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Coarse-grained transport studies about local equilibrium and negative Cooper-Frye

Hannah Petersen
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FIAS Frankfurt Institute for Advanced Studies

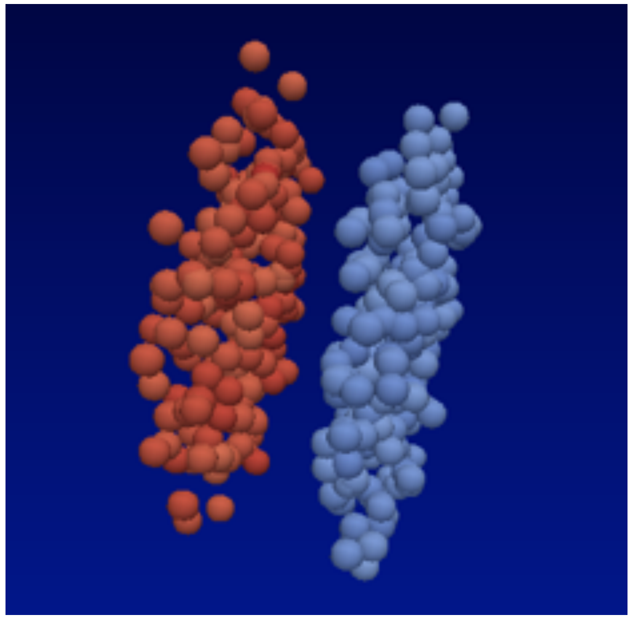
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Motivation

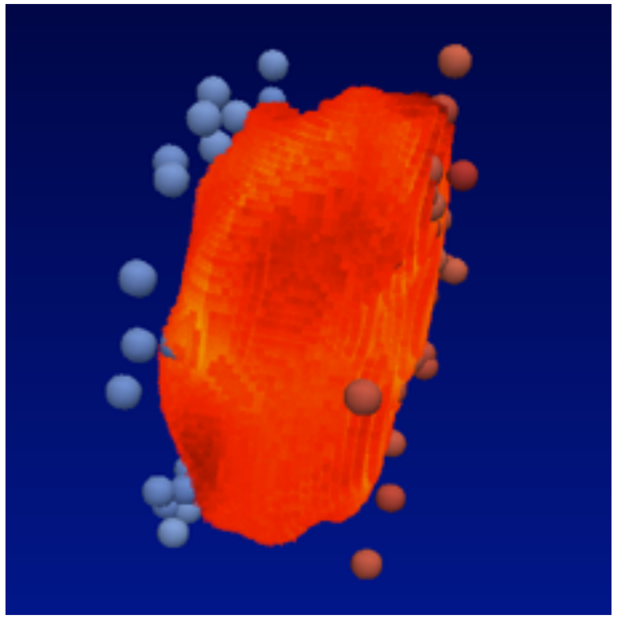
- Hybrid transport+hydrodynamics approaches are successfully applied for the description of the dynamics of heavy ion collisions
- There are 2 ad hoc transitions
  - Initial assumption on local equilibration
    - Might not be fulfilled for lower beam energies, smaller systems, larger centralities
  - Final Cooper-Frye sampling/Particlization
    - Negative contributions: How large?
    - Are hydro and transport equivalent?
- In this talk: Investigation of these transitions in coarse-grained transport approach

Evolution of Heavy Ion Reactions

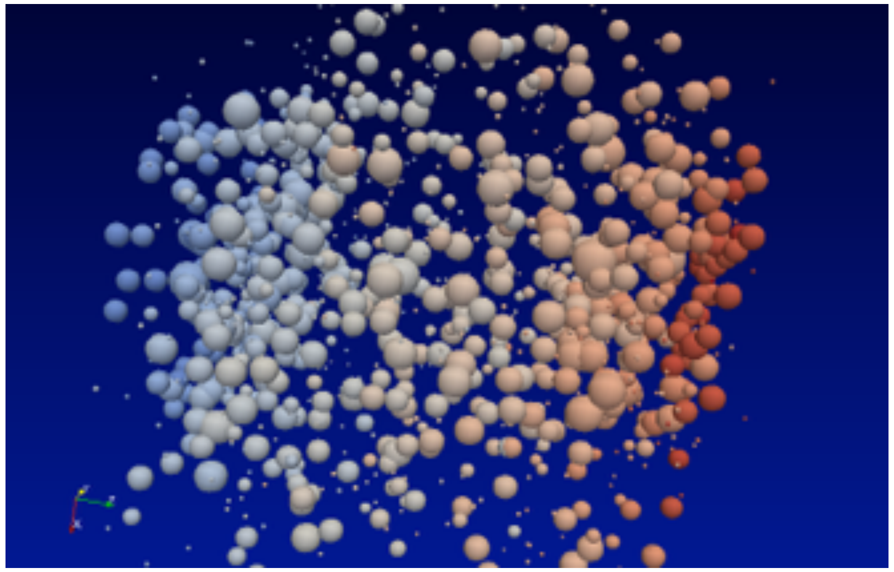
Nuclei at 99 % speed of light



Quark gluon plasma



Observable fragments in the detector



<1 fm/c

1-10 fm/c

10-30 fm/c

- Initial and final state require non-equilibrium treatment
- Nearly ideal hydrodynamics provides framework for the hot and dense stage of the evolution including a phase transition

Hybrid models achieve realistic description

Hybrid approaches

Transport

Microscopic description of the whole phase-space distribution

Non-equilibrium evolution based on the Boltzmann equation

$$\left(p^{\mu}\partial_{\mu}\right)f = I_{coll}$$

Partonic or hadronic degrees of freedom

Cross-sections are calculable using different techniques

Phase transition?

Hydrodynamics

Macroscopic description

Local equilibrium is assumed

$$\partial_{\mu} T^{\mu\nu} = 0 \quad \partial_{\mu}\left(n u^{\mu}\right) = 0$$

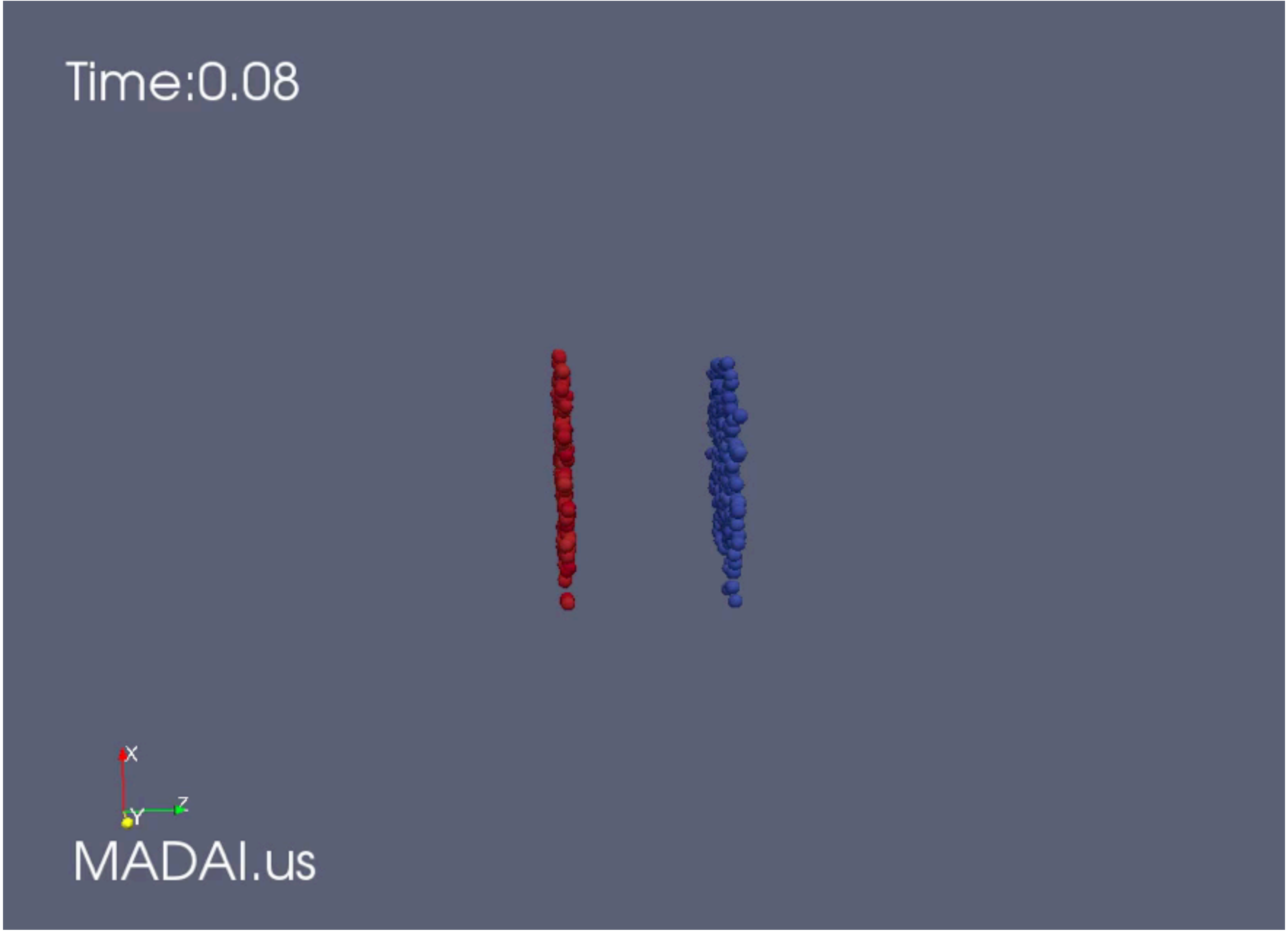
Propagation according to conservation laws

Equation of state is an explicit input

Boundary conditions: Breakdown of equilibrium assumptions?

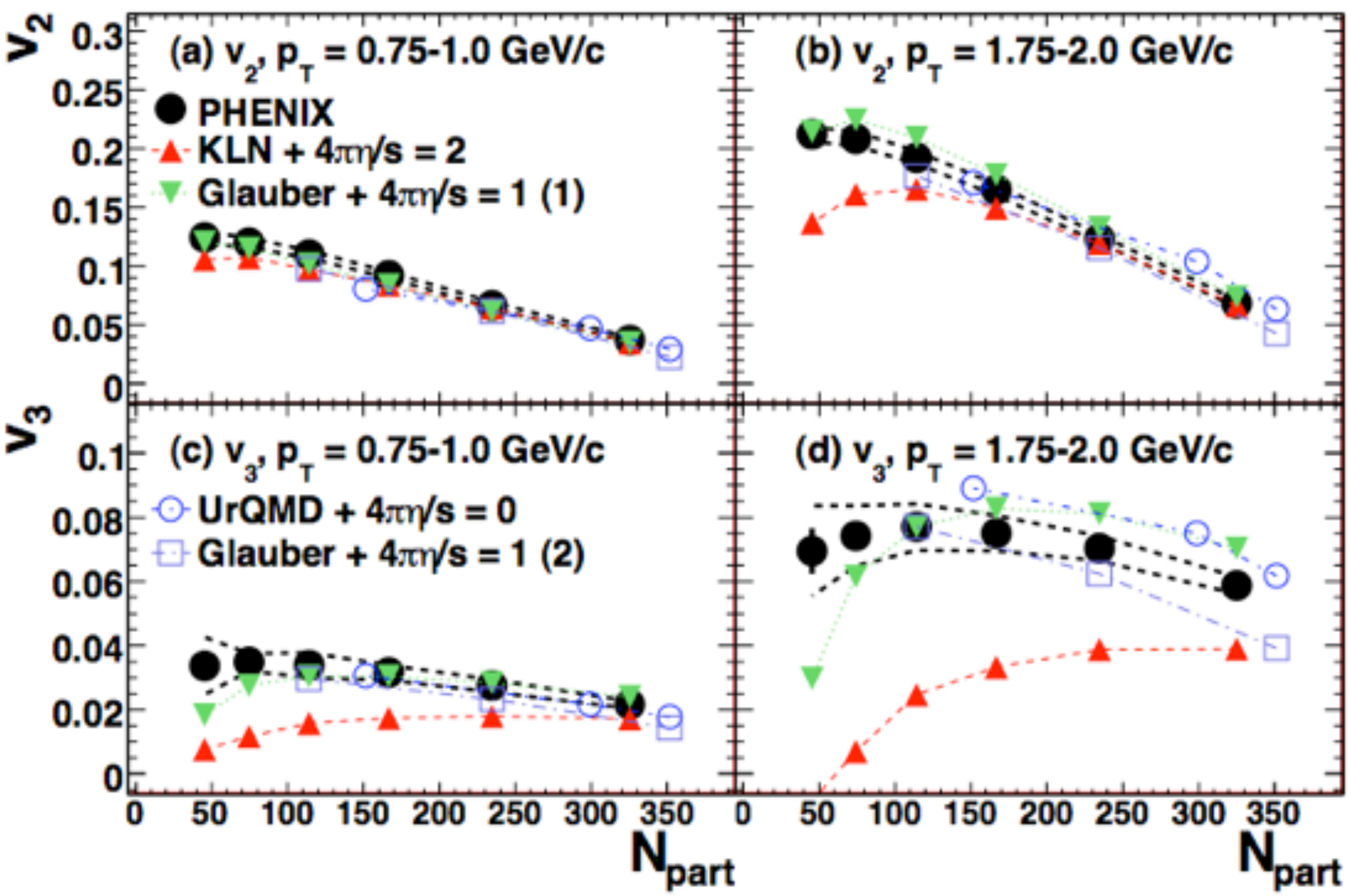
- Combine the advantages of both approaches
- Successful description from initial to final state

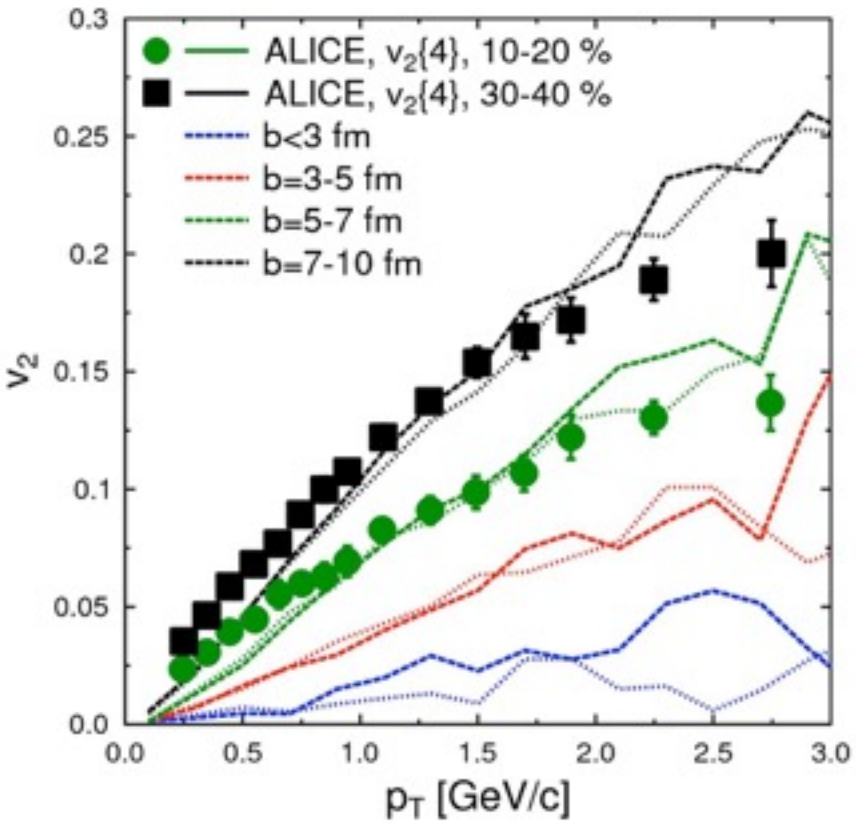
One Event at RHIC Energies



Comparison to Experimental Data

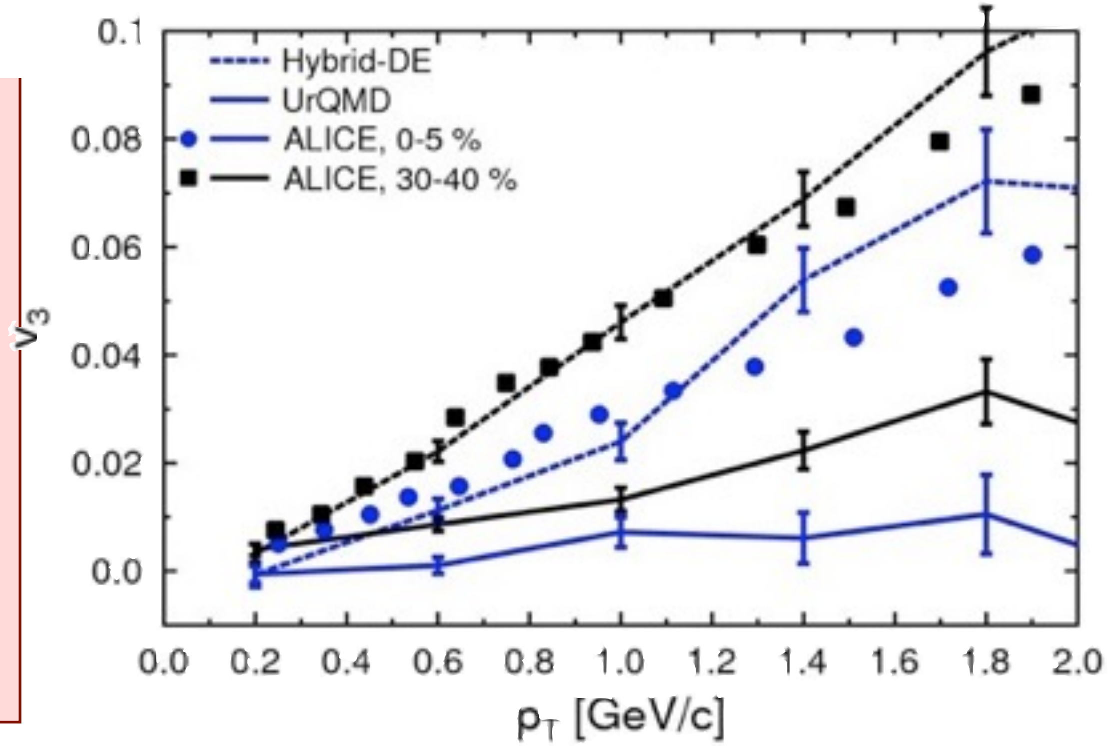
PHENIX collaboration, Phys.Rev.Lett. 107 (2011) 252301





H.P., Phys.Rev. C84 (2011) 034912

- Fluctuations from nucleon positions and energy deposition in binary collisions included
- Without tuning anything v_3 at RHIC and flow at LHC in agreement with experimental data



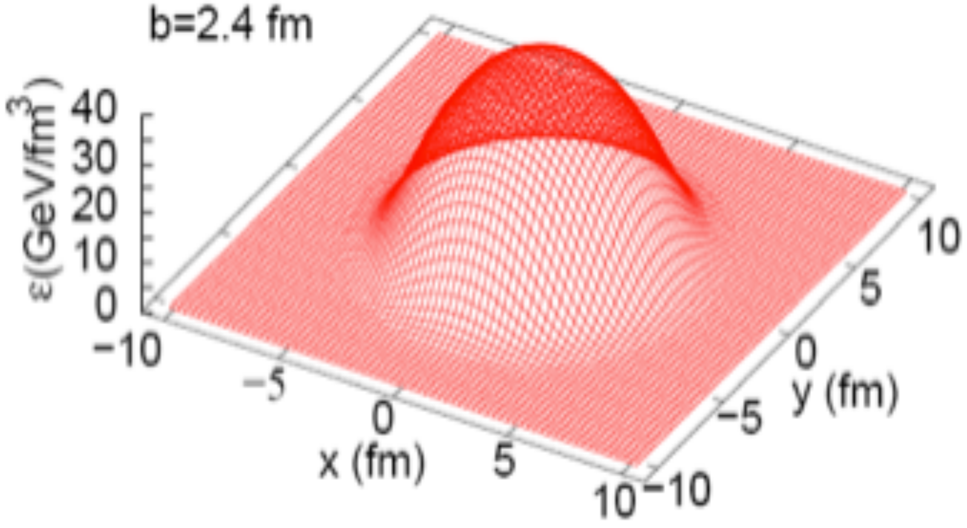
Initial State Transition

based on work with D. Oliinychenko,
in preparation

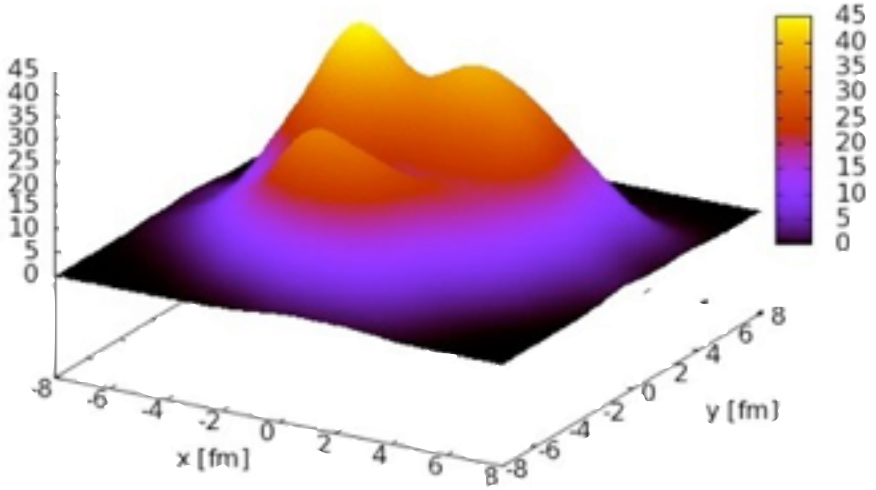
Fluctuating IC from Transport Approaches

- Density profiles are not smooth, but there are **local peaks** in transverse and longitudinal direction
- **Impact parameter** fluctuations within one specific centrality class, multiplicity fluctuations and differences in initial geometry
- Event plane **rotation** with respect to reaction plane in the laboratory

→ All these effects are **averaged out** if assuming a smooth symmetric initial density profile



C. Nonaka and S.A. Bass, PRC 75, 014902, 2007



J.Steinheimer et al., PRC 77,034901,2008

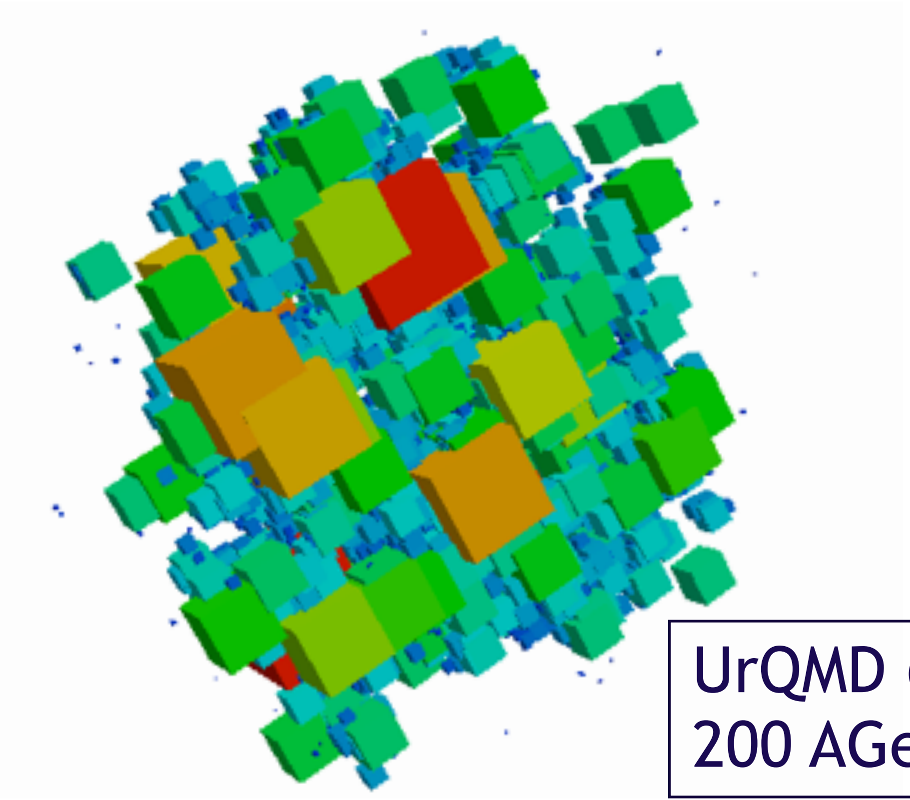
Included in dynamical models of the initial state (e.g. a parton cascade, NEXUS/EPOS, UrQMD) or in Glauber or CGC Monte Carlo approaches

Initial Conditions from Dynamical Approaches

- The **initial $T^{\mu\nu}$** for ideal hydrodynamics has to be given via:

$$\boxed{\epsilon(x,y,z),\ p(x,y,z)\ \text{and}\ n(x,y,z)}$$

- **Energy deposition** model needs to describe final dE_T/dy in p-p and A-A correctly
- Granularity is influenced by
  - Shape of the incoming nuclei
  - Distribution of binary collisions
  - Interaction mechanism
  - Degree of thermalization


UrQMD @
200 AGeV

- Differences in **shape** and **fluctuations** need to be quantified
  - Challenge: How is local equilibrium reached so fast?

What is Usually Done?

- To calculate the energy-momentum tensor and four-current from particles a **smearing kernel** (Gaussian) is used:

$$T^{\mu\nu}_{init}(r) = \sum_i \frac{p_i^\mu p_i^\nu}{p_i^0} K(\boldsymbol{r} - \boldsymbol{r_i}, \boldsymbol{p})$$

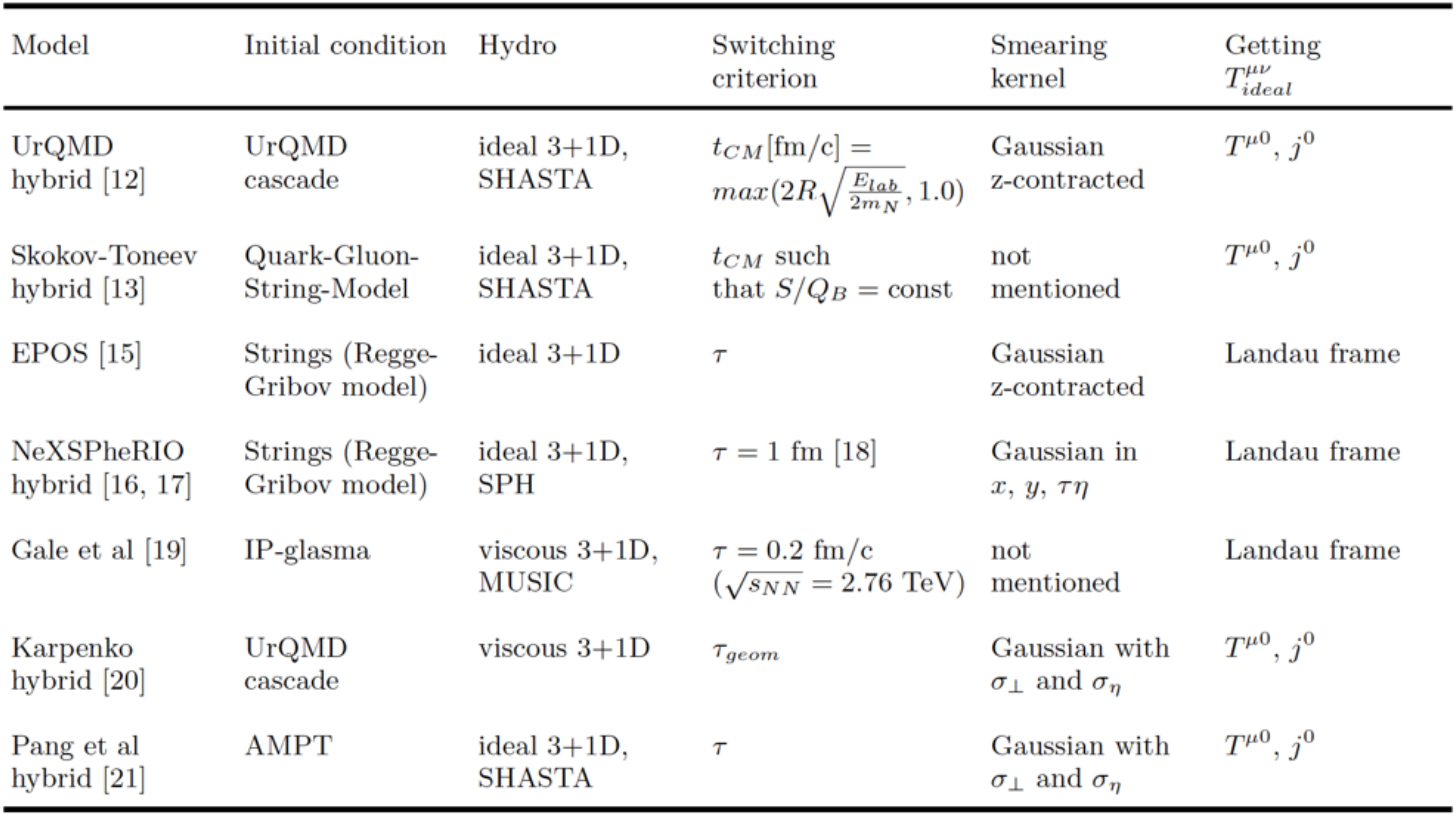
$$j^{\mu}_{init}(r) = \sum_i \frac{p_i^\mu}{p_i^0} K(\boldsymbol{r} - \boldsymbol{r_i}, \boldsymbol{p})$$

- **Assuming** that the resulting tensor has the form for relativistic ideal fluid dynamics, the following equations are solved iteratively

$$\begin{cases} T^{00} = (\epsilon + p)\gamma^2 - p \\ T^{0i} = (\epsilon + p)\gamma^2 \boldsymbol{v} \\ j_B^0 = n\gamma \\ p = p_{EoS}(n, \epsilon) \end{cases}$$

- The other option: Solve the eigenvalue problem and decompose the tensor in the **Landau frame**

Different Approaches



Model	Initial condition	Hydro	Switching criterion	Smearing kernel	Getting $T^{\mu\nu}_{ideal}$
UrQMD hybrid [12]	UrQMD cascade	ideal 3+1D, SHASTA	t_{CM}[fm/c] $= max(2R\sqrt{\frac{E_{lab}}{2m_N}}, 1.0)$	Gaussian z-contracted	$T^{\mu 0}$, j^0
Skokov-Toneev hybrid [13]	Quark-Gluon-String-Model	ideal 3+1D, SHASTA	t_{CM} such that $S/Q_B =$ const	not mentioned	$T^{\mu 0}$, j^0
EPOS [15]	Strings (Regge-Gribov model)	ideal 3+1D	τ	Gaussian z-contracted	Landau frame
NeXSPheRIO hybrid [16, 17]	Strings (Regge-Gribov model)	ideal 3+1D, SPH	$\tau = 1$ fm [18]	Gaussian in x, y, $\tau\eta$	Landau frame
Gale et al [19]	IP-glasma	viscous 3+1D, MUSIC	$\tau = 0.2$ fm/c ($\sqrt{s_{NN}} = 2.76$ TeV)	not mentioned	Landau frame
Karpenko hybrid [20]	UrQMD cascade	viscous 3+1D	τ_{geom}	Gaussian with $\sigma_\perp$ and σ_η	$T^{\mu 0}$, j^0
Pang et al hybrid [21]	AMPT	ideal 3+1D, SHASTA	τ	Gaussian with $\sigma_\perp$ and σ_η	$T^{\mu 0}$, j^0

Coarse-Grained UrQMD

1. Several thousands Au+Au collisions at E_{lab} = 5-160 AGeV beam energy and different centralities
2. Calculate $T^{\mu\nu}$ on a space-time grid
3. Transform to the Landau rest frame

- Investigate **locally** two measures of isotropization:
  - Pressure anisotropy:

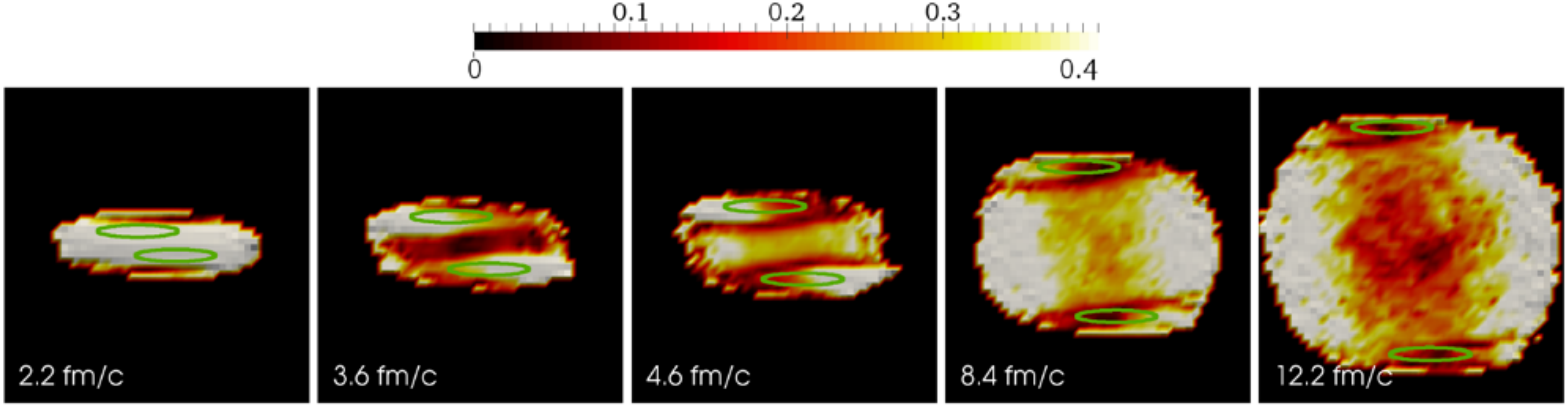
$$X \equiv \frac{|T_L^{11} - T_L^{22}| + |T_L^{22} - T_L^{33}| + |T_L^{33} - T_L^{11}|}{T_L^{11} + T_L^{22} + T_L^{33}} \ll 1$$

  - Off-diagonality:

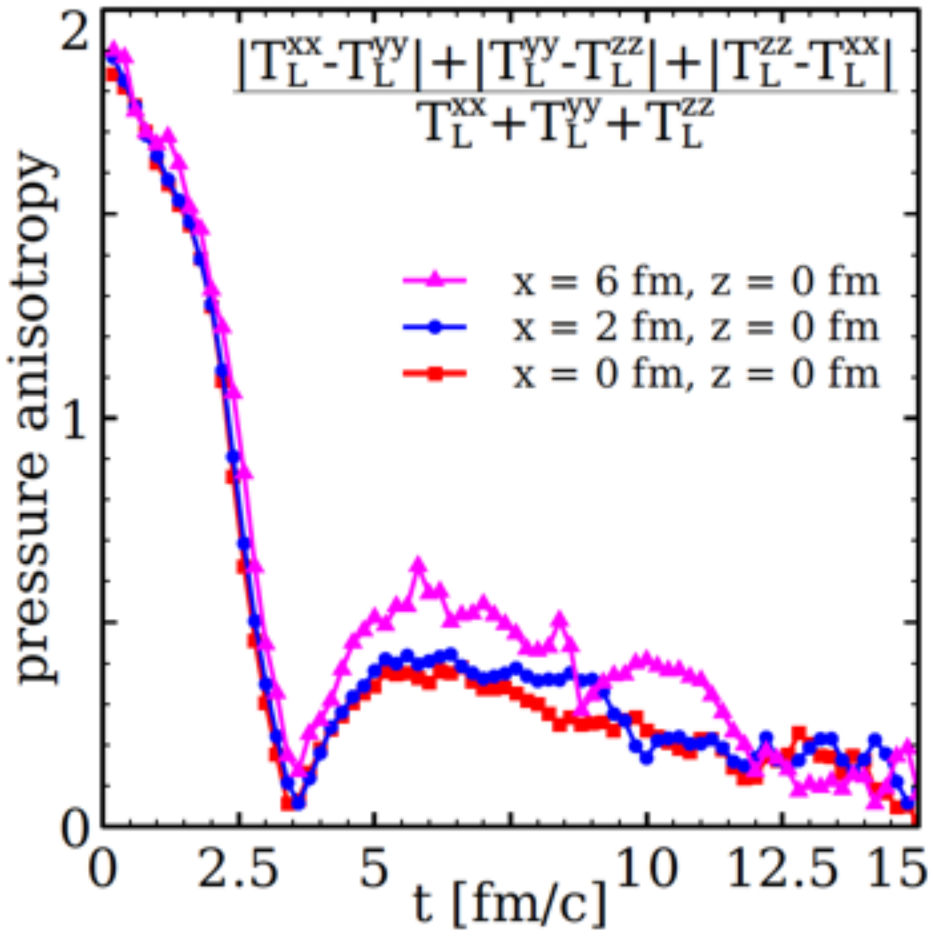
$$Y \equiv \frac{3(|T_L^{12}| + |T_L^{23}| + |T_L^{13}|)}{T_L^{11} + T_L^{22} + T_L^{33}} \ll 1$$

- X,Y ≤ 0.3 → viscous hydrodynamics applicable

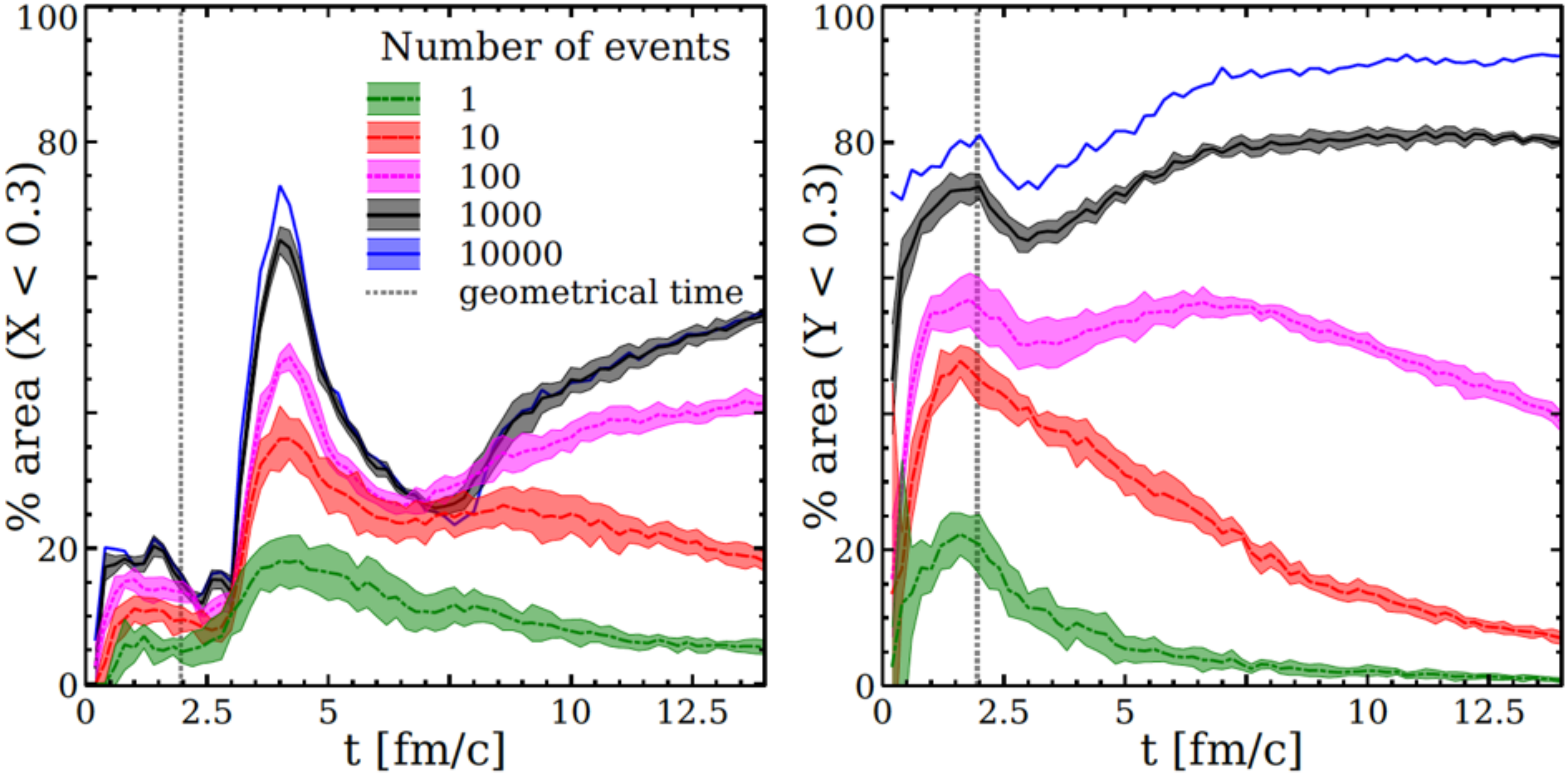
Time Evolution



- E_{lab} = 80A GeV, b=6 fm, pressure anisotropy
- After initial collisions anisotropy develops minimum over a large region in space
- Later stages: Rise due to resonance decays



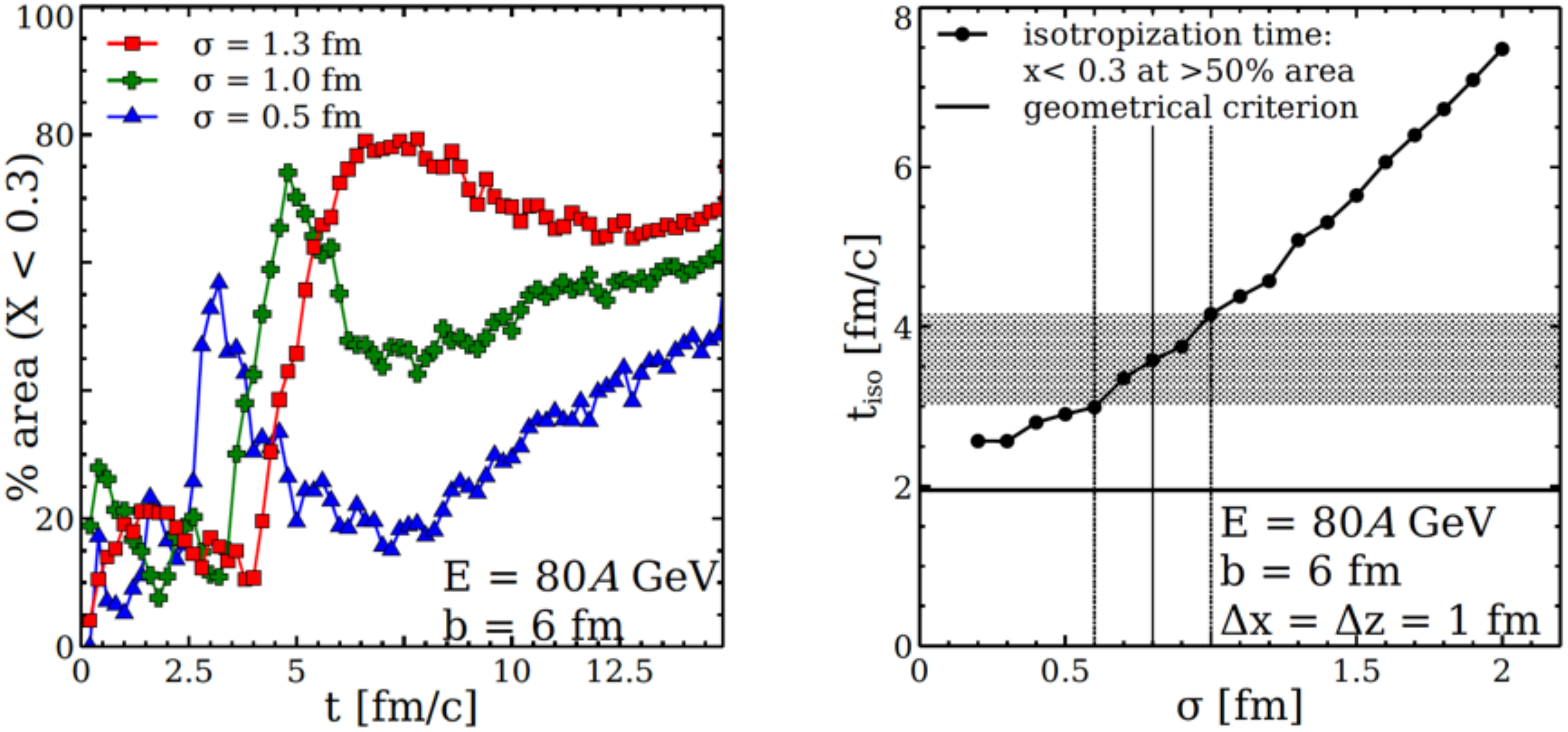
Number of Events



- In single events only small amount of the area is isotropic
- Off-diagonality is small in more than 80 % of area

Dependence on Gaussian Width

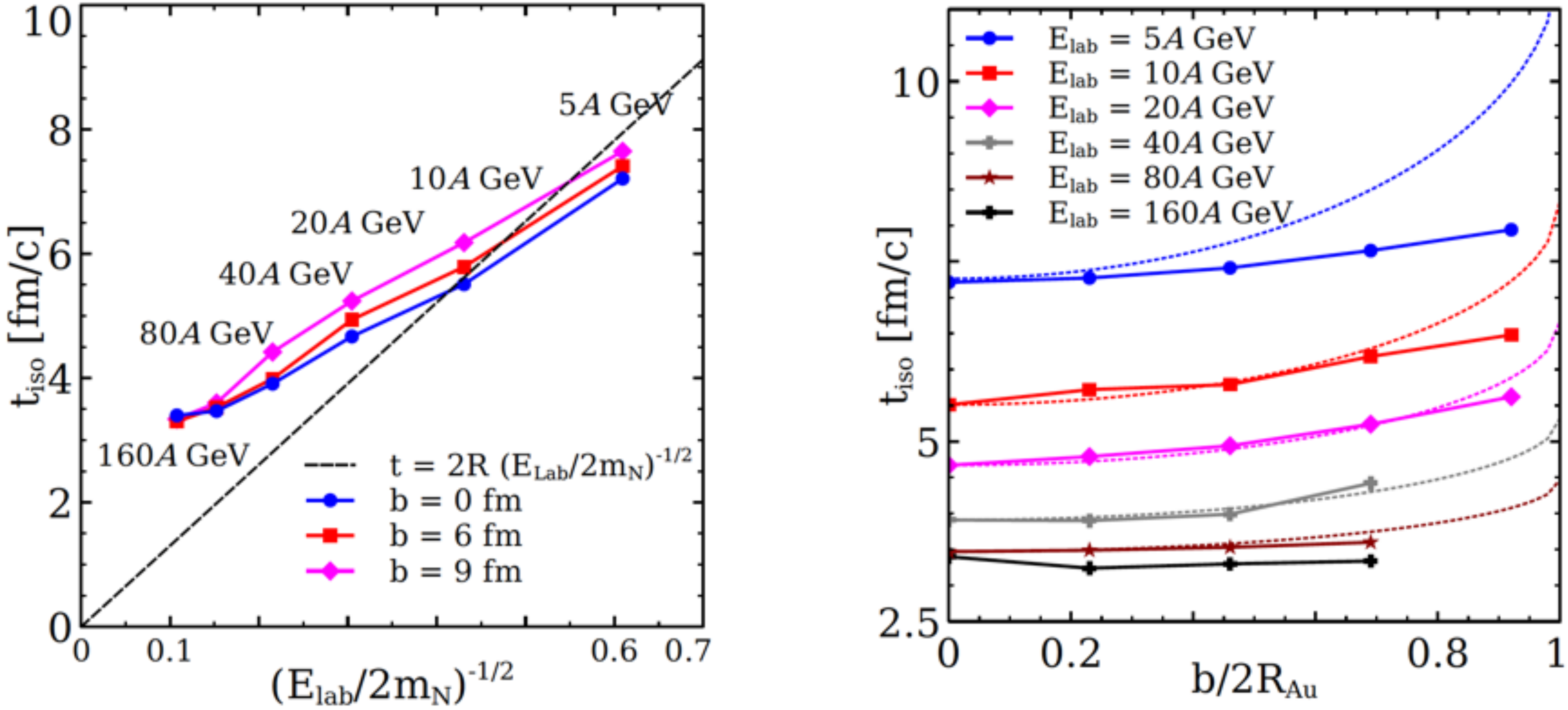
- Estimate systematic error associated with smearing parameter



- The qualitative pattern does not change

Centrality Dependence

- Isotropization time deviates from geometrical overlap criterion for higher beam energies



- Centrality dependence is weaker than expected from geometry

$$t_0(b) = t_0(b=0) + \frac{R}{\gamma v}\left(1 - \sqrt{1-(b/2R)^2}\right)$$

Cooper-Frye - Negative Contributions

based on work with D. Oliinychenko and P. Huovinen,
Phys.Rev. C91 (2015) 2, 024906

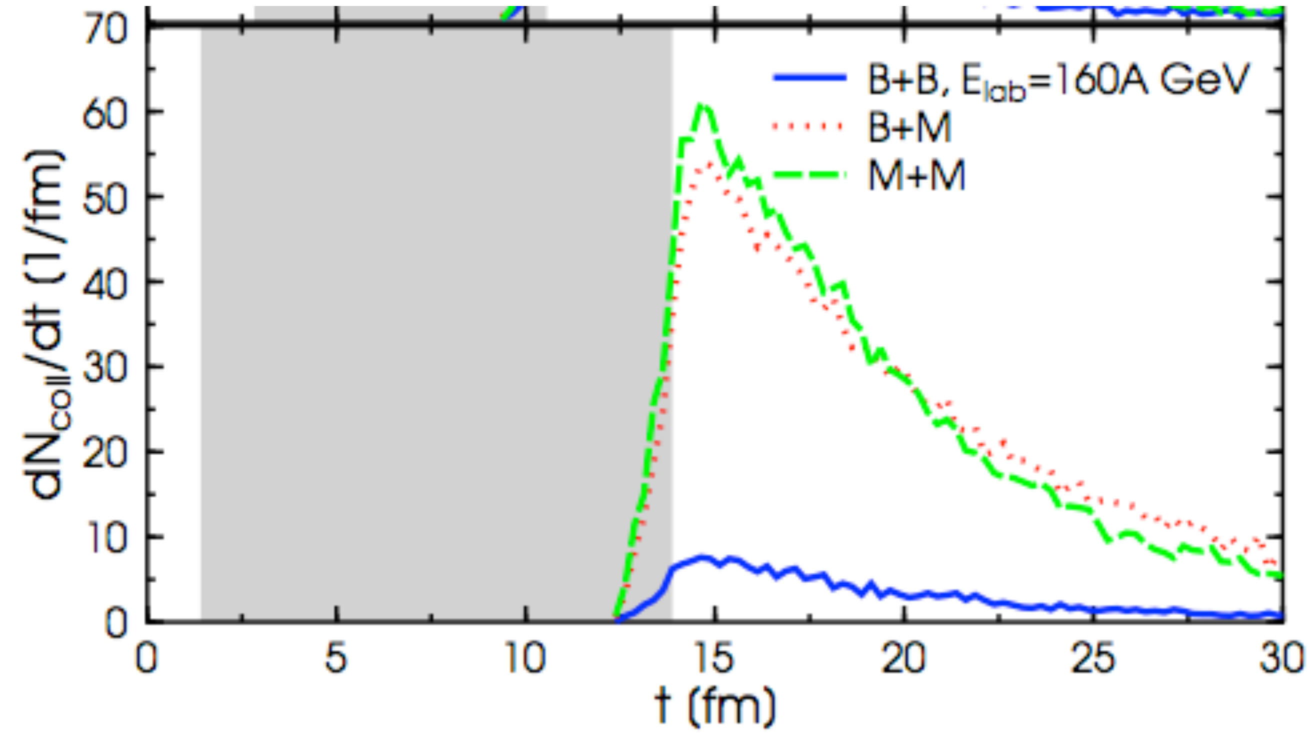
Freeze-out Procedure

- **Deconfinement/Confinement** transition happens through equation of state in hydrodynamics
- **Transition** from hydro to transport when temperature/energy density is smaller than **critical value**
- Particle distributions are generated according to the **Cooper-Frye** formula

$$E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu$$

- Same EoS on both sides of the transition hypersurface
- Rescatterings and final decays calculated via **hadronic cascade** (UrQMD)

- Separation of **chemical** and **kinetic** freeze-out is taken into account
- **Large viscosity** in hadron gas stage!



H.P. et al, Phys.Rev. C78 (2008) 044901

Hypersurface Finding

- **Cornelius**: 3D hypersurface in 4 dimensions
- Constant energy density
- Avoiding holes and double-counting
- Applicable as a subroutine
  - Input: 16-tuples of spatio-temporal information
  - Output: Hypersurface vectors and interpolated thermodynamic quantities

The European Physical Journal

volume 48 · number 11 · november · 2012

EPJ A

Recognized by European Physical Society

Hadrons and Nuclei

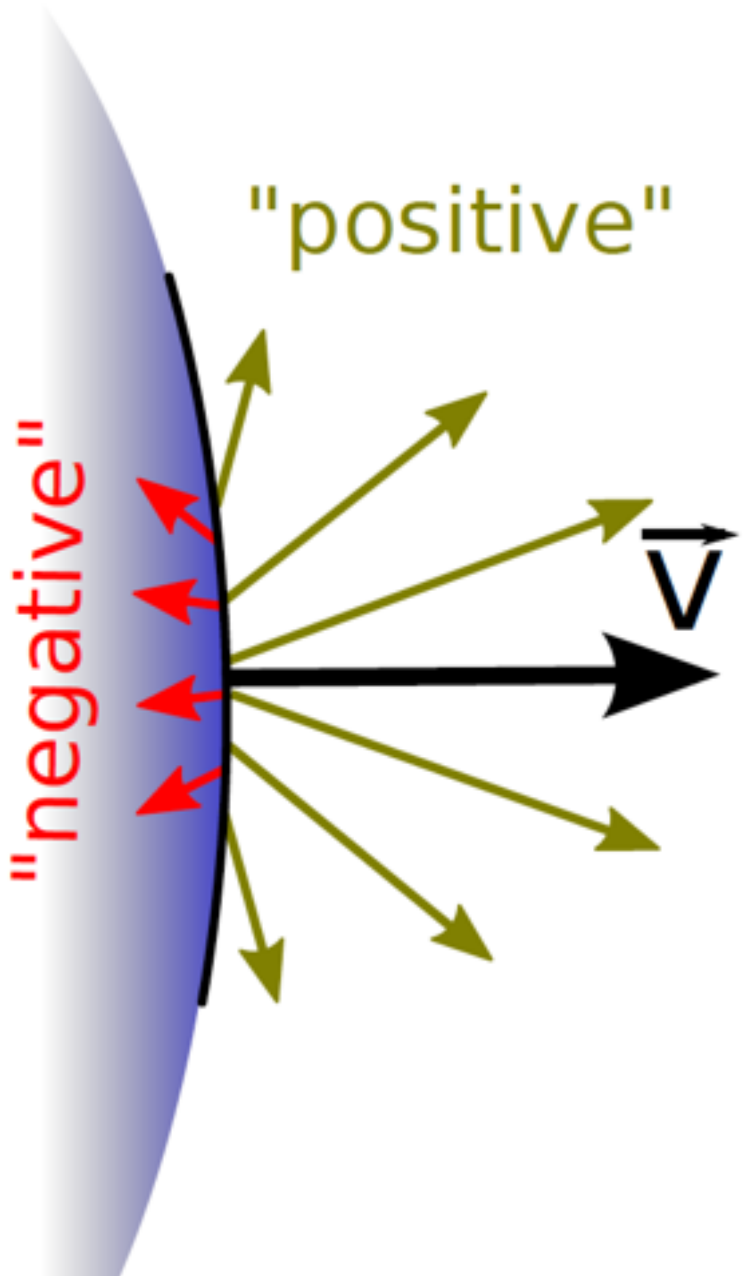
From: Particlization in hybrid models
by P. Huovinen and H. Petersen

Società Italiana
di Fisica

Springer

P. Huovinen, H.P. arXiv: 1206.3371
Fortran and C++ subroutines, cornelius, are implementations of this algorithm in 3D and 4D, are available at https://karman.physics.purdue.edu/OSCAR

Negative Contributions

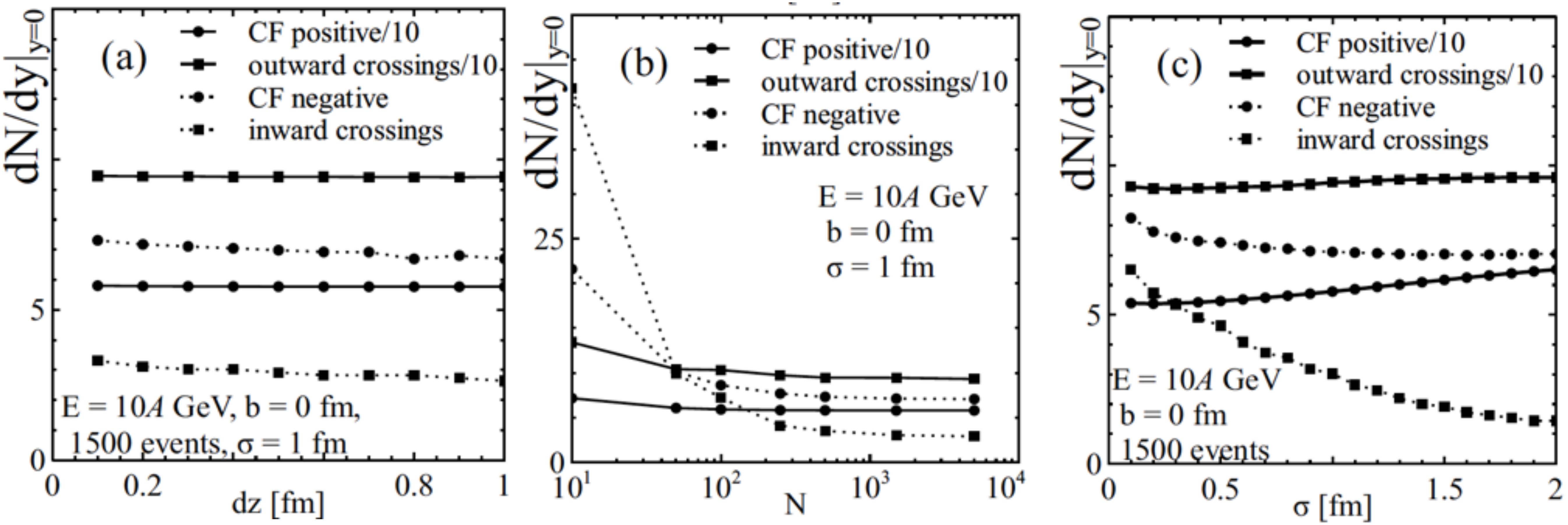


$d\sigma_\mu$ - normal 4-vector
$u_\mu = (\gamma, \gamma \vec{v})$ - 4-velocity
T - temperature
μ - chemical potential

- Definition:
  - Particles outward: $p^\mu d\sigma_\mu > 0$
  - Particles inward: $p^\mu d\sigma_\mu < 0$
- Different options:
  - Account for feedback in hydro
    K. Bugaev, Phys Rev Lett. 2003; L. Czernai, Acta Phys. Hung., 2005
  - Account effectively by weights in transport
    S. Pratt, Phys.Rev. C89 (2014) 2, 024910
  - Neglect them and violate conservation laws
- **Systematic study** of the size of negative contributions by comparison to **actual transport**

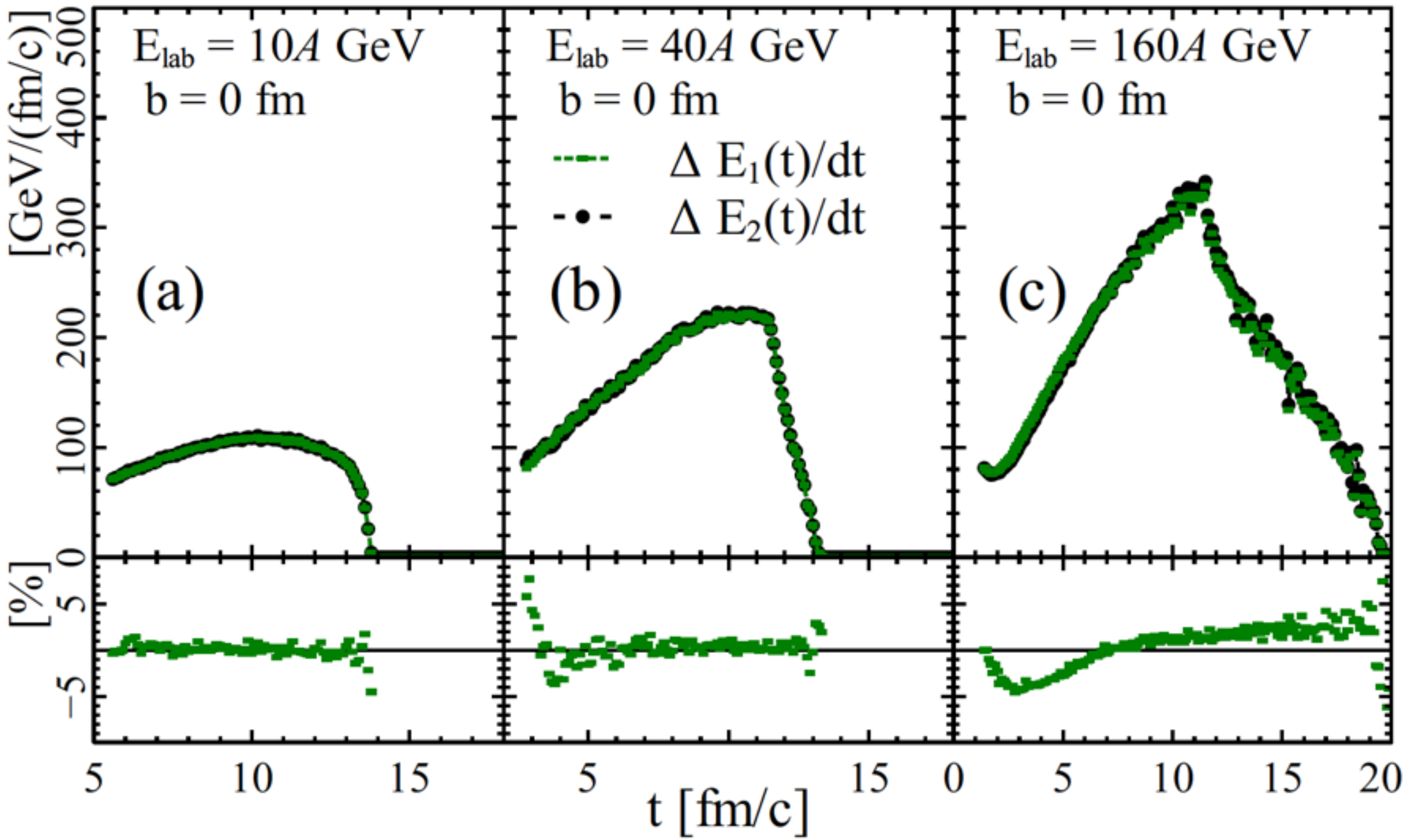
Parameter Sensitivities

- Comparison of coarse-grained transport with Cooper-Frye calculation vs actual particles



- No significant dependence on **cell sizes**
- **Saturation** for large enough number of events
- Dependence on σ due to **smearing** of surface velocities

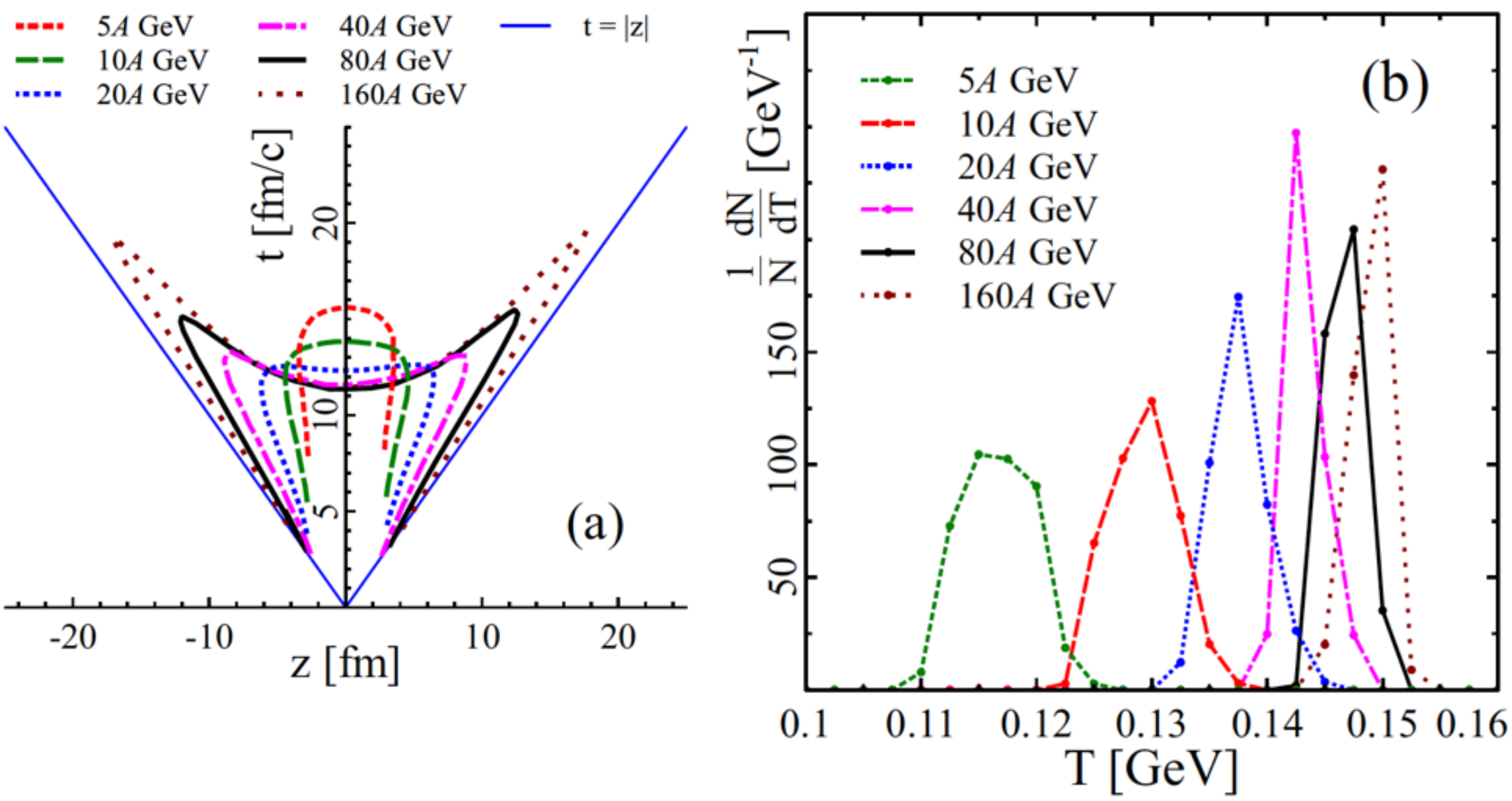
Cross-Check Energy Conservation



- Energy is conserved at all times on hypersurface

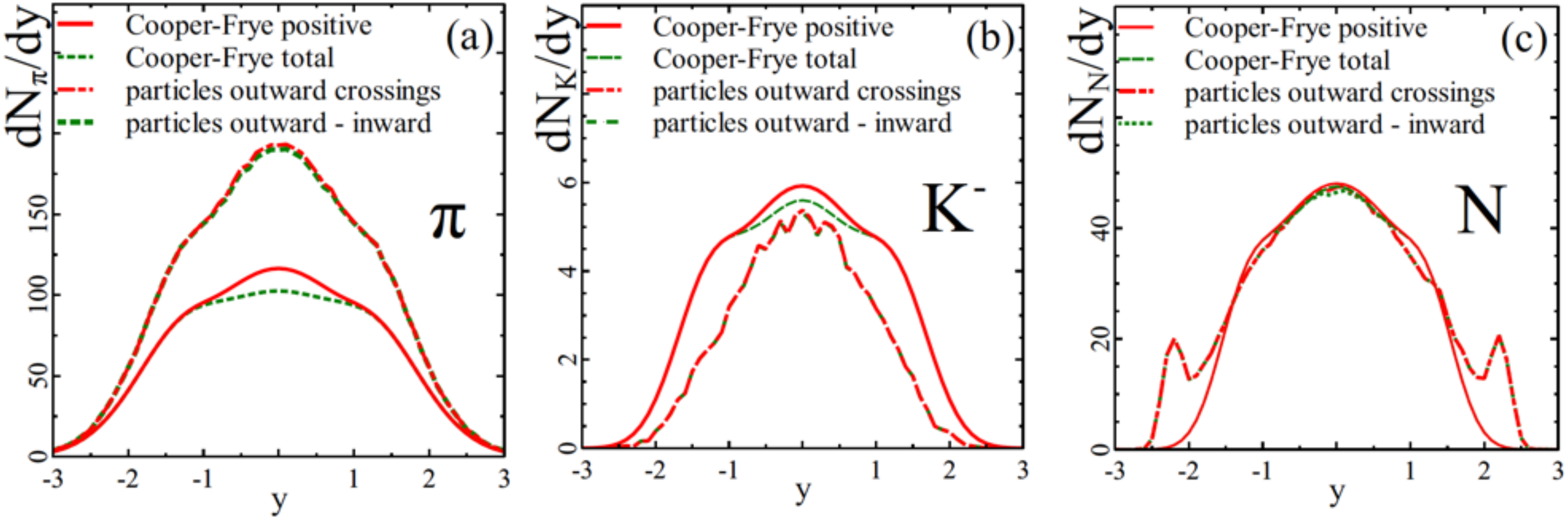
Hypersurfaces

- Iso-energy density hypersurfaces (ε_C = 0.3 GeV/fm^3) represent distributions in temperature



Mass Dependence

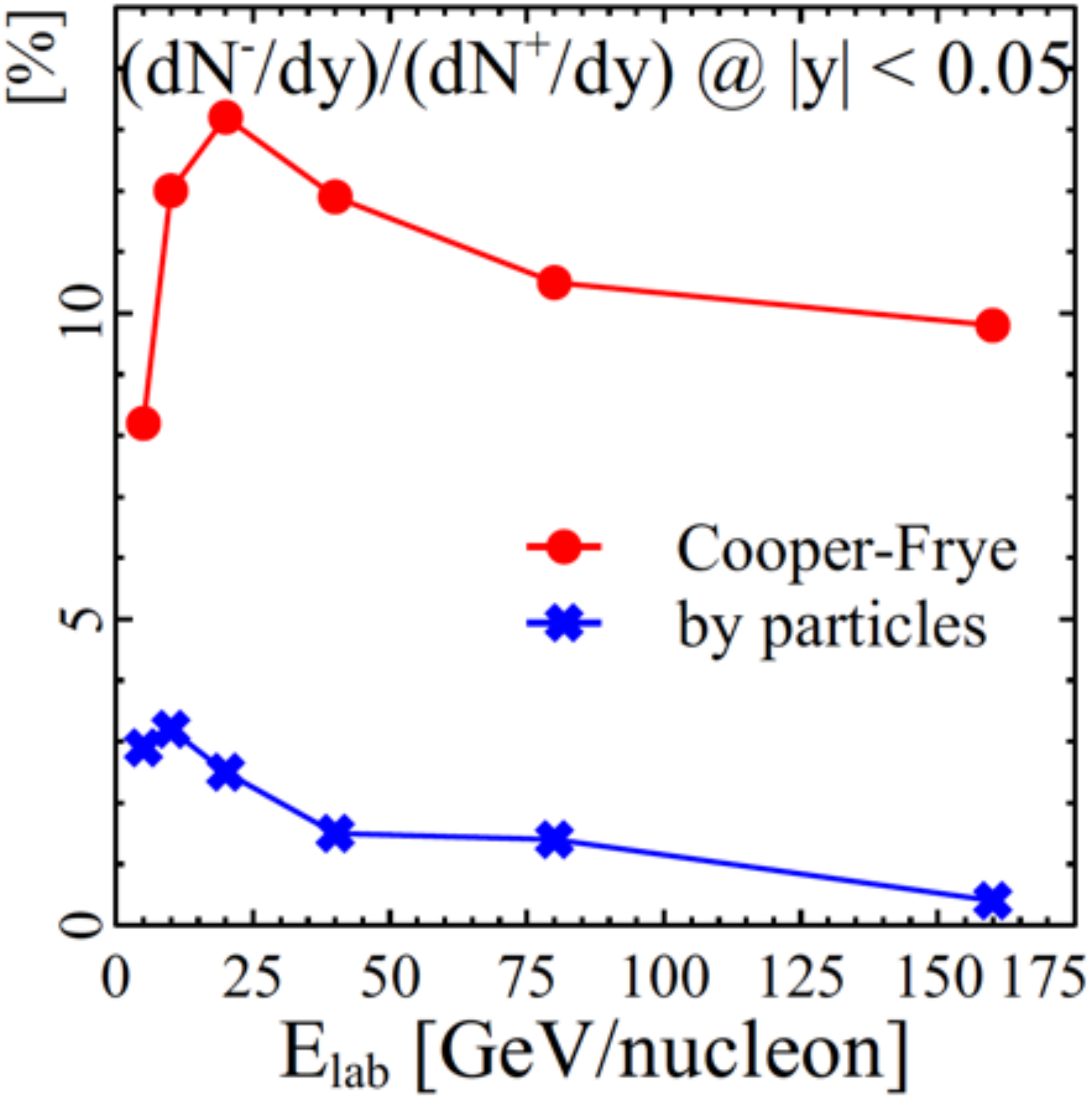
- Rapidity spectra of pions, kaons and protons at E_{lab} = 40A GeV central Au+Au collisions

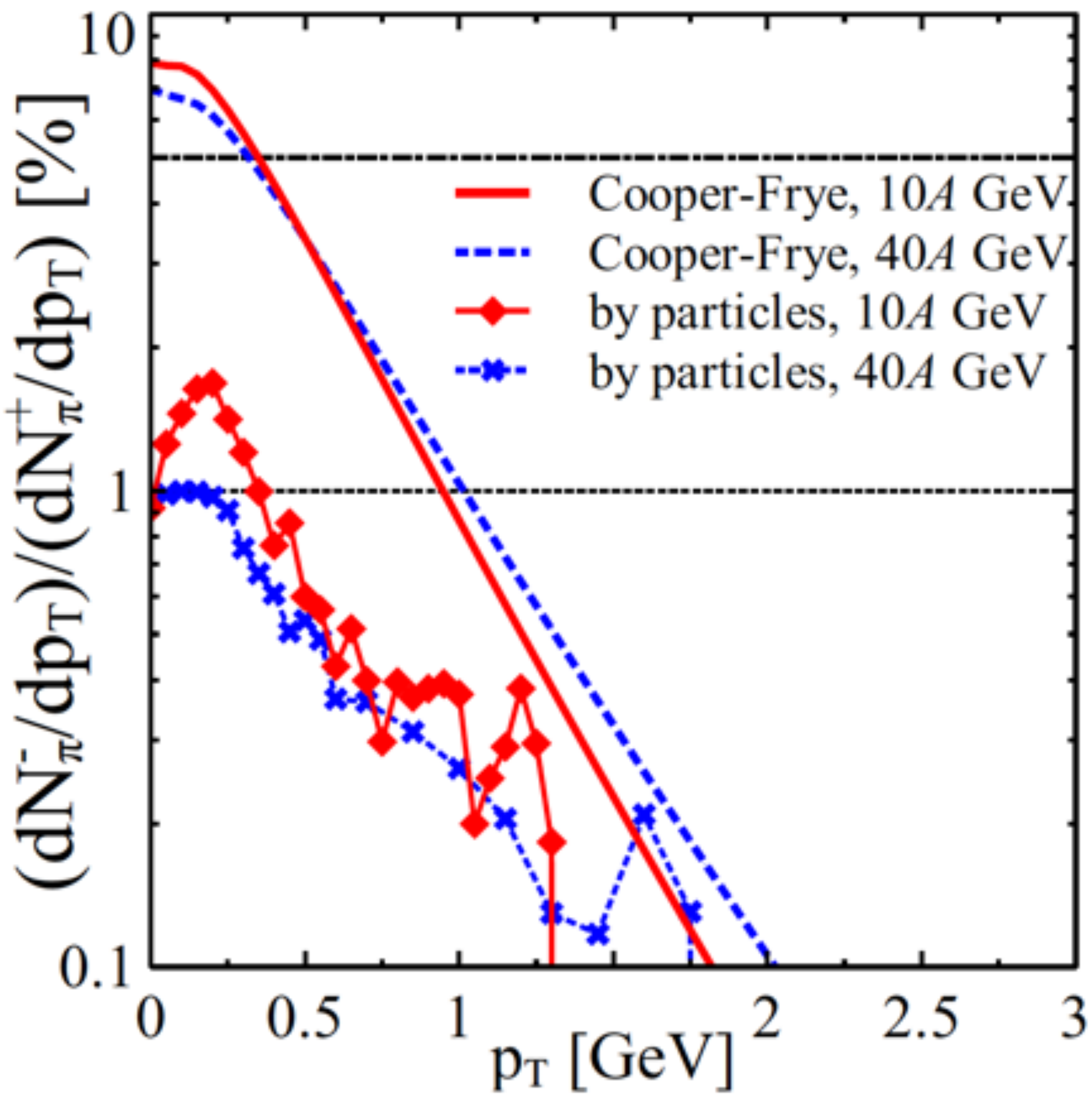


- Negative contributions are negligible for more massive particles
  - Concentrate on pions in the following

Energy Dependence

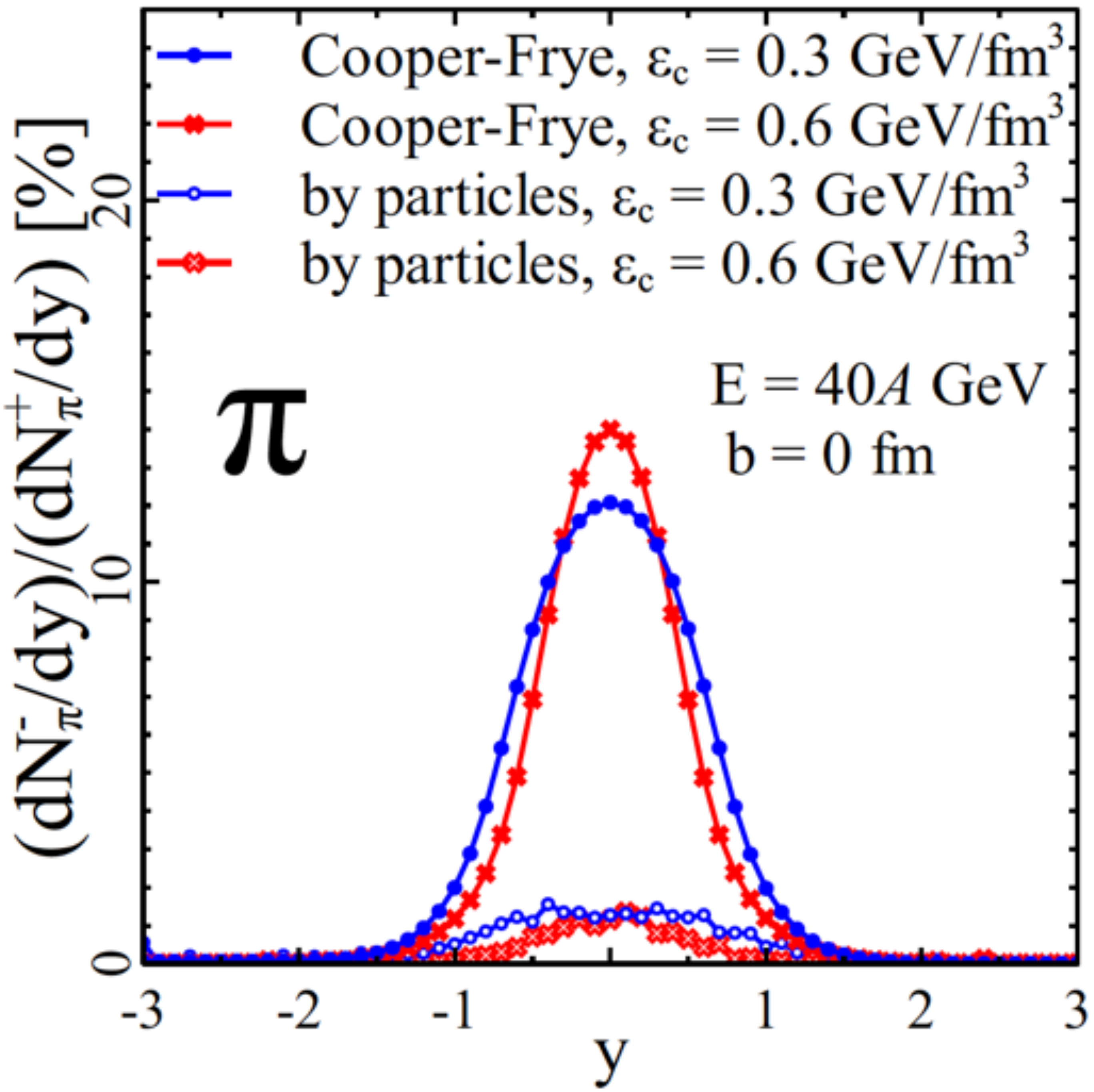
- Maximum at E_{lab}~25 AGeV, decreasing at higher energies
- Actual particles are always less likely to fly inward





- Negative contributions are larger at small p_T

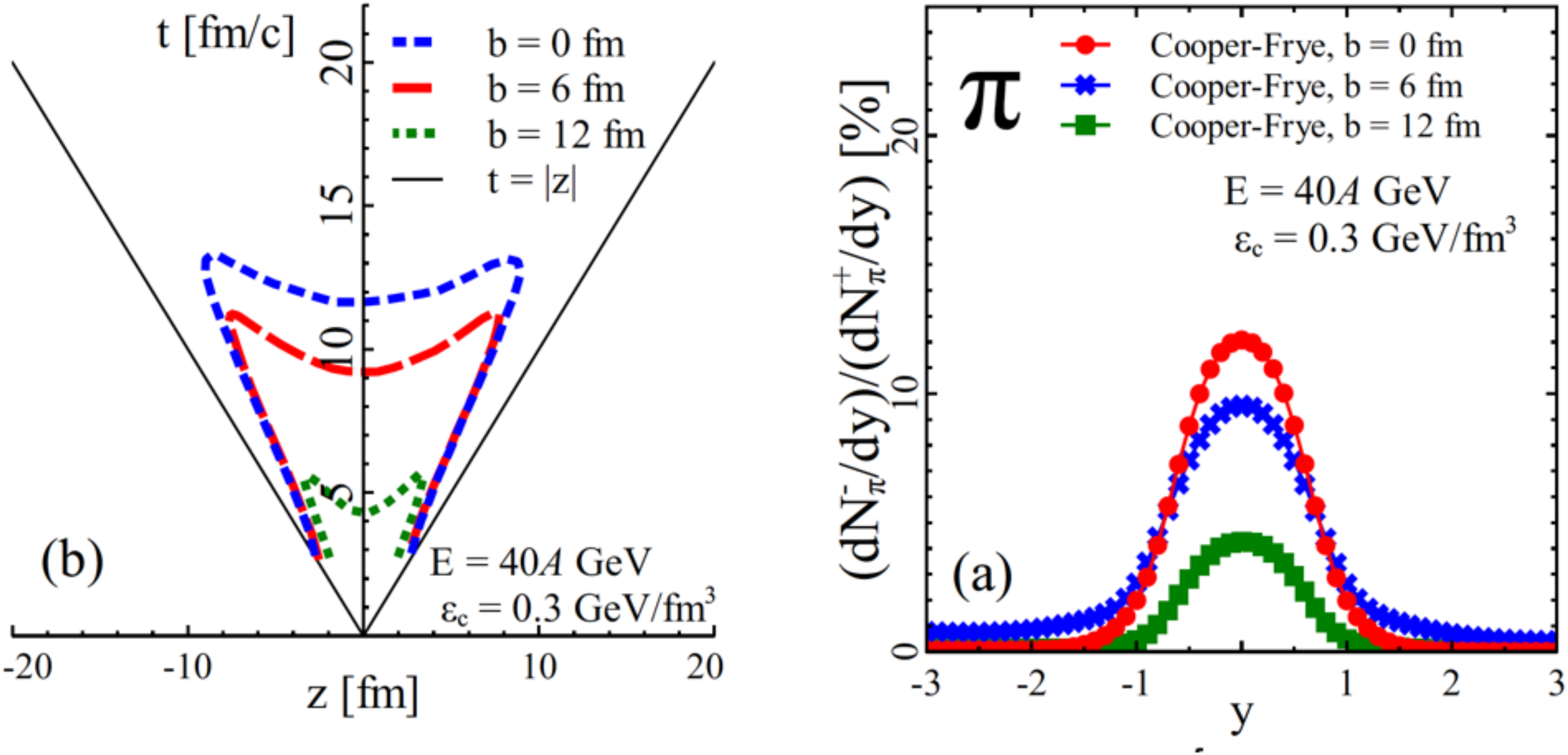
Switching Criterion



- Shape of the negative contributions as a function of rapidity depends slightly on switching criterion

Centrality Dependence

- Ratio of surface to volume emission varies with centrality
- Due to larger relative flow velocities the negative contributions are larger in more central events



Summary

- Hybrid approaches based on relativistic hydrodynamics and hadron transport provide realistic dynamical description
- Two transitions have been studied systematically using coarse-grained UrQMD calculations
- Initial switching transition:
  - Off-diagonality is small for a large fraction of the system in the coarse-grained scenario, event by event larger effect
  - Isotropy (according to the weak criterion) is reached at times at maximum 3 fm/c larger than geometrical overlap criterion
- Cooper Frye negative contributions:
  - Decrease for higher masses and higher beam energies
  - Largest at low transverse momentum
  - Always smaller for actual particles in transport calculation
- Is dynamic switching between hydro and transport feasible?

Backup

Influence of Statistics

- From N random thermal pions, the effect of finite particle statistics on the deviations of the energy-momentum tensor from equilibrium can be estimated