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Constraining Nuclear Symmetry Energy from Converting Neutron Star EoS into HI Collisions

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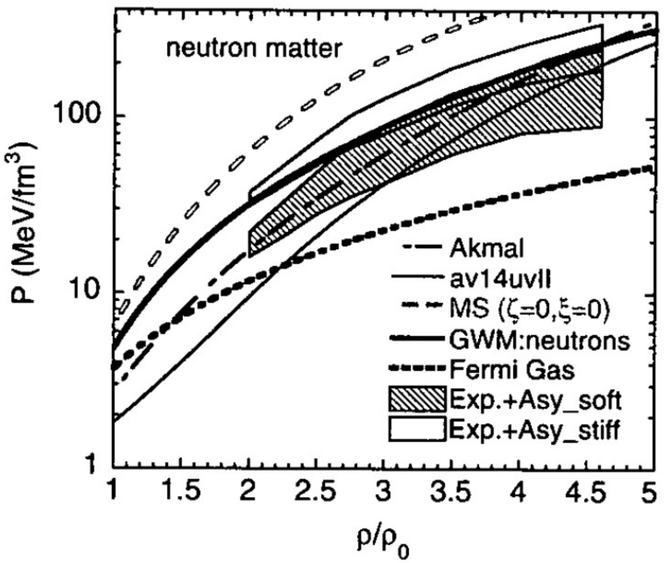
Using HIC to constrain NS EOS

- "Determination of the equation of state of dense matter." Danielewicz et al. Science 298 (2002), pp. 1592–1596.
  - Analyzes flow of matter in nuclear collision to determine P(ρ/ρ_0)
  - Constrains the EOS of symmetric nuclear matter and thus $E_{sym}(\rho)$ which has been parametrized by asymmetric energy term with strong and weak density dependence respectively
  - Obtain predictions for EOS of neutron stars
- Can we use NS EOS to constrain HIC EOS?

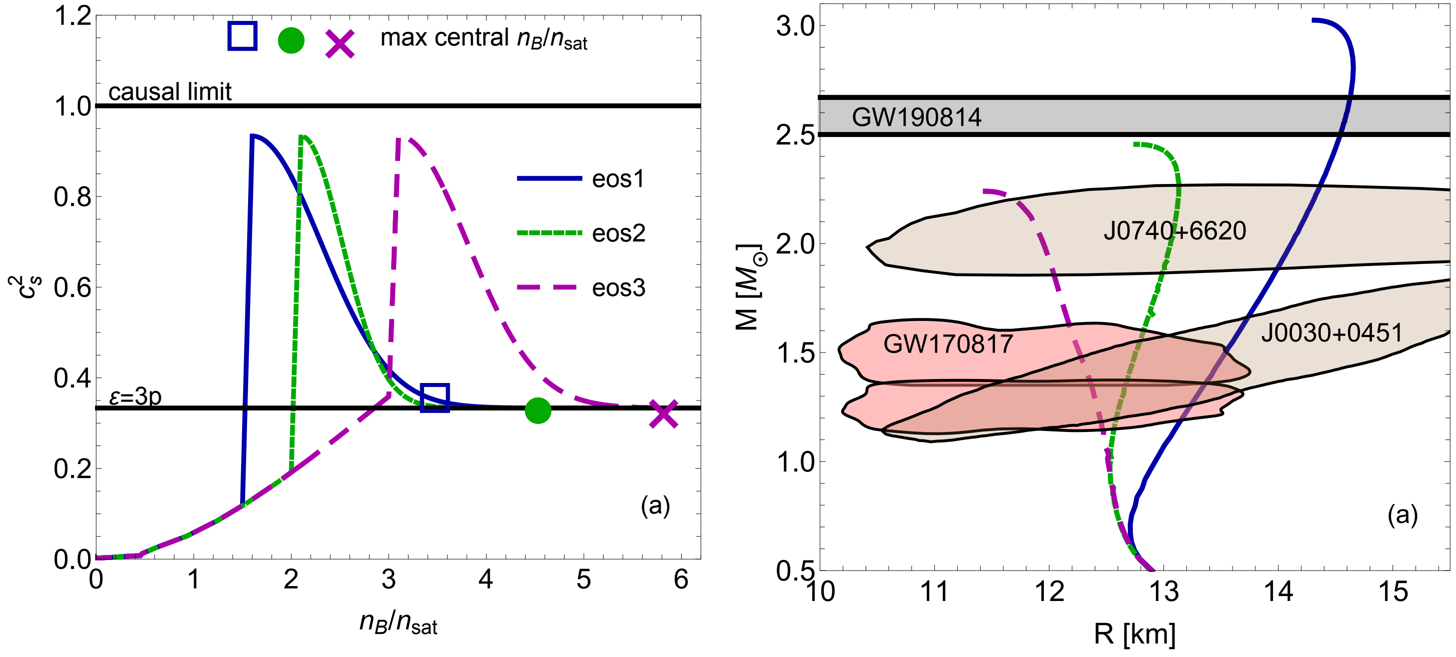


Introduction

- Previous studies: EOS of NS with mass >2.6 $M_\odot$ not consistent with HIC data (F. J. Fattoyev et al. Phys. Rev. C **102**, 065805)
  - Mystery object of 2.5 $M_\odot$, maybe is NS or BH
    - (R. Abbott et al 2020 ApJL **896** L44)
  - Assumed hadronic degrees of freedom
    - no large bump at the c_s^2
- Cold neutron stars (NS) equations of state (EOS) can sustain heavy neutron stars over 2 $M_\odot$
  - Need large, rapid rise in the speed of sound (c_s^2)
- Possible a large bump of c_s^2 at $2n_0$ ~ $3n_0$ shown within SMASH (D. Oliinychenko, A. Sorensen, V. Koch, and L. McLerran, 2022)
- We want to investigate this with different NS EOS: **are the nuclear matter EOSs from astrophysics consistent with heavy-ion collision observables in the range rho < 4.0rho_0?**

Example of Neutron Star EOS

- A steep rise in c_s^2 at intermediate densities
  - associated with higher-order repulsive terms in the description of the strong force among nucleons and hyperons
  - Quarkyonic matter, deconfinement crossover phase transition, new hadronic degrees of freedom
- Easily create a family of EoSs that reach M ≥ 2.5 $M_\odot$, either by implementing a narrow peak at low $n_B$or a wide peak at higher n_B
- EOS 1 – extreme heavy NS
- EOS 2&3 –consistent with most of the experimental data



H. Tan, J. Noronha-Hostler, and N. Yunes, Phys. Rev. Lett. 125, 261104 (2020)

HIC vs Neutron Star

- Cold NS are at T=0 and contain few positively charged particles

$$Y_Q = Z/A$$

  - Z=# of protons, A=# of nucleons ($Y_Q \lesssim 0.2$)
    - EOS is also probed in heavy-ion collisions (HIC) but for nearly symmetric nuclear matter ($Y_Q \sim 0.39$).
  - Example: for Au, Y_Q=79/197=0.4

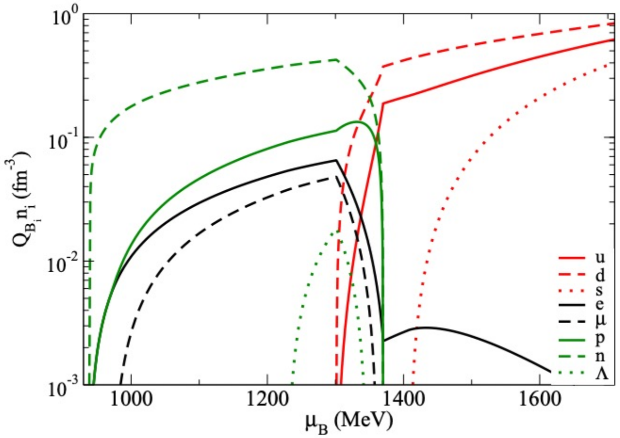


FIG. 7. Particle populations for neutron-star matter with globally conserved electric charge, at $T = 0$.

J. Roark and V. Dexheimer. PRC 98 (2018).

- Use particle distributions for neutron star to get proton fraction (charge fraction)

Nuclear Symmetry Energy Expansion

- Energy per nucleon $E(n, \delta)$ is the most basic term used to obtain EOS of NS, regardless of model used
  - $n \equiv$ baryon number density, $\delta \equiv$ isospin asymmetry
  - $\delta = 1 - 2\, Y_Q$
- $E(n, \delta)$ has a symmetry energy term E_{sym} which quantifies the energy needed to make nuclear matter more neutron rich
- $E_{sym}(n, \delta) = E_{asym} - \left(E_{sym,0} + \frac{L_{sym}}{3}\left(\frac{n_B}{n_0} - 1\right) + \frac{k_{sym}}{18}\left(\frac{n_B}{n_0} - 1\right)^2 + \frac{J_{sym}}{162}\left(\frac{n_B}{n_0} - 1\right)^3\right)\delta^2$
  - Magnitude of the symmetry energy: $E_{sym}(n = n_{sat})$, 31.7 ± 3.2 MeV[1]
  - Slope: $L_{sym} \equiv 3n \frac{dE_{sym}}{dn}\Big|n = n_{sat}$, 58.7 ± 28.1 MeV[1] or 106 ± 37 MeV, PREXII
  - Curvature: $K_{sym} \equiv 9n^2 \frac{d^2E_{sym}}{dn^2}\Big|n = n_{sat}$, -120^{+80}_{-100} MeV[2]
  - Skewness: $J_{sym} \equiv 27n^3 \frac{d^3E_{sym}}{dn^3}\Big|n = n_{sat}$, 300 ± 500 MeV[3]

[1]M. Oertel et al. Rev. Mod. Phys. 89, 015007 (2017)
[2]W.-J. Xie et al, Astrophys. J. 899, 4 (2020)
[3]I, TEWS et al. Astrophys. J. 848, 105 (2017)

Nuclear Symmetry Energy Expansion

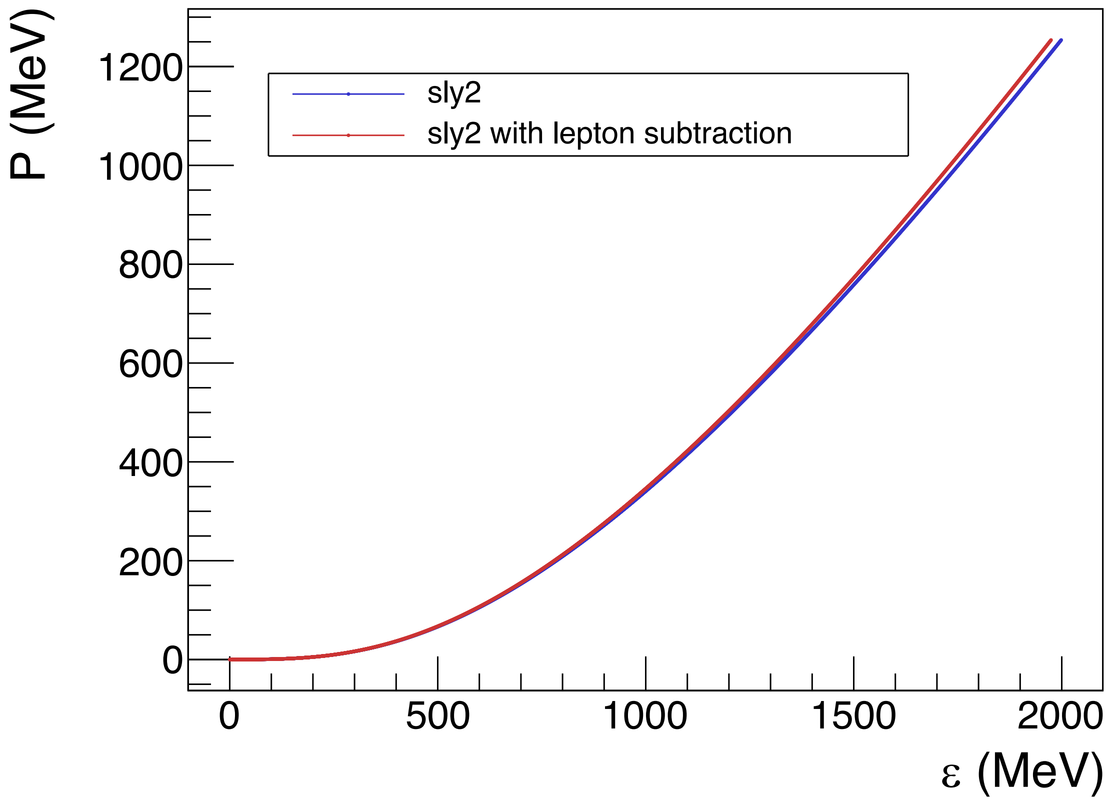
- For HIC, we do not have perfectly symmetry nuclear matter
  - $Y_{HIC} = 0.39$
- $Y_Q(n_B)$ dependence on baryon density
- Thus, we obtain the asymmetric energy density for HIC from symmetric energy density through a double expansion:
  - We vary Y_{HIC} to study the dependence of EOS on Y_{HIC}

$$\epsilon_{HIC} = \epsilon_{NS} - 4\left[E_{sym,0} + \frac{L_{sym}}{3}\left(\frac{n_B}{n_0} - 1\right) + \frac{K_{sym}}{18}\left(\frac{n_B}{n_0} - 1\right)^2 + \frac{J_{sym}}{162}\left(\frac{n_B}{n_0} - 1\right)^3\right]\left[\left(\boldsymbol{Y_{HIC}} - \boldsymbol{Y_Q}(\boldsymbol{n_B})\right) + \left(\boldsymbol{Y_Q^2}(\boldsymbol{n_B}) - \boldsymbol{Y_{HIC}^2}\right)\right] n_B$$

[1]N. Yao, D. Oliinychenko, A. Sorensen, V. Dexheimer and J. Noronha-Hostler in preparation

Subtraction of leptons

- To obtain pure nucleon energy density, we subtract lepton's Fermi contribution
- Low density NS EOS from SLY2
- Minor effect at high baryon density but important to get correct binding energy at n_{sat}



Algorithm of obtaining HIC EOS at T=0

Input: NS EOS

Symmetry Energy Expansion Coefficients

Subtract Fermi energy contribution of lepton

Convert NS energy density to HIC energy density

Obtain pressure via

$$p = n_B^2 \frac{d\frac{\epsilon}{n_B}}{dn_B}$$

Calculate Speed of Sound via

$$c_s^2 = \frac{dP}{d\epsilon}$$

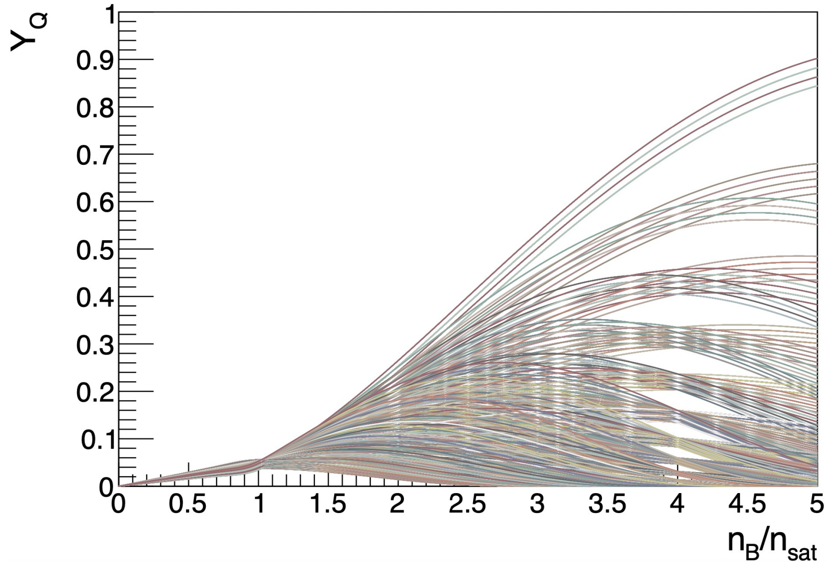
Y_Q dependence on density

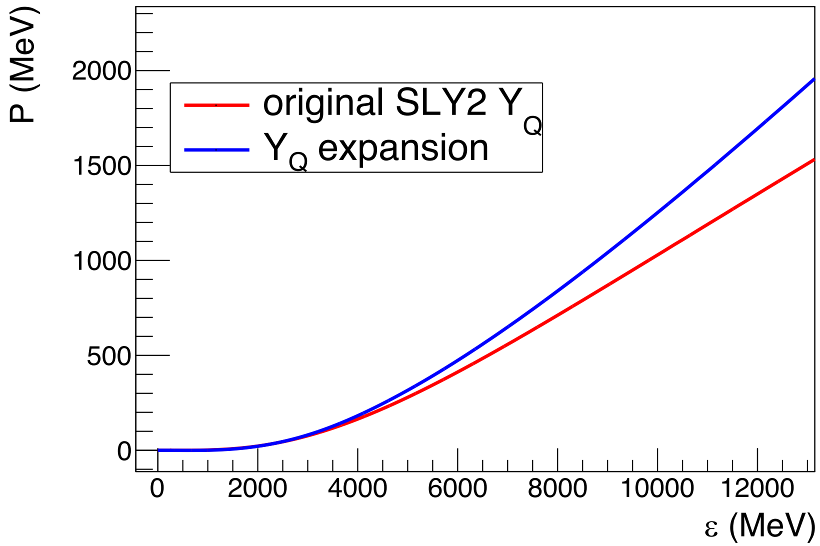
Courtesy M. Mendes, F. J. Fattoyev, A. Cumming, and C. Gale

$$Y_Q \cong \frac{64}{3\pi^2 n_{sat}(3x+1)}\left(\frac{E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2}{\hbar c}\right)^3$$

- Varying E_{sym}, L_{sym}, K_{sym}
- For $n_B < n_{sat}$, since Y_Q would diverge, we use a transition function tanh so that Y_Q converges to 0

- Proof of principle: converted EOS from SLY2 with known symmetry energy coefficients
- Shows range of applicability of the Y_Q expansion





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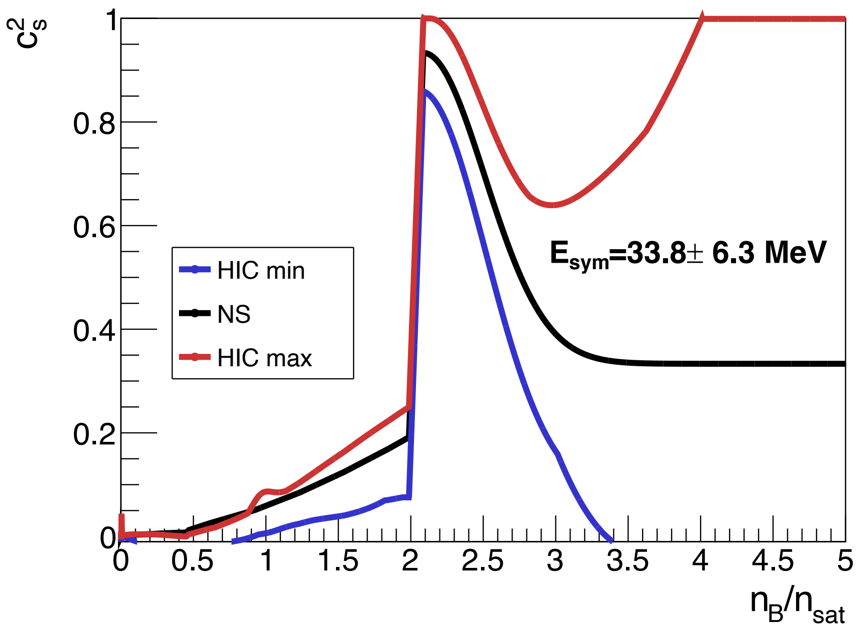
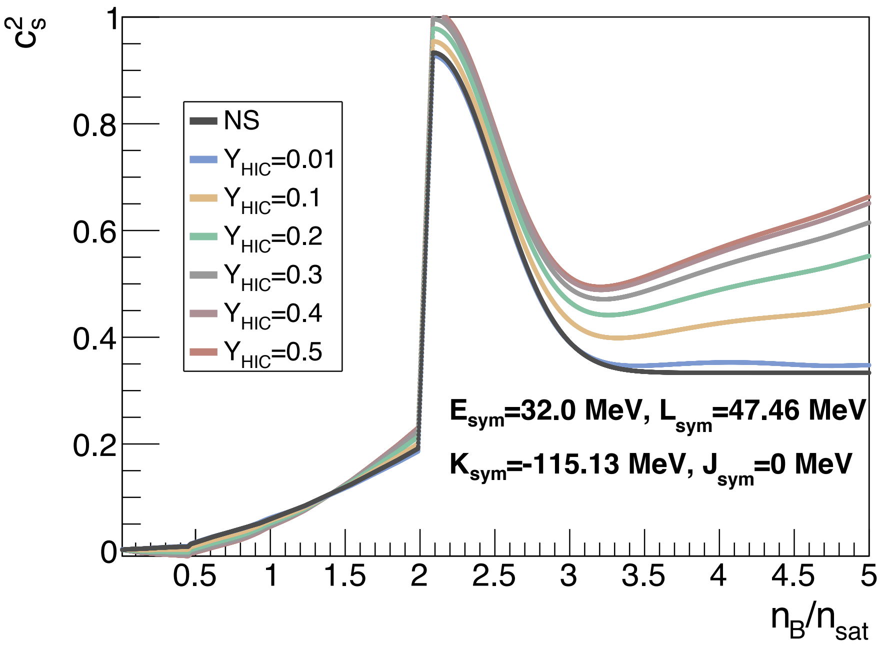
Results: Converted EOS

- Bump is preserved
- Different Y_{HIC} slices: The converted EOS with lower Y_{HIC} is more similar to original NS EOS
- If from quarkyonic matter, then YQ expansion doesn't really work at high density





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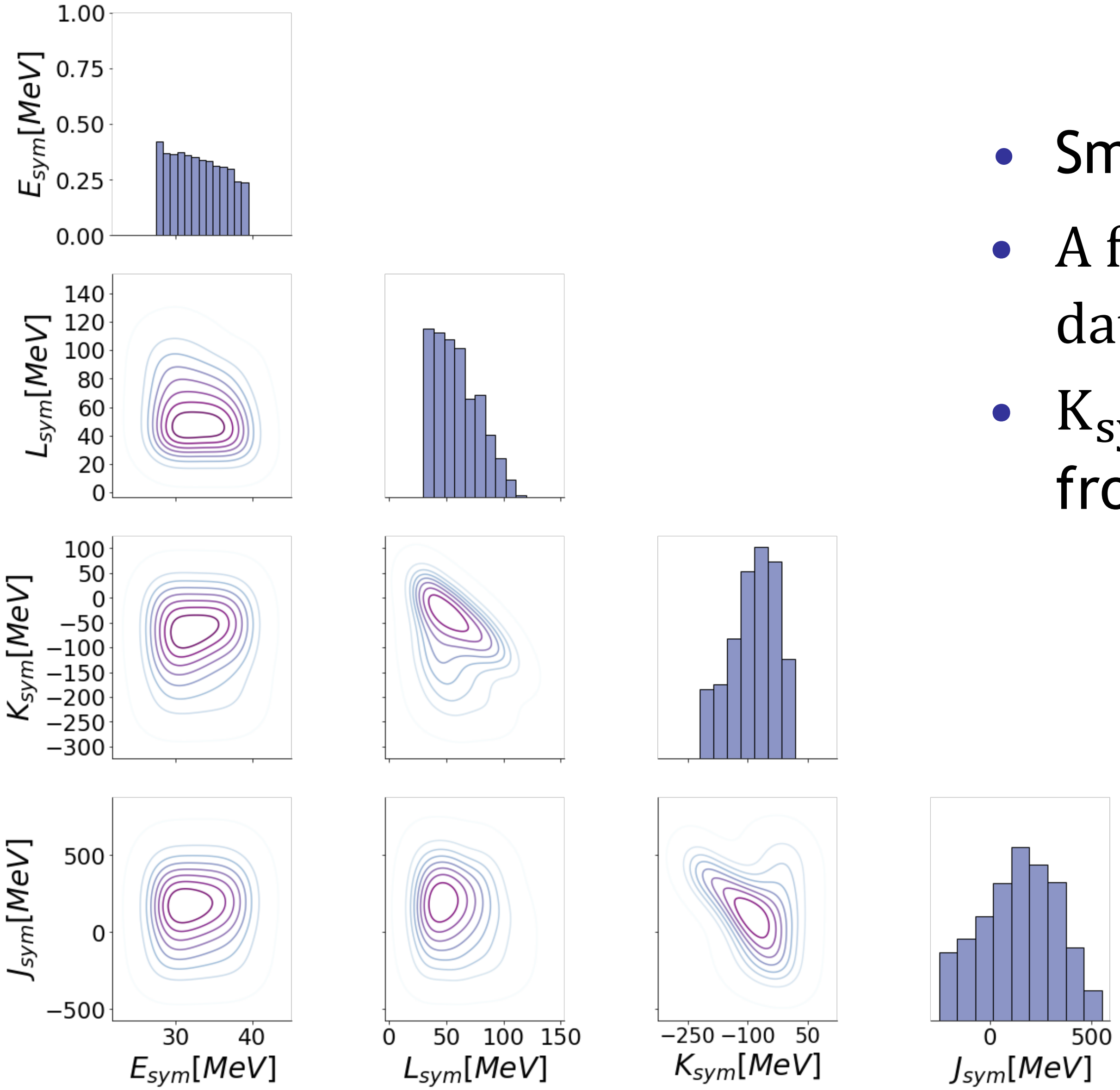
Results: Constrained Coefficients



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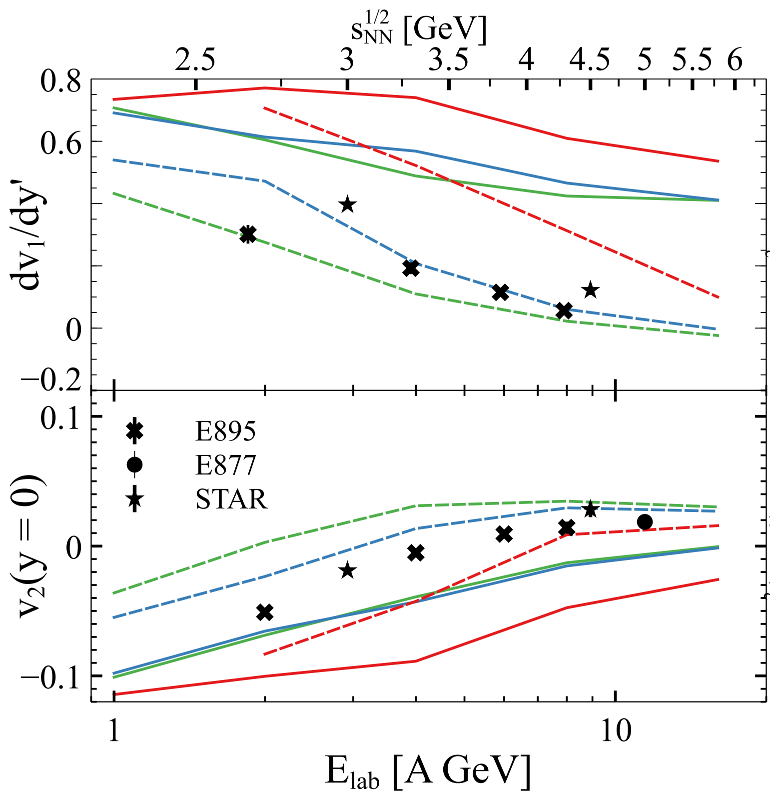
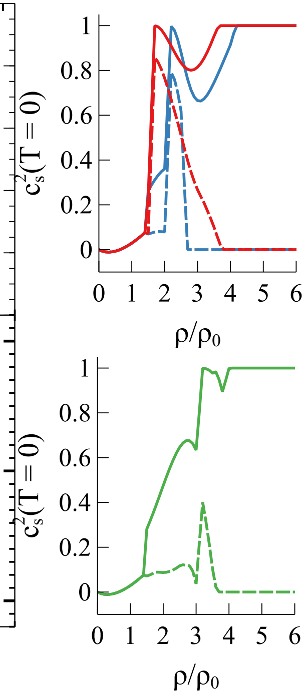
- Smaller L_{sym} is preferred
- A few L_{sym} >100 MeV data points
- K_{sym} is constrained from -200 to 50 MeV

SMASH results





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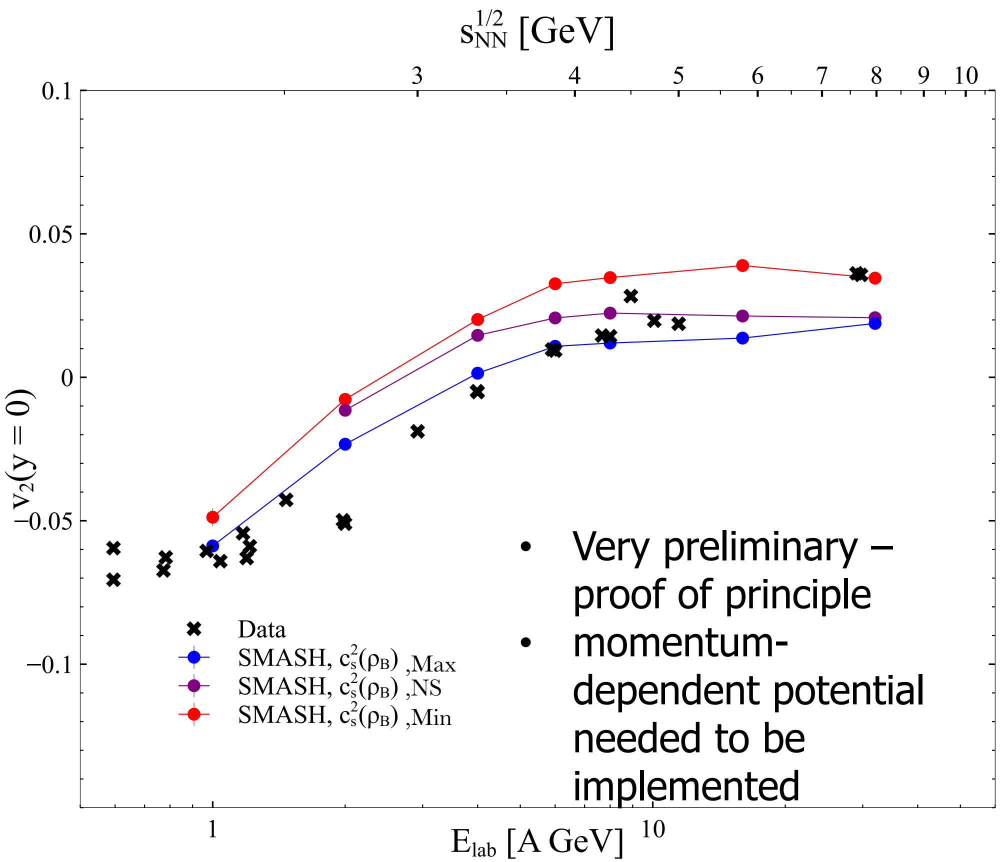
- SMASH: a new hadronic transport approach to provide descriptions of heavy-ion reactions at low and intermediate beam energy
  - *Input: converted HIC EOS from NS EOS*
  - *Compare HIC observables simulated from SMASH with experimental data*
  - *Au + Au collisions*
- Parametrized c_s^2 based on our EOS
- EOS with sharp rise at $2\rho_0$ is favored by the flow data
- Preliminary - momentum-dependent potential needed

Conclusion & Outlook

- Converted HIC EOS preserves the large rise of c_s^2
- Constrained the symmetry energy coefficients further
- Proof of principle – once momentum dependent potential is implemented in SMASH, we can check with experimental data
- Strangeness?
- Compare with different data – consider hydro?

SMASH results



- Very preliminary – proof of principle
- momentum-dependent potential needed to be implemented

- SMASH: a new hadronic transport approach to provide descriptions of heavy-ion reactions at low and intermediate beam energy

J. Weil et al., Phys. Rev. C 94, 054905 (2016)

- Motivation:
  - *Input converted HIC EOS from NS EOS*
  - *Compare HIC observables simulated from SMASH with experimental data*
- Au + Au collisions
- Parametrized c_s^2 based on our EOS