HBT, Flow, Fluctuations etc.: Confronting Models with BES Data

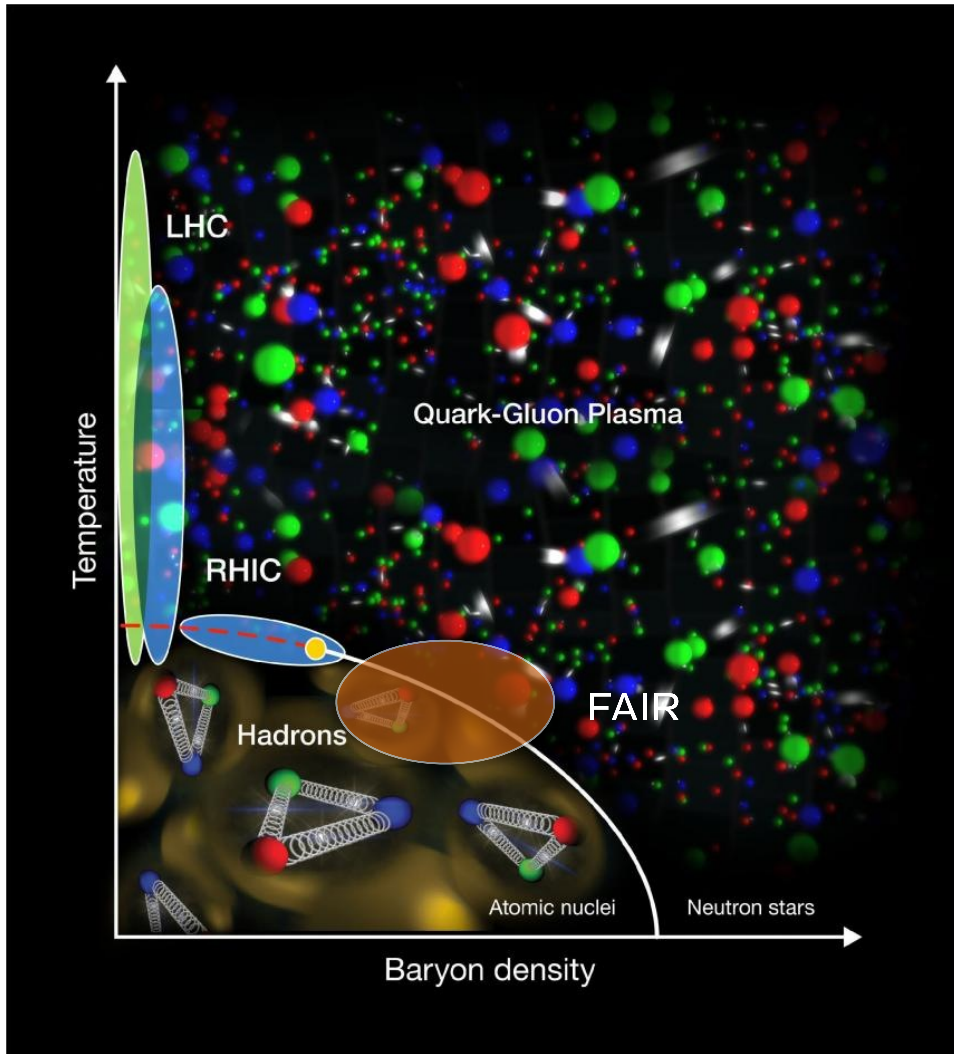
Hannah Elfner

28.03.19, EMMI Workshop, GSI, Darmstadt

Introduction

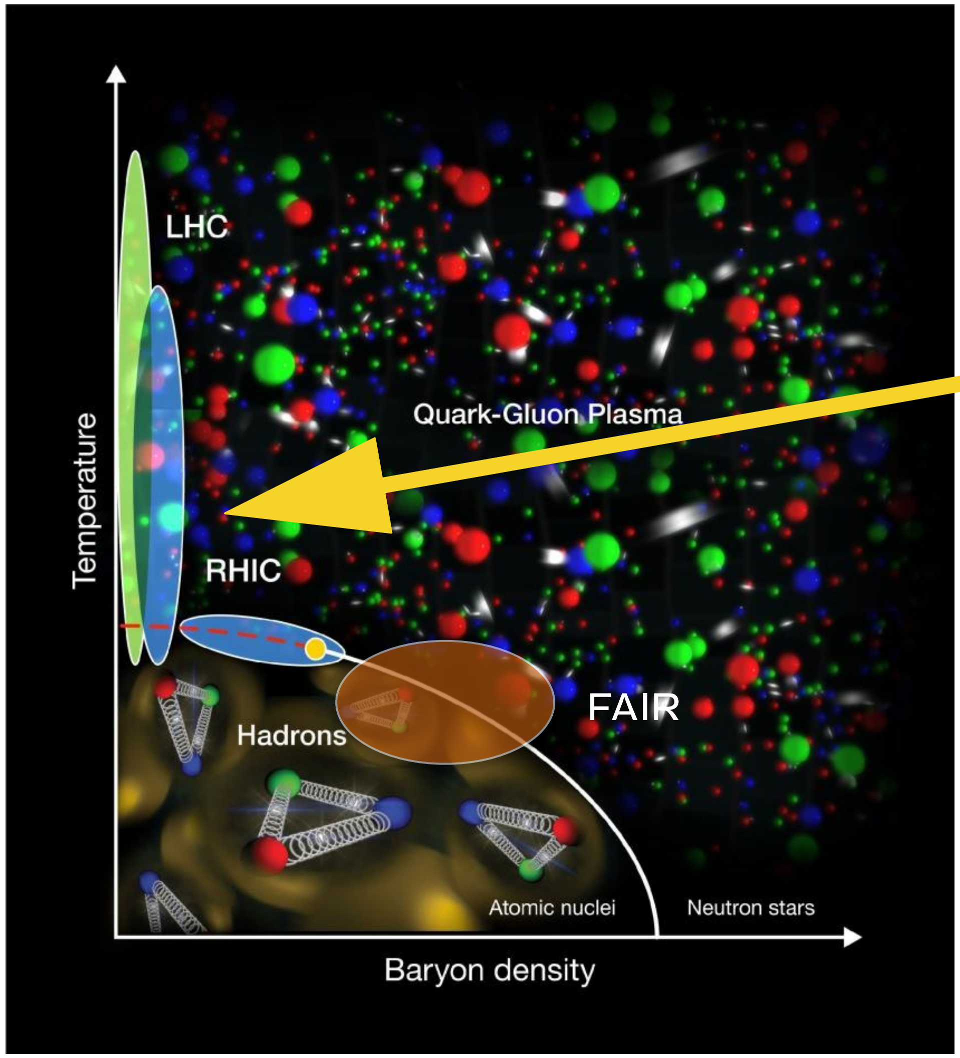
Dynamical Description of Heavy Ion Collisions

- 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+):

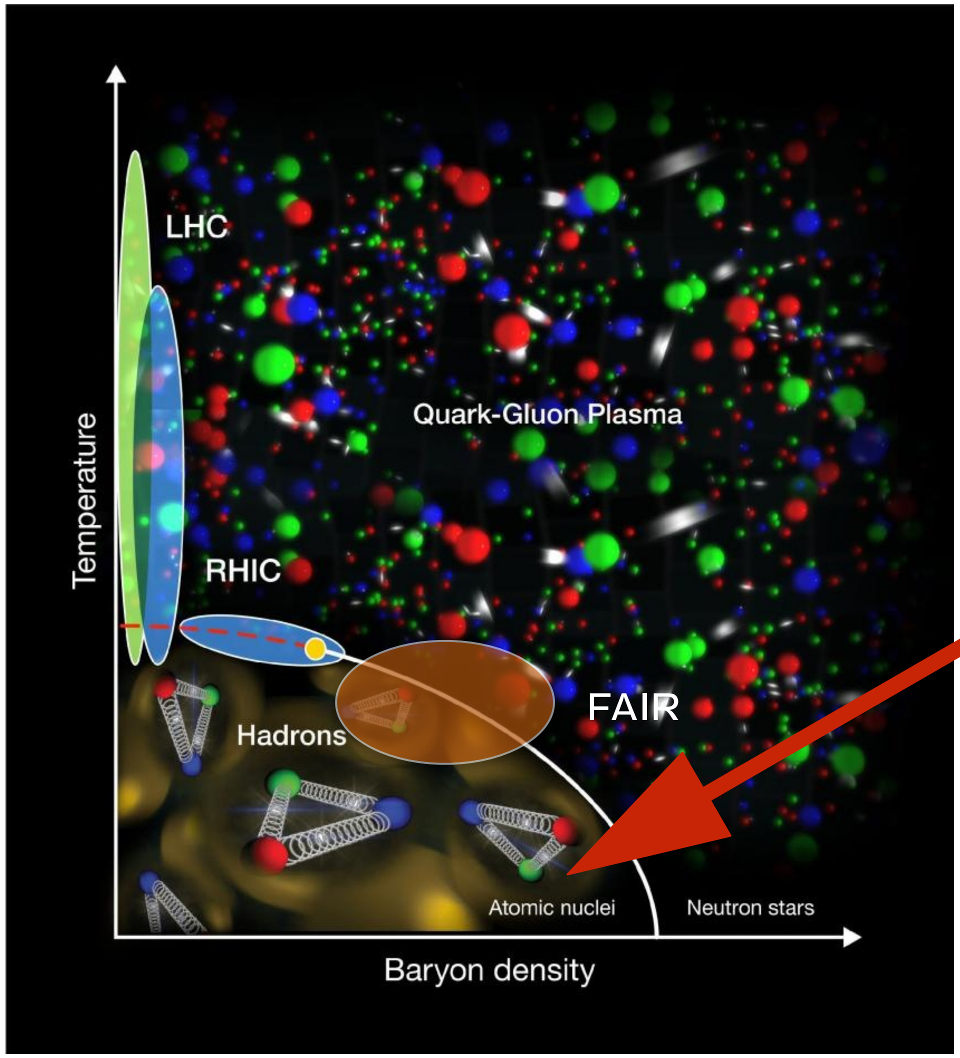
- Non-equilibrium initial evolution
- Viscous hydrodynamics
- Hadronic transport

—> Refinement and Bayesian multi-parameter analysis

J. Putschke et al., arXiv:1903.07706

Dynamical Description of Heavy Ion Collisions

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



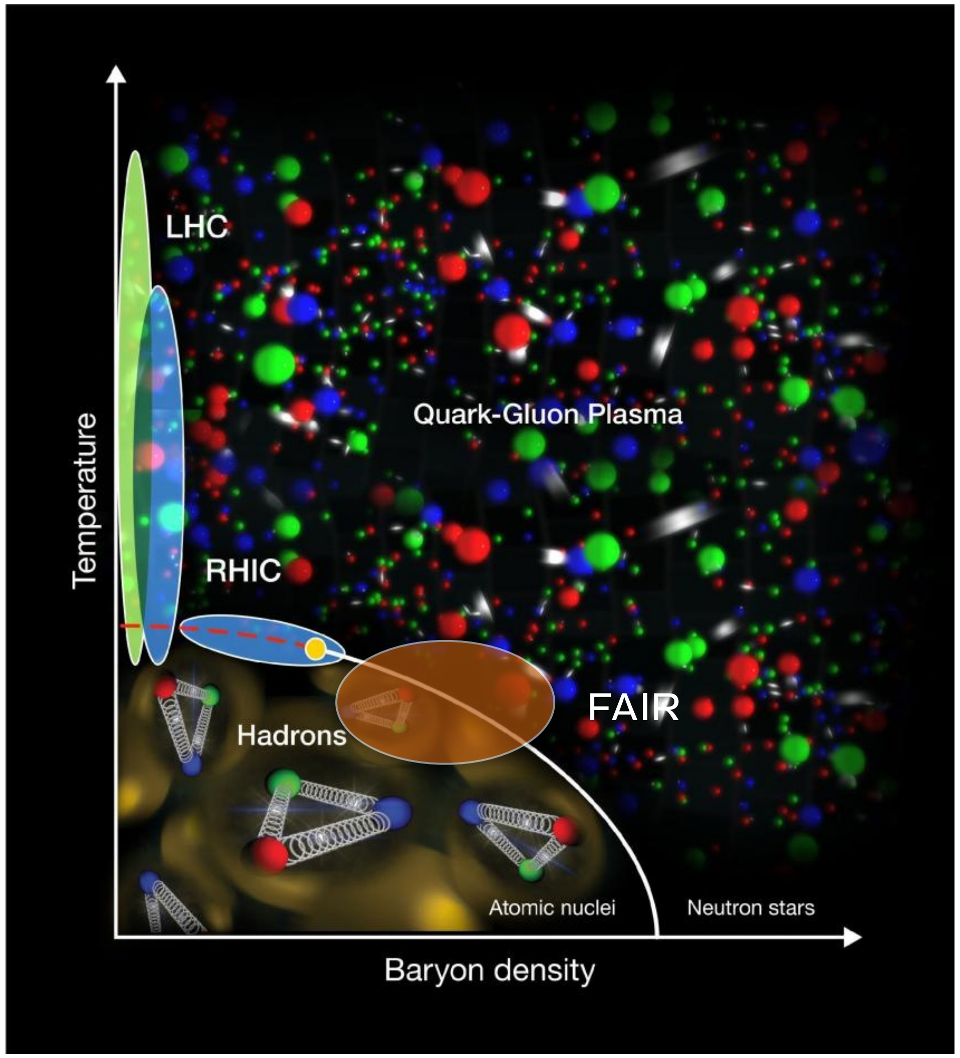
At very low beam energies ($\sqrt{s_{\mathrm{NN}}}$ < 3 GeV):

- **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 ($\sqrt{s_{\rm NN}}$ = 39 GeV-5.5 TeV+)

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

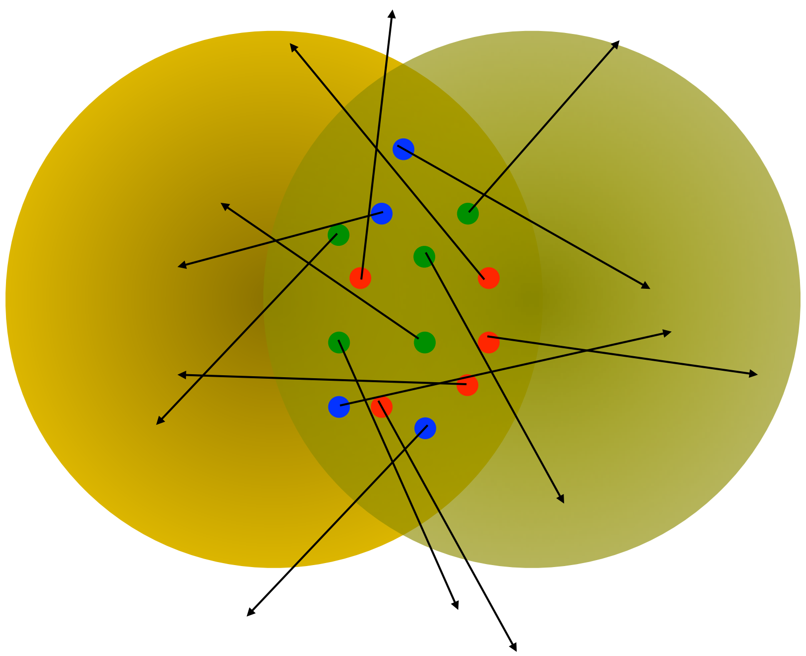
- How to **interpolate** between the two? Transport with hydro bubbles? Hydro with transport corona?
- How to model the phase transition/critical point?

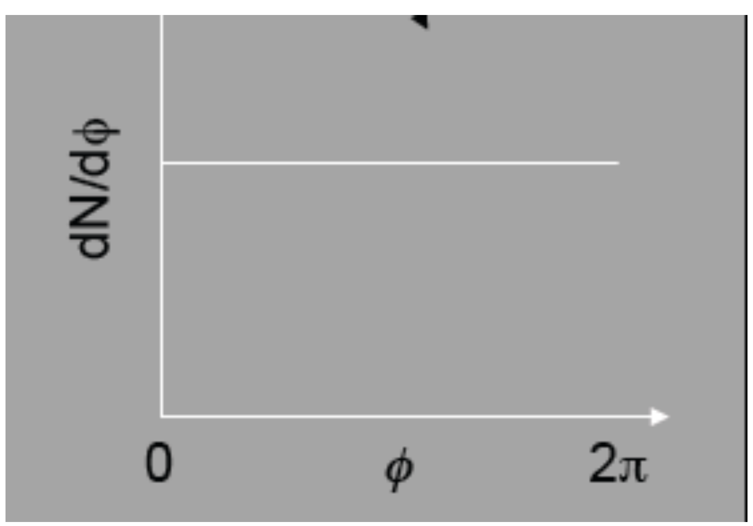
Collective Flow

Collective Behaviour

- Response of the system to initial spatial anisotropy

No secondary interactions
mean free path $\lambda \to \infty$





Spatial anisotropy

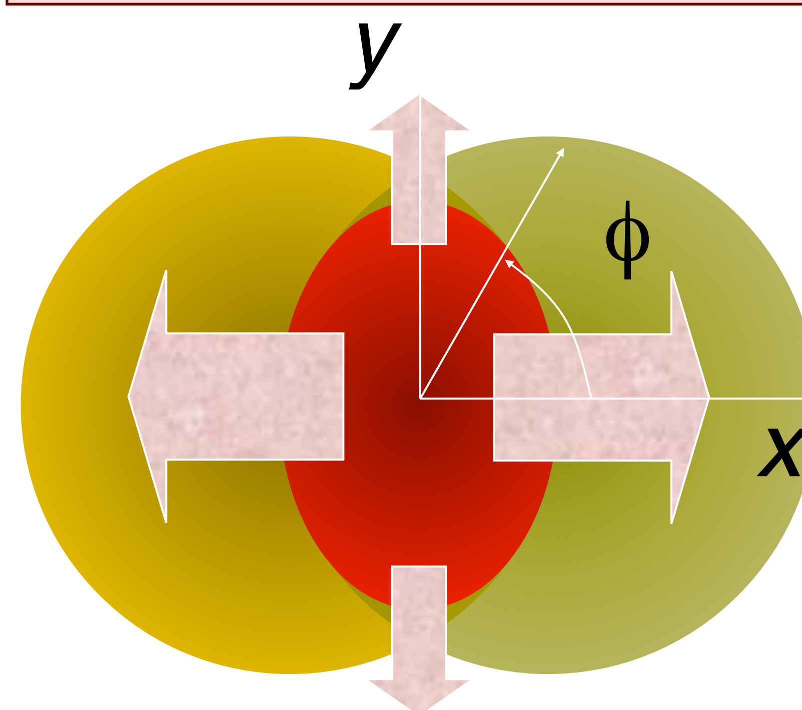
$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

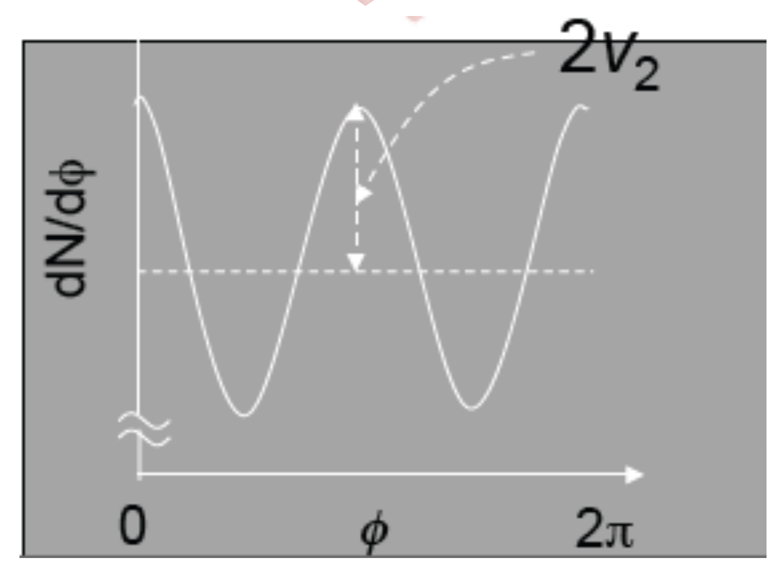
Interactions between particles

Momentum anisotropy

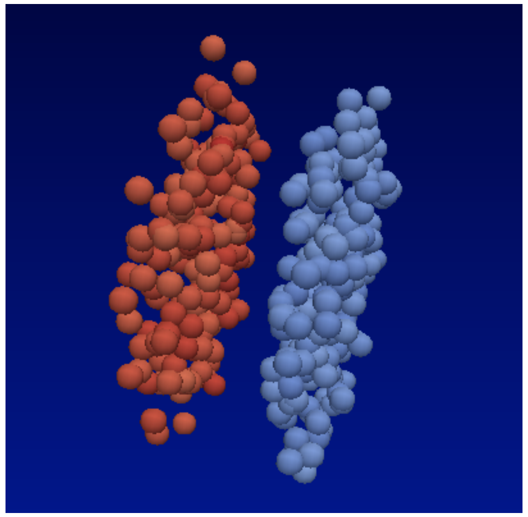
$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

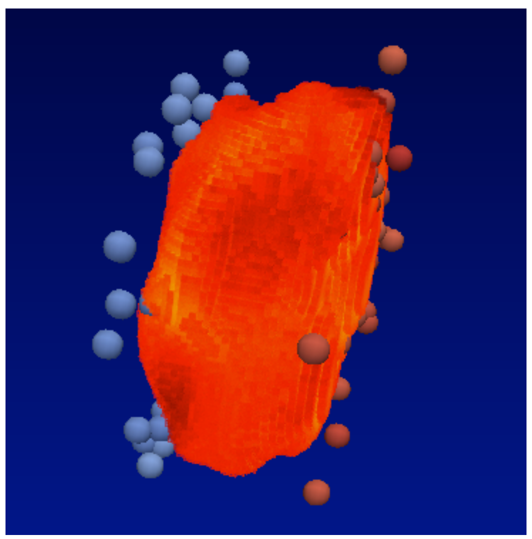
Hydrodynamic behaviour
mean free path $\lambda \to 0$

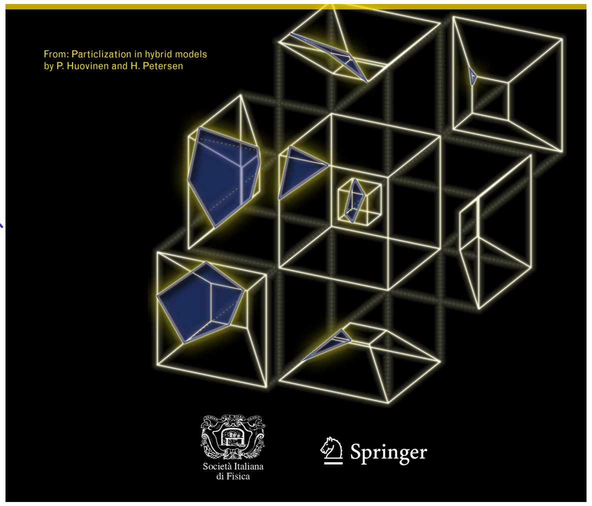




Hybrid Approach







P. Huovinen, HP EPJ A48 (2012) 171

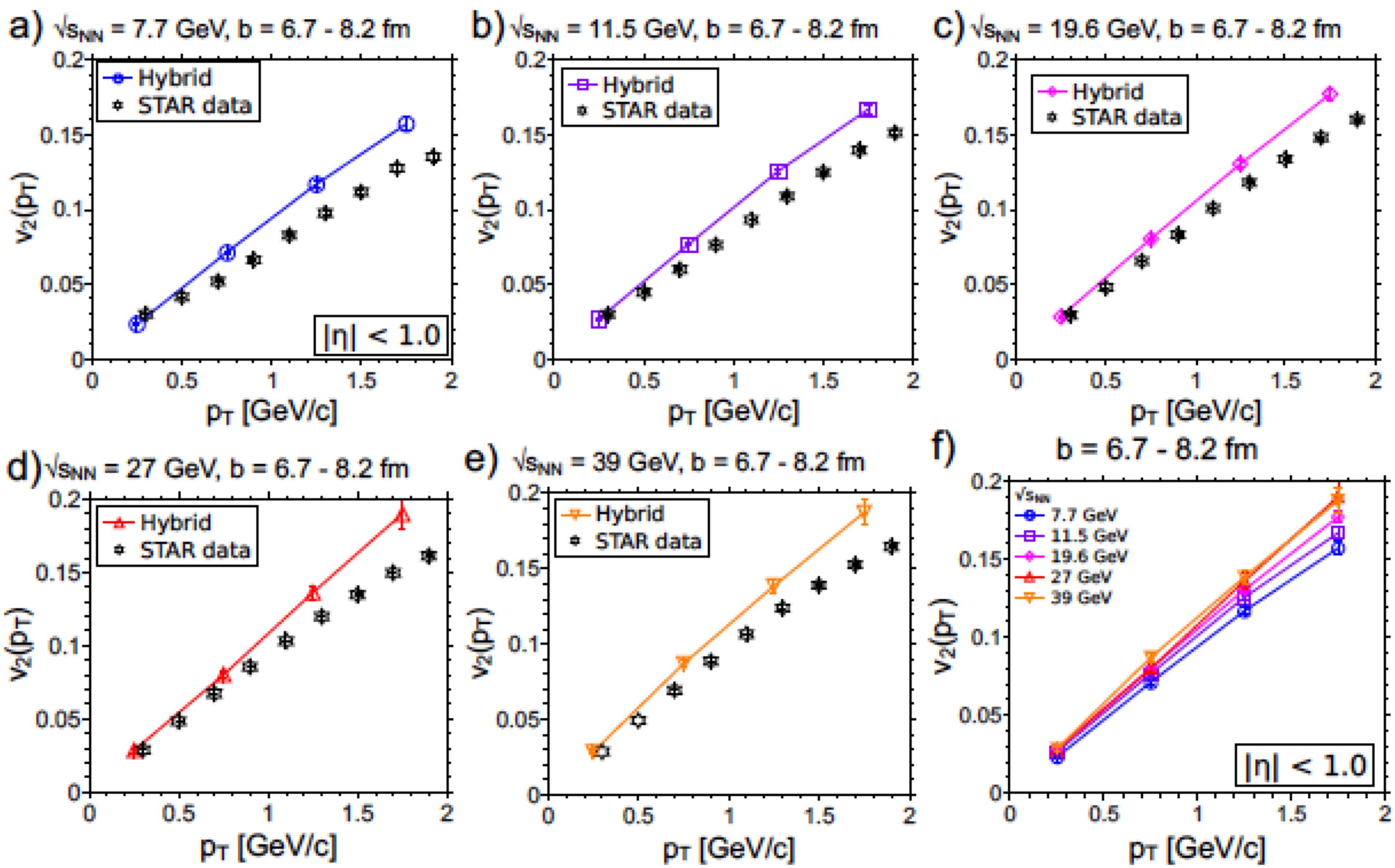
HP, arXiv:1404.1763 (special issue)
J. Phys. G: Nucl. Part. Phys. 41 (2014) 124005

- 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)

Differential Elliptic Flow

- Hybrid approach reproduces small energy dependence

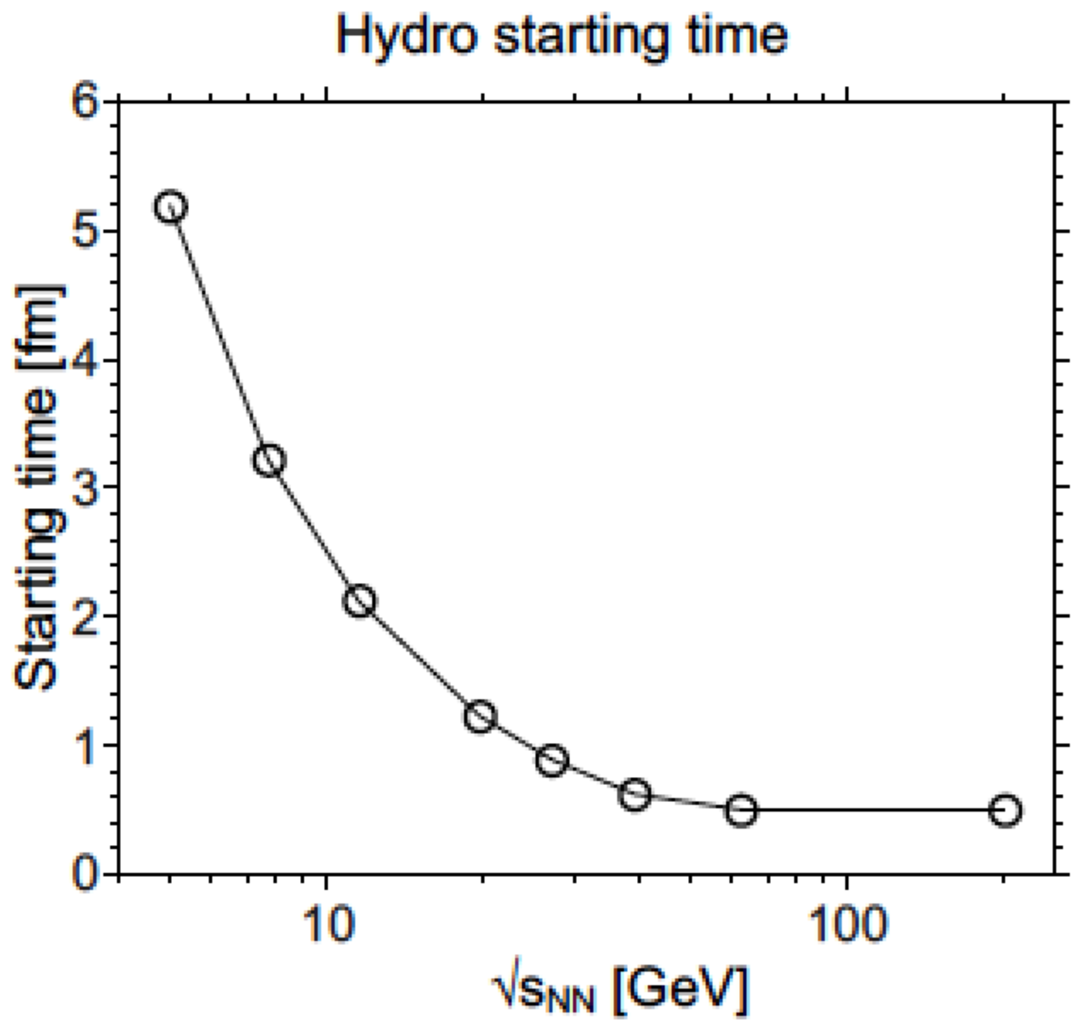


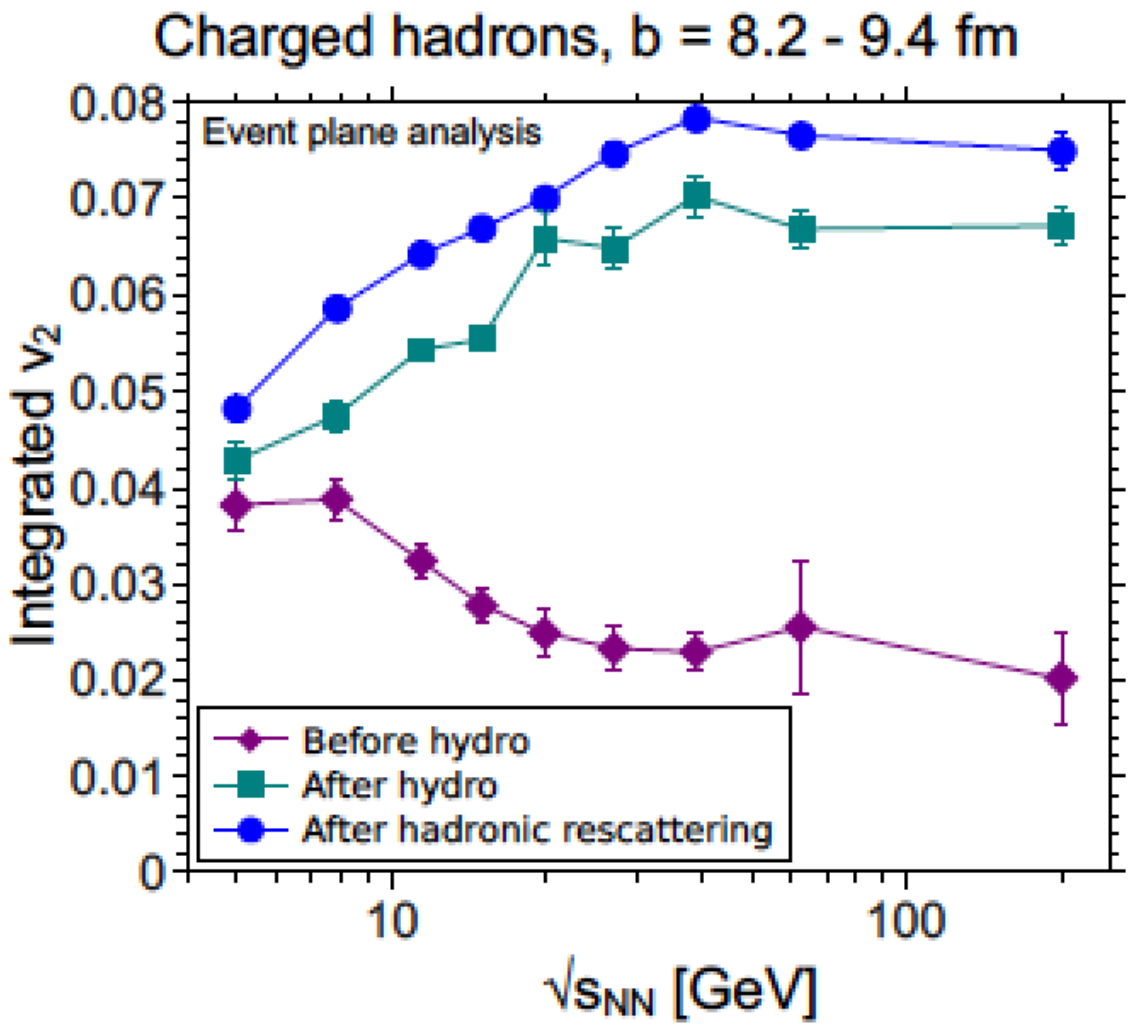
- Overestimation at higher p_T due to missing viscosity
- Sensitive to particlization switching criterion

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

Interplay of Hydro + Transport

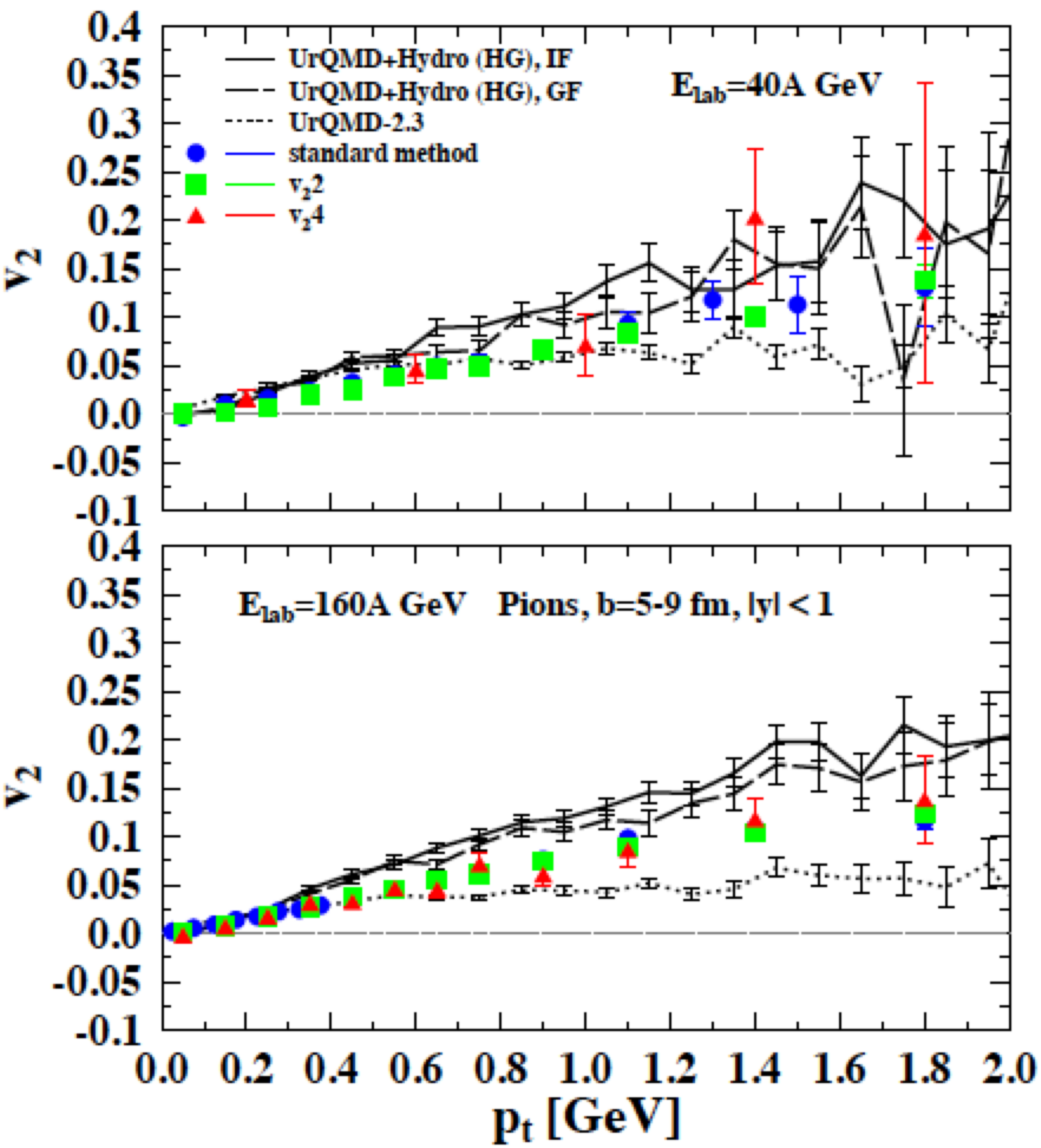
- Initial non-equilibrium evolution compensates for diminished hydrodynamic stage at lower beam energies
- Contribution of late stage hadronic rescattering ~10%





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

NA49 Data on Elliptic Flow



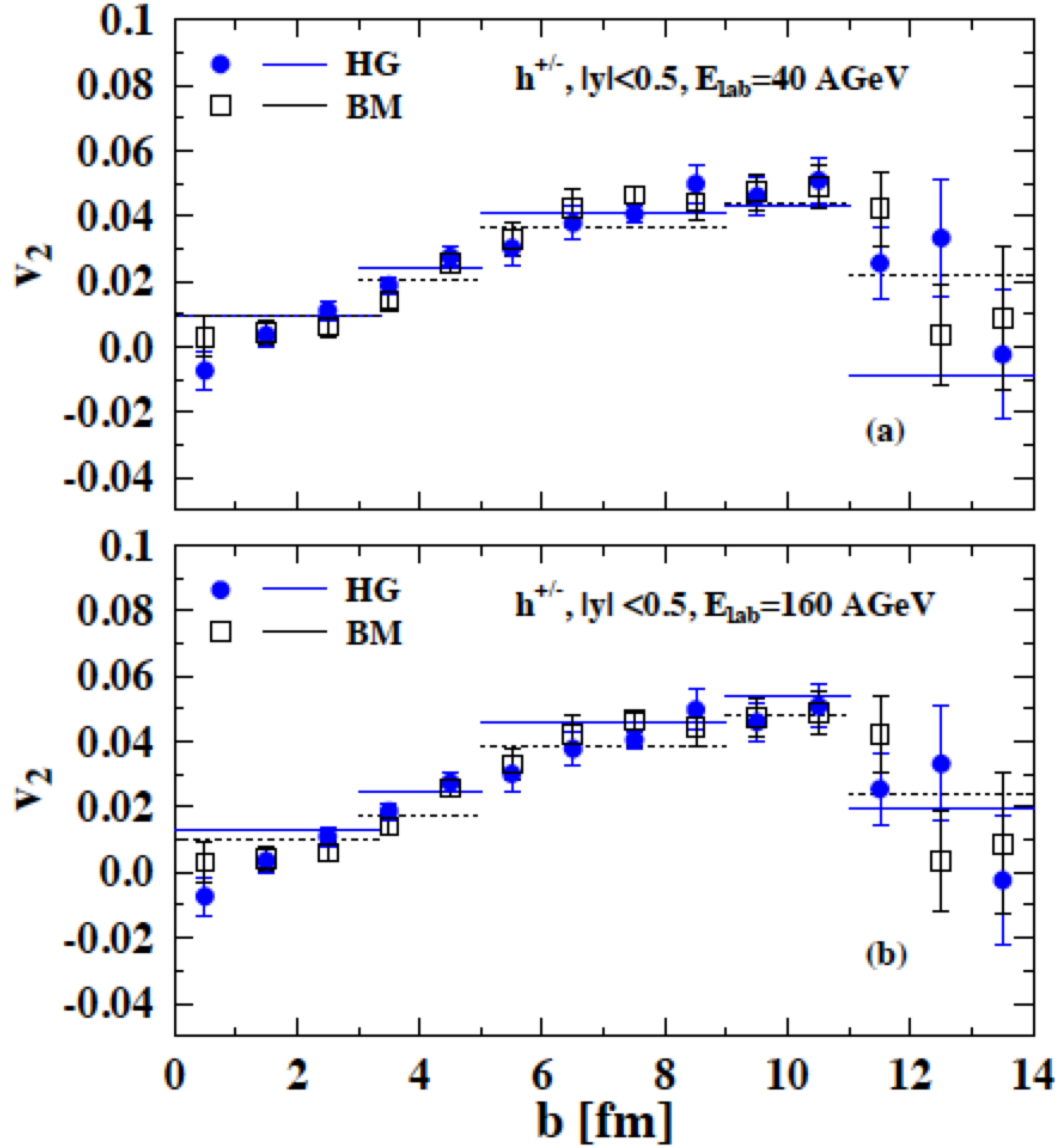
- Elliptic flow for pions as a function of transverse momentum:
  - 40A GeV:
    - Pure transport and hybrid approach give similar results
  - 160A GeV:
    - Hadron transport underestimates elliptic flow by a factor of 2

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

Equation of State and IC Fluctuations

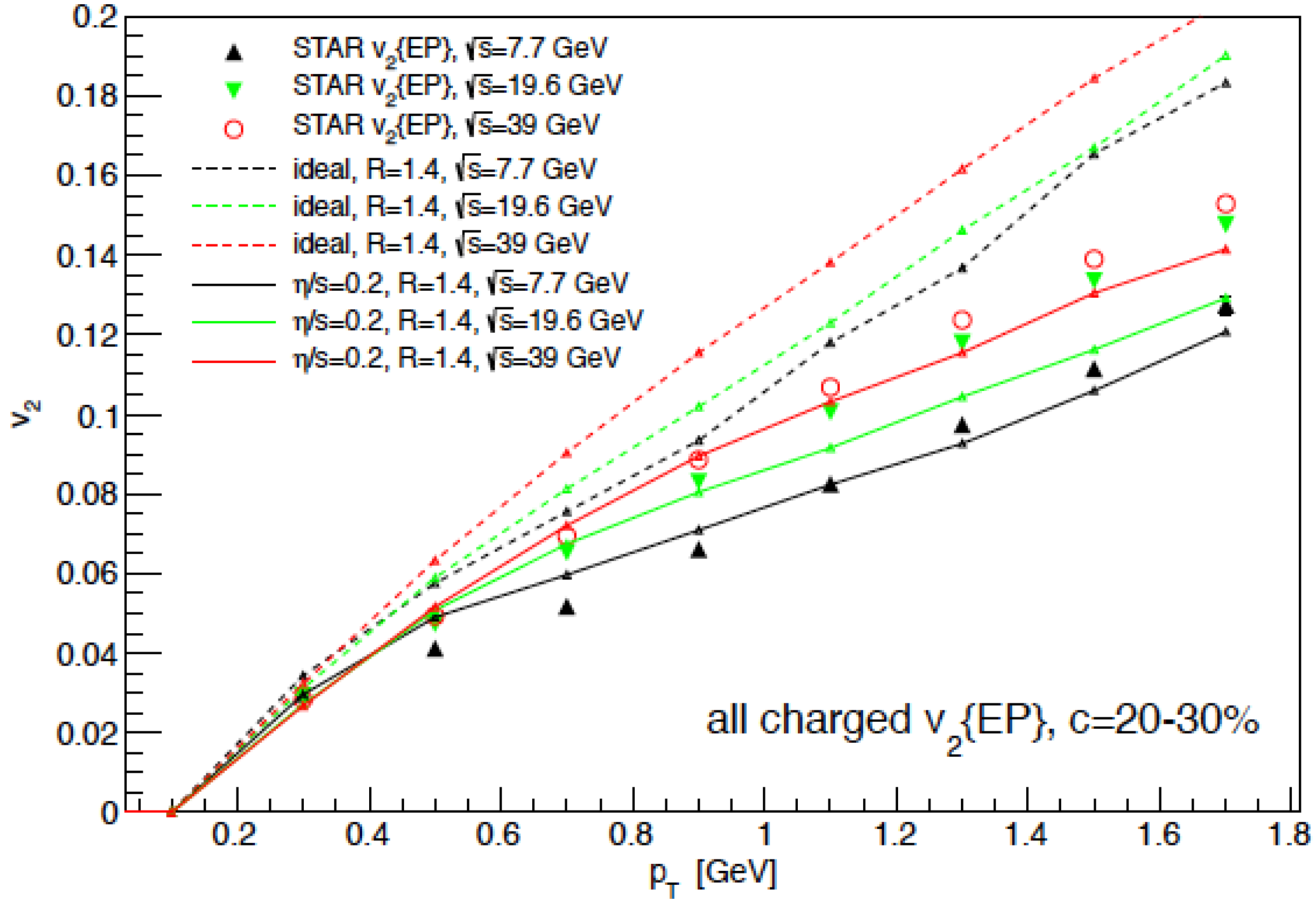
- Symbols: Event-by-event calculations
- Horizontal lines: Averaged results
- Blue: Hadron Gas EoS
- Black: Bag Model EoS with first order phase transition

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



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

Viscous Hybrid

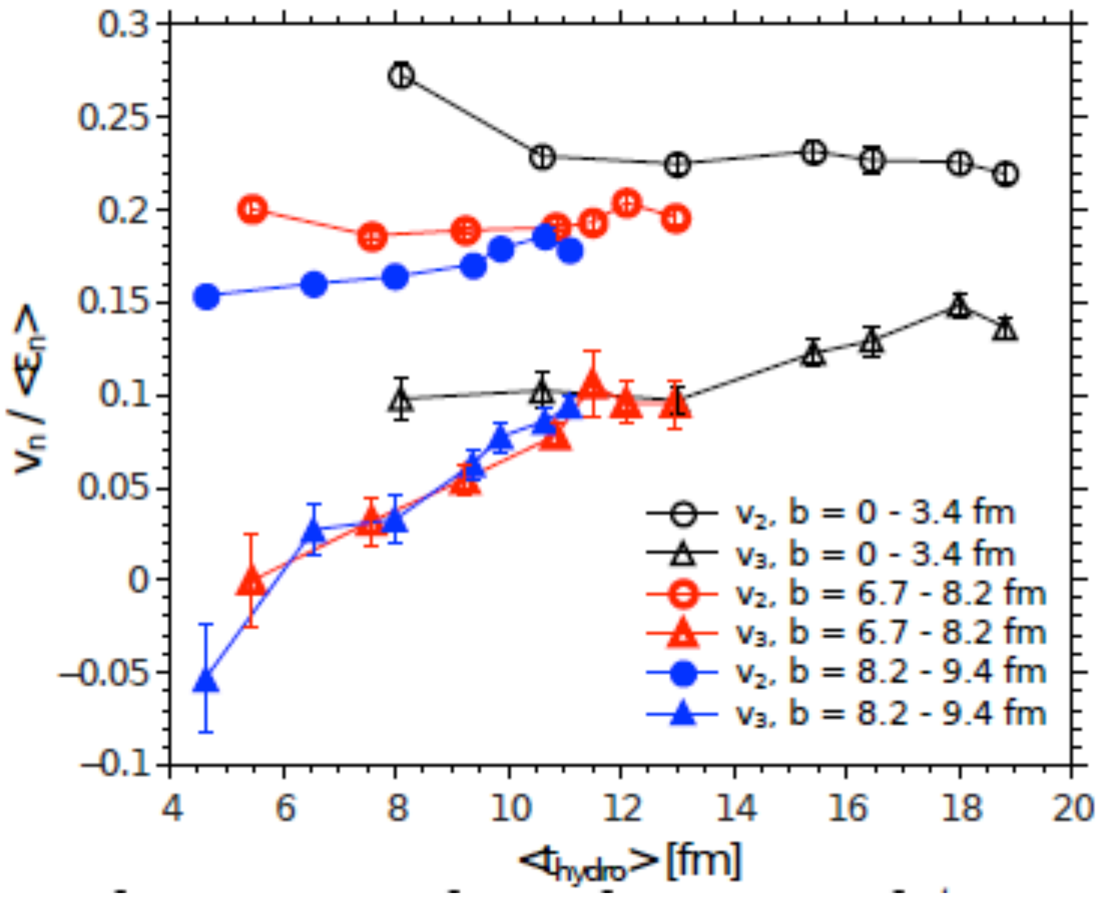


- (Viscous) hybrid approach reproduces weak energy dependence
  - Parameters are fitted to reproduce spectra and yields
  - $\eta/s = 0.2$ results in reasonable description of $v_2(p_T)$

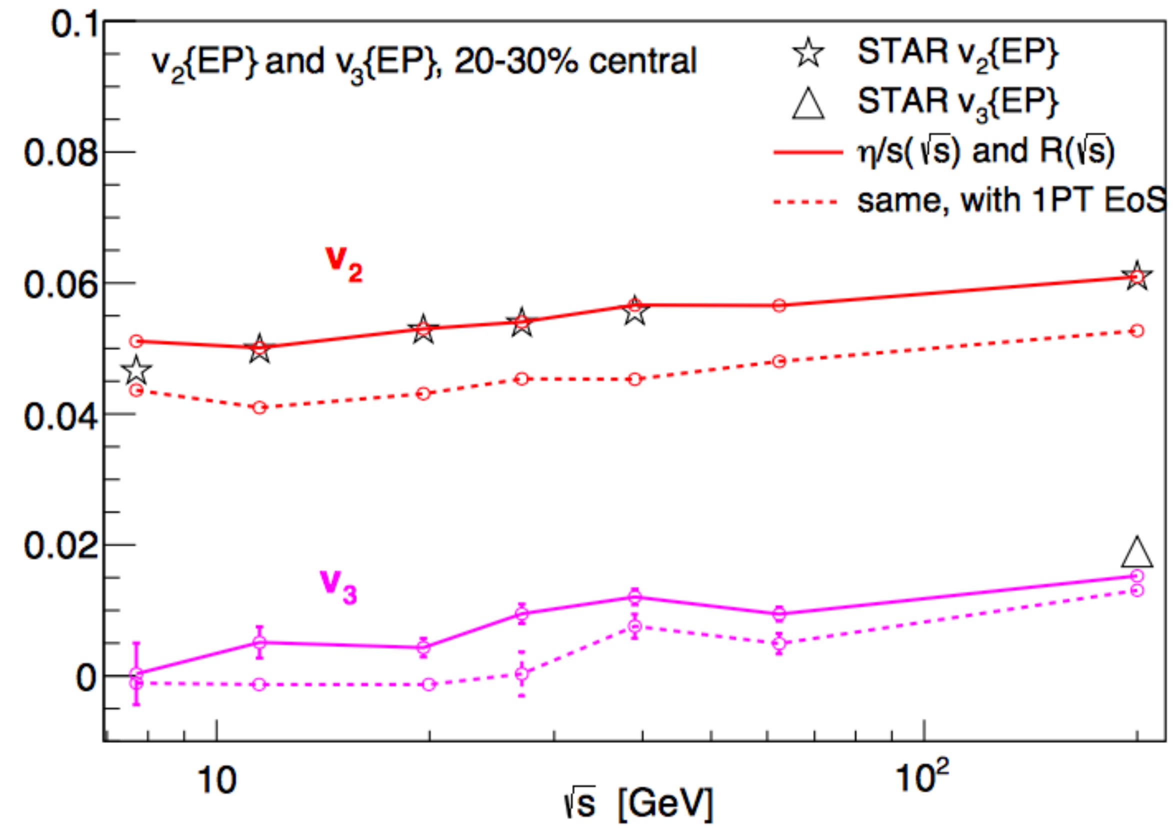
v_2/v_3 Excitation Function

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

Hydrodynamic response in ideal UrQMD hybrid approach



Prediction of triangular flow in Karpenko viscous hybrid approach



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

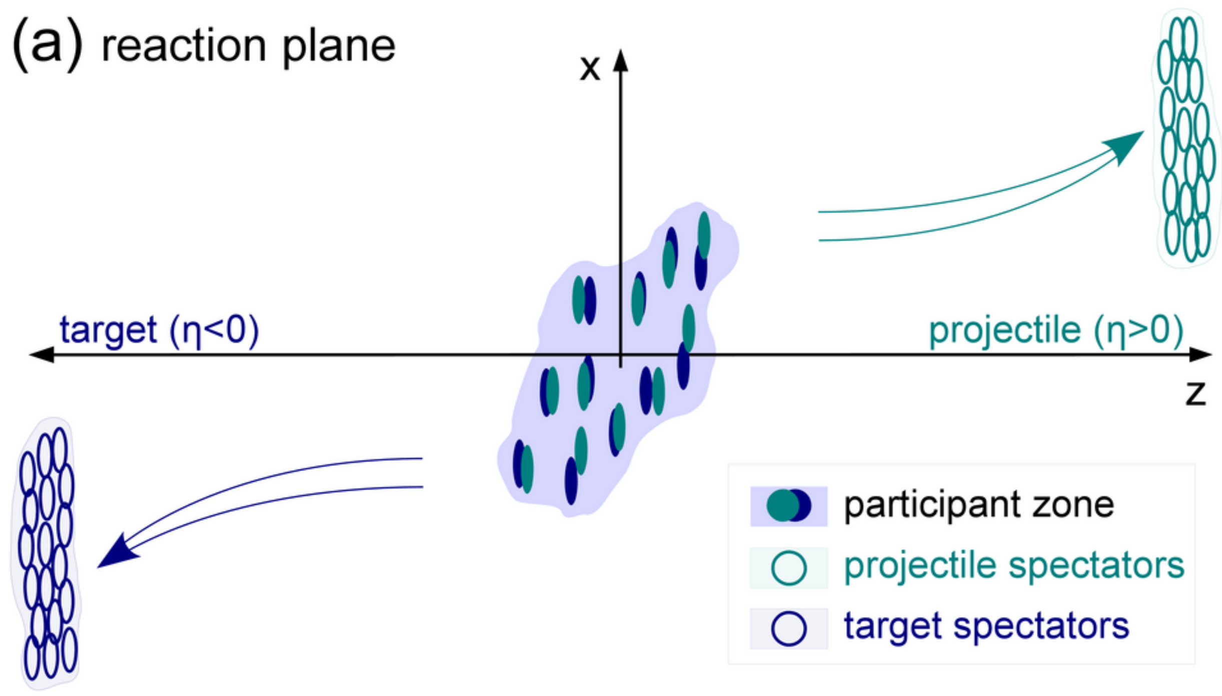
Y. Karpenko et al, Nucl.Phys. A956

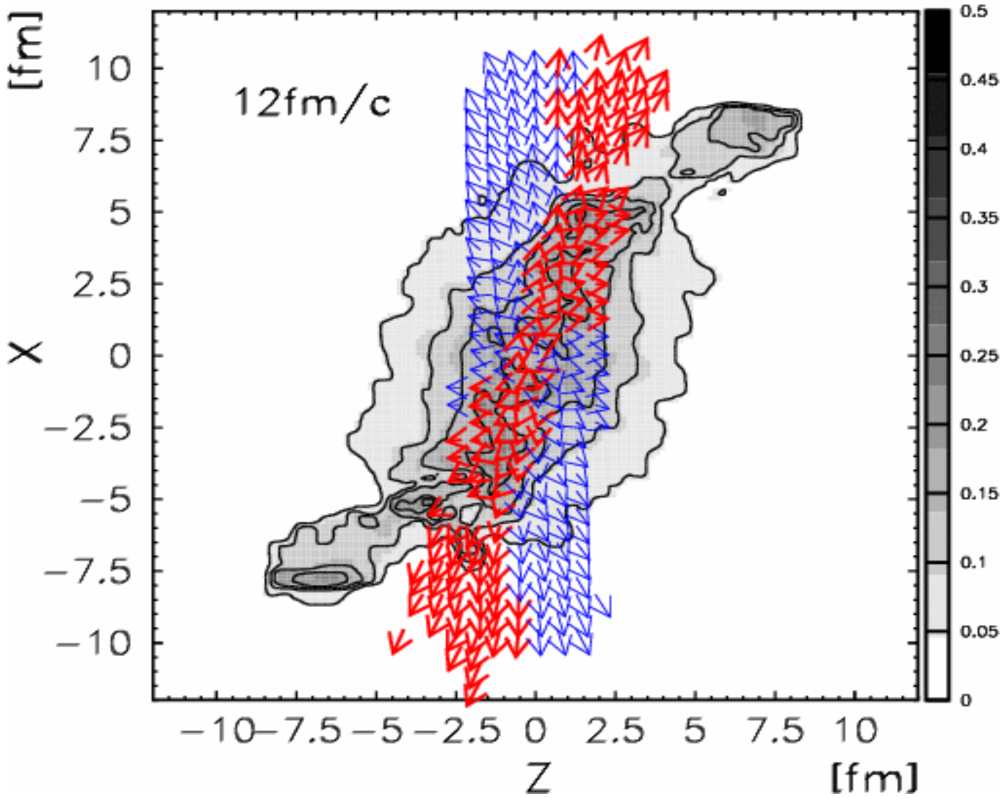
- Elliptic flow also builds up in hadronic transport approach
- v_3 is more sensitive to the viscosity
- **Disappearance of v_3** as a signal of the disappearance of the quark-gluon plasma?

Directed Flow

- Collective deflection of particles in reaction plane

sketch from ALICE, Phys. Rev. Lett. 111





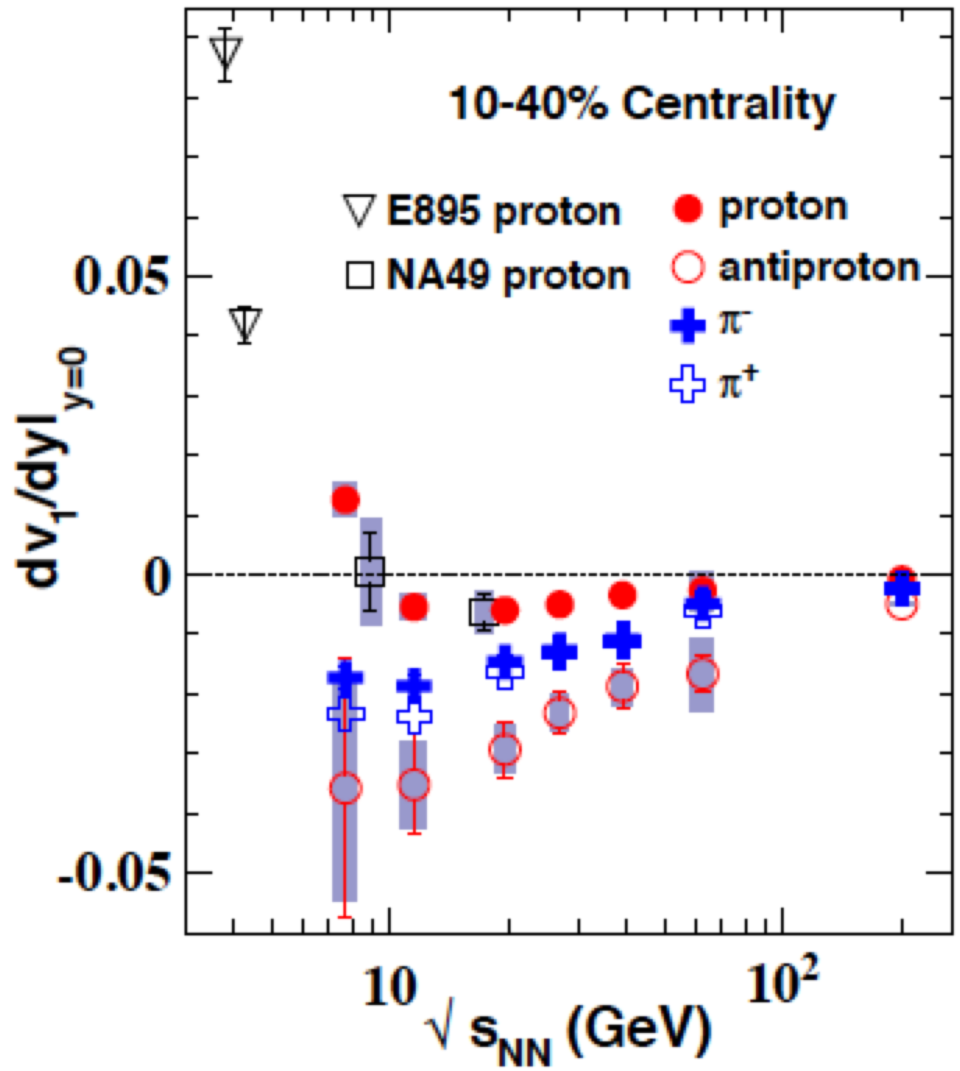
J.Brachmann et al., Phys.Rev. C, 61, 2000

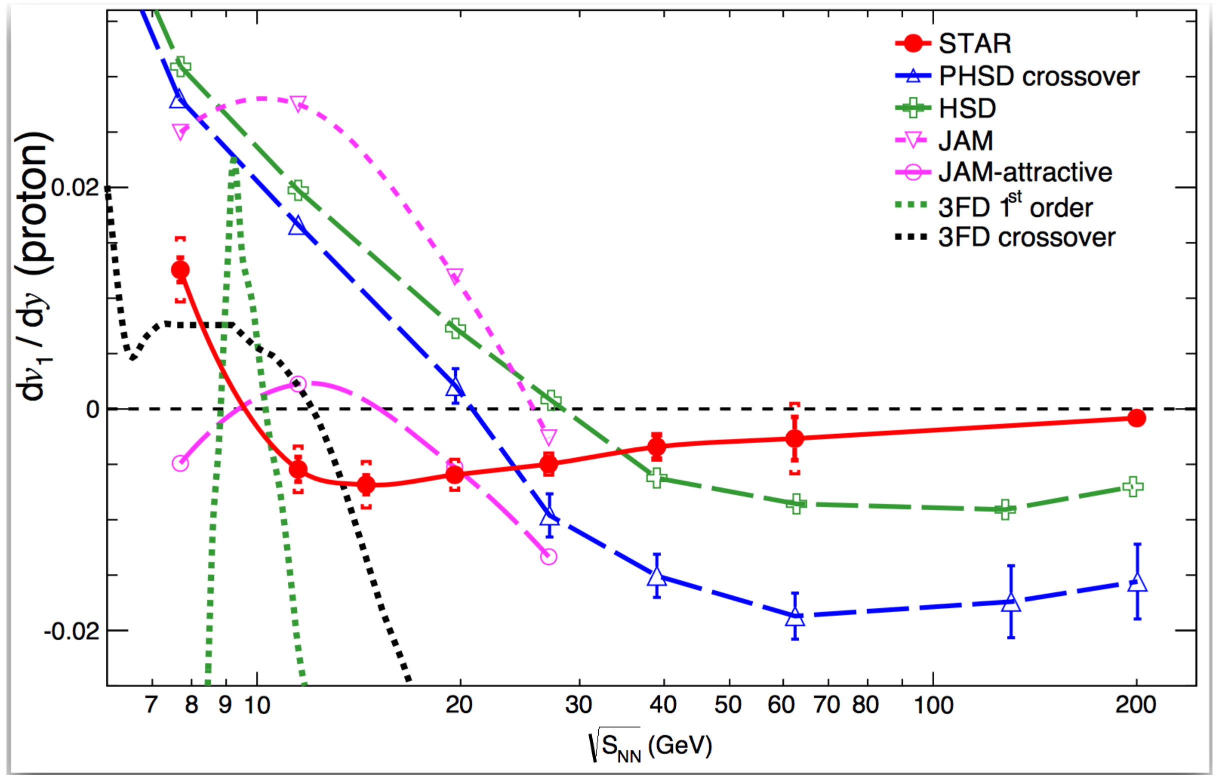
- Non-monotonic energy dependence of v1 slope
  - First order phase transition?

Directed Flow

- Collective deflection of particles in reaction plane

STAR, PRL 112, (2014) 162301

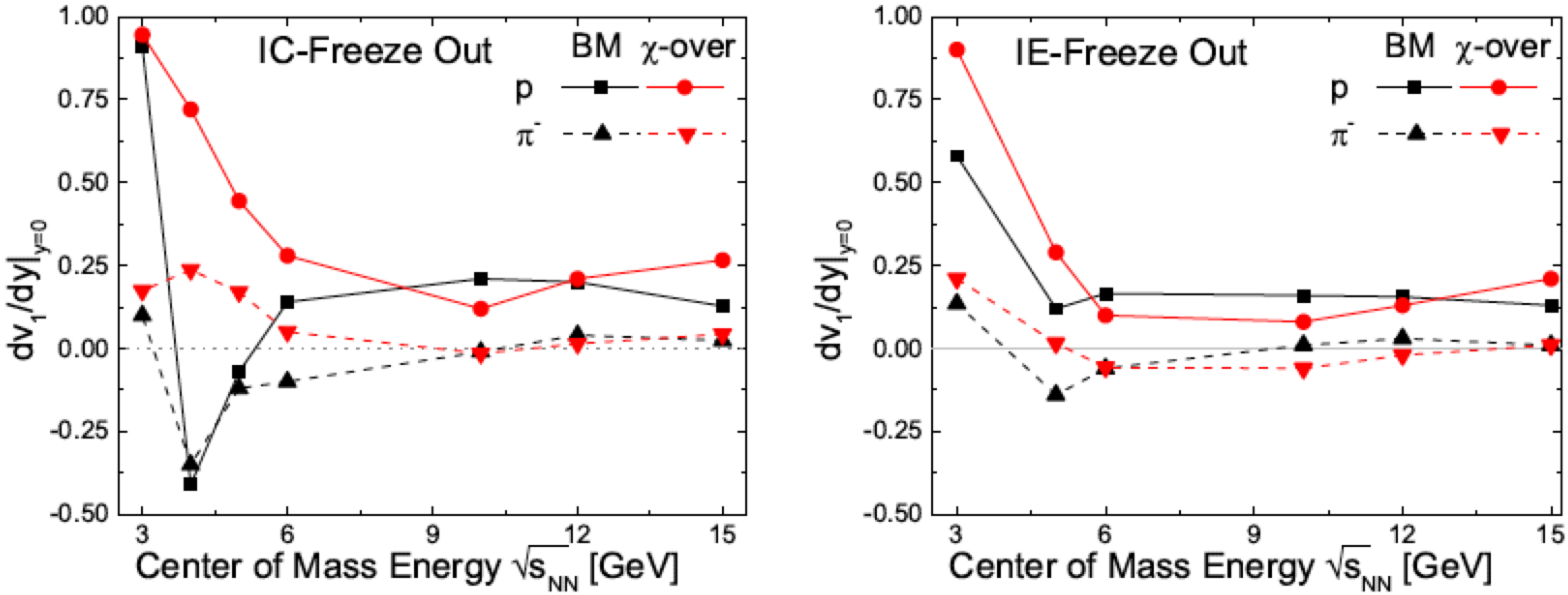




S. Singha, talk at INT-16-3

- Non-monotonic energy dependence of v1 slope
  - First order phase transition?
  - No quantitative theory description so far, stopping dynamics, spectators…

v_1 Slope for Pions and Protons



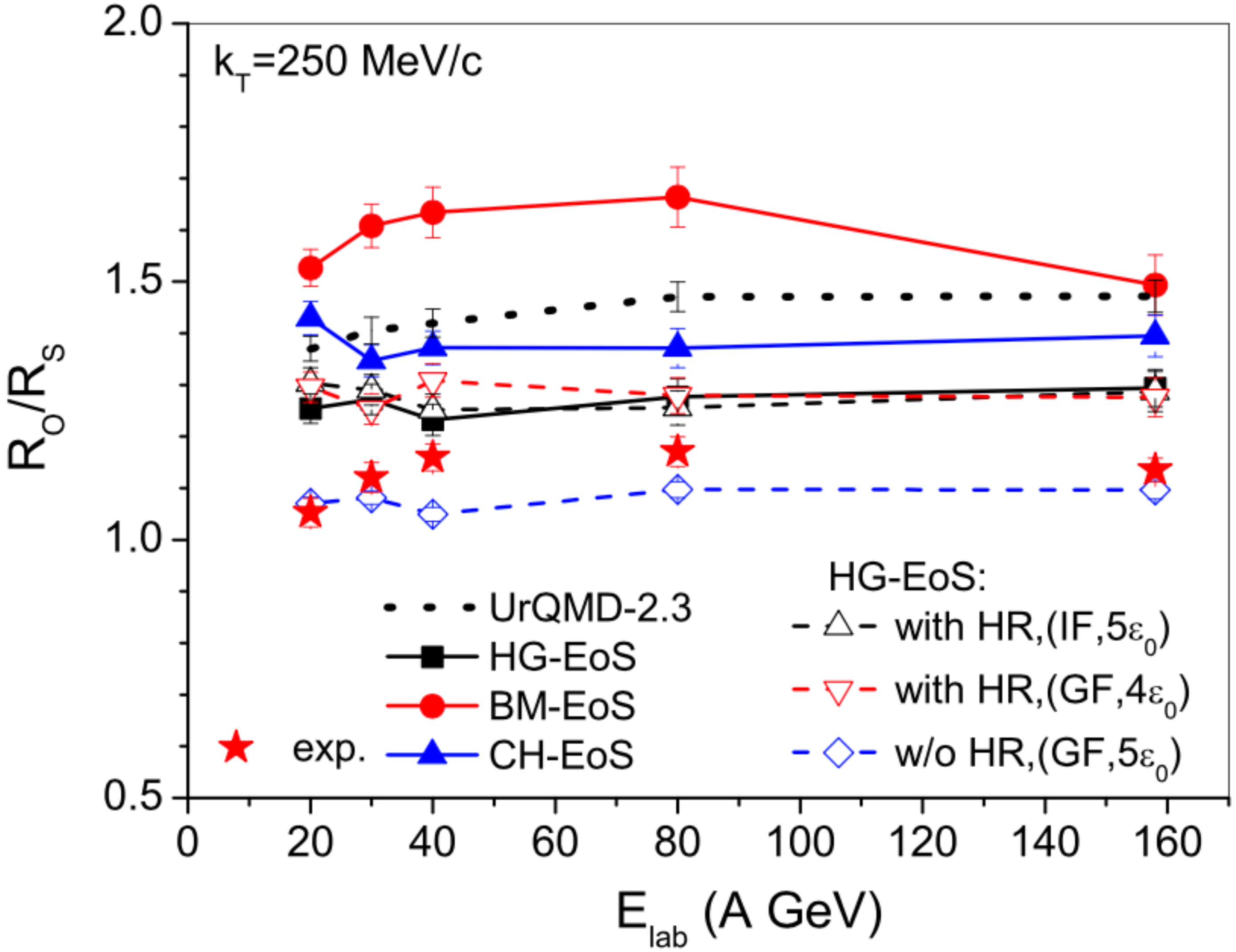
- Particlization added including hadronic rescattering
- Isochronous versus iso-energy density transition criterion
  - Drastic effect on dip structure

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

HBT and Fluctuations

R_O/R_S Ratio

- Idea: Softest point increases the lifetime of the system

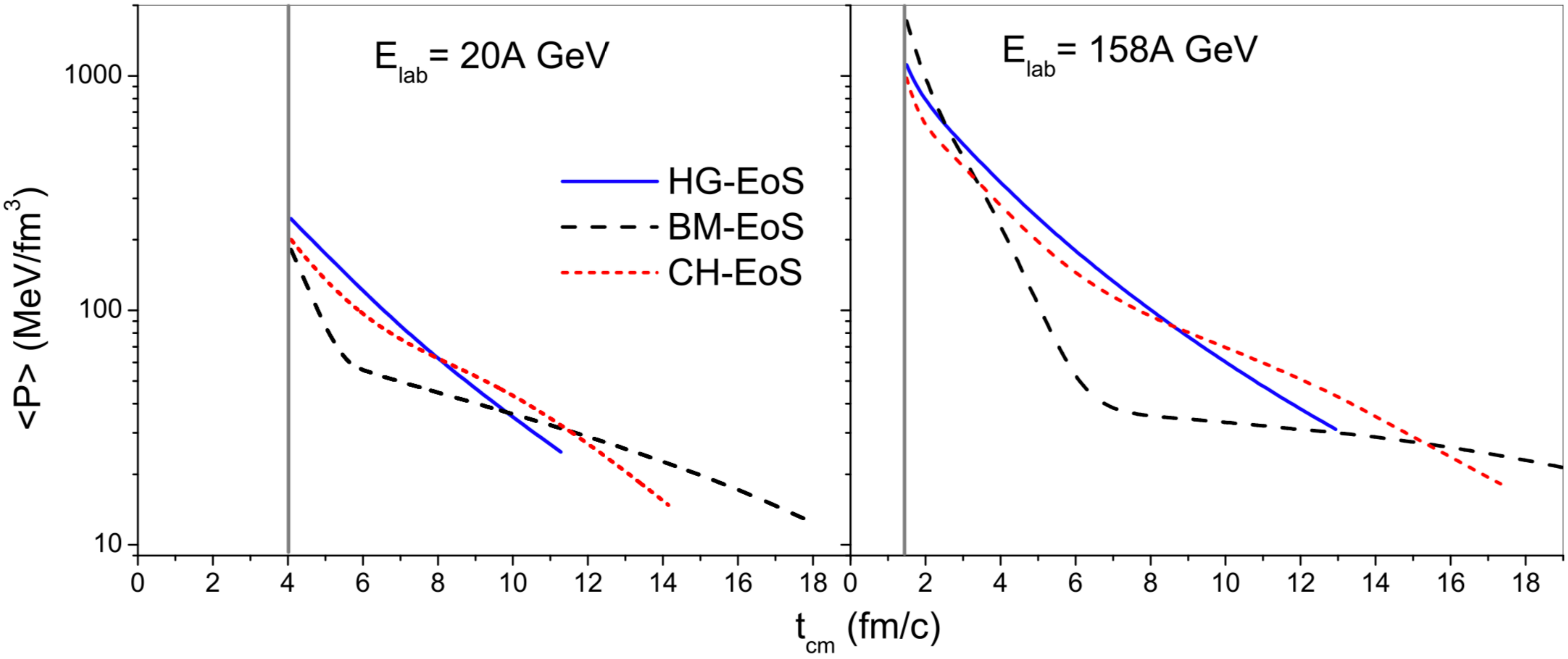


Q. Li et al, Phys.Lett. B674 (2009)

- NA49 and STAR data show a **slight** peak
- Hybrid approach confirms larger ratio for **first order** transition

Pressure in Hybrid Approach

- For different equations of state the pressure behaves rather differently as expected

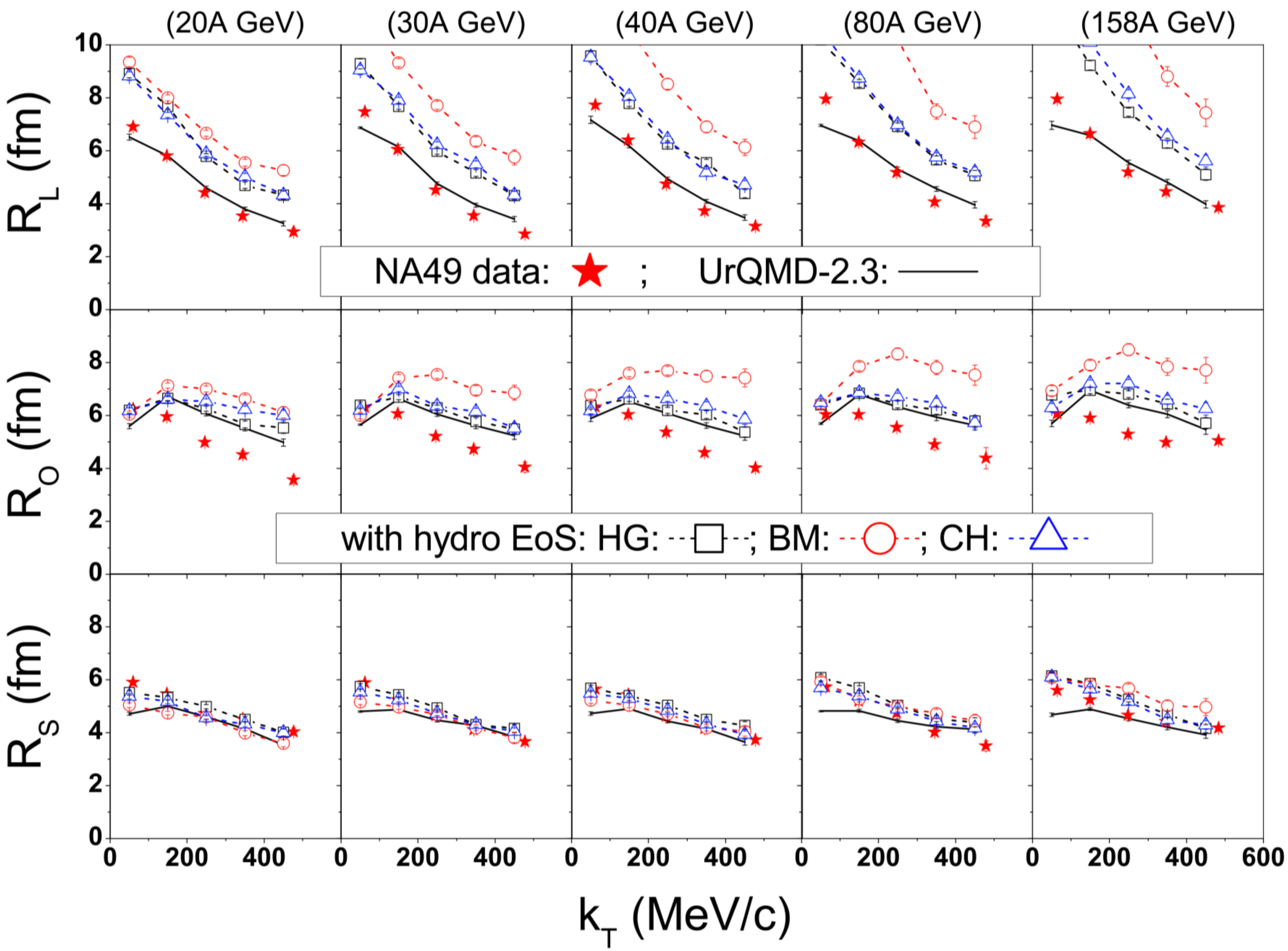


Q. Li et al, Phys.Lett. B674 (2009)

- Initial time is the starting time (overlap time)

HBT Radii at SPS Energies

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

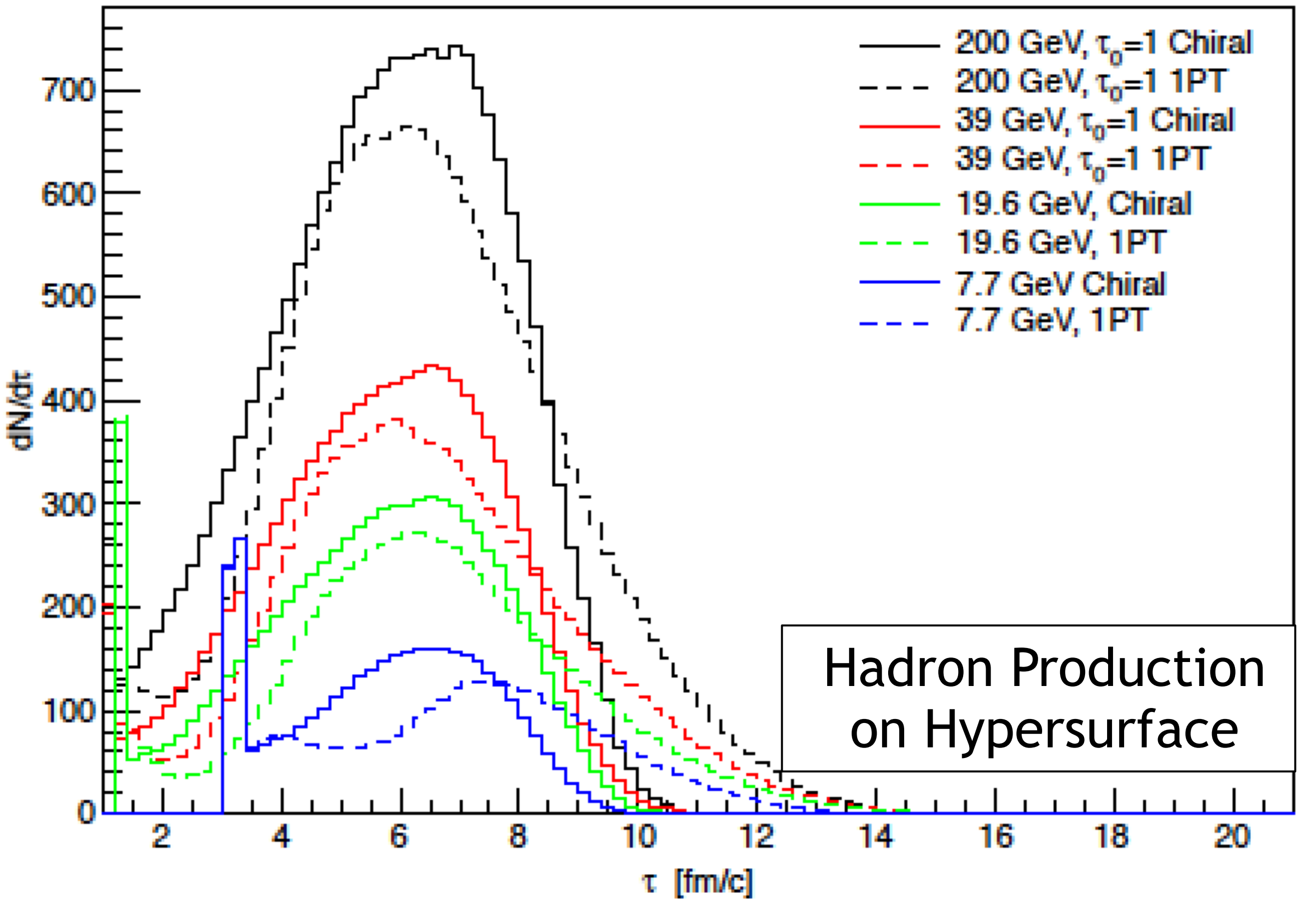


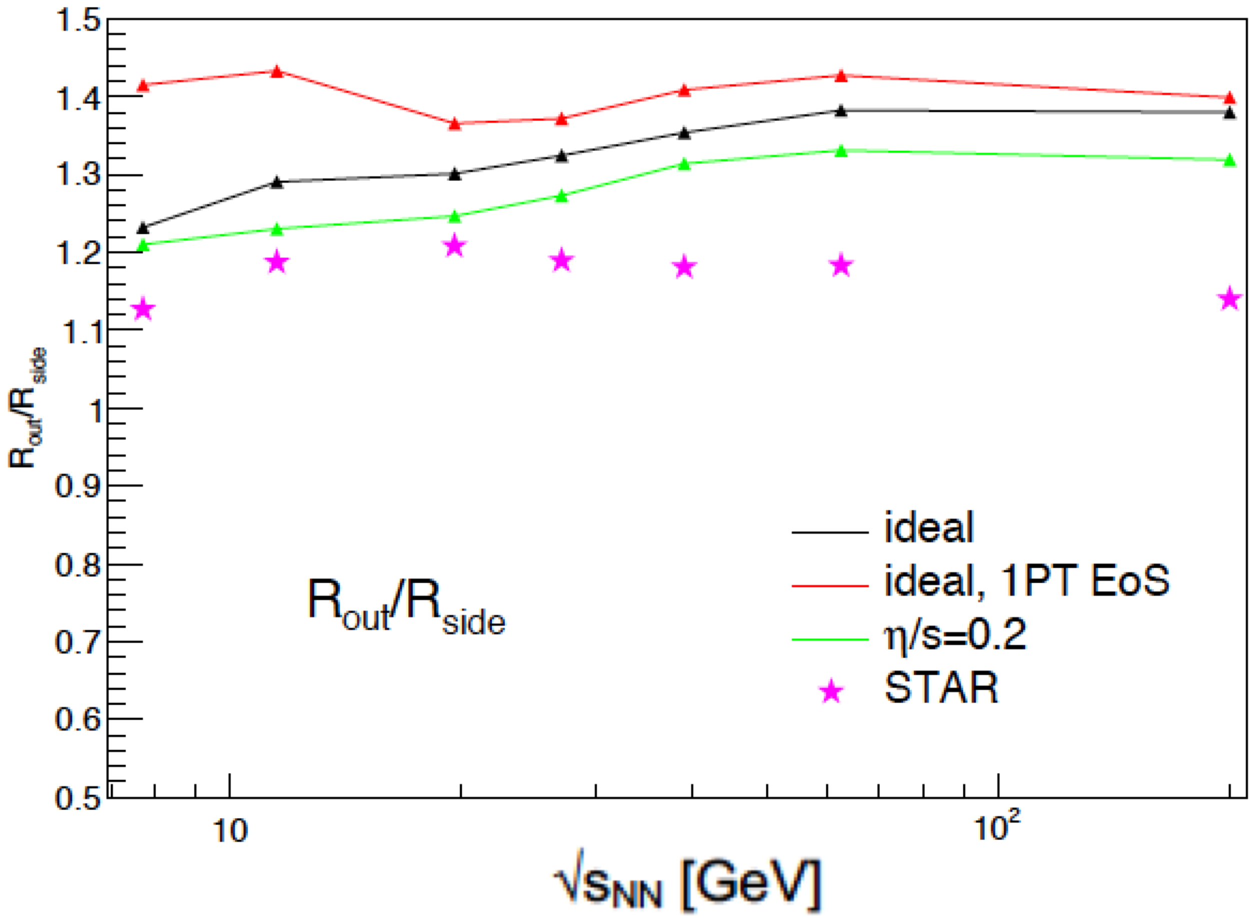
- First order transition leads to larger radii

R_O/R_S Ratio

- When are the particles freezing out?

Y. Karpenko, WPCF 14

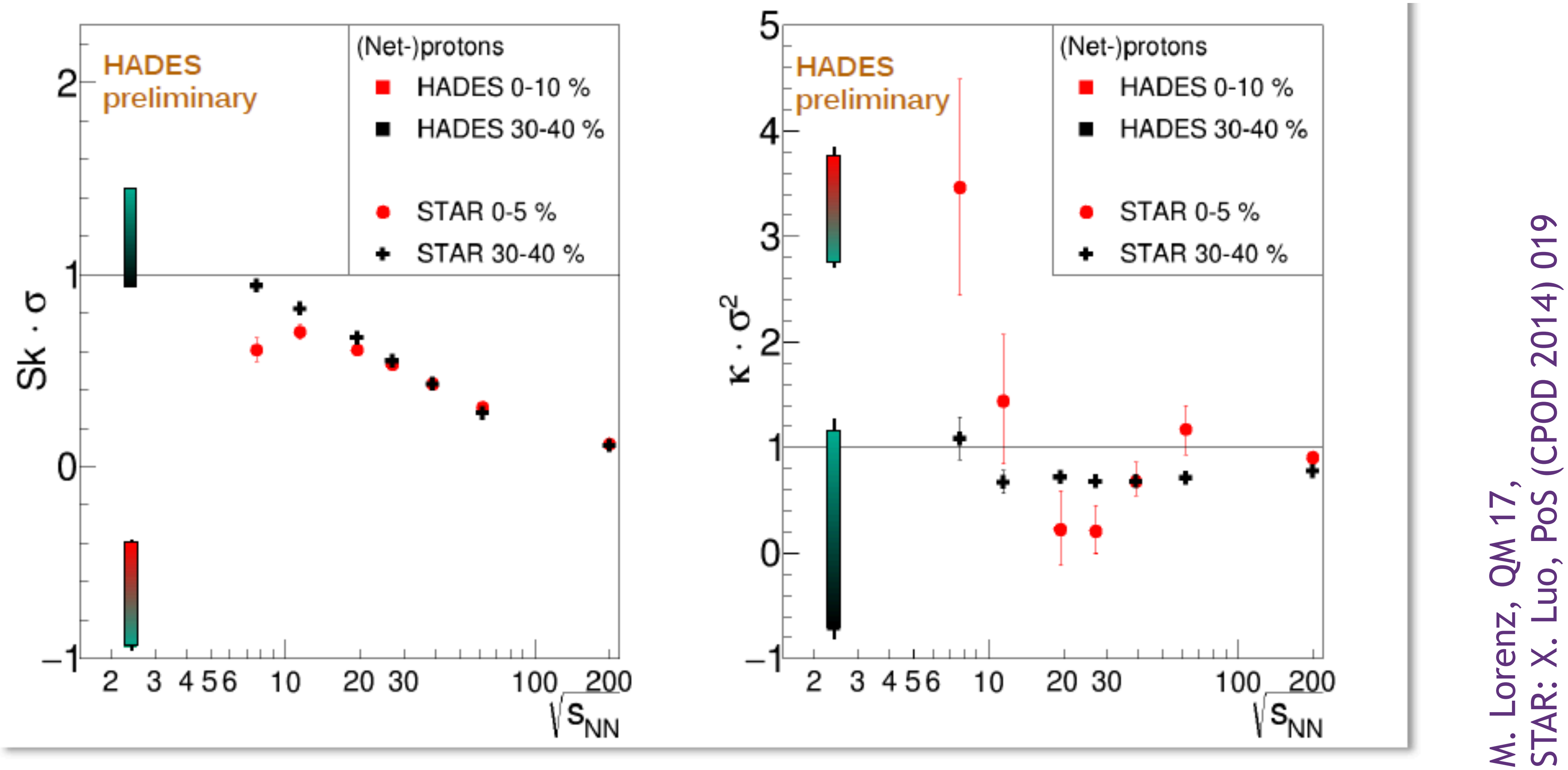




- First order transition leads to longer fireball lifetimes
- Rather weak effect of EoS on HBT radii, finite viscosity has similar influence

Higher Moments

- Skewness and kurtosis show **non-trivial** energy dependence



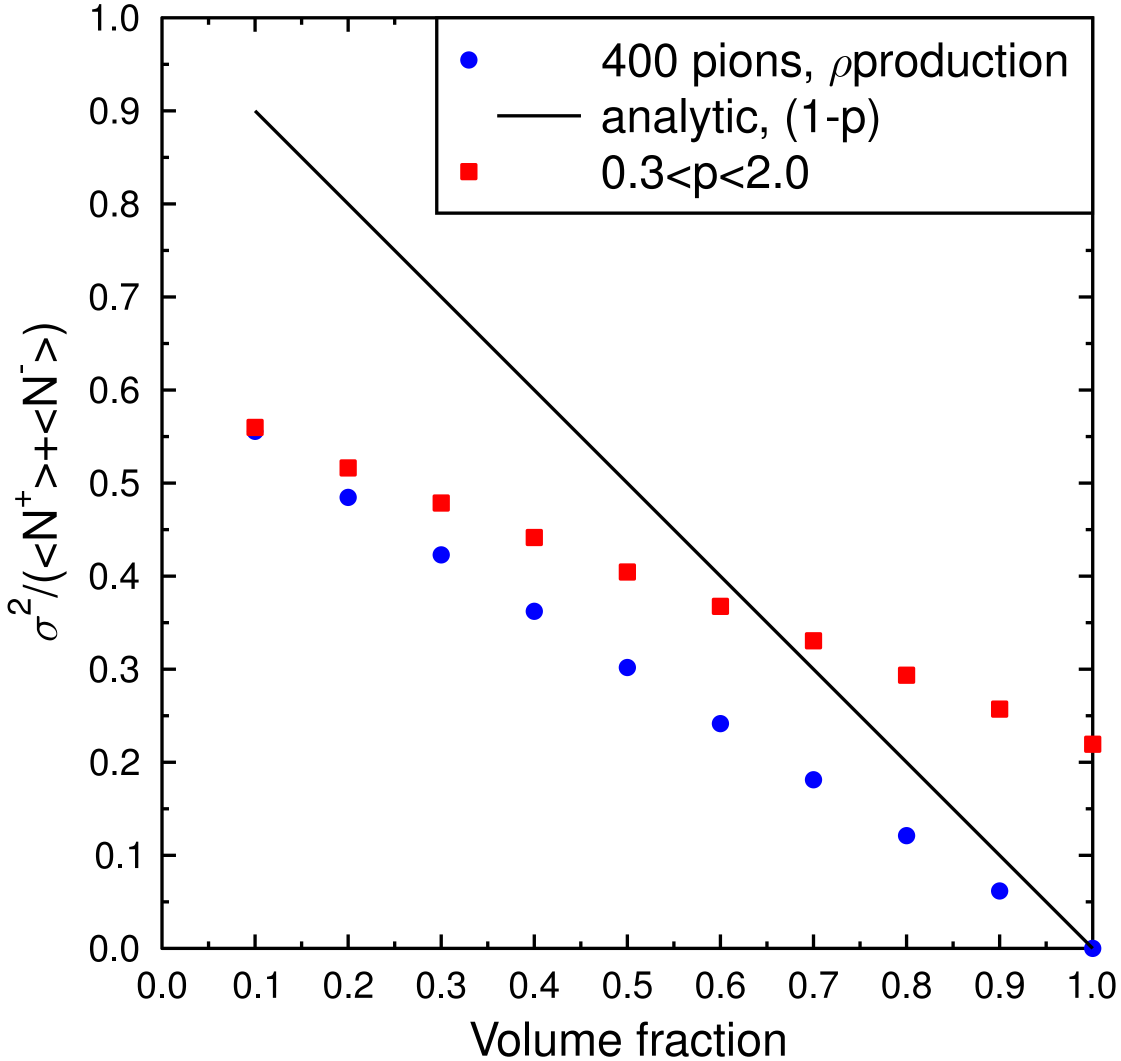
- New experimental results from BES II, cross-check between fixed target and collider setup are crucial
- Propagation of fluctuations through hydro, Cooper-Frye and hadron cascade -> addressed in other talks at this meeting

Systematic Investigations within SMASH

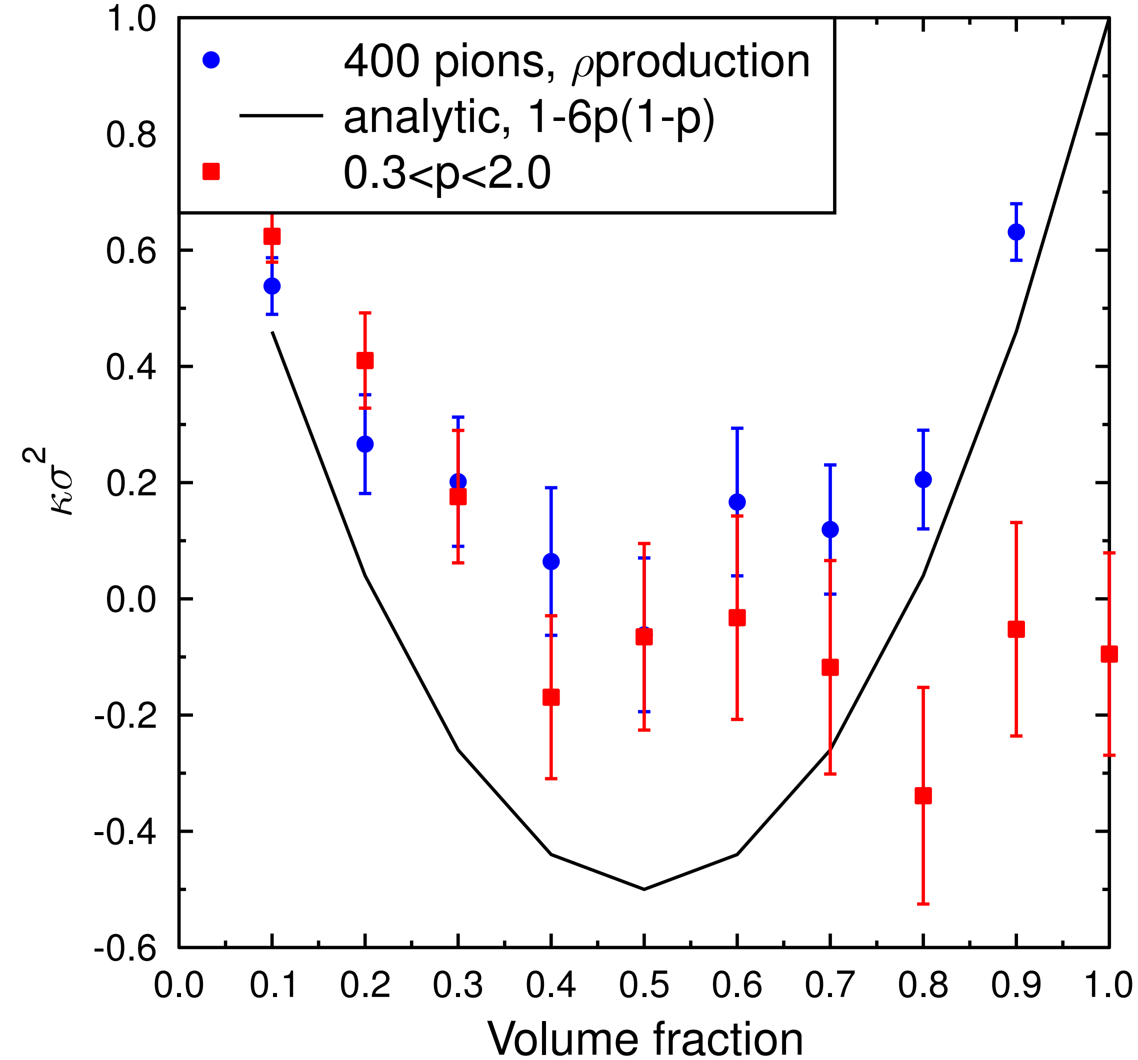
- Net charge distribution with p cut

HP at QM15, will be picked up and extended within SinoGerman DFG grant in 2019

Variance



Kurtosis

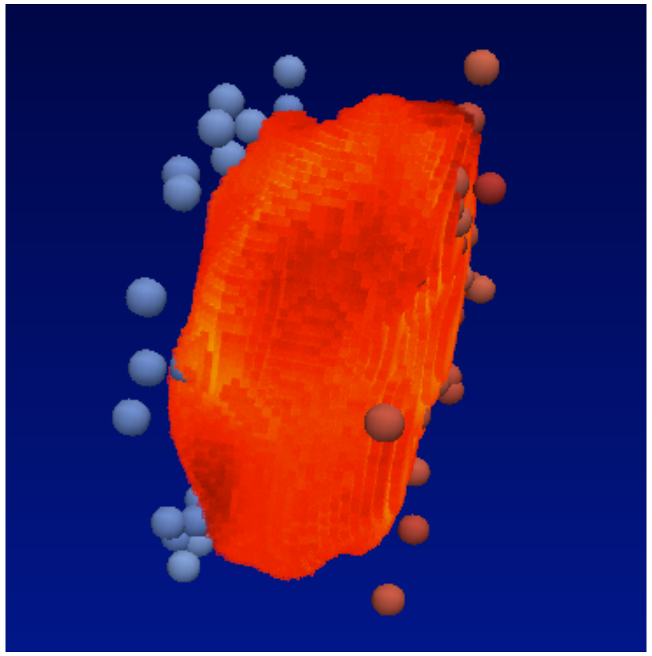


- Fluctuations are increased due to fluctuating particle number in the full volume

SMASH
A Hadron Transport Approach

Why a new Approach?

- Hadronic transport approaches are successfully applied for the dynamical evolution of heavy ion collisions
- Hadronic **non-equilibrium** dynamics is crucial for
  - Full/partial evolution at **low/** intermediate **beam energies**
  - Late stage **rescattering** at high beam energies (RHIC/LHC)



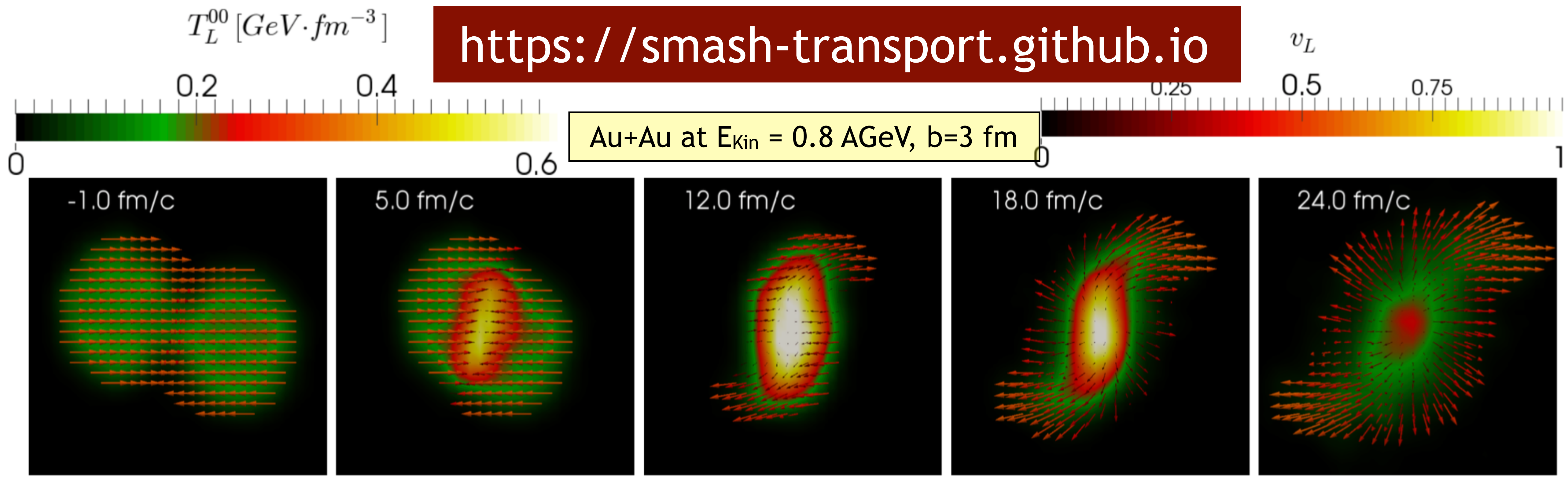
- New experimental data for cross-sections and resonance properties is available (e.g. COSY, GSI-SIS18 pion beam etc)
- Philosophy: Flexible, modular approach condensing knowledge from existing approaches
- Goal: Baseline calculations with hadronic vacuum properties essential to identify phase transition

SMASH*

J. Weil et al, PRC 94 (2016)

- Hadronic transport approach:
  - Includes all mesons and baryons up to ~2 GeV
  - Geometric collision criterion
  - Binary interactions: Inelastic collisions through resonance/string excitation and decay
  - Infrastructure: C++, Git, Doxygen, (ROOT)

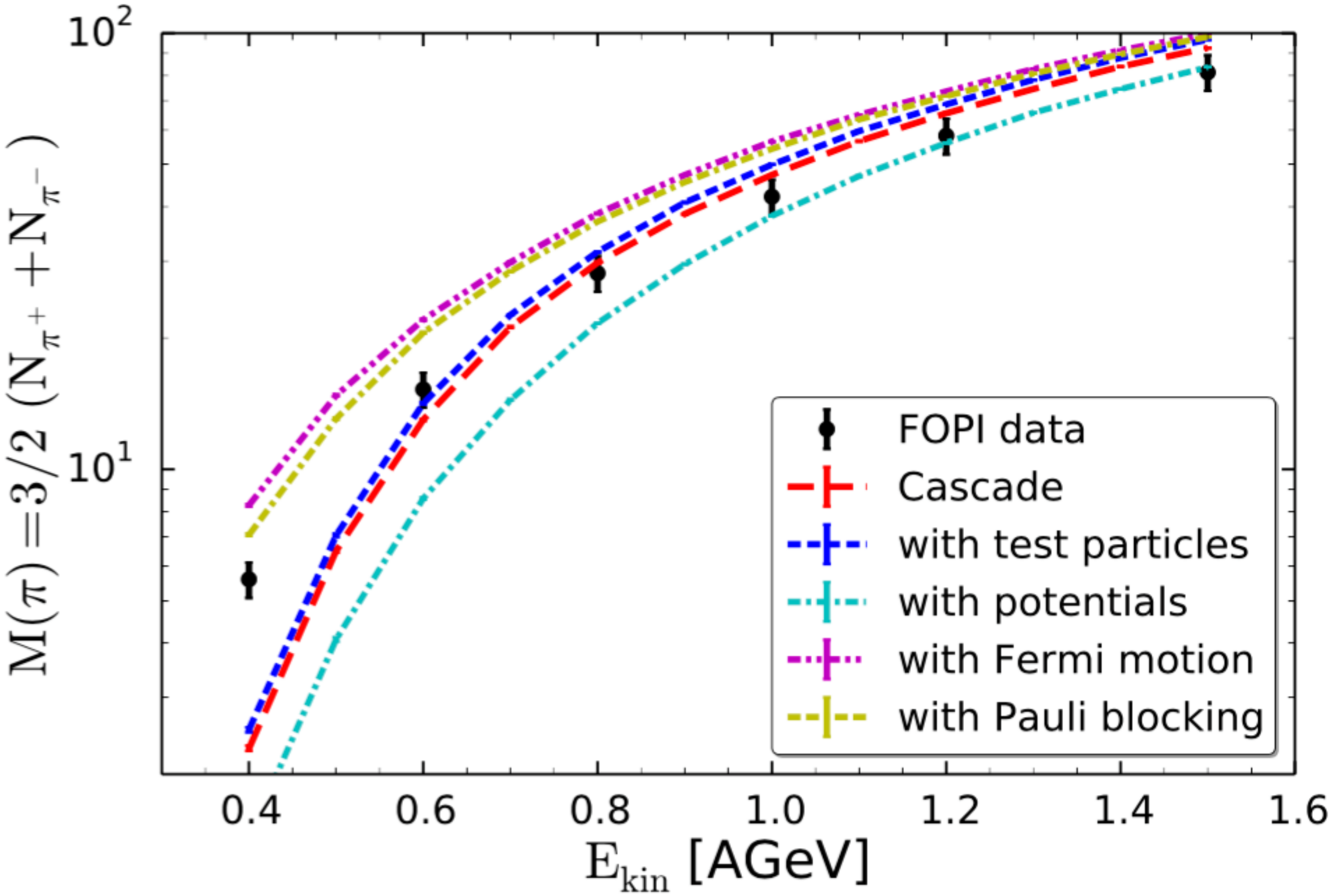
https://smash-transport.github.io

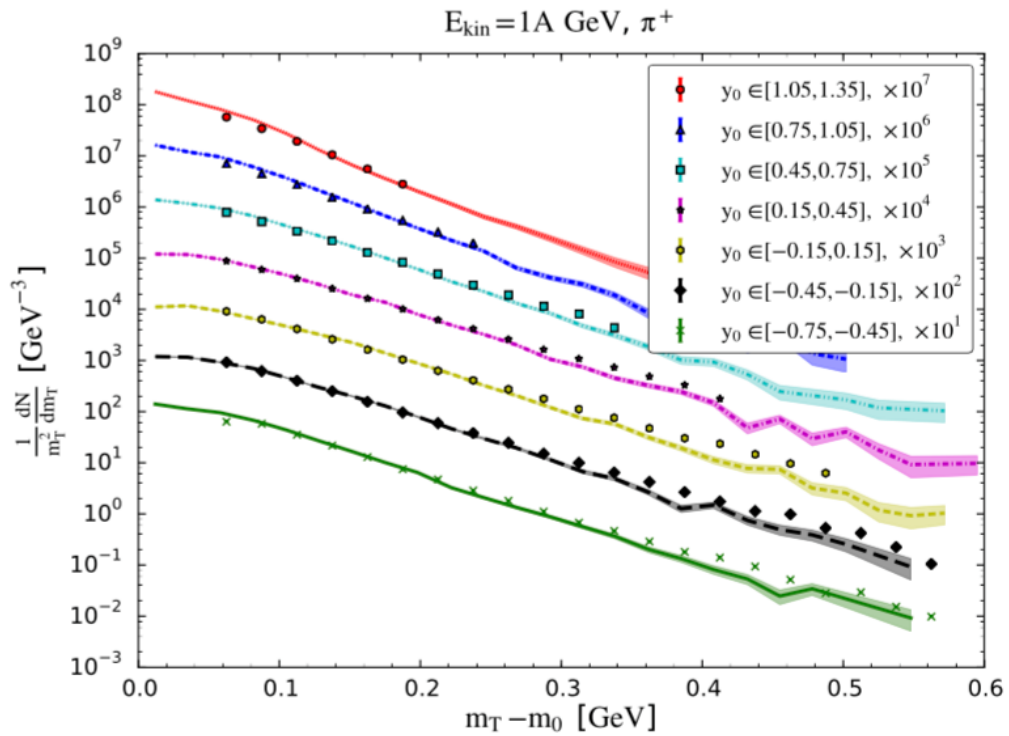


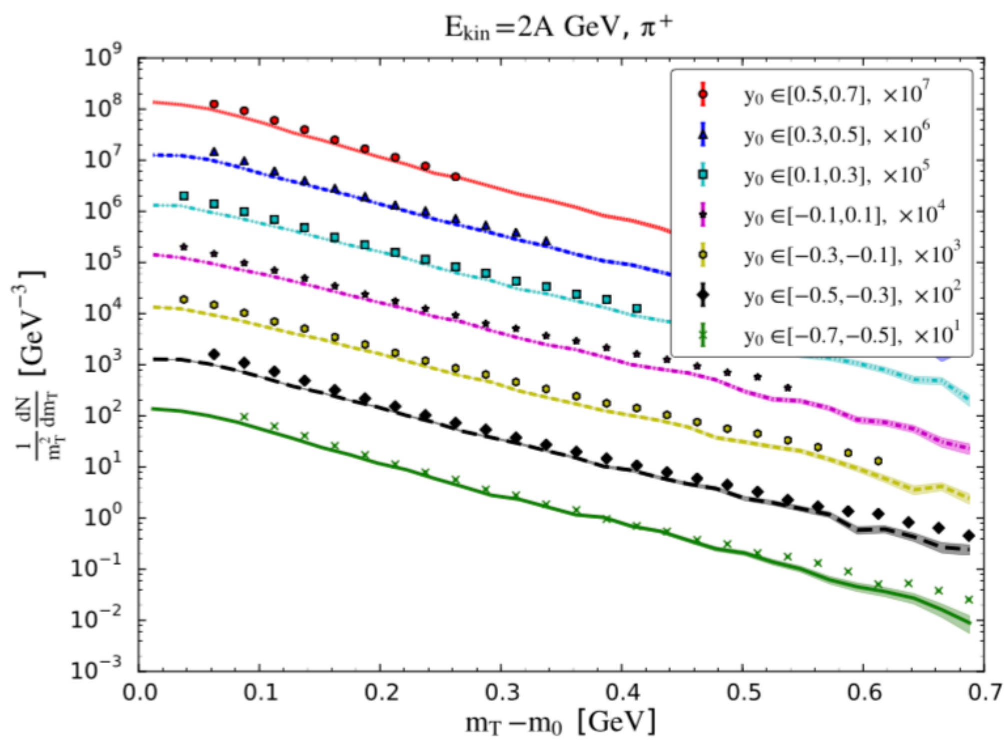
* Simulating Many Accelerated Strongly-Interacting Hadrons

Pion Production in Au+Au

- Potentials decrease pion production, while Fermi motion increases yield
- Nice agreement with SIS experimental data







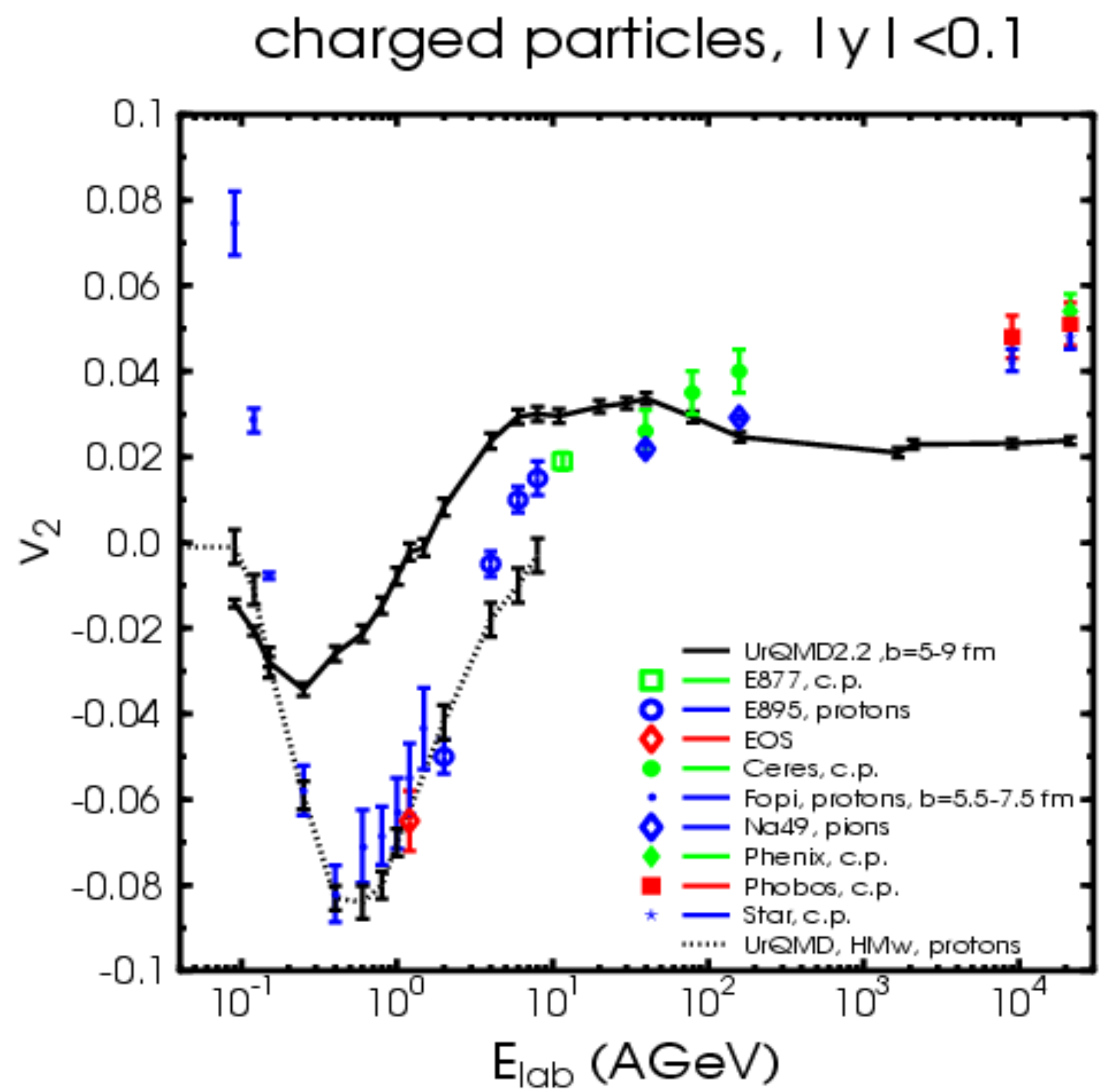
Note: consecutive addition of features

J. Weil et al, PRC 94 (2016)

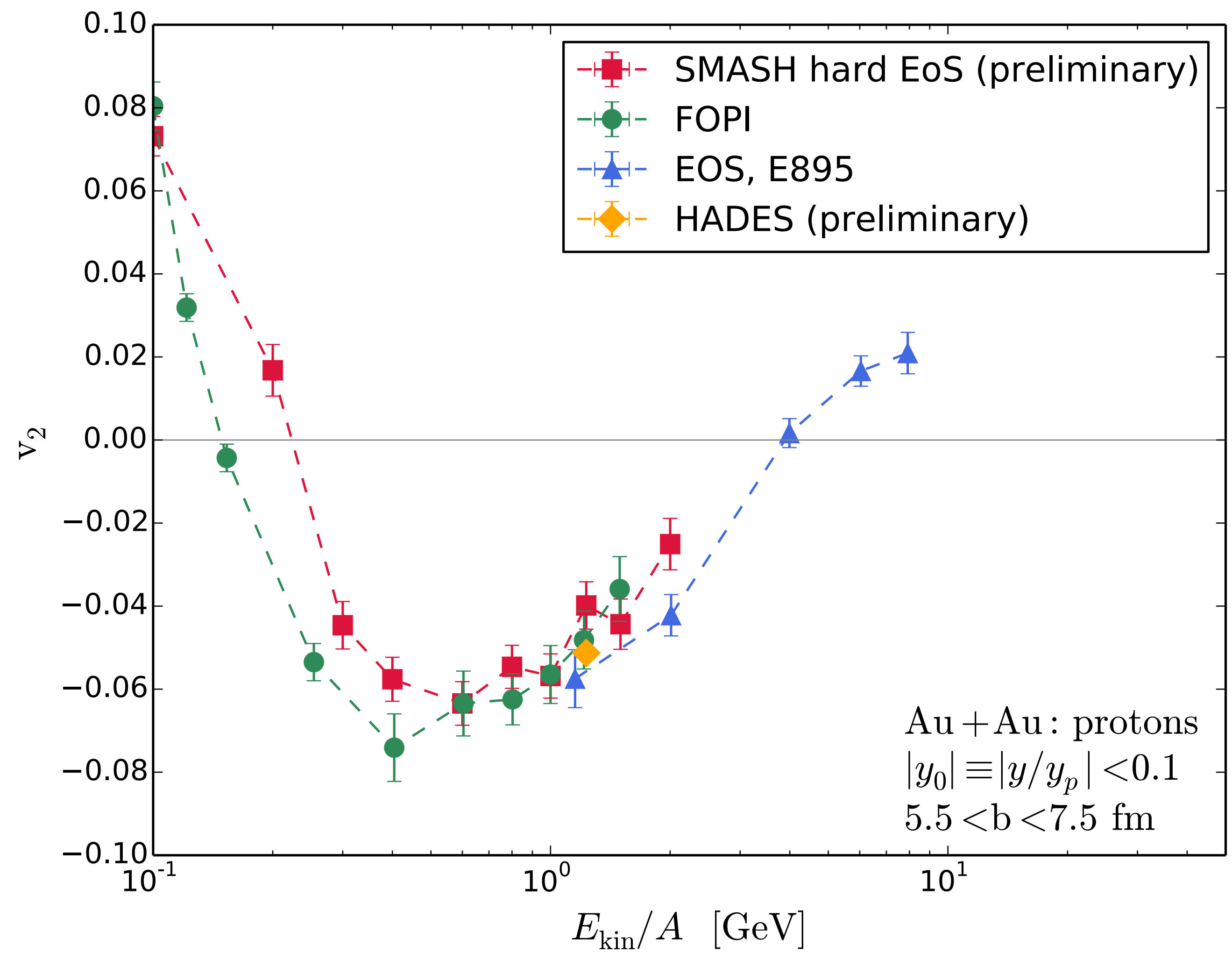
Collective Flow -v_2

- Directed and elliptic flow are compared to available data from FOPI and HADES

HP et al, Phys.Rev. C74 (2006) 064908



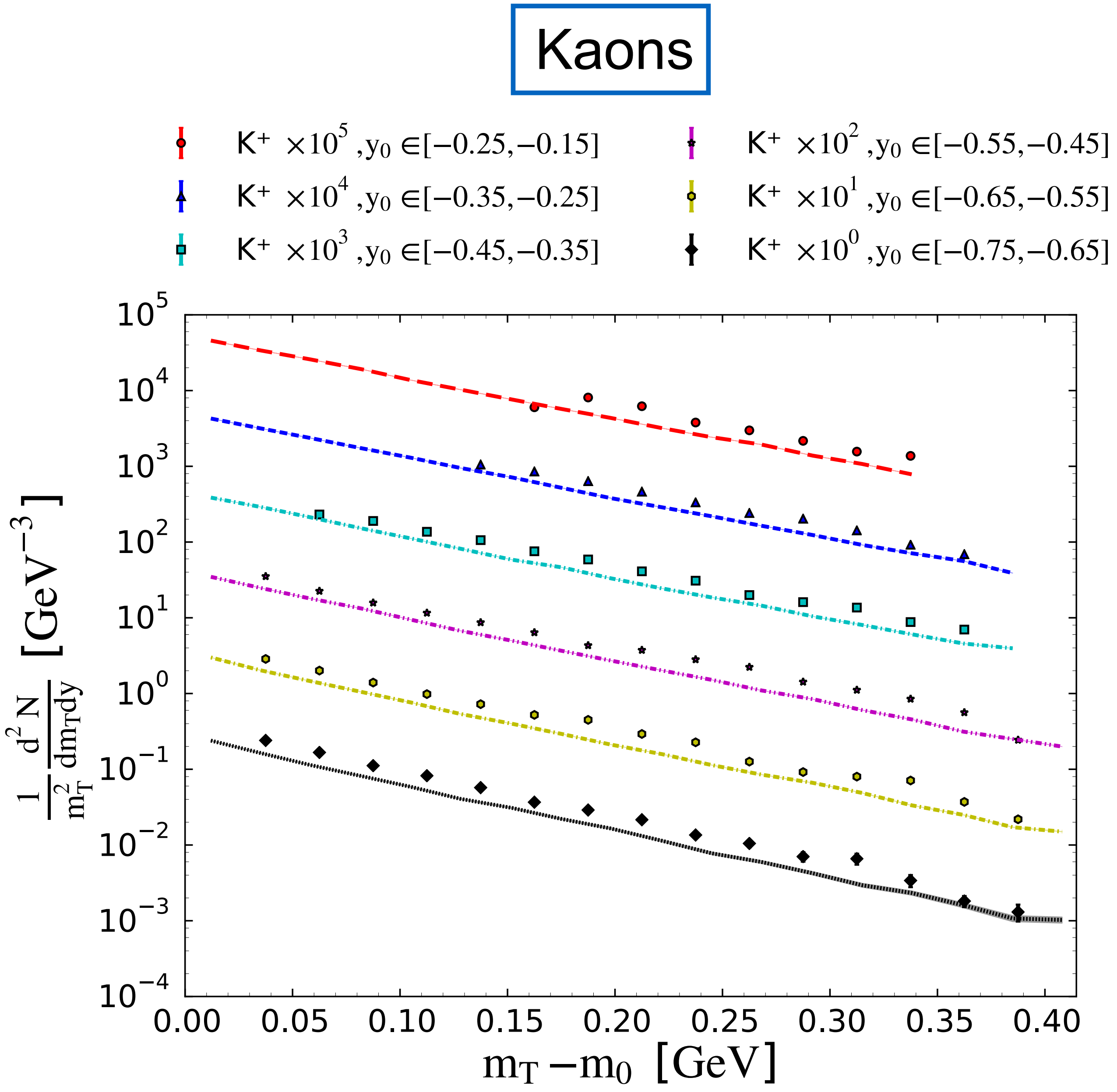
by Markus Mayer

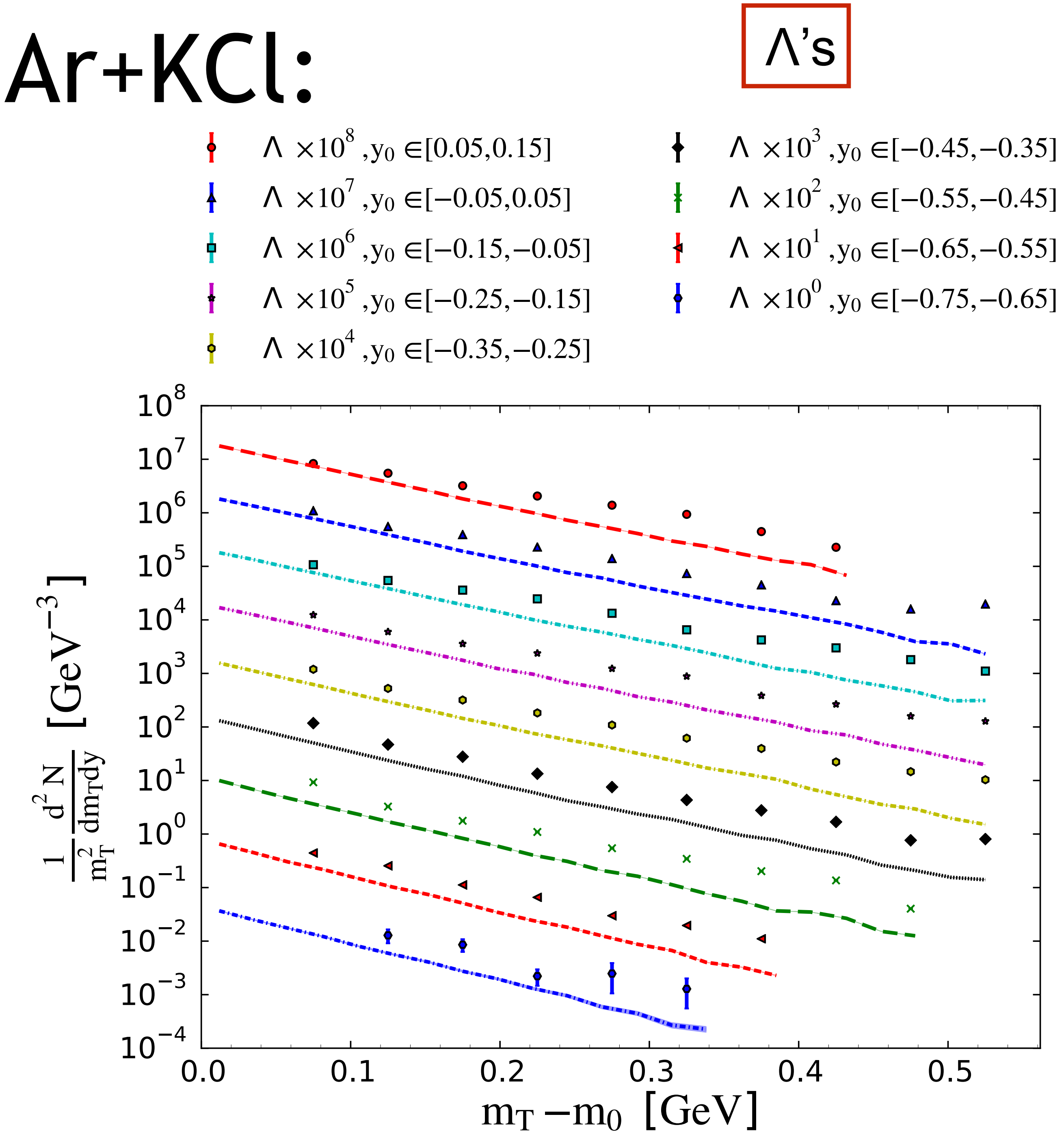


- SMASH agrees well with previous UrQMD calculation for v_2 excitation function

Strangeness Production

- Kaons and Lambdas in Ar+KCl:



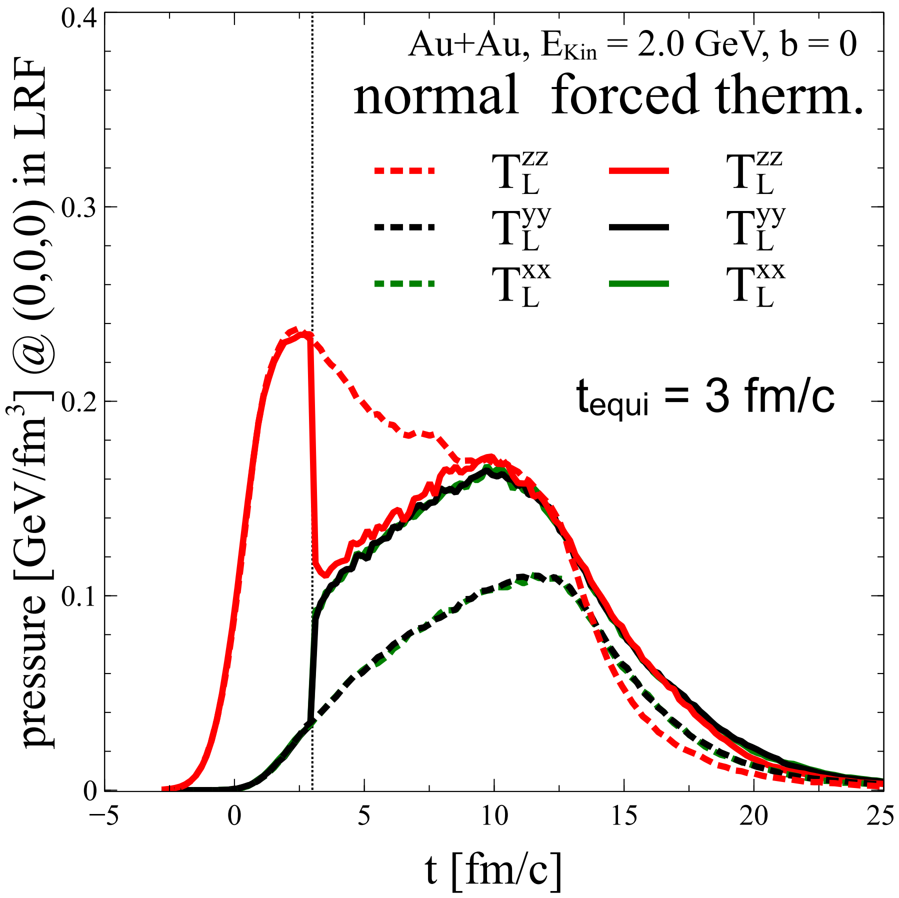


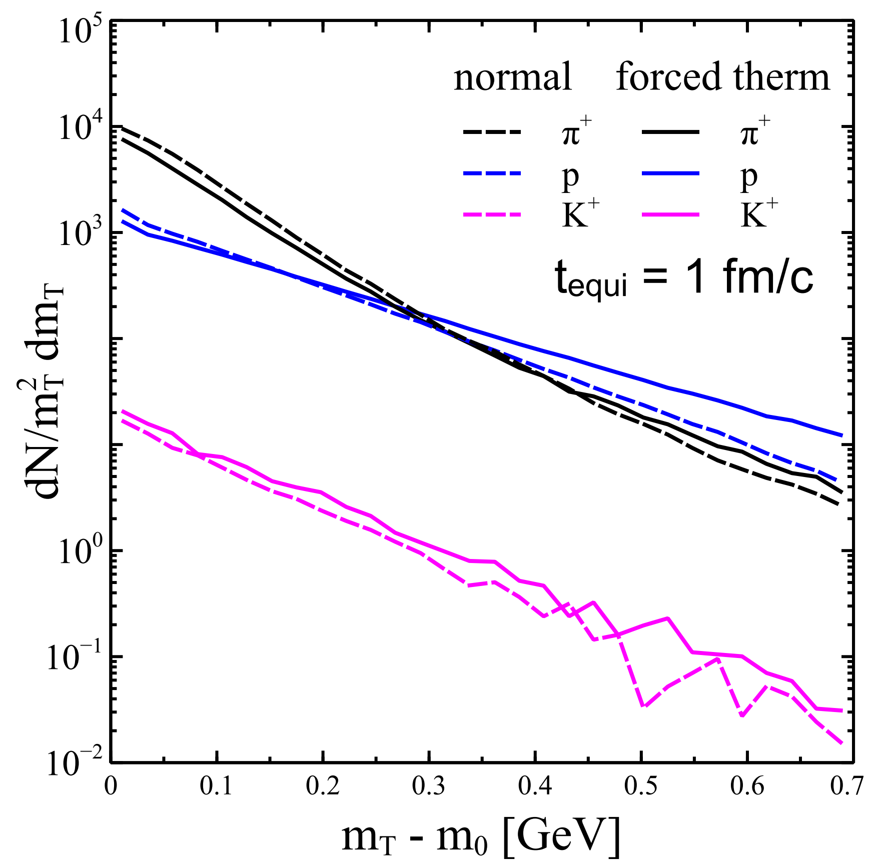
V. Steinberg et al., arXiv:1809.03828

- Ongoing work: system size dependence and predictions for pion beam and hyperon potentials

Effective N-particle Scattering

- At higher densities multi-particle scattering becomes important -> here: extreme limit
- Above 0.3 GeV/fm^3 local kinetic equilibrium is enforced by replacing the distribution function with a thermal one



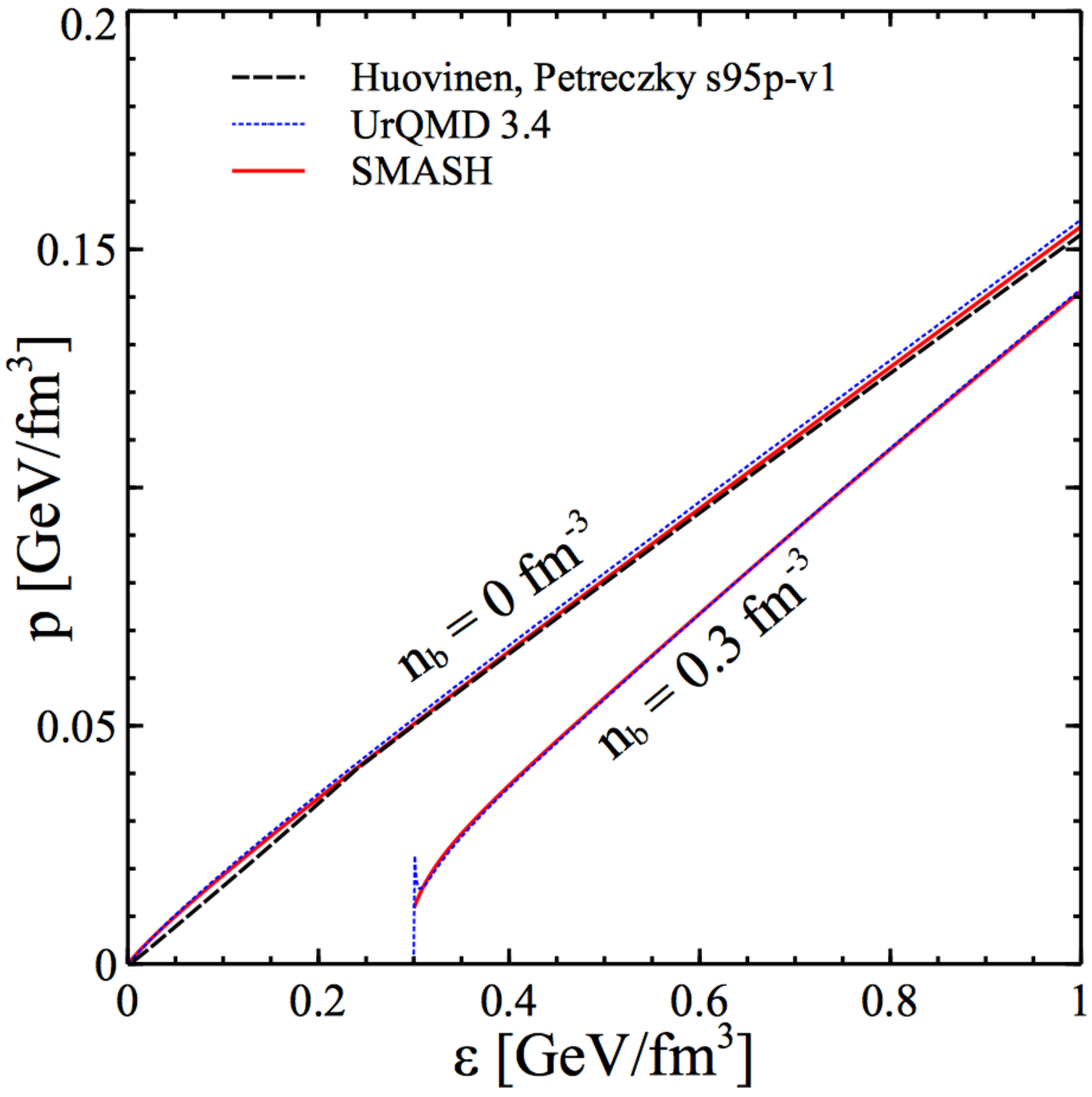


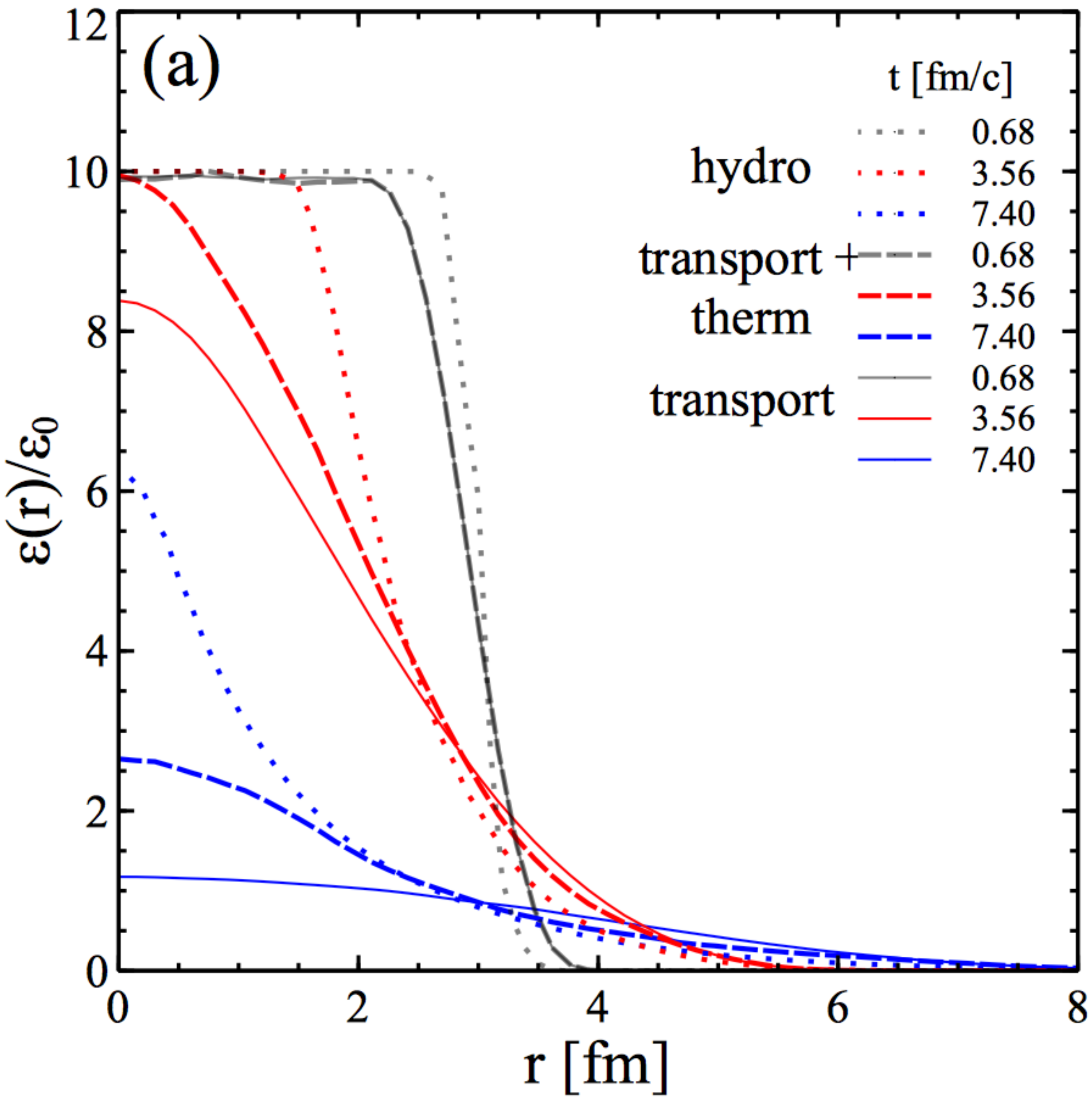
- Spectra are more „thermal“ and strangeness enhanced

Dmytro Oliinychenko, HP, JPG 44, 2017

EoS and Hydro Comparison

- Equation of state fits lattice hadron gas



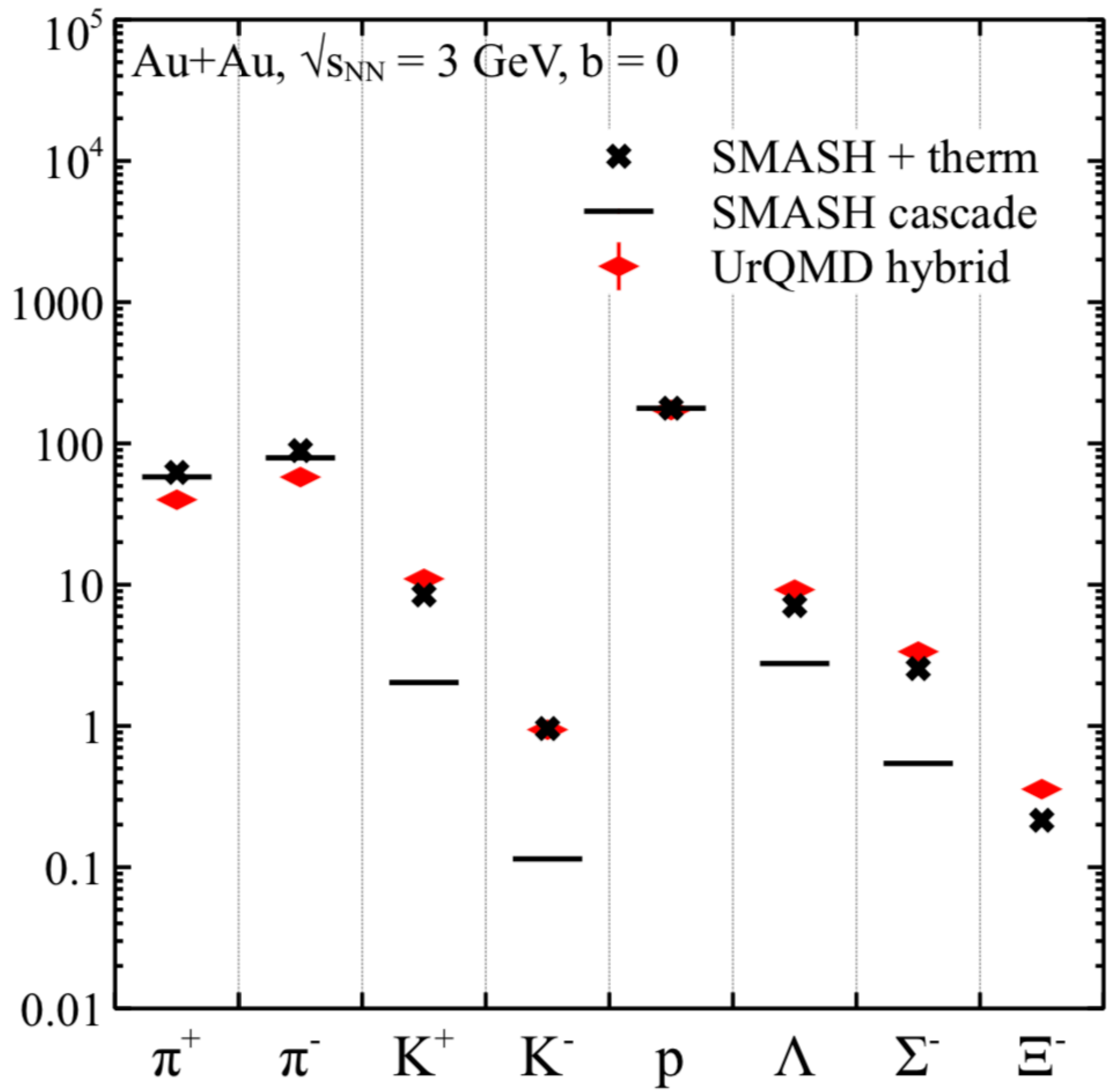


- Interpolation between transport and hydrodynamics

Dmytro Oliinychenko, HP, JPG 44, 2017

Strangeness Production

- Comparison of particle yields



- Strange particle yields similar to hybrid results

Strings and Stopping

Initial Conditions: 3 Options

- Color Glass/Gluon **saturation** approach
  - Down to which energy do the assumptions hold?
  - How to generalize this formalism to three dimensions and beam velocities smaller than the speed of light?

See e.g. L. McLerran, S. Schlichting, S. Sen arXiv: 1811.04089

- Hadron-string approach
  - Can the **string model** reproduce the stopping mechanism properly?

To be addressed here

- **3-fluid** hydrodynamics
  - Baryon-rich projectile and target fluids feed the fireball fluid via source terms
  - Can these be used to provide an understanding of baryon stopping?

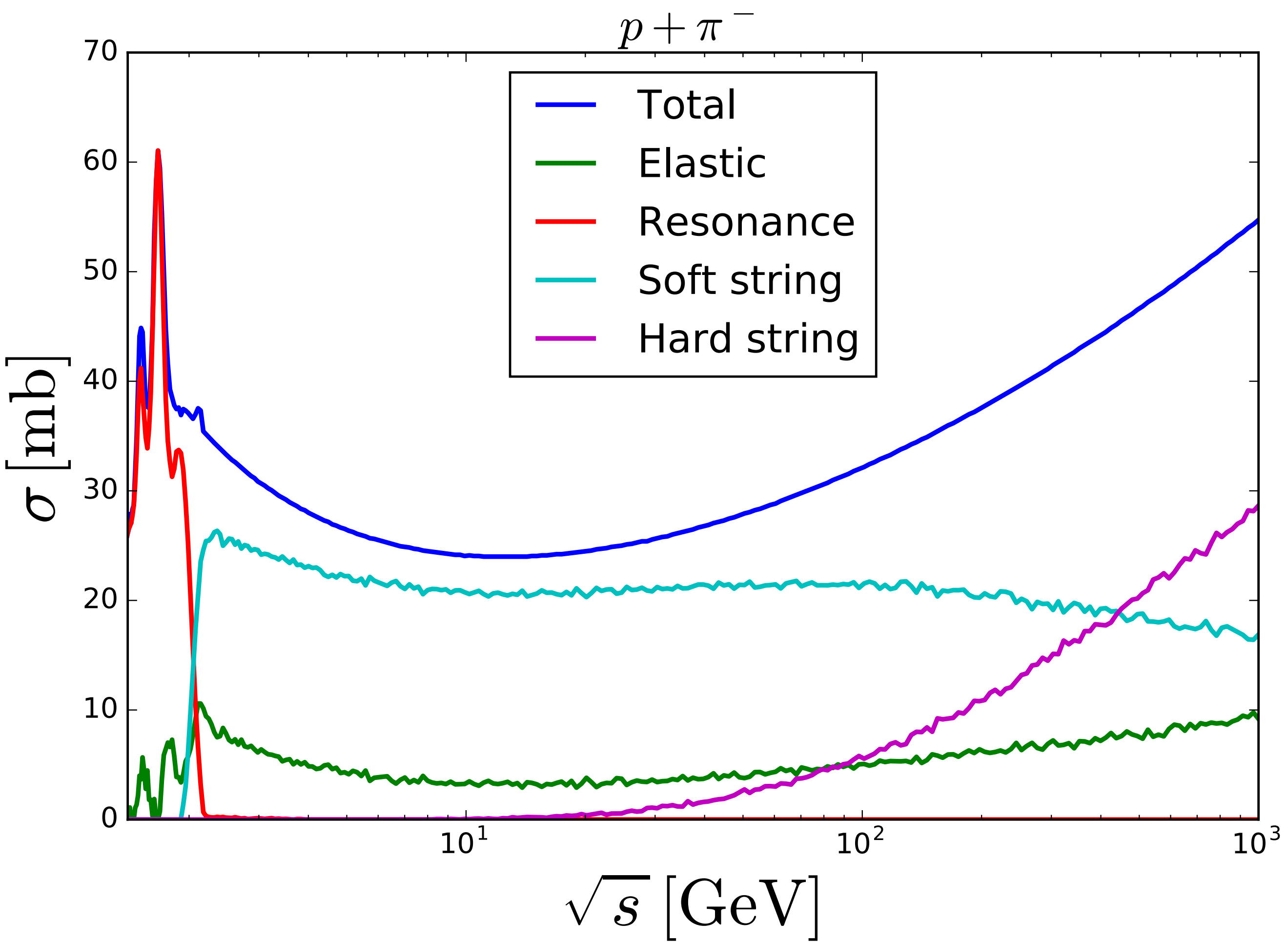
THESEUS by P. Batyuk et al, Phys.Rev. C94 (2016)

- All possibilities need detailed **exploration** and data **confrontation**

Moving to Higher Energies

- High energy cross-section is dominated by string excitation and fragmentation

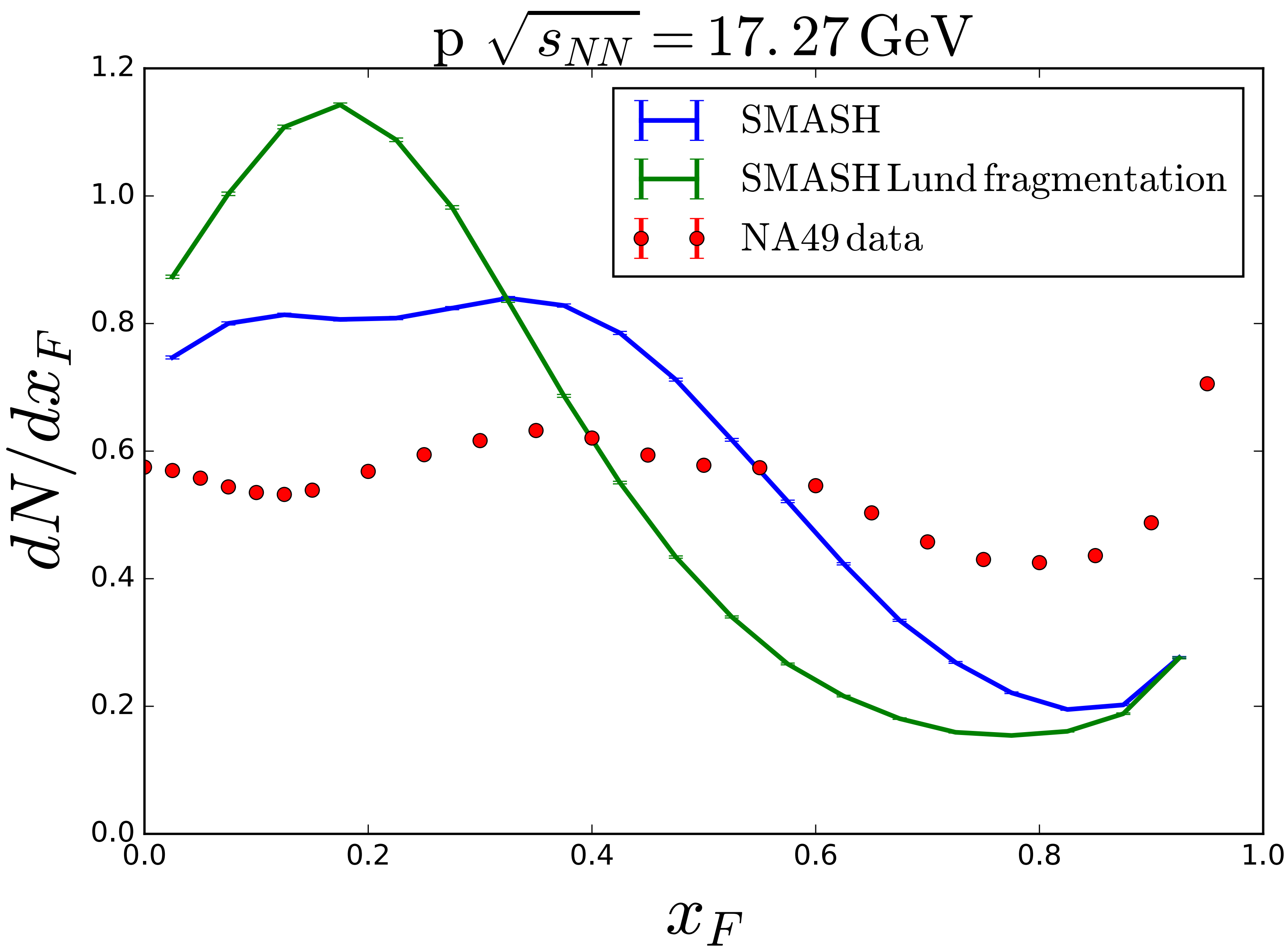
- **Soft strings**
  - Pythia is only employed for fragmentation
  - single-diffractive, double diffractive and non-diffractive processes
- **Hard strings**
  - Fully treated by Pythia
  - All species mapped to pions and nucleons



J. Mohs and S. Ryu

Fragmenting Leading Baryons

- Different parameters for the fragmentation function of leading baryons to increase longitudinal momentum of protons

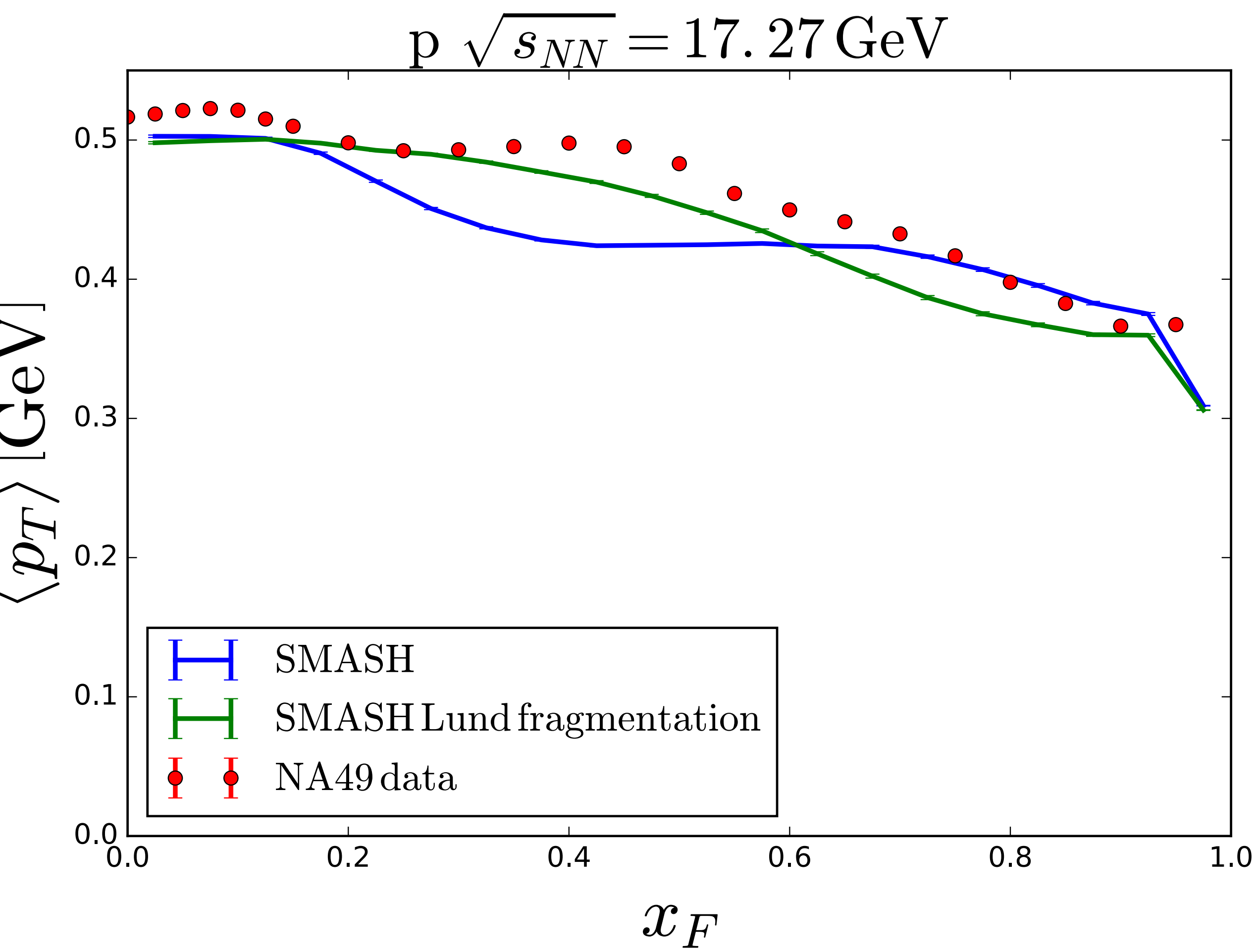


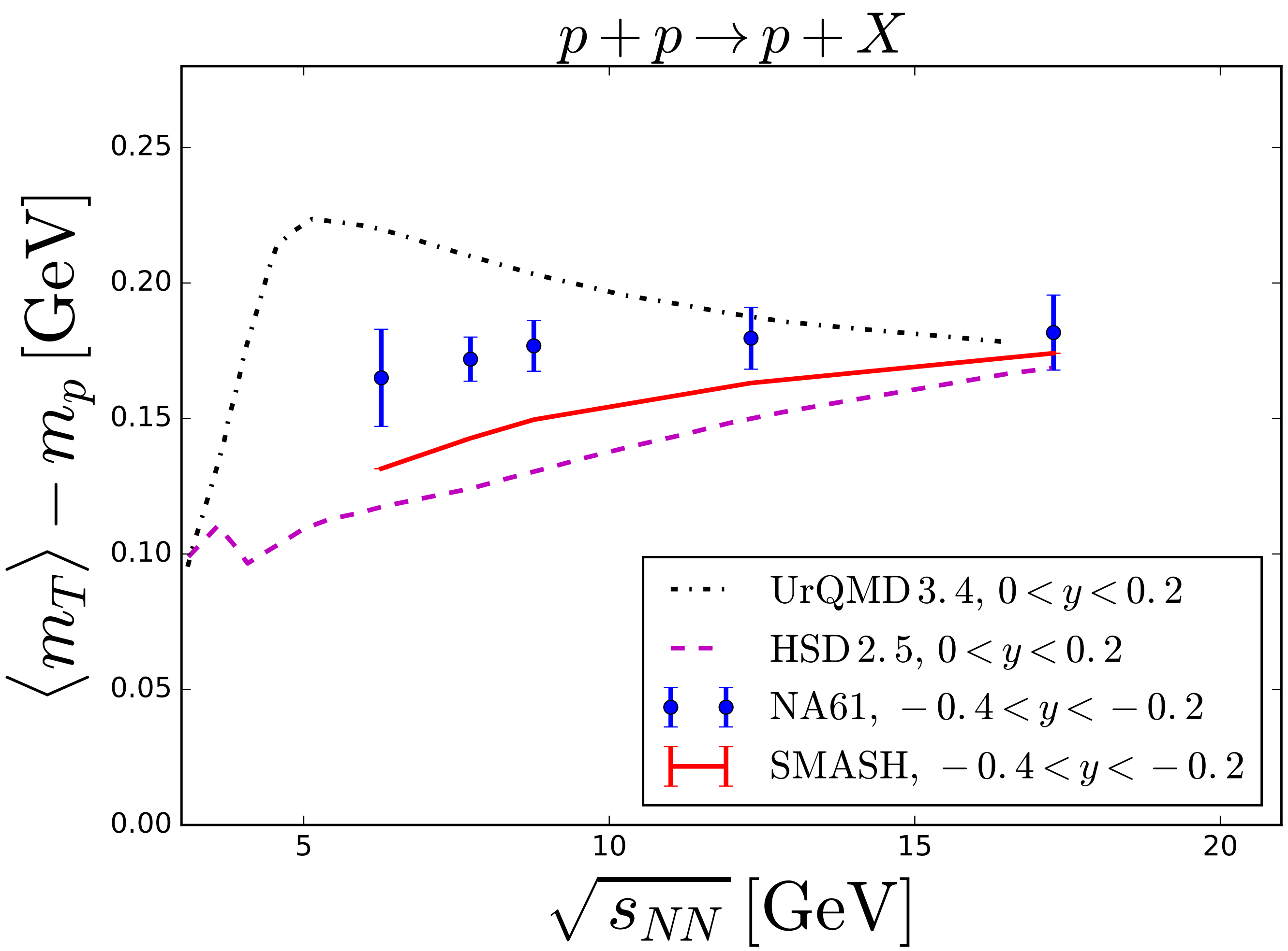
- Slightly better agreement for Feynman x distribution

Transverse Momentum

- Benchmark in elementary collisions

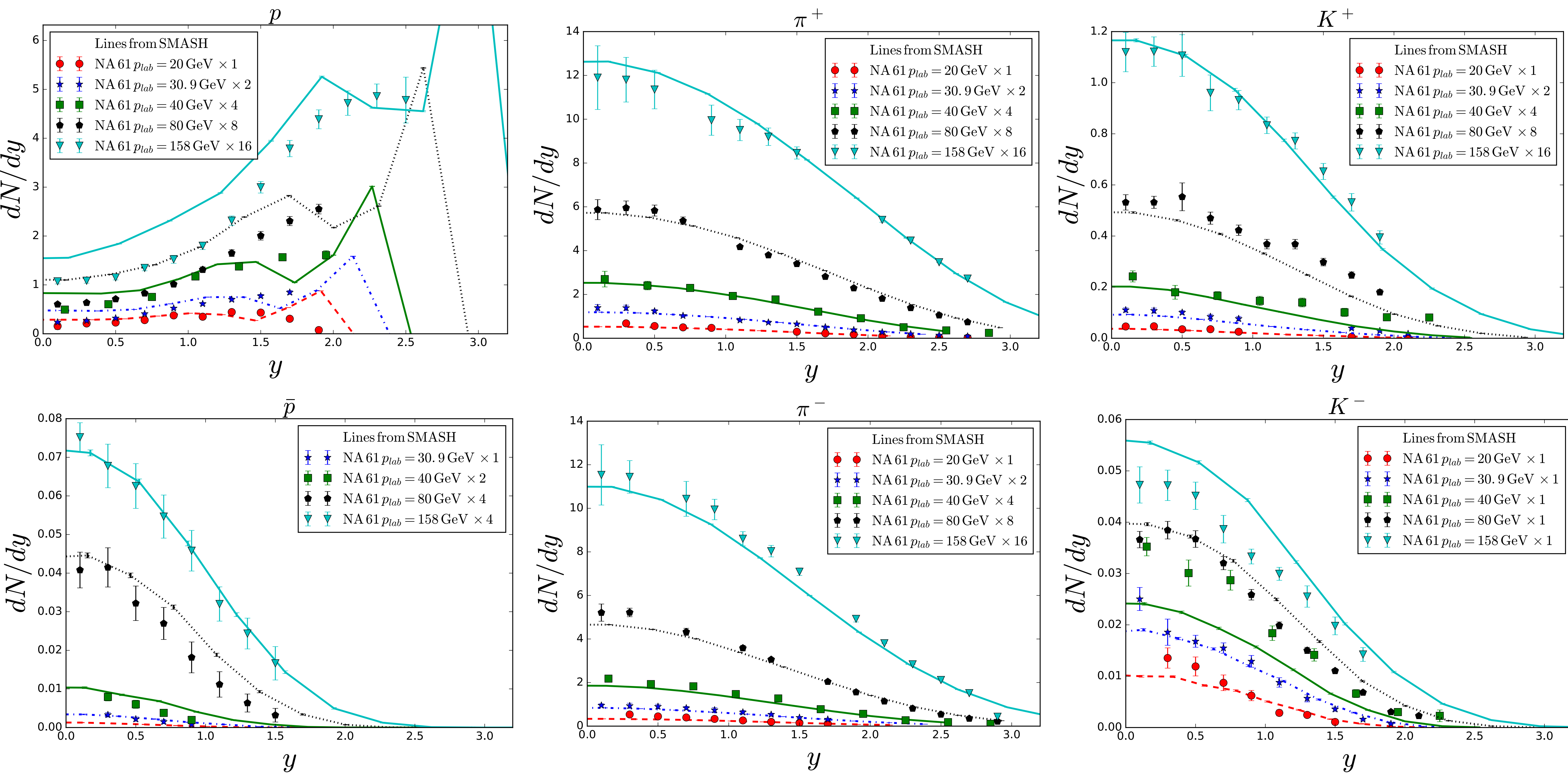
$$x_F = \frac{p_z}{p_{z,beam}}$$





- Mean p_T smooth behaviour as a function of beam energy
- Work in progress: Find final set of parameters that allows for best fit of pp data

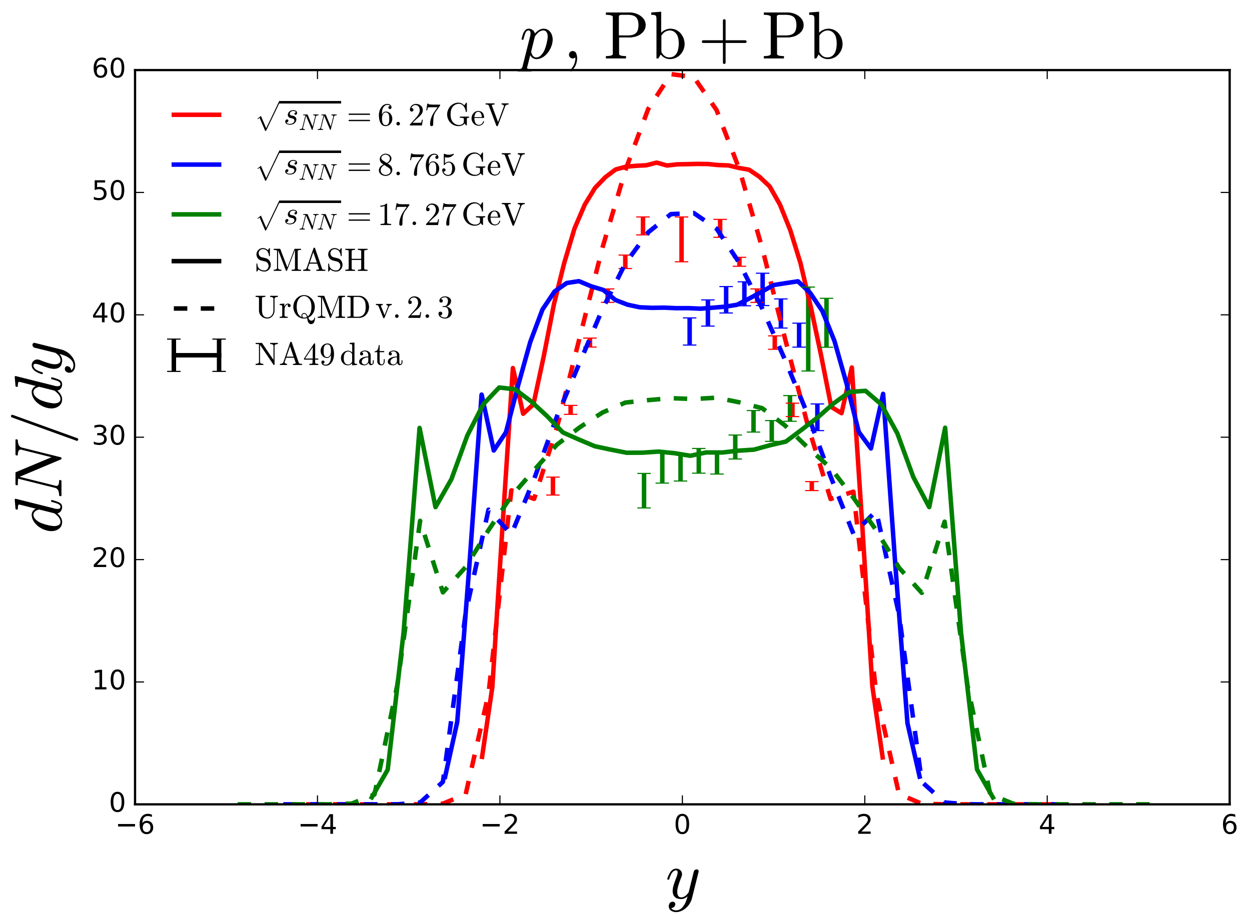
Results in pp

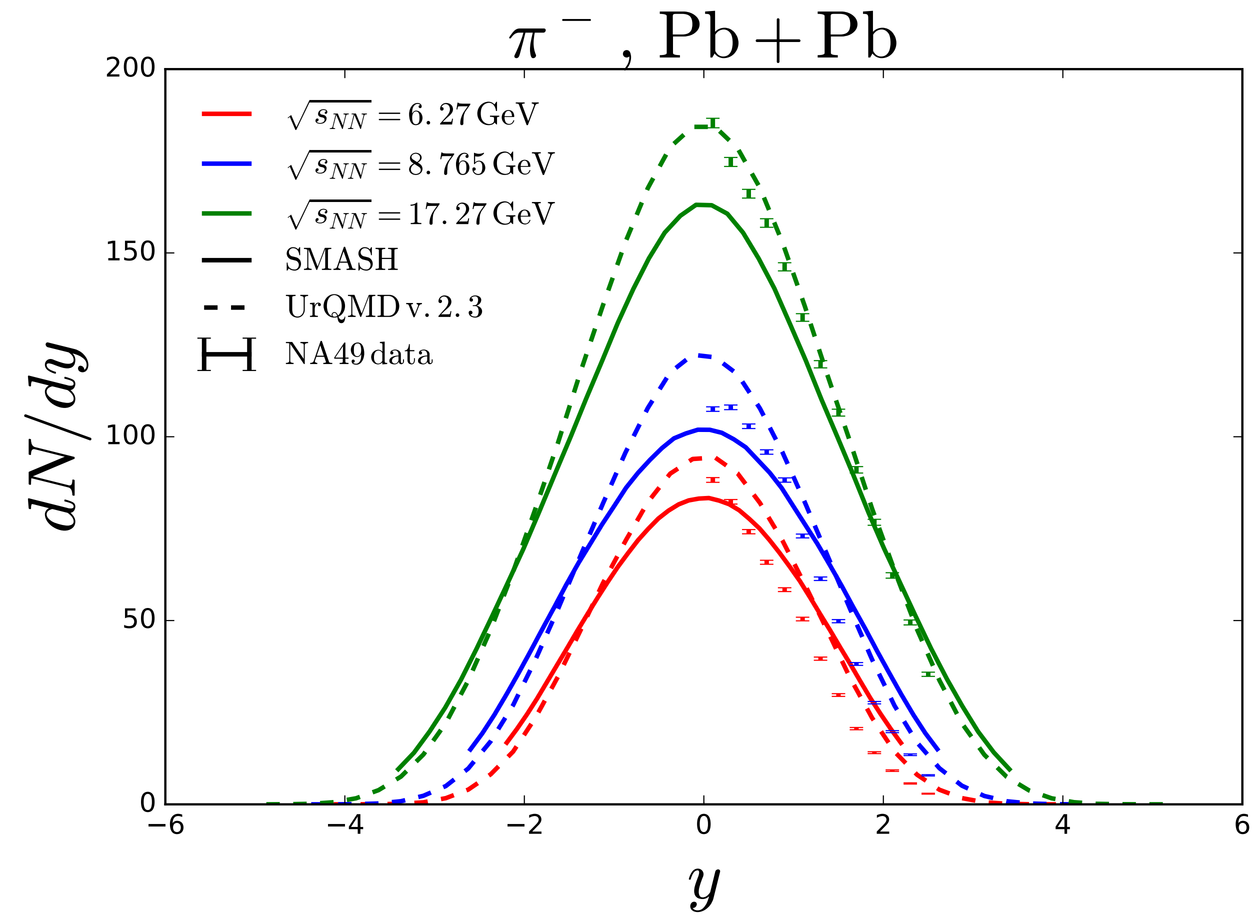


- Fragmentation function, strangeness suppression and diquark suppression tuned to reproduce data

Results in AA

- Baryon stopping well reproduced
- At low beam energies, clusters have to be subtracted

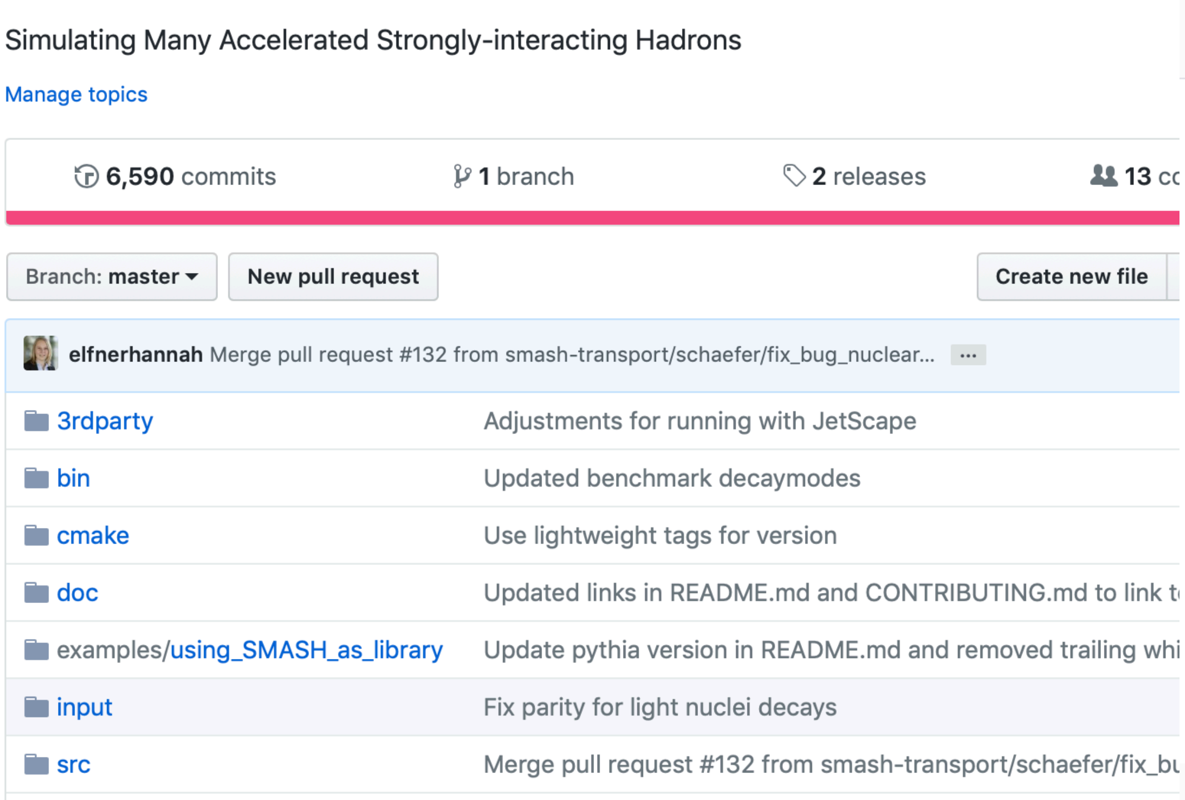


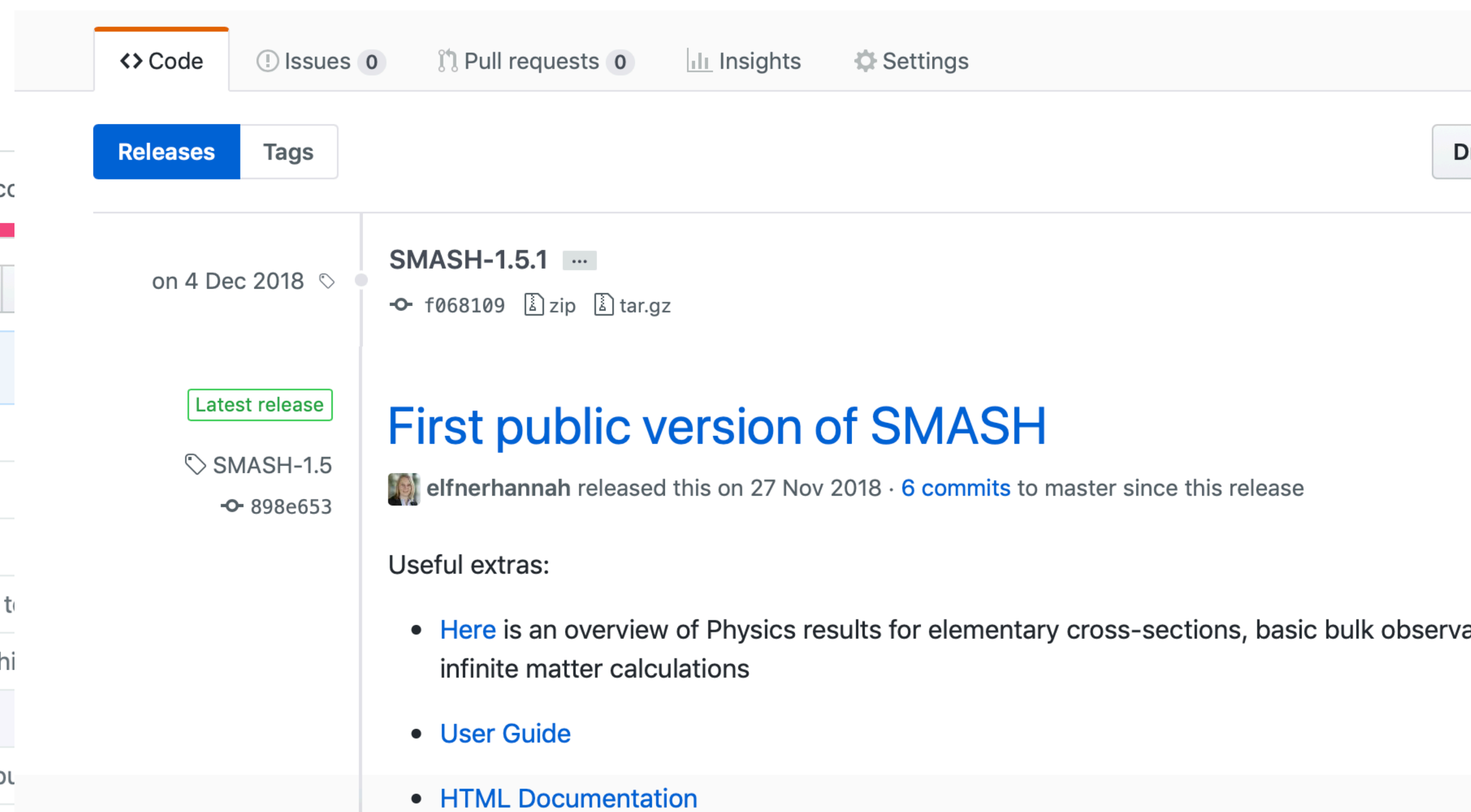


- Shape of pion spectrum agrees with data
- Work in progress: Study influence of formation times and cross-section scaling factors

How to SMASH?

- Visit the webpage to find publications
  https://smash-transport.github.io
- Download the code at
  https://github.com/smash-transport/smash
- Checkout the Analysis Suite at
  http://theory.gsi.de/~smash/analysis_suite/SMASH-1.5/
- Find user guide and documentation at
  https://github.com/smash-transport/smash/releases





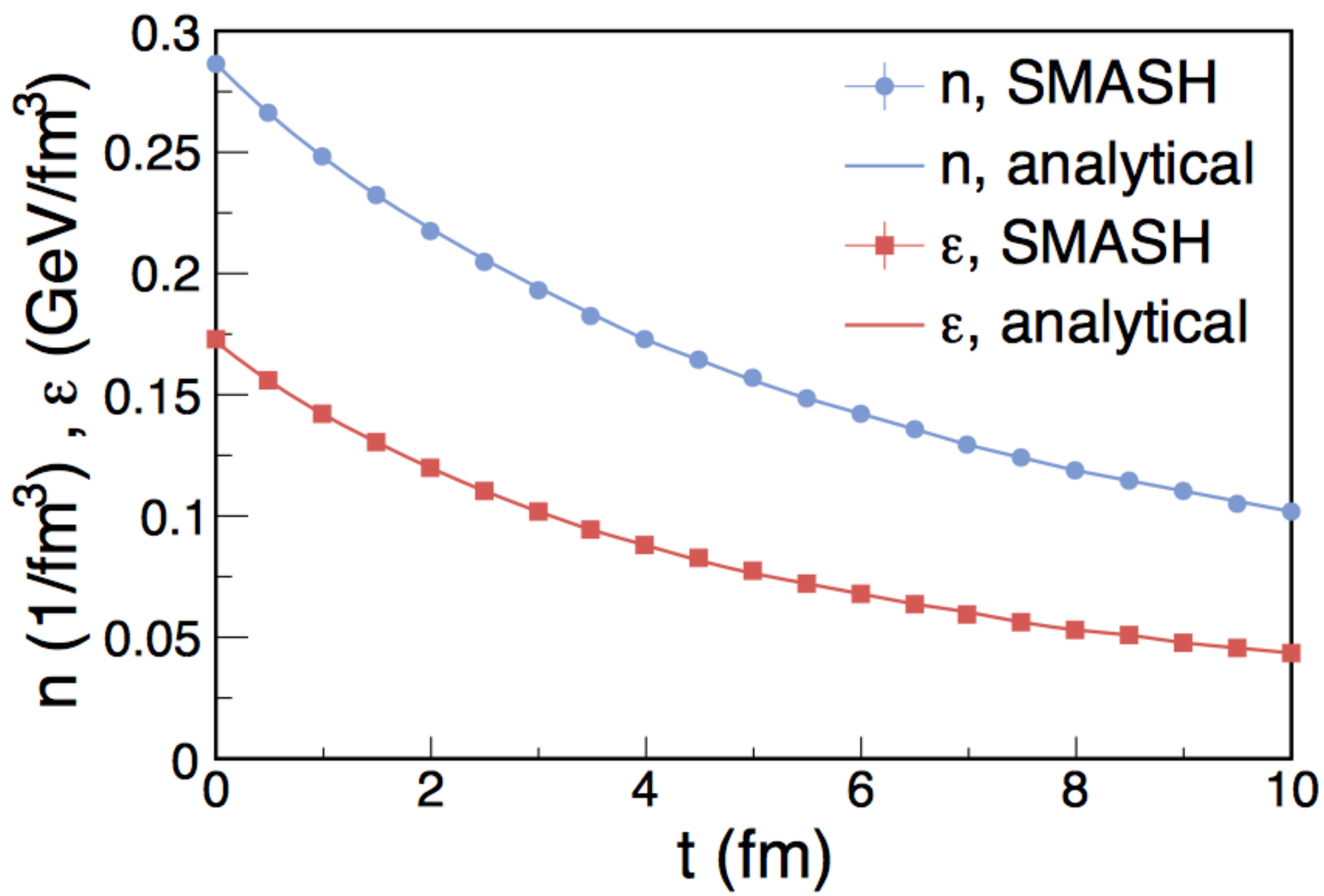
Summary and Outlook

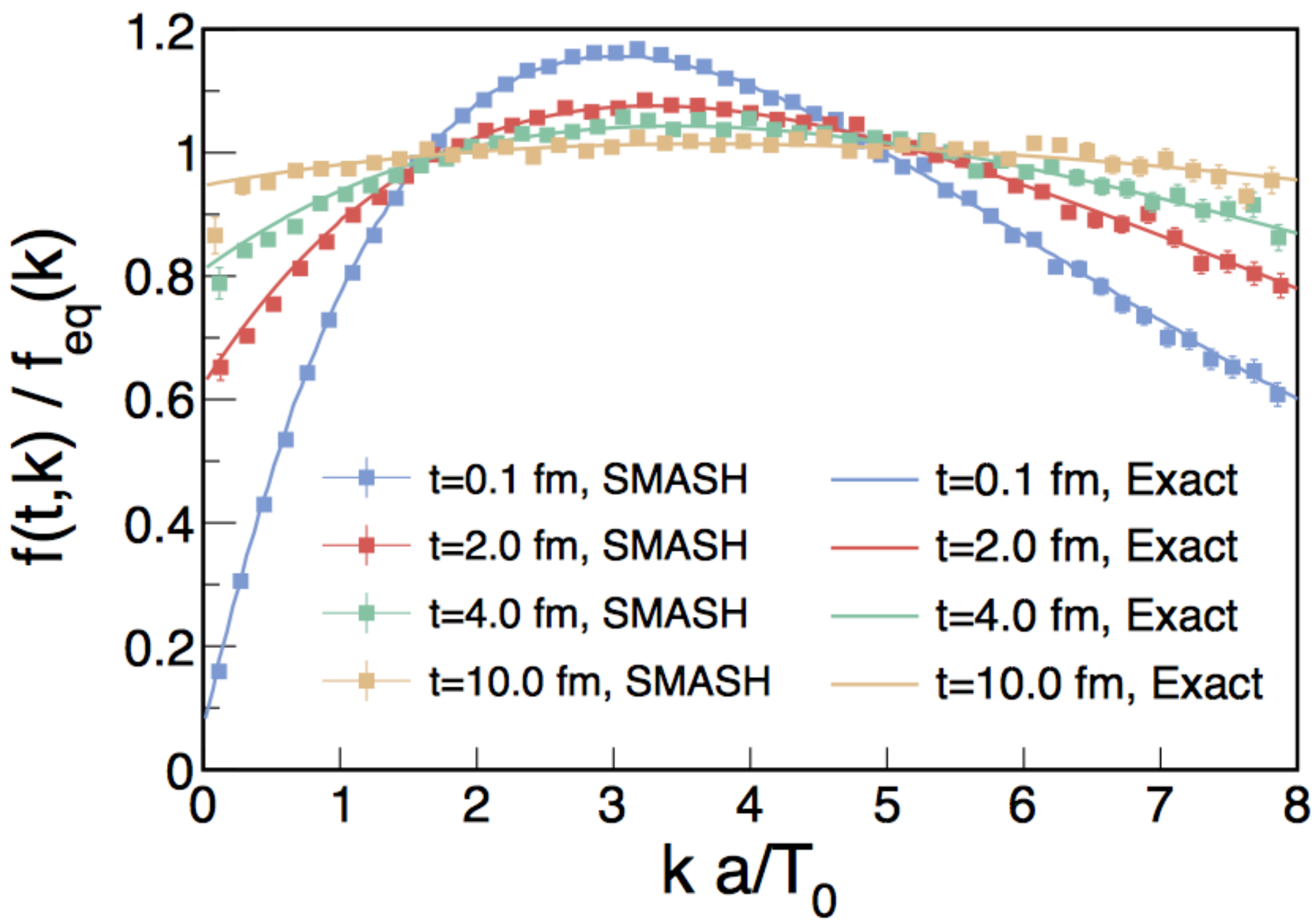
- Realistic dynamical approaches are the necessary link between theory expectations and experimental measurements
- Many observables simultaneously within one approach
  - Elliptic and triangular flow more sensitive to viscosity than equation of state
  - Directed flow still requires quantitative understanding
  - HBT radii are sensitive to the phase transition
  - Fluctuation observables are very complex
- SMASH is available as a new hadronic transport approach
  - GSI-SIS 18 data nicely described
  - Download on Github https://smash-transport.github.io
  - Work in progress: Understanding stopping with strings

Backup

Analytic Solution

- Comparison to analytic solution of Boltzmann equation within expanding metric





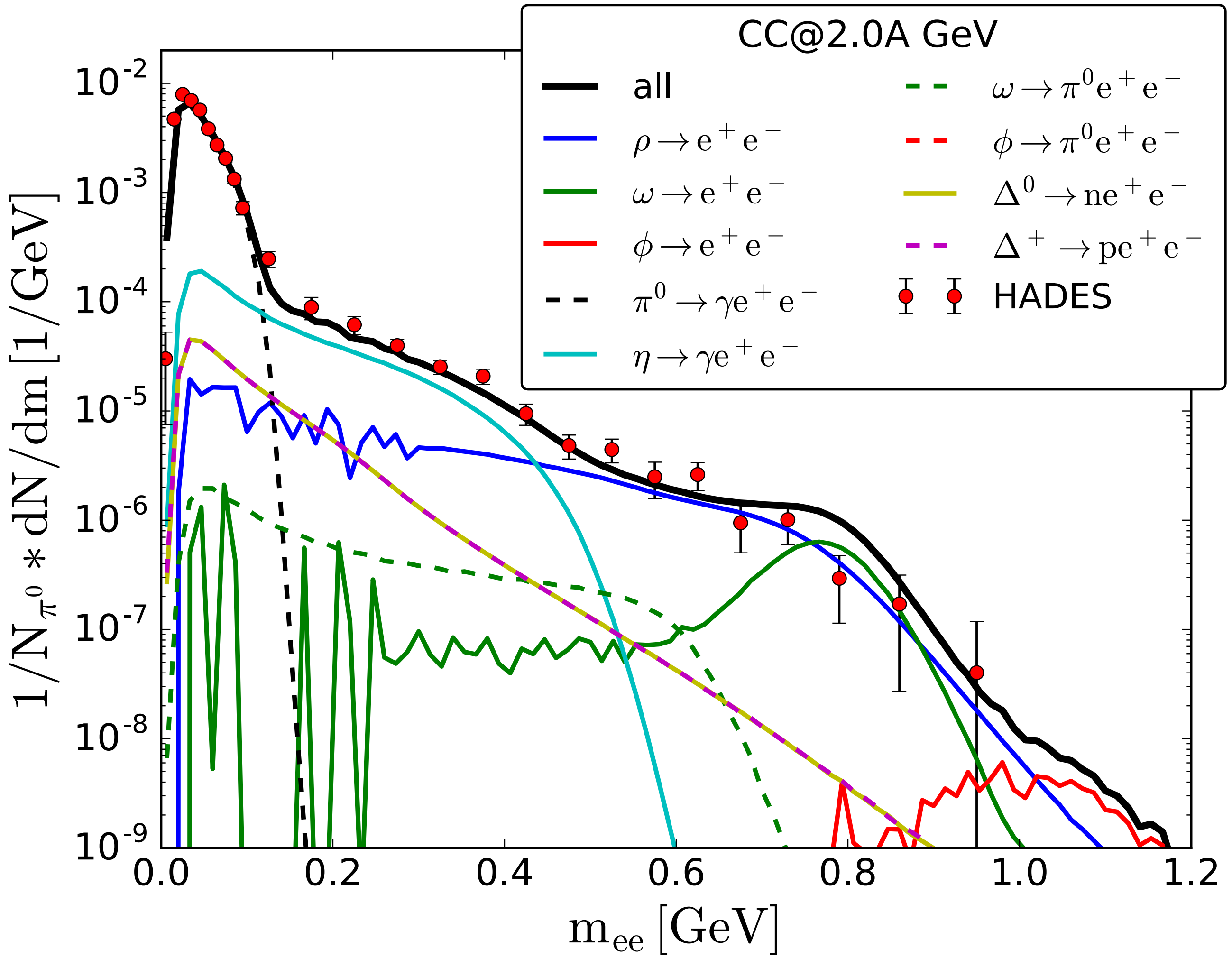
- Perfect agreement proves correct numerical implementation of collision algorithm

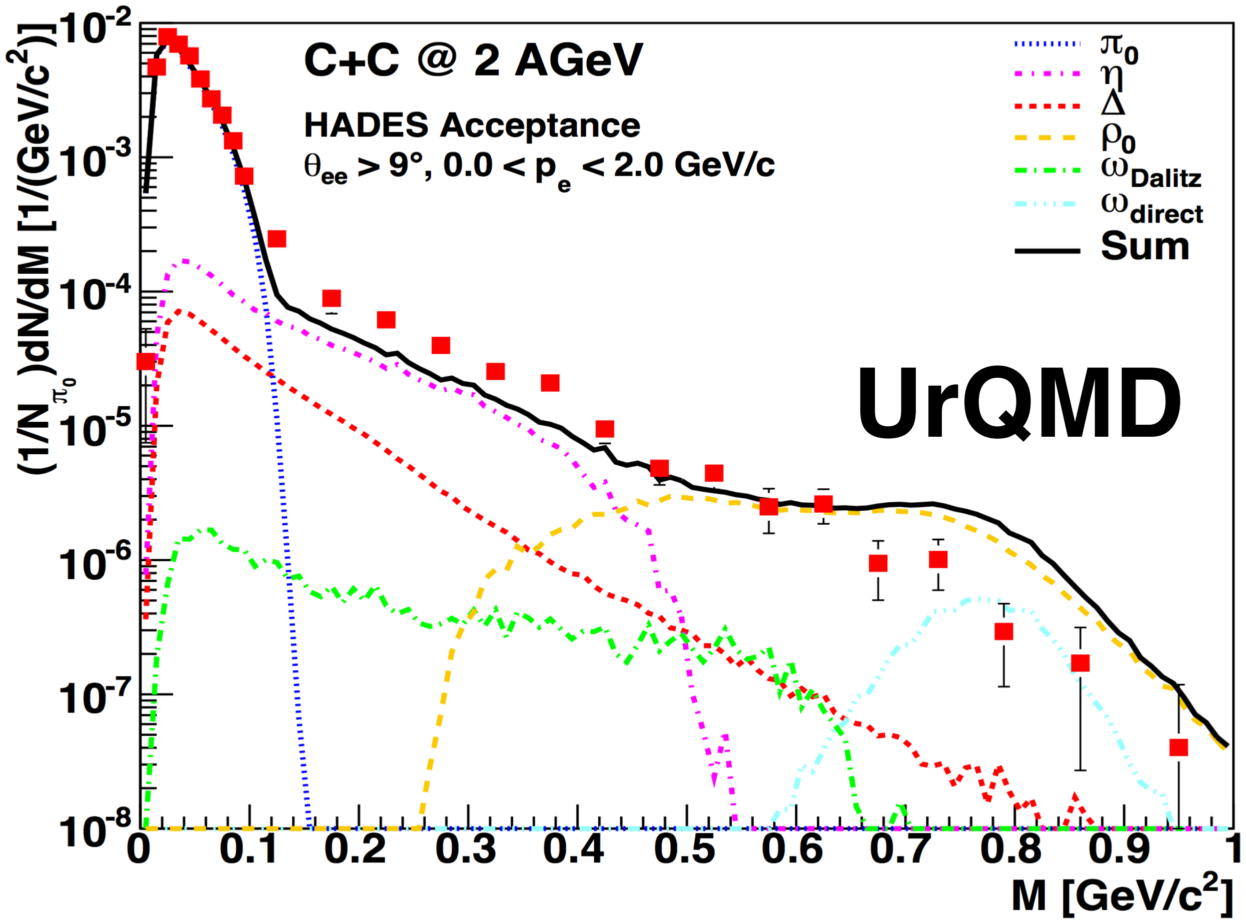
D. Bazow et al., PRL 116 (2016) and PRD 94 (2016)

J. Tindall et al., PLB 770 (2017)

Dilepton Production

HADES, PRL 98 (2007)





J. Staudenmaier et al, PRC 98 (2018)

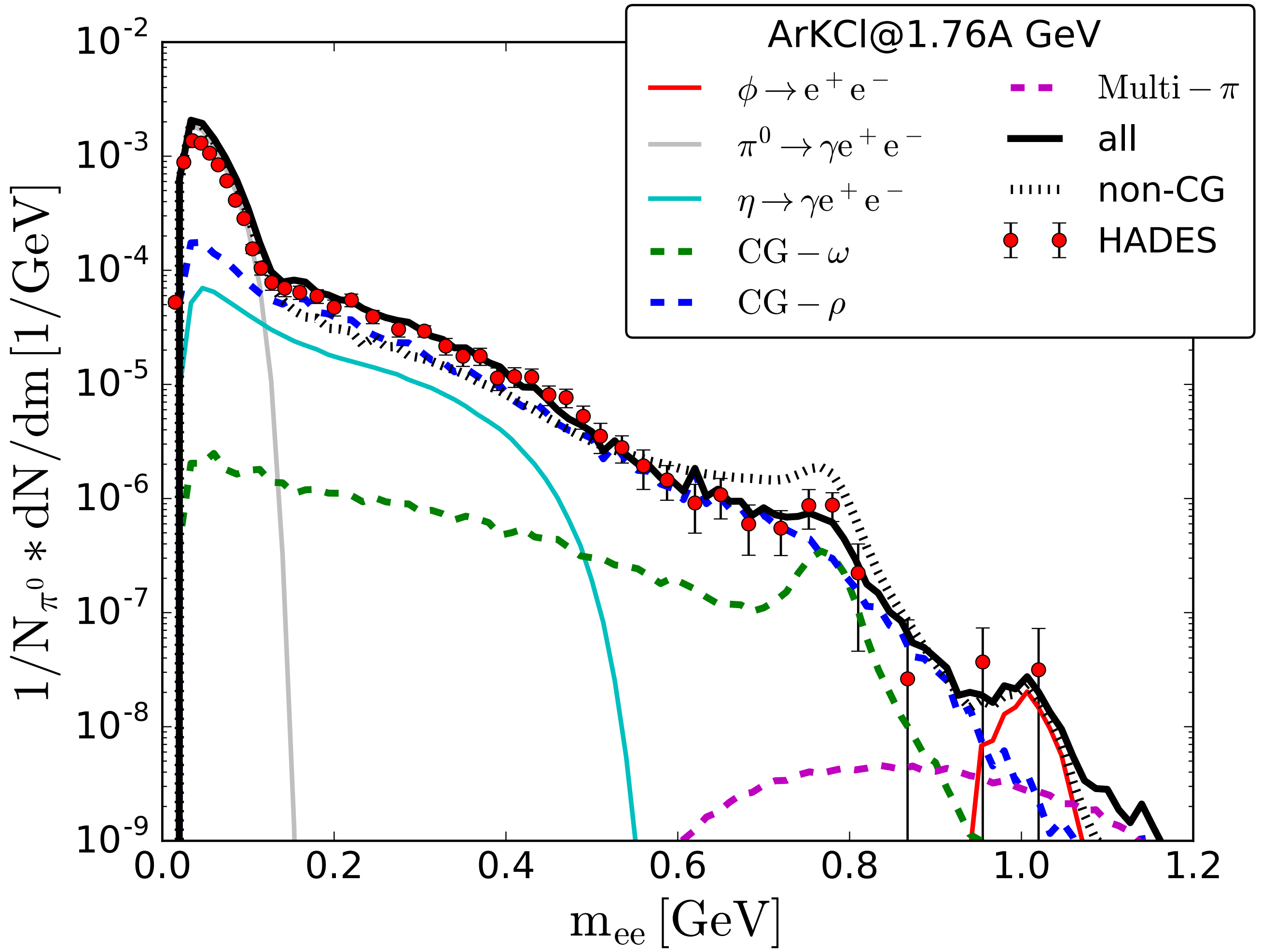
S. Endres et al., J.Phys.Conf.Ser. 426 (2013)

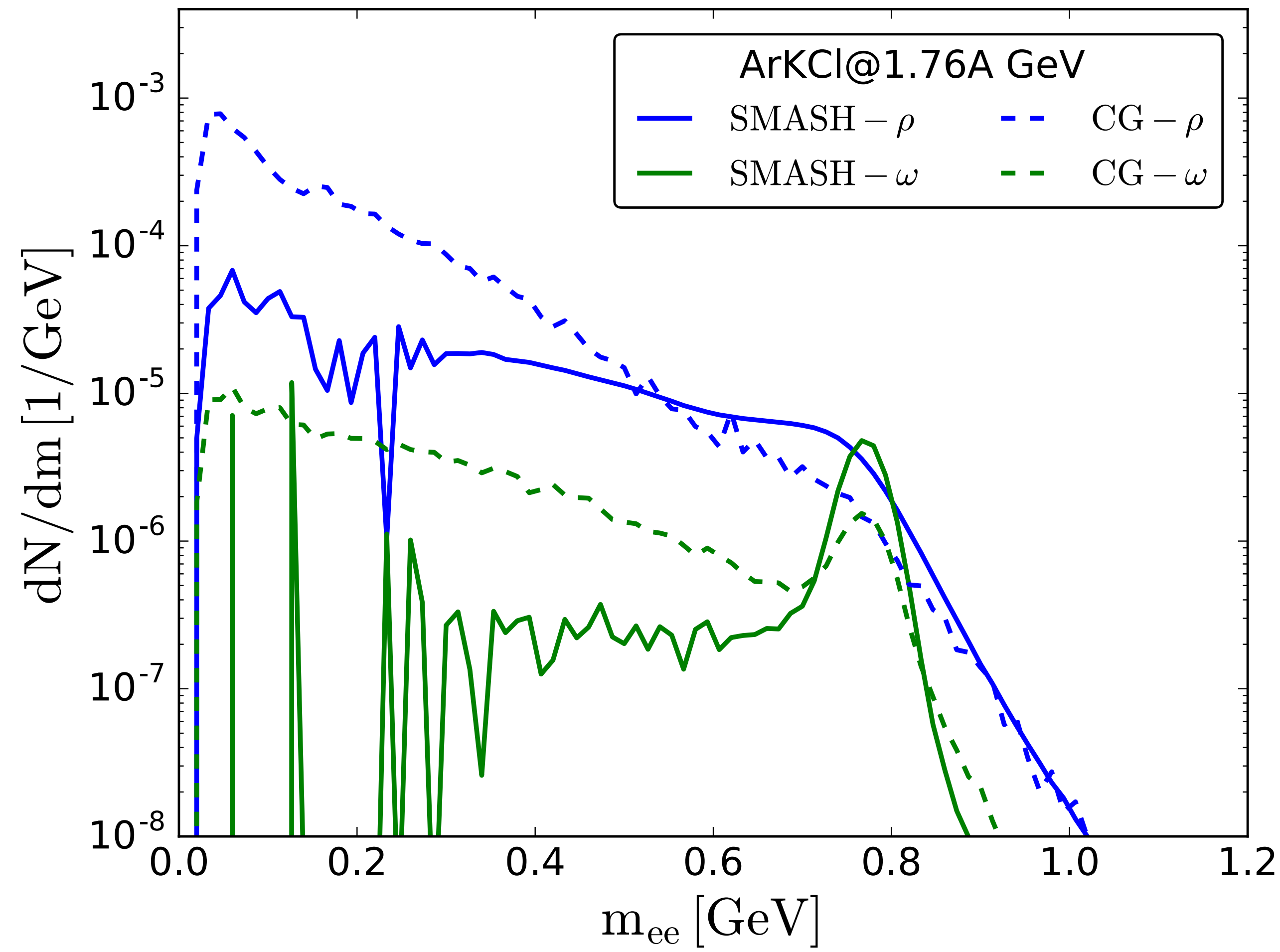
- SMASH and UrQMD compare very similar to data
- Different vector meson thresholds at low masses
- Adjusted branching ratios of N* and Δ resonances for ρ peak

Medium Modifications

- Dynamical collisional broadening is included in default SMASH calculation

J. Staudenmaier et al., PRC98 (2018)





- Coarse-grained transport evolution allows for full medium-modified spectral function

S. Endres et al., PRC 92, 2015
R. Rapp et al, EPJA 6, 1999, PRC 63, 2001

- First time: Comparison of both approaches based on the same medium evolution

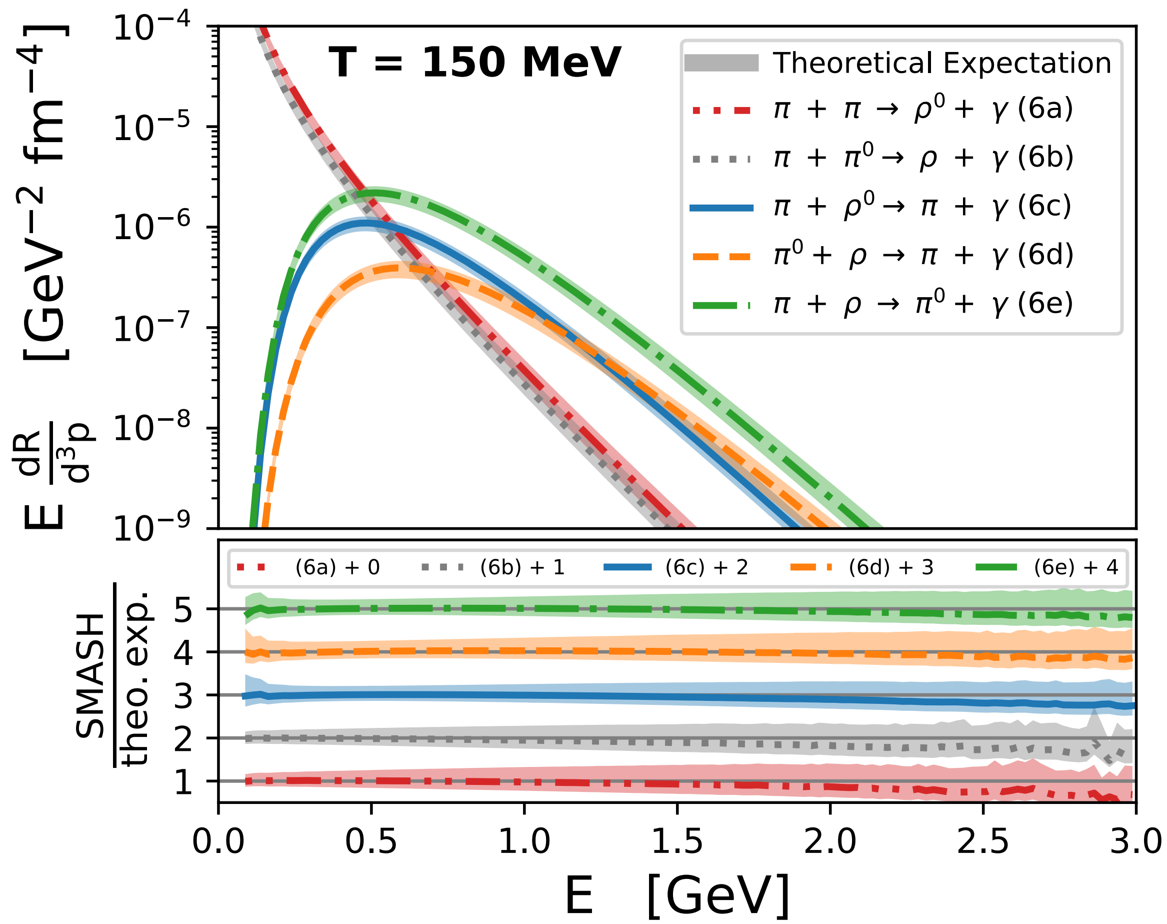
J. Staudenmaier et al, PRC 98 (2018)

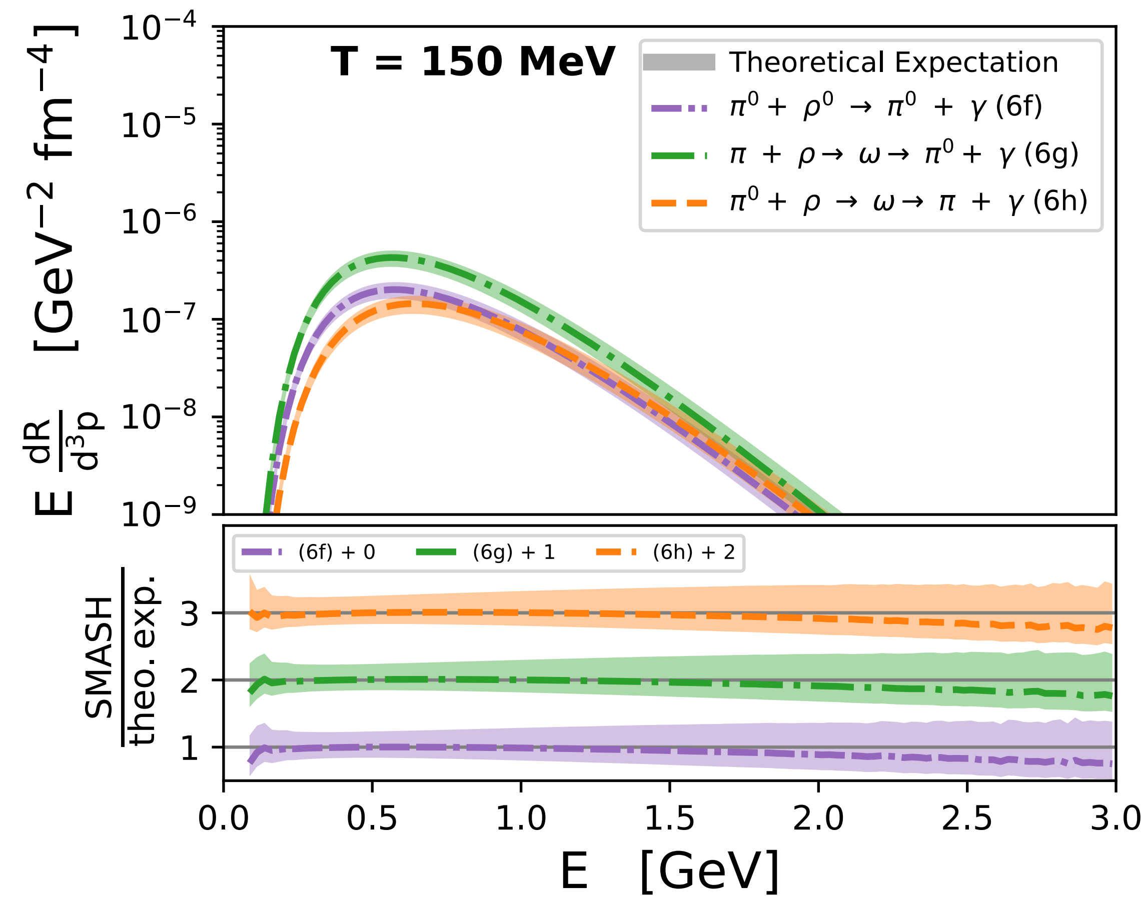
Photons

- Perturbative photon production in hadronic scatterings of pions and ρ mesons

Turbide et al.: Int.J.Mod.Phys. A19 (2004)

- Cross-sections calculated within effective field theory





- Rates in thermal box nicely reproduced
- Next: Photons from late non-equilibrium stage at RHIC/LHC

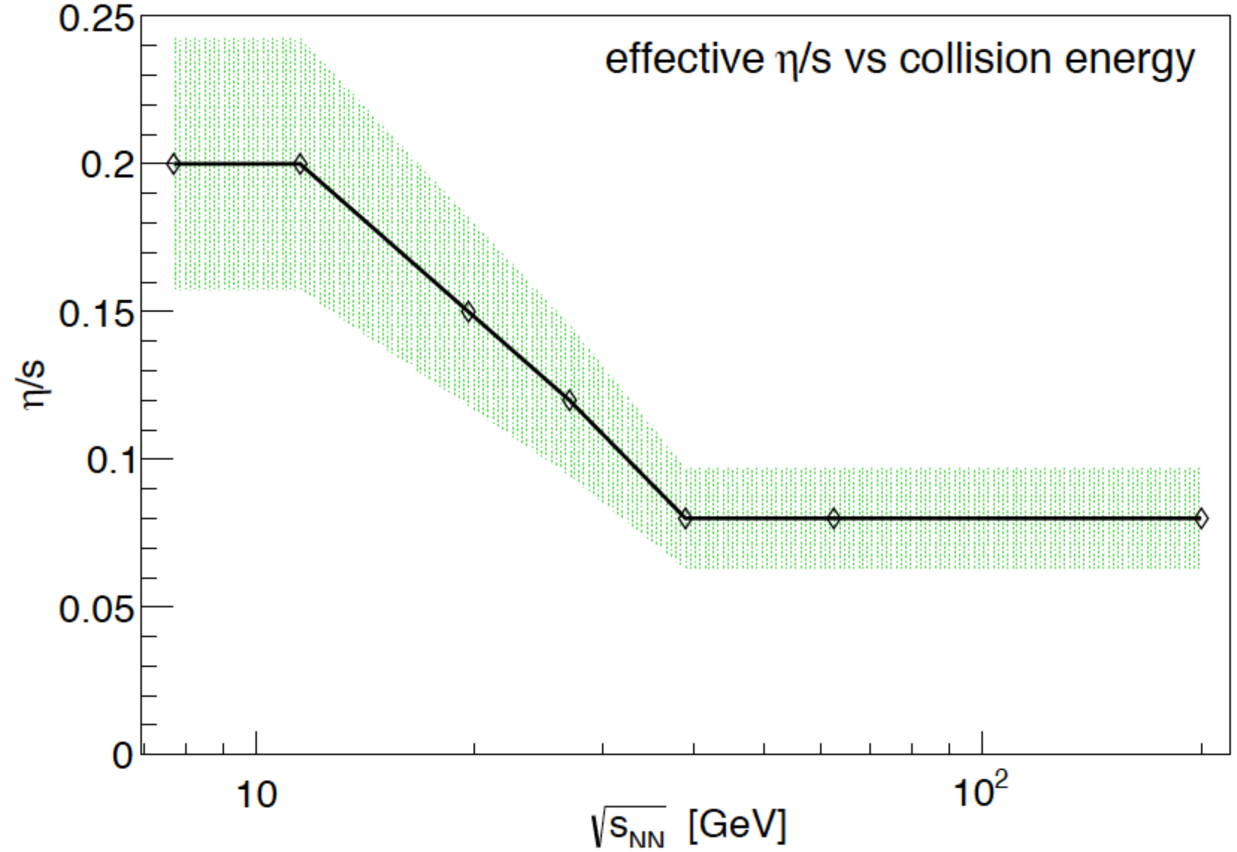
A. Schäfer et al, arXiv:1902.07564

η/s Energy Dependence

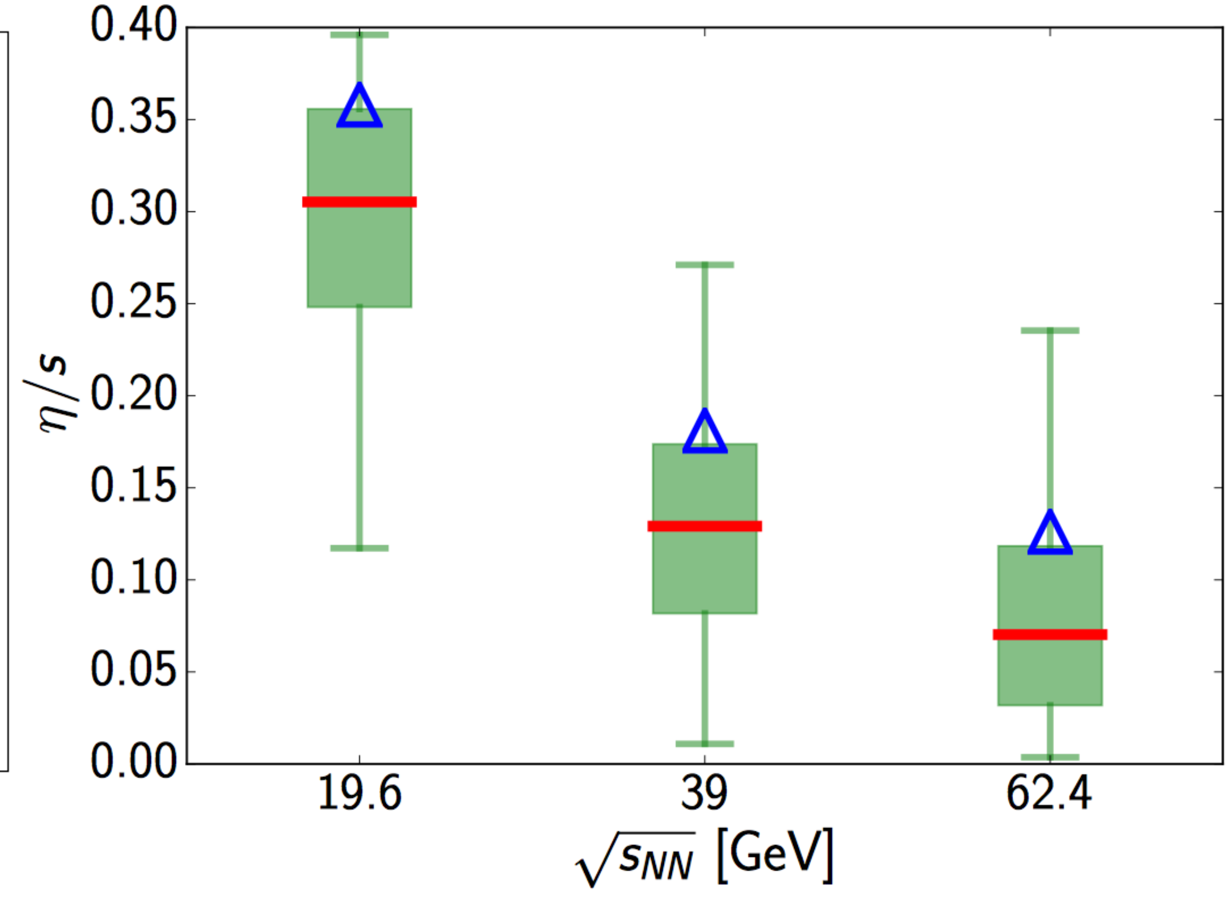
- Viscous UrQMD hybrid fitted to beam energy scan and SPS data allows to extract **effective** shear viscosity of the hydrodynamic stage

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

Analysis „by eye“



Bayesian framework



Auvinen et al., PRC 97 (2018)

- More insights on transport coefficients especially at **finite μ_B** are needed