Cooper-Frye negative contributions at FAIR energies

Dmytro Oliinychenko

Frankfurt Institute of Advanced Studies
oliiny@fias.uni-frankfurt.de
In collaboration with Pasi Huovinen and Hannah Petersen

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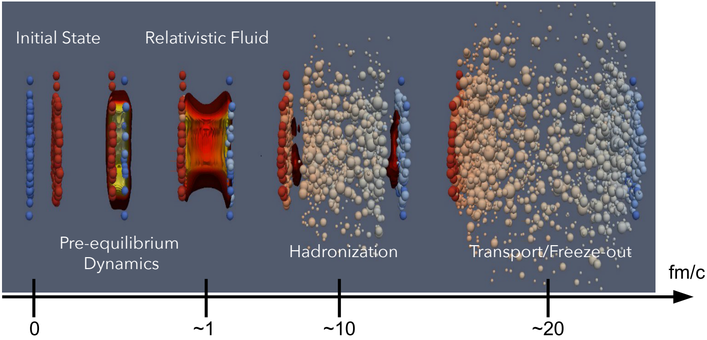
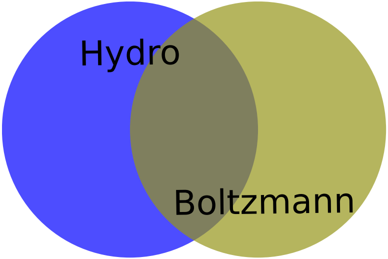
Description of heavy ion collision: hybrid models



- Hydro: local thermal equilibrium, mean free path $\ll$ system size
  $\partial_\mu T^{\mu\nu} = 0$, $\partial_\mu j^\mu = 0$, EoS, boundary conditions
- Transport: Monte-Carlo solution of Boltzmann equation
- Hydrodynamics and transport are solved independently
- Transition - on a predefined hypersurface

Transition in hybrid models

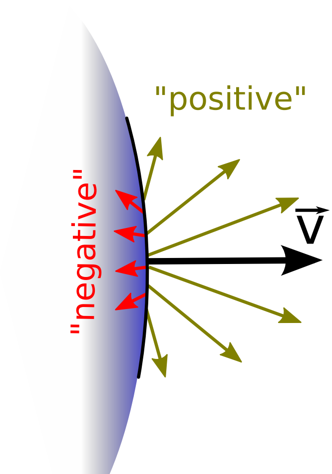


- Criterion for transition surface: "hydro equivalent to transport"
  - Constant energy density surface $\epsilon(t, x, y, z) = \epsilon_0 = 0.3 - 0.6$ GeV/fm^3

    H. Petersen, Phys.Rev. C78 (2008)
  - Constant temperature surface $T = 150 - 170$ MeV

    D. Teaney et al., 2001, nucl-th/0110037; T. Hirano Phys.Lett.B636, 2006

Particlization and negative contributions



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

- Particlization
  - know ϵ, p, u_μ on the surface
  - from EoS - T, μ
  - want particles
- "Cooper-Frye formula"

  $$d^3N(p) = f(p)\frac{d^3p}{(2\pi\hbar)^3}\frac{p^\mu}{p^0}d\sigma_\mu$$

  $\frac{p^\mu}{p^0} \cdot d\sigma_\mu$ - analog of $n \cdot V$

  e.g. ideal hydro $f(p) = \left(e^{\frac{p^\mu u_\mu - \mu}{T}} \pm 1\right)^{-1}$
- Negative contribution
  - $p^\mu d\sigma_\mu > 0$: positive contribution, particles fly out
  - $p^\mu d\sigma_\mu < 0$: negative contribution, particles fly in

Negative contributions: options

- Account feedback to hydro - great increase in complexity

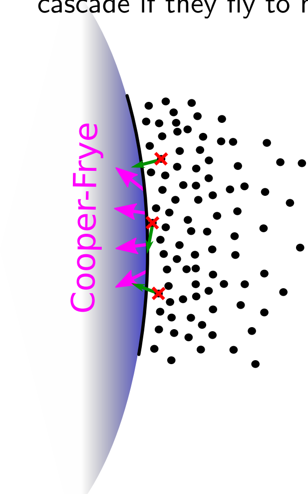
  K. Bugaev, Phys Rev Lett. 2003; L. Czernai, Acta Phys. Hung., 2005
- Account effectively - artificial constructions

  S. Pratt, 2014, nucl-th1401.0136
- Neglect - violate conservation laws

How large are negative contributions?
What changes if we neglect them and how much?
How much does the choice of transition surface influence results?
Is hydro equivalent to cascade in the transition region?

Negative contributions: possible solution

- Hybrid model
- Assume: transport equivalent to hydrodynamics
- Neglect negative Cooper-Frye contributions + remove particles from cascade if they fly to hydrodynamical region



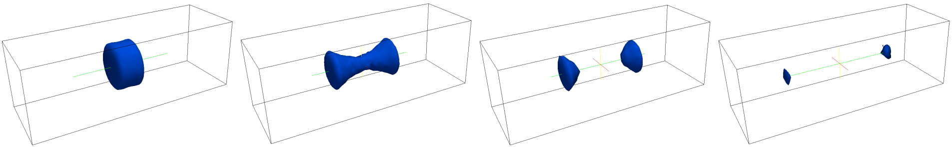
Is it possible to compensate negative Cooper-Frye contributions?
That would solve problem with conservation laws.

Coarse-grained microscopic transport approach

Hypersurface of constant Landau rest frame energy density:
mimic hybrid model transition surface

- Generate many UrQMD events
- On a (t,x,y,z) grid calculate $T^{\mu\nu} = \left\langle \frac{1}{V_{cell}} \sum_{i \in cell} \frac{p_i^\mu p_i^\nu}{p_i^0} \right\rangle_{\text{event average}}$
- In each cell go to Landau frame: $T_L^{0\nu} = (\epsilon_L, 0, 0, 0)$
- Construct surface $\epsilon_L(t, x, y, z) = \epsilon_0$

Example: E = 160 AGeV, Au+Au central collision, $\epsilon_0 = 0.3$ GeV/fm^3



t = 4 fm/c   t = 11 fm/c   t = 13 fm/c   t = 18 fm/c

Definitions for negative contributions

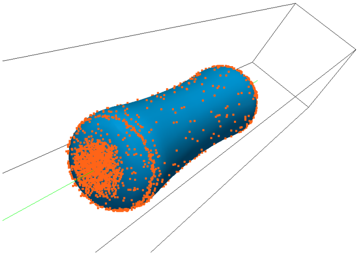
- Hypersurface Σ: $\epsilon_L(t, x, y, z) = const$
  - A) Cooper-Frye formula on Σ
  - B) count UrQMD particles crossing Σ
- $A \equiv B$ if particle distribution from UrQMD is exactly equilibrated

A) Cooper-Frye

$$p^0 \frac{d^3N^+}{dp^3} = \frac{p^\mu d\sigma_\mu}{exp(p^\nu u_\nu / T) \pm 1} \theta(p^\nu d\sigma_\nu)$$

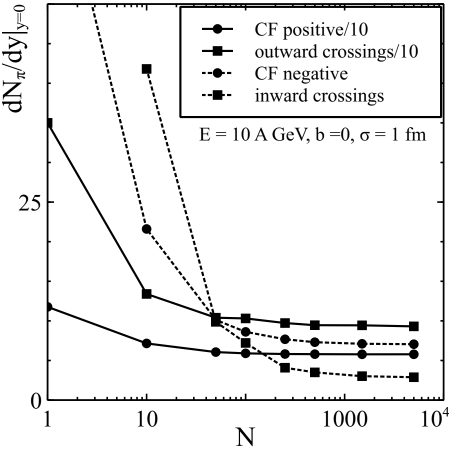
$$p^0 \frac{d^3N^-}{dp^3} = \frac{p^\mu d\sigma_\mu}{exp(p^\nu u_\nu / T) \pm 1} \theta(-p^\nu d\sigma_\nu)$$

B) "by particles"



Gaussian smearing and statistics

Results are very sensitive to surface lumpiness



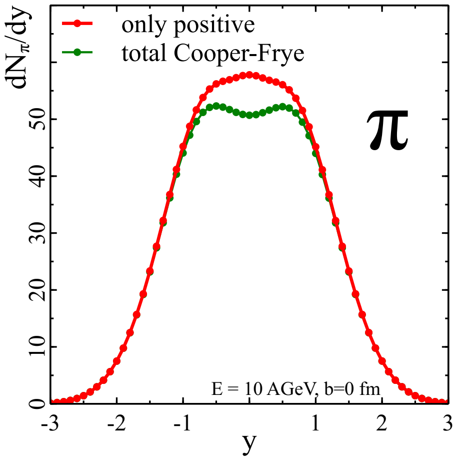
Saturation of results against statistics

To get a smooth surface gaussian smearing with $\sigma = 1$ fm was used.

What changes if we neglect negative contributions

- Conservation laws will be violated
- Spectra will change depending on
  - collision energy
  - centrality
  - particle sort
  - transition surface
- We further investigate $[dN^{-}/dy]/[dN^{+}/dy]$ in %

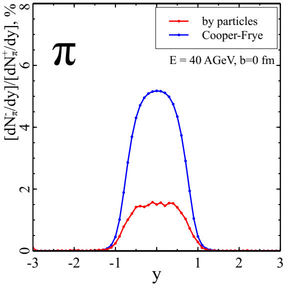
Example:



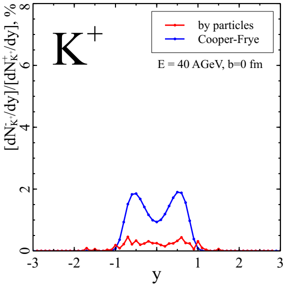
Negative contributions: particle mass dependence

E = 40 AGeV, b = 0, $\epsilon_0 = 0.3$ GeV/fm^3, dN/dy distributions

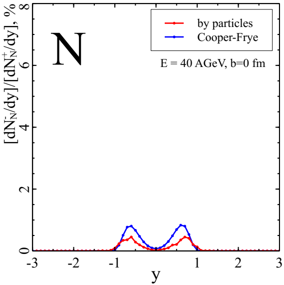
π ($m_\pi = 139$ MeV)



K^+ ($m_K = 495$ MeV)



N ($m_N = 938$ MeV)

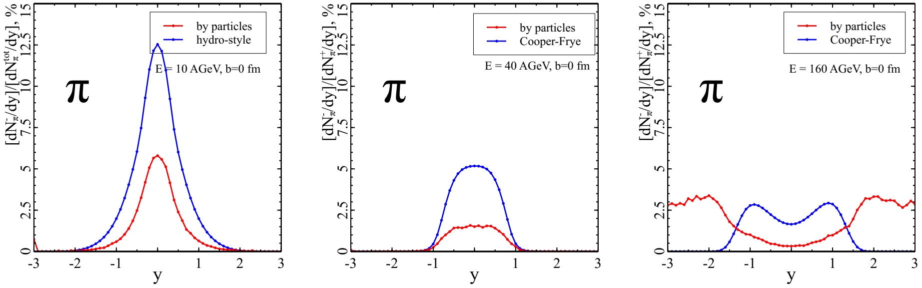


Smaller mass - larger negative contribution

Negative contributions: energy dependence

Pions, $\epsilon_0 = 0.3$ GeV/fm^3, dN/dy distributions

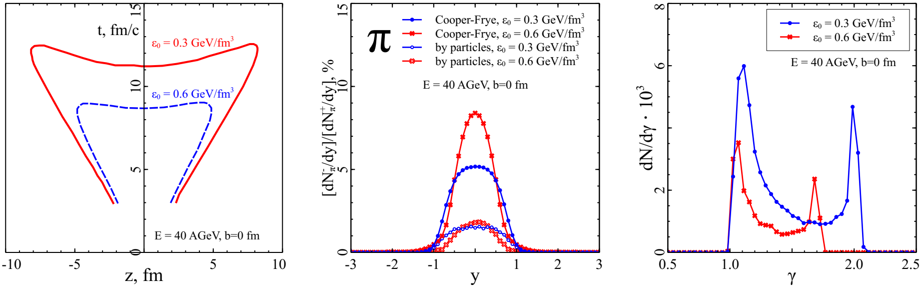
10 AGeV 40 AGeV 160 AGeV



Lower collision energy - slower expansion - larger negative contributions

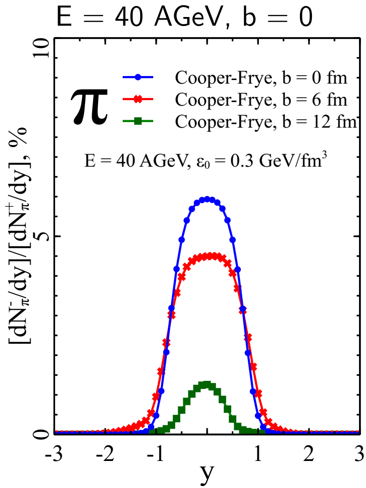
Negative contributions: dependence on surface ϵ_0

$E = 40$ AGeV, $b = 0$



Larger ϵ_0 - slower surface expansion - larger negative contributions

Negative contributions: dependence on centrality



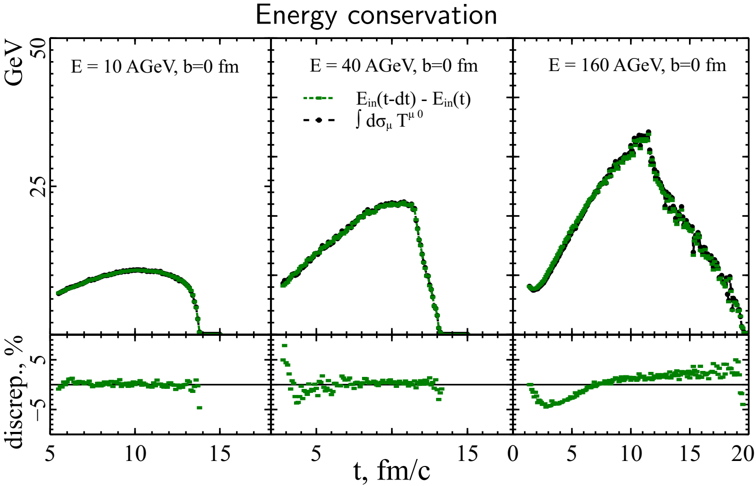
More peripheral collision - smaller negative contributions

Summary

- Hydro-transport transition ("particlization") was studied
  - Coarse-grained UrQMD was used to construct $\epsilon(t, x, y, z) = \epsilon_0$ isosurface
  - Negative contributions on this surface are calculated in two ways: from Cooper-Frye formula and explicitly counting particles
- Negative contributions are larger
  - for smaller collision energies
  - for central collisions than for peripheral
  - for smaller particle masses
  - for larger ϵ_0
  - for lumpy transition surface
- Negative contributions by particles are smaller than Cooper-Frye ones
  - no compensation by accident

Backup: surface quality check

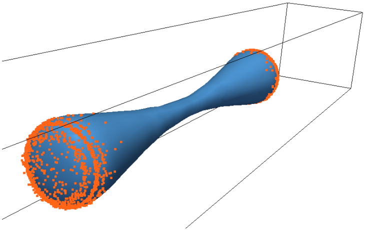
Surface - no holes or double counting: Cornelius routine
Conservation laws on hypersurface: accuracy better than 1%

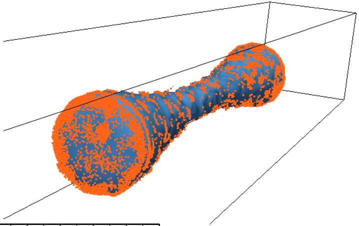


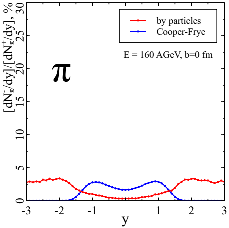
Backup: statistics matters

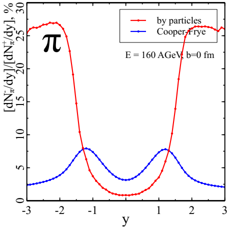
E = 160 AGeV, b = 0

Smooth surface | Lumpy surface





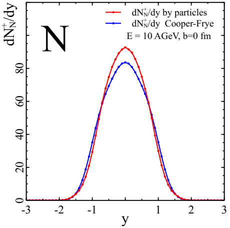
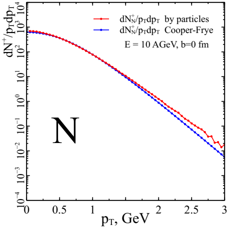
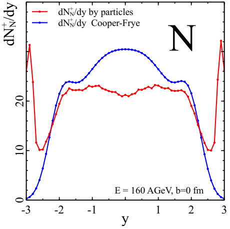
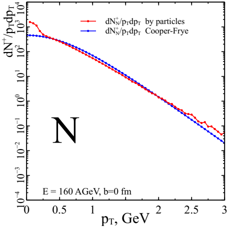




Lumpier surface - larger negative contributions

Spectra: nucleons

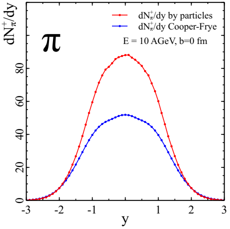
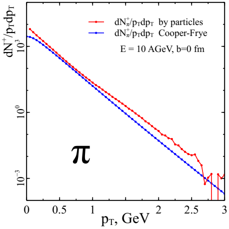
Red lines - by particles, blue lines - Cooper-Frye. $\epsilon_0 = 0.3$ GeV/fm^3

E_{coll}	y	p_T	Conclusion
10 AGeV			Cooper-Frye works well. Spectra are close.
160 AGeV			At high $\|y\|$ distribution is not thermal.

Similar picture for Δ, Λ, K^+, K^-, but ...

Spectra: pions

Red lines - by particles, blue lines - Cooper-Frye. $\epsilon_0 = 0.3$ GeV/fm^3

<table>
<tr><th>E_{coll}</th><th>y</th><th>p_T</th><th>Conclusion</th></tr>
<tr><td>10 AGeV</td><td>
</td><td>
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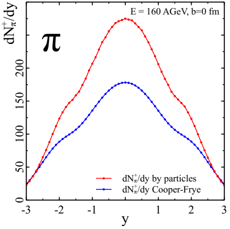
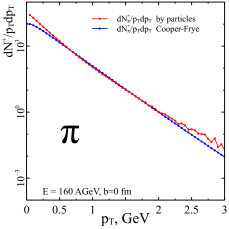
<tr><td>160 AGeV</td><td>
</td><td>
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