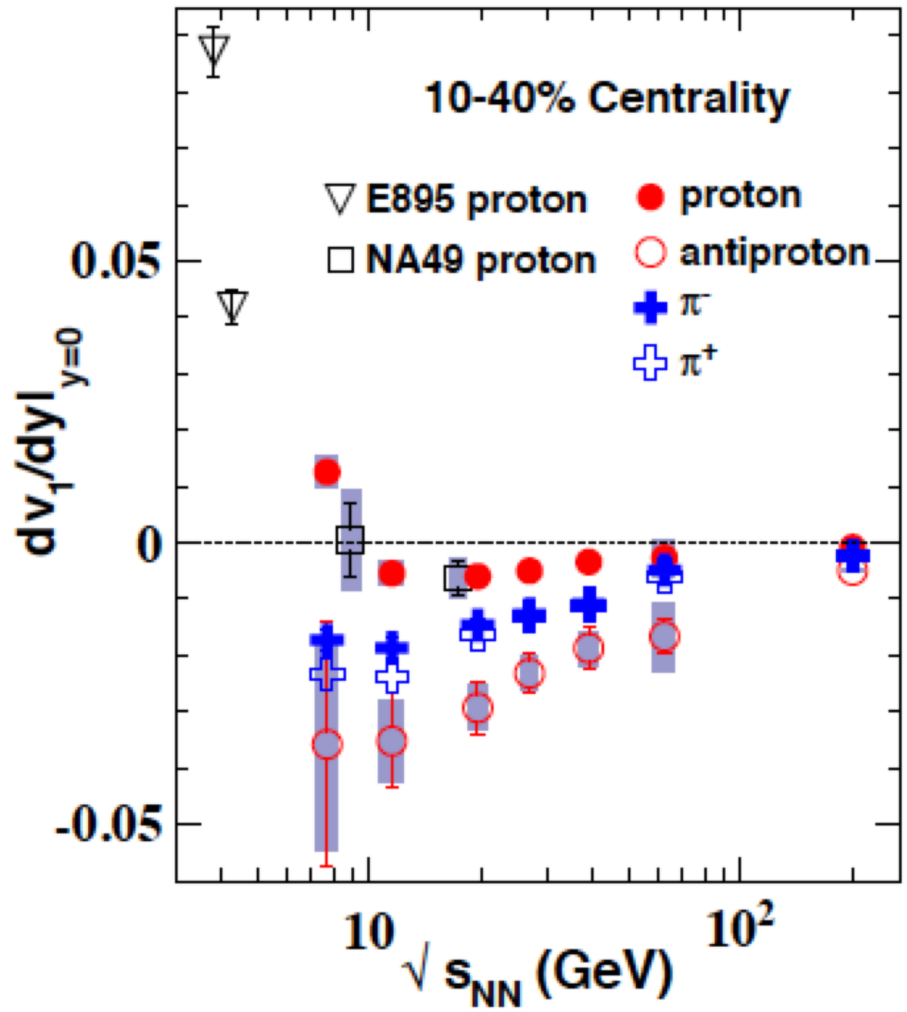
J.Brachmann et al., Phys.Rev. C, 61, 2000

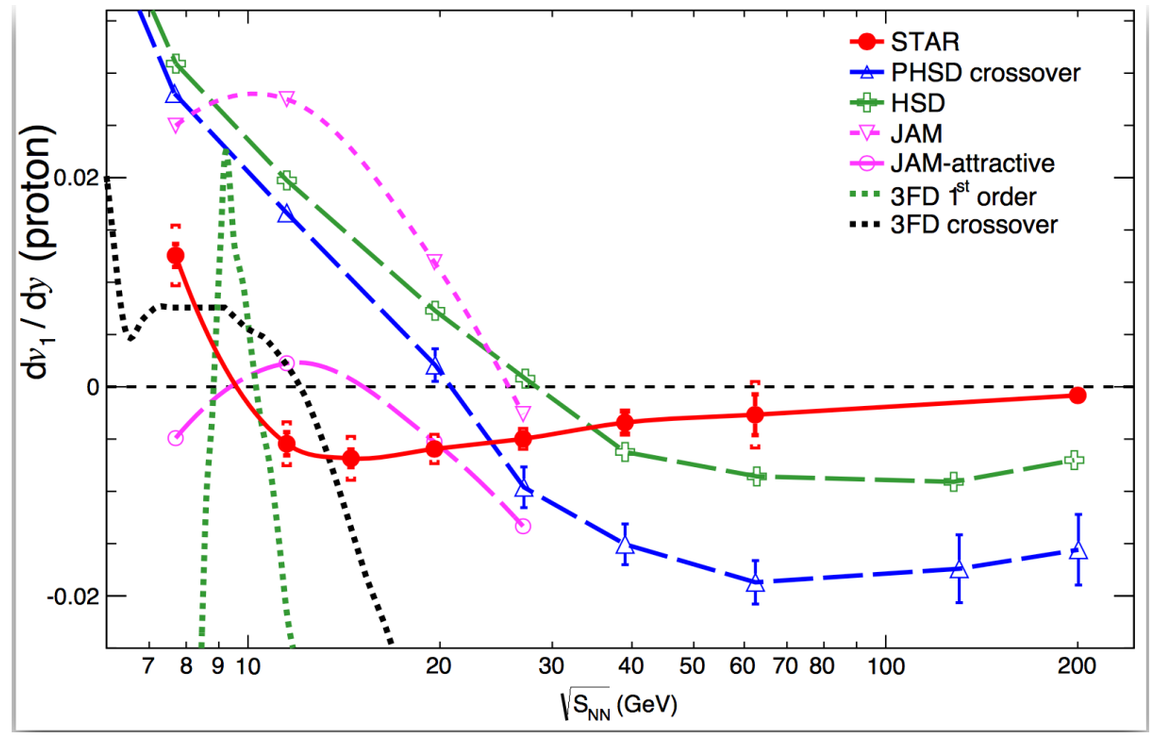
- Non-monotonic energy dependence of v1 slope
  - First order phase transition?

Directed Flow

- Collective deflection of particles in reaction plane

STAR, PRL 112, (2014) 162301





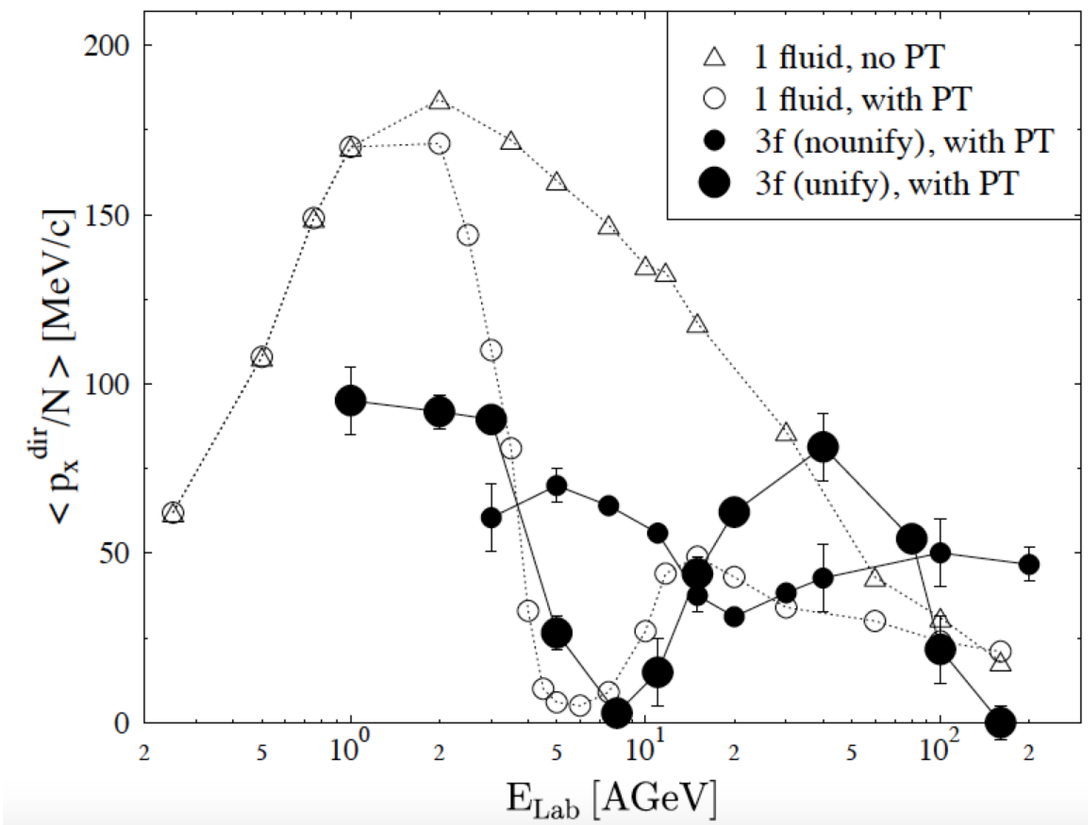
S. Singha, talk at INT-16-3

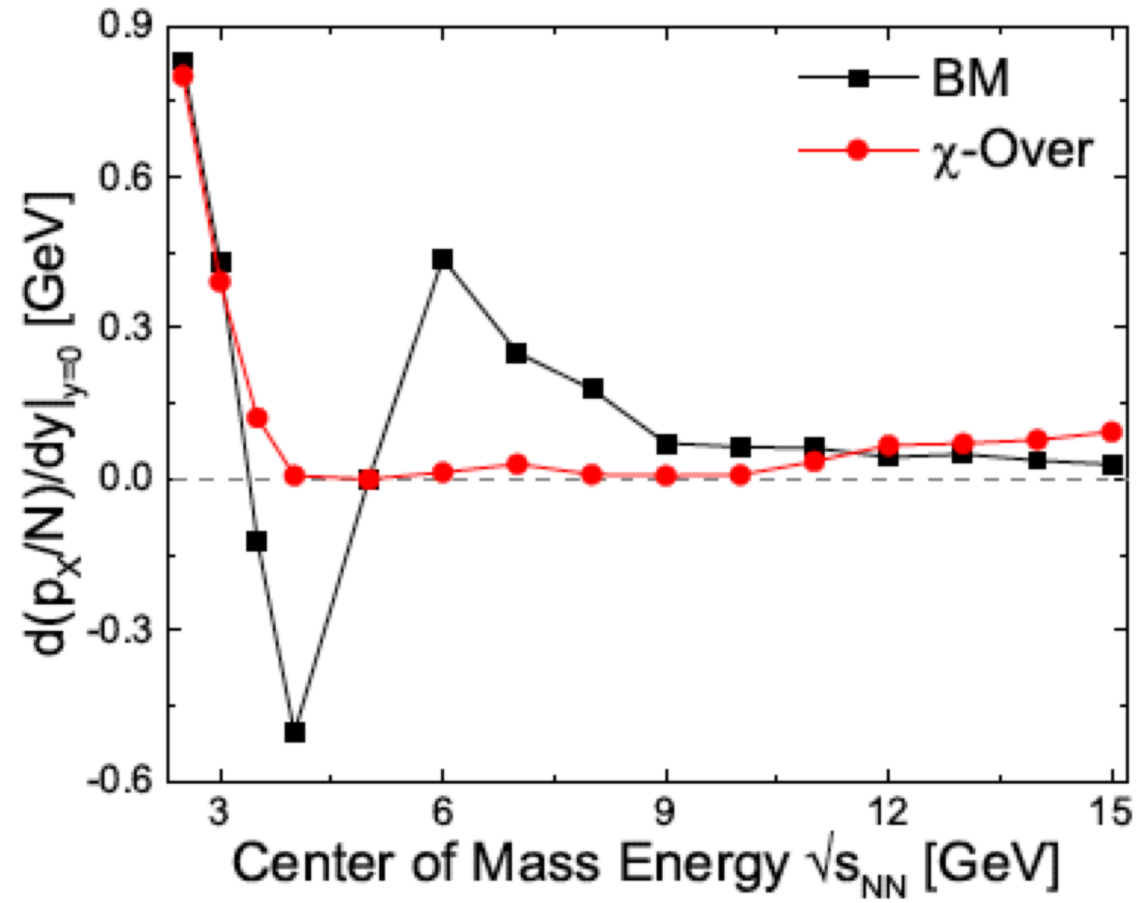
- Non-monotonic energy dependence of v1 slope
  - First order phase transition?
  - No quantitative theory description so far

Pure Fluid Calculations

- Negative slope is reproduced in fluid dynamic calculation

J.Brachmann et al., Phys.Rev. C, 61, 2000

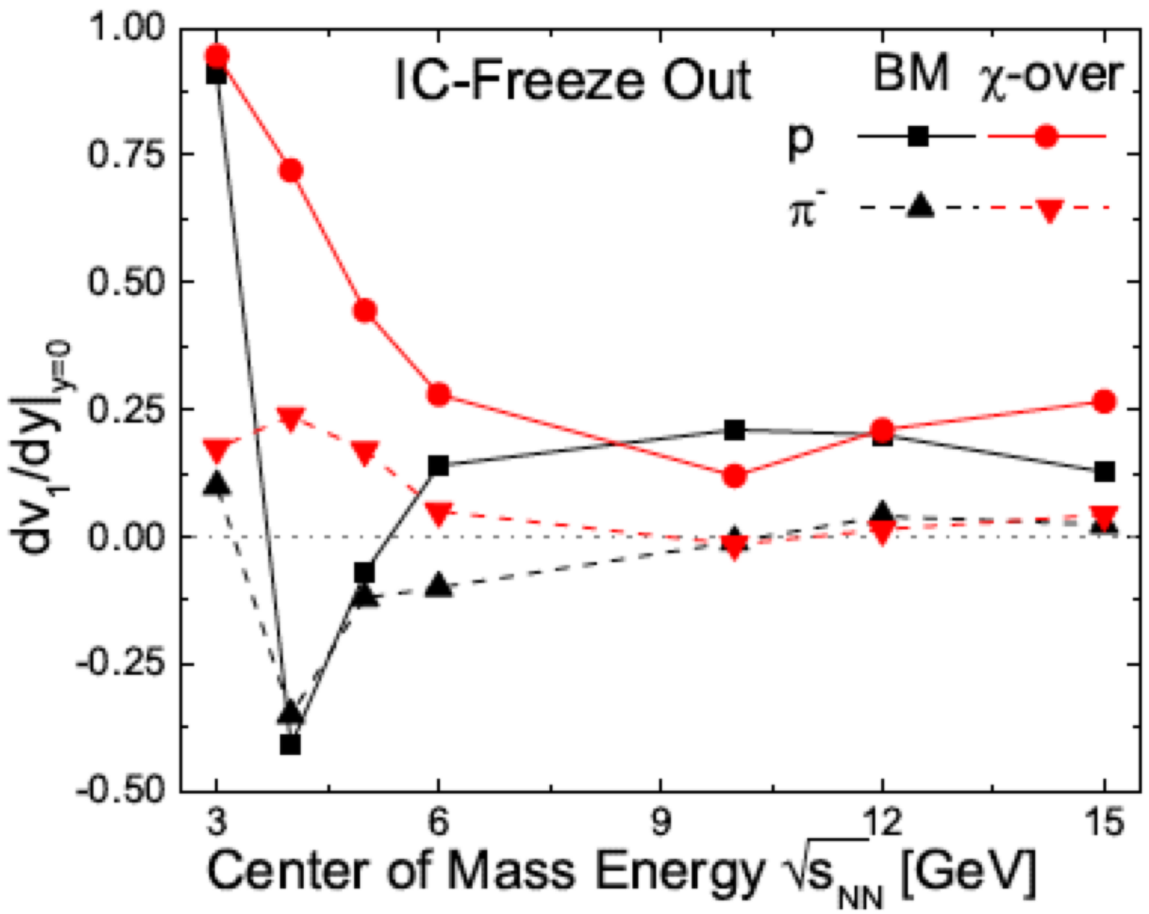


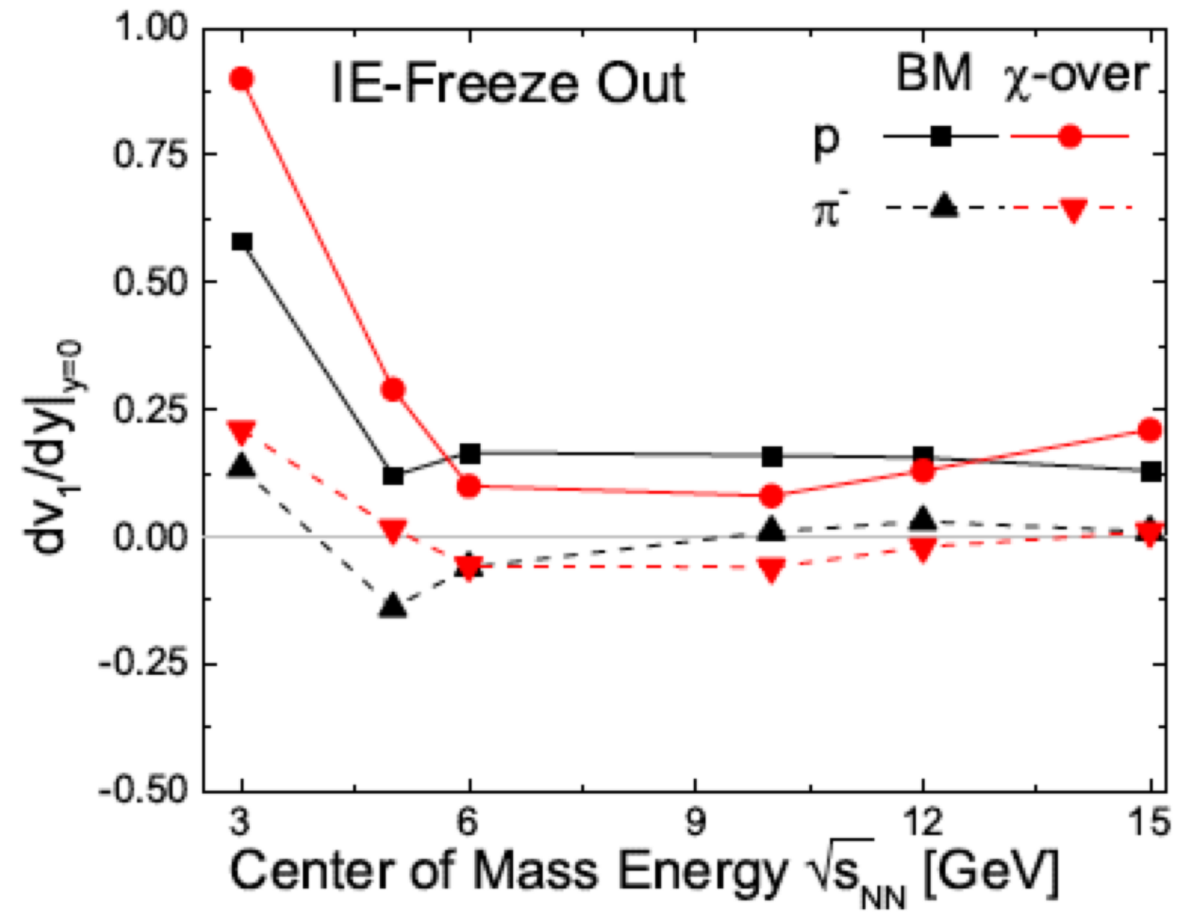


- Assumptions
  - Cold nuclear matter initialization (no pre-equilibrium transport)
  - Direct integration of momentum in x-direction without hadronic rescattering

J. Steinheimer, J. Auvinen, HP, M. Bleicher and H. Stöcker, Phys.Rev. C89 (2014) 054913

v_1 Slope for Pions and Protons



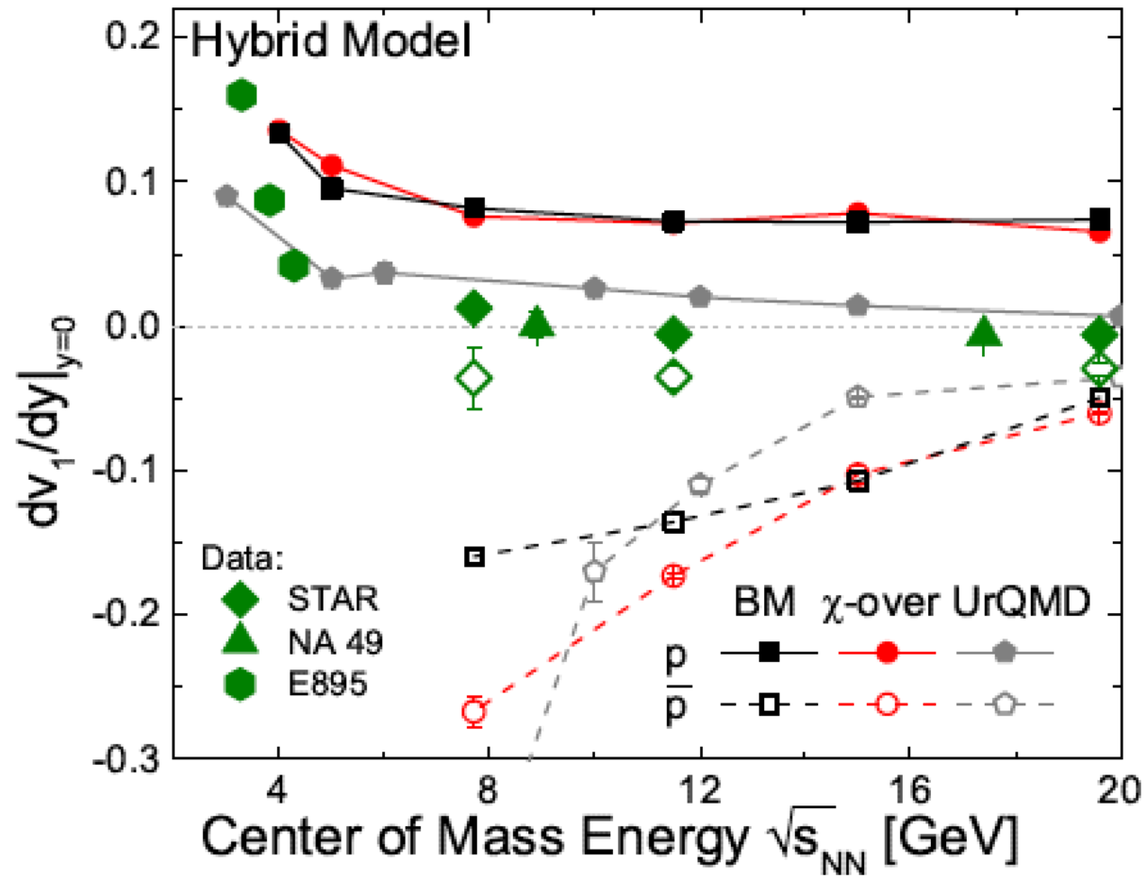


- Particlization added including hadronic rescattering
- Isochronous versus iso-energy density transition criterion
  - Drastic effect on dip structure

J. Steinheimer, J. Auvinen, HP, M. Bleicher and H. Stöcker, Phys.Rev. C89 (2014) 054913

Full Hybrid Approach

- Hybrid approach with different equations of state shows similar results



- Alternative calculations within transport/3fluid dynamics confirm complexity of this observable

Konchakovski et al, Phys.Rev. C90 (2014) 014903

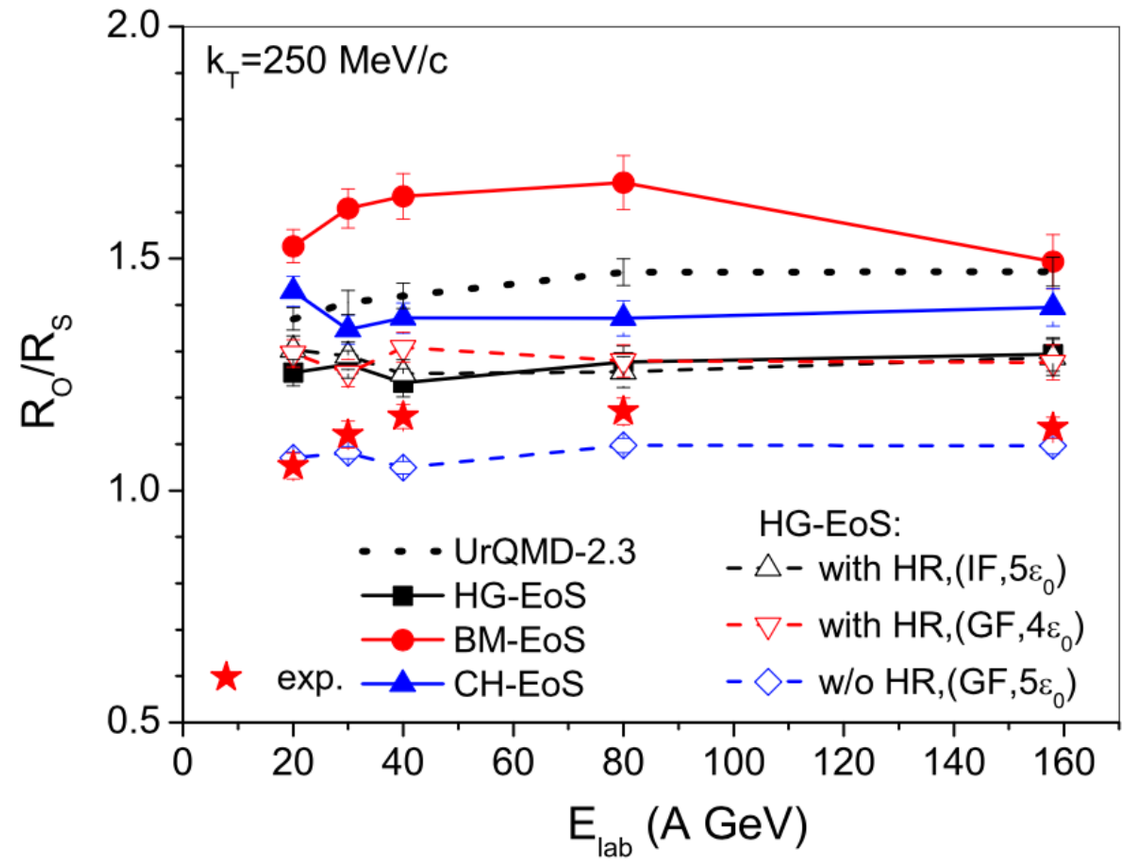
- **Additional issues** that influence the energy dependence like nucleon potentials, interactions with spectators have to be sorted out by looking at different particle species and the centrality dependence

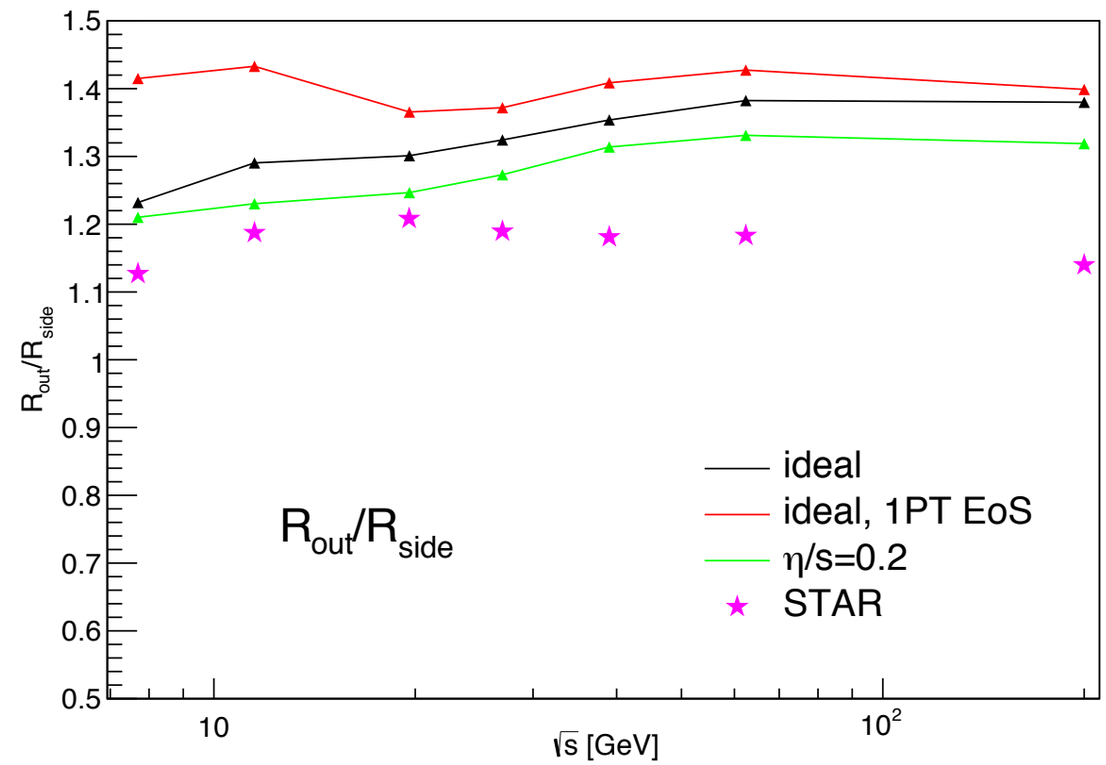
J. Steinheimer, J. Auvinen, H.P., M. Bleicher and H. Stöcker, PRC 89 (2014) 054913

R_O/R_S Ratio

- Idea: Softest point increases the lifetime of the system

Q. Li et al, Phys.Lett. B674 (2009)



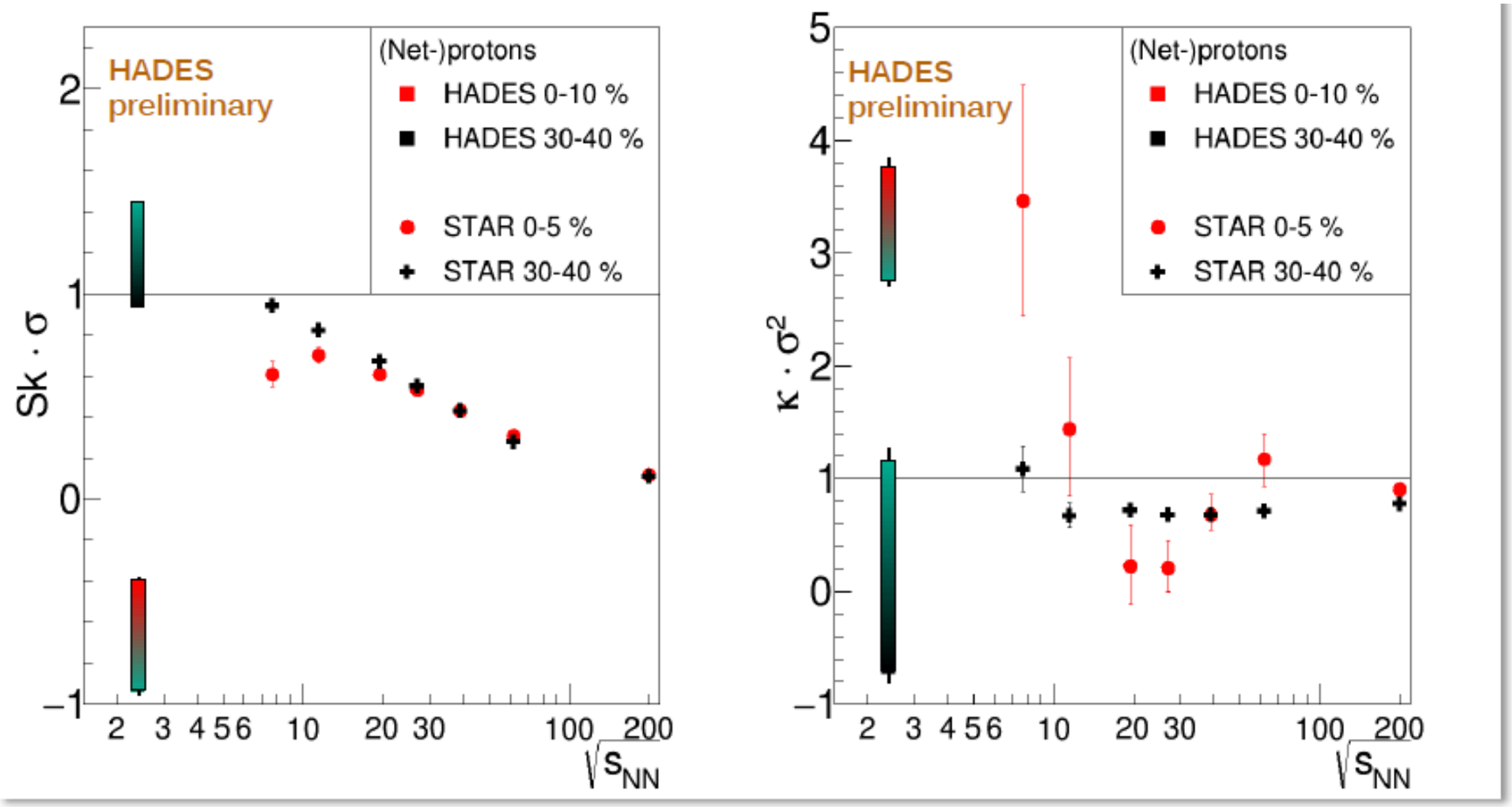


Y. Karpenko, WPCF 2014

- NA49 and STAR data show a **slight** peak
- Hybrid approach confirms larger ratio for **first order** transition
- Open question: **Cluster** formation from phase separation?

Higher Moments

- New result from HADES Au+Au collisions:
  Skewness and kurtosis show **non-trivial** energy dependence



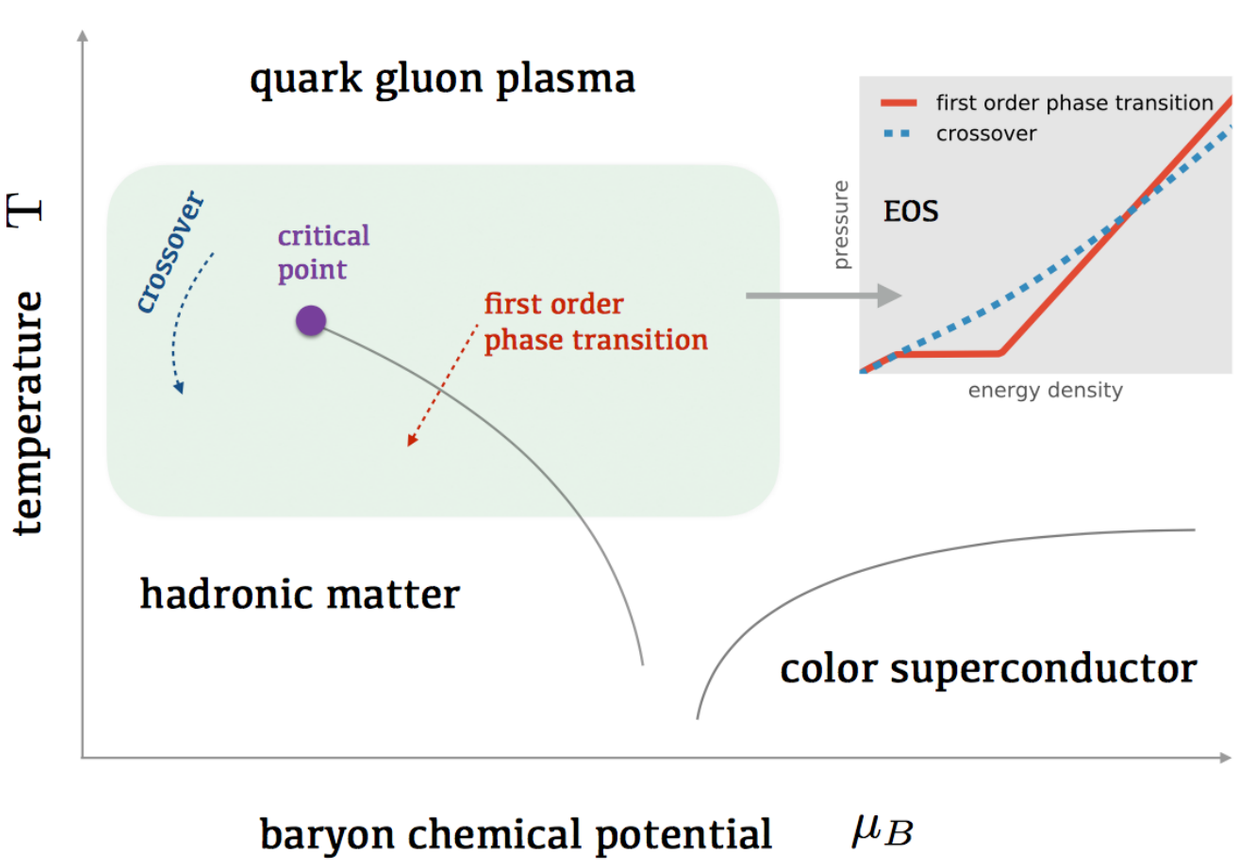
M. Lorenz, QM 17,
STAR: X. Luo, PoS (CPOD 2014) 019

- Experimental results are **scrutinised**
- Can we draw **exclusion plots** on the phase diagram by extracting 2-, 3- and 4-particle correlations?

A. Bzdak, V. Koch and N. Strodthoff, arxiv:1607.07375

Deep Learning Techniques

- First proof-of-principle application of deep learning to heavy ion physics



TRAINING DATASET	$\eta/s = 0$		$\eta/s = 0.08$	
	EOSL	EOSQ	EOSL	EOSQ
Au-Au $\sqrt{s_{NN}} = 200$ GeV	7435	5328	500	500
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV	4967	2828	500	500

TESTING ACCURACIES	GROUP 1		GROUP 2	
	EOSL	EOSQ	EOSL	EOSQ
Number of events	3349	3994	4164	4752
Accuracy	98.5%	91.6%	99.2%	99.2%

- Extraction of QCD equation of state seems possible
- Plans: Device new observables and apply to real data

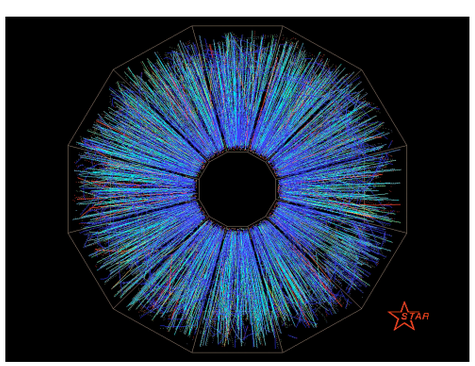
K. Zhou, L.-G. Pang, N. Su, V. Vovchenko, HP, H. Stöcker, X.-N. Wang, arXiv: 1612.04262, accepted in Nature Communications

Inspired from Brain/CNN

- As in image recognition, raw (p_T,Φ) data is classified

„DOG“

„CAT“

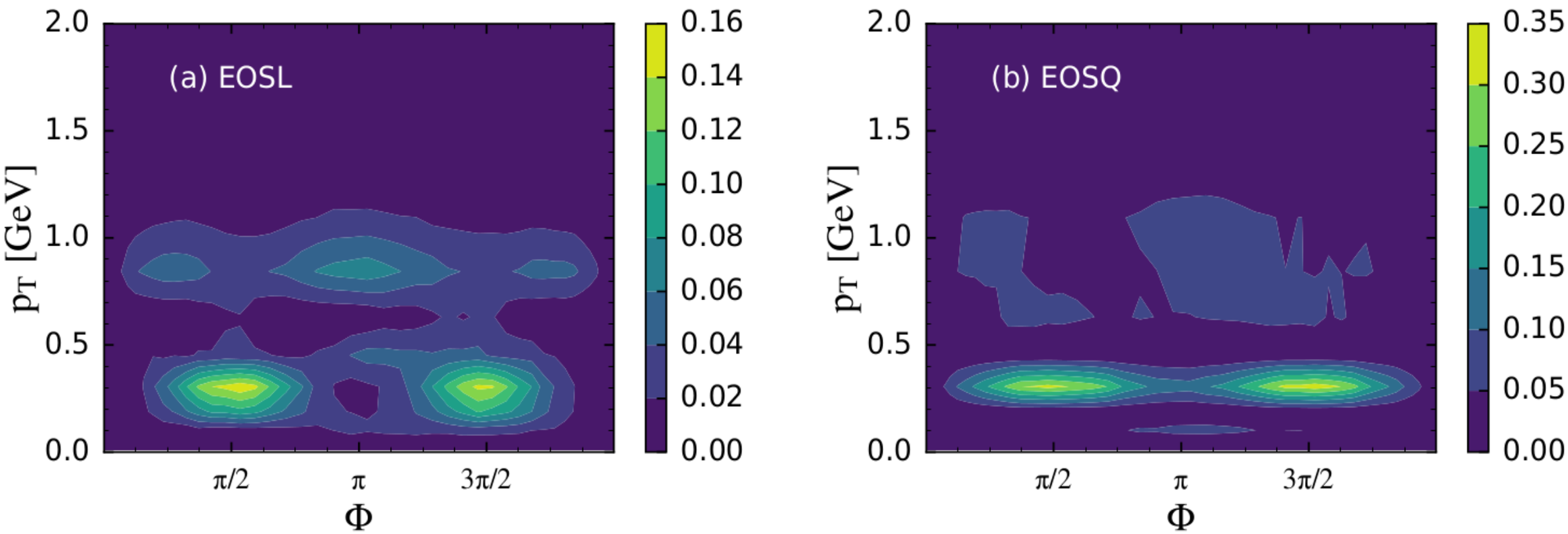


Cross-Over „(0,1)“

First-Order „(1,0)“

Importance Maps

- By replacing individual pixels, one can extract crucial features



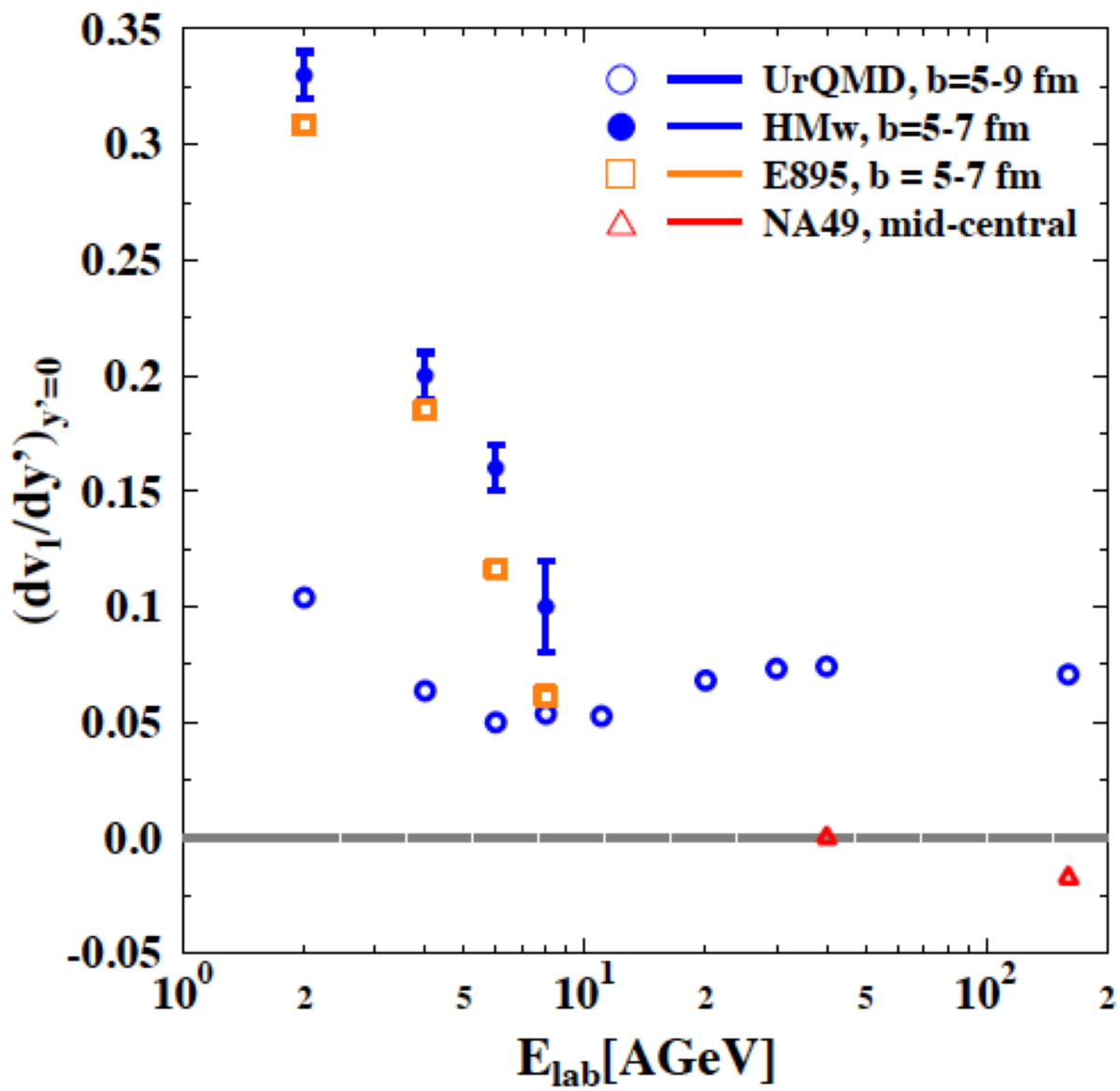
- Helpful to understand sensitivities and device new observables

Summary

- Heavy ion collisions at low beam energies reach the high density region to **explore structures** in phase diagram
- **Hybrid** hydrodynamic + transport approaches are extended to finite net baryon density
  - Elliptic flow is sensitive to overall dynamics
  - Vanishing triangular flow is a possible sign for **vanishing** quark-gluon plasma
  - **Directed flow** poses a challenge to theory interpretations
- Deep learning techniques might help to identify **new sensitive** observables
- New results by BNL-BES I and NA61 at SPS and **exciting future** experimental programs coming up at BNL -BES II, FAIR, NICA and JPARC-HI

Backup

Excitation Function



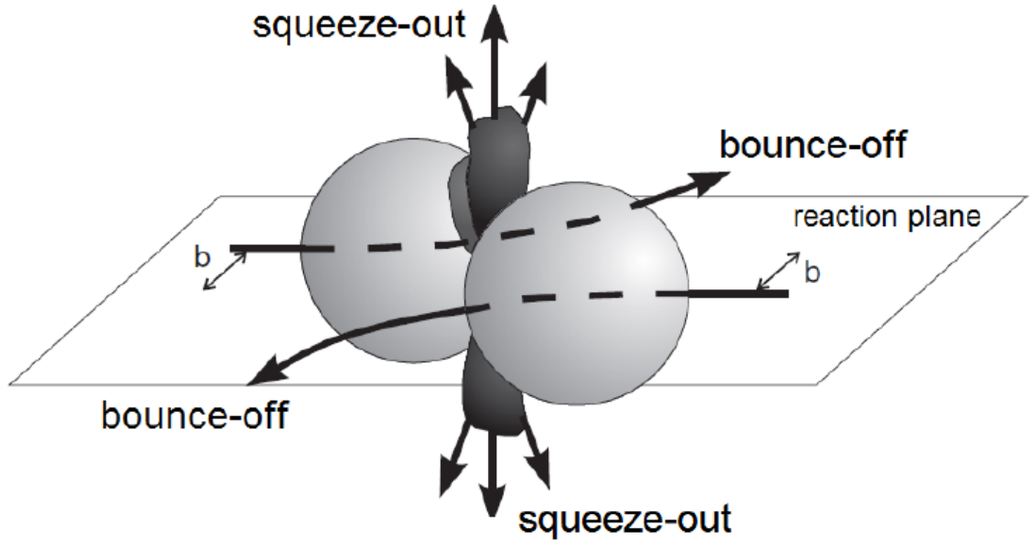
- At low energies:
  - Nuclear potentials are crucial to explain the magnitude of the v_1 slope
- NA 49 data:
  - Hints for negative slope - antiflow?
- Pure hadron transport shows different energy dependence

H.P. et al, Phys.Rev. C74 (2006) 064908

Directed and Elliptic Flow

Directed flow v_1

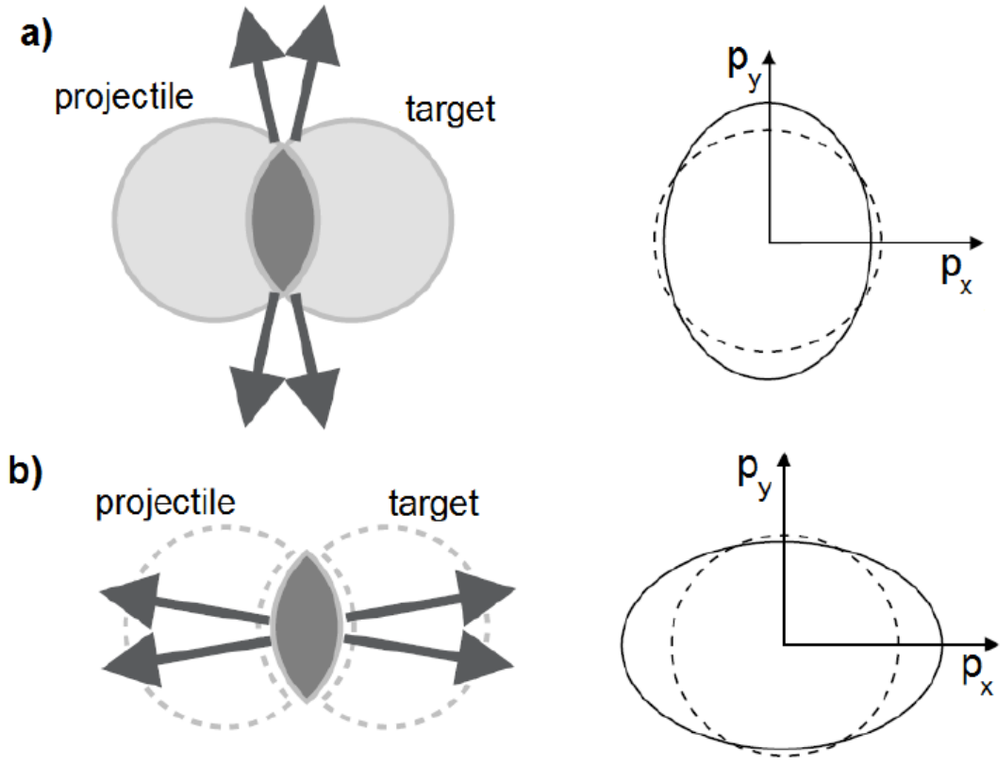
- $v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$
- Bounce-off at low beam energies



Taken from: S. Soff. Kollektiver Fluss in Schwerionenkollisionen - Deduktion elementarer Eigenschaften angeregter Kernmaterie. (1995)

Elliptic flow v_2

- $v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$
- Lower energies: Out-of-plane flow due to blocking spectators
- Higher energies: In-plane flow due to pressure gradients



Taken from: H. Büsching. Azimutale Photonen-Korrelationen in ultrarelativistischen p+A-, Pb+Pb- und Au+Au-Reaktionen. (2002)

by M. Mayer

Potentials in SMASH

- Skyrme potential: $U_{\mathrm{Sk}} = \alpha(\rho/\rho_0) + \beta(\rho/\rho_0)^{\tau}$
- Skyrme potential describes effective interaction between nucleons
- Skyrme potential acts repulsively at high nucleon densities

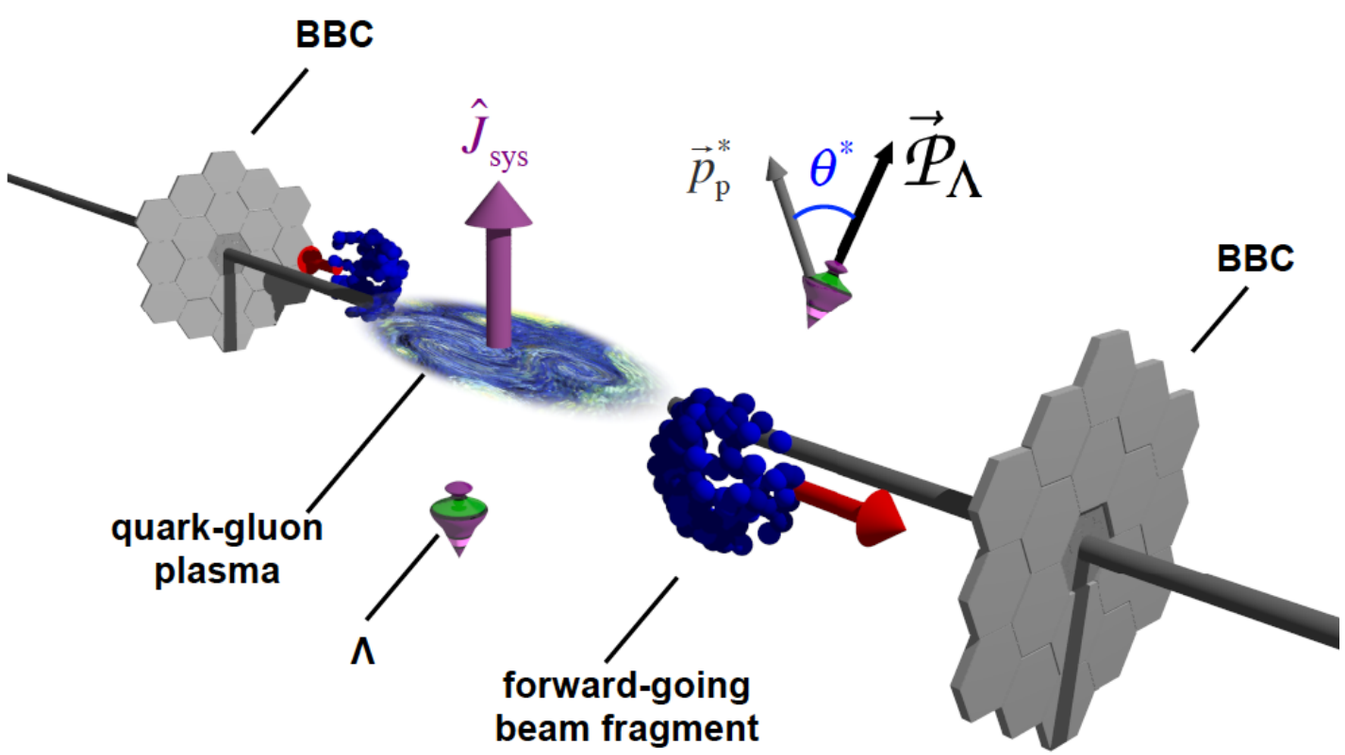
	soft EoS	default EoS	hard EoS
α	-356.0 MeV	-209.2 MeV	-124.0 MeV
β	303.0 MeV	156.4 MeV	71.0 MeV
τ	1.17	1.35	2.00
κ	200 MeV	240 MeV	380 MeV

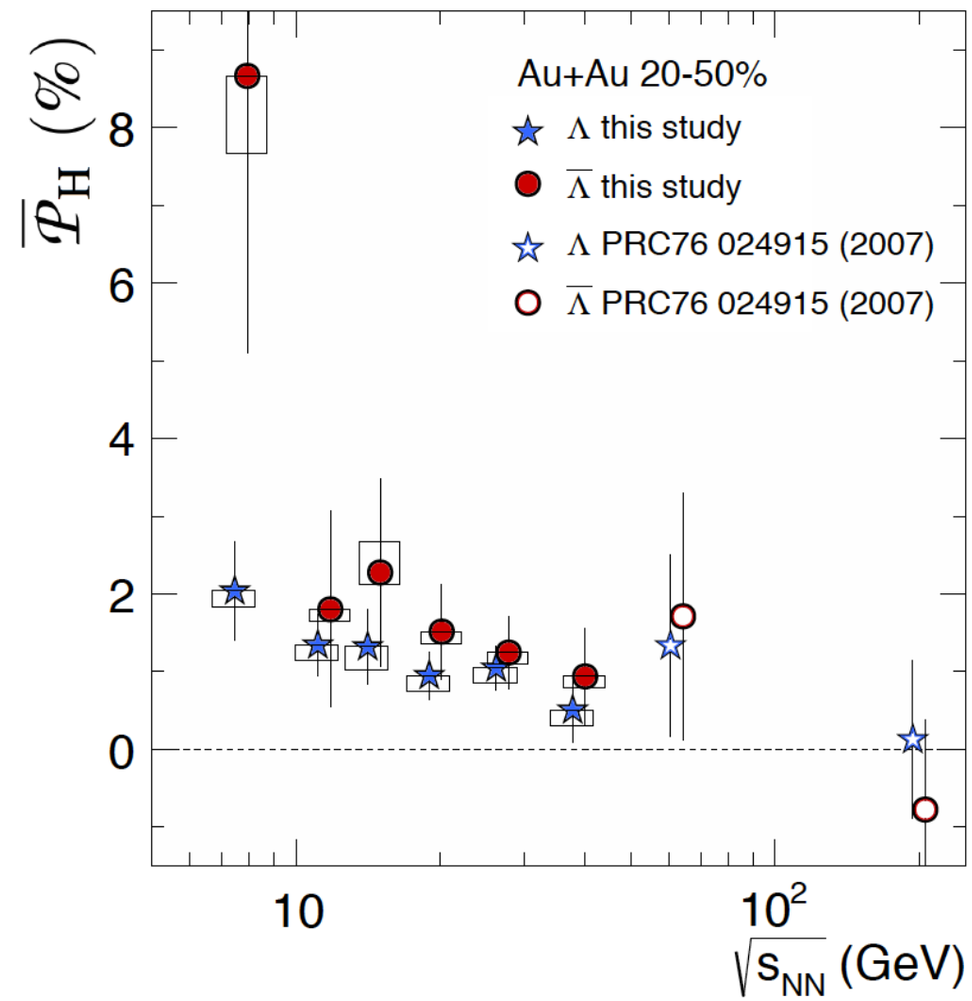
- Symmetry potential: $U_{\mathrm{Sym}} = \pm 2\, S_{\mathrm{Pot}} \dfrac{\rho_{I3}}{\rho_0}$
- Fermi motion, Pauli blocking

by M. Mayer

Λ Polarization

- Global hyperon polarization has been measured

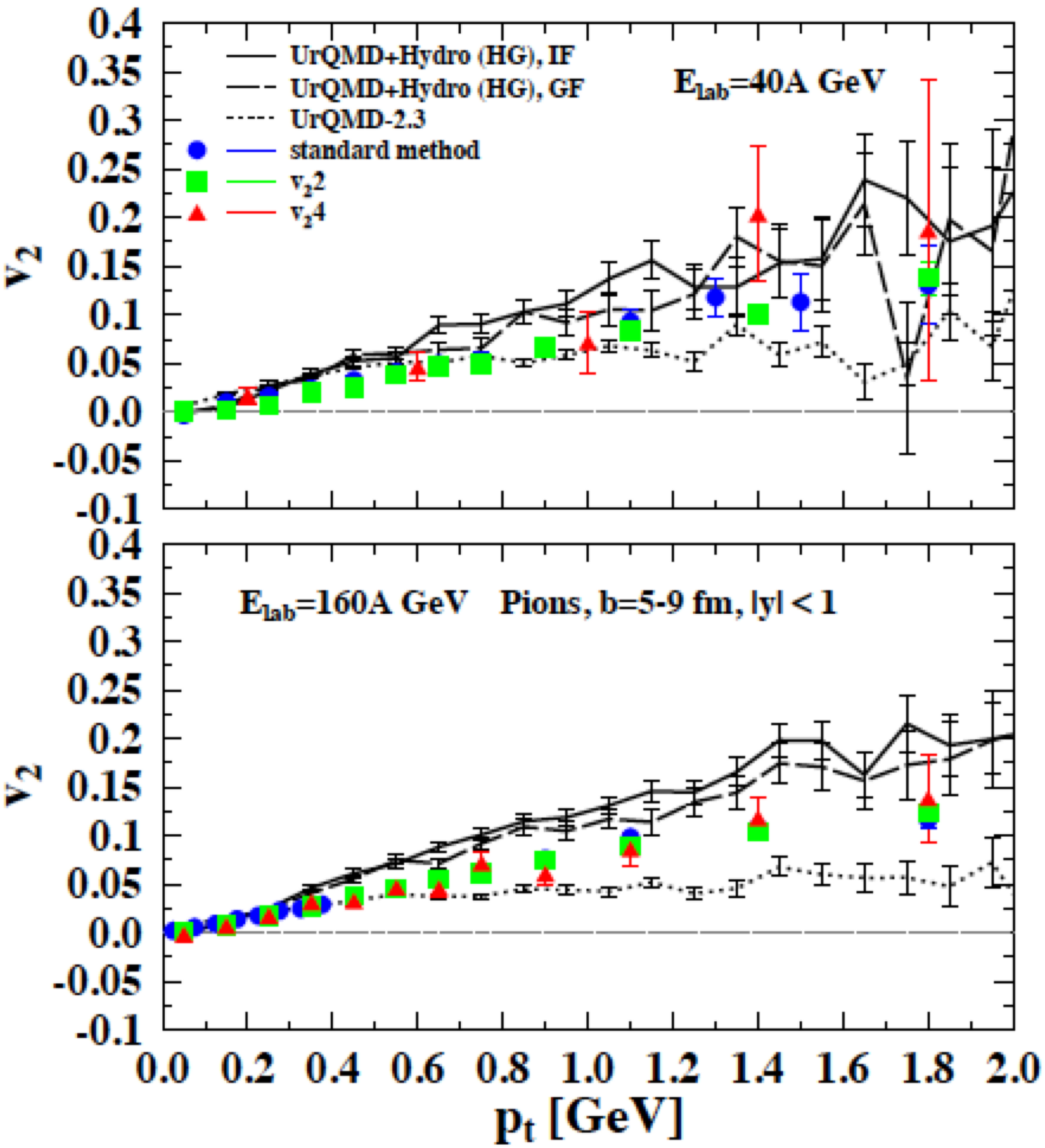




STAR collaboration, arXiv:1701.06657

- Exciting possibility to constrain final **magnetic field** and vorticity

NA49 Data on Elliptic Flow



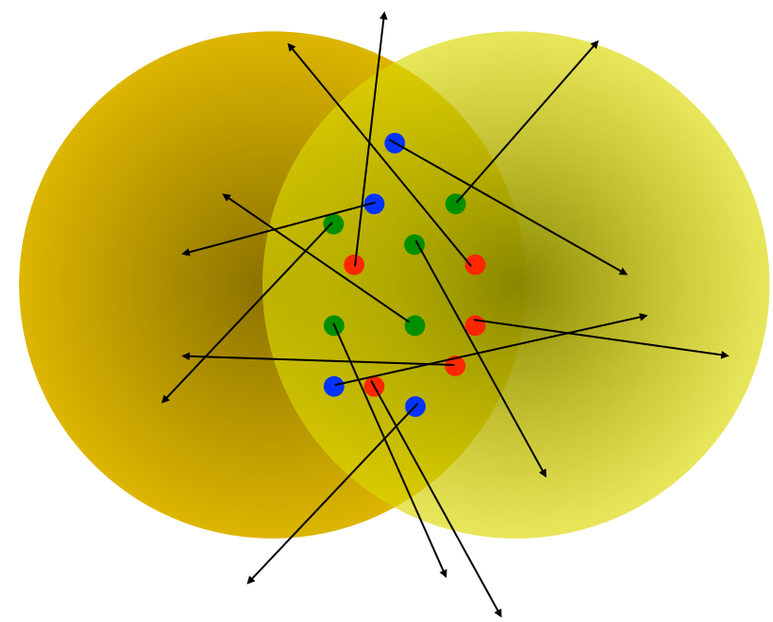
- Elliptic flow for pions as a function of transverse momentum:
  - 40A GeV:
    - Pure transport and hybrid approach give similar results
  - 160A GeV:
    - Hadron transport underestimates elliptic flow by a factor of 2

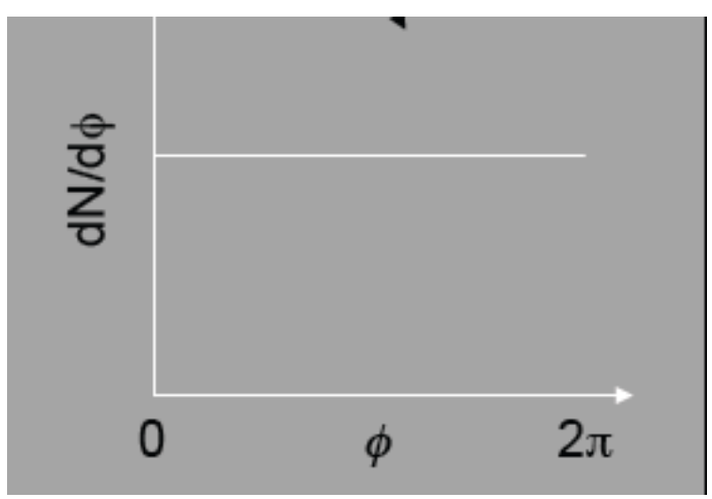
HP et al, Phys.Rev. C79 (2009) 054904

Collective Behaviour

- Response of the system to initial spatial anisotropy

No secondary interactions
mean free path λ→∞





Spatial anisotropy

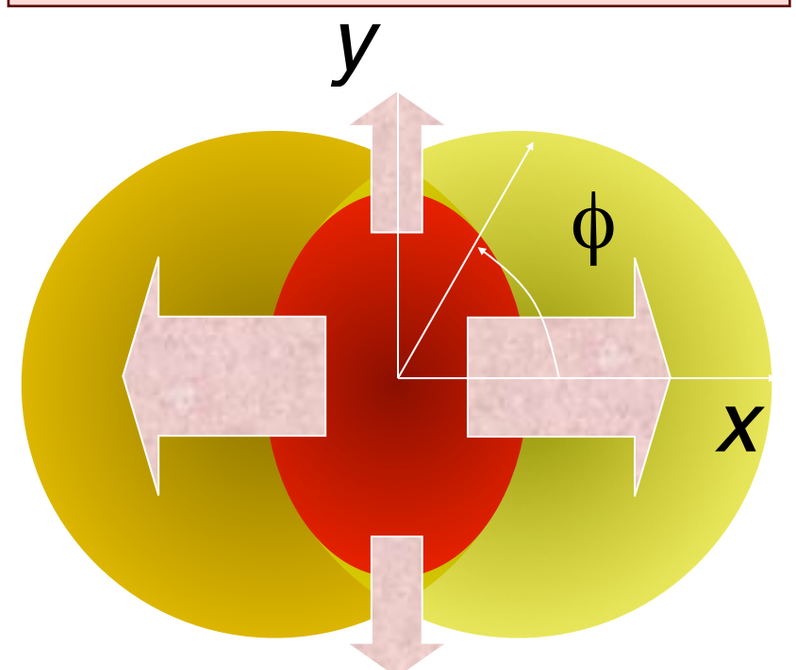
$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

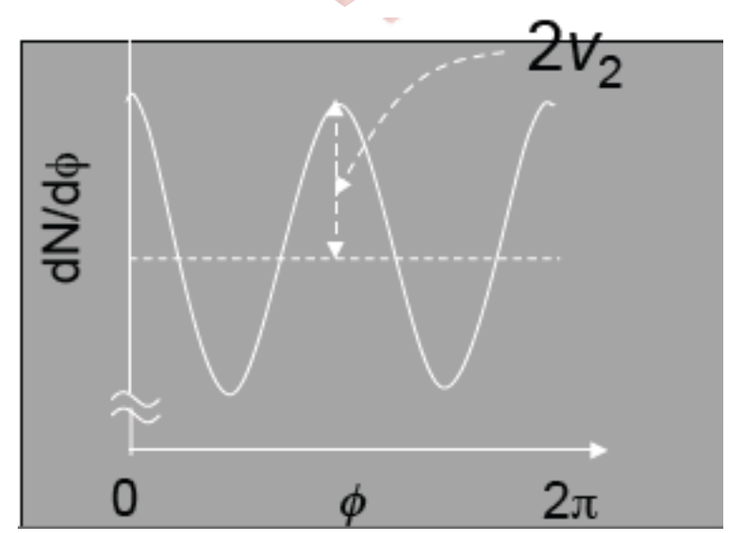
Interactions between particles

Momentum anisotropy

$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

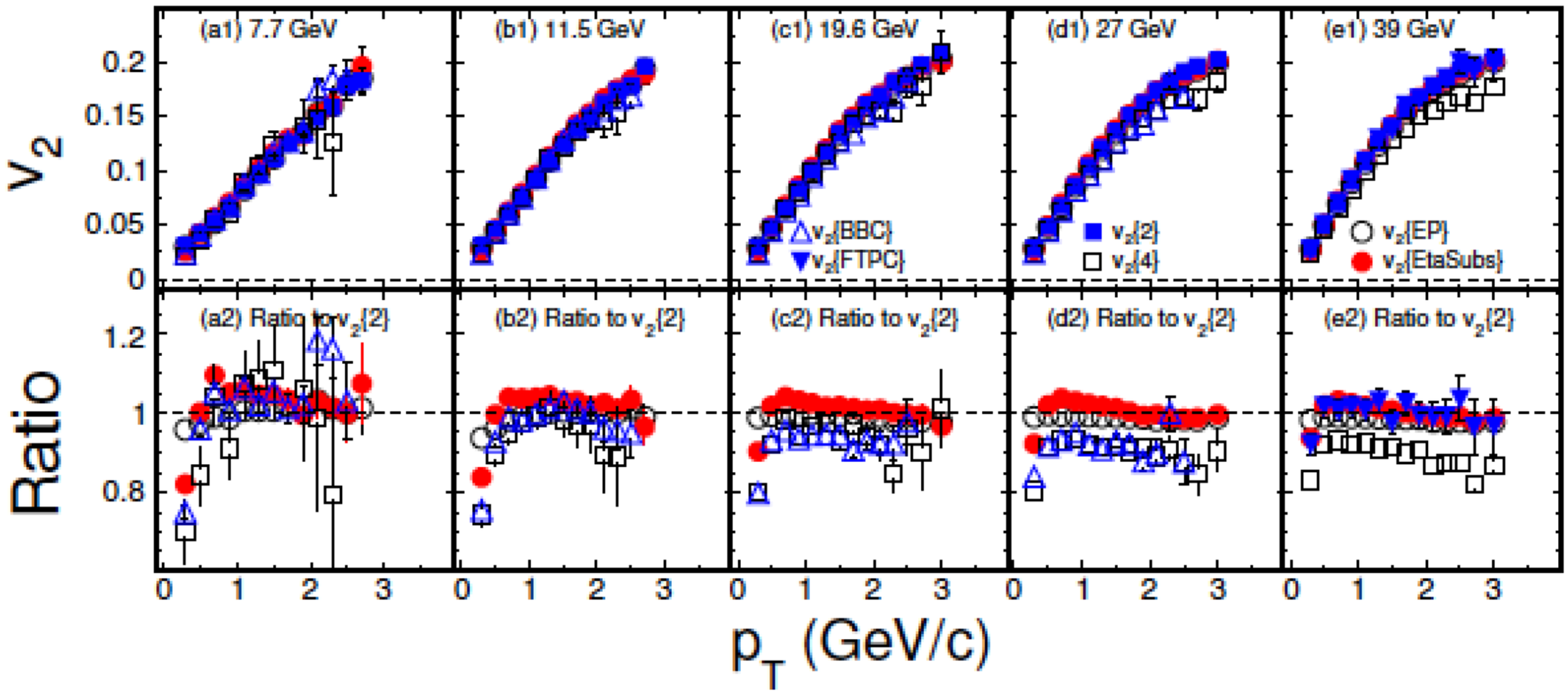
Hydrodynamic behaviour
mean free path λ→0





RHIC Beam Energy Scan

- Flow observables considered as evidence for QGP formation - does it disappear at lower energies?



- Differential v_2 for charged hadrons almost identical for all beam energies

STAR, PRC 86 (2012) 054908