The equation of state of symmetric nuclear matter from heavy-ion collisions

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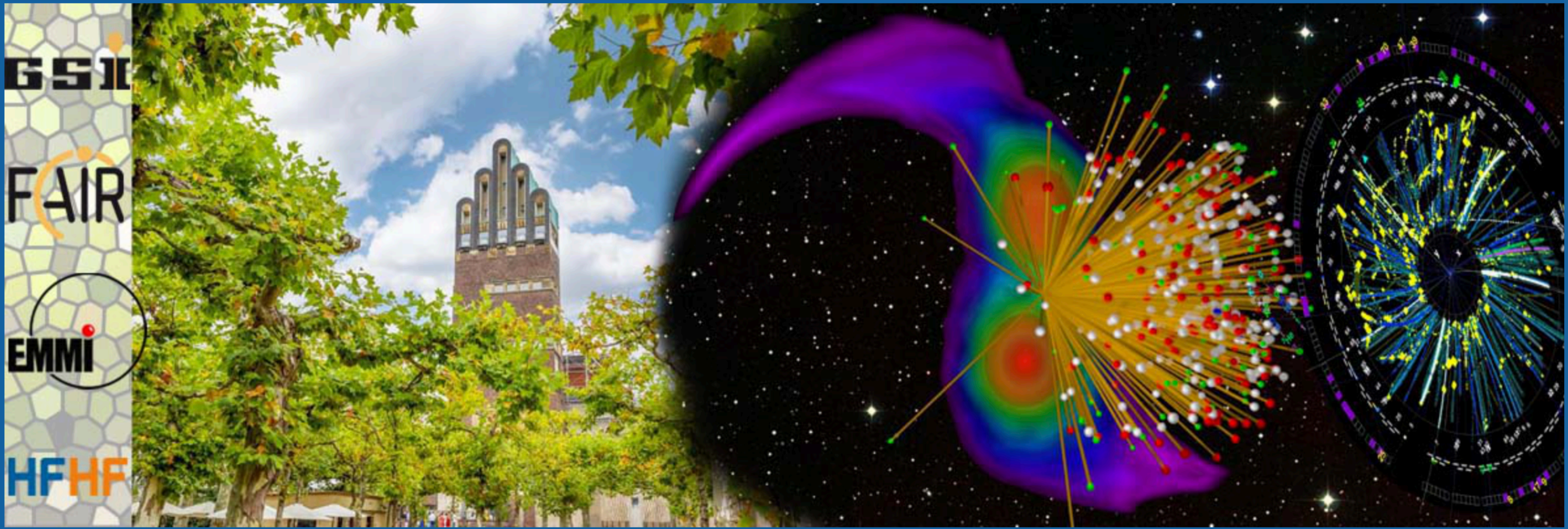
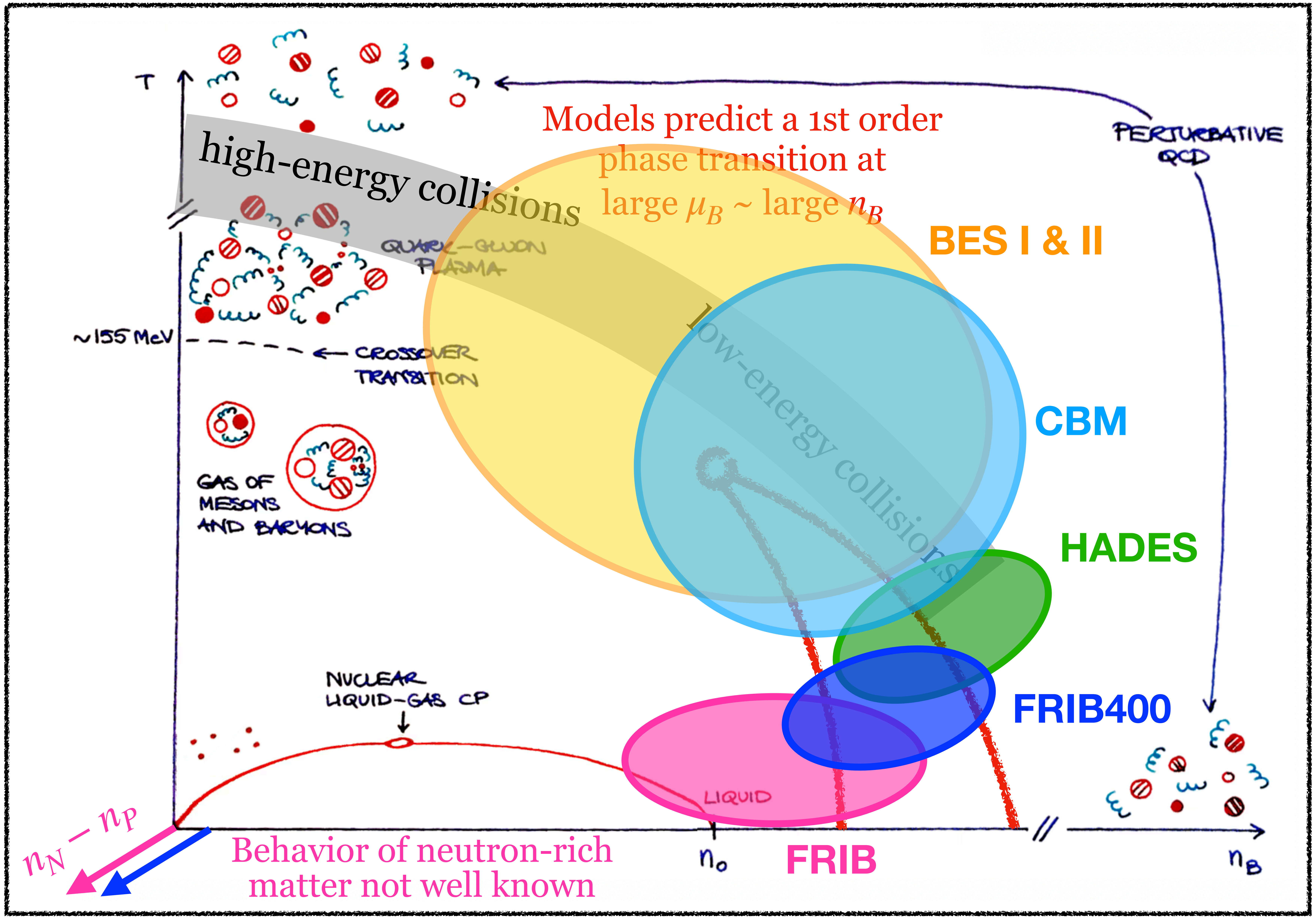
Institute for Nuclear Theory, University of Washington



NuSym23, XIth International Symposium on Nuclear Symmetry Energy 09/18/2023

The QCD phase diagram: great interest in behavior at high n_B



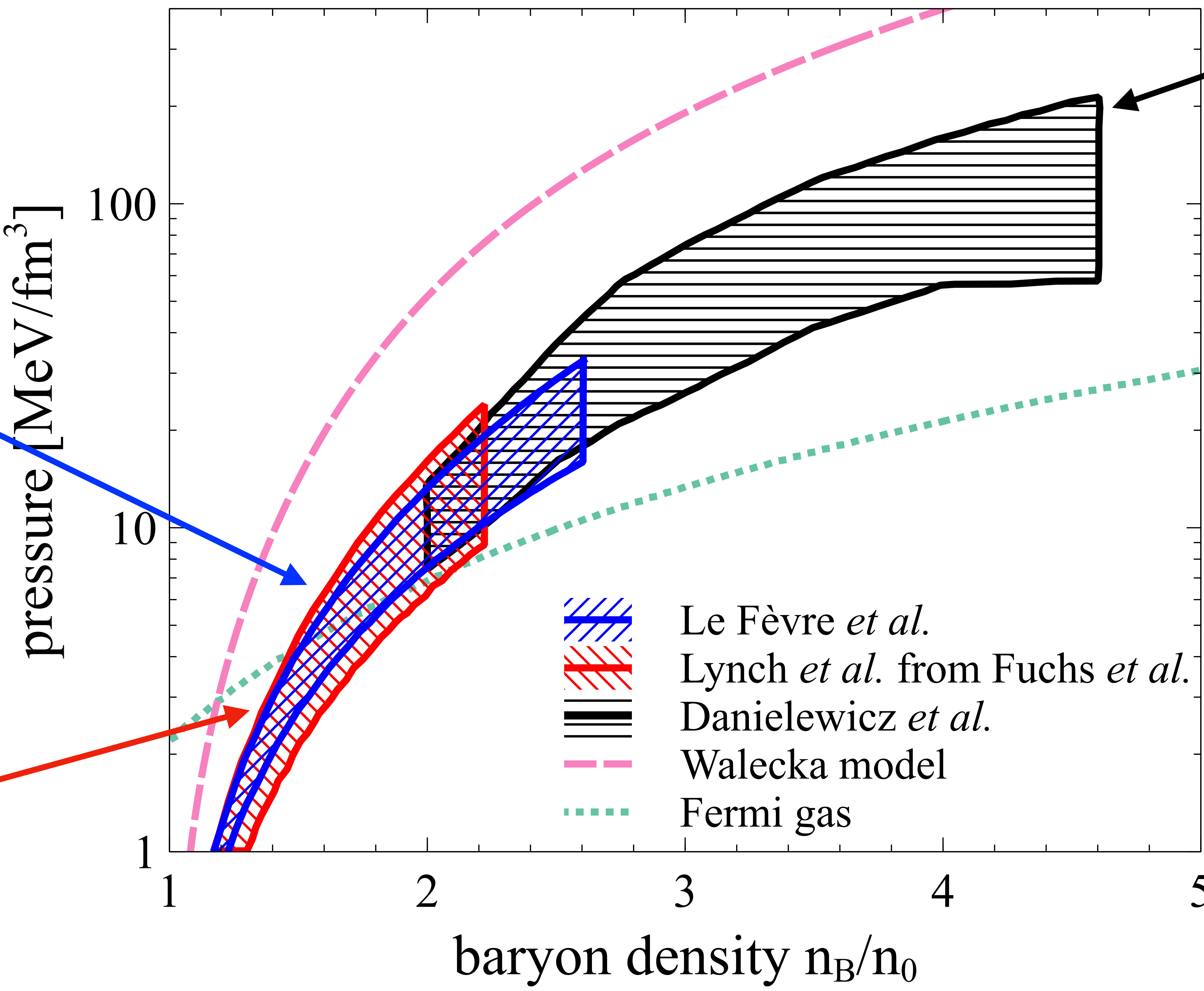
- HICs = the only means to probe densities away from n_0 in controlled terrestrial experiments
- Hadronic transport is necessary to interpret the results: BES FXT, HADES, CBM, FRIB, FRIB400

EOS of symmetric nuclear matter: selected (*few*) results

Symmetric nuclear matter

197Au+197Au @ 0.4—1.5 GeV/u
($\sqrt{s_{NN}}$ = 2.07 — 2.52 GeV)
observables: proton flow (FOPI)
model used: isospin QMD (IQMD) w/ nucleons, Δ, N*(1440), deuterons, tritons;
EOS parametrized by K_0;
momentum dependence
A. Le Fèvre, Y. Leifels, W. Reisdorf, J. Aichelin, C. Hartnack, Nucl. Phys. A 945, 112 (2016), arXiv:1501.05246

197Au+197Au & 12C+12C @ < 1.5 GeV/u
($\sqrt{s_{NN}}$ < 2.5 GeV)
observables: subthreshold kaon production (KaoS)
model used: QMD w/ nucleons, Δ, N*(1440), pions, kaons;
EOS parametrized by K_0;
kaon potentials, momentum dependence
C. Fuchs *et al.*, Prog. Part. Nucl. Phys. **53**, 113–124 (2004) arXiv:nucl-th/0312052

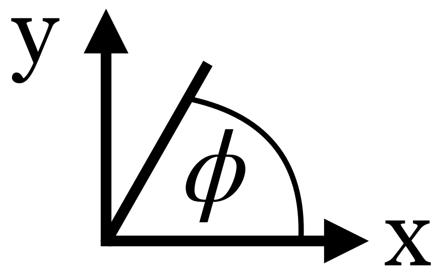


A. Sorensen *et al.*, arXiv:2301.13253
to appear in JPPNP

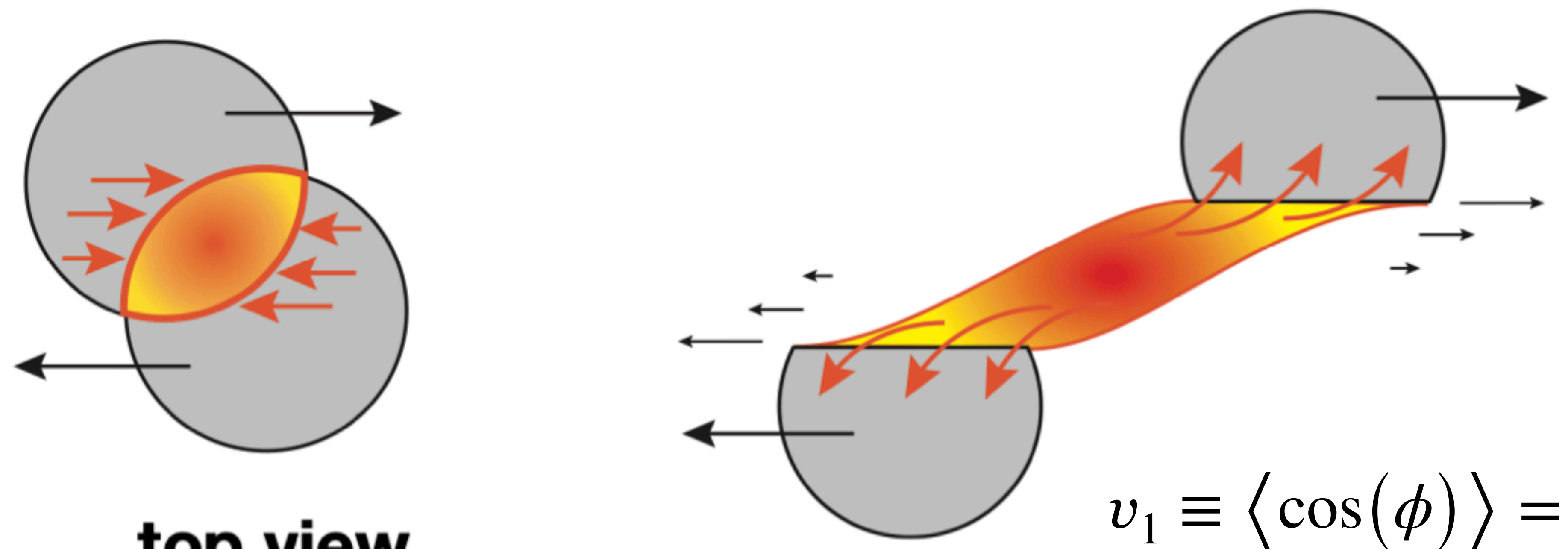
197Au+197Au @ 0.15—10 GeV/u
($\sqrt{s_{NN}}$ = 1.95 — 4.72 GeV)
observables: proton flow
(Plastic Ball, EOS, E877, E895)
model used: pBUU w/ nucleons, Δ, N*(1440), pions;
EOS parametrized by K_0;
momentum dependence
P. Danielewicz, R. Lacey, W. G. Lynch, Science **298**,1592–1596 (2002)

EOS from flow observables in heavy-ion collisions

Flow $v_n \equiv \langle \cos(n\phi) \rangle$



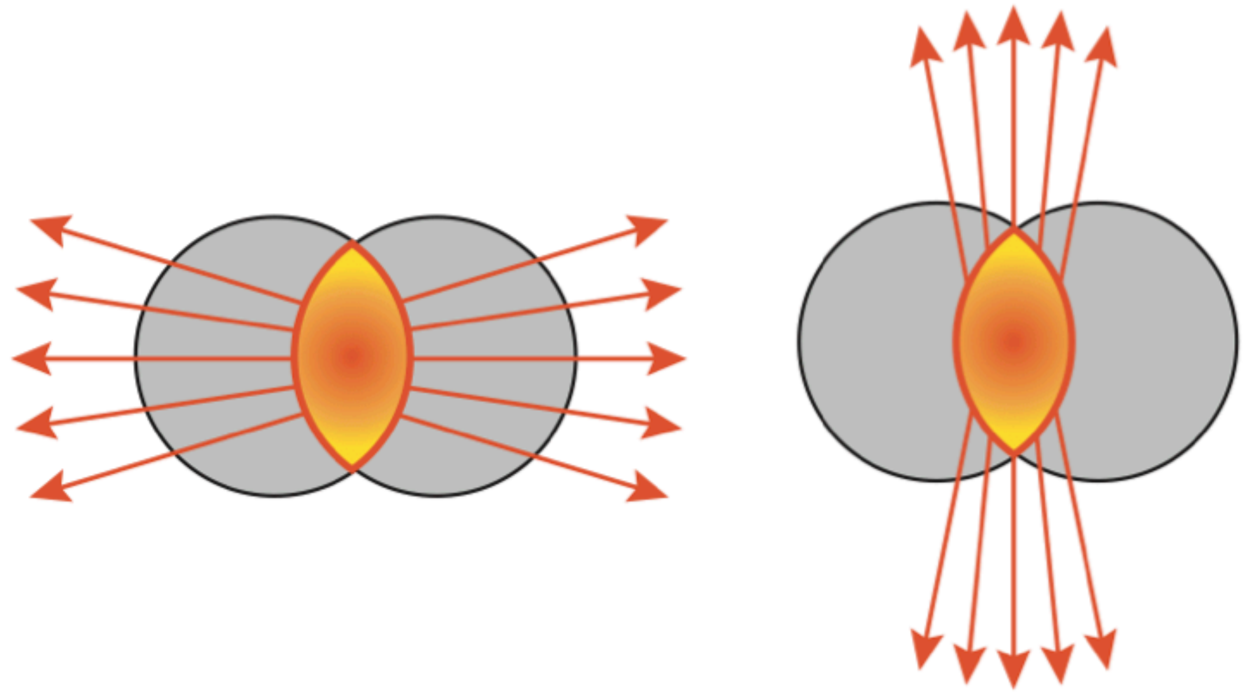
directed flow v_1 (dv_1/dy ~ longitudinal expansion)



$v_1 \equiv \langle \cos(\phi) \rangle = \langle \frac{p_x}{p_T} \rangle$

elliptic flow v_2 ($v_2(y \approx 0)$ ~ midrapidity)

$v_2 \equiv \langle \cos(2\phi) \rangle$

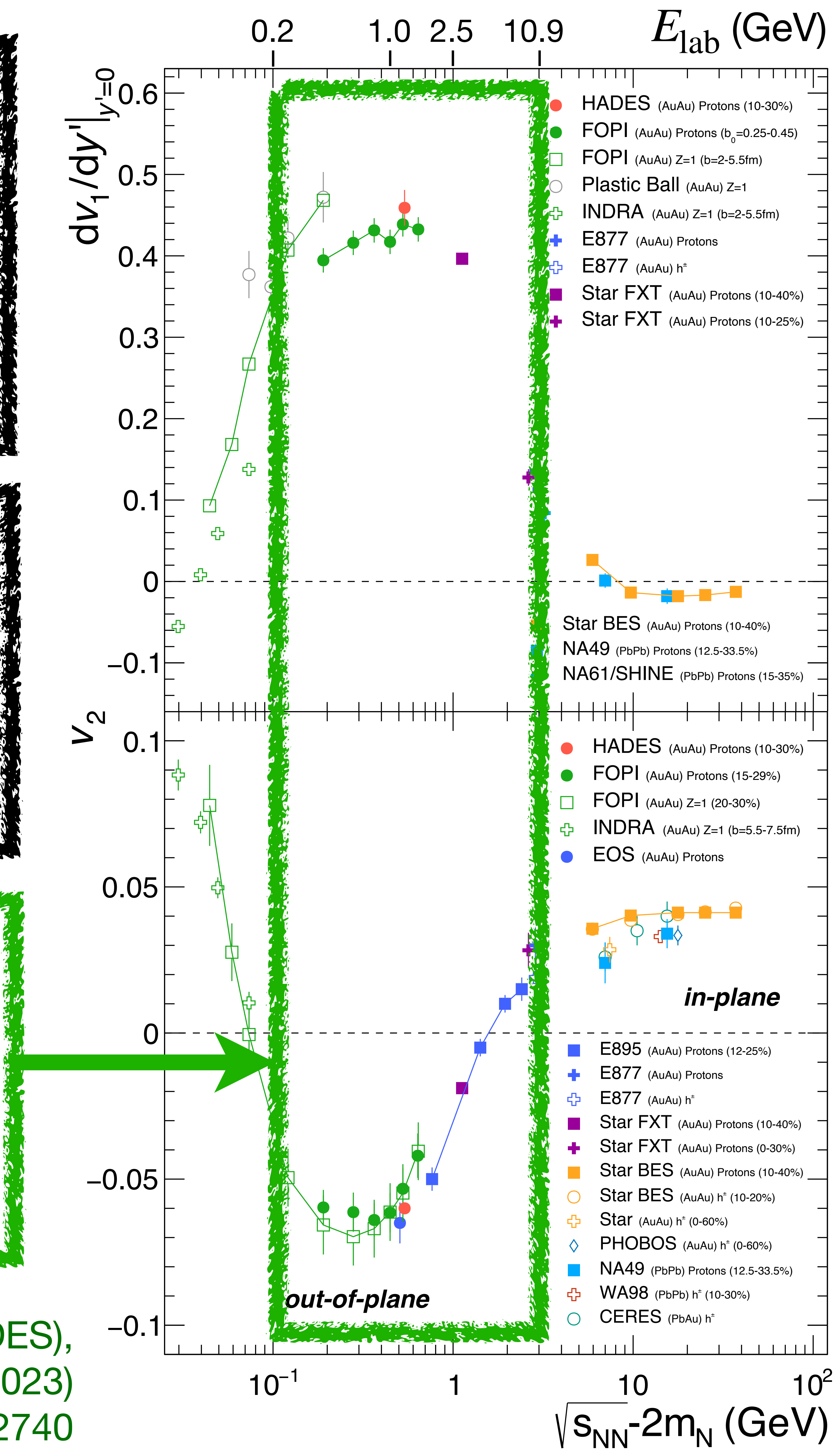


illustrations from a presentation by B. Kardan (HADES)

3 aspects lead to flow:
- collision geometry
- dynamics
- EOS

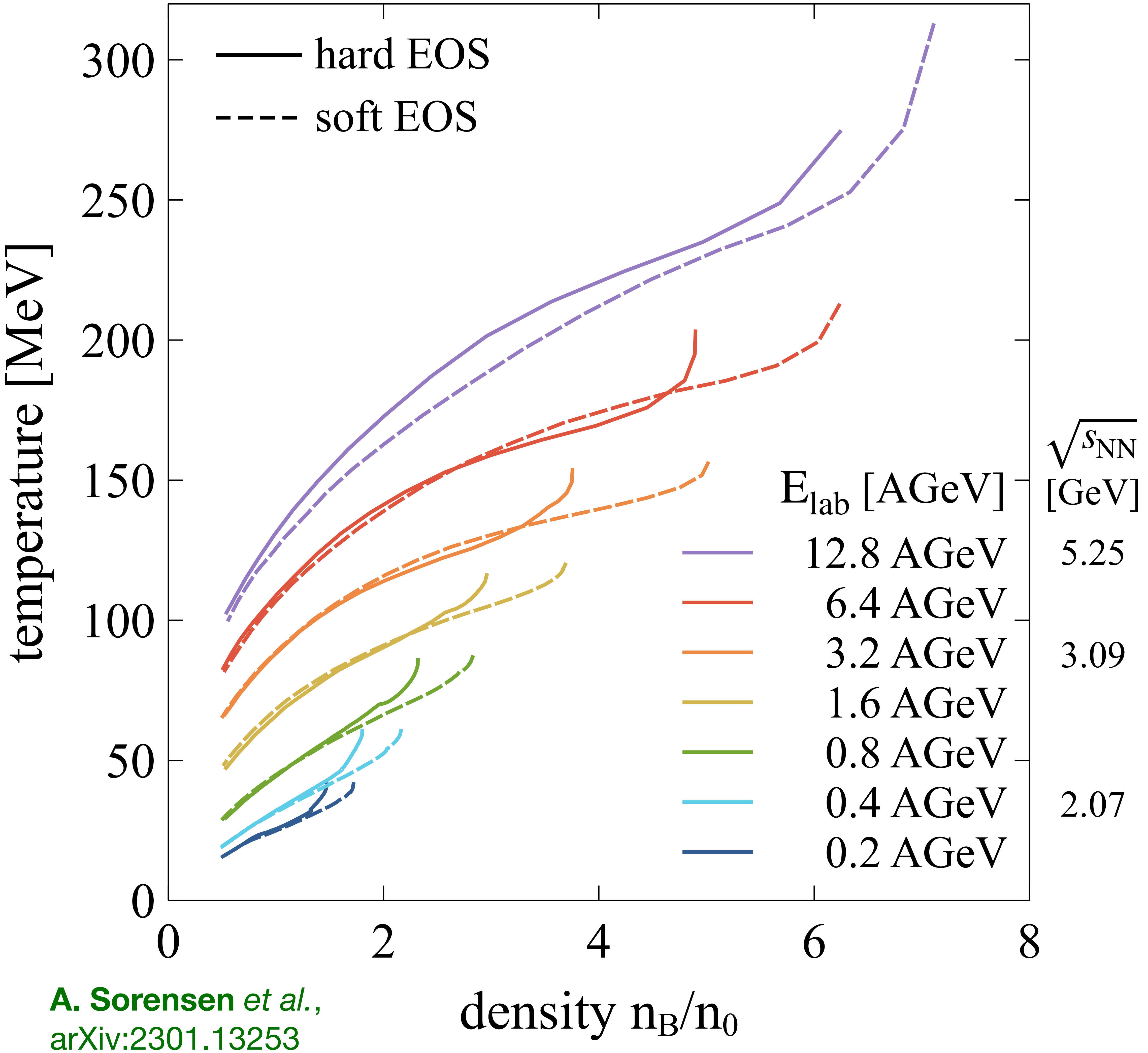
Flow is extremely sensitive to the EOS (more on that later)

Upcoming experiments: FRIB / FRIB400, HADES, CBM, ...



J. Adamczewski-Musch *et al.* (HADES), Eur.Phys.J.A **59** 4, 80 (2023) arXiv:2208.02740

EOS from flow observables in heavy-ion collisions



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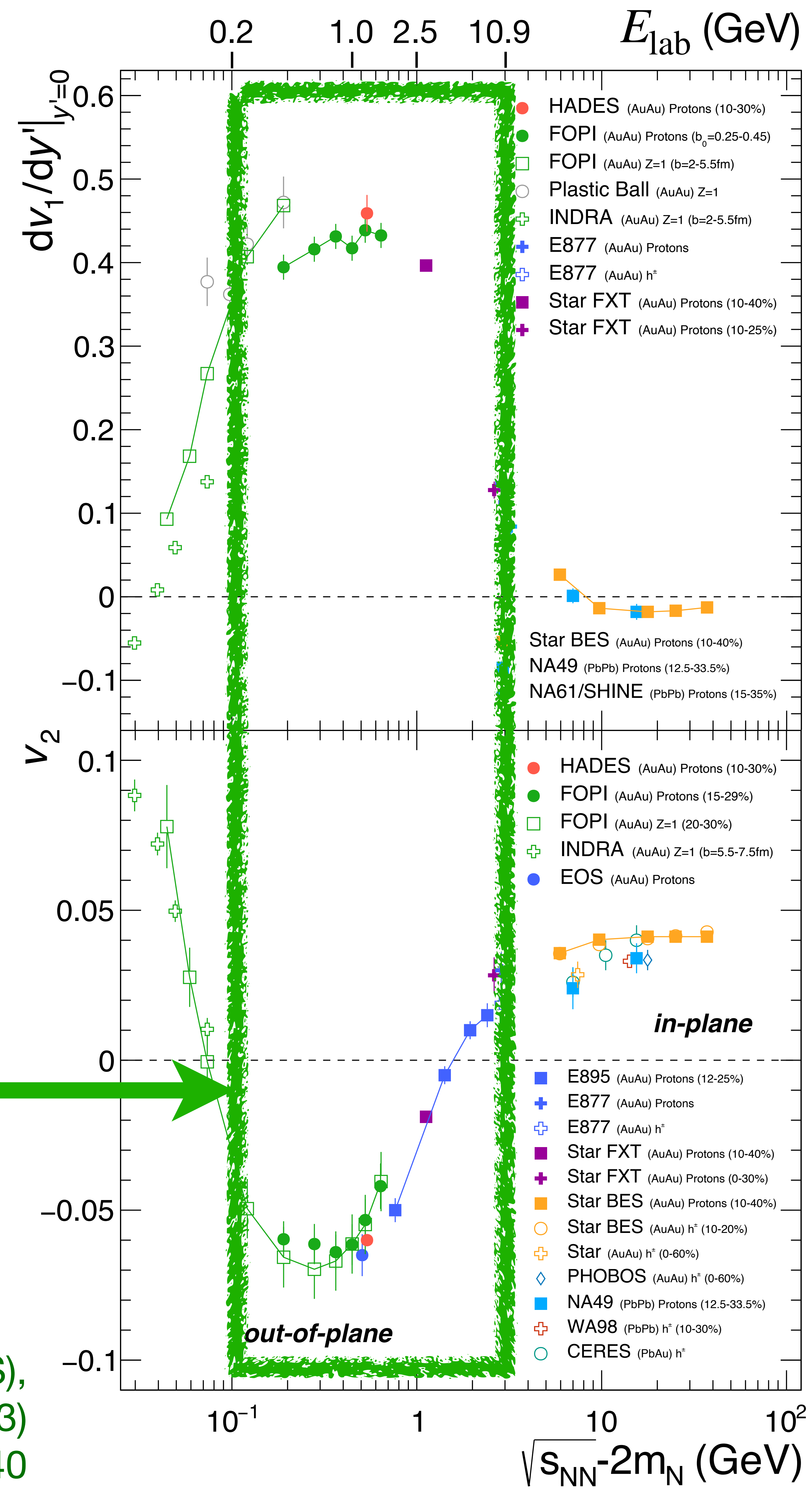
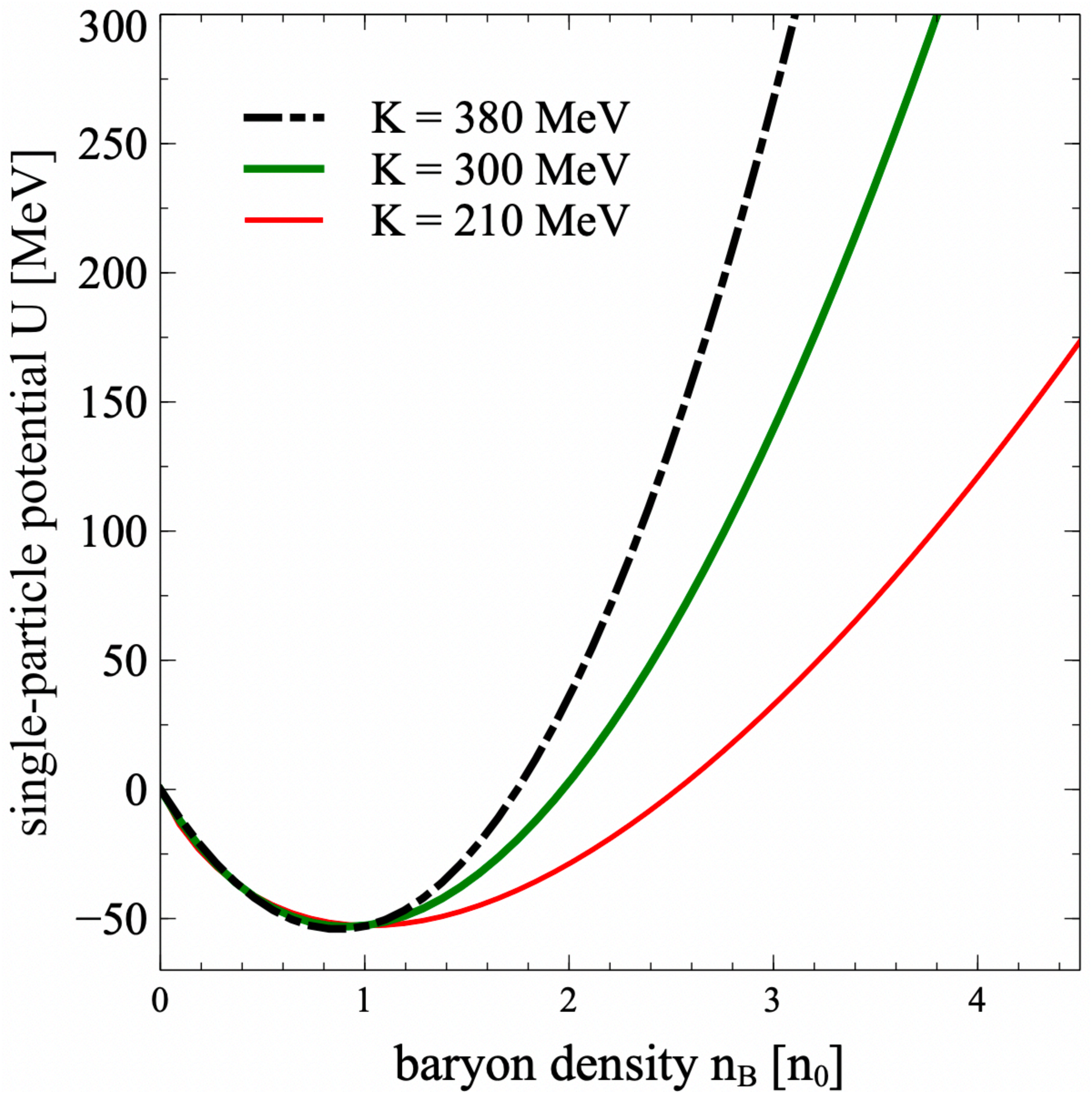


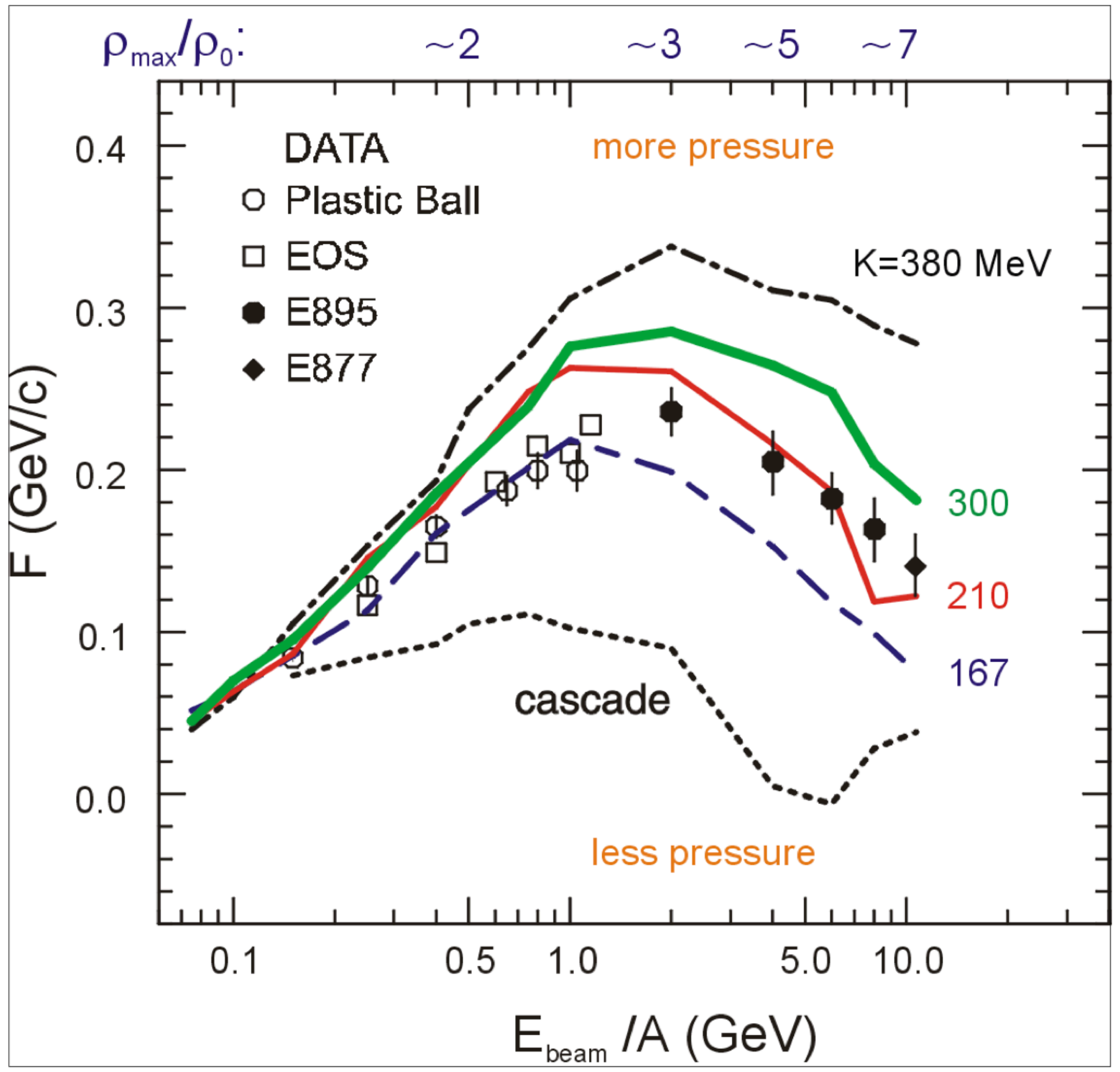
J. Adamczewski-Musch *et al.* (HADES),
Eur.Phys.J.A **59** 4, 80 (2023)
arXiv:2208.02740

Standard way of modeling the EOS: Skyrme potential

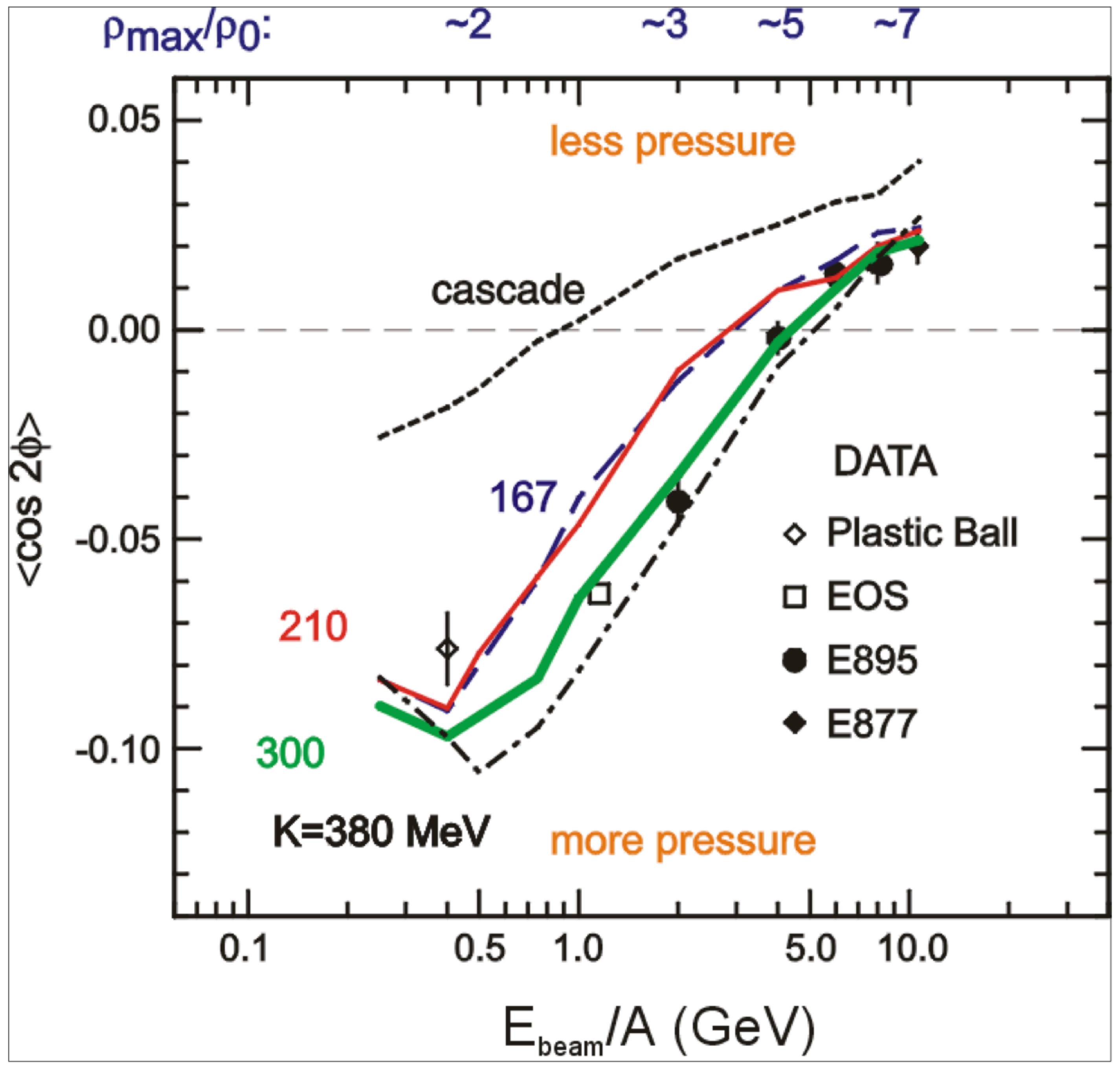
The most common form of the EOS is the “Skyrme potential”: $U(n_B) = A\left(\frac{n_B}{n_0}\right) + B\left(\frac{n_B}{n_0}\right)^{\tau}$

(note: in DLL $U(n_B)$ a bit more complicated, also momentum dependence!)





$$F = \left.\frac{d\langle p_x/A\rangle}{d(y/y_{cm})}\right|_{y/y_{cm}=1}$$

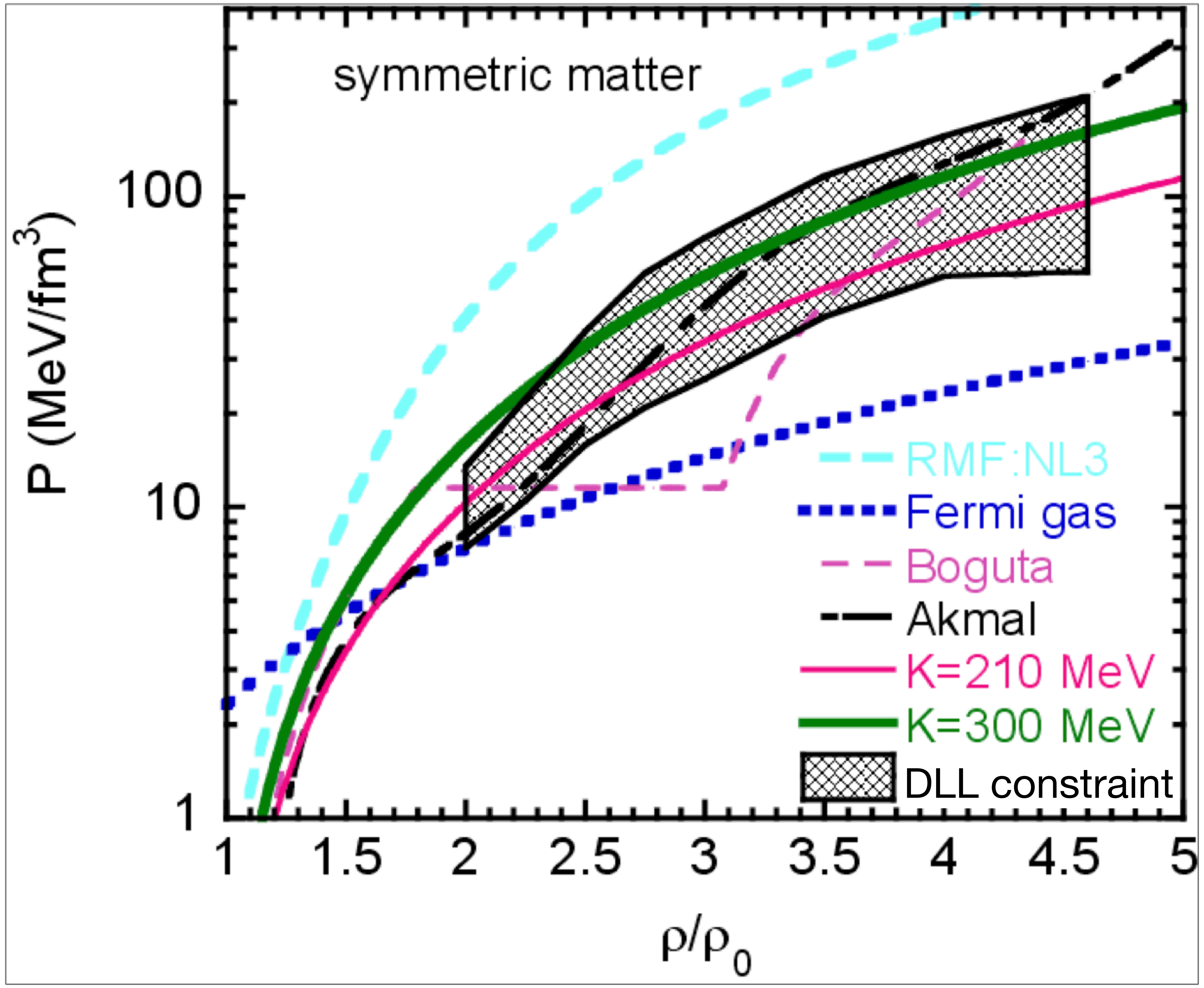


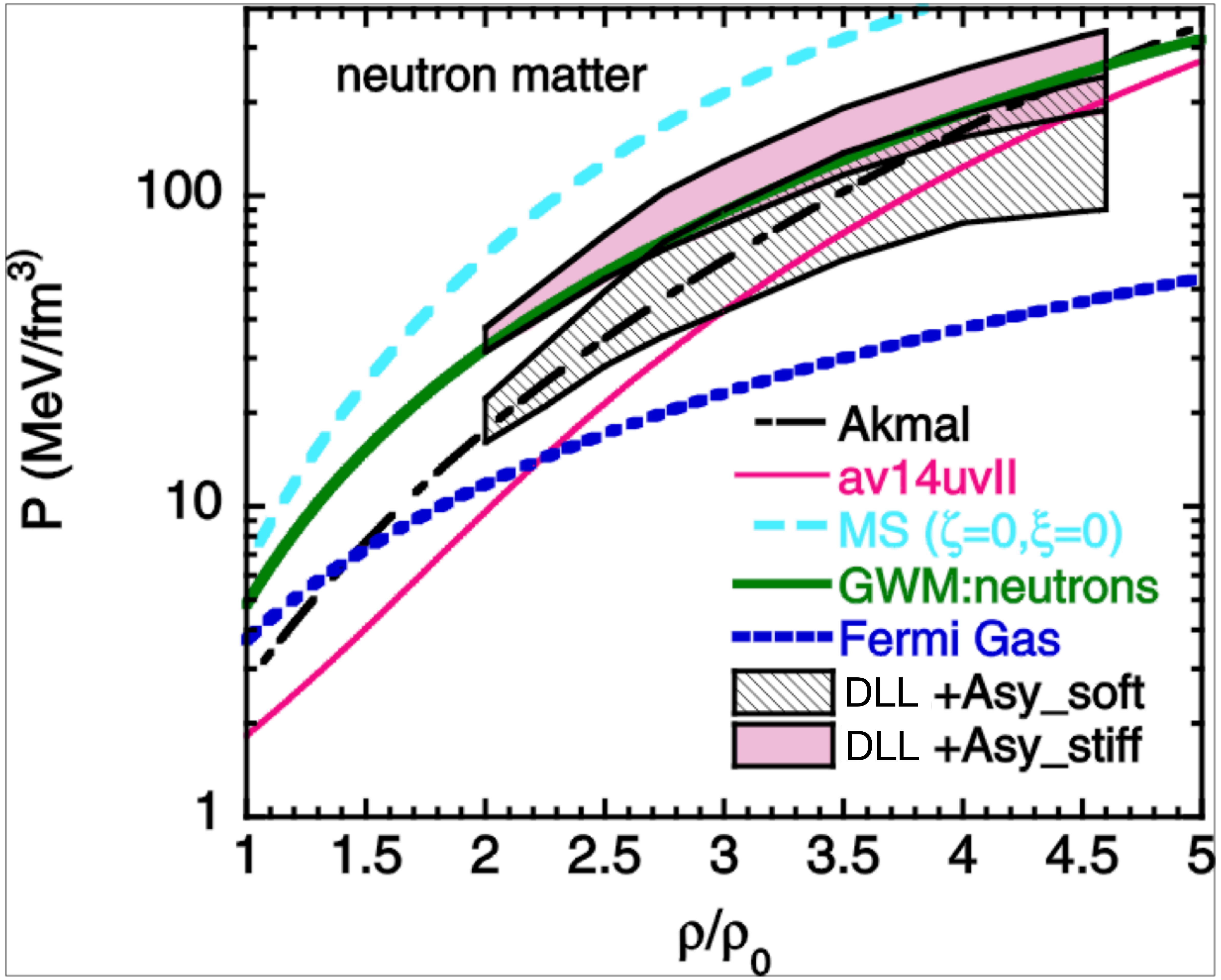
P. Danielewicz, R. Lacey, W. G. Lynch, Science **298**, 1592–1596 (2002), arXiv:nucl-th/0208016

Standard way of modeling the EOS: Skyrme potential

P. Danielewicz, R. Lacey, W. G. Lynch,
Science **298**, 1592–1596 (2002), arXiv:nucl-th/0208016

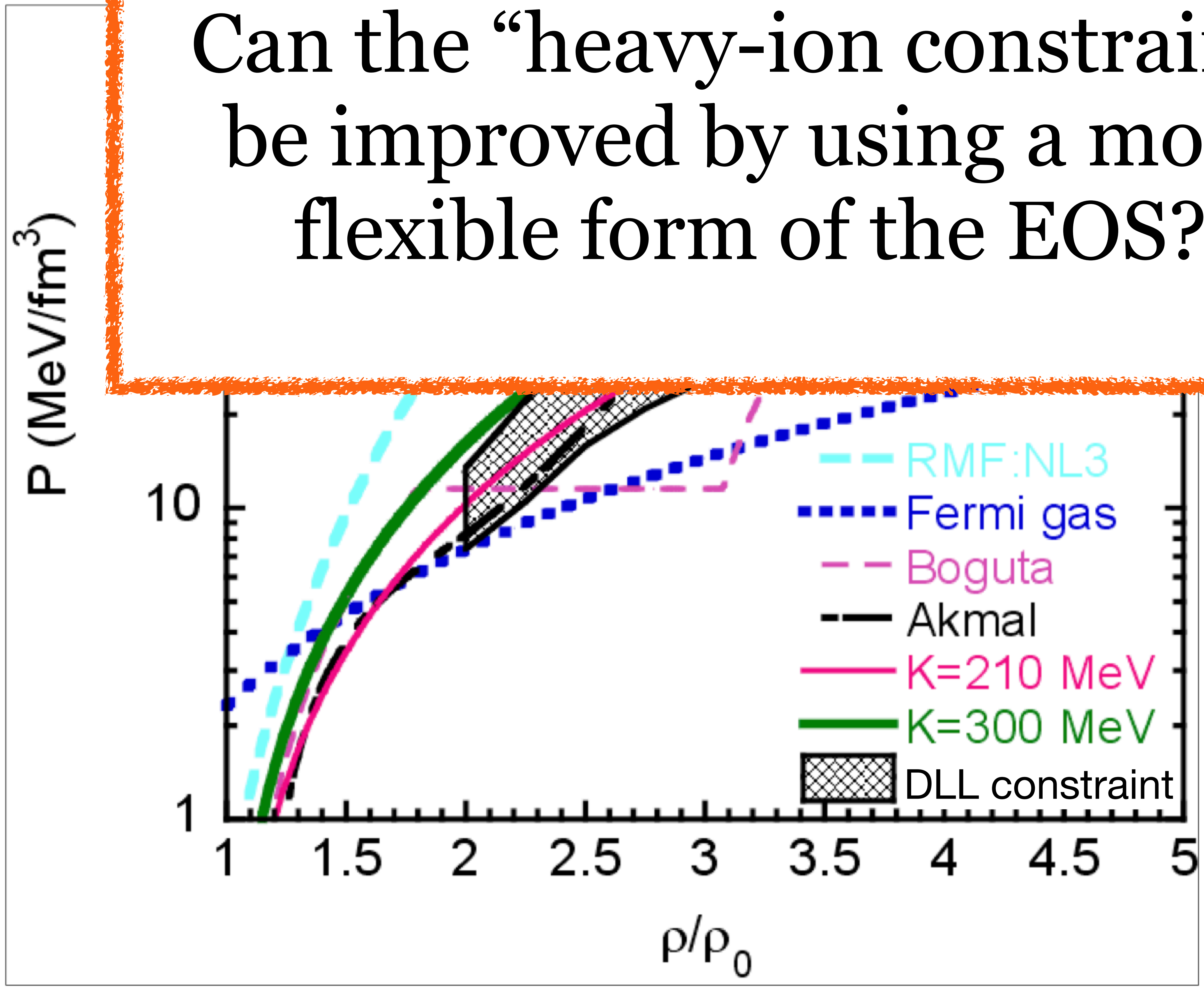
“the heavy-ion constraint”



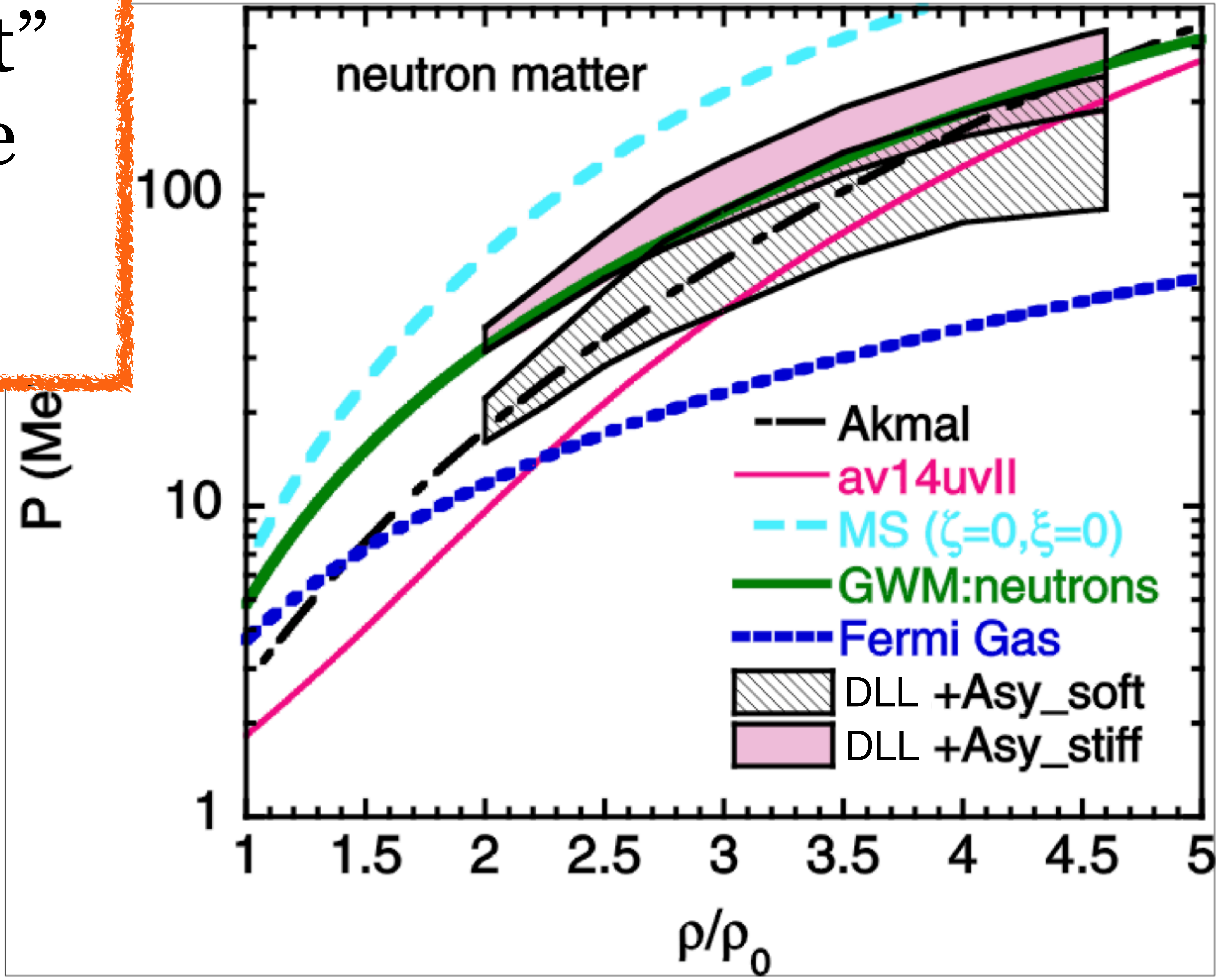


Standard way of modeling the EOS: Skyrme potential

Can the “heavy-ion constraint” be improved by using a more flexible form of the EOS?



“the heavy-ion constraint”



$y/y_{cm}=1$

Relativistic vector density functional (VDF) model

A. Sorensen, V. Koch, Phys. Rev. C **104** (2021) 3, 034904, arXiv:2011.06635

inspired by relativistic Landau Fermi-liquid theory: G. Baym, S. A. Chin, Nucl. Phys. A **262**, 527 (1976)

$$j_\mu j^\mu = n_B^2$$

$$\epsilon_{\text{kin}} = \sqrt{\left(\vec{p} - \sum_{i=1}^{N} C_i (j_\mu j^\mu)^{\frac{b_i}{2}-1} \vec{j}\right)^2 + m^2}$$

1) Postulate the energy density of the system:

$$\mathscr{E}_N = \mathscr{E}_N[f_{\mathbf{p}}] = g \int \frac{d^3p}{(2\pi)^3}\, \epsilon_{\text{kin}}\, f_{\mathbf{p}} + \sum_{i=1}^{N} C_i \left(j_\mu j^\mu\right)^{\frac{b_i}{2}-1} \left[j^0 j^0 - g^{00} \left(\frac{b_i - 1}{b_i}\right) j_\lambda j^\lambda \right]$$

⟵ Lorentz covariant

$$\mathscr{E}_N \Big|_{\substack{\text{rest}\\\text{frame}}} = g \int \frac{d^3p}{(2\pi)^3} \sqrt{\vec{p}^{\,2} + m^2}\, f_{\mathbf{p}} + \sum_{i=1}^{N} \frac{C_i}{b_i} n_B^{b_i}$$

⟵ mean-field interactions parameterized by C_i and b_i

thermodynamically consistent

2) Quasiparticle energy:

$$\varepsilon_{\mathbf{p}} \equiv \frac{\delta \mathscr{E}[f_{\mathbf{p}}]}{\delta f_{\mathbf{p}}} = \epsilon_{\text{kin}} + \sum_{i=1}^{N} C_i \left(j_\mu j^\mu\right)^{\frac{b_i}{2}-1} j^0$$

3) Get EOMs:

$$\frac{dx^i}{dt} \equiv -\frac{\partial \varepsilon_{\mathbf{p}}}{\partial p_i}, \qquad \frac{dp^i}{dt} \equiv \frac{\partial \varepsilon_{\mathbf{p}}}{\partial x_i}$$

⟵ input to transport code; use in Boltzmann eq. to obtain $T^{\mu\nu}$

4) Use $T^{\mu\nu}$ to get the pressure:

$$P_N = \frac{1}{3} \sum_k T^{kk} \Big|_{\substack{\text{rest}\\\text{frame}}} = g \int \frac{d^3p}{(2\pi)^3}\, T \ln\left[1 + e^{-\beta(\varepsilon_{\mathbf{p}} - \mu_B)}\right] + \sum_{i=1}^{N} C_i \frac{b_i - 1}{b_i} n_B^{b_i}$$

VDF model: two 1st order phase transitions

A. Sorensen, V. Koch, Phys. Rev. C **104** (2021) 3, 034904, arXiv:2011.06635

Systems with two 1st order phase transitions: nuclear and "quark/hadron", or "QGP-like"

- degrees of freedom: nucleons
- "QGP-like" PT: "more dense" matter coexists with "less dense" matter
- minimal model: 4 interactions terms = 8 parameters to fix:

$$P = g\int \frac{d^3p}{(2\pi)^3}\, T\, \ln\left[1 + e^{-\beta(\varepsilon_{\mathbf{p}}-\mu_B)}\right] + \sum_{i=1}^{N=4} C_i \frac{b_i - 1}{b_i} n_B^{b_i}$$

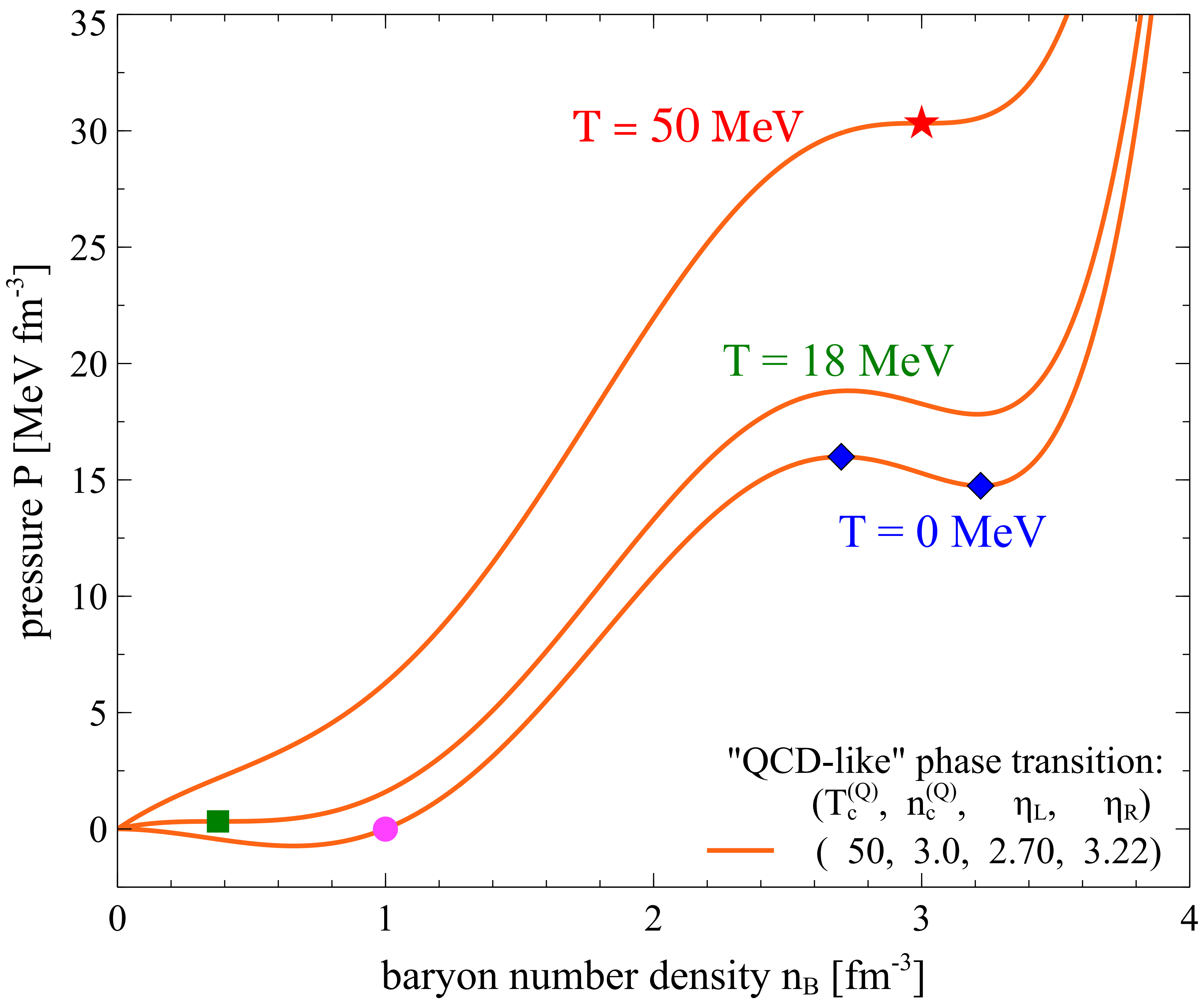
C_i and b_i are fitted to reproduce:

$n_0 = 0.160\ \mathrm{fm}^{-3}$, $E_B = -16.3$ MeV

$T_c^{(N)} = 18$ MeV, $n_c^{(N)} = 0.375 n_0$

$T_c^{(Q)} = ?$, $n_c^{(Q)} = ?$

$\eta_L = ?$, $\eta_R = ?$



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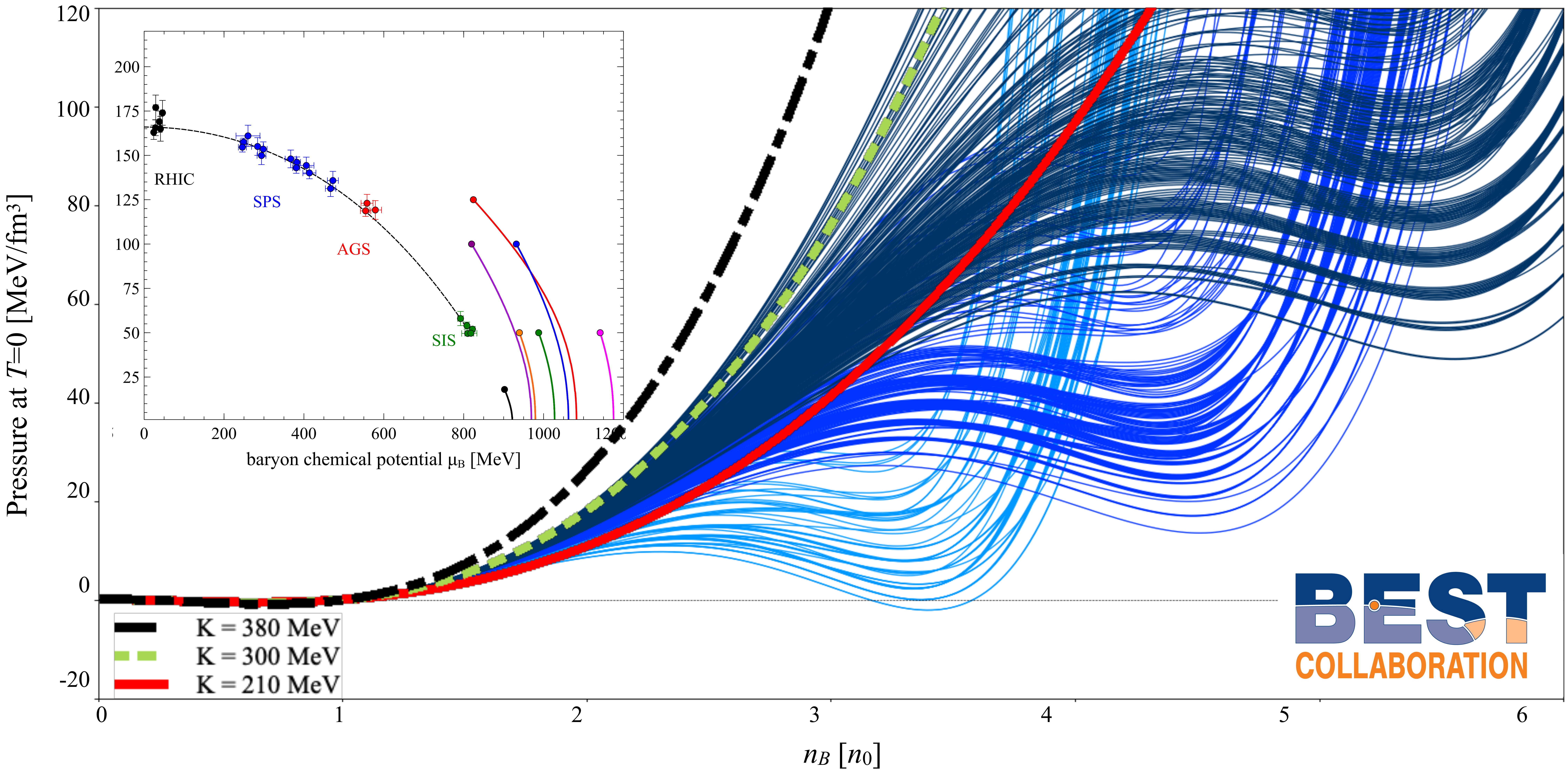

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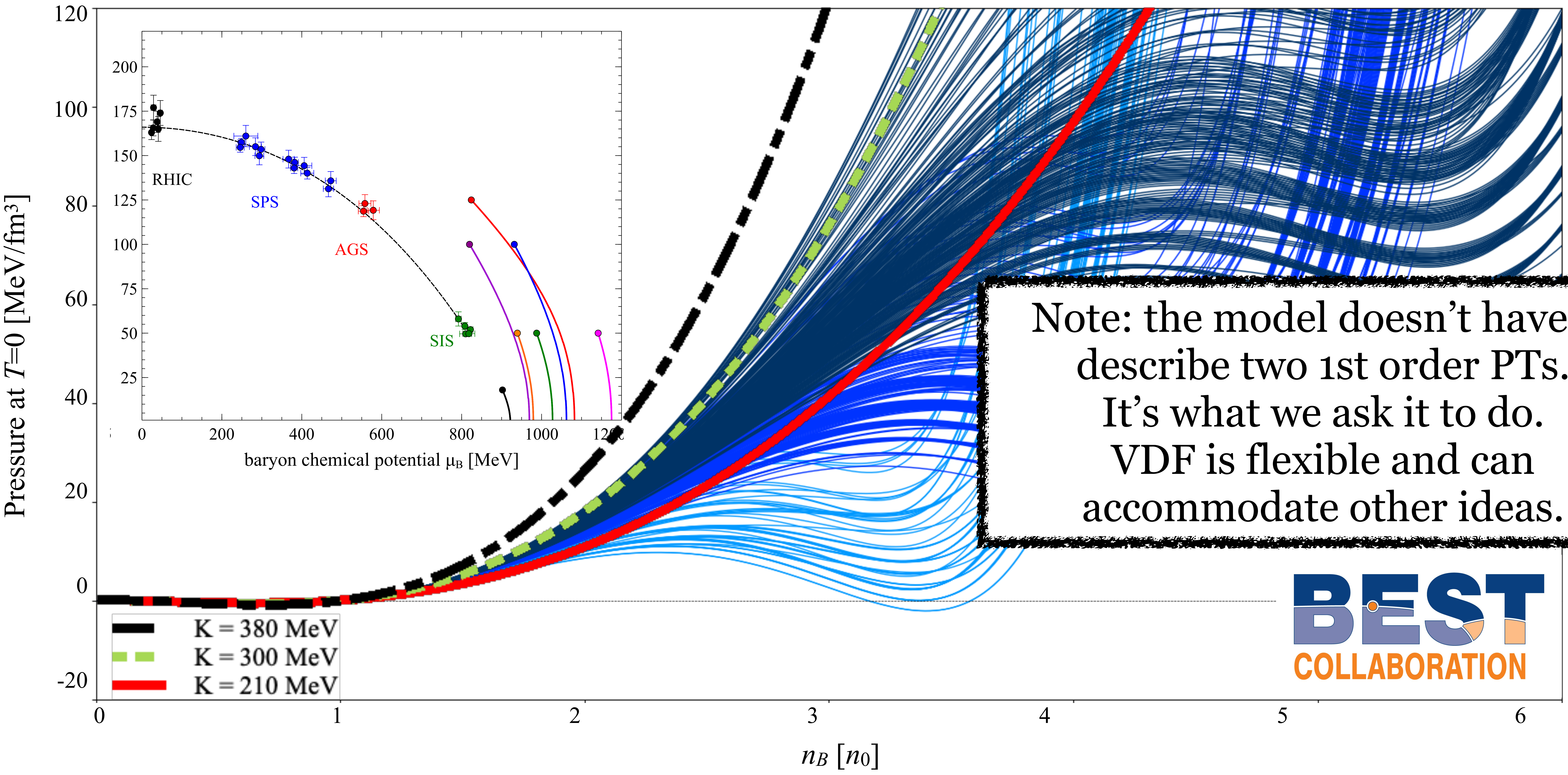
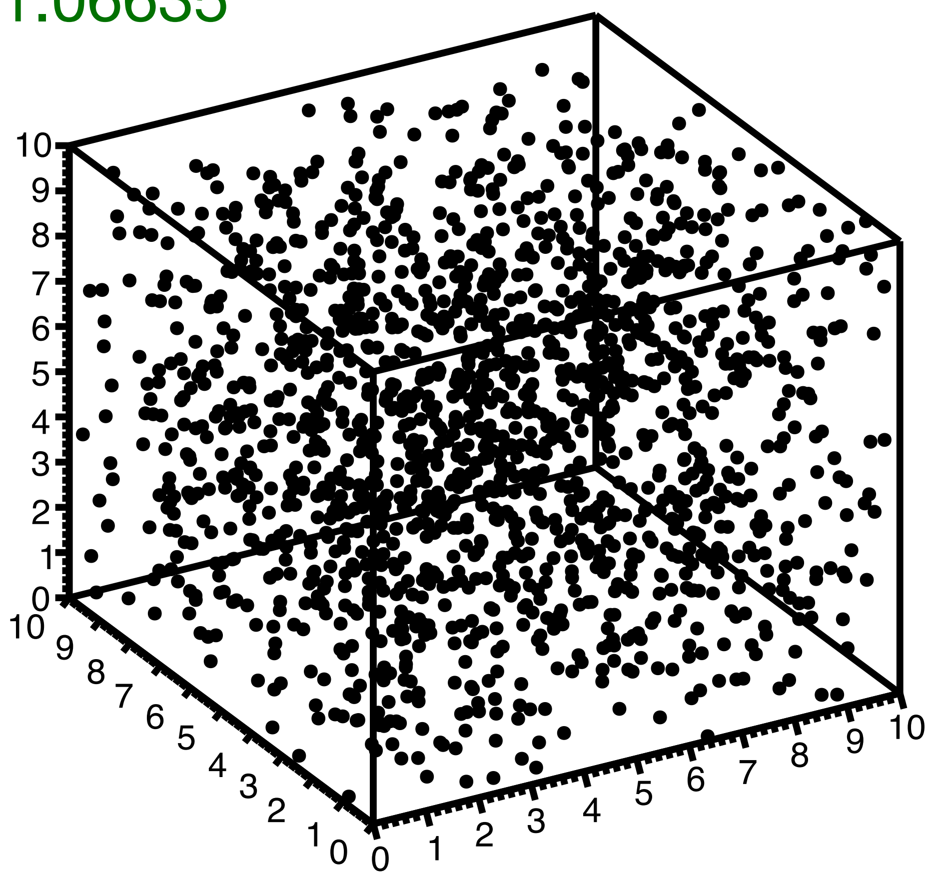


Note: the model doesn't have to describe two 1st order PTs. It's what we ask it to do. VDF is flexible and can accommodate other ideas.

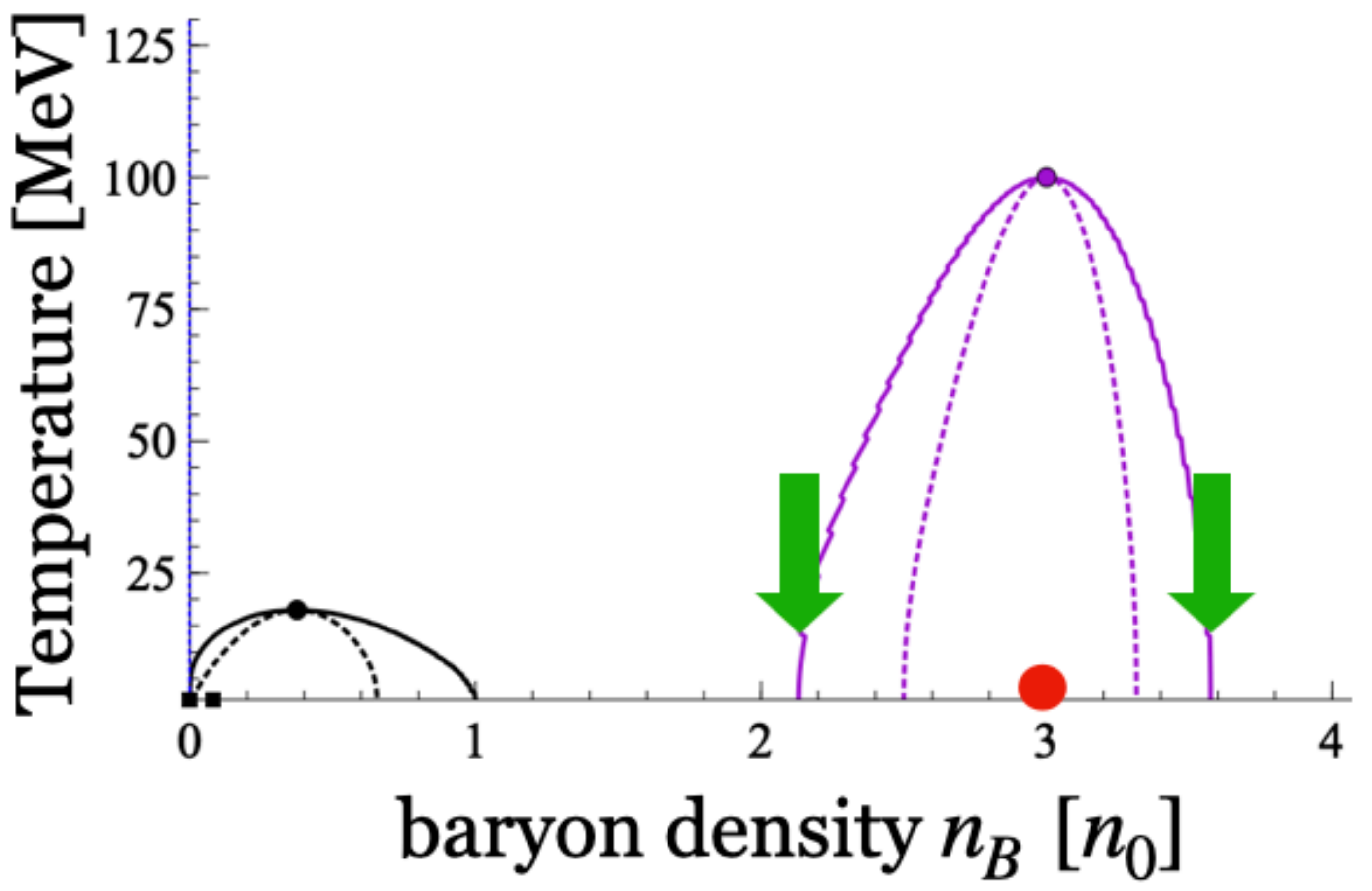
BEST COLLABORATION

VDF in SMASH: tests in the spinodal region

A. Sorensen, V. Koch, Phys. Rev. C **104**, 3, 034904 (2021)
arXiv:2011.06635



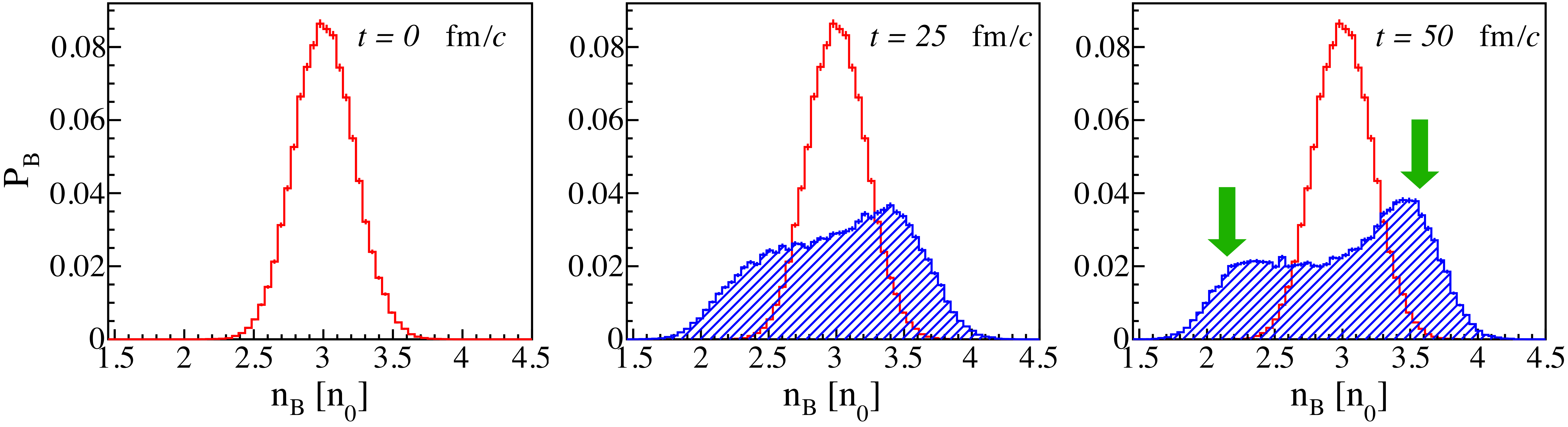
t = 0 fm/c



Simulation info for practitioners:

time step: 0.1 fm/c
smearing: triangular with range 2 fm
lattice: cubic cells with 1 fm on a side
collisions: off

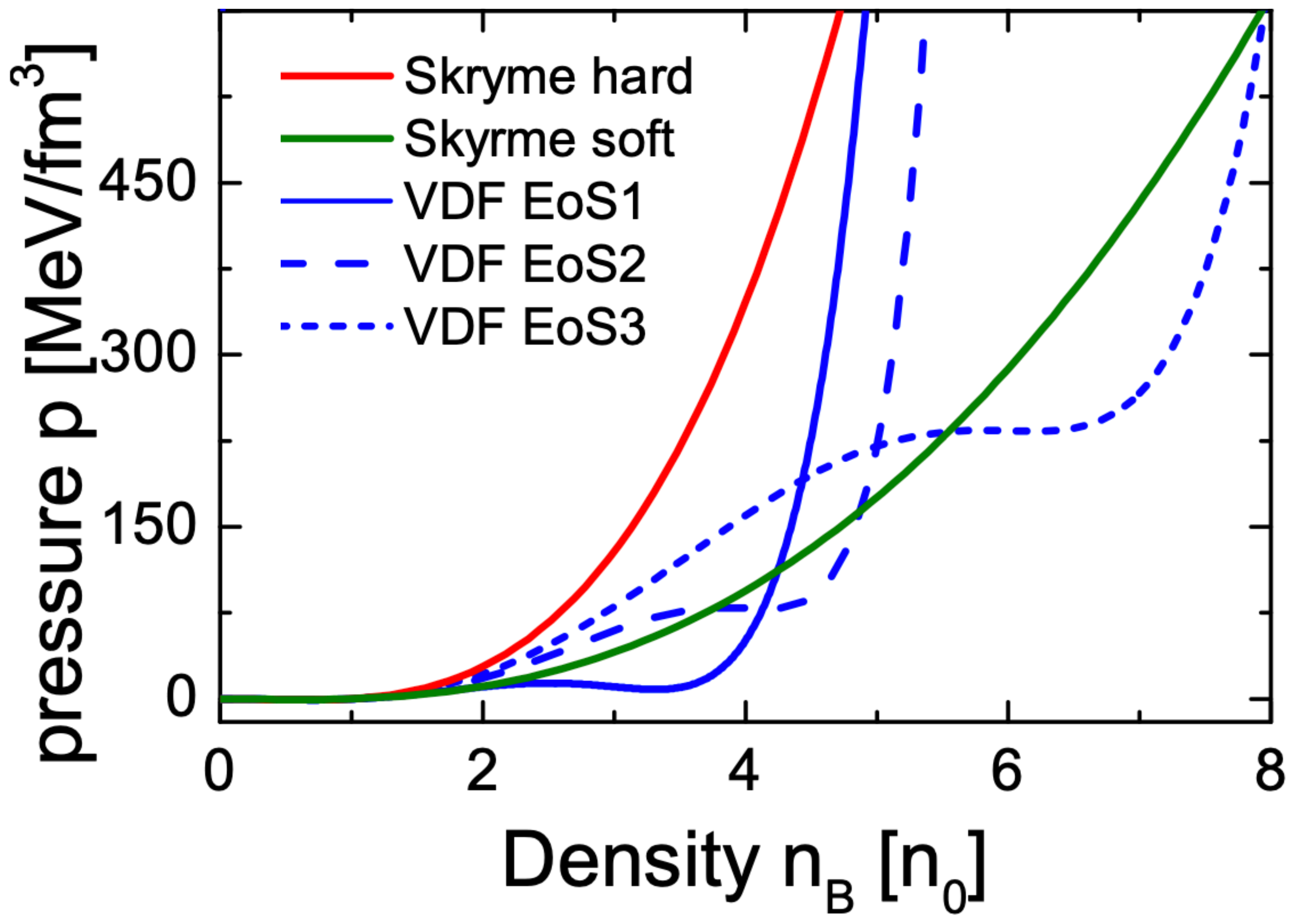
500 events
bin width = 2 fm



The distribution becomes bimodal as the system separates!

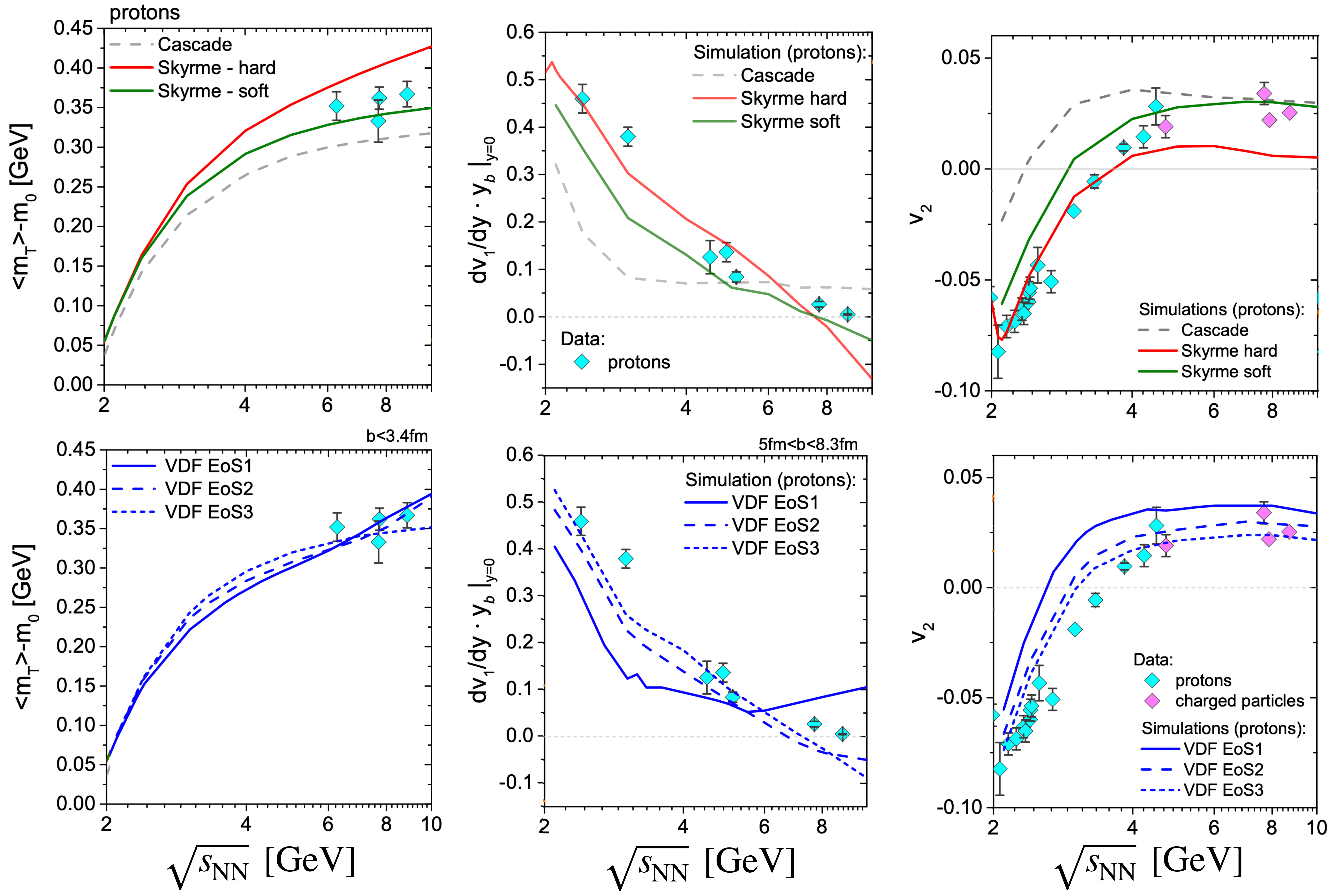
Results from UrQMD with (non-relativistic) VDF

J. Steinheimer, A. Motornenko, **A. Sorensen**, Y. Nara, V. Koch,
M. Bleicher, Eur. Phys. J. C **82**, 10, 911 (2022) arXiv:2208.12091



EoS	$T_c^{(N)}$[MeV]	$n_c^{(Q)}[n_0]$	$T_c^{(Q)}$[MeV]	K_0[MeV]
VDF1	18	3.0	100	261
VDF2	18	4.0	50	279
VDF3	22	6.0	50	356

Very soft EOS at $n_B \in (2,3)n_0$
not supported in VDF+UrQMD

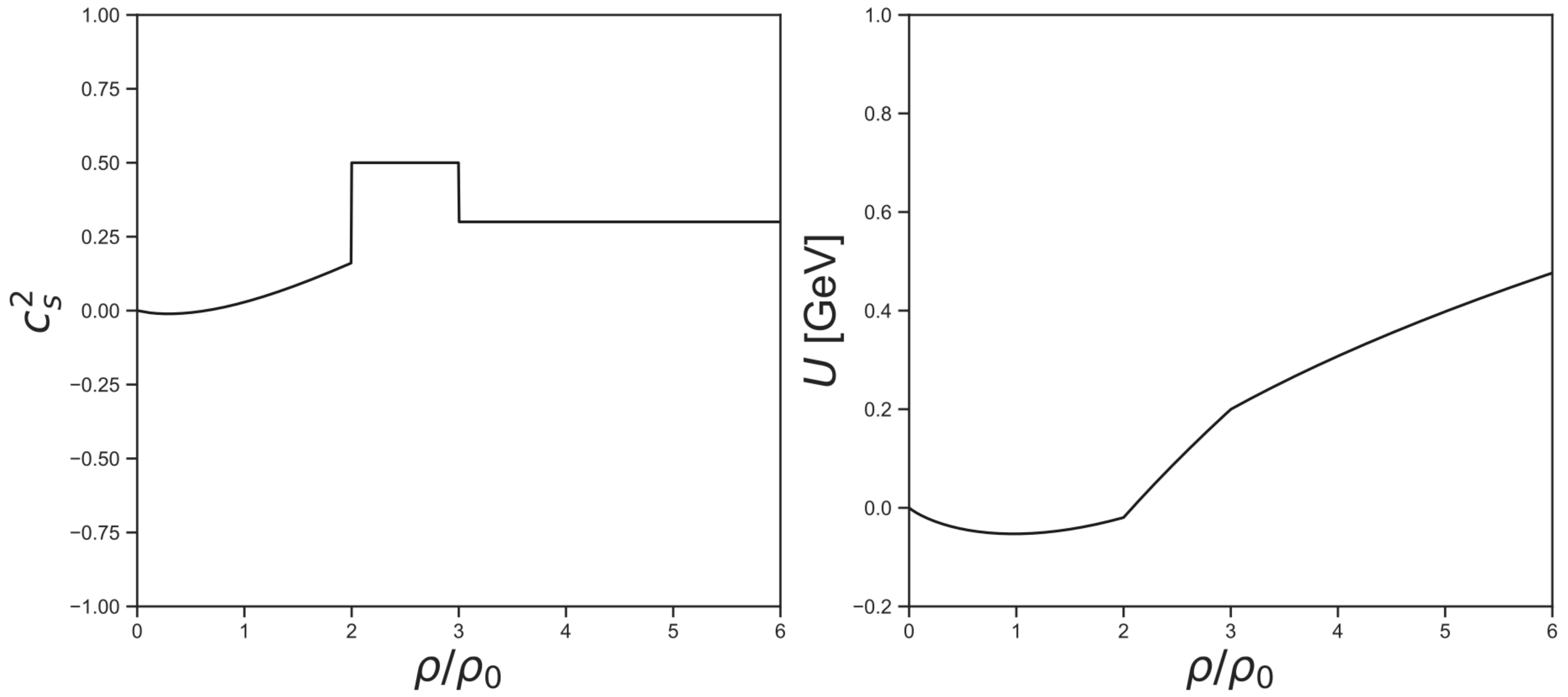


Better suited for Bayesian analyses: piecewise parametrization of c_s^2

Generalized VDF (n_B-dependent interaction coefficients):

Piecewise parametrization of $c_s^2(n_B)$:

$$c_s^2(n_B) = \begin{cases} c_s^2(\text{Skyrme}), & n_B < n_1 = 2n_0 \\ c_1^2, & n_1 < n_B < n_2 \\ c_2^2, & n_2 < n_B < n_3 \\ \ldots \\ c_m^2, & n_m < n_B \end{cases}$$



Single-particle potential $U(n_B) = \alpha(n_B)n_B$:

$$U(n_B) = \begin{cases} U_{\text{Sk}}(n_B)\ , & n_B < n_1 = 2n_0 \\ \left[U_{\text{Sk}}(n_1) + \mu^*(n_1)\right]\left(\frac{n_B}{n_1}\right)^{c_1^2} - \mu^*(n_B)\ , & n_1 < n_B < n_2 \\ \left[U_{\text{Sk}}(n_1) + \mu^*(n_1)\right]\left(\frac{n_B}{n_k}\right)^{c_k^2} \prod_{i=2}^{k}\left(\frac{n_i}{n_{i-1}}\right)^{c_{i-1}^2} - \mu^*(n_B)\ , & n_k < n_B < n_{k+1} \end{cases}$$

D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran,
Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

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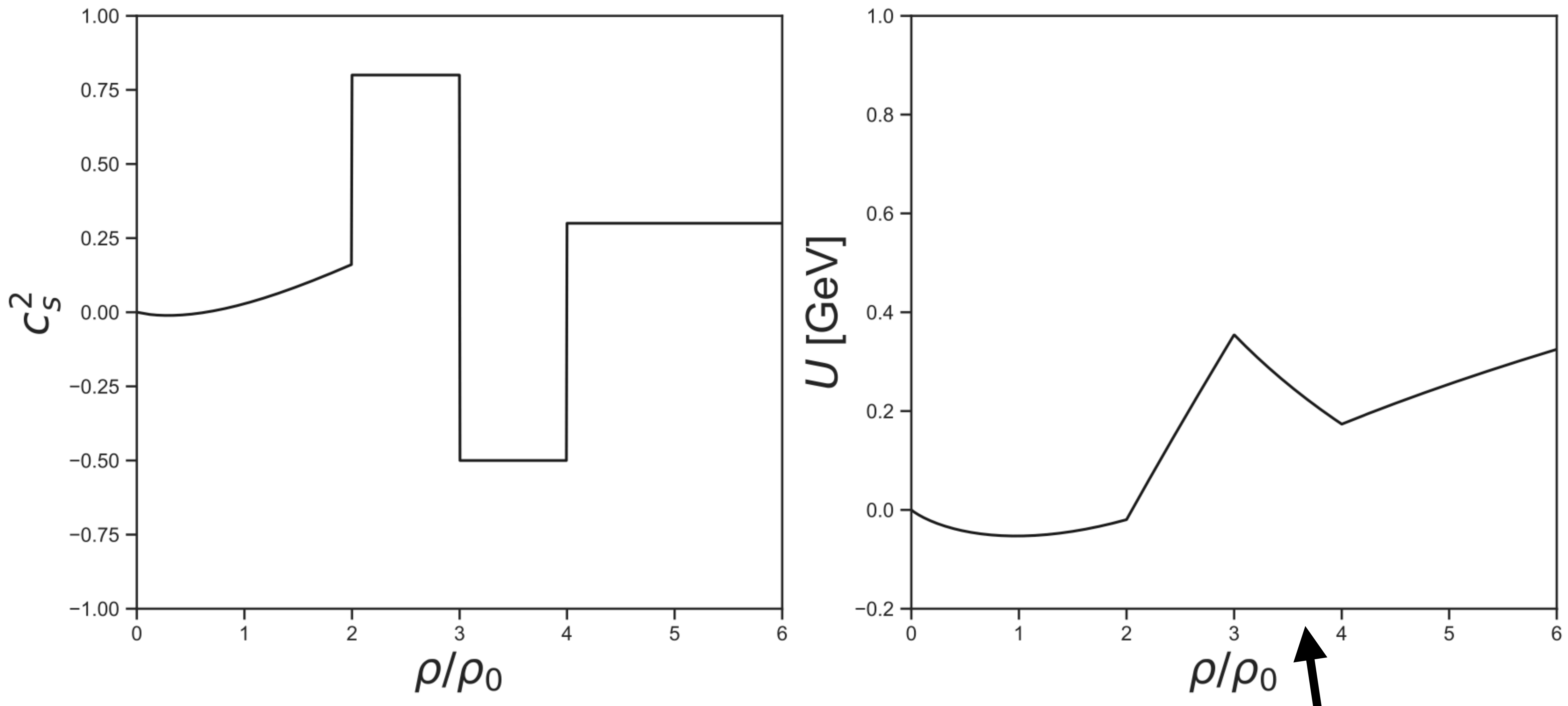

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Gradients of $A^\mu(j_B^\mu) \equiv \alpha(n_B) j_B^\mu$ enter the EOMs!

D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran,
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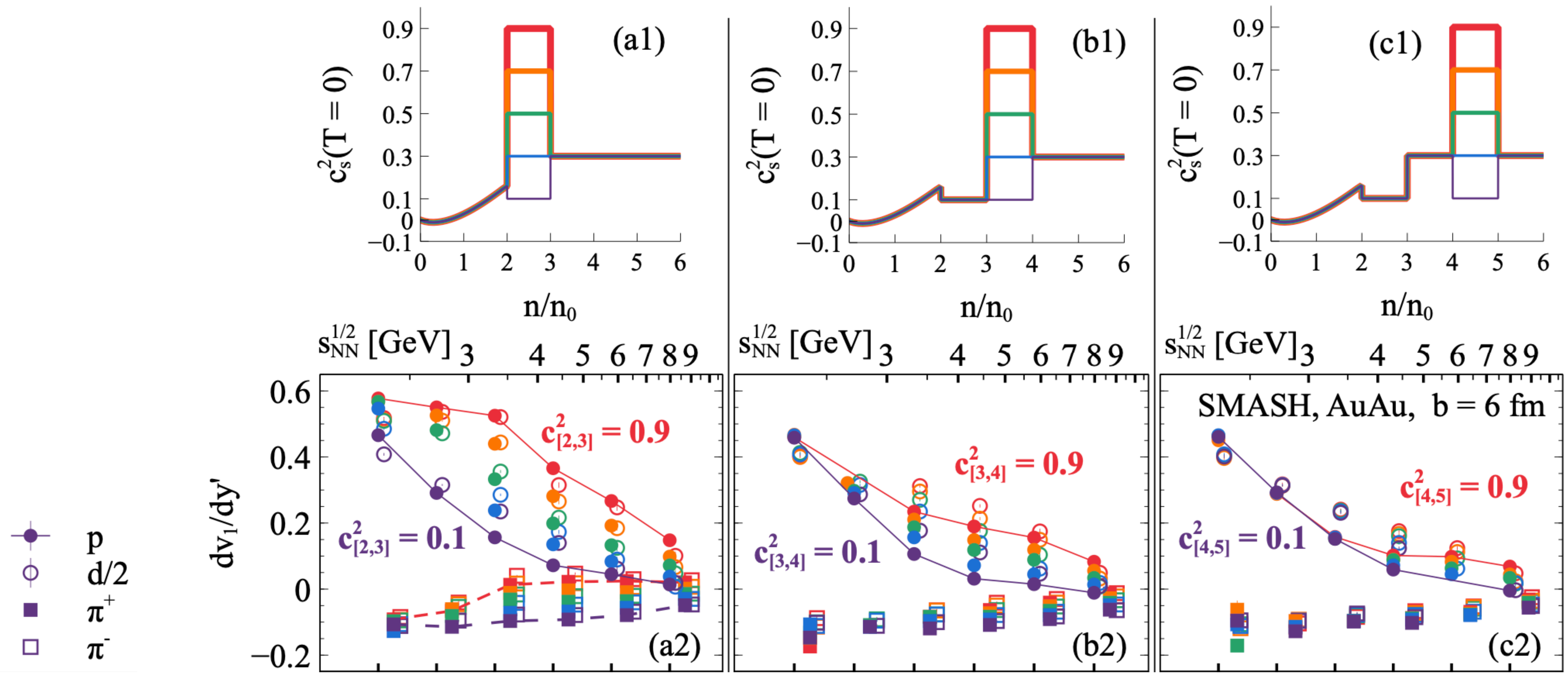
Hadronic transport with c_s^2-parametrized mean-fields

D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

Generalized VDF (n_B-dependent interaction coefficients):

mean-field potential piecewise parametrized by (constant) values of c_s^2 for $n_i < n_B < n_j$



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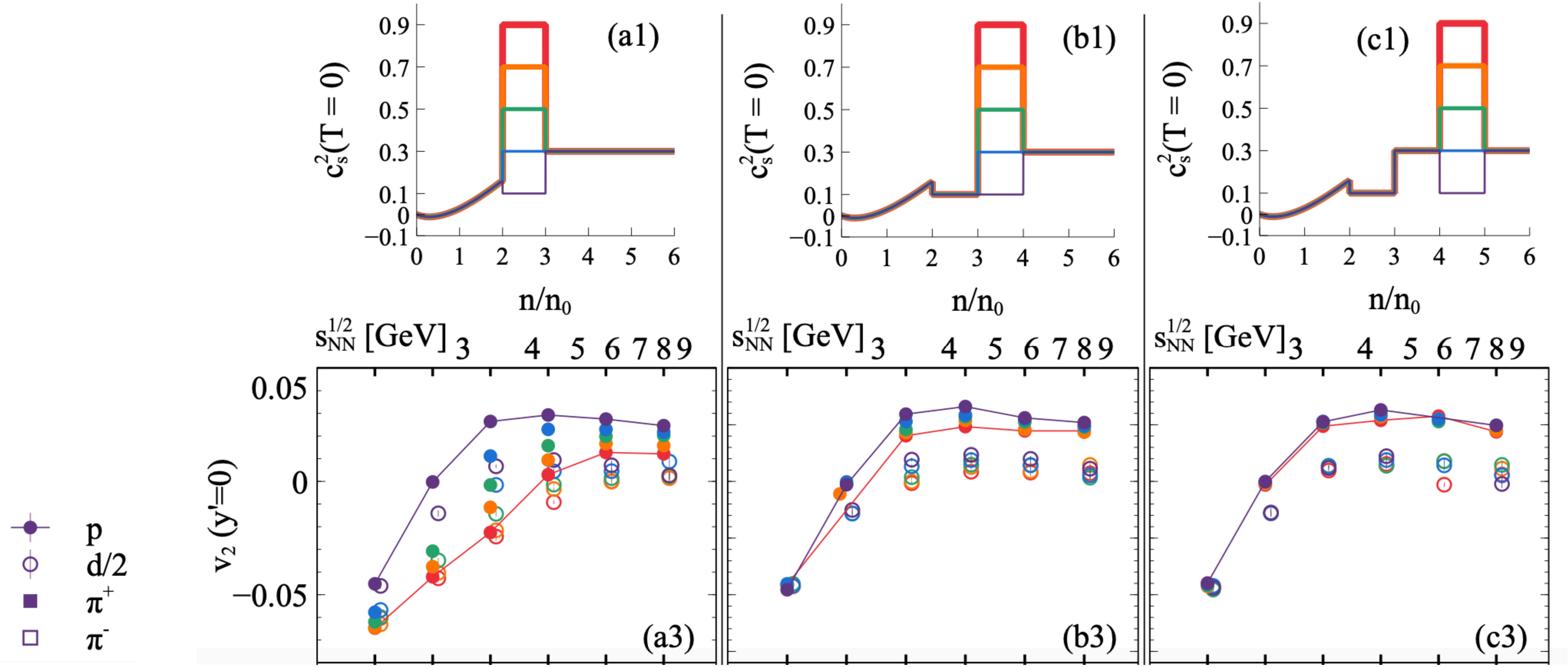
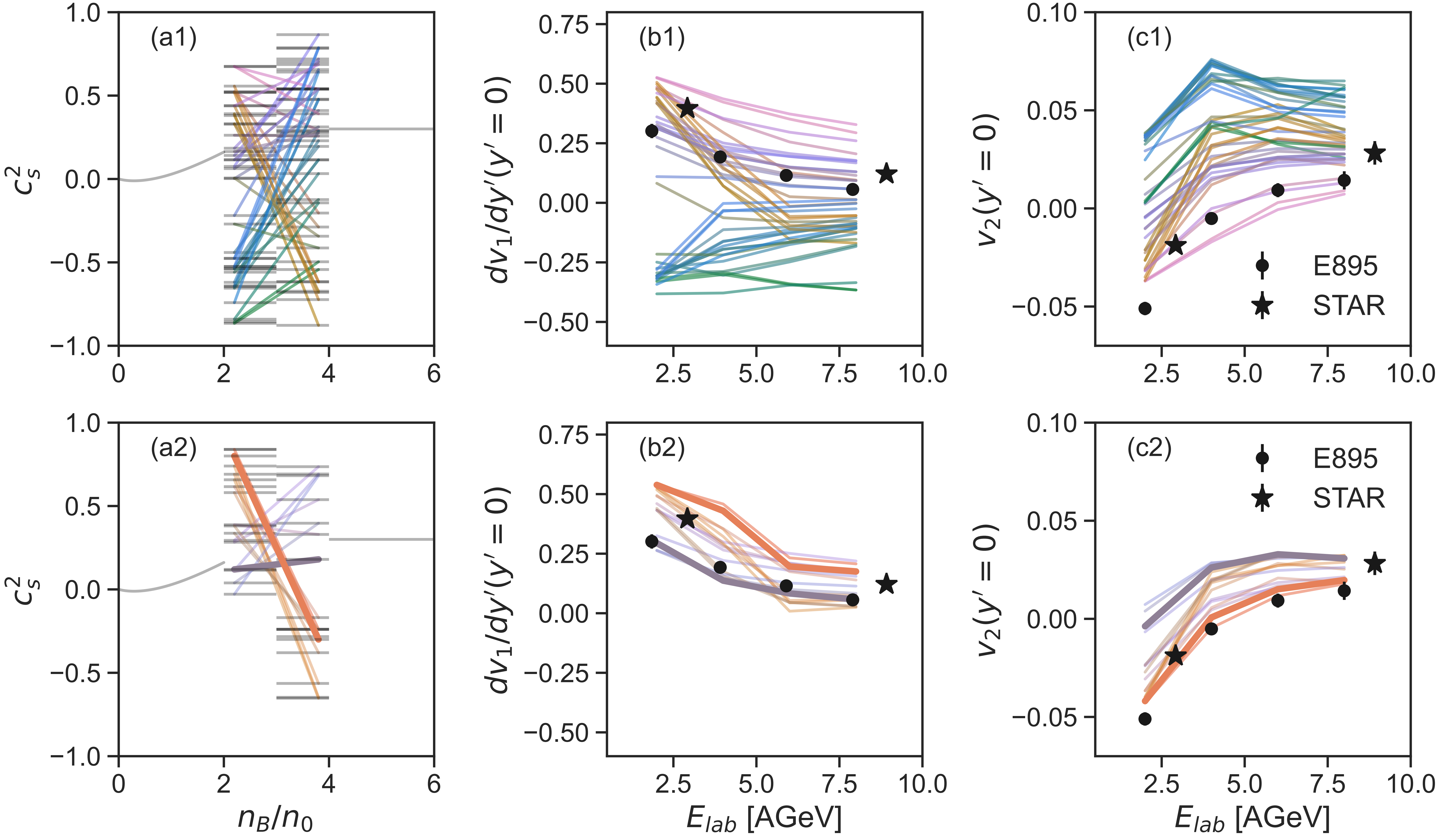
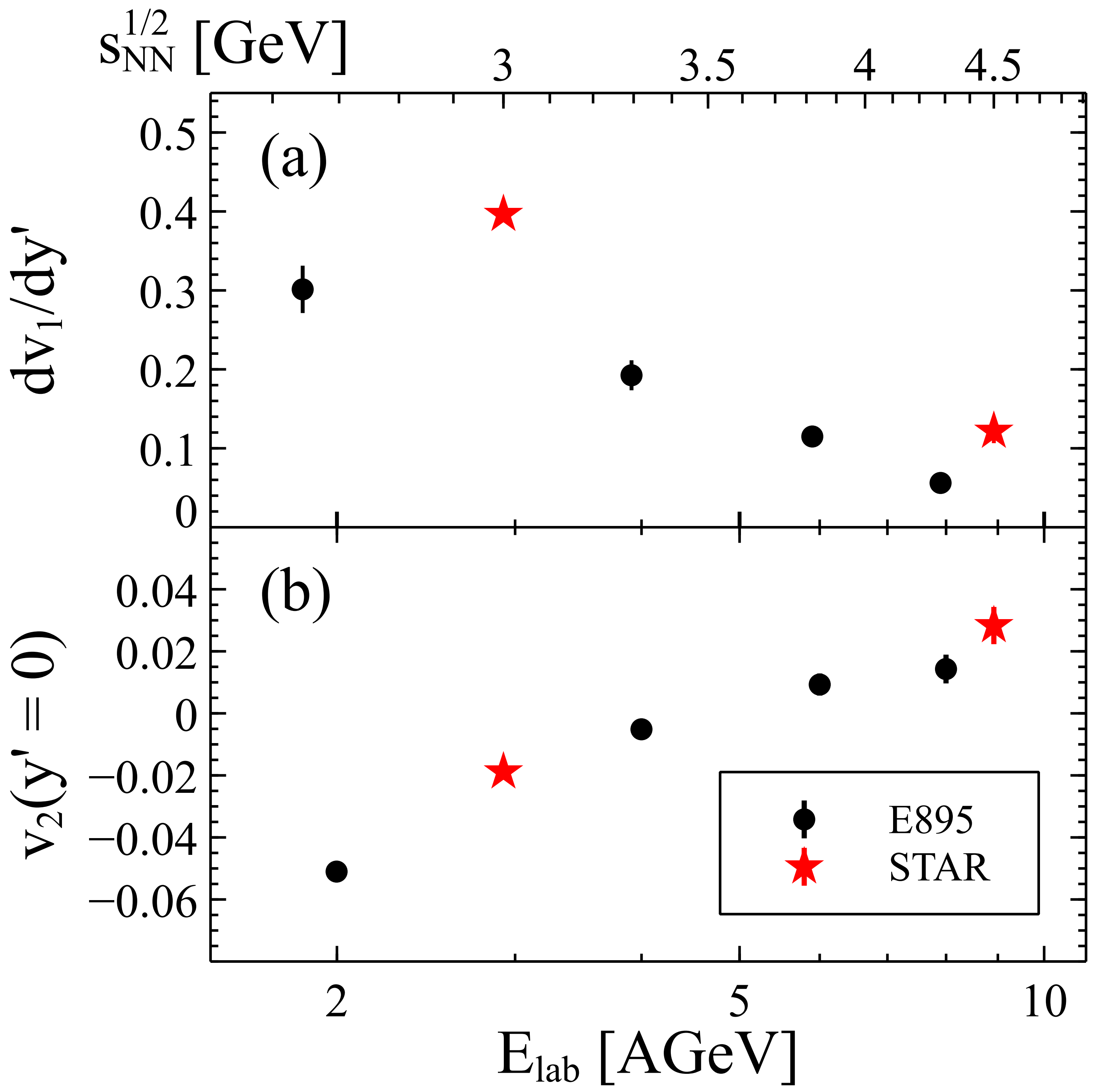


STAR and E895 data cannot be simultaneously described





tension between the data sets

D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran,
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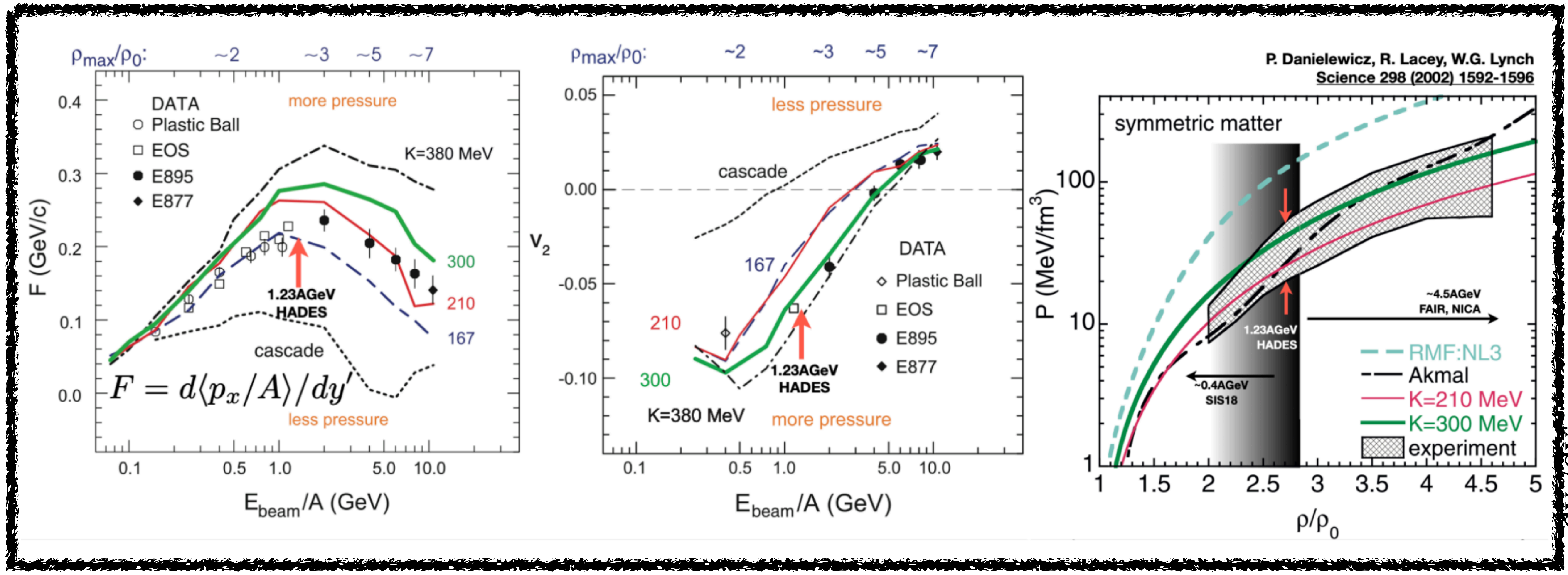
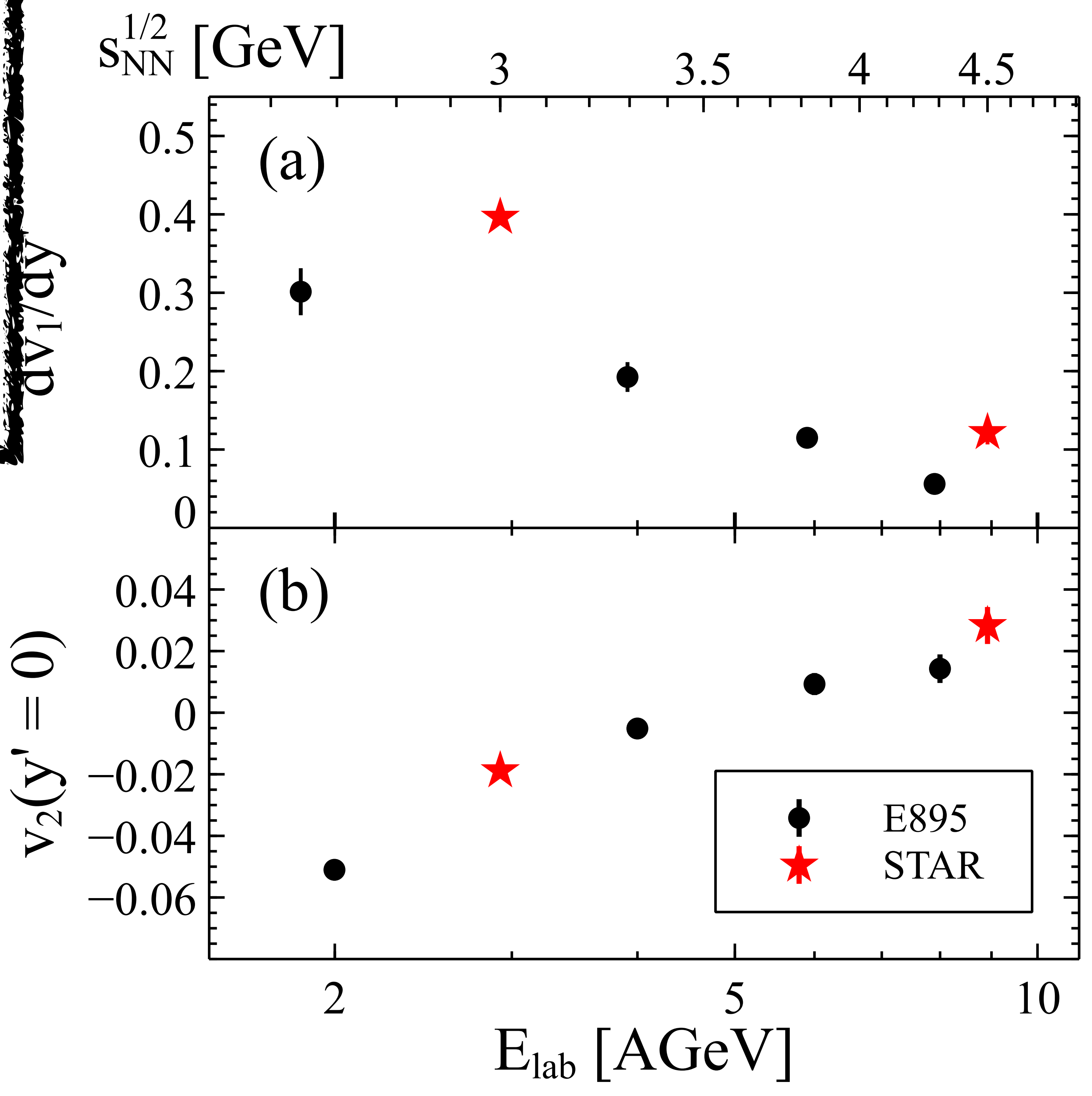
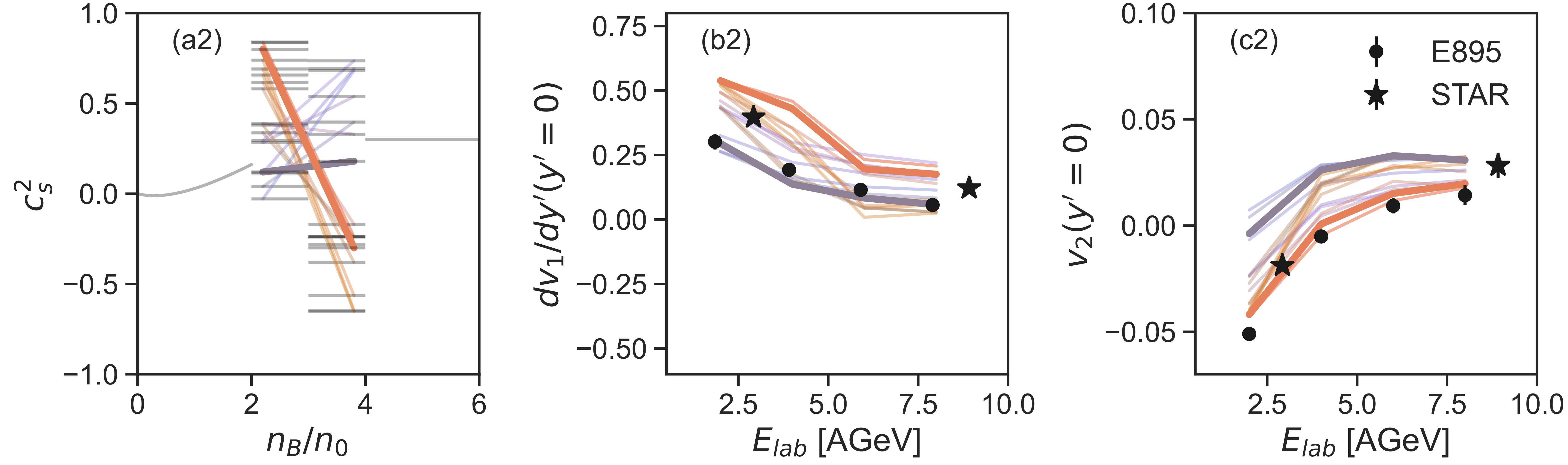


Same problem as in the DLL constraint!

Danielewicz, Lacey, Lynch, Science **298**,1592–1596 (2002)





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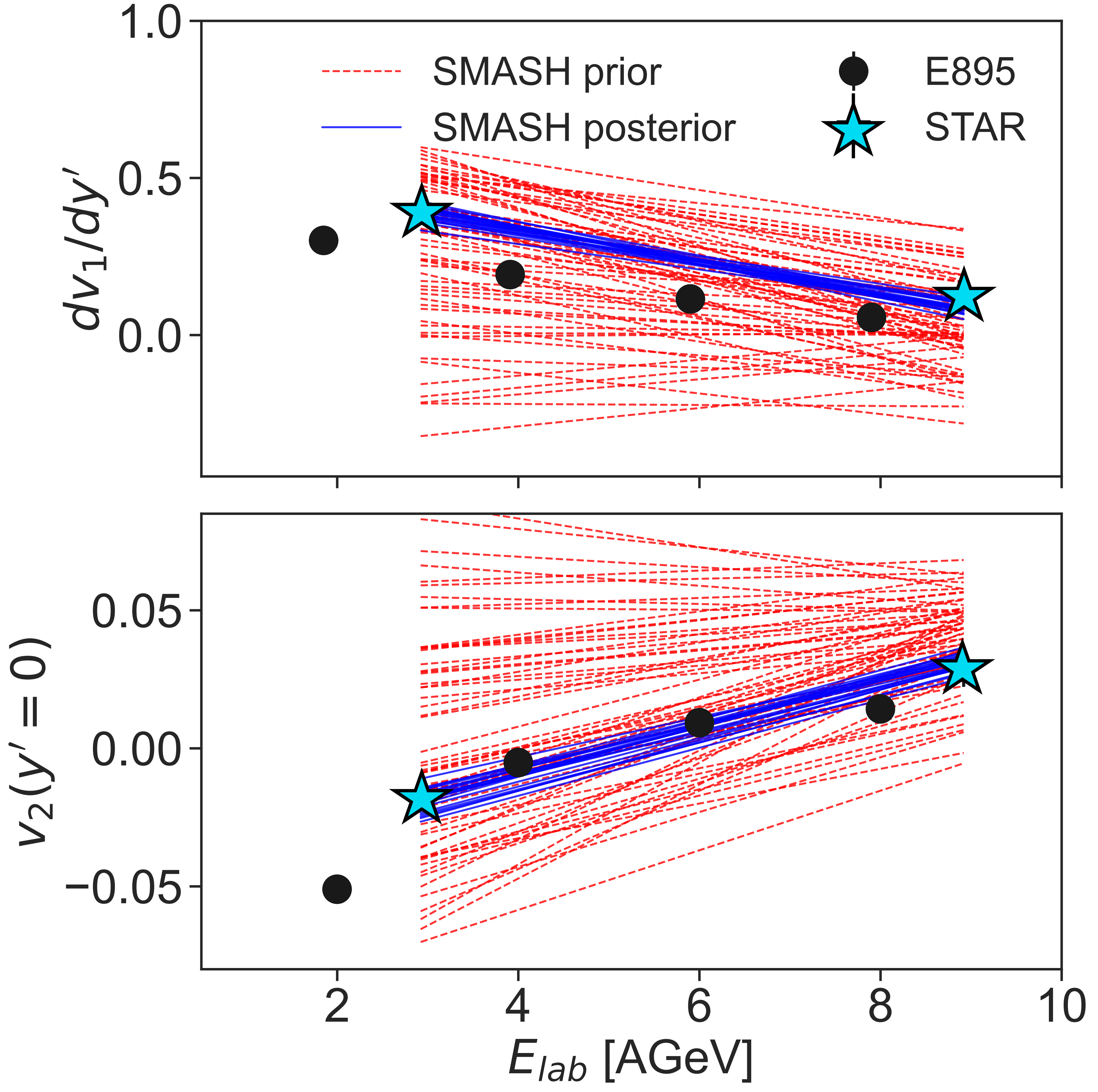
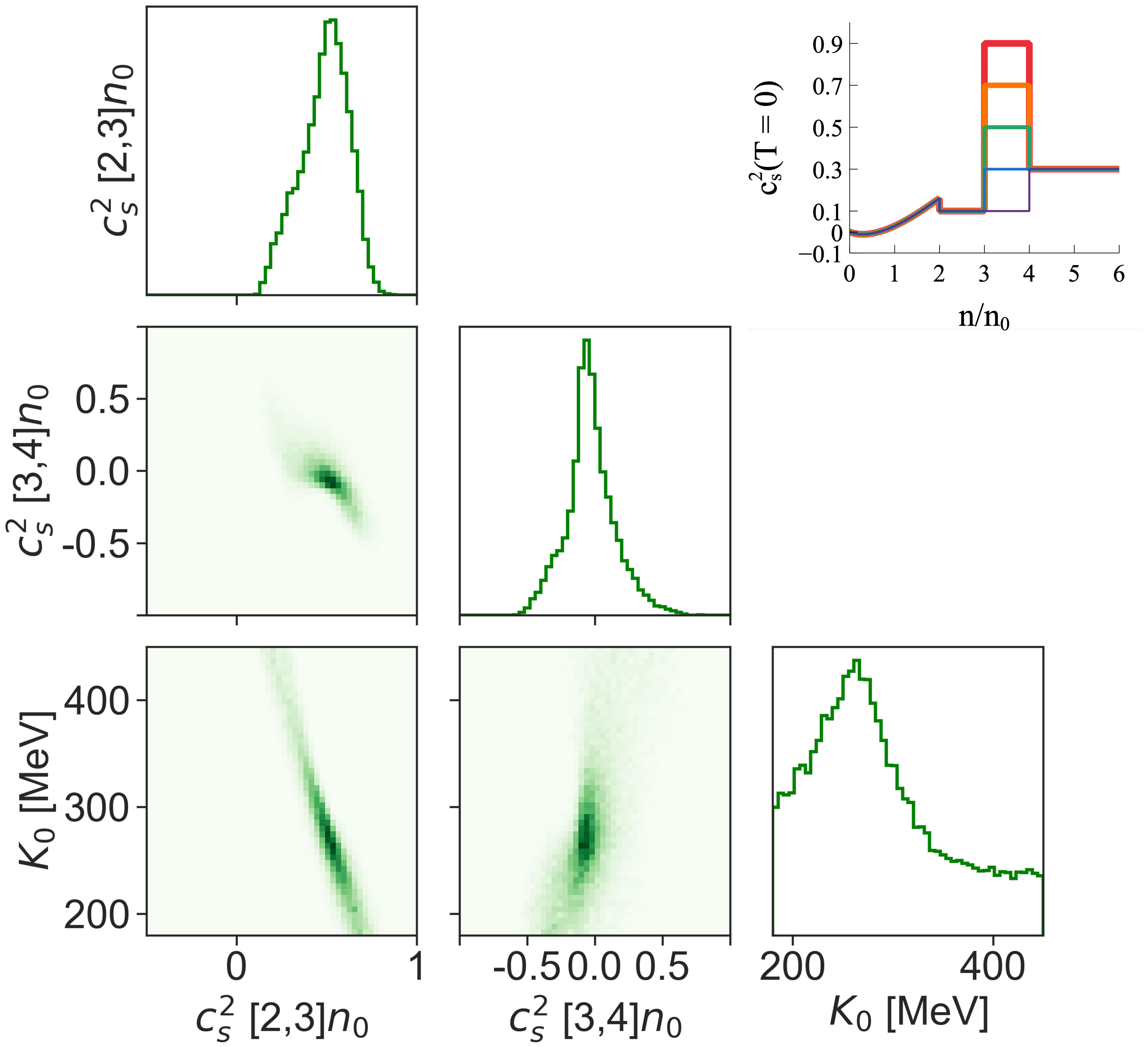
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

Bayesian analysis of STAR flow data with varying K_0, $c^2_{[2,3]n_0}$, $c^2_{[3,4]n_0}$





The maximum a posteriori probability (MAP) parameters are

$K_0 = 285 \pm 67$ MeV, $\quad c^2_{[2,3]n_0} = 0.49 \pm 0.13, \quad c^2_{[3,4]n_0} = -0.03 \pm 0.15$

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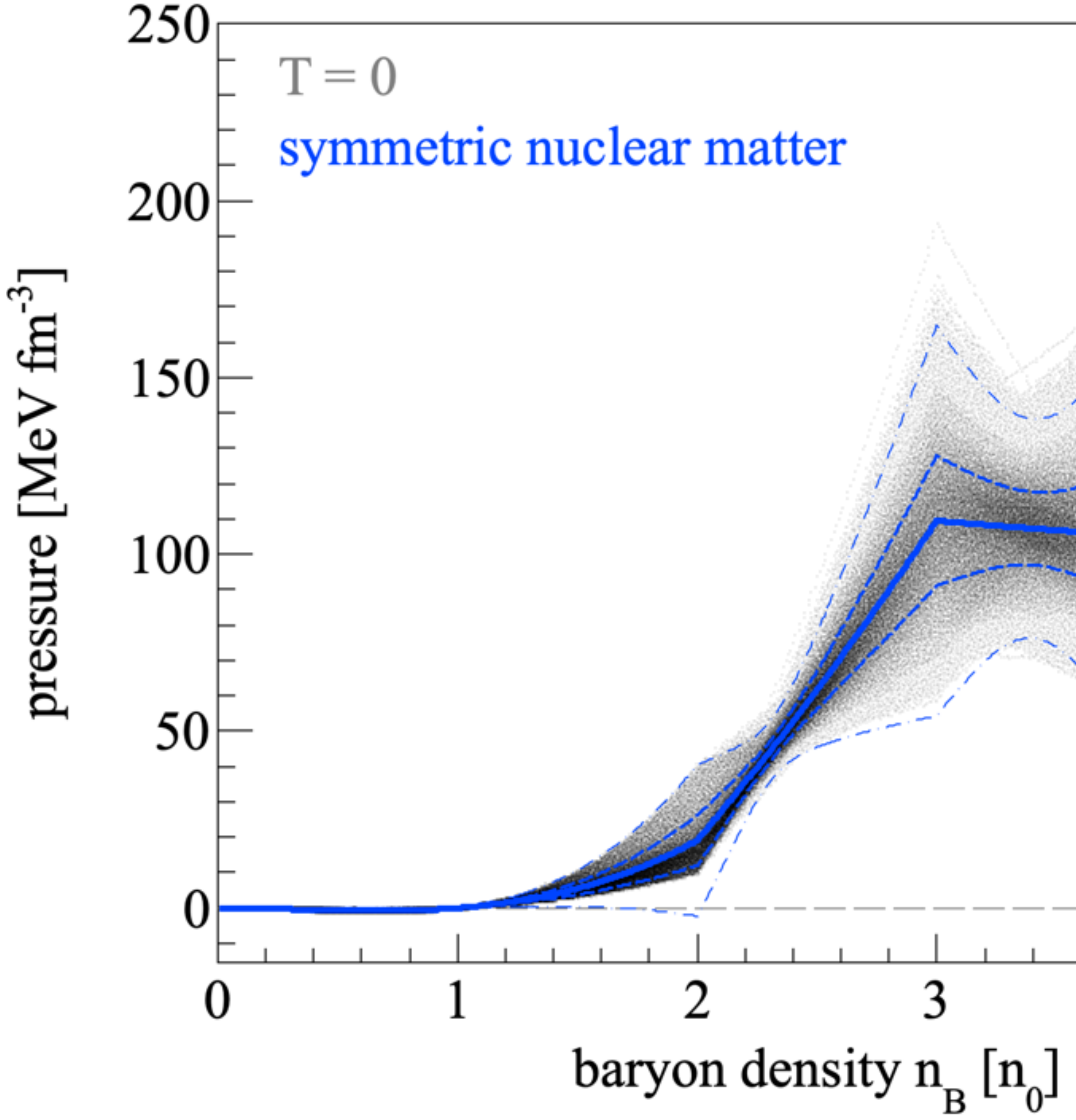
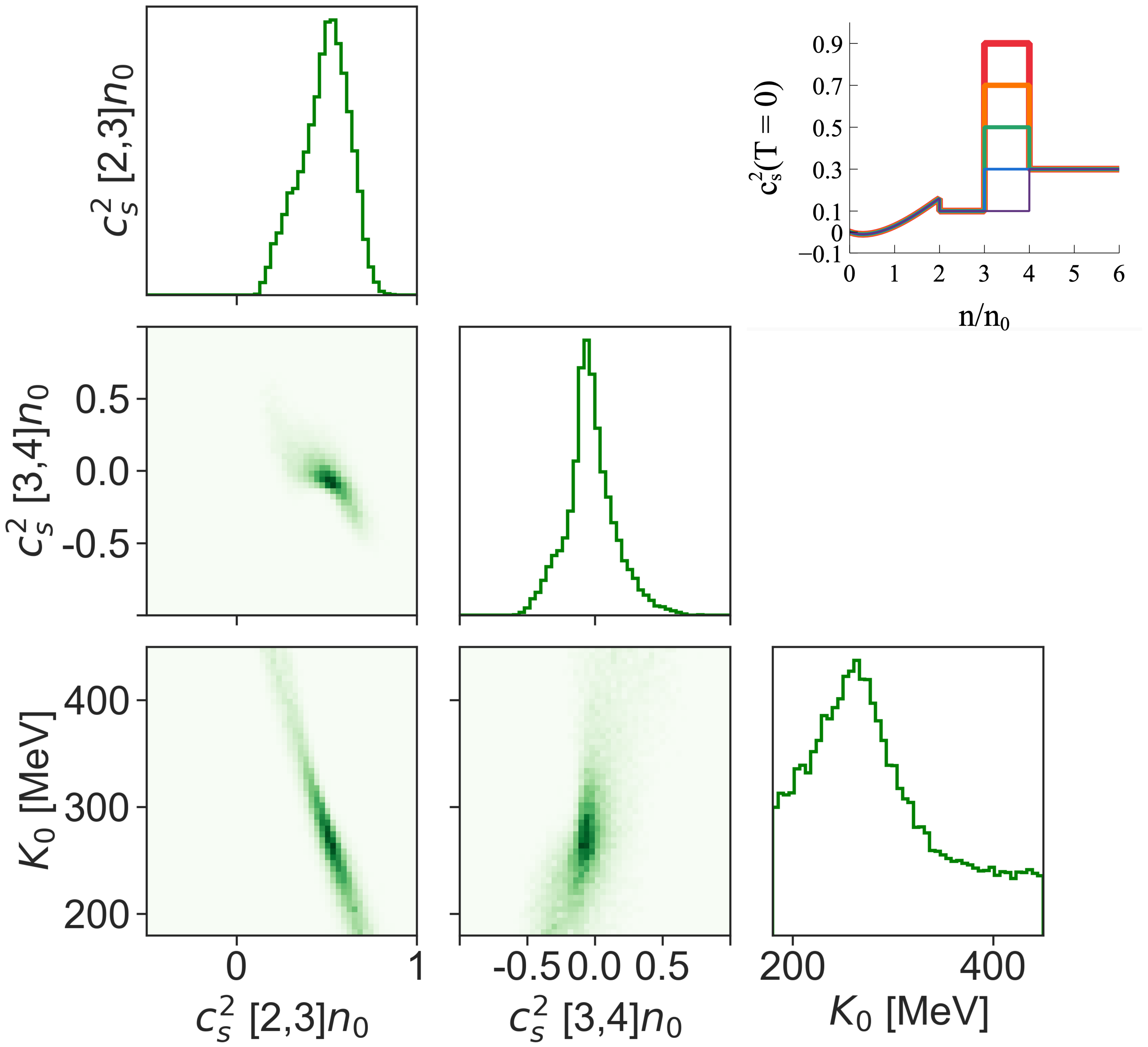
Bayesian analysis of STAR flow data with varying K_0, $c^2_{[2,3]n_0}$, $c^2_{[3,4]n_0}$



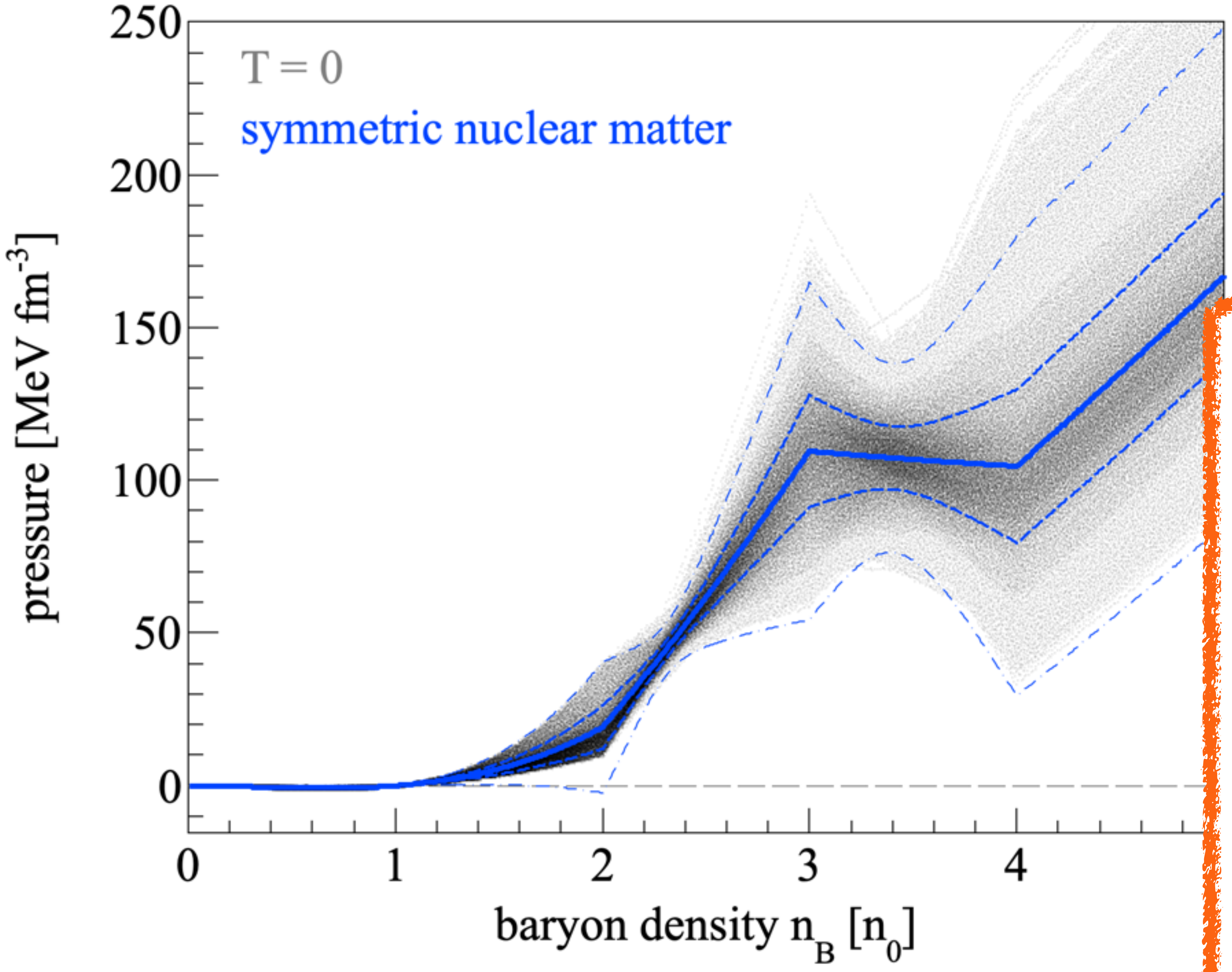


The maximum a posteriori probability (MAP) parameters are

$K_0 = 285 \pm 67$ MeV, $\quad c^2_{[2,3]n_0} = 0.49 \pm 0.13, \quad c^2_{[3,4]n_0} = -0.03 \pm 0.15$

D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

Bayesian analysis of STAR flow data with varying K_0, $c^2_{[2,3]n_0}$, $c^2_{[3,4]n_0}$



The constrained EOS is very stiff at $n_B \in (2,3)n_0$ and very soft at $n_B \in (3,4)n_0$

Taken at face value, results suggest that:

- at $\sqrt{s_{\mathrm{NN}}} = 4.5$ GeV, collisions probe QGP
- at $\sqrt{s_{\mathrm{NN}}} = 3.0$ GeV, *some* QGP probed?
- *therefore*, using EOSs parametrized only by K_0 (like the canonical Skyrme EOSs which do not have a nontrivial high-density behavior) is **NOT ENOUGH** to describe this region

The maximum a posteriori probability (MAP) parameters are

$K_0 = 285 \pm 67$ MeV, $\quad c^2_{[2,3]n_0} = 0.49 \pm 0.13, \quad c^2_{[3,4]n_0} = -0.03 \pm 0.15$

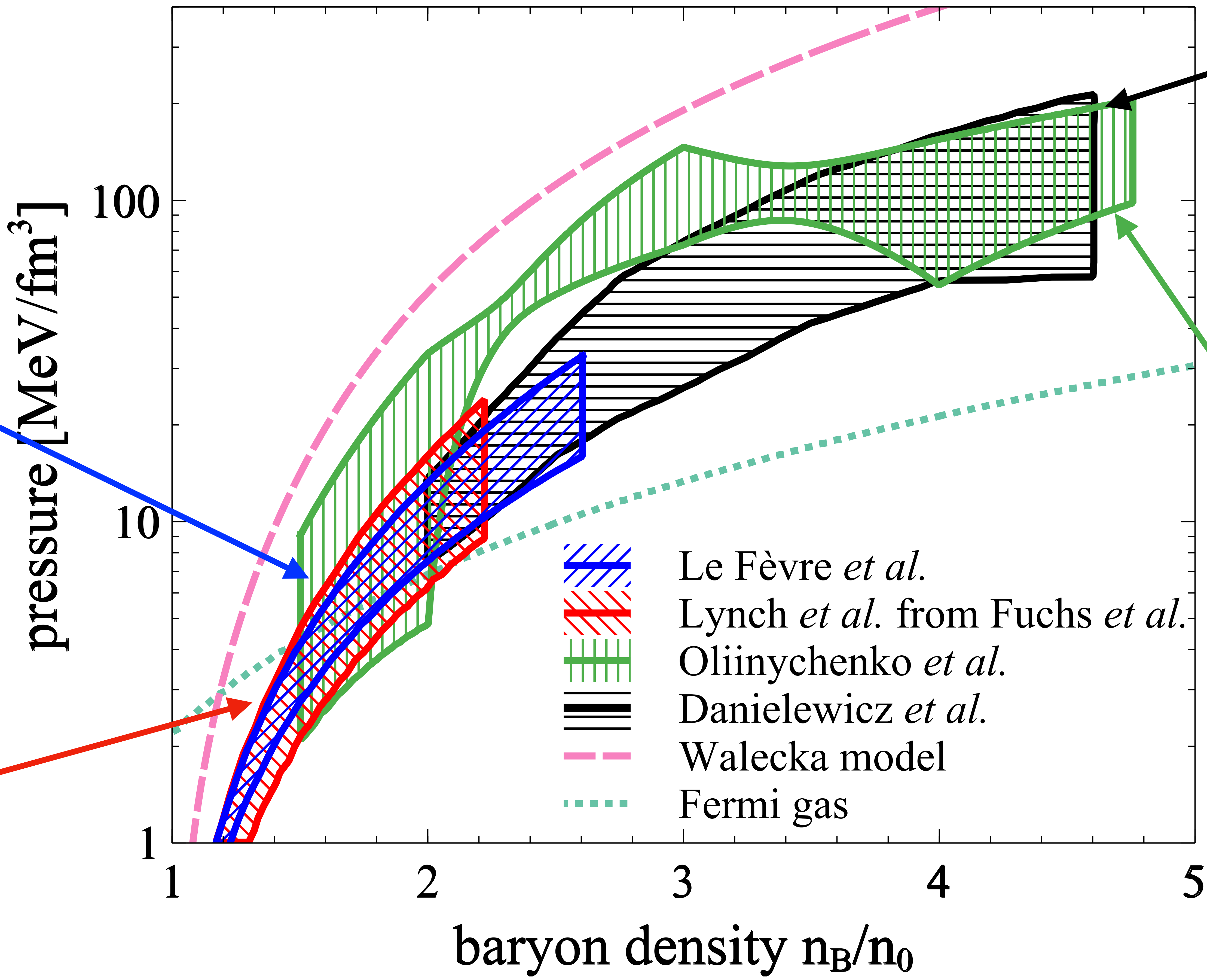
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

EOS of symmetric nuclear matter: selected (*few*) results

Symmetric nuclear matter

197Au+197Au @ 0.4—1.5 GeV/u
($\sqrt{s_{NN}}$ = 2.07 — 2.52 GeV)
observables: proton flow (FOPI)
model used: isospin QMD (IQMD) w/ nucleons, Δ, N*(1440), deuterons, tritons;
EOS parametrized by K_0;
momentum dependence
A. Le Fèvre, Y. Leifels, W. Reisdorf, J. Aichelin, C. Hartnack, Nucl. Phys. A 945, 112 (2016), arXiv:1501.05246

197Au+197Au & 12C+12C @ < 1.5 GeV/u
($\sqrt{s_{NN}}$ < 2.5 GeV)
observables: subthreshold kaon production (KaoS)
model used: QMD w/ nucleons, Δ, N*(1440), pions, kaons;
EOS parametrized by K_0;
kaon potentials, momentum dependence
C. Fuchs *et al.*, Prog. Part. Nucl. Phys. **53**, 113–124 (2004) arXiv:nucl-th/0312052



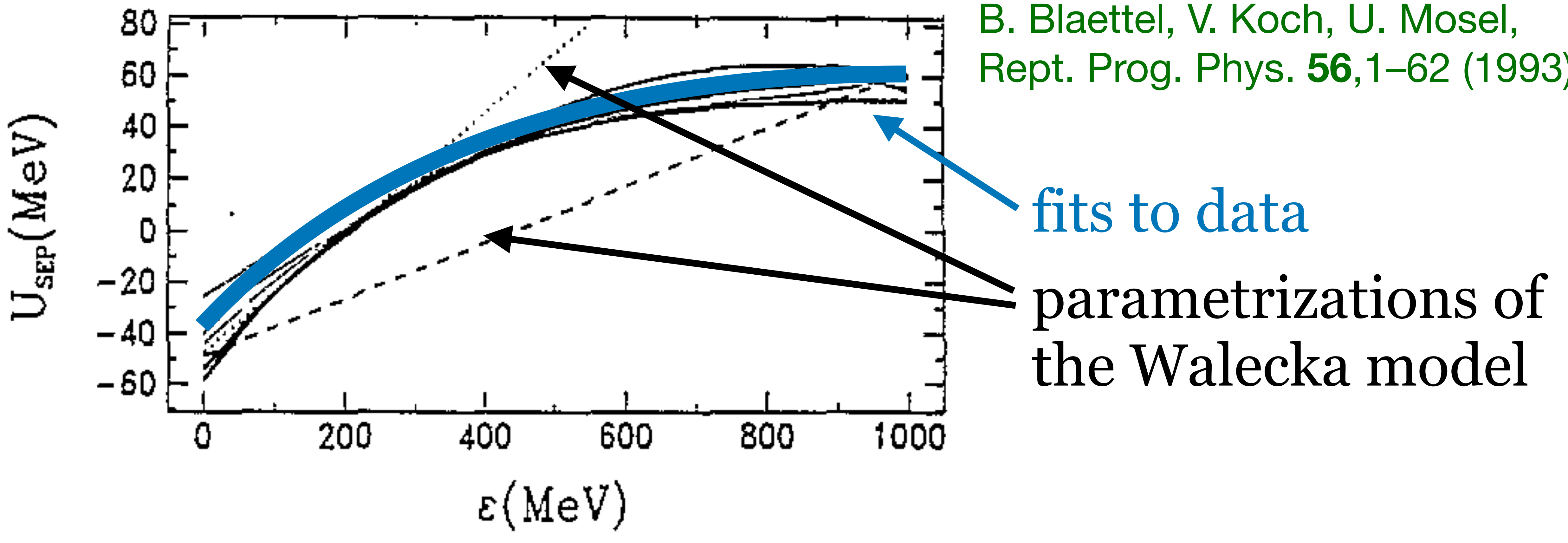
A. Sorensen *et al.*, arXiv:2301.13253
to appear in JPPNP

197Au+197Au @ 0.15—10 GeV/u
($\sqrt{s_{NN}}$ = 1.95 — 4.72 GeV)
observables: proton flow
(Plastic Ball, EOS, E877, E895)
model used: pBUU w/ nucleons, Δ, N*(1440), pions;
EOS parametrized by K_0;
momentum dependence
P. Danielewicz, R. Lacey, W. G. Lynch, Science **298**,1592–1596 (2002)

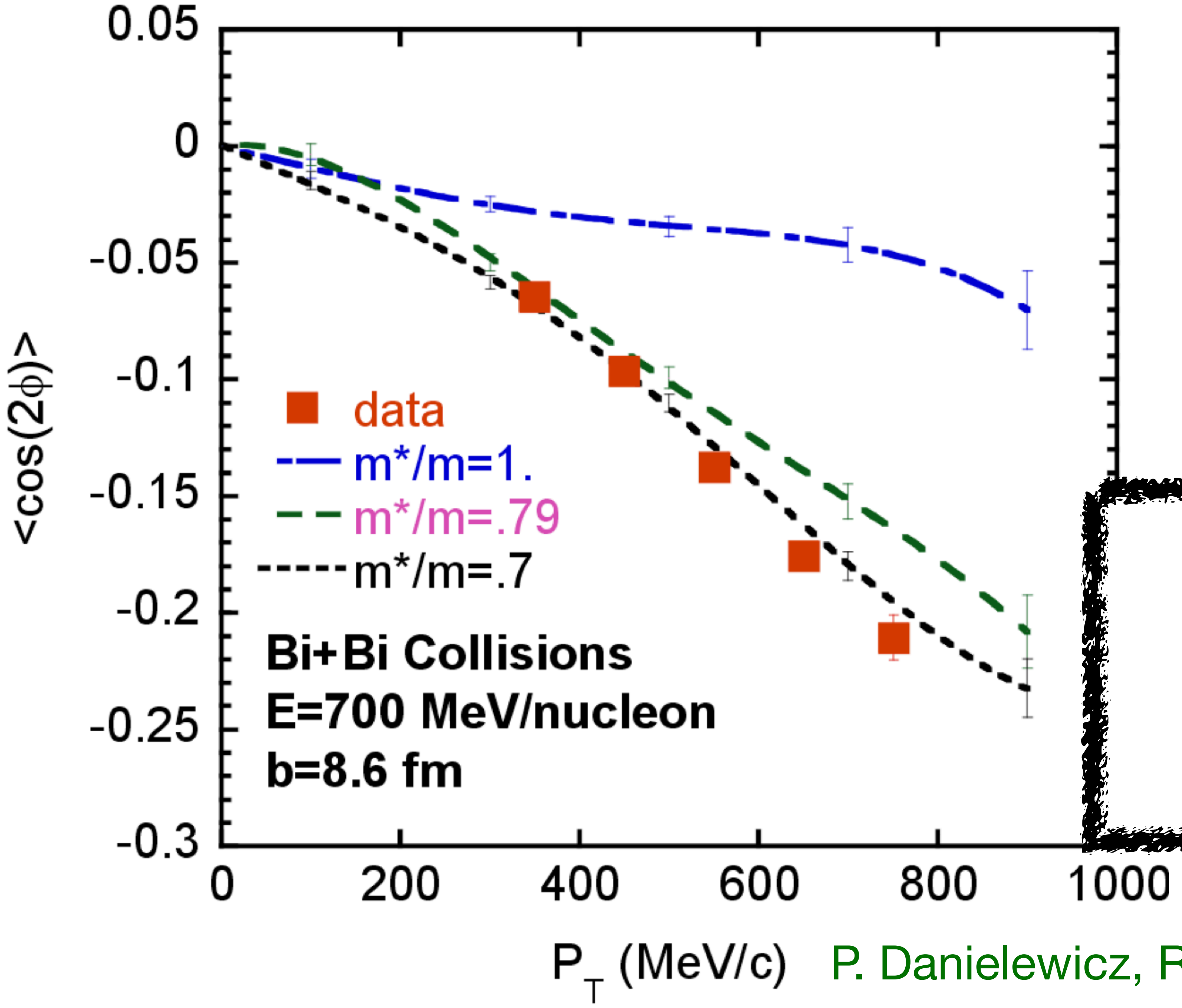
197Au+197Au @ 2.9—9 GeV/u
($\sqrt{s_{NN}}$ = 3 — 4.5 GeV)
observables: proton flow (STAR)
model used: SMASH w/ over 120 hadronic species, including deuterons;
relativistic EOS parametrized independently in different density regions;
NO momentum dependence
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

Momentum-dependent mean-fields are a necessary component

Measured in scattering experiments:

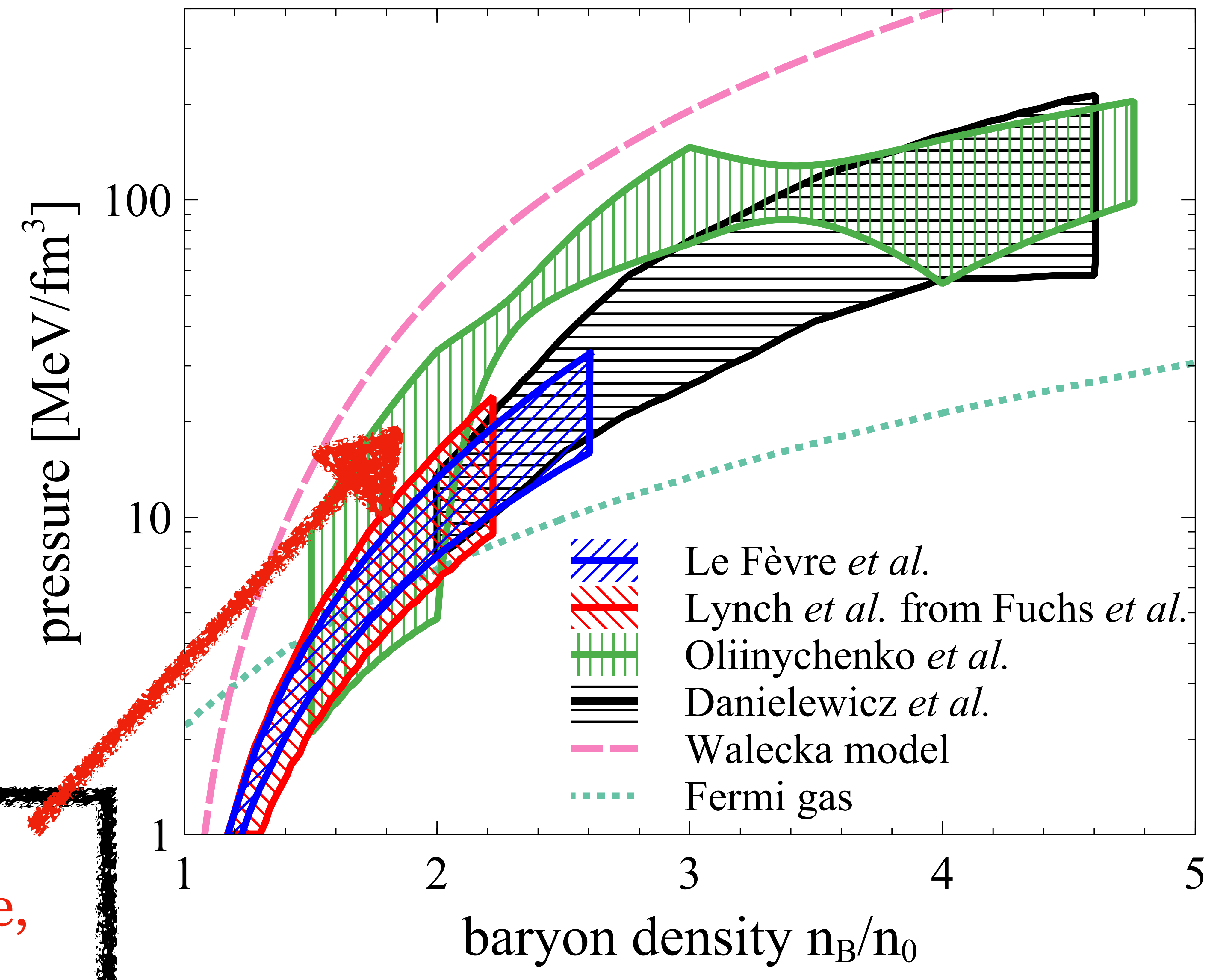


B. Blaettel, V. Koch, U. Mosel, Rept. Prog. Phys. **56**,1–62 (1993)



Affects the p_T-dependence of the elliptic flow

Without momentum dependence, the extracted EOS is too stiff!

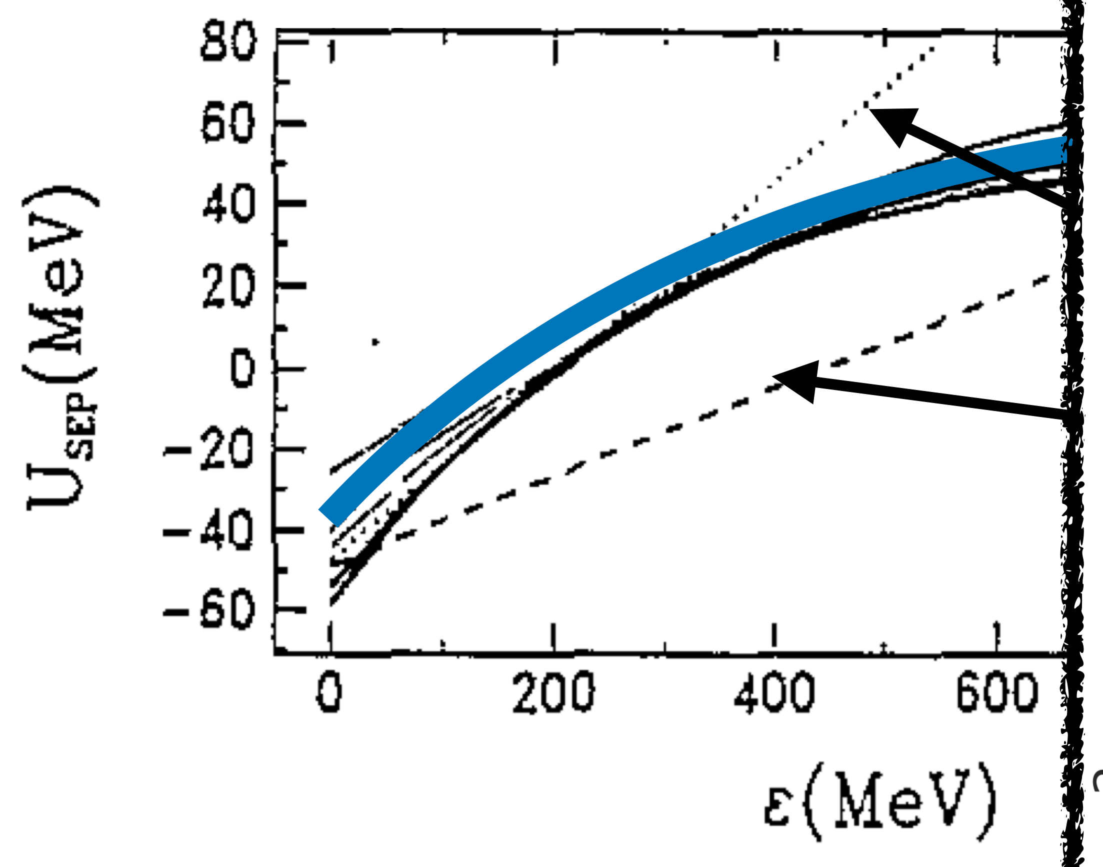


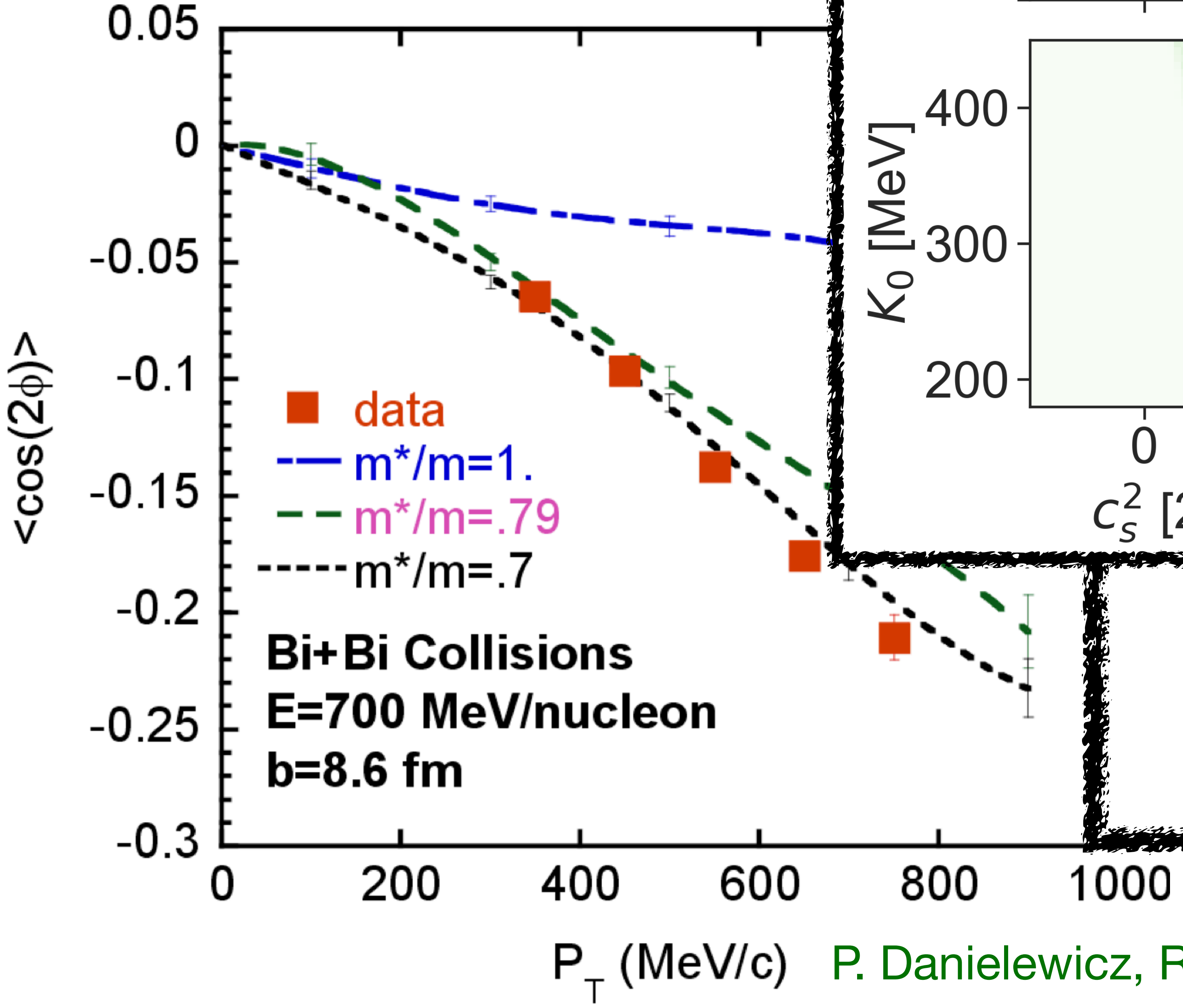
A. Sorensen *et al.*, arXiv:2301.13253 to appear in JPPNP

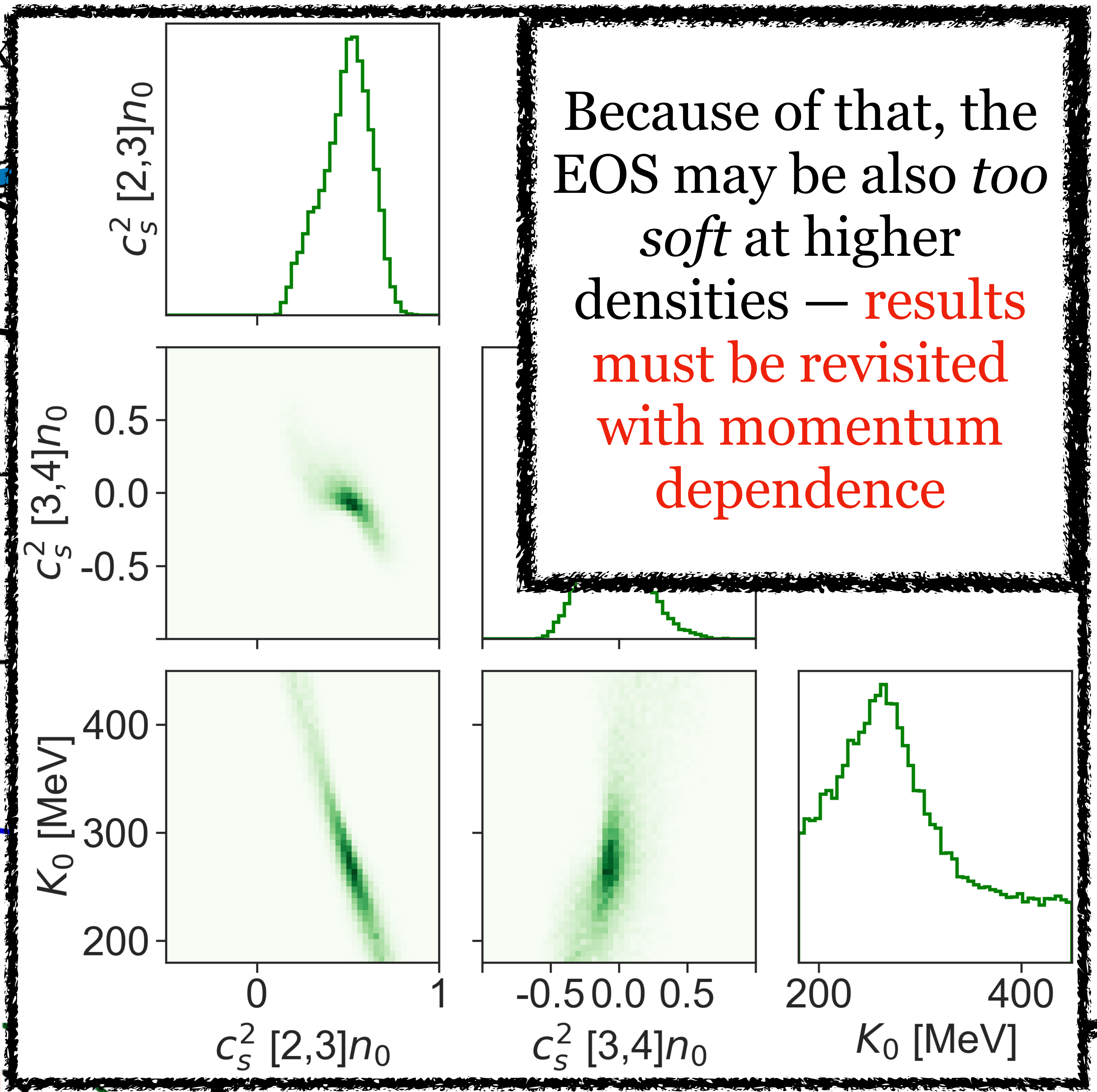
P. Danielewicz, R. Lacey, and W. G. Lynch, Science **298**, 1592 (2002), arXiv:nucl-th/0208016

Momentum-dependent mean-fields are a necessary component

Measured in scattering ex

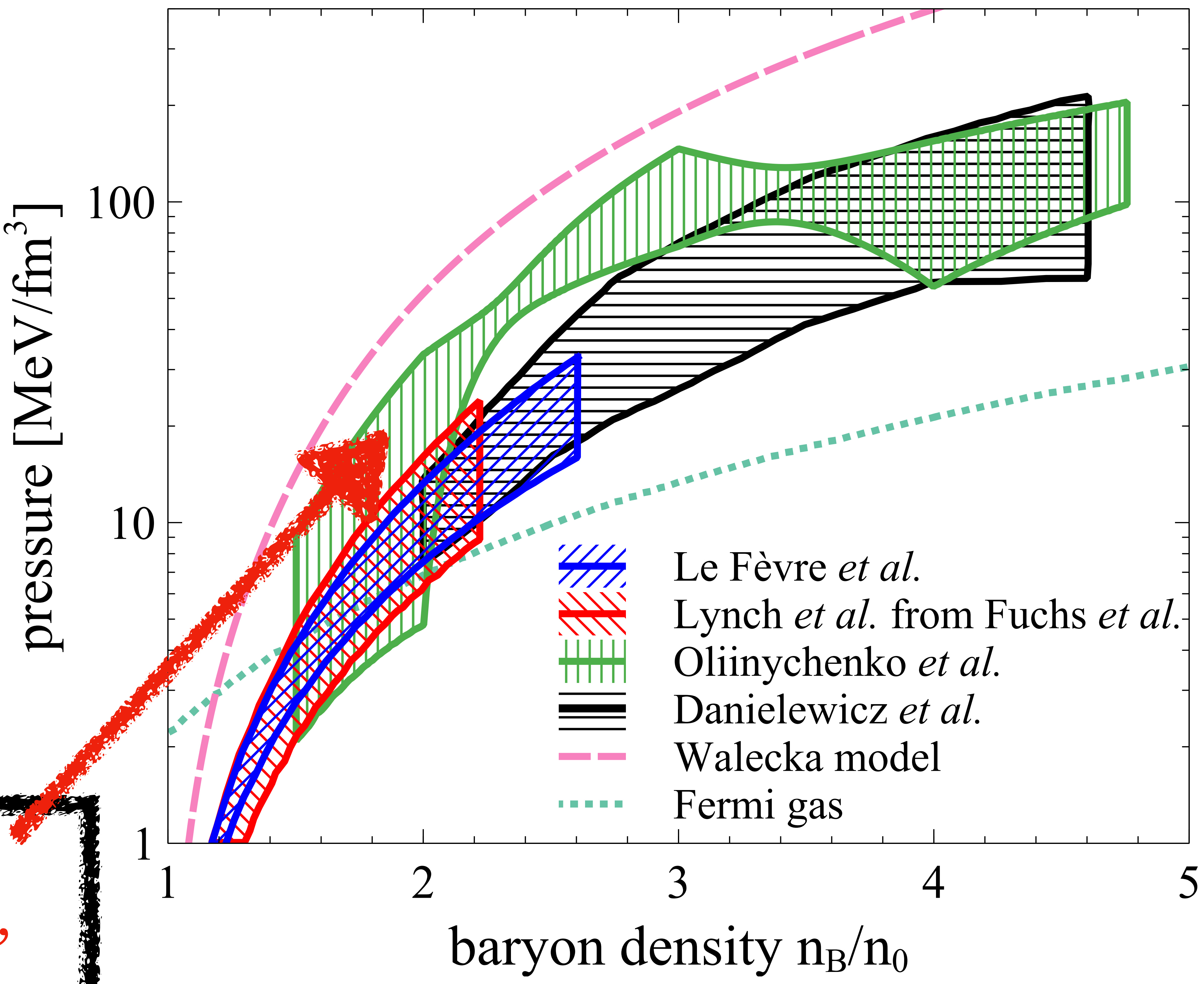






Because of that, the EOS may be also *too soft* at higher densities — results must be revisited with momentum dependence

Without momentum dependence, the extracted EOS is too stiff!

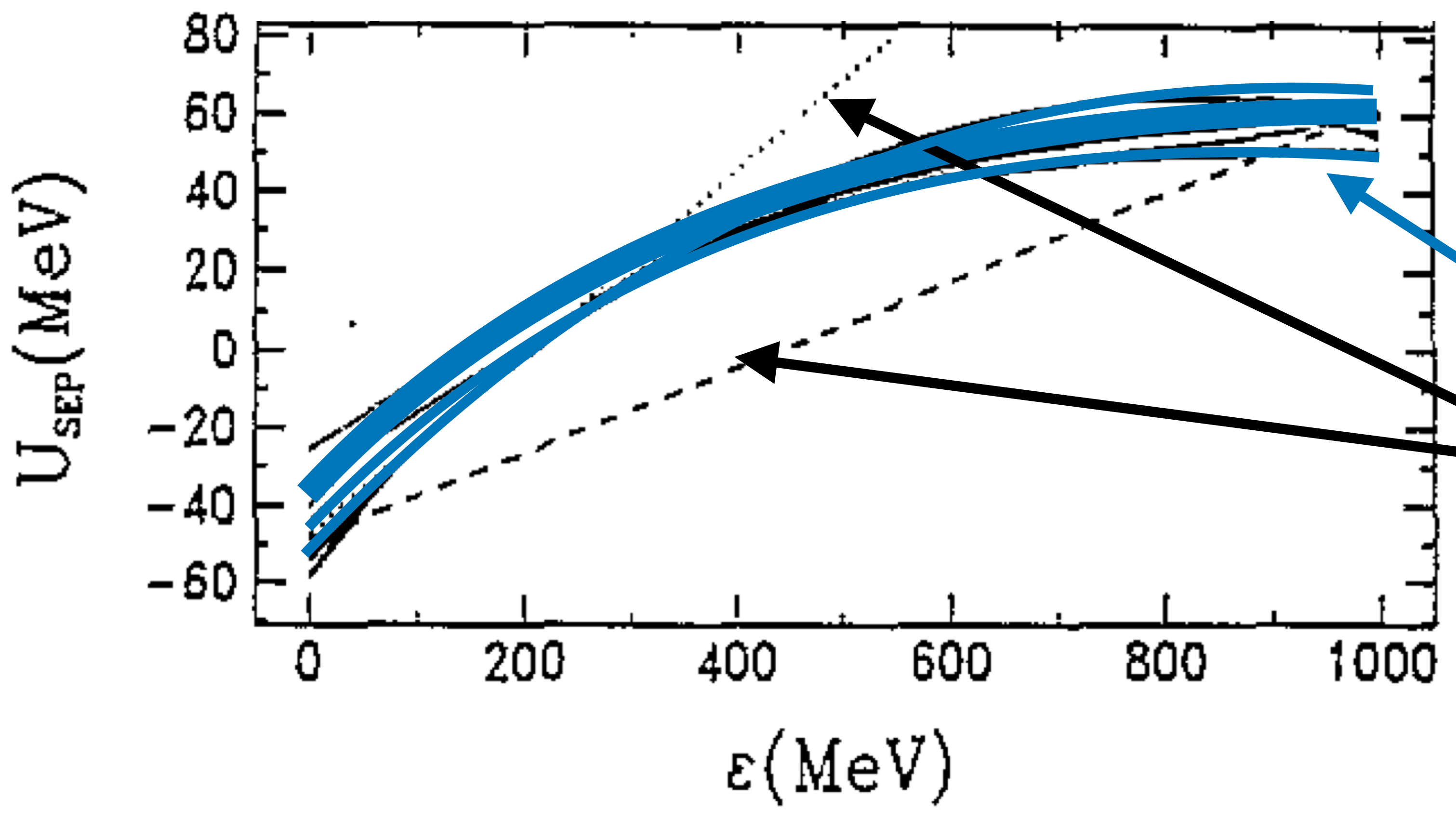


A. Sorensen *et al.*, arXiv:2301.13253 to appear in JPPNP

P. Danielewicz, R. Lacey, and W. G. Lynch, Science **298**, 1592 (2002), arXiv:nucl-th/0208016

Work in progress: Flexible momentum-dependent mean-fields

Measured in scattering experiments:



B. Blaettel, V. Koch, U. Mosel, Rept. Prog. Phys. **56**,1–62 (1993)

Solution:
vector+scalar density functional model (VSDF)

Challenge: scalar fields are costly to compute

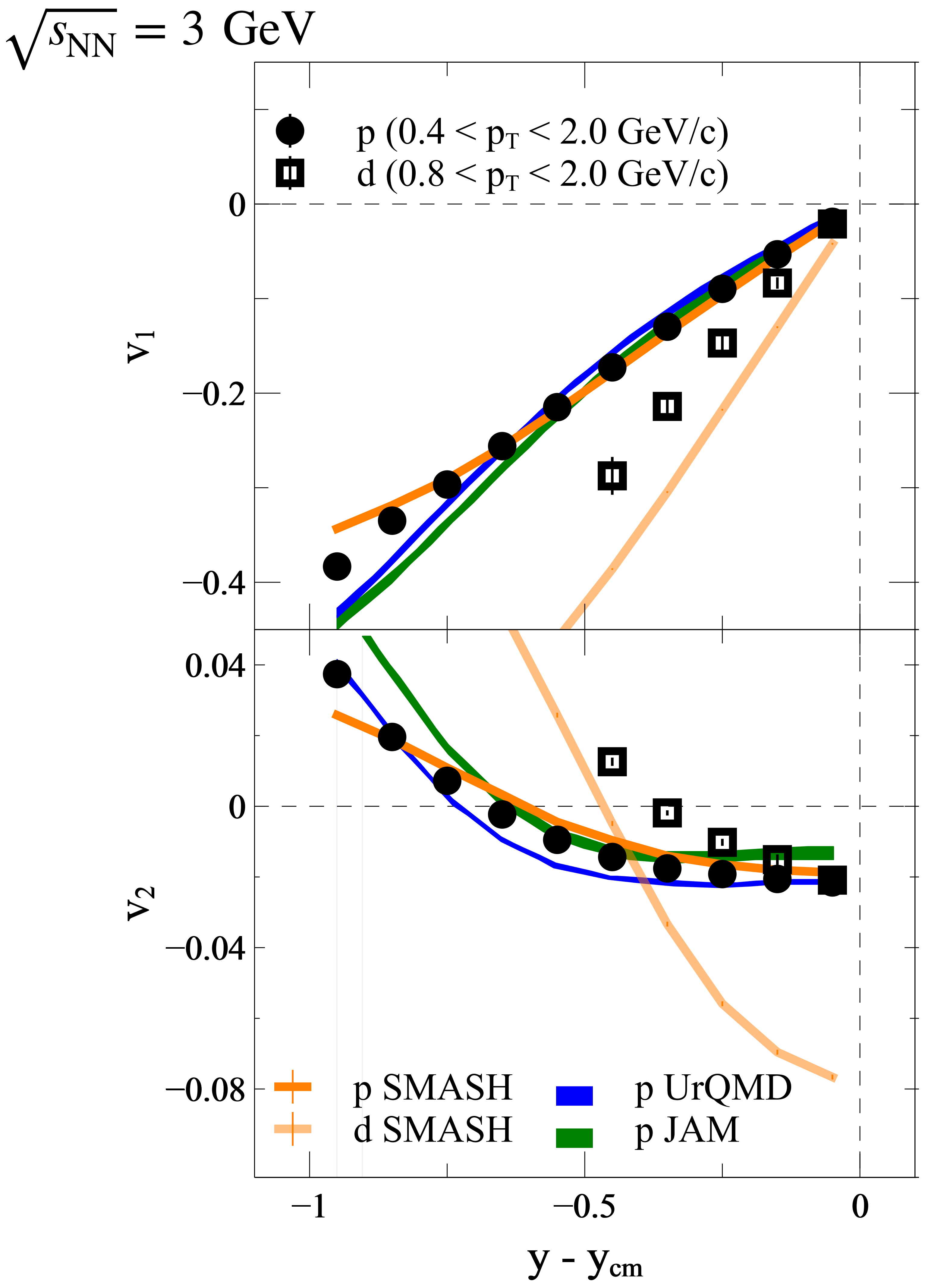
VDF model:
$$\mathcal{E}_N = g\int \frac{d^3p}{(2\pi)^3}\,\epsilon_{\text{kin}}\,f_{\mathbf{p}} + \sum_{i=1}^{N} A_k^0 j_0 - g^{00}\sum_{i=1}^{N}\left(\frac{b_i-1}{b_i}\right)A_k^\lambda j_\lambda \qquad A_k^\mu = C_k\left(j_\lambda j^\lambda\right)^{\frac{b_k}{2}-1} j^\mu$$

VSDF model:
$$\mathcal{E}_{N,\,M} = g\int \frac{d^3p}{(2\pi)^3}\,\epsilon^*_{\text{kin}}\,f_{\mathbf{p}} + \sum_{i=1}^{N} A_k^0 j_0 - g^{00}\sum_{i=1}^{N}\left(\frac{b_i-1}{b_i}\right)A_k^\lambda j_\lambda + g^{00}\sum_{m=1}^{M} G_m\left(\frac{d_m-1}{d_m}\right)n_s^{d_m}$$

$$m^* = m_0 - \sum_{m=1}^{M} G_m n_s^{d_m-1} \qquad n_s = g\int \frac{d^3p}{(2\pi)^3}\,\frac{m^*}{\epsilon^*_{\text{kin}}}\,f_{\mathbf{p}}$$

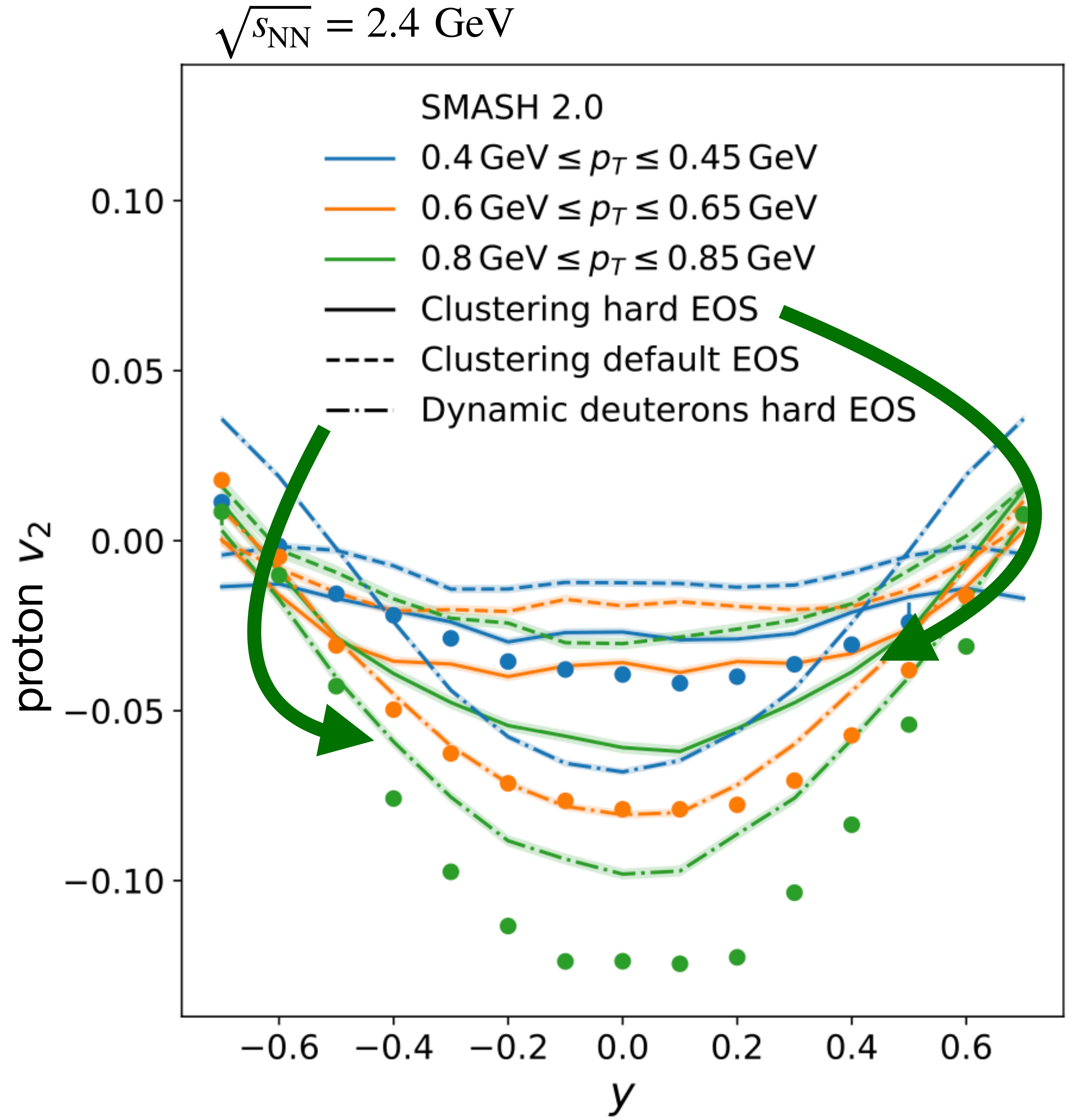
A. Sorensen, "Density Functional Equation of State and Its Application to the Phenomenology of Heavy-Ion Collisions," arXiv:2109.08105

Describing proton flow is not enough



Description of light cluster production needed:

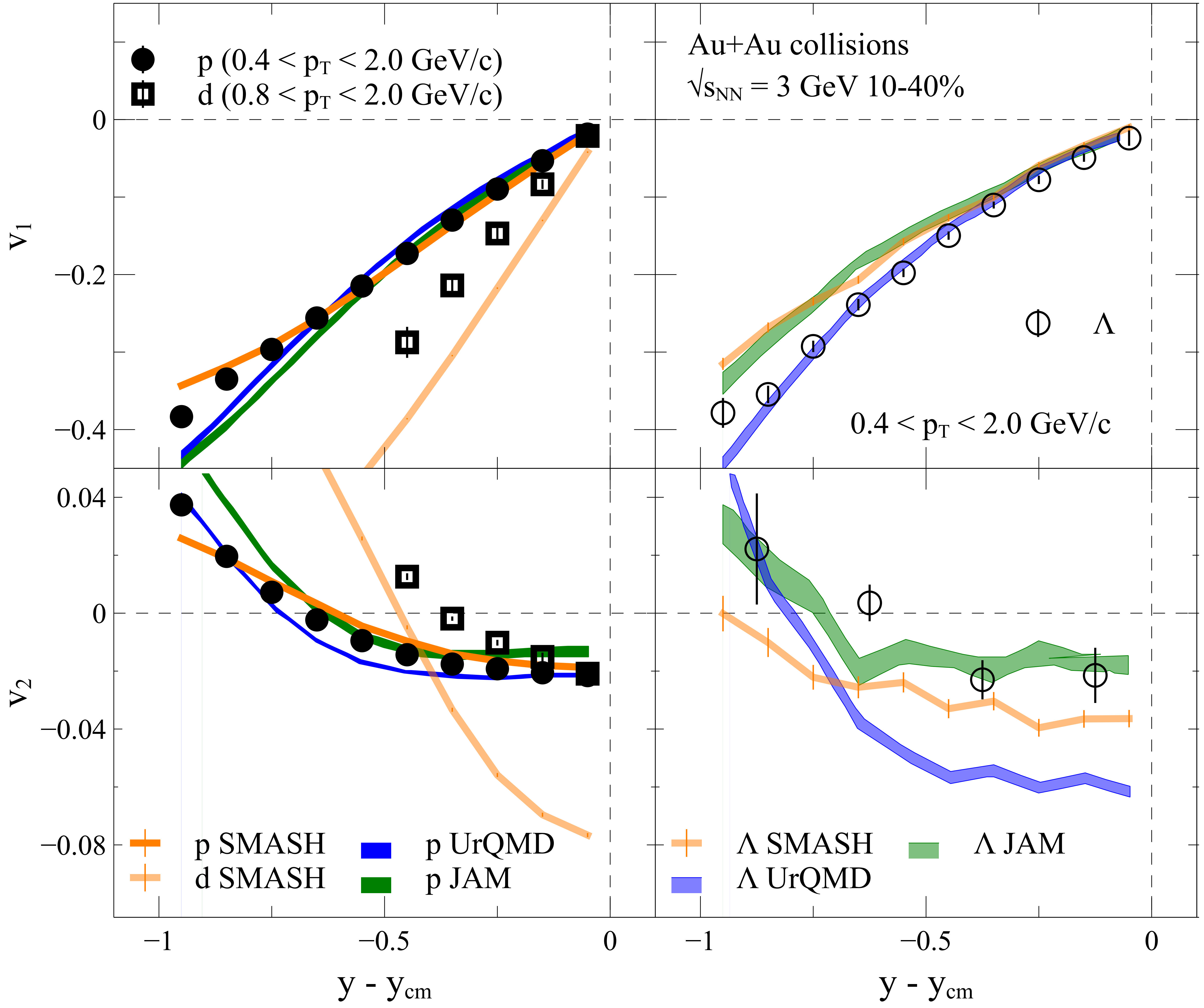
- coalescence: doesn't take into account the dynamic role of light clusters throughout the evolution
- nucleon/pion catalysis: consider as separate degrees of freedom (pBUU, SMASH), produced through N or π collisions
- dynamical production through potentials???



STAR, Phys. Lett. B **827**, 137003 (2022) arXiv:2108.00908
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996
A. Sorensen *et al.*, arXiv:2301.13253, to appear in JPPNP

J. Mohs, M. Ege, H. Elfner, M. Mayer, Phys. Rev. C **105** 3, 034906 (2022), arXiv:2012.11454

Describing proton flow is not enough



Strange baryons are not well described — the results may depend on:

- nucleon-hyperon and hyperon-hyperon interactions
- in-medium modifications of interactions

Models of interactions exist and could be tested; interactions could be based on those obtained within first-principle calculations (e.g., HALQCD collaboration HAL QCD, Nucl. Phys. A **998** 121737 (2020), arXiv:1912.08630)

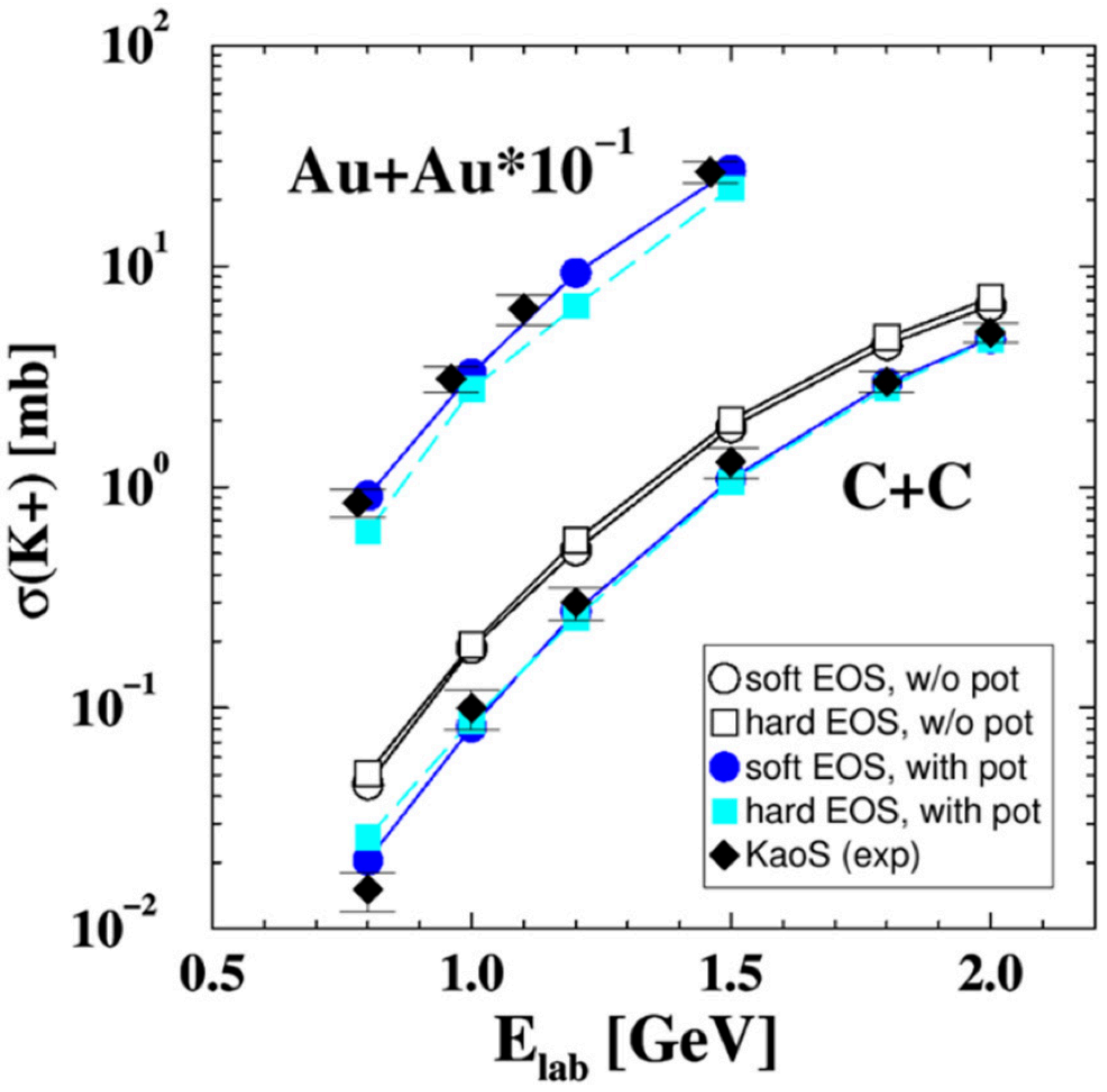
STAR, Phys. Lett. B **827**, 137003 (2022) arXiv:2108.00908

D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

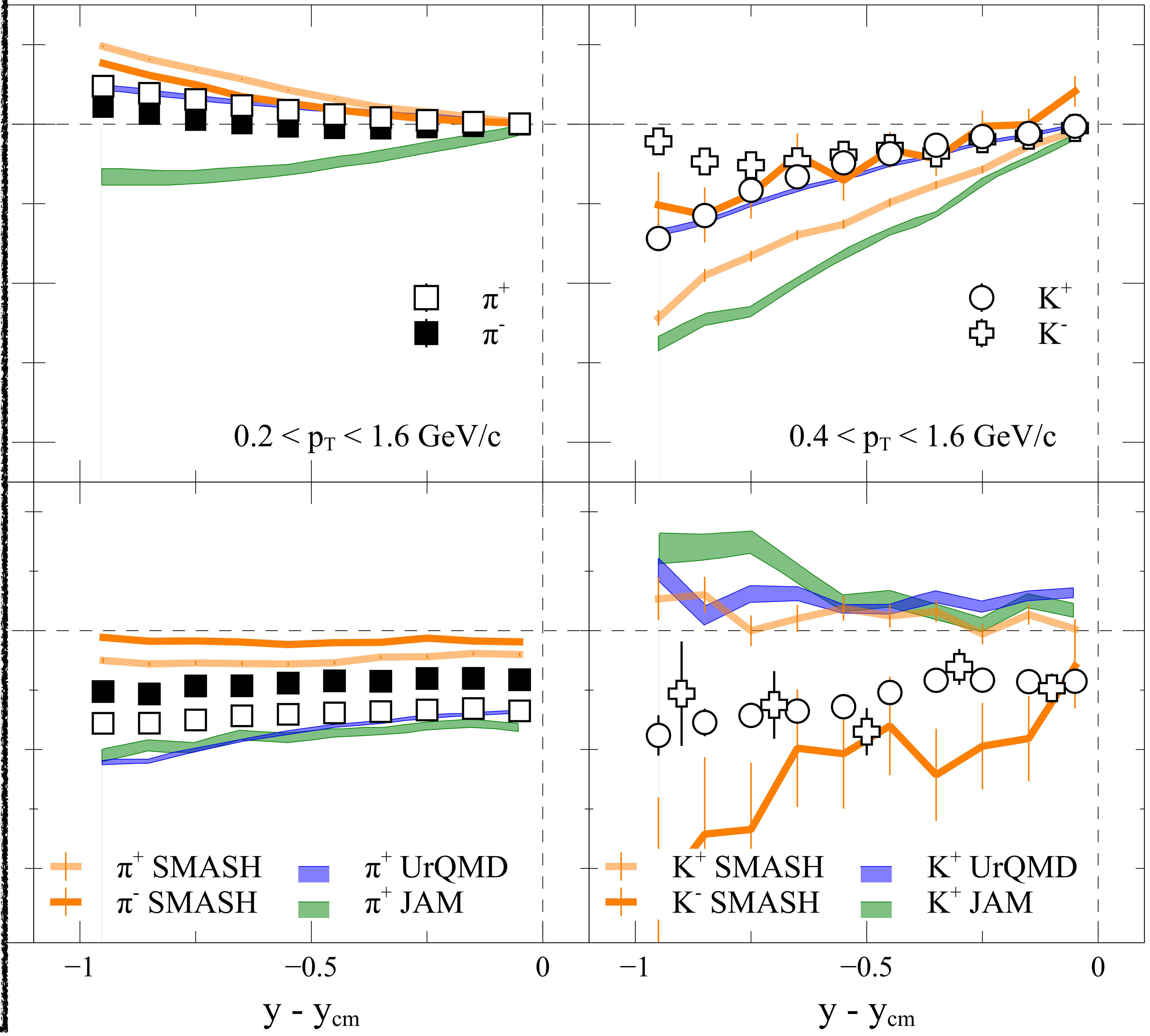
A. Sorensen *et al.*, arXiv:2301.13253, to appear in JPPNP

Describing proton flow is not enough

Pions and kaons NOT described!
Not very surprising: UrQMD, JAM, and SMASH don't have mean-fields for mesons

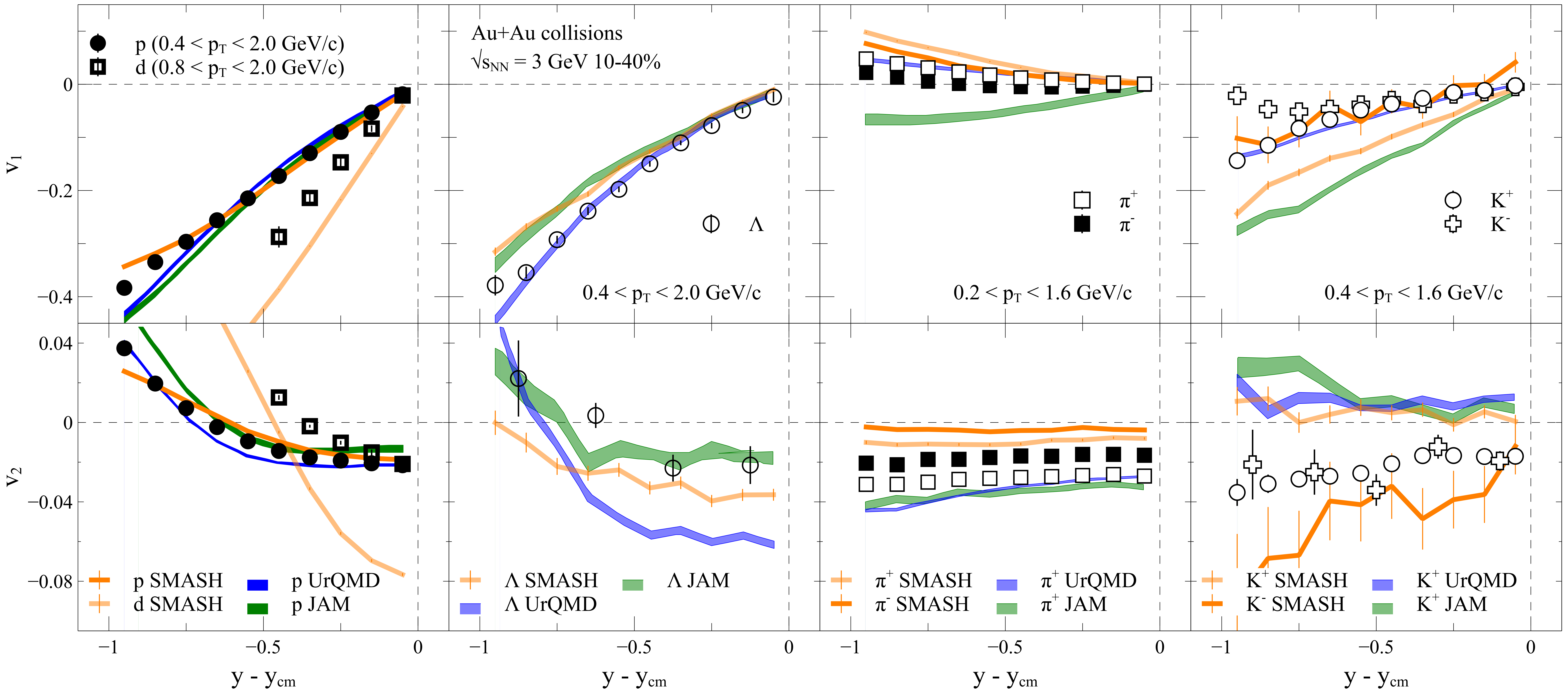


C. Fuchs, A. Faessler, E. Zabrodin, Y.-M. Zheng,
Phys. Rev. Lett. **86** 1974–1977 (2001) arXiv:nucl-th/0011102



STAR, Phys. Lett. B **827**, 137003 (2022) arXiv:2108.00908
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996
A. Sorensen *et al.*, arXiv:2301.13253, to appear in JPPNP

Describing proton flow is not enough



STAR, Phys. Lett. B **827**, 137003 (2022) arXiv:2108.00908
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996
A. Sorensen *et al.*, arXiv:2301.13253, to appear in JPPNP

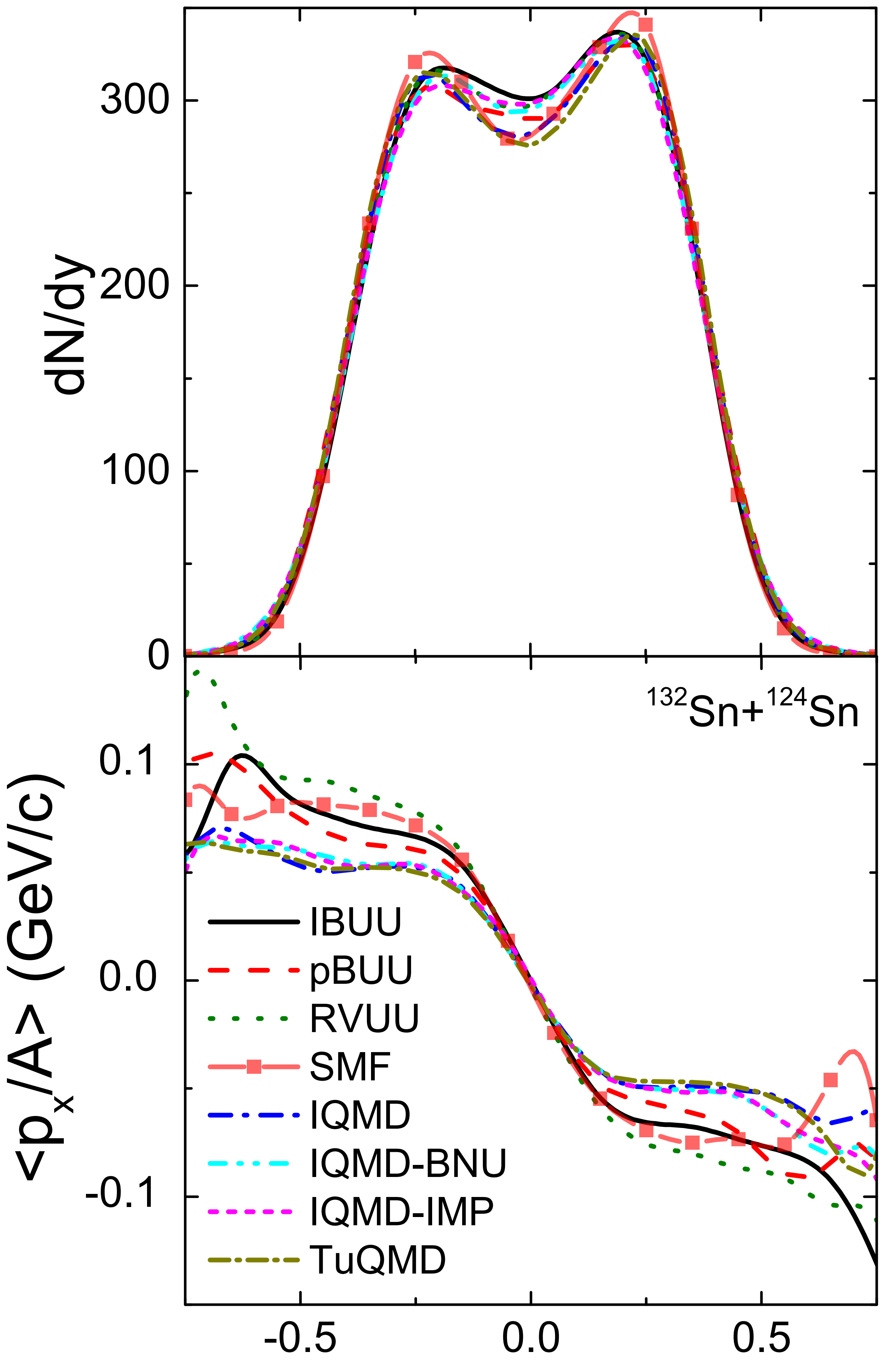
Better modeling is necessary

Ideas to pursue/explore/revisit:

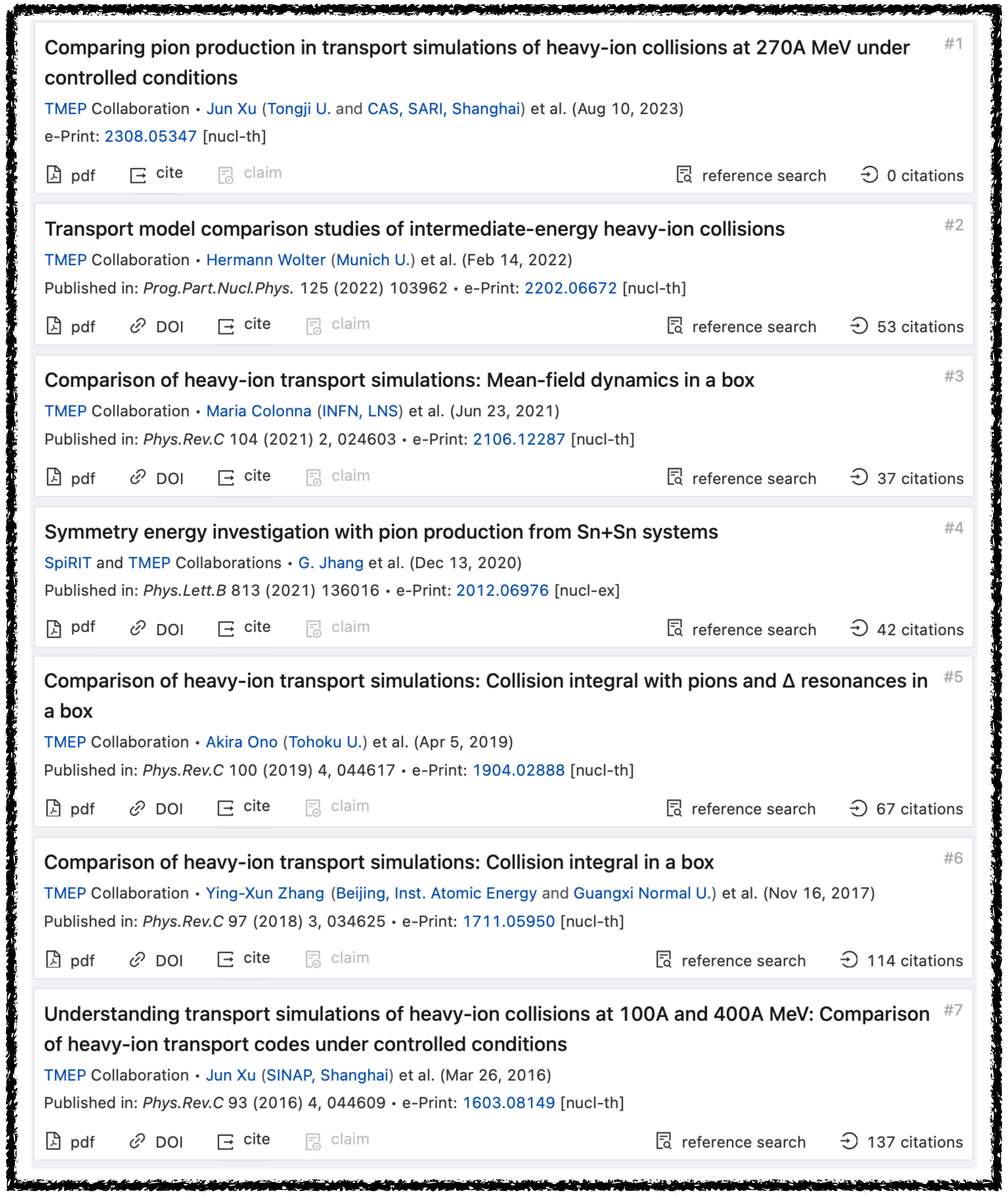
- *p*-dependent potentials,
- meson potentials,
- in-medium effects,
- light cluster production,
- …

Strong efforts by the TMEP Collaboration to identify code-dependencies and best model practices!

There is code-dependence:



J. Xu *et al.* (TMEP Collaboration), arXiv:2308.05347



#1 Comparing pion production in transport simulations of heavy-ion collisions at 270A MeV under controlled conditions
TMEP Collaboration • Jun Xu (Tongji U. and CAS, SARI, Shanghai) et al. (Aug 10, 2023)
e-Print: 2308.05347 [nucl-th]
pdf · cite · claim · reference search · 0 citations

#2 Transport model comparison studies of intermediate-energy heavy-ion collisions
TMEP Collaboration • Hermann Wolter (Munich U.) et al. (Feb 14, 2022)
Published in: *Prog.Part.Nucl.Phys.* 125 (2022) 103962 • e-Print: 2202.06672 [nucl-th]
pdf · DOI · cite · claim · reference search · 53 citations

#3 Comparison of heavy-ion transport simulations: Mean-field dynamics in a box
TMEP Collaboration • Maria Colonna (INFN, LNS) et al. (Jun 23, 2021)
Published in: *Phys.Rev.C* 104 (2021) 2, 024603 • e-Print: 2106.12287 [nucl-th]
pdf · DOI · cite · claim · reference search · 37 citations

#4 Symmetry energy investigation with pion production from Sn+Sn systems
SpiRIT and TMEP Collaborations • G. Jhang et al. (Dec 13, 2020)
Published in: *Phys.Lett.B* 813 (2021) 136016 • e-Print: 2012.06976 [nucl-ex]
pdf · DOI · cite · claim · reference search · 42 citations

#5 Comparison of heavy-ion transport simulations: Collision integral with pions and Δ resonances in a box
TMEP Collaboration • Akira Ono (Tohoku U.) et al. (Apr 5, 2019)
Published in: *Phys.Rev.C* 100 (2019) 4, 044617 • e-Print: 1904.02888 [nucl-th]
pdf · DOI · cite · claim · reference search · 67 citations

#6 Comparison of heavy-ion transport simulations: Collision integral in a box
TMEP Collaboration • Ying-Xun Zhang (Beijing, Inst. Atomic Energy and Guangxi Normal U.) et al. (Nov 16, 2017)
Published in: *Phys.Rev.C* 97 (2018) 3, 034625 • e-Print: 1711.05950 [nucl-th]
pdf · DOI · cite · claim · reference search · 114 citations

#7 Understanding transport simulations of heavy-ion collisions at 100A and 400A MeV: Comparison of heavy-ion transport codes under controlled conditions
TMEP Collaboration • Jun Xu (SINAP, Shanghai) et al. (Mar 26, 2016)
Published in: *Phys.Rev.C* 93 (2016) 4, 044609 • e-Print: 1603.08149 [nucl-th]
pdf · DOI · cite · claim · reference search · 137 citations

The EOS is a common effort within the nuclear physics community

A. Sorensen *et al.*, arXiv:2301.13253, to appear in JPPNP

Dense Nuclear Matter Equation of State from Heavy-Ion Collisions *

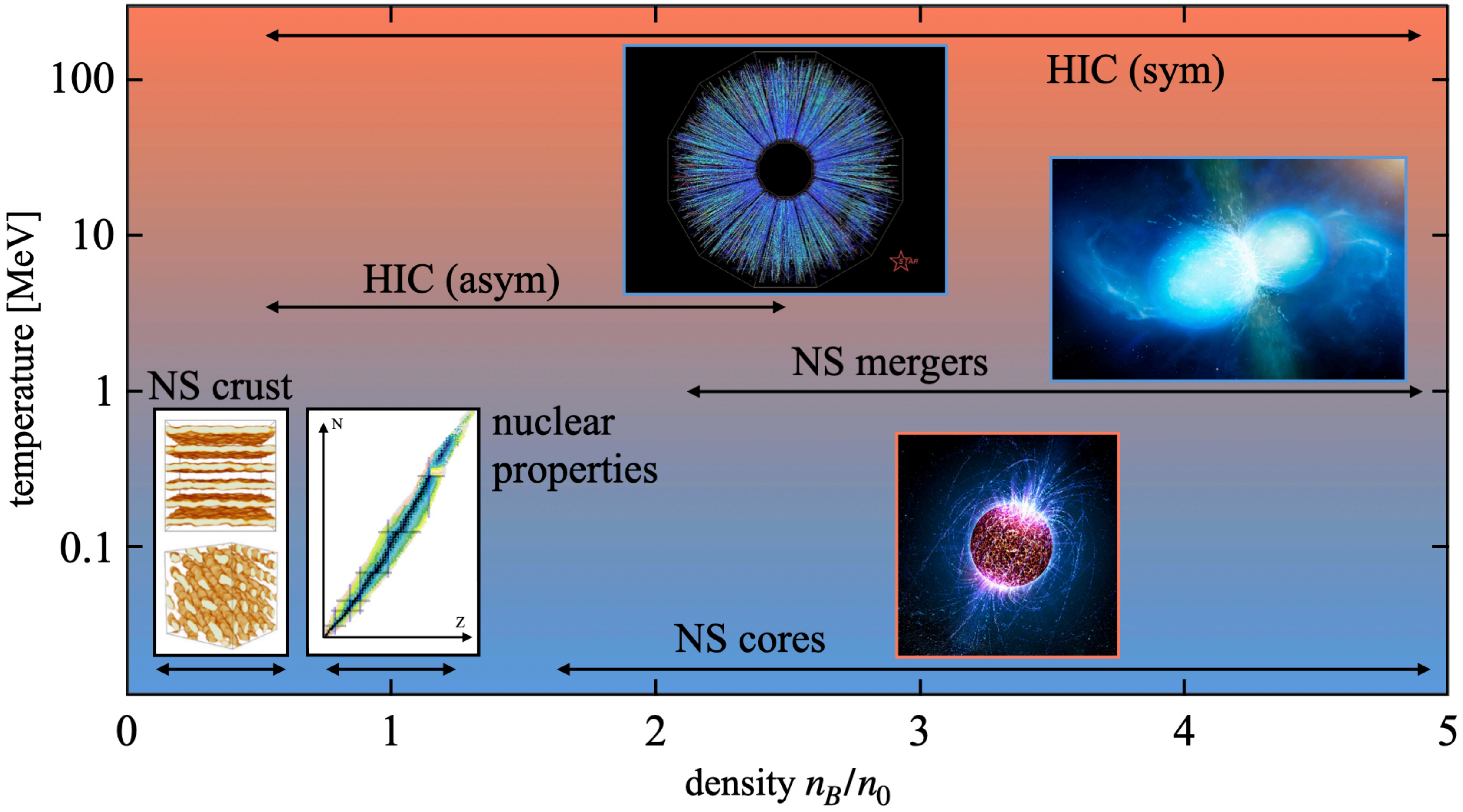
Agnieszka Sorensen[1], Kshitij Agarwal[2], Kyle W. Brown[3,4], Zbigniew Chajecki[5], Paweł Danielewicz[3,6], Christian Drischler[7], Stefano Gandolfi[8], Jeremy W. Holt[9,10], Matthias Kaminski[11], Che-Ming Ko[9,10], Rohit Kumar[3], Bao-An Li[12], William G. Lynch[3,6], Alan B. McIntosh[10], William G. Newton[12], Scott Pratt[3,6], Oleh Savchuk[3,13], Maria Stefaniak[14], Ingo Tews[8], ManYee Betty Tsang[3,6], Ramona Vogt[15,16], Hermann Wolter[17], Hanna Zbroszczyk[18]

Endorsing authors:

Navid Abbasi[19], Jörg Aichelin[20,21], Anton Andronic[22], Steffen A. Bass[23], Francesco Becattini[24,25], David Blaschke[26,27,28], Marcus Bleicher[29,30], Christoph Blume[31], Elena Bratkovskaya[14,29,30], B. Alex Brown[3,6], David A. Brown[32], Alberto Camaiani[33], Giovanni Casini[25], Katerina Chatziioannou[34,35], Abdelouahad Chbihi[36], Maria Colonna[37], Mircea Dan Cozma[38], Veronica Dexheimer[39], Xin Dong[40], Travis Dore[41], Lipei Du[42], José A. Dueñas[43], Hannah Elfner[14,21,29,30], Wojciech Florkowski[44], Yuki Fujimoto[1], Richard J. Furnstahl[45], Alexandra Gade[3,6], Tetyana Galatyuk[14,46], Charles Gale[42], Frank Geurts[47], Sašo Grozdanov[48,49], Kris Hagel[10], Steven P. Harris[1], Wick Haxton[40,50], Ulrich Heinz[45], Michal P. Heller[51], Or Hen[52], Heiko Hergert[3,6], Norbert Herrmann[53], Huan Zhong Huang[54], Xu-Guang Huang[55,56,57], Natsumi Ikeno[10,58], Gabriele Inghirami[14], Jakub Jankowski[26], Jiangyong Jia[59,60], José C. Jiménez[61], Joseph Kapusta[62], Behruz Kardan[31], Iurii Karpenko[63], Declan Keane[39], Dmitri Kharzeev[60,64], Andrej Kugler[65], Arnaud Le Fèvre[14], Dean Lee[3,6], Hong Liu[66], Michael A. Lisa[45], William J. Llope[67], Ivano Lombardo[68], Manuel Lorenz[31], Tommaso Marchi[69], Larry McLerran[1], Ulrich Mosel[70], Anton Motornenko[21], Berndt Müller[23], Paolo Napolitani[71], Joseph B. Natowitz[10], Witold Nazarewicz[3,6], Jorge Noronha[72], Jacquelyn Noronha-Hostler[72], Grażyna Odyniec[40], Panagiota Papakonstantinou[73], Zuzana Paulínyová[74], Jorge Piekarewicz[75], Robert D. Pisarski[60], Christopher Plumberg[76], Madappa Prakash[7], Jørgen Randrup[40], Claudia Ratti[77], Peter Rau[1], Sanjay Reddy[1], Hans-Rudolf Schmidt[2,14], Paolo Russotto[37], Radoslaw Ryblewski[78], Andreas Schäfer[79], Björn Schenke[60], Srimoyee Sen[80], Peter Senger[81], Richard Seto[82], Chun Shen[67,83], Bradley Sherrill[3,6], Mayank Singh[62], Vladimir Skokov[83,84], Michał Spaliński[85,86], Jan Steinheimer[21], Mikhail Stephanov[87], Joachim Stroth[14,31], Christian Sturm[14], Kai-Jia Sun[88], Aihong Tang[60], Giorgio Torrieri[89,90], Wolfgang Trautmann[14], Giuseppe Verde[91], Volodymyr Vovchenko[77], Ryoichi Wada[10], Fuqiang Wang[92], Gang Wang[54], Klaus Werner[20], Nu Xu[40], Zhangbu Xu[60], Ho-Ung Yee[87], Sherry Yennello[9,10,93], Yi Yin[94]

Hot QCD | Cold QCD

Nucl. reactions + astro | Fundamental sym.



Exploring synergies between communities:

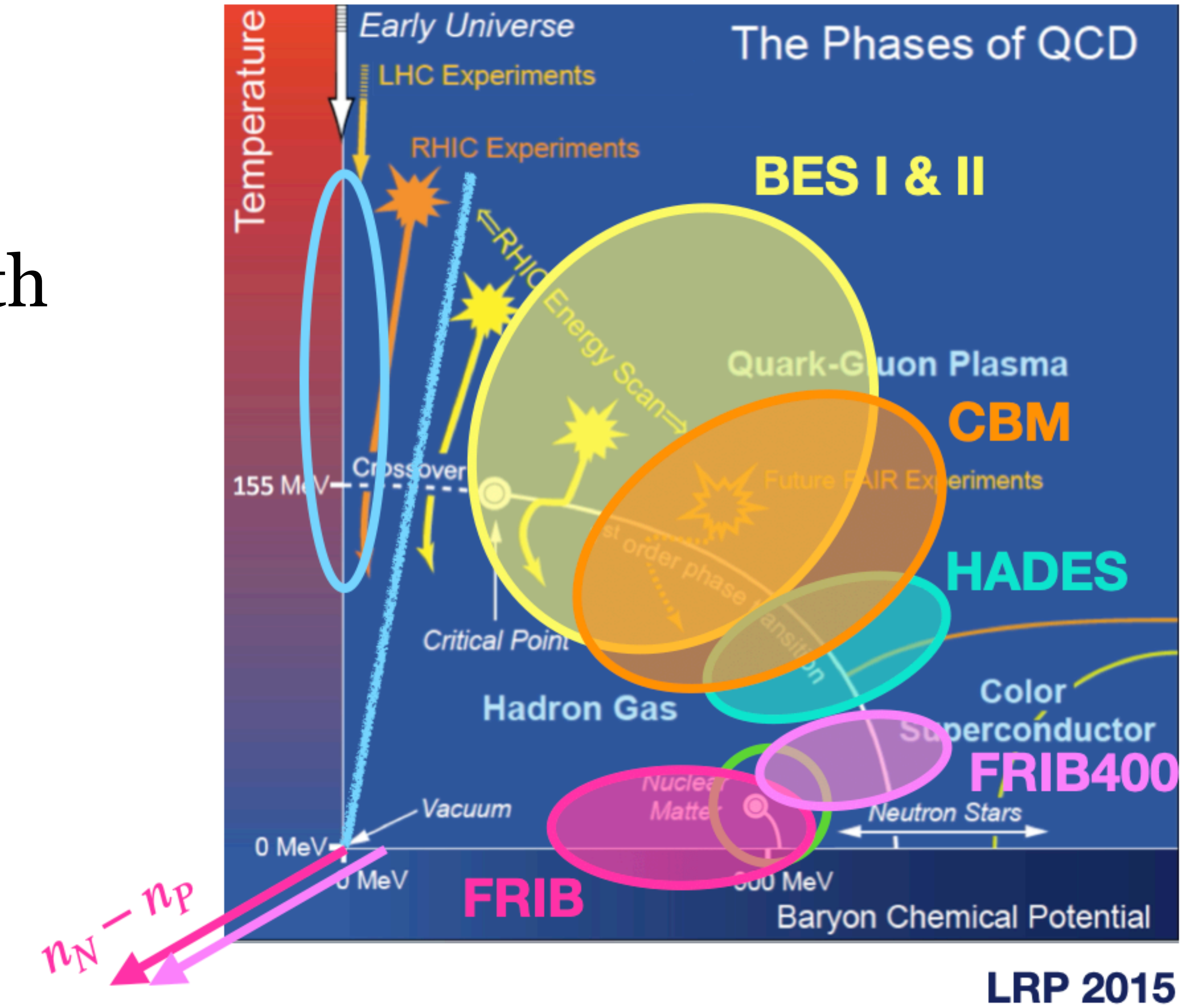
- exposure to varied scientific ideas, approaches
- increased support for EOS physics

Summary: Established heavy-ion EOS constraints still unbeatable

What's different, new, exciting about *now*?

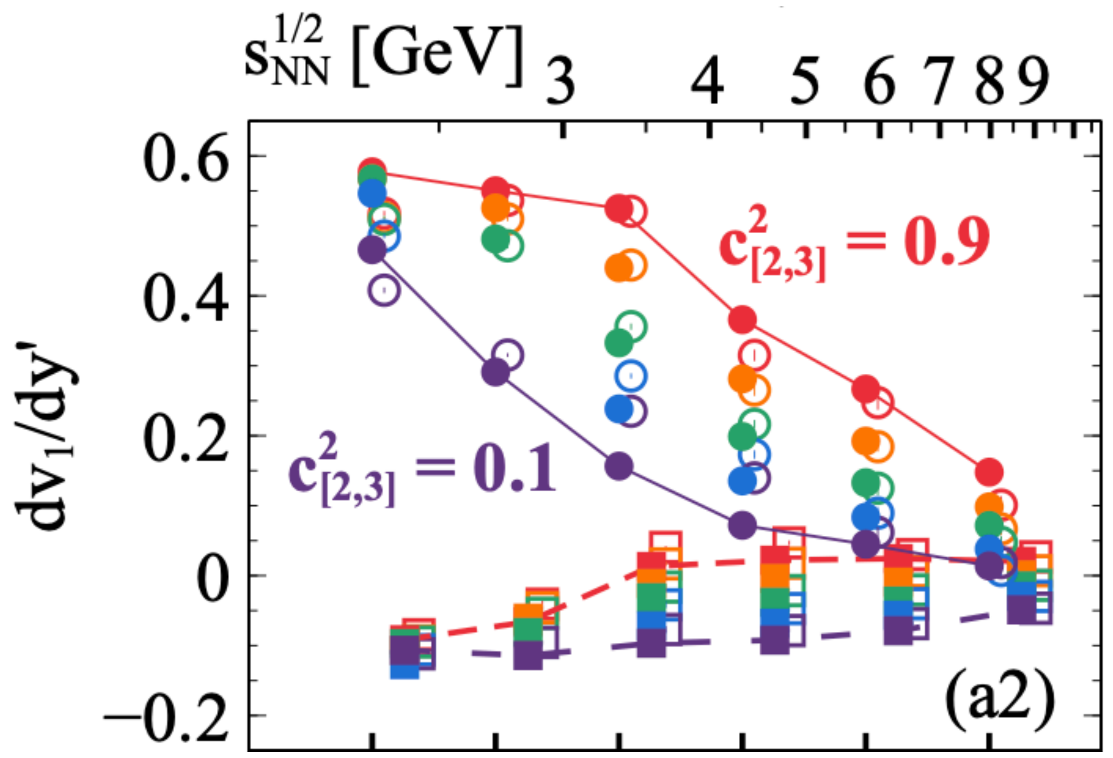
- New detectors, new data: ultra-precise triple-differential flow observables, hyperon-hyperon interactions, ...
- New computing capabilities: large-scale simulations possible with state-of-the-art, benchmarked hadronic transport codes
- New approach to constraining the EOS: Bayesian analyses using flexible parametrizations of the EOS

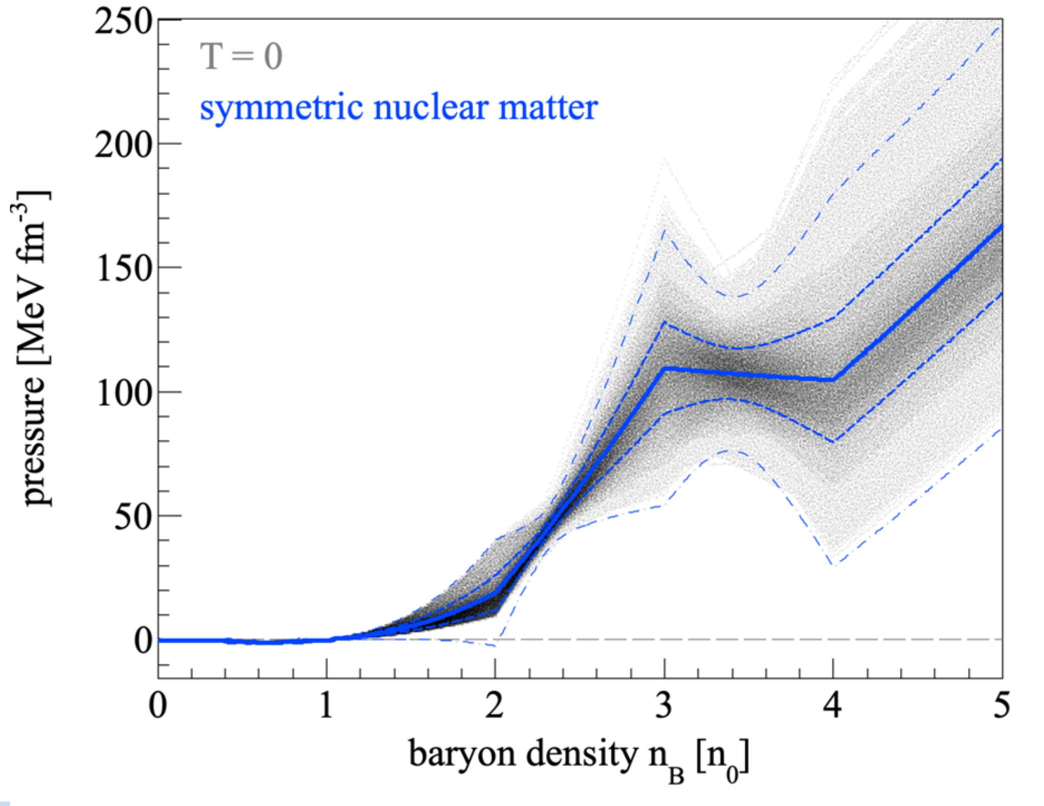
Key questions *for me*:
What needs to be done to consistently describe flow of most abundant species?
How to assign error due to model dependencies?

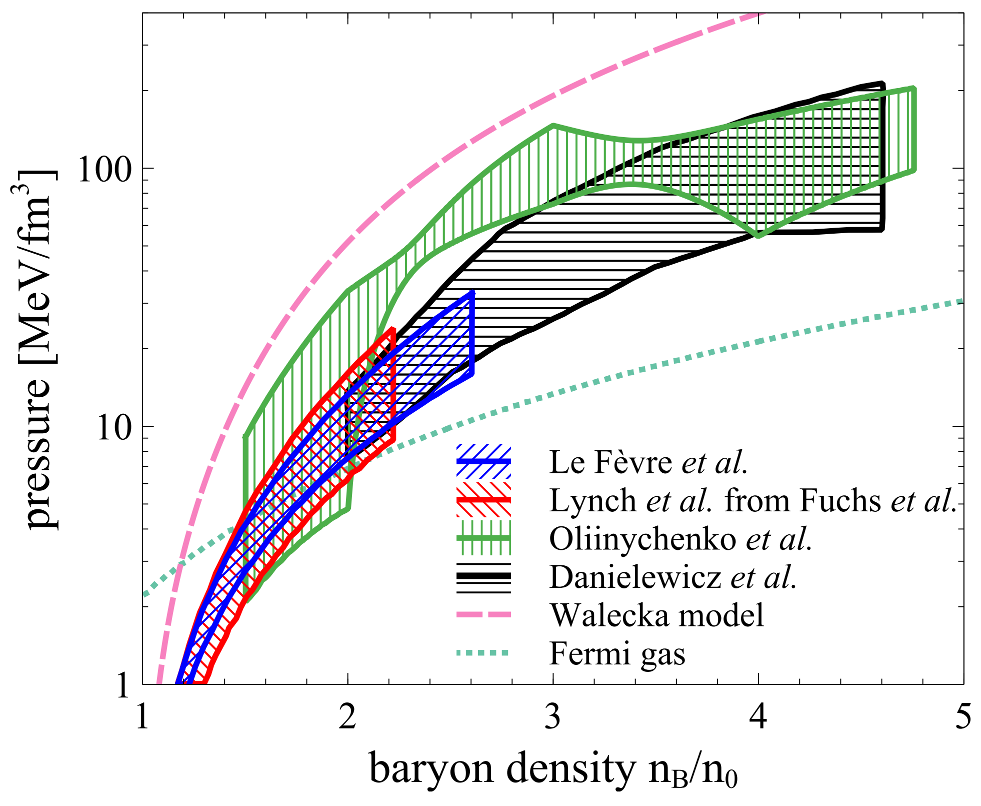


LRP 2015

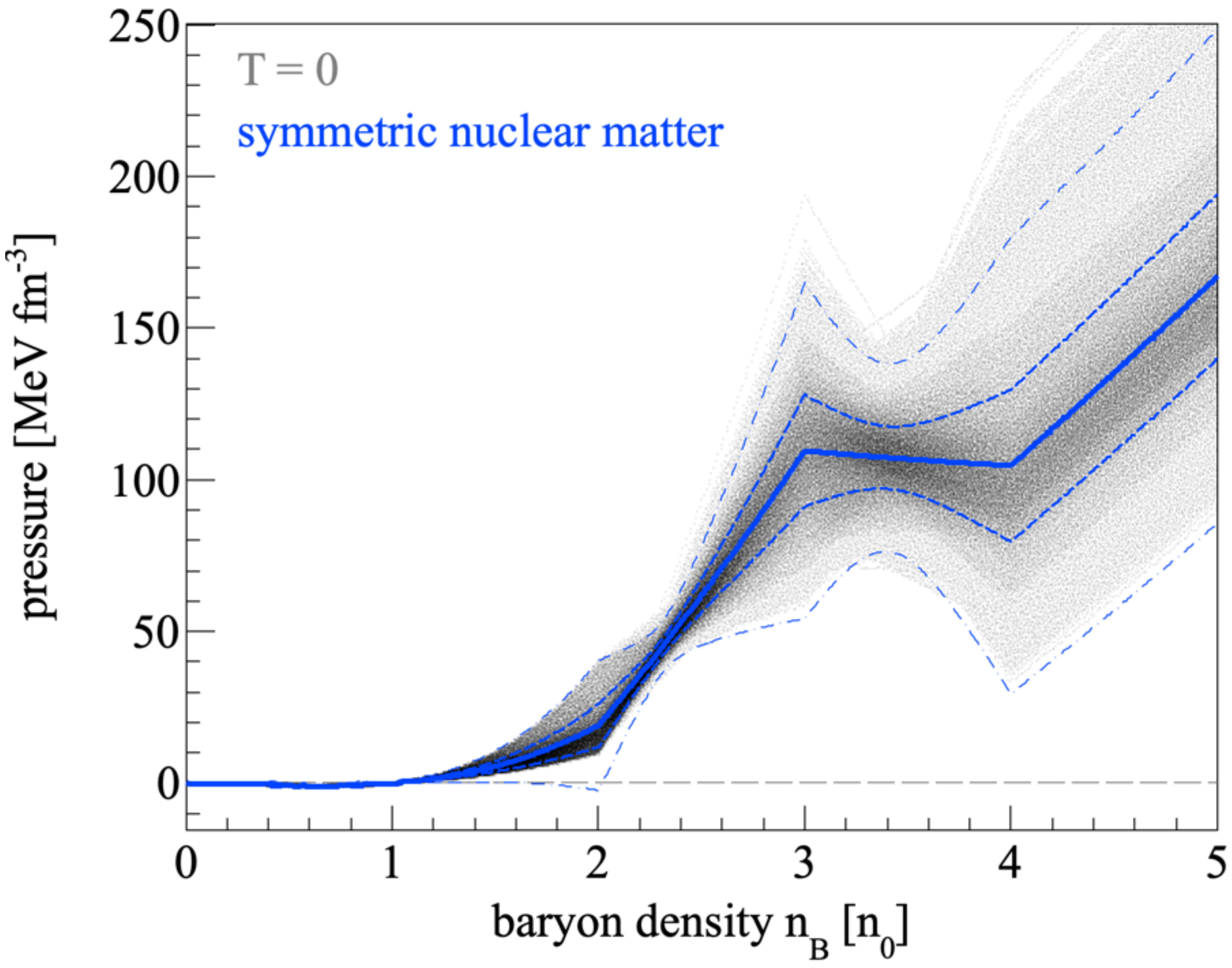
Thank you
for your attention

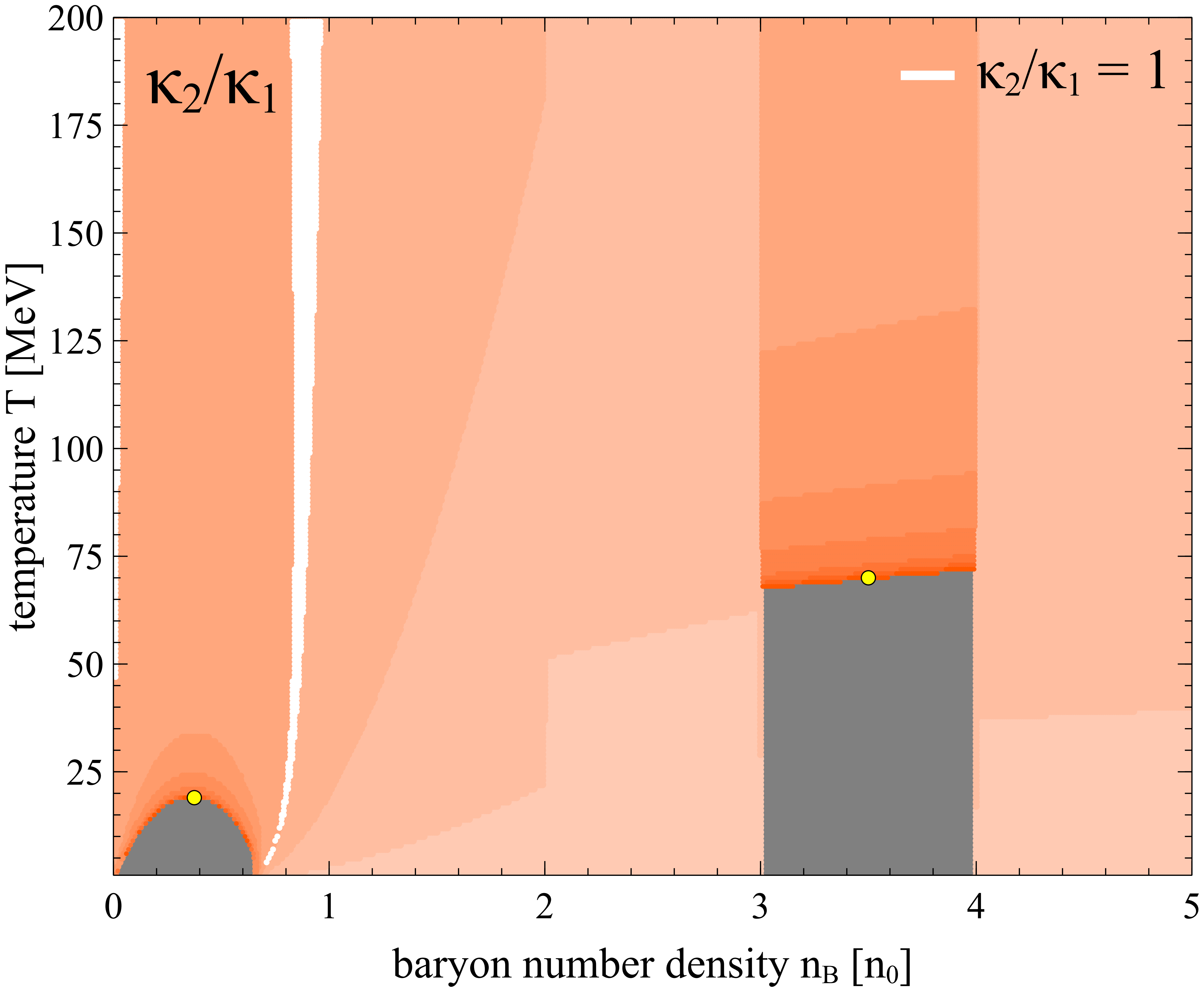






Bayesian analysis of STAR flow data with varying K_0, $c^2_{[2,3]n_0}$, $c^2_{[3,4]n_0}$



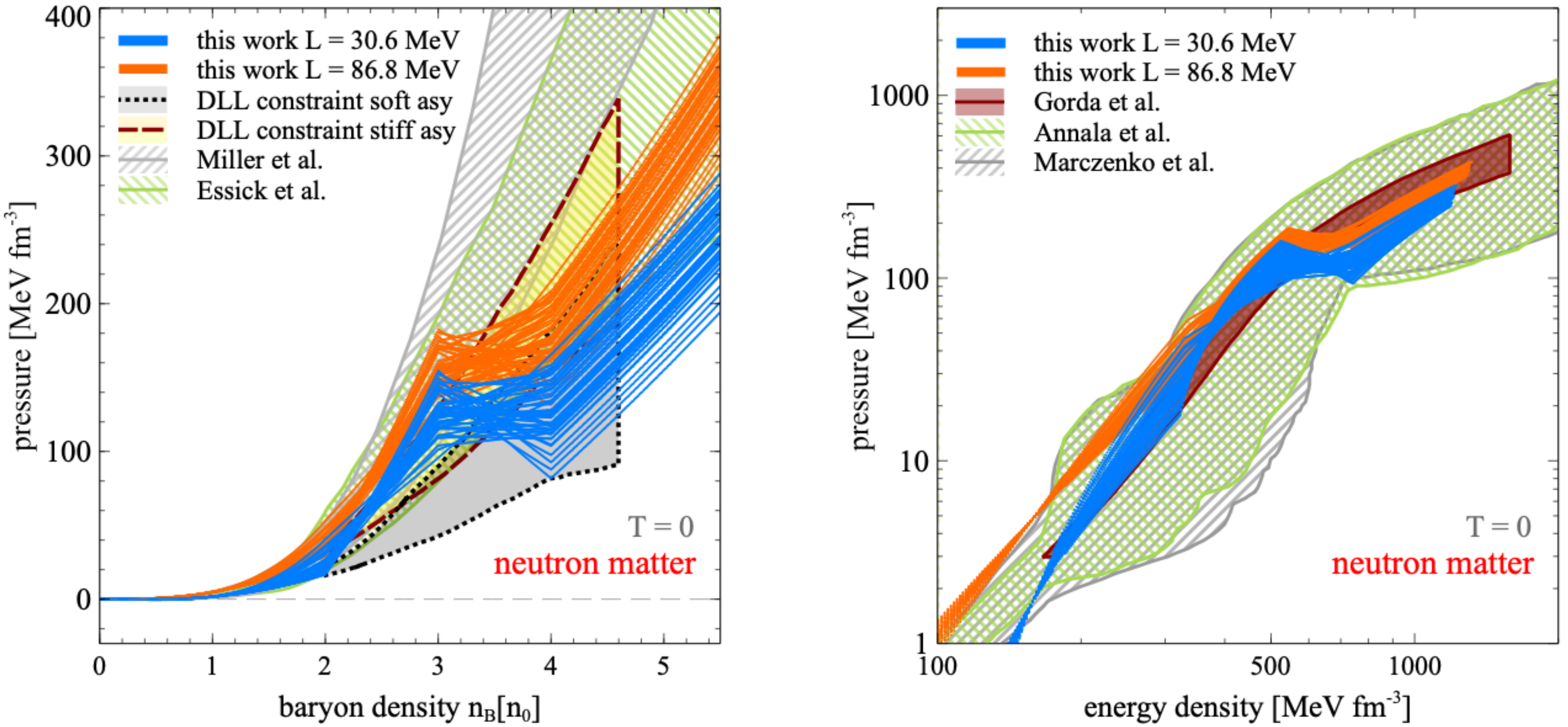


The maximum a posteriori probability (MAP) parameters are

$K_0 = 300 \pm 60\text{MeV}, \quad c^2_{[2,3]n_0} = 0.47 \pm 0.12, \quad c^2_{[3,4]n_0} = -0.08 \pm 0.14$

D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

Bayesian analysis of STAR flow data with varying K_0, $c^2_{[2,3]n_0}$, $c^2_{[3,4]n_0}$



D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran,
Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

Generalized VDF model: custom c_s^2

VDF model: $\mathcal{E}_N = g\int \frac{d^3p}{(2\pi)^3}\, \epsilon^*_{\text{kin}}\, f_{\mathbf{p}} + \sum_{i=1}^{N} A_k^0 j_0 - g^{00}\sum_{i=1}^{N}\left(\frac{b_i - 1}{b_i}\right) A_k^\lambda j_\lambda$ $\quad A_k^\mu = C_k\left(j_\lambda j^\lambda\right)^{\frac{b_k}{2}-1} j^\mu$ $\quad \varepsilon_{\mathbf{p}} = \epsilon_{\text{kin}} + \sum_{i=1}^{N} A_i^0$

Assume arbitrary vector interactions: $A^\mu = \alpha(n_B) j^\mu$

The effective chemical potential defined as $\mu^* = \mu_B - \alpha(n_B) n_B$

At $T = 0$, $\epsilon_F = \mu^*$ and the density is given by $n_B = \frac{g}{6\pi^2}\left(\mu^{*2} - m^2\right)^{3/2}$

Combining the two allows one to solve for $\mu_B(n_B) = \alpha(n_B) n_B + \sqrt{m^2 + \left(\frac{6\pi n_B}{g}\right)^{2/3}}$

On the other hand, $c_s^2\Big|_{T=0} = \frac{d\ln\mu_B}{d\ln n_B}$, and solving for μ_B: $\mu_B(n_B) = \mu_B\left(n_B^{(0)}\right)\exp\left(\int_{n_B^{(0)}}^{n_B} d\ln n\ c_s^2(n)\right)$

Solve for vector interactions: $\alpha(n_B) = \frac{1}{n_B}\left[\mu_B\left(n_B^{(0)}\right)\exp\left(\int_{n_B^{(0)}}^{n_B} d\ln n\ c_s^2(n)\right) - \sqrt{m^2 + \left(\frac{6\pi n_B}{g}\right)^{2/3}}\right]$

D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran,
Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

Generalized VDF model: custom c_s^2

VDF model: $\mathcal{E}_N = g \int \frac{d^3p}{(2\pi)^3}\, \epsilon^*_{\rm kin}\, f_{\mathbf{p}} + \sum_{i=1}^{N} A_k^0 j_0 - g^{00} \sum_{i=1}^{N} \left(\frac{b_i - 1}{b_i}\right) A_k^\lambda j_\lambda$ $\quad A_k^\mu = C_k \left(j_\lambda j^\lambda\right)^{\frac{b_k}{2}-1} j^\mu \quad \varepsilon_{\mathbf{p}} = \epsilon_{\rm kin} + \sum_{i=1}^{N} A_i^0$

Assume arbitrary vector interactions: $A^\mu = \alpha(n_B) j^\mu$

These interactions, parametrized with a chosen shape of c_s^2 as a function of n_B, can be used in hadronic transport simulations!

On the other hand, $c_s^2\Big|_{T=0} = \frac{\quad}{d \ln n_B}$, and solving for μ_B: $\mu_B(n_B) = \mu_B(n_B^{(0)}) \exp\left(\int_{n_B^{(0)}} d \ln n \;\, c_s^2(n)\right)$

Solve for vector interactions: $\alpha(n_B) = \frac{1}{n_B}\left[\mu_B\left(n_B^{(0)}\right)\exp\left(\int_{n_B^{(0)}}^{n_B} d \ln n \;\, c_s^2(n)\right) - \sqrt{m^2 + \left(\frac{6\pi n_B}{g}\right)^{2/3}}\,\right]$

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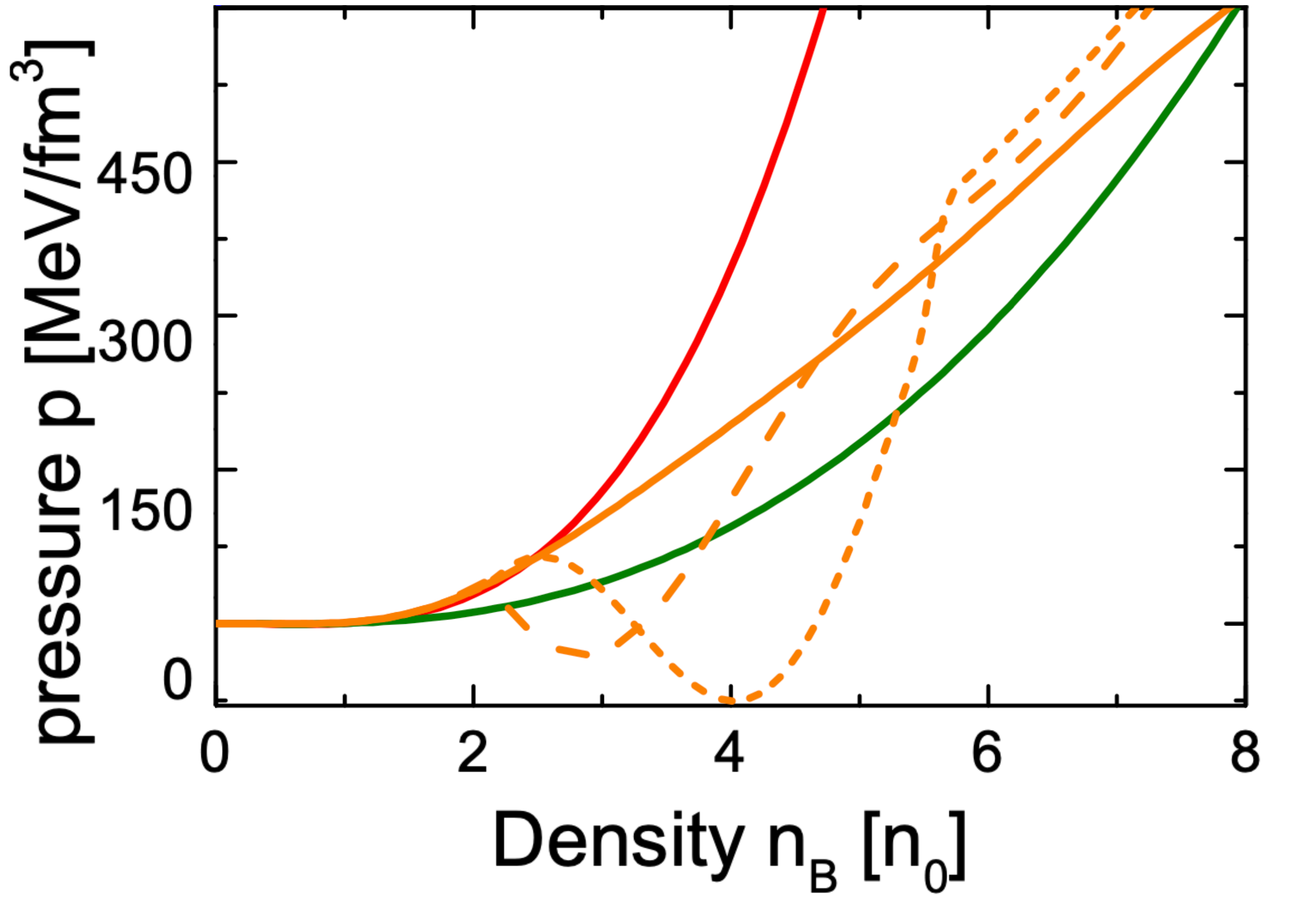
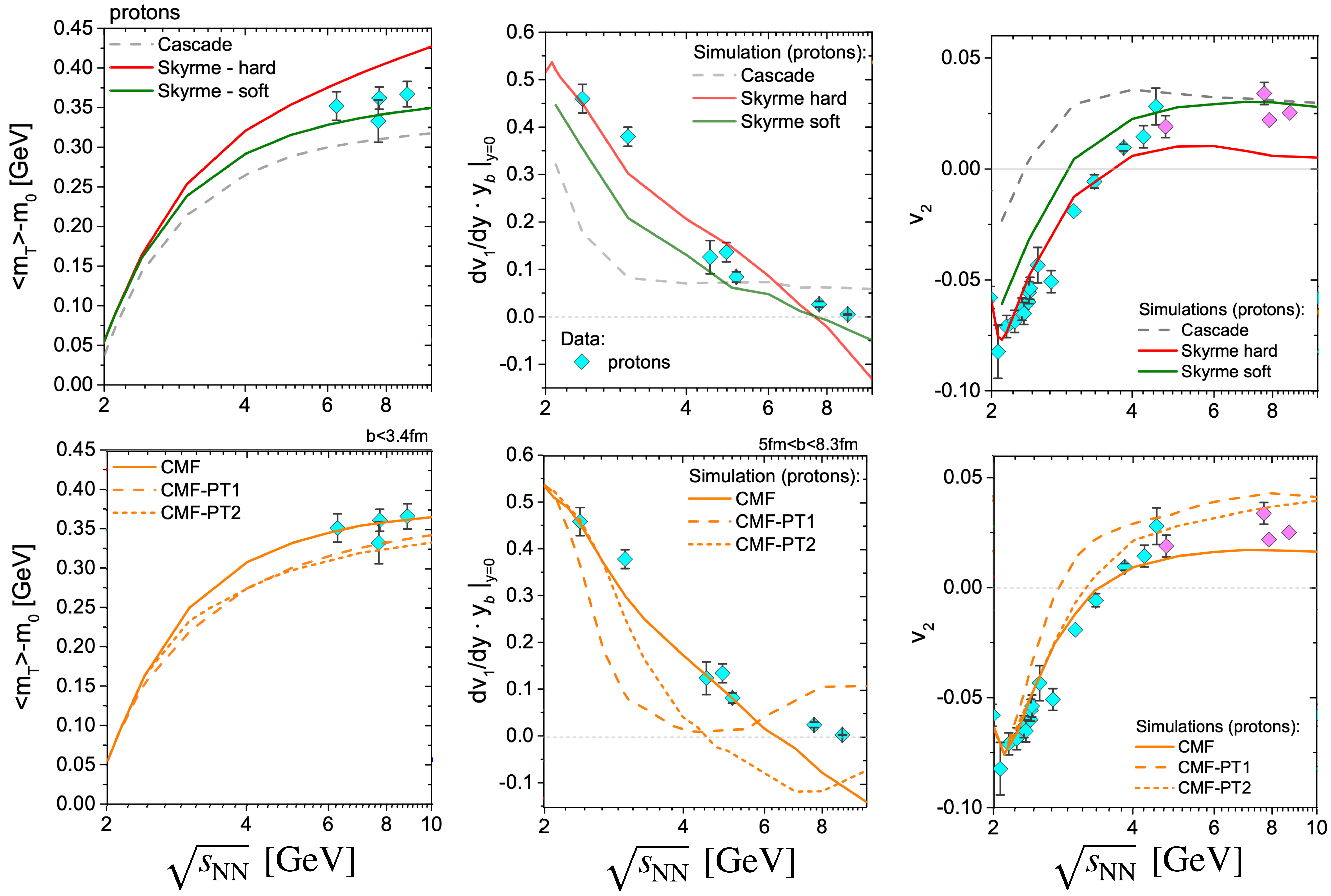
Results from UrQMD with (non-relativistic) CMF

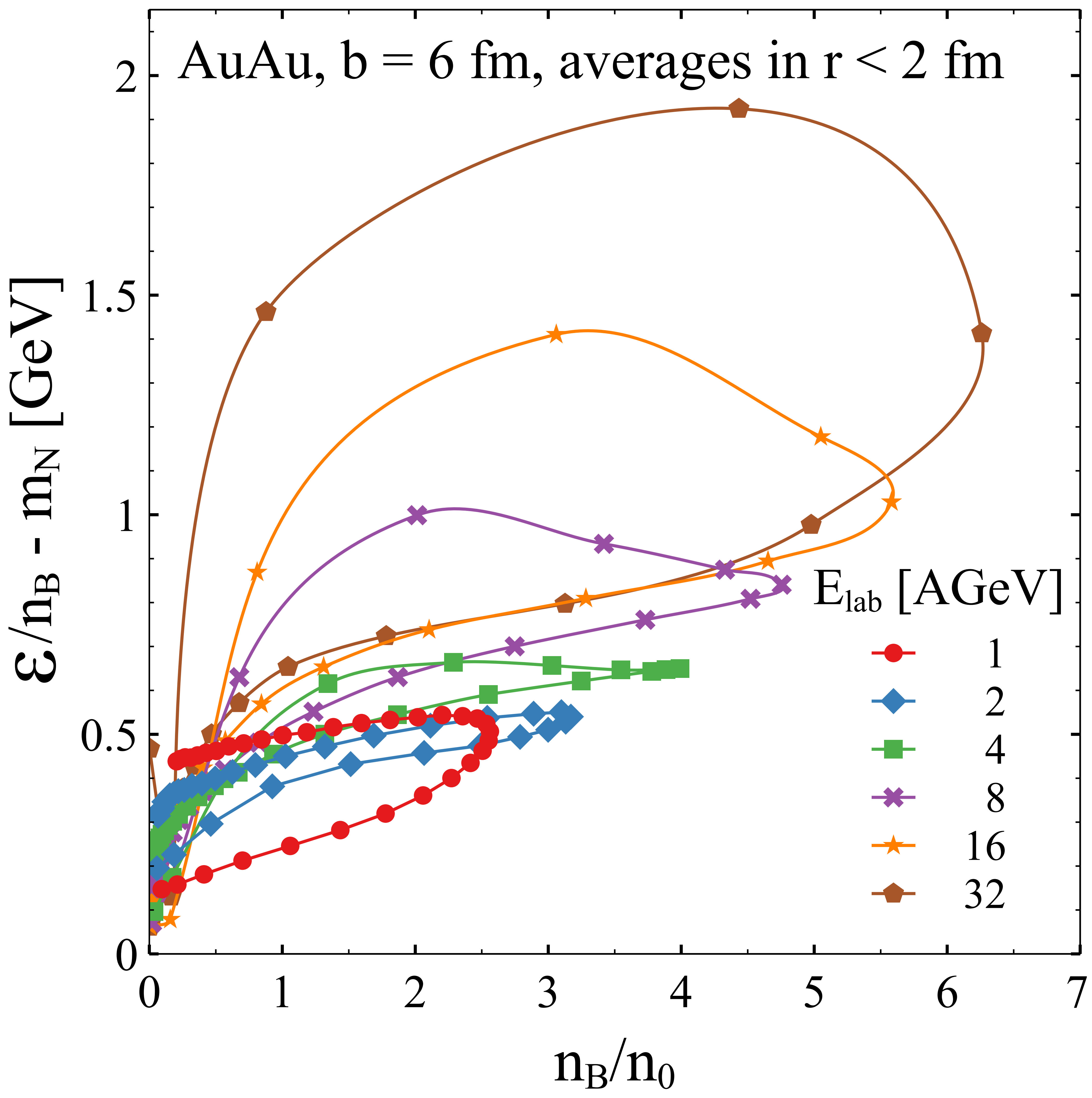
J. Steinheimer, A. Motornenko, **A. Sorensen**, Y. Nara, V. Koch, M. Bleicher, Eur. Phys. J. C **82**, 10, 911 (2022) arXiv:2208.12091

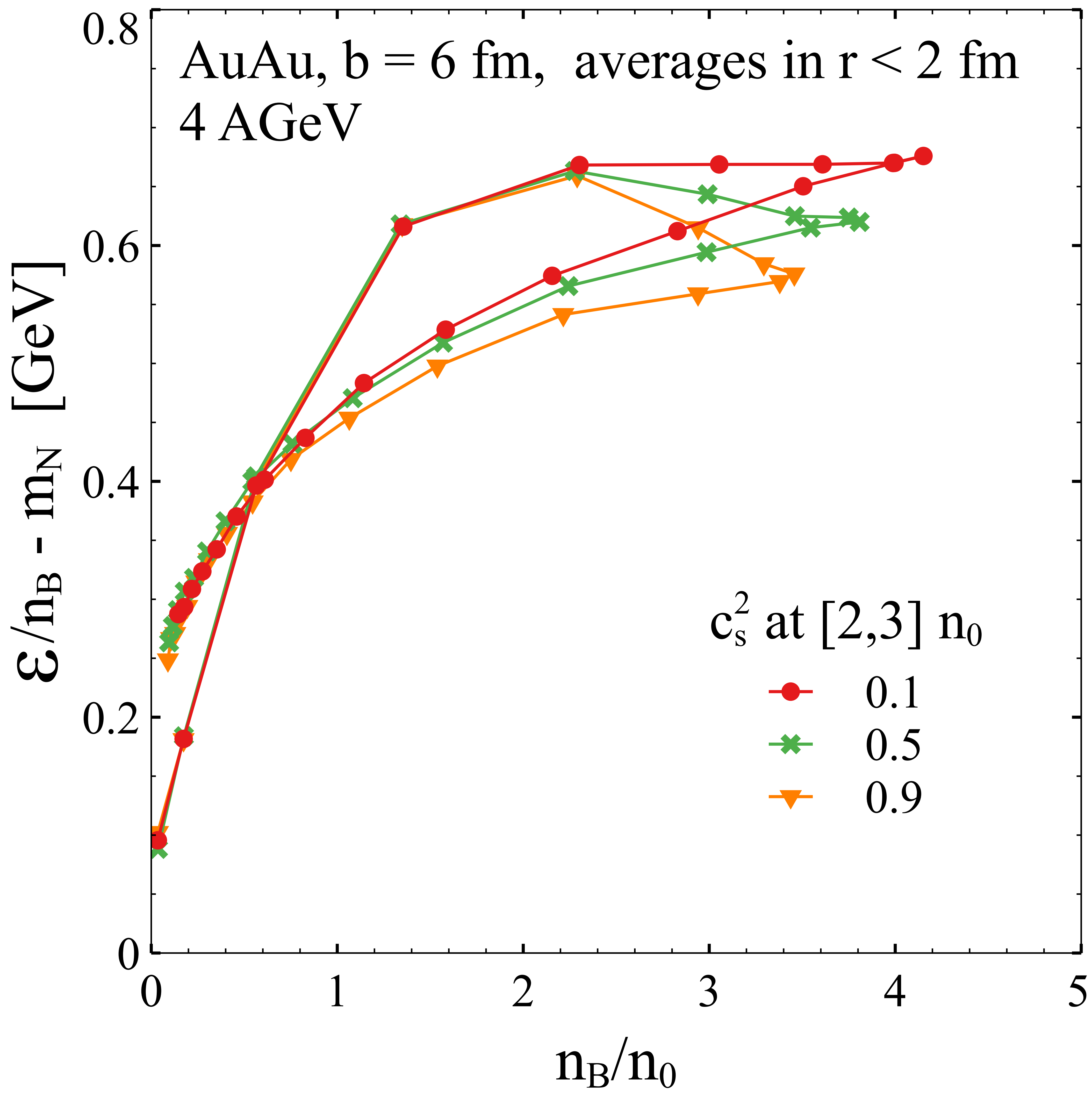




Very soft EOS at $n_B \in (2,3)n_0$ not supported in CMF+UrQMD

Bayesian analysis of STAR flow data with varying K_0, $c^2_{[2,3]n_0}$, $c^2_{[3,4]n_0}$





D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

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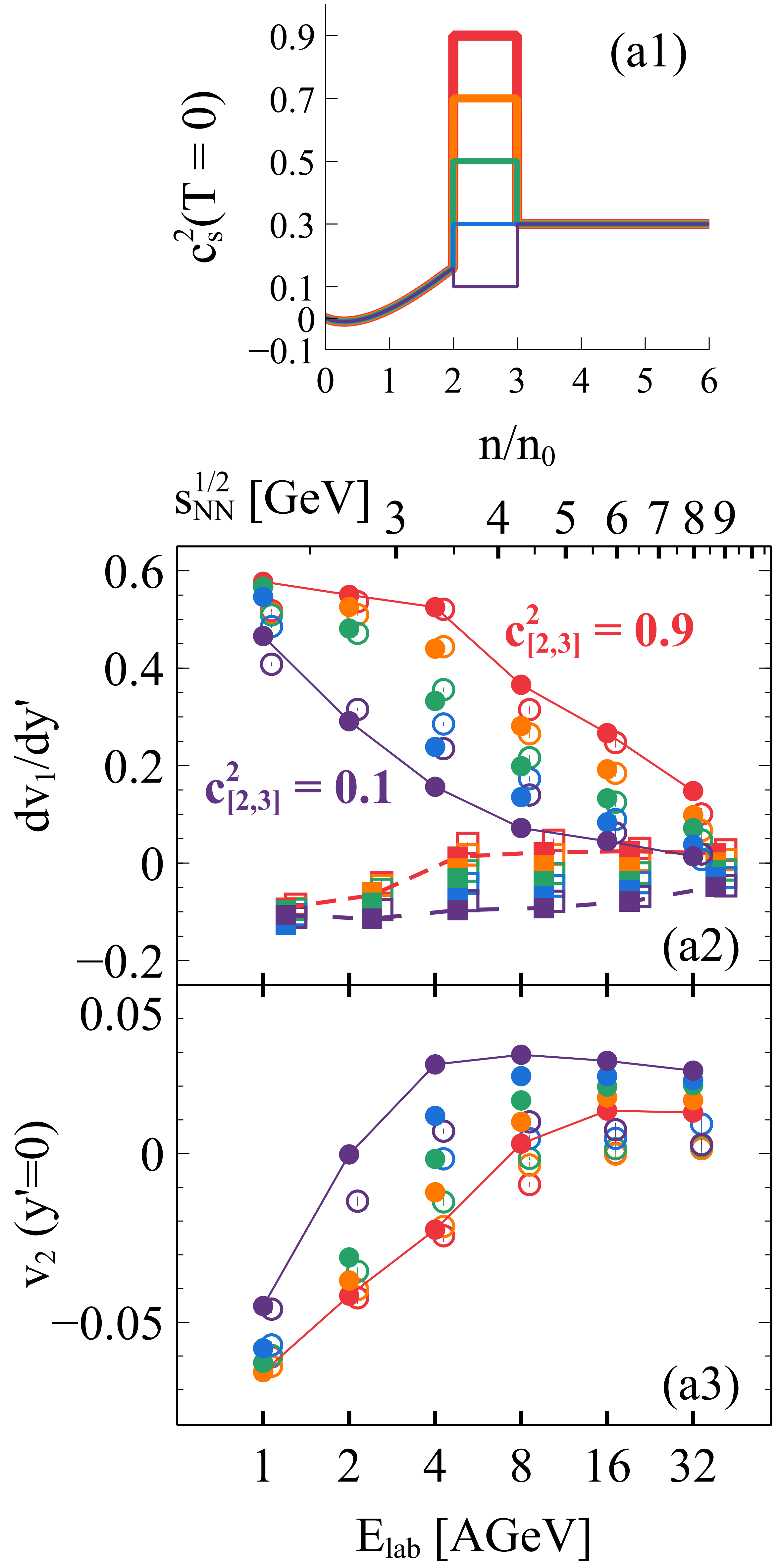

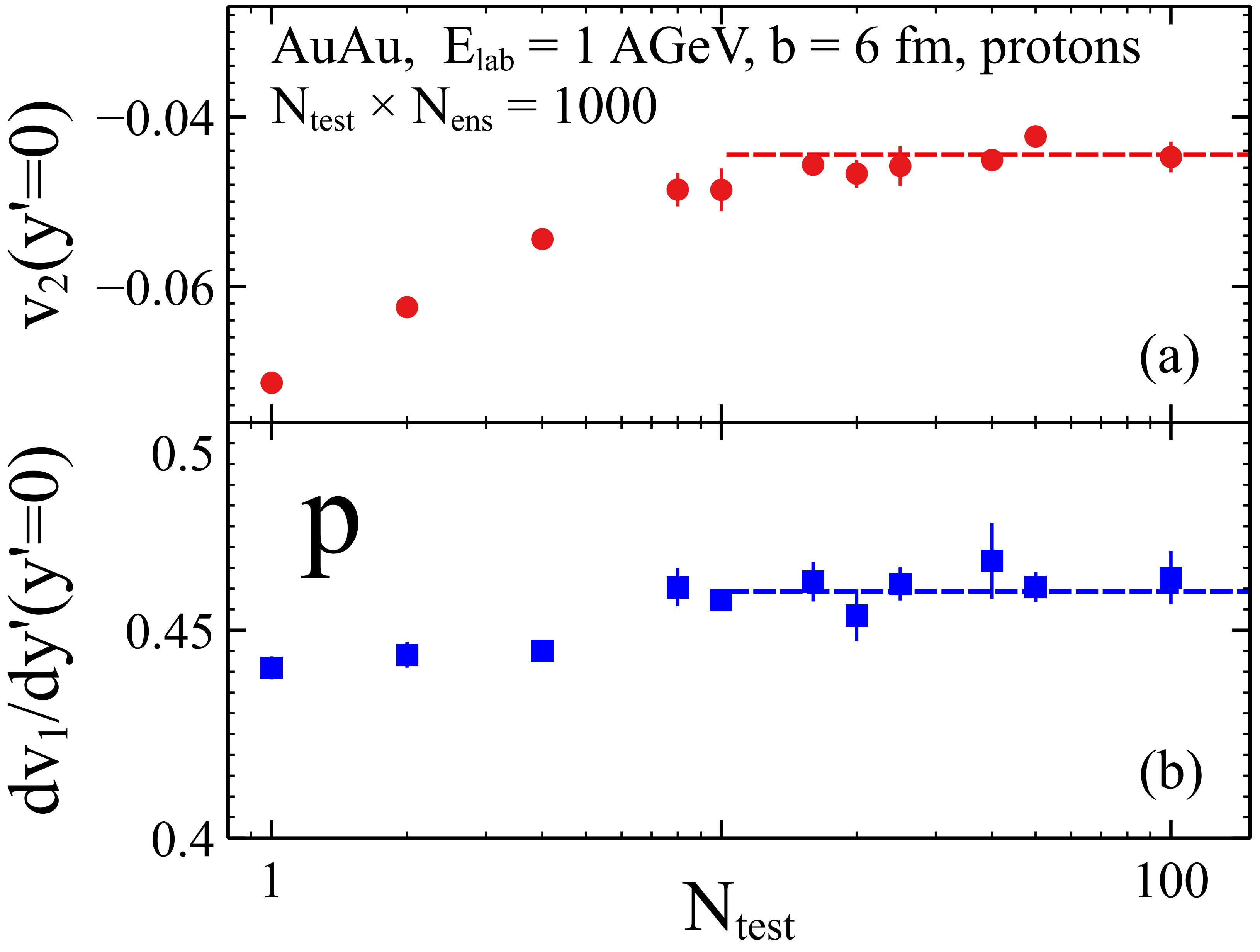

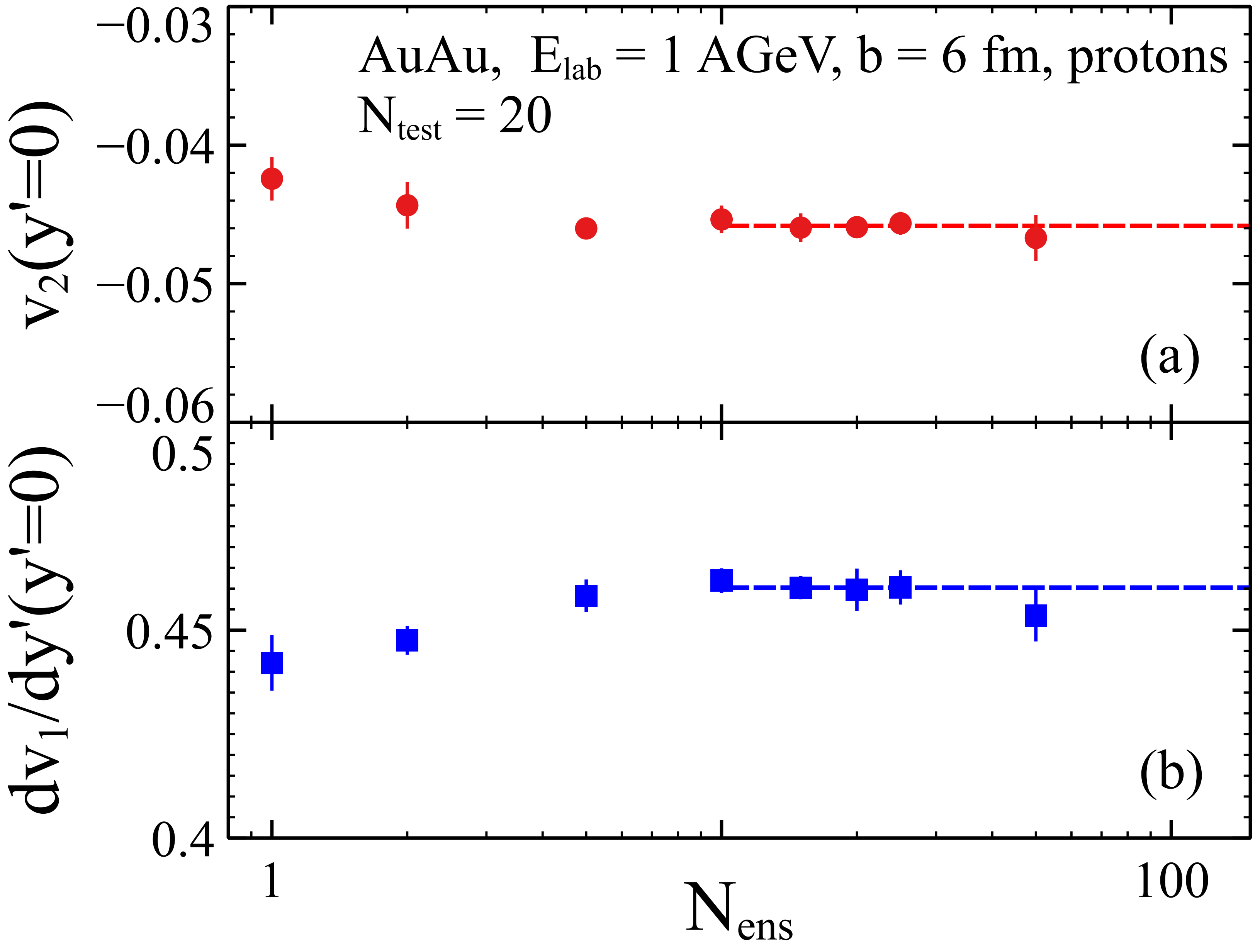

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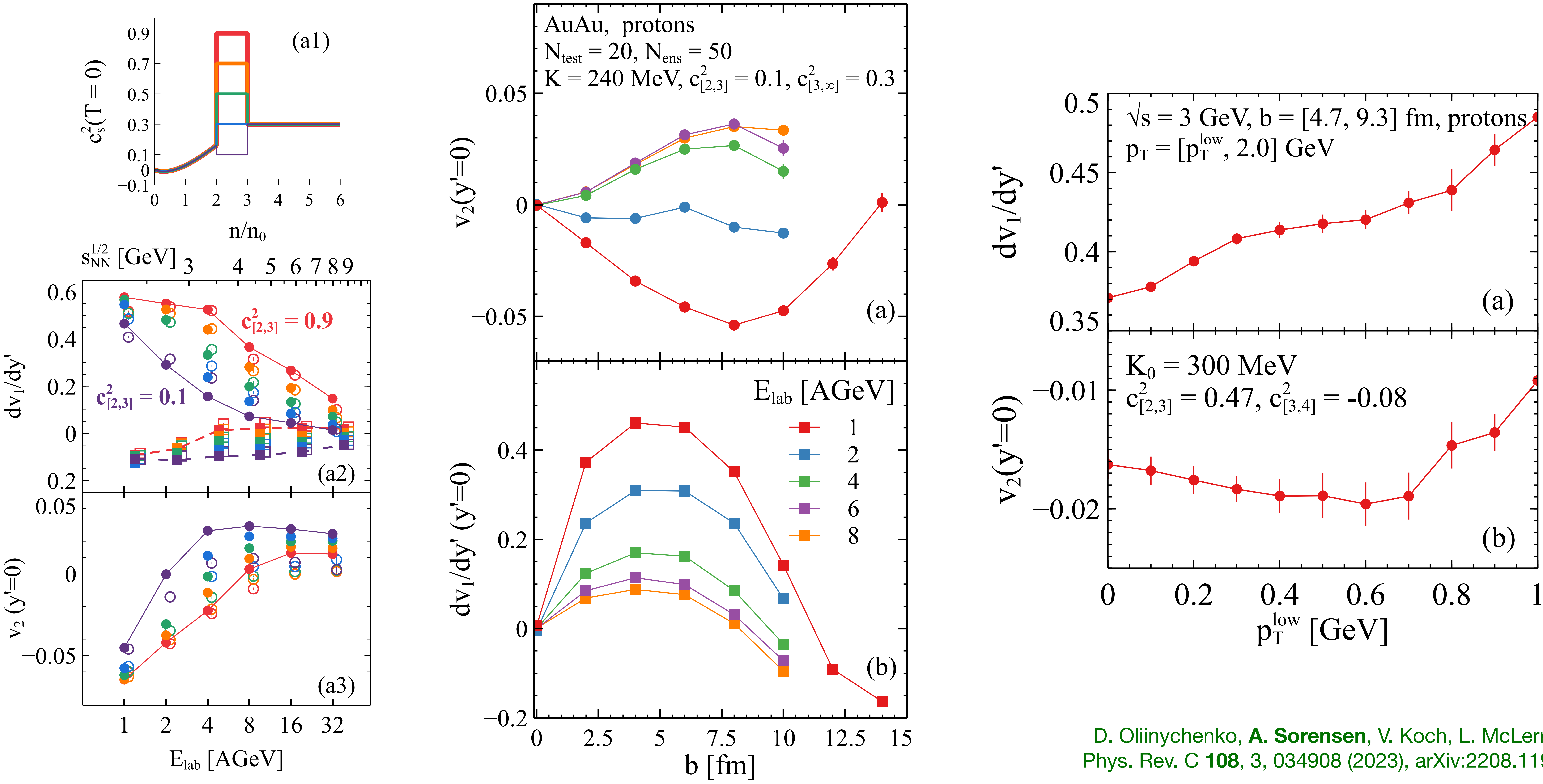

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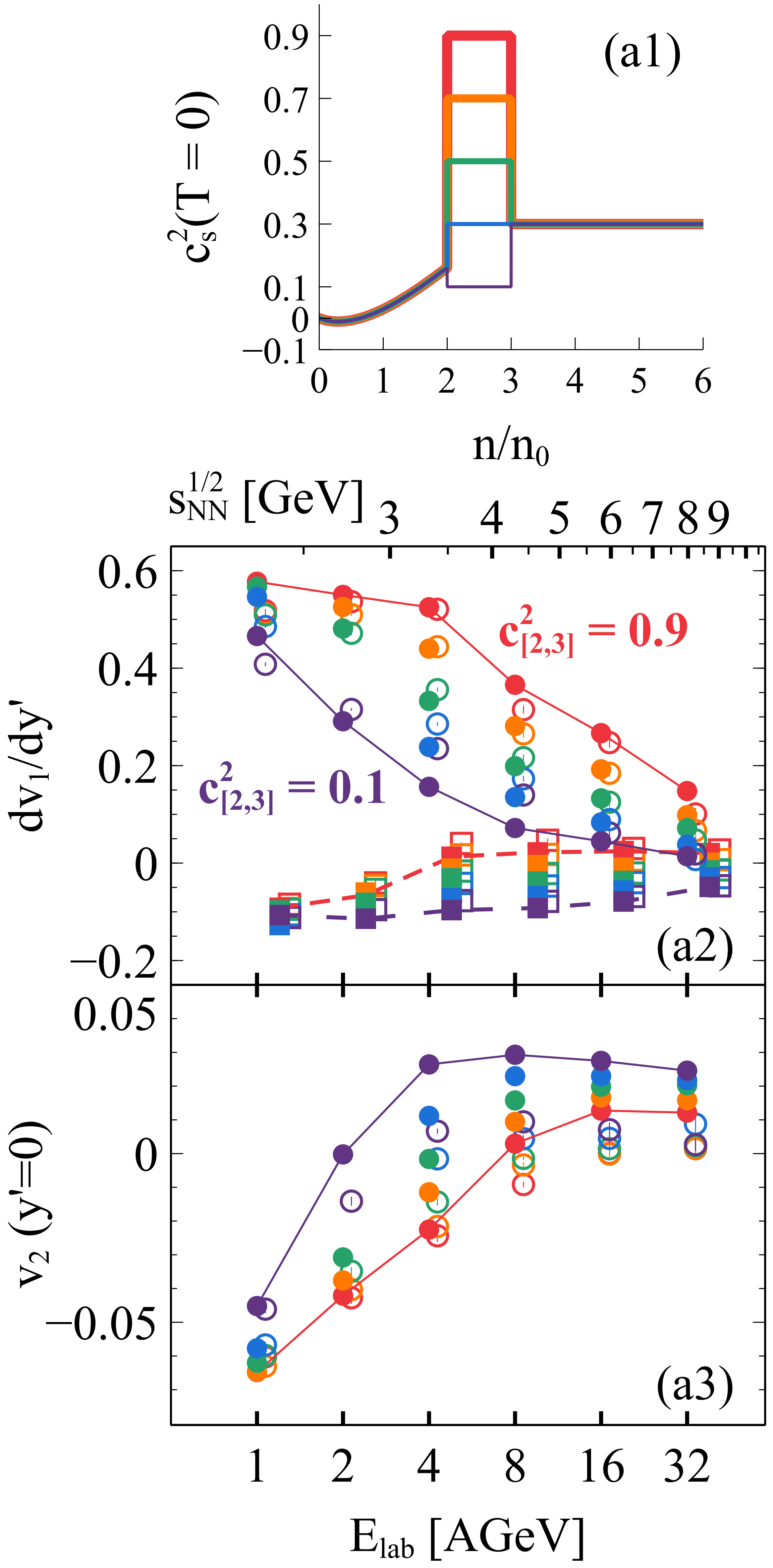

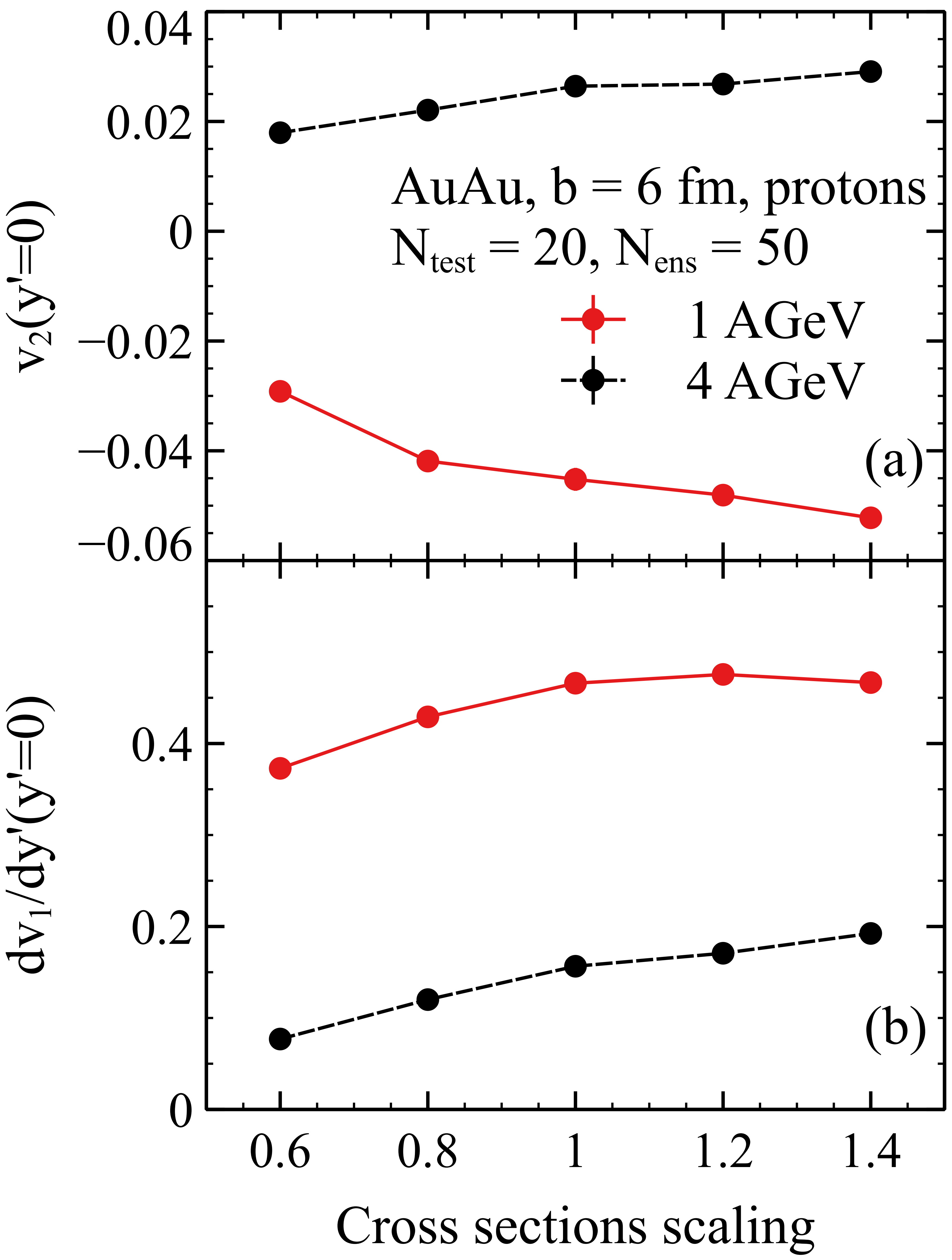

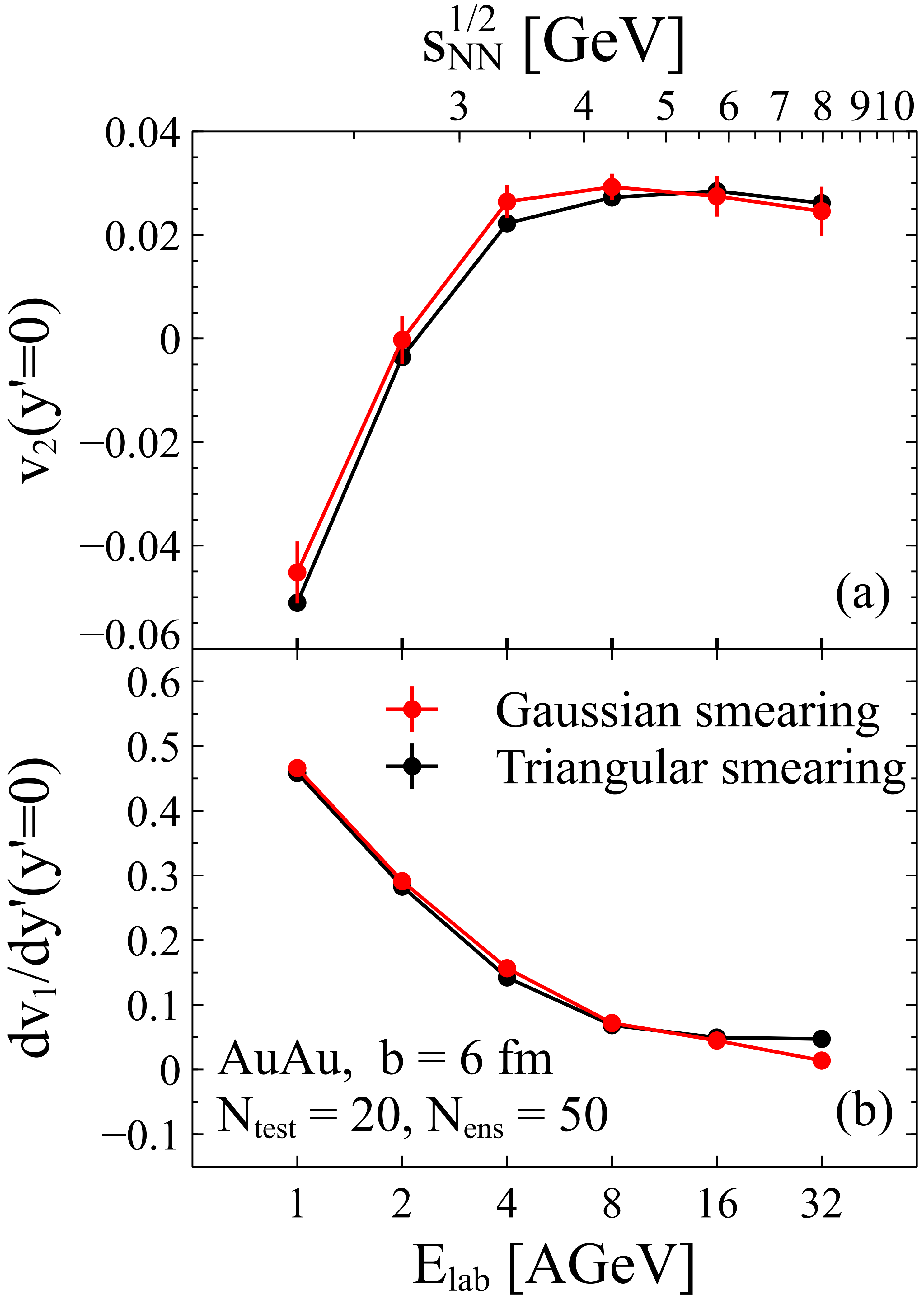

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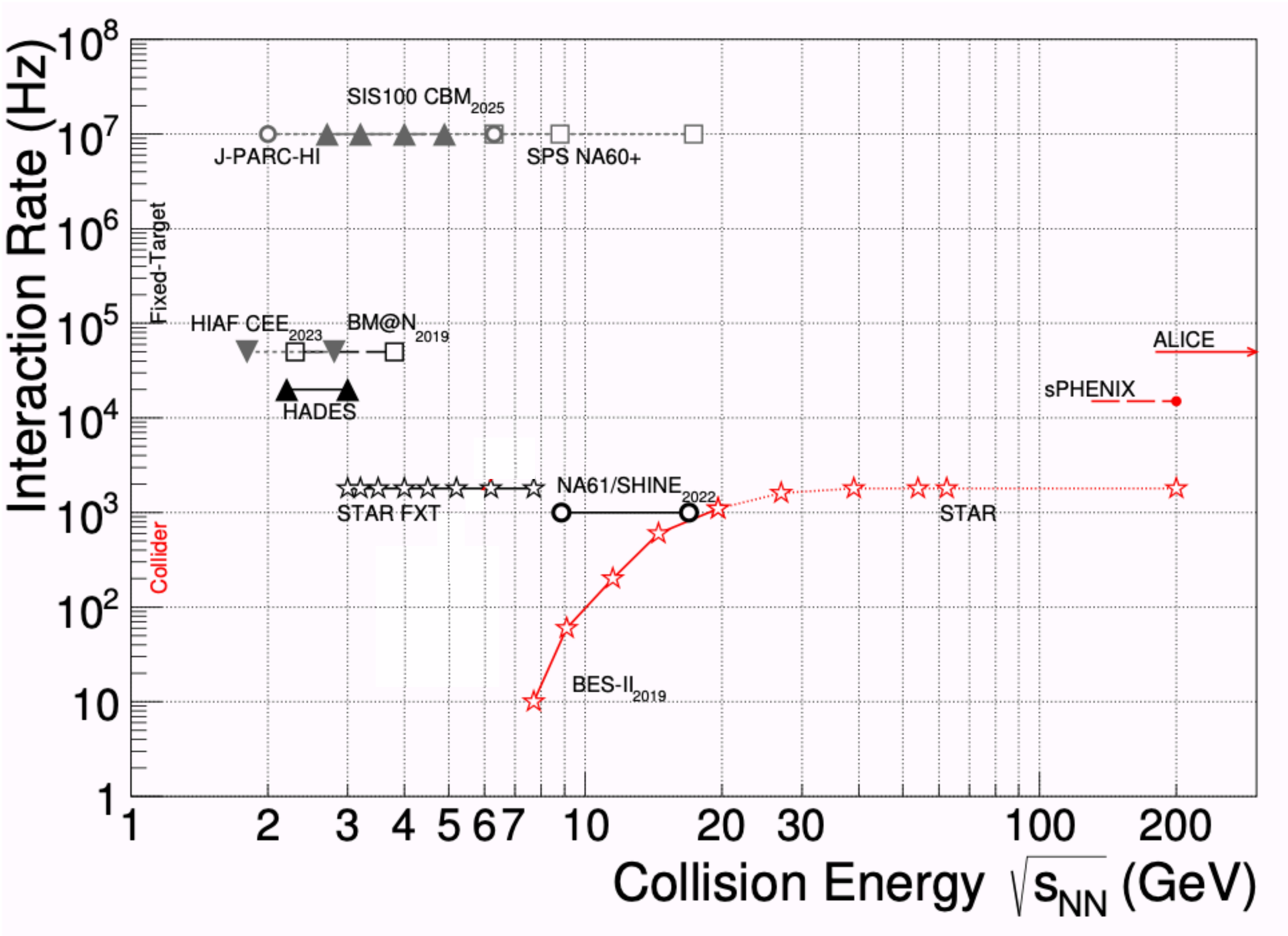
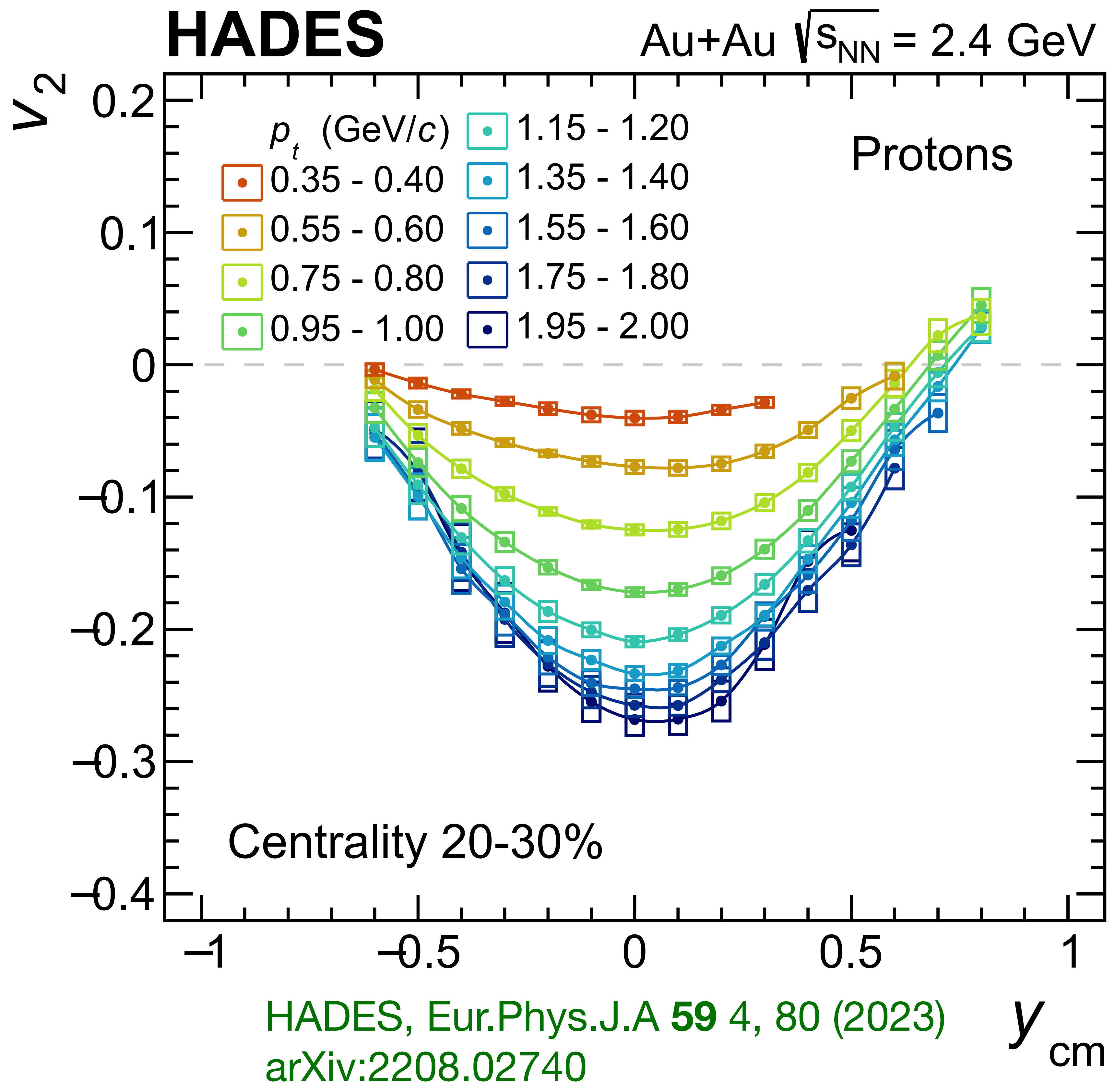
Precision era of heavy-ion collisions





Precision experiments
NEED precision simulations