Baryon stopping signal for mixed phase formation in HIC

Yuri B. Ivanov

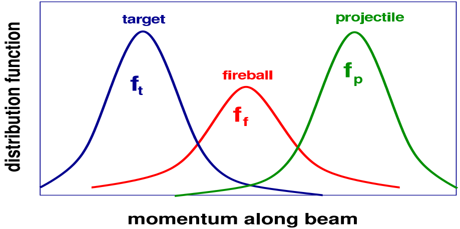
NRC "Kurchatov Institute" & NRNU "MEPhI"

3 Fluids: minimal extension of hydro required by heavy-ion dynamics

- Distributions are separated in momentum space
  $\Rightarrow$ different fluids
- Leading particles carry baryon charge
  $\Rightarrow$ 2 baryon-rich fluids: **projectile-like** and **target-like**

At high incident energies ($E_{lab} \gtrsim 10A$ GeV)

- **Produced particles populate mid-rapidity**
  $\Rightarrow$ **fireball fluid**

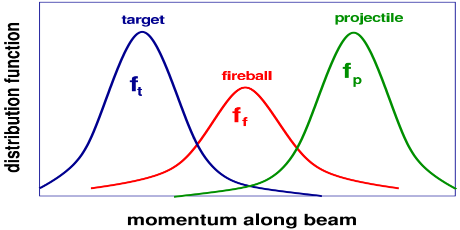


- **Kurchatov Inst. 1988–1991: 2-fluid hydro with free-streaming radiation of pions**, Mishustin, Russkikh, and Satarov
- **Frankfurt University 1993–2000: 3-fluid hydrodynamics with instant formation of fireball**
  Brachmann, Katscher, Dumitru, Rischke, Maruhn, Stöcker, Greiner, Mishustin, Satarov, *et al.*
- **GSI&Kurchatov Inst. 2003–now: 3-fluid hydrodynamics with delayed formation of fireball**, Ivanov, Russkikh, Toneev

3-Fluid Dynamics, present version

Produced particles populate mid-rapidity

$\Rightarrow$ fireball fluid



Target-like fluid: $\partial_\mu J_t^\mu = 0$ $\quad \partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

Leading particles carry bar. charge — exchange/emission

Projectile-like fluid: $\partial_\mu J_p^\mu = 0,$ $\quad \partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

Fireball fluid: $J_f^\mu = 0,$ $\quad \partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

Baryon-free fluid — Source term — Exchange

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

Equation of State

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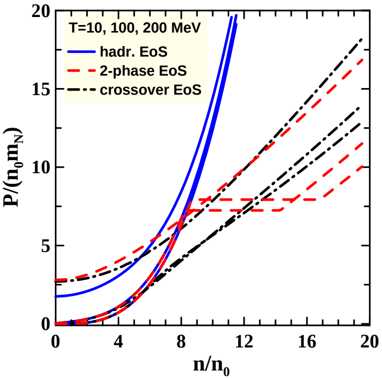
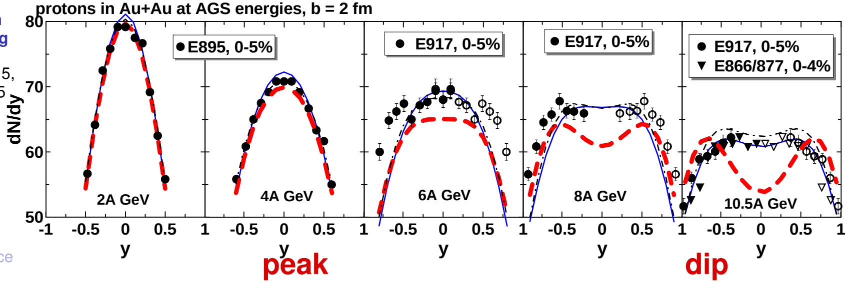
- **Hadronic EoS**
  Galitsky&Mishustin (1979)
- 1st-order transition to QGP **(2-phase EoS*)**
- **crossover EoS***

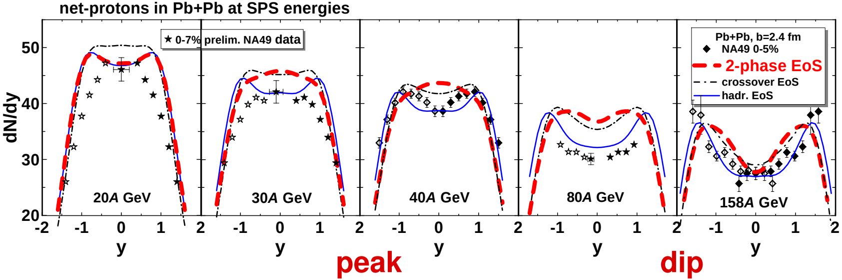
*[Khvorostukhin, Skokov, Redlich, Toneev, (2006)]



Phase transition $\Longrightarrow$ EoS softening

Net-Proton Rapidity distributions





”peak-dip-peak-dip” irregularity at midrapidity

Robust with respect to variation of friction and freeze-out energy density

Physical Origin of the Irregularity

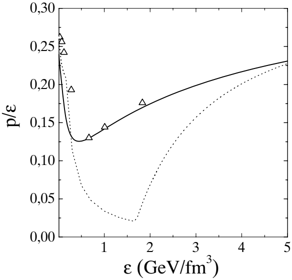
The irregularity is an effect of

- **softest point** of a EoS
  (a minimum of the sound speed)

  spherical fireball
  $\Rightarrow$ essentially 3D expansion
  $\Rightarrow$ **a peak at midrapidity**

  strongly deformed fireball
  $\Rightarrow$ approximately 1D expansion
  $\Rightarrow$ **a dip at midrapidity**

  the softer matter is
  $\Rightarrow$ the more deformed fireball
  $\Rightarrow$ **a dip at midrapidity**



from E. G. Nikonov, A. A. Shanenko and V. D. Toneev, Heavy Ion Phys. 8, 89 (1998)

This irregularity is a signal from hot and dense stage of nuclear collision

If description of the compression stage is insensitive to the EoS (e.g. hadronic cascade for all scenarios), this effect is absent.

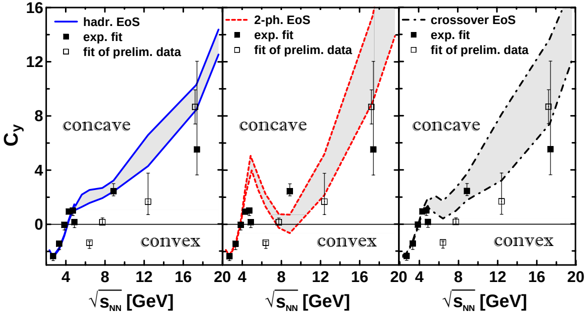
Reduced Curvature at Midrapidity

To quantify this irregularity, net-proton rapidity distributions are fitted by

$$\frac{dN}{dy} = a\left(\exp\{-(1/w_s)\cosh(y-y_s)\} + \exp\{-(1/w_s)\cosh(y+y_s)\}\right) ,$$

A reduced curvature of the spectrum at midrapidity

$$C_y = \left(y^3_{\rm beam}\frac{d^3N}{dy^3}\right)_{y=0} \Big/ \left(y_{\rm beam}\frac{dN}{dy}\right)_{y=0} = (y_{\rm beam}/w_s)^2\left(\sinh^2 y_s - w_s\cosh y_s\right) .$$



Yu.B. Ivanov,
PL B721 (2013) 123
arXiv:1211.2579

Wiggle in C_y in the mixed-phase region!

Experimental Acceptance

- **"full acceptance"**: $0 < p_T < 2$ GeV/c and $|y| < 0.7\ y_{\rm beam}$, $y_{\rm beam}$ = beam rapidity in the collider mode
- $0.4 < p_T < 1$ GeV/c and $|y| < 0.5$, **the expected MPD-NICA acceptance**
- $1 < p_T < 2$ GeV/c and $|y| < 0.5$, p_T**-range beyond the expected MPD-NICA acceptance**
- $0.4 < p_T < 3$ GeV/c and $|y| < 0.5$, **the range of the STAR acceptance**

If the baryon-stopping signal of deconfinement onset survives?
Y. B. Ivanov and D. Blaschke, arXiv:1504.03992 [nucl-th].

Impact of Experimental p_T Acceptance

Baryon stopping

SQM 2015, 09.07.15

3FD

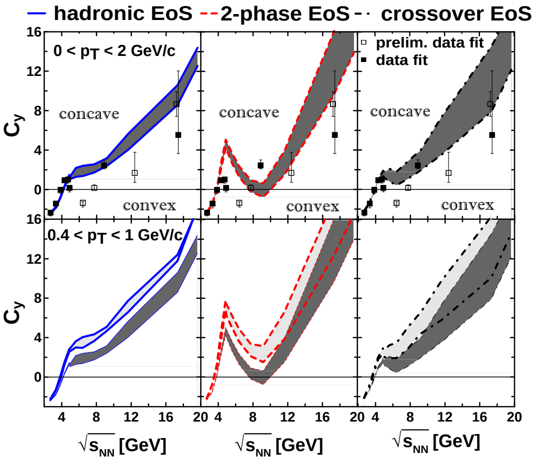
EoS

Baryon Stopping

Acceptance Impact

Summary

First, without restrictive constraints on y range



Dark bands:

"full acceptance"

Light-grey bands:

p_T constraints

upper border:

$|y| < 0.7\, y_{\text{beam}}$

lower border:

$|y| < 0.5\, y_{\text{beam}}$

The wiggle survives!

Wiggle location depends on p_T acceptance

Measurements should be taken at the same p_T acceptance for all energies

Impact of Experimental p_T and y Acceptance

Baryon stopping

SQM 2015, 09.07.15

3FD

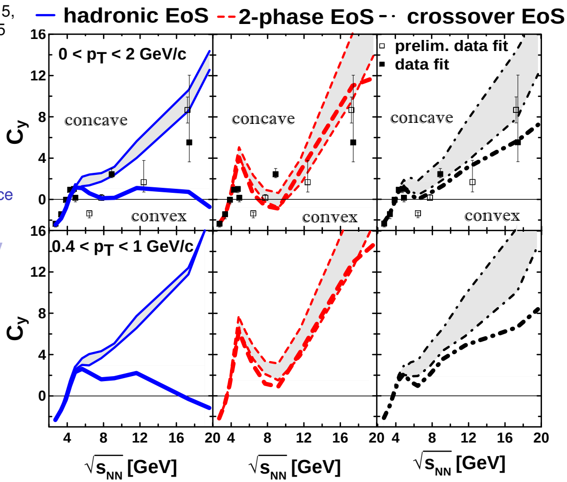
EoS

Baryon Stopping

Acceptance Impact

Summary

with restrictive constraints on y range



Light-grey bands:

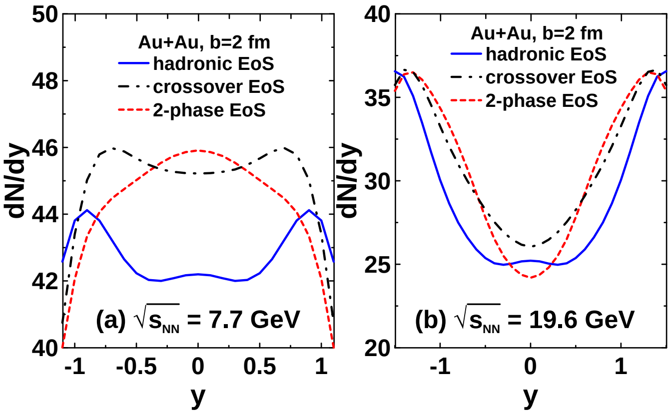
only p_T constraints

Bold lines: $|y| < 0.5$

Strong wiggle survives for the 1st-order phase transition!

Hadronic scenario ⇒ a weak wiggle similar to that in crossover scenario

Problems with Narrow *y* Acceptance



Fine structure near midrapidity becomes dominant in a narrow rapidity *y* window.

Global shape can be inaccessible in a narrow rapidity *y* window!

Summary

- Net-proton rapidity distributions:
  Irregularity signaling deconfinement onset
  It is an effect of the softest point of an EoS
- This irregularity is a robust signal of a first-order phase transition
  It survives even at a very restrictive acceptance.
- **To observe this irregularity, measurements should be taken at the same acceptance for all collision energies**
  because the shape of the net-proton rapidity distribution depends on the experimental p_T-acceptance.
- This irregularity (in a weaker form) can be inherent in distributions of other hadrons

J. Steinheimer and M. Bleicher, "Extraction of the sound velocity from rapidity spectra: Evidence for QGP formation at FAIR/RHIC-BES energies," Eur. Phys. J. A 48, 100 (2012) [arXiv:1207.2792 [nucl-th]].