Light-nuclei production in heavy-ion collisions in Three-fluid Hydrodynamics-based Event Simulator (THESEUS)

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ICNFP 2021
August, 2021

Introduction

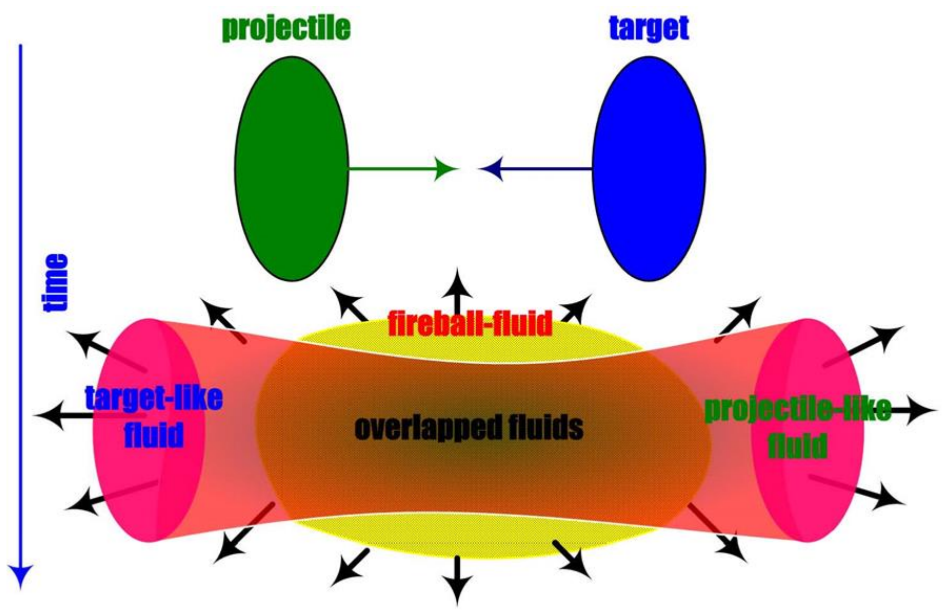
- Light-nuclei production is related to search for critical point in QCD phase diagram.
- The existing 3D dynamical models with coalescence mechanism of the light-nuclei production.
- Microscopic approaches – PHQMD and SMASH
- **The thermodynamical approach**: no additional parameters needed for light-nuclei production.
- THESEUS generator is based on the thermodynamical approach.

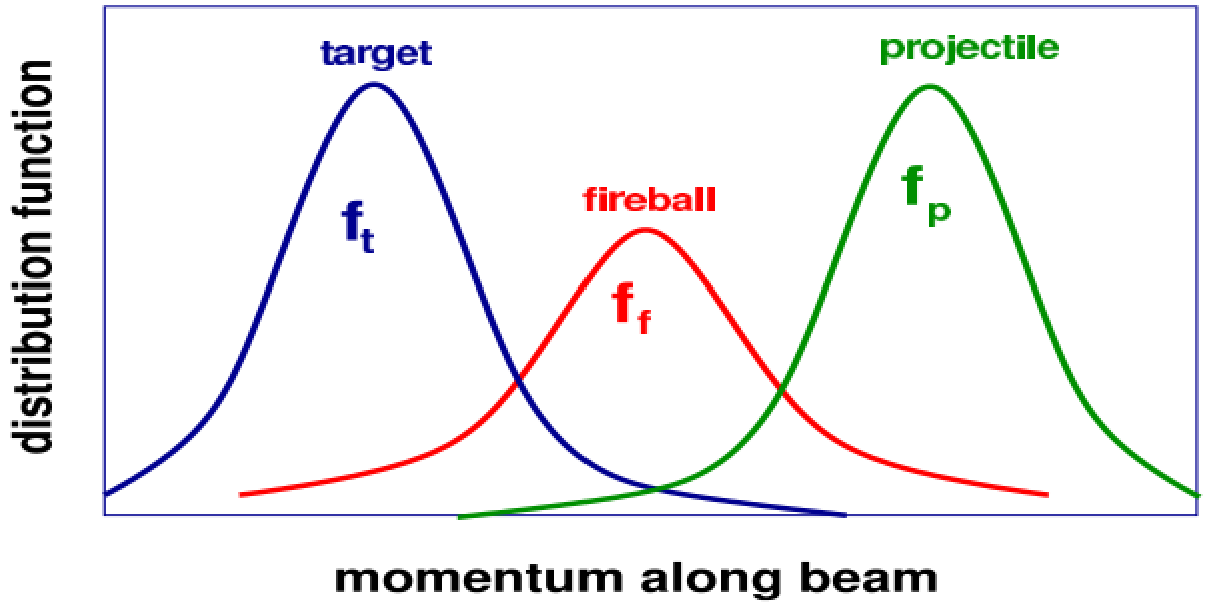
Main areas of research: study the light-nuclei production at collision energies of the BES-RHIC, SPS, NICA and FAIR.

Three-fluid dynamics (3FD) model

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

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

Leading particles carry bar. charge $\quad$ 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 $\quad$ Source term $\quad$ 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
- ✓ Friction
- ✓ Freeze-out energy density ε_{frz} = 0.4 GeV/fm^3

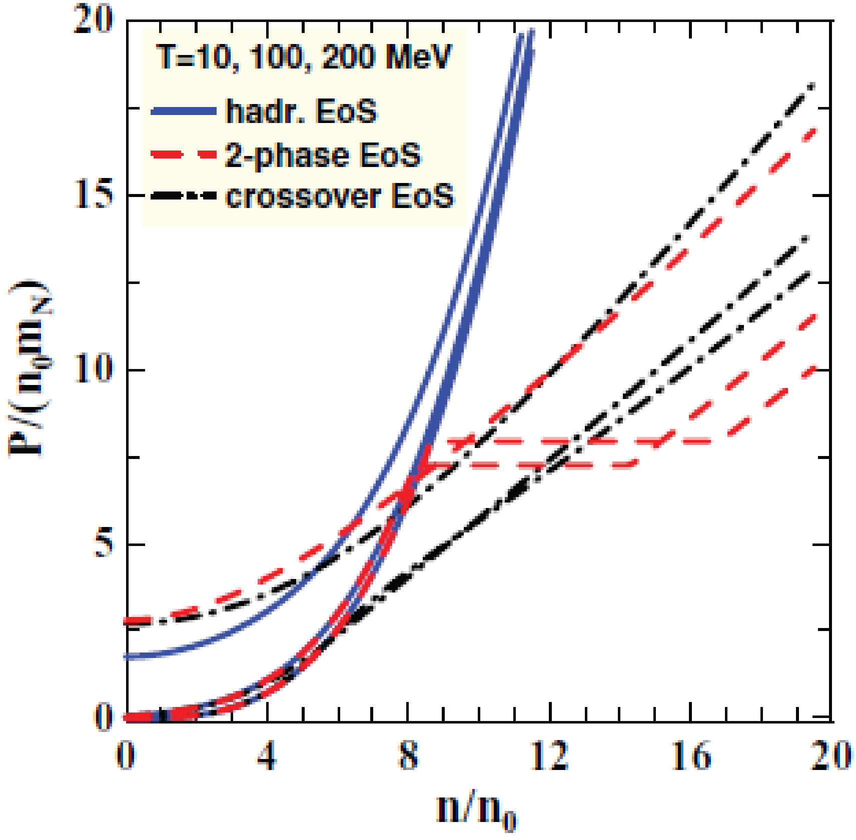
The output = Lagrangian test particles (i.e. fluid droplets) for each fluid α(= p, t or f).

Fluid droplets = elements of freeze-out surface in hydrodynamic models.

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

3FD model: Equations of State (EoS)

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



3FD output = fluid characteristics.
Observables = 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)

THESEUS event generator

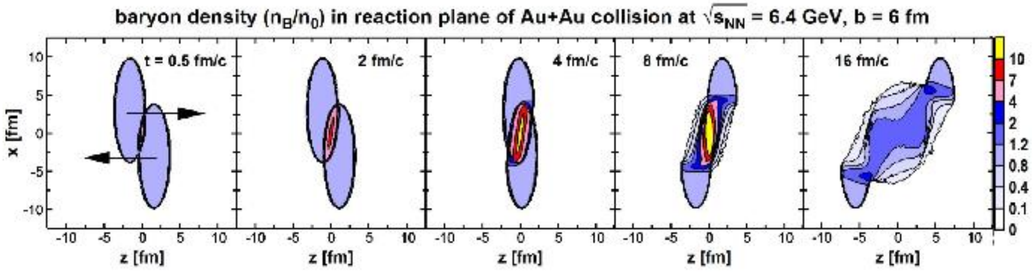
- In 2016 the THESEUS event generator was introduced.

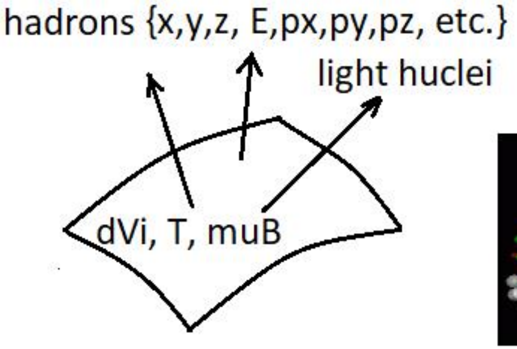
(3FD+Particlization+UrQMD): P. Batyuk et al., PHYSICAL REVIEW C 94, 044917 (2016)

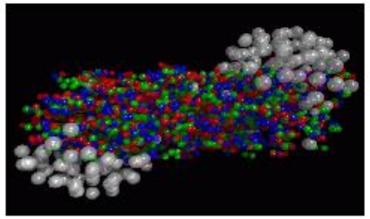
- **THESEUS = 3FD + Monte Carlo hadron sampling + rescatterings/decays via UrQMD**
- There were no light nuclei included.
- THESEUS presents the 3FD output in terms of a set of observed particles.
- Since the time THESEUS was first presented, certain updates have been made, further referred to as THESEUS-v2.

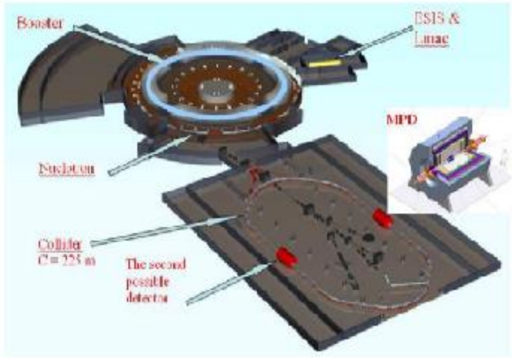
Kozhevnikova, Ivanov, Karpenko, Blaschke, Rogachevsky, PRC 103 (2021) 4, 044905

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

No clusters 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:

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

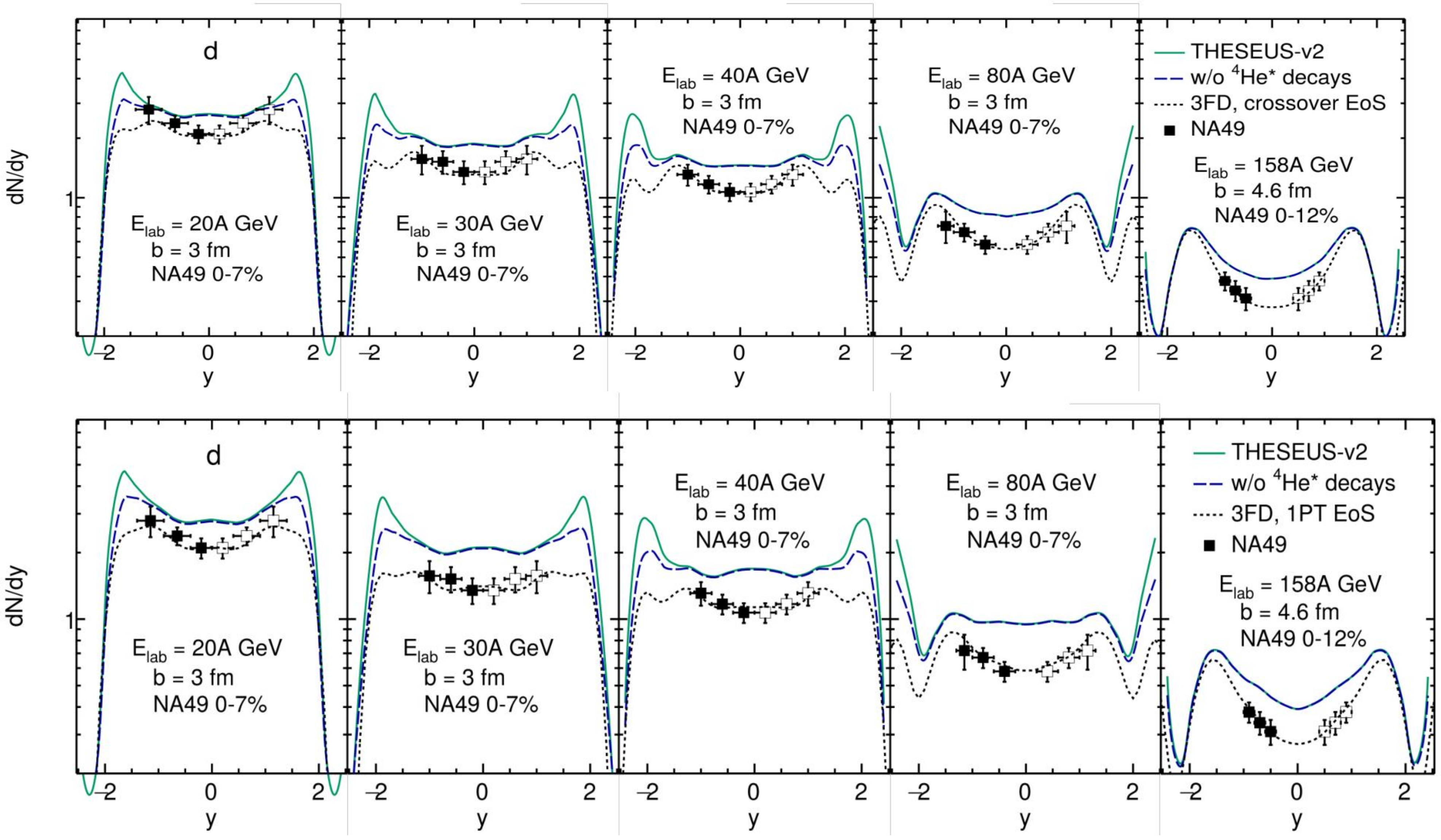
The list of light-nuclei species is shown in Table.

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 ^{4}He system (from BNL properties of nuclides).

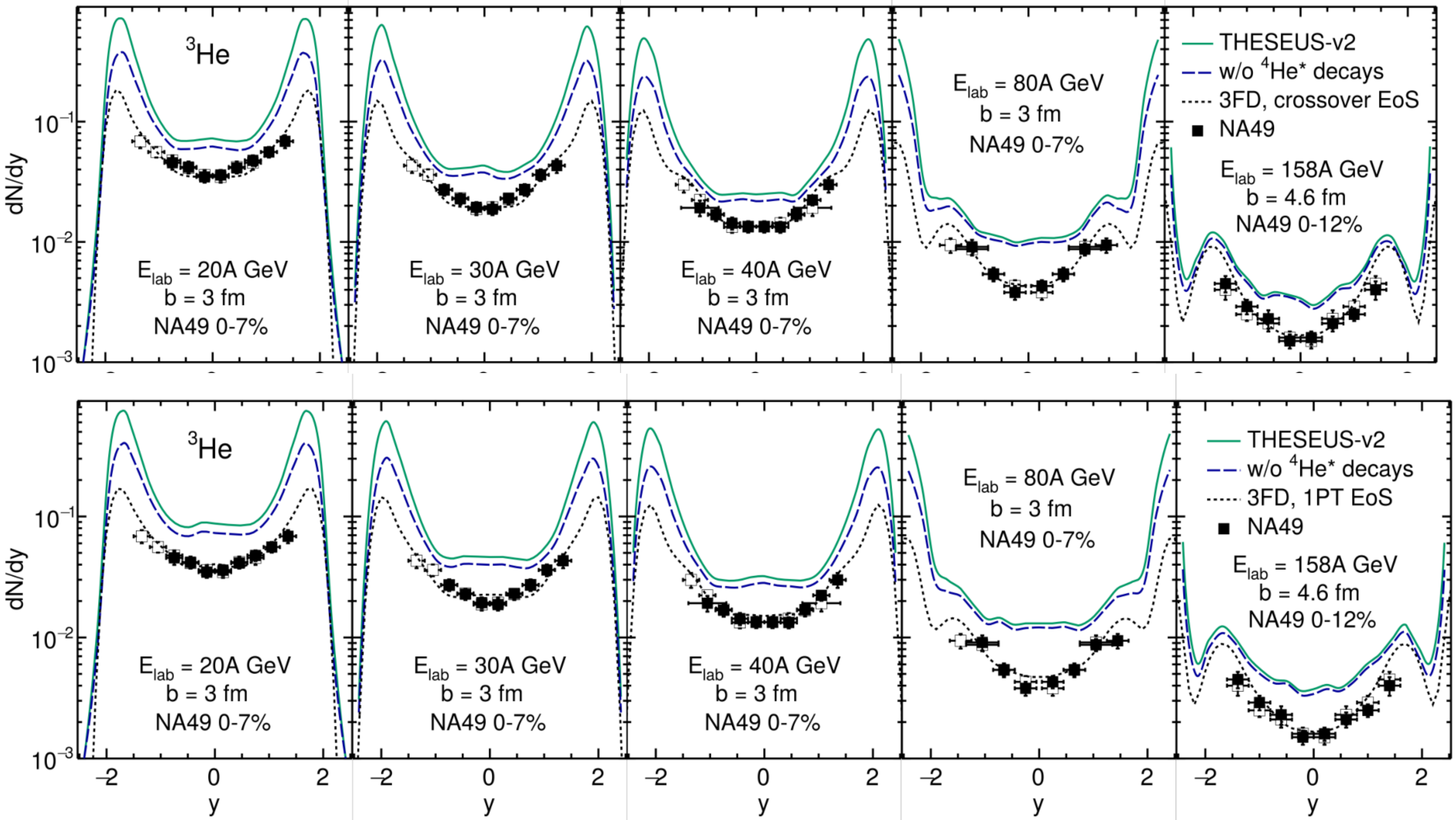
Preliminary results

THESEUS-v2: rapidity distributions.



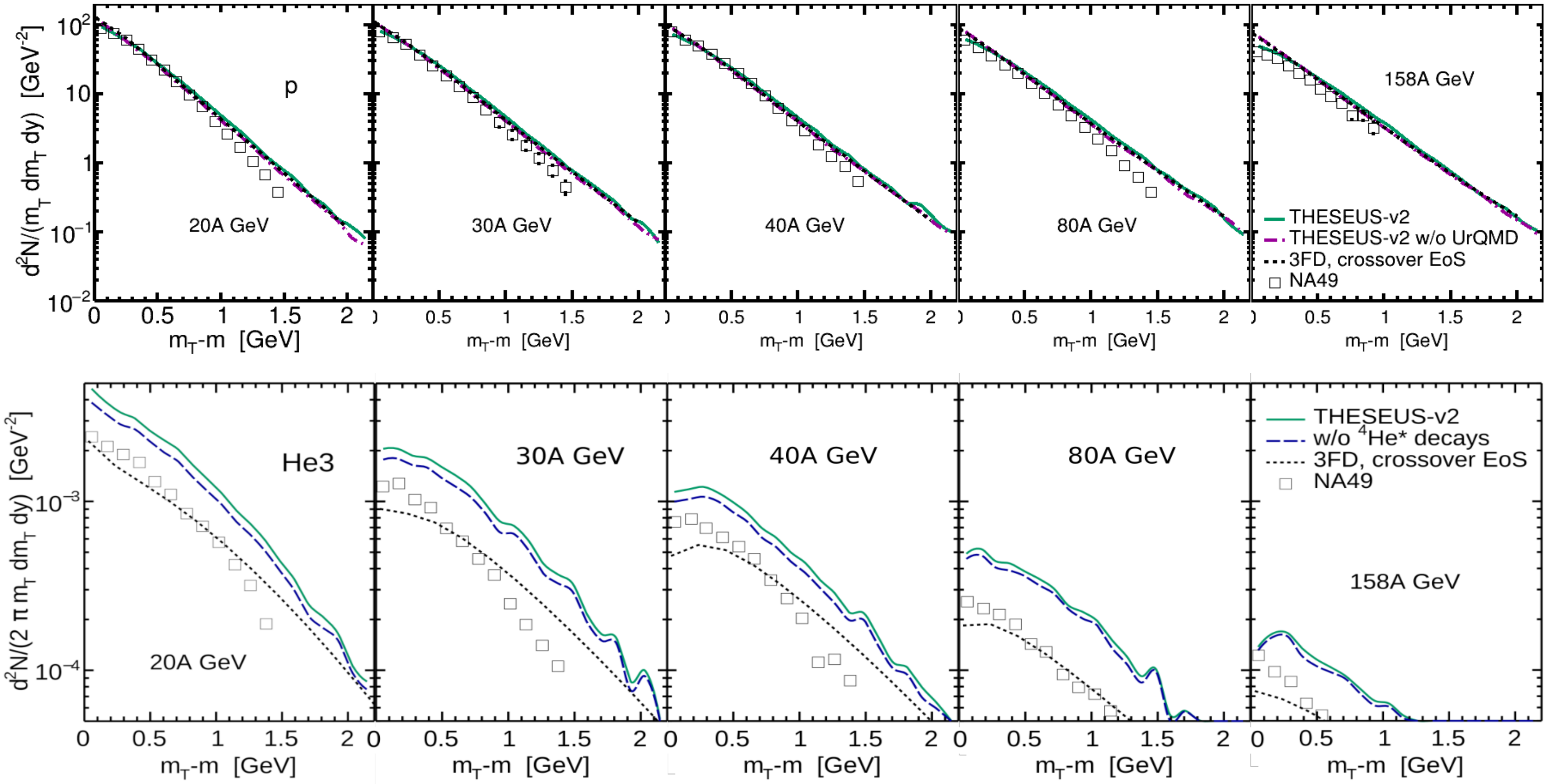
Possible reasons of discrepancies: no UrQMD afterburner for light nuclei

THESEUS-v2: rapidity distributions.



no UrQMD afterburner for light nuclei

mT-spectra: protons and Helium 3

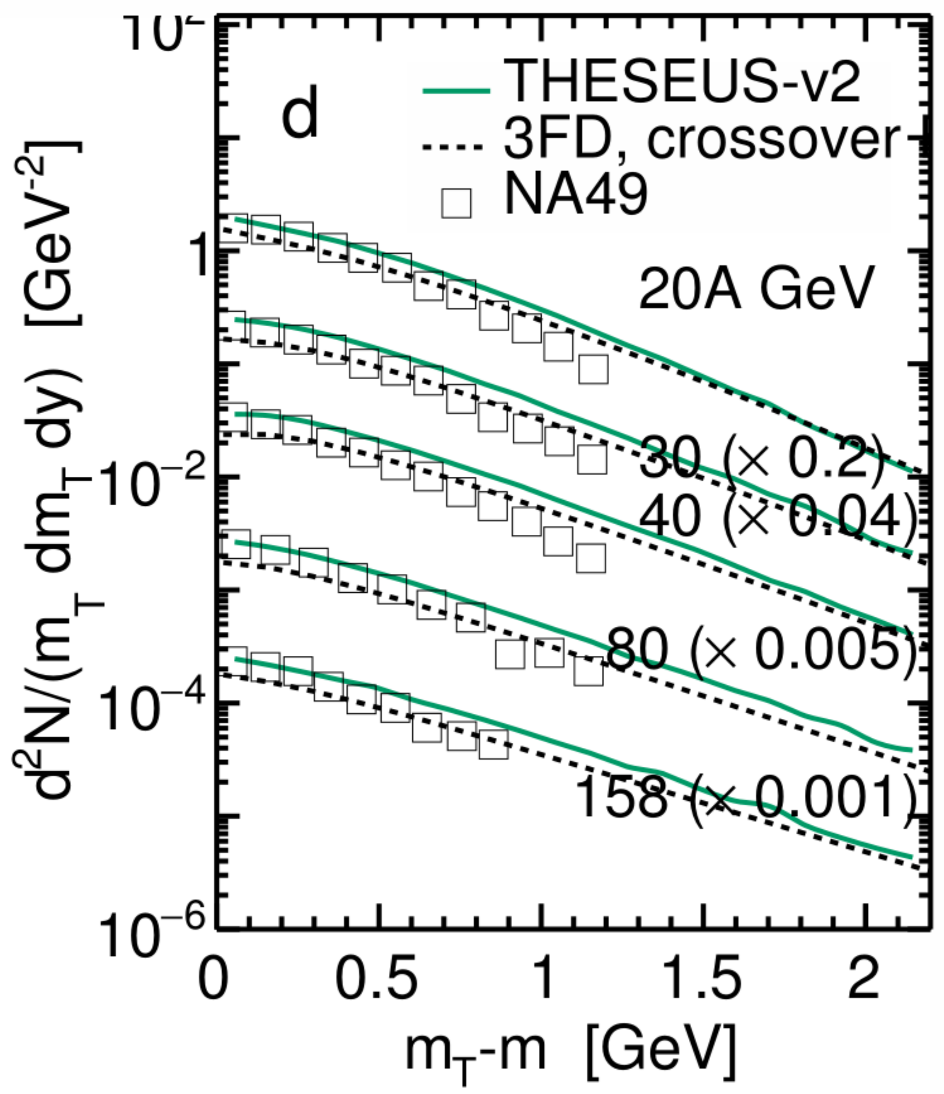


Overestimate of 3He yields but slopes practically correspond to the NA49 data.

The 4He* do not play significant role at this energies.

Absence of UrQMD afterburner

mT-spectra: deuterons



The same effects as in previous figure. 1PT EoS results are very similar.

pT-spectra: deuterons

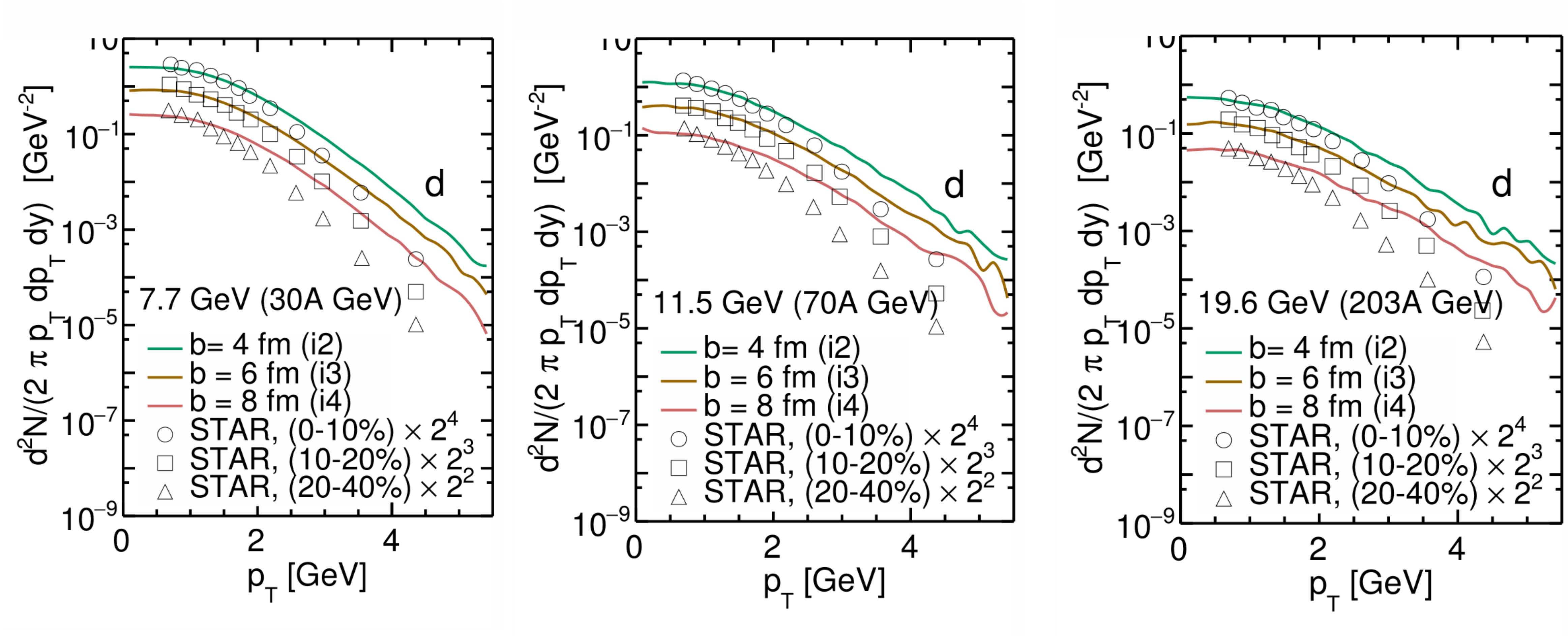


Fig.: pT-spectra of deuterons with using of crossover EoS at different energies and centralities.

Good agreement with STAR at low pT.

Slopes of pT spectra are smaller than those of the data -> too strong radial flow

Probably due to absence of afterburner?

pT-spectra: tritons

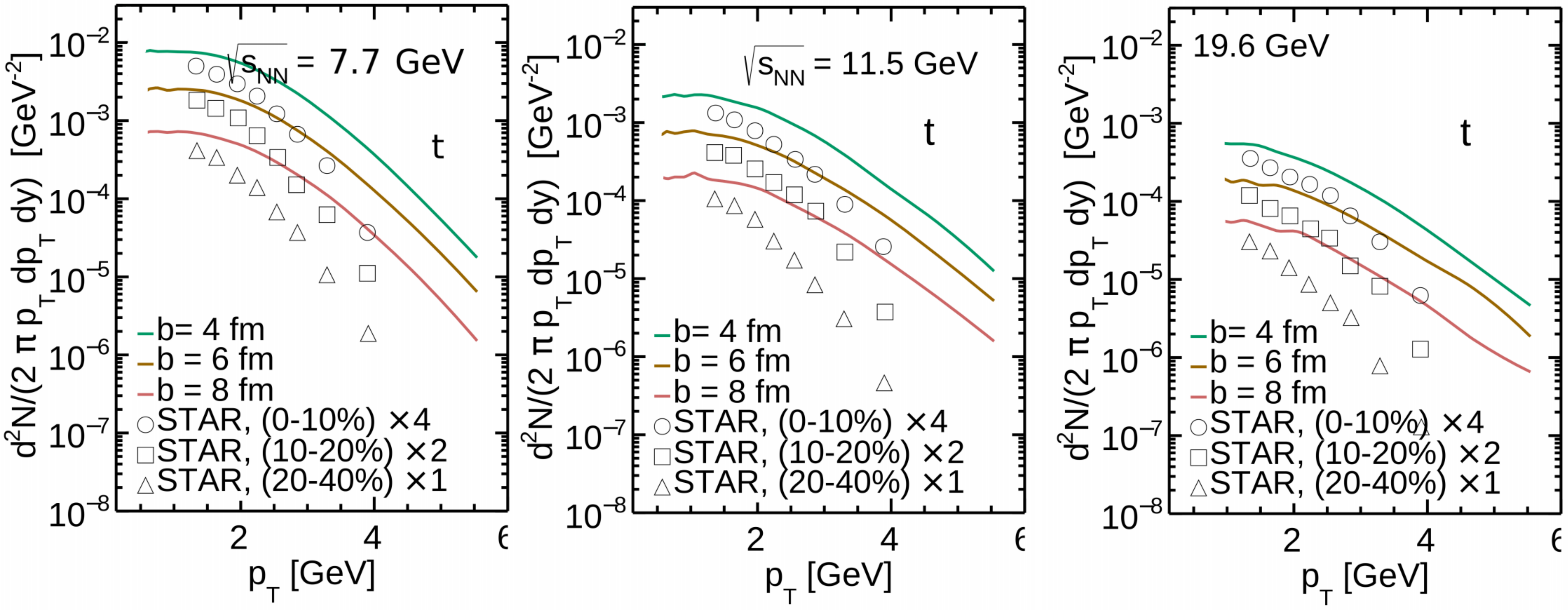
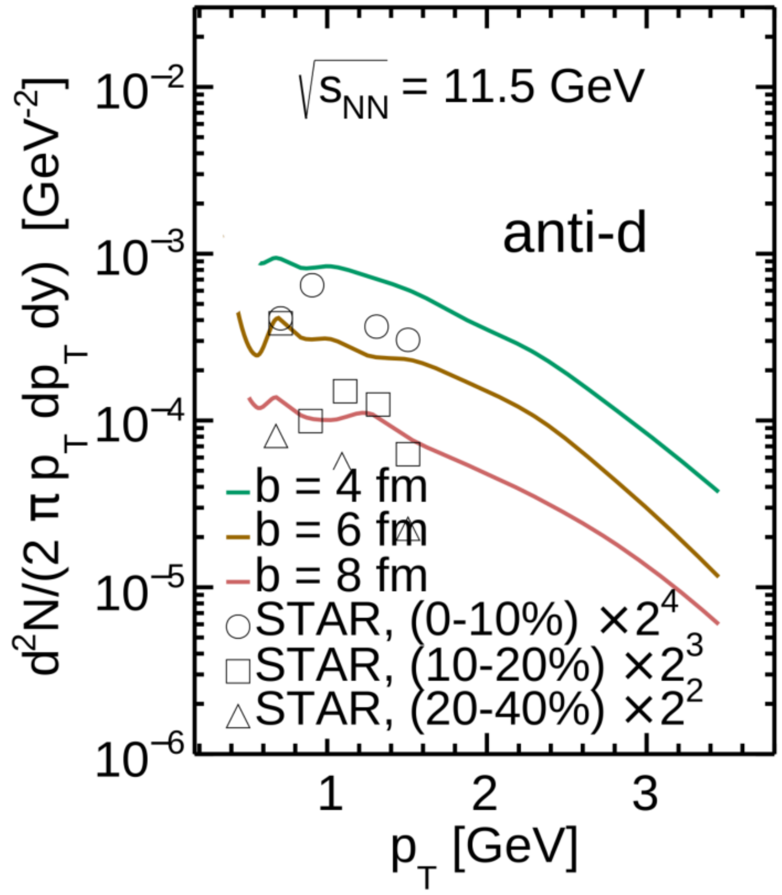


Fig.: pT-spectra of tritons with crossover EoS at different energies and centralities in comparison with STAR data.

Too flat spectra indicate too strong radial flow light nuclei produced in 3FD/THESEUS

pT-spectra: anti-deuterons



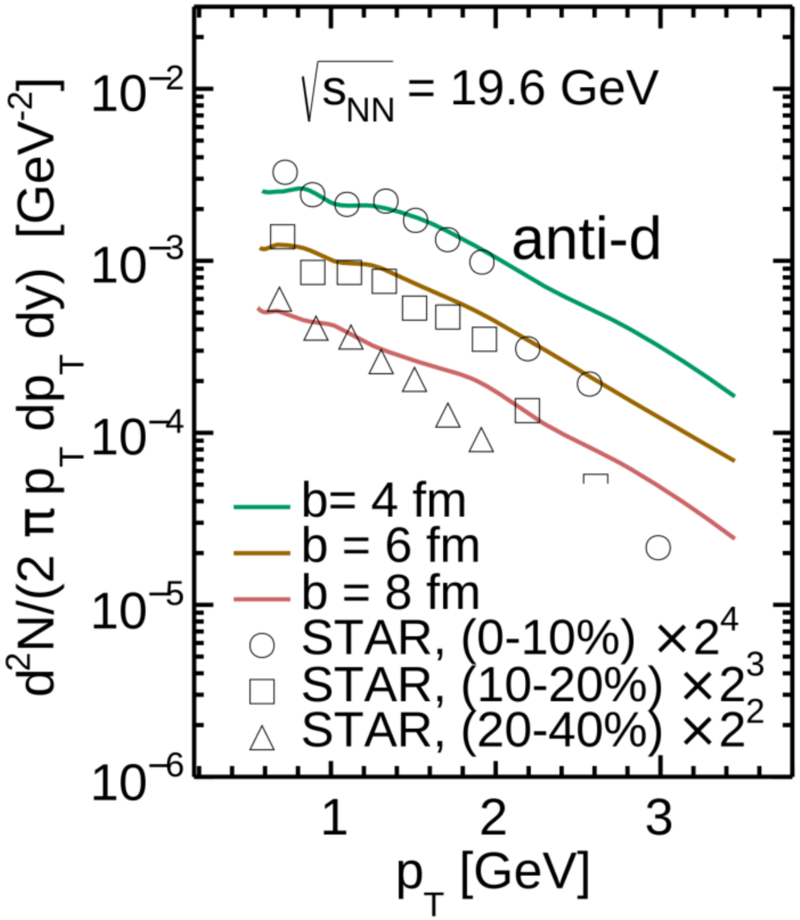


Fig.: pT-spectra of anti-d with using of crossover EoS at different energies and centralities in comparison with STAR data.

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

pT spectra of anti-deuterons well agree with STAR data at low pt.

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

The single particle distribution function:

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

The first coefficient of Fourier expansion, i.e. directed flow:

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

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

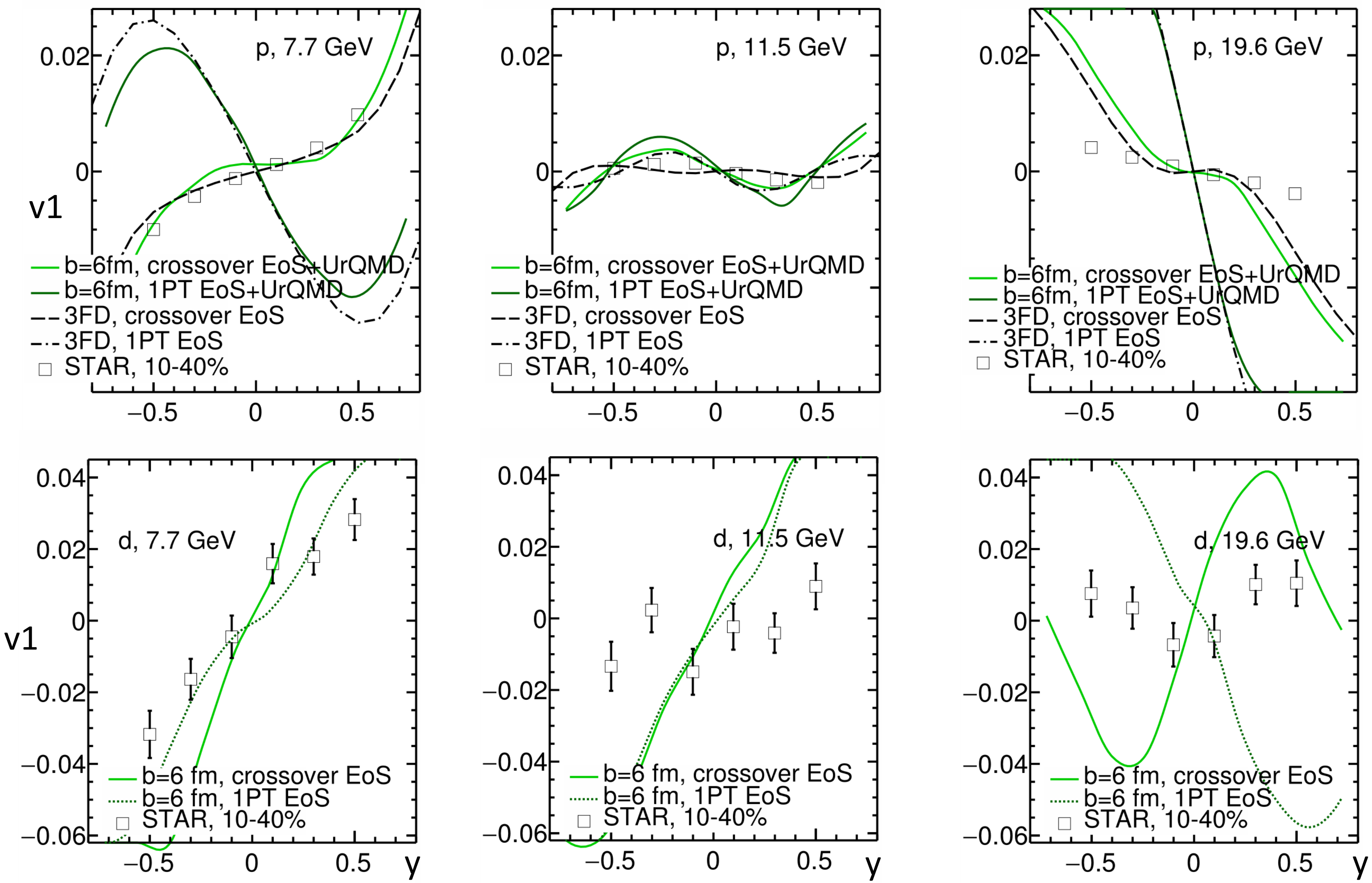
Elliptic flow is the second coefficient of Fourier expansion:

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

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

In THESEUS-v2: v1 and v2 are in terms of sums over hadrons rather than integrals over momentum space

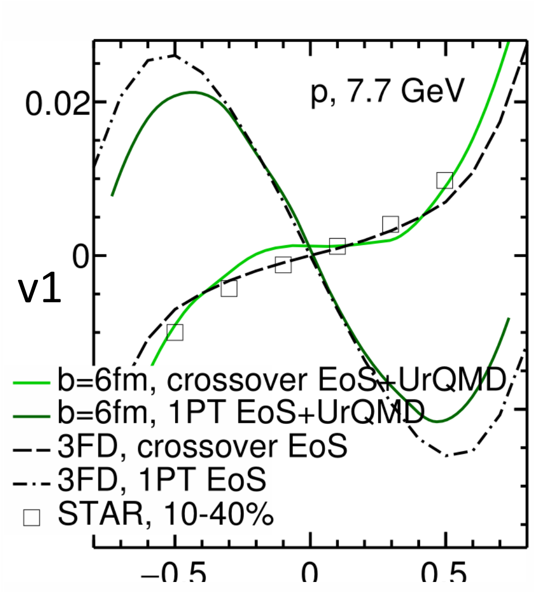
Directed flow v1(y): protons and deuterons



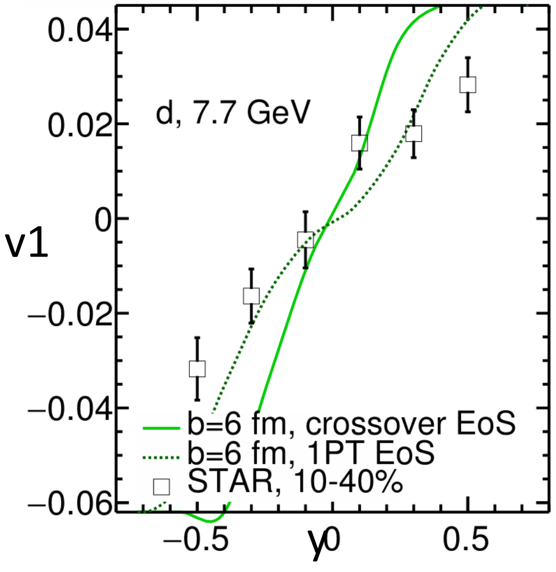
Sometimes, deuteron v1 is similar with proton v1, sometimes do not. This is a puzzle.

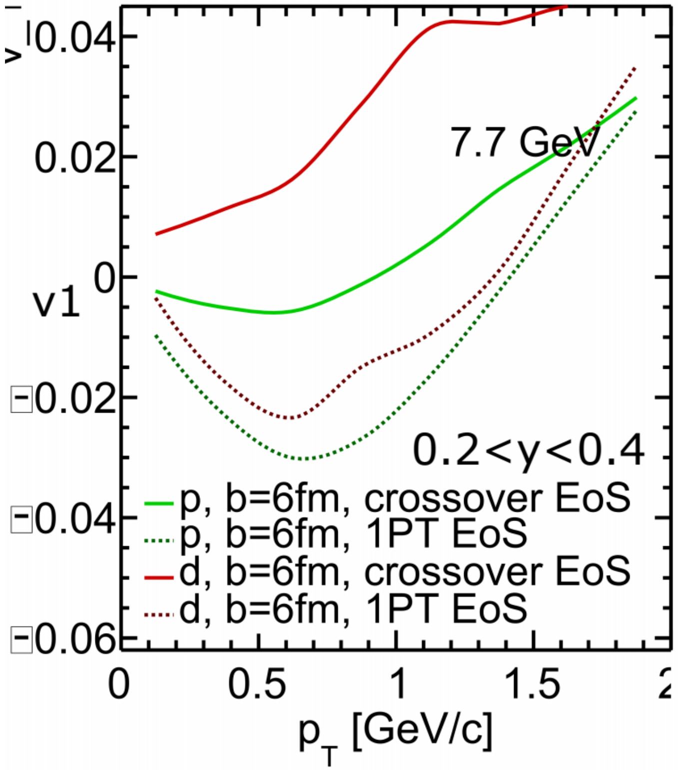
Directed flow v1(y) and differential v1(pt): protons and deuterons

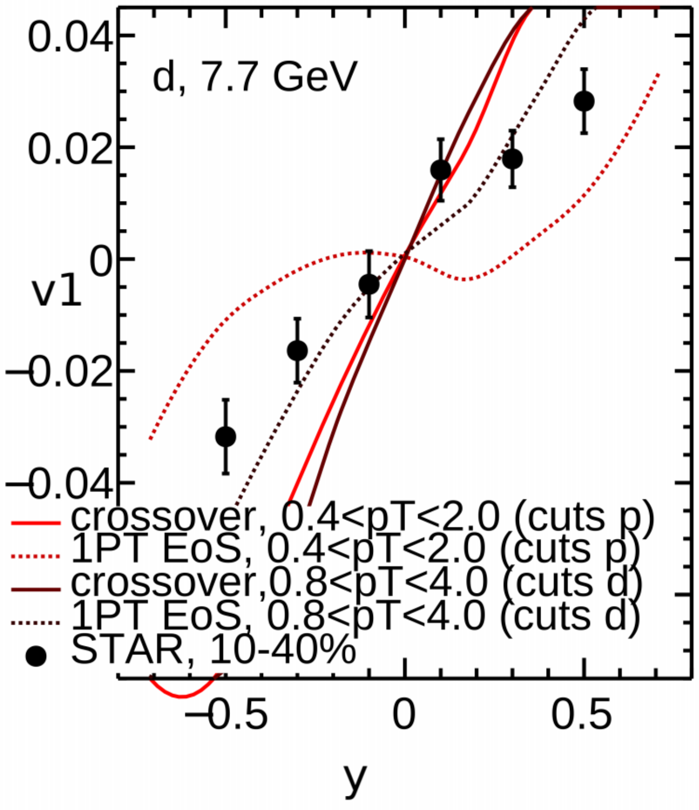
Cuts for p:
0.4<pT<2.0 GeV/c



Cuts for d:
0.8<pT<4.0 GeV/c

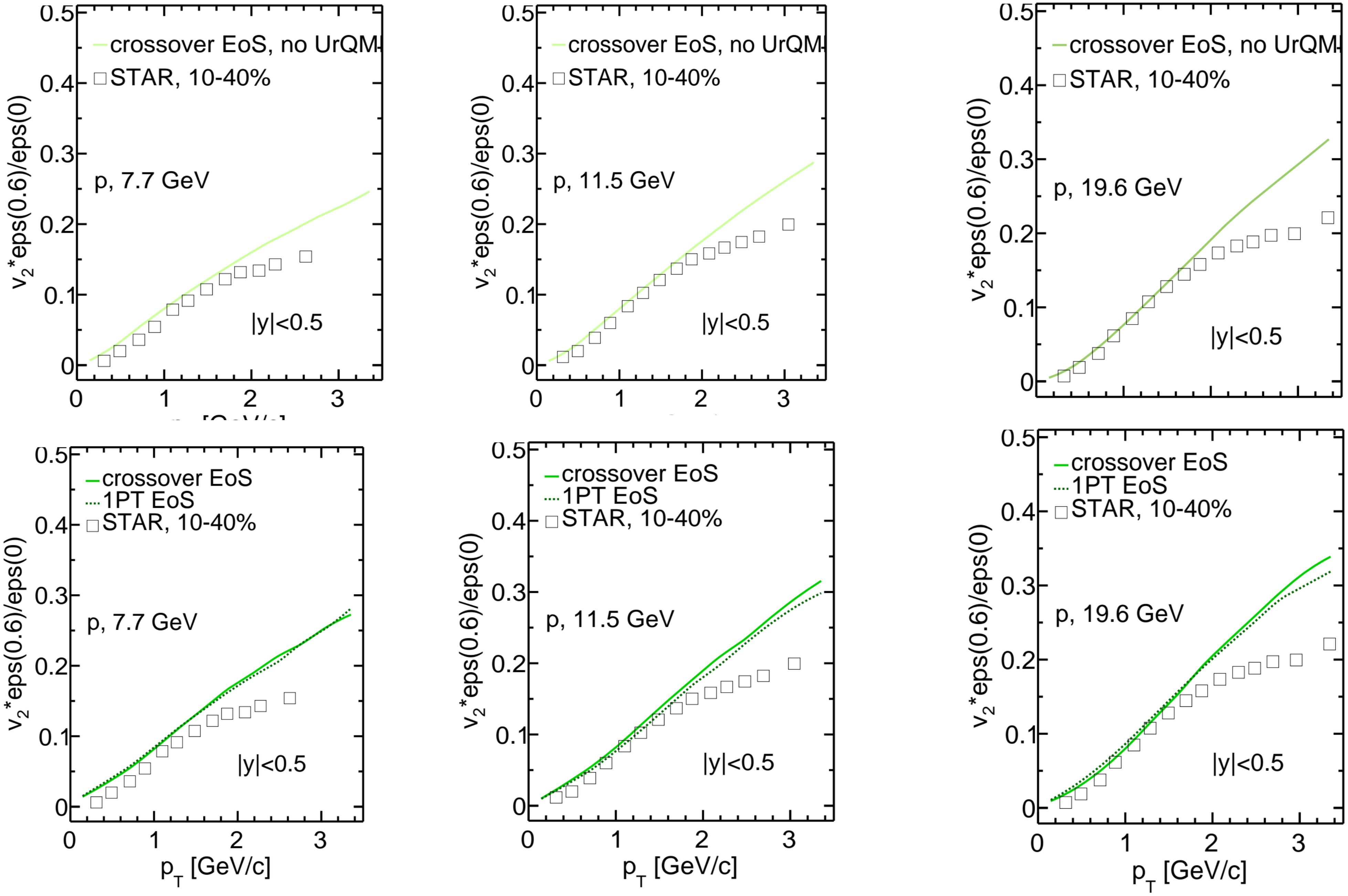




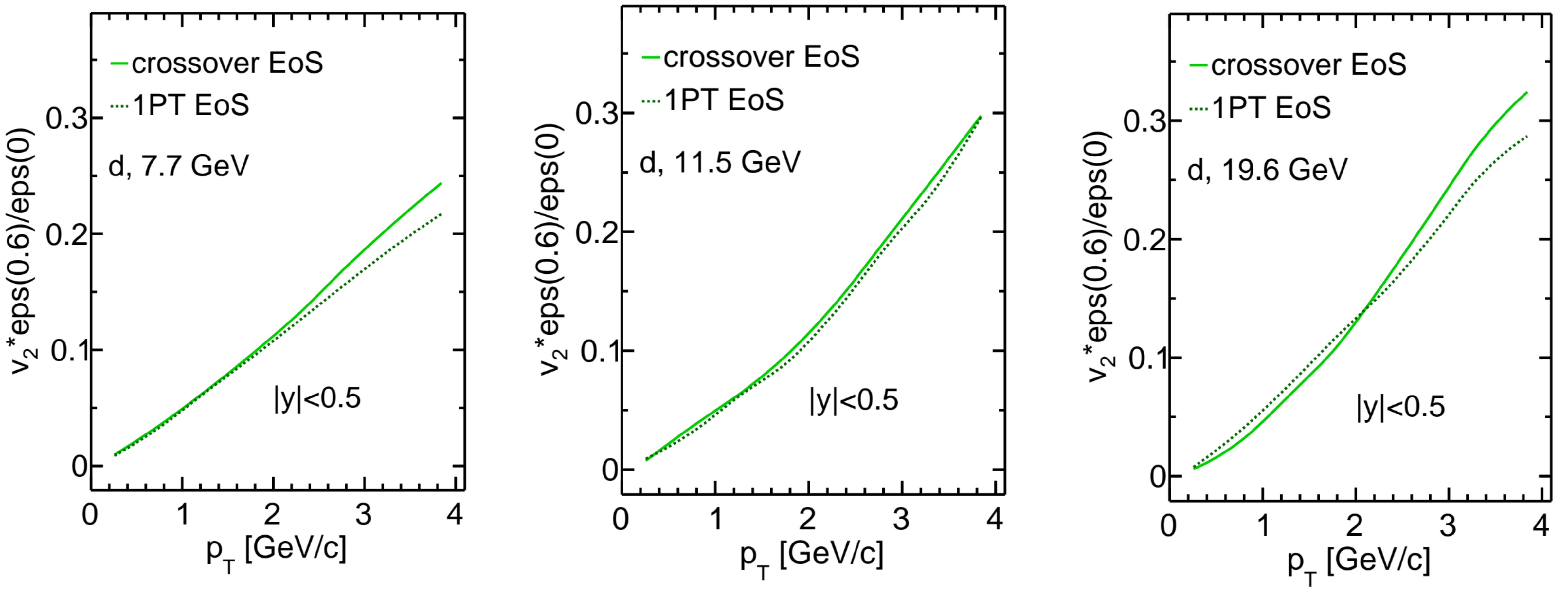


v1(pT) in 1PT scenario is strongly non-monotonous.
Therefore,
v1(y) of deuterons strongly depends on pT cuts.

Elliptic flow v2(pT): protons



Elliptic flow v2(pT): deuterons



- v2 is rescaled with the factor of εBN(d = 0.6 fm)/εBN(d = 0) because nuclei are sharp-edged spheres in 3FD, see [1304.2307](1304.2307).

v1 and v2:

- Strong difference between v1 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
- UrQMD afterburner somewhat increases v2

Summary

- The thermodynamical approach **approximately** reproduces data on 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

Afterburner for light nuclei may resolve the above problems(?)

Nearest plans

- Imitation of afterburner for light nuclei by late freeze-out;
- Study of v1 puzzle for deuterons: pT-differential v1(pT);
- Elliptic flow v2, try different ways to calculate: event plane method, cumulant method;
- Calculation of ratio of light nuclei yields (Shuryak et al.): $N_t N_p / N_d^2$

Further plans

- Predictions for NICA energies;
- Medium effects;
- HADES and AGS data;
- Hyper-(anti)nuclei.

Thank you

for your attention!

Backup

Plan of the presentation

- Introduction: existing models and hydrodynamical approach
- 3FD model and event generator THESEUS: short description.
- THESEUS-v2: updates, physical reasons.
- 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: rapidity distributions, pT, mT-spectra, directed flow v1 and elliptic flow v2 of light nuclei and protons.
- Summary
- Outlook

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
Phys.Rev.C 103 (2021) 4, 044905; arXiv:2012.11438

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

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

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 p and n are different particles, fraction of protons:

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

$B_{\text{participants}}$ is total baryon number of participants;

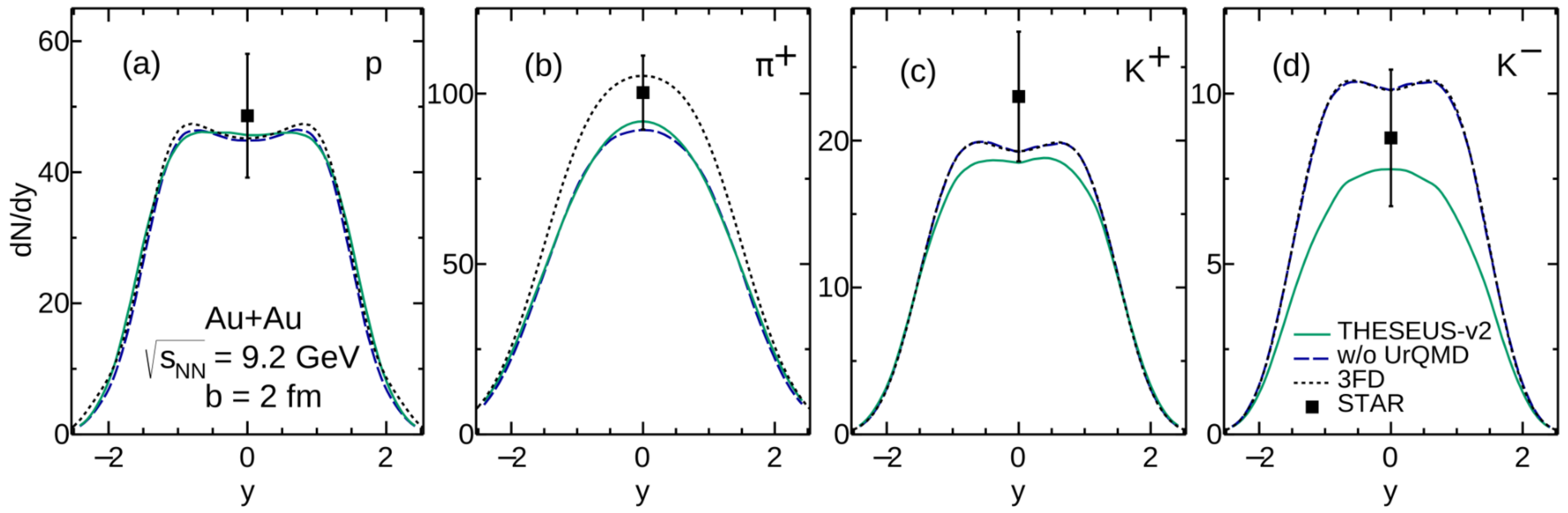
$Z_{\text{participants}} = B_{\text{participants}}(Z_1 + Z_2)/(A_1 + A_2)$ is total electrical charge of participants,

N_{nucleus} is the multiplicity of the produced light nucleus.

The formula reflects that some protons are bounded in light nuclei.

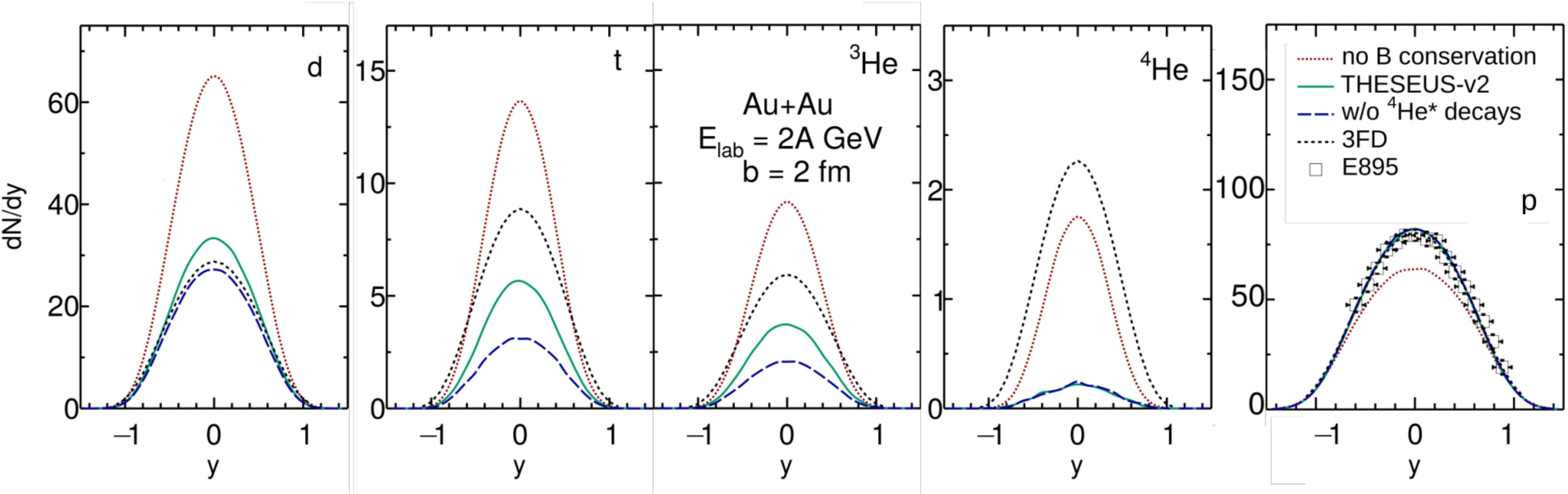
Scaling factors tritium and ^{3}He: $(N_1+N_2)/(A_1+A_2)$ and $(Z_1+Z_2)/(A_1+A_2)$.

THESEUS-v2: rapidity distributions. muB recalculation



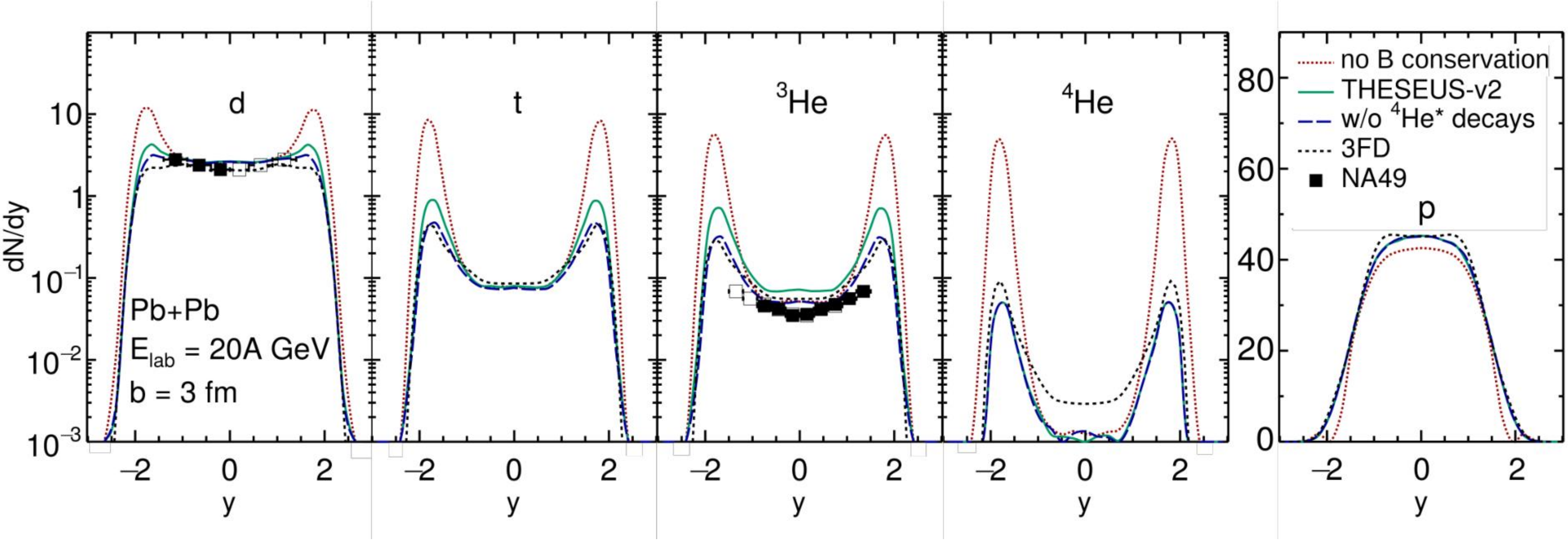
- Consistency check: dN/dy of p, K+, K- without UrQMD are in perfect agreement with 3FD.
- UrQMD significantly affects K+, K- , because of strong absorption of K− , K− + n → Λ + π−.
- The π+ distribution: different tables of decays of resonances in 3FD and THESEUS.
- In 3FD: π+ = (All pions)/3.

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

Directed flow v1(y): protons and deuterons