Three fluids for BES and resonance widths for LHC

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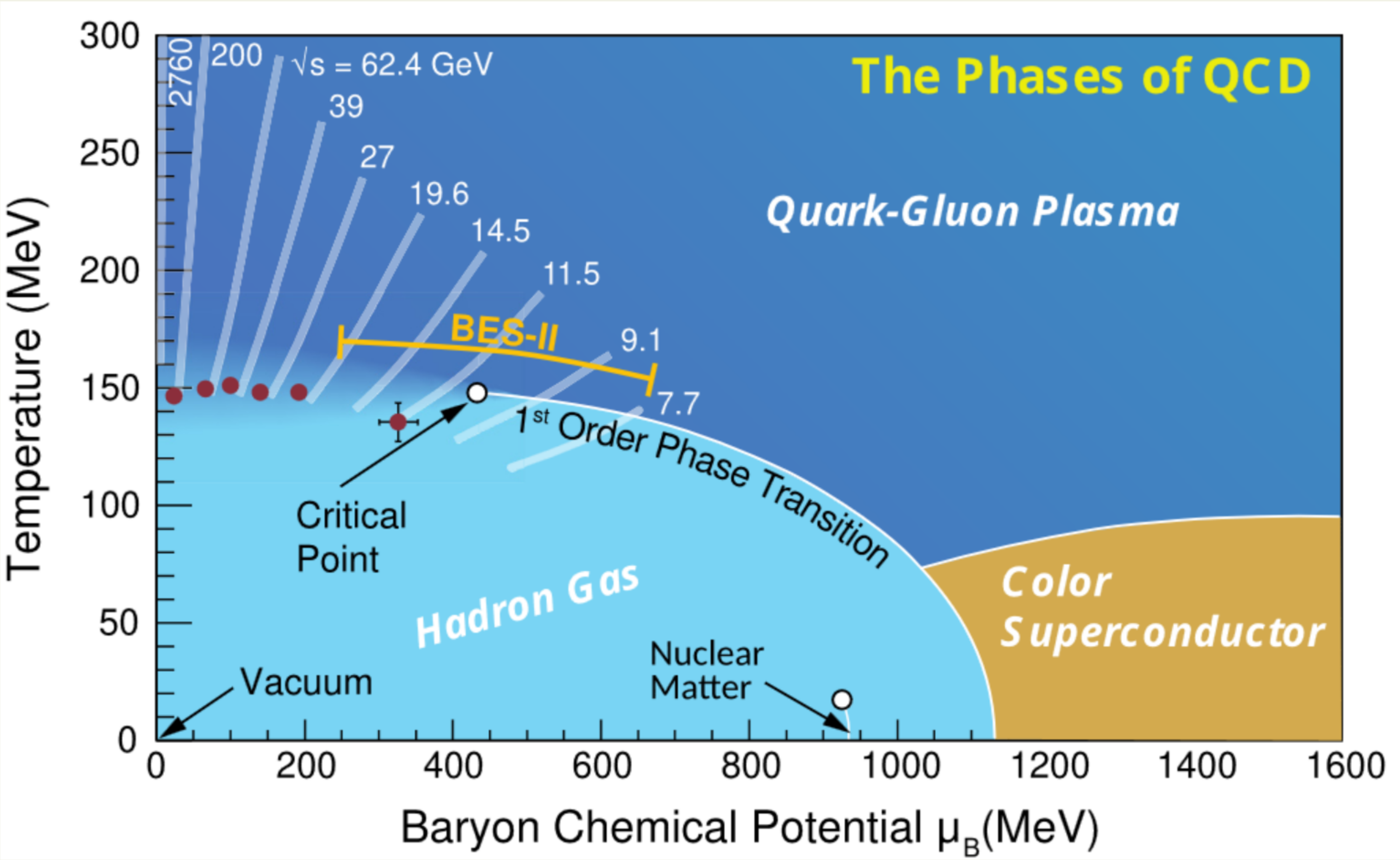
Incubator of Scientific Excellence—Centre for Simulations of Superdense Fluids

University of Wrocław

Heavy Ion Physics in the EIC Era

July 30, 2024, Institute for Nuclear Theory

work done by Jakub Cimerman, Iurii Karpenko, Boris Tomasik, Clemens Werthmann, Bithika Karmakar, Pok Man Lo and Michał Marczenko


The Phases of QCD
Temperature (MeV)
Baryon Chemical Potential μB(MeV)
2760
200
√s = 62.4 GeV
39
27
19.6
14.5
11.5
9.1
7.7
BES-II
Quark-Gluon Plasma
1st Order Phase Transition
Critical Point
Hadron Gas
Color Superconductor
Nuclear Matter
Vacuum
300
250
200
150
100
50
0
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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2. **model for primary processes?**

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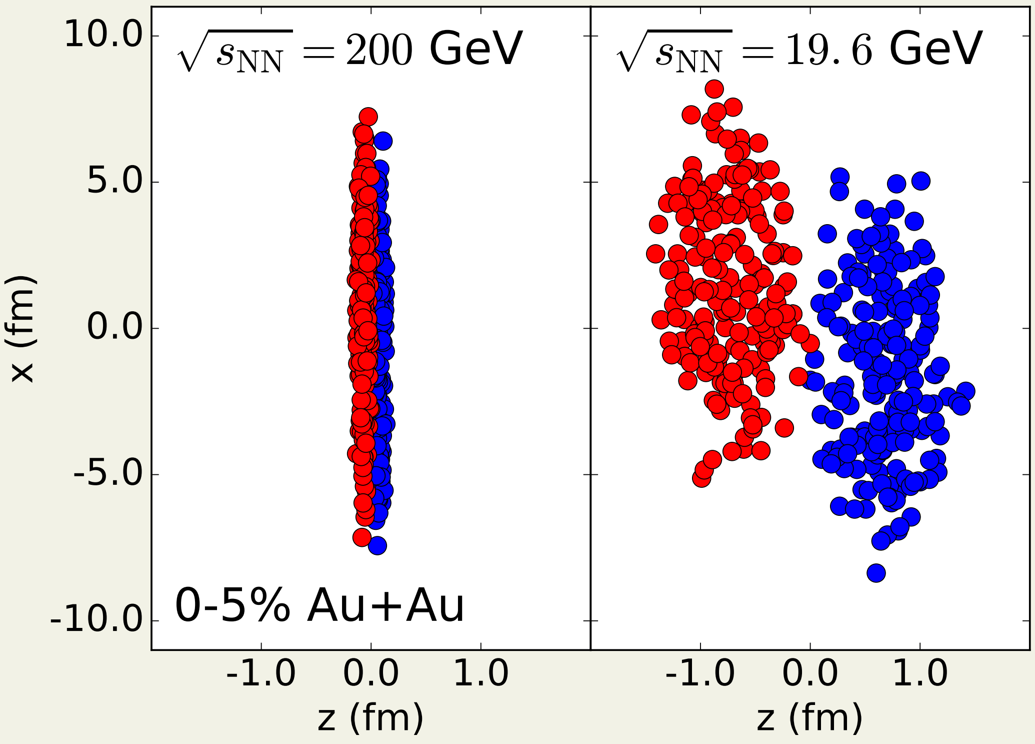

Shen & Schenke, PRC97, 024907 (2018)

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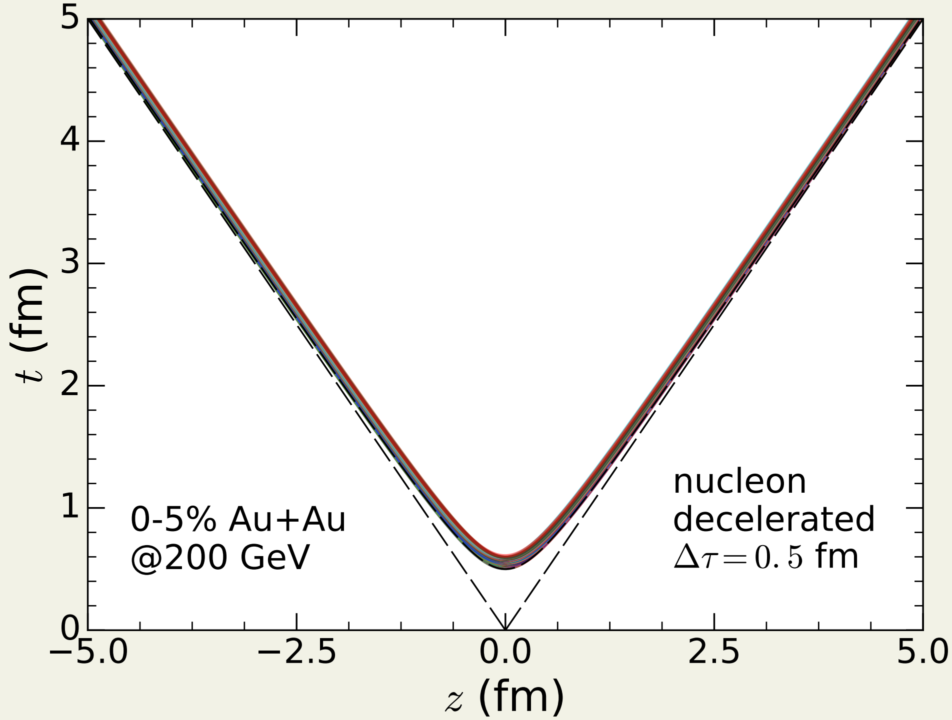
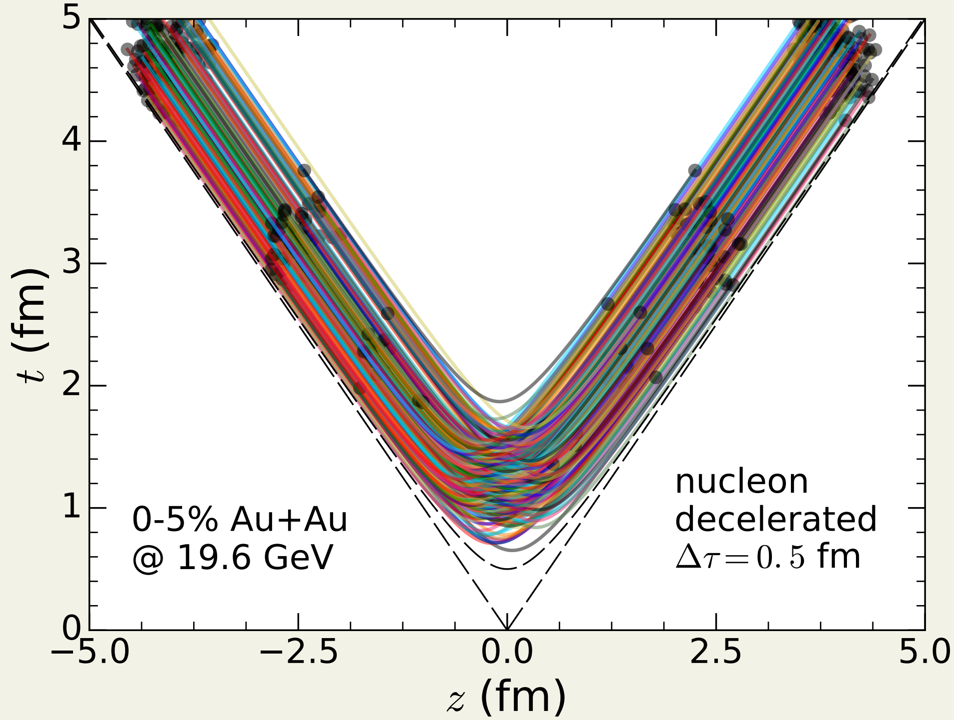
   $\Longrightarrow$ larger deviations from equilibrium?

2. model for primary processes?

3. primary collisions overlap with secondary collisions

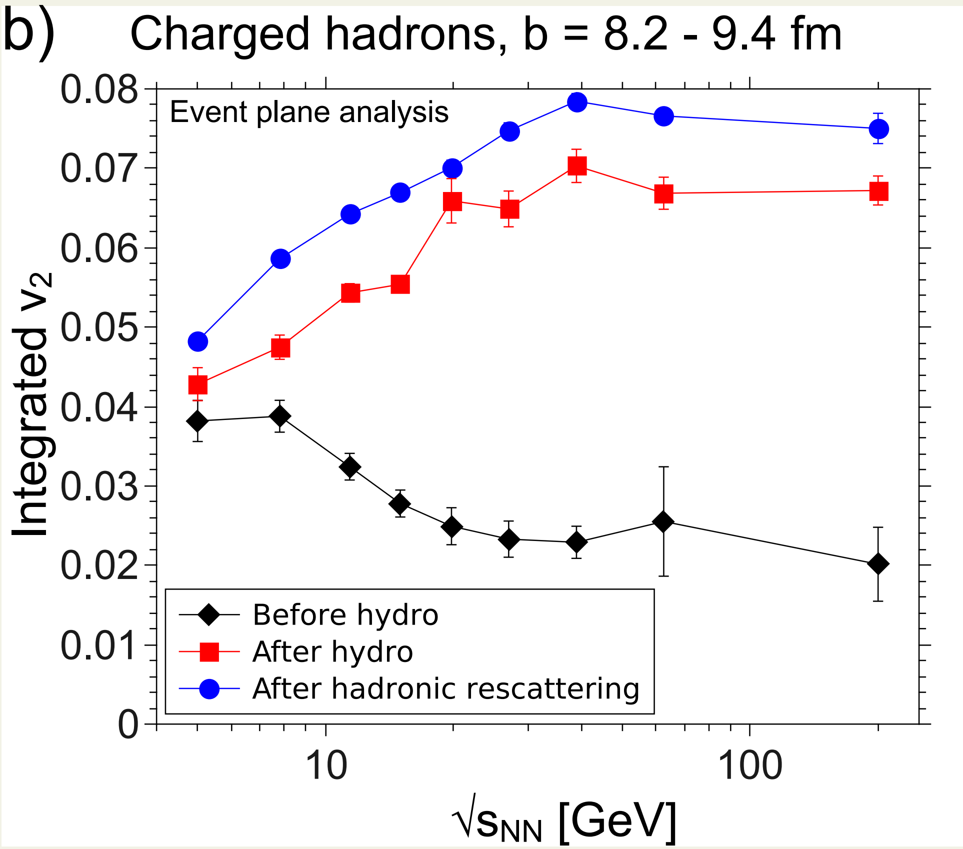




Shen & Schenke, PRC97, 024907 (2018)

Solutions

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



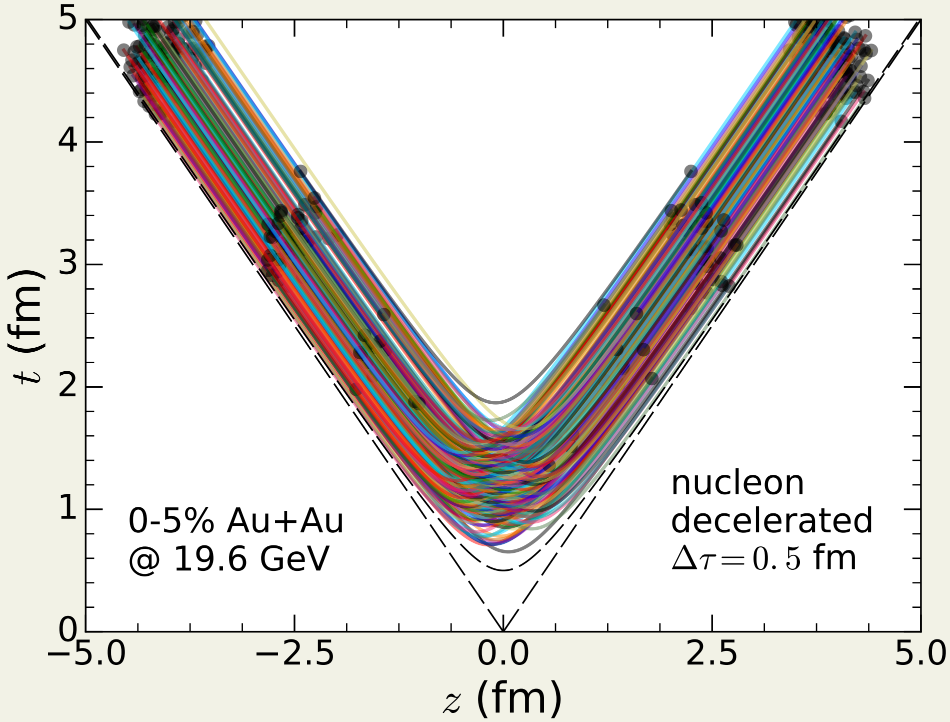
Auvinen & Petersen, PRC88, 064908 (2013)

- **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

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

$T_{\mathrm{t}}^{\mu\nu}$ = **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**

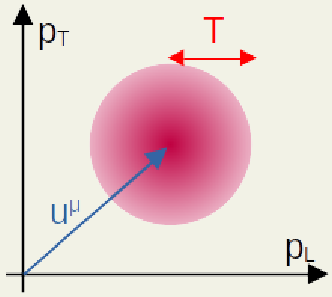
$T^{\mu\nu}_{\mathrm{p}} =$ **projectile fluid**

$T^{\mu\nu}_{\mathrm{fb}} =$ **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

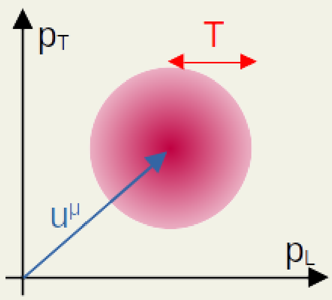
- **distributions in momentum space**



one fluid

3-fluid dynamics

- **distributions in momentum space**



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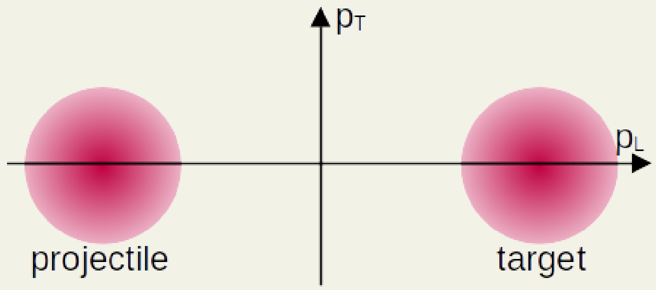
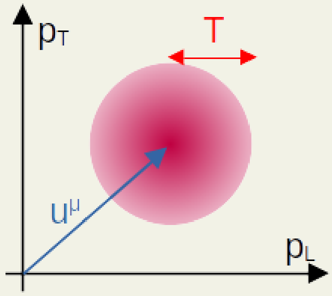


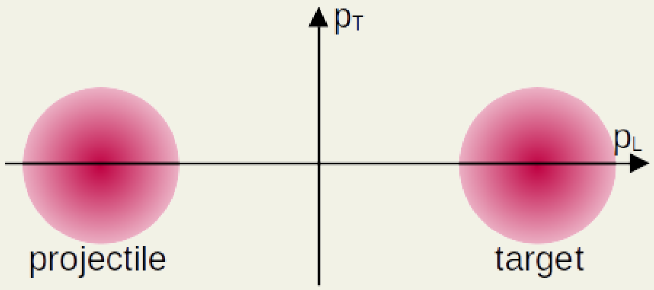
2 fluids

3-fluid dynamics

- **distributions in momentum space**



one fluid



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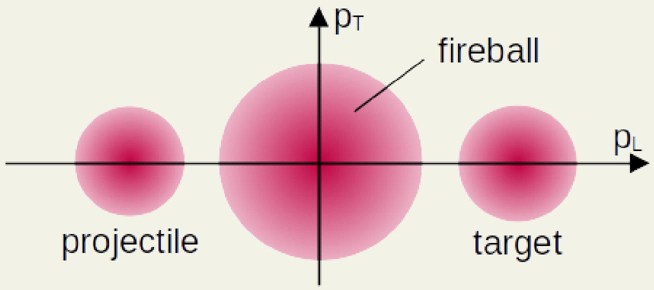
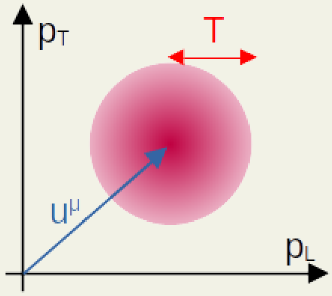


3 fluids

3-fluid dynamics

- distributions in momentum space



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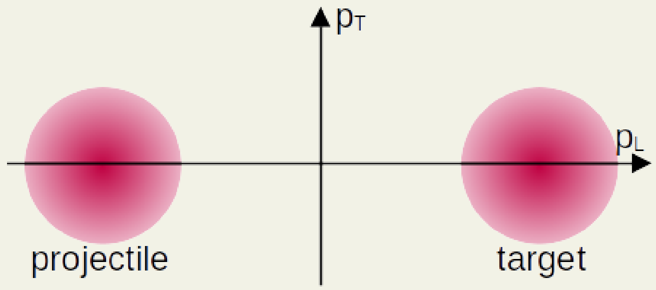
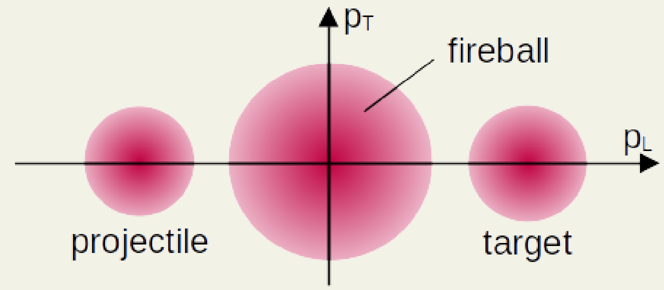


2 fluids



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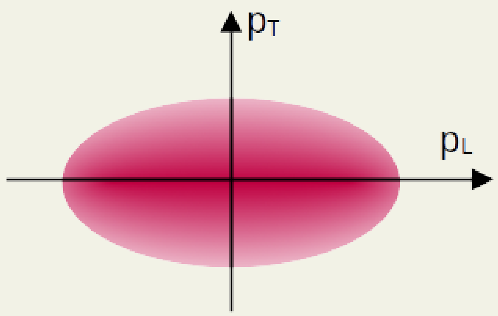
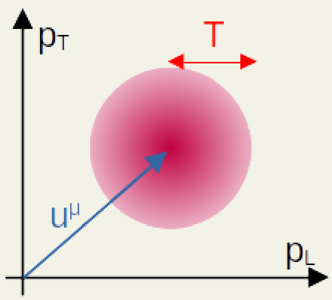


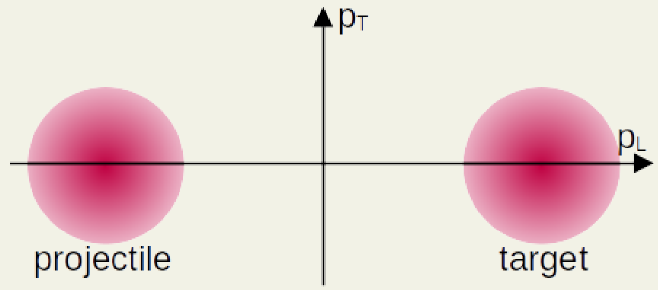
anisotropic hydro

3-fluid dynamics

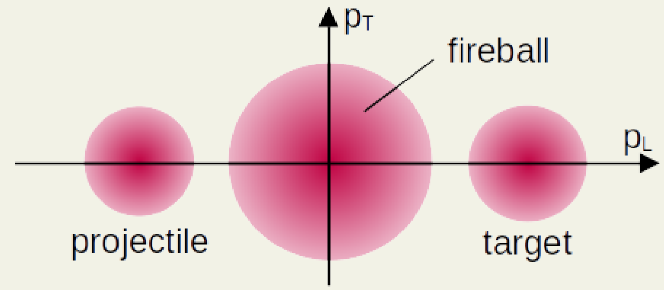
- **distributions in momentum space**



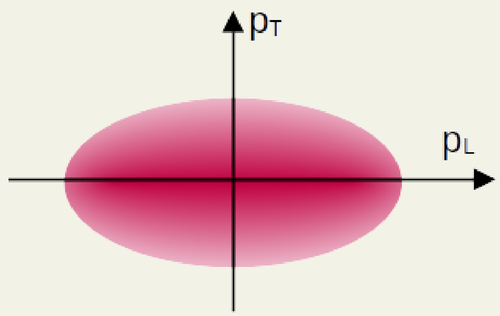
one fluid



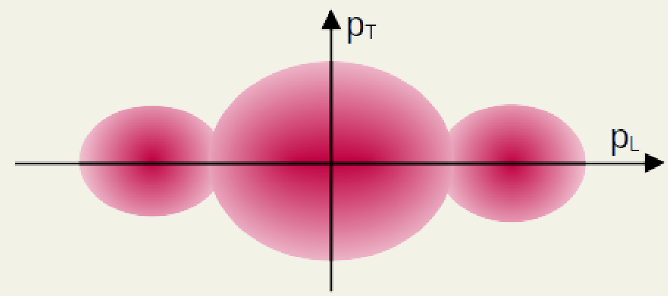
2 fluids



3 fluids



anisotropic hydro



somewhat realistic distribution

3-fluid dynamics

$$
\begin{aligned}
\partial_\mu T^{\mu\nu}_{\mathrm{t}}(x) &= -F^\nu_{\mathrm{t}}(x) + F^\nu_{\mathrm{ft}}(x) \\
\partial_\mu T^{\mu\nu}_{\mathrm{p}}(x) &= -F^\nu_{\mathrm{p}}(x) + F^\nu_{\mathrm{fp}}(x) \\
\partial_\mu T^{\mu\nu}_{\mathrm{fb}}(x) &= F^\nu_{\mathrm{p}}(x) + F^\nu_{\mathrm{t}}(x) - F^\nu_{\mathrm{fp}}(x) - F^\nu_{\mathrm{ft}}(x)
\end{aligned}
$$

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

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

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

from these, approximative friction formulae are derived

problems:

- **cross sections may not be fully measured in experiment**
- **what stays in a fluid, what's moved to another?**
- **d.o.f. change in deconfinement transition**

Csernai approach

Csernai, Lovas, Maruhn, Rosenhauer, Zimányi, Greiner PRC 26, 149 (1982)

- **all that scatters goes to the fireball**
- **projectile and target stay cold**
- **no baryon transparency!**

Csernai approach

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- all that scatters goes to the fireball
- projectile and target stay cold
- no baryon transparency!

Note:

- dynamical initialization is analogous to this approach!
- finite formation time & spatial distribution $\Rightarrow$ baryon transparency

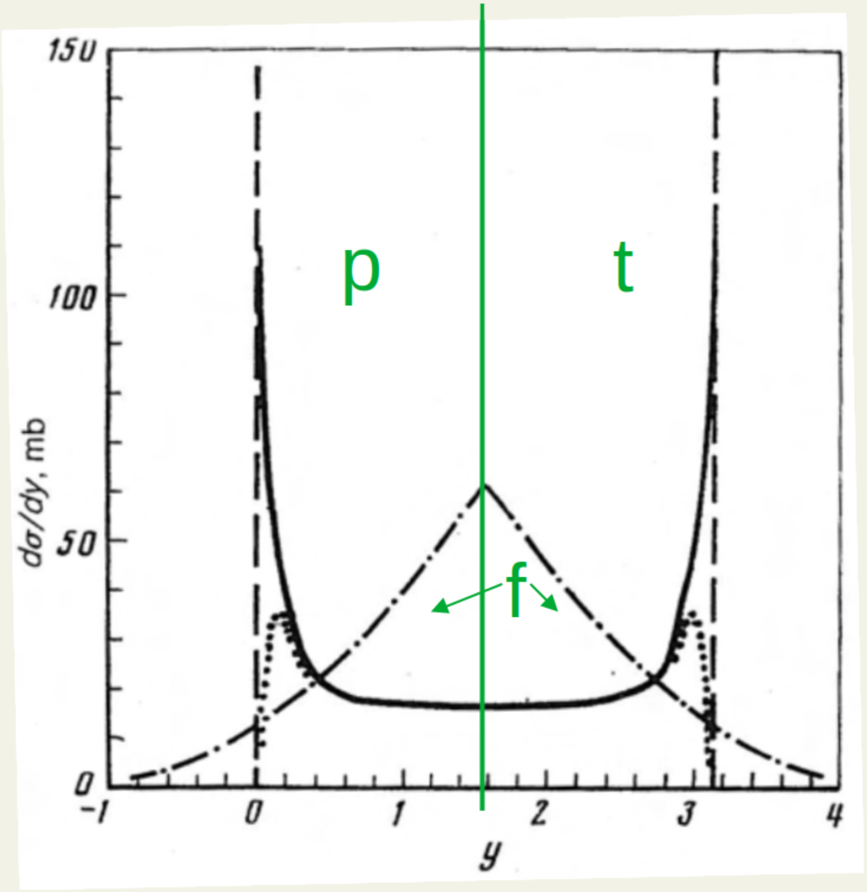
Satarov/Ivanov approach

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



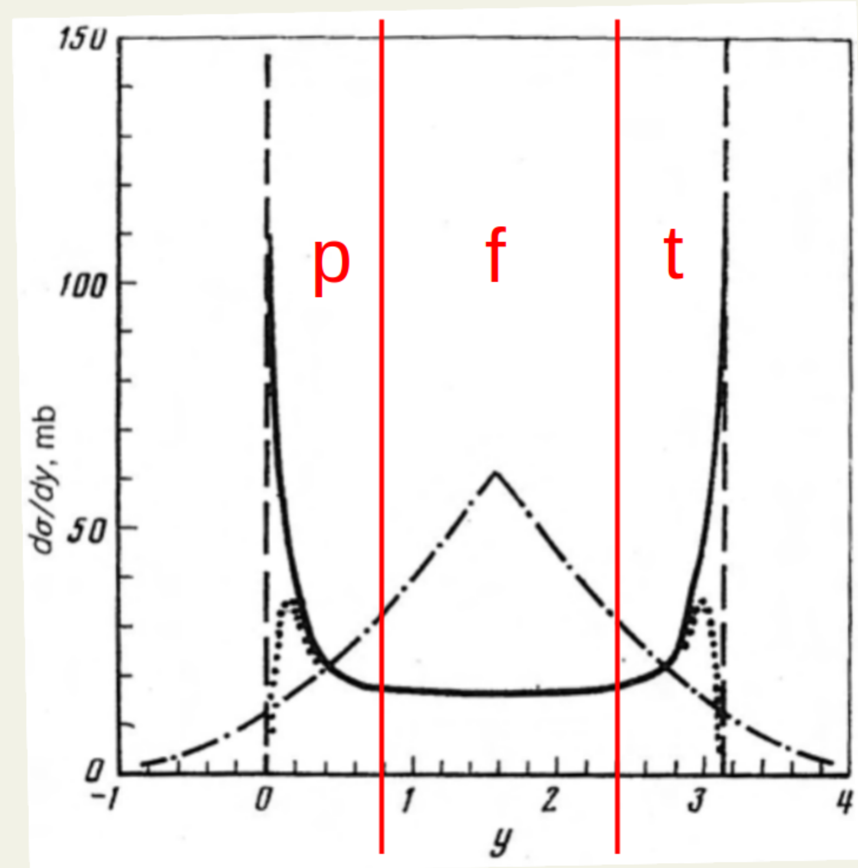
pros: only need total crosssections.
can describe the double peak in baryon distributions!
cons: $\mu_B = 0$ in fireball

modified Satarov/Ivanov approach

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

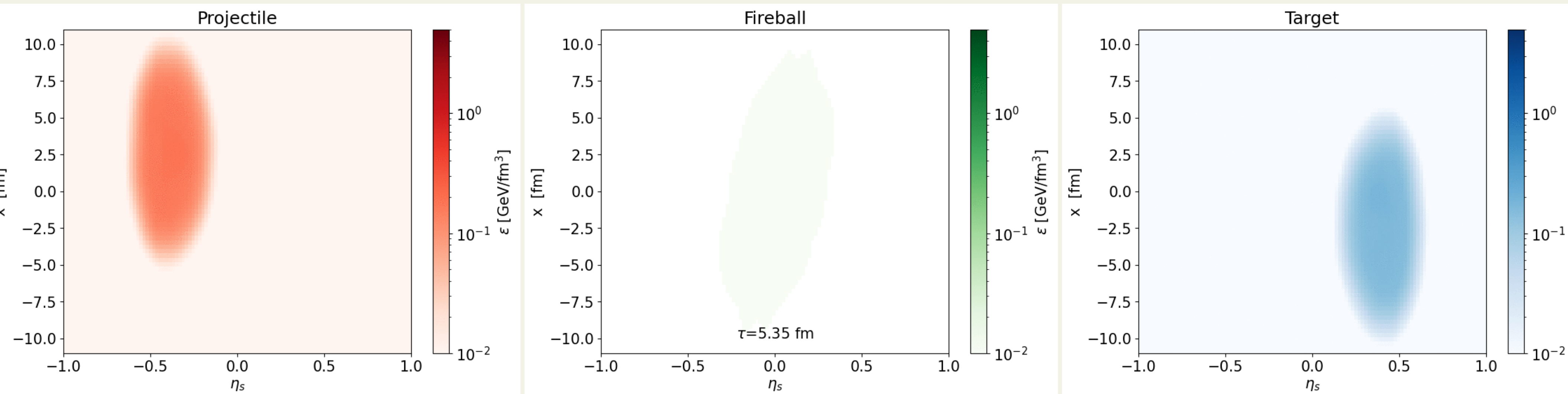
- idea: divide outgoing N from N+N
  into **3** regions
  $\Rightarrow$ modified p+t friction moves B
  to fireball

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



Evolution of energy density

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



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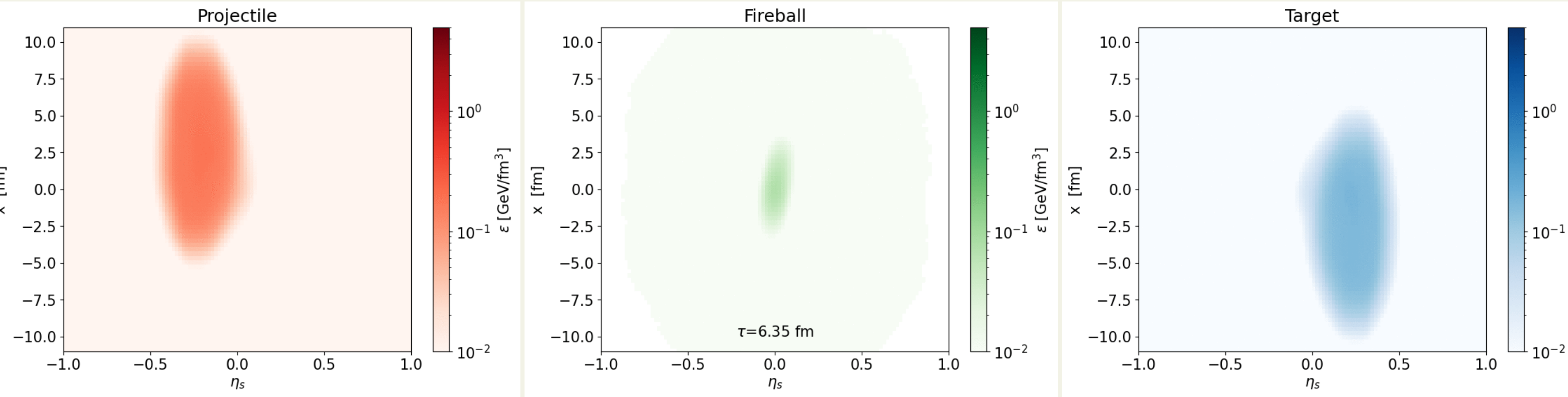

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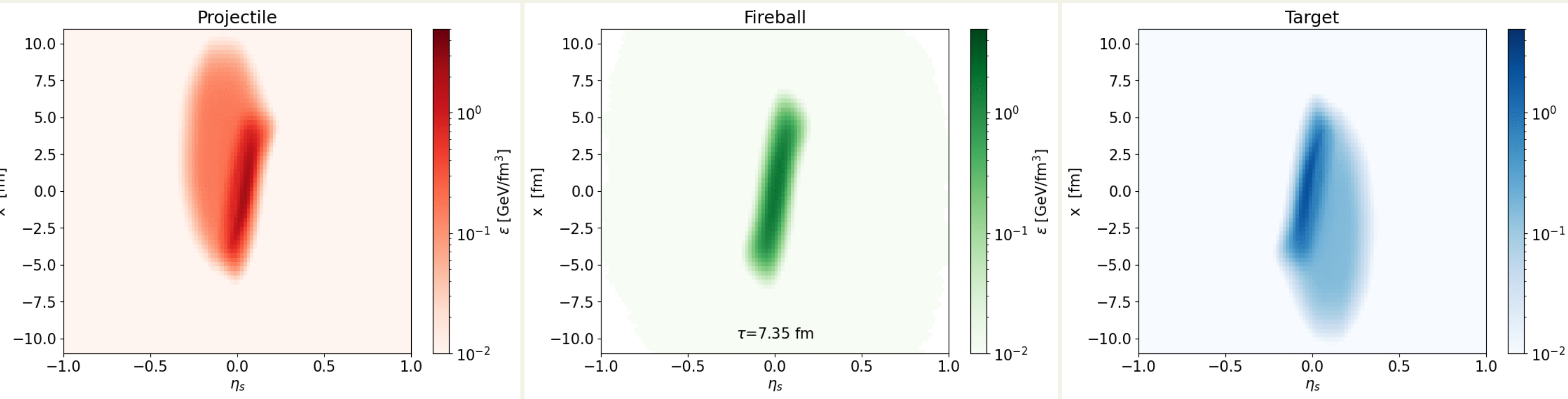

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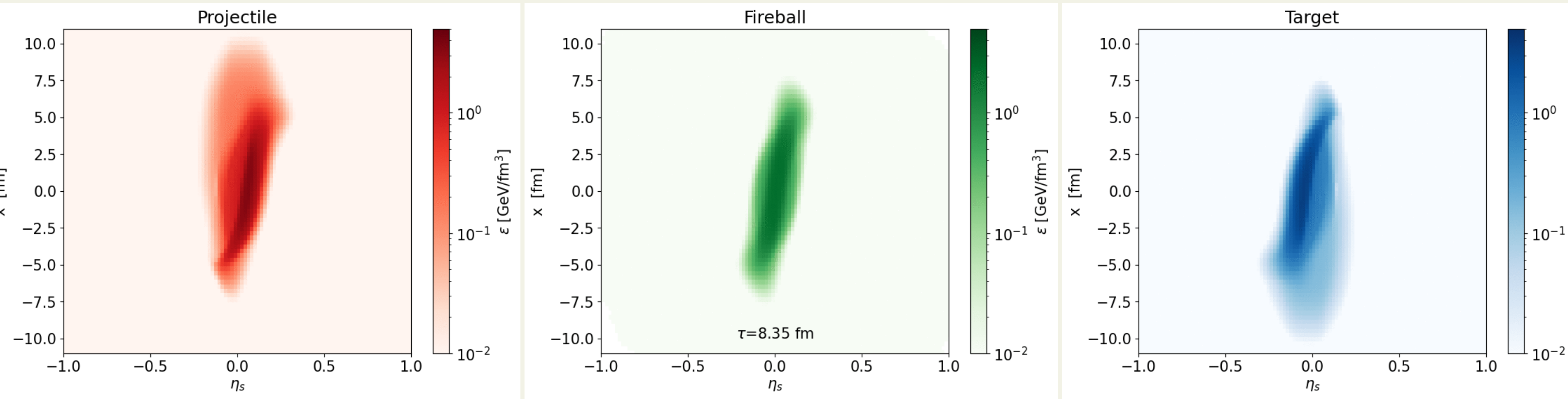

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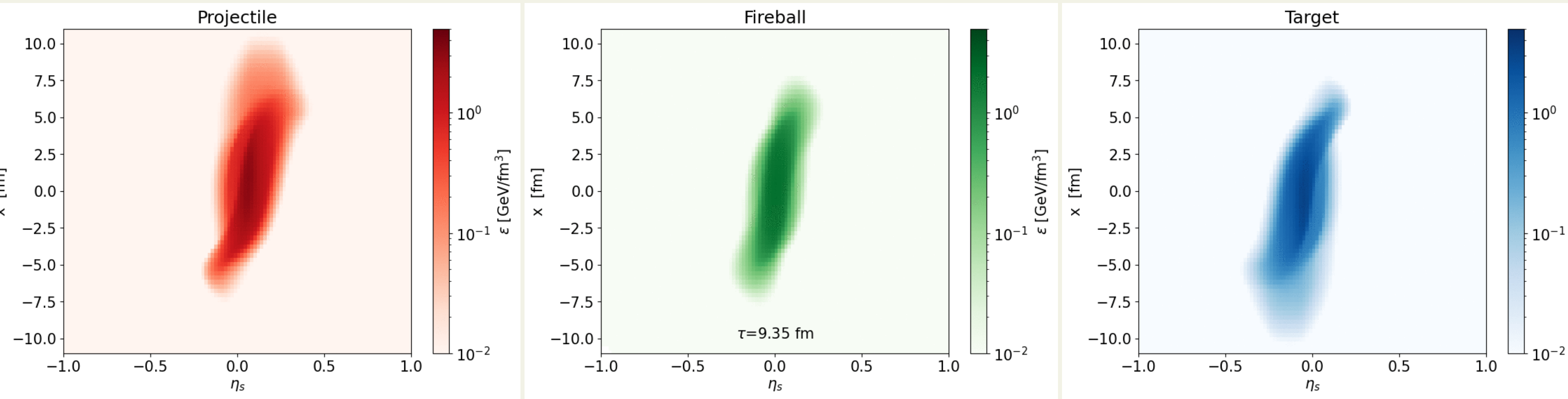

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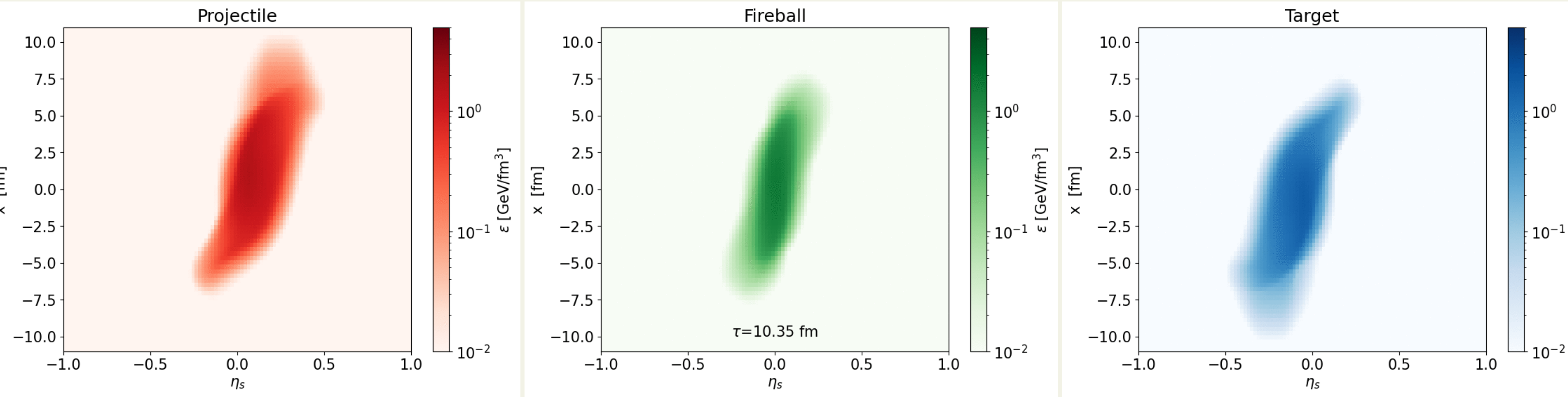

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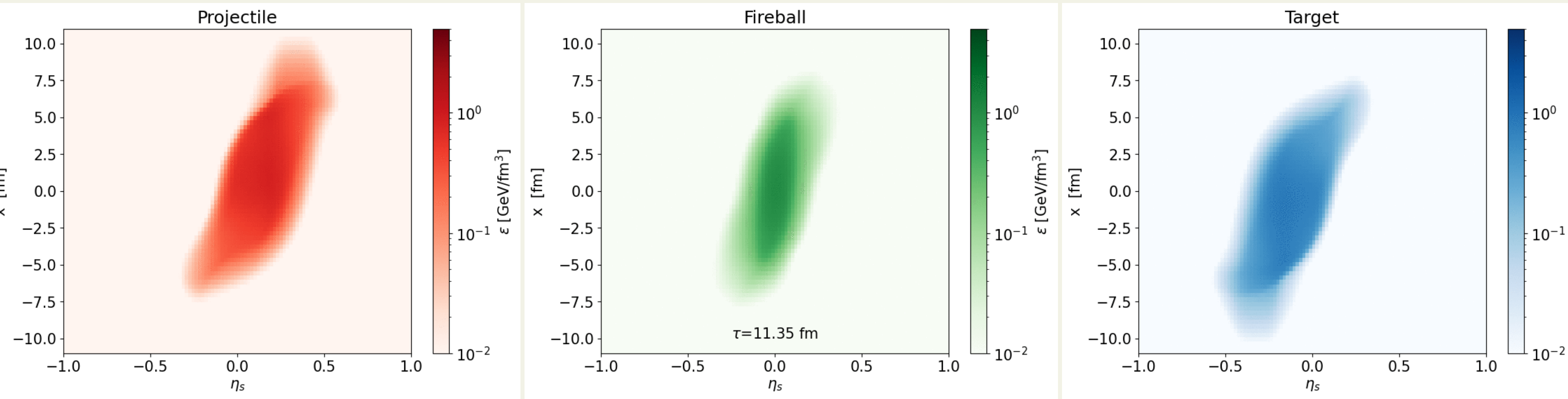

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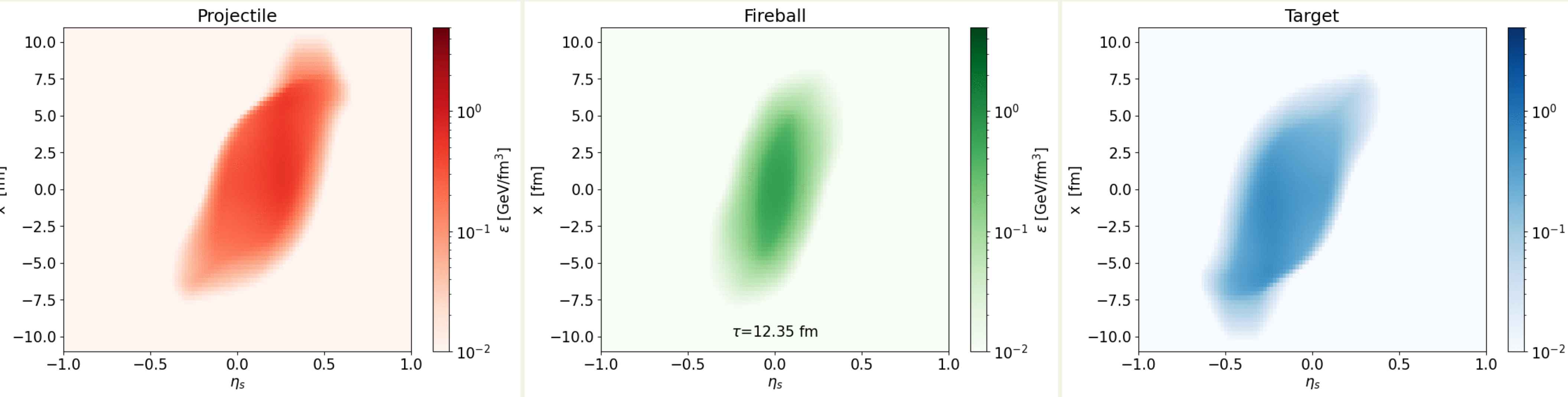

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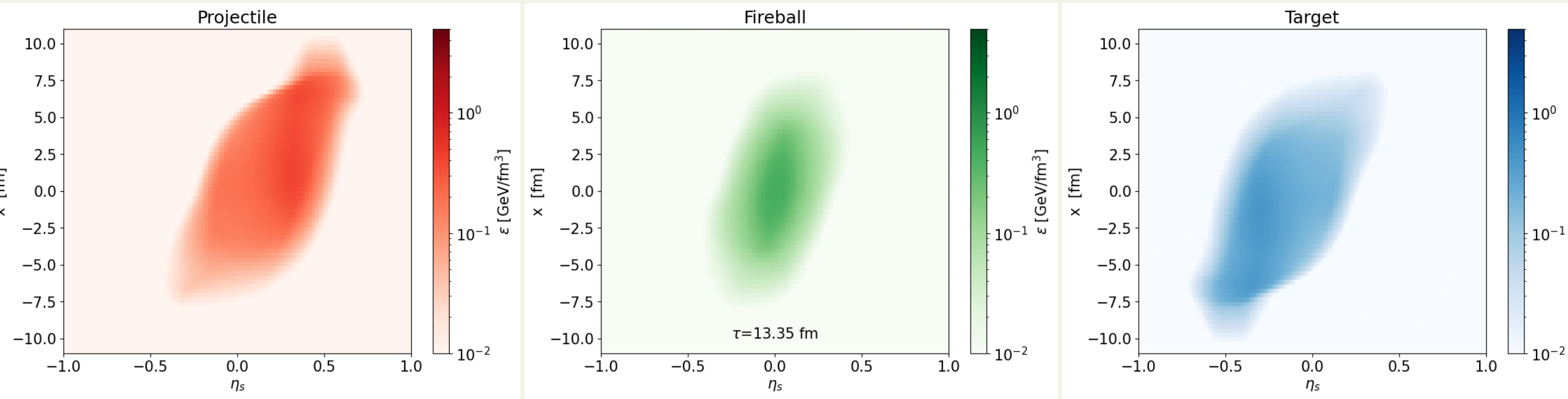

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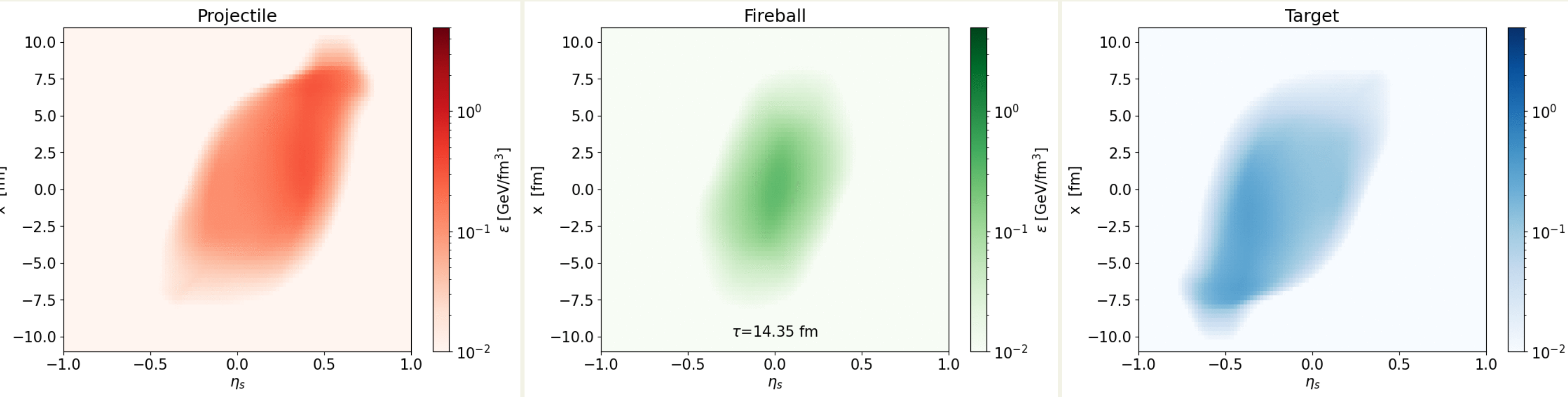
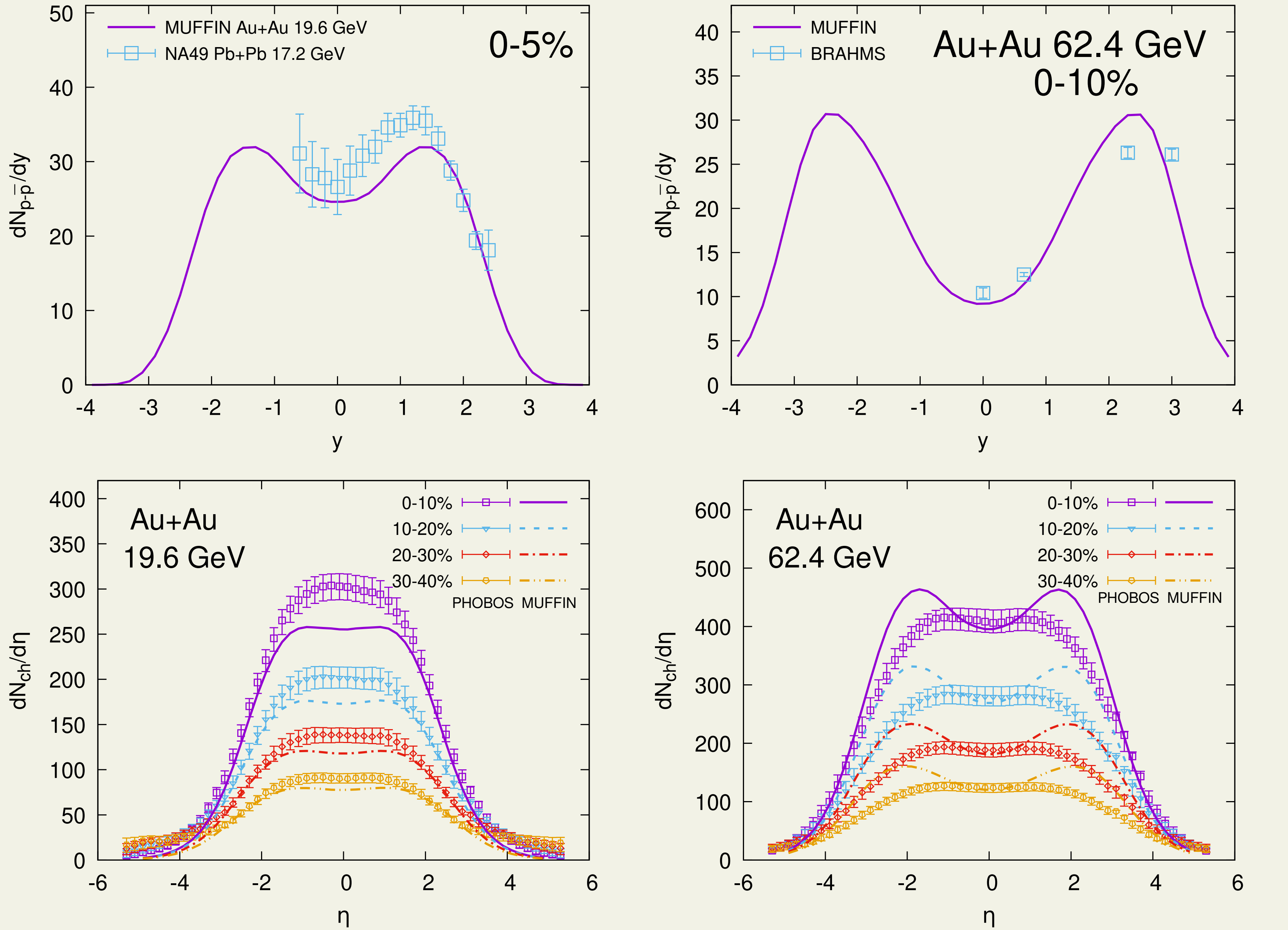
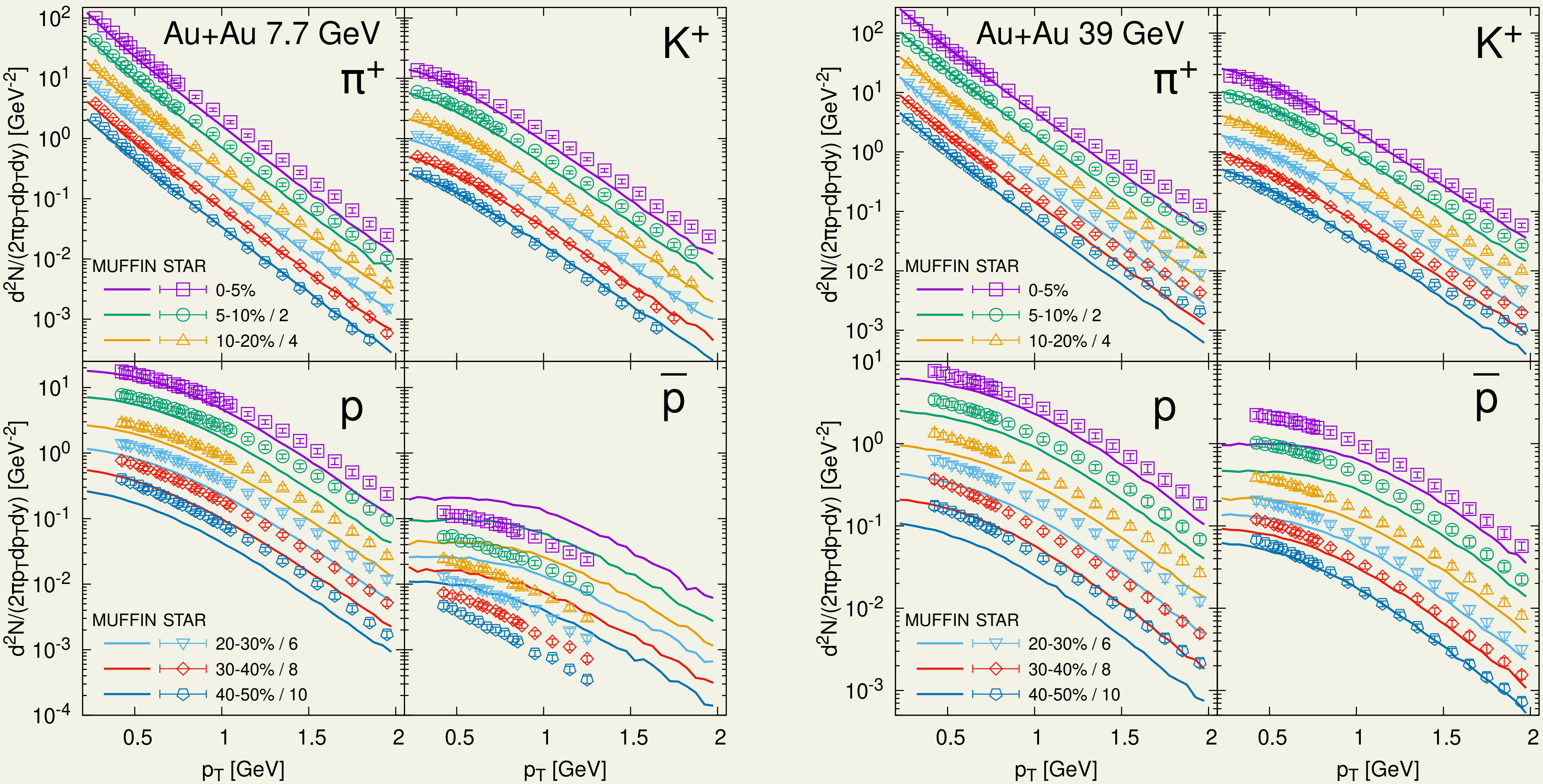


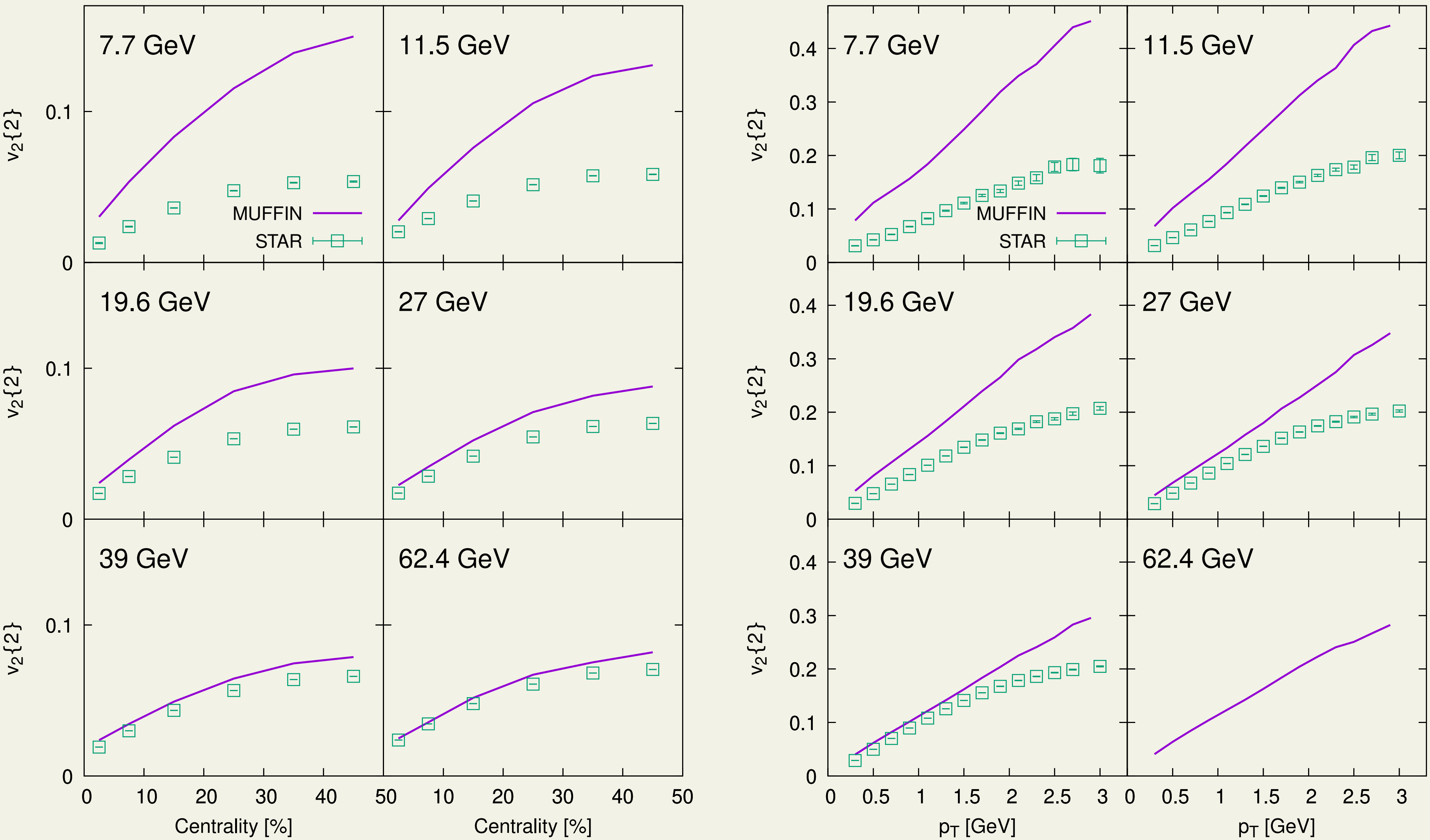
Results: (pseudo)rapidity distributions



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**

- **rederive DMNR—work in progress**

End of part I

- 3-fluid approach to collisions at BES energies
  - projectile, target, produced particles described as separate fluids

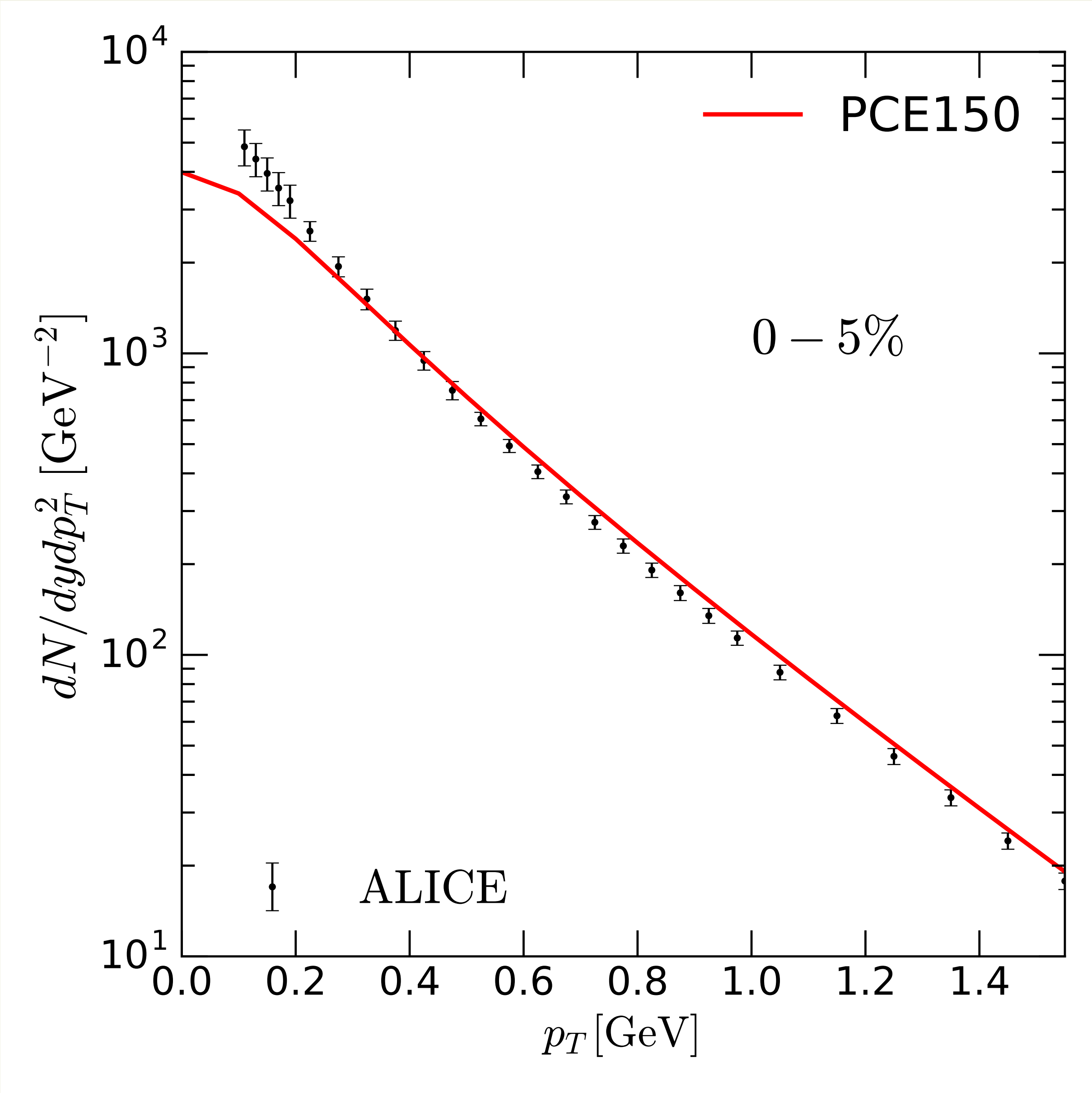
- rough reproduction of rapidity and p_T distributions

- overshoots anisotropies—no viscosity

- work in progress—stay tuned!

Effects of resonance widths on EoS and particle distributions

Pion p_T spectrum at LHC (Pb+Pb at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$)



- **viscous hydro**
- **initial state:**
pQCD+saturation
- $\tau_0 \approx 0.2\mathrm{fm}/c$

PCE150:
fit to π, K, p yields
no fit to spectrum

©**H. Niemi**

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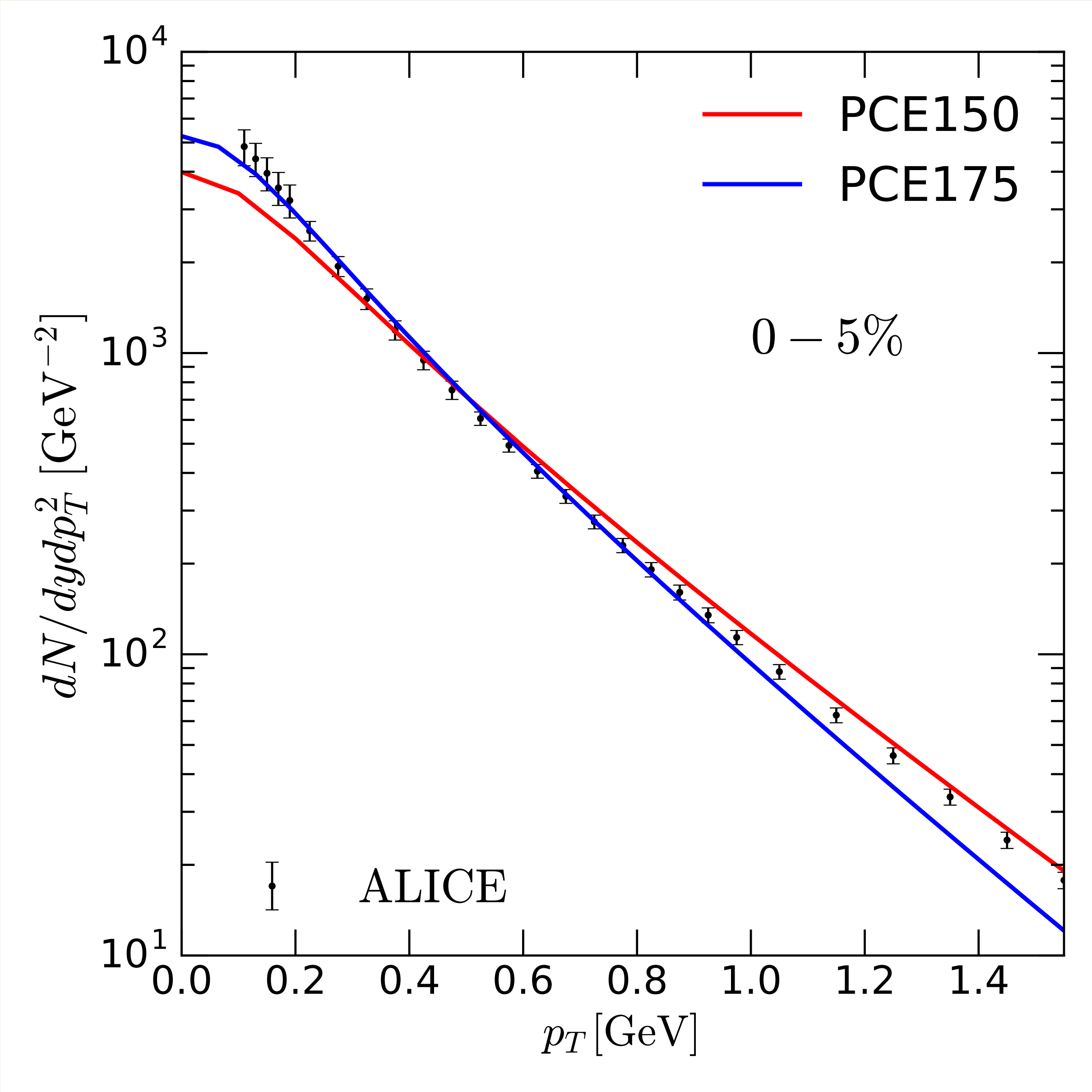

- **viscous hydro**
- **initial state:** **pQCD+saturation**
- $\tau_0 \approx 0.2\mathrm{fm}/c$

PCE150:
fit to π, K, p yields
no fit to spectrum

PCE175:
no fit to yields
fits the spectrum

©H. Niemi

- **need more resonances**

- **yield proportional to Boltzmann factor**

$$N \propto \exp\left(-\frac{m}{T}\right)$$

- need more resonances
- yield proportional to Boltzmann factor

$$N \propto \exp\left(-\frac{m}{T}\right)$$

- resonance mass?

- **need more resonances**
- **yield proportional to Boltzmann factor**

$$N \propto \exp\left(-\frac{m}{T}\right)$$

- **resonance mass?**
- **usually no width, i.e. resonances have their pole mass**

Dashen-Ma-Bernstein:

If interactions mediated by *narrow* resonances, properties of interacting hadron gas are those of noninteracting hadron-resonance gas

$\Rightarrow$ **Hadron resonance gas model**

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$\Rightarrow$ **Hadron resonance gas model**

Dashen-Ma-Berstein: S-matrix formulation of statistical mechanics:

$\Rightarrow$ **Second virial coefficient can be evaluated in terms of scattering phase shift (as far as interaction is manifested in elastic scattering)**

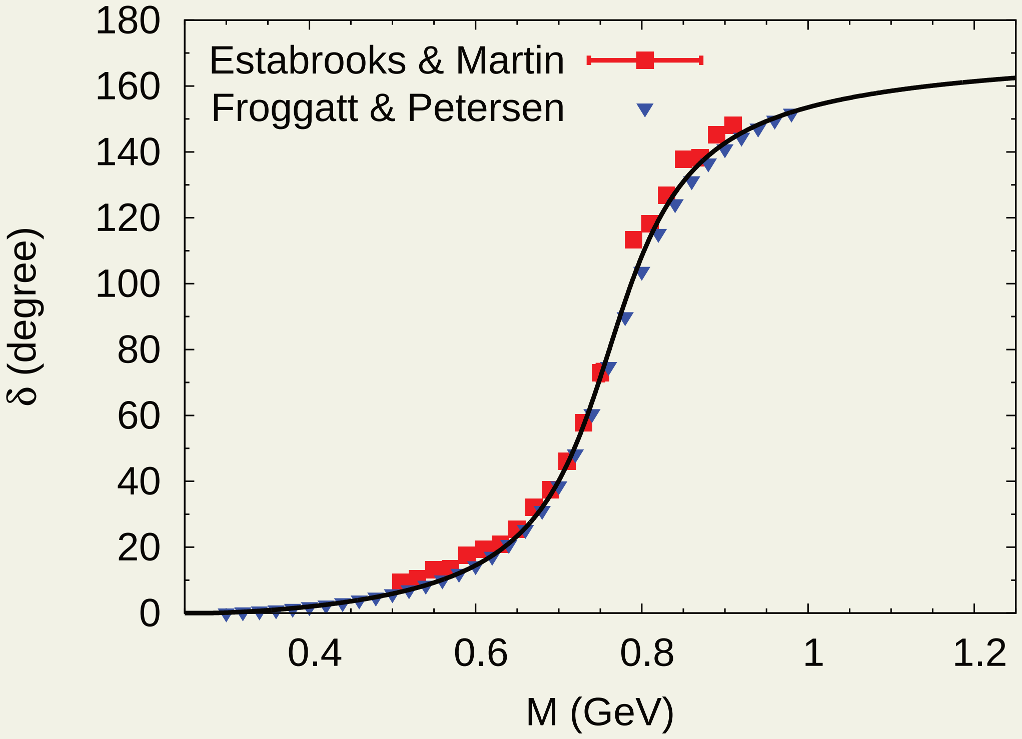
$\Rightarrow$ **relativistic Beth-Uhlenbeck form**

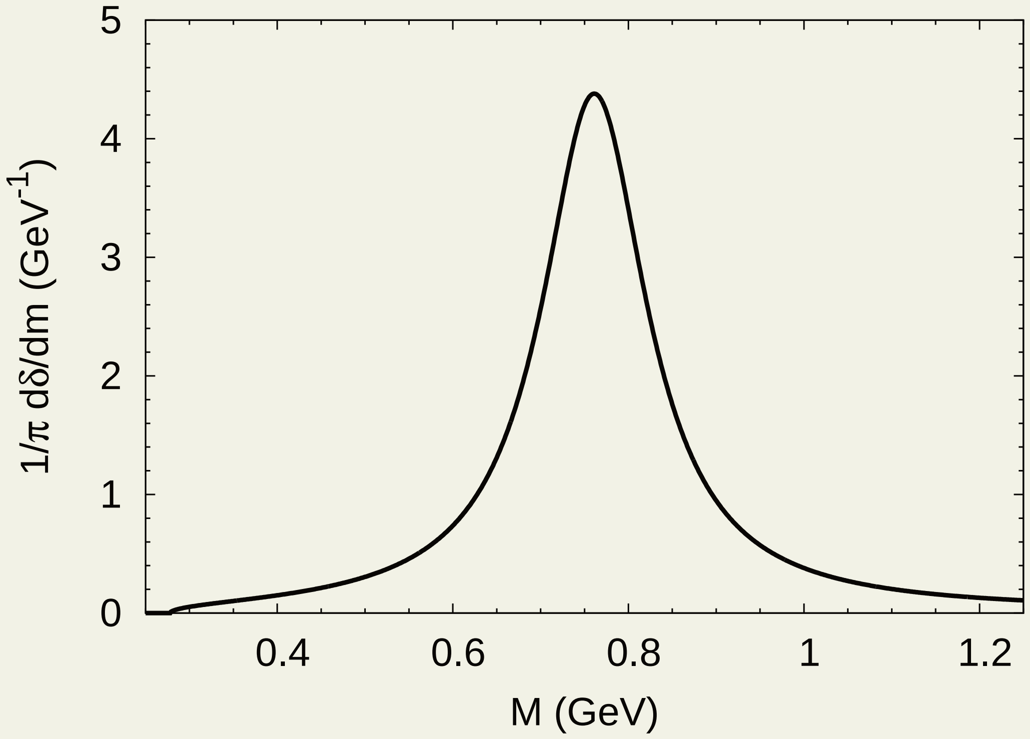
S-matrix

- **effects of interactions expressed in terms of scattering phase shifts**

$$n = \int \mathrm{d}^3\mathbf{p} \int \mathrm{d}m \frac{\mathrm{d}\rho}{\mathrm{d}m} f(p,m) \qquad \text{with} \qquad \frac{\mathrm{d}\rho}{\mathrm{d}m} = \frac{1}{\pi}\frac{\mathrm{d}\delta}{\mathrm{d}m}$$

- $\pi\pi$ **scattering, P-wave, i.e.** ρ **resonance**





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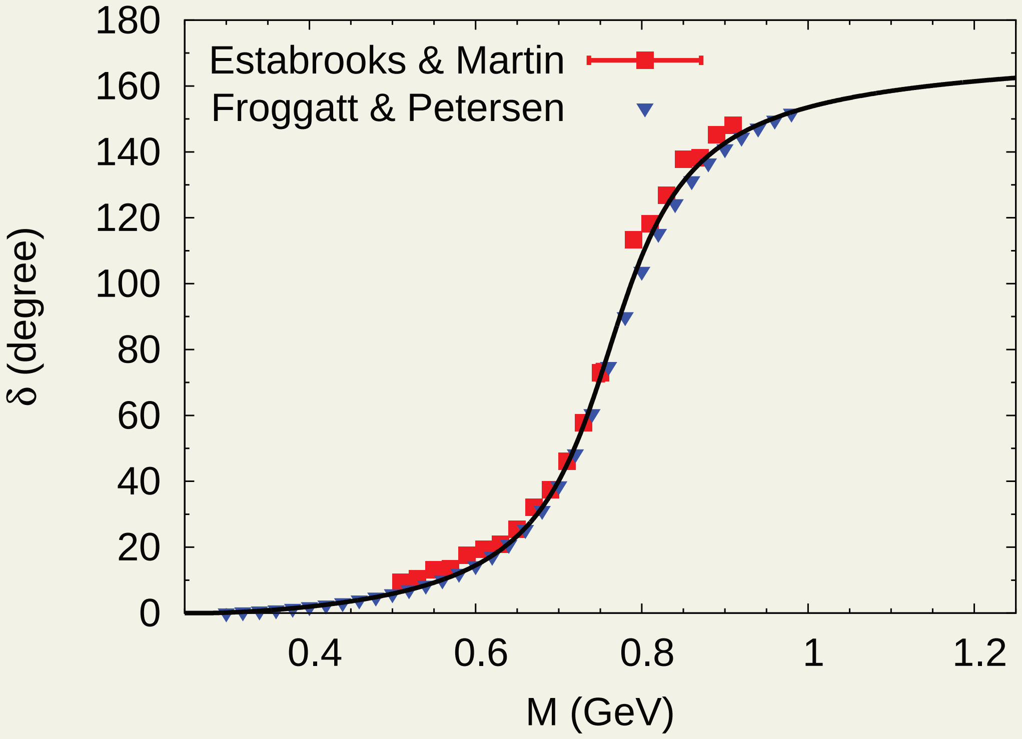

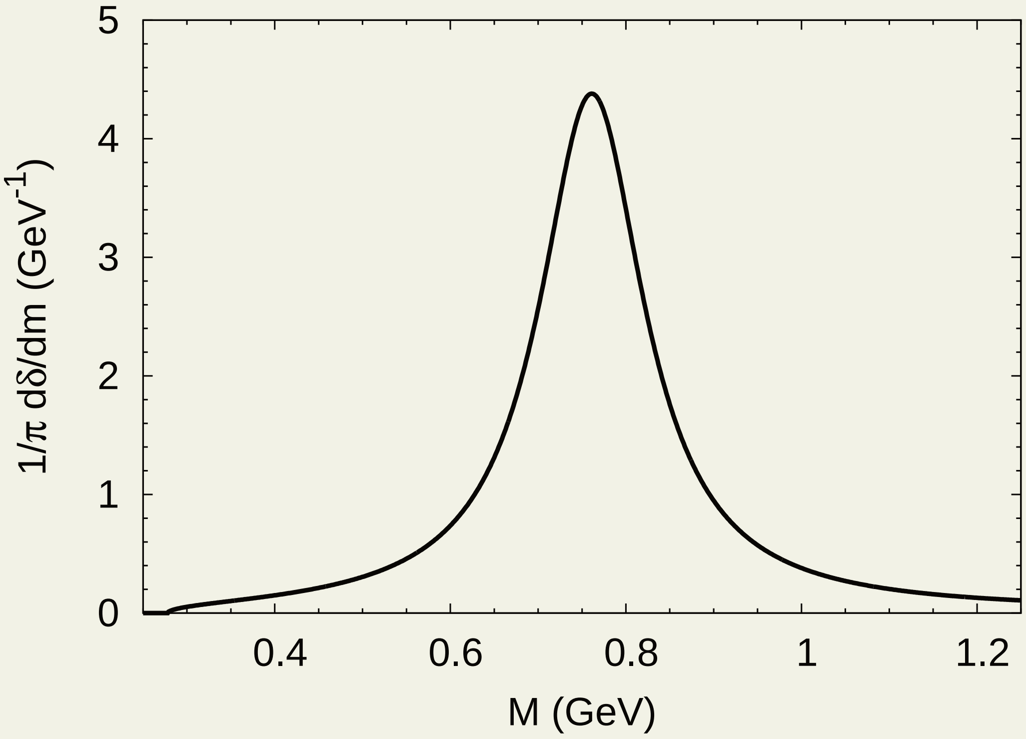

S-matrix

- **effects of interactions expressed in terms of scattering phase shifts**

$$n = \int \mathrm{d}^3\mathbf{p} \int \mathrm{d}m \frac{\mathrm{d}\rho}{\mathrm{d}m} f(p,m) \qquad \text{with} \qquad \frac{\mathrm{d}\rho}{\mathrm{d}m} = \frac{1}{\pi}\frac{\mathrm{d}\delta}{\mathrm{d}m}$$

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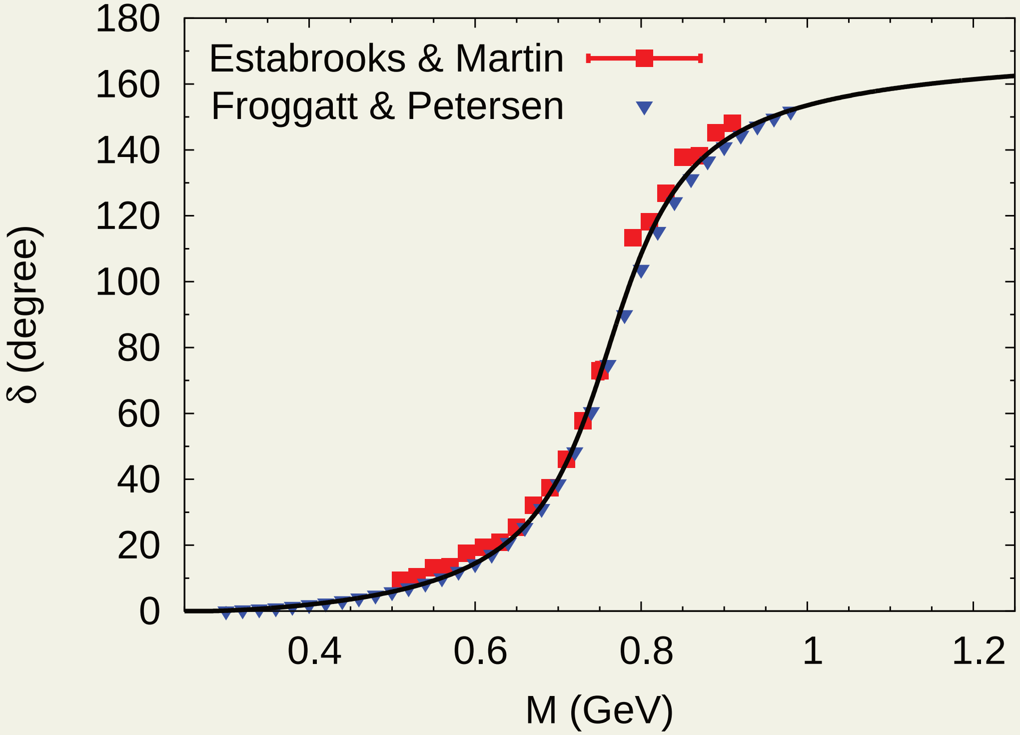

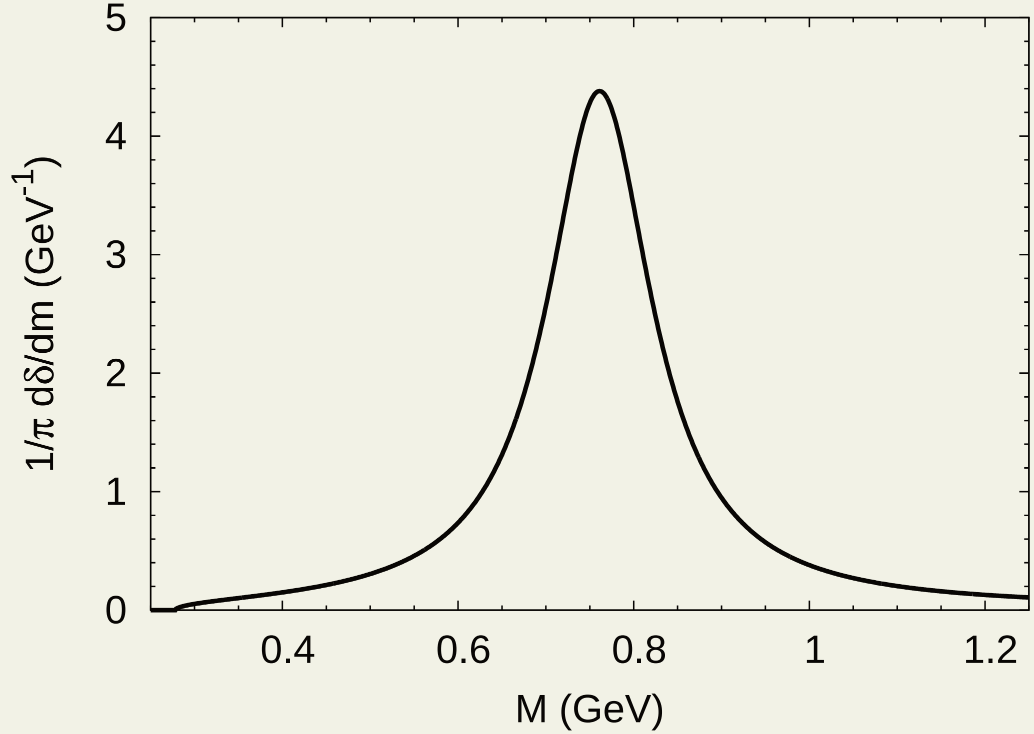

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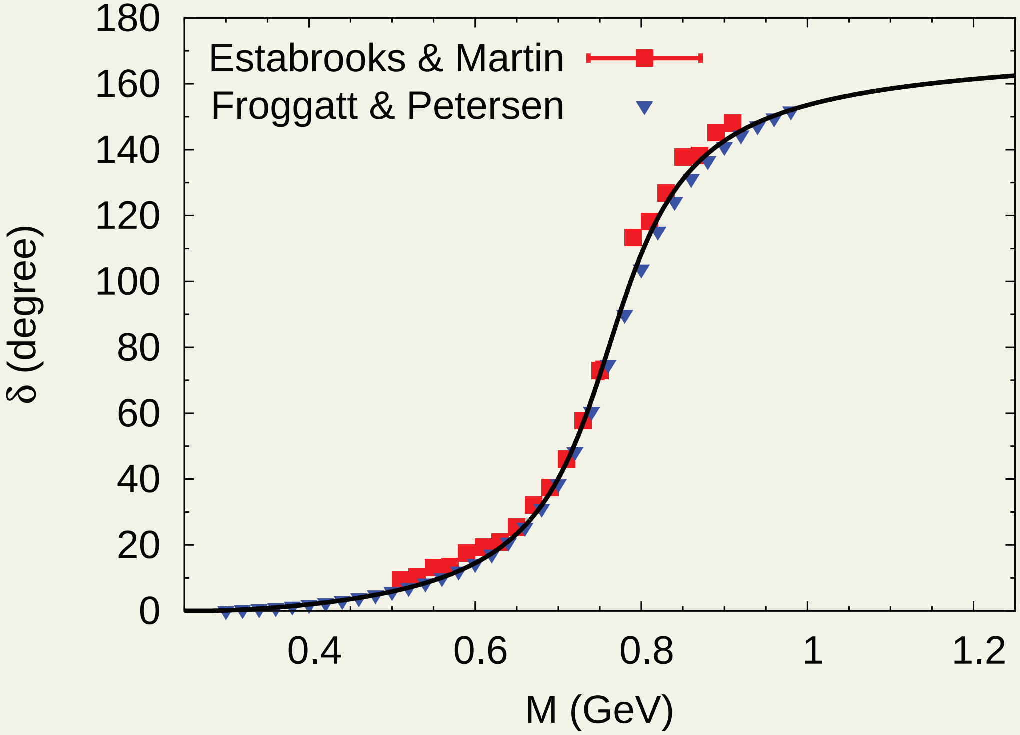

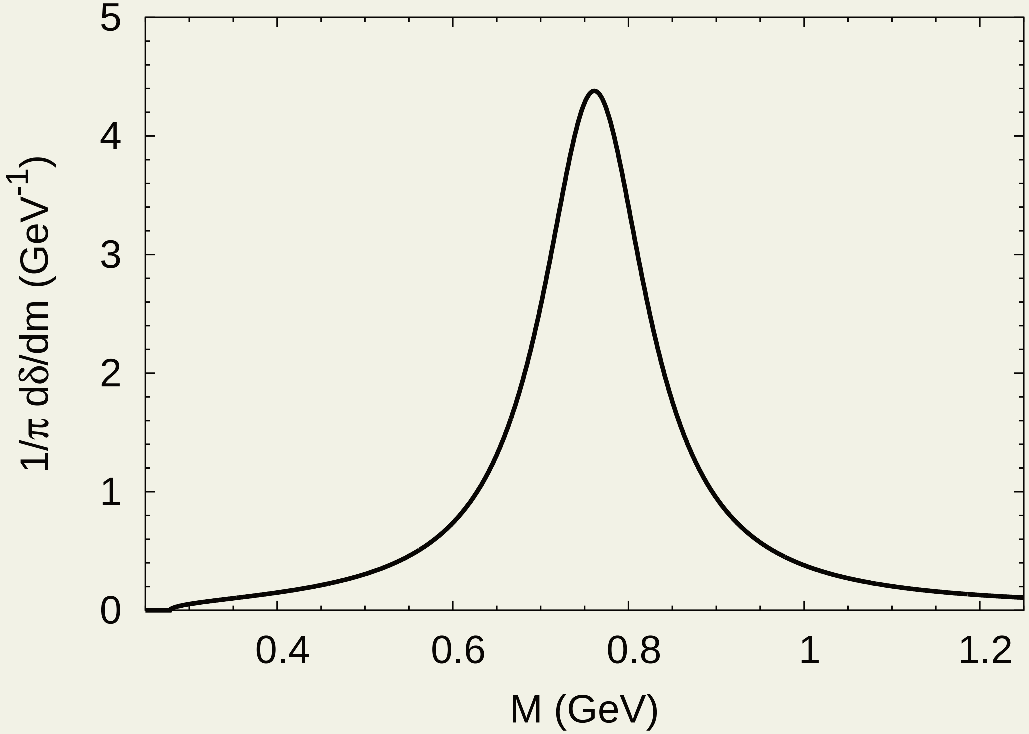

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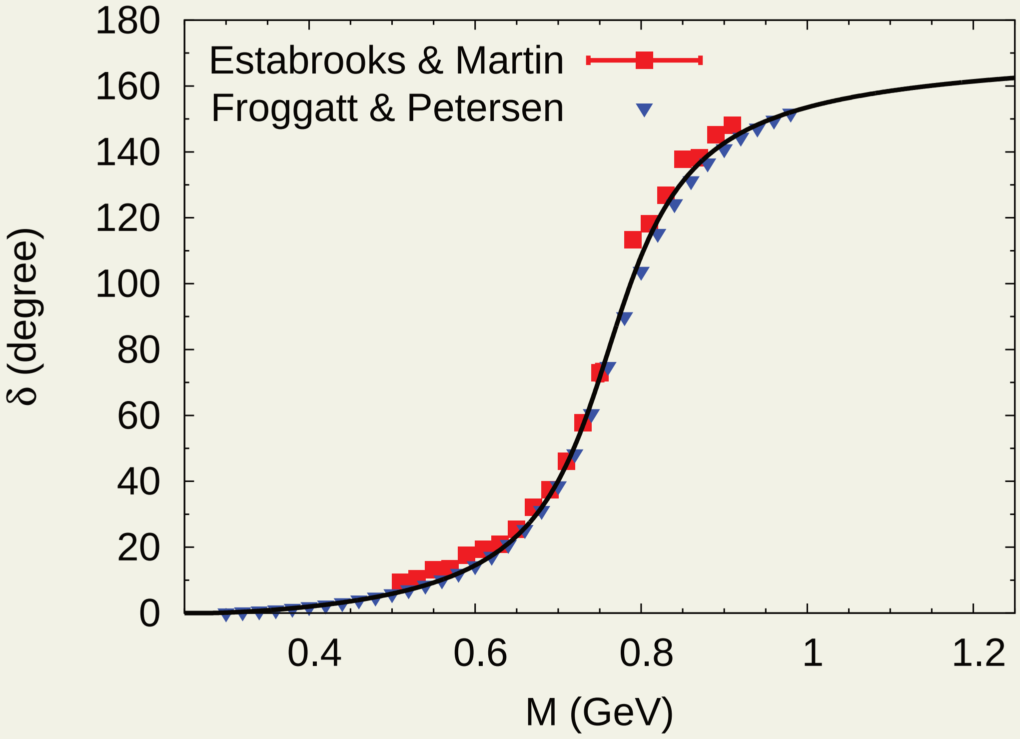

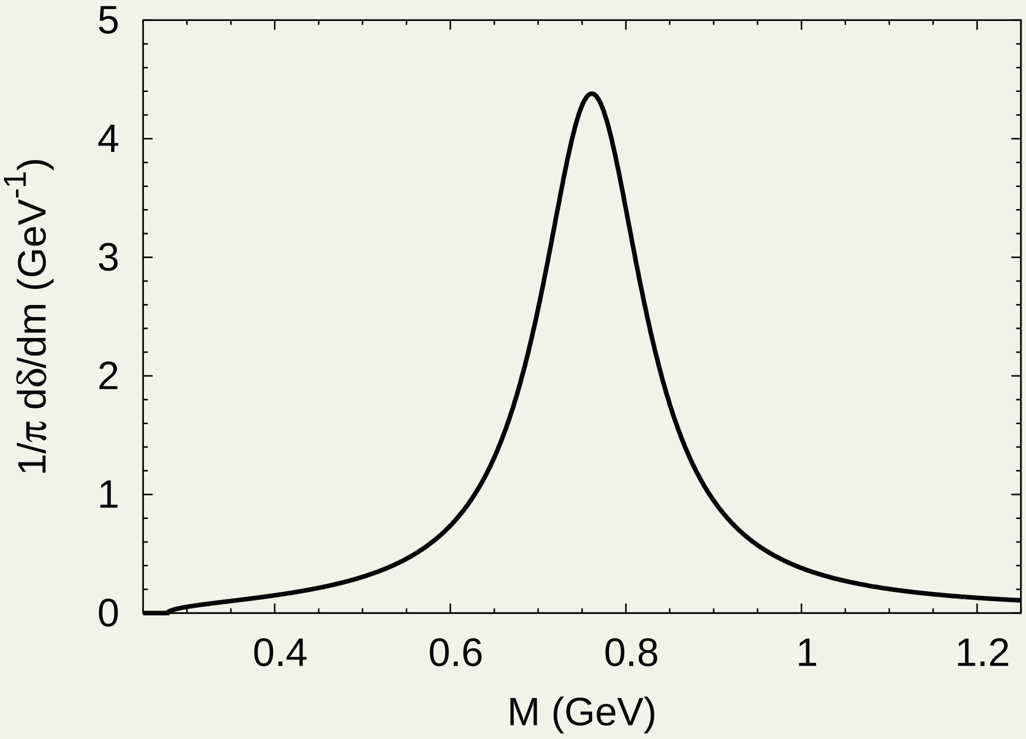

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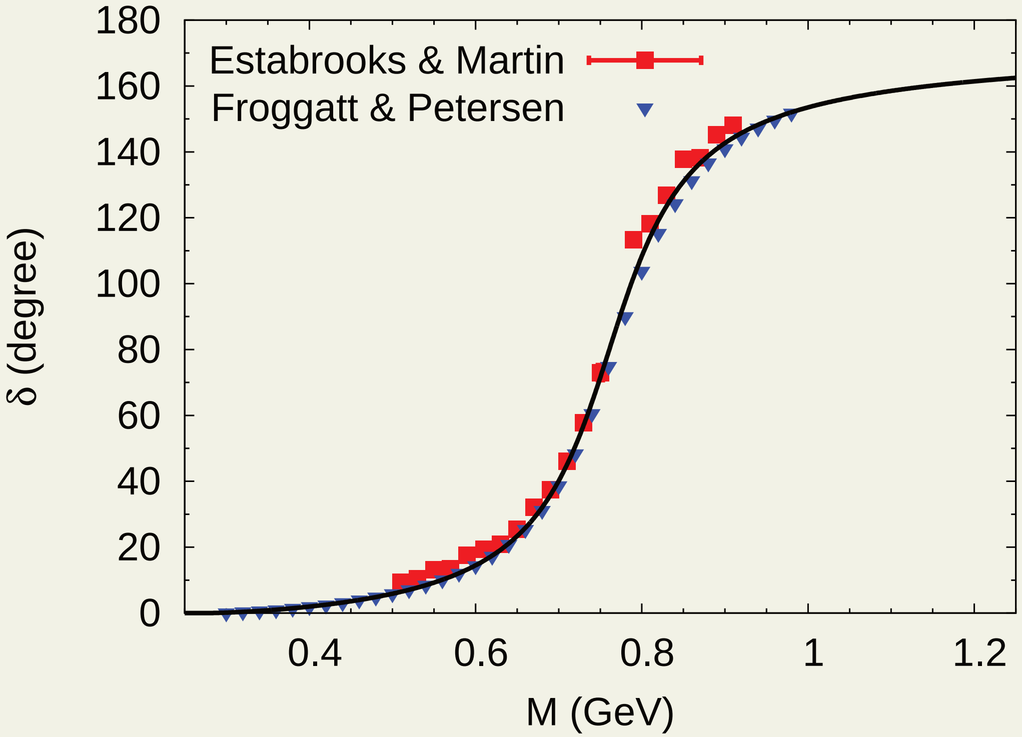
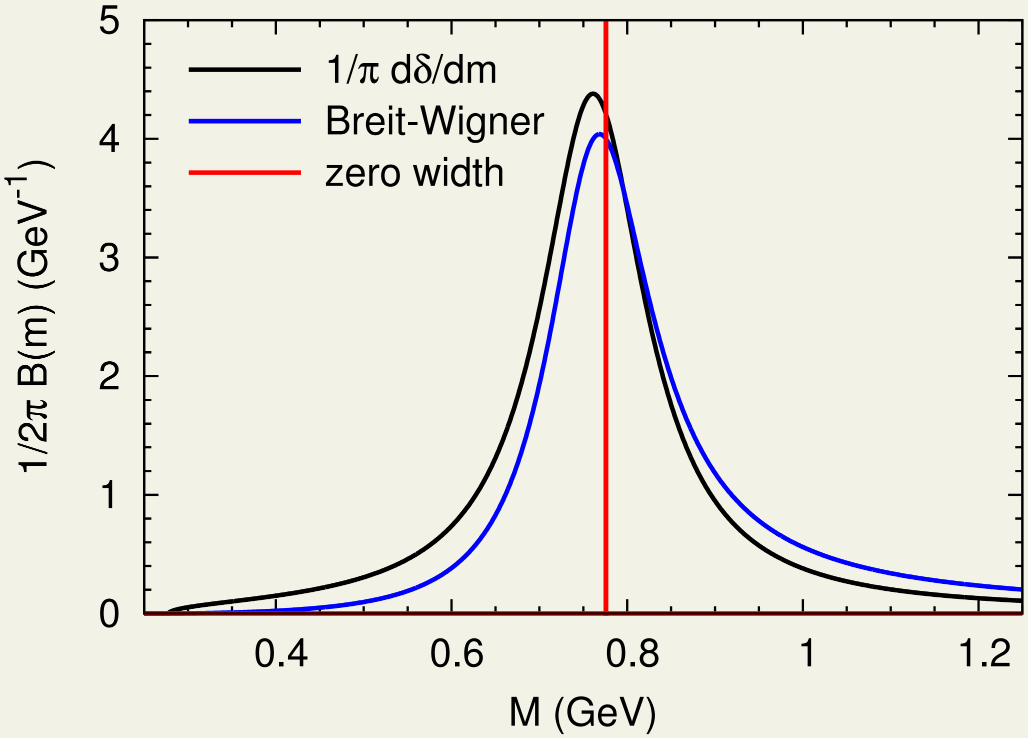
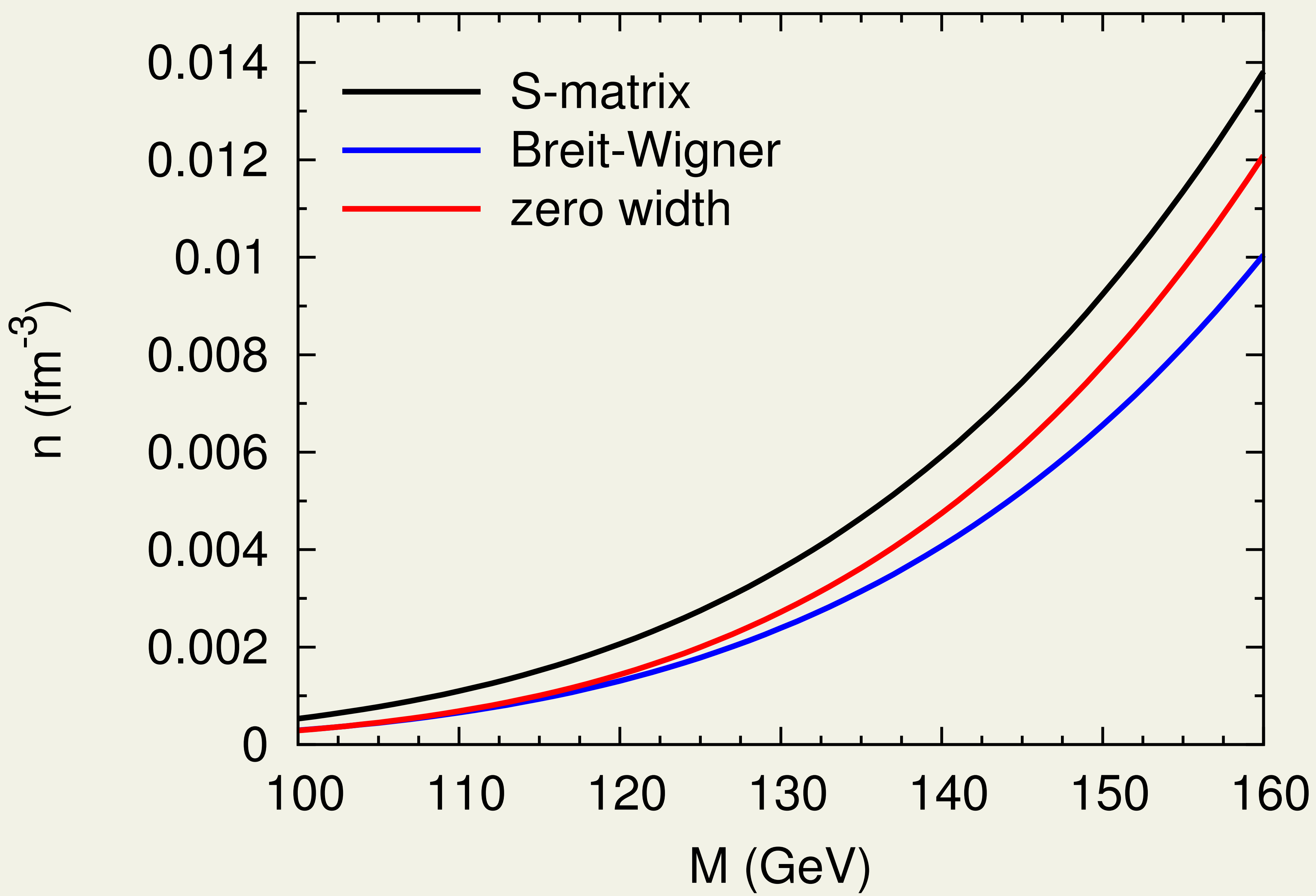


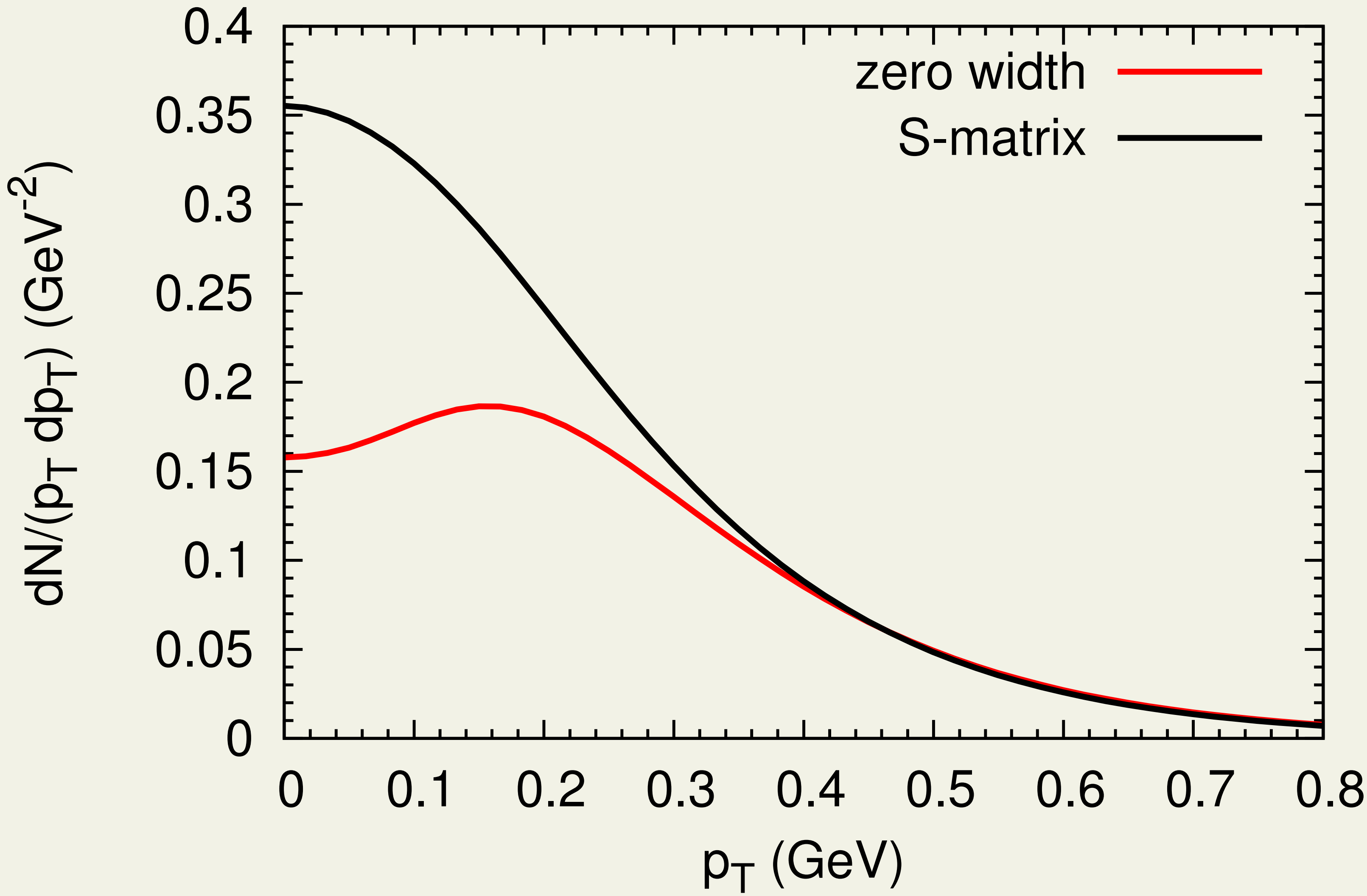


ρ-density



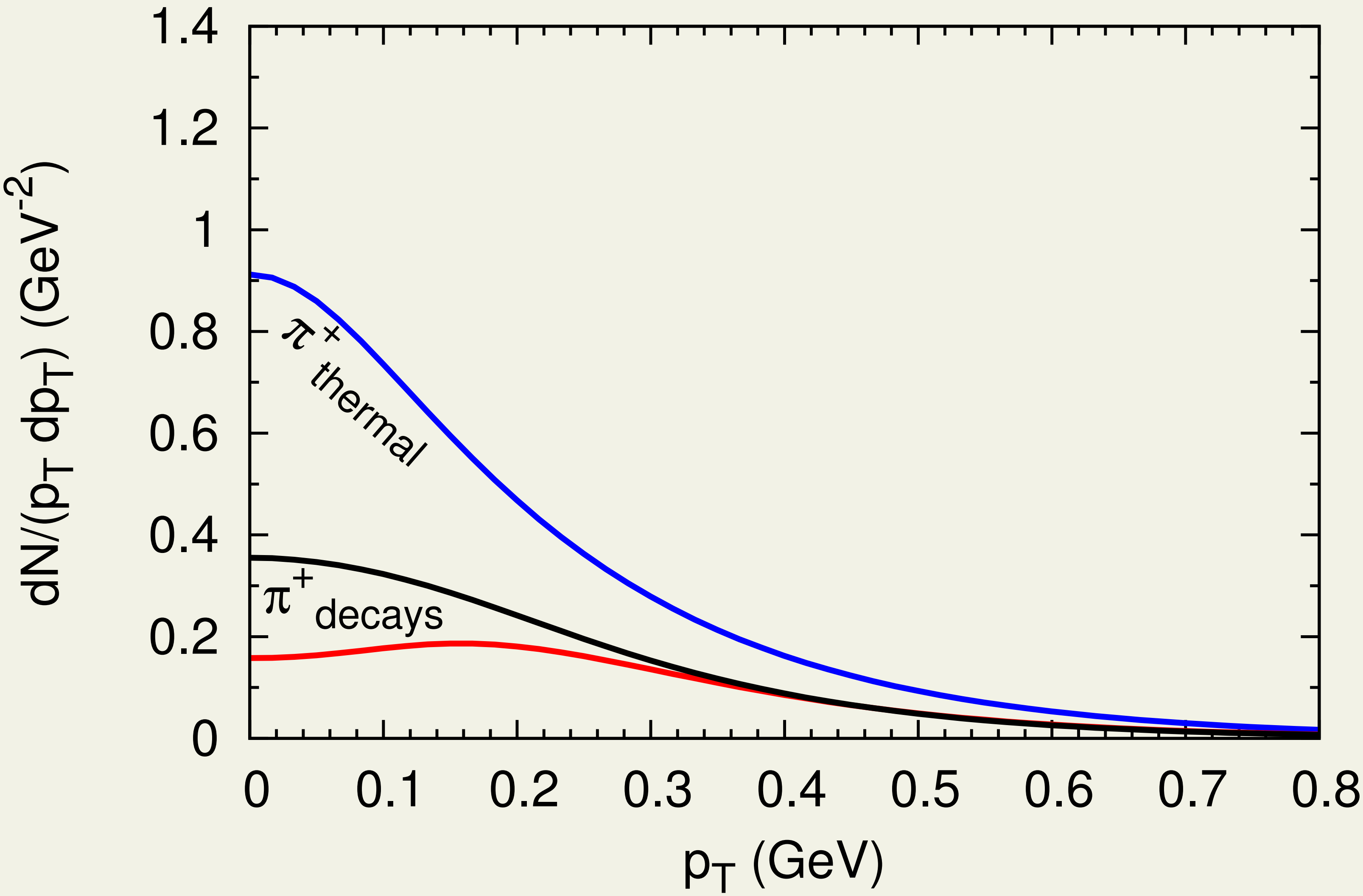
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
n (fm^-3)
S-matrix
Breit-Wigner
zero width
100
110
120
130
140
150
160
M (GeV)

Pions from ρ decays



- **static source,** $T = 155\,\mathrm{MeV}$

Thermal pions + pions from ρ decays



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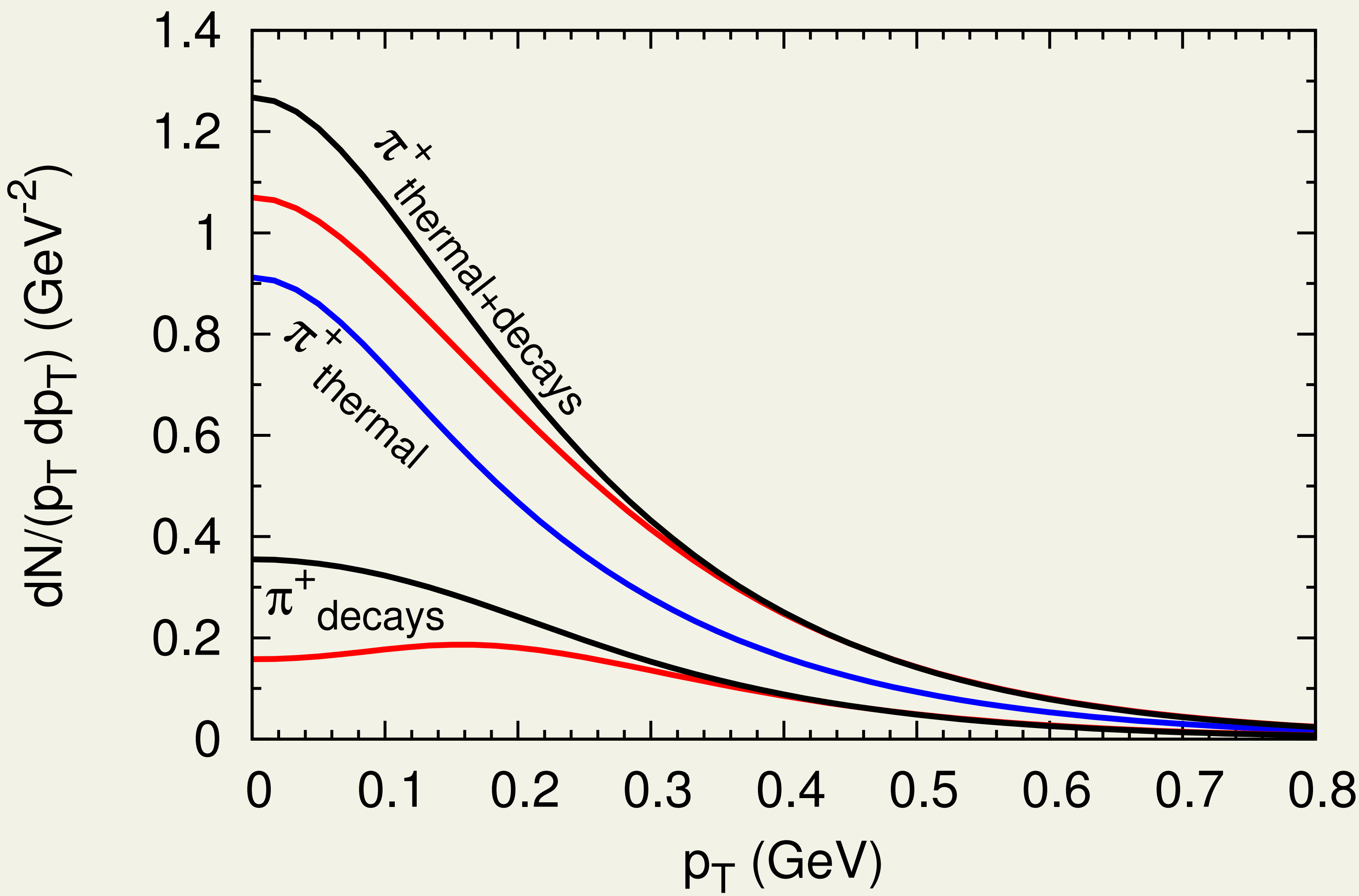
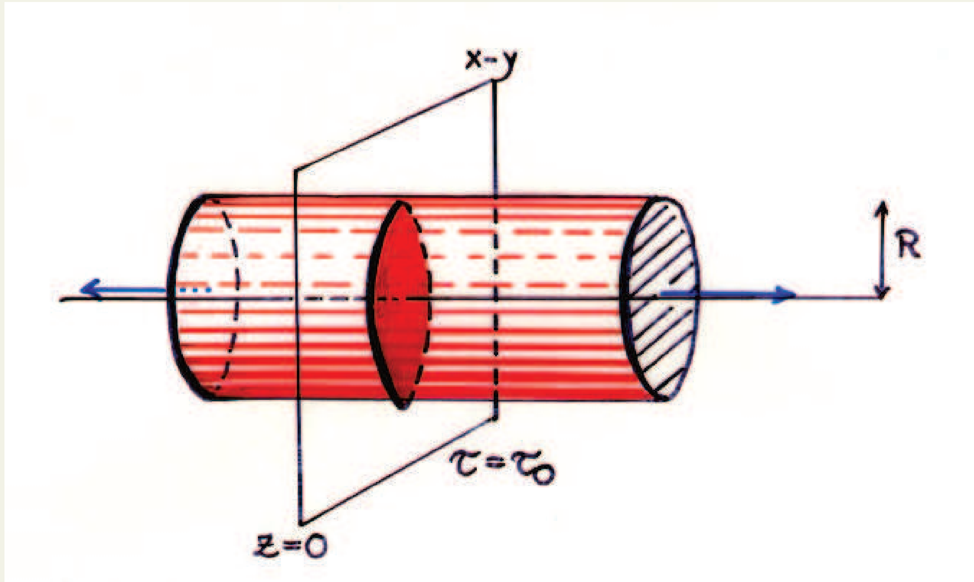


- **static source,** $T = 155\,\mathrm{MeV}$

blast-wave parametrisation

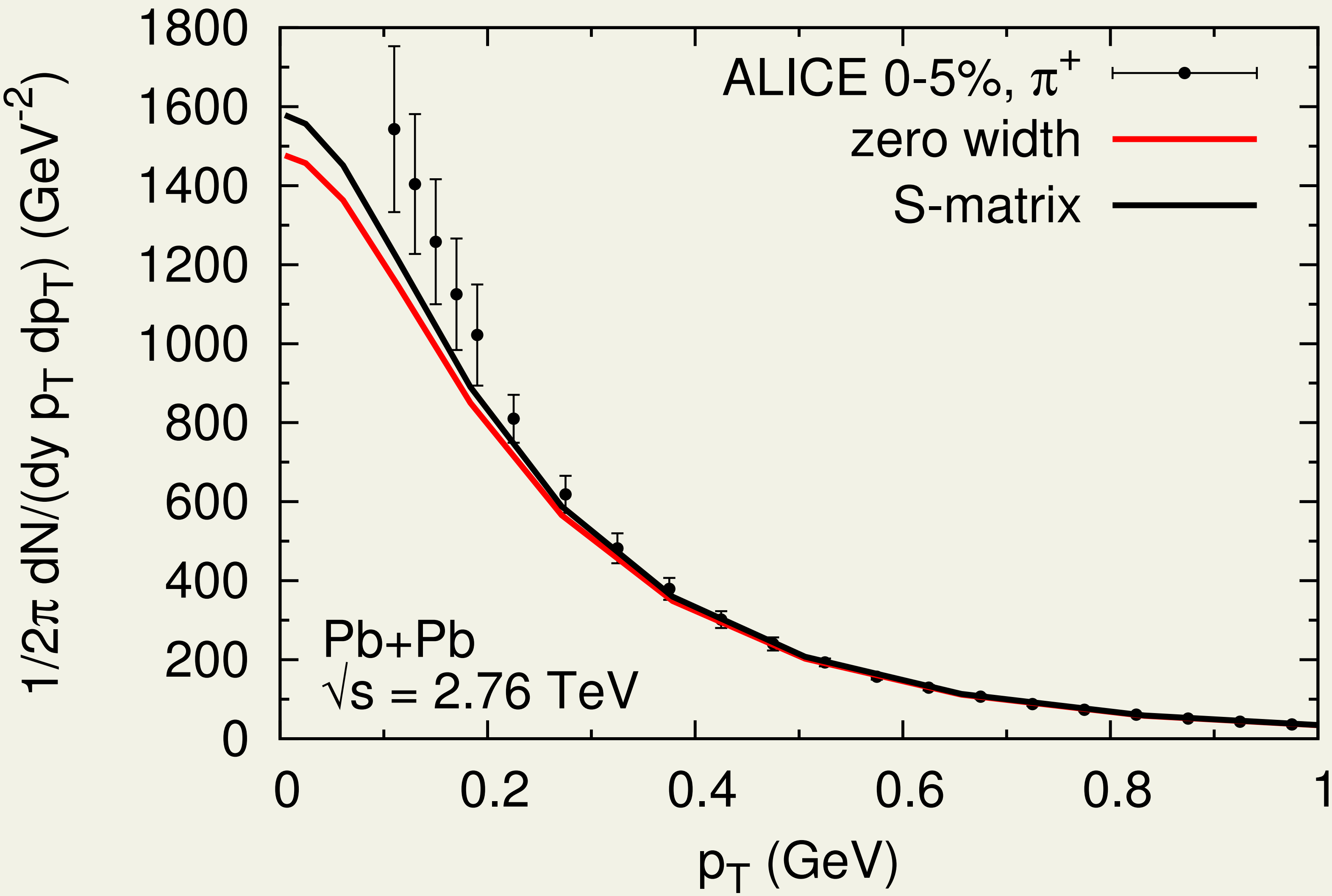


- **boost invariant & cylindrically symmetric**
- **decoupling at constant τ, i.e. volume emission**
- **transverse velocity $v = v(r)$**

$$E\frac{\mathrm{d}N}{\mathrm{d}p^3} = \frac{g\tau m_T}{2\pi^2}\int_0^R r\,\mathrm{d}r\int_{m_{\mathrm{th}}}^{\infty}\mathrm{d}m\frac{\mathrm{d}\rho}{\mathrm{d}m}\sum_{n=1}^{\infty}(\mp 1)^{n+1} I_0\left(n\frac{p_T\gamma_r(r)v_r(r)}{T}\right) K_1\left(n\frac{m_T\gamma_r(r)}{T}\right)$$

$\tau = 13.7\,\mathrm{fm}, \quad R = 10\,\mathrm{fm}, \quad v_{max} = 0.78$

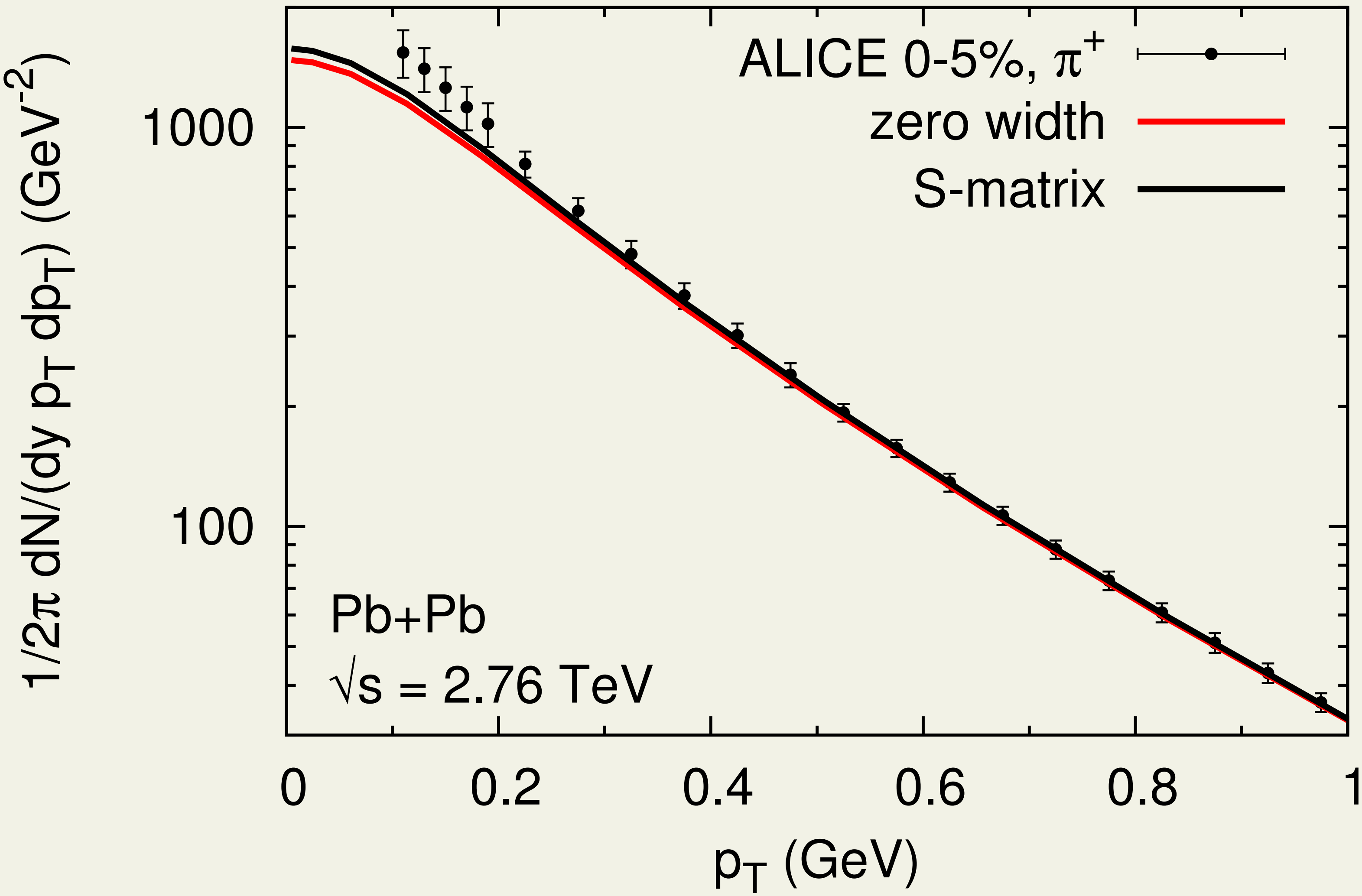
Pions from blast wave



- $\tau = 14.1\,\mathrm{fm}$
- $R = 10\,\mathrm{fm}$
- $v_{max} = 0.8$

- **all resonances up to 2 GeV**
- **Beth-Uhlenbeck for rhos**
- **zero width for everything else**

Pions from blast wave



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- $\Lambda(1405)$, $\Xi(1530)$ applicable
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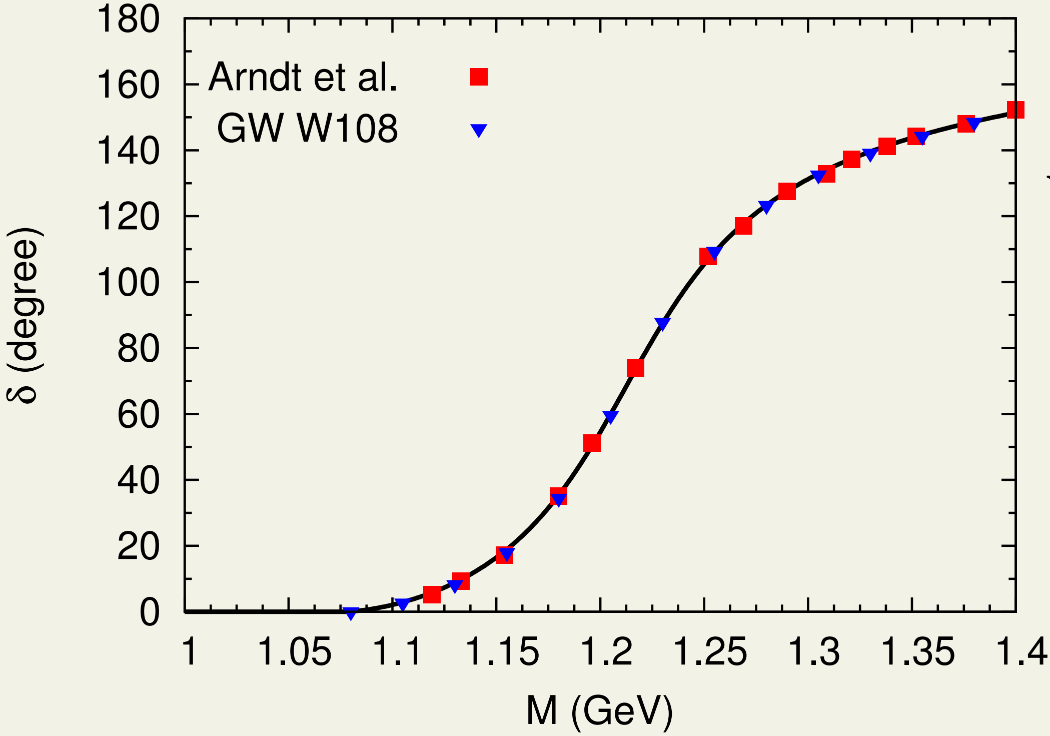
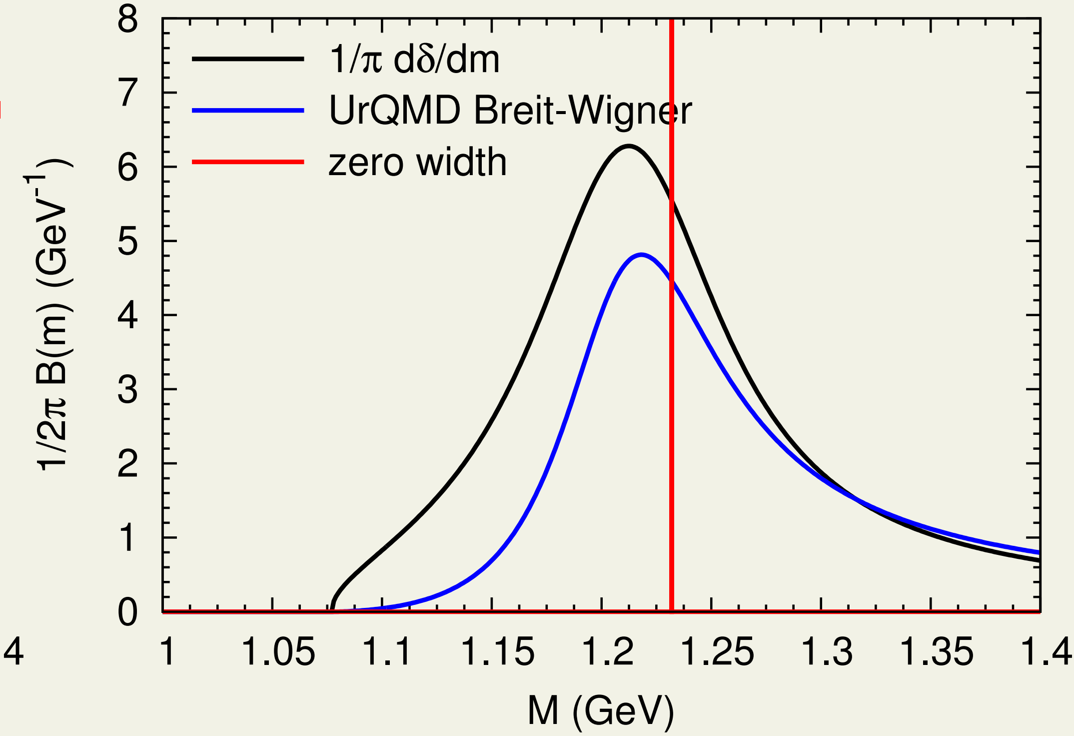
  - no data
- and everything else?

P_{33} πN scattering, a.k.a. Δ





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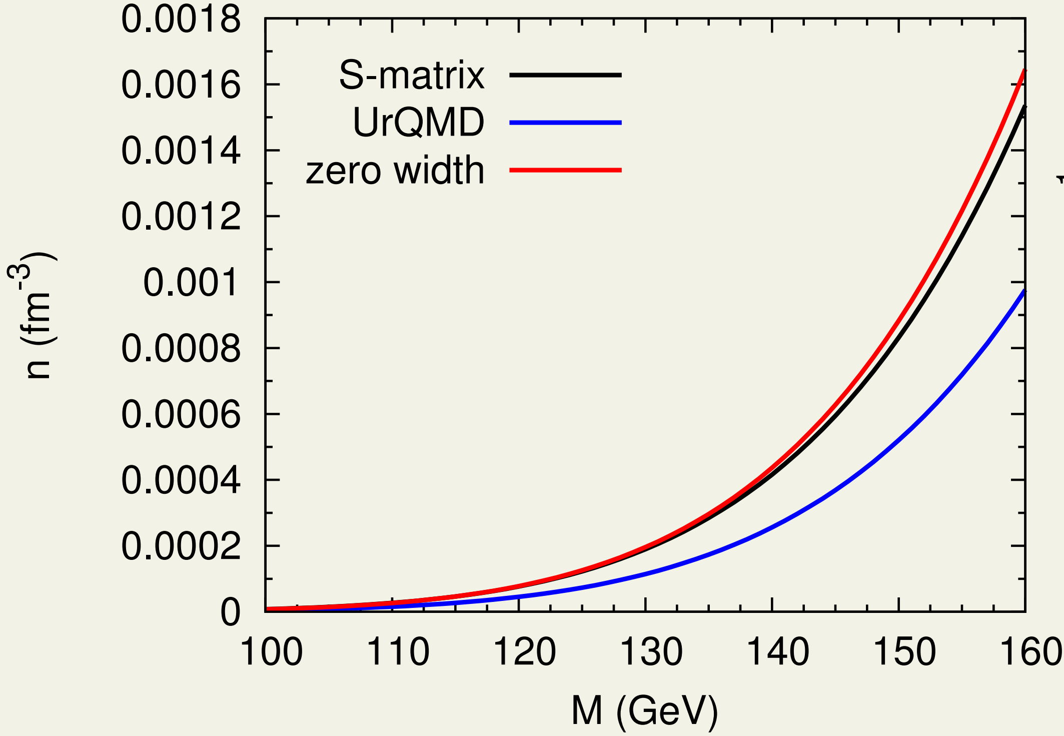
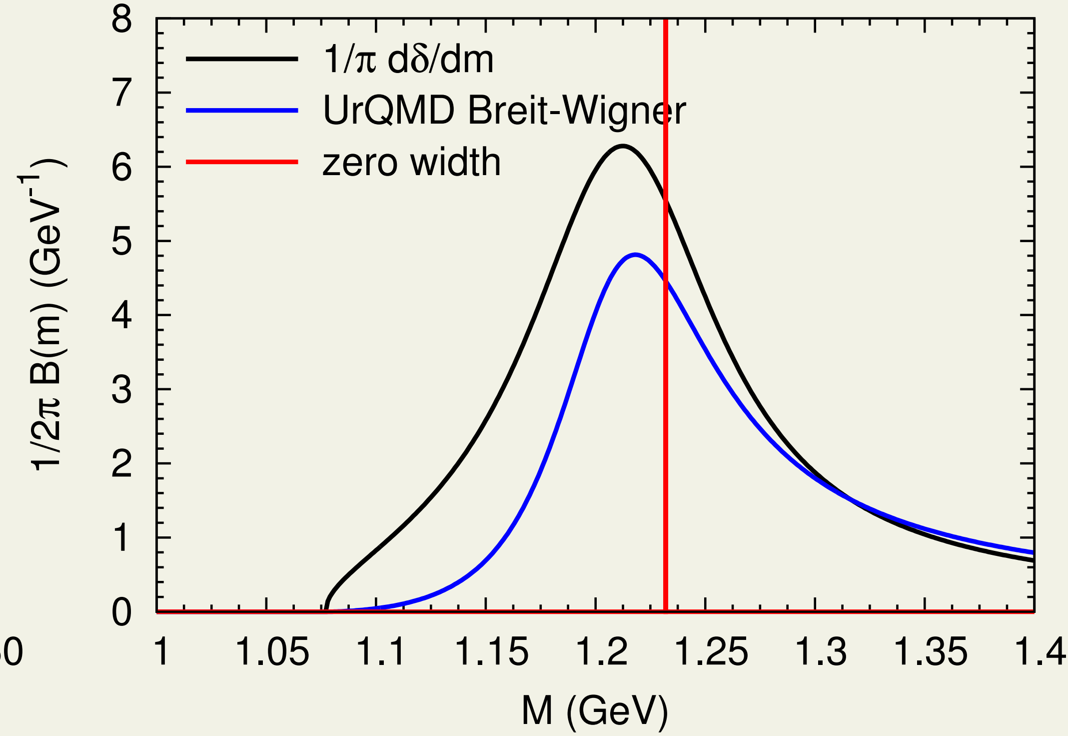
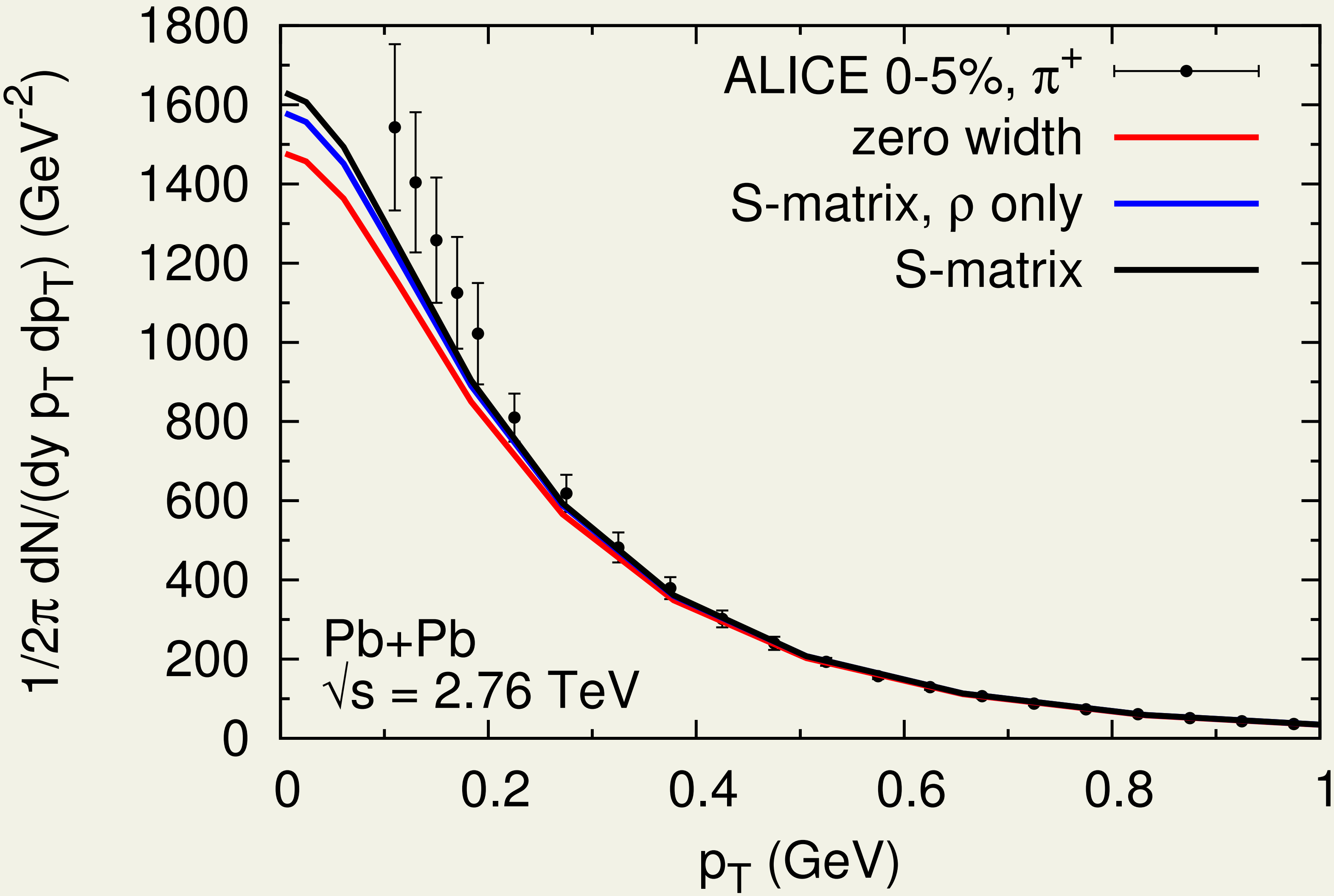




Pions from blast wave, $T = 150$ MeV



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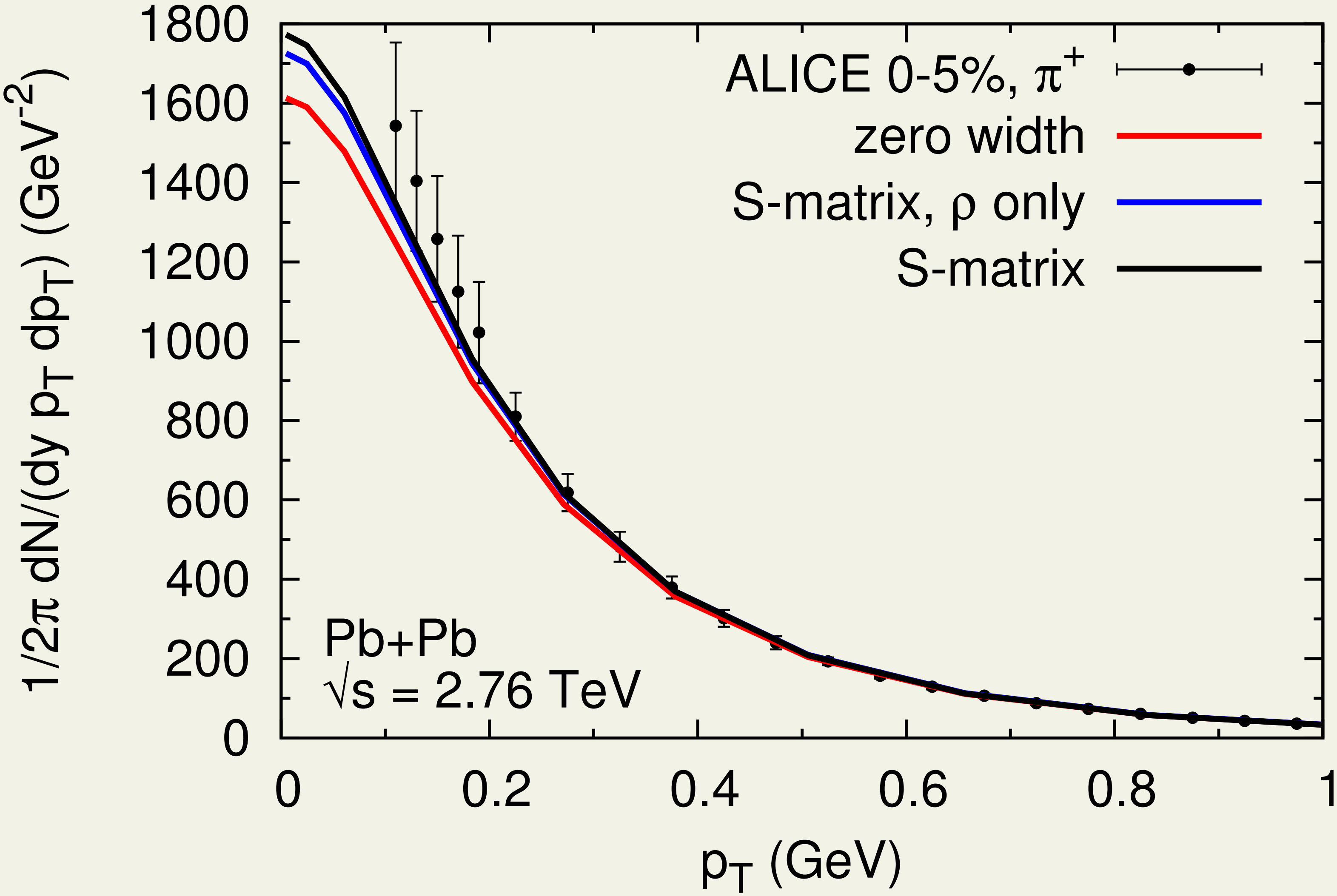
Pions from blast wave, $T = 120$, $T_{\rm chem} = 150$ MeV



- $\tau = 31.0\,\mathrm{fm}$
- $R = 10\,\mathrm{fm}$
- $v_{max} = 0.87$

- **all resonances up to 2 GeV**
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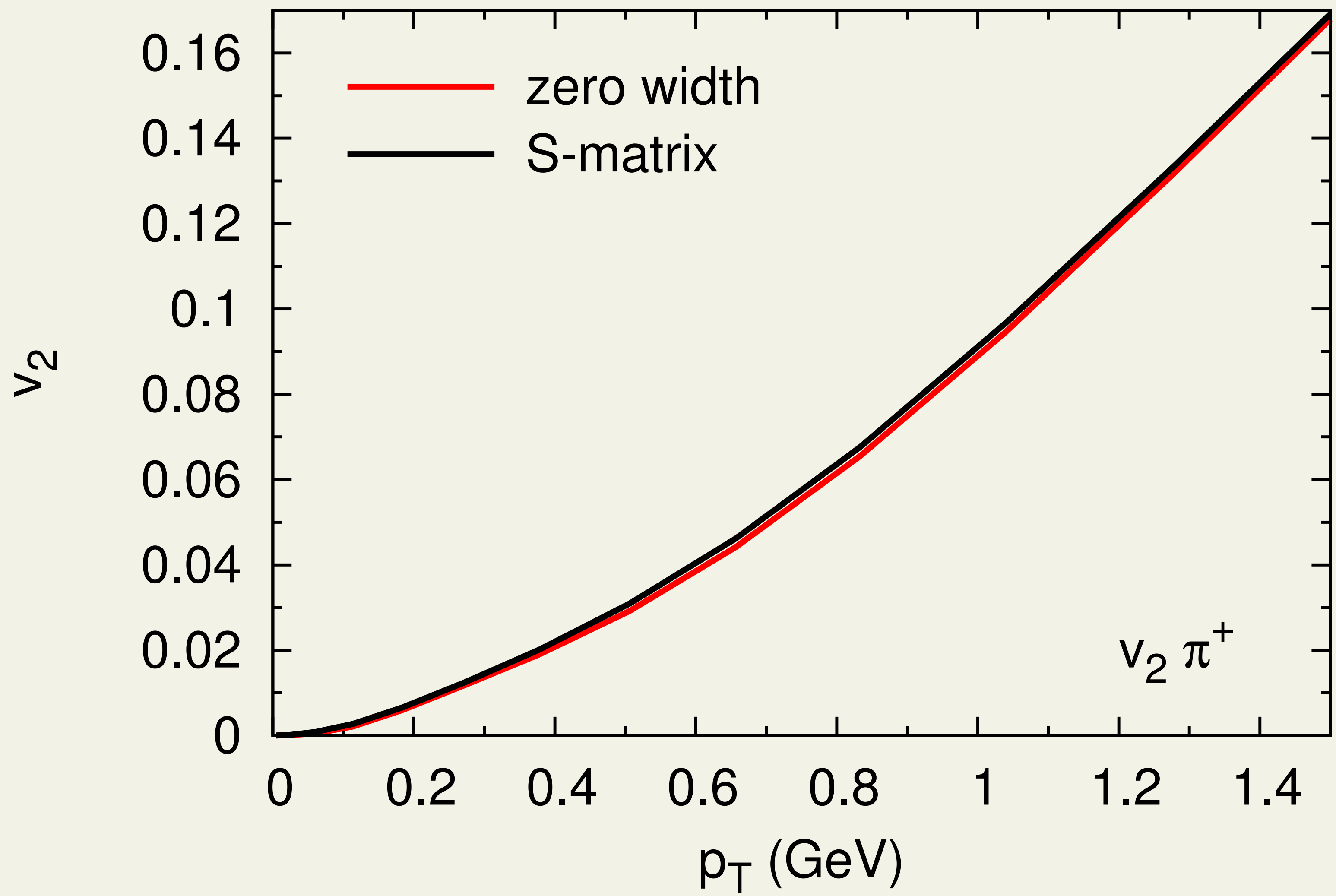
v_2 of pions from blast wave, $T = 120$, $T_{\mathrm{chem}} = 150$ MeV



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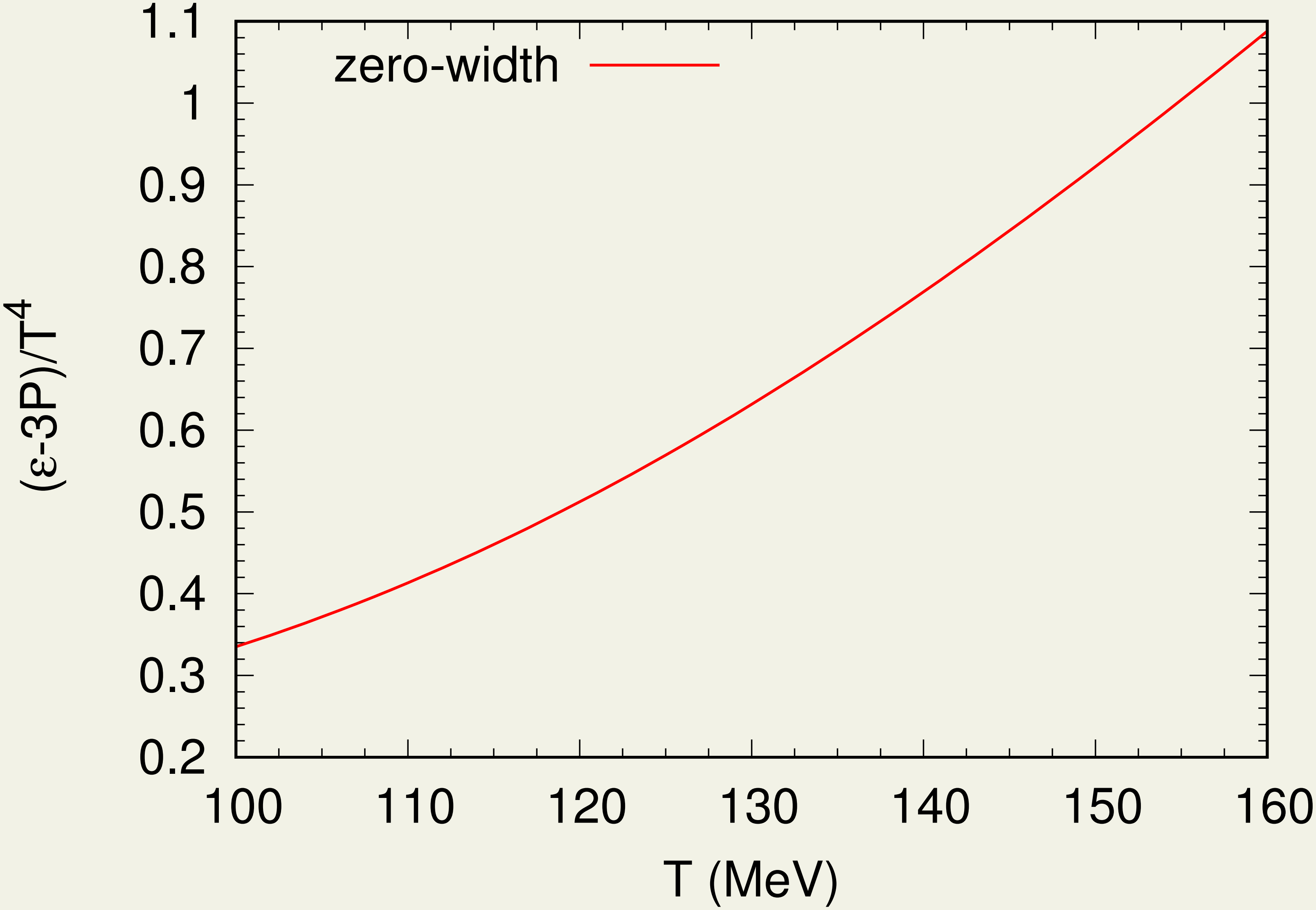
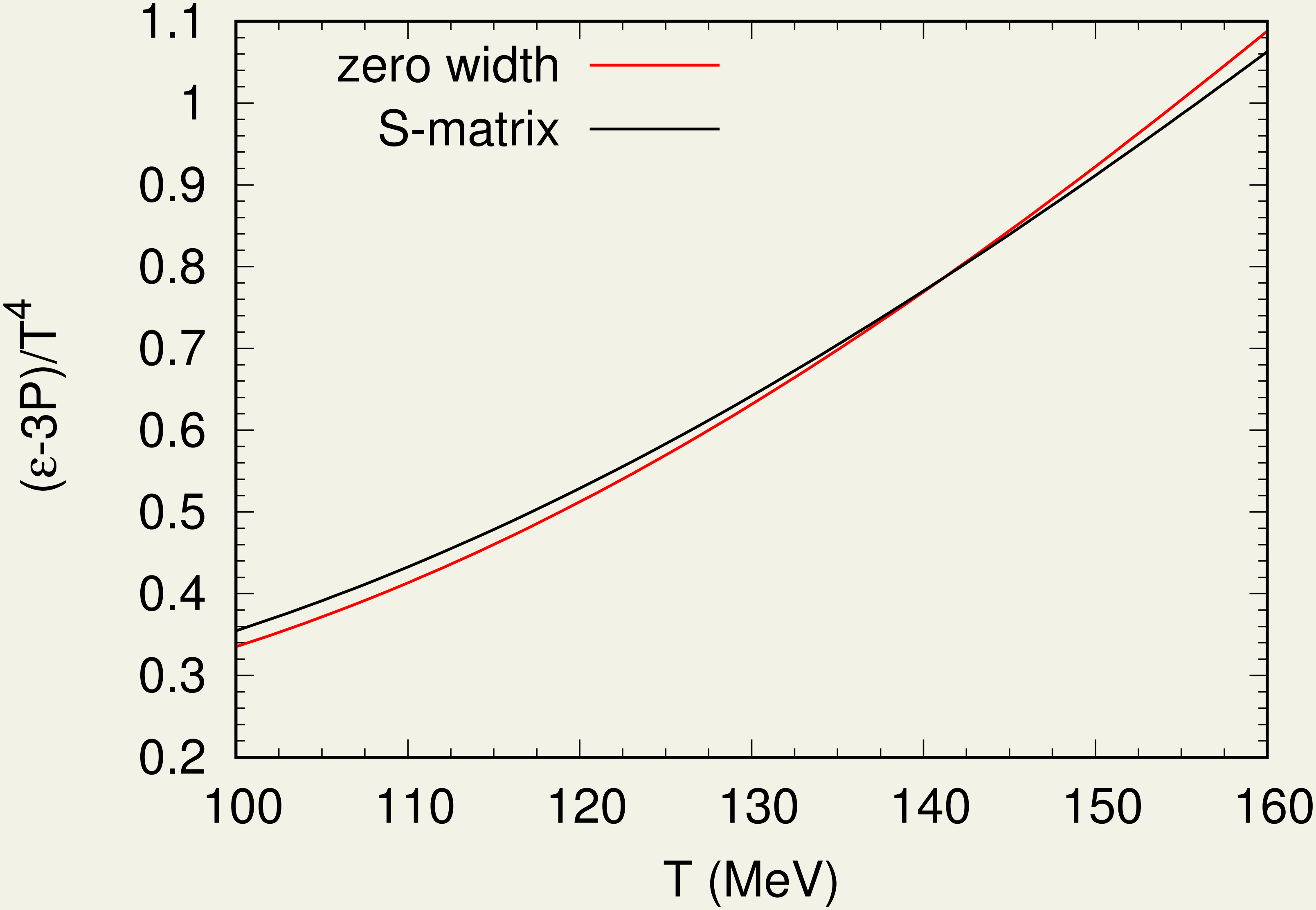
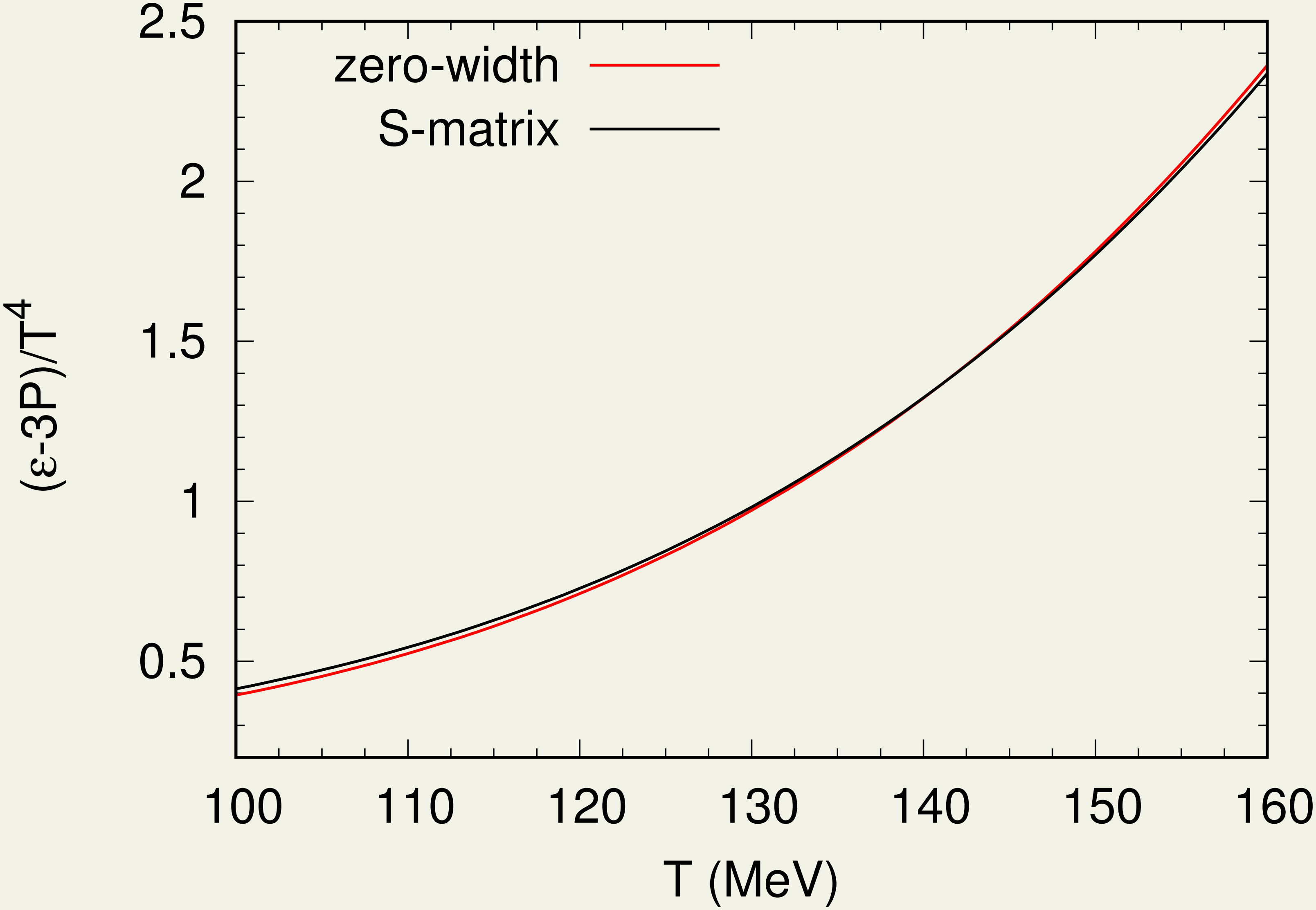
$\pi, K, N, \rho, f_0(980), K^*, K_0(1430), \Delta$



π, K, N, ρ, $f_0(980)$, K^*, $K_0(1430)$, Δ



the whole zoo



Summary of part II

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- **Better treatment of resonances needed**

♻ **This talk consisted of 100% recycled electrons**