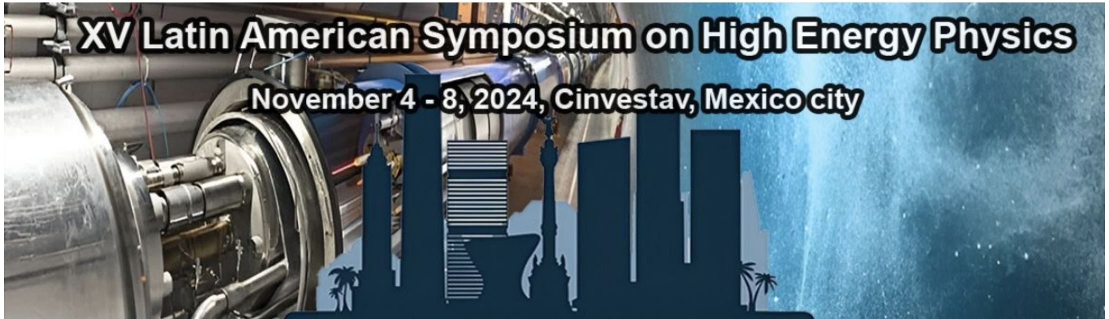
UNIVERSIDAD AUTÓNOMA METROPOLITANA
Casa abierta al tiempo
Unidad Iztapalapa

Departamento de Física

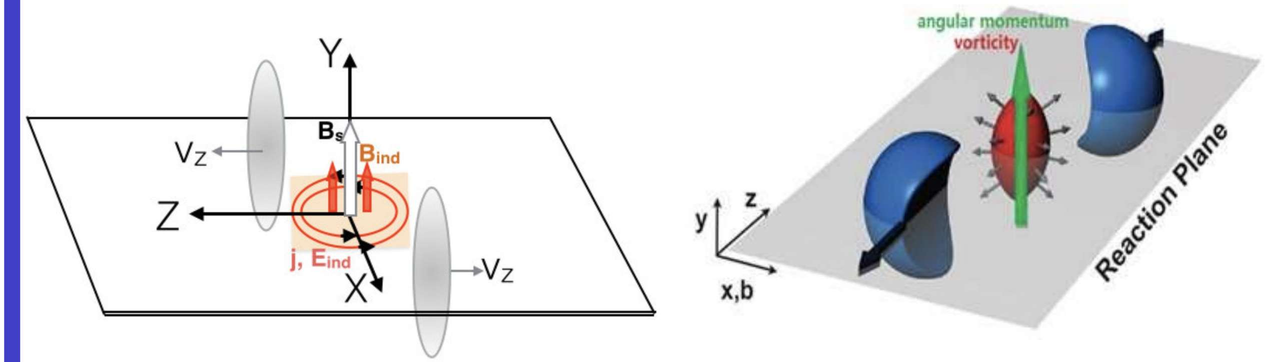
Área de Física Teórica

Exploring Multiple QCD Phase Diagrams

Luis Alberto Hernández Rosas
Universidad Autónoma Metropolitana



CONTENT

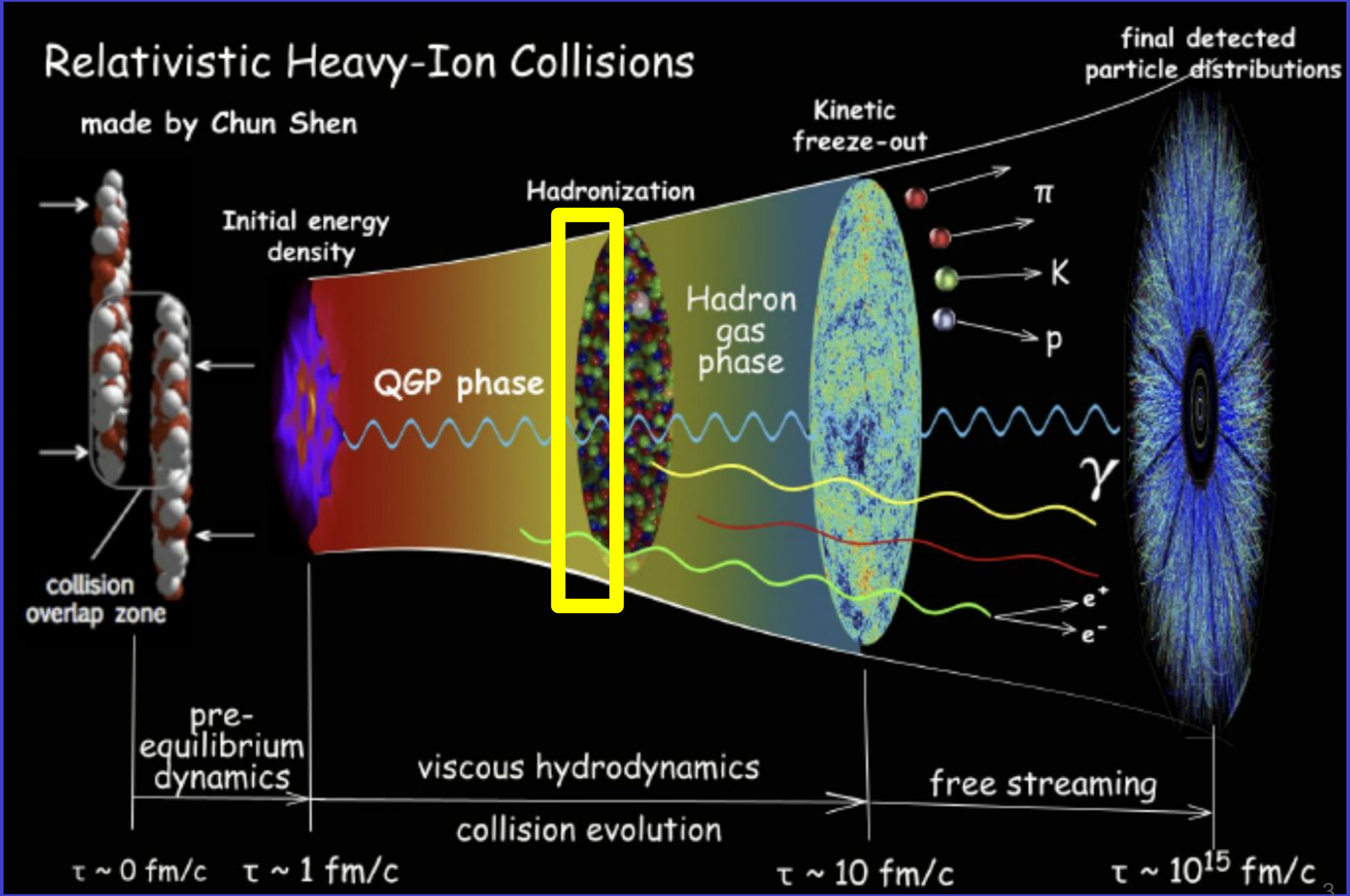


- PHYSICS MOTIVATION

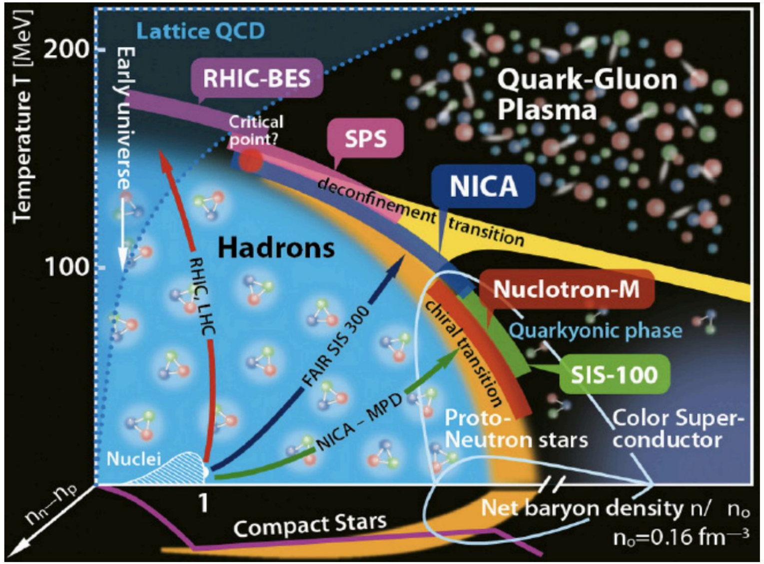
- LSMq AND THE EFFECTIVE POTENTIAL

- PHASE DIAGRAMS & FINAL REMARKS

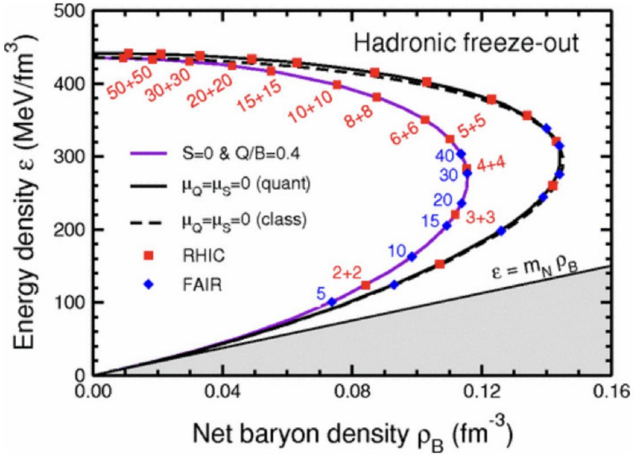
HIC


Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected
particle distributions
Kinetic
freeze-out
Hadronization
Initial energy
density
Hadron
gas
phase
QGP phase
π
K
p
γ
e+
e-
collision
overlap zone
pre-
equilibrium
dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

QCD Phase Diagram ↔ Heavy-ion Collisions



Different **T** and μ_B combinations →Different collision energies in HIC



QCD PHASE TRANSITION IS A NON PERTURBATIVE PHENOMENON

Linear Sigma model coupled to quarks

Effective theory which is usefull to emulate the low energy regime of Quantum Chromodynamics. It exhibits a symmetry spontaneously broken.

$$\mathscr{L} = \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \vec{\pi})^2 + \frac{a^2}{2}(\sigma^2 + \vec{\pi}) - \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2)^2 + i\bar{\psi}\gamma^\mu \partial_\mu \psi - ig\bar{\psi}\gamma^5 \vec{\tau}.\vec{\pi}\psi - g\bar{\psi}\psi\sigma$$

letting the sigma-field to develop a vacuum expectation value v, we have

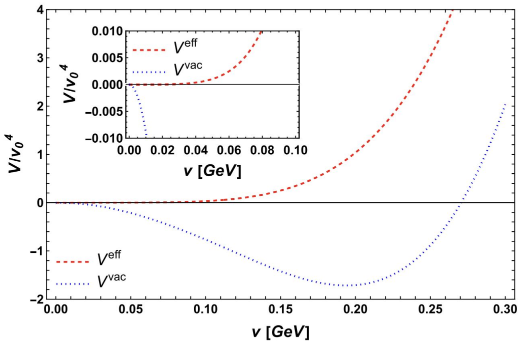
$$\sigma \to \sigma + v$$

$$V^{tree} = -\frac{a^2}{2}v^2 + \frac{\lambda}{4}v^4$$

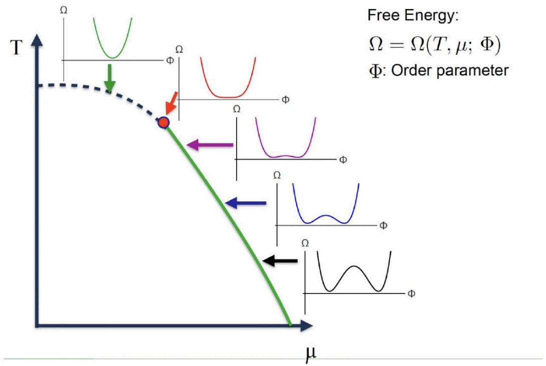
$$m_\sigma^2 = 3\lambda v^2 - a^2 \quad , \quad m_0^2 = \lambda v^2 - a^2 \quad , \quad m_f = gv$$

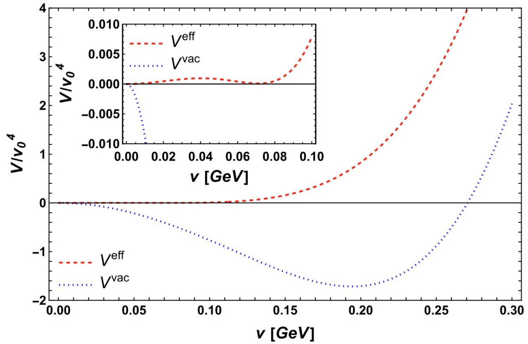
$$\boxed{a^2, \lambda, g}$$

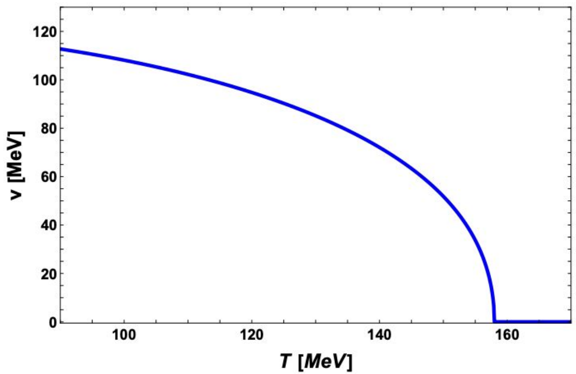
CHIRAL SYMMETRY RESTORATION



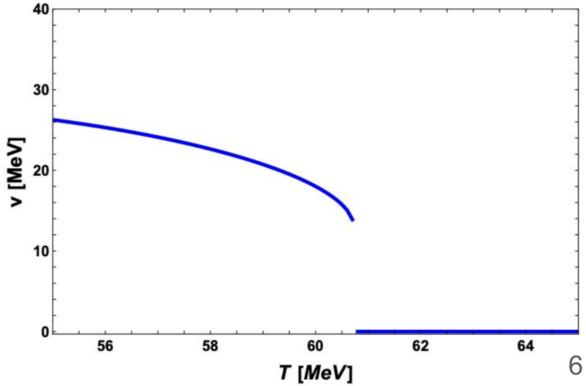
v= vacuum expectation value → order parameter







low ← μ_q → high



EFFECTIVE POTENTIAL

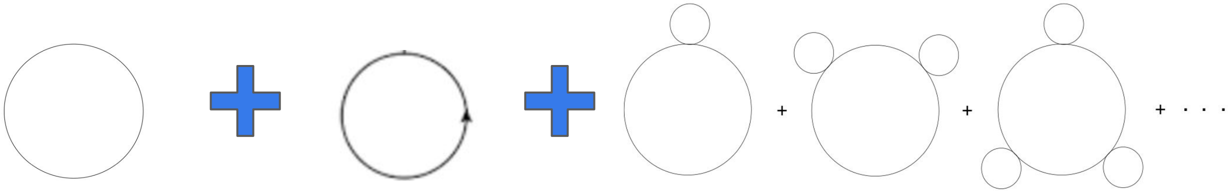
Imaginary Time Formalism

$$V^{\text{eff}} = V^{\text{tree}} + V_b^1 + V_f^1 + V^{\text{rings}}$$

$$V_b^1 = -\frac{i}{2}\int \frac{d^4k}{(2\pi)^4}\ln(D_b^{-1}(k)) \ , \ V_f^1 = iN_c \int \frac{d^4k}{(2\pi)^4} Tr[\ln(S_f^{-1}(k))]$$

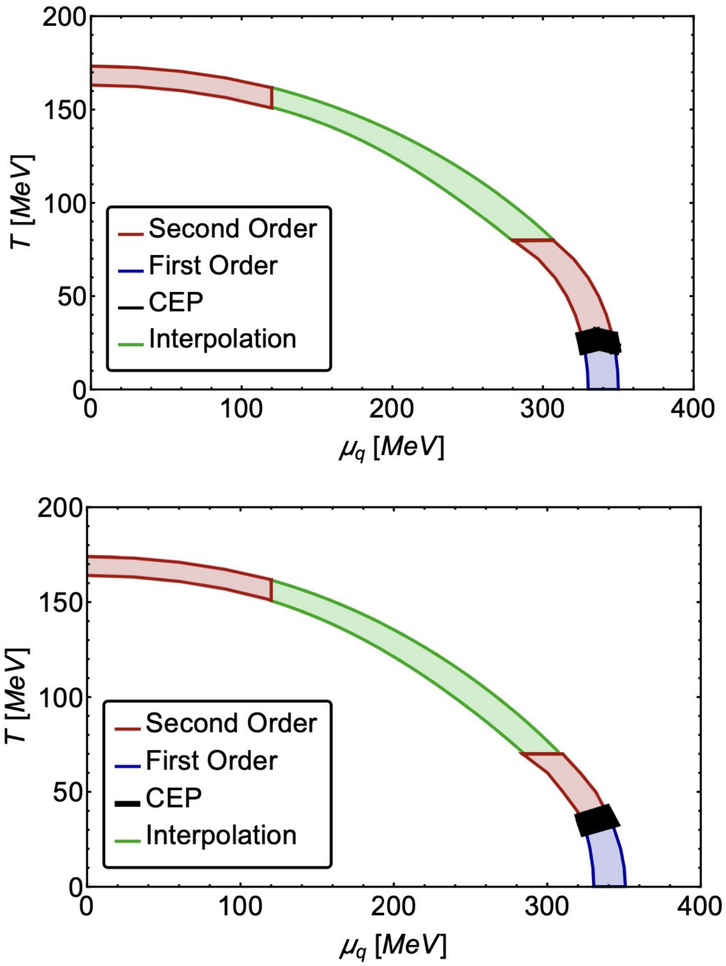
screening effects

$$V^{\text{ring}} = \frac{T}{2}\sum_{n=-\infty}^{\infty}\int \frac{d^3k}{(2\pi)^3}\ln\left(1 + \Pi D(\omega_n, \Omega, \vec{k})\right),$$



WE GO BACK TO 2018

- Effective potential with the LSMq at finite T and $\boldsymbol{\mu}_q$ in the high- and low-T approximation.
- 2nd order and 1st order phase transition.
- CEP appears.

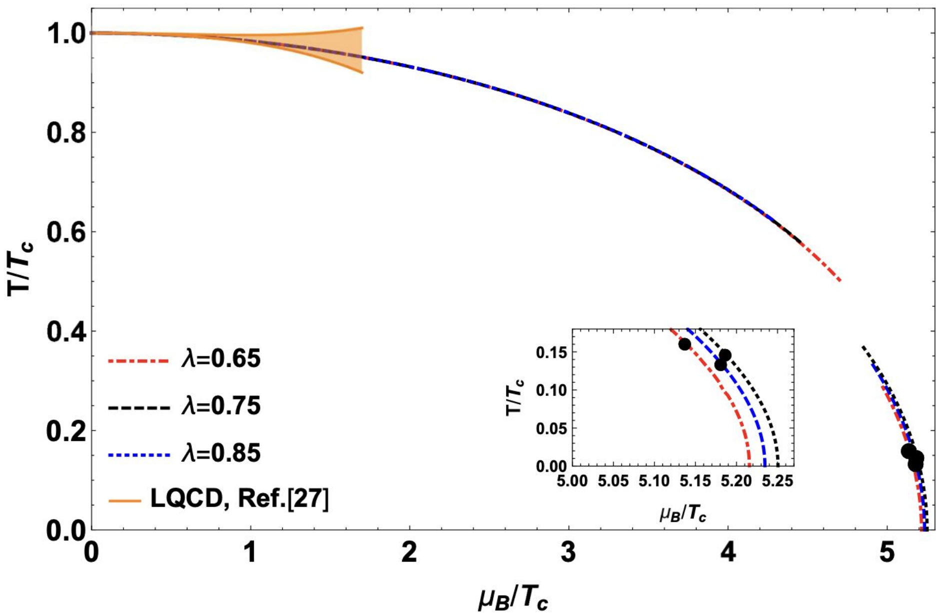


Two different sets of λ, g and a

A. Ayala, S. Hernandez-Ortiz and LAH, Rev. Mex. Fis. **64**, no.3, 302-313 (2018)

IMPROVING RESULTS

- Effective potential with the LSMq at finite T and μ_q in the high- and low-T approximation.
- 2nd order and 1st order phase transition.
- CEP appears.
- **Following LQCD curvature**



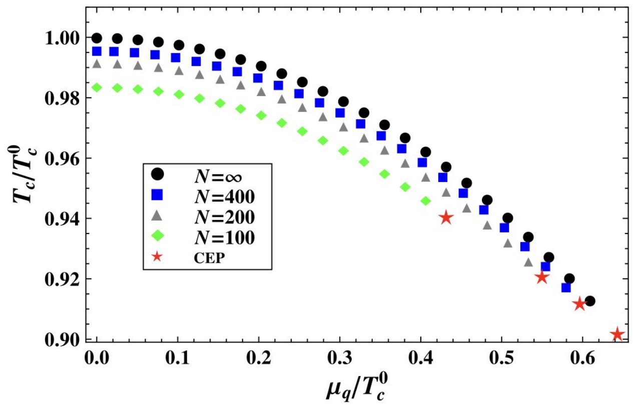
A. Ayala, LAH, M. Loewe, J. C. Rojas and R. Zamora, Eur. Phys. J. A **56**, no.2, 71 (2020)

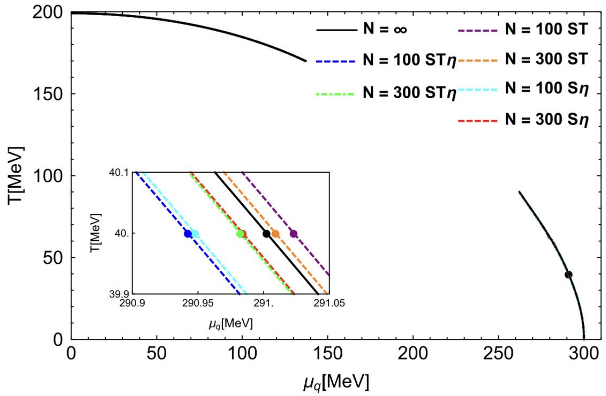
NEW INGREDIENTS

- Effective potential with the LSMq at finite T and μ_q in the high- and low-T approximation.
- 2nd order and 1st order phase transition.
- CEP appears.
- Following LQCD curvature
- **Superstatistics**

A. Ayala, M. Hentschinski, LAH, M. Loewe and R. Zamora, Phys. Rev. D **98**, no.11, 114002 (2018)

A. Ayala, S. Hernandez-Ortiz, LAH, V. Knapp-Perez and R. Zamora, Phys. Rev. D **101**, no.7, 074023 (2020)

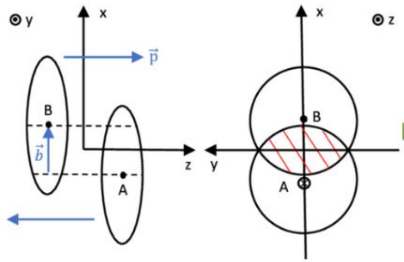




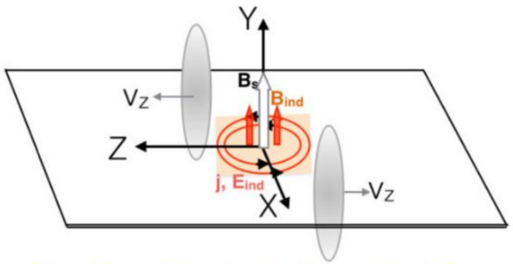
HICs

1. **Phase transition**
   Quark-Gluon Plasma → Chiral Symmetry
2. **Baryon Chemical Potential**
   Region of maximum baryon density (MPD-NICA)
3. **Effective models**
   Low energies of QCD
4. **Non-central collisions**
   Finite Impact Parameter **b**
5. **Angular velocity**
   Maximum value ~0.1 fm^{-1} (~20 MeV)
6. **Magnetic Fields**
   Short pulse with maximum high ~ $(m_\pi)^2$
7. **Collision Energy**
   Effects more important at low energies

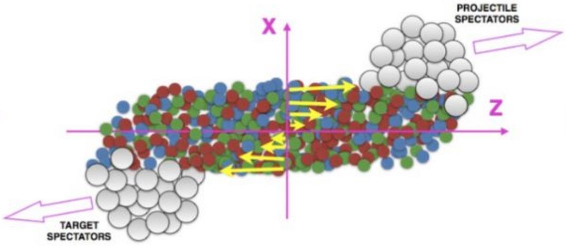
NON CENTRAL COLLISION



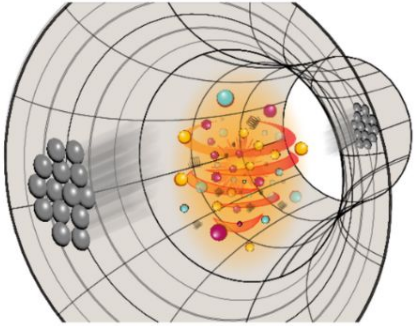
Eur.Phys.J.C 83 (2023) 1, 96



Phys.Rev.C 96 (2017) 5, 054909

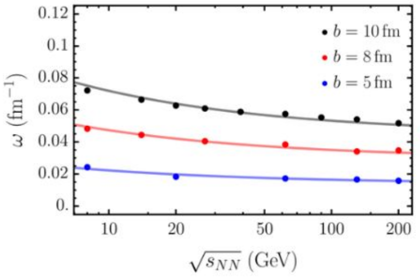


EPJ Web Conf. 171 (2018) 07002

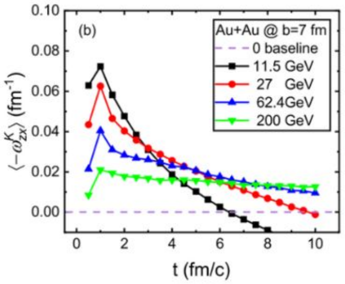


Nucl.Sci.Tech. 34 (2023) 1, 15

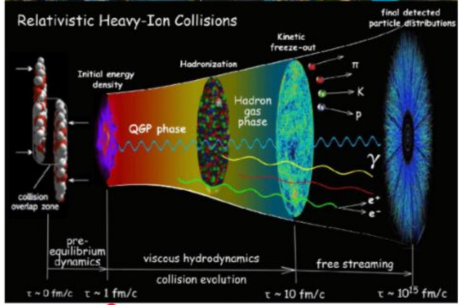
ANGULAR VELOCITY

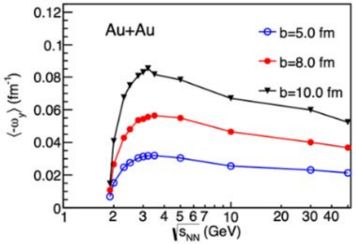


Initial angular velocity ω for Au + Au collisions at impact parameters b= 5, 8, 10 fm as functions of collision energy (UrQMD). Phys. Rev. D **102** (2020), 056019

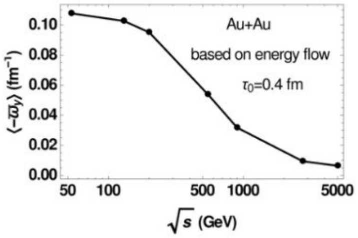


Time evolution of angular velocity at b=7 fm and four different energies (PACIAE). Phys.Rev.C **104** (2021) 5, 054903



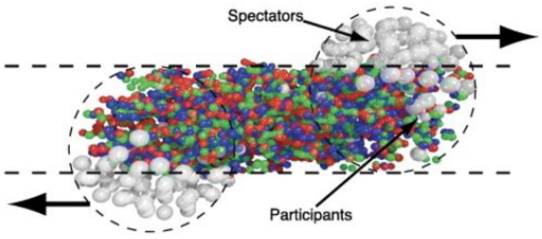


Initial angular velocity at mid rapidity as a function of the collision energy for impact parameters b = 5, 8, and 10 fm (UrQMD). Phys.Rev.C **101** (2020) 6, 064908

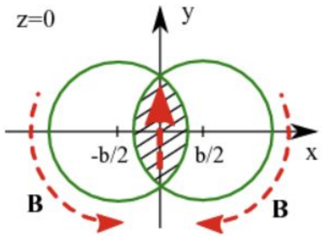


Angular velocity at fixed τ = 0.4 fm and η = 0 as function of collision energy (HIJING). Phys. Rev. C **93** (2016), 064907

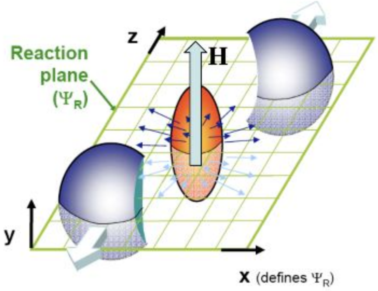
MAGNETIC FIELDS



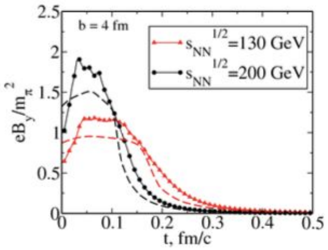
R. Snellings, J. Phys. **13**, (2011) 055008



V. Voronyuk *et al.*,Phys. Rev. C **83**, 054911 (2011)

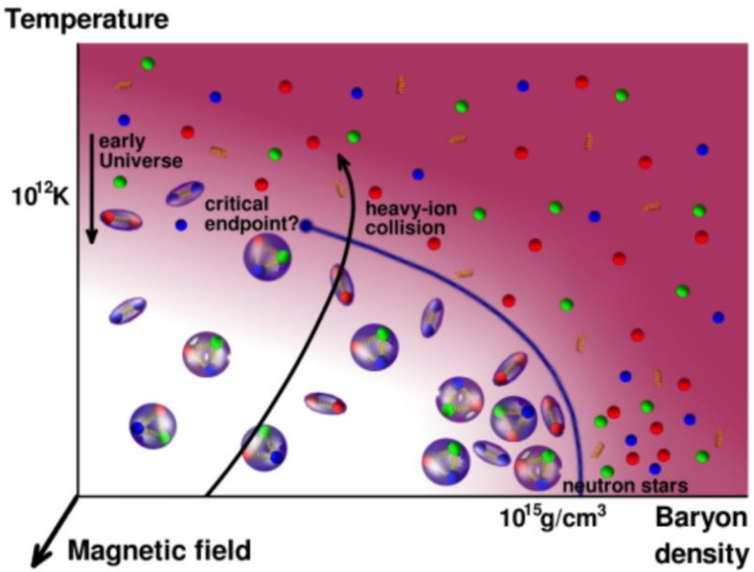


D. E. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A **803**, 227 (2008)

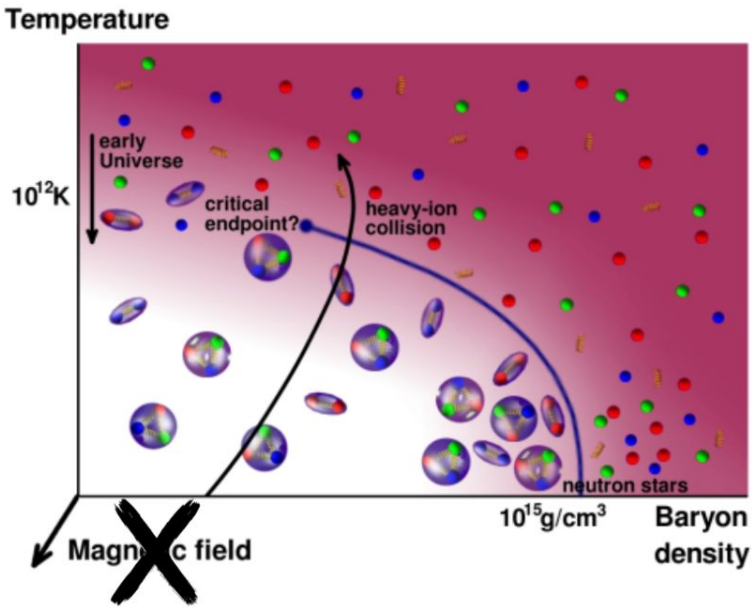


V. Skokov, A. Y. Illarionov and V. Toneev, Int. J. Mod. Phys. A **24**, 5925 (2009)

QCD phase diagram

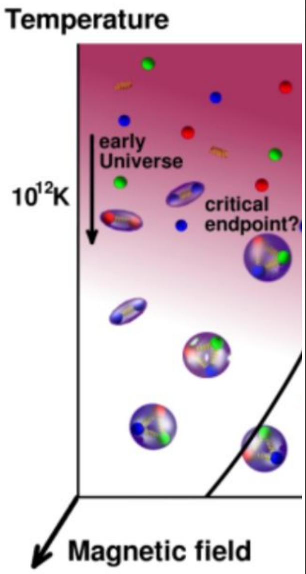


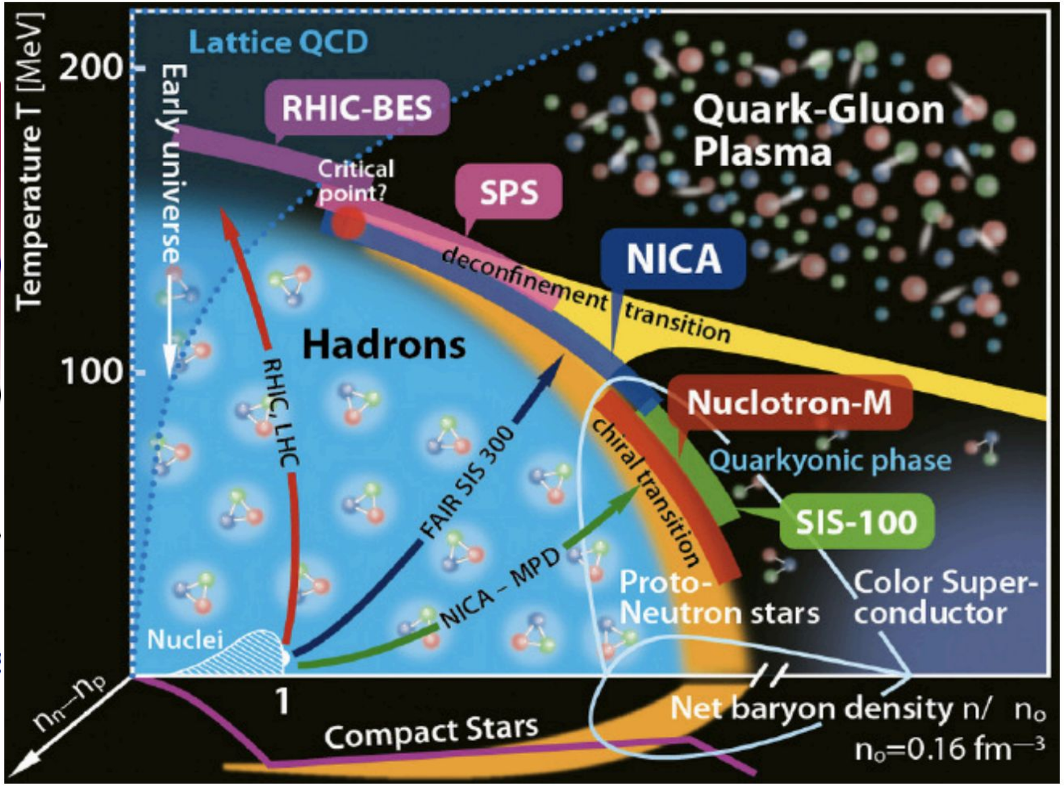
J.Phys.Conf.Ser. 503 (2014) 012009

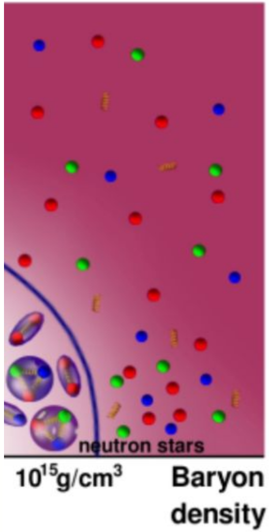


Vorticity

QCD phase diagram







J.Phys.Conf.S

Linear Sigma model coupled to quarks

Effective theory which is usefull to emulate the low energy regime of Quantum Chromodynamics. It exhibits a symmetry spontaneously broken.

$$\mathscr{L} = \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \vec{\pi})^2 + \frac{a^2}{2}(\sigma^2 + \vec{\pi}) - \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2)^2 + i\bar{\psi}\gamma^\mu \partial_\mu \psi - ig\bar{\psi}\gamma^5 \vec{\tau}.\vec{\pi}\psi - g\bar{\psi}\psi\sigma$$

letting the sigma-field to develop a vacuum expectation value v, we have

$$\sigma \to \sigma + v$$

$$V^{tree} = -\frac{a^2}{2}v^2 + \frac{\lambda}{4}v^4$$

$$m_\sigma^2 = 3\lambda v^2 - a^2 \quad , \quad m_0^2 = \lambda v^2 - a^2 \quad , \quad m_f = gv$$

$$\boxed{a^2, \lambda, g}$$

EFFECTIVE POTENTIAL

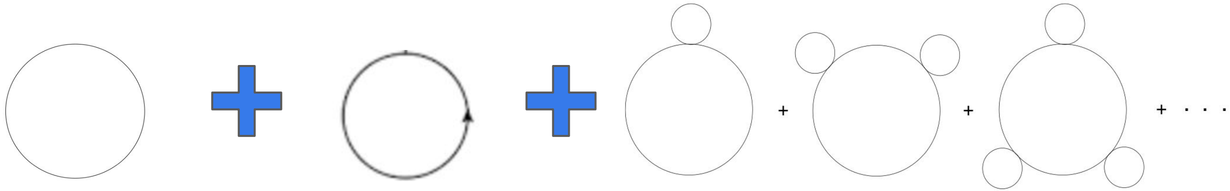
Imaginary Time Formalism

$$V^{\text{eff}} = V^{\text{tree}} + V_b^1 + V_f^1 + V^{\text{rings}}$$

$$V_b^1 = -\frac{i}{2}\int \frac{d^4k}{(2\pi)^4} \ln(D_b^{-1}(k)) \;,\quad V_f^1 = iN_c \int \frac{d^4k}{(2\pi)^4} Tr[\ln(S_f^{-1}(k))]$$

screening effects

$$V^{\text{ring}} = \frac{T}{2}\sum_{n=-\infty}^{\infty}\int \frac{d^3k}{(2\pi)^3} \ln\left(1 + \Pi D(\omega_n, \Omega, \vec{k})\right),$$



PROPAGATORS

Finite **eB**

Boson

$$D(p) = \int_0^\infty \frac{ds}{\cos(|q_b B|s)} e^{is\left(p_\parallel^2 - p_\perp^2 \frac{\tan(|q_b B|s)}{|q_b B|s} - m_b^2 + i\epsilon\right)},$$

Fermion

$$\begin{aligned} S_f(p) &= \int_0^\infty \frac{ds}{\cos(|q_f B|s)} e^{is\left(p_\parallel^2 - p_\perp^2 \frac{\tan(|q_f B|s)}{|q_f B|s} - m_f^2 + i\epsilon\right)} \\ &\times \left[\left(\cos(|q_f B|s) + \gamma_1\gamma_2 \sin(|q_f B|s)\mathrm{sign}(q_f B)\right)\right. \\ &\times \left.\left(m_f + \not{p}_\parallel\right) - \frac{\not{p}_\perp}{\cos(|q_f B|s)}\right], \end{aligned}$$

Phys.Rev. 82 (1951) 664-679

Finite **Ω**

Boson

$$D(p) = \frac{1}{(p_0 + \Omega)^2 - p_\perp^2 - p_z^2 - m^2 + i\epsilon}$$

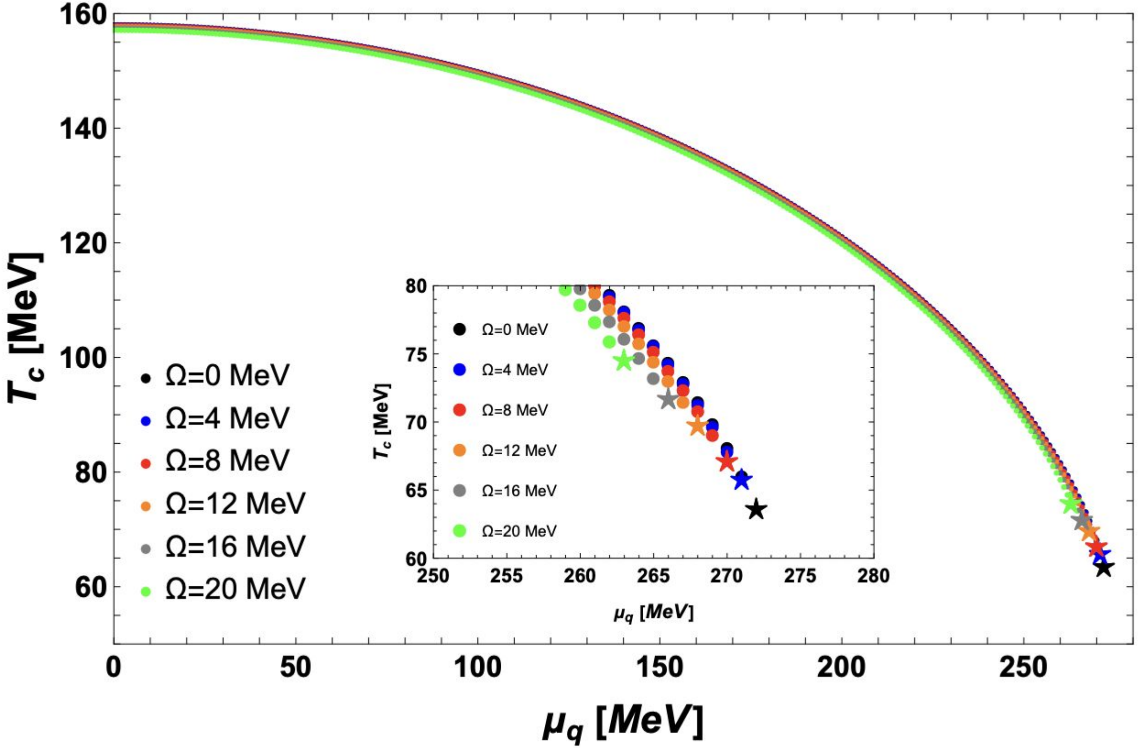
Phys.Rev.D 108 (2023) 9, 094020

Fermion

$$\begin{aligned} S(p) = &\frac{(p_0 + \Omega/2 - p_z + ip_\perp)(\gamma_0 + \gamma_3) + m(1 + \gamma_5)}{(p_0 + \Omega/2)^2 - \bar{p}^2 - m^2 + i\epsilon}\mathcal{O}^+ \\ &+ \frac{(p_0 - \Omega/2 + p_z - ip_\perp)(\gamma_0 - \gamma_3) + m(1 + \gamma_5)}{(p_o - \Omega/2)^2 - \bar{p}^2 - m^2 + i\epsilon}\mathcal{O}^-, \end{aligned}$$

Phys.Rev.D 103 (2021) 7, 076021

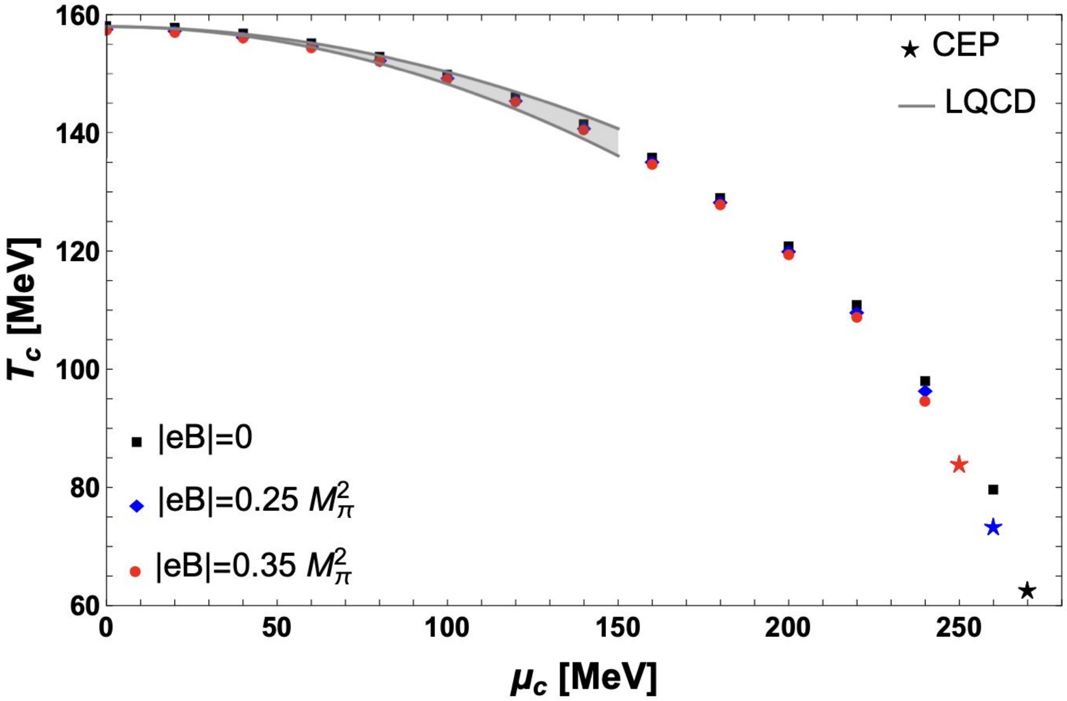
PHASE DIAGRAM Ω



- The $\mathbf{T_c}$ decreases as the **Ω** increases.
- Larger **Ω** moves the CEP to lower $\boldsymbol{\mu_q}$ and higher T.
- The **Ω** not only modifies the conditions under which the phase transition occurs, but also the nature of the transition

LAH and R. Zamora, [arXiv:2410.17874 [hep-ph]].

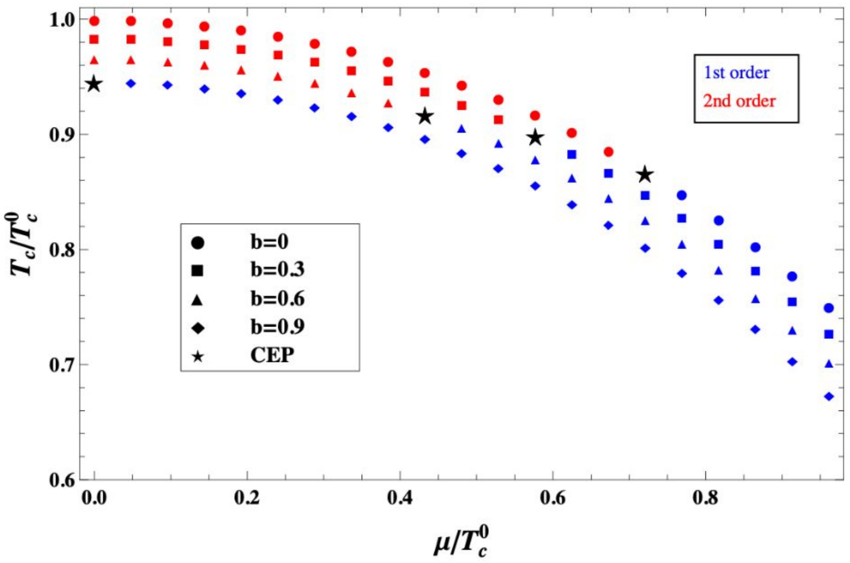
PHASE DIAGRAM eB

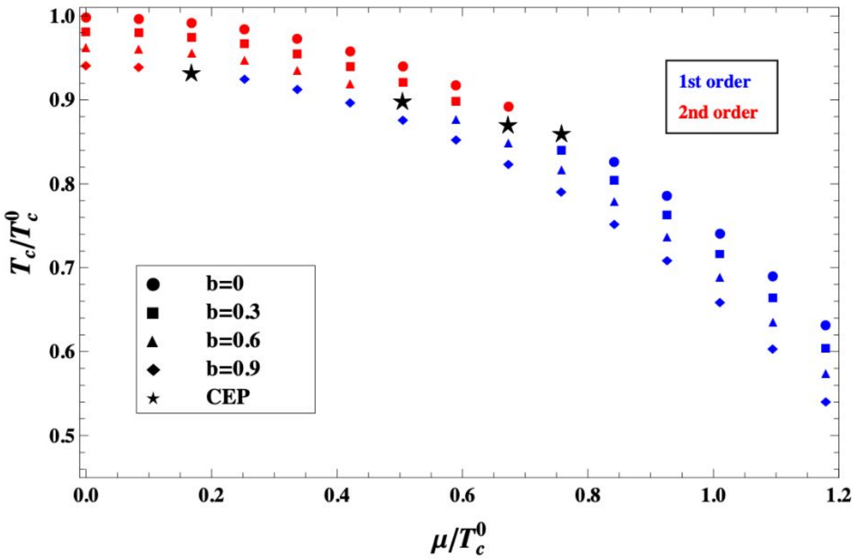


- The $\mathbf{T}_c$ decreases as the **eB** increases.
- Larger **eB** moves the CEP to lower $\boldsymbol{\mu}_q$ and higher T.
- The **eB** not only modifies the conditions under which the phase transition occurs, but also the nature of the transition

A. Ayala, <u>LAH</u>, M. Loewe and C. Villavicencio, Eur. Phys. J. A **57**, no.7, 234 (2021)

THE TRUE BEGINNING





Inverse Magnetic Catalysis was obtained

A. Ayala, C. A. Dominguez, LAH, M. Loewe and R. Zamora, Phys. Rev. D **92**, no.9, 096011 (2015)

SUMMARY

- The LSMq has been successful in exploring the phase transition of QCD.
- The possible location of the CEP has been inspected
- **T-μ_B** plane + **eB**, **Ω**, **eE**, **μ_I** or …
- Translating phase diagram information into observables in HIC

Thanks for your attention!

lhernandez.rosas@izt.uam.mx
luis.hr@xanum.uam.mx

BARYON NUMBER FLUCTUATION

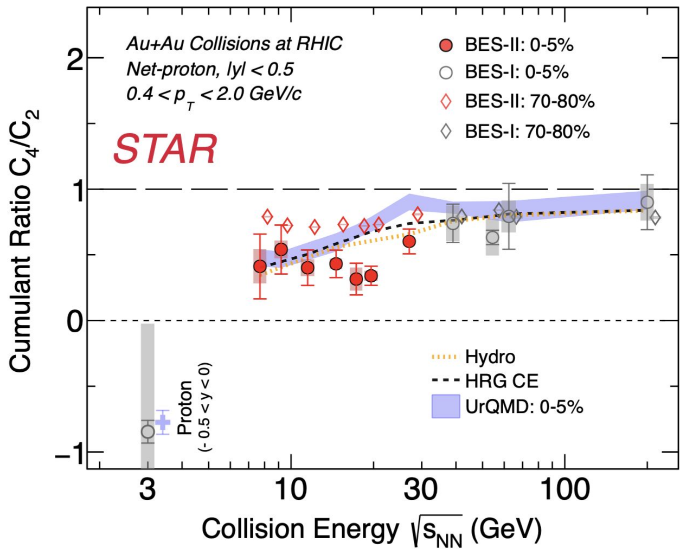
Conserved Charges: Net Baryon Number (B), Net Charge (Q), Net Strangeness (S)

Measured multiplicity N, $\langle \delta N \rangle = \mathbf{N} - \langle N \rangle$

$$\begin{array}{llll} \text{mean:} & M & = \langle N \rangle & = C_1 \\ \text{variance:} & \sigma^2 & = \langle (\delta N)^2 \rangle & = C_2 \\ \text{skewness:} & S & = \langle (\delta N)^3 \rangle / \sigma^3 & = C_3 / C_2^{3/2} \\ \text{kurtosis:} & \kappa & = \langle (\delta N)^4 \rangle / \sigma^4 - 3 & = C_4 / C_2^2 \end{array}$$

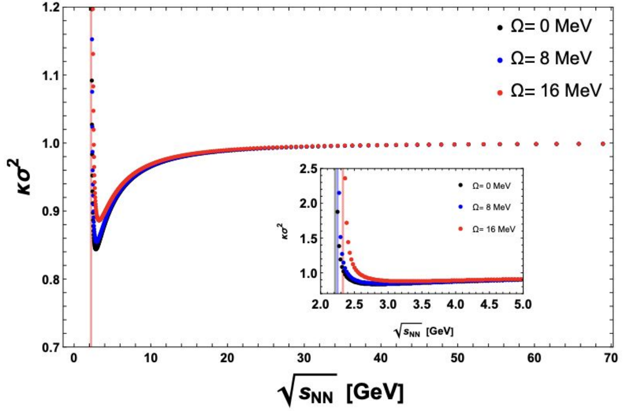
Moments, cumulants and susceptibilities:

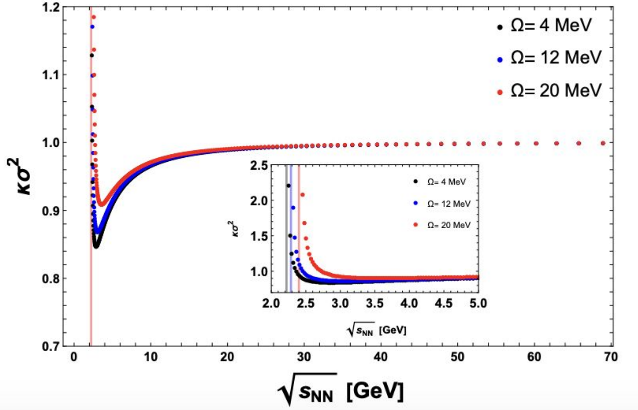
$$\begin{array}{lllll} 2^{nd} \text{ order:} & \sigma^2/M & \equiv C_2/C_1 & = & \chi_2/\chi_1 \\ 3^{rd} \text{ order:} & S\sigma & \equiv C_3/C_2 & = & \chi_3/\chi_2 \\ 4^{th} \text{ order:} & \kappa\sigma^2 & \equiv C_4/C_2 & = & \chi_4/\chi_2 \end{array}$$

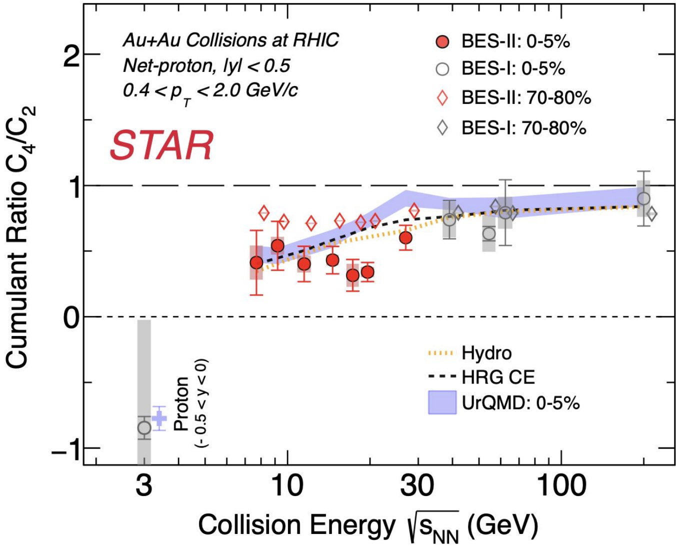


A. Pandav (STAR collaboration), plenary talk at CPOD 2024, https:// conferences.lbl.gov/event/1376/contributions/8772/

BARYON NUMBER FLUCTUATION







A. Pandav (STAR collaboration), plenary talk at CPOD 2024, https:// conferences.lbl.gov/event/1376/contributions/8772/

SUMMARY 2.0

- As the energy approaches the CEP position, the fourth moment exhibits a sharp increase, suggesting that the CEP location can be identified by this abrupt rise. This behavior is also influenced by vorticity, as higher values of $\boldsymbol{\Omega}$ shift the CEP to higher collision energies.