Jet Quenching at BES energies and Partonic Critical Opalescence

arXiv:2208.14297

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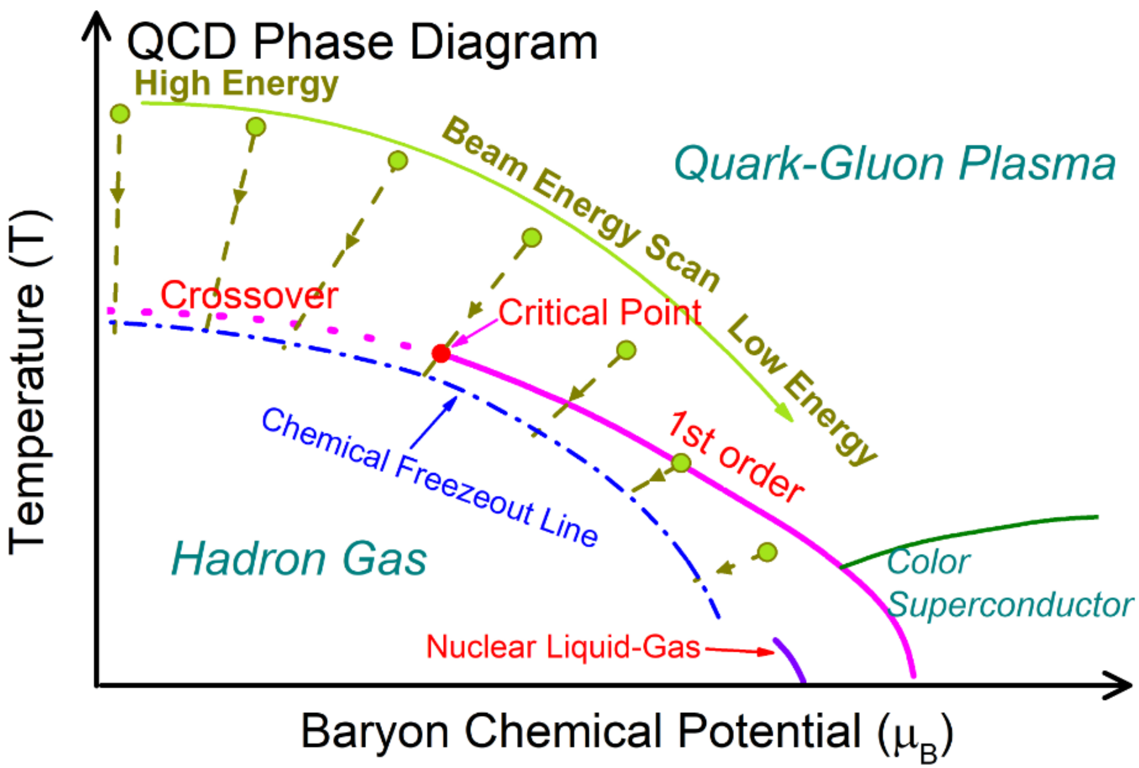
- **"Jet" @ BES energeis**
- Jet Quenching & Correlation Function
- Jet Quenching at Finite μB (up to 1-loop)
- Partonic Critical Opalescence
- Summary & Outlook

Seeking QCD CEP



- **BES experiments**
- Soft Probes:
  - High moments of net-proton fluctuations @ Chemical freeze-out
  - Light nuclei yield ratio @ Kinetic freeze-out
- Critical Opalescence
  Where is our light?
- Jets @ BES energies

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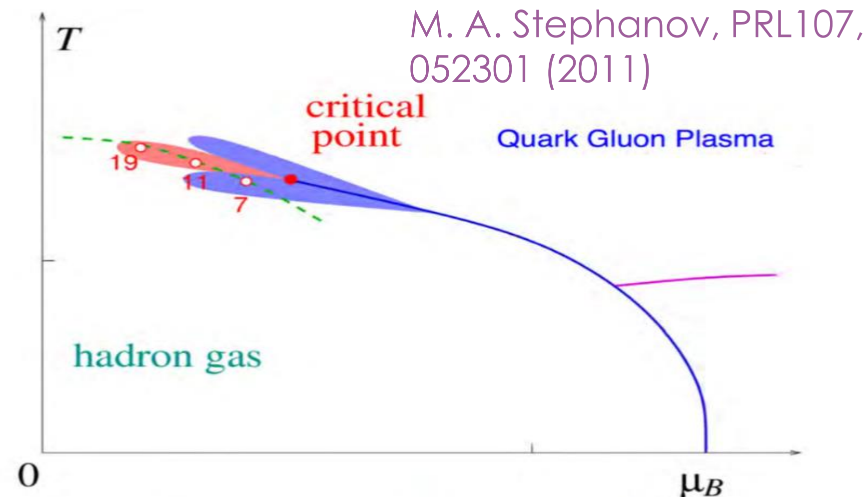

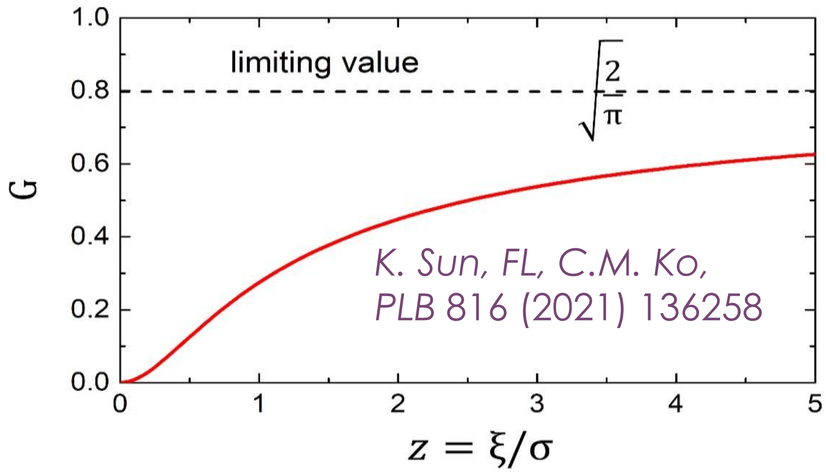

$$\frac{N_t N_p}{N_d^2} \approx \frac{1}{2\sqrt{3}}\left[1 + \Delta\rho_n + \frac{\lambda}{\sigma} G\left(\frac{\xi}{\sigma}\right)\right] + \mathcal{O}(G^2)$$

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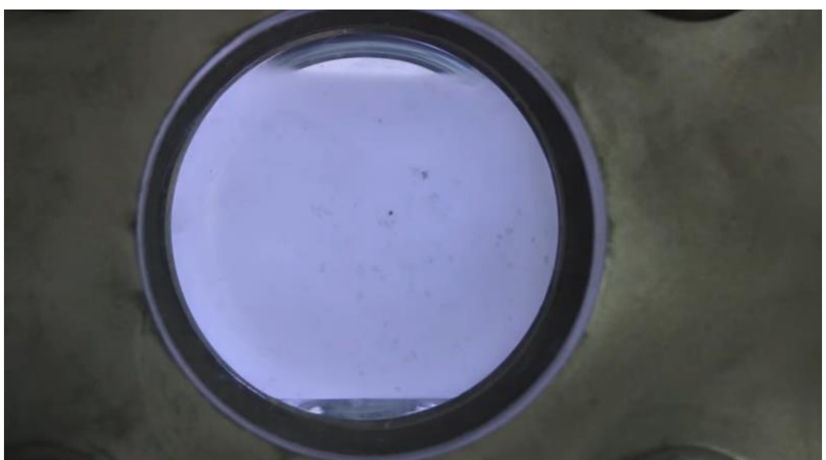

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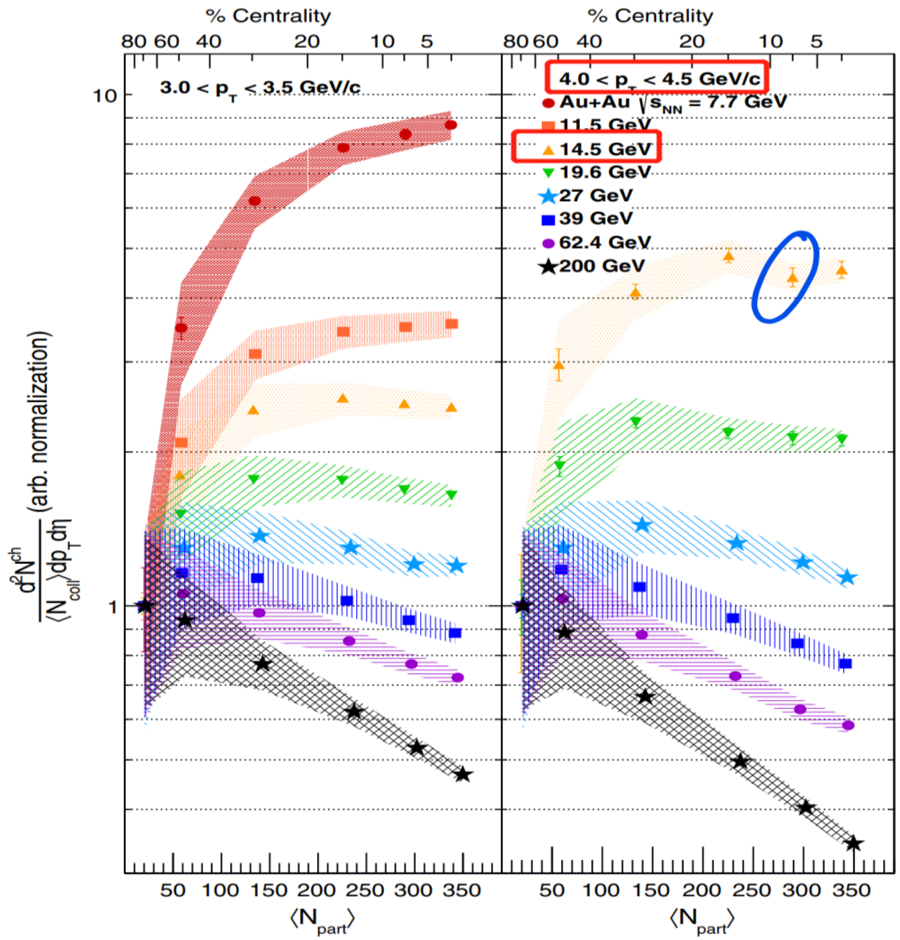
PHYSICAL REVIEW LETTERS **121**, 032301 (2018)

Beam Energy Dependence of Jet-Quenching Effects in Au + Au Collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, and 62.4 GeV



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Transverse Momenta Broadening

$$\hat{q} = \frac{\langle \vec{k}_{\perp}^2 \rangle}{t} = \sum_k \frac{\vec{k}_{\perp}^2}{t} \sum_{X,M} \rho(M) |\langle q, M | U_I(t) | q + k, X \rangle|^2$$

Transition Probability

A. Majumder, PRC87, 034905 (2013)

Transverse Momenta Broadening

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$$= \sum_k \frac{\vec{k}_\perp^2}{t} Tr[\rho(M) |\langle q | U_I(t) | q + k \rangle|^2]$$

$$\approx \sum_k \frac{\vec{k}_\perp^2}{t} \int_0^t dx^0 dy^0\, Tr\big[\rho(M) \langle q \big| H_I(x^0) \big| q + k \rangle \langle q + k \big| H_I(y^0) \big| q \rangle\big]$$

In quark-meson (QM) model:

$$H_I = g \int d^3\vec{x}\, \bar{q} (\sigma' + i\gamma_5\, \vec{\pi} \cdot \vec{\tau}) q$$

- Gluon contributions replaced by the mesonic field
- Applicable near phase boundary

A. Majumder, PRC87, 034905 (2013)

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$$\approx \sum_k \frac{\vec{k}_\perp^2}{t} \int_0^t dx^0 dy^0 \, Tr\left[\rho(M) \langle q \middle| H_I\left(x^0\right) | q + k \rangle \langle q + k \middle| H_I\left(y^0\right) | q \rangle\right]$$

$$\approx g^2 \sum_k \frac{\vec{k}_\perp^2}{t} \int_0^t d^4x d^4y \, Tr[\rho(M) \langle q | \bar{q} \Sigma(x) q | q + k \rangle \langle q + k | \bar{q} \Sigma(y) q | q \rangle]$$

$$\Sigma \equiv \sigma' + i\gamma_5 \, \vec{\pi} \cdot \vec{\tau}$$

A. Majumder, PRC87, 034905 (2013)

Transverse Momenta Broadening

$$\hat{q} = \hat{q}_\sigma + \hat{q}_\pi$$

$$\hat{q}_{\sigma/\pi} = \frac{g^2}{N_c N_F} \int \frac{d^3\vec{k}}{q\, E_{q+k}}\, \vec{k}_\perp^2 q\cdot(q+k)\tilde{G}_{\sigma/\pi}(k^0,\vec{k})$$

$$= \frac{g^2}{N_c N_F} \int \frac{d^3\vec{k}}{q\, E_{q+k}}\, \vec{k}_\perp^2 q\cdot(q+k)\frac{D_{\sigma/\pi}}{e^{\beta k^0}-1}\rho_{\sigma/\pi}(k^0,\vec{k})$$

Degeneracy

Spectral Function of Mesonic Field

$$\tilde{G}_\sigma(k) = \int d^4x \langle \sigma'(0)\sigma'(x)\rangle e^{ik\cdot x}$$

$$\tilde{G}_\pi(k) = \int d^4x \langle \vec{\pi}(0)\cdot\vec{\pi}(x)\rangle e^{ik\cdot x}$$

Minor Correlation (of the fluctuation of order parameter)

A. Majumder, PRC87, 034905 (2013)

Transverse Momenta Broadening

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$$k^0 = -q + |\vec{q} + \vec{k}|$$

$$k^2 < 0$$

A. Majumder, PRC87, 034905 (2013)

- Seek the QCD Critical End Point
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- **Jet Quenching at Finite μB (up to 1-loop)**
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Quark Meson Model

$$L = \bar{q}[i\gamma \cdot \partial - g(\sigma + i\gamma_5 \vec{\pi} \cdot \vec{\tau})]q + \frac{1}{2}\left(\partial_\mu \sigma\right)^2 + \frac{1}{2}\left(\partial_\mu \vec{\pi}\right)^2 - U(\sigma, \vec{\pi})$$

$$U = \frac{\lambda}{4}\left(\sigma^2 + \vec{\pi}^2 - v^2\right)^2 - c\sigma$$

- **Lagrangian**
- Chiral symmetry breaking – restoration
- CEP & 1-st order phase transitoin

Quark Meson Model

chiral order parameter

$\sigma = \sigma^* + \sigma'$ breaks chiral symmetry

$$L = \bar{q}[i\gamma \cdot \partial - g(\sigma + i\gamma_5 \vec{\pi} \cdot \vec{\tau})]q + \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \vec{\pi})^2 - U(\sigma, \vec{\pi})$$

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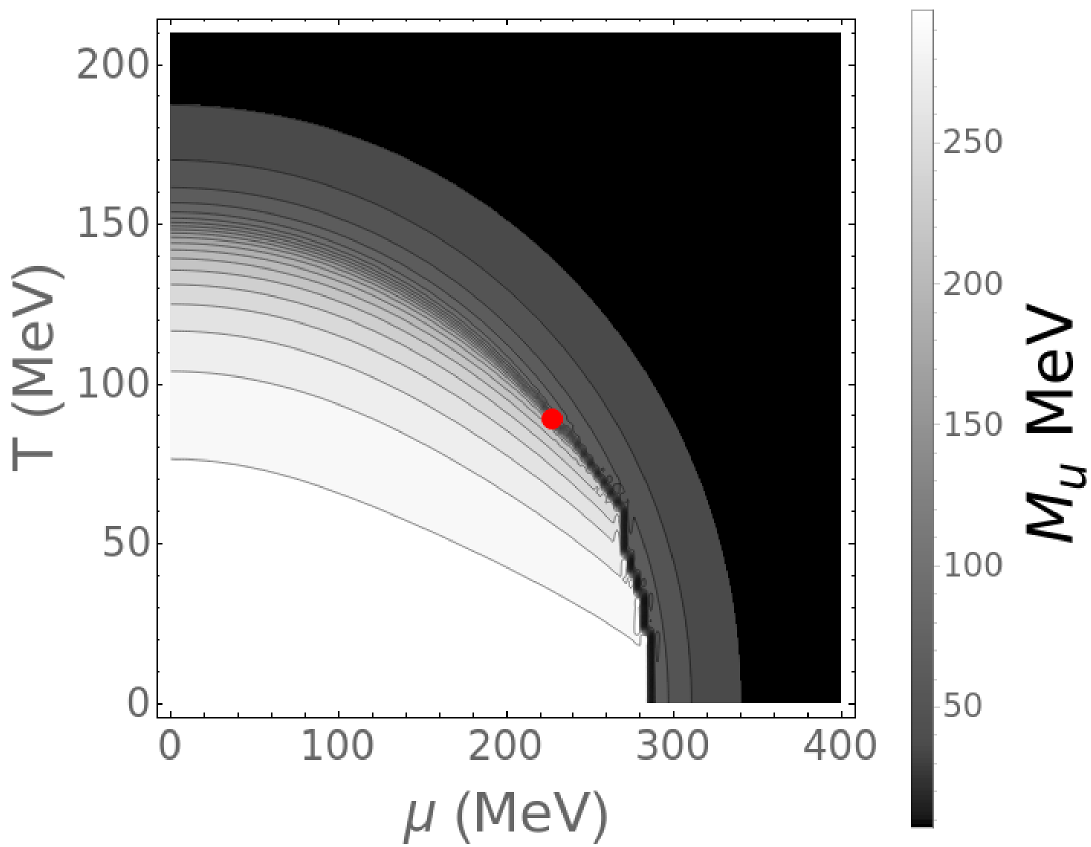
Quark Meson Model



- Lagrangian
- **Chiral symmetry breaking – restoration**
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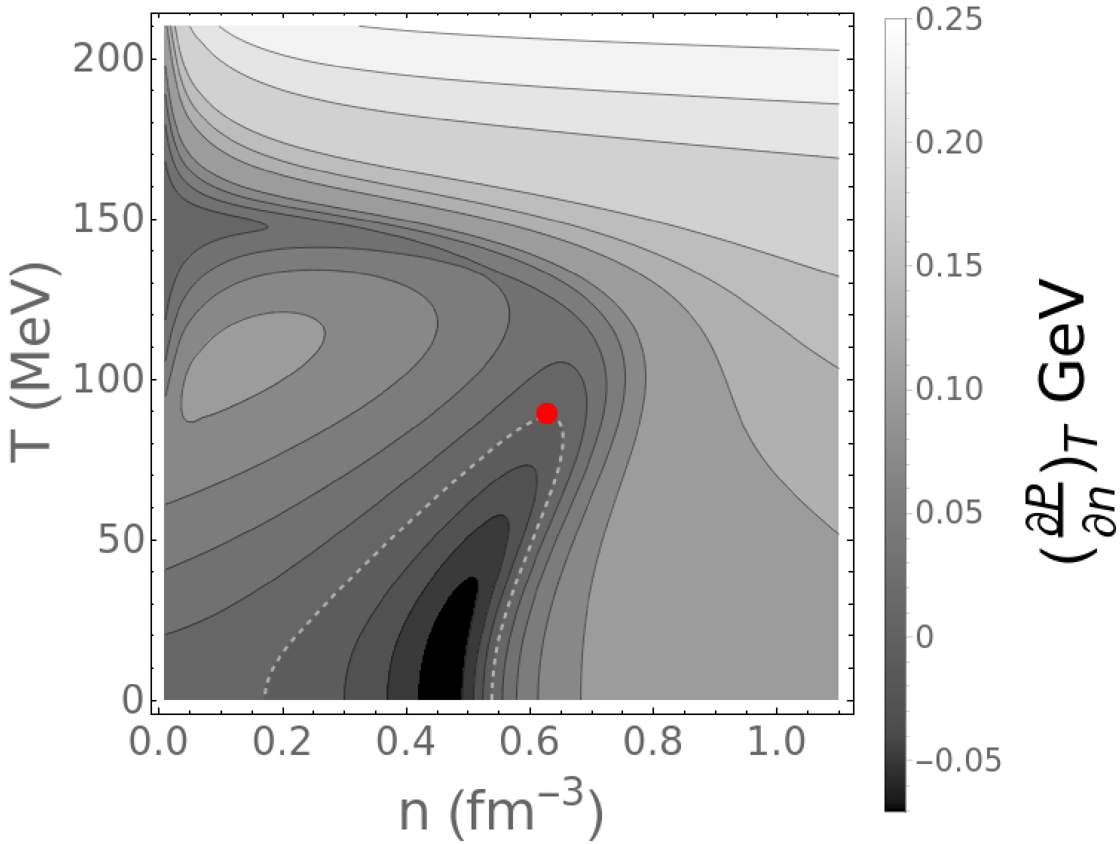
Quark Meson Model

$T_c = 89\ \mathrm{MeV};\ \ \mu_c = 228\ \mathrm{MeV};\ \ n_c = 0.63\ \mathrm{fm}^{-3}$



- Lagrangian
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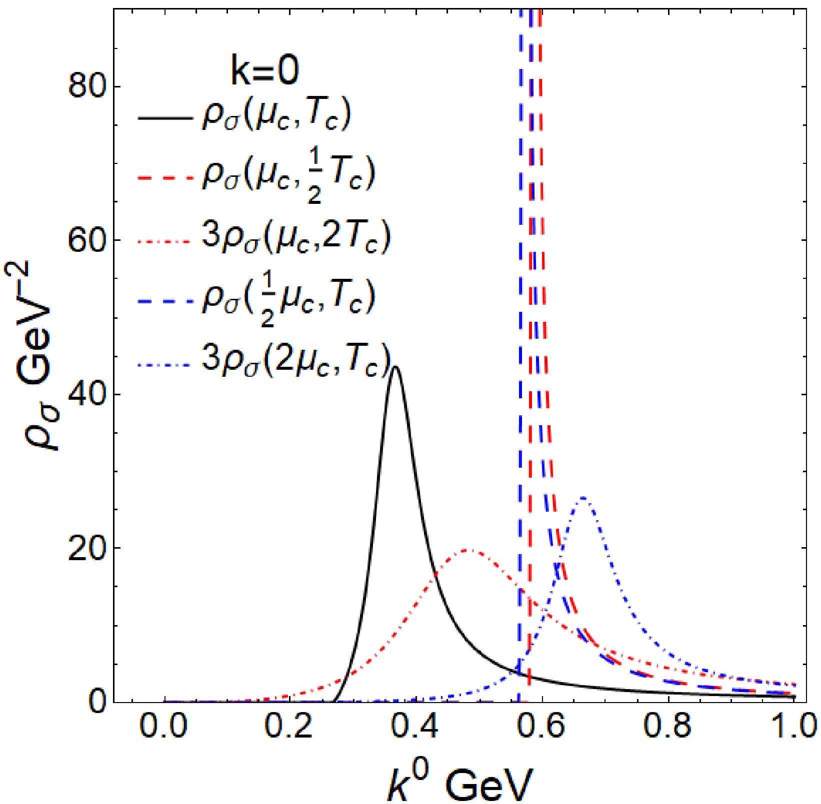
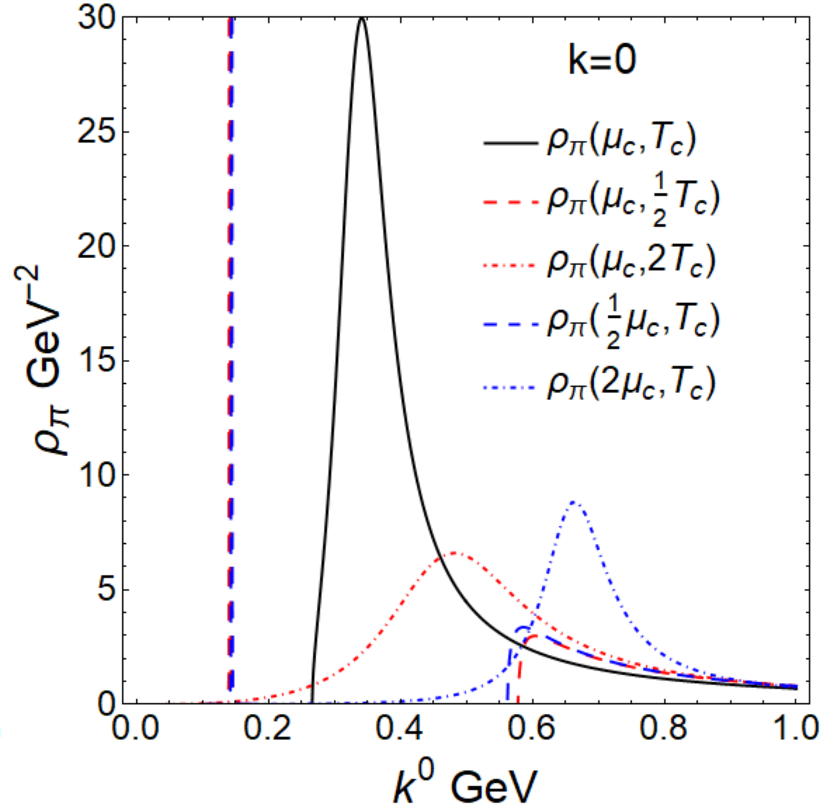
Spectral Function up to 1-loop





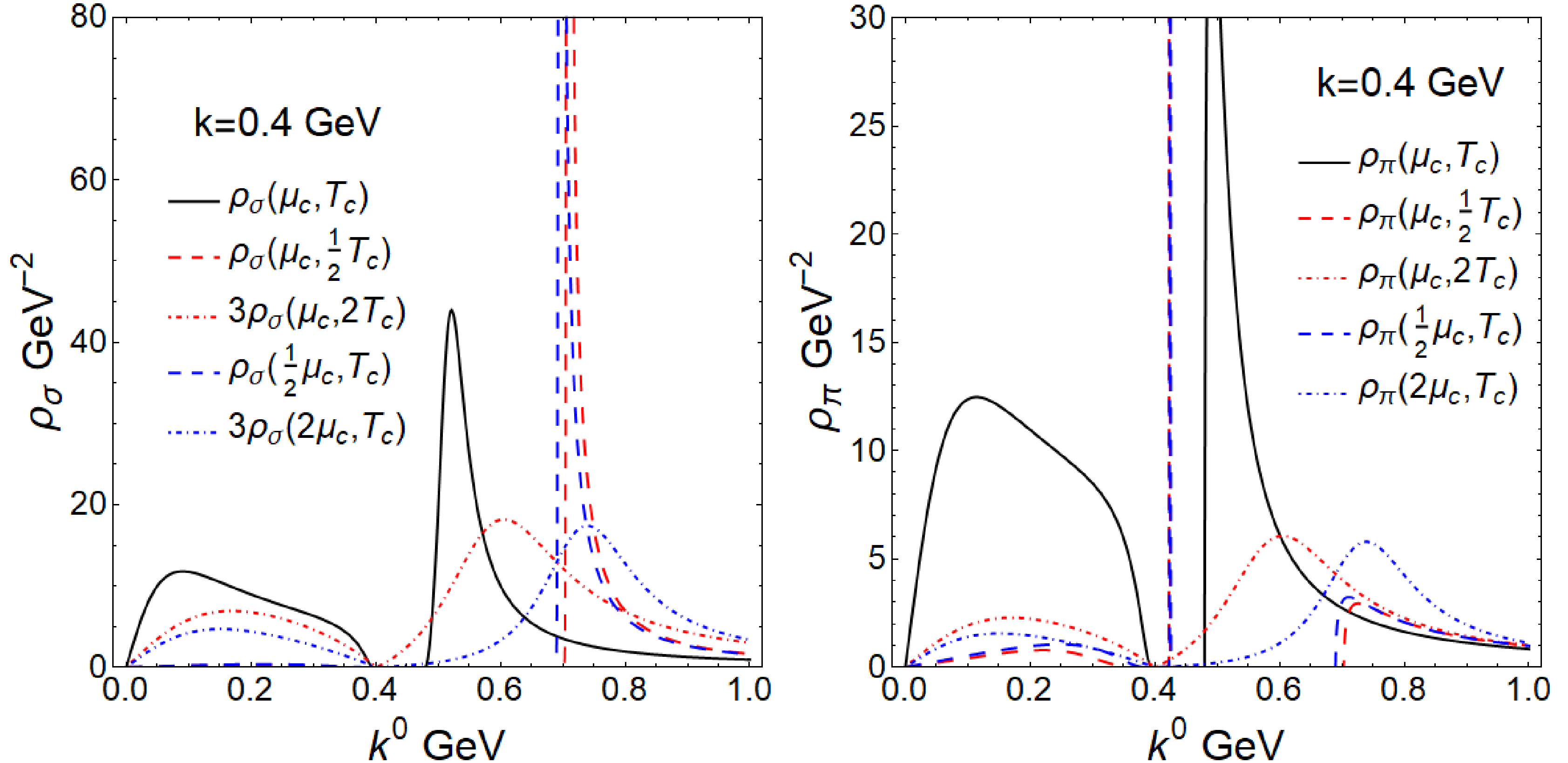
$m^*_\pi\,(H.G.) < m^*_\pi\,(CEP) < m^*_\pi\,(QGP)$

$m^*_\sigma\,(CEP) < m^*_\sigma\,(H.G.or\ QGP)$

$\rho_\pi(\mu_c, 2T_c) \sim \rho_\sigma(\mu_c, 2T_c)$ $\rho_\pi(2\mu_c, T_c) \sim \rho_\sigma(2\mu_c, T_c)$

- Expression
- **K=0**
- K>0

Spectral Function up to 1-loop

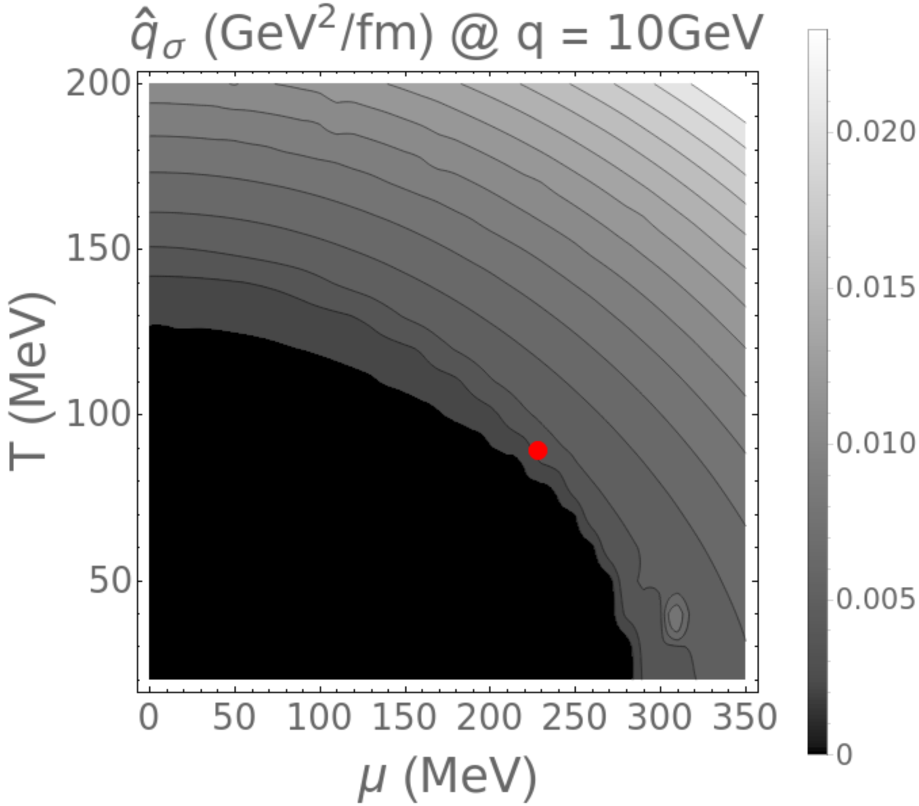


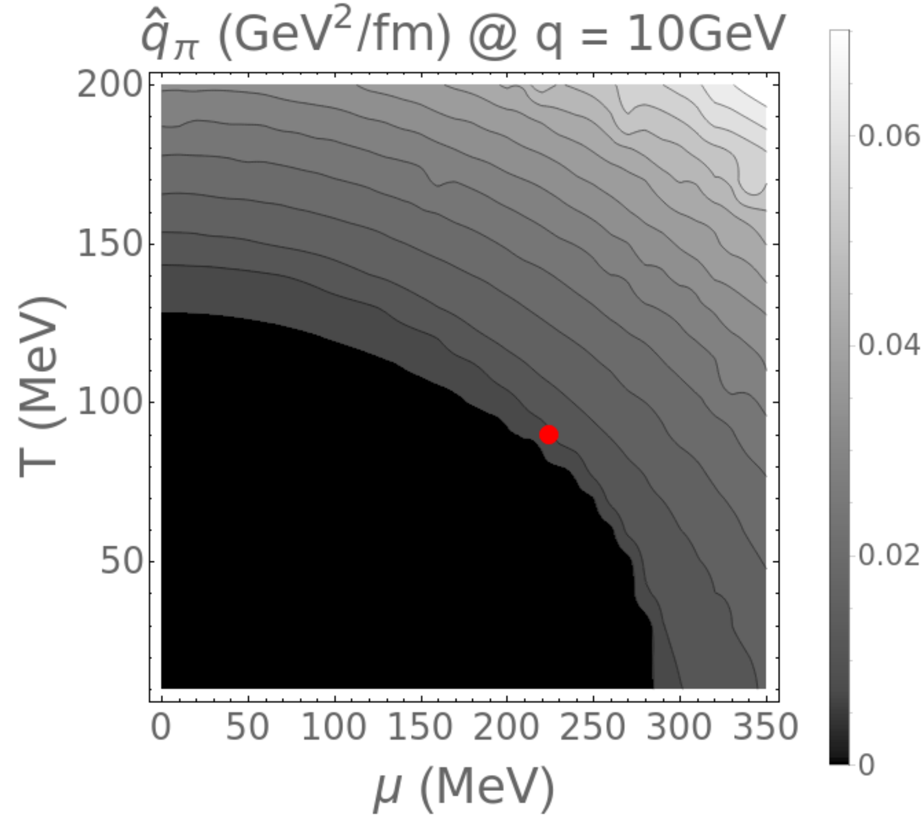
For $\left|\vec{k}\right| = 0.4\ \mathrm{GeV}\ \&\ k^2 < 0$:

- $\rho(CEP)$ is the maximum
- $\rho(H.G.)$ is negligible

- Expression
- K=0
- **K>0**

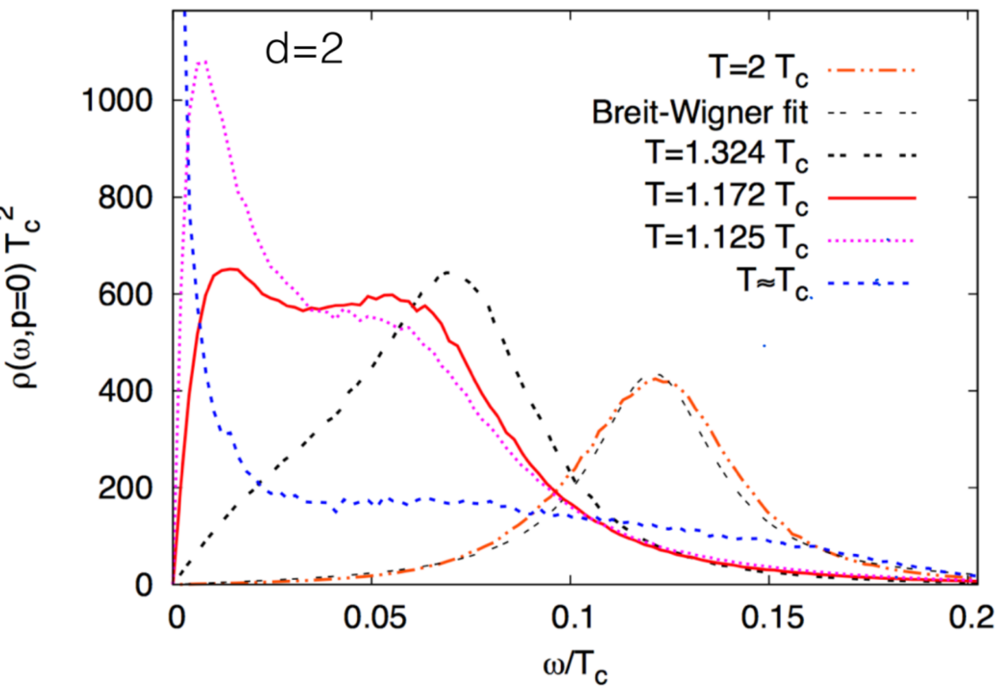
Q-hat up to 1-loop

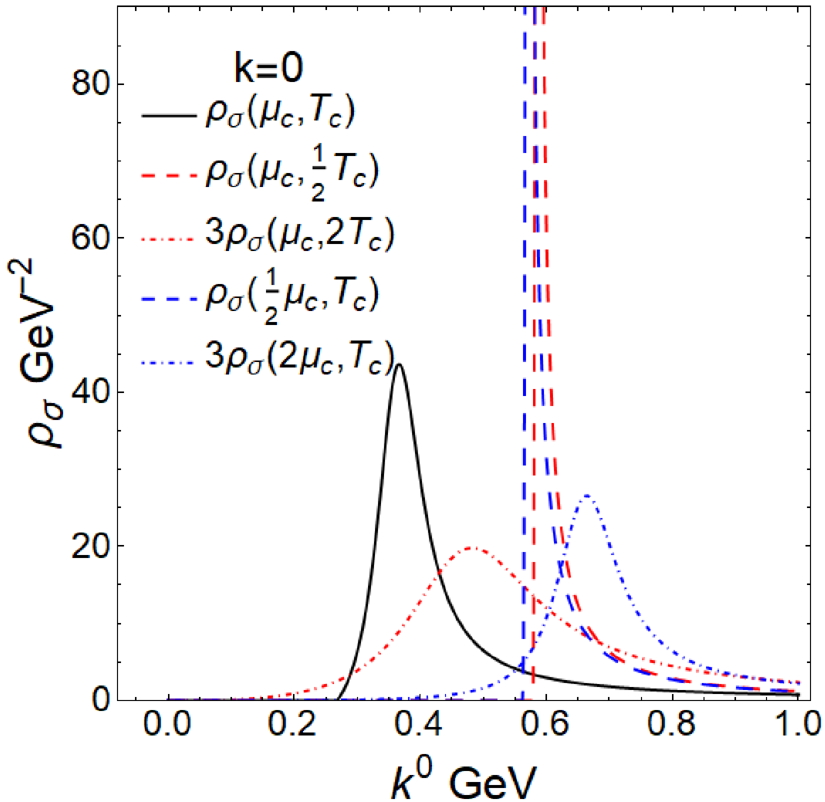




$\hat{q}_\sigma \sim 0.12\, n_{parton}$ $\hat{q}_\pi \sim 0.35\, n_{parton}$ $\hat{q} \sim 0.47\, n_{parton}$

Defect of 1-loop Spectral





J. Berges, SS, D. Sexty, NPB832 (2010) 228

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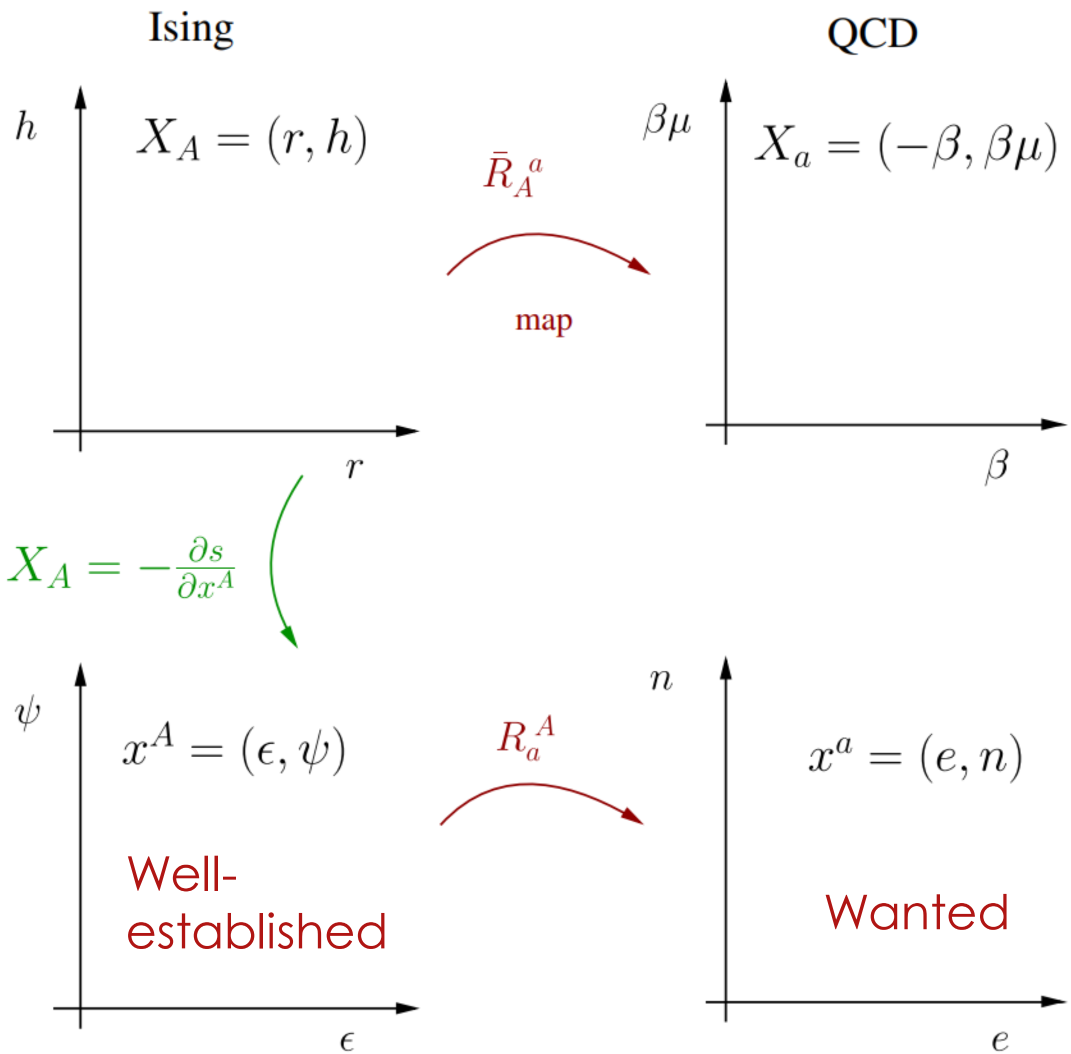
Map between QCD & Ising Model



M.Martinez, PRD 100, 074017(2019)

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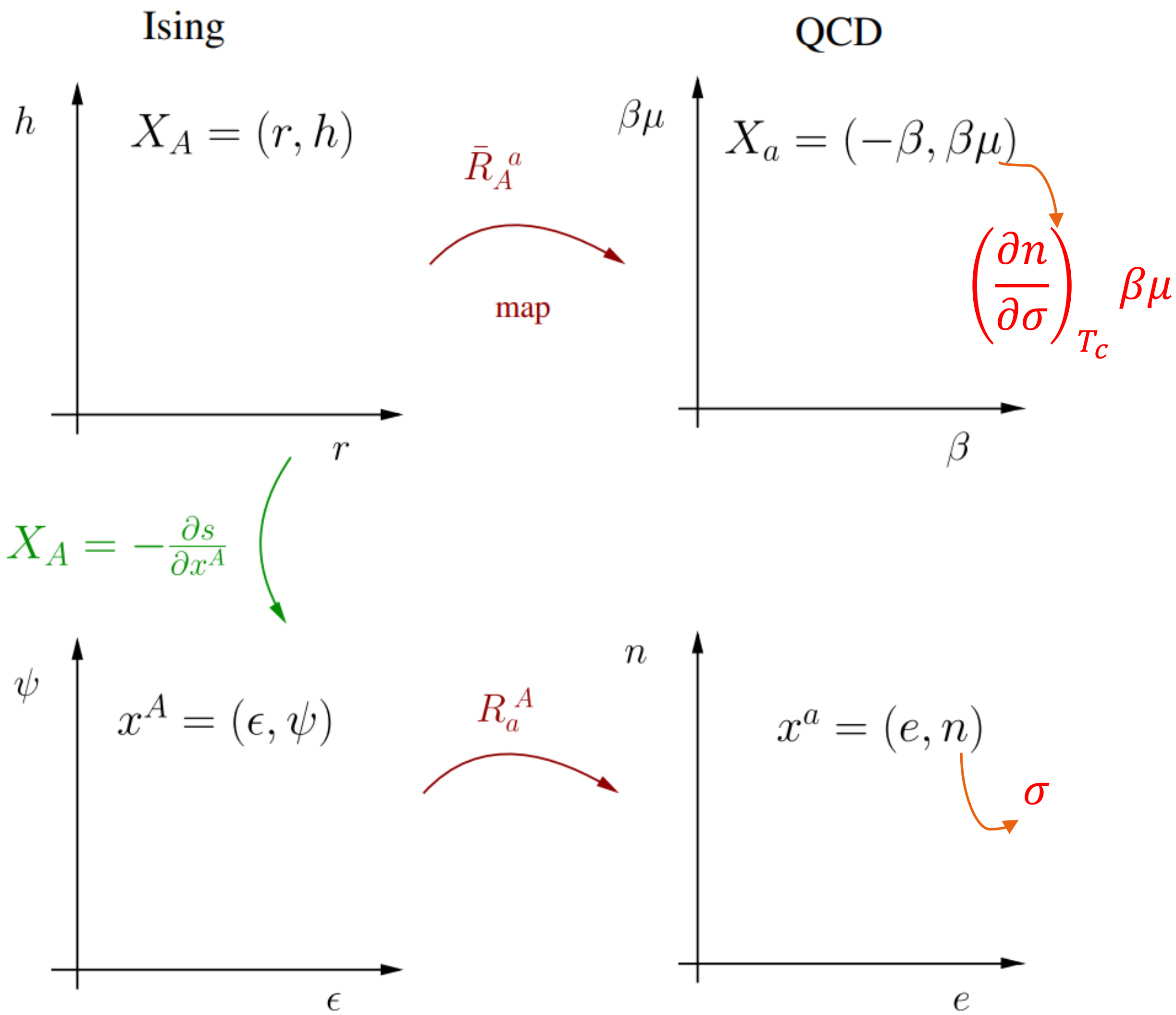

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Map between QCD & Ising Model

Observables

$$\begin{pmatrix}\delta e\\ \delta n/\sigma'\end{pmatrix} = \begin{bmatrix}0 & 1\\ -\frac{1}{2} & 0\end{bmatrix}\begin{pmatrix}\delta \epsilon\\ \delta\psi\end{pmatrix}$$

⇩

$$\rho^{\mathrm{QCD}}_{n/\sigma} \propto \rho^{\mathrm{Ising}}_{\epsilon}$$

$$\epsilon = \frac{\delta G}{\delta r}$$

$$\beta_c G = \int d^3x \left(\kappa(\nabla\psi)^2 + \left(\frac{v}{2} + \gamma C_0 \beta_c r\right)\psi^2 + \tilde{u}\psi^4\right)$$

Thermal Parameters

$$\frac{T - T_c}{T_c} = h$$

$$\left(\frac{\partial n}{\partial \sigma}\right)_{T_c} \frac{\mu - \mu_c}{T_c} = -2r$$

$$r = R(1 - \theta^2)$$

$$h = h_0 R^{\beta\delta}\tilde{h}(\theta)$$

CEP @ R=0

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$$\rho^{\mathrm{QCD}}_{n/\sigma} \propto \rho^{\mathrm{Ising}}_{\epsilon} \propto \rho^{\mathrm{Ising}}_{\psi^2}$$

$$\widetilde{\rho_{\psi^2}}(k) = 4\mathrm{Im}\left[\int \frac{d^4\bar{k}}{(2\pi)^4} \Delta_S\left(\frac{k}{2}+\bar{k}\right)\Delta_R\left(\frac{k}{2}-\bar{k}\right)\right]$$

$$\Delta_S(k) = \coth\frac{k^0}{2T_{\mathrm{Ising}}}\ \mathrm{Im}\,\Delta_R$$

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$$\Delta_R = \frac{\chi_k(\xi)\Gamma_k(\xi)}{\Gamma_k(\xi) - ik^0}$$

Thermal Parameters

$$\frac{T - T_c}{T_c} = h$$

$$\left(\frac{\partial n}{\partial \sigma}\right)_{T_C} \frac{\mu - \mu_c}{T_c} = -2r$$

$$r = R(1-\theta^2)$$

$$h = h_0 R^{\beta\delta} \tilde{h}(\theta)$$

$$\xi = \xi_0 R^{-\nu} \sqrt{1 - \frac{5\theta^2}{18}}$$

CEP @ R=0

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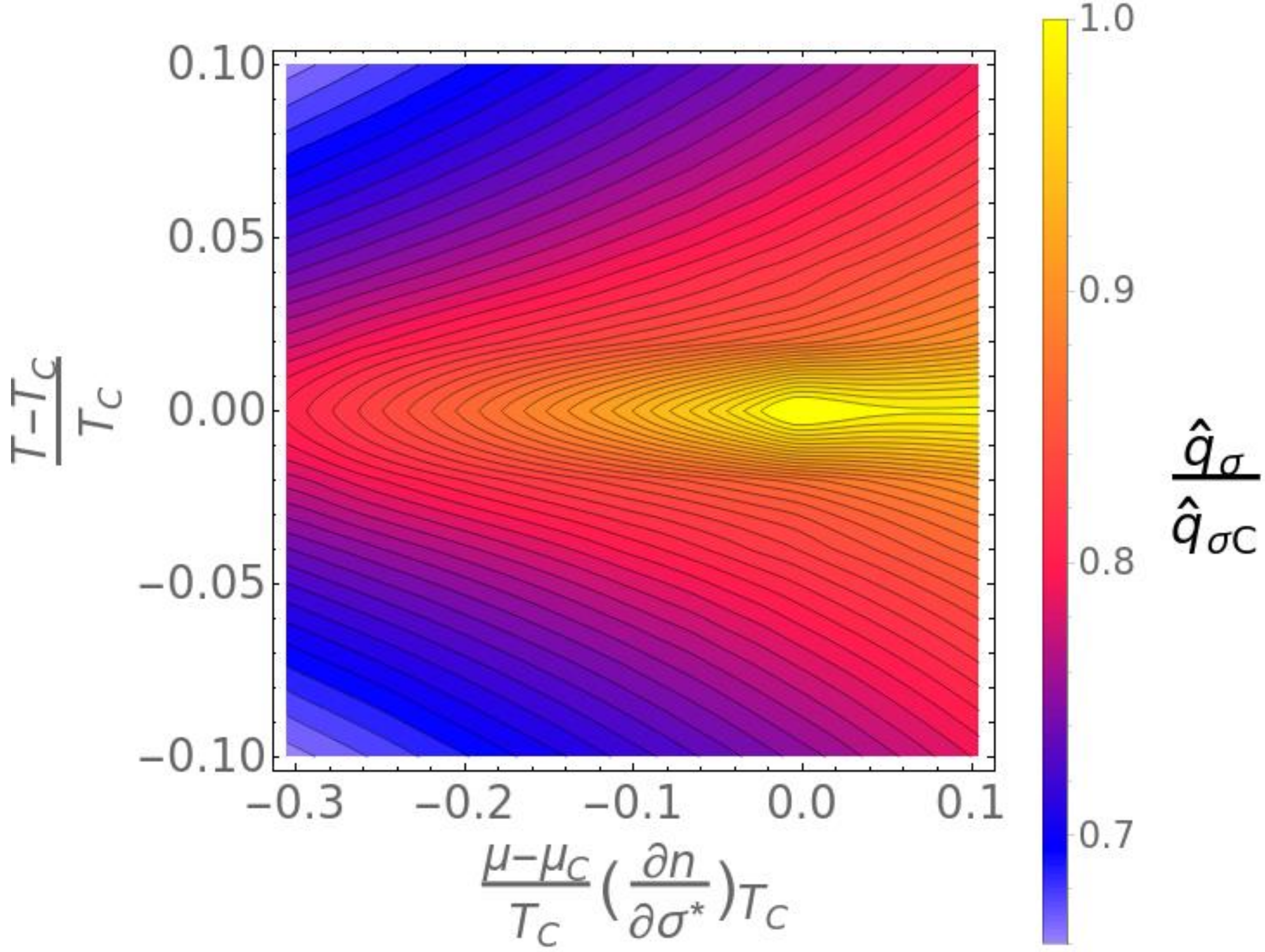
Q-hat near CEP



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Summary

- Establish a new formalism studying jet quenching at finite μB
- Q-hat ~ 0.47 parton number density in the QGP phase
- Q-hat prominently enhanced at CEP (PCO)
- **For the first time, the hard probes, such as jet, are proposed as the signal of CEP**.
- Affect on jet substructure will be looked into in the near future.