Unfolding strongly correlated QCD

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Universität Heidelberg & ExtreMe Matter Institute

Hirschegg, September 11th 2023

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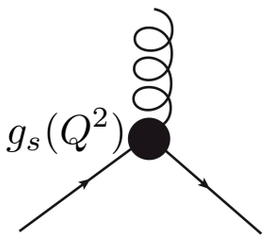
EMMI

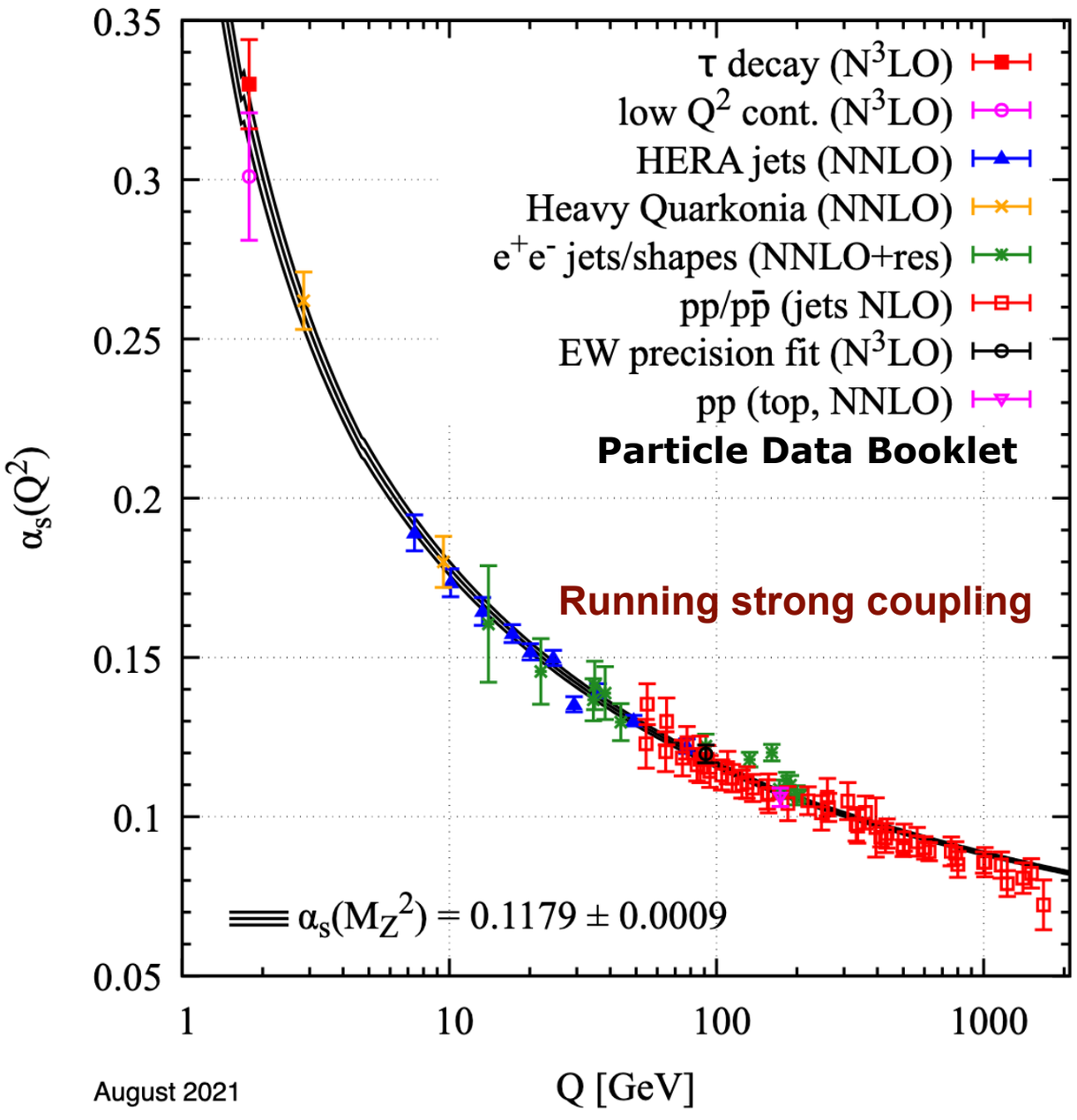
What's hot in QCD?

Low Temperatures, densities ⟵

⟶ **Large Temperatures, densities**



$$\alpha_s(Q^2) = \frac{g_s(Q^2)}{4\pi}$$



What's hot in QCD?

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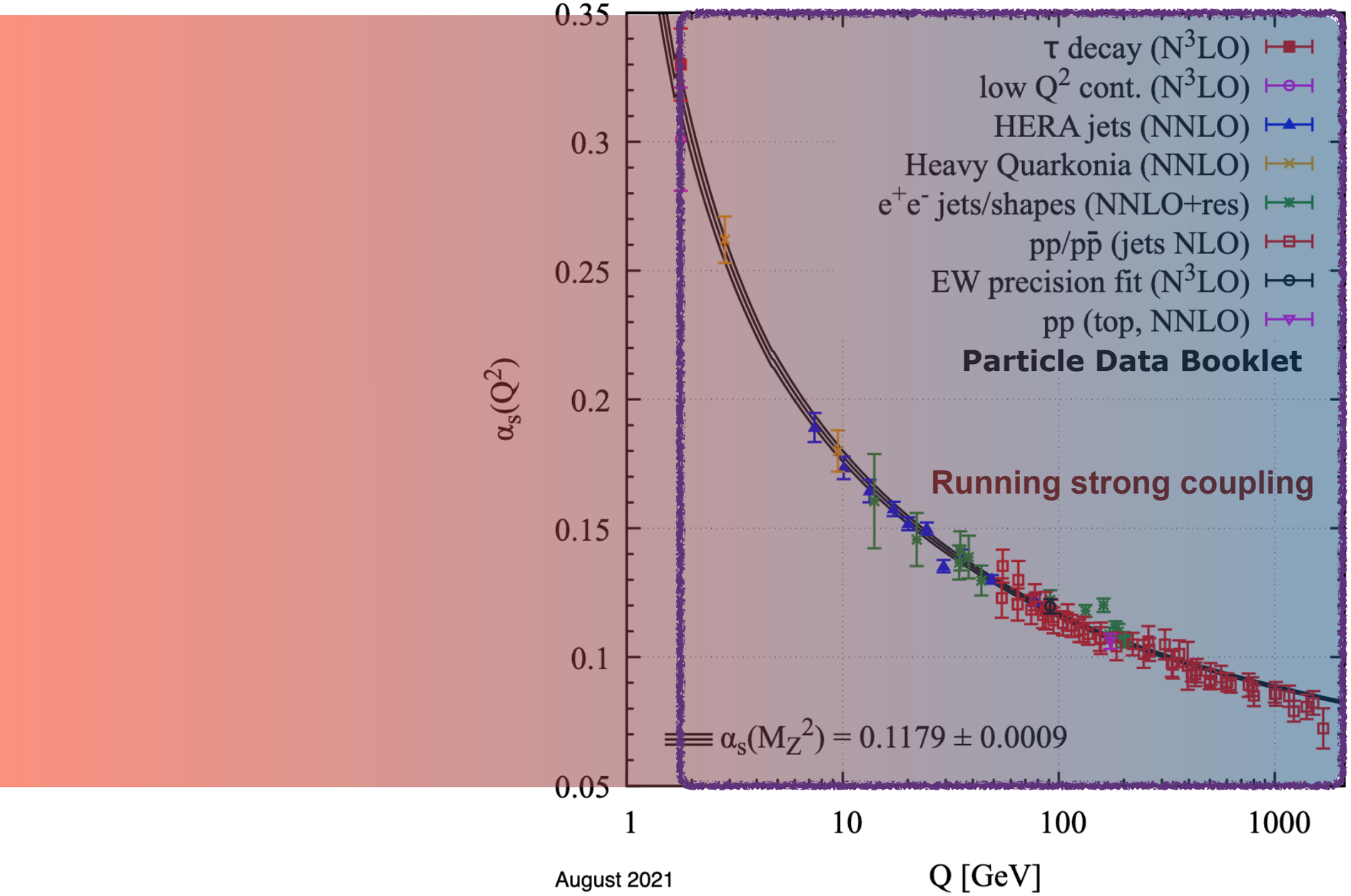
Large Temperatures, densities



QCD background
for
SM & BSM physics

crucial for 'unfolding'

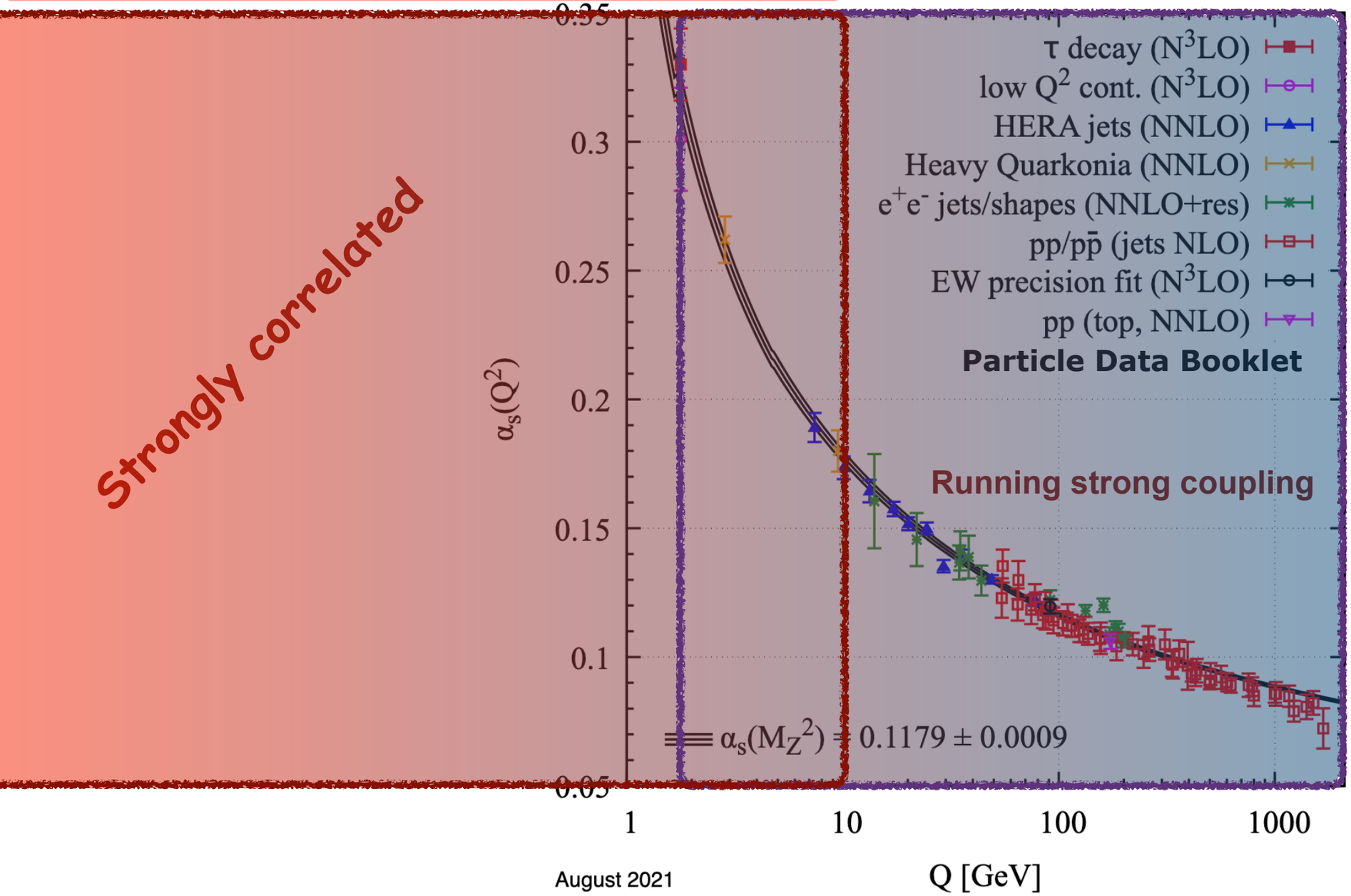
deconvolution
reconstruction
⋮

UV: weakly coupled quarks and gluons

What's hot in QCD? The cool stuff!

For the purpose of the talk/workshop!!

IR: confinement & chiral symmetry breaking



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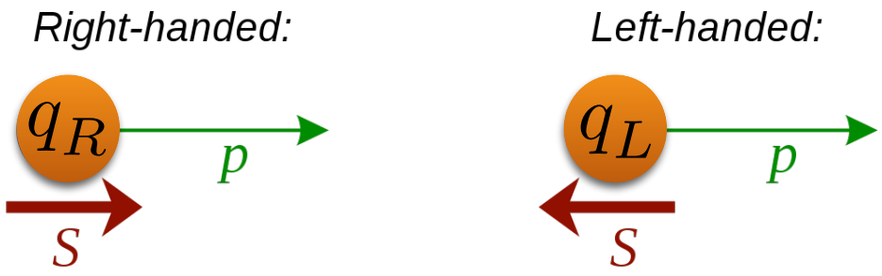
UV: weakly coupled quarks and gluons

Chiral symmetry breaking

Chirality for massless particles

helicity



Chiral symmetry breaking

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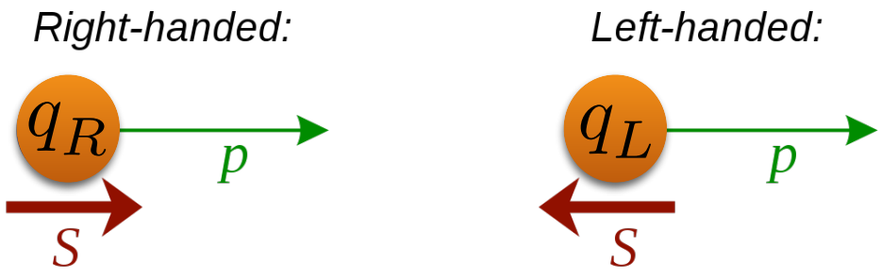


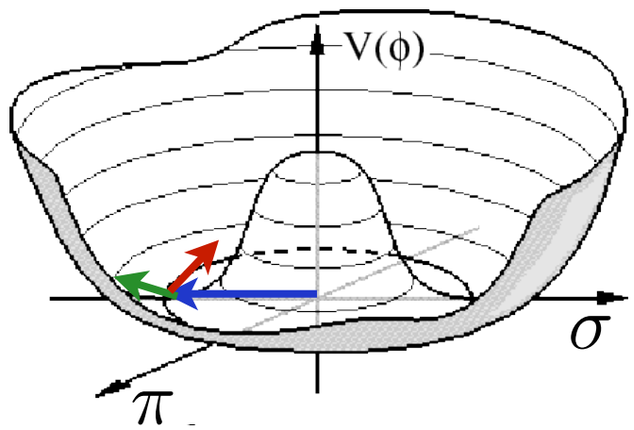
Order parameter

$$\sigma \propto \langle \bar{q} q \rangle = \langle q_L^\dagger q_R + q_R^\dagger q_L \rangle$$

chiral condensate

- **Chiral symmetry** $\sigma = 0$
- **Symmetry broken** $\sigma \neq 0$

Meson potential

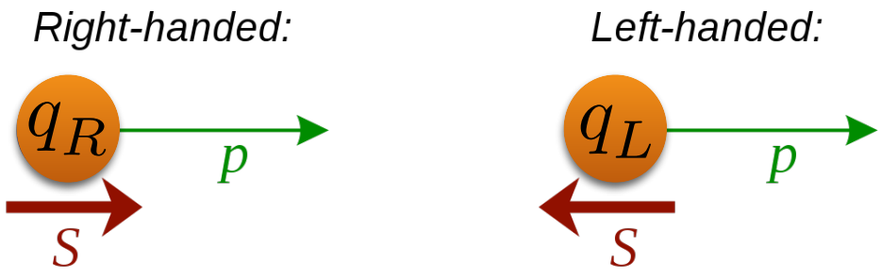


$$\vec{\pi} \simeq i \langle \bar{q} \vec{\sigma} \gamma_5 q \rangle$$

Chiral symmetry breaking

Chirality for massless particles

helicity



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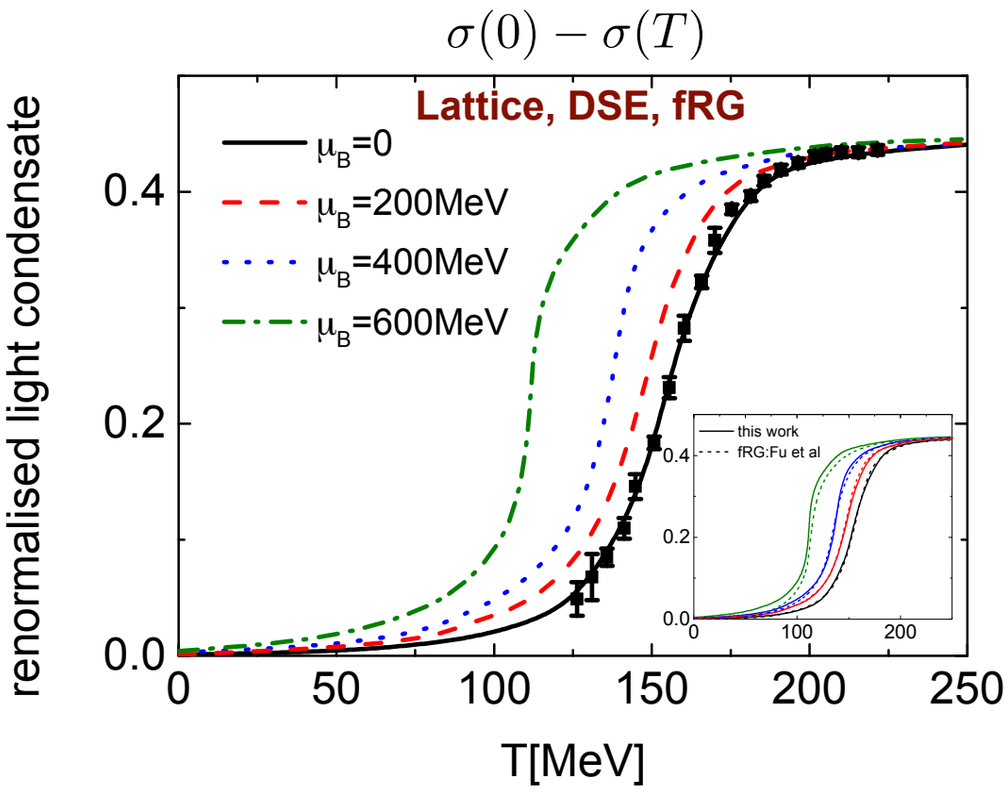

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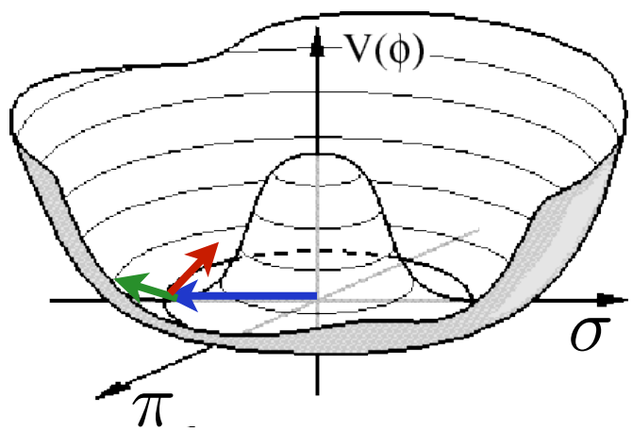

$$\vec{\pi} \simeq i \langle \bar{q} \vec{\sigma} \gamma_5 q \rangle$$

Chiral symmetry breaking

chiral symmetry

$$\langle \bar{q} q \rangle = 0$$

Mean field expansion

$$\int_x (\bar{q} q)^2 = \int_x \langle \bar{q} q \rangle \bar{q} q + \cdots$$

Chiral symmetry breaking

chiral symmetry

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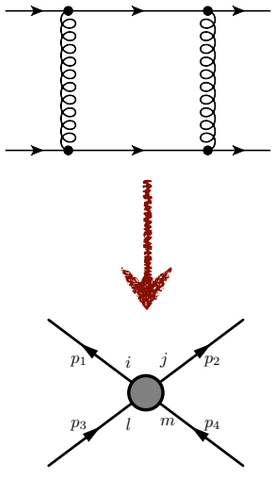
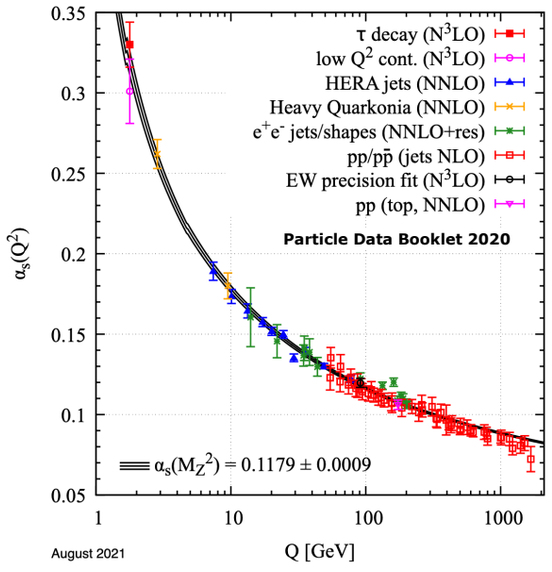


$$\propto \alpha_s^2$$



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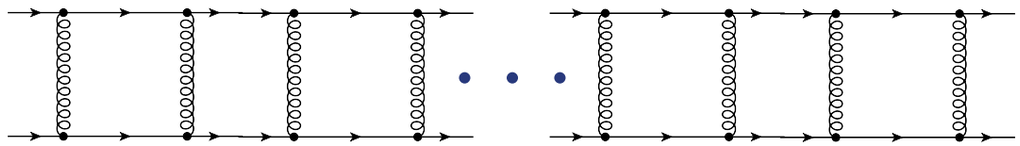

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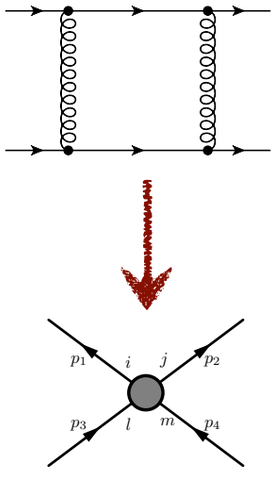

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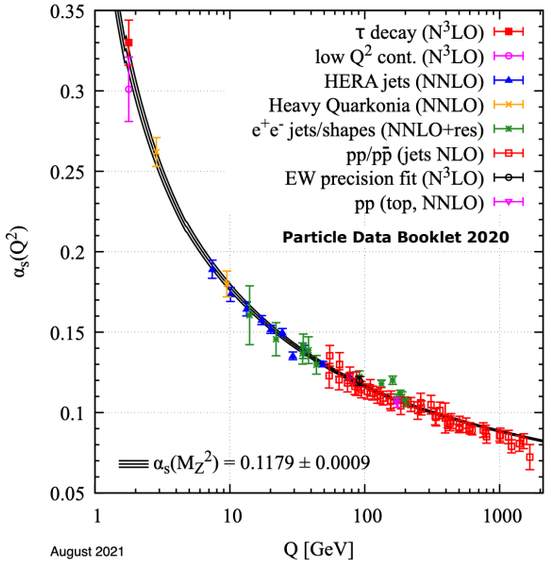

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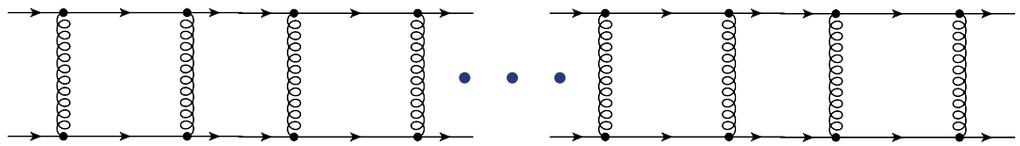

$$\langle \bar{q} q \rangle \neq 0$$

critical strong coupling $\alpha_{\mathbf{s}}^{\mathrm{cr}}$

chiral symmetry broken

Chiral symmetry breaking

chiral symmetry

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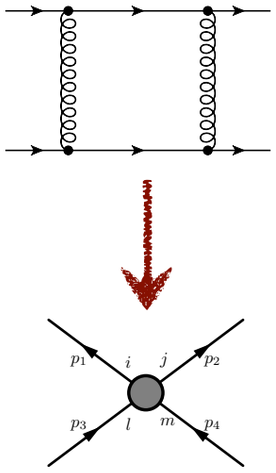
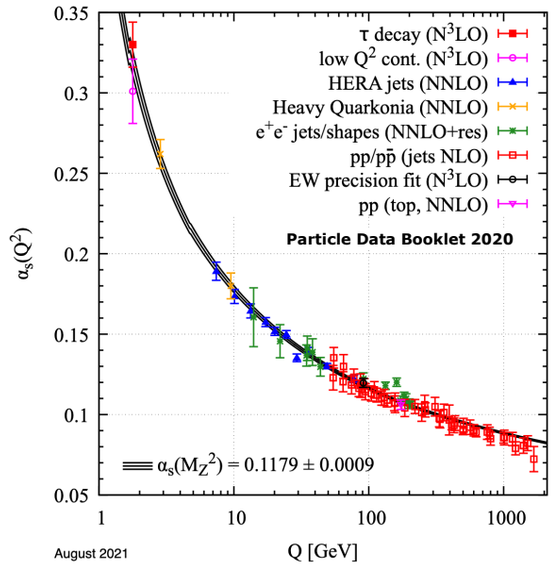


$\propto \alpha_s^2$



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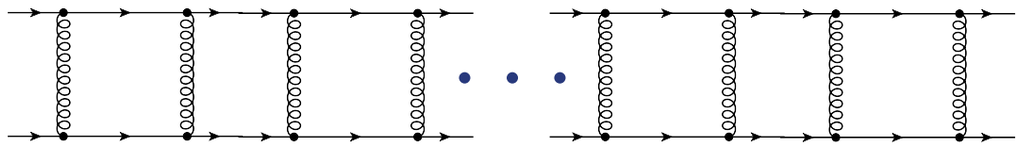

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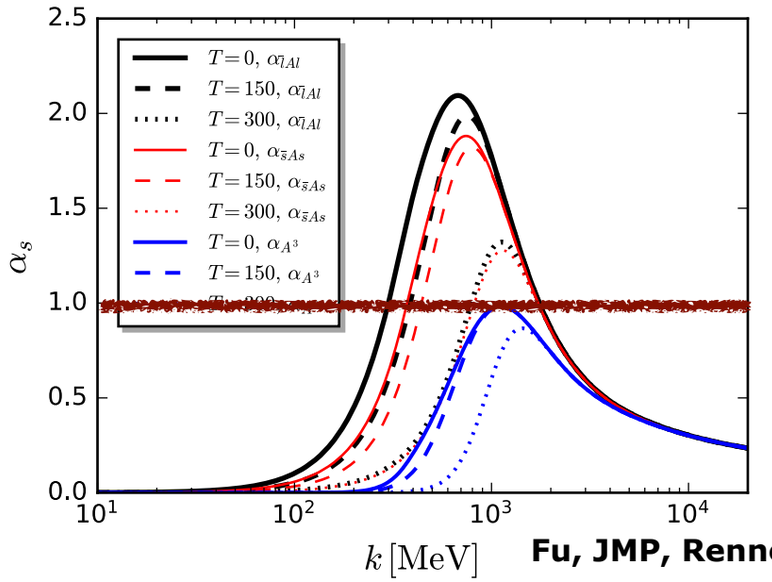


critical strong coupling α_s^{cr}

Fu, JMP, Rennecke, PRD 101, (2020) 054032

Chiral symmetry breaking

physical masses

strong chiral symmetry breaking $\Delta m_{\chi SB} \approx 400\,\mathrm{MeV}$

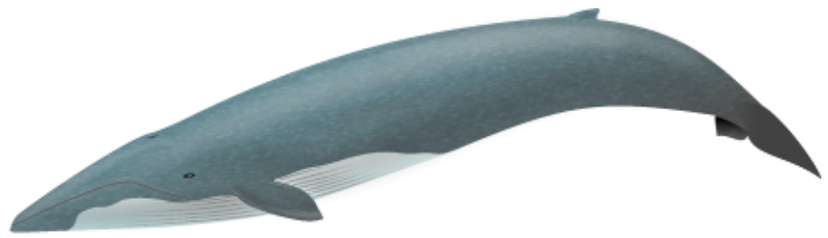
up

down

charm

strange

top

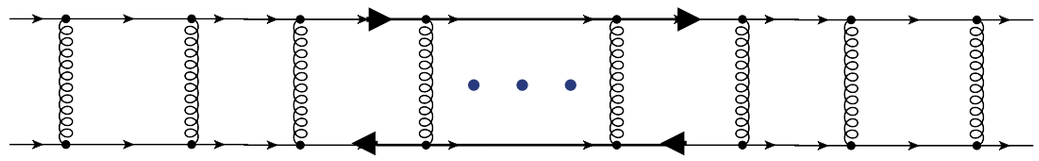


bottom

2 light flavours, one heavy flavour 2+1

Confinement

Free energy $F_{q\bar{q}}$ of a quark - antiquark pair



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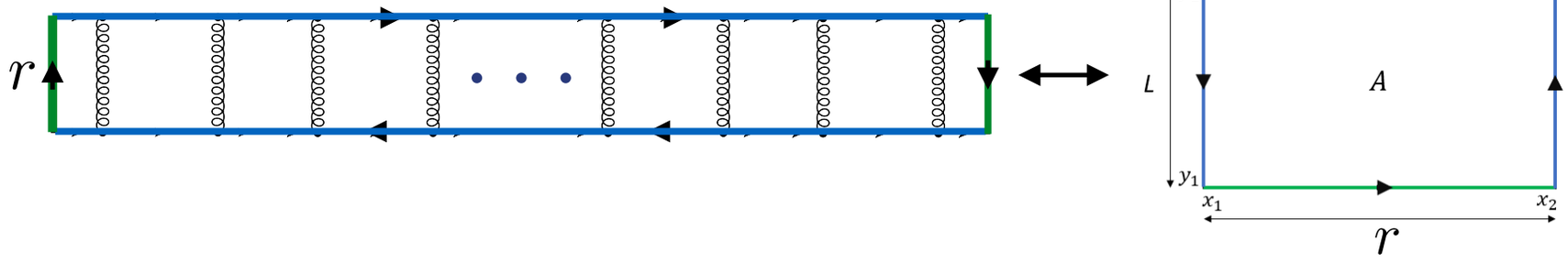

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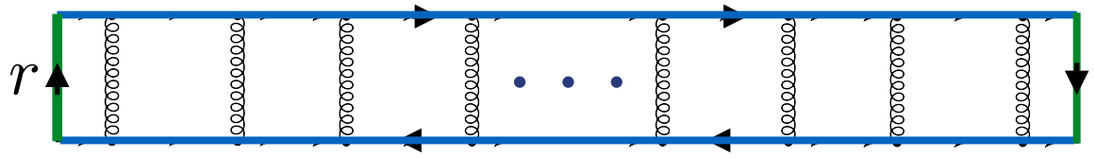
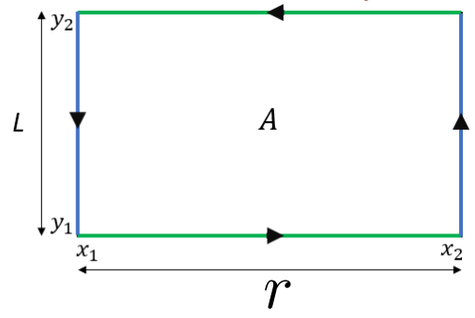
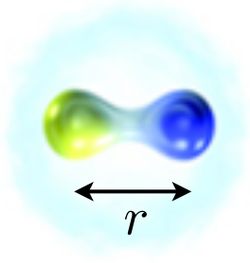
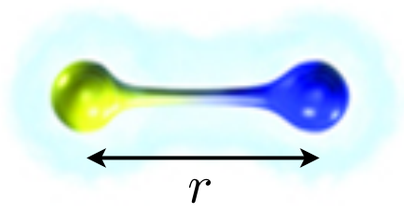




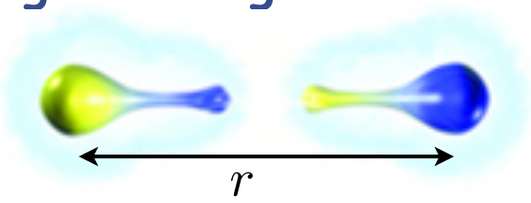


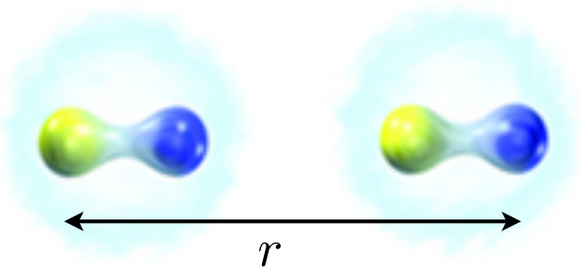
$$F_{q\bar{q}} \simeq -\frac{1}{r}$$



$$F_{q\bar{q}} \simeq \sigma r$$

string breaking at $\mathrm{r} \approx 1\mathrm{fm}$





$$F_{q\bar{q}} \simeq \text{const.}$$

Confinement

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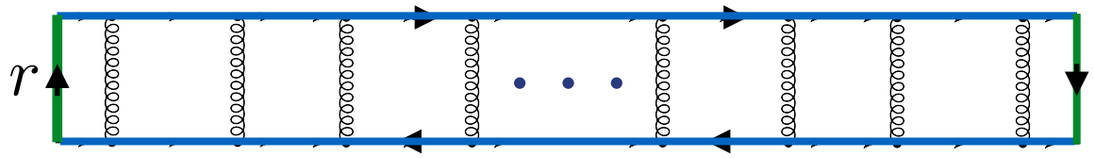
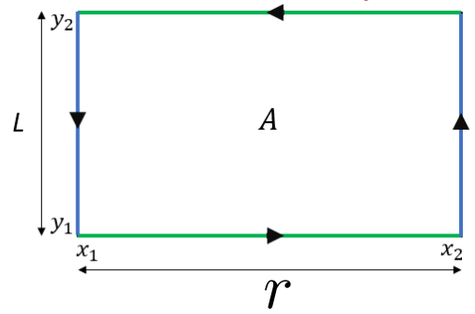
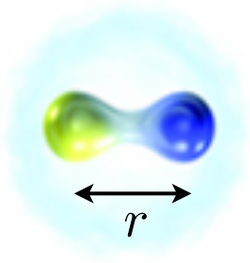


Wilson loop





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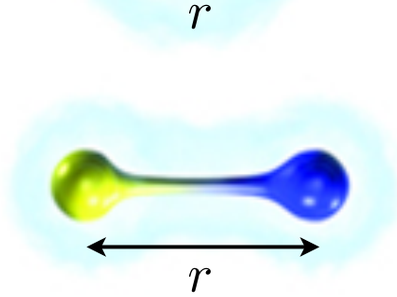

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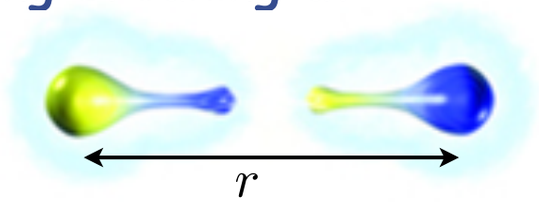

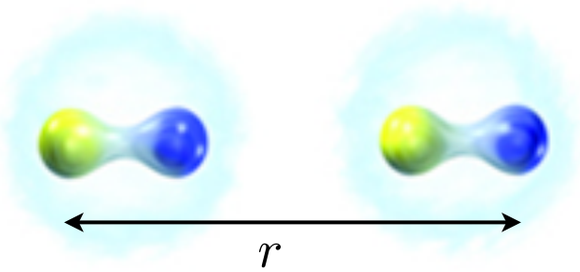

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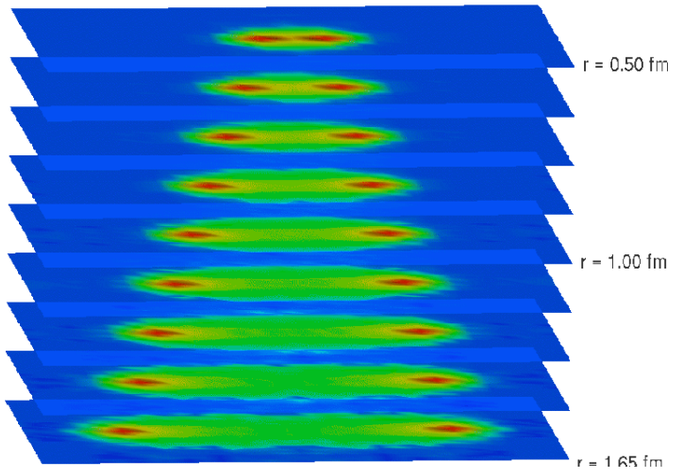
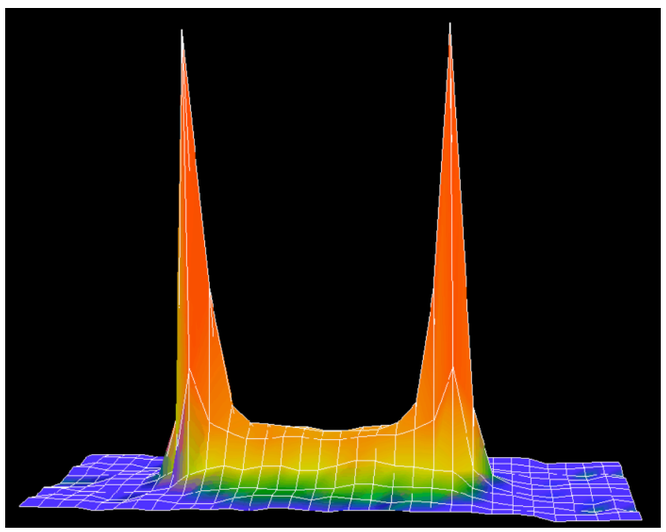


Energy density

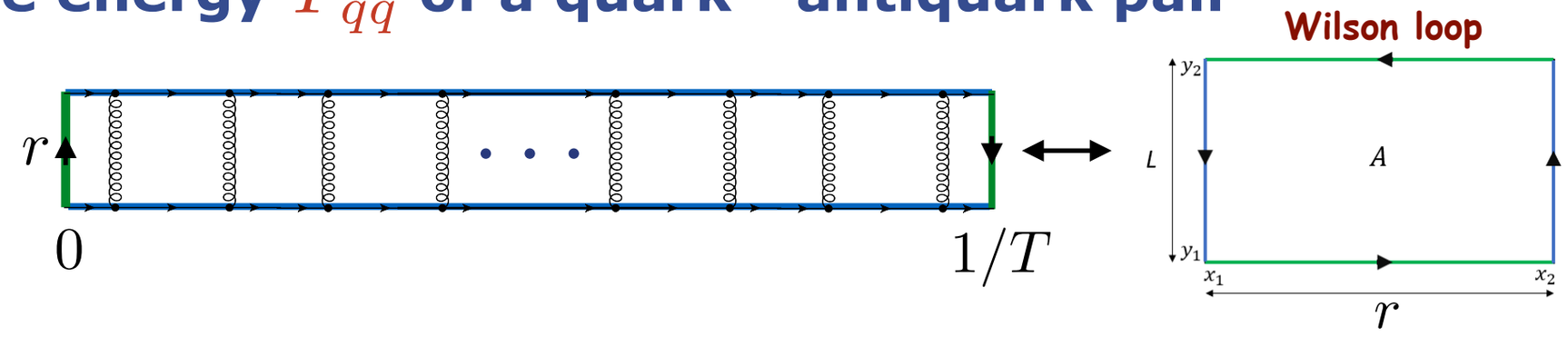
Bali et al. '94



Confinement

Free energy $F_{q\bar{q}}$ of a quark - antiquark pair

finite T



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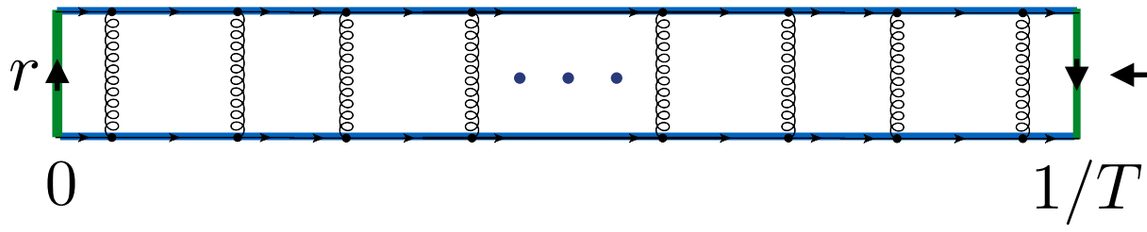

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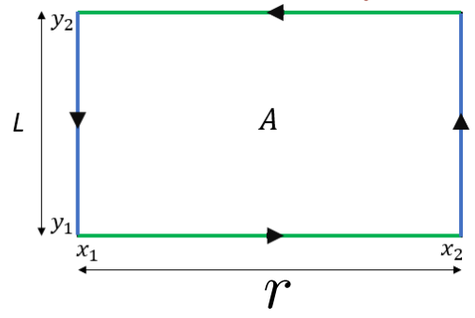
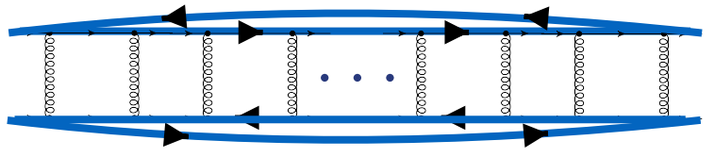


'non-local'

Polyakov loop correlator

$$\langle q(0)\bar{q}(r)\rangle \sim \langle P(0)P^{\dagger}(r)\rangle \sim V(r,T)/T$$



'local order parameter'

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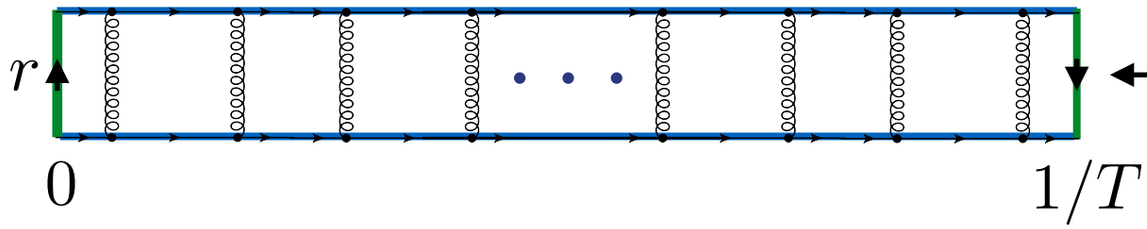

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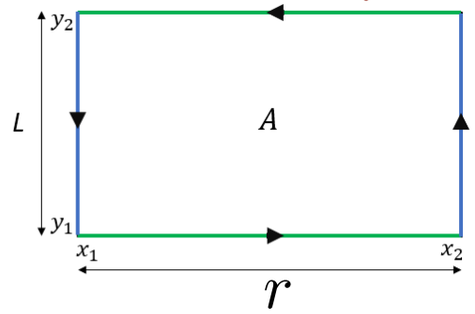

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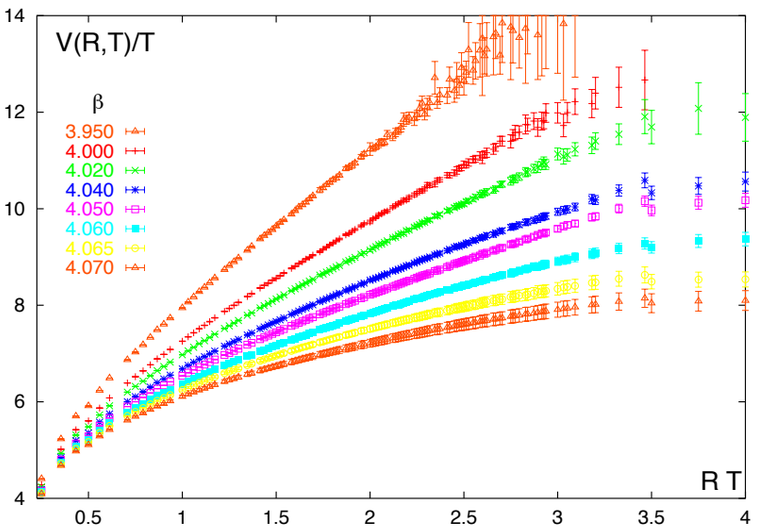

Kaczmarek et al '99

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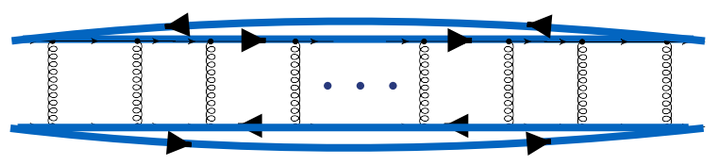

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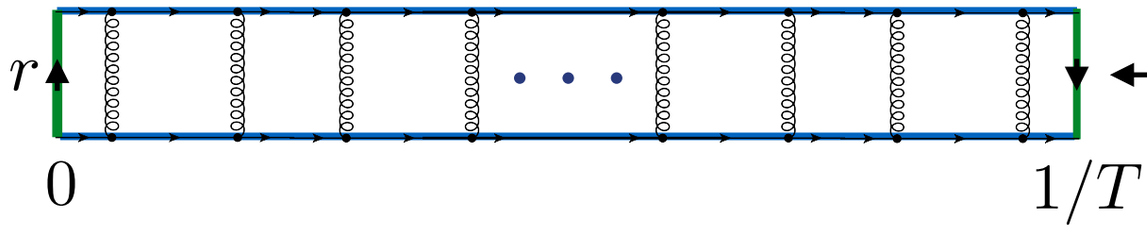

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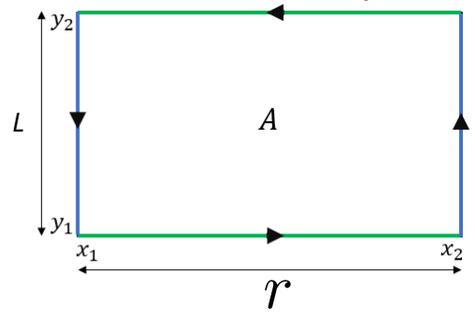

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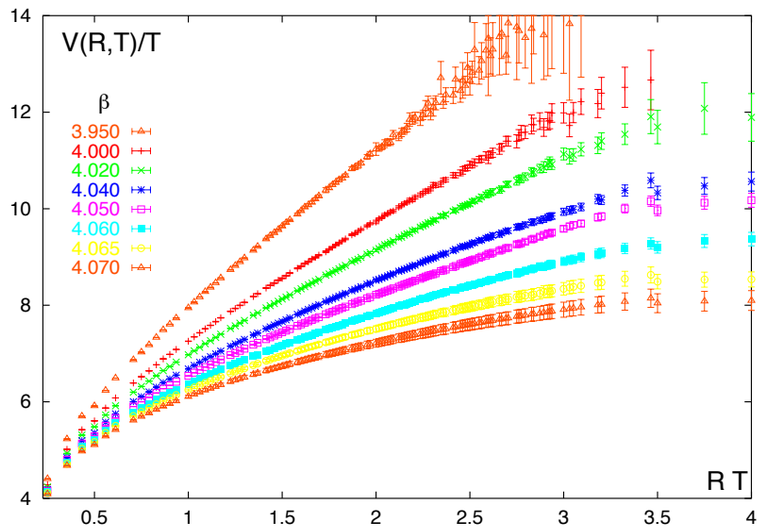
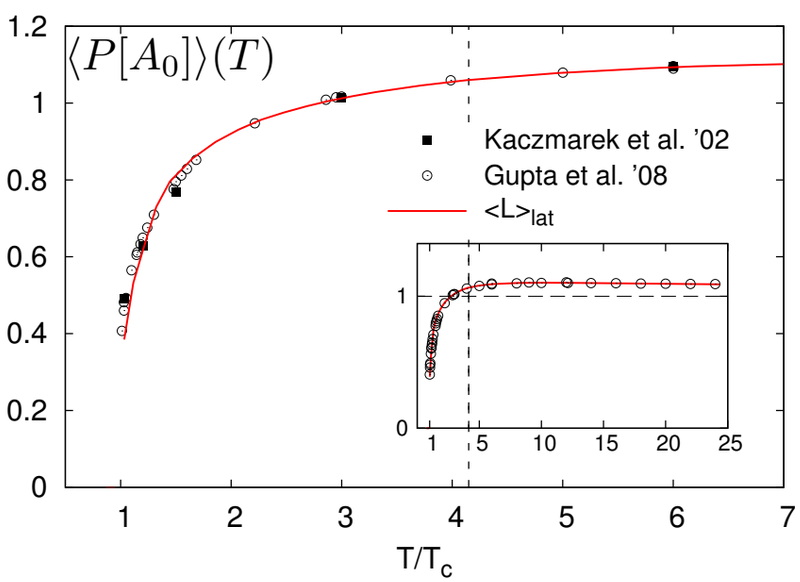


Kaczmarek et al '99



Herbst, Lücker, JMP, 2015

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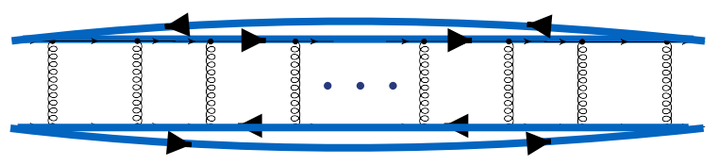

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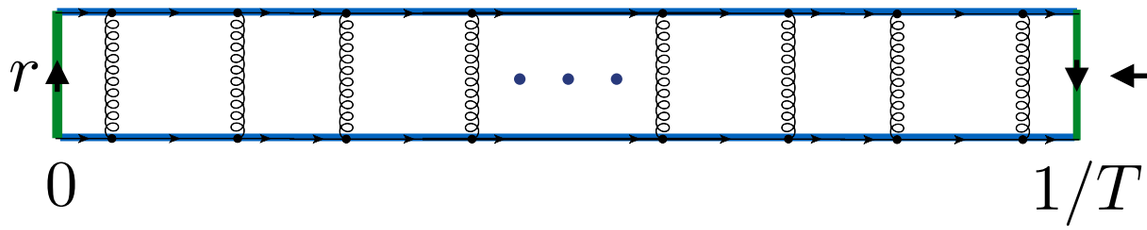
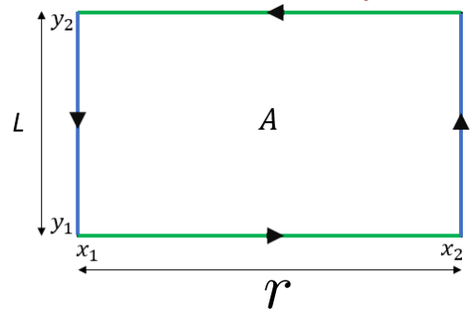
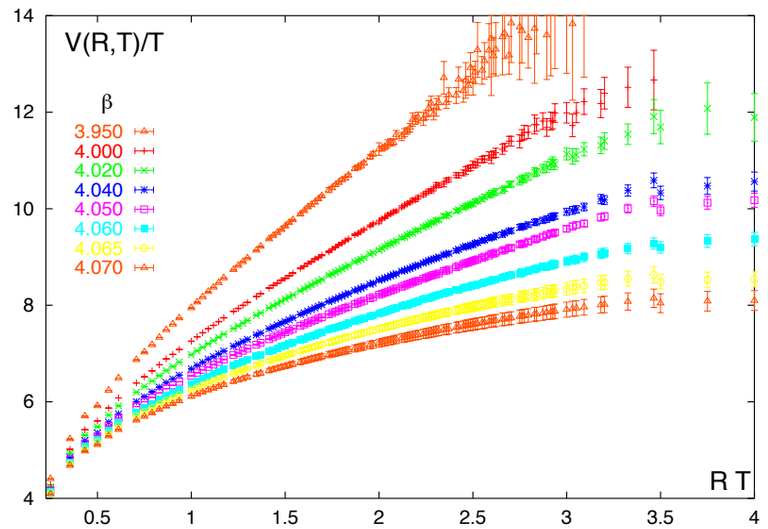


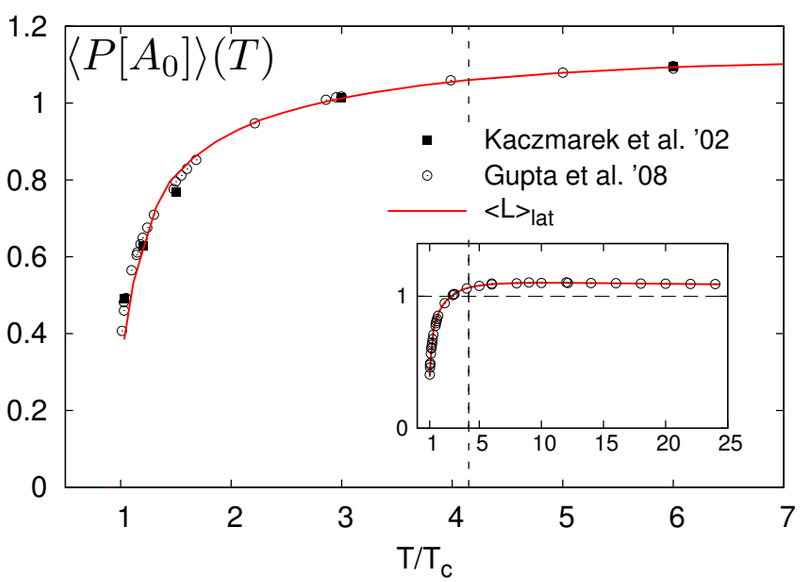
Wilson loop



'non-local'



Kaczmarek et al '99



Herbst, Lücker, JMP, 2015

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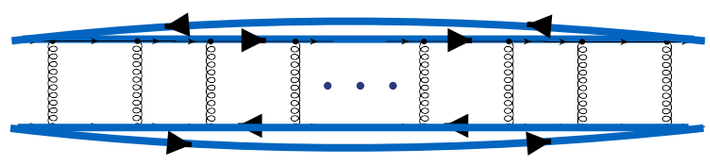

'local order parameter'

Center symmetry of the gauge group

$\mathrm{SU}(2)$: Z_2 **Ising**

$\mathrm{SU}(3)$: Z_3 **Potts**

Confinement

Free energy $F_{q\bar{q}}$ of a quark - antiquark pair

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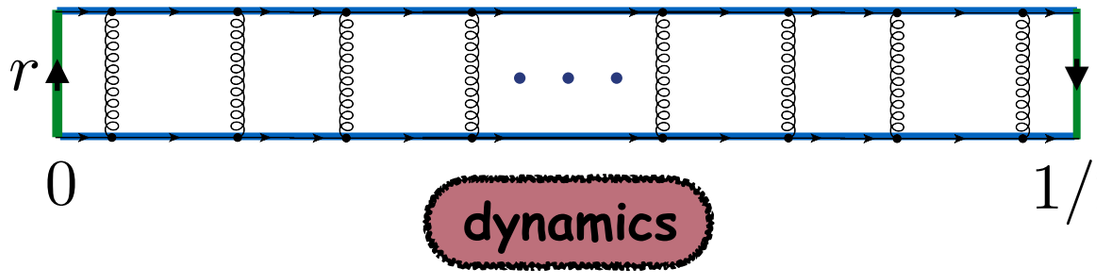

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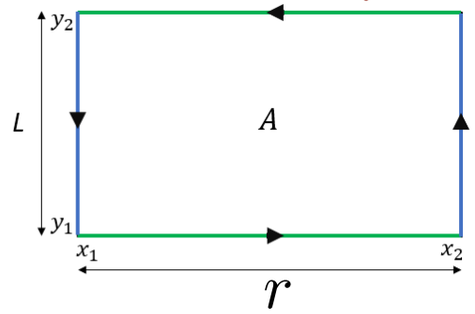

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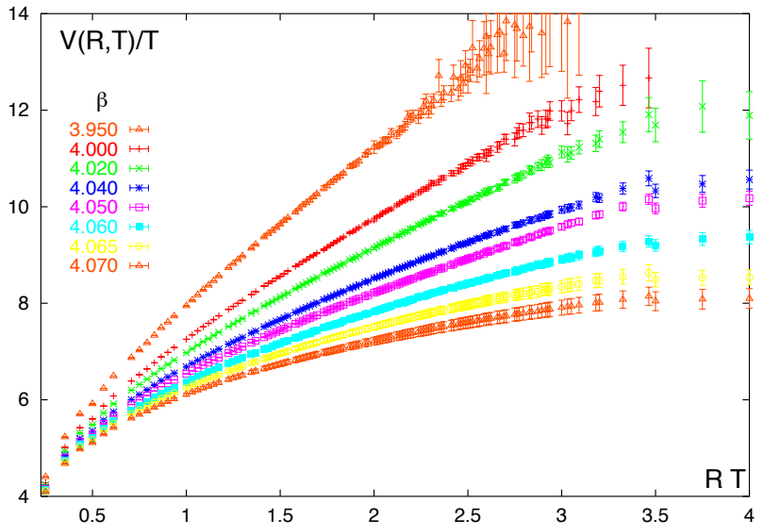

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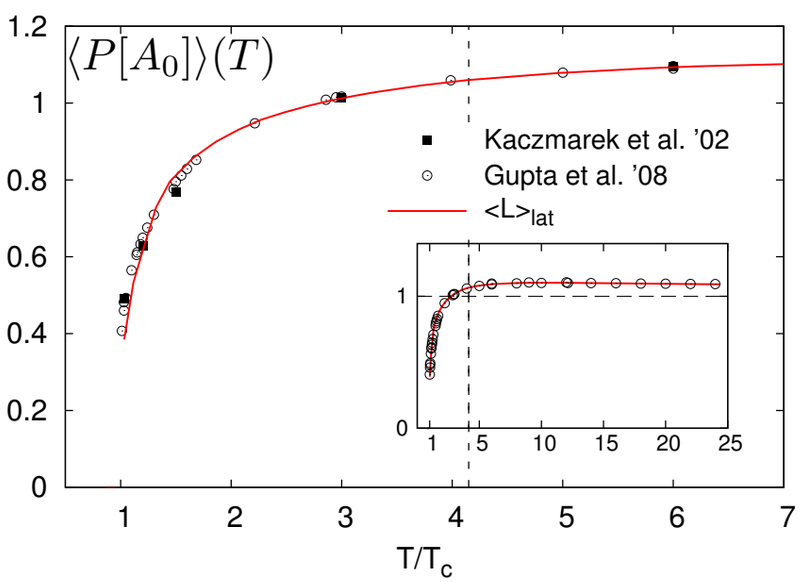

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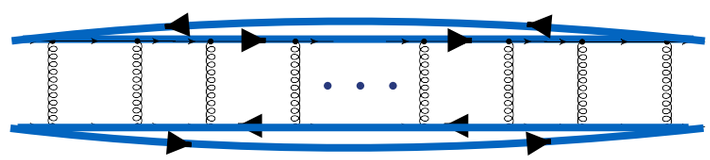

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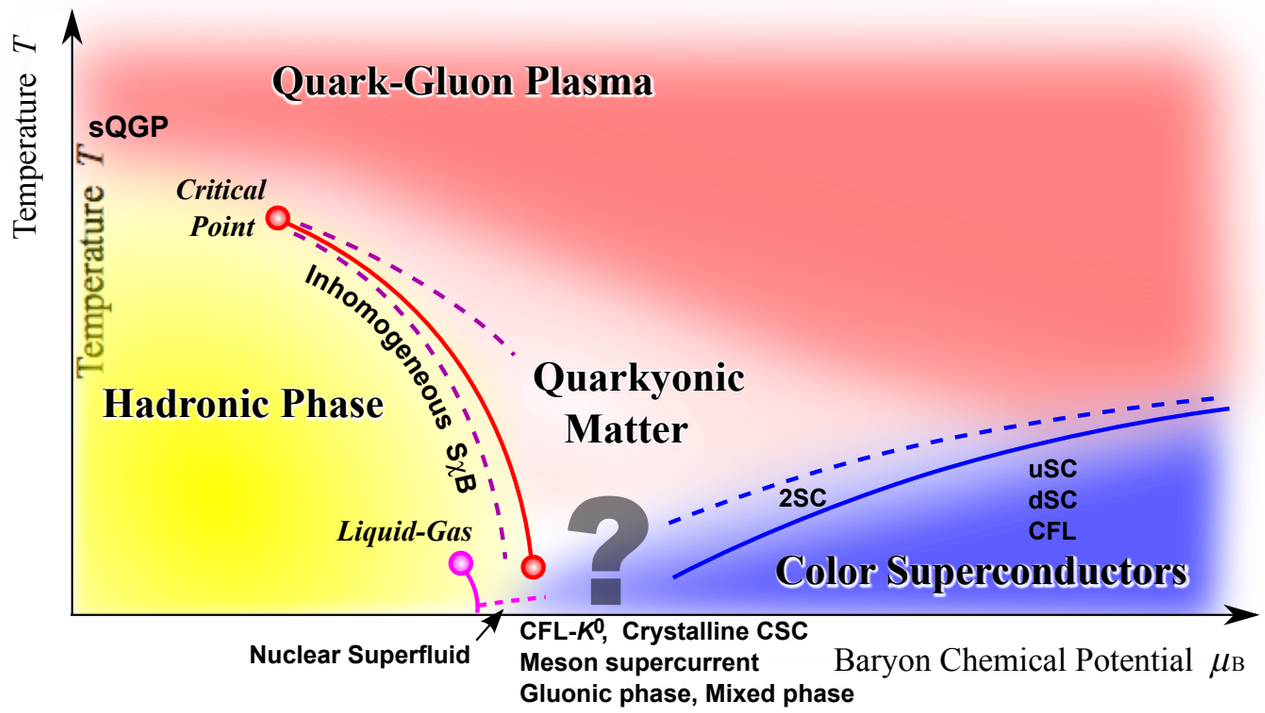
It's the dynamics, stupid!

Strongly correlated QCD



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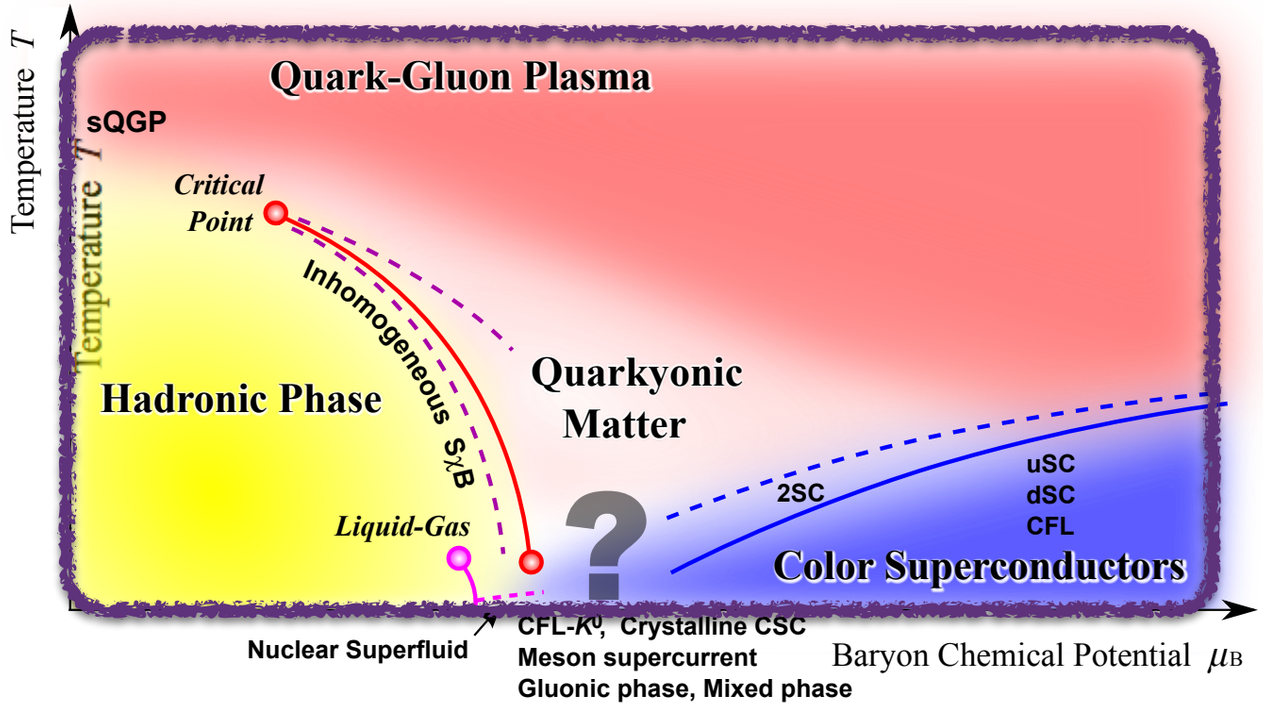
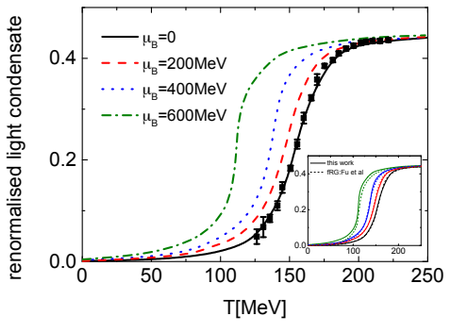
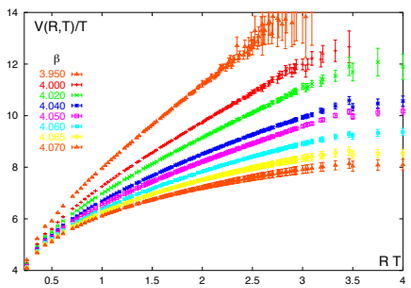


Chiral symmetry breaking & Confinement





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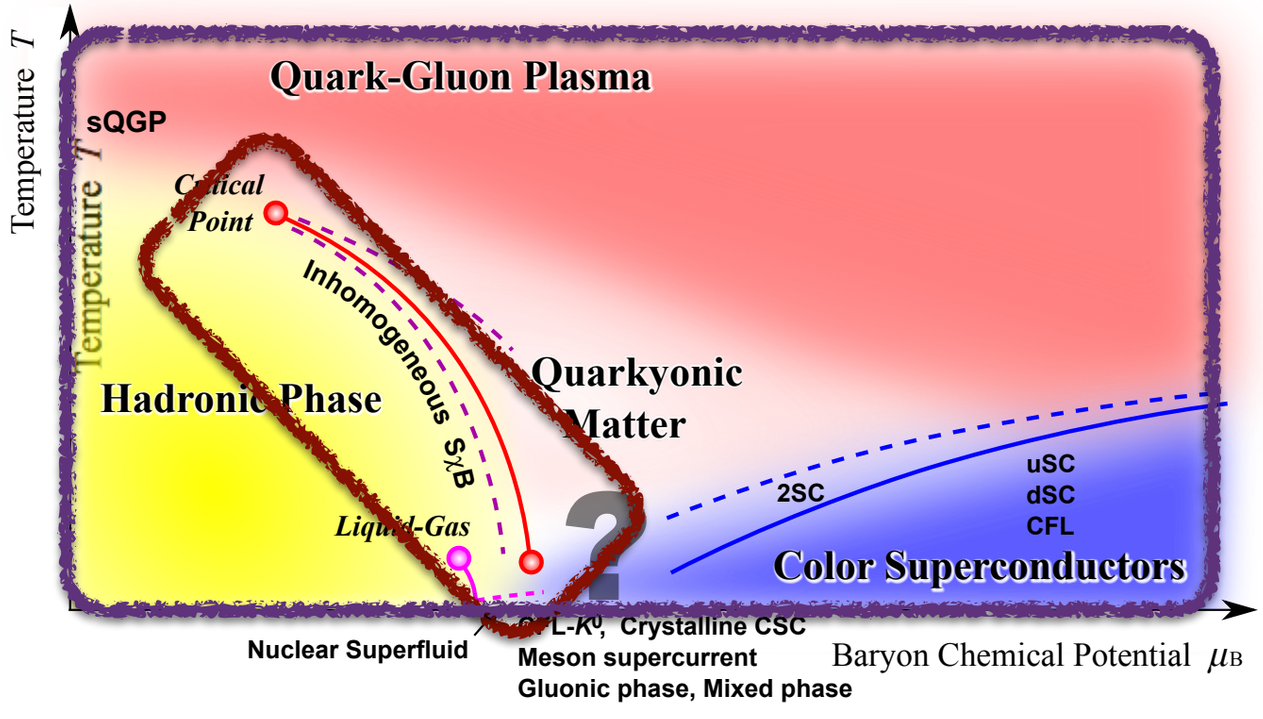

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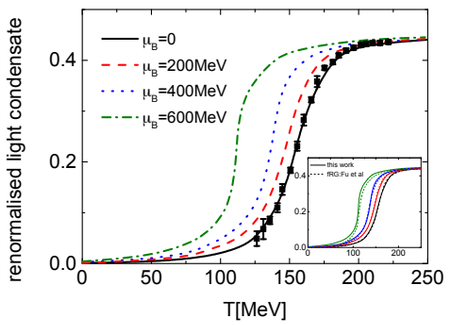
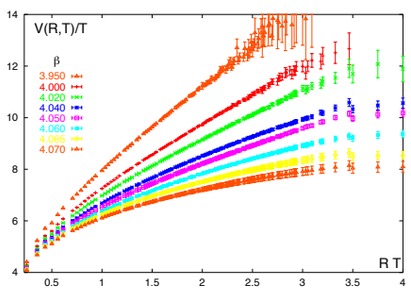
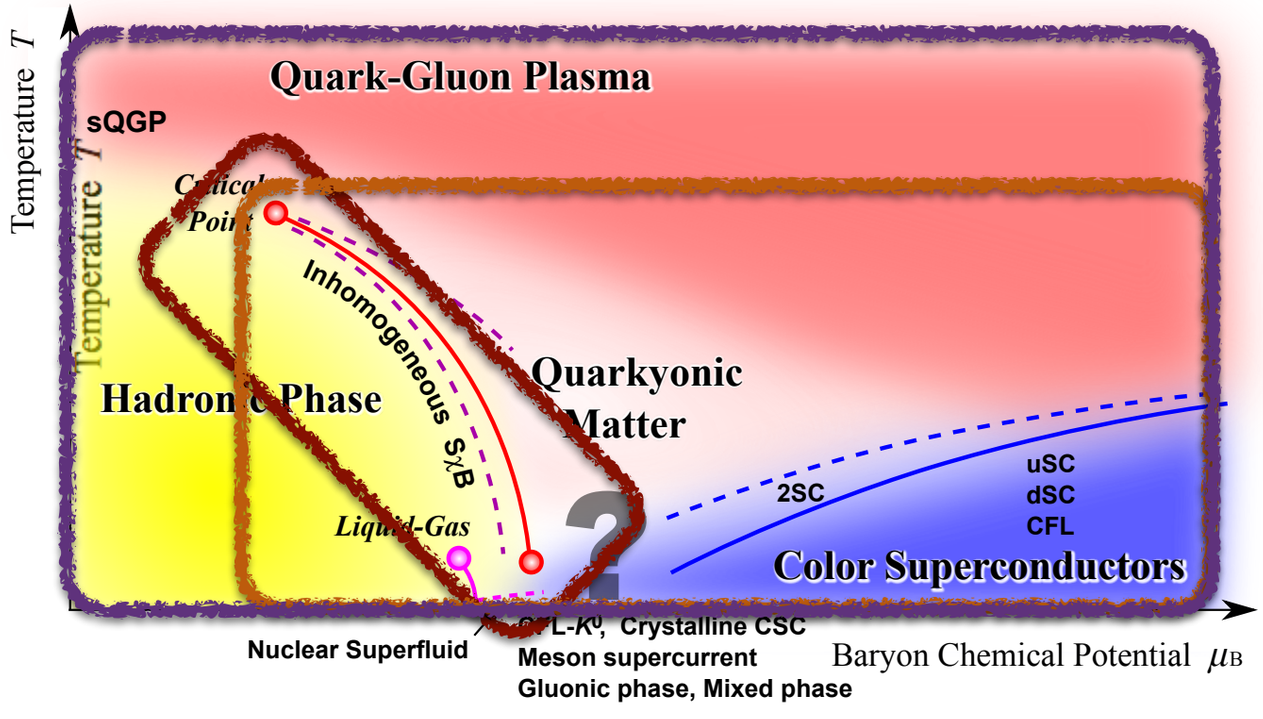




Moat regime & inhomogeneous phases

Strongly correlated QCD



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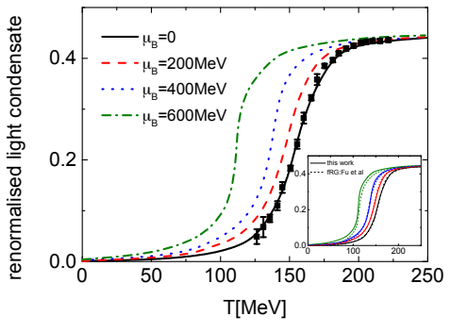

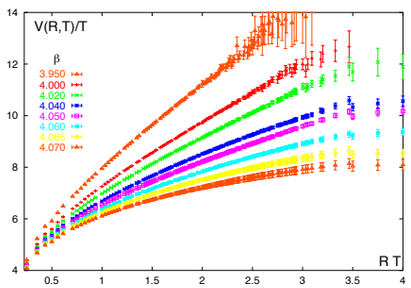

Different & competing orders

$$(\bar{q}\,\mathcal{T}_i\,q)^2 \qquad\qquad (q\,\mathcal{E}_j\,q)^2$$

Moat regime & inhomogeneous phases

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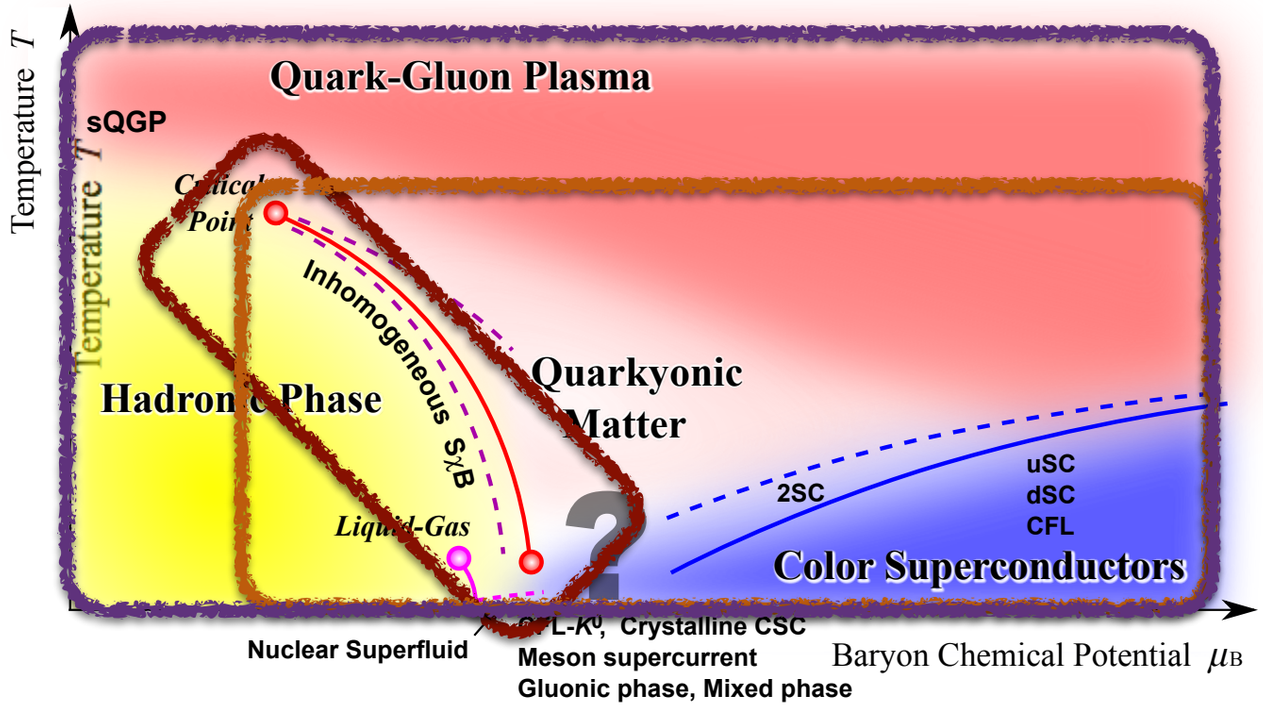

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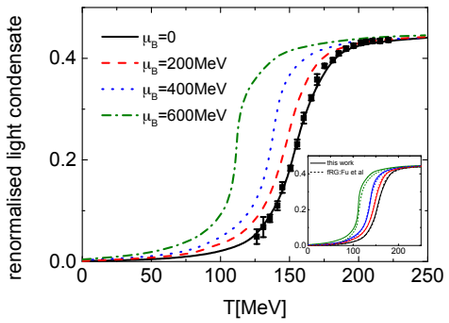

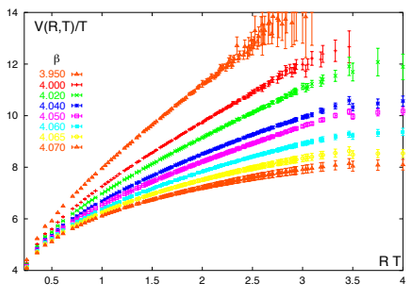

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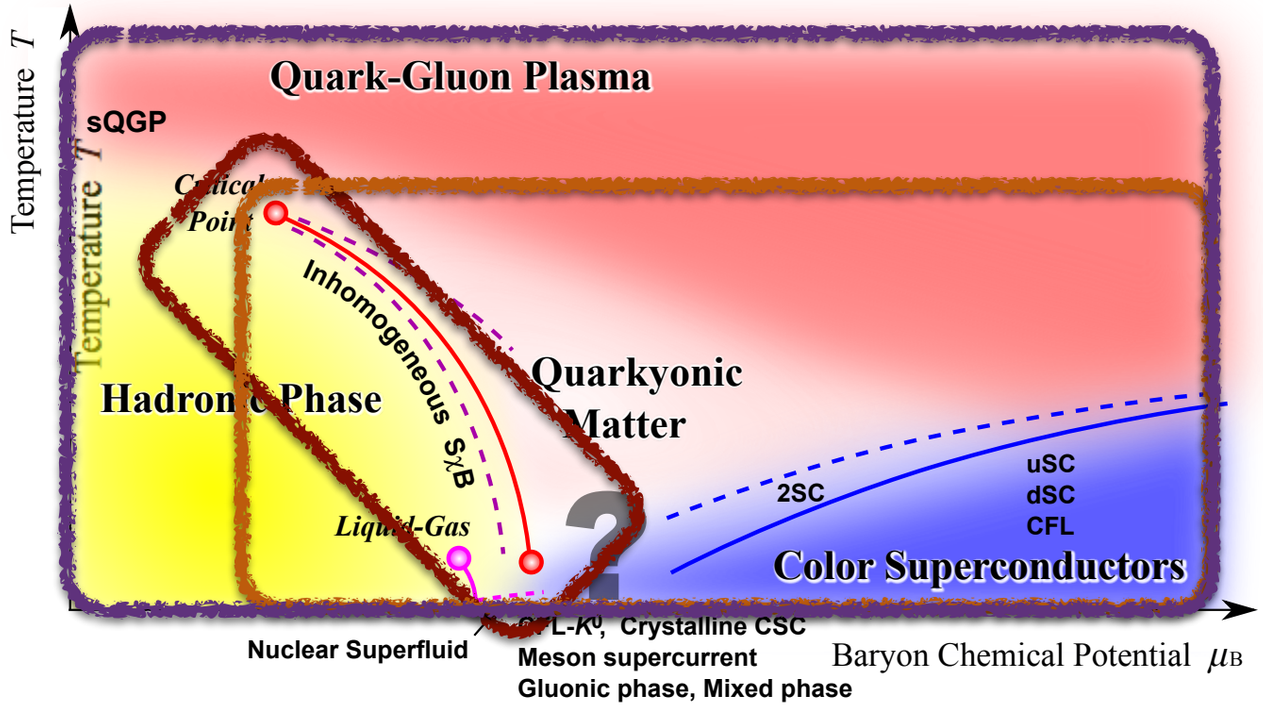
$(\bar{q}\,\mathcal{T}_i\,q)^2$ $\qquad$ $(q\,\mathcal{E}_j\,q)^2$

$\frac{\mu_B}{T} \lesssim 6$ $\qquad$ $\vec{\pi}, \sigma$ $\qquad$ $\frac{\mu_B}{T} \gtrsim 6$ $\qquad$ d

Pion, sigma mode $\qquad$ **diquark**

Moat regime & inhomogeneous phases

Strongly correlated QCD



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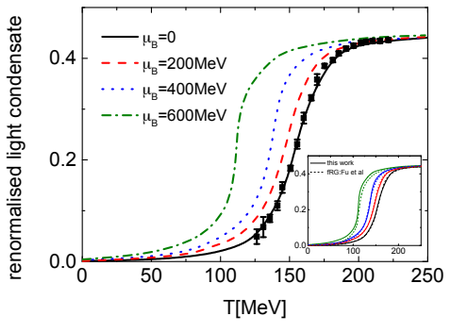

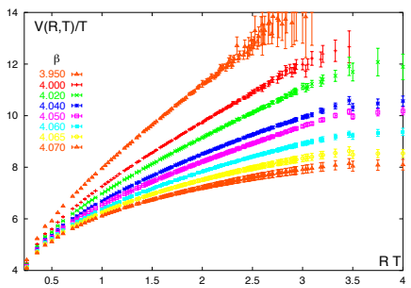

early Universe, HIC, nuclear Astrophysics

Moat regime & inhomogeneous phases

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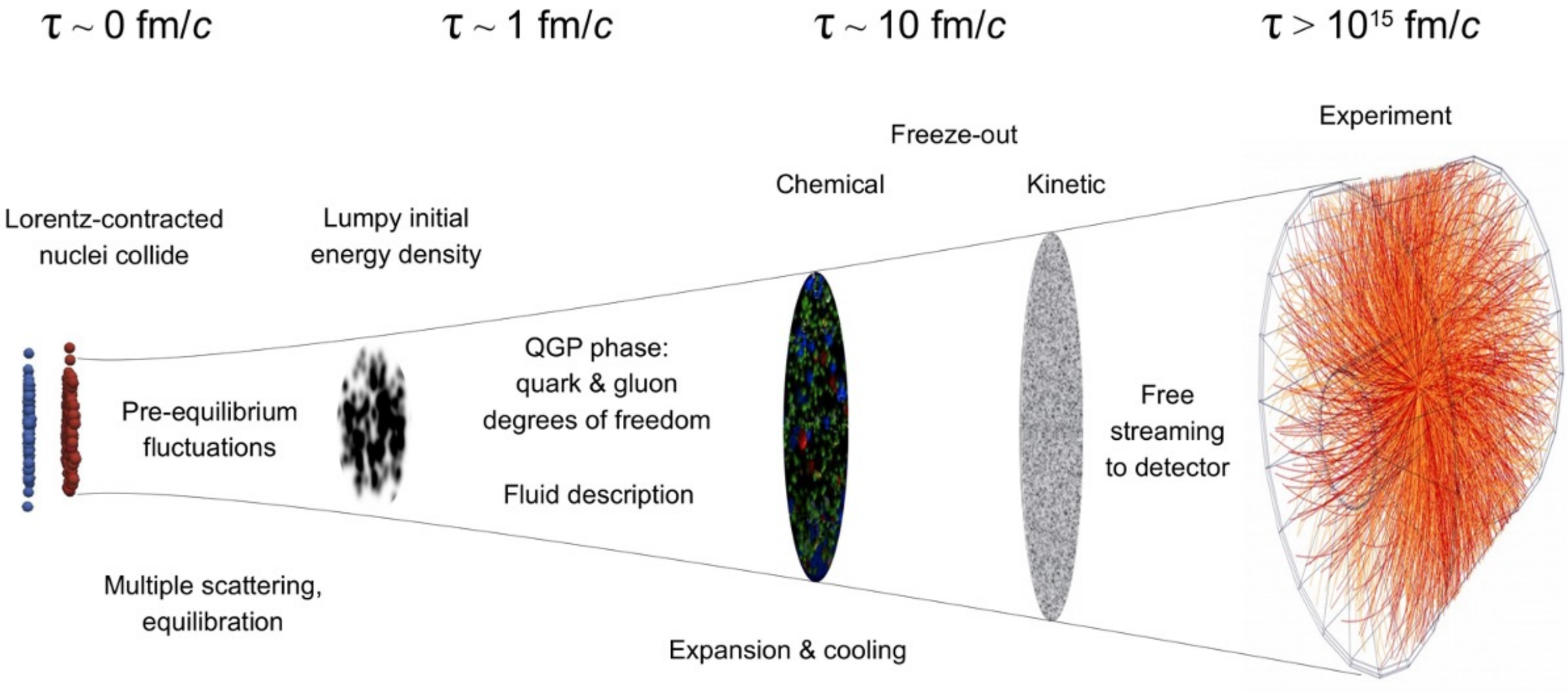
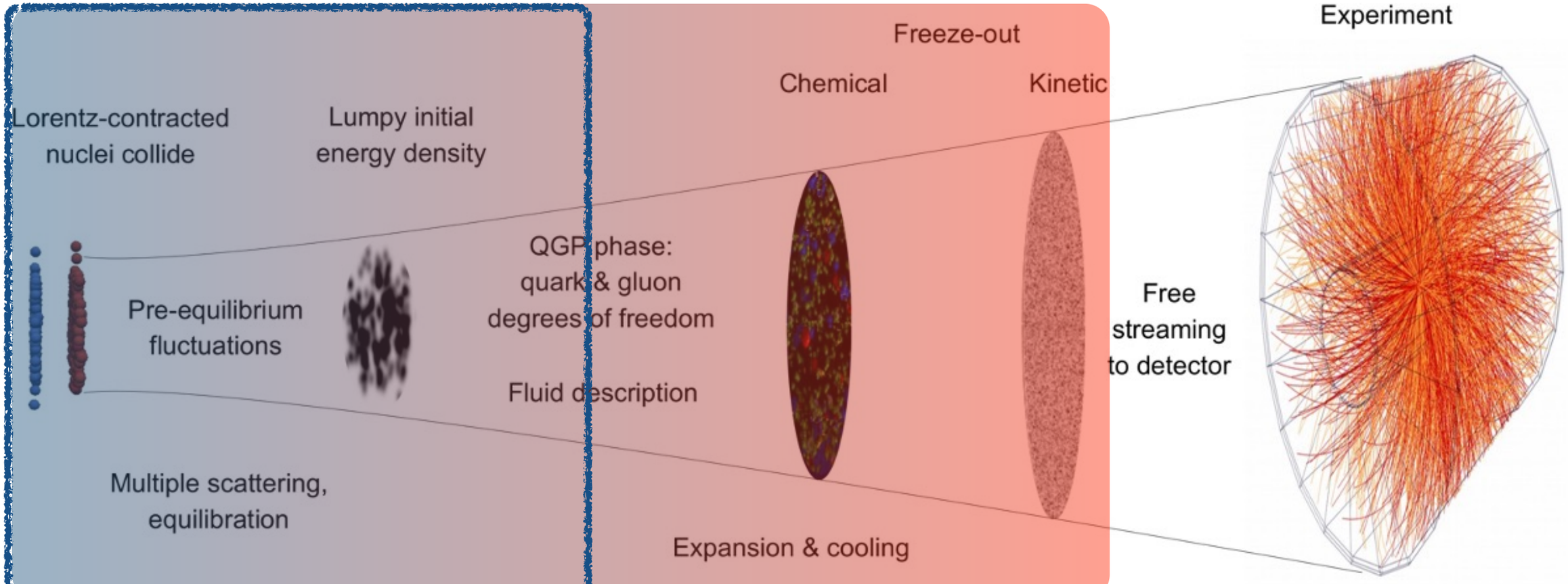
Unfolding strongly correlated QCD with heavy ion collisions



Unfolding strongly correlated QCD with heavy ion collisions

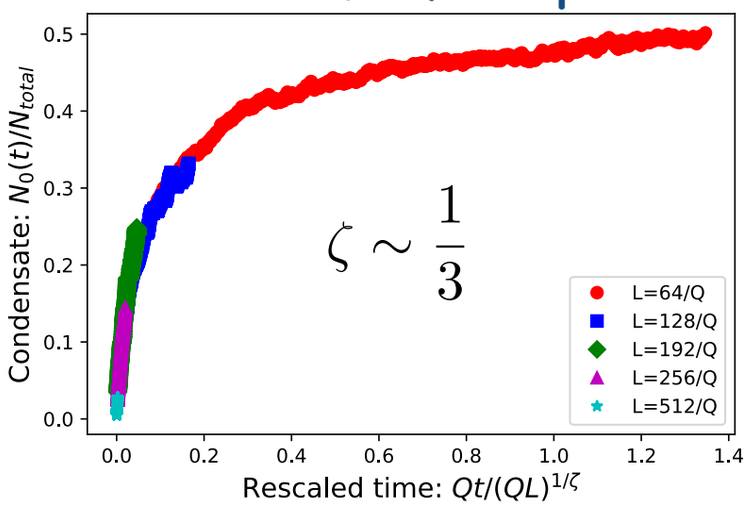
$\tau \sim 0$ fm/c $\tau \sim 1$ fm/c $\tau \sim 10$ fm/c $\tau > 10^{15}$ fm/c



large occupancies

Classical-statistical

non-thermal fixed point



$$\sim \int_{\rm vol} \langle P(0) P^\dagger(r) \rangle$$

Berges, Boguslavski, Butler, de Bruin, JMP, arXiv:2307.13669

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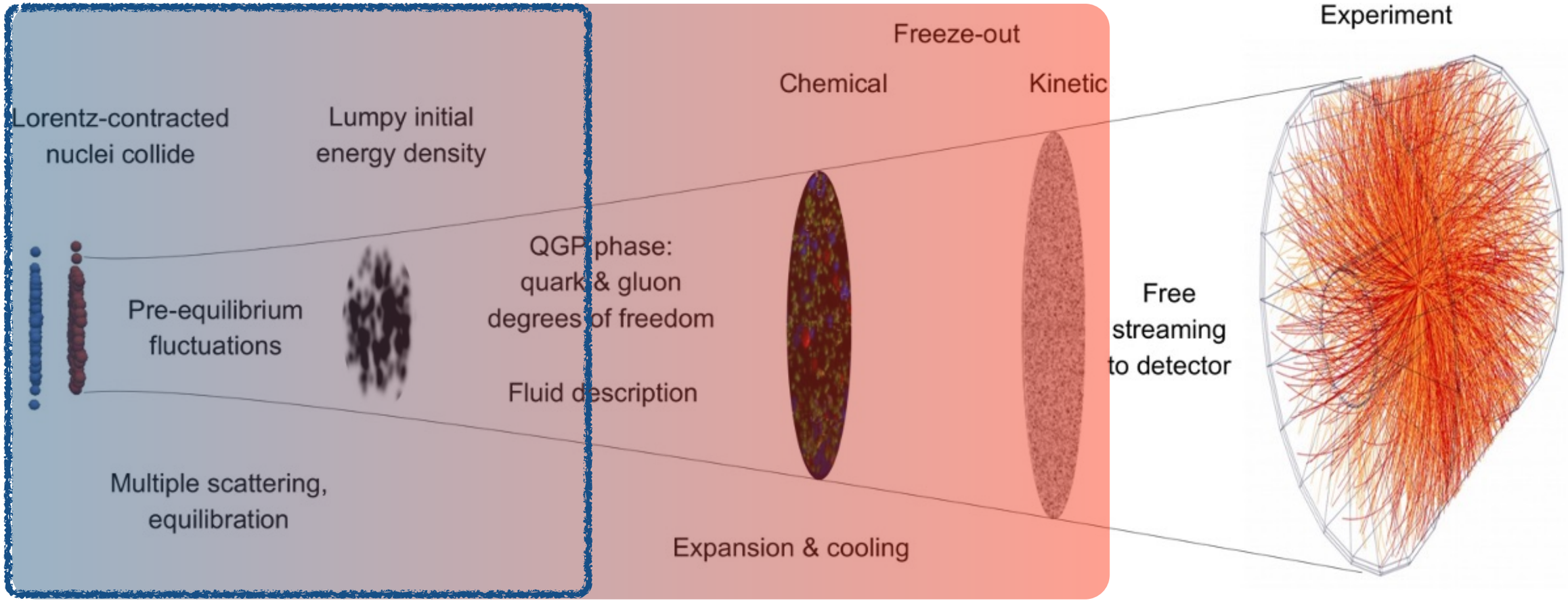

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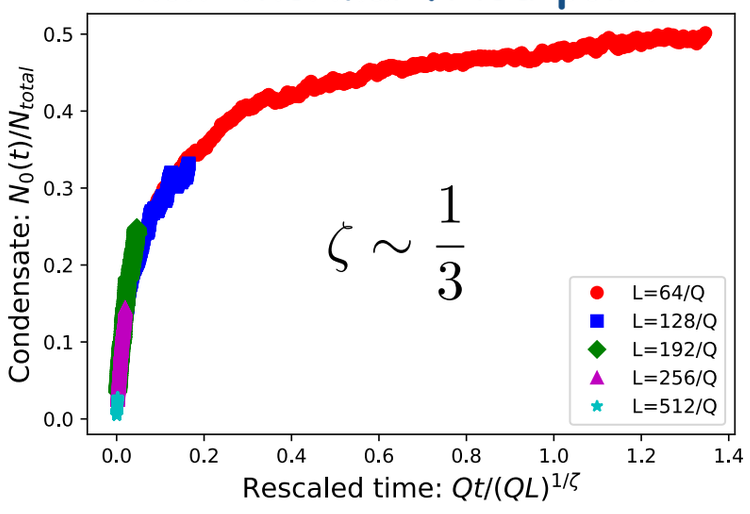

Classical-statistical

statistics + collective behaviour

&

strongly correlated quantum dynamics

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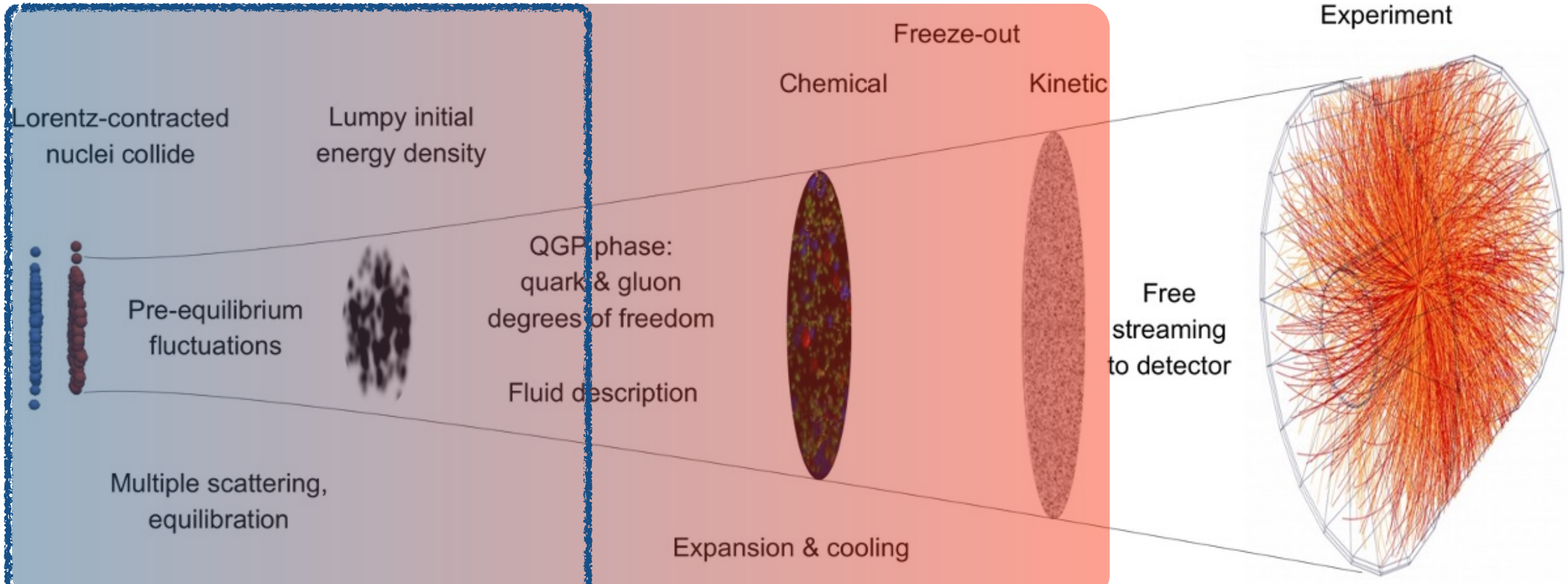

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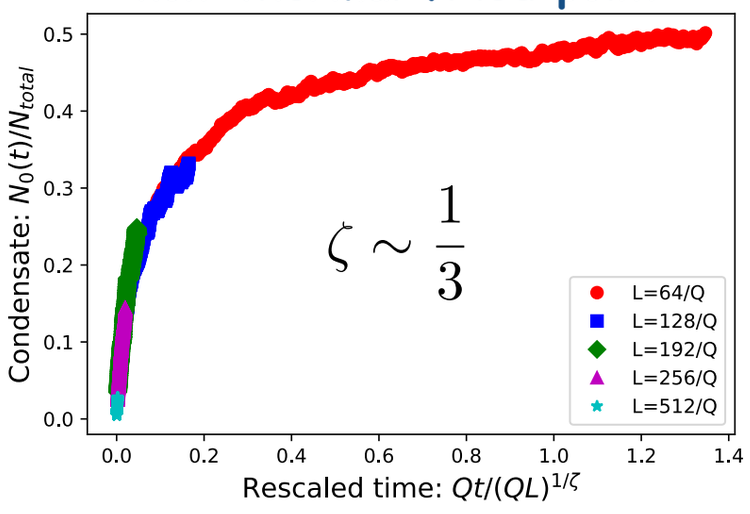

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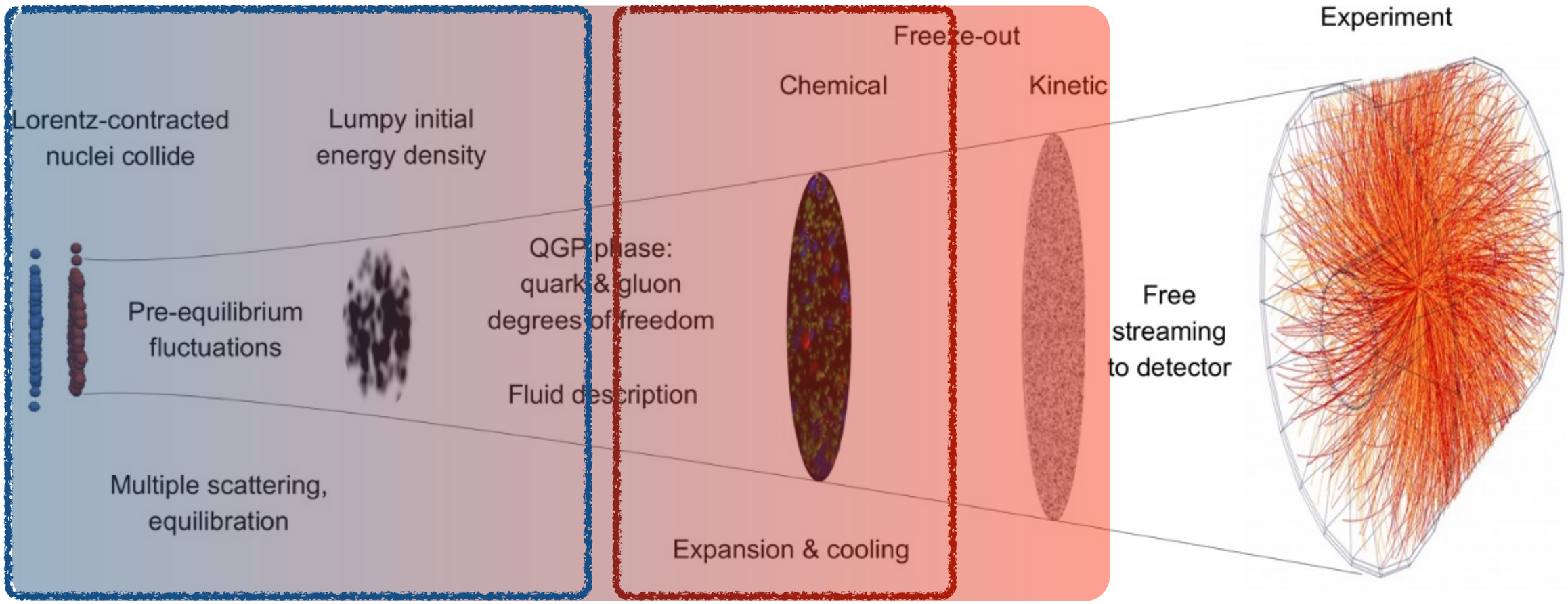

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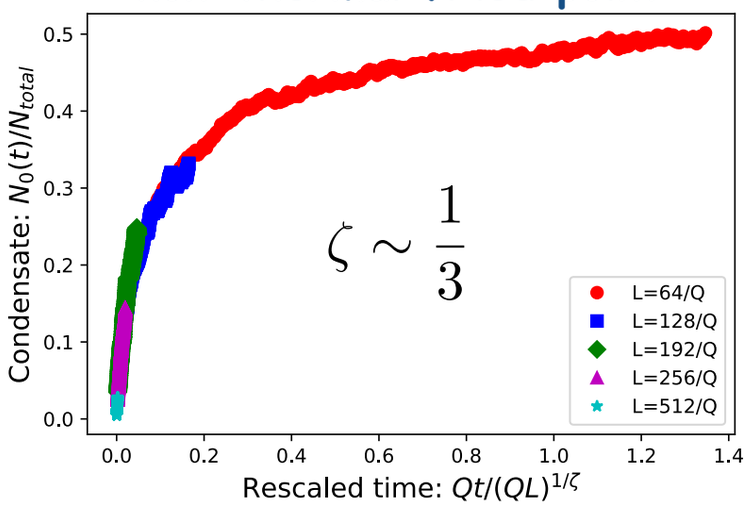

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The cool stuff!

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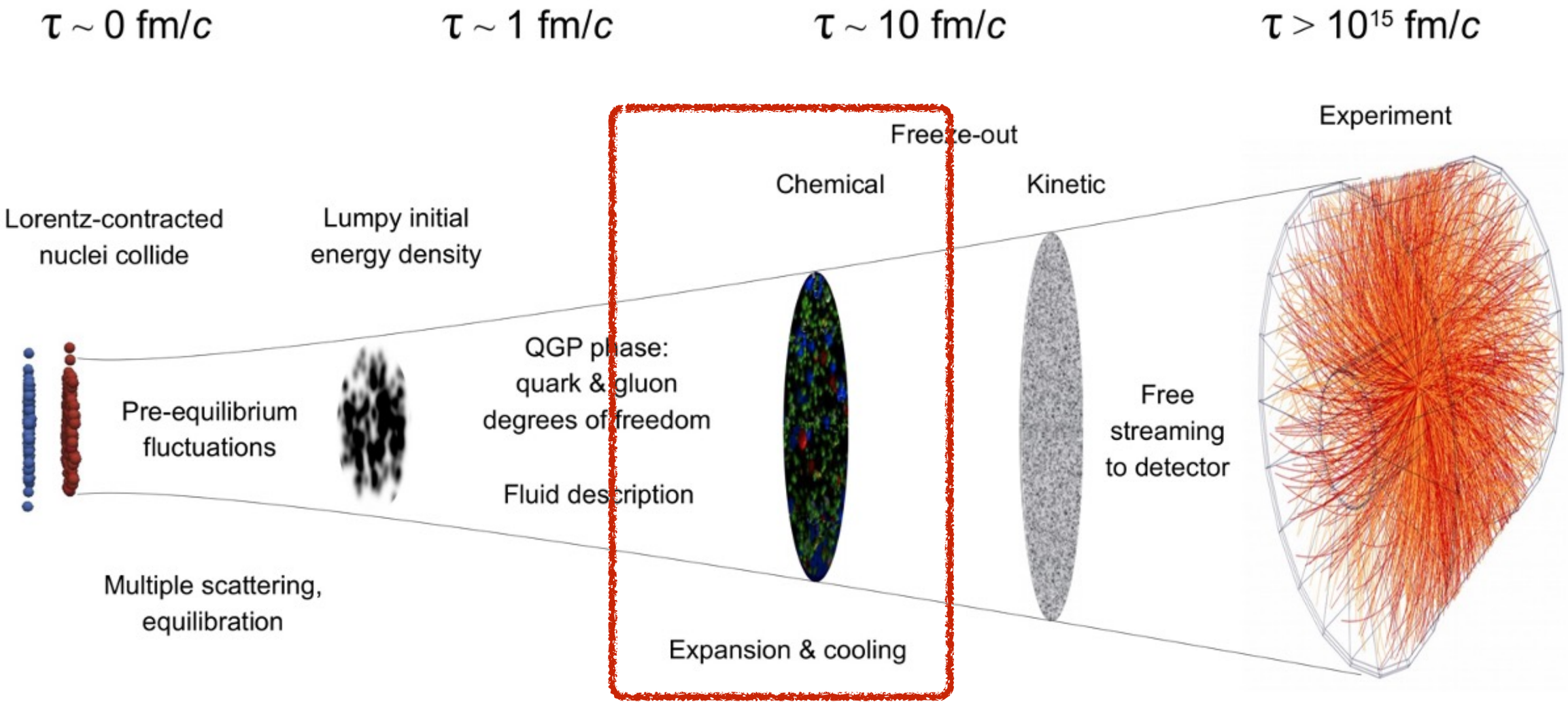


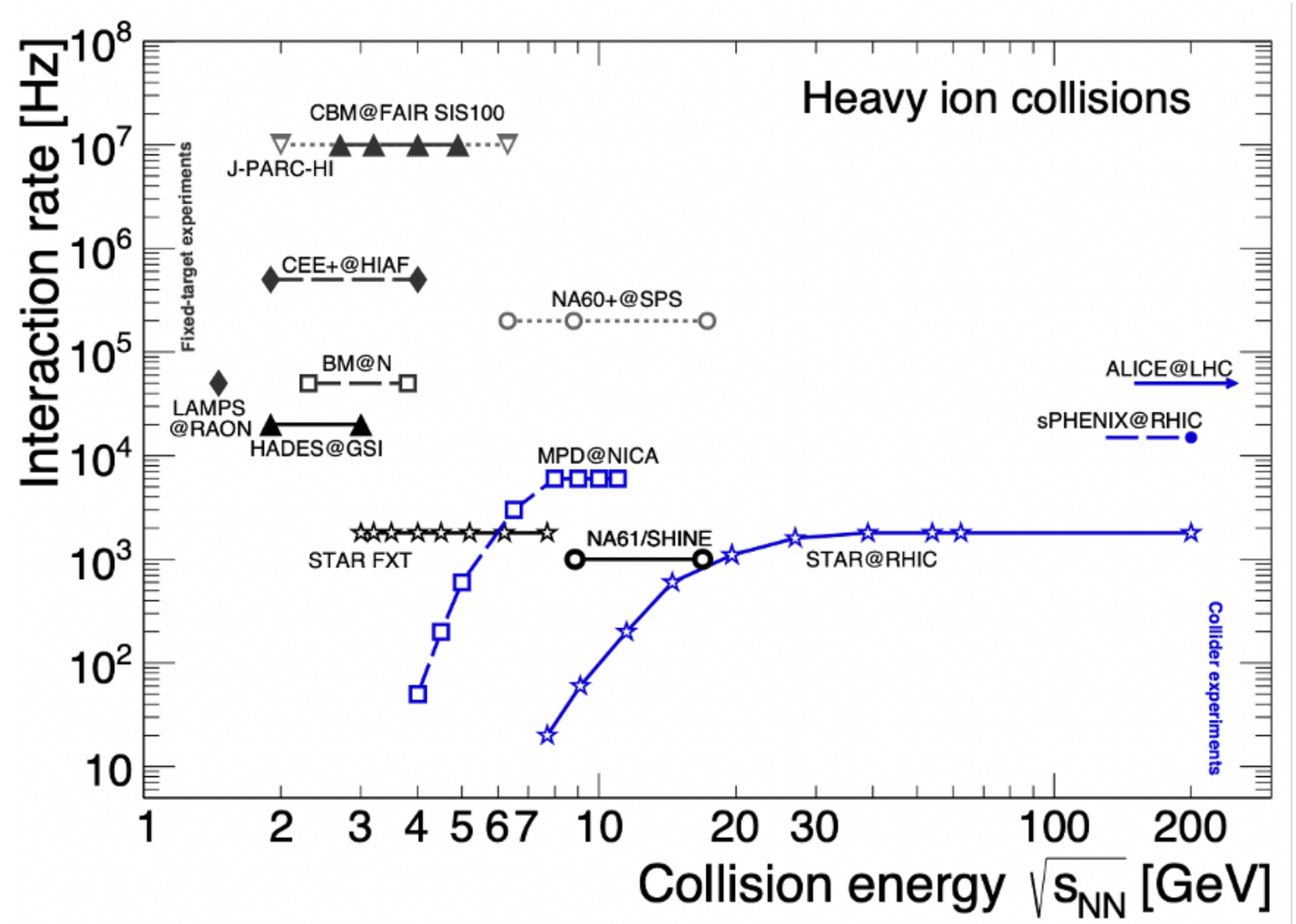
How to unfold: inverse problem!

strongly correlated quantum dynamics

Experimental landscape

'The (experimental) future is bright'

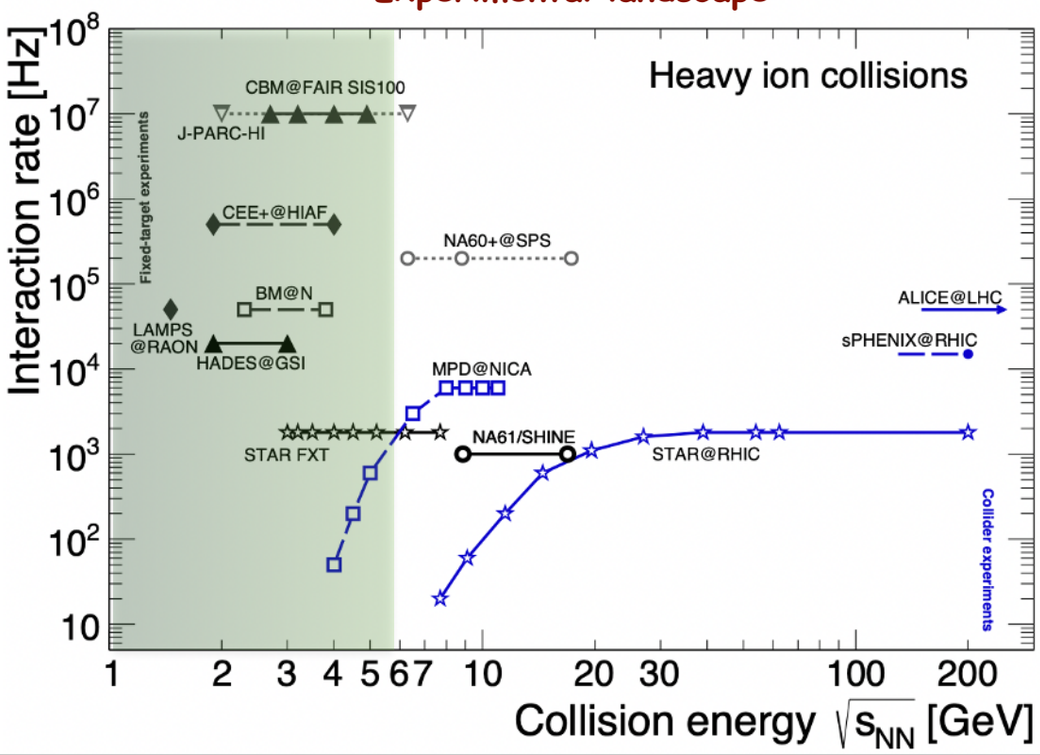
Tetyana Galatyuk, Erice 2021



Galatyuk, A982 (2019) update 2021; CBM, EPJA 53 3 (2017) 60

How bright does it get?

Experimental landscape



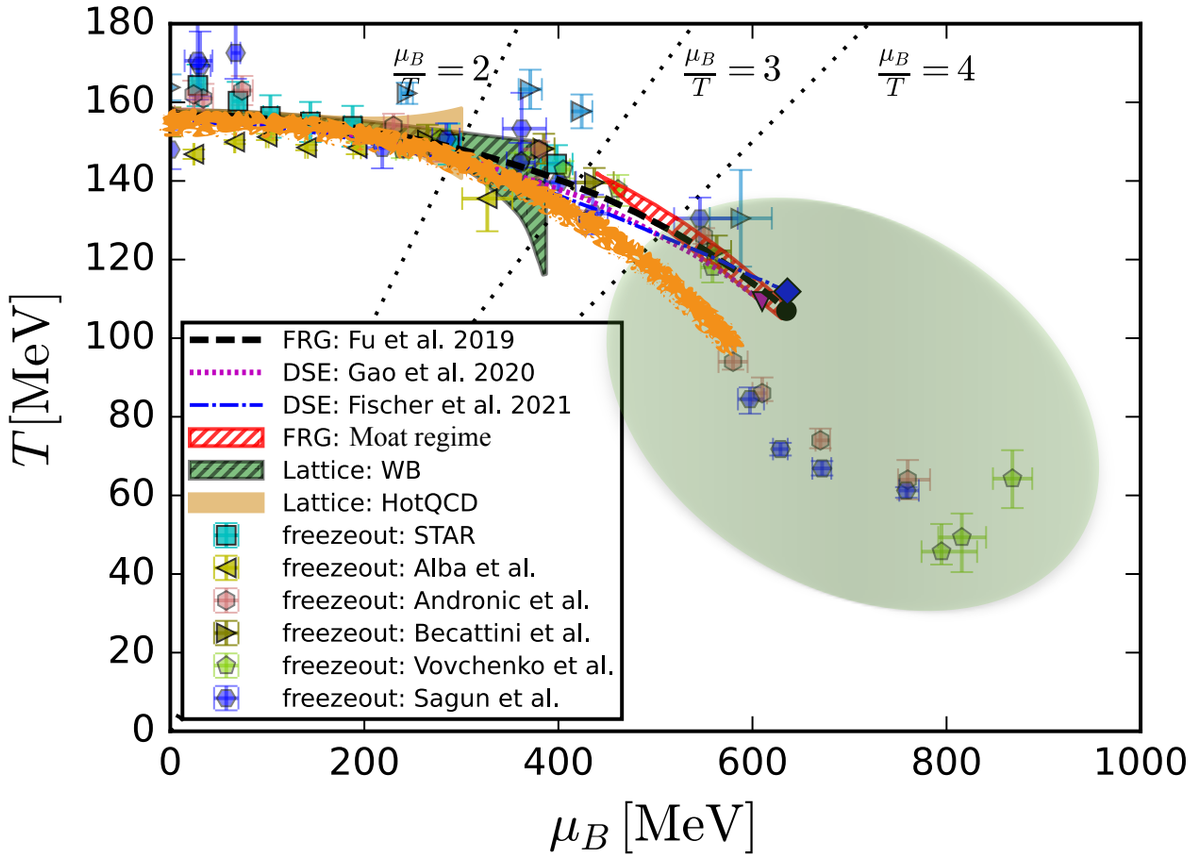
Galatyuk, A982 (2019) update 2021
CBM, EPJA 53 3 (2017) 60

Freezeout curve

Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 104 (2021) 9

CEP or other NEW physics/phases

Chiral phase structure (theory) & freeze out data (Exp. data+Pheno)



Fu, JMP, Rennecke, PRD 101 (2020) 054032

Gao, JMP, PLB 820 (2021) 136584

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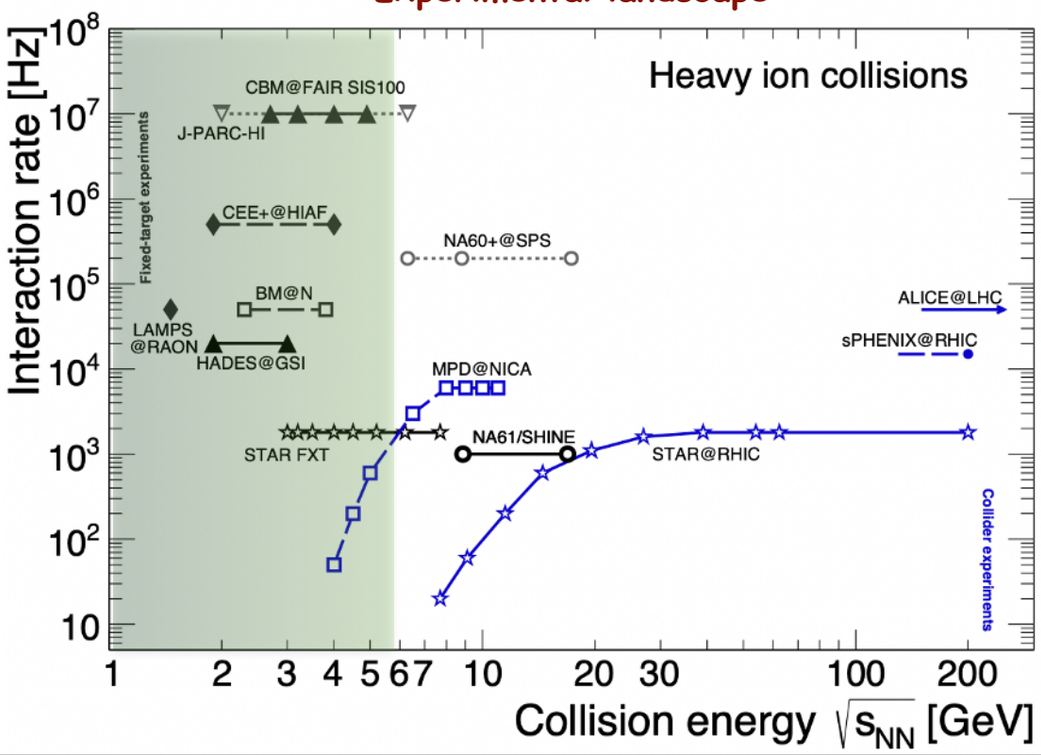

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CBM/STAR

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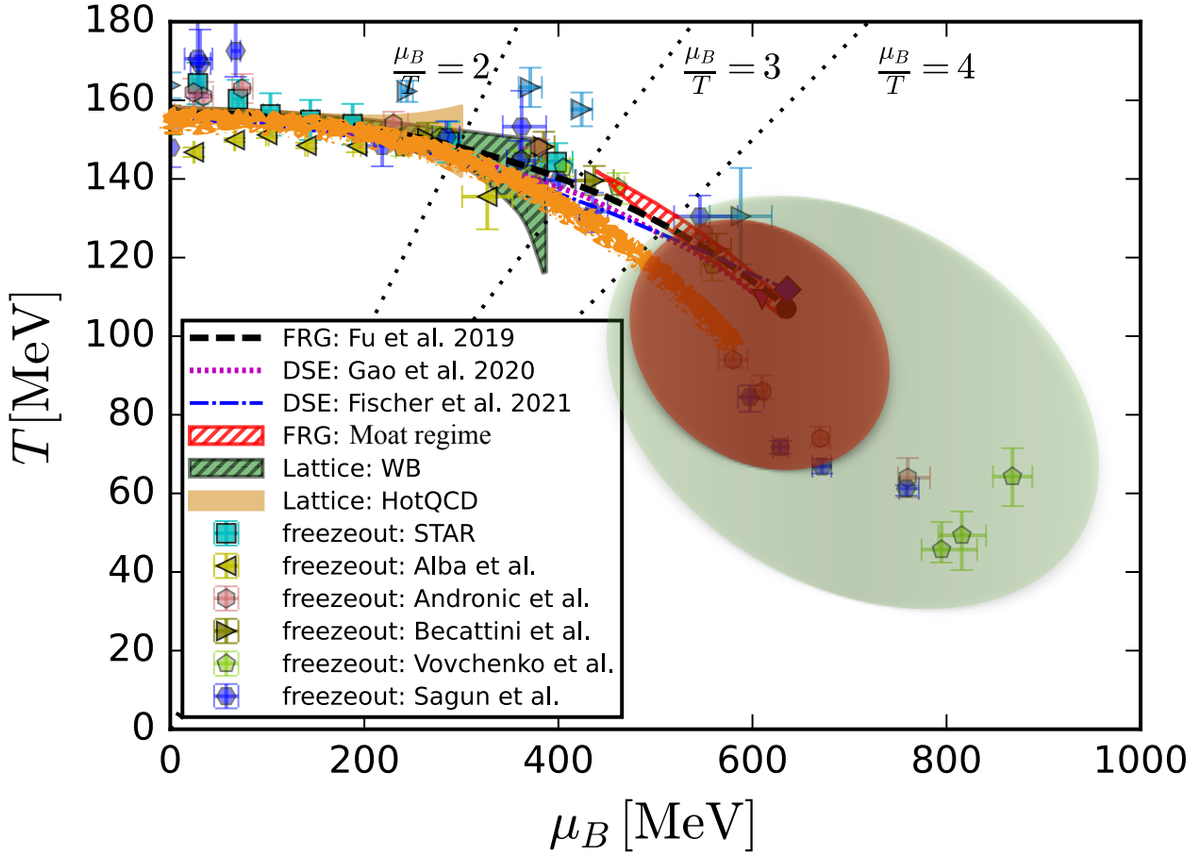

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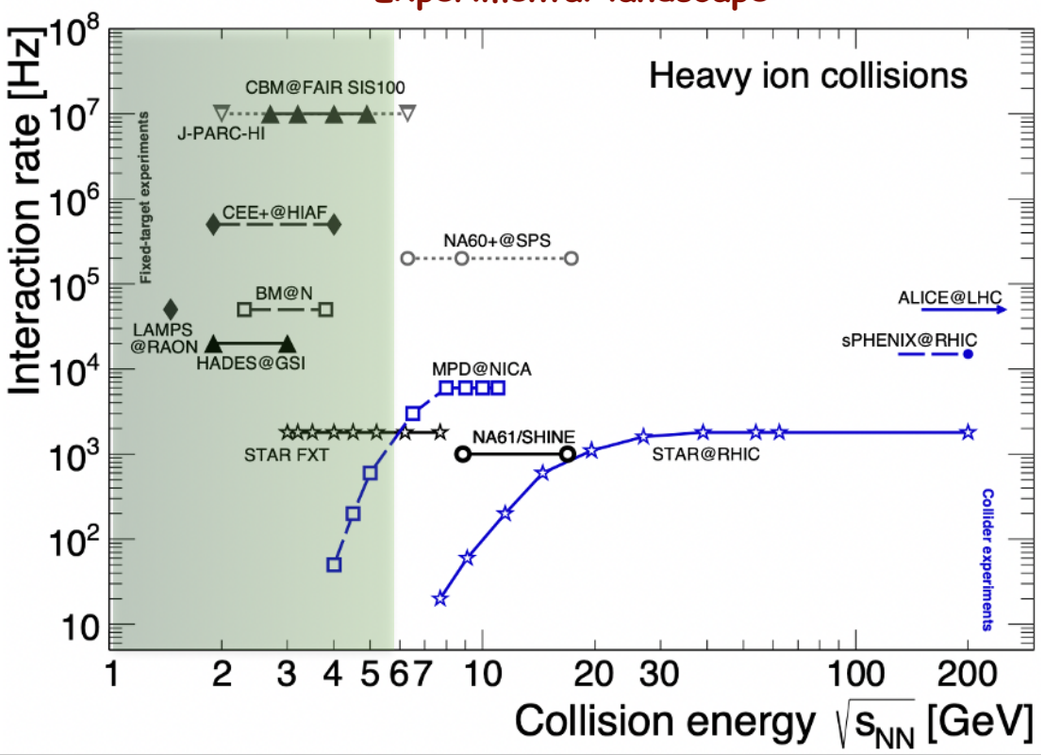

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CBM/STAR

HADES

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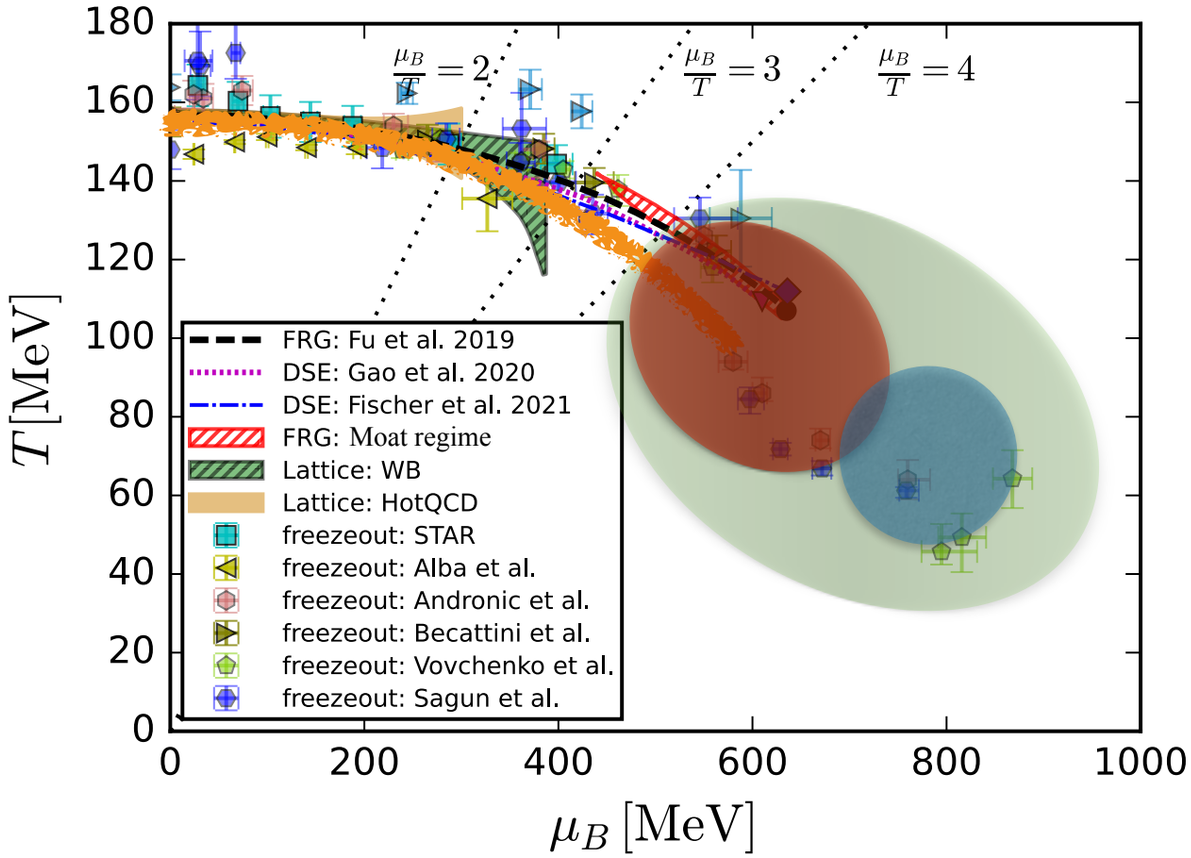

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Sneak preview on some results

- QCD phase structure, 'CEP' estimate & phenomenological applications

- (Non-critical) chiral dynamics & fluctuations of observed charges

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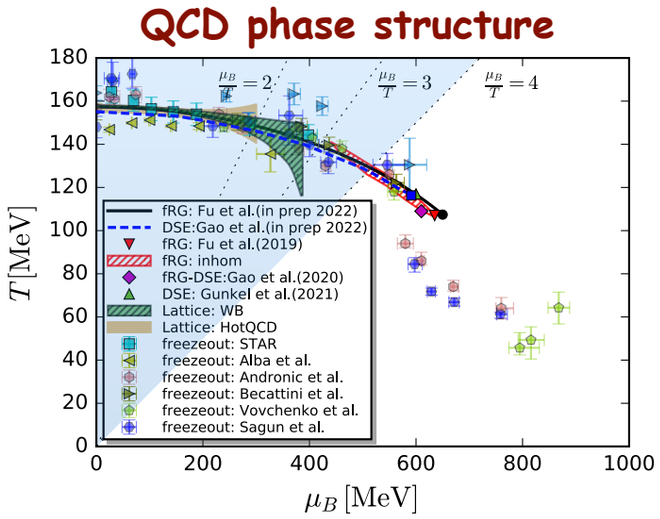

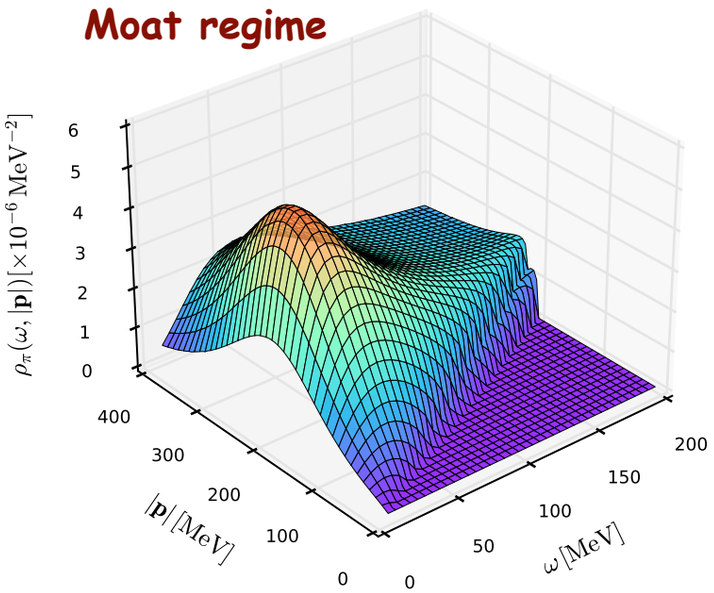

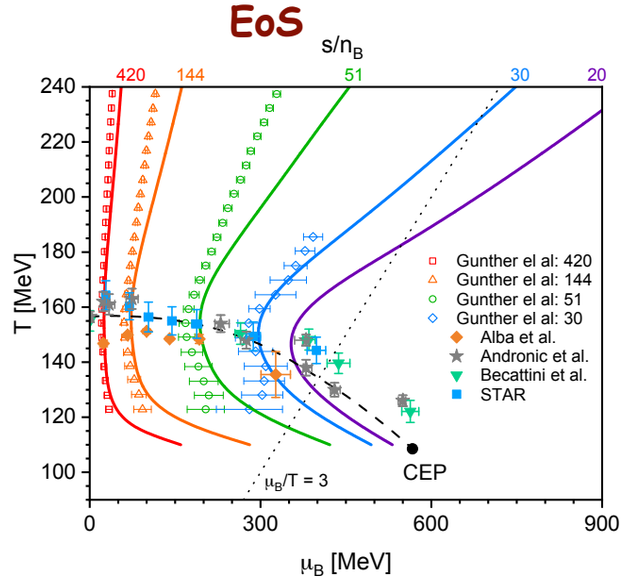

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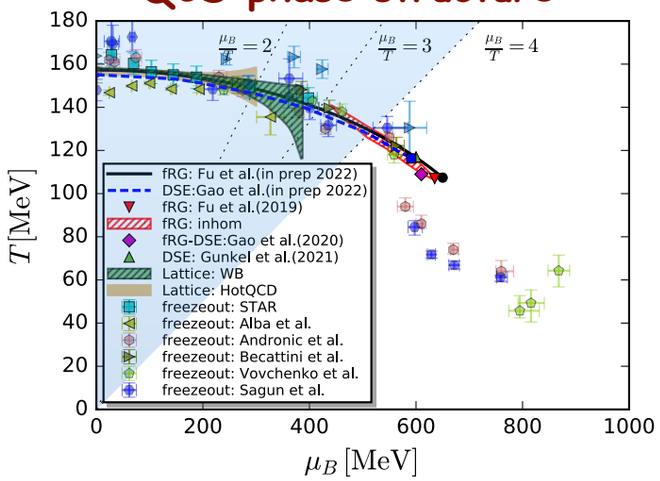
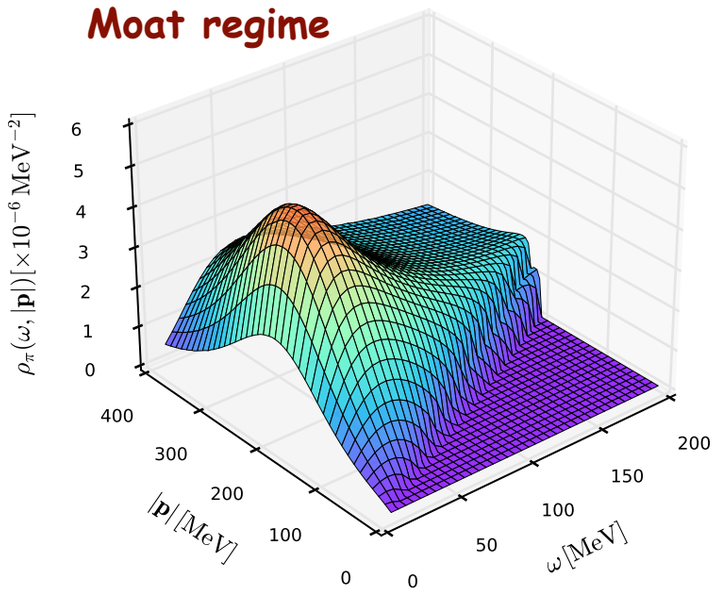
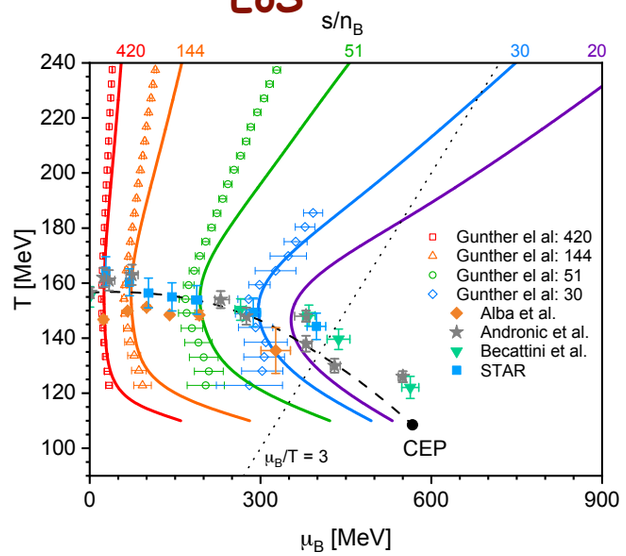
QCD phase structure



Moat regime

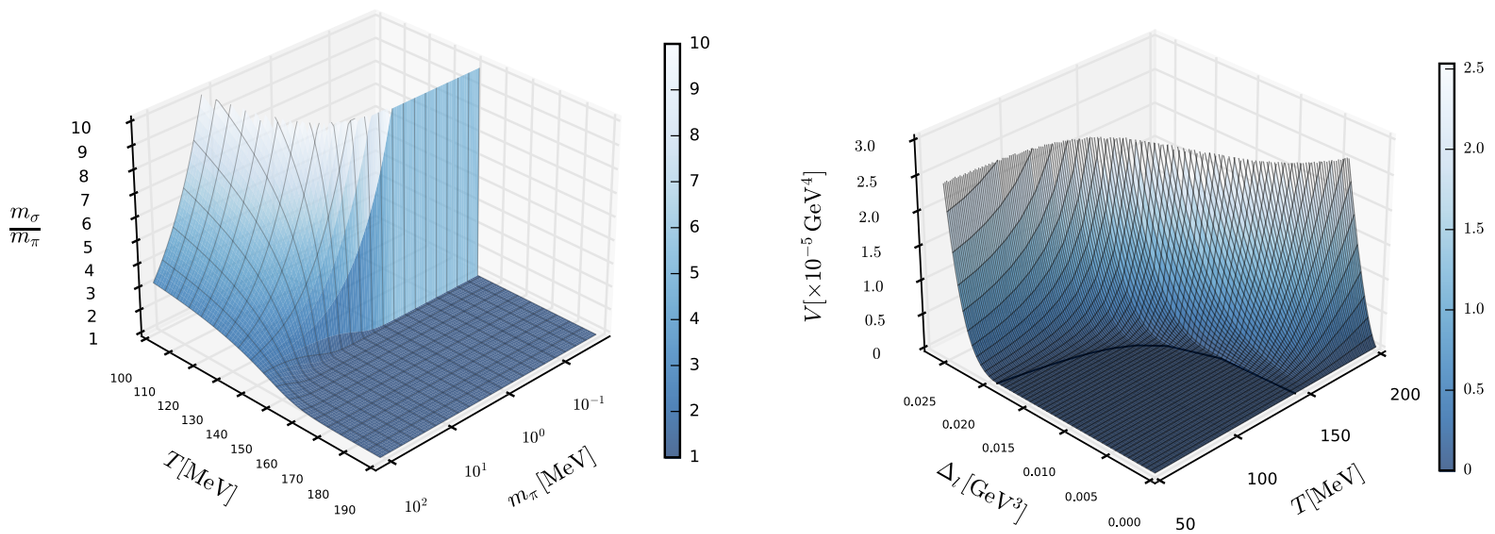


EoS

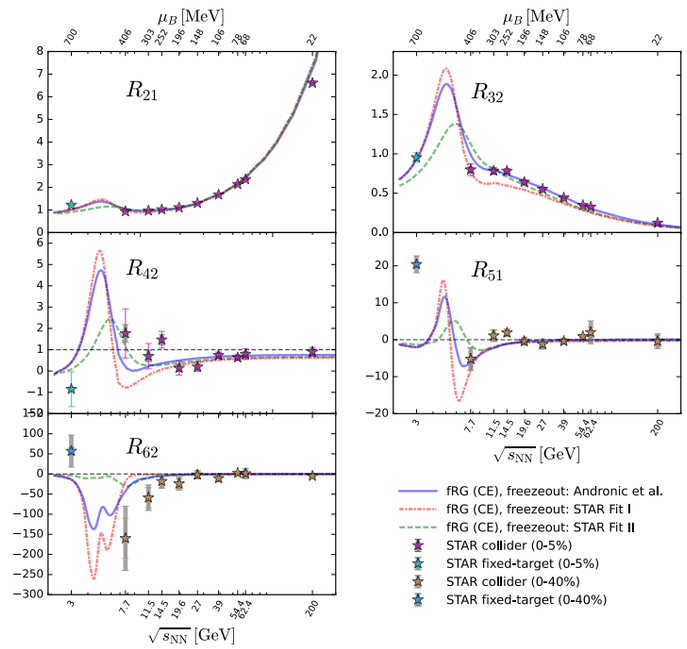


- (Non-critical) chiral dynamics & fluctuations of observed charges

Chiral dynamics



Fluctuations of conserved charges



Additional material & technical details

fQCD collaboration

Braun, Chen, Fu, Gao, Geissel, Horak, Huang, Lu, Ihssen, JMP, Rennecke, Sattler, Schallmo, Tan, Töpfel, Turnwald, Wen, Wessely, Wink, Yin

Dalian, Beijing, Darmstadt, Heidelberg, Gießen

Outline

- QCD phase structure: Where do we stand?

- Chiral dynamics

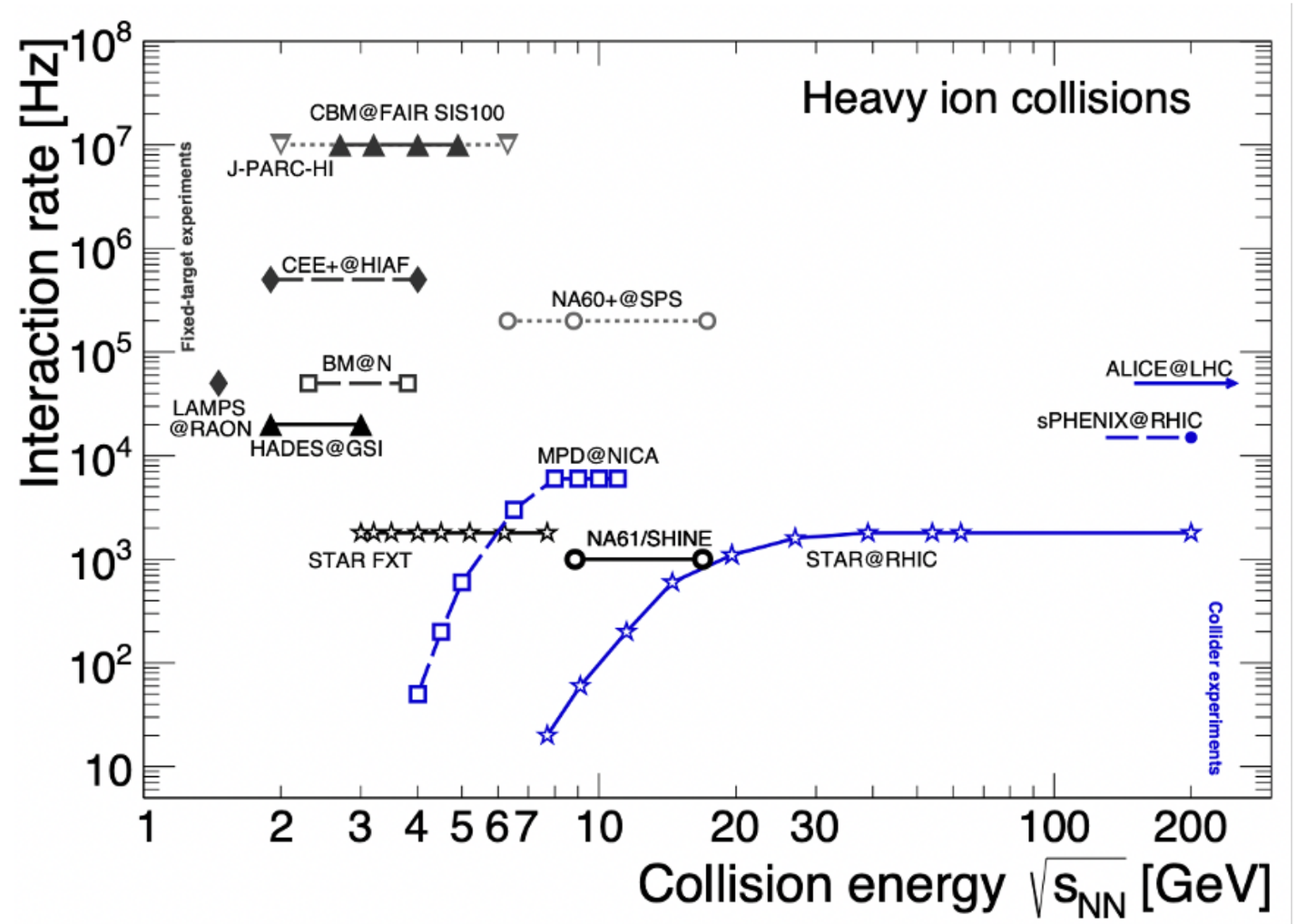
- Fluctuations of conserved charges

- Summary & outlook

Experimental landscape

'The (experimental) future is bright'

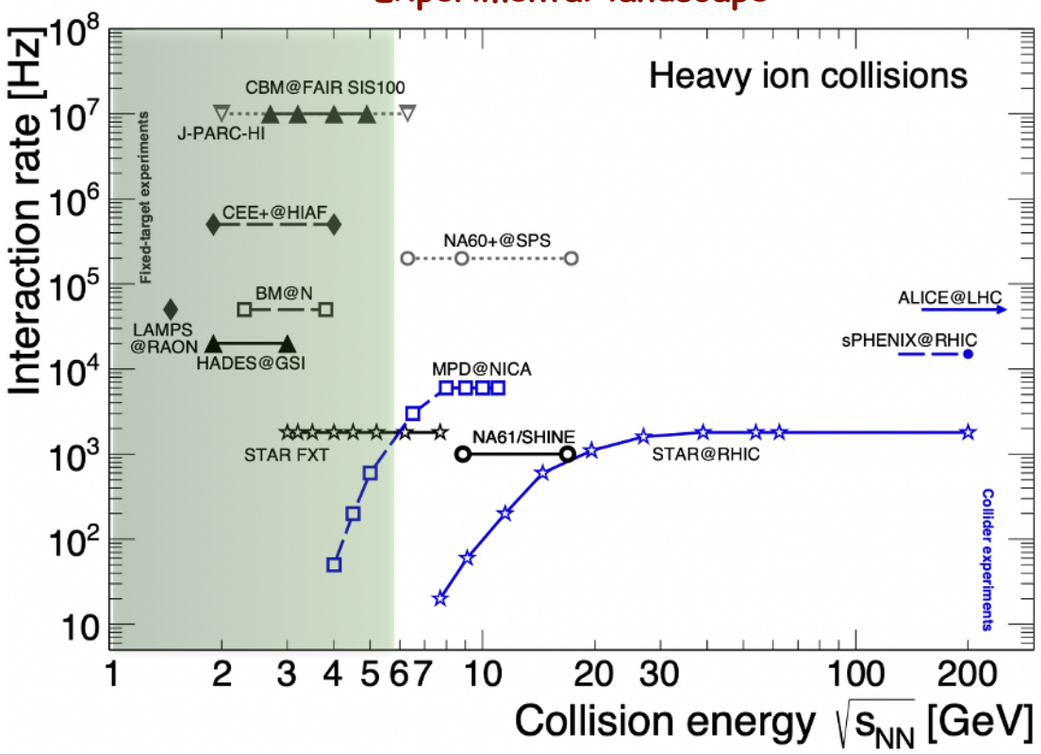
Tetyana Galatyuk, Erice 2021



Galatyuk, A982 (2019) update 2021; CBM, EPJA 53 3 (2017) 60

How bright does it get?

Experimental landscape



Galatyuk, A982 (2019) update 2021
CBM, EPJA 53 3 (2017) 60

Freezeout curve

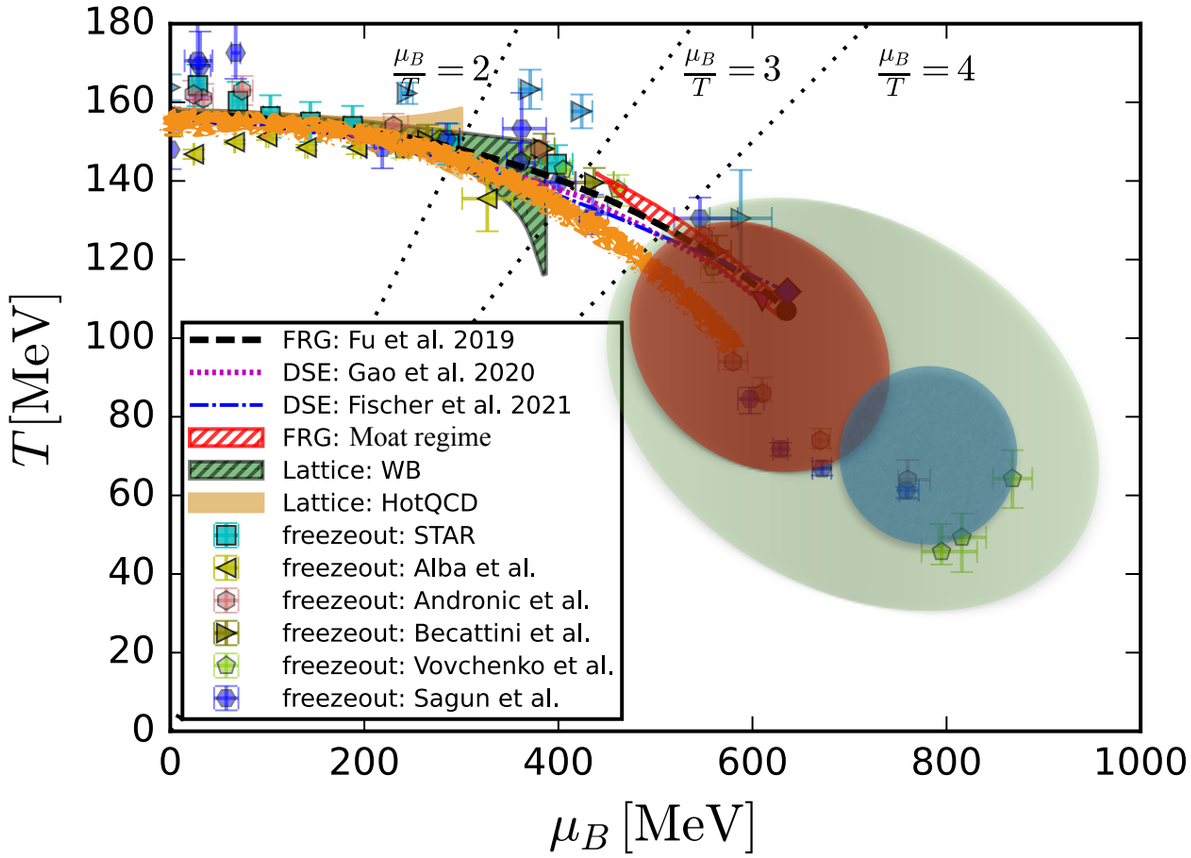
Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 104 (2021) 9

CBM/STAR

HADES

CEP or other NEW physics/phases

Chiral phase structure (theory) & freeze out data (Exp. data+Pheno)



Fu, JMP, Rennecke, PRD 101 (2020) 054032

Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 054022

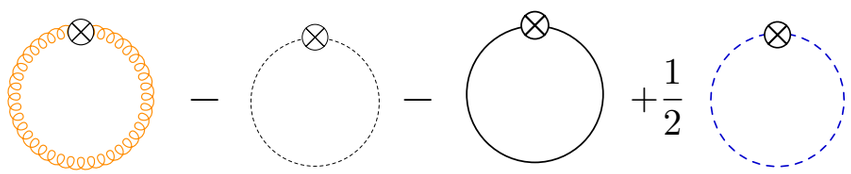
QCD with Functional Approaches

ab initio & closed form

Diagrammatic functional relations for the free energy $\Gamma[\phi]$

functional RG:

$$\partial_t \Gamma_k[\phi] = \frac{1}{2}$$



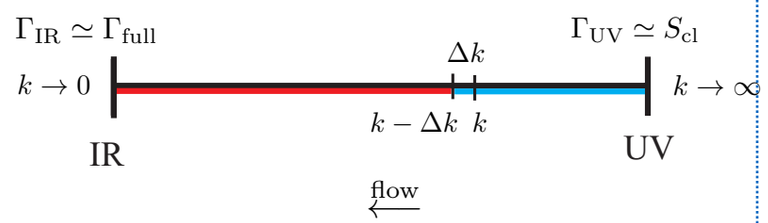
$$+\frac{1}{2}$$

free energy/ grand potential

glue quantum fluctuations

hadronic quantum fluctuations

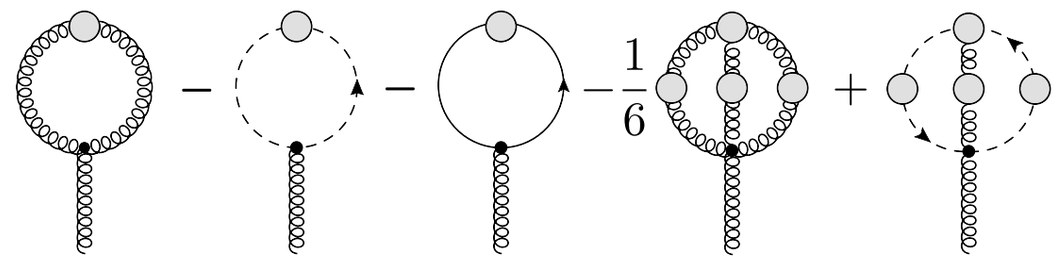
quark quantum fluctuations



RG-scale k: $t = \ln k$

functional DSE :

$$\frac{\delta\,(\Gamma - S)}{\delta A_0} = \frac{1}{2}$$



$$-\frac{1}{6}$$

$$+$$

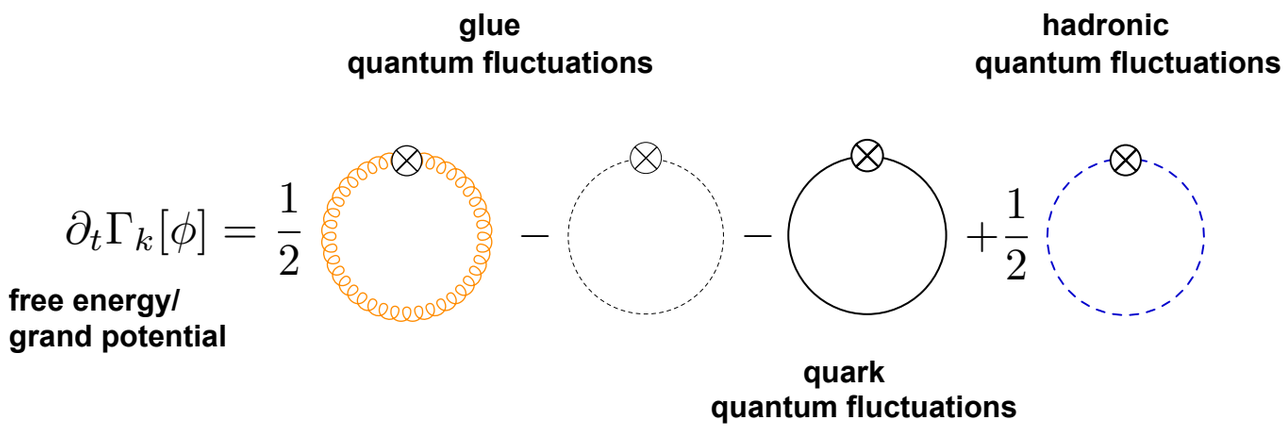
A_0 **: background field**

fRG: Fu, Commun.Theor.Phys. 74 (2022) 097304
Dupuis et al, Phys.Rept. 910 (2021) 1

DSE: Fischer, PPNP 105 (2019) 1

Functional Methods for QCD

functional RG:



Correlation functions

Functional Methods for QCD

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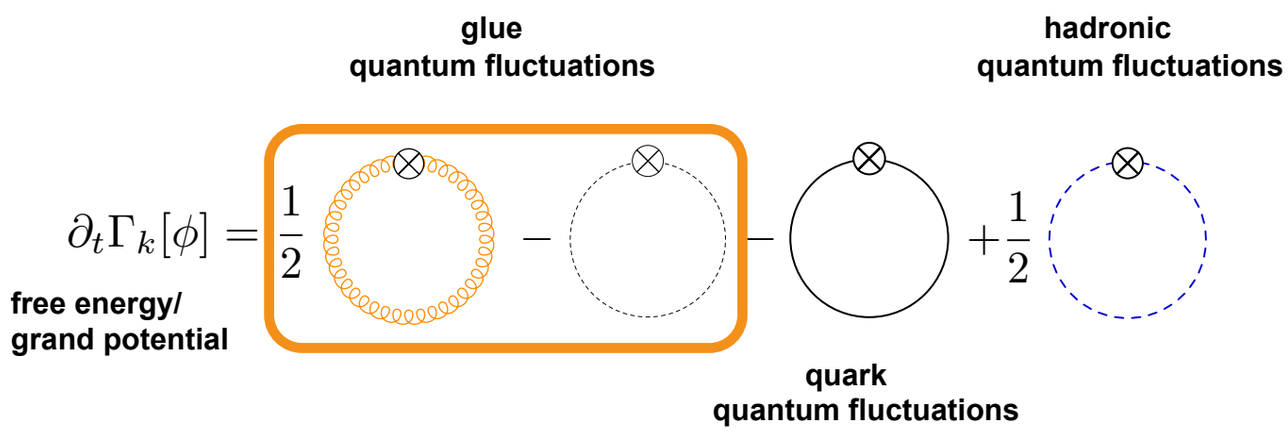

Correlation functions

gluon propagator

$$\langle A_\mu A_\nu \rangle(p)$$

Functional Methods for QCD

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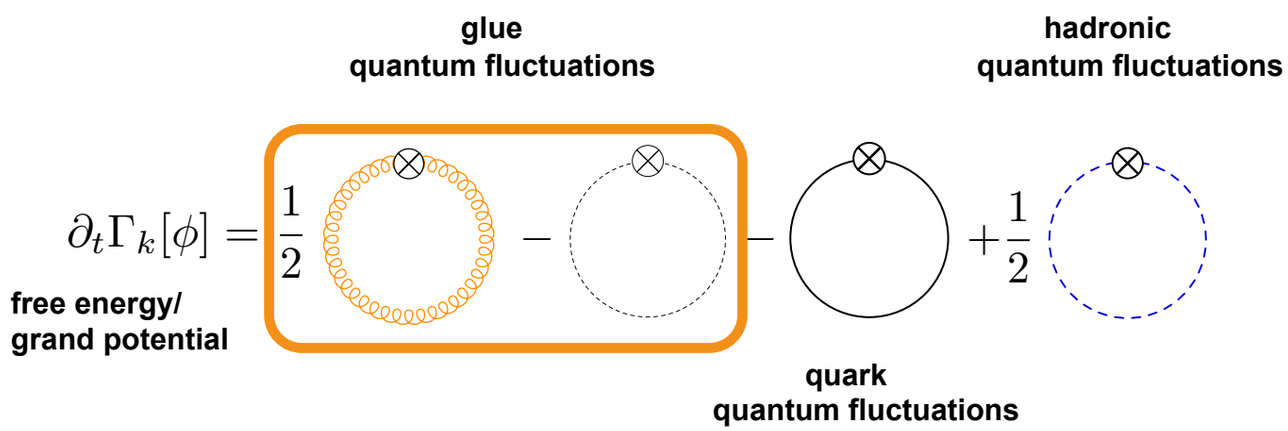

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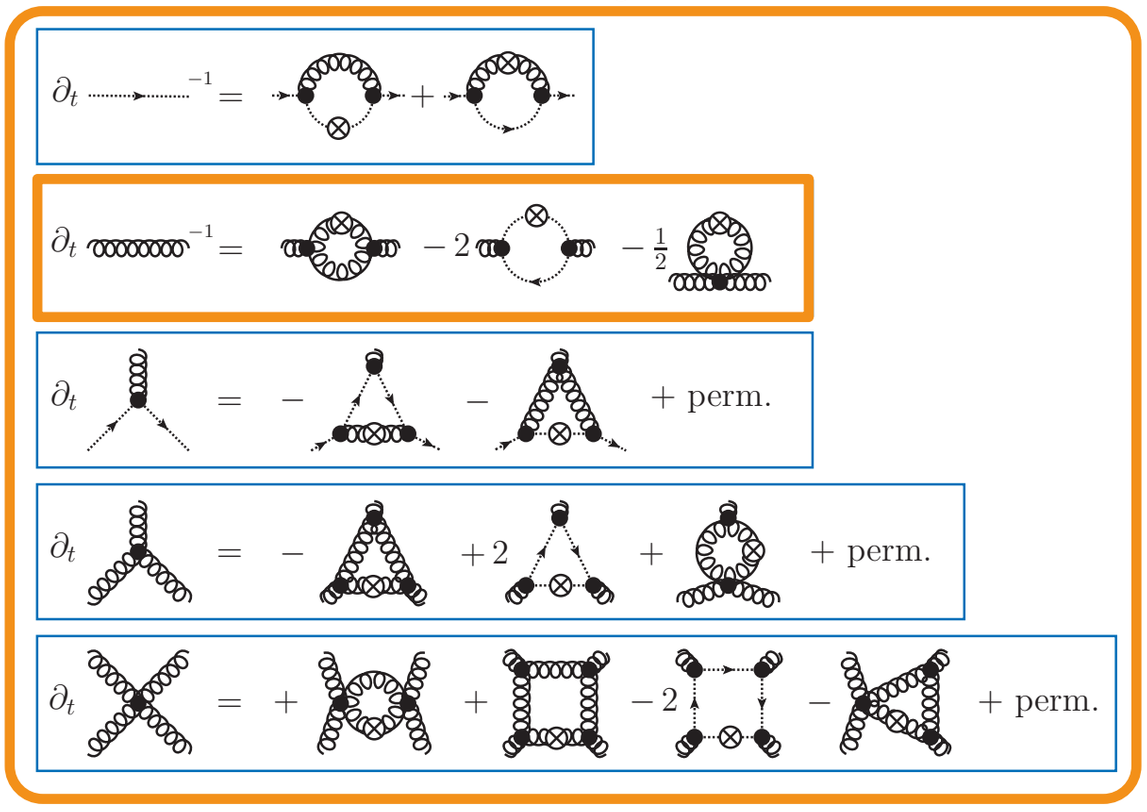
Pure glue



+ matter loops

Functional Methods for QCD

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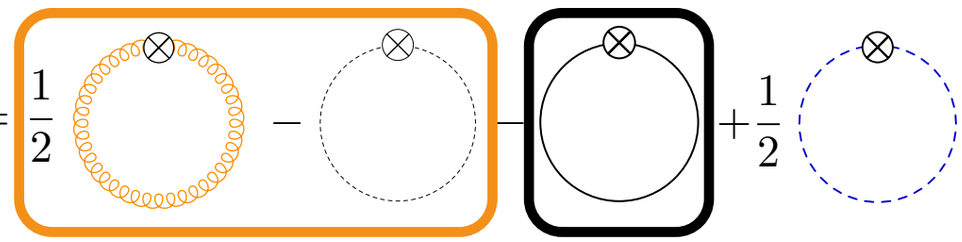

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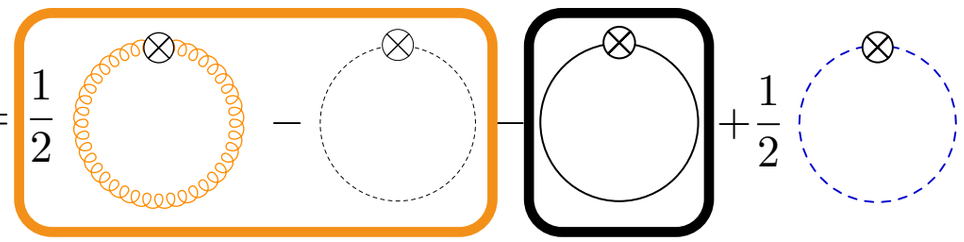

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Eight tranverse tensor structures

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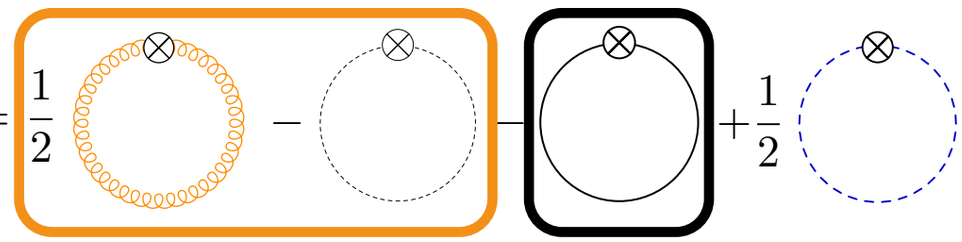

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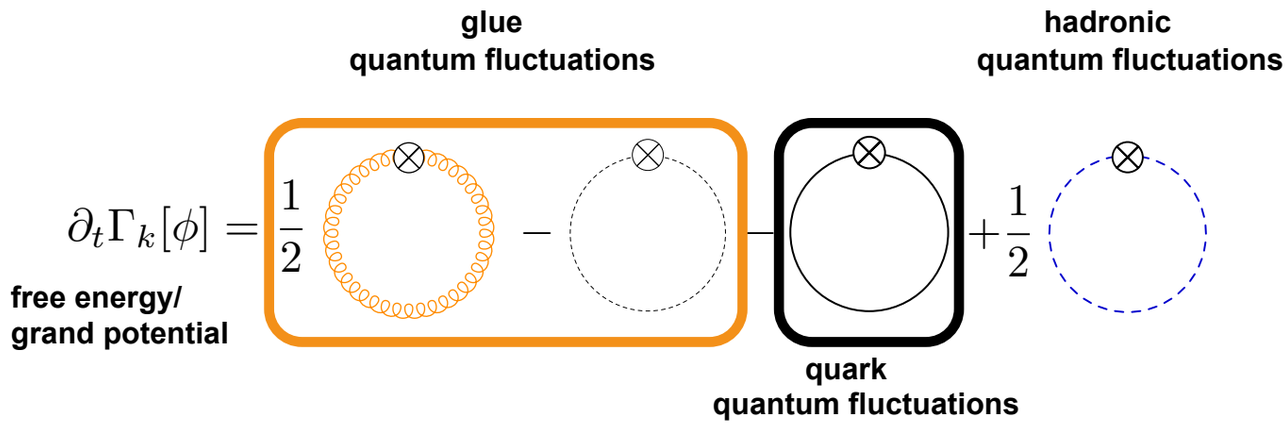

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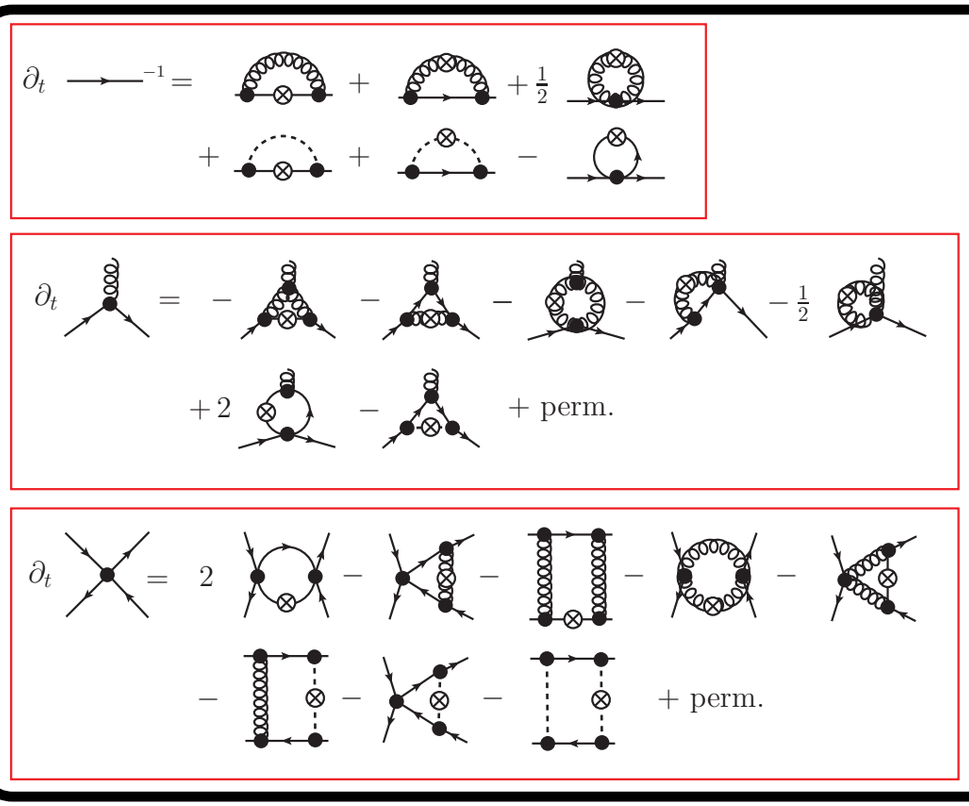

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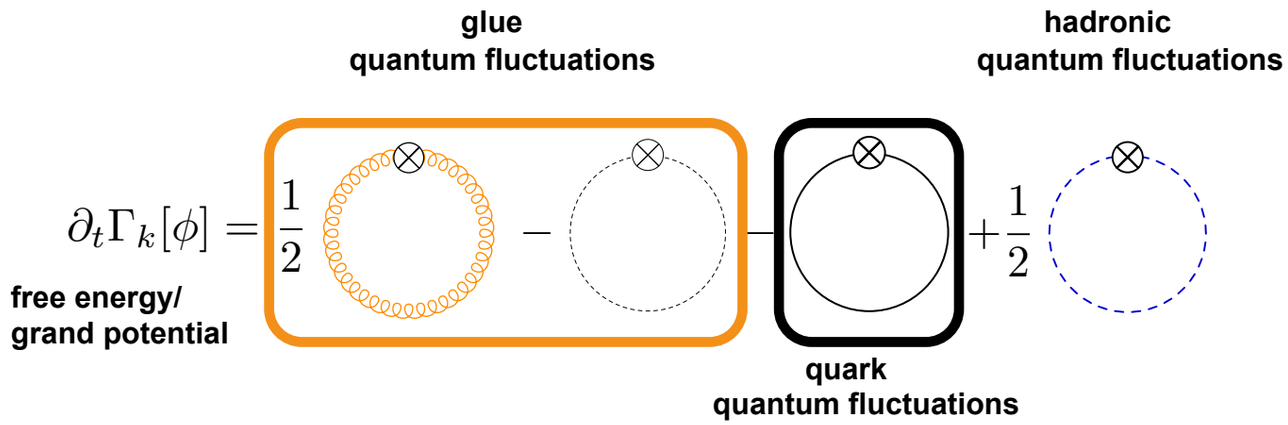

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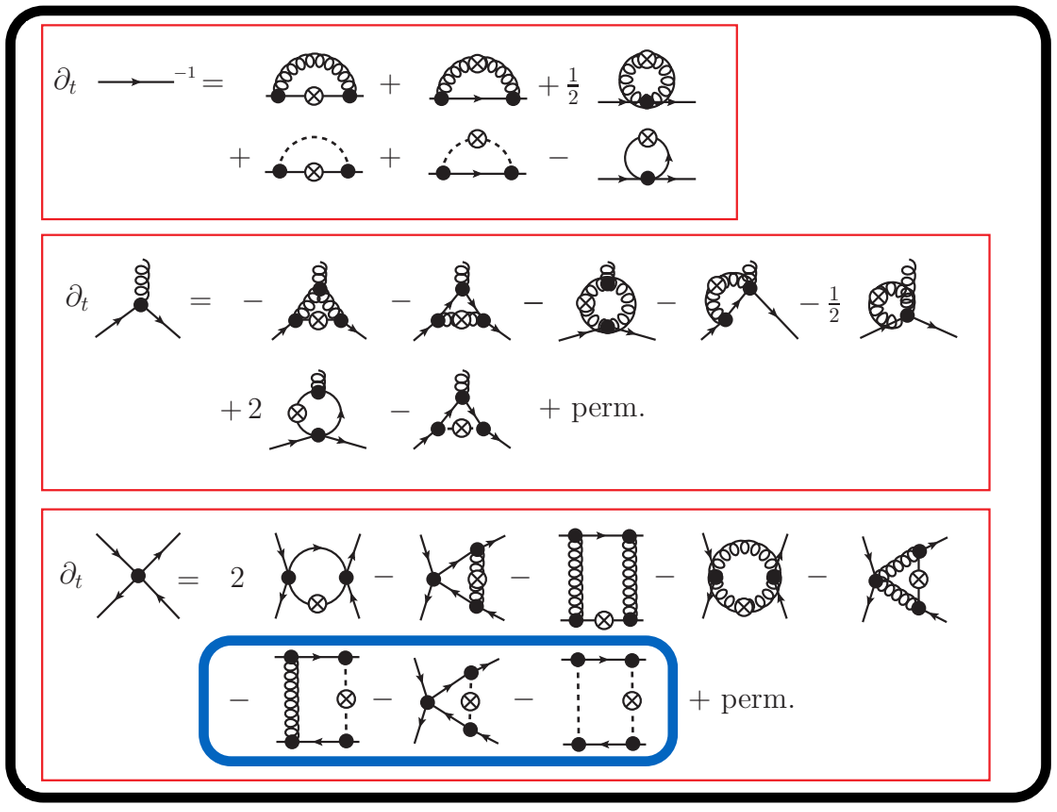

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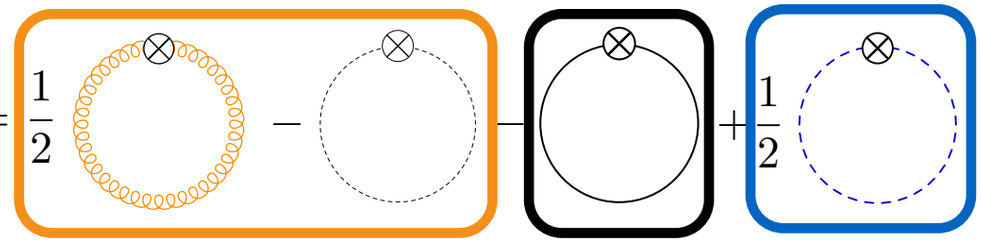

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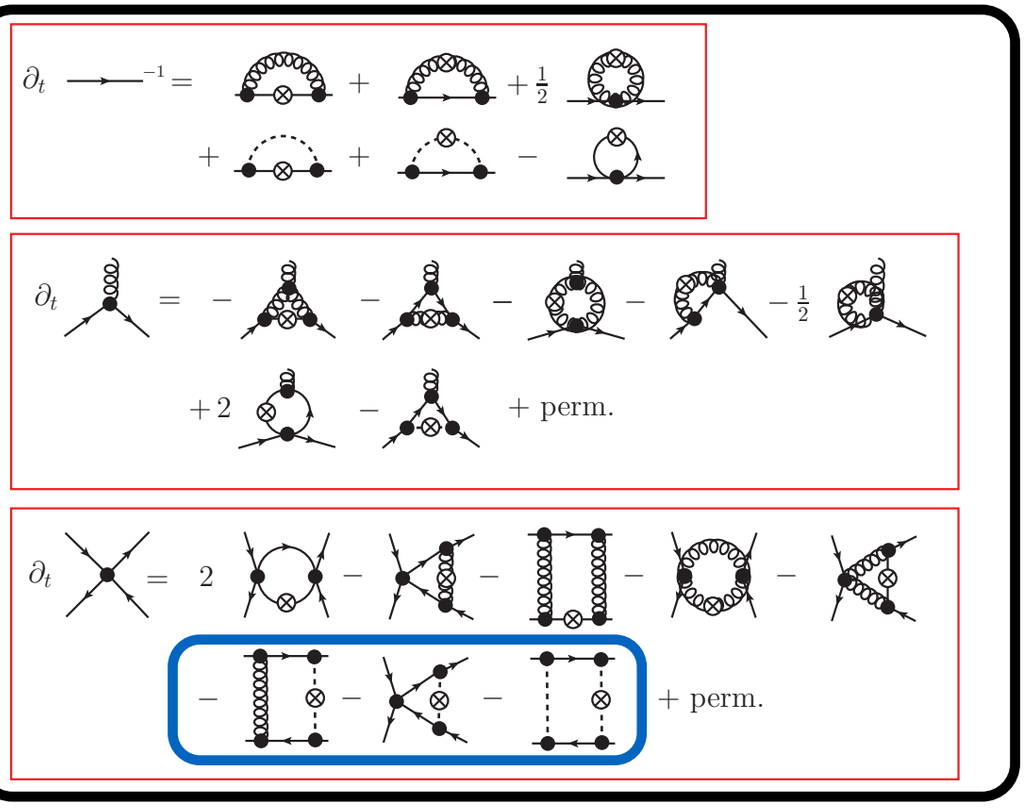
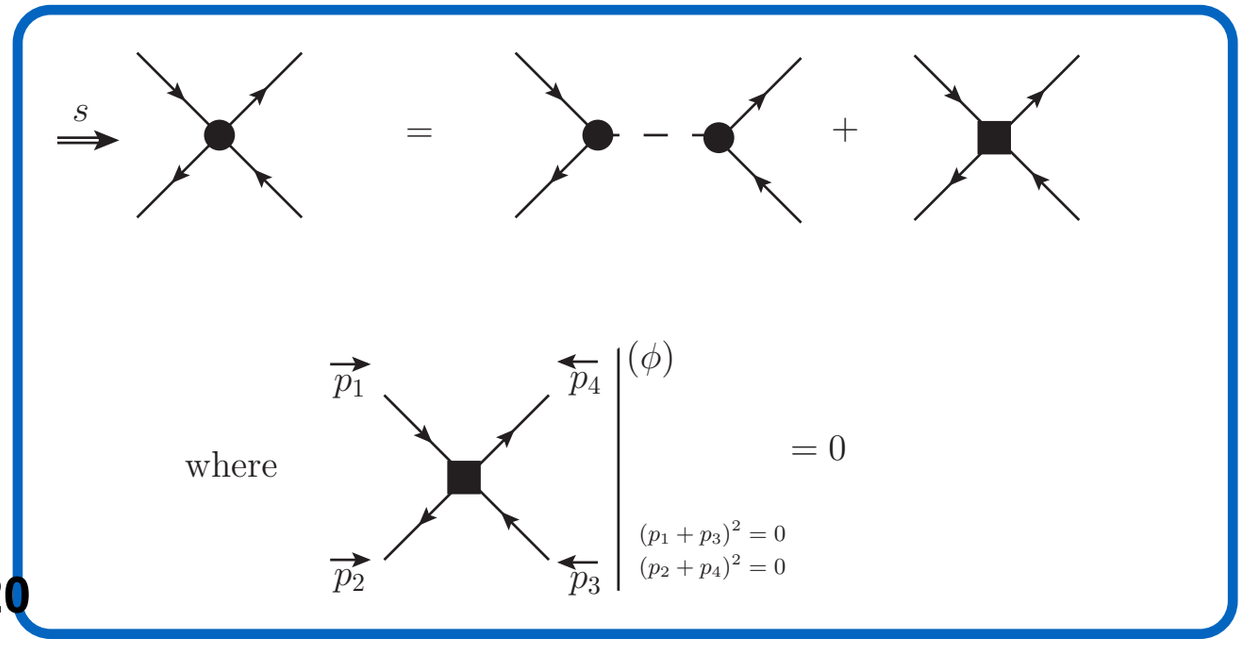
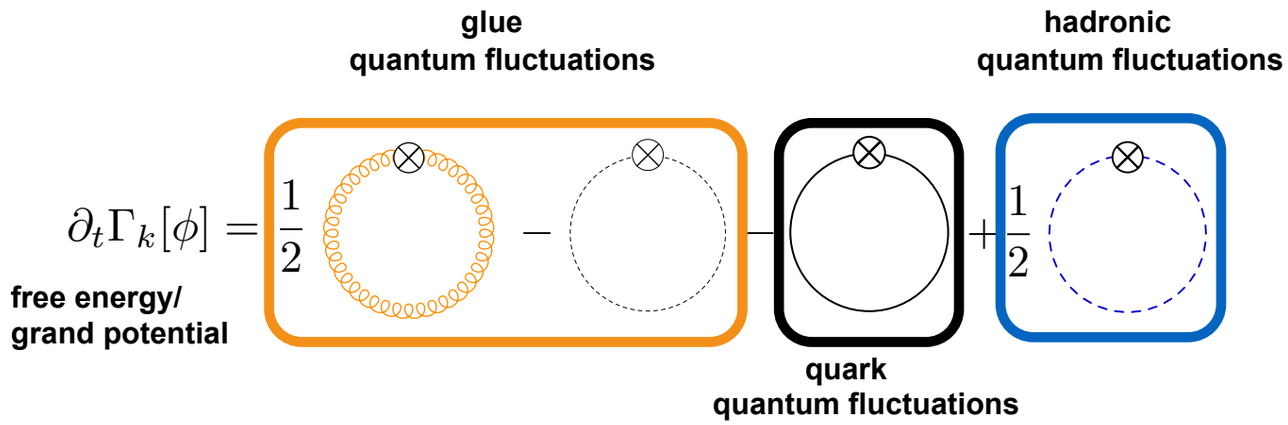


Emergent composites



Functional Methods for QCD

functional RG:



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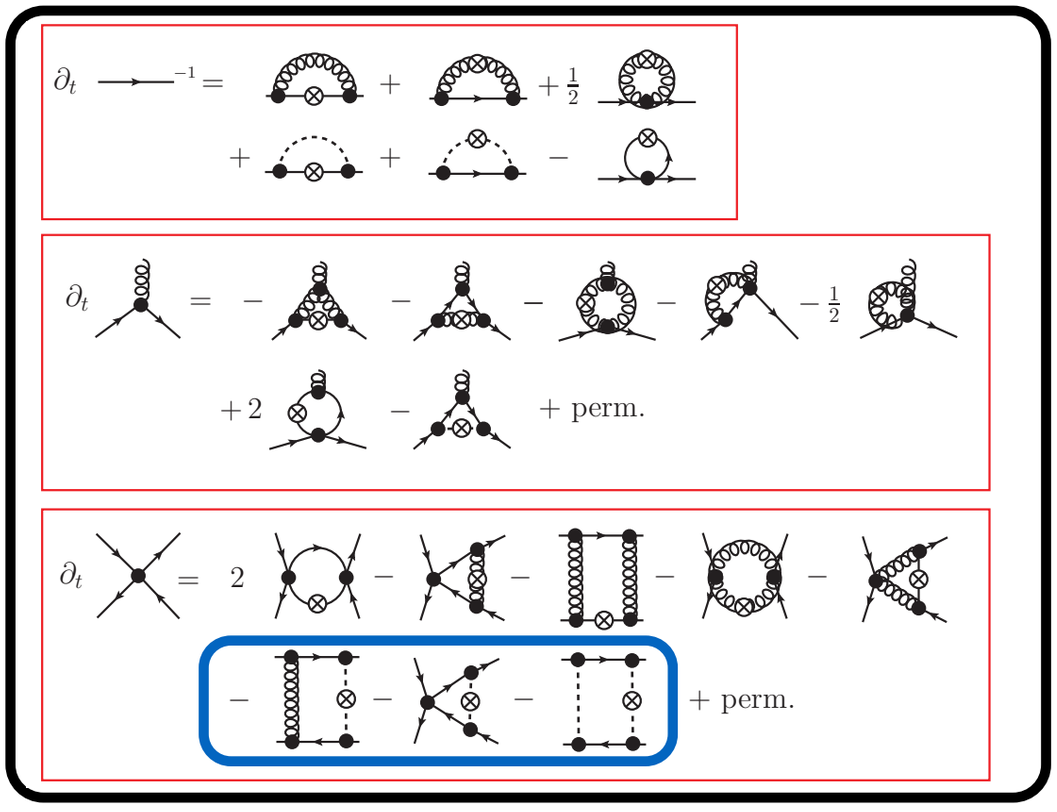

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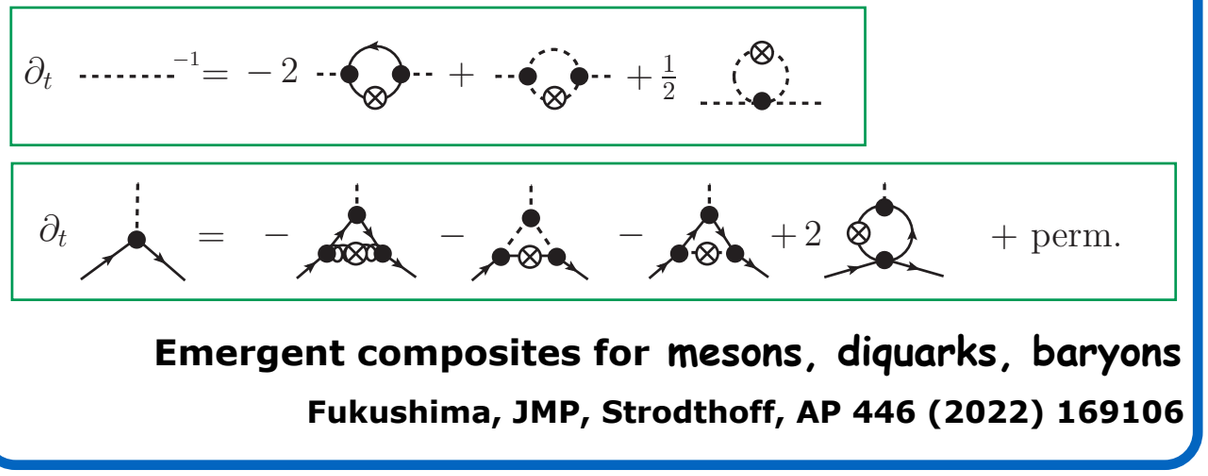
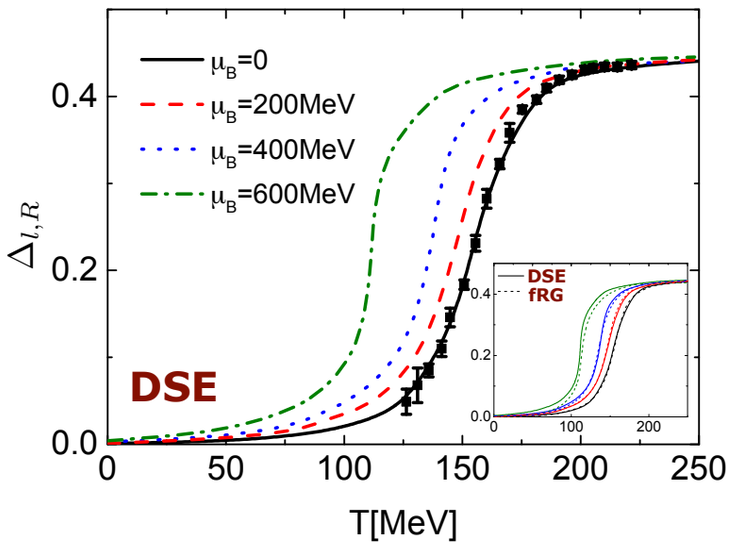


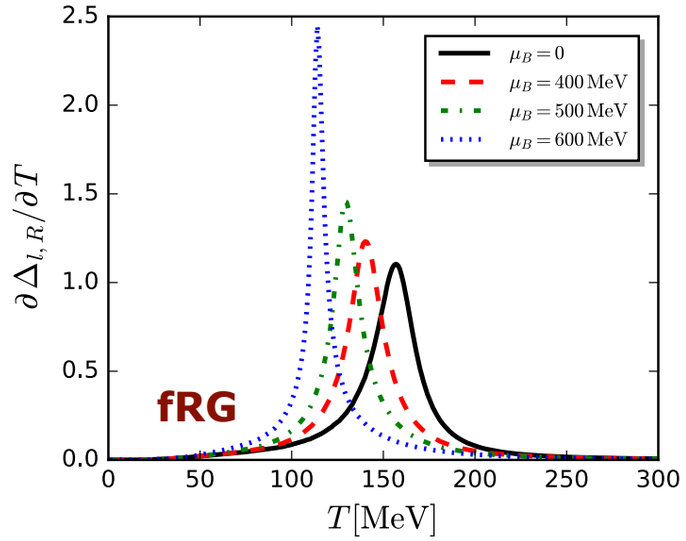
Emergent composites for mesons, diquarks, baryons

Fukushima, JMP, Strodthoff, AP 446 (2022) 169106

Chiral condensates

renormalised condensate





$$\Delta_{l,R}(T,\mu_B) \simeq \Delta_l(T,\mu_B) - \Delta_l(0,0)$$

$$\Delta_q(T,\mu_B) = \frac{T}{\mathcal{V}}\, m_q^0 \int_x \langle \bar{q}(x) q(x) \rangle$$

lattice: S. Borsanyi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, C. Ratti, and K. K. Szabo, JHEP 09, 073 (2010)

DSE: quark condensates

See also

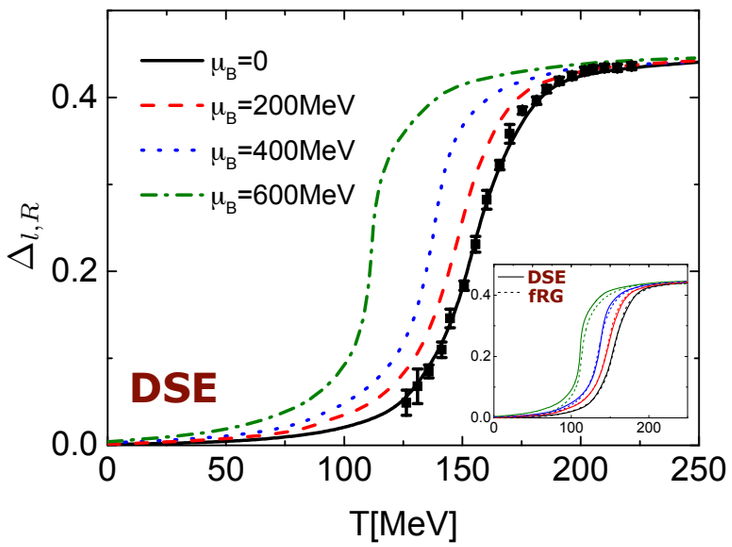
Fischer, Luecker, PLB 718 (2013) 1036
Fischer, Luecker,Welzbacher, PRD 90 (2014) 034022
Isserstedt, Buballa, Fischer, Gunkel, PRD 100 (2019) 074011

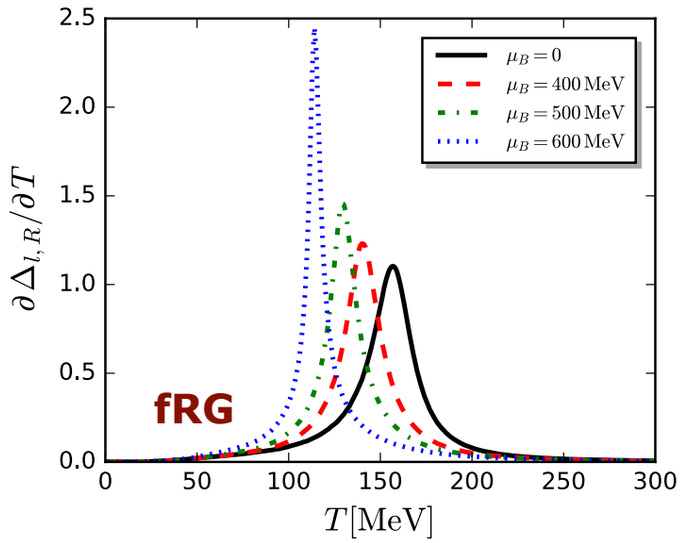
fRG: Fu, JMP, Rennecke, PRD 101 (2020) 054032

DSE: Gao, JMP, PLB 820 (2021) 136584

Chiral condensates

renormalised condensate





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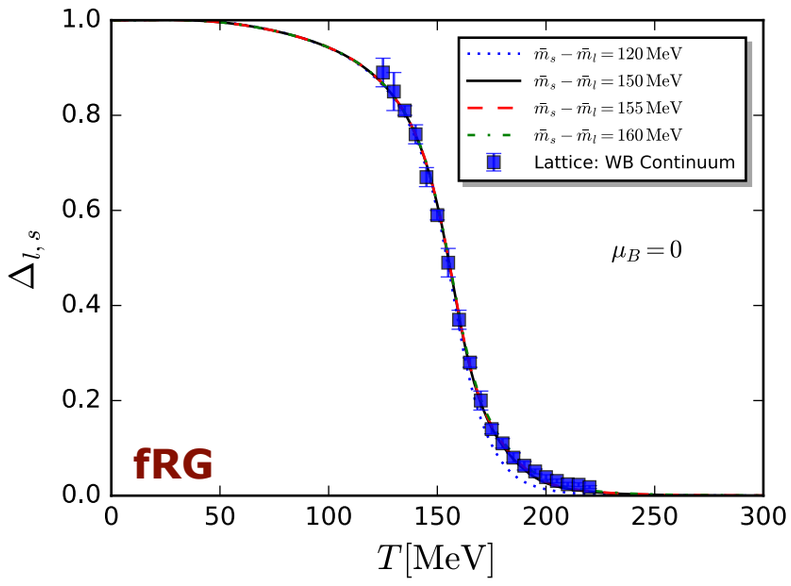
reduced condensate



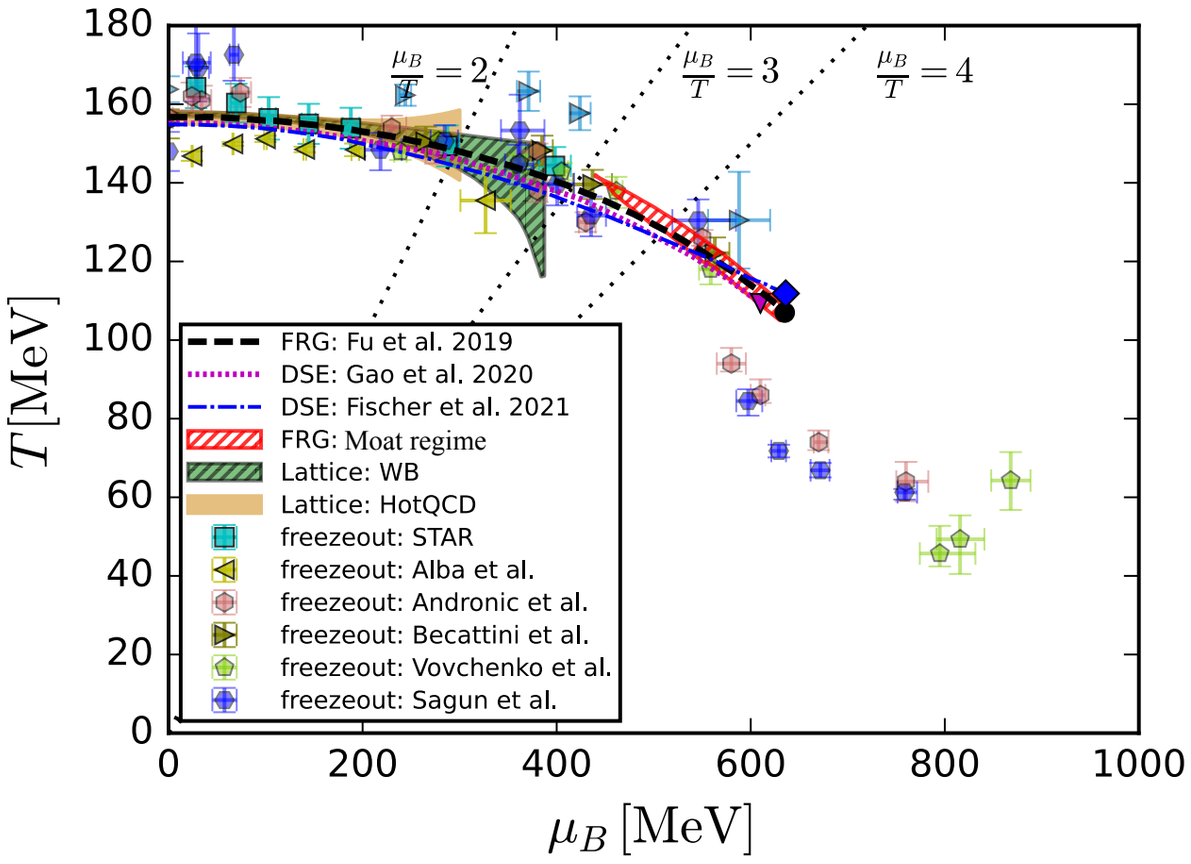
$$\Delta_{l,s}(T,\mu_B) = \frac{\Delta_l(T,\mu_B) - \left(\frac{m_l^0}{m_s^0}\right)^2 \Delta_s(T,\mu_B)}{\Delta_l(0,0) - \left(\frac{m_l^0}{m_s^0}\right)^2 \Delta_s(0,0)}$$

fRG: Fu, JMP, Rennecke, PRD 101 (2020) 054032

DSE: Gao, JMP, PLB 820 (2021) 136584

lattice: S. Borsanyi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, C. Ratti, and K. K. Szabo, JHEP 09, 073 (2010)

Curvature of the chiral transition line



fQCD

$$\kappa_{\mathrm{FRG}} = 0.0142(2)$$

$$\kappa_{\mathrm{DSE}} = 0.0147(5)$$

lattice

$$\kappa_{\mathrm{WB}} = 0.0149(21)$$

WB, PLB 751 (2015) 559

$$\kappa_{\mathrm{hotQCD}} = 0.015(4)$$

hotQCD, PLB 795 (2019) 15

Quantitative reliability: $\mu_{\mathrm{B}}/\mathrm{T} \lesssim 4$

fRG: Fu, JMP, Rennecke, PRD 101 (2020) 054032

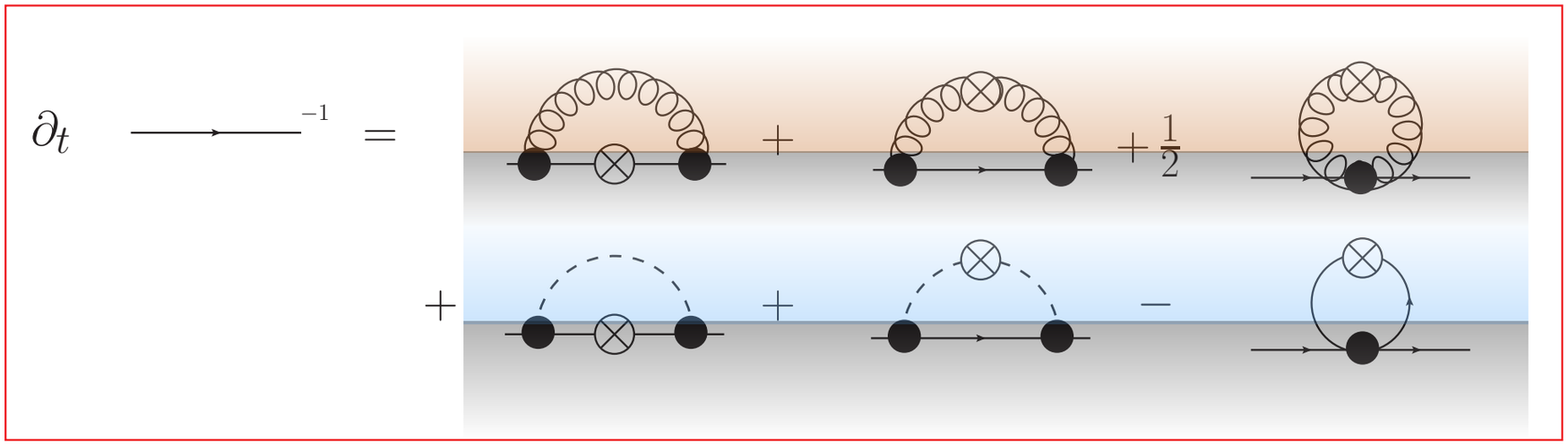
DSE: Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 054022

Analyticity considerations at finite density

- **Self-consistent truncations to functional relations define analytic functions in μ_B, eg:**

$$\partial_t \Big\langle q(x)\bar{q}(y)\Big\rangle(\mu_B) = \mathrm{Loop}\left[\Big\langle q(x)\bar{q}(y)\Big\rangle(\mu_B),\ \Big\langle q(x)A_\mu(y)\bar{q}(z)\Big\rangle(\mu_B),\cdots;\ \mu_B\right]$$



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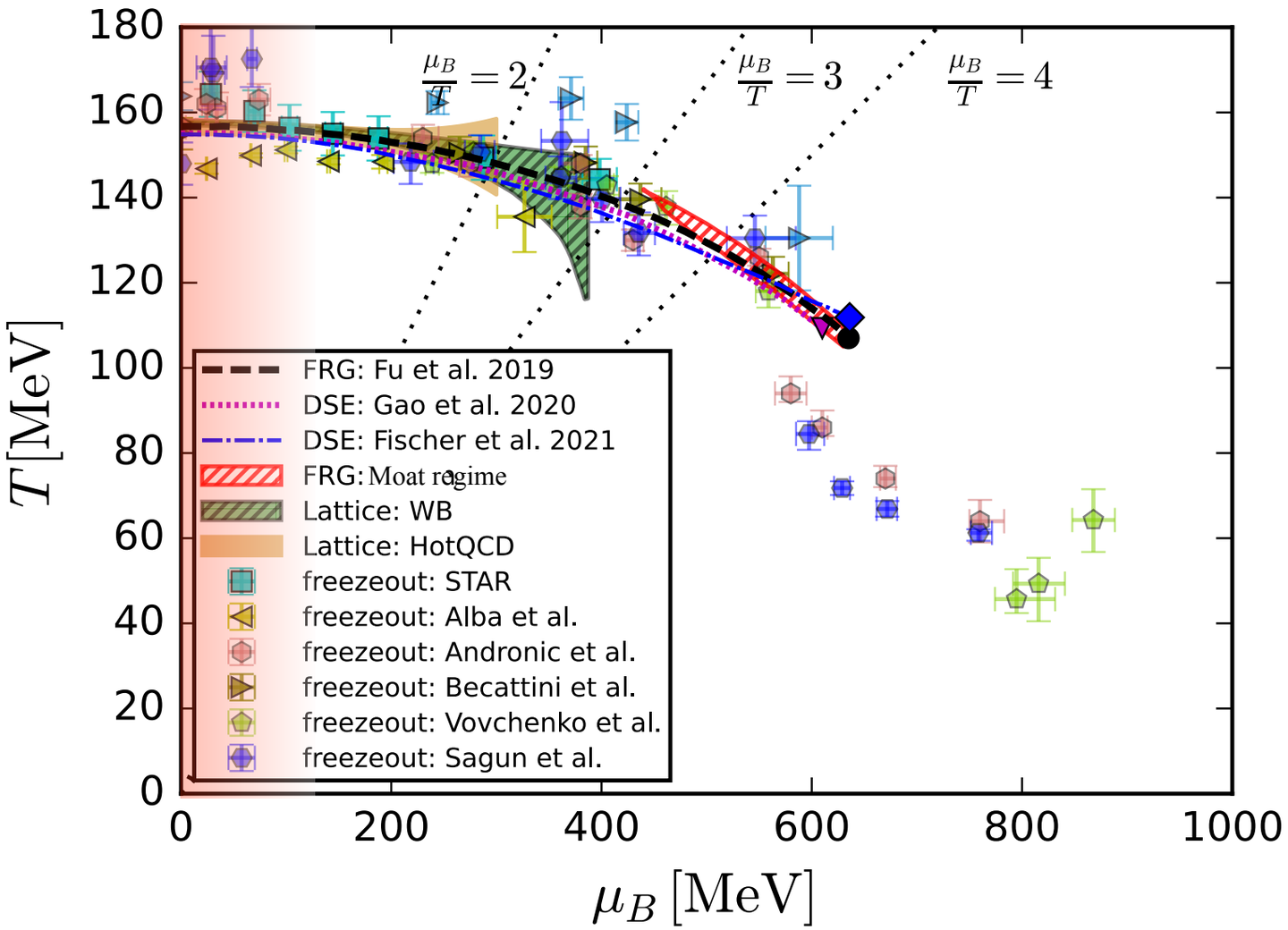
- **Consequences for functional QCD predictions at finite density**



By now the best truncations to functional QCD pass lattice benchmark tests at vanishing and small chemical potential

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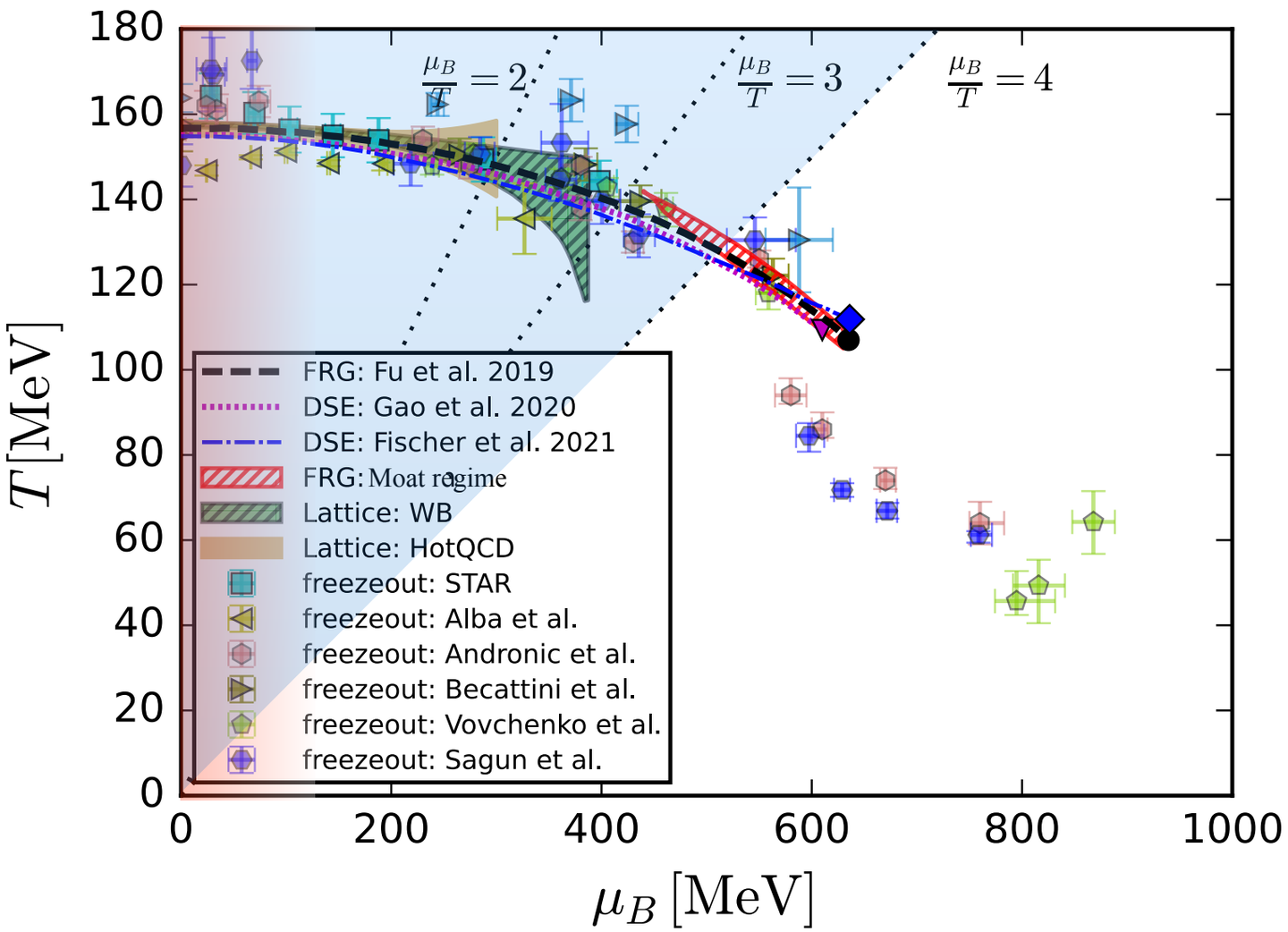

By now the best truncations to functional QCD pass lattice benchmark tests at vanishing and small chemical potential

Regime of reliability of current best truncation

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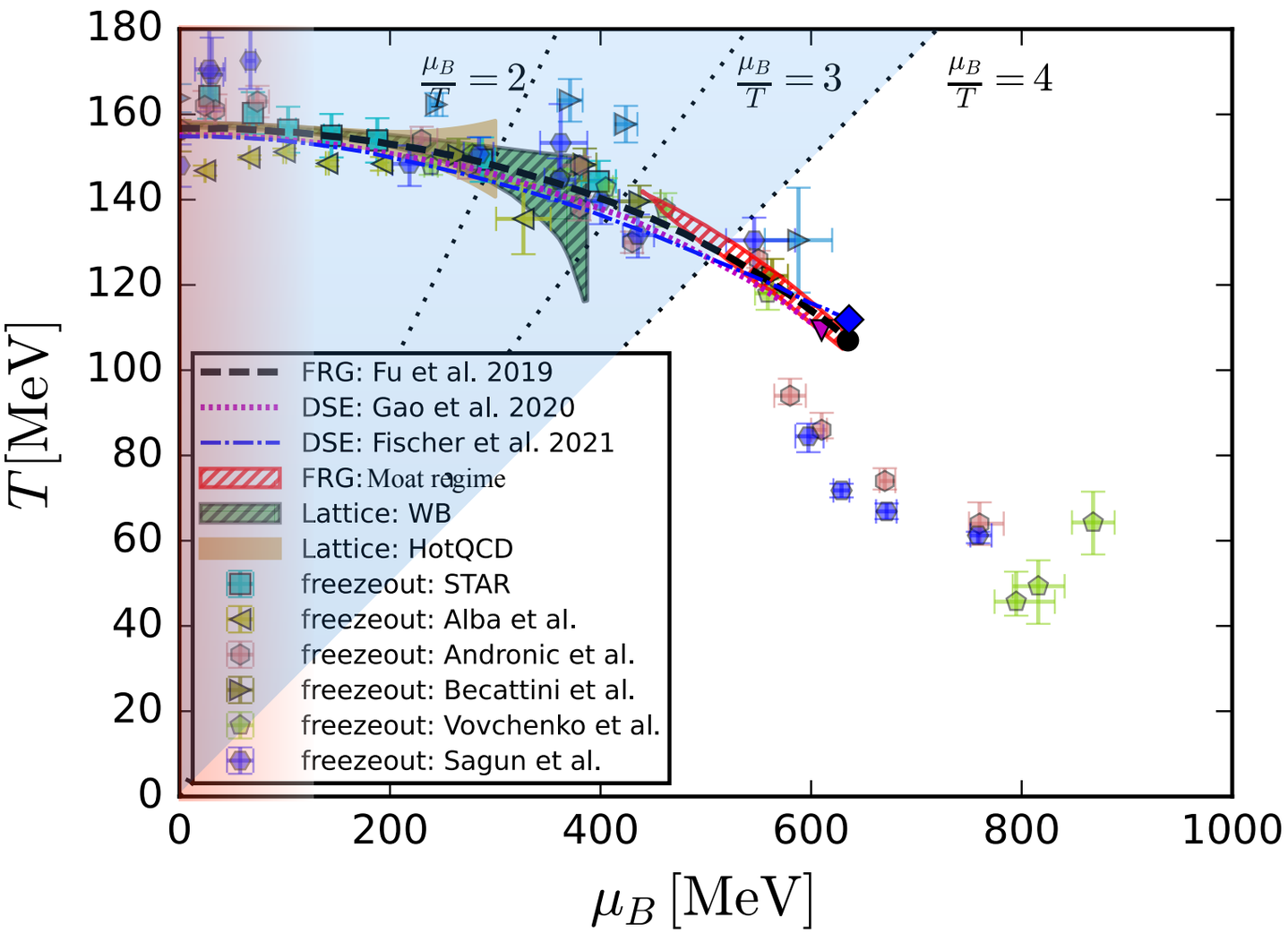


By now the best truncations to functional QCD pass lattice benchmark tests at vanishing and small chemical potential

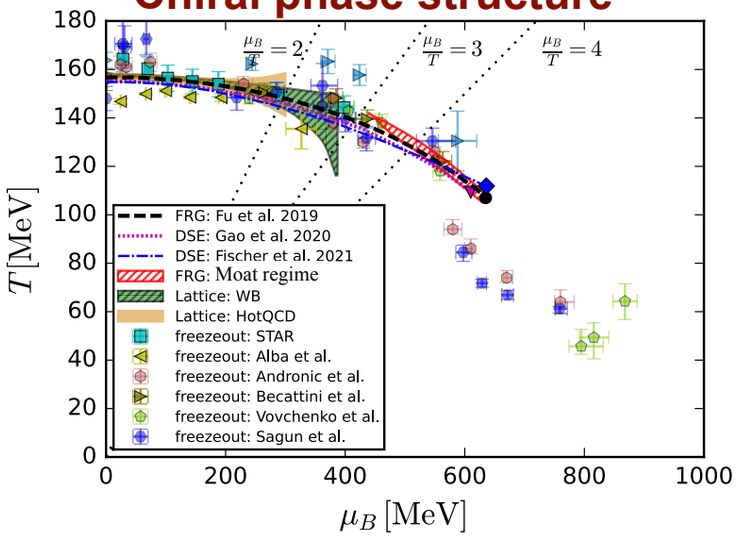
Regime of reliability of current best truncation

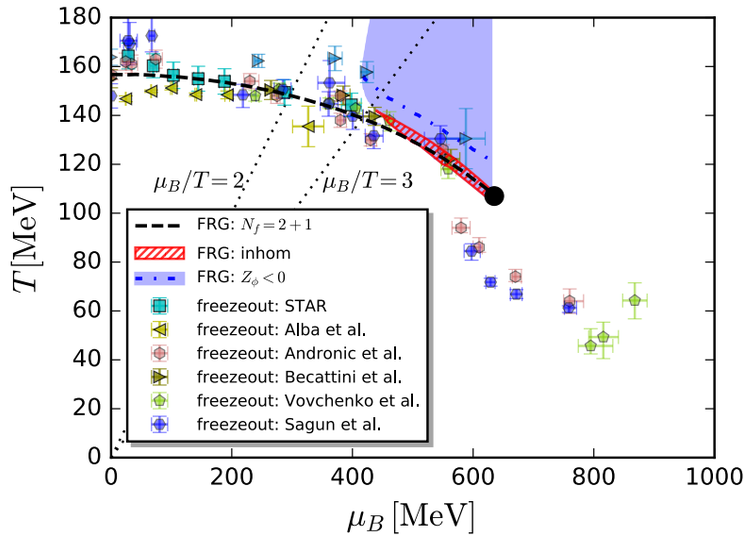
Unique: QCD-based analytic continuations that satisfy the lattice benchmarks at small chemical potential.

Great opportunity for a combined analysis of high density QCD (Exp. data + lattice QCD + functional QCD)

Sneak preview on the QCD moat

Chiral phase structure





Fu, JMP, Rennecke, PRD 101 (2020) 054032

Chinese moat

Wikipedia

German moat

Wikimedia commons: © Günter Seggebäing, CC BY-SA 3.0

US moat

Wikipedia

Physics moat

Pisarski, Rennecke, PRL 127 (2021) 152302
Rennecke, Pisarski, Rischke, PRD 107 (2023) 11, 11601

Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, in preparation

Sneak preview on the QCD moat

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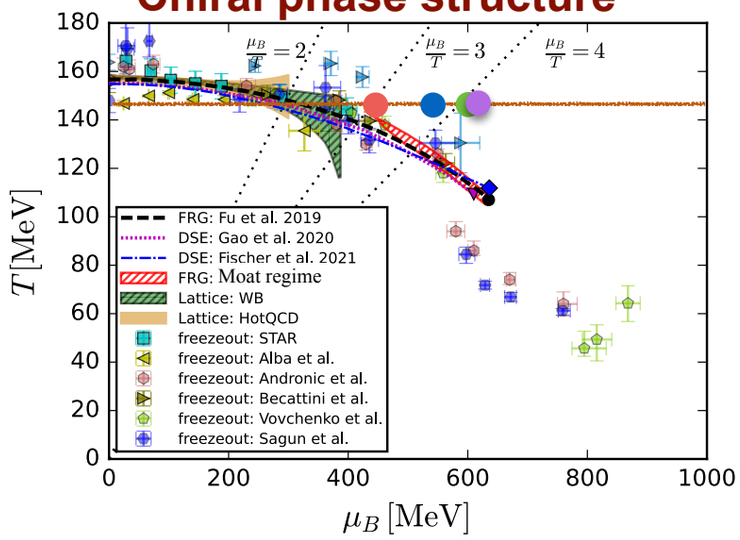
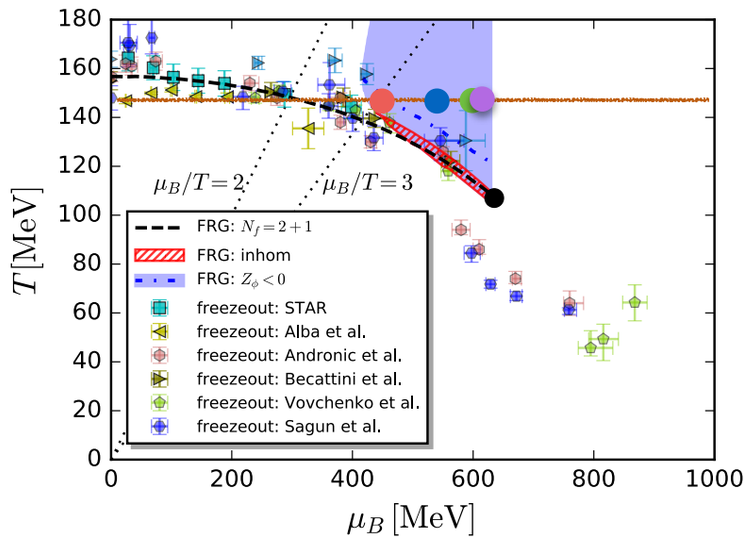


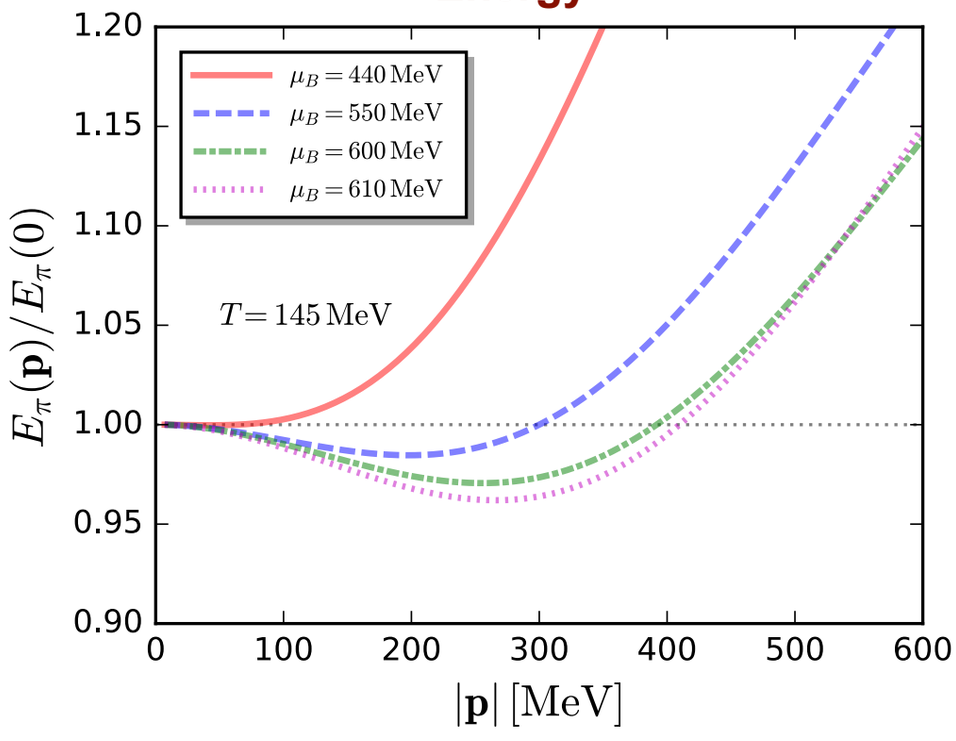
145 Me



Fu, JMP, Rennecke, PRD 101 (2020) 054032

preliminary

Energy



Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, in preparation

Sneak preview on the QCD moat

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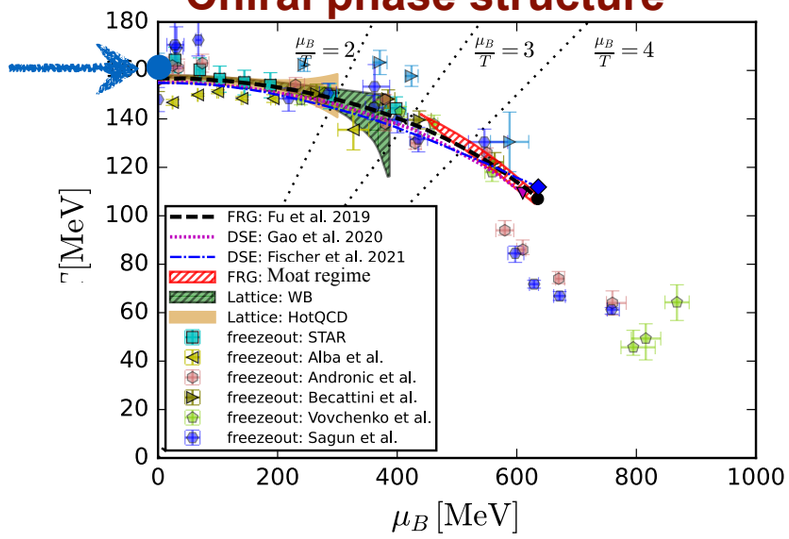
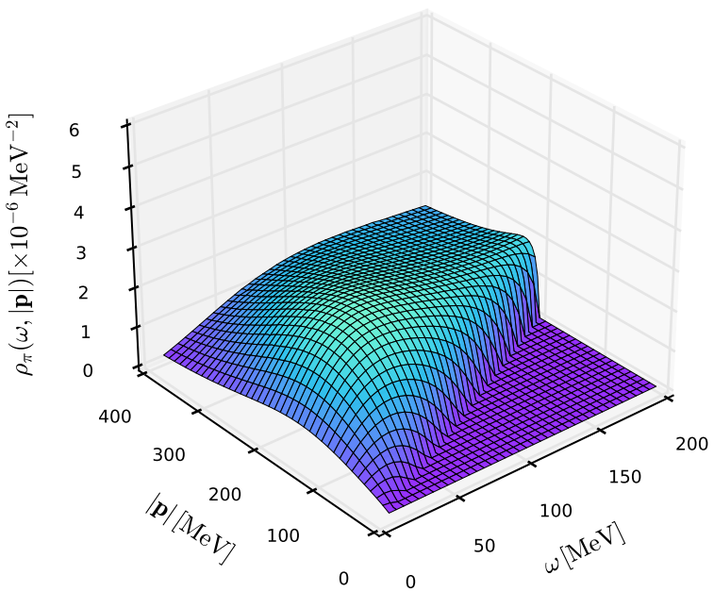
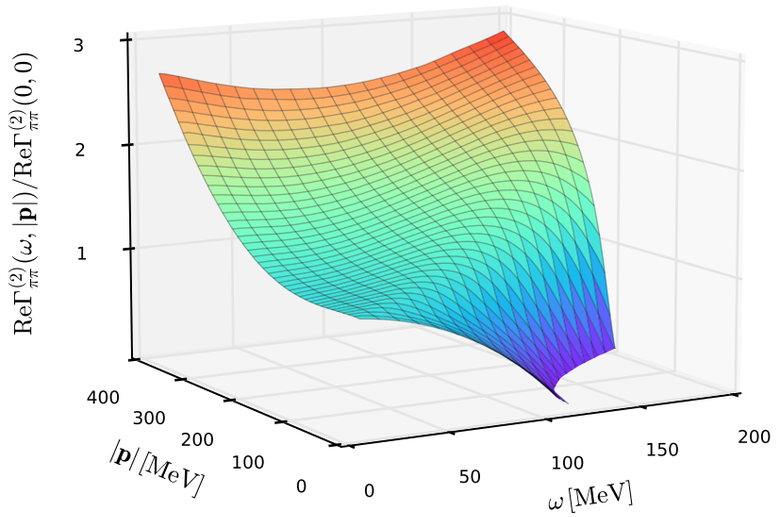


Pion spectral function



Pion correlation function



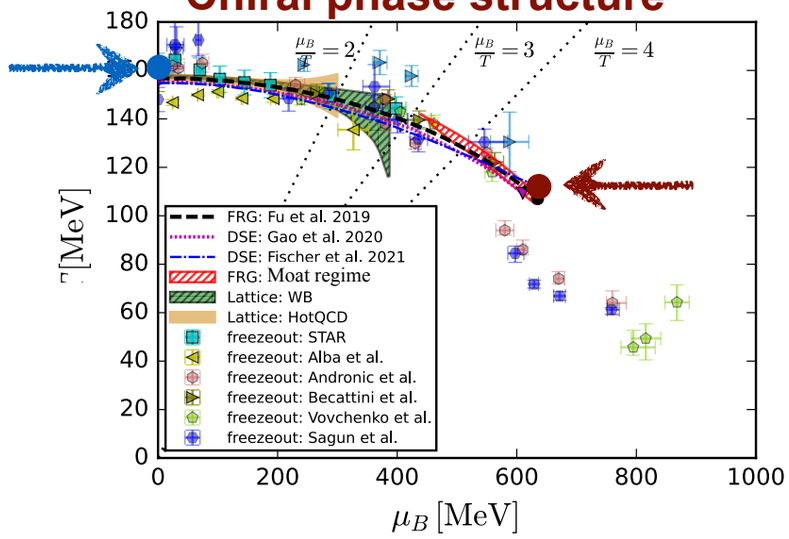
preliminary

$$(T\,,\,\mu_B) = (160\,\mathrm{MeV}, 0)$$

Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, in preparation

Sneak preview on the QCD moat

Chiral phase structure



preliminary

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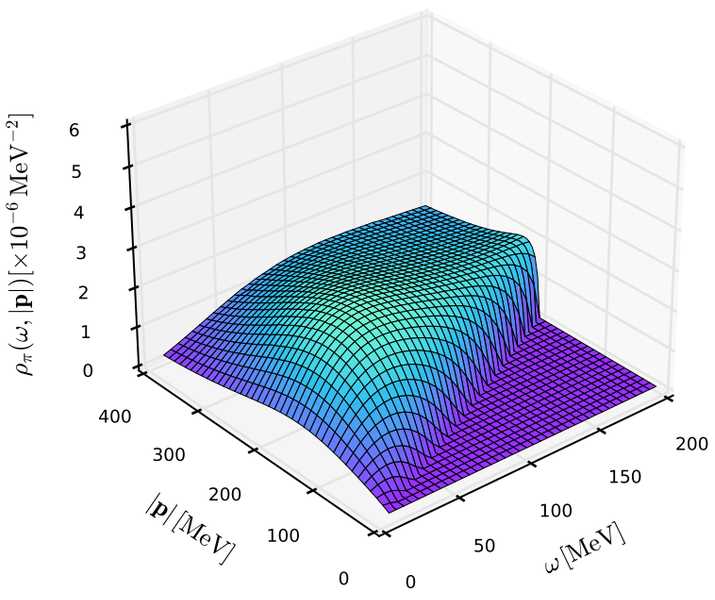
Pion spectral function



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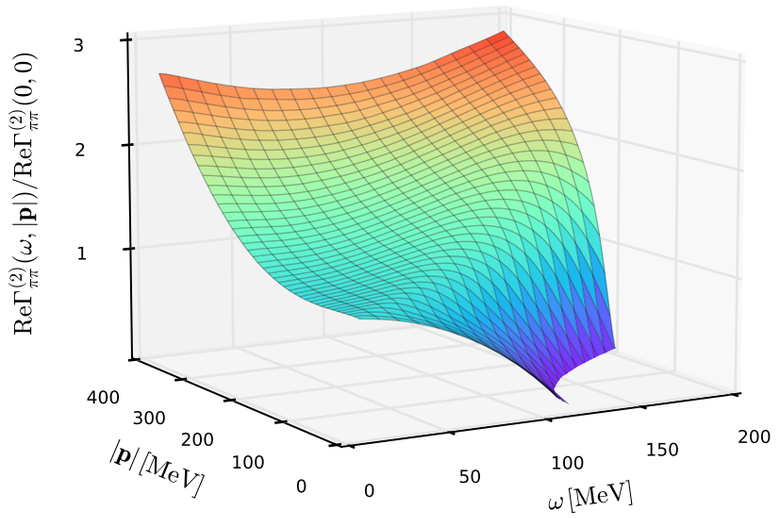
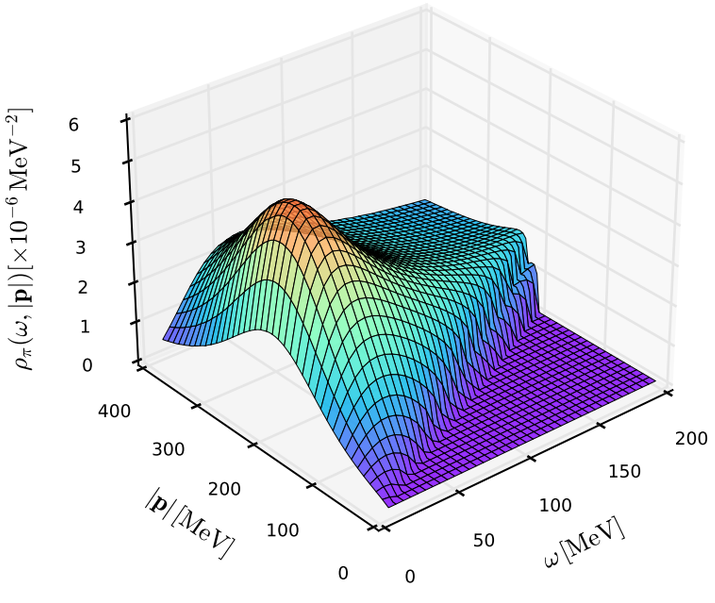
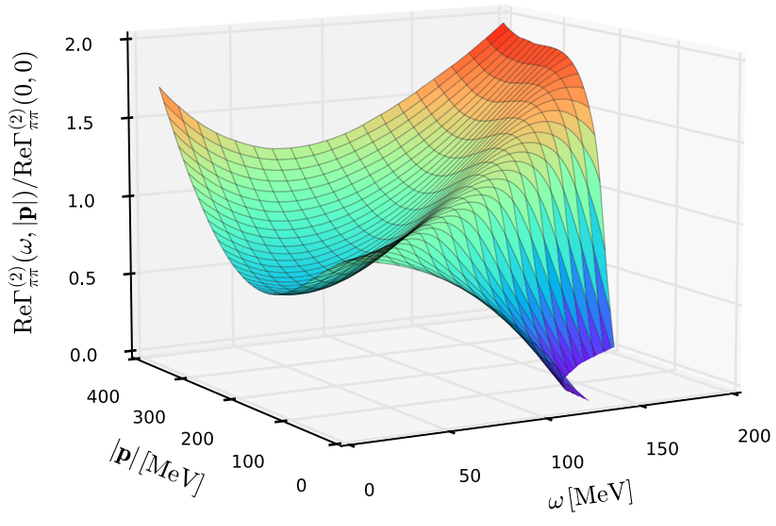


Moat

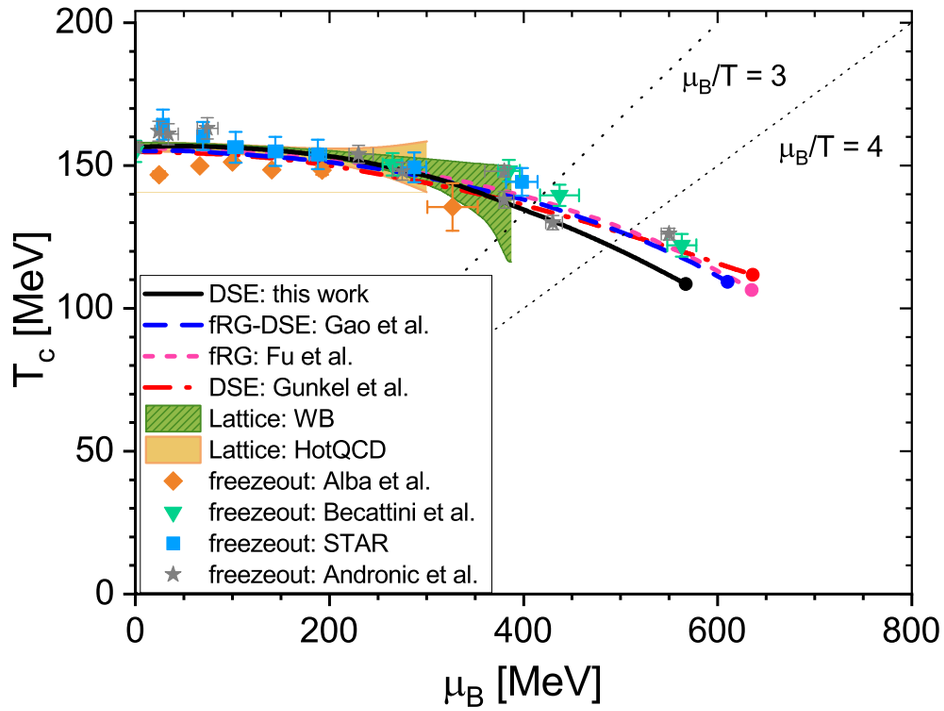
$(T\,,\,\mu_B) = (114\,\mathrm{MeV}, 630\,\mathrm{MeV})$





Fu, JMP, Pisarski, Rennecke, Wen, Shi Yin, in preparation

EoS with the minimal DSE



preliminary

Yi Lu, Gao, Liu, JMP, in preparation

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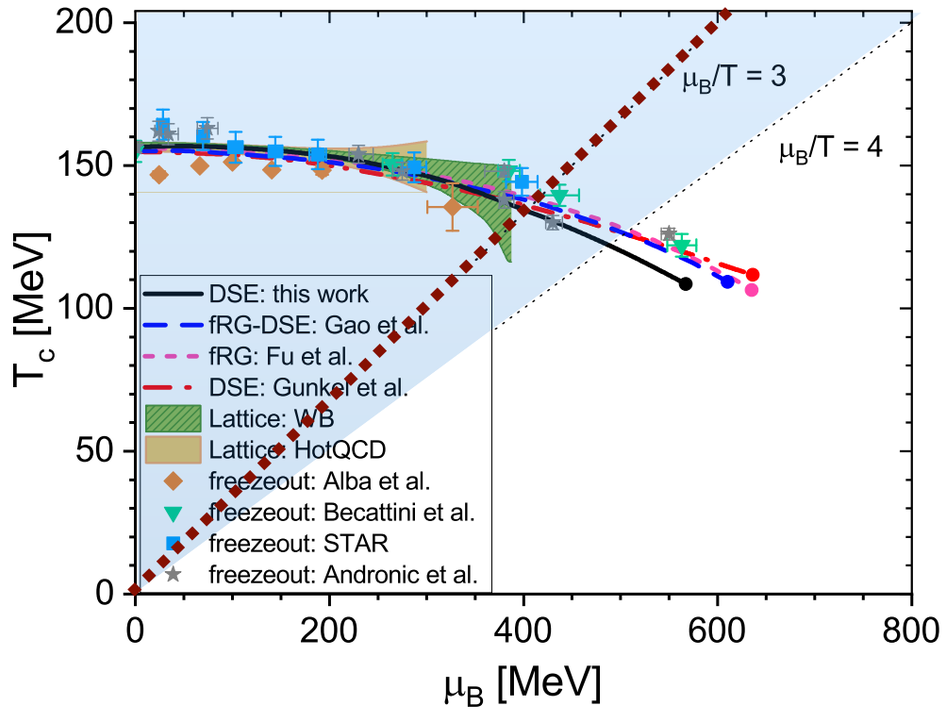

preliminary

Yi Lu, Gao, Liu, JMP, in preparation

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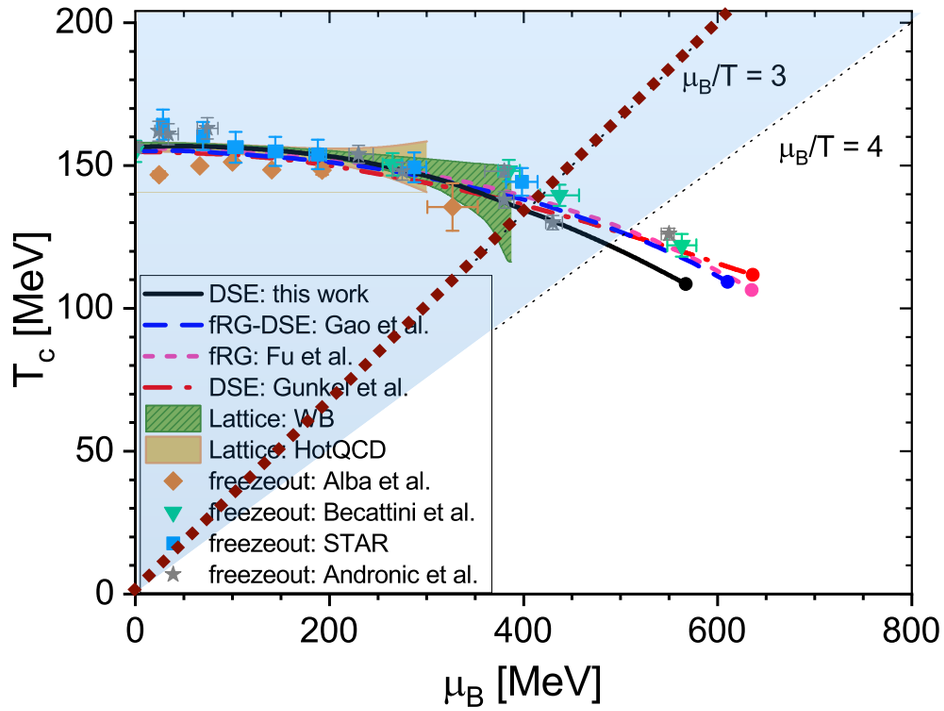
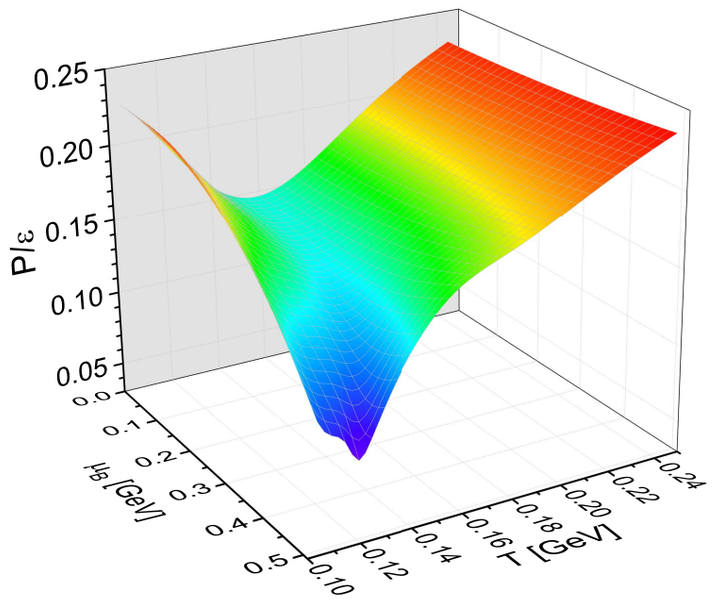


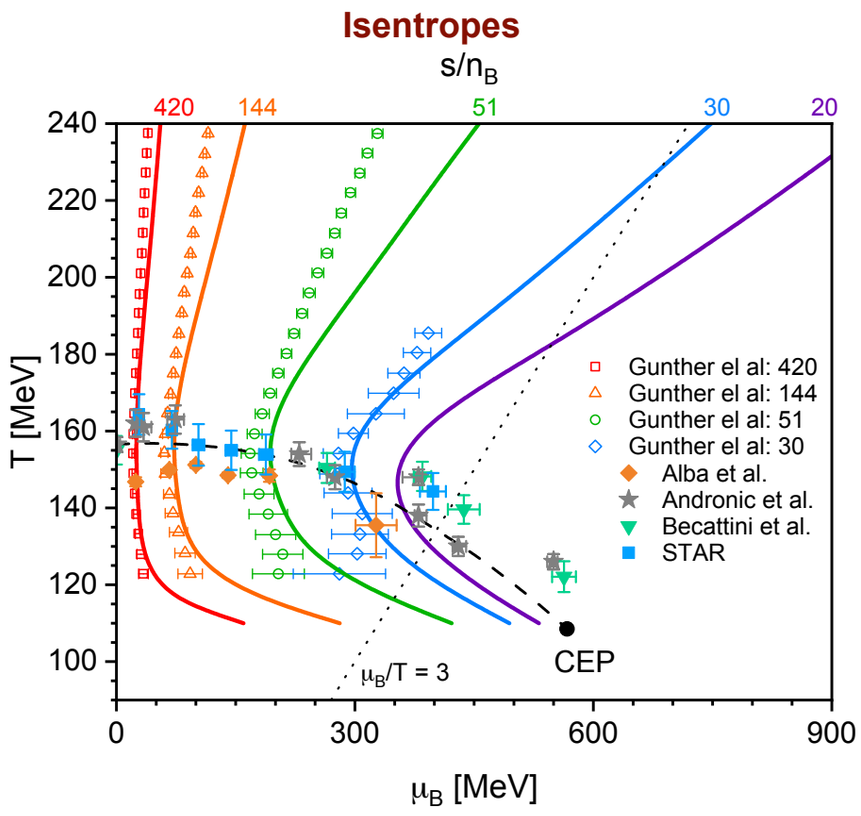
preliminary

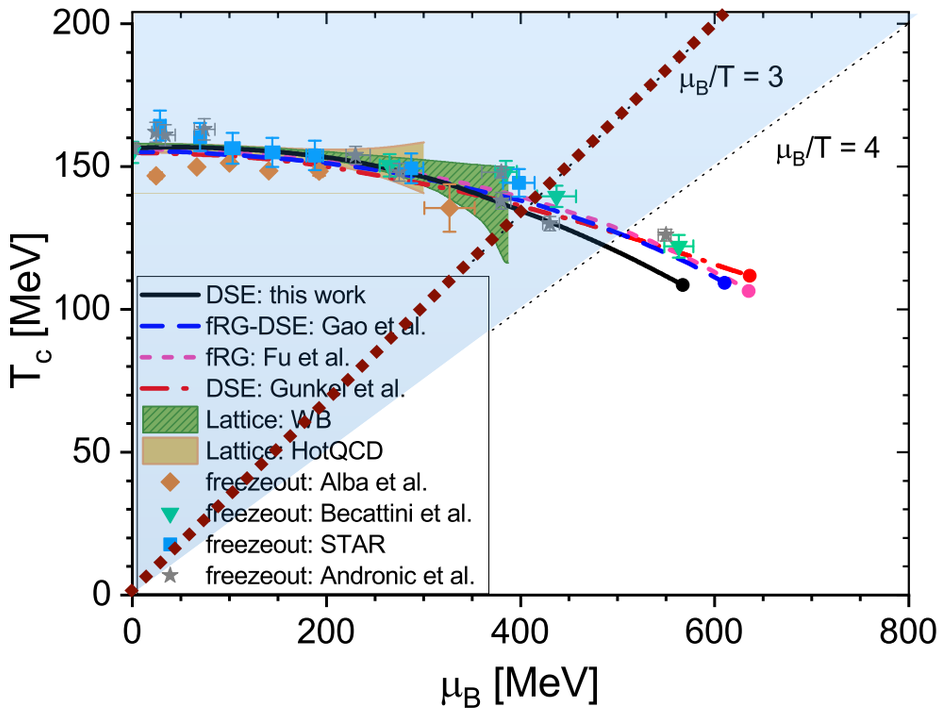
Pressure over energy density

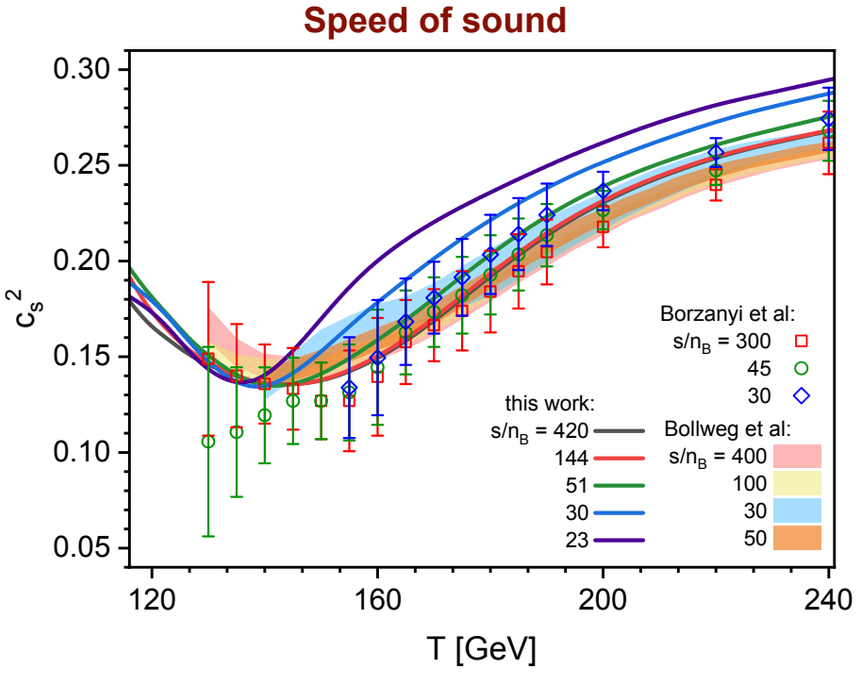


Yi Lu, Gao, Liu, JMP, in preparation

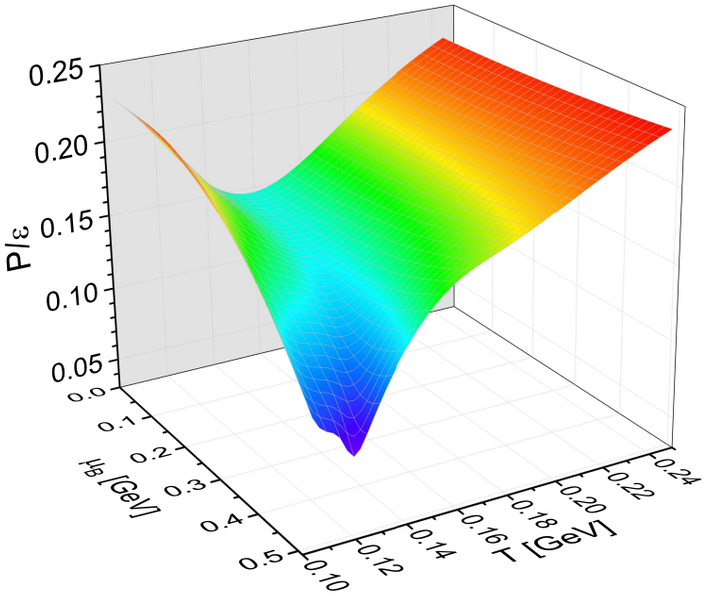
EoS with the minimal DSE







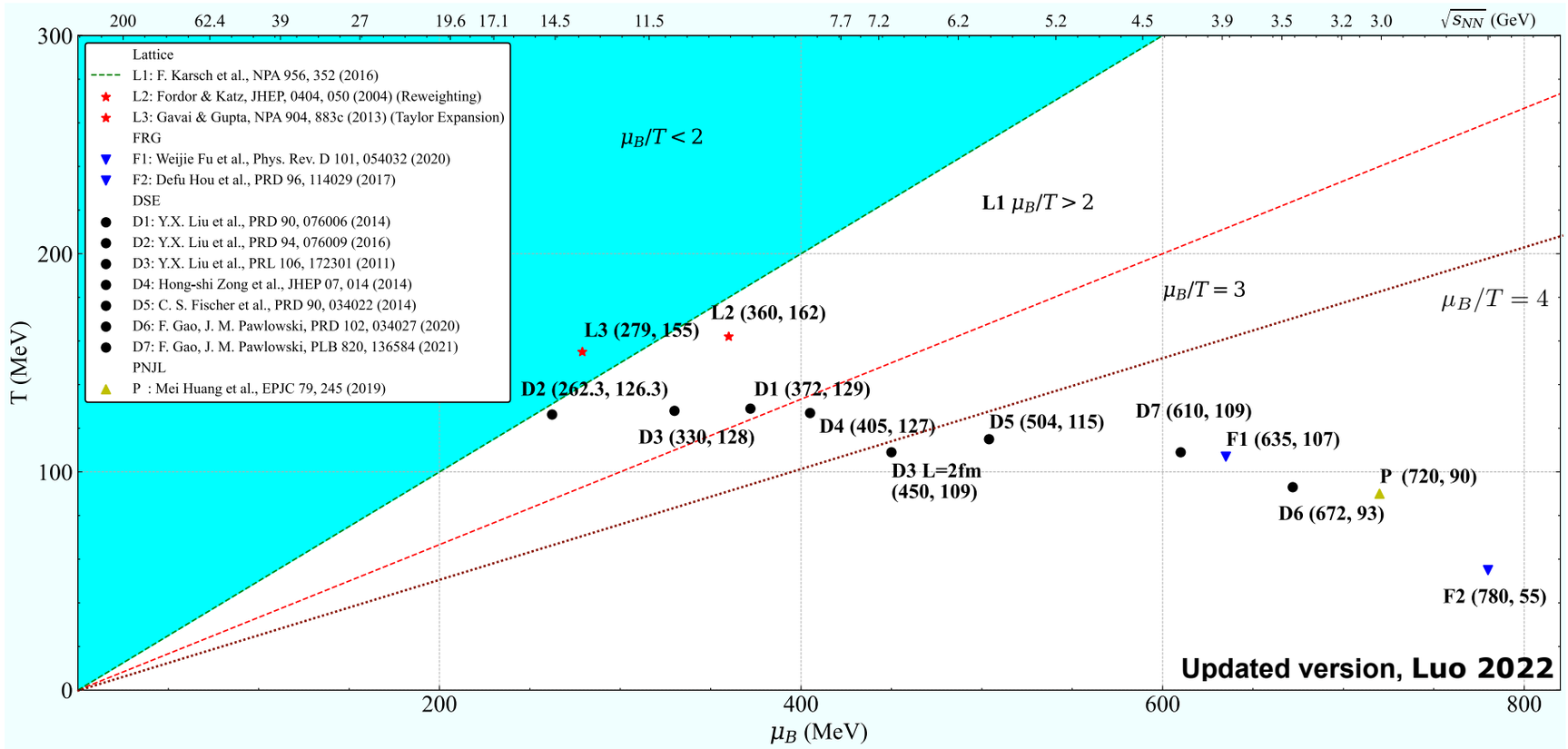
preliminary



Yi Lu, Gao, Liu, JMP, in preparation

Location of CP : Theoretical Prediction

Preliminary collection from Lattice, DSE, FRG and PNJL (2004-2020)



Large uncertainties for the estimation of CP location.

Disclaimer

Most functional computations (LEFT or QCD) have not been set-up for CEP-predictions!

Lack of predictive power for CEP-predictions is no quality measure!

CEP is standing for 'regime with new physics'

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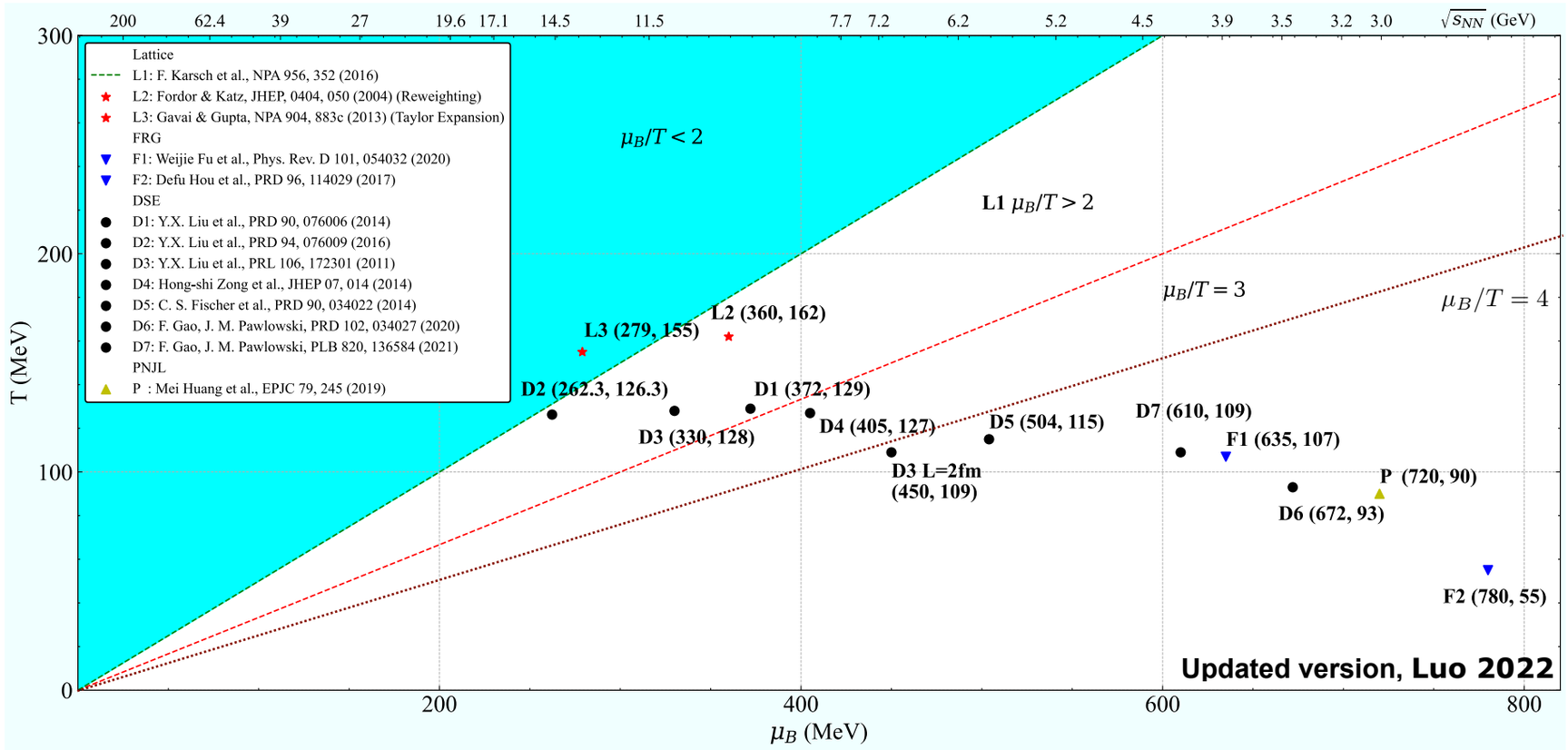

Common folklore since ~2004 ⟷ Large uncertainties for the estimation of CP location.

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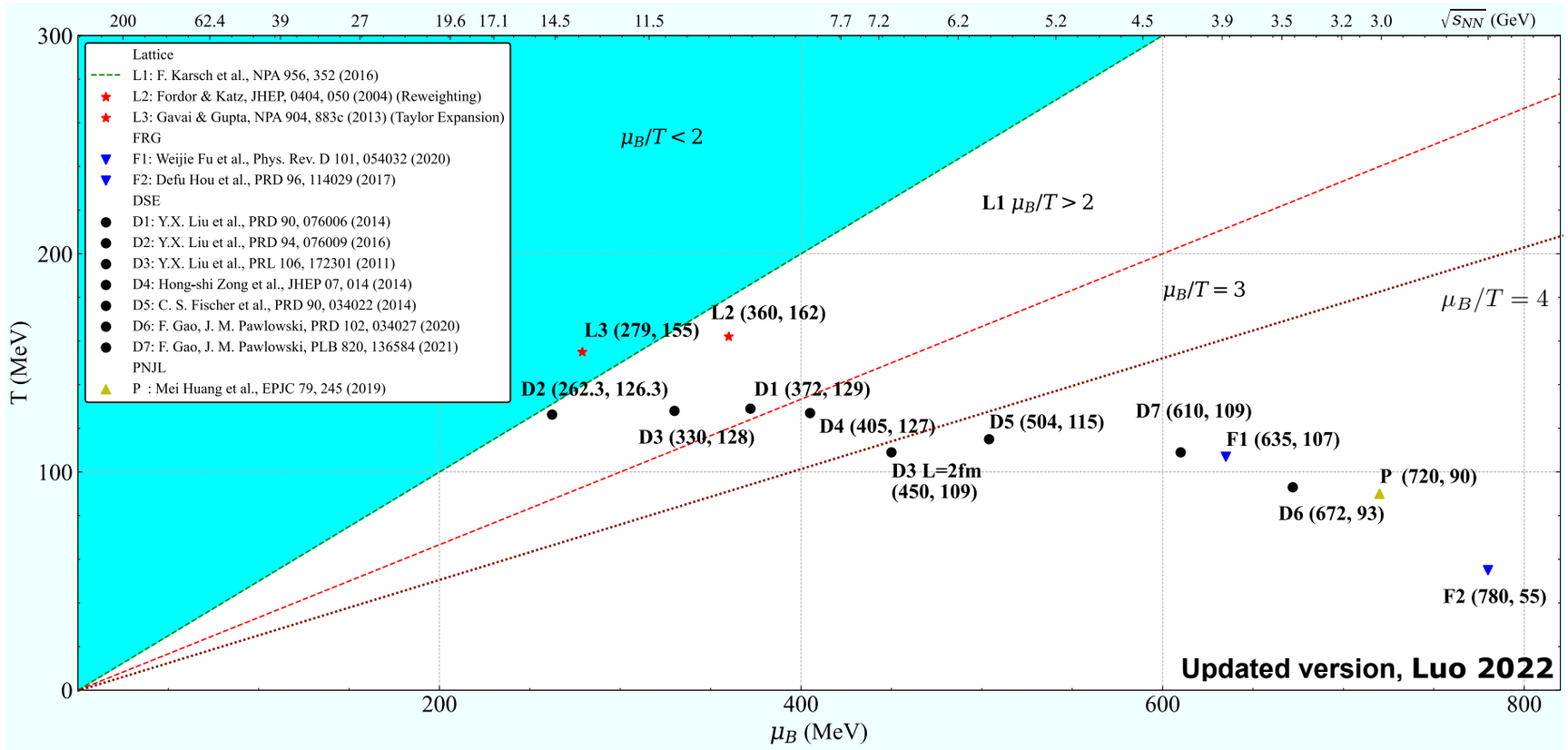

Large uncertainties for the estimation of CP location.

Remove CEP-predictions

(i) 'old' CEPs: lattice, Functional QCD approaches, LEFTS (updated computations available)

(ii) LEFTs & Functional Results (qualitative approximations) that miss lattice benchmarks at μ_B=0

(iii) LEFTs with CEPs at large density (missing quark-gluon back reaction)

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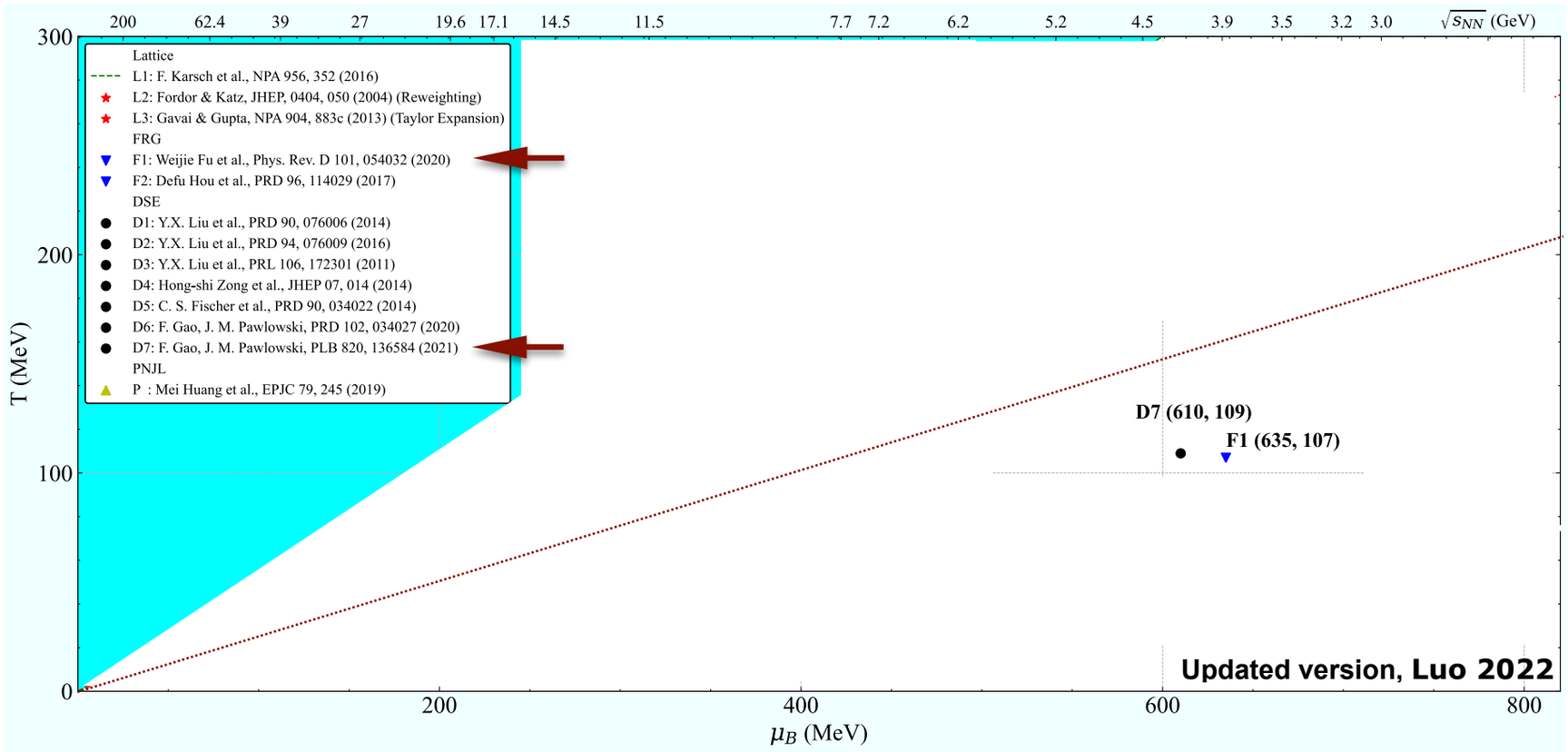

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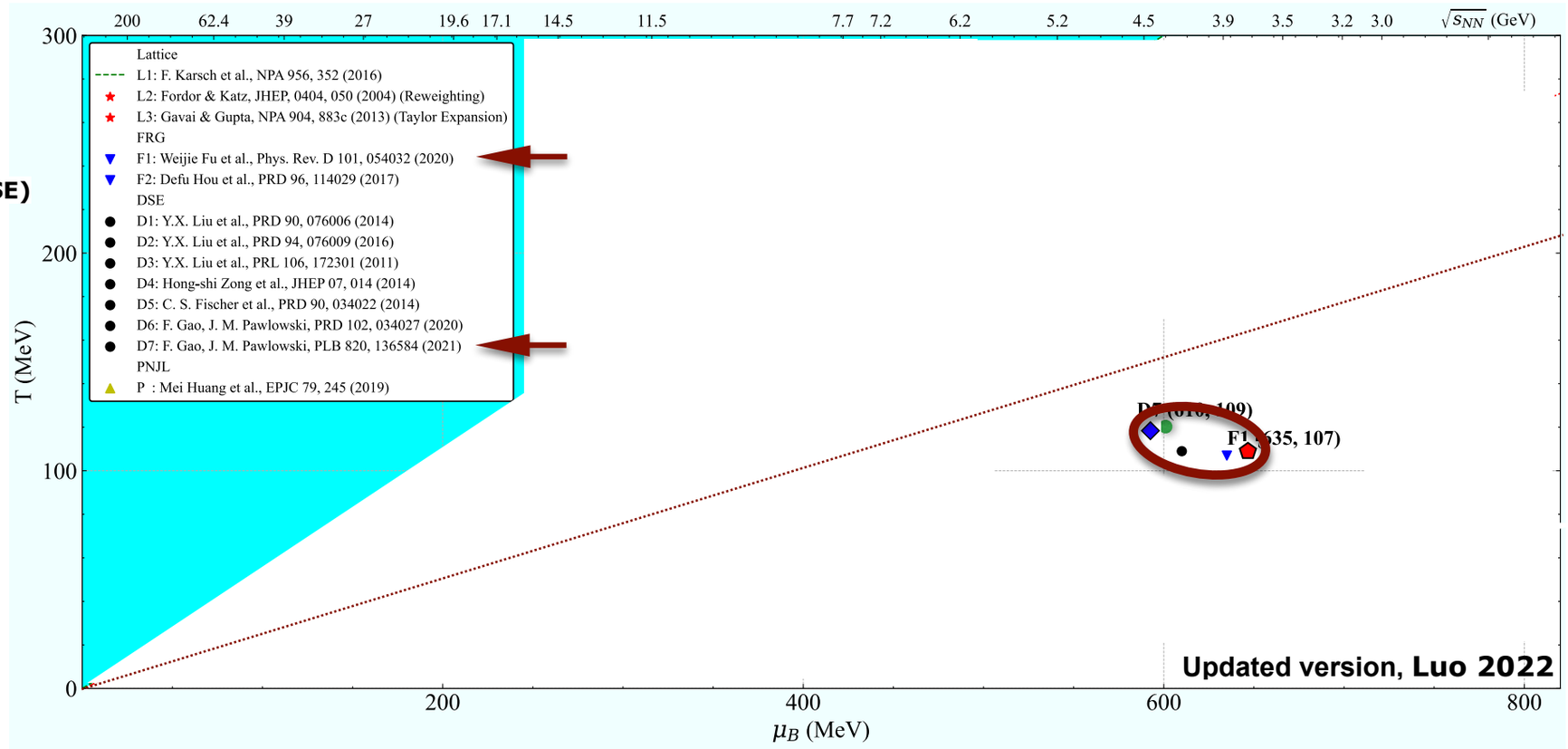
Gao, JMP, Schneider, in prep (DSE)

Fu, JMP, Rennecke, Wen, Yin, in prep (fRG)

Gunkel, Fischer, PRD 104 (2021) 054022 (DSE)



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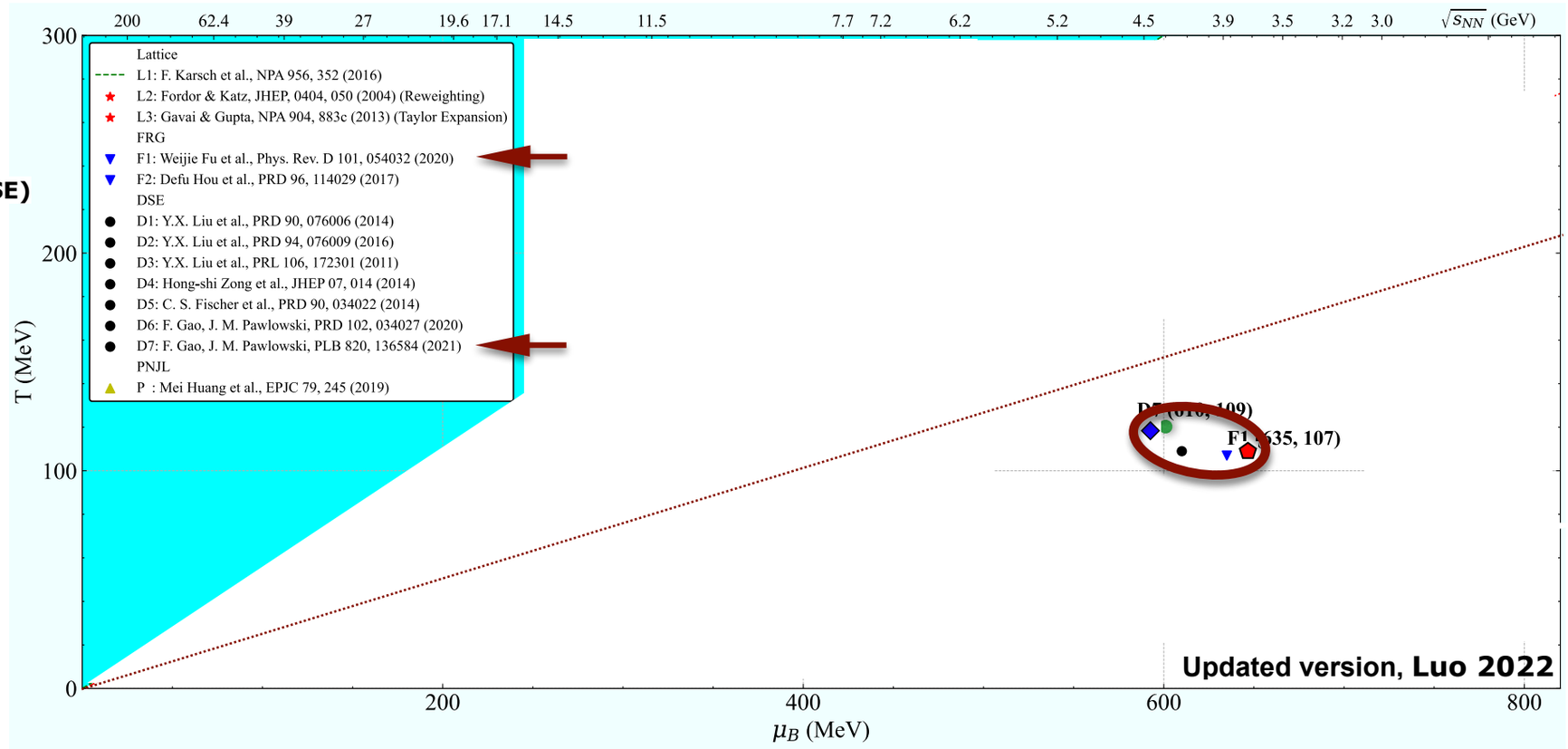

Still uncertainties for the estimation of CP location.

Remove CEP-predictions

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Outline

- QCD phase structure: Where do we stand?

- Chiral dynamics

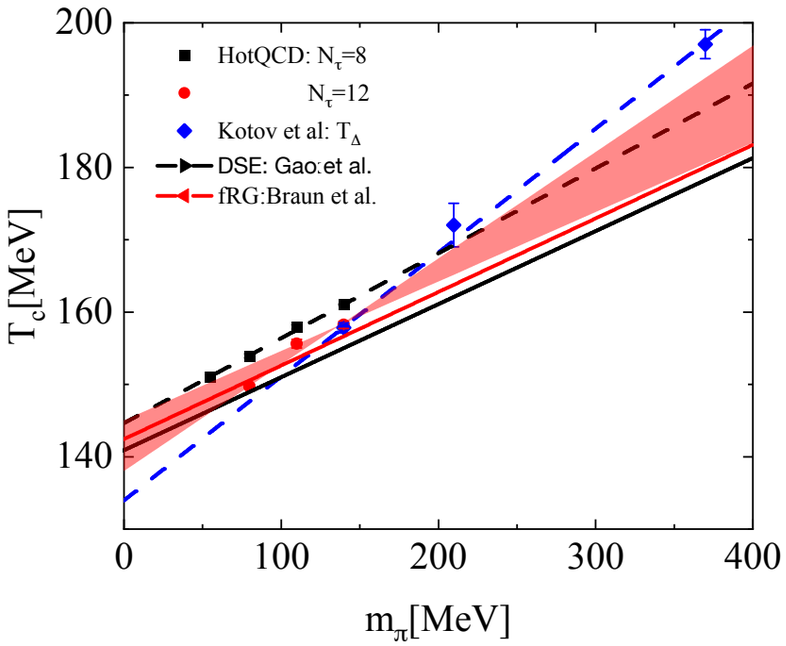
- Fluctuations of conserved charges

- Summary & outlook

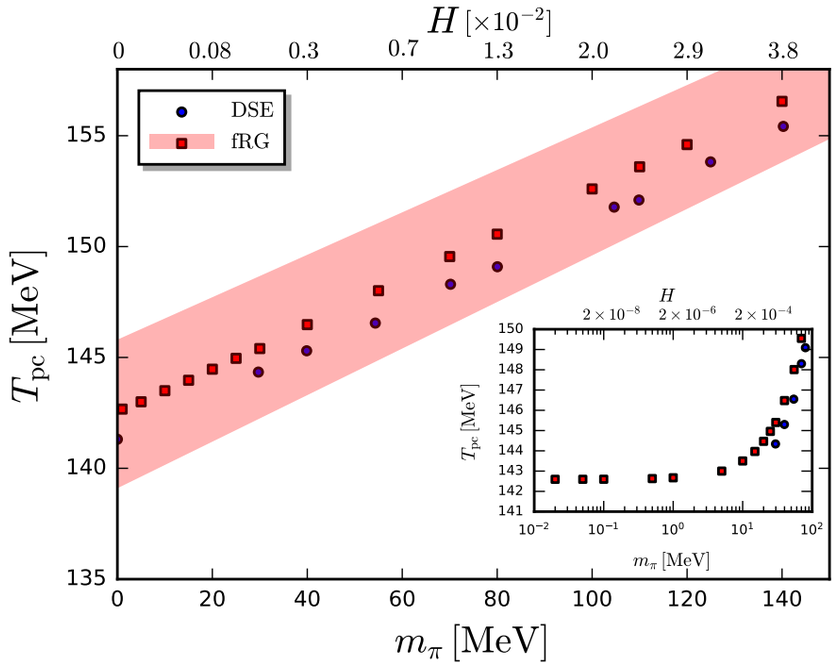
To be (critical) or not (to be)

fQCD

Chiral transition temperature

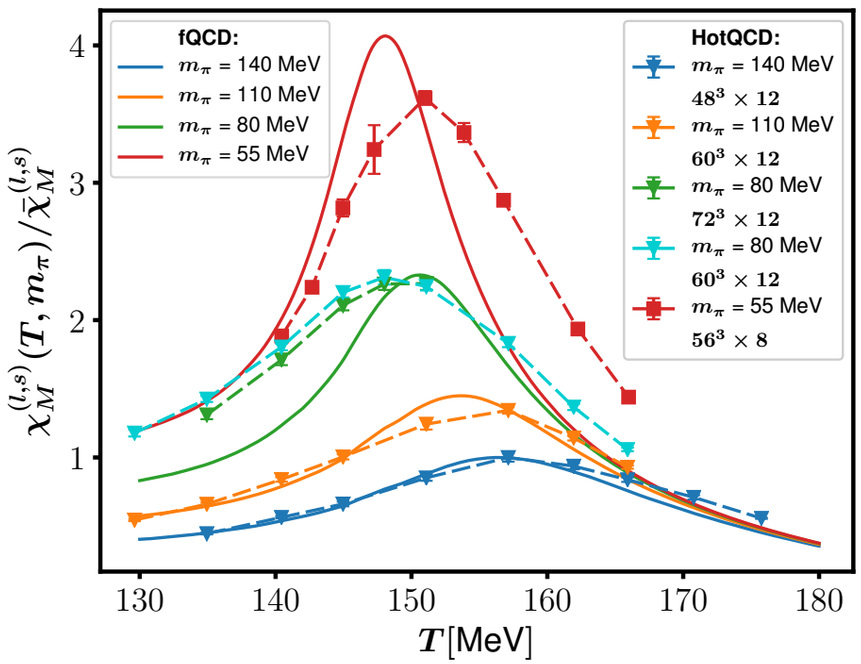


$$H = \frac{m_l}{m_s}$$



fQCD collaboration, in preparation

Magnetic susceptibility



Braun, Fu, JMP, Rennecke, Rosenblüh, Yin, PRD 102 (2020) 056010

Gao, JMP, PRD 105 (2022) 094020

To be (critical) or not (to be)

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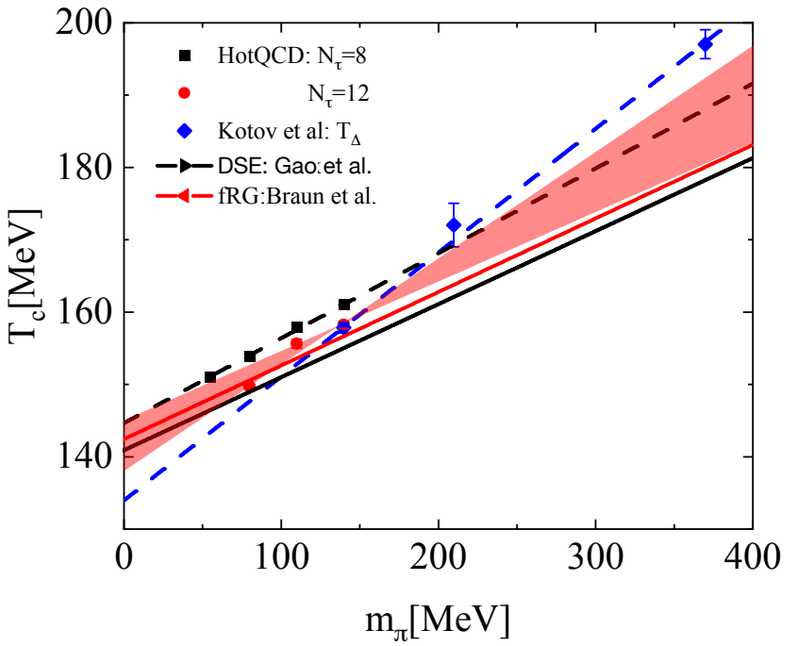

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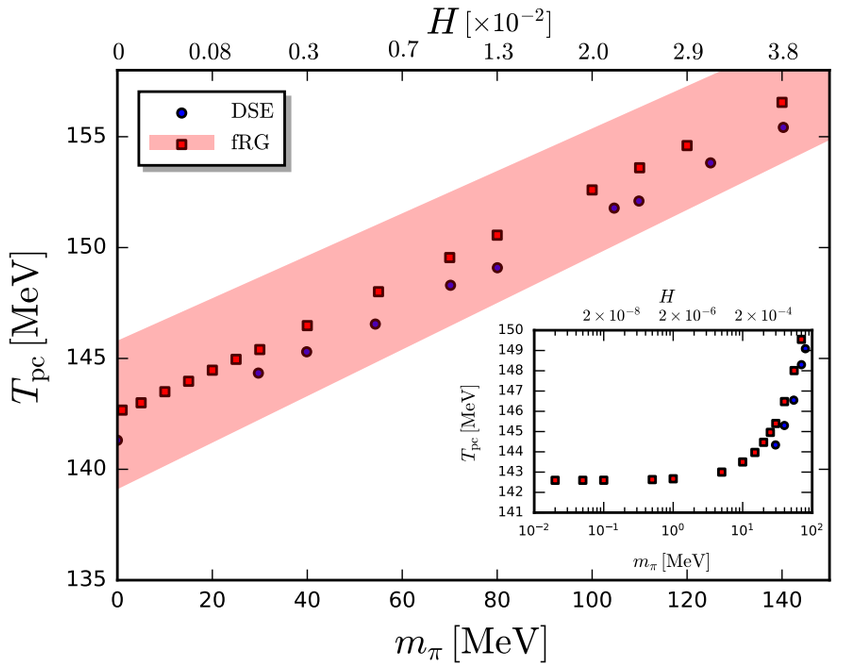
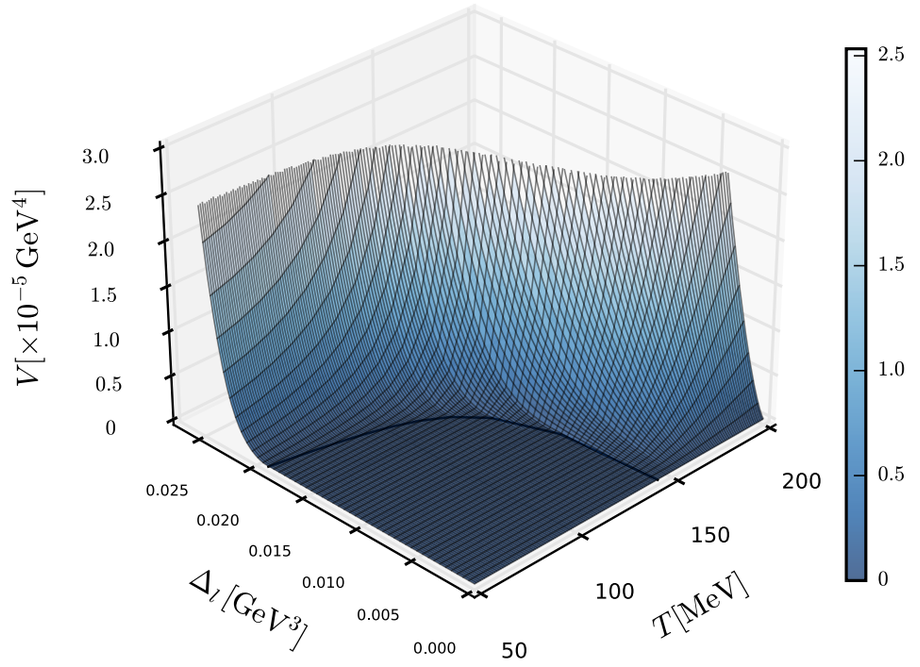


fQCD collaboration, in preparation $V_\chi^{(\mathrm{fRG})} \approx V_\chi^{(\mathrm{DSE})}$

Order parameter potential & scaling

$$V_\chi \approx \Delta_l^n \quad \Longleftrightarrow \quad \Delta_l(H) \propto H^{\frac{1}{n-1}}$$

(Critical) exponent: $\dfrac{1}{\delta} = \dfrac{1}{n-1}$



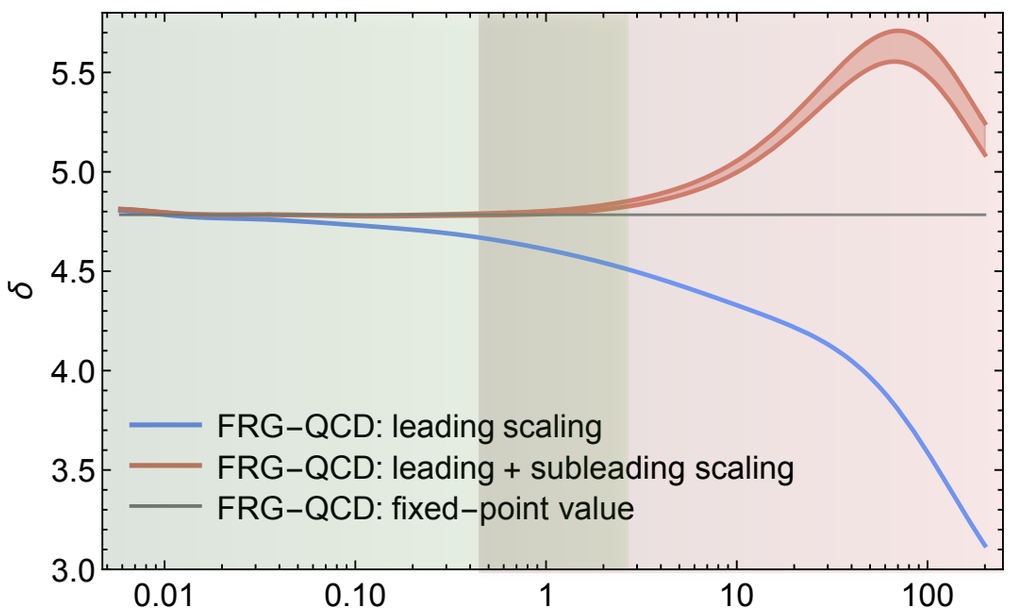
Braun, Fu, JMP, Rennecke, Rosenblüh, Yin, PRD 102 (2020) 056010

Gao, JMP, PRD 105 (2022) 094020

Chiral dynamics & quasi-massless modes

Critical O(4) scaling

Scaling coefficient as function of the pion mass



$$\Delta_l(m_\pi) \propto m_\pi^{2/\delta}\left[1 + a_m m_\pi^{2\theta_H} + \cdots\right]$$

'chiral scaling'

Trivial $\Delta_l^{1+\delta}$ scaling

fQCD collaboration, in preparation

QM: Chen, Wen, WF, PRD 104 (2021) 054009

Chiral dynamics & quasi-massless modes

fQCD

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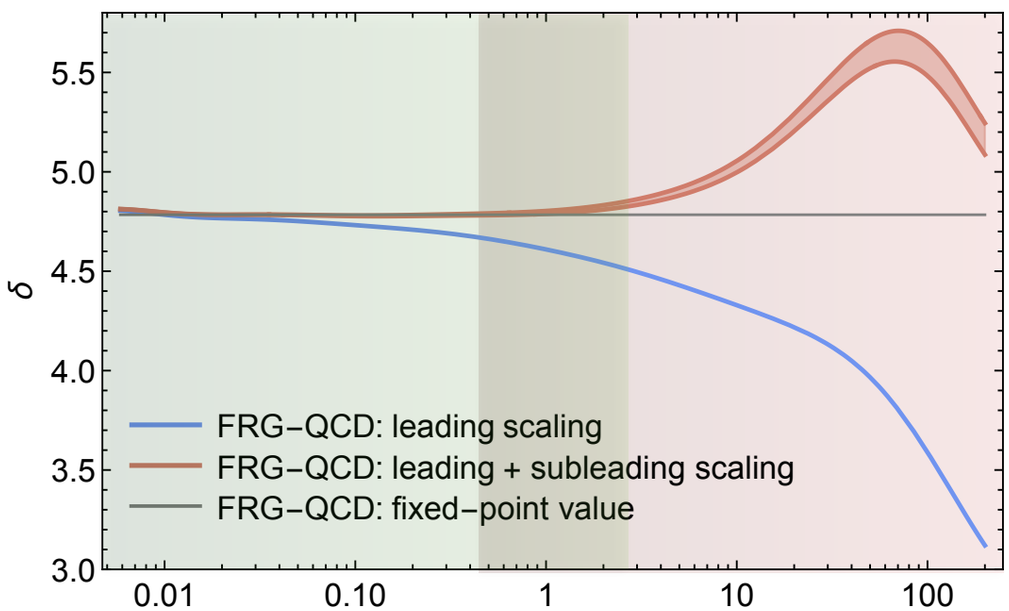

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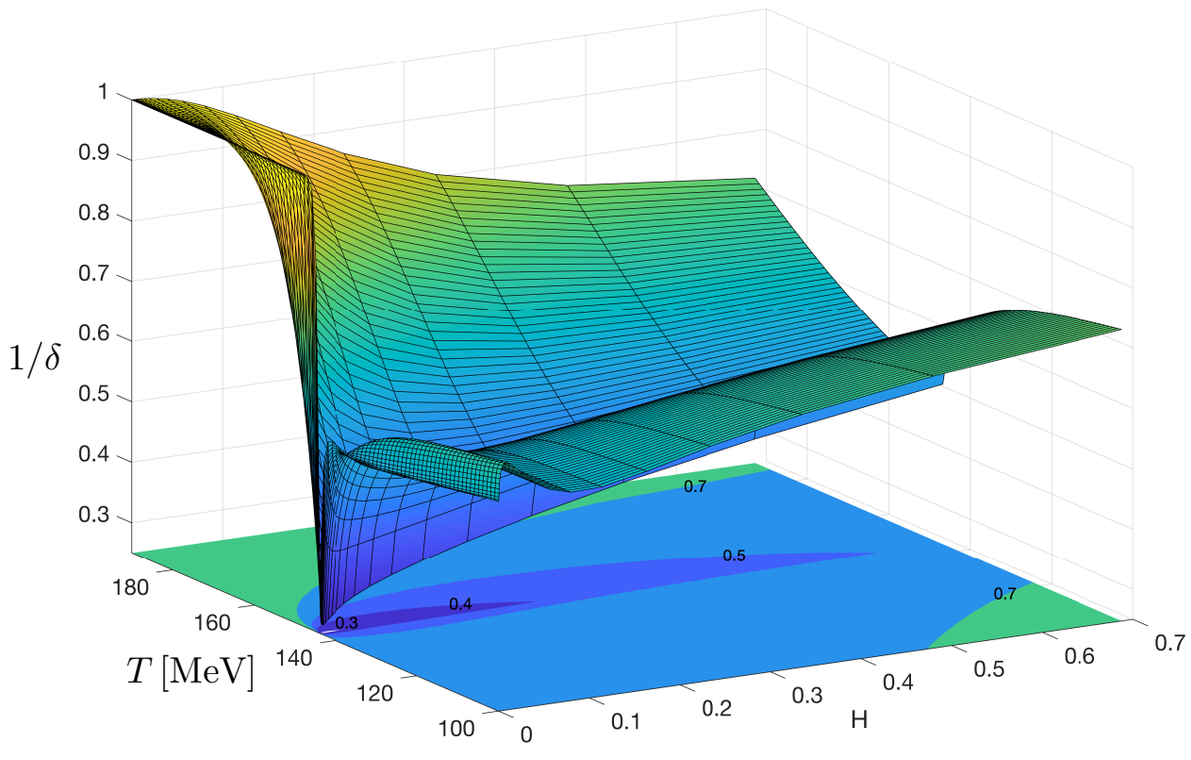

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fQCD collaboration, in preparation

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Small chiral scaling regime

↓

Small critical regime around pot. CEP

Chiral dynamics & quasi-massless modes

fQCD

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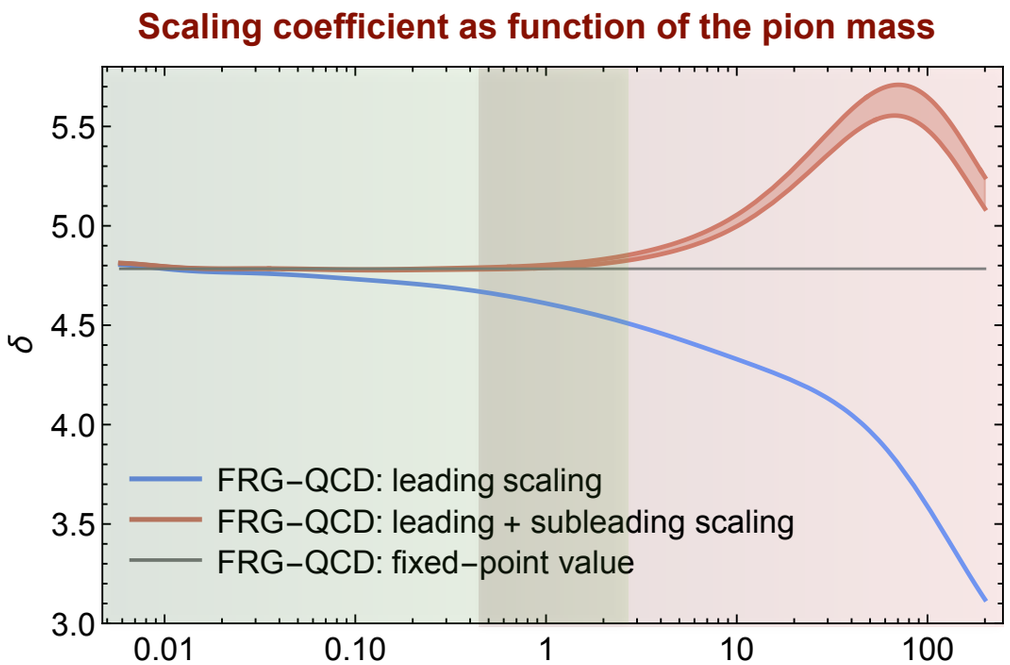

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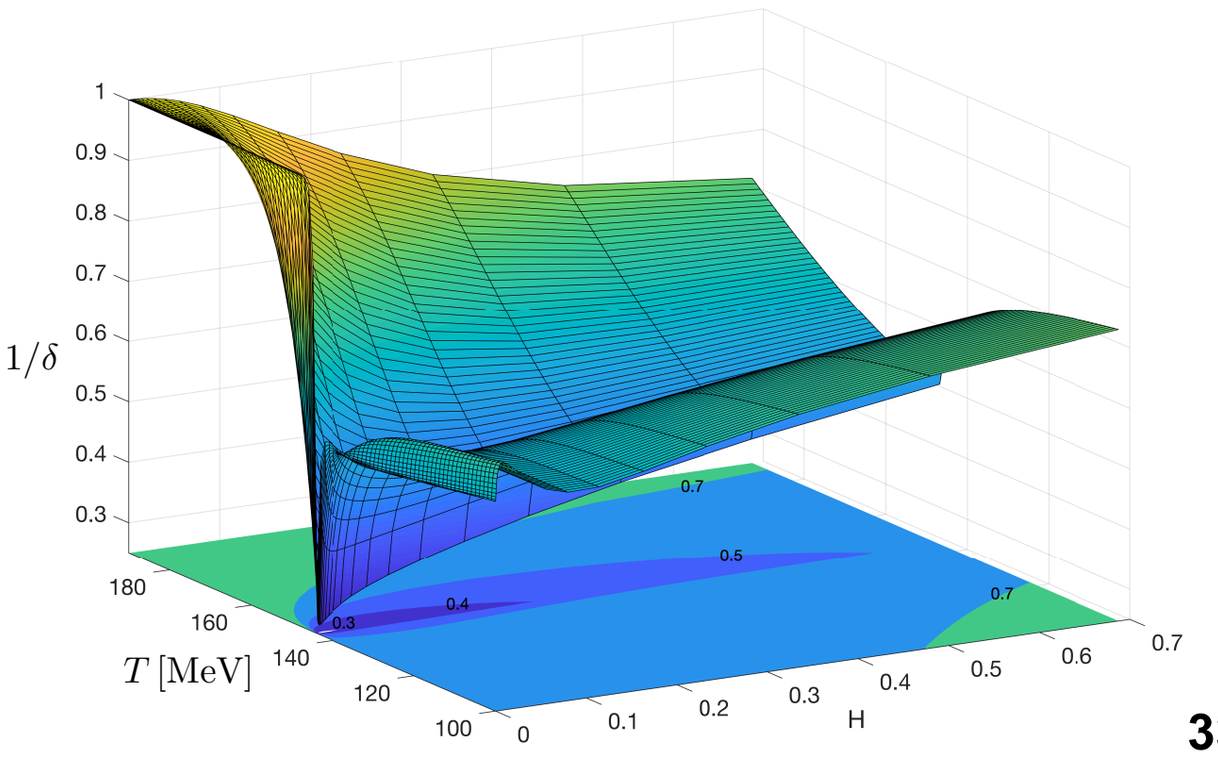

Small chiral scaling regime

↓

Small critical regime around pot. CEP

!!Great News!!

Location of CEP/New phase accessible via combination of precision measurements & computations

Chiral dynamics & quasi-massless modes

fQCD

Critical O(4) scaling

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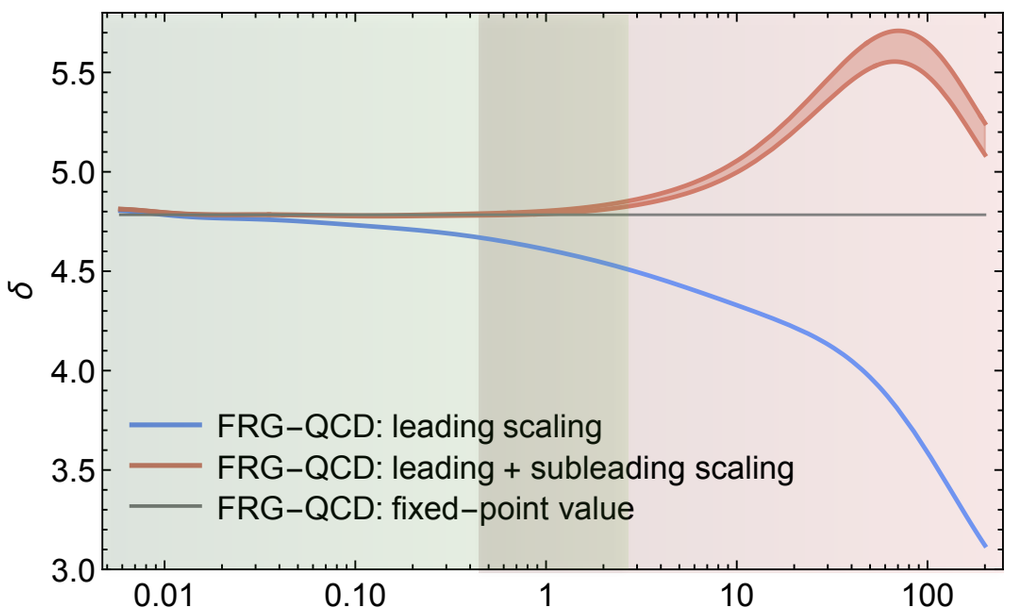

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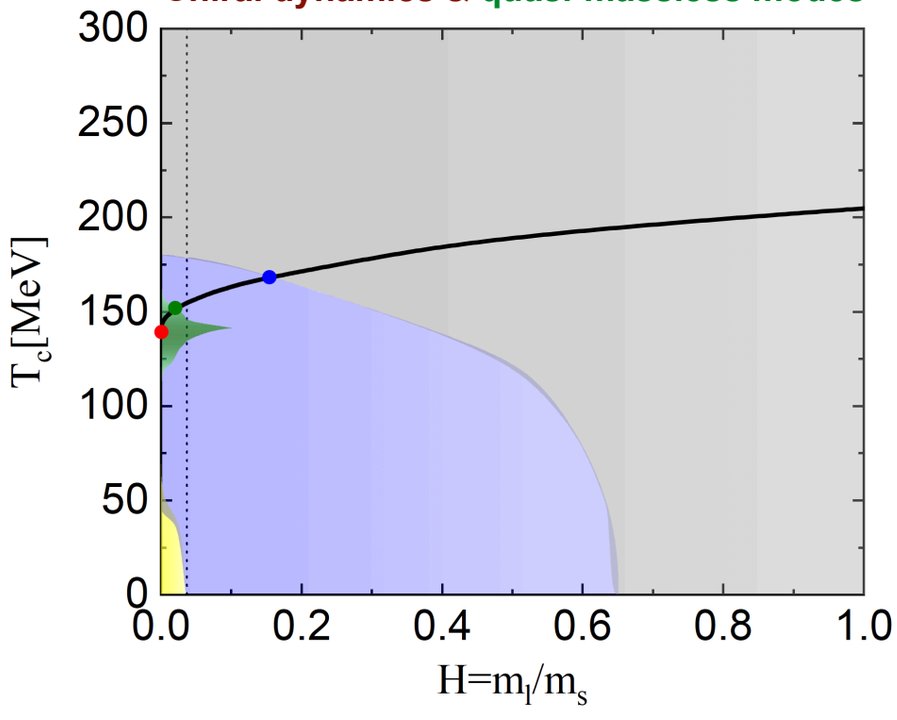
fQCD collaboration, in preparation

QM: Chen, Wen, WF, PRD 104 (2021) 054009

Chiral dynamics & quasi-massless modes

Critical scaling



Gao, JMP, PRD 105 (2022) 094020

'Non-critical chiral scaling'

Far away from the critical regime for $m_\pi \gtrsim 1\,\mathrm{MeV}$

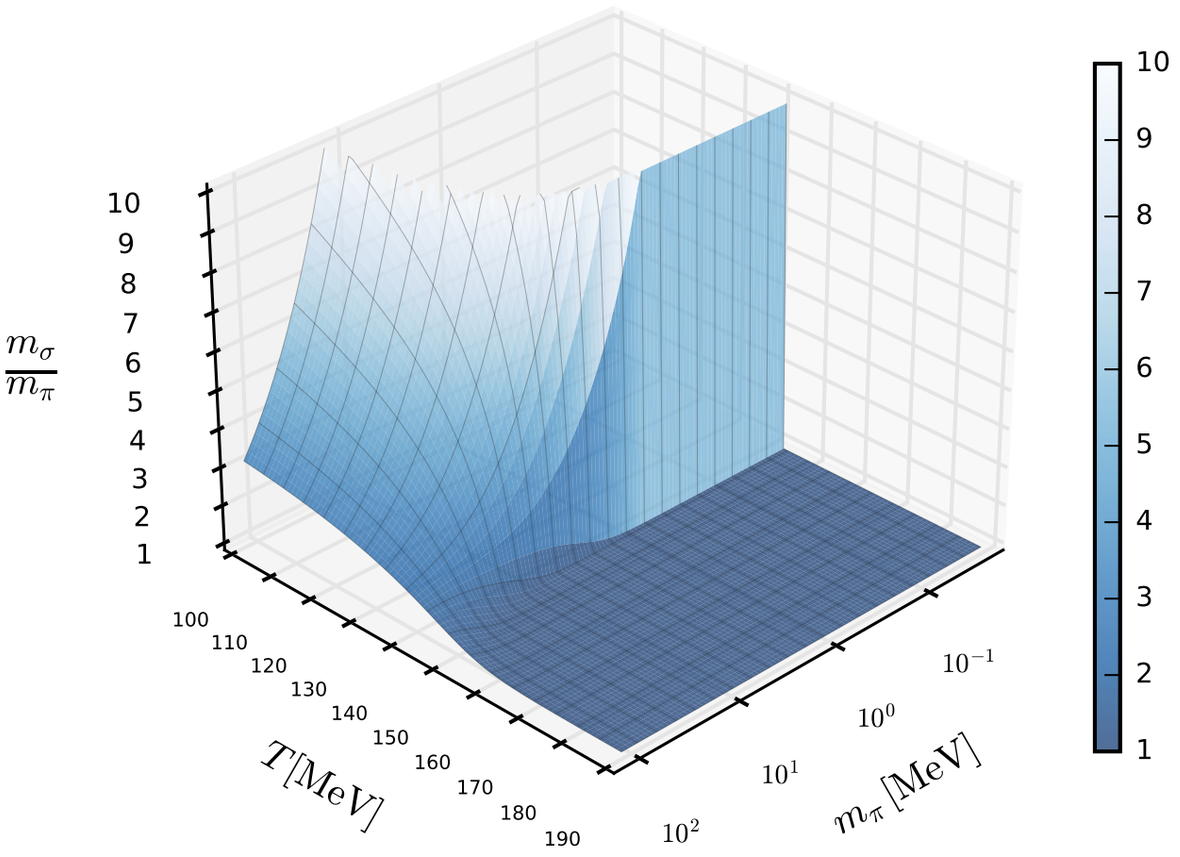
$$\Delta_l(T,H) \approx \Delta_{l,\chi}(0)\left(c_0 + c_{\frac{1}{5}} H^{\frac{1}{5}} + c_{\frac{1}{3}} H^{\frac{1}{3}} + c_1 H\right)$$

$$V_\chi(\Delta_l) \propto \quad \Delta_l^6 \quad \Delta_l^4 \quad \Delta_l^2$$

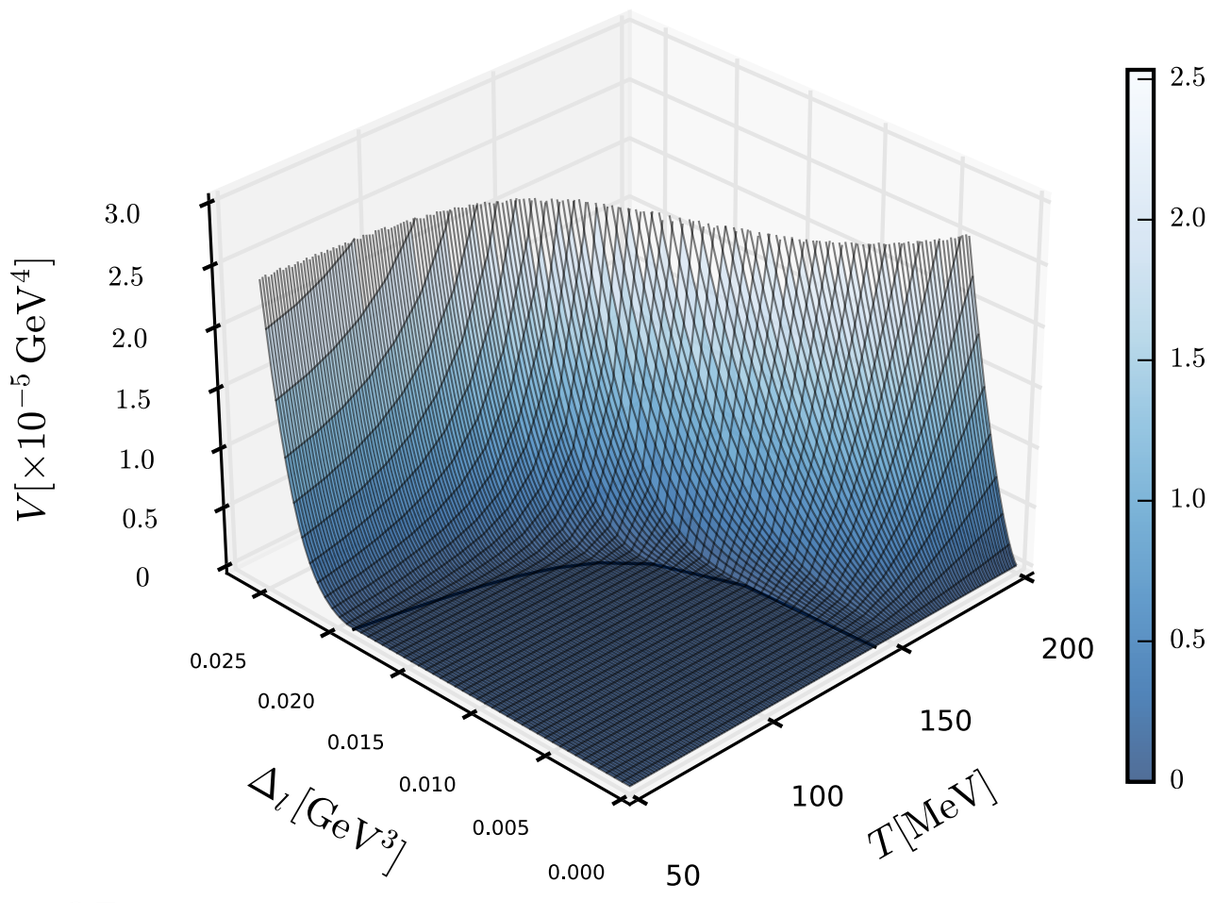
Chiral dynamics & quasi-massless modes

fQCD

Measure: correlation length



Use for chiral dynamics in heavy ion collisions



QCD: fQCD collaboration, in preparation

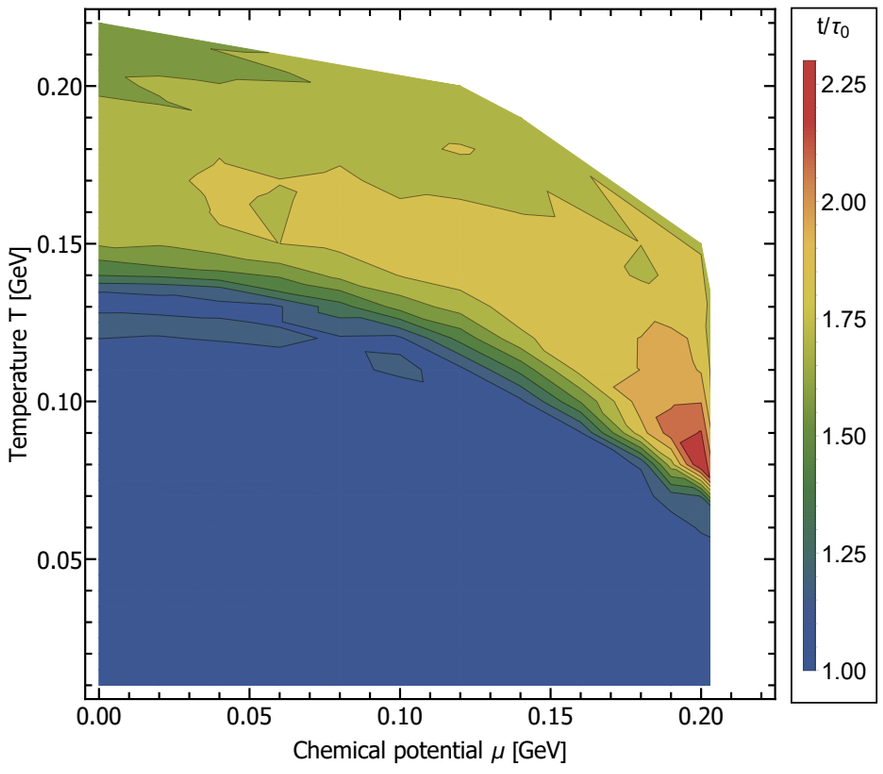
Dynamics and the size of the critical regime

fQCD

Showcases in linear sigma models

Transport with fRG spectral functions & effective potential

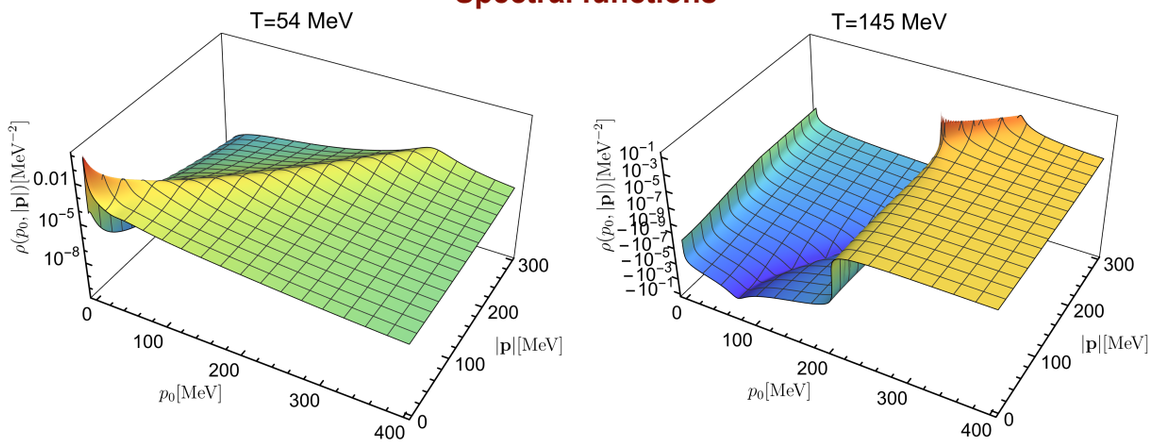
Equilibration time of sigma-kurtosis



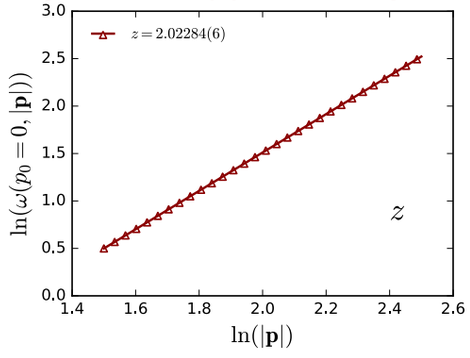
Blum, Jiang, Nahrgang, JMP, Rennecke, Wink, NPA 982 (2019) 871

Dynamical universality

Spectral functions



Dynamical O(4) critical exponent



$$\omega \propto \left(\vec{p}^{\,2}\right)^{\frac{z}{2}}$$

Tan, Chen, Fu, SciPost Phys. 12 (2022) 026

QM: **Roth, Schweitzer, Rieke, von Smekal , PRD 105 (2022) 116017**

Outline

- QCD phase structure: Where do we stand?

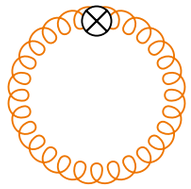
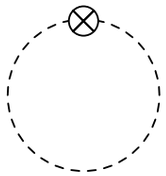
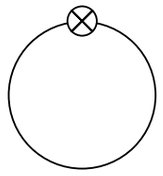
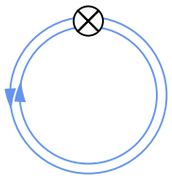
- Chiral dynamics

- Fluctuations of conserved charges

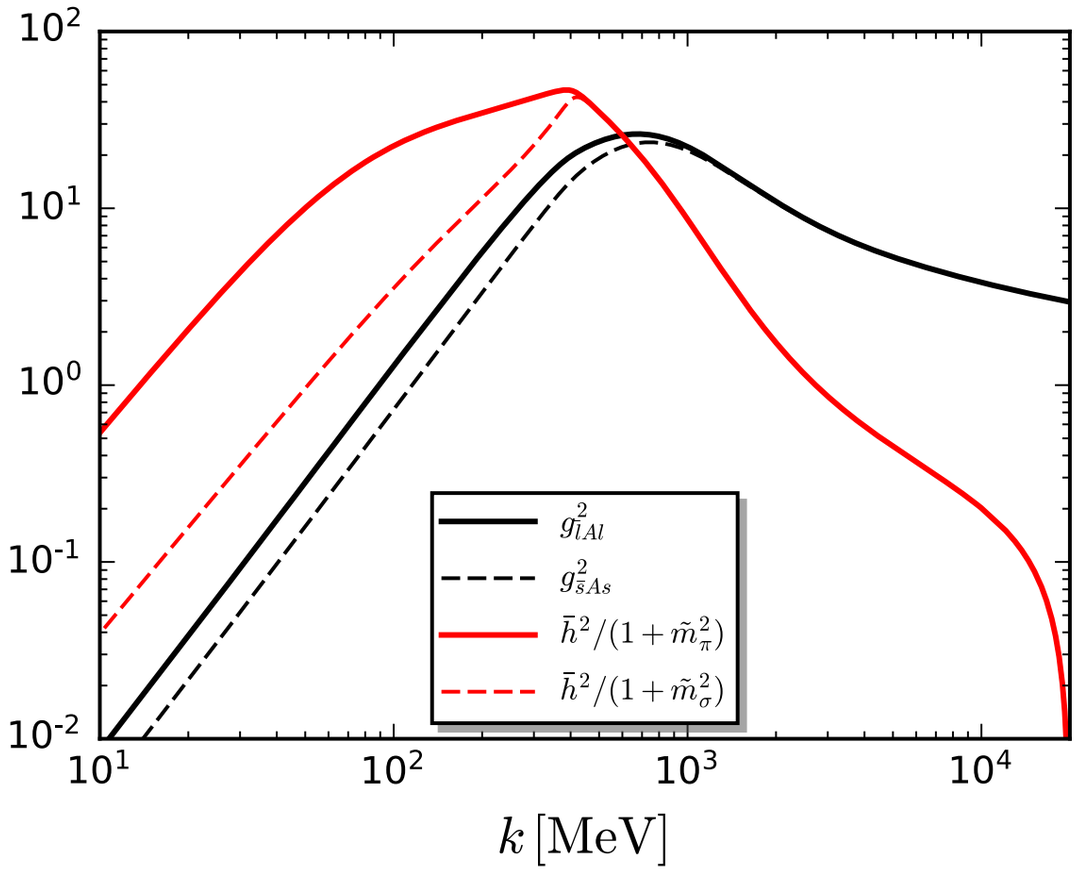
- Summary & outlook

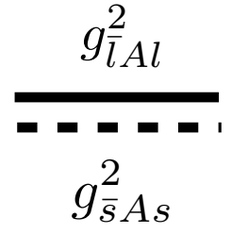
On the unreasonable effectiveness of low energy effective theories

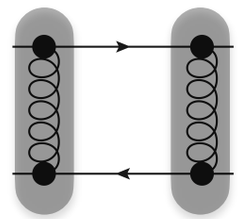
fQCD

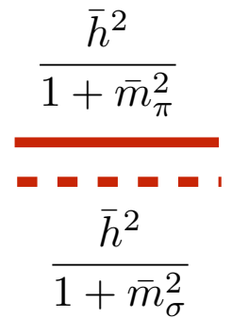
$$\partial_t \Gamma_k[\Phi] = \frac{1}{2}$$  $$-$$  $$-$$  $$+\frac{1}{2}$$ 

Sequential decoupling of gluon, quark, sigma, pion fluctuations









Fu, JMP, Rennecke, PRD 101, (2020) 054032

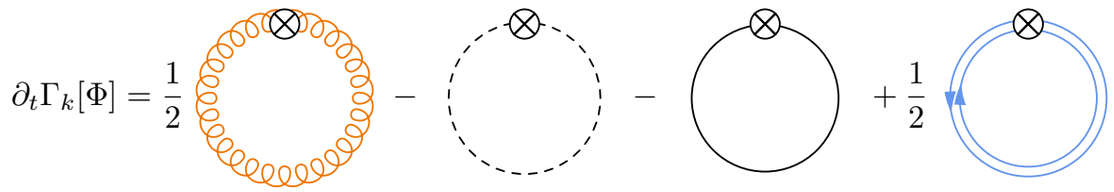
Based on:

Braun, Fister, Haas, JMP, Rennecke, PRD 94 (2016) 034016

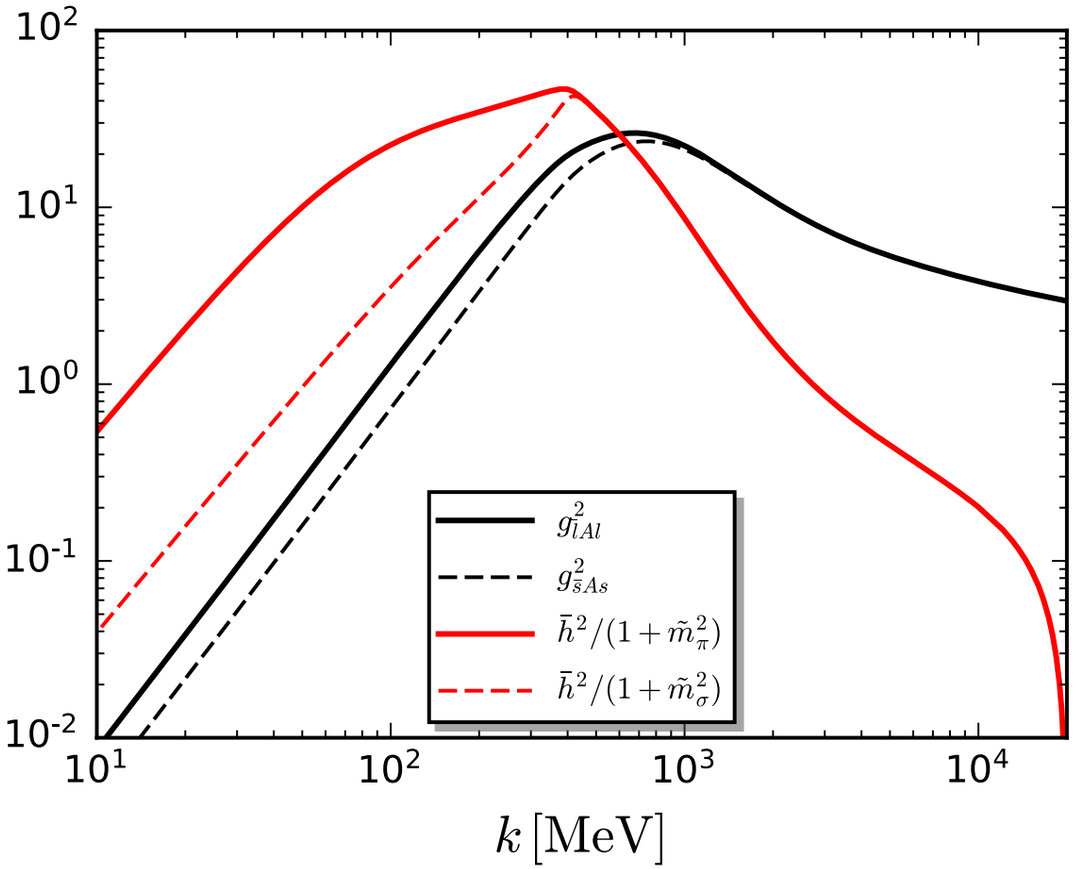
Rennecke, PRD 92 (2015) 076012

On the unreasonable effectiveness of low energy effective theories

fQCD



Sequential decoupling of gluon, quark, sigma, pion fluctuations

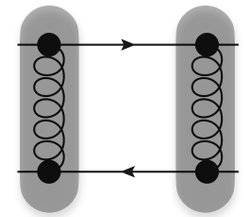


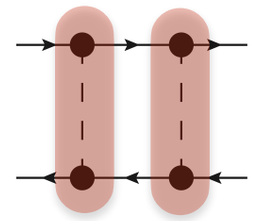
$g^2_{\bar{l}Al}$

$g^2_{\bar{s}As}$

$\dfrac{\bar{h}^2}{1+\bar{m}^2_\pi}$

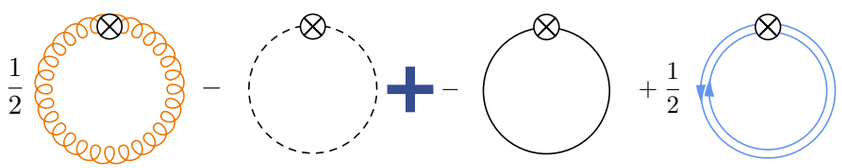
$\dfrac{\bar{h}^2}{1+\bar{m}^2_\sigma}$



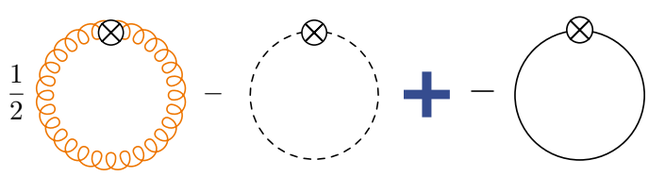


Fu, JMP, Rennecke, PRD 101, (2020) 054032

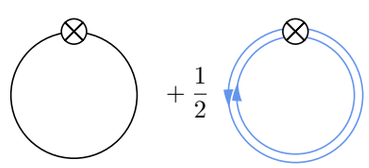
PQM-model



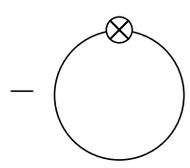
PNJL-model



QM-model



NJL-model



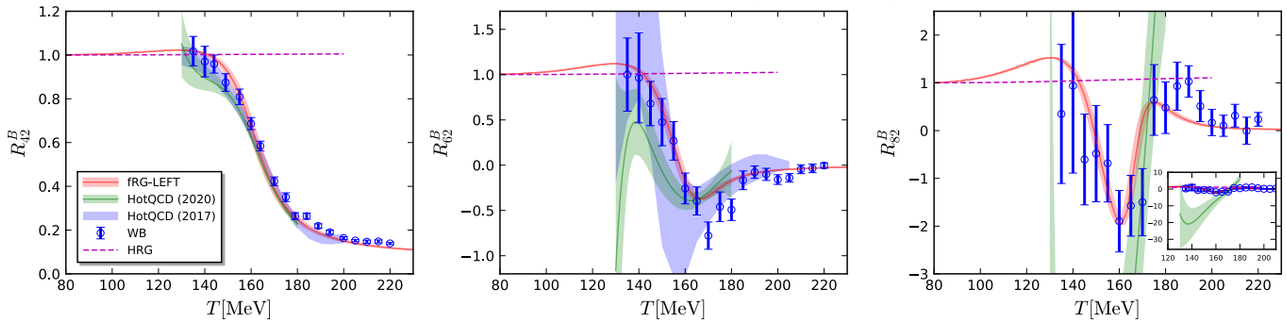
QCD-assisted low energy effective theories

Fluctuations of conserved charges

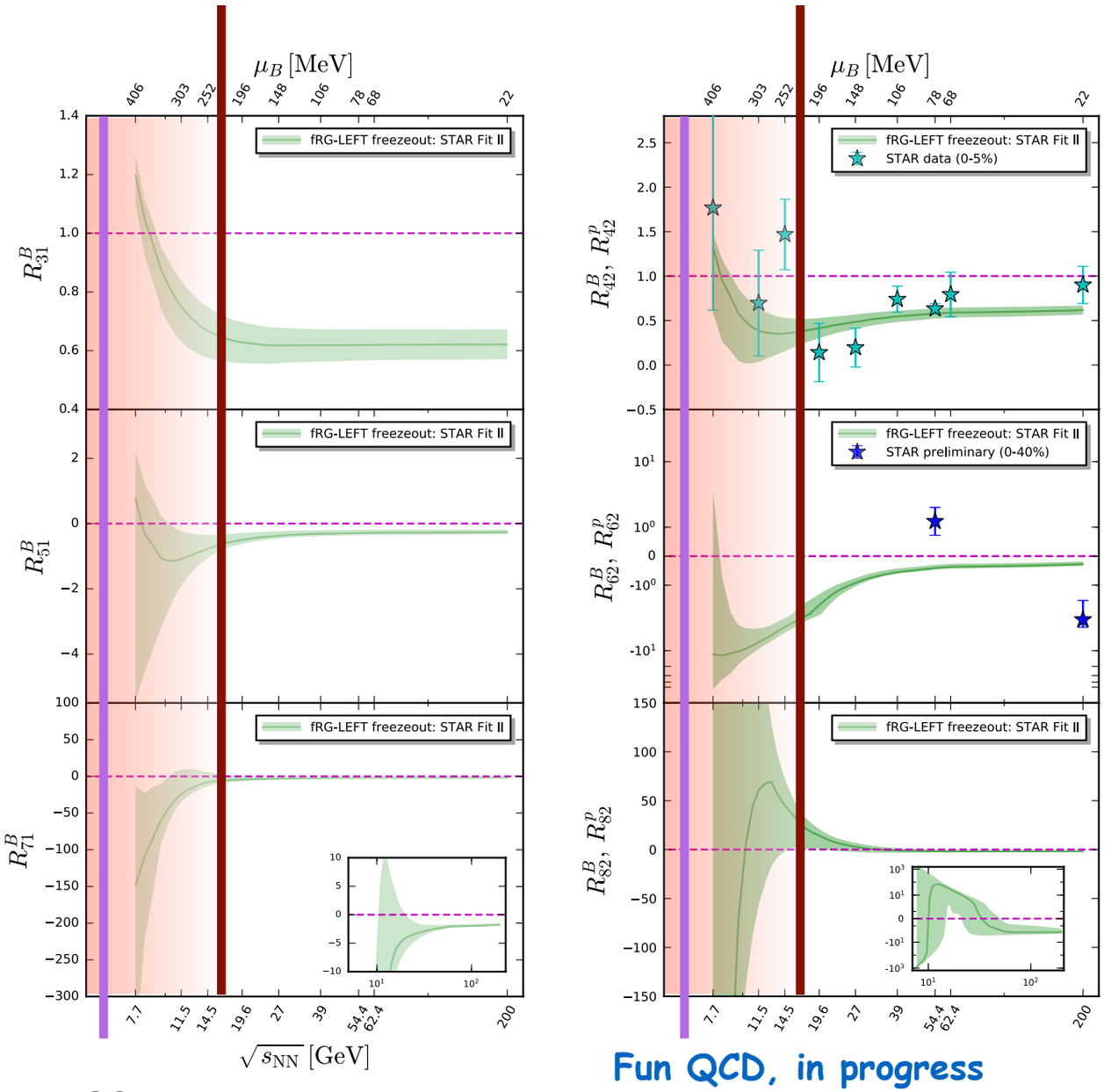
fQCD

QCD-assisted LEFT

Benchmark at vanishing density

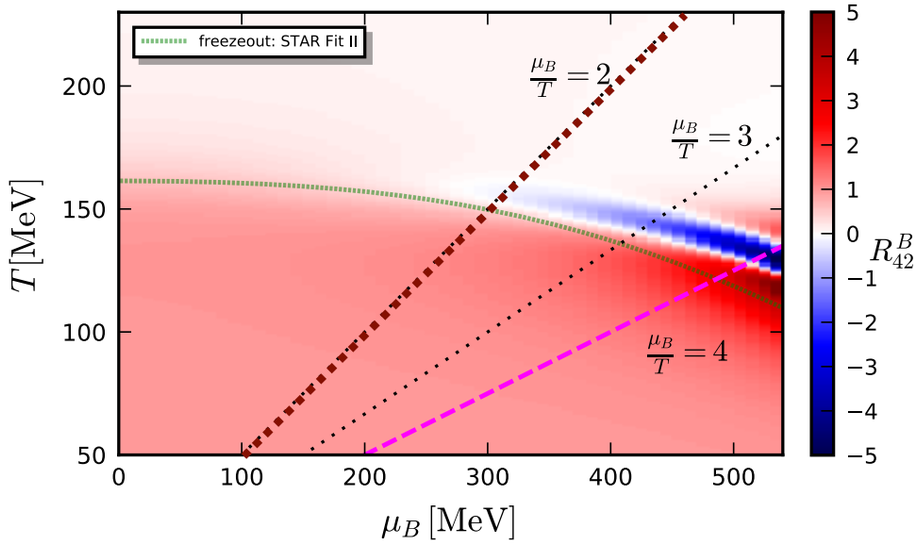


QCD-assisted LEFT



Fun QCD, in progress

Freezeout curve

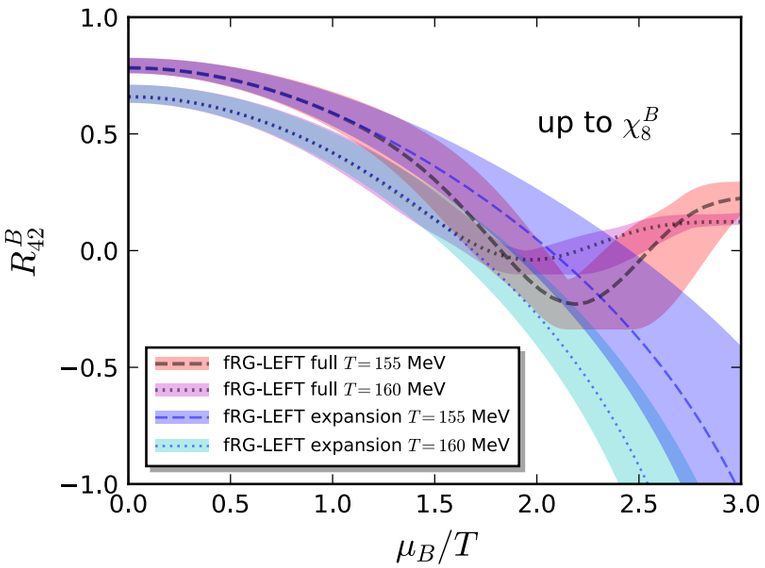


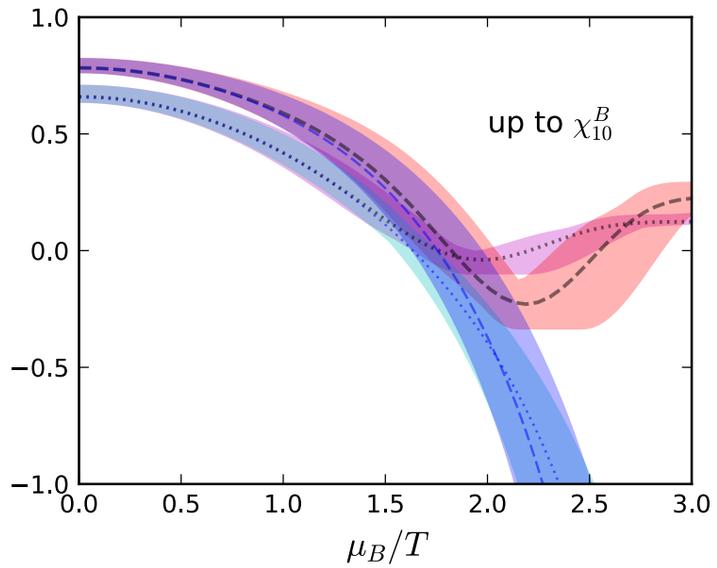
Great opportunity for a combined analysis of high density QCD (Exp. data + lattice QCD + functional QCD)

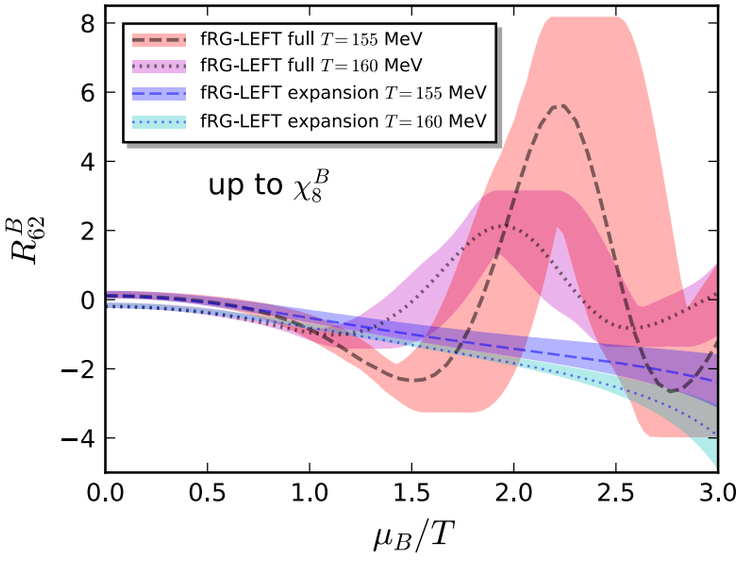
Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 104 (2021) 9

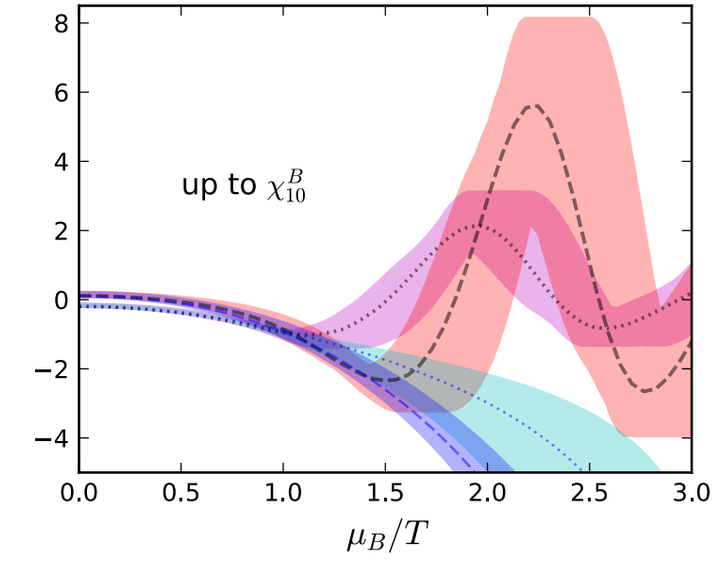
Fluctuations of conserved charges

Fluctuations of conserved charges









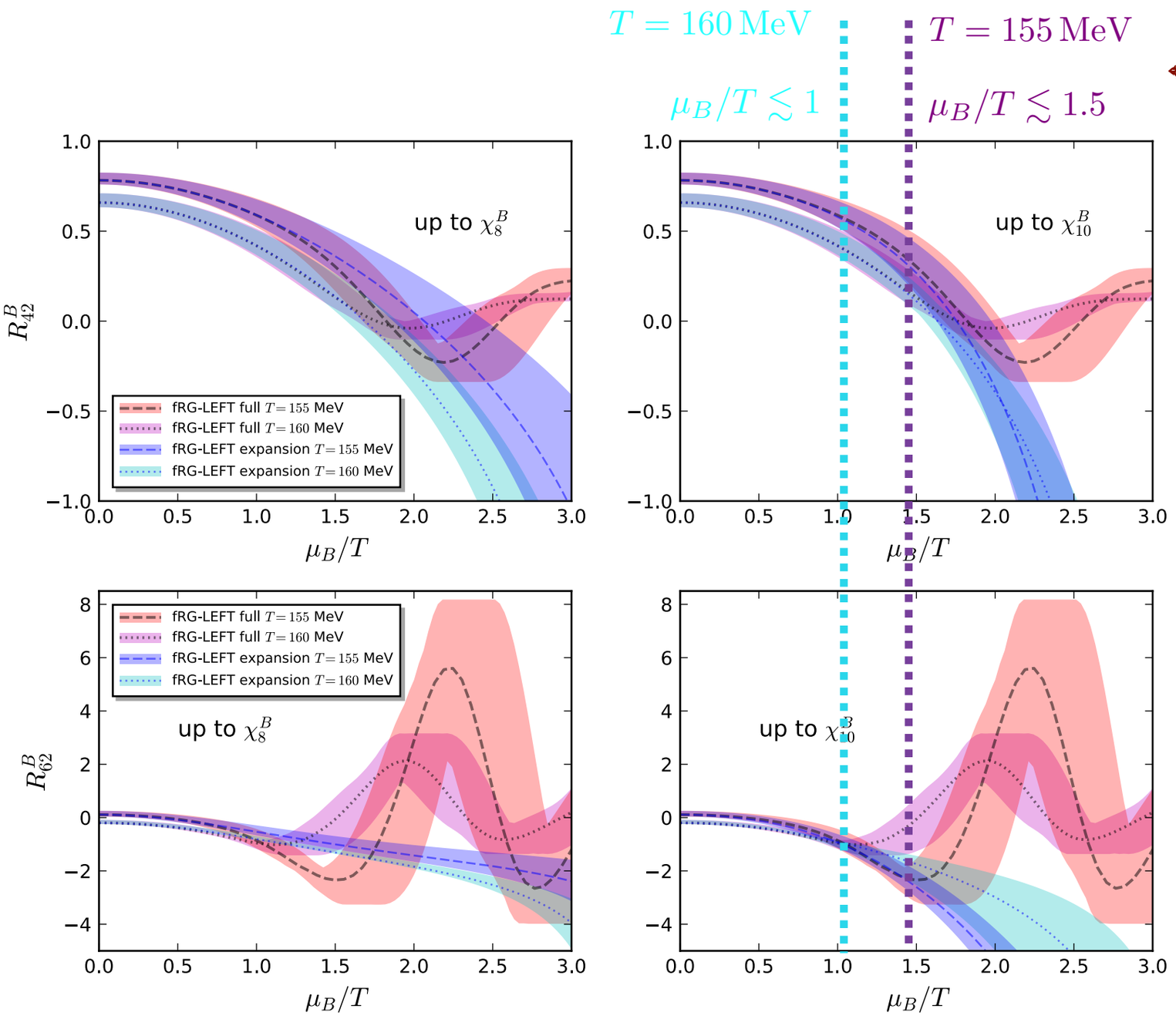
Unique: QCD-based analytic continuations that satisfy the lattice benchmarks at small chemical potential.

Great opportunity for a combined analysis of high density QCD (Exp. data + lattice QCD + functional QCD)

Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 104 (2021) 9

Fluctuations of conserved charges

Fluctuations of conserved charges



Validity of Taylor expansion

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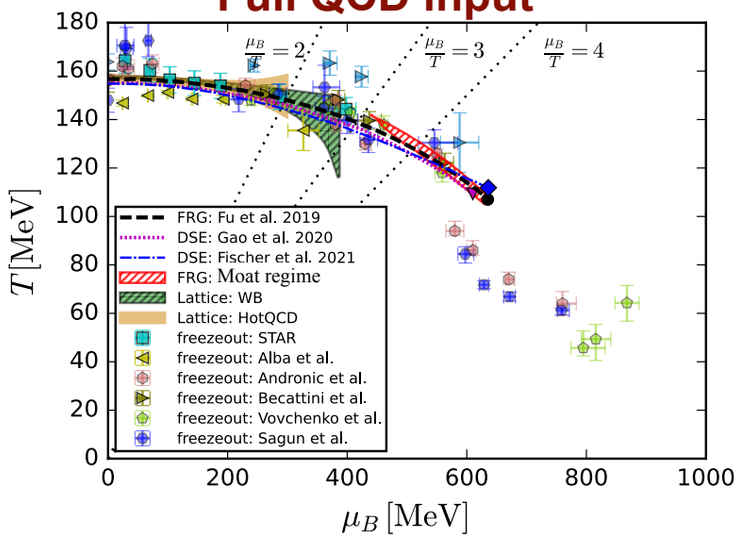
Fluctuations of conserved charges

fQCD

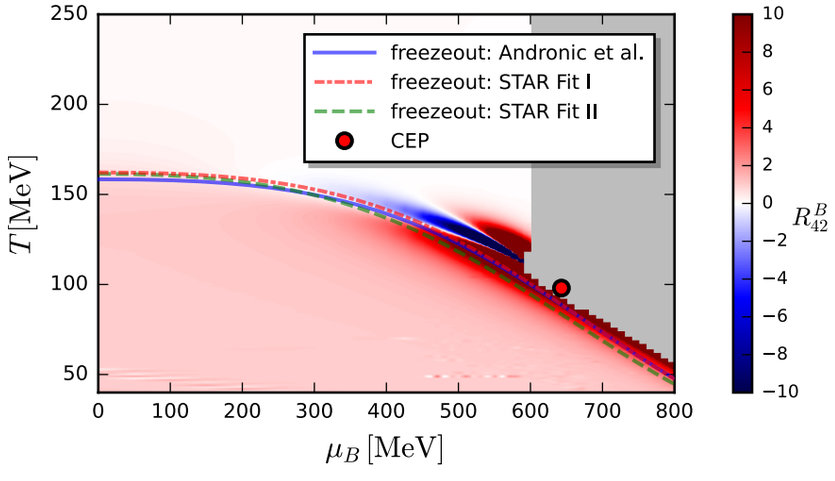
Sneak preview towards QCD

Full QCD input

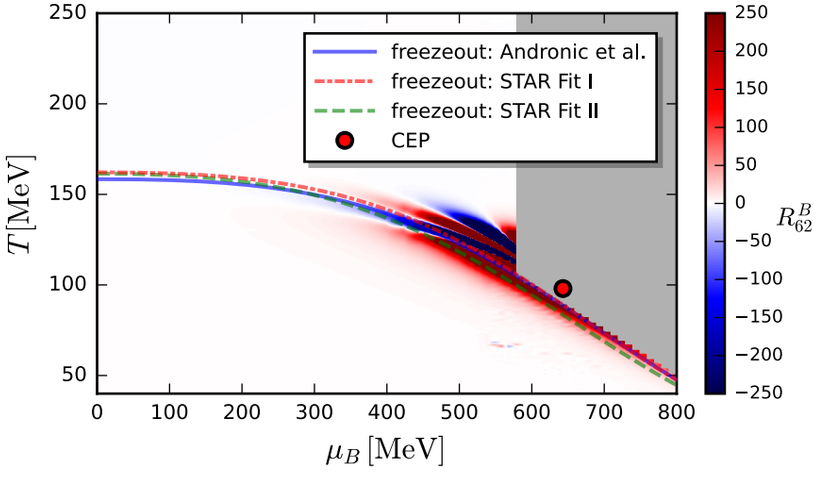


Towards QCD

'Use QCD flows for quark-meson couplings
in
low energy effective theory'



preliminary

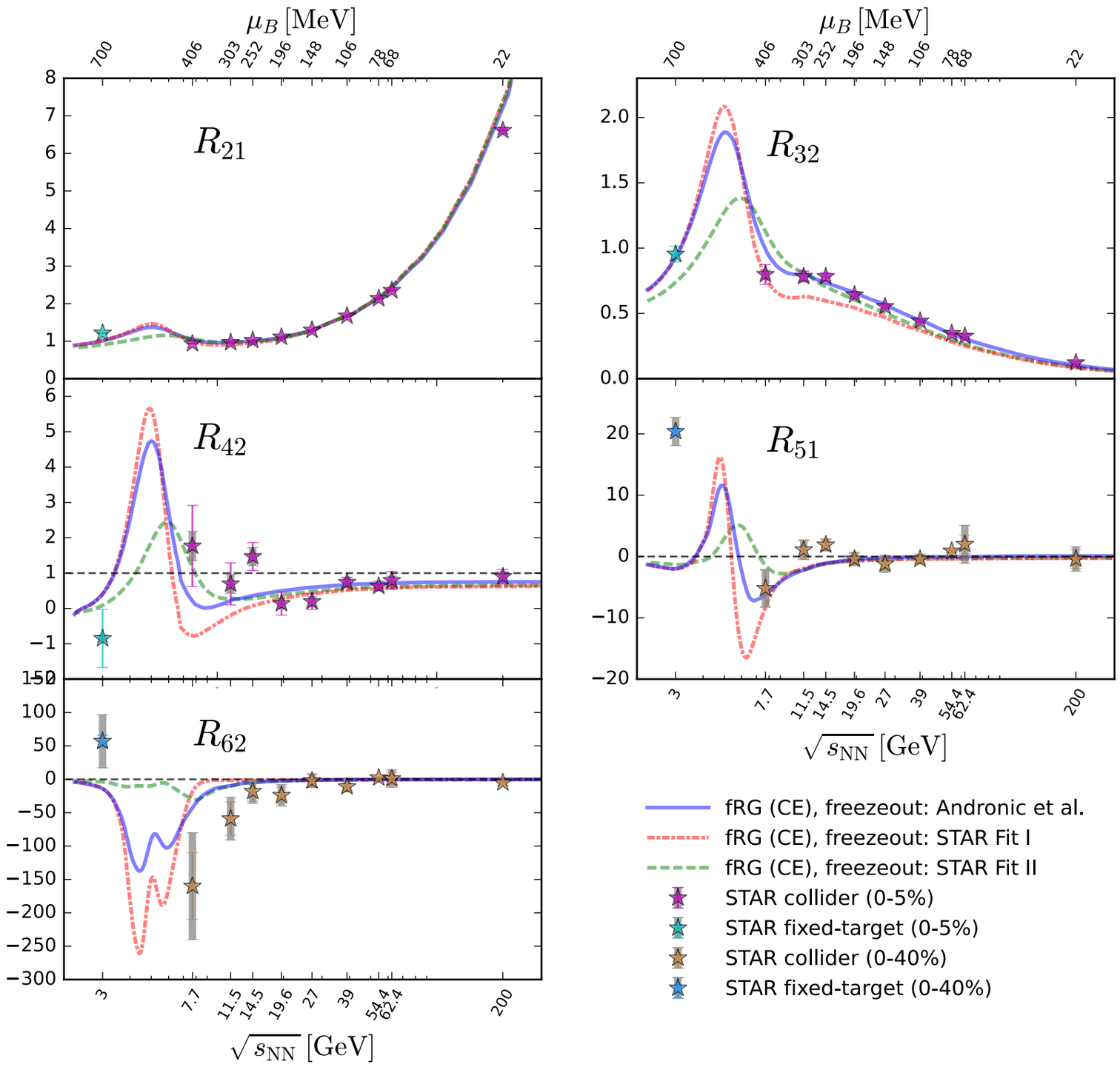


Fu, Luo, JMP, Rennecke, Yin, in preparation

Fluctuations of conserved charges

fQCD

Canonical ensemble



Fu, Luo, JMP, Rennecke, Yin, in preparation