Update of the Three-fluid Hydrodynamics-based Event Simulator (THESEUS) and light-nuclei production in heavy-ion collisions

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Plan of the presentation

- Introduction
- 3FD model. Hydrodynamical approach.
- Event generator THESEUS: short description.
- THESEUS-v2 update
- Benchmark of the generator: production of protons and light nuclei (deuterons, tritons, 3He, 4He, anti-deuterons) in Au+Au and Pb+Pb collisions at different energies and impact parameters and comparison with the 3FD model and existing experimental data.
- Preliminary results, unpublished: rapidity distributions, pT, mT-spectra, directed flow v1 of light nuclei.
- Summary
- Outlook

Introduction

At present, there are few 3D dynamical models which include the coalescence mechanism of the light-nuclei production. The coalescence-based models use fitting parameters from comparison with data on the light-nuclei production, so their predictive power is restricted.

Hyrodynamical and kinetic models with the following types of clusters formation:

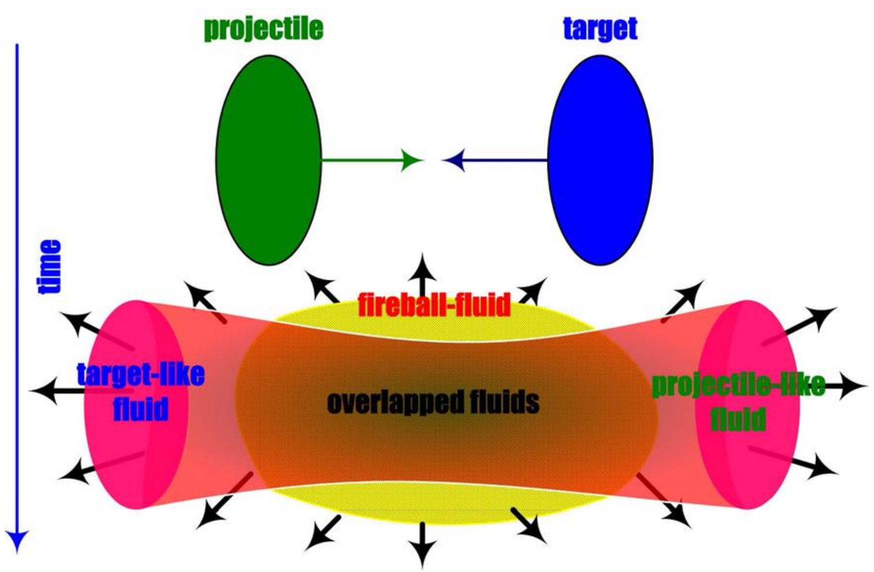
- various types of coalescence-based models
- thermal + blast wave models
- and dynamical models (SMASH, PHQMD)

We present an update of the event generator based on the three-fluid dynamics (3FD), complemented by Ultra-relativistic Quantum Molecular Dynamics (UrQMD) for the late stage of the nuclear collision - the Three-fluid Hydrodynamics-based Event Simulator Extended by UrQMD final State interactions (THESEUS).

THESEUS use thermodynamic approach of the 3FD model, alternative to another’s.

Main areas of research: study the light-nuclei production at collision energies of the BES-RHIC, SPS, NICA and FAIR.

Three-fluid dynamics (3FD) model



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

- There are two counterstreaming baryon-rich fluids: nucleons of the projectile (p) and the target (t) nuclei. Later, these fluids may consist of any type of constituents (rather than only nucleons).
- fireball (f) fluid: newly produced particles which dominantly populate the midrapidity region.
- On each of these fluids work hydrodynamic equations coupled by friction terms in the right-hand sides of the Euler equations.
- When the system becomes dilute, the 3FD evolution is stopped and the system is frozen out.
- The output of the model is recorded in terms of Lagrangian test particles (i.e. fluid droplets) for each fluid α(= p, t or f). Fluid droplets = elements of particlization surface in hydrodynamic+cascade models.

3FD model

Target-like fluid: $\partial_\mu J^\mu_t = 0$ $\quad$ $\partial_\mu T^{\mu\nu}_t = -F^\nu_{tp} + F^\nu_{ft}$

Leading particles carry bar. charge $\quad$ exchange/emission

Projectile-like fluid: $\partial_\mu J^\mu_p = 0,$ $\quad$ $\partial_\mu T^{\mu\nu}_p = -F^\nu_{pt} + F^\nu_{fp}$

Fireball fluid: $J^\mu_f = 0,$ $\quad$ $\partial_\mu T^{\mu\nu}_f = F^\nu_{pt} + F^\nu_{tp} - F^\nu_{fp} - F^\nu_{ft}$

Baryon-free fluid $\quad$ Source term $\quad$ Exchange

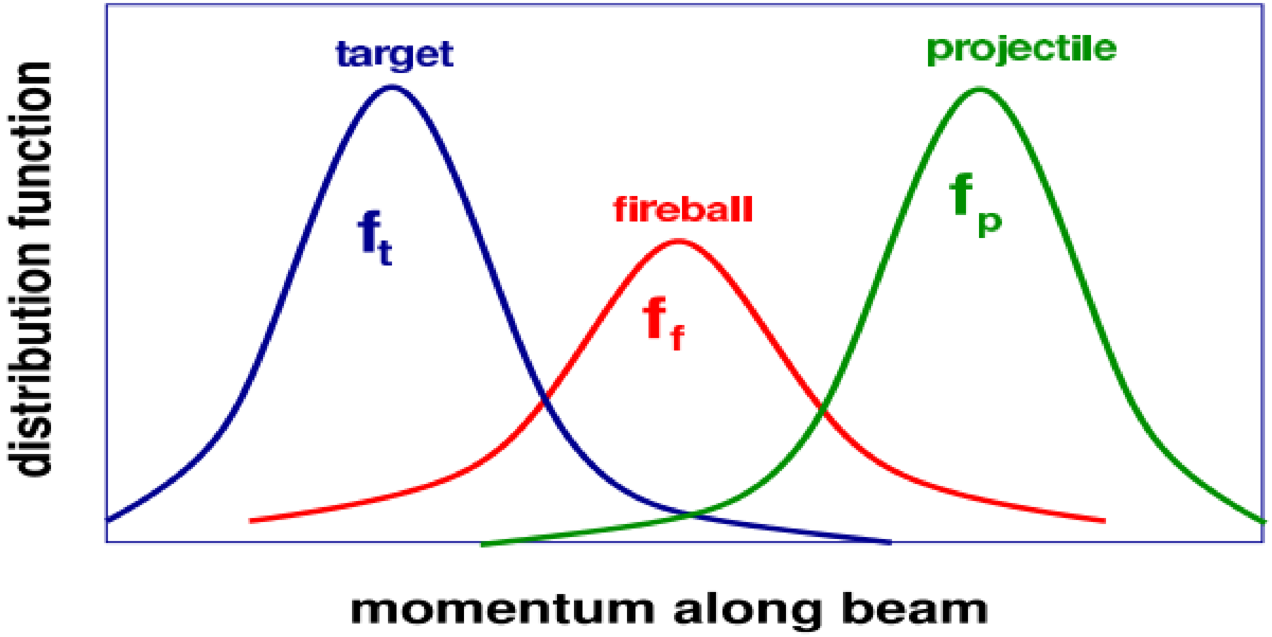
The source term is delayed due to a formation time τ

Total energy-momentum conservation:

$$\partial_\mu (T^{\mu\nu}_p + T^{\mu\nu}_t + T^{\mu\nu}_f) = 0$$

Physical Input

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



3FD: Yu.B. Ivanov, V.N. Russkikh, V.D. Toneev, PHYSICAL REVIEW C 73, 044904 (2006)

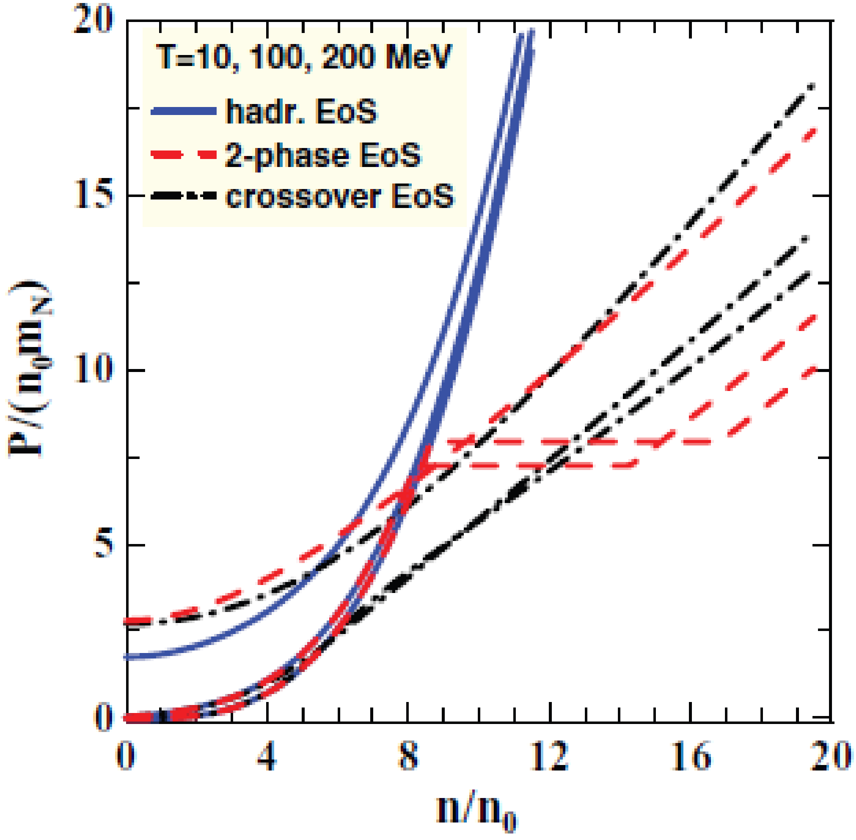
Three-fluid dynamics (3FD) model

Equations of State (EoS) in 3FD:

- hadronic EoS (no phase transition)
- hadronic+QGP EoS with 1st-order PT
- hadronic+QGP EoS with crossover PT

In the original 3FD output consists of fluid characteristics. In the original 3FD the output consists of fluid characteristics. Observables are computed by numerically integrating hadron distribution functions over the set of droplets.
Therefore,

- Implementing experimental conditions (cuts etc) in 3FD is difficult.
- There is no afterburner stage in 3FD



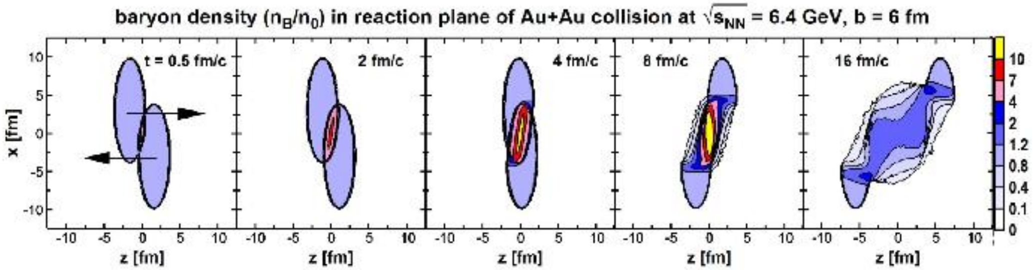
A. Khvorostukhin, V.V. Skokov, V.D. Toneev, K. Redlich, EPJ C48, 531 (2006)
Yu. B. Ivanov, D. Blaschke, PRC 92, 024916 (2015)

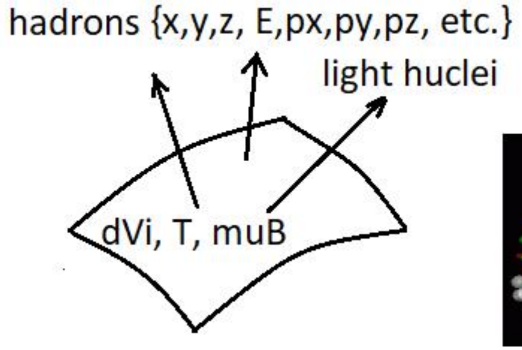
THESEUS event generator

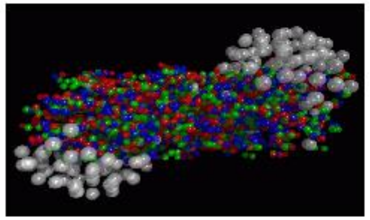
- In 2016 the THESEUS event generator was introduced.
- **THESEUS = 3FD + Monte Carlo hadron sampling + rescatterings/decays via UrQMD**
- There were no light nuclei included.
- THESEUS presents the 3FD output in terms of a set of observed particles.
- Since the time THESEUS was first presented, certain updates have been made, further referred to as THESEUS-v2.

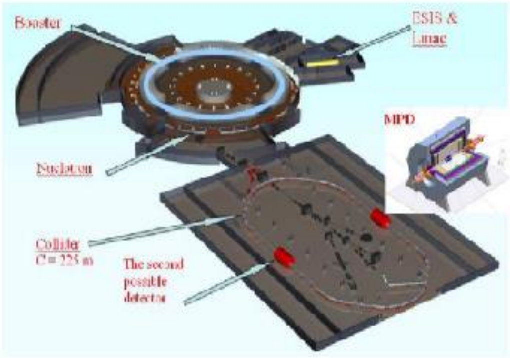
THESEUS (3FD+Particlization+UrQMD): P. Batyuk et al., PHYSICAL REVIEW C 94, 044917 (2016)

Hydrodynamic modelling of nuclear collisions for NICA / FAIR









Initial state → hydrodynamic evolution → particlization → afterburner → detector response

3-fluid hydrodynamical model
(Y.Ivanov et al.)

THESEUS generator

(optionally) UrQMD, etc.
(Iu. Karpenko, H.Elfner)

GEANT, MPD,BM@N
(O.Rogachevsky,
P.Batuyk, S.Merts et al.)

THESEUS-v2: updates

Updated list of hadronic resonances

- identical to the list of hadronic resonances in the underlying 3FD model
- only hadrons with well-known decay modes (PDG) - sufficient for 3FD model (moderately high energies).
- the relative contribution from highly excited resonances is quite small at moderately high energies.

M. Kozhevnikova, Yu. B. Ivanov, Iu. Karpenko, D. Blaschke, O. Rogachevsky
arXiv:2012.11438 (2020) , PRC in press.

Table: List of hadrons incorporated in the original THESEUS.
The resonances used in 3FD simulations are marked by bold font.

light unflavored mesons	flavored mesons	N and Δ baryons	flavored baryons
$\boldsymbol{\pi}$	$\boldsymbol{K}$	$\boldsymbol{N}$	$\boldsymbol{\Lambda}$
$\boldsymbol{\eta}$	$K_0^*(800)$	$\boldsymbol{N(1440)}$	$\Lambda(1405)$
$\boldsymbol{f_0(600)}$	$\boldsymbol{K^*(892)}$	$\boldsymbol{N(1520)}$	$\Lambda(1520)$
$\boldsymbol{\rho(770)}$	$K_1(1270)$	$\boldsymbol{N(1535)}$	$\Lambda(1600)$
$\boldsymbol{\omega(782)}$	$K_1(1400)$	$\boldsymbol{N(1650)}$	$\Lambda(1670)$
$\boldsymbol{\eta'(958)}$	$K^*(1410)$	$\boldsymbol{N(1675)}$	$\Lambda(1690)$
$\boldsymbol{f_0(980)}$	$K_0^*(1430)$	$\boldsymbol{N(1680)}$	$\Lambda(1800)$
$\boldsymbol{a_0(980)}$	$K_2^*(1430)$	$\boldsymbol{N(1700)}$	$\Lambda(1810)$
$\boldsymbol{\phi(1020)}$	$K(1460)$	$\boldsymbol{N(1710)}$	$\Lambda(1820)$
$h_1(1170)$	$K_2(1580)$	$\boldsymbol{N(1720)}$	$\Lambda(1830)$
$b_1(1235)$	$K_1(1650)$	$N(2190)$	$\Lambda(1890)$
$a_1(1260)$	$K^*(1680)$	$\boldsymbol{\Delta(1232)}$	$\Lambda(2100)$
$f_2(1270)$	$K_2(1770)$	$\boldsymbol{\Delta(1600)}$	$\Lambda(2110)$
$f_1(1285)$	$K_3^*(1780)$	$\boldsymbol{\Delta(1620)}$	$\boldsymbol{\Sigma}$
$\eta(1295)$	$K_2(1820)$	$\boldsymbol{\Delta(1700)}$	$\boldsymbol{\Sigma(1385)}$
$f_1(1420)$	$K_3(2320)$	$\Delta(1950)$	$\Sigma(1940)$
...	...		...
$f_2(1430)$	D		$\boldsymbol{\Xi}$
...	...		...
$\eta(1475)$	$D_0^*(2400)$		$\boldsymbol{\Omega}$
...	...		...
$f_2(2340)$	$\Upsilon(11020)$		Ξ_b

THESEUS-v2: updates

Nucleon clusters are not included in 3FD originally.

To include light nuclei in thermodynamics, baryon chemical potential should be recalculated.

Recalculation of baryon chemical potential taking into account light nuclei production, proceeding from the local baryon number conservation:

$$
\begin{aligned}
& n_{\text{primordial } N}(x;\mu_B,T) + \sum_{\text{hadrons}} n_i(x;\mu_B,\mu_S,T) \\
&= n_{\text{observable } N}(x;\mu'_B,T) + \sum_{\text{hadrons}} n_i(x;\mu'_B,\mu_S,T) \\
&\quad + \sum_{\text{nuclei}} n_c(x;\mu'_B,\mu_S,T).
\end{aligned}
$$

The list of light-nuclei species is shown in Table.

Nucleus(E[MeV])	J	decay modes, in %
d	1	Stable
t	1/2	Stable
^{3}He	1/2	Stable
^{4}He	0	Stable
^{4}He(20.21)	0	$p = 100$
^{4}He(21.01)	0	$n = 24,\ p = 76$
^{4}He(21.84)	2	$n = 37,\ p = 63$
^{4}He(23.33)	2	$n = 47,\ p = 53$
^{4}He(23.64)	1	$n = 45,\ p = 55$
^{4}He(24.25)	1	$n = 47,\ p = 50,\ d = 3$
^{4}He(25.28)	0	$n = 48,\ p = 52$
^{4}He(25.95)	1	$n = 48,\ p = 52$
^{4}He(27.42)	2	$n = 3,\ p = 3,\ d = 94$
^{4}He(28.31)	1	$n = 47,\ p = 48,\ d = 5$
^{4}He(28.37)	1	$n = 2,\ p = 2,\ d = 96$
^{4}He(28.39)	2	$n = 0.2,\ p = 0.2,\ d = 99.6$
^{4}He(28.64)	0	$d = 100$
^{4}He(28.67)	2	$d = 100$
^{4}He(29.89)	2	$n = 0.4,\ p = 0.4,\ d = 99.2$

Table: Stable light nuclei and low-lying resonances of The 4He system (from BNL properties of nuclides).

THESEUS-v2: updates. Isotopic content of produced hadrons.

In the 3FD model, particles are not isotopically distinguished: protons and neutrons are identic.

In THESEUS-v2 fraction of protons:

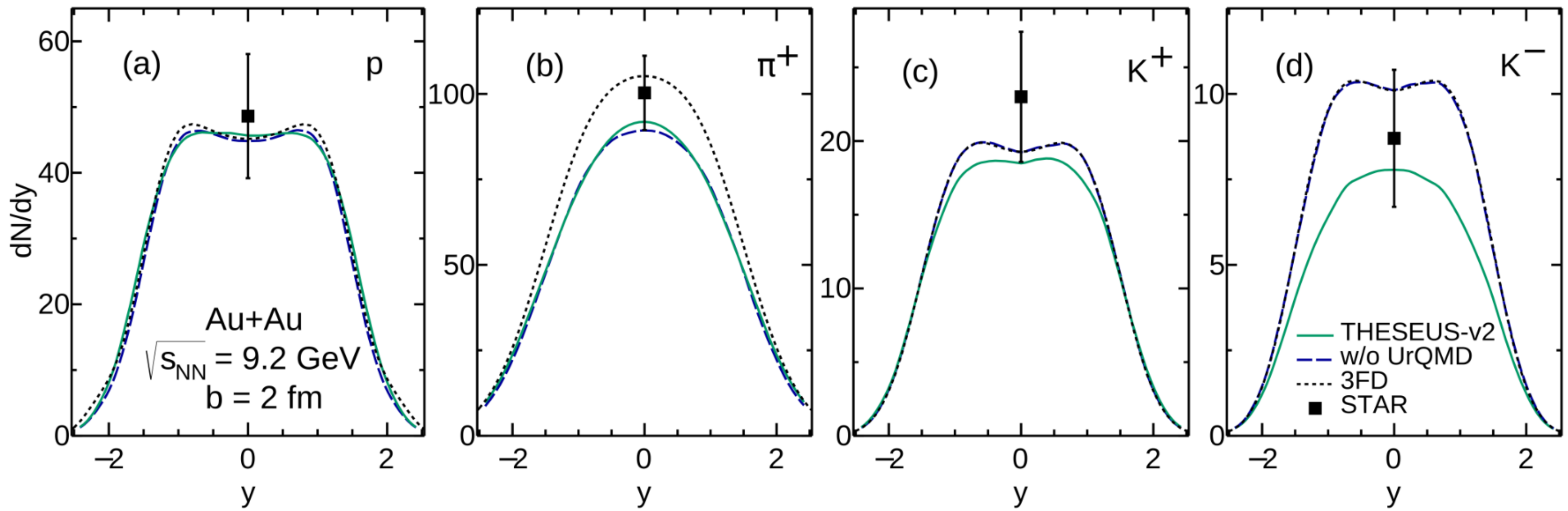
$$R_{\text{proton}} = \frac{Z_{\text{participants}} - N_d - N_t - 2N_{^3\text{He}} - 2N_{^4\text{He}}}{B_{\text{participants}} - 2N_d - 3N_t - 3N_{^3\text{He}} - 4N_{^4\text{He}}}$$

Where *B*participants and $Z_{\text{participants}} = B_{\text{participants}}(Z_1 + Z_2)/(A_1 + A_2)$ are the total baryon number and electrical charge of participants, *N*nucleus is the multiplicity of the produced light nucleus. The formula reflects that some protons are bounded in light nuclei.

Tritium and 3He are also scaled with the factors

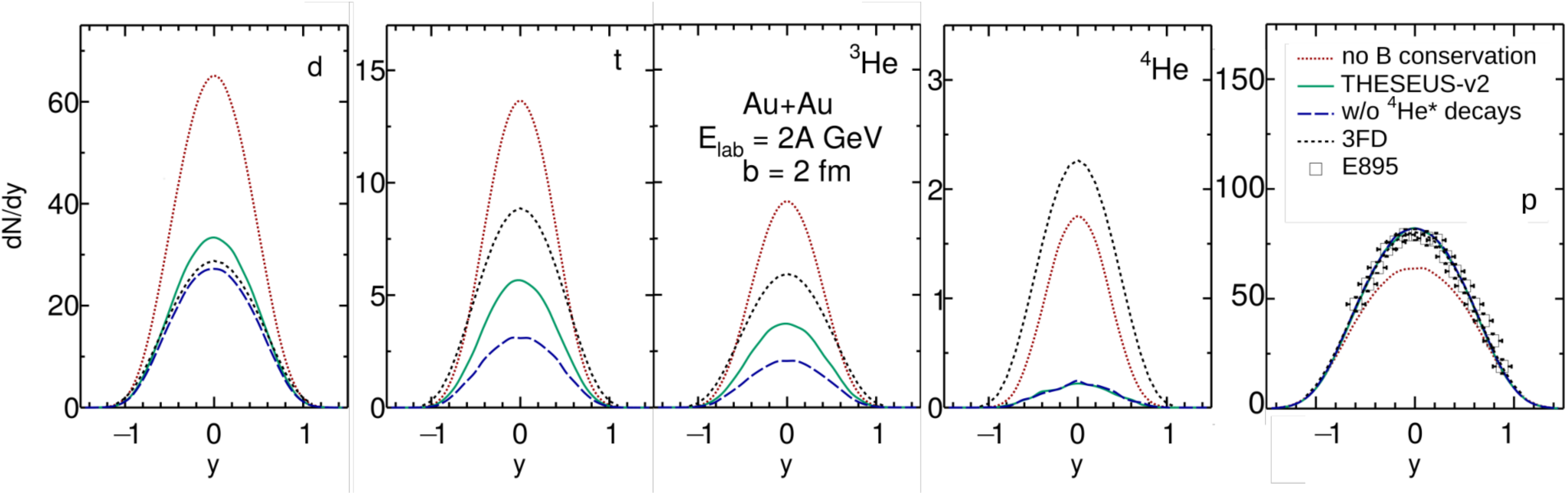
$(N1 + N2)/(A1 + A2)$ and $(Z1 + Z2)/(A1 + A2)$.

THESEUS-v2: rapidity distributions. muB recalculation



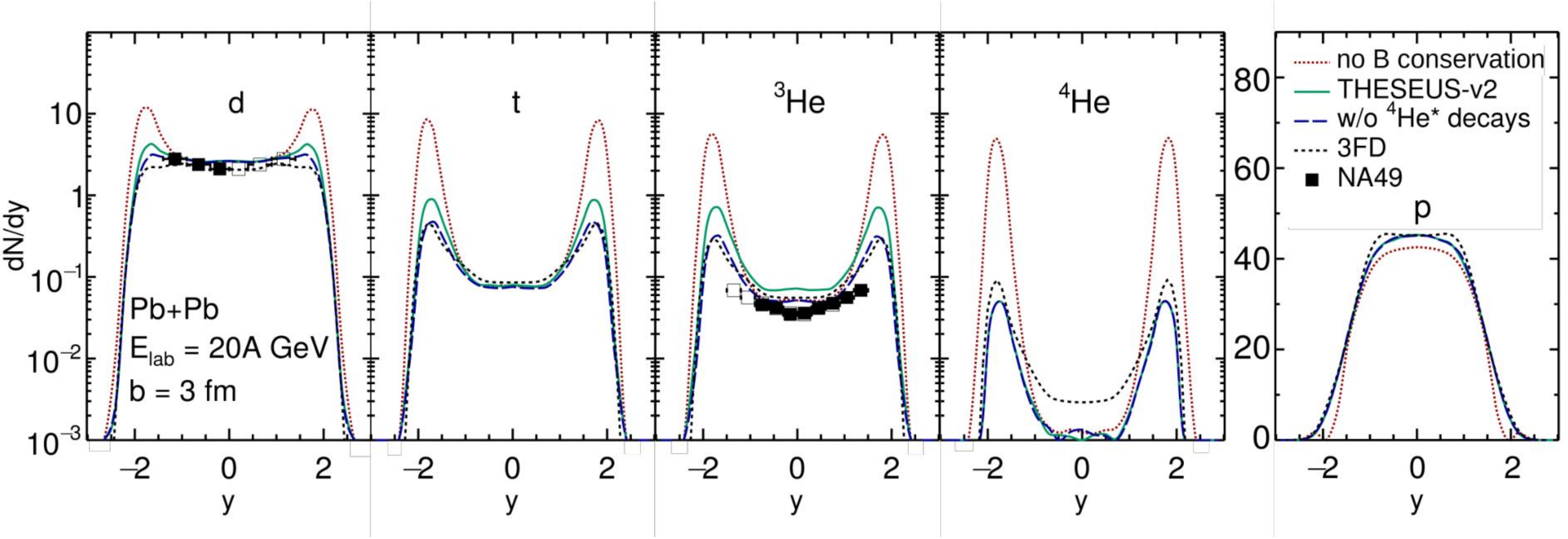
- Consistency check: dN/dy of p, K+, K- without UrQMD are in perfect agreement with 3FD.
- UrQMD significantly affects K+, K- , because of strong absorption of K− , K− + n → Λ + π−.
- The π+ distribution: different tables of decays of resonances in 3FD and THESEUS.
- In 3FD: π+ = (All pions)/3.

THESEUS-v2: rapidity distributions. 4He decays



- Large overestimate of d, t, 3He without recalculation of μB (red curve) in THESEUS-v1.
- Significant contribution of 4He* decays at low energies.
- Proton yield is noticeably affected by subtraction of light-nuclei contribution.

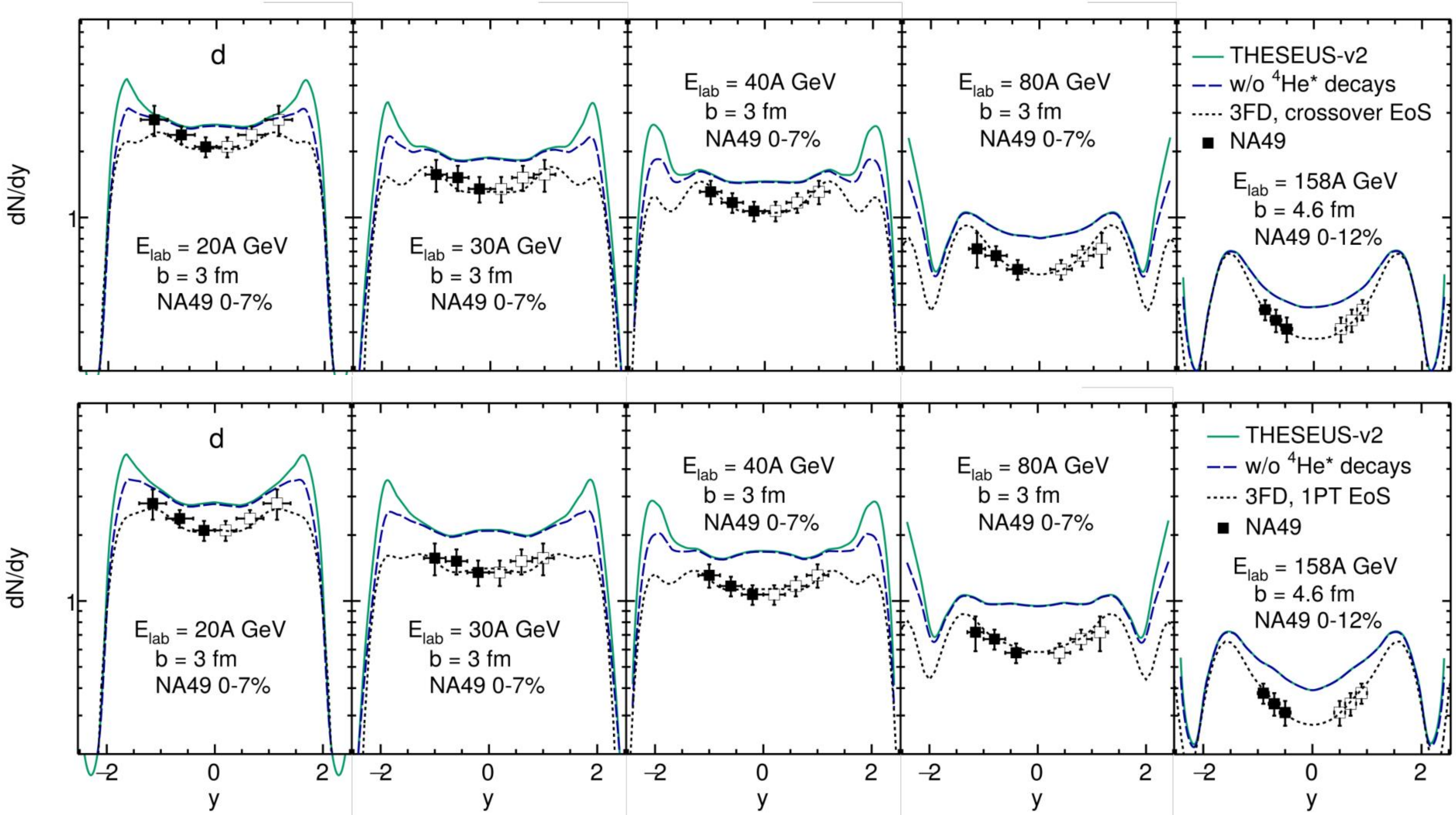
THESEUS-v2: rapidity distributions. 4He decays



- The same for 20A GeV: the effect light nuclei is weaker.
- The effect of the recalculation of μB is still strong.
- 4He* decays are less important at higher energies

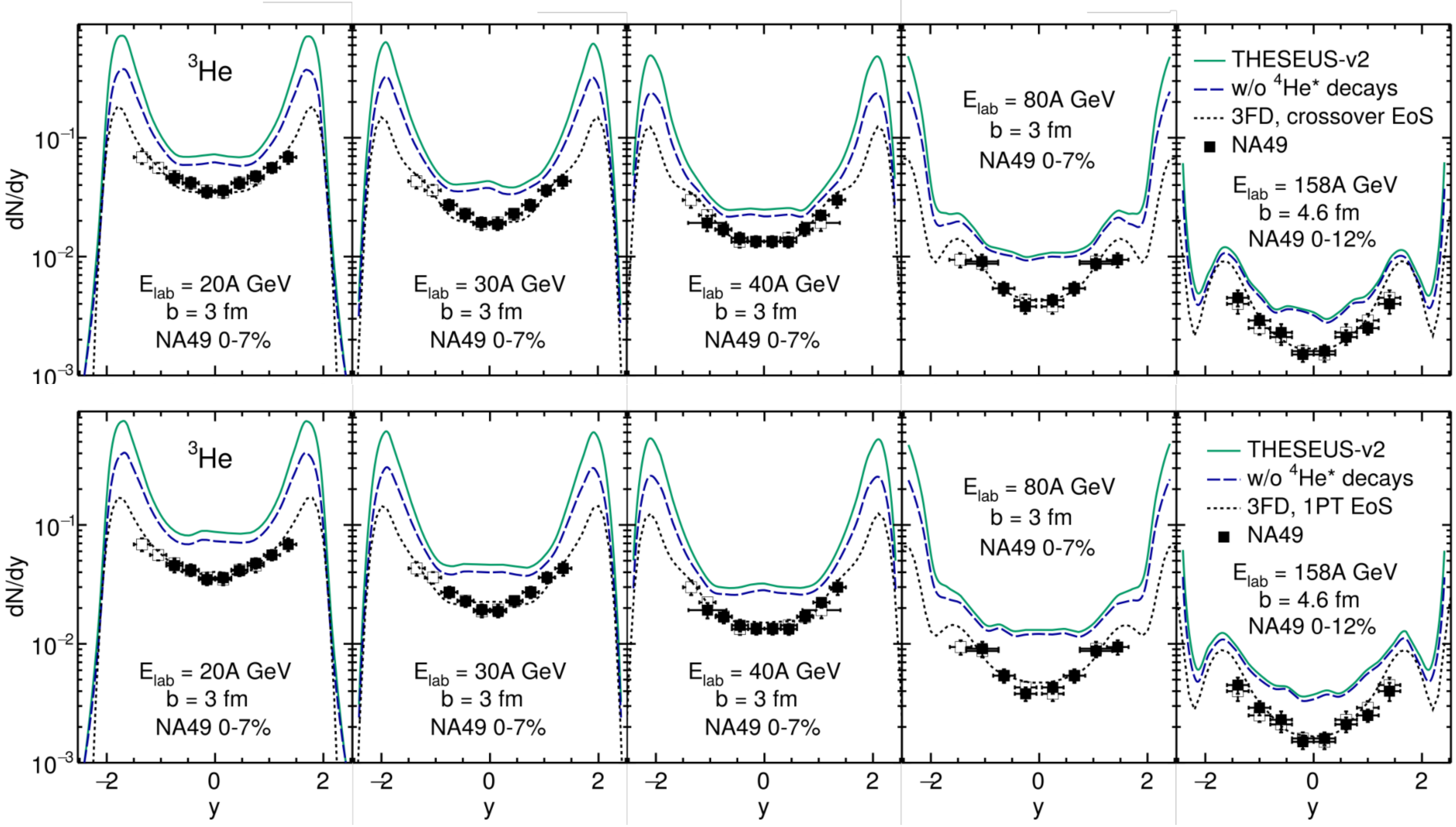
Preliminary results

THESEUS-v2: rapidity distributions. 4He* decays.



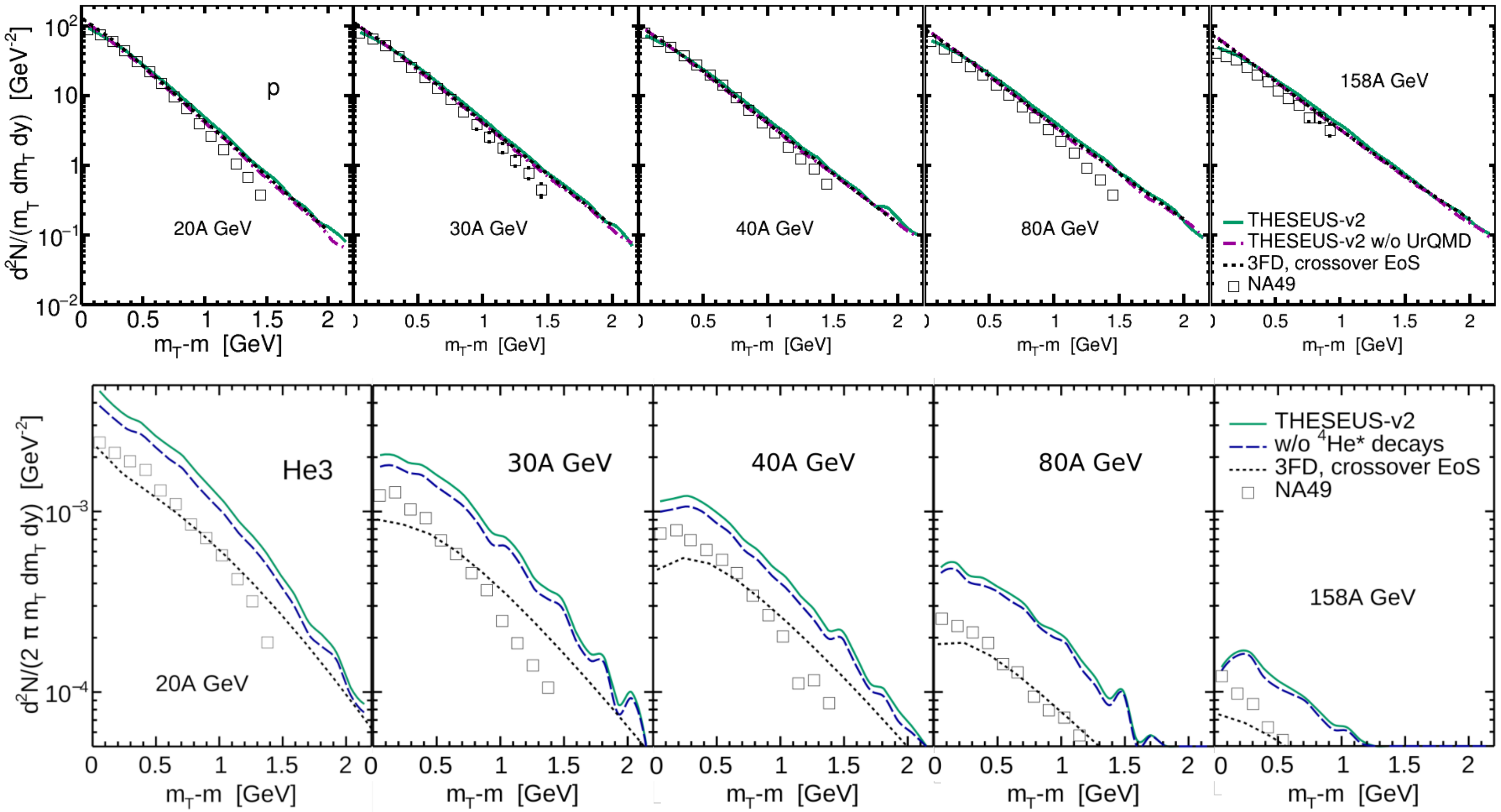
Possible reasons of discrepancies: no UrQMD afterburner for light nuclei, no meduim effects.

THESEUS-v2: rapidity distributions. 4He* decays



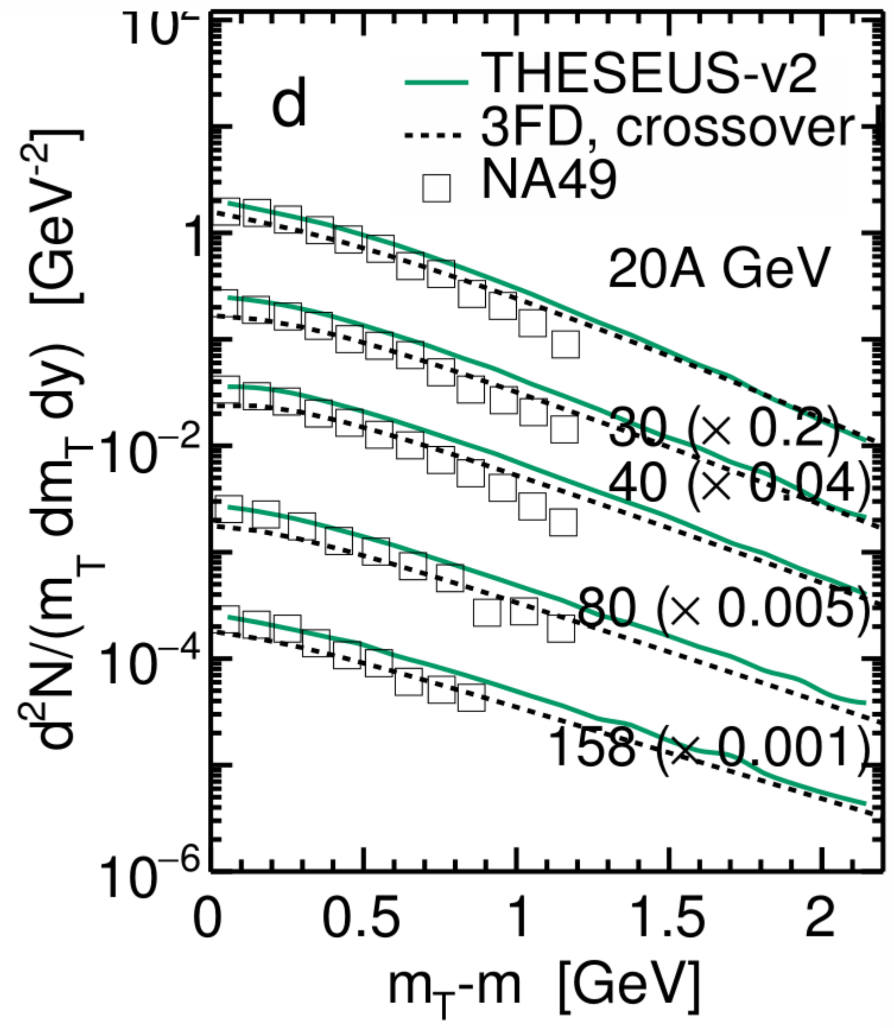
The same as in prev. fig. but for 3He.

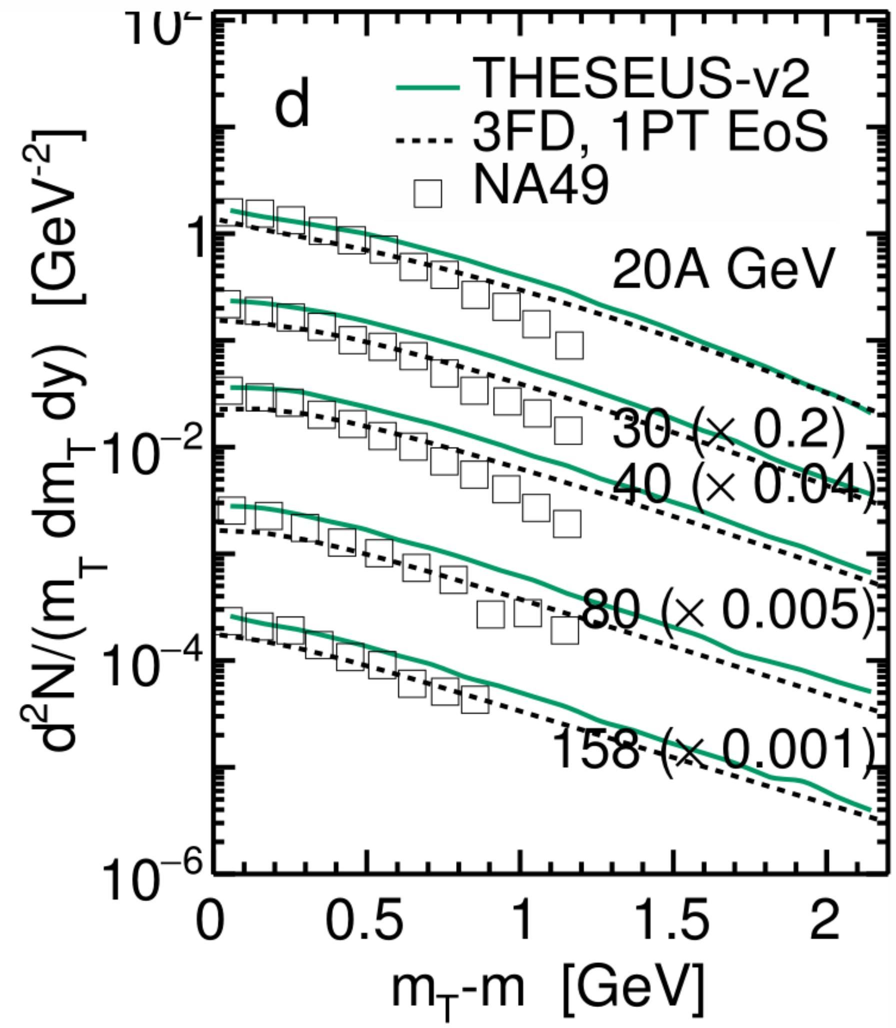
mT-spectra: protons and Helium 3



Overestimate of 3He yields but slopes practically correspond to the NA49 data.
The 4He* do not play significant role at this energies.
The absence of UrQMD afterburner and of medium effects?

mT-spectra: deuterons





The same effects as in previous figure.

pT-spectra: deuterons

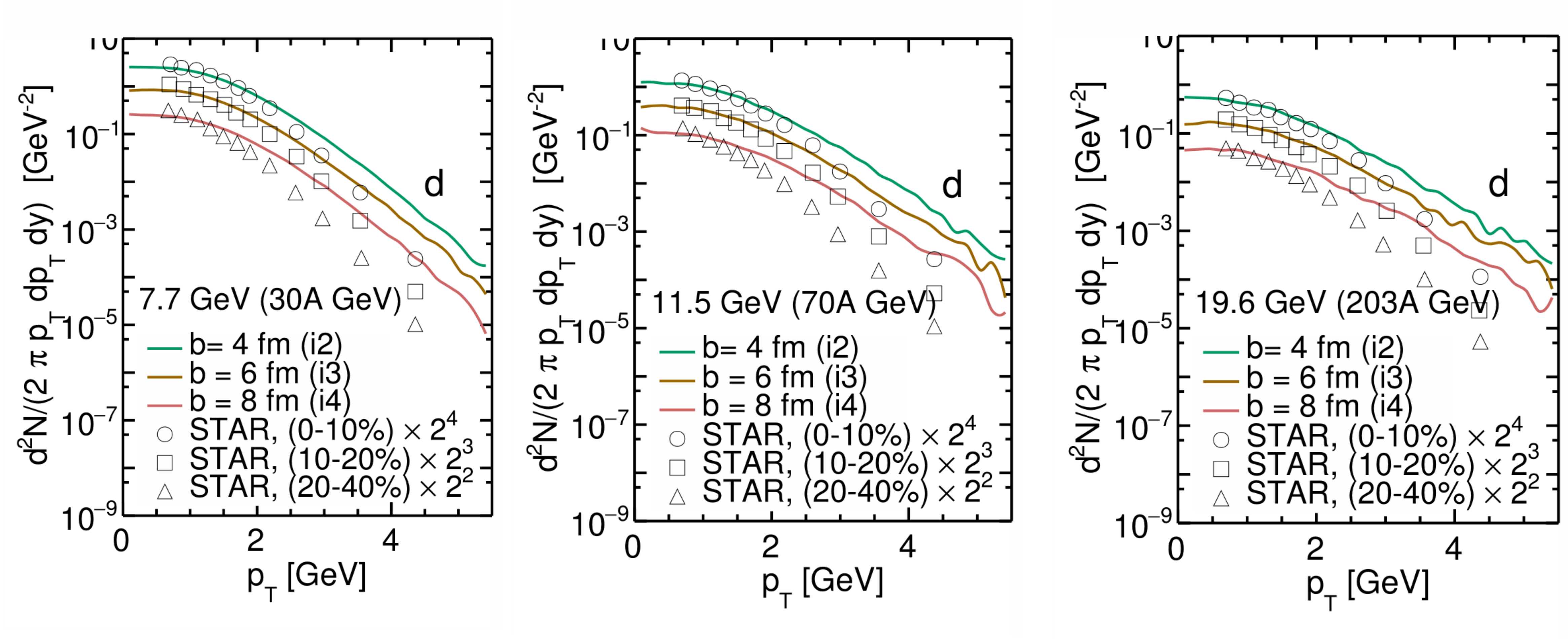


Fig.: pT-spectra of deuterons with using of crossover EoS at different energies and centralities.
Good agreement with STAR at low pT.
The slopes of pT spectra are flatter than the data -> too strong radial flow in 3FD?

pT-spectra: tritons

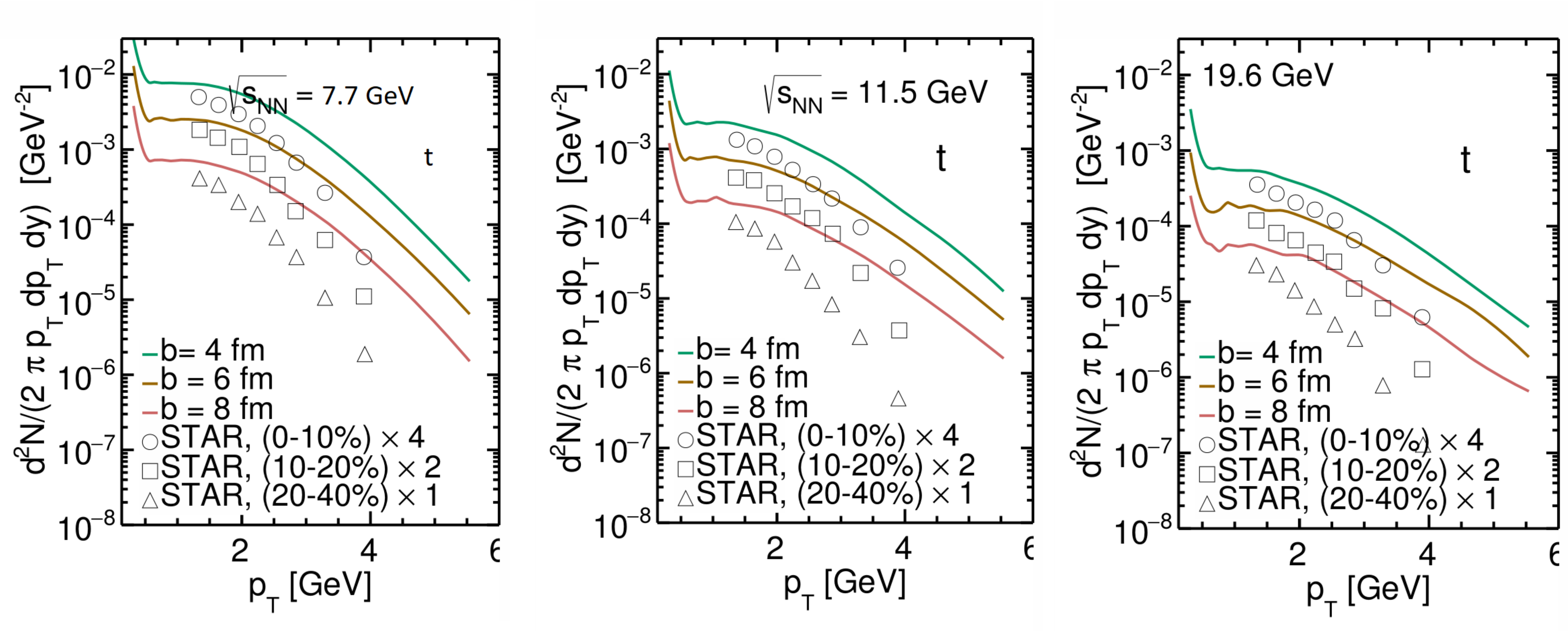


Fig.: pT-spectra of tritons with using of crossover EoS at different energies and centralities in comparison with STAR experiment.

Same thing here: too flat spectra indicate too strong radial flow light nuclei produced in 3FD/THESEUS

pT-spectra: anti-deuterons

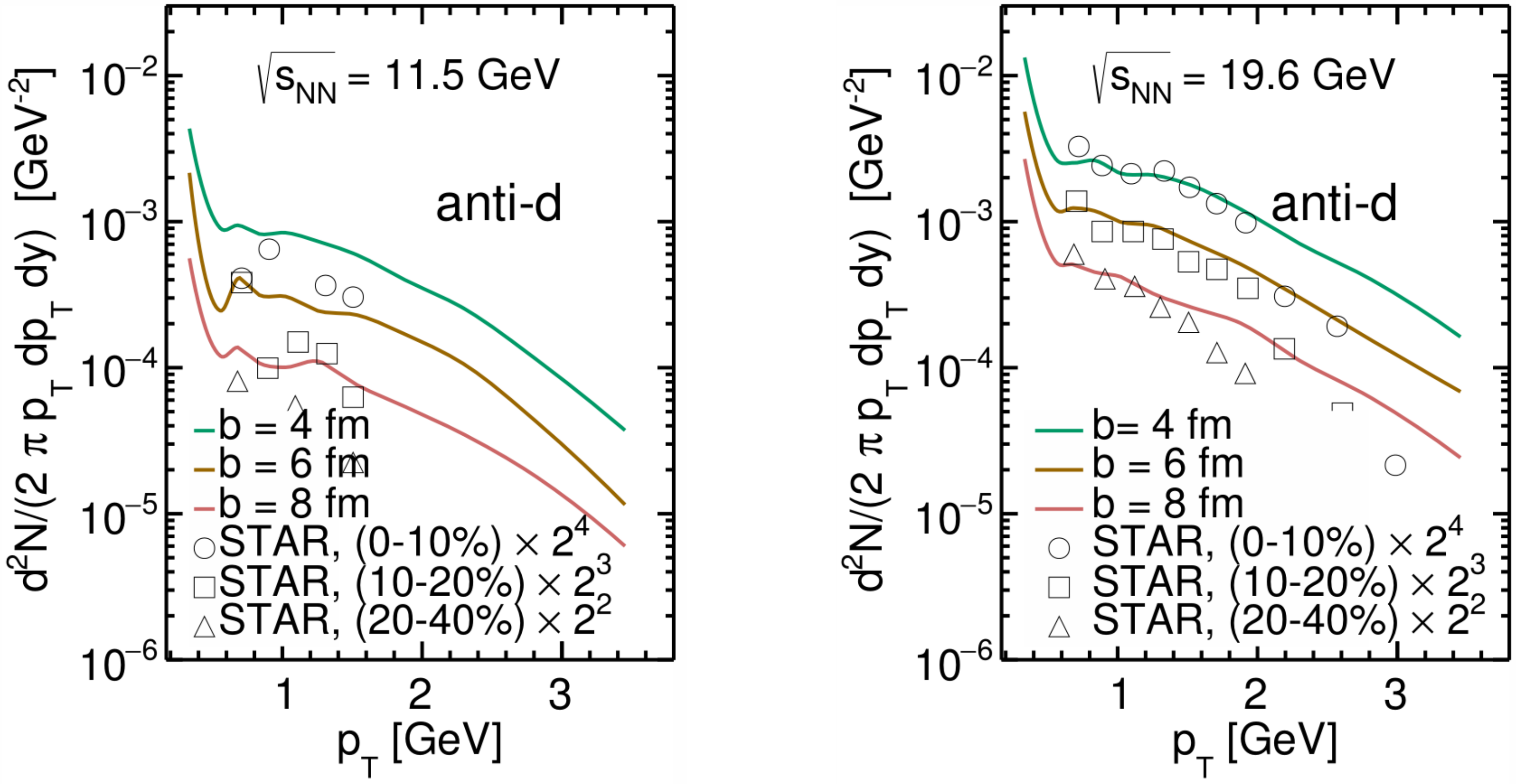


Fig.: pT-spectra of anti-d with using of crossover EoS at different energies and centralities in comparison with STAR experiment.

Anti-deuterons are reproduced similarly to deuterons and even better than t.

The slope of pT spectra for anti-deuterons is ok vs. the data - this is interesting result.

Directed flow v1(y) and elliptic flow v2(y)

The first coefficients of Fourier expansion of the azimuthal-angle dependence of the single particle distribution function, i.e. directed flow:

$v_1 = \langle \cos \phi \rangle$, ϕ – azimuthal angle

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_{RP}))\right)$$

$$v_1^{(a)}(y) = \frac{\int d^2p_T\,(p_x/p_T)\,E\;dN_a/d^3p}{\int d^2p_T E\;dN_a/d^3p}.$$

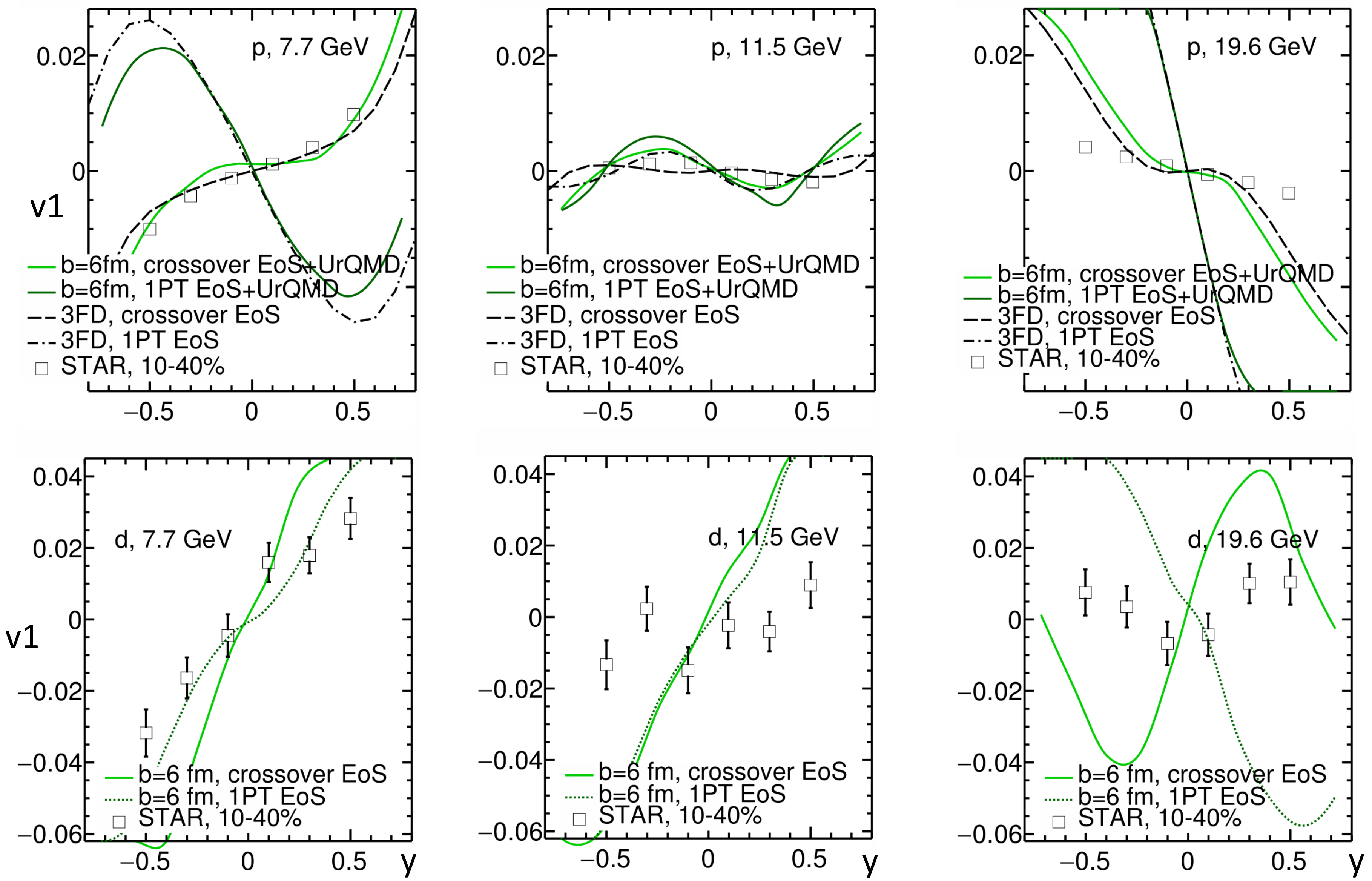
In THESEUS-v2 we calculate v1 not through integrals over momentum space but involving sums over hadrons.

Elliptic flow is the second coefficient of Fourier expansion:

$v_2 = \langle \cos 2\phi \rangle$

$$v_2^{(a)}(y) = \frac{\int d^2p_T\;\left[(p_x^2 - p_y^2)/p_T^2\right]E\;dN_a/d^3p}{\int d^2p_T E\;dN_a/d^3p}.$$

Directed flow v1(y): protons and deuterons



In some cases THESEUS-v2 curves agree with experimental data, in anothers do not – this is a puzzle.

Directed flow v1: discussion

- Strong difference between results of crossover and 1PT EoS
- Puzzle: different v1 slopes for p and d within 1PT EoS at 7.7 GeV and within crossover EoS at 19.6 GeV

Summary

- The thermodynamical approach gives reasonable reproduction of light nuclei, including anti-deuterons without any fitting parameters.

- This reproduction gets worse for heavier light nuclei

- The functional dependencies (on y, pT, centrality, mass of light nuclei) qualitatively are reproduced

- Still there is a puzzle with v1 of deuterons

Outlook

- Study of v1 puzzle for deuterons: pT-differential v1(pT)
- Elliptic flow v2.
- Inclusion of medium effects
- HADES and AGS data
- Including of hyper-(anti)nuclei

Thank you
for your attention!