Dynamical chiral condensate as a coherent $\sigma/f_0(500)$ field

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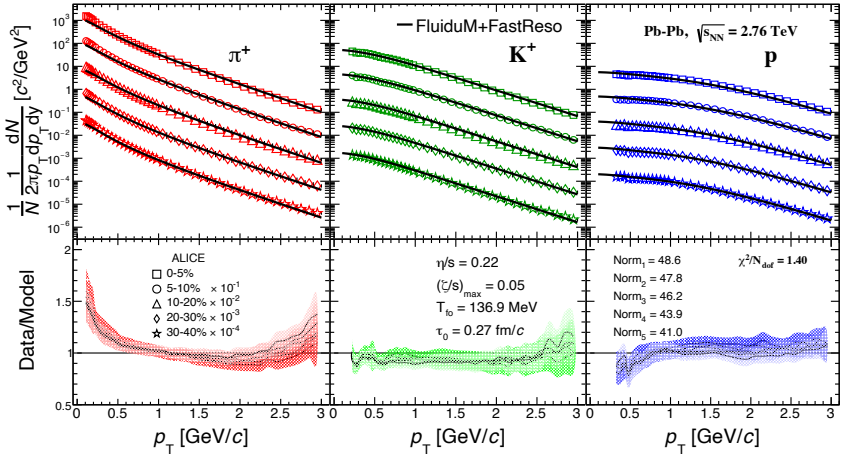
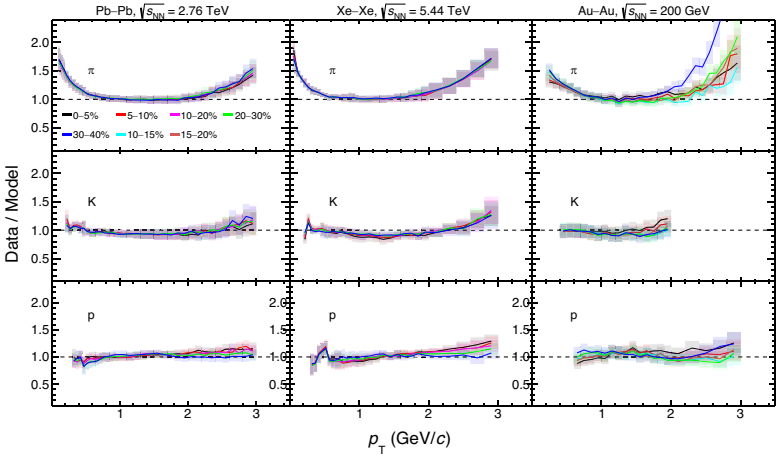
Transverse momentum spectra from Pb-Pb collisions at the LHC

[Devetak, Dubla, Floerchinger, Grossi, Masciocchi, Mazeliauskas & Selyuzhenkov, JHEP 06(2020)044]



Quantification of the low p_T pion excess

[Lu, Kavak, Dubla, Masciocchi & Selyuzhenkov, Nucl. Sci. Techn. 36, 142 (2025)]



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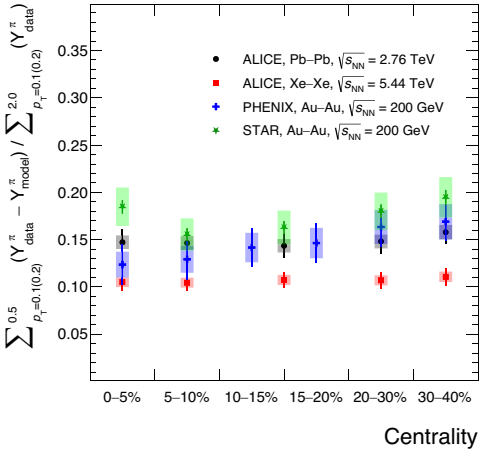
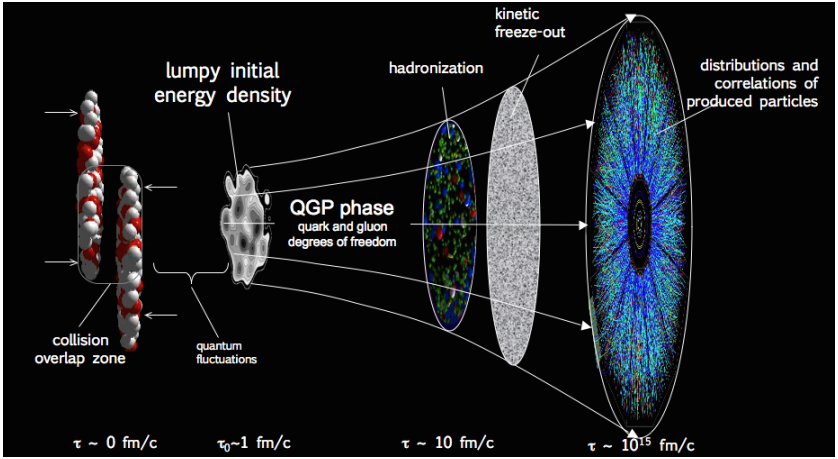


Dynamical chiral condensate as a coherent $\sigma/f_0(500)$ field

- Dynamics
- Chiral symmetry breaking
- Condensate / coherent field
- The $\sigma/f_0(500)$

Dynamics of a heavy ion collision

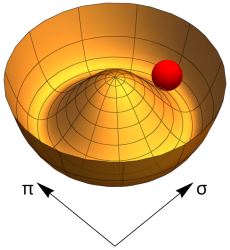


Chiral symmetry breaking

$$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1) \rightarrow \mathrm{SU}(2)_V \times \mathrm{U}(1)$$

- (approximate) symmetry for almost massless up and down quarks
- broken spontaneously by chiral condensate
- (almost) massless pions $\pi^{\pm}$, π^0 as pseudo Goldstone bosons

Chiral condensate



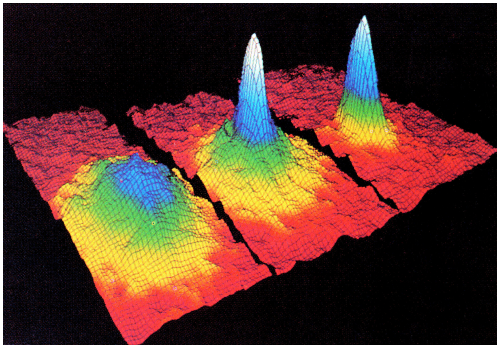
- chiral symmetry spontaneously broken by vacuum expectation value

$$\langle \sigma(x) \rangle = f_\pi \approx 93 \text{ MeV}$$

- chiral symmetry restoration at

$$T > T_c \approx 155 \text{ MeV}$$

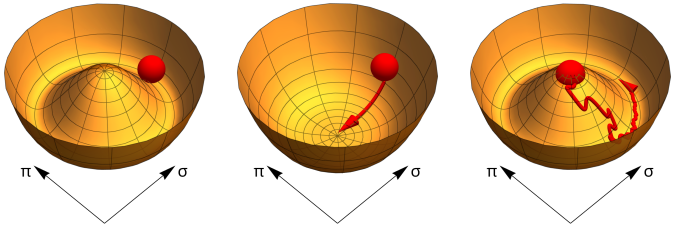
Condensate / coherent field



- field modes has large occupation
- similar to classical field
- can be seen as shifted vacuum state $|\alpha\rangle = e^{\alpha a^\dagger - \alpha^* a}|0\rangle$
- example: Bose-Einstein-Condensate of rubidium atoms [NIST/JILA/CU-Boulder]

The disoriented chiral condensate

[Anselm (1989), Blaizot & Krzywicki (1992), Bjorken, Kowalski & Taylor (1993), Rajagopal & Wilczek (1993), …, Bjorken (1997), Mohanty & Serreau (2005)]



- chiral field σ could do excursions into pion direction: disoriented chiral condensate
- has been looked for experimentally, for example in fluctuations of π^0 to $\pi^\pm$ ratio

The $\sigma/f_0(500)$ resonance

- "Higgs boson" of chiral symmetry breaking in QCD
- broad resonance because of quick decay into pions, expected by Schwinger
- long debated but now established[1] $\sqrt{s} = [(400 - 550) - i(200 - 350)]$ MeV

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From controversy to precision on the sigma meson: A review on the status of the non-ordinary $f_0(500)$ resonance

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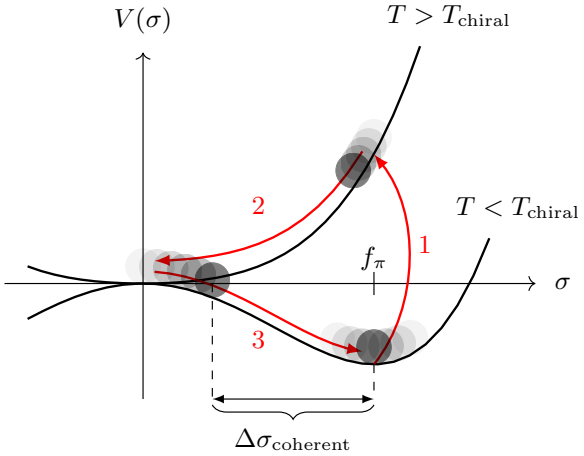
[1] S. Navaset al.(Particle Data Group), Phys. Rev. D110, 030001 (2024) and 2025 update

Chiral condensate dynamics



Equation of motion for coherent field and and momentum distribution

- equation of motion with source field $J(t, \mathbf{x})$

$$\left[\frac{\partial^2}{\partial t^2} - \boldsymbol{\nabla}^2 + \mu^2\right][\sigma(t, \mathbf{x}) - f_\pi] = J(t, \mathbf{x})$$

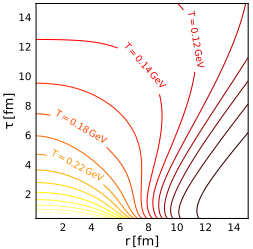
- momentum distribution of $\sigma/f_0(500)$ particles[2]

$$E_{\mathbf{p}} \frac{\mathrm{d}N}{\mathrm{d}^3 p} = \frac{1}{2} \frac{J(\mathbf{p})^* J(\mathbf{p})}{(2\pi)^3}$$

- with $E_p = \sqrt{\mathbf{p}^2 + \mu^2}$ and distribution of masses μ according to spectral function

[2] [Amelino-Camelia, Bjorken, & Larsson, PRD 56, 6942 (1997)

Fourier transform on a freeze-out surface



- particle production source from integral over freeze-out surface

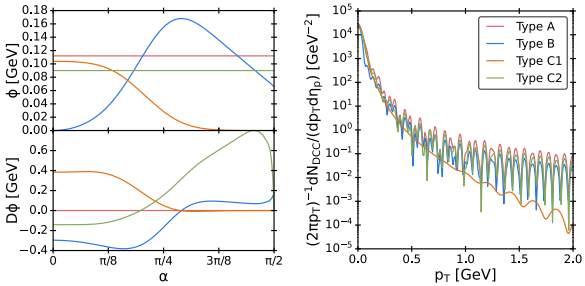
$$J(\mathbf{p}) = \int_{\Sigma} \mathrm{d}\Sigma^{\mu} j_{\mu}(t, \mathbf{x}, \mathbf{p})$$

- momentum-dependent current

$$j_{\mu}(t, \mathbf{x}, \mathbf{p}) = \left(\partial_{\mu}\sigma(t, \mathbf{x}) + i p_{\mu}[\sigma(t, \mathbf{x}) - f_{\pi}]\right) e^{iE_{\mathbf{p}}t - i\mathbf{p}\mathbf{x}}$$

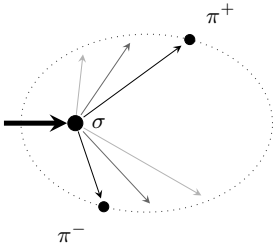
Modeling the chiral condensate dynamics

- we need $\sigma(t, \mathbf{x})$ and $\partial_\mu \sigma(t, \mathbf{x})$ on three-dimensional hypersurface Σ
- needs in principle advanced dynamical modelling
- for now: make plausible assumptions and study influence[3]
- influence is small, one may take $\sigma(t, \mathbf{x}) = \text{const.}$



[3] T. Bruschke, Master thesis, Uni Jena (2025), https://doi.org/10.22032/dbt.67475

Decay on $\sigma/f_0(500)$ into pions

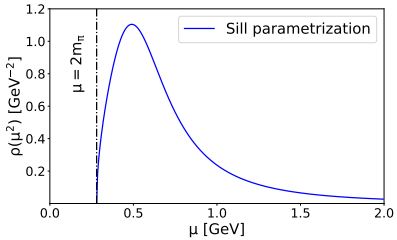


- dominant decay

$$\sigma/f_0(500) \to \pi^+\pi^-$$

- momentum distribution of pions can be calculated from momentum distribution of $\sigma/f_0(500)$
- needs spectral function

Spectral function of $\sigma/f_0(500)$



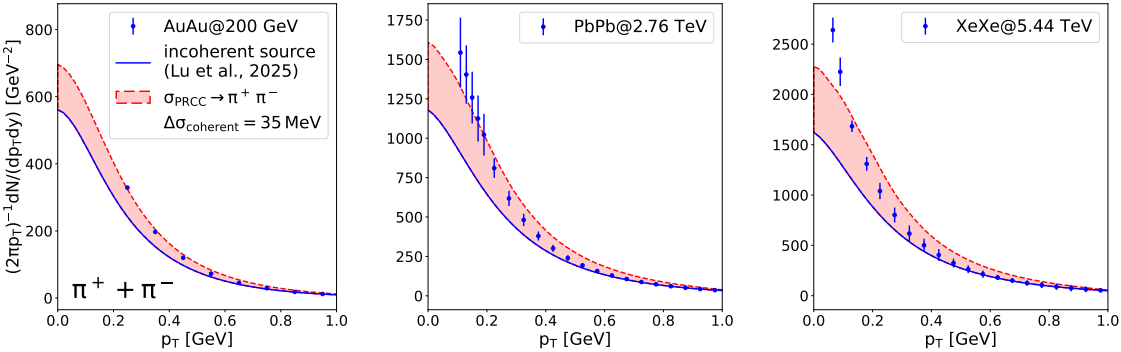
- Sill parametrization

$$\rho(\mu^2) = -\mathrm{Im}\left(\frac{1}{\mu^2 - M^2 + i\Gamma\sqrt{\mu^2 - 4m_\pi^2}}\right)\theta(\mu^2 - 4m_\pi^2)$$

- M and Γ are chosen such that pole mass is at

$$\sqrt{s_\sigma} = m_\sigma - \frac{i}{2}\Gamma_\sigma = 449\ \mathrm{MeV} - i275\ \mathrm{MeV}$$

Transverse momentum spectra with coherent $\sigma/f_0(500)$ field



- comparison to experimental data taken at RHIC and LHC
- fluid dynamic model for incoherent source[4]

[4] Lu, Kavak, Dubla, Masciocchi & Selyuzhenkov, Nucl. Science and Techn. 36, 142 (2025).

Conclusions

- dynamical chiral condensate can be seen as coherent $\sigma/f_0(500)$ field
- momentum distribution is essentially square of Fourier transform of source field
- can be calculated on freeze-out surface
- momentum distribution of pions from resonance decay
- improves transverse momentum spectra in the very soft regime
- to do: dynamical modeling, azimuthal dependence, simultaneous fits, …