Simulating collectivity in dense baryon matter with multiple fluids

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Aspects of Criticality II

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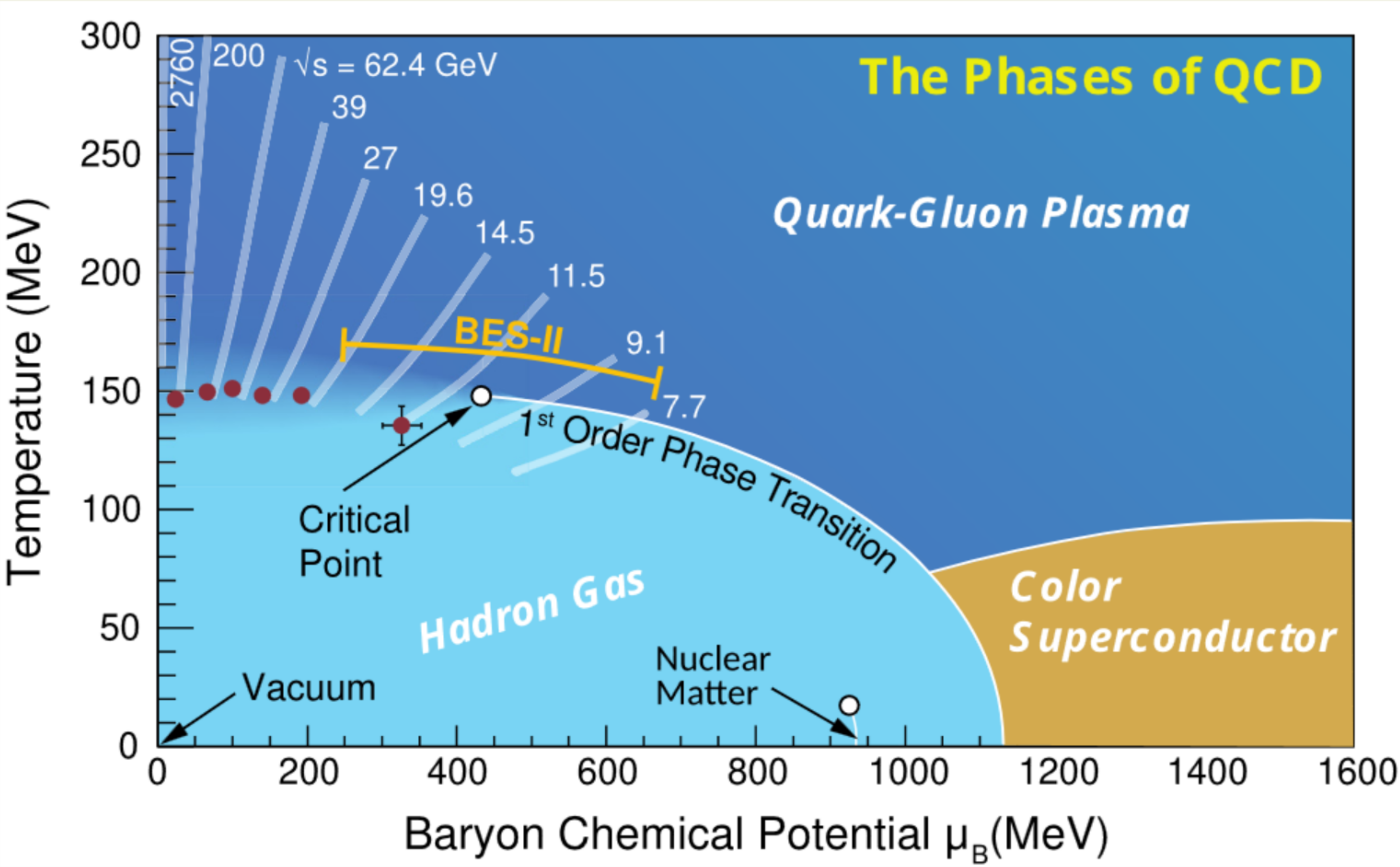
with Jakub Cimerman, Iurii Karpenko, Boris Tomasik
and Clemens Werthmann
PRC107, 044902 (2023)


The Phases of QCD
Quark-Gluon Plasma
Hadron Gas
Color Superconductor
1st Order Phase Transition
Critical Point
Vacuum
Nuclear Matter
BES-II
√s = 62.4 GeV
2760
200
39
27
19.6
14.5
11.5
9.1
7.7
Temperature (MeV)
Baryon Chemical Potential μB(MeV)
0
50
100
150
200
250
300
0
200
400
600
800
1000
1200
1400
1600

Challenges

1. **lower multiplicity $\Longrightarrow$ smaller system**
   $\Longrightarrow$ larger deviations from equilibrium?

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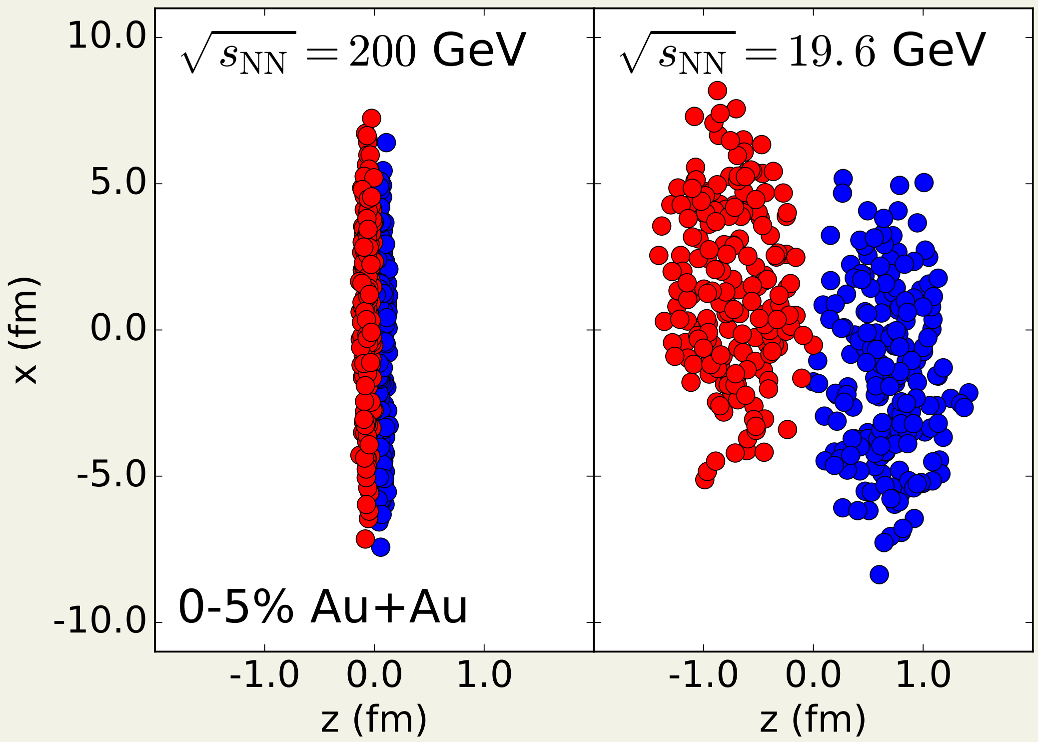

Shen & Schenke, PRC97, 024907 (2018)

Challenges

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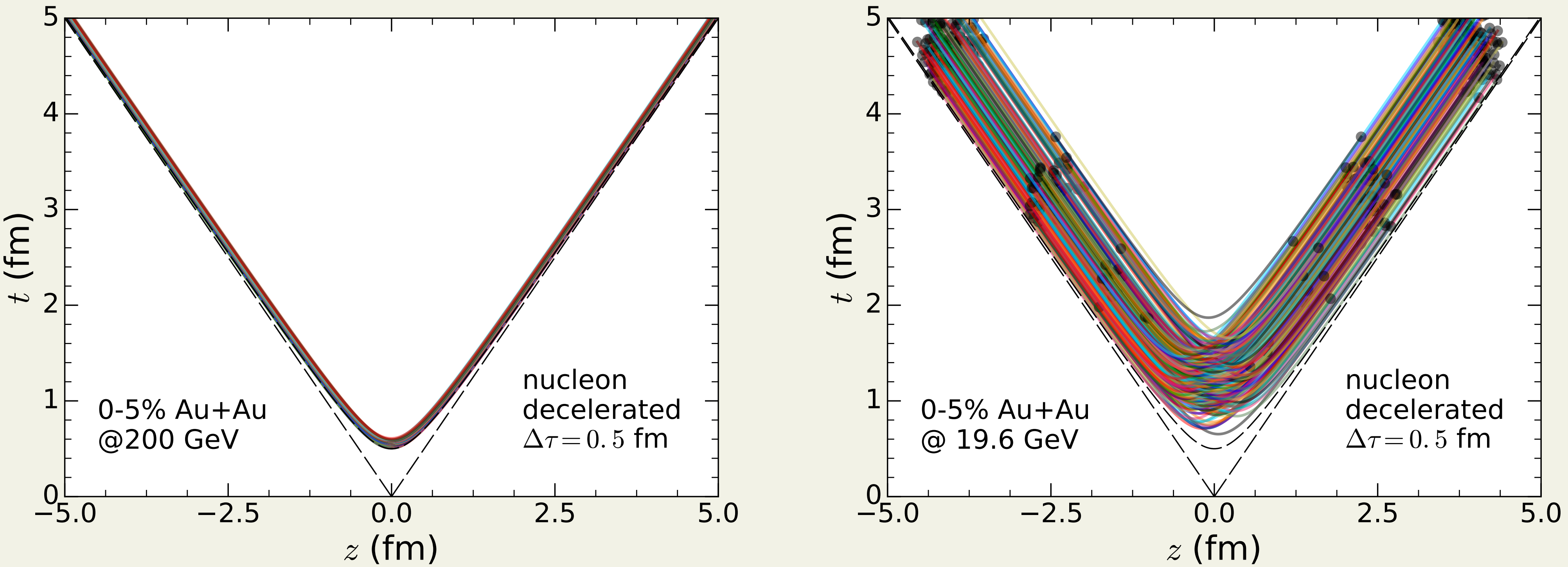
   $\Longrightarrow$ larger deviations from equilibrium?

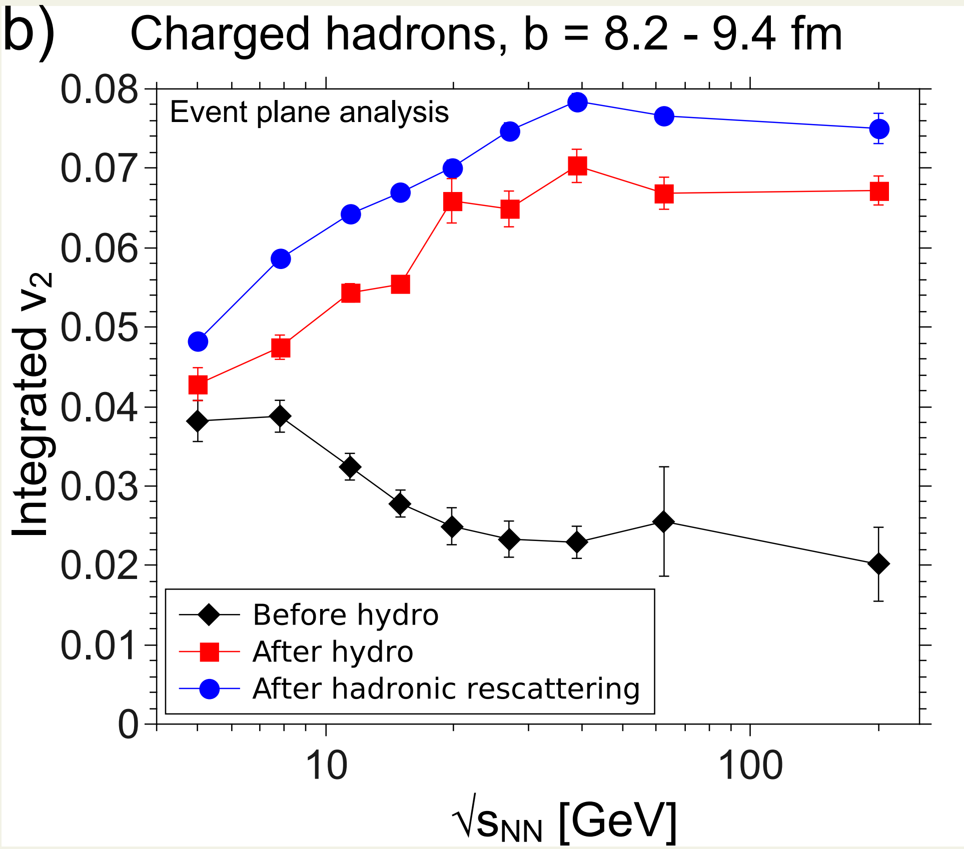
2. primary collisions overlap with secondary collisions



Shen & Schenke, PRC97, 024907 (2018)

Solutions

- **"Sandwich hybrid"**
  - **cascade until the nuclei have passed each other**
  - **fluid until hadronisation**
  - **cascade until freeze out**



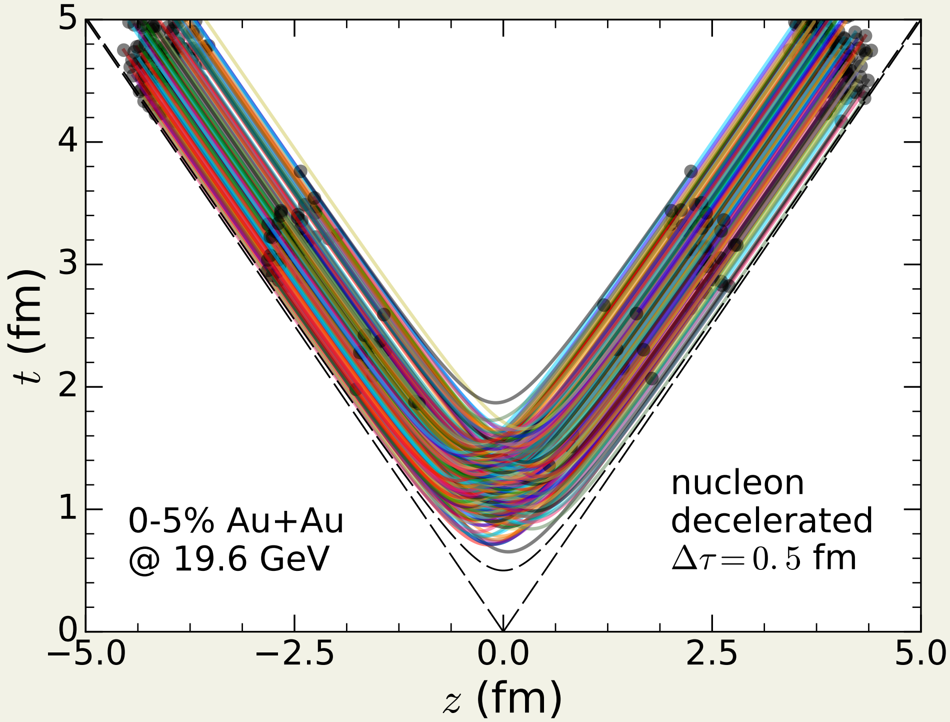
Auvinen & Petersen, PRC88, 064908 (2013)

- **at $\sqrt{s_{NN}} < 10$ GeV not much happens during the hydro stage**

- **sensitivity to EoS?**

Solutions

- **Dynamical initialisation**
  - **each primary collision a source term for fluid**
  - $\partial_\mu T^{\mu\nu} = J^\nu$
  - $\partial_\mu N_B^\mu = \rho_B$



Shen & Schenke, PRC97, 024907 (2018)

- **no interaction between incoming nucleons and produced particles**

3-fluid dynamics

$$0 = \partial_\mu T^{\mu\nu}$$

3-fluid dynamics

$$\begin{aligned} 0 &= \partial_\mu T^{\mu\nu} \\ &= \partial_\mu T_{\rm t}^{\mu\nu} \end{aligned}$$

$T_{\rm t}^{\mu\nu}$ = **target fluid**

3-fluid dynamics

$$\begin{aligned} 0 &= \partial_\mu T^{\mu\nu} \\ &= \partial_\mu T^{\mu\nu}_{\mathrm{t}} + \partial_\mu T^{\mu\nu}_{\mathrm{p}} \end{aligned}$$

$T^{\mu\nu}_{\mathrm{t}}$ = **target fluid**

$T^{\mu\nu}_{\mathrm{p}}$ = **projectile fluid**

3-fluid dynamics

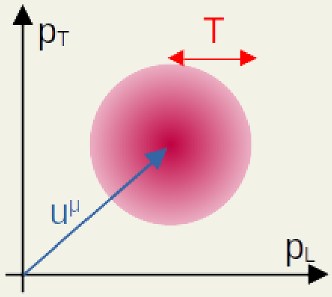
$$
\begin{aligned}
0 &= \partial_\mu T^{\mu\nu} \\
&= \partial_\mu T^{\mu\nu}_{\mathrm{t}} + \partial_\mu T^{\mu\nu}_{\mathrm{p}} + \partial_\mu T^{\mu\nu}_{\mathrm{fb}}
\end{aligned}
$$

$T^{\mu\nu}_{\mathrm{t}} =$ **target fluid**
$T^{\mu\nu}_{\mathrm{p}} =$ **projectile fluid**
$T^{\mu\nu}_{\mathrm{fb}} =$ **fireball fluid**

- **target and projectile represent colliding nucleons**
- **fireball (loosely) represents produced particles**
- **three fluids, each with temperature and flow velocity of its own**

3-fluid dynamics

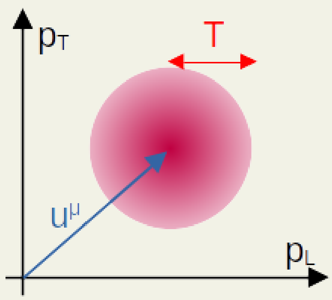
- **distributions in momentum space**



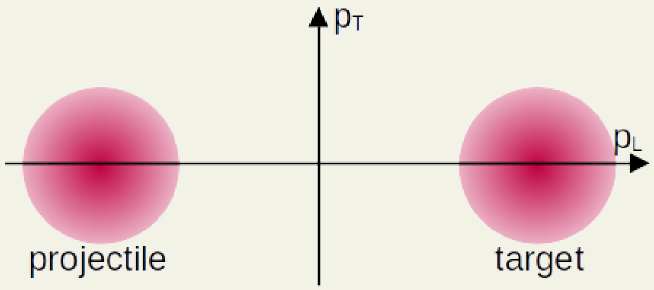
one fluid

3-fluid dynamics

- **distributions in momentum space**



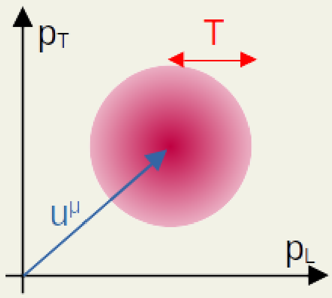
one fluid



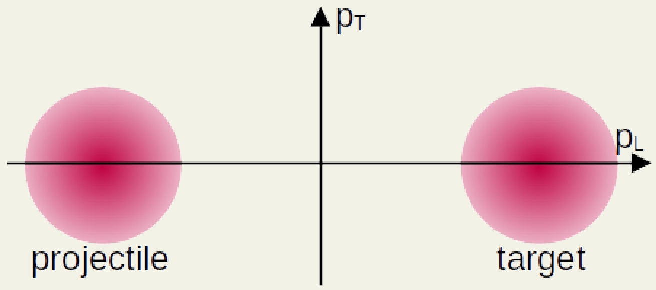
2 fluids

3-fluid dynamics

- **distributions in momentum space**



one fluid



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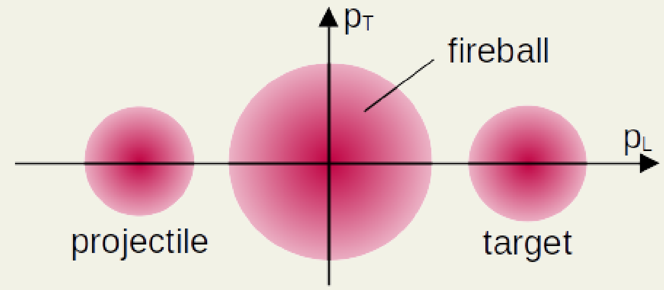

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3-fluid dynamics

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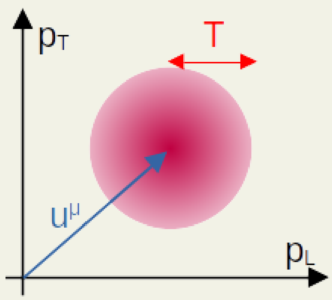
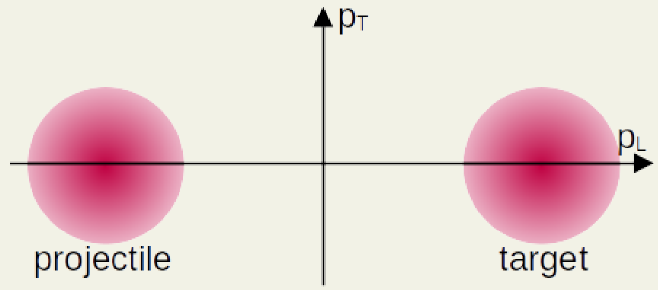


one fluid



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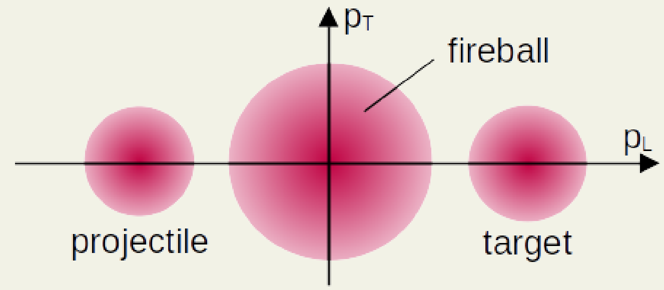

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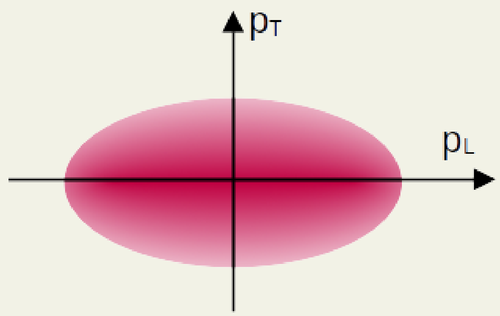
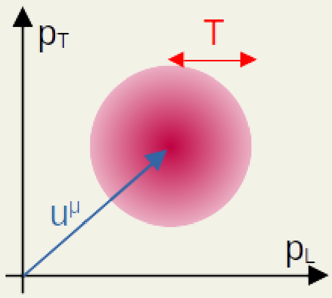


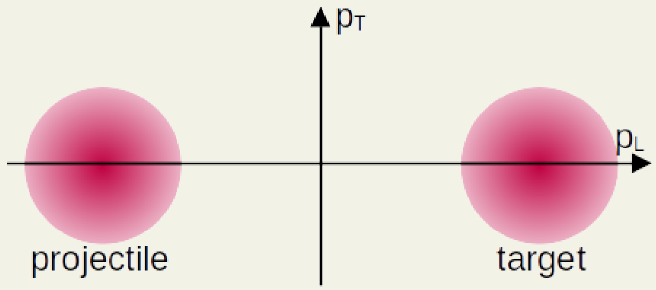
anisotropic hydro

3-fluid dynamics

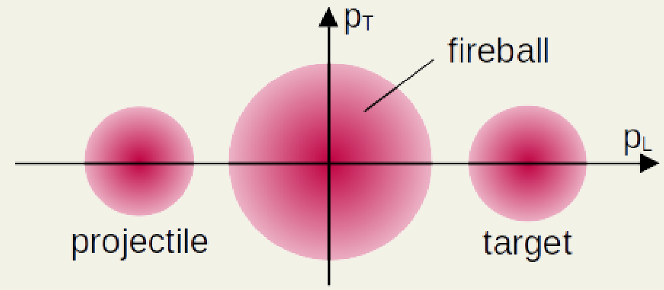
- **distributions in momentum space**



one fluid



2 fluids



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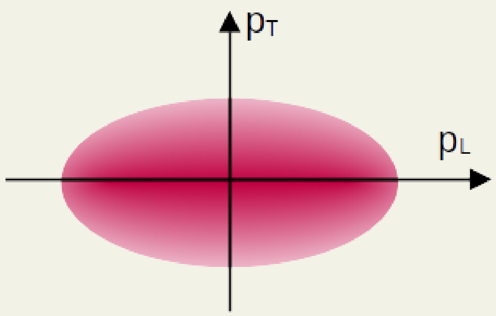

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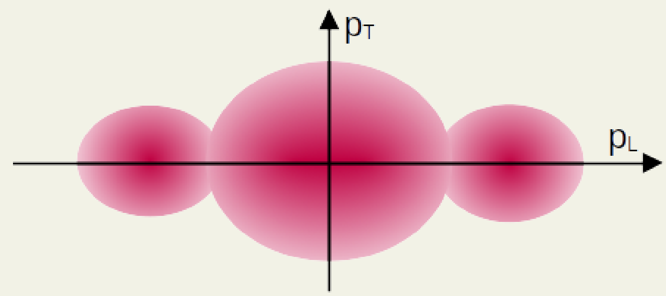


somewhat realistic distribution

3-fluid dynamics

$$\partial_\mu T^{\mu\nu}_{\rm t}(x) = -F^\nu_{\rm t}(x) + F^\nu_{\rm ft}(x)$$
$$\partial_\mu T^{\mu\nu}_{\rm p}(x) = -F^\nu_{\rm p}(x) + F^\nu_{\rm fp}(x)$$
$$\partial_\mu T^{\mu\nu}_{\rm fb}(x) = F^\nu_{\rm p}(x) + F^\nu_{\rm t}(x) - F^\nu_{\rm fp}(x) - F^\nu_{\rm ft}(x)$$

- **interaction between target and projectile:**
  friction terms $-F^\nu_{\rm t}(x)$ **and** $-F^\nu_{\rm p}(x)$
- **interaction between fireball and target/projectile:**
  friction terms $F^\nu_{\rm fp}(x)$ **and** $F^\nu_{\rm ft}(x)$

Friction from kinetic theory

Boltzmann equation for three fluids

$$p^\mu \partial_\mu f_i = C_i[f_p, f_t, f_f] = \sum_{j,k} C_i^{jk}[f_j, f_k], \qquad i,j,k \in \{p,t,f\}$$

C_i^{jk}**: change in distribution/fluid i due to interactions of particles in j and k**

for given C_i^{jk}, friction obtained as

$$\partial_\mu T_i^{\mu\nu} = \int \frac{\mathrm{d}^3 p}{p^0} p^\nu C_i = F_i^\nu\,, \quad \partial_\mu J_{B,i}^\mu = B_i \int \frac{\mathrm{d}^3 p}{p^0} C_i = R_{B,i}$$

Friction from kinetic theory

collision integrals in terms of scattering cross sections

$$C_i^{ij}[f_i, f_j](p_i) = \int \mathrm{d}^3 p_j \, p_i^0 \Big[\underbrace{-f_i(p_i) f_j(p_j) v_{\mathrm{rel}} \sigma_{ij\to X}}_{\text{loss}} + \underbrace{\int \mathrm{d}^3 q_i f_i(q_i) f_j(p_j) v_{\mathrm{rel}} \frac{\mathrm{d}\sigma_{ij\to iX}}{\mathrm{d}^3 p_i}}_{\text{gain}} \Big]$$

from these, approximative friction formulae are derived

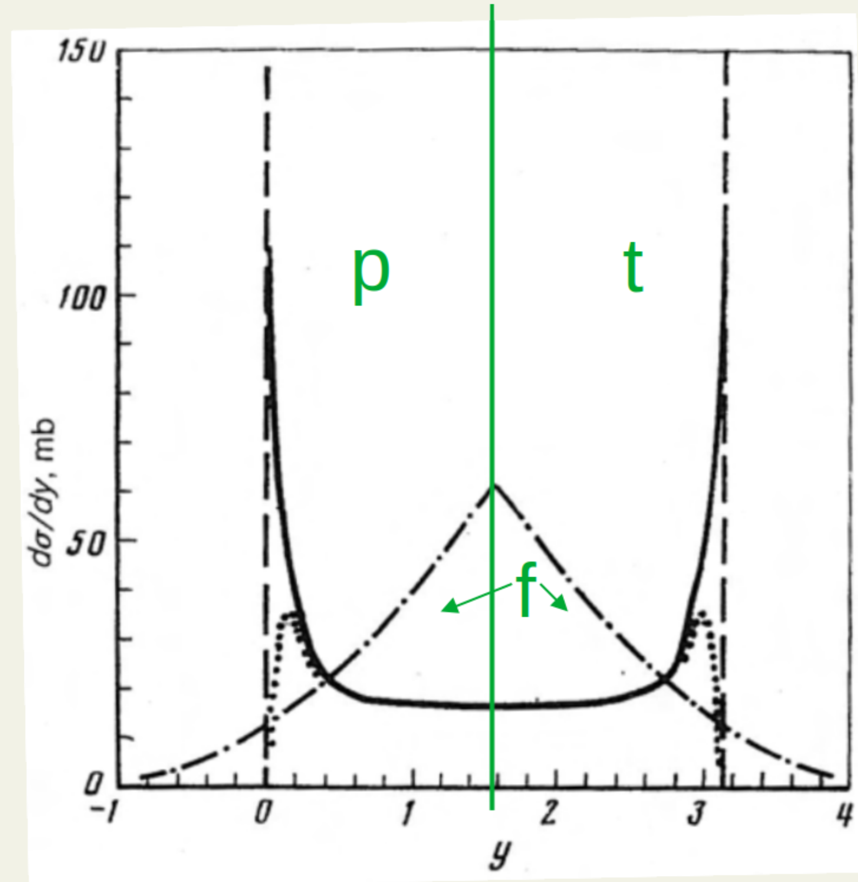
problems:

- **cross sections may not be fully measured in experiment**
- **d.o.f. change in deconfinement transition**

Satarov/Ivanov approach

Ivanov, Russkikh, Toneev PRC 73, 044904 (2006)

- **N+N scattering: N strongly peaked at ingoing rapidities, π at midrapidity $\Rightarrow$ in p-t friction: N stay in p/t, π go to f**
- **$\pi + N$ mostly resonance formation $\Rightarrow$ all outgoing particles from p-f friction go to p**
- **uncertainty in deconfined phase: densities multiplied with $\sqrt{s}$-dependent prefactor**



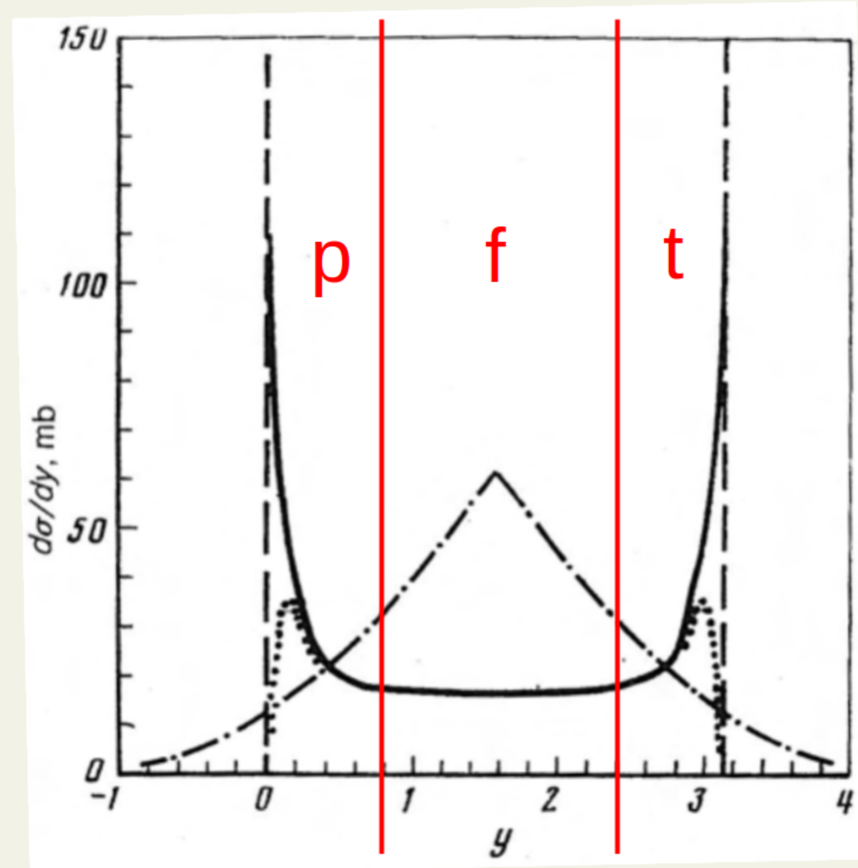
**pros: only need total crosssections.
can describe the double peak in baryon distributions!
cons: $\mu_B = 0$ in fireball**

modified Satarov/Ivanov approach

- **for our purposes:**
  need high μ_B also in fireball!

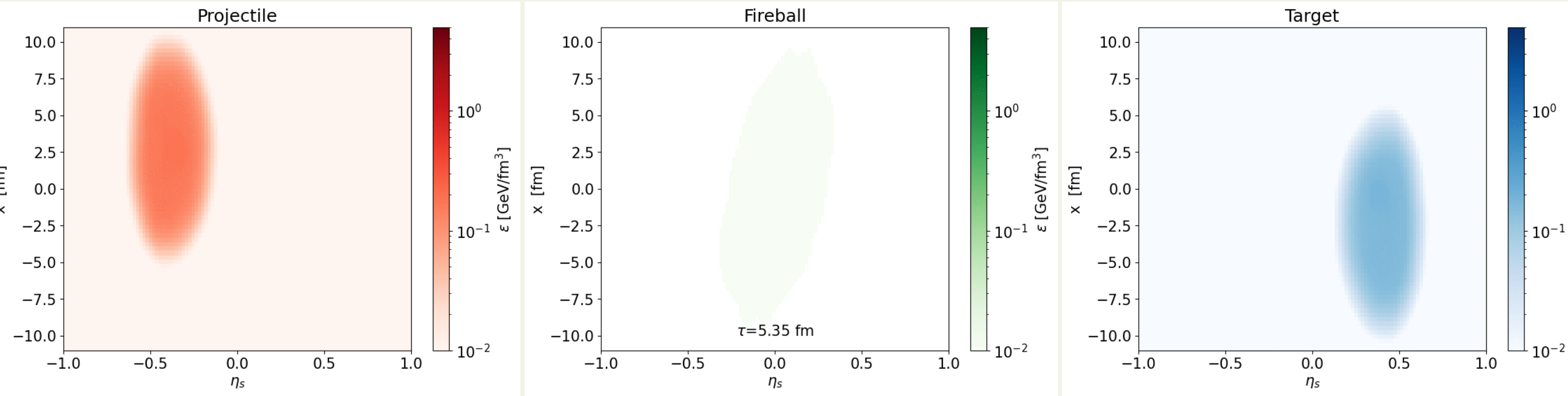
- **idea: divide outgoing N from N+N into 3 regions**
  $\Rightarrow$ modified p+t friction moves B to fireball

  <u>but:</u> need doubly differential cross sections! (y, E)



Evolution of energy density

- **Au+Au collision at $\sqrt{s_{\mathrm{NN}}} = 7.7$ GeV**



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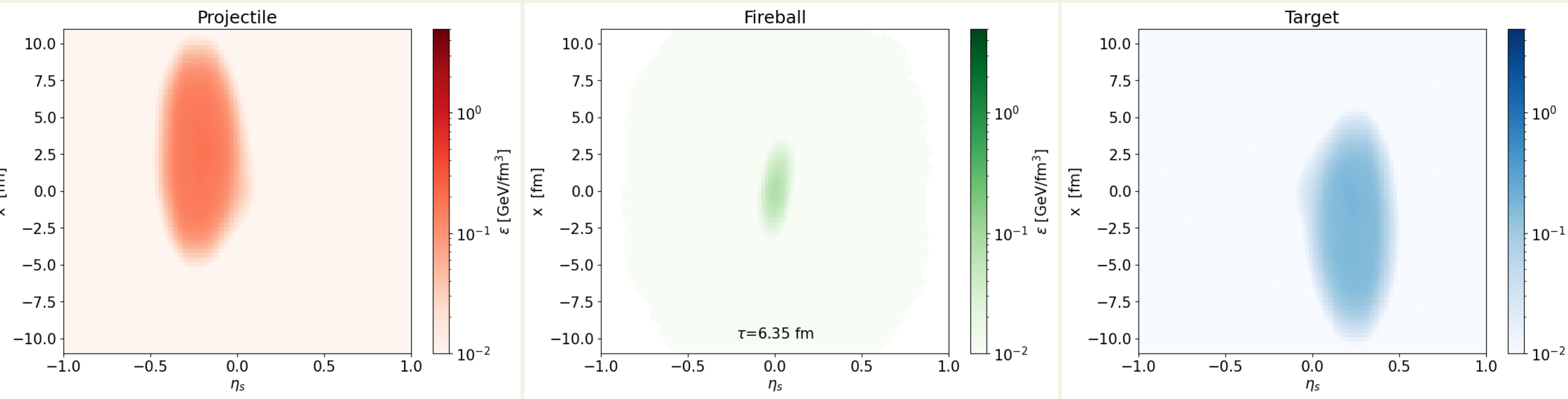

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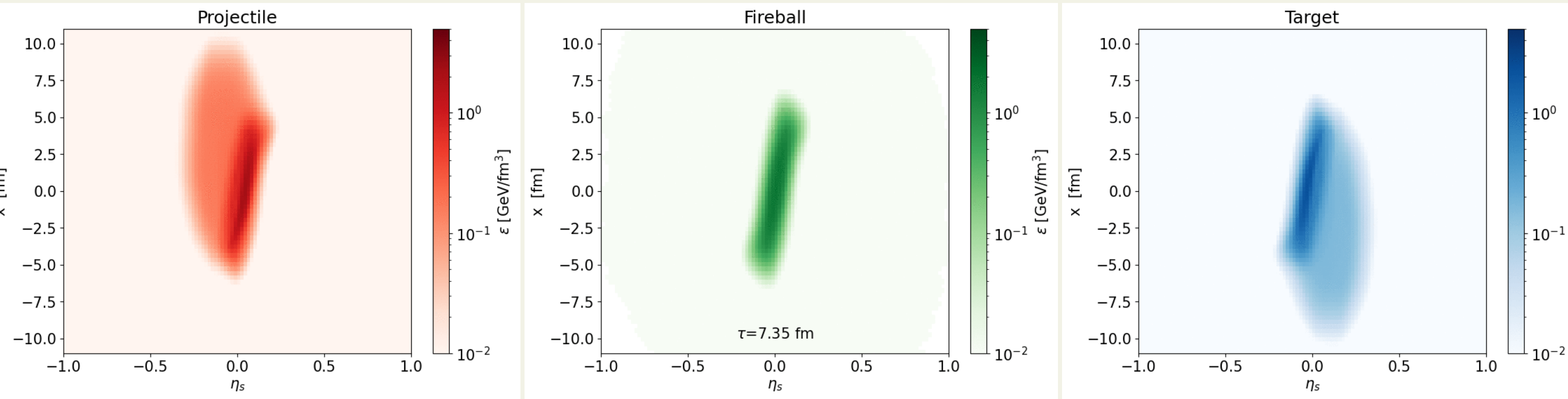

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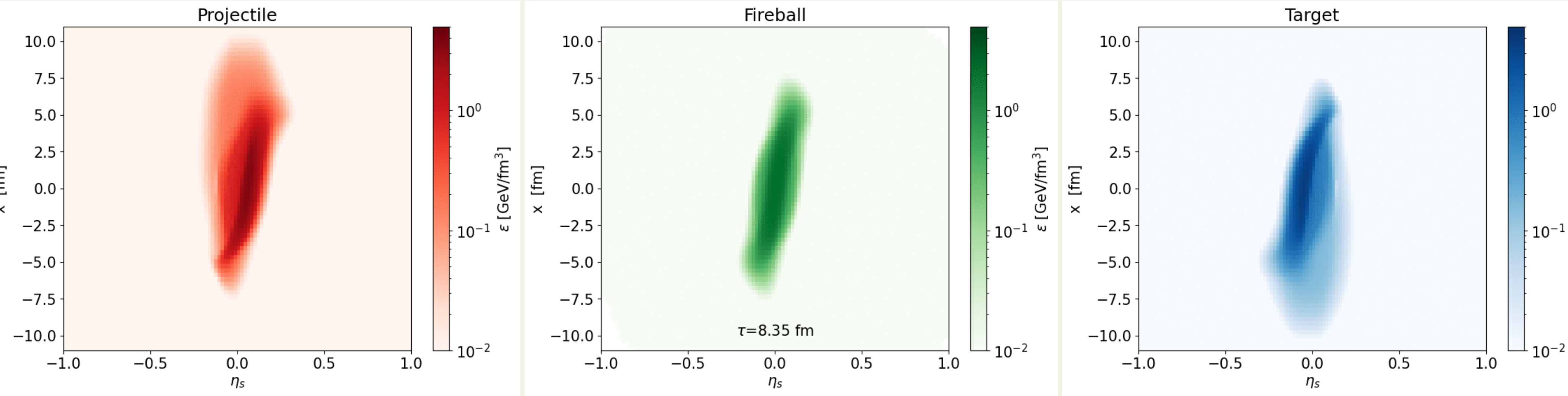

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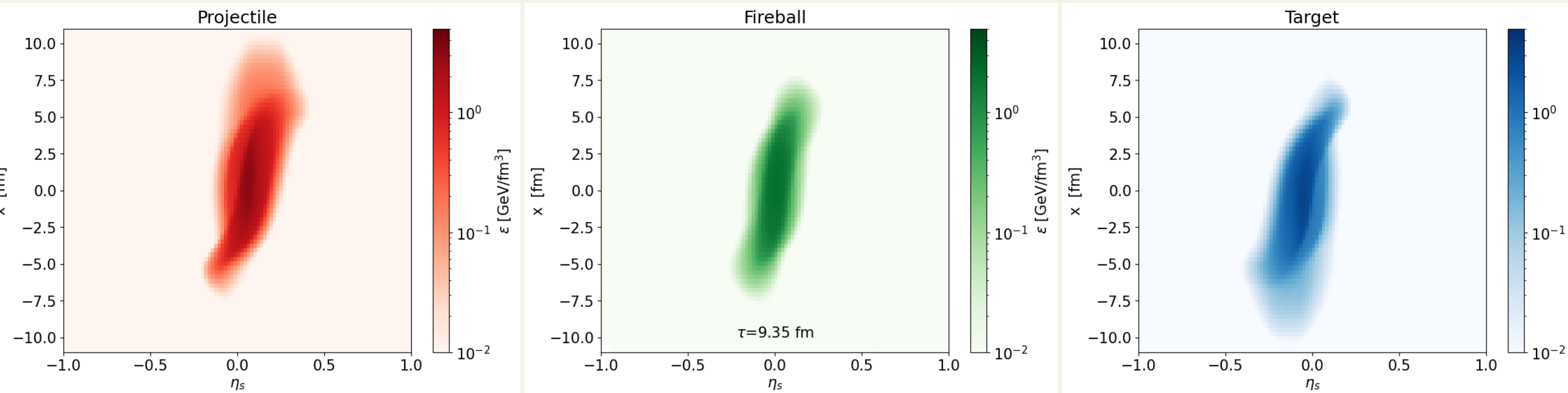

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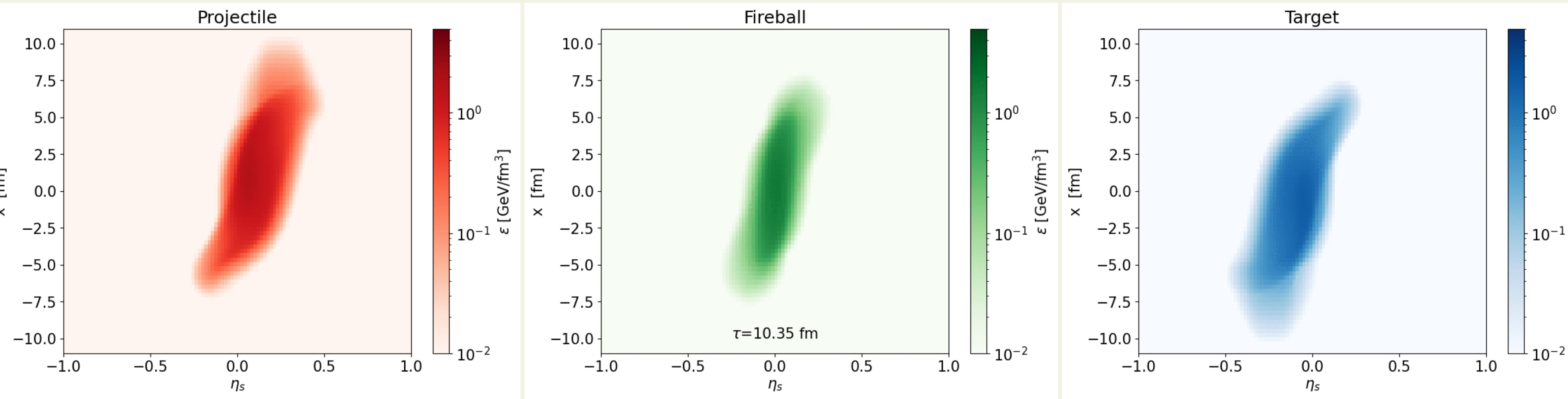

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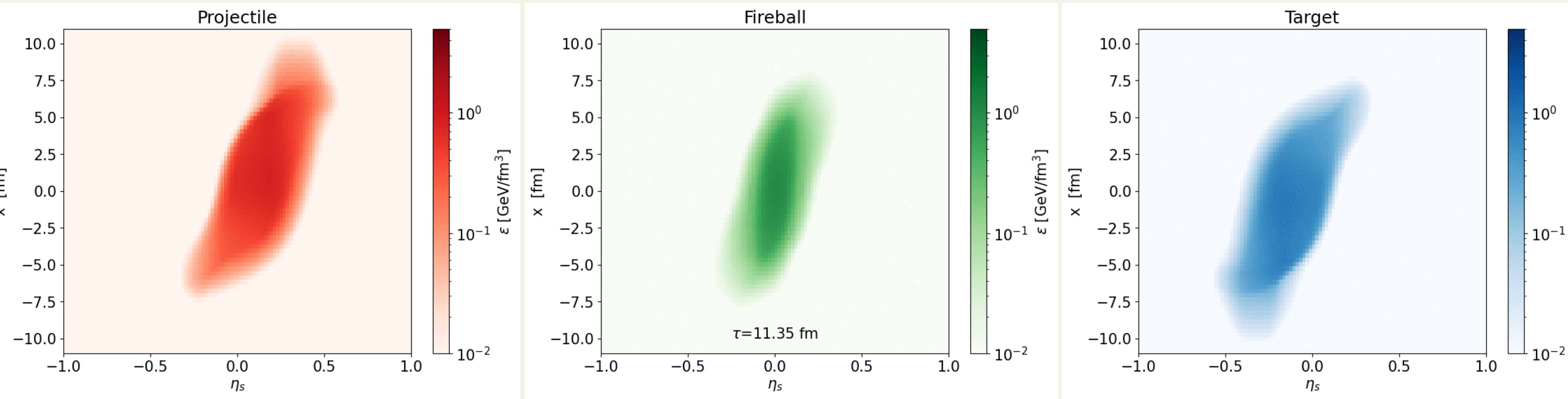

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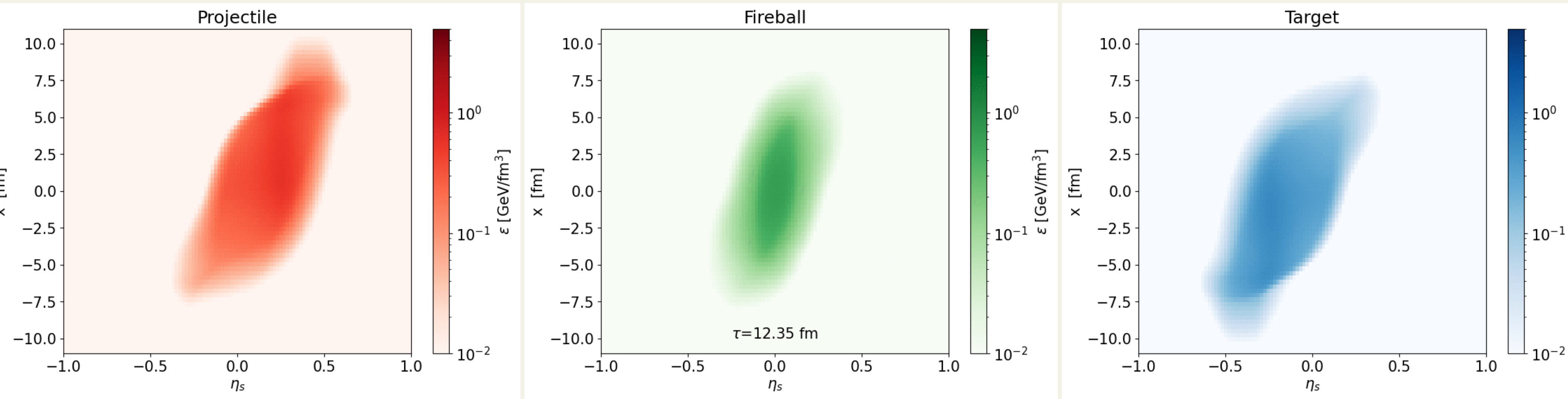

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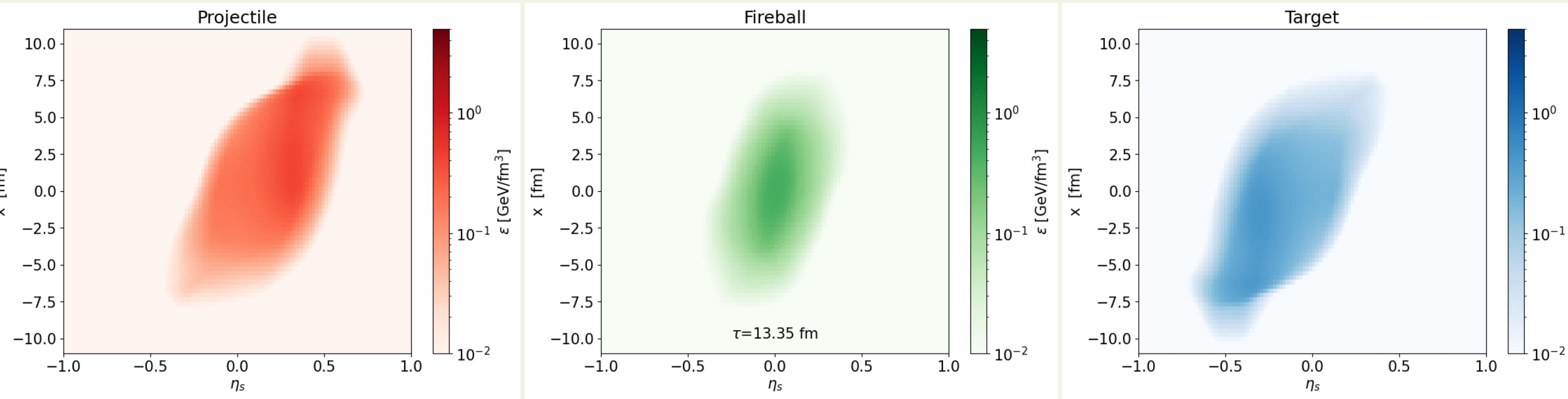

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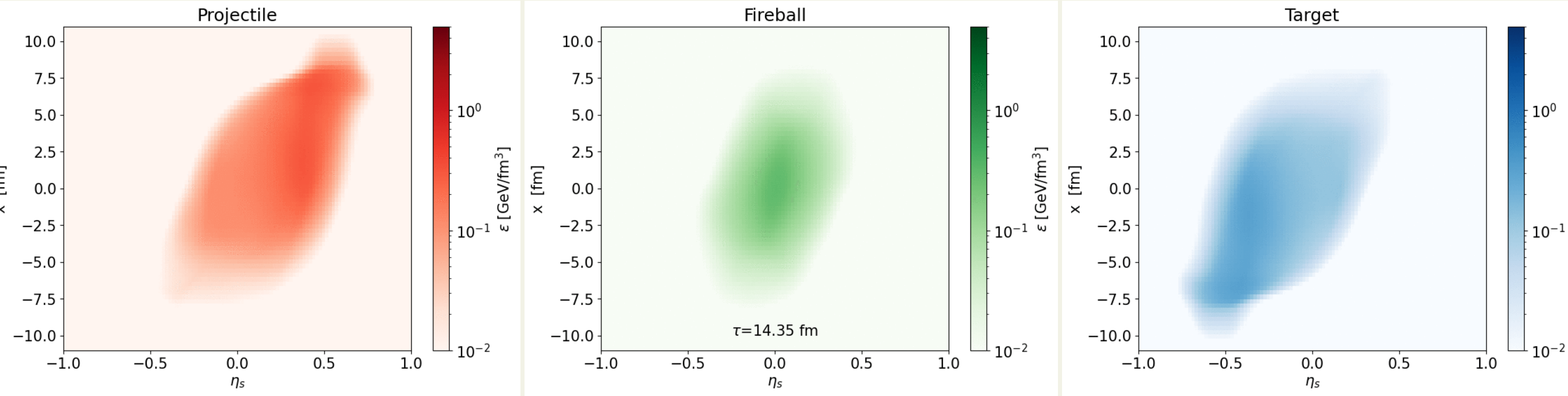
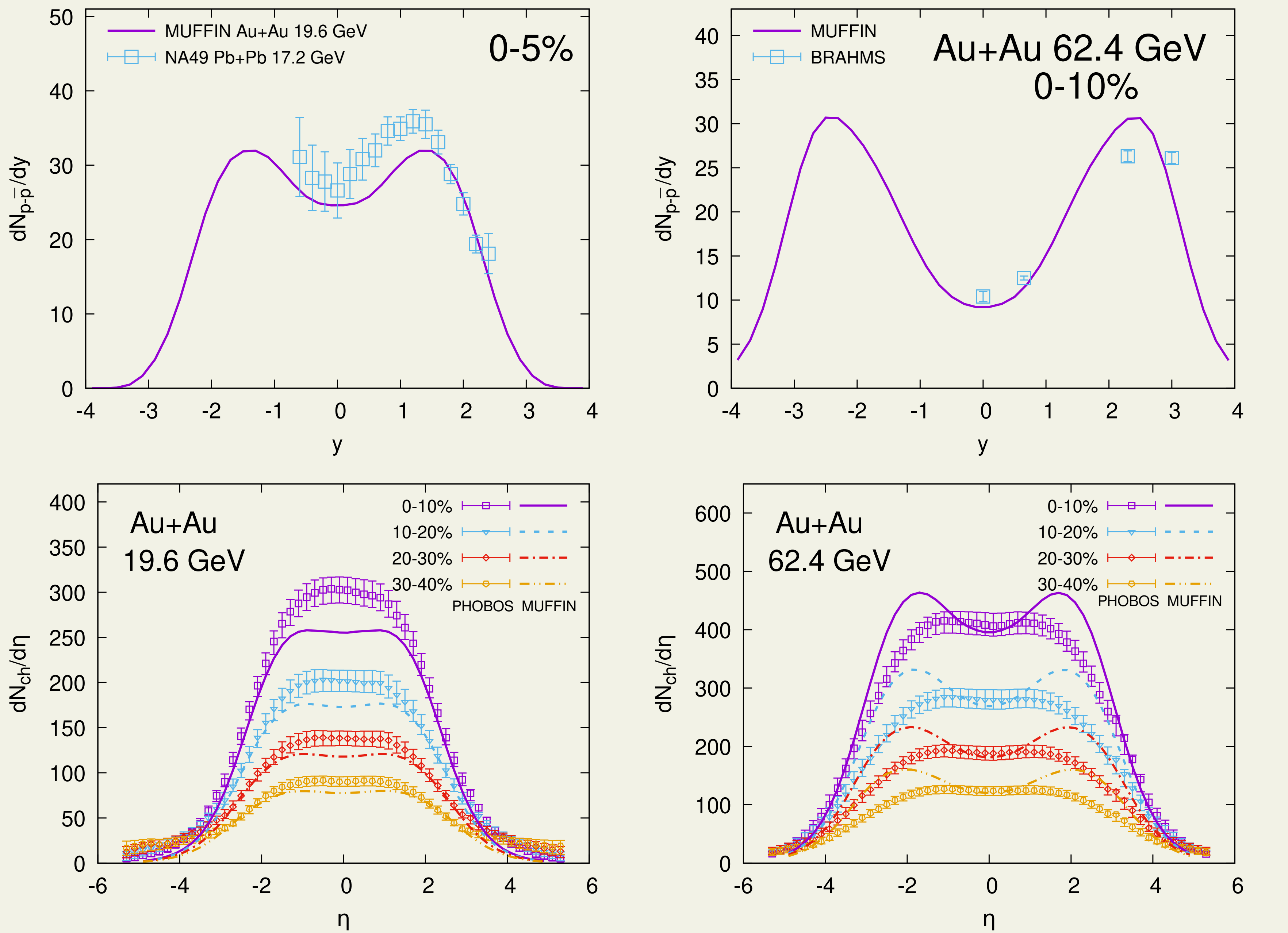
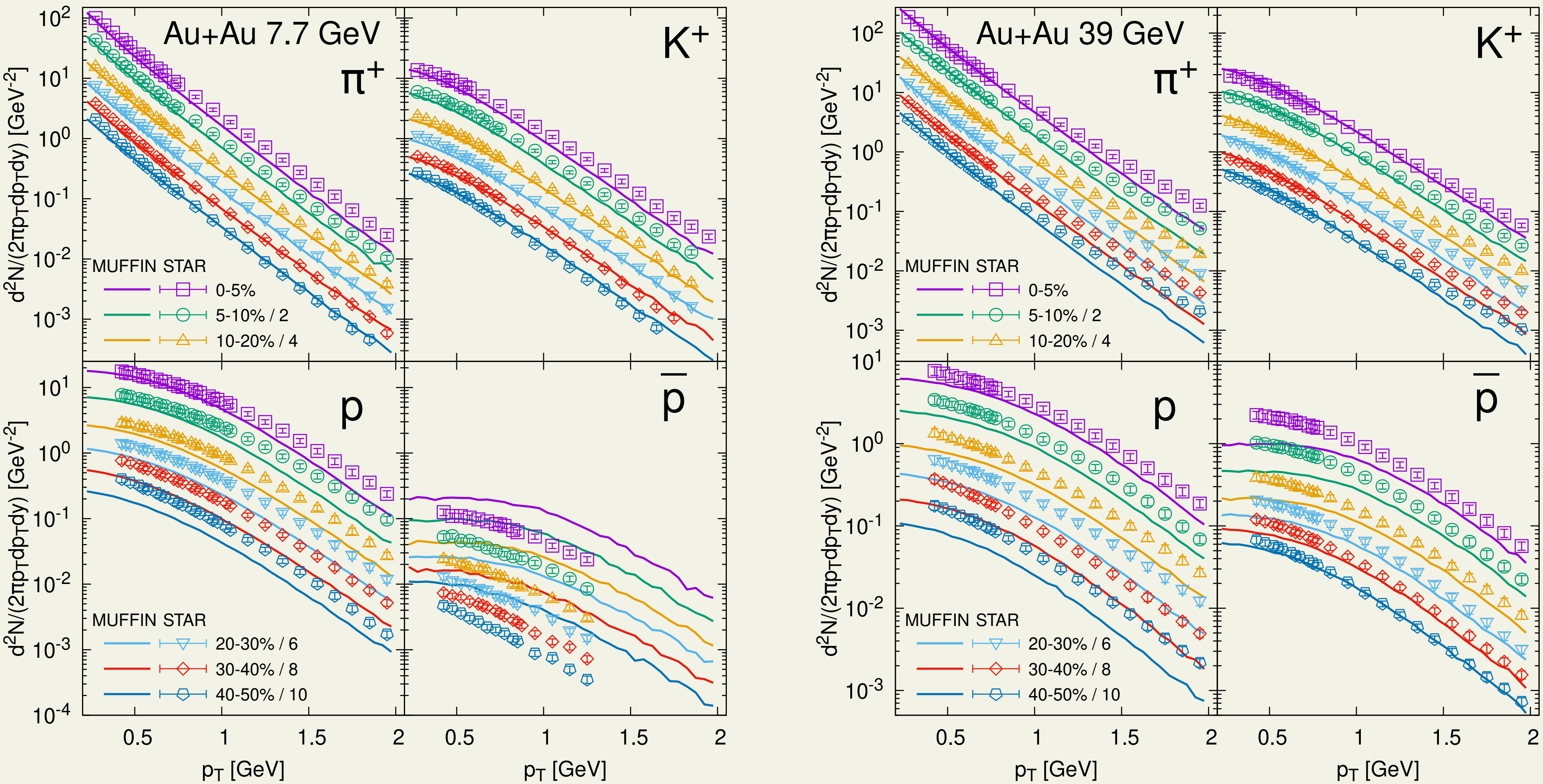


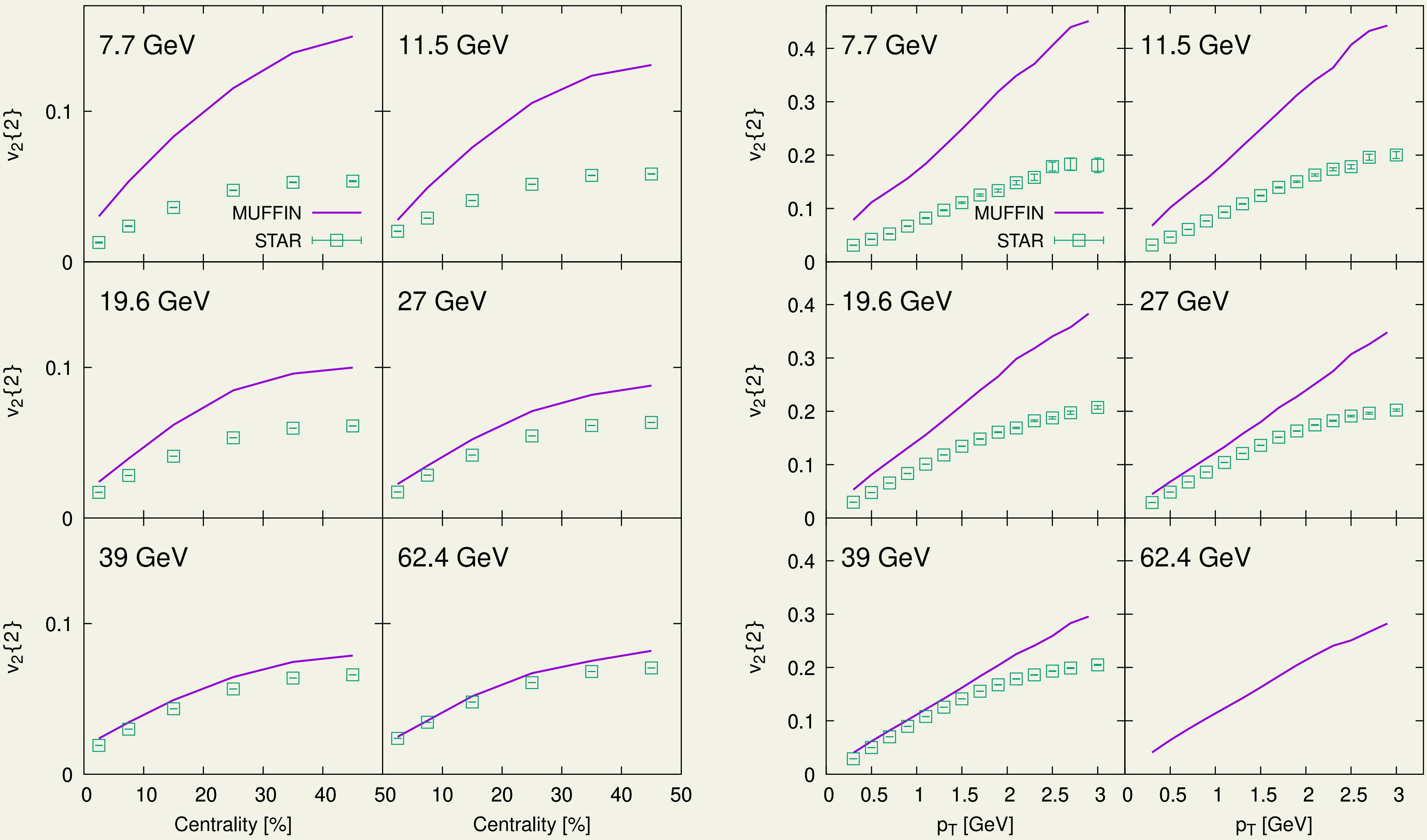
Results: (pseudo)rapidity distributions



Results: transverse momentum distributions



Results: elliptic flow



Viscosity not yet included!

Dissipation

$$T_i^{\mu\nu} = \epsilon_i u_i^\mu u_i^\nu + P_i \Delta_i^{\mu\nu} + \pi_i^{\mu\nu}, \qquad i \in \{t, p, f\}$$

$$\partial_\mu T_i^{\mu\nu} = \partial_\mu(\epsilon_i u_i^\mu u_i^\nu) + \partial_\mu(P_i \Delta_i^{\mu\nu}) + \partial_\mu \pi_i^{\mu\nu} = F_i^\nu$$

where $\pi_i^{\mu\nu}$ obeys

$$u^\alpha \partial_\alpha \pi_i^{\mu\nu} = -\frac{1}{\tau_\pi}\left(\pi_i^{\mu\nu} - 2\eta \nabla^{\langle\mu} u_i^{\nu\rangle}\right) + \cdots$$

independent of F_i^μ?

$\Longrightarrow$ **corrections to the evolution equations needed**

- **second moment of Boltzmann equation—work in progress**

Summary

- **3-fluid approach to collisions at BES energies**
  - **projectile, target, produced particles described as separate fluids**
- **rough reproduction of rapidity and p_T distributions**
- **overshoots anisotropies—no viscosity**
- **work in progress—stay tuned!**