Baryon Stopping and the EoS

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Baryon Stopping

Net-baryon rapidity distribution
is a direct measure of nuclear stopping
because number of net-baryon is confined by conservation law.

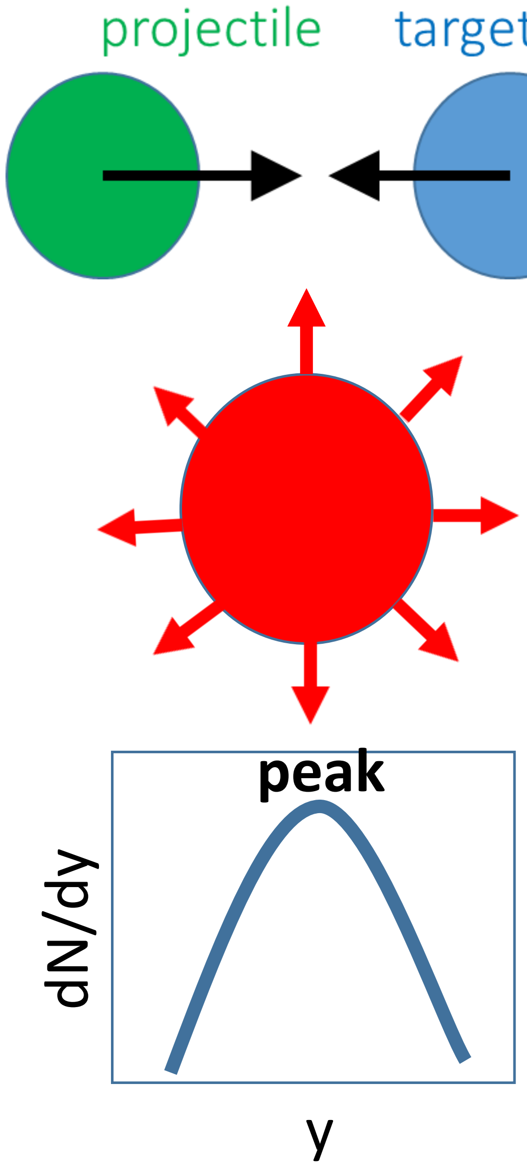
Net-baryons = Baryons - Anti-baryons

longitudinal rapidity = analog of v in non-relativistic case

However, we have to rely on net-proton data.

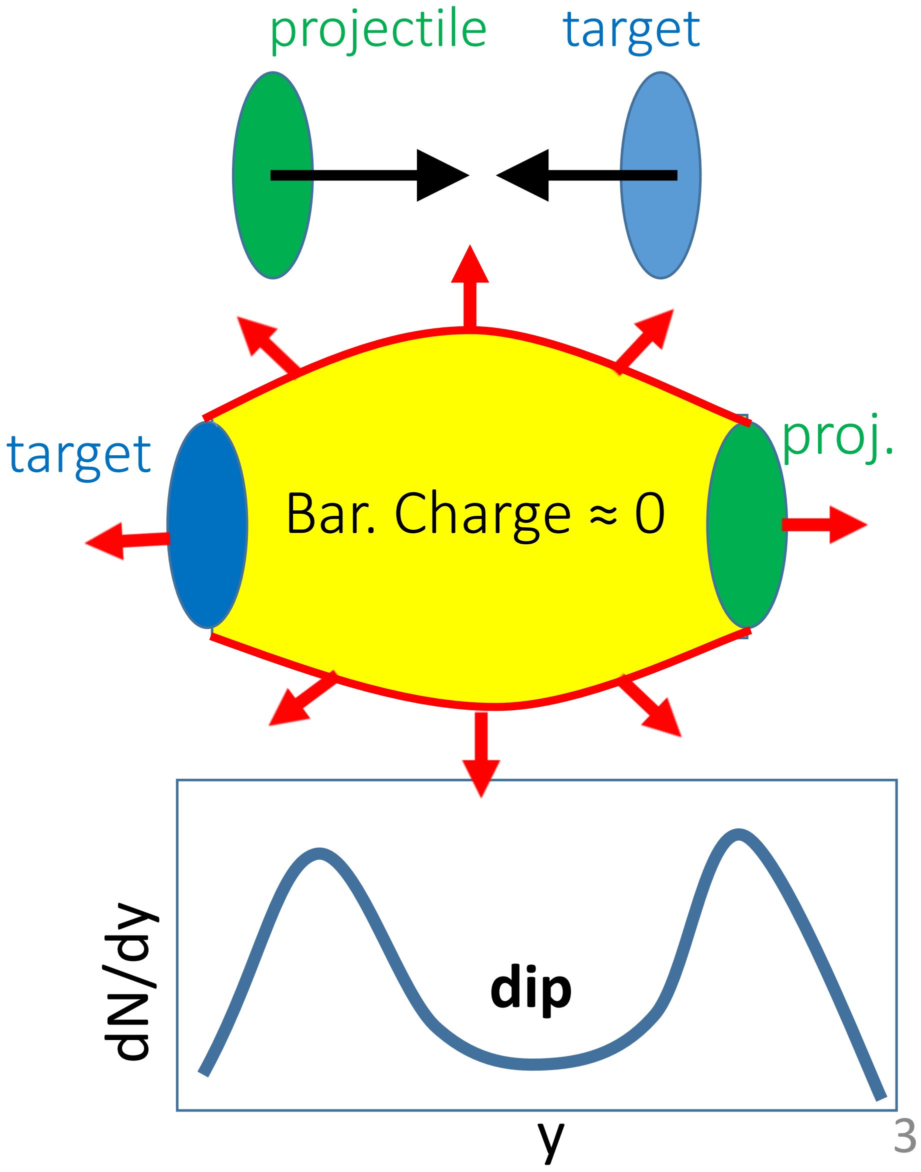
We consider only central collisions:
Au+Au at AGS and Pb+Pb at SPS.
[Y.I., Phys. Lett. B 690 (2010) 358]

Complete stopping
At moderate energies

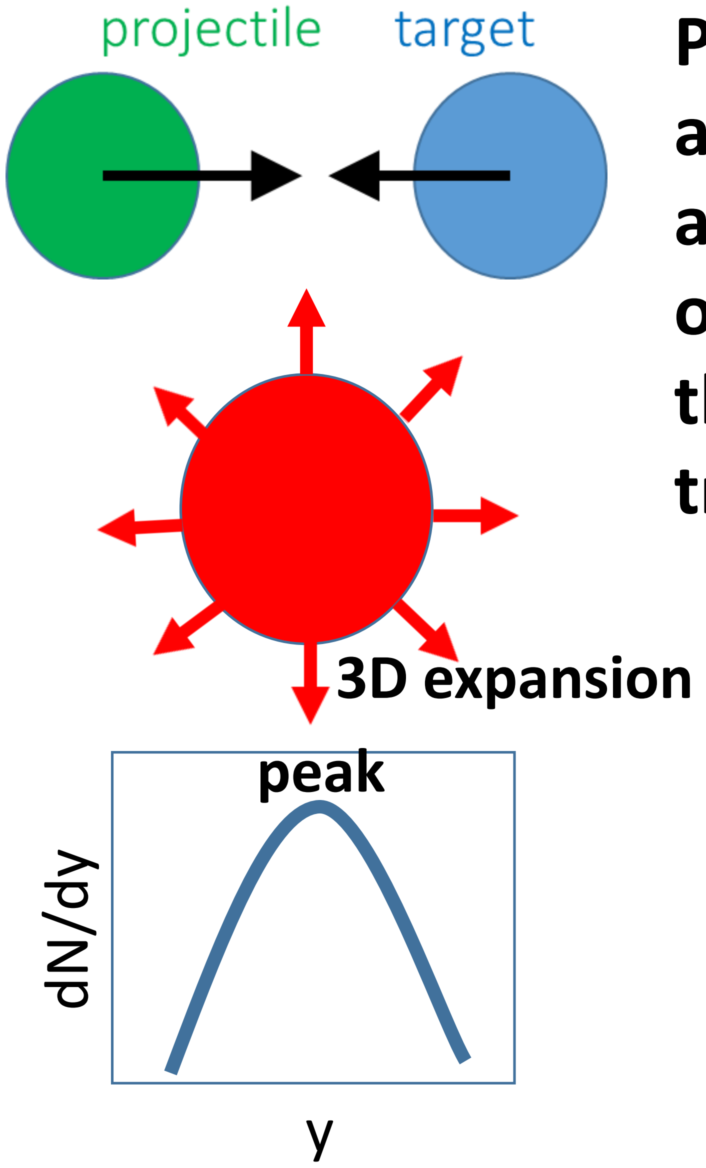


Transition from complete stopping to transparency at NICA energies

Transparency
At ultrarel. energies

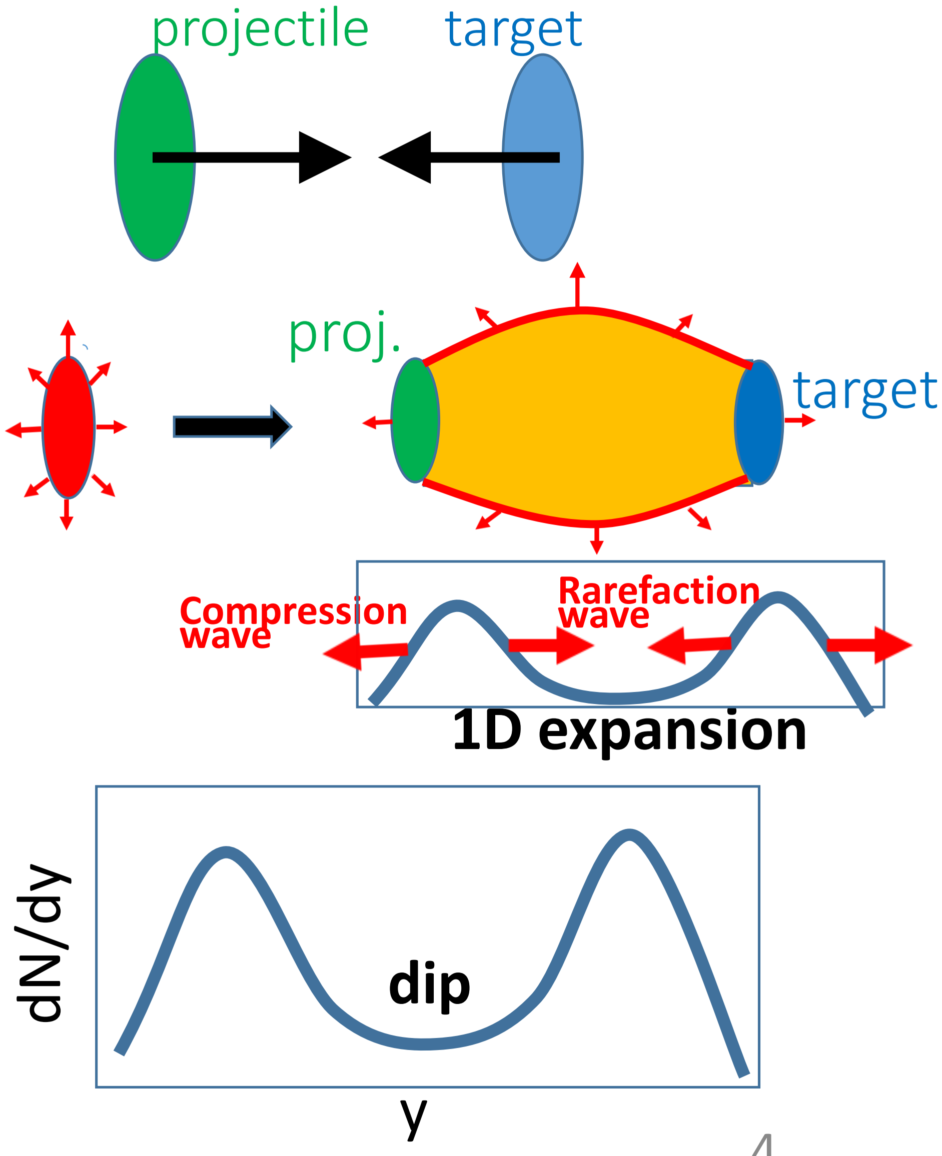


Complete stopping
At moderate energies



Peak-to-dip transition at NICA energies is a combined effect of onset of this 1D expansion and transparency

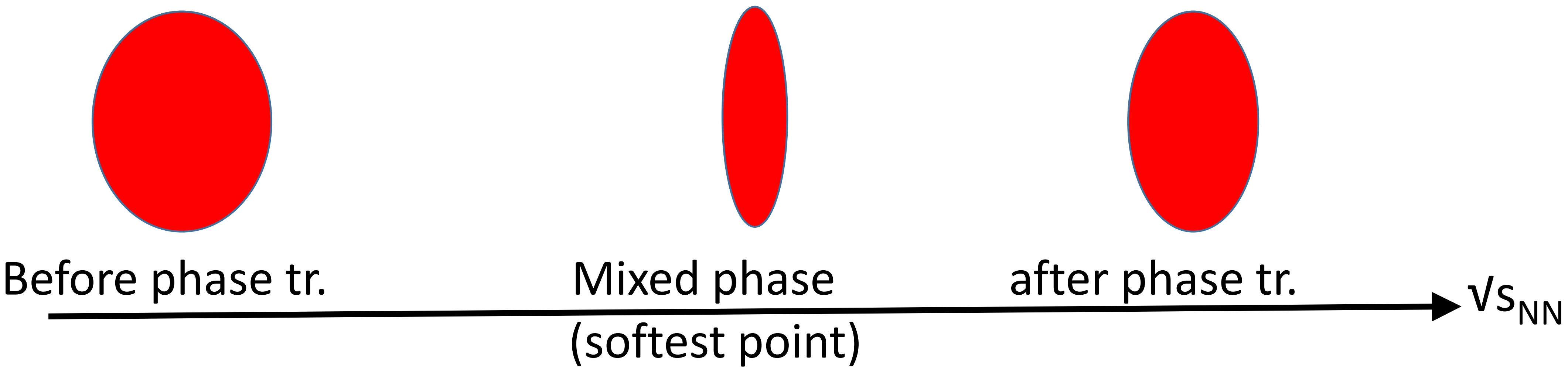
If complete stopping
At ultrarel. energies



EoS effect

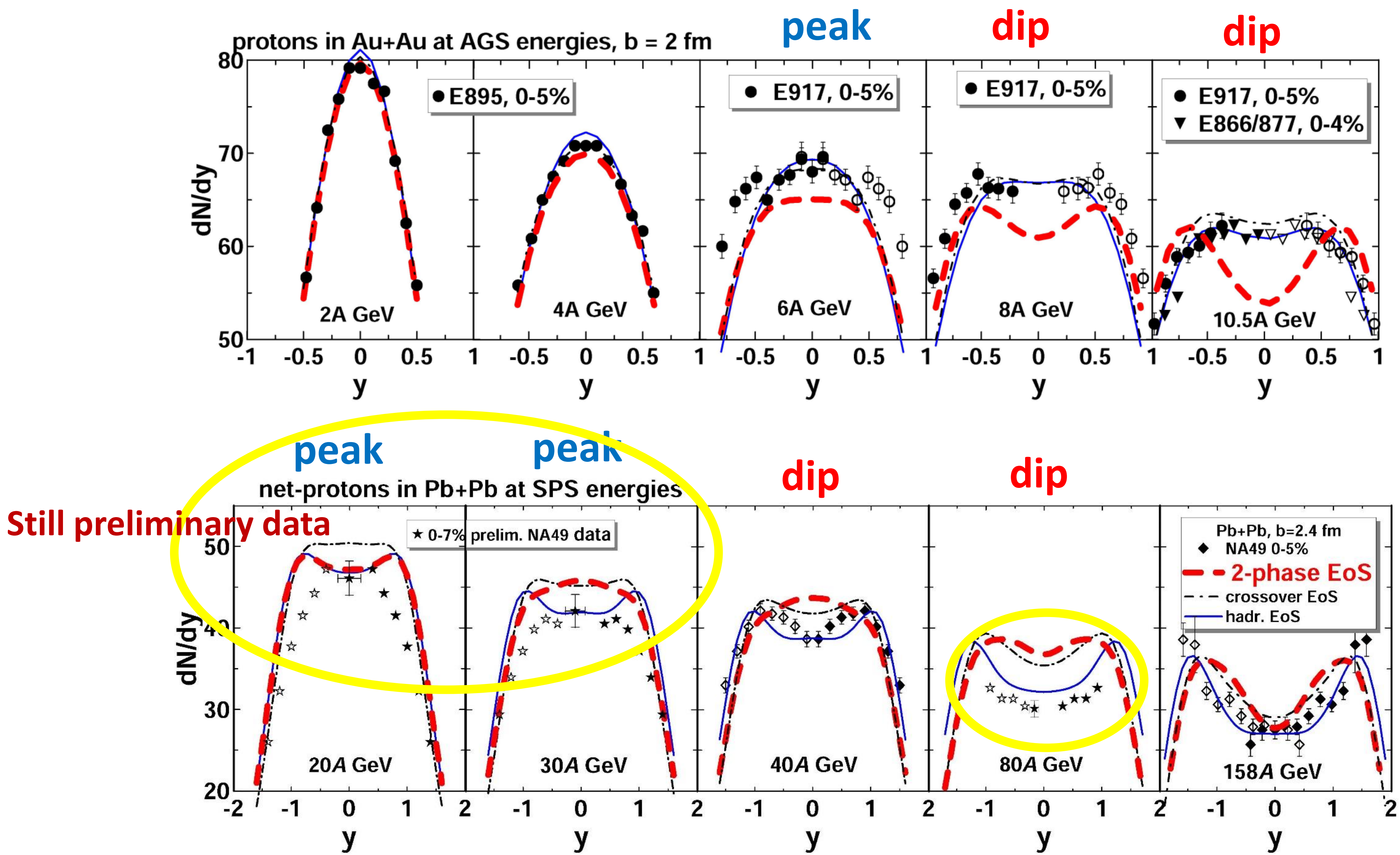
Gradual onset of this 1D expansion and transparency leads to monotonous peak-to-dip transition at NICA energies

EoS (phase transition) may disturb this monotonous evolution.
Shape of initial fireball may change as follows



which can even result in **peak-dip-peak-dip singularity** in dN/dy excitation function

Available data hint to such peak-dip-peak-dip behavior

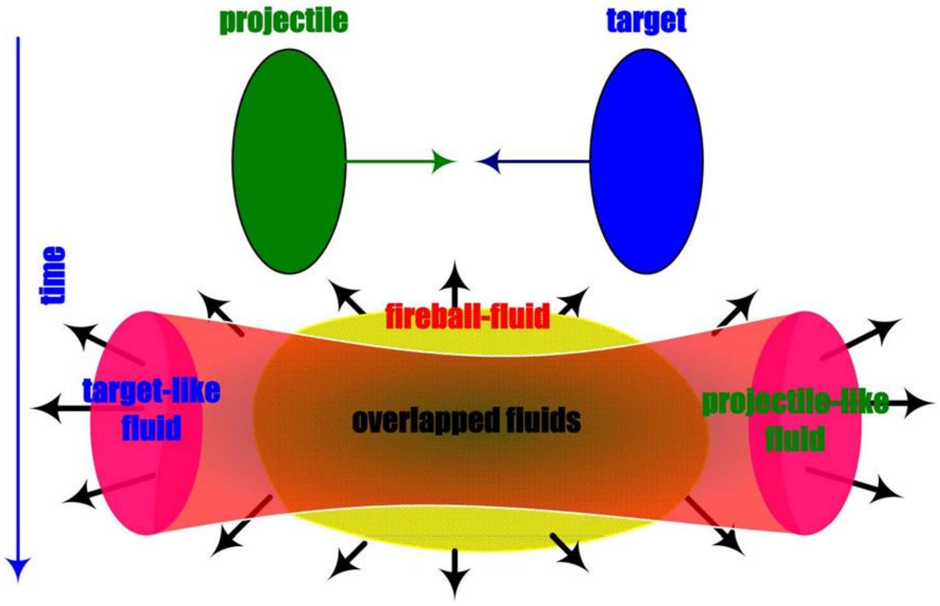


EoS with 1^{st}-order phase transition (2-phase EOS) qualitatively reproduce this behavior

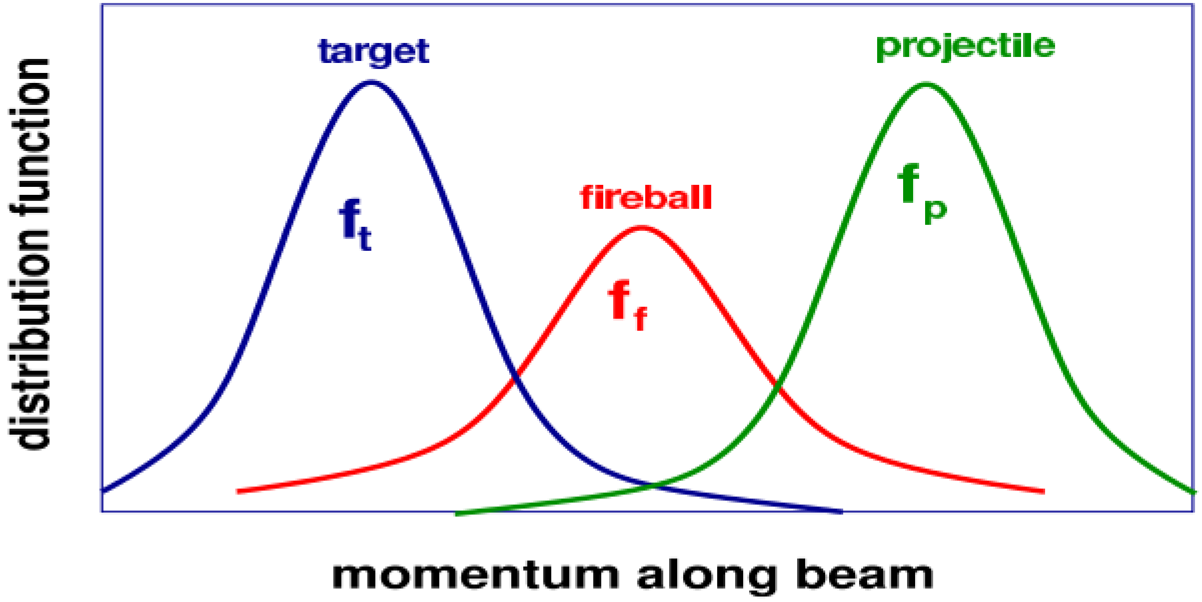
EoS with **crossover** transition semi-quantitively reproduce this behavior

Three-fluid dynamics (3FD) model

The 3FD approximation simulate the early, nonequilibrium stage of the strongly-interacting matter:



- ✓ baryon-rich fluids: nucleons of the projectile (p) and the target (t) nuclei.
- ✓ fireball (f) fluid: newly produced particles which dominantly populate the midrapidity region.



3FD model

Target-like fluid: $\partial_\mu J_t^\mu = 0$ — Leading particles carry bar. charge

$\partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$ — exchange/emission

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

Fireball fluid: $J_f^\mu = 0,$ — Baryon-free fluid

$\partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$ — Source term, Exchange

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

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

Physical Input

- ✓ Equation of State (**EoS**)
- ✓ Friction
- ✓ Freeze-out energy density ε_{frz} = 0.4 GeV/fm^3

3FD: YI, Russkikh, Toneev, PRC 73, 044904 (2006)

EoS:

- hadronic EoS (no phase transition)

Mishustin, Russkikh and Satarov,

Sov. J. Nucl. Phys. 54, 260 (1991)

- hadronic+QGP EoS with 1st-order PT
- hadronic+QGP EoS with crossover

EoS: Khvorostukhin, Skokov, Toneev, Redlich, EPJ C48, 531 (2006)

Equation of State

Hadronic EoS (H-EoS)

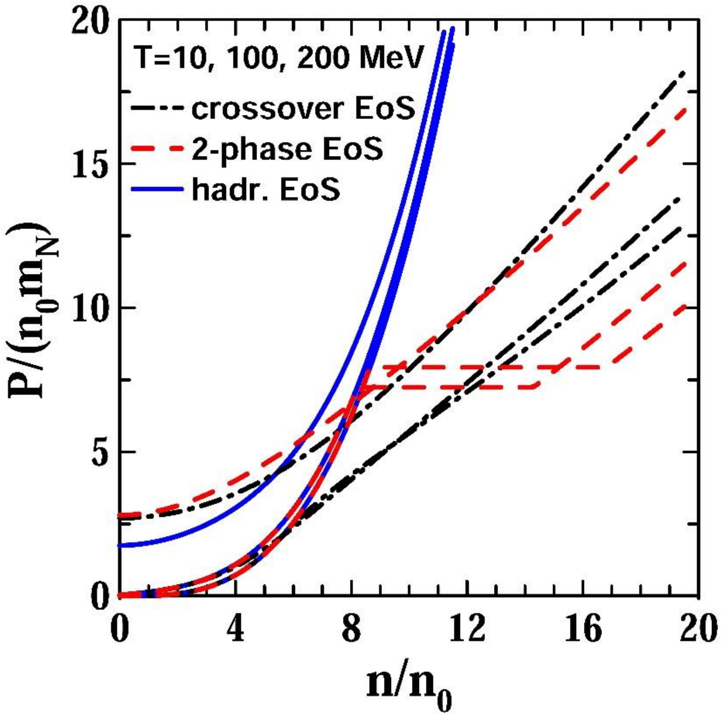
[Mishustin, Russkikh Satarov, Sov. J. Nucl. Phys. 54, 260 (1991)]

1st-order transition to QGP (2P-EoS)

[Khvorostukhin, Skokov, Redlich, Toneev, EPJ **C48**, 531 (2006)]

crossover transition to QGP (2P-EoS)

[Khvorostukhin, Skokov, Redlich, Toneev, EPJ **C48**, 531 (2006)]

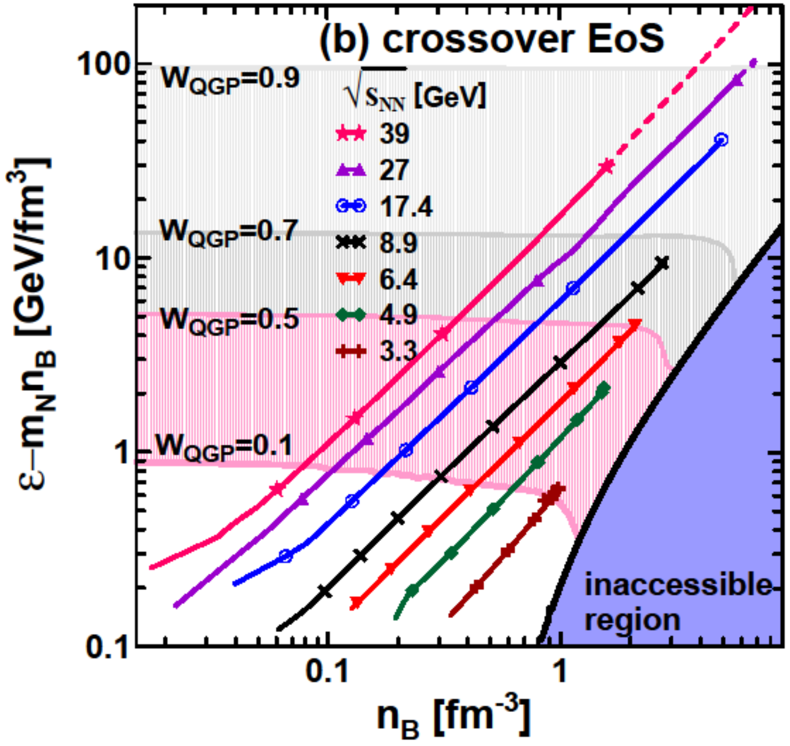


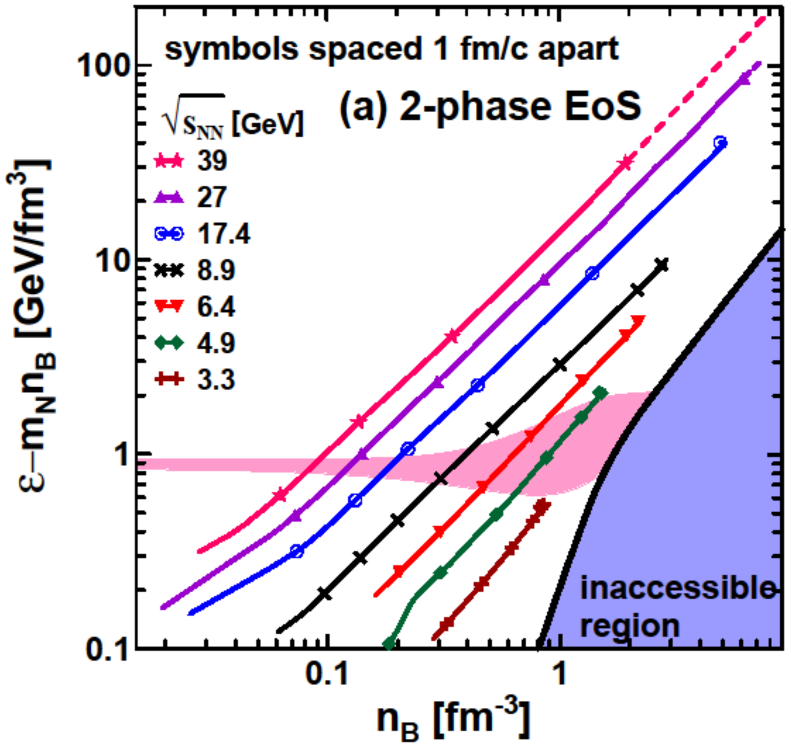
Phase transition → **EoS softening** (in dense baryon matter) and **change of stopping power**

QGP Transition in central region [Y.I., PRC 87 (2013) 064904]

$|x| \le 2$ fm, $|y| \le 2$ fm and $|z| \le \gamma_{cm}$ 2 fm, γ_{cm} = Lorentz factor of initial motion in cm frame

EoS's: Khvorostukhin, Skokov, Redlich, Toneev, EPJ C48, 531 (2006)





Slow crossover EoS
lattice QCD: fast crossover

deconfinement transition starts at $\sqrt{s_{NN}} \ge 4$ GeV .

To quantify the above-discussed "peak-dip-peak-dip" irregularity we do

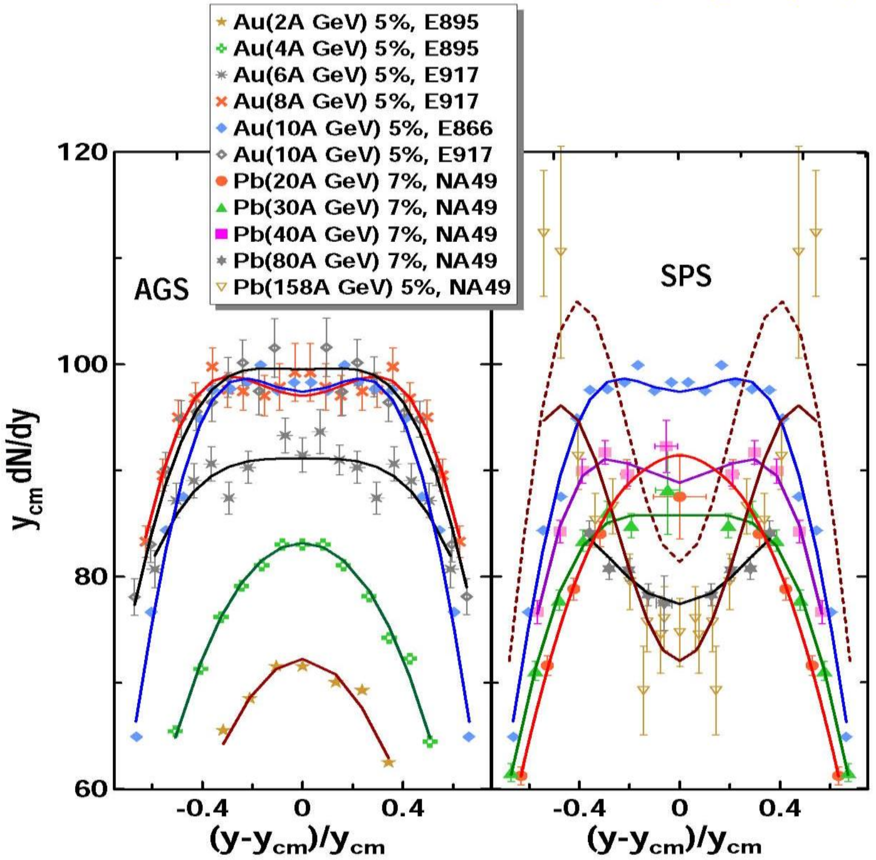
Two-Thermal-Sources Fit

Baryon Stopping

GSI, 18.11.2010

MFD Models
2-Fluid Models
3-Fluid Models
3FD
Baryon Stopping
Fit
Reduced curvature
Trajectories
Crossover
Summary1
Other Signals
Summary

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



$y_{cm} = y_{beam}$ in collider regime

Two thermal sources shifted by $\pm y_s$ from the midrapidity.

w_s = width of the sources

Reduced curvature in the midrapidity

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

with respect to the "dimensionless" rapidity $(y - y_{cm})/y_{cm}$.

C_y is independent of the overall normalization

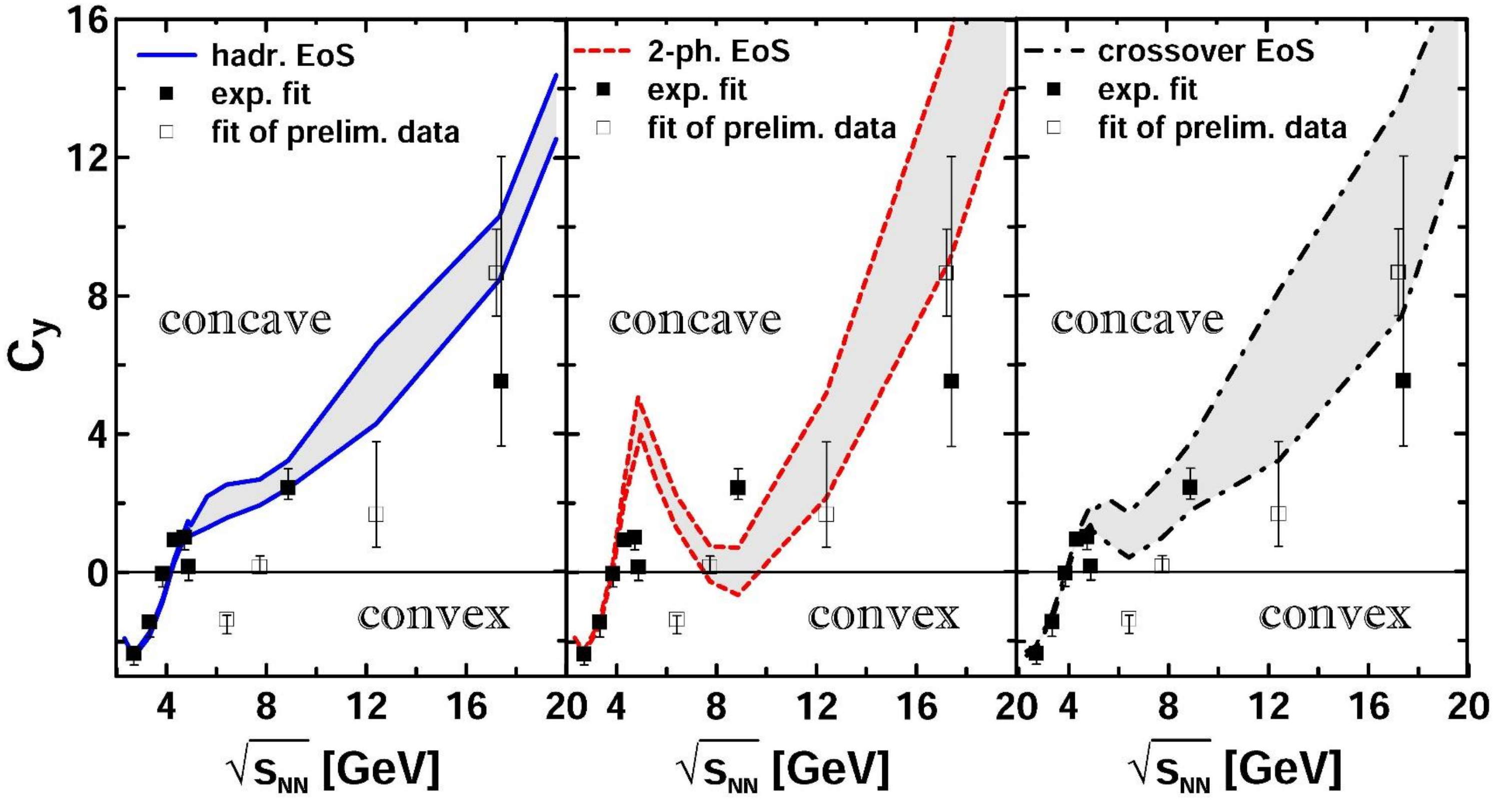
$C_y =$ **shape (concave or convex) at midrapidity**

and

$(y_{cm} dN/dy)_{y=y_{cm}} =$ **magnitude at midrapidity**

two independent characteristics of a spectrum

Wiggle in $C_y(\sqrt{s_{NN}})$?



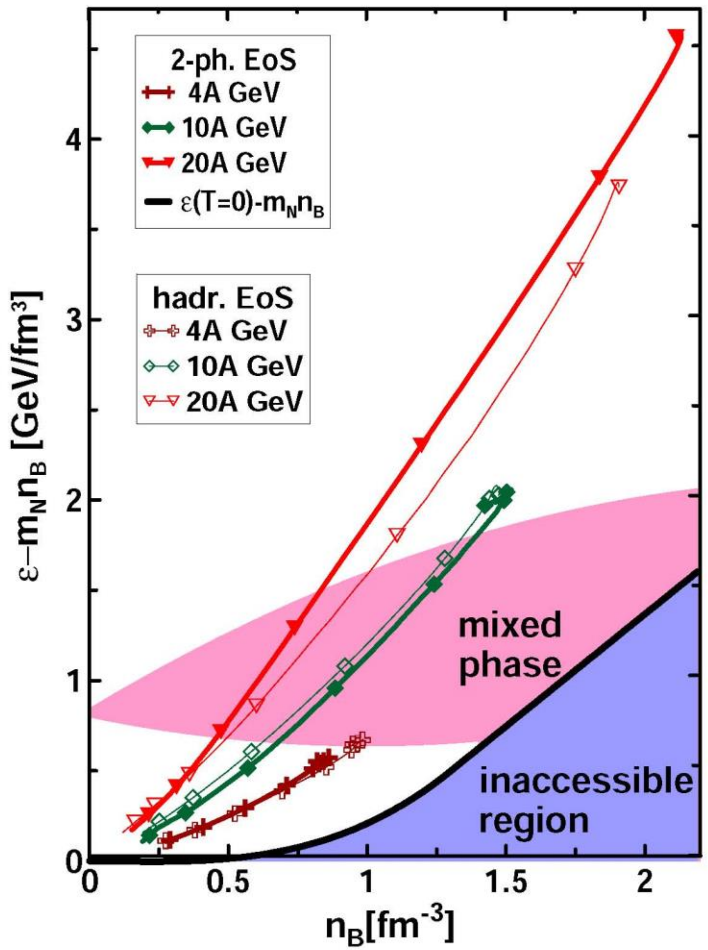
Wiggle in exp. $C_y(\sqrt{s_{NN}})$ is only due to preliminary data.

The question of its existence is still open.

Crossover EoS (weak wiggle) is the best in reproduction of exp. $C_y(\sqrt{s_{NN}})$ so far.

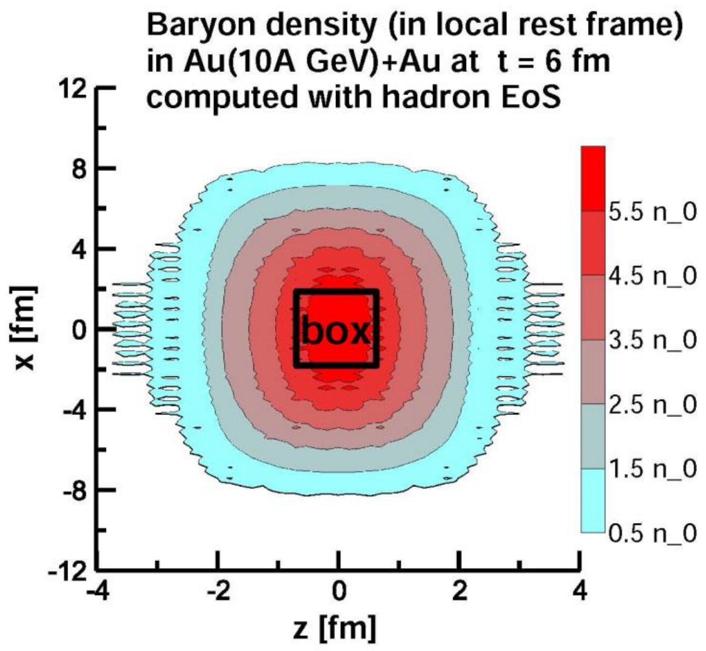
Upper bounds: fit at $|y|/y_{beam} < 0.7$
Lower bounds: fit at $|y|/y_{beam} < 0.5$
Ivanov and Blaschke, PRC 92 (2015) 024916

Trajectories of matter evolution in the center box



Densities in the center box

$4 \times 4 \times 4\gamma_{cm}$



System gets into phase-transition region ⇒ wiggle starts

Light-nuclei contribution

In presented calculations:
Light-nuclei contribution (coalescence) was subtracted from primordial net-protons

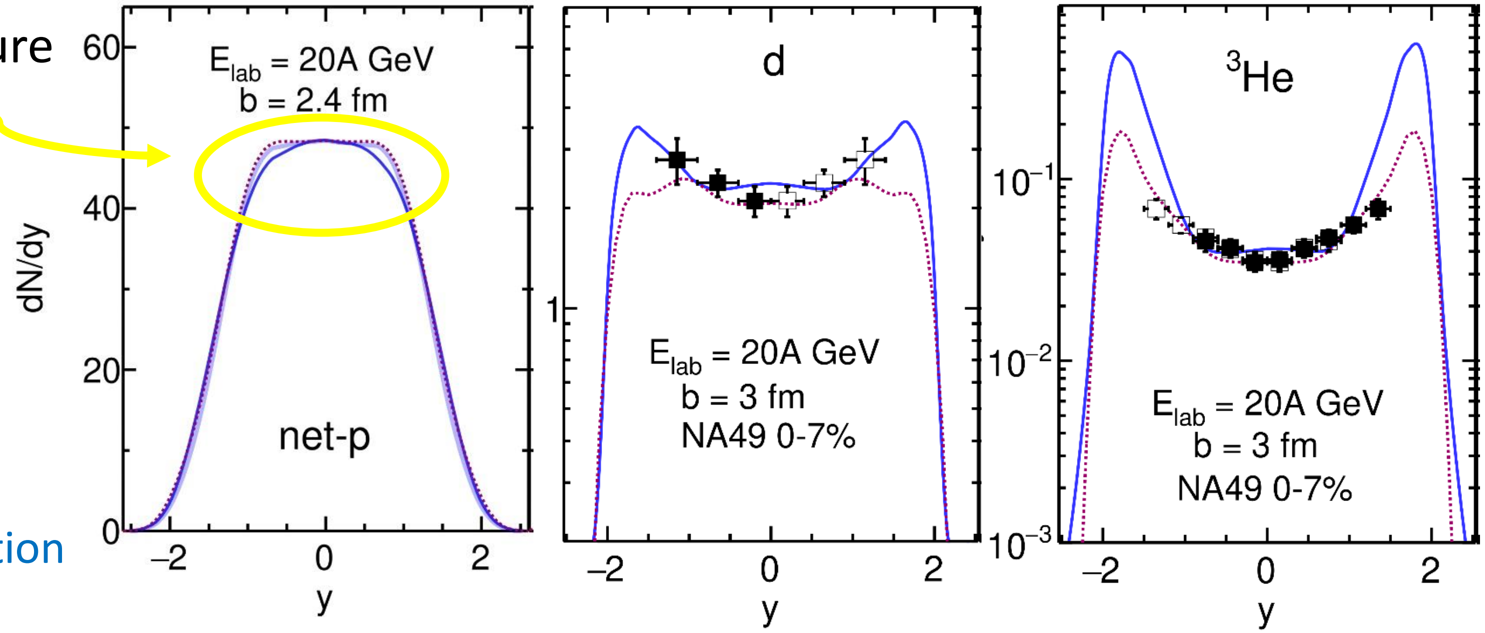
Now we have a model (THESEUS) that automatically subtract light-nuclei contribution
[talk by M. Kozhevnikova]

Subtraction of different light-nuclei contributions may change curvature (C_y) of net-p dN/dy

Dotted line: coalescence
Solid line: THESEUS

Just a remark:
This is a reliable prediction for net-p at 20A GeV in view of good reproduction of d and ^{3}He

Pb + Pb [Kozhevnikova&Ivanov, PRC 107 (2023), 024903]



Summary

✓Baryon stopping is sensitive to (phase) transition into QGP

✓ This stopping can be quantified by net-proton dN/dy:

wiggle in $C_y(\sqrt{s_{NN}})$

✓Data qualitatively favor onset of a phase transition between 4 and 8 GeV (in terms of $\sqrt{s_{NN}}$)

✓Data in this region are still preliminary

✓Data are required within a wide rapidity windows $|y| < 0.7\ y_{beam}$:

from $|y| < 0.8$ at 4 GeV to $|y| < 1.7$ at 11.5 GeV

Thank you

for your attention!