Pre-clustering near the QCD critical point: nuclear correlations and light-nuclei production

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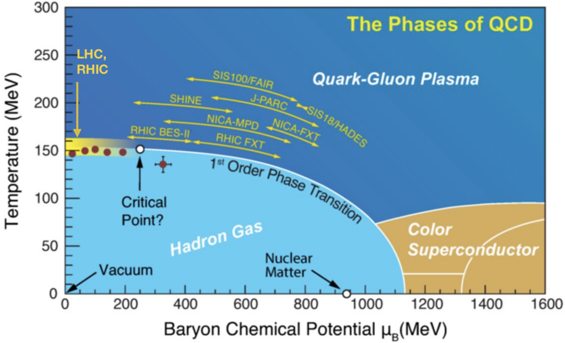
HOT PROBLEMS OF STRONG INTERACTIONS

QCD phase diagram and critical point

from Bazavov et al., *1904.09951*



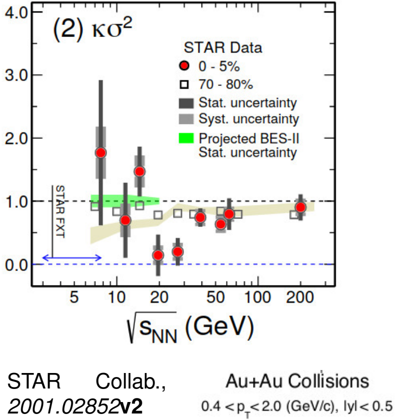
- Hypothetical QCD critical point in baryon-rich region
- Lattice-QCD favors $\mu_B/T > 2-3$ (e.g. Bazavov et al., *PRD95, 054504 (2017)*. $\mu_B/T = 4-5$ in DSE/FRG (C. Fischer and J. Pawlowski talks)
- Nucleon physics relevant in this region $\rightarrow$ Net-proton observables

Net-proton kurtosis

$$C_2 = \langle \delta N^2_{p-\bar{p}} \rangle$$

$$C_4 = \langle \delta N^4_{p-\bar{p}} \rangle - 3\langle \delta N^2_{p-\bar{p}} \rangle^2$$

$$\kappa\sigma^2 = C_4/C_2$$



STAR Collab., *2001.02852***v2**

- Proton-proton interaction contained in cumulants of (net) proton distribution

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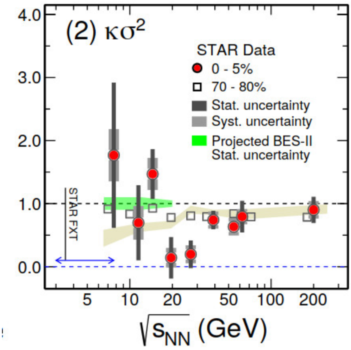
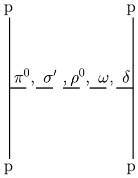


STAR Collab., *2001.02852***v2**

Au+Au Collisions
0.4 < p_T < 2.0 (GeV/c), |y| < 0.5

- Proton-proton interaction contained in cumulants of (net) proton distribution
- Baryon interaction potential V_{NN} modeled via boson exchange



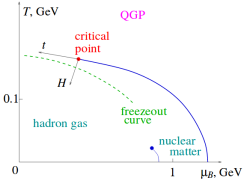
(from Machleidt and Slaus, *J.Phys.G:Nucl.Part.Phys.27 R69*)

- $T \simeq m_0$, in-medium modifications
- **Main** effect of critical point on V_{NN}?

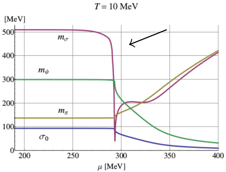
QCD critical mode

σ mass drops at critical point

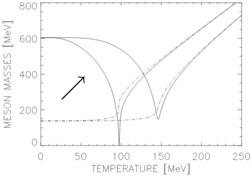
$$m_\sigma \sim \frac{1}{\xi} \sim \left(\frac{|T-T_c|}{T_c}\right)^\nu$$



Stephanov, *PRL 102 (2009) 032301, PRL 107 (2011) 052301*



Tripolt et al., *PRD89 (2014),034010*



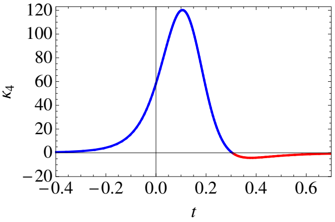
Scavenius et al., *PRC64 (2001) 045202*

$$P[\sigma] \sim \exp\left(-\Omega/T\right)$$

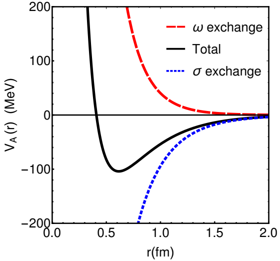
$$\Omega = \int d^3x \, \frac{(\nabla\sigma)^2}{2} + \frac{m_\sigma^2}{2}\sigma^2 + \frac{\lambda_3}{3}\sigma^3 + \frac{\lambda_4}{4}\sigma^4$$

$$\kappa_2 = \langle\sigma_0^2\rangle \quad , \quad \kappa_4 = \langle\sigma_0^4\rangle - 3\langle\sigma_0^2\rangle^2$$

$$\textit{Kurtosis} = \kappa_4/\kappa_2^2$$

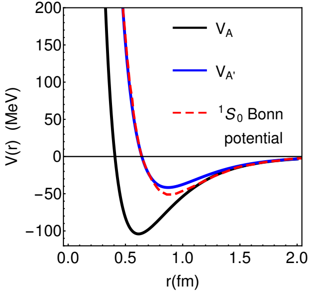


Serot-Walecka model for *NN* interaction (*Adv.Nucl.Phys.16 (1986) 1*)



- σ controls attraction
- Cancellation between attraction and repulsion leads to bound nuclear matter
- Small imbalance would substantially modify physics

$$V_A(r) = -\frac{\alpha_\sigma}{r} e^{-m_\sigma r} + \frac{\alpha_\omega}{r} e^{-m_\omega r}$$

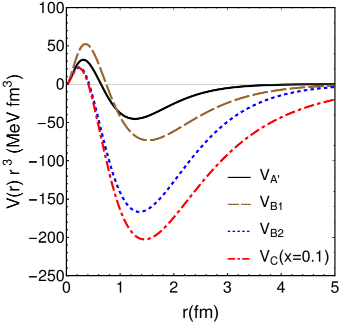


What happens to V_{NN} around T_c?

NN potential modifications

Shuryak and JMT-R,*PRC100 (2019), 024903, PRC 101 (2020) 034914*

- Decrease of m_σ not compensated by repulsion
- Net nuclear attraction generates proton-proton correlations

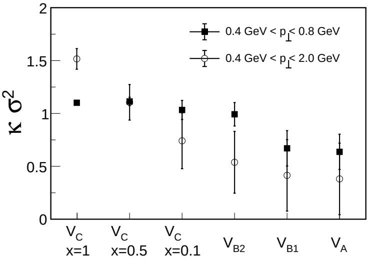


- $V_{A'}$: Serot-Walecka with extra repulsion ($\sim$ Bonn potential)
- V_{B1}: $\{m_\sigma^2, \alpha_\sigma\} = \{m_{\sigma,0}^2/2, \alpha_{\sigma,0}/2\}$
- V_{B2}: $m_\sigma^2 = m_{\sigma,0}^2/2$
- V_C: $m_\sigma^2 \in (m_{\sigma,0}^2/2, m_{\sigma,0}^2/6)$

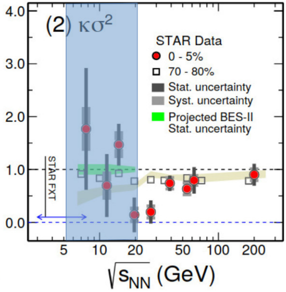
Implications in dynamics?

Caveat very close to T_c: σ self-interaction can lead to repulsion (DeMartini, Shuryak, *2010.02785*)

- Molecular Dynamics of a nucleon gas in thermal equilibrium (Shuryak and JMT-R, *PRC100 (2019), 024903)*
- Mimicking STAR freeze-out conditions for $\sqrt{s_{NN}} < 19.6$ GeV



Shuryak, JMT-R, *PRC100 (2019), 024903*



STAR Collab., *2001.02852v2*

Results of **simple** model same order as STAR data (also skewness). **STAR data might be showing us effects of modified potential**

Pre-cluster vs nuclei

Pre-clusters

- Formed by strong nuclear correlations (modified *NN* potential) until freeze-out.
- $T \sim 120$ MeV. Mostly classical states.
- Broad ($\Delta E \sim T$) states with characterized by Wigner distribution

Nuclei

- Final state, measured by experiment.
- $T \simeq 0$. Quantum states. No critical modification.
- Characterized by wave function $\Psi_{\rm nuclei}$

Pre-clusters can decay into ground state, into stable products or survive as excited states until final decay.

E (MeV)	J^P	Γ (MeV)	decay modes, in %
20.21	0^+	0.50	$p = 100$
21.01	0^-	0.84	$n = 24,\ p = 76$
21.84	2^-	2.01	$n = 37,\ p = 63$
23.33	2^-	5.01	$n = 47,\ p = 53$
23.64	1^-	6.20	$n = 45,\ p = 55$
24.25	1^-	6.10	$n = 47,\ p = 50,\ d = 3$
25.28	0^-	7.97	$n = 48,\ p = 52$
25.95	1^-	12.66	$n = 48,\ p = 52$
27.42	2^+	8.69	$n = 3,\ p = 3,\ d = 94$
28.31	1^+	9.89	$n = 47,\ p = 48,\ d = 5$
28.37	1^-	3.92	$n = 2,\ p = 2,\ d = 96$
28.39	2^-	8.75	$n = 0.2,\ p = 0.2,\ d = 99.6$
28.64	0^-	4.89	$d = 100$
28.67	2^+	3.78	$d = 100$
29.89	2^+	9.72	$n = 0.4,\ p = 0.4,\ d = 99.2$

Excited states of ^{4}He (*www.nndc.bnl.gov/nudat2/*)

Excited states of Helium-4

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- **Statistical thermal model:** all states equally populated at finite T
- They necessarily account for feed-down in t, d, p yields
- Practical implementation by Vovchenko et al. *PLB 809 (2020) 135746* using Thermal-FIST: *5-10 % effect at RHIC/SPS and $\sim$ 60 % effect GSI/FAIR for final t, ^{3}He, ^{4}He*

Feed down particularly important if V_{NN} is modified

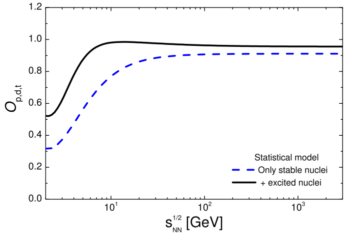
How to observe the effect when overall multiplicity is low?

$$\frac{N_t N_p}{N_d^2} = g \qquad (g = 0.29)$$

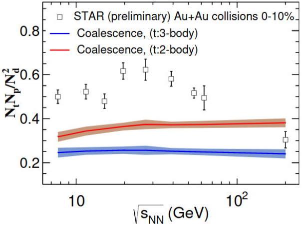
- Assumption: **Statistical thermal model** provides a fair description

$$N = \mathcal{V}\,\frac{(2S+1)}{2\pi^2}\,m^2 T\, K_2(m/T)\,\exp\left(\frac{B\mu_B + q\mu_q}{T}\right)$$

- Feed down corrections are also important
- Ratio introduced by Sun et al. *PLB 774, 103 (2017)* in coalescence model



Vovchenko et al., *PLB 809 (2020) 135746*

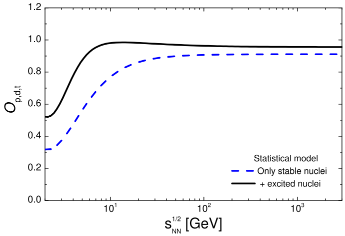


Zhao et al., *PRC 102, 044912 (2020)*

Non-ideal effects

$$\frac{N_t N_p}{N_d^2} \simeq g \frac{\langle \exp\left(-\frac{3V_{NN}(r)}{T}\right)\rangle}{\langle \exp\left(-\frac{V_{NN}(r)}{T}\right)\rangle^2} \sim g \left\langle e^{-\frac{V_{NN}(r)}{T}} \right\rangle$$

If $|V_{NN}| \simeq T$ close to the critical point, then a nonmonotonous behavior for the ratio is to be expected (enhancement factor *e*)



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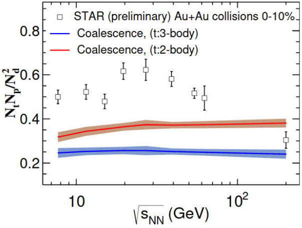
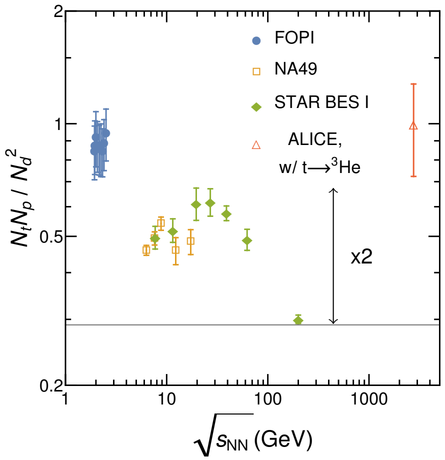


Zhao et al., *PRC 102, 044912 (2020)*

Some experimental data:



- FOPI, total yields, 4π reconstruction, Au+Au collisions, most central [*NPA848, (2010) 366-427*]
- STAR BES-I, preliminary 0%-10% Au+Au, ratios based on extrapolated yields at midrapidity (arXiv:1909.07028)
- Sun et al. *PLB 774, 103 (2017)* based on NA49 data. dN/dy at midrapidity, Pb+Pb central (typically 0-7%)
- ALICE, Pb+Pb @ $\sqrt{s_{NN}} = 2.76$ TeV (data from several sources). dN/dy at midrapidity (^{3}He used instead triton)

New light-nuclei yield ratios

Ratios involving ^{4}He (=α) with higher global powers of $e^{|V(r)/T|}$

$$\mathcal{O}_2 \equiv \frac{N_\alpha N_p}{N_{^3\mathrm{He}} N_d} \simeq 0.18 \frac{\langle e^{-6V(r)/T} \rangle}{\langle e^{-3V(r)/T} \rangle \langle e^{-V(r)/T} \rangle}$$

$$\mathcal{O}_3 \equiv \frac{N_\alpha N_t N_p^2}{N_{^3\mathrm{He}} N_d^3} \simeq 0.05 \frac{\langle e^{-6V(r)/T} \rangle}{\langle e^{-V(r)/T} \rangle^3}$$

(in practice, $N_t \simeq N_{^3\mathrm{He}}$) (Shuryak, JMT-R, *PRC 101 (2020) 034914*)

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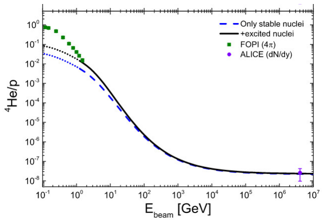
^{4}He production not negligible at low energies (Vovchenko et al. *PLB 809 (2020) 135746*)

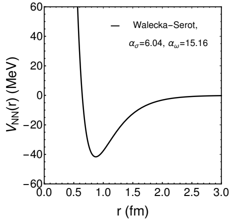
Data exist at very low (FOPI) and high energies (ALICE)



Fluctuon solution for 2 particles

Euclidean action

$$S_E = \int d\tau \left[\frac{m_N}{2}(\dot{x}_1^2 + \dot{x}_2^2) + V_{NN}(|\mathbf{x}_1 - \mathbf{x}_2|) \right]$$
$$= \int d\tau \left(\frac{m_N}{4}\dot{r}^2 + V_{NN}(r) \right) + C.M.$$

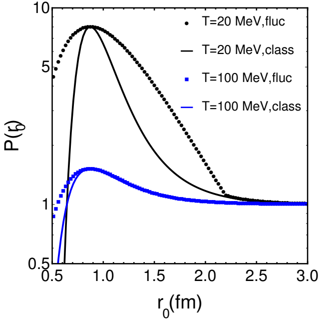


1. Experimental $N_t N_p / N_d^2$ ratio fixes $V_{NN}/T(r, m_\sigma, T)$ via flucton method
2. Spatial averages using

$$\langle A \rangle \equiv \frac{4\pi \int dr r^2 A(r)[P(r) - 1]}{4\pi \int dr r^2 [P(r) - 1]}$$

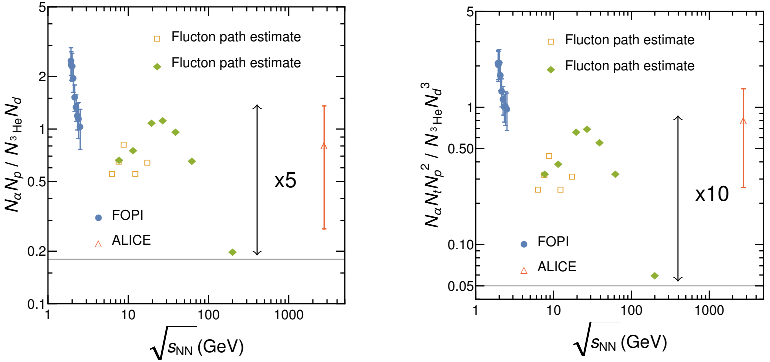
3. New ratios can be computed with calibrated $V_{NN}/T(r, m_\sigma, T)$

$$P(r_0) = e^{-S_E[r_{fluc}(\tau, r_0)]} \; ; \; P_{class}(r_0) = e^{-V(r_0)/T}$$



Shuryak, *NPB 302 (1988) 621*
Shuryak and JMT-R, *EPJA 56 (2020) 9, 24*

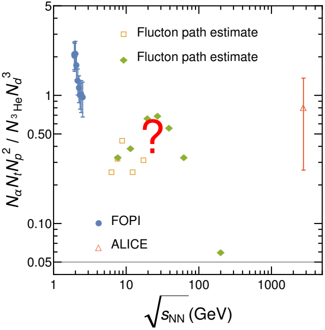
Shuryak and JMT-R, *EPJA 56 (2020) 9, 24*



- ^{4}He enhances the expected effect a factor 5 wrt $N_t N_p / N_d^2$
- Good observable for testing nuclear modification
- **We need ^{4}He measurement at intermediate energies!**

Summary

- Significant attractive and long-ranged NN potential near T_c
- Increased correlations among nucleons
  Affect proton distribution probability and its cumulants
- Formation of pre-clusters (statistical correlations of nucleons)
  Generation and later decay of ^{4}He (and other) excited states
- Possible enhanced production of light nuclei at "critical $\sqrt{s_{NN}}$"
  Light-nuclei yield ratios using ^{4}He to test the proposed effect



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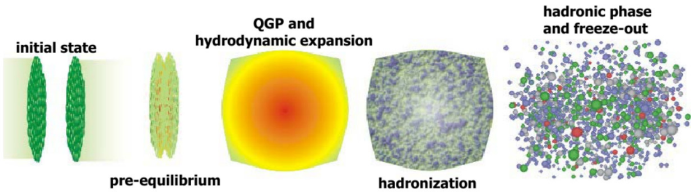
Approaching the physical case

Effects preventing clustering

- Expansion, radial collective flow
- Freeze-out temperatures $T \sim 150$ MeV
- Finite time effects (duration of hadronic phase)

We need to address these for RHIC collisions at the Beam Energy Scan



Focus on BES I at $\sqrt{s_{NN}} < 19.6$ GeV, as measured by STAR @ RHIC (STAR Collab. 2016 & 2017)

BES STAR freeze out

We try to mimic as much as possible experimental situation in BES I, as measured by STAR @ RHIC (STAR Collab. 2016 & 2017)

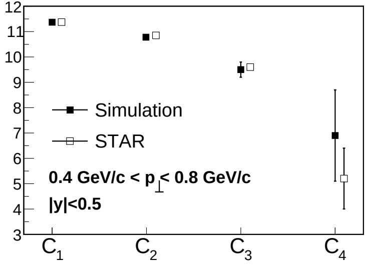
- Temperature $T \simeq 150$ MeV
- Densities: 1-2 n_0
- Finite time evolution: $t = 5$ fm
- Non-relativistic nucleon dynamics
- Fireball expansion: mapping of y and p_T distributions to experimental measured distributions
- Simulations: 32 nucleons, 10^5 events (similar to experiment for 5% most central events)
- Antinucleons: For $\sqrt{s_{NN}} < 19.6$ GeV they are suppressed, at least, a factor of 10 w.r.t. protons

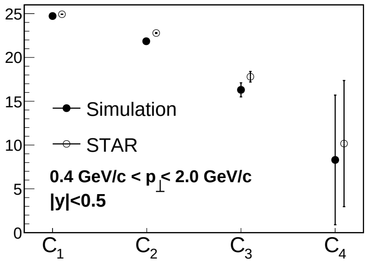
Note: It is a crude model and several effects not covered.
Understand as a first approximation to the physical situation.

Poisson distribution at $\sqrt{s_{NN}} = 19.6$ GeV $\leftrightarrow$ Noncritical potential $V_{A'}$

- $|y| < 0.5, \quad 0.4$ GeV/$c < p_\perp < 0.8$ GeV/c
- $|y| < 0.5, \quad 0.4$ GeV/$c < p_\perp < 2$ GeV/c

protons

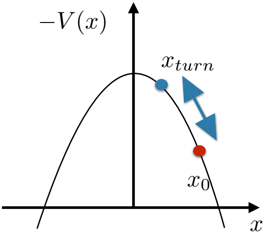


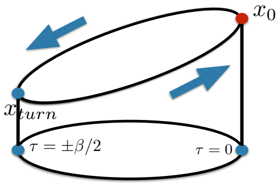


$$C_1 = \langle N_p \rangle \ , \quad C_2 = \langle \delta N_p^2 \rangle \ , \quad C_3 = \langle \delta N_p^3 \rangle \ , \quad C_4 = \langle \delta N_p^4 \rangle - 3 \langle \delta N_p^2 \rangle^2$$

Quantum effects: Fluction solution

The flucton is a semiclassical solution of the EoMs in Euclidean time with period $\beta = 1/T$ (Shuryak, 1988). Conceptually similar to the instanton.





Unlike the instanton it is periodic $x(\beta) = x(0) = x_0$, and it does not require a double well. We applied to 2,3,4-body systems at finite temperature

$$P(x_0) = \langle x_0 | e^{-\hat{H}\beta} | x_0 \rangle = \int_{x(0)=x_0}^{x(\beta)=x_0} \mathcal{D}x(\tau)\ e^{-S_E[x(\tau)]}$$