Phase structure and dynamics of QCD at high densities

Jan M. Pawlowski

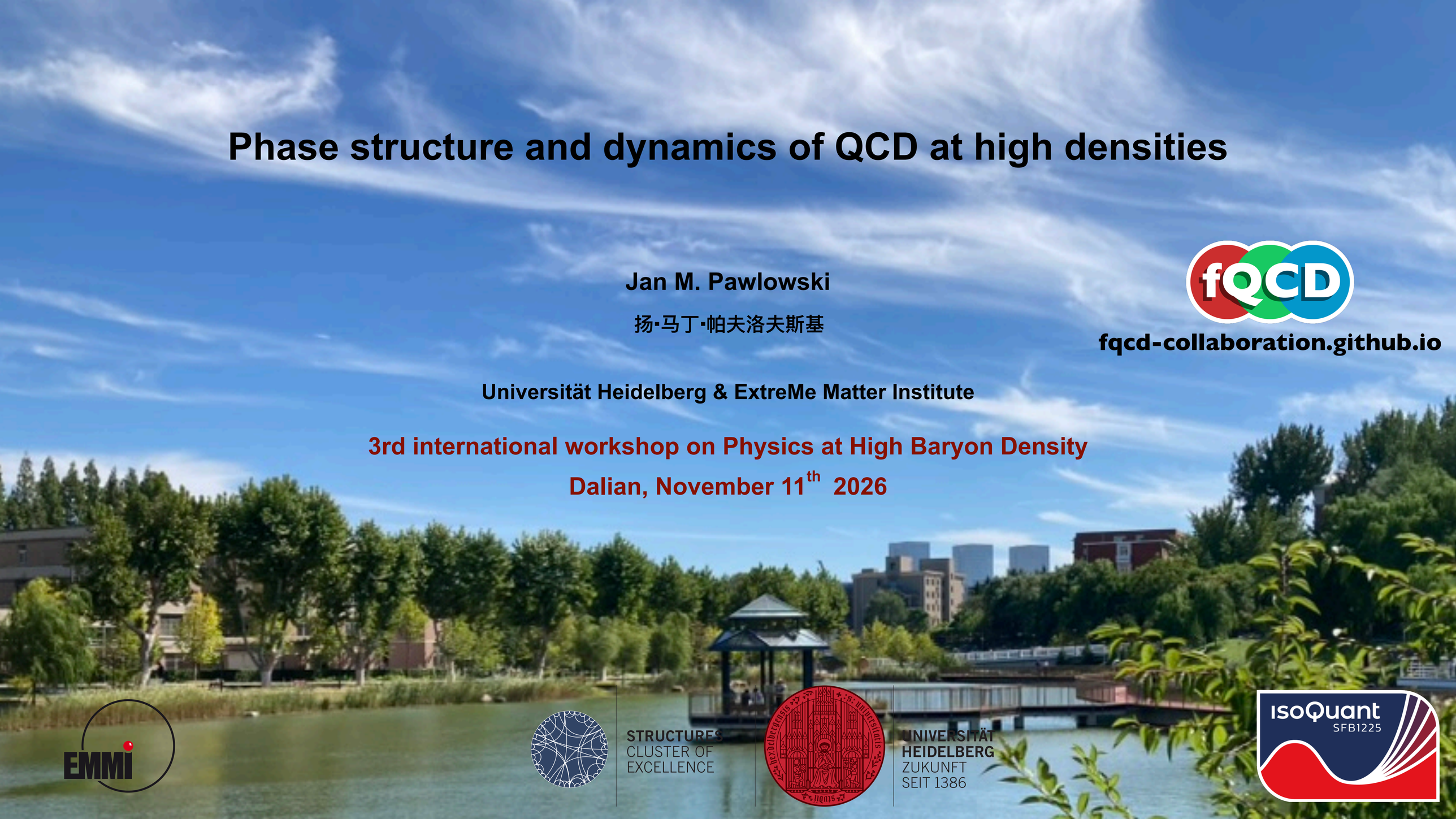
扬·马丁·帕夫洛夫斯基

Universität Heidelberg & ExtreMe Matter Institute

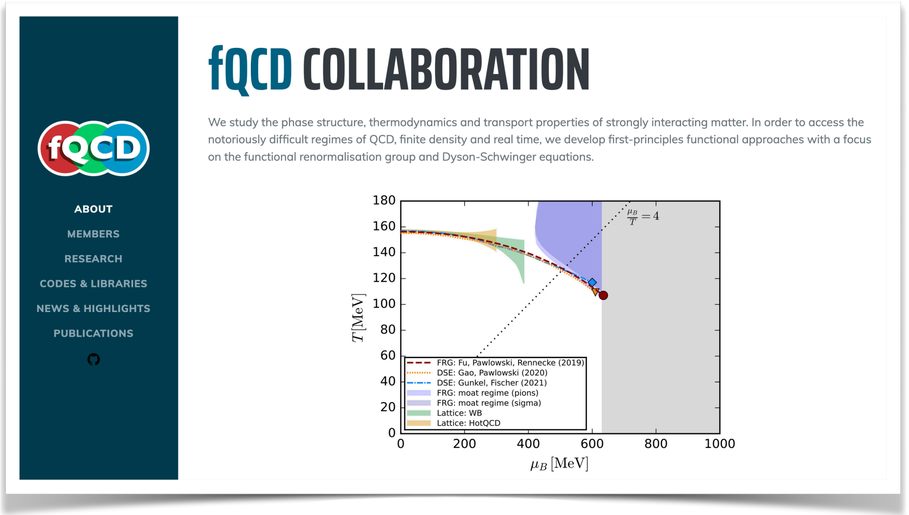
fqcd-collaboration.github.io

3rd international workshop on Physics at High Baryon Density

Dalian, November 11th 2026



fQCD collaboration

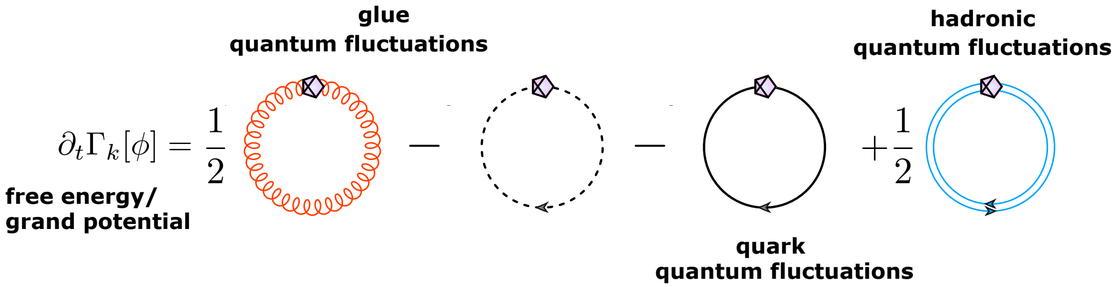


github

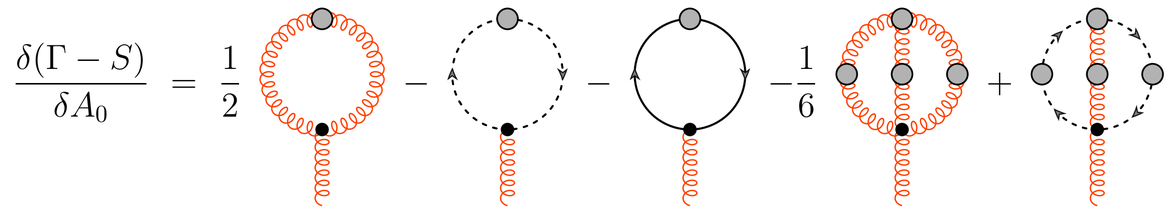
Dalian, Beijing, Darmstadt, Heidelberg, Gießen

Braun, Chen, Fu, Gao, Gan, Huang, Ihssen, Kockler, Lu, Mire, Pawlowski, Rennecke, Sattler, Tan, Wang, Wen, Wessely, Wu, Yamada, Yin

Functional renormalisation group



Dyson-Schwinger equations



Phase structure and dynamics of QCD at high densities

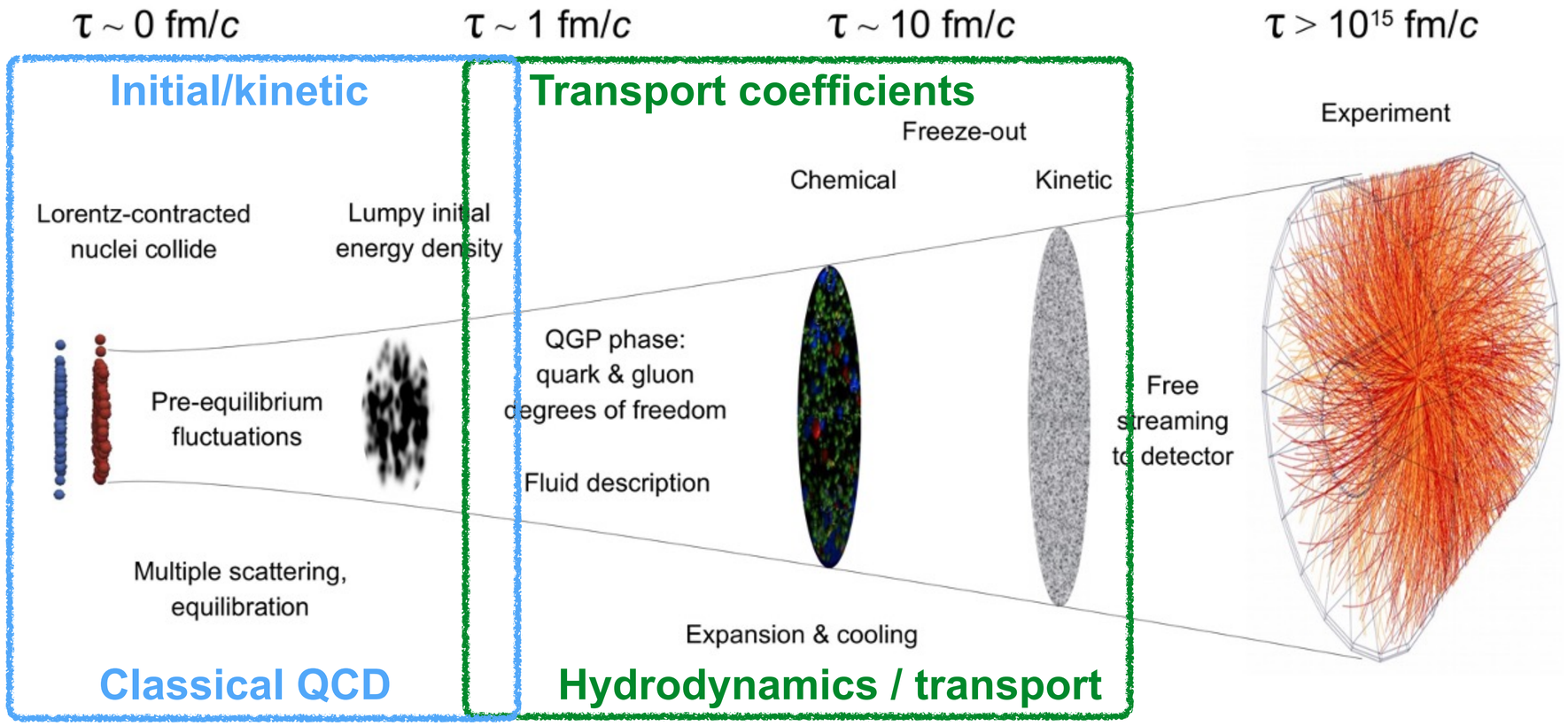
- **Critical end point and new phases: where do we stand?**
- **QCD moat and inhomogeneous phases**
- **Disecting the moat with observables**
- **Conclusions**

See also talks by

Christian Fischer, Wednesday 11:45

Fei Gao, Thursday 12:00

Unfolding strongly correlated QCD with heavy ion collisions (extreme QCD)



Experiment

How to unfold: inverse problem!

Theory

Initial state model QCD kinetic theory Hydrodynamics transport

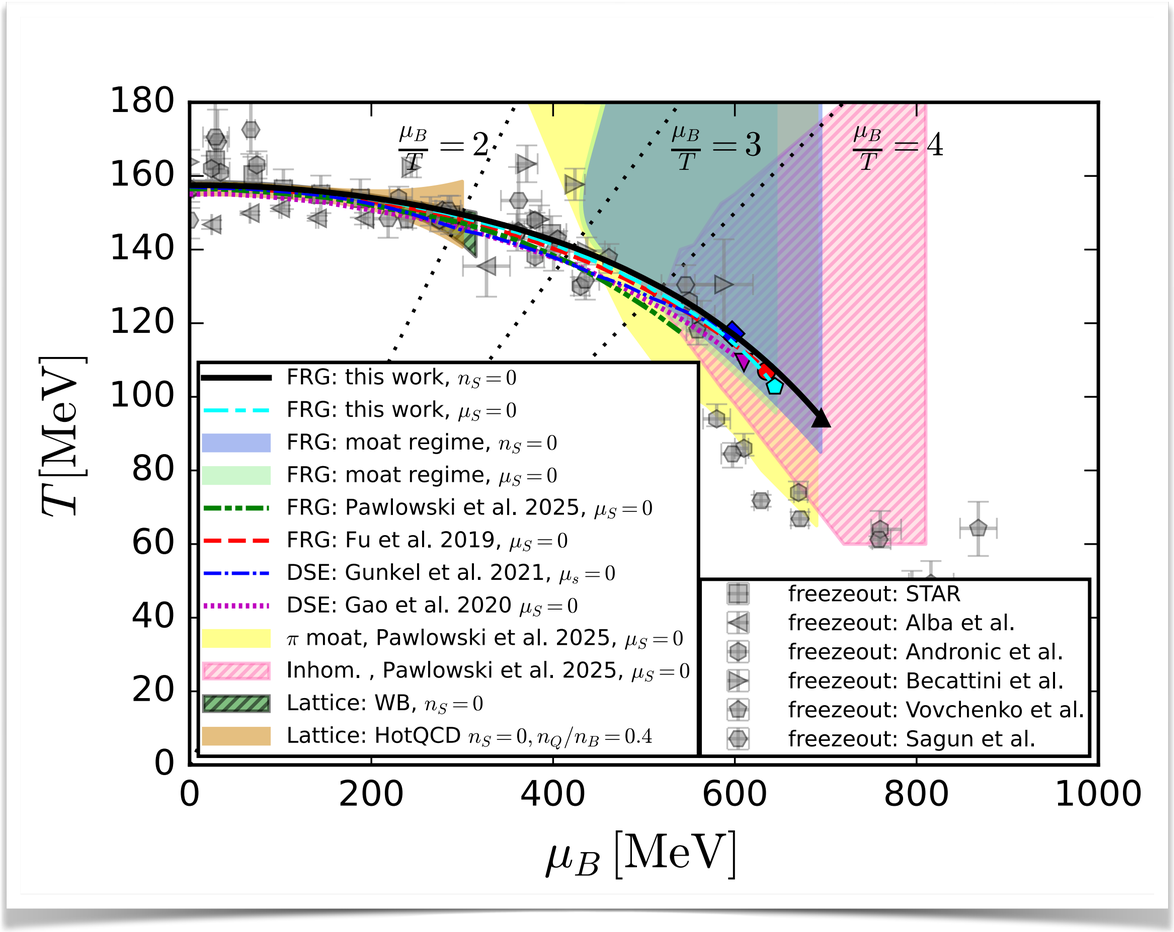
Baseline: Equilibrium QCD

Baryon vs proton fluctuations

grand canonical vs canonical

Finite volume effects

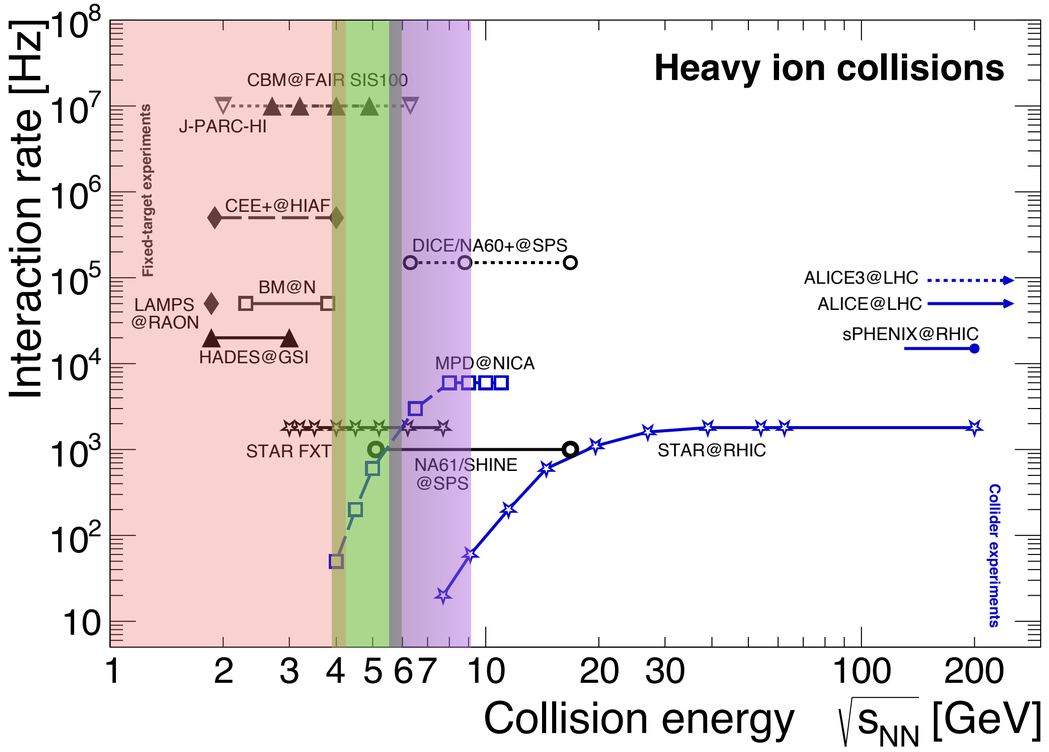
Critical end point and new phases: where do we stand?



Experimental & Theoretical Landscape

Experimental landscape

New phases



Peak of kurtosis on the freeze-out line

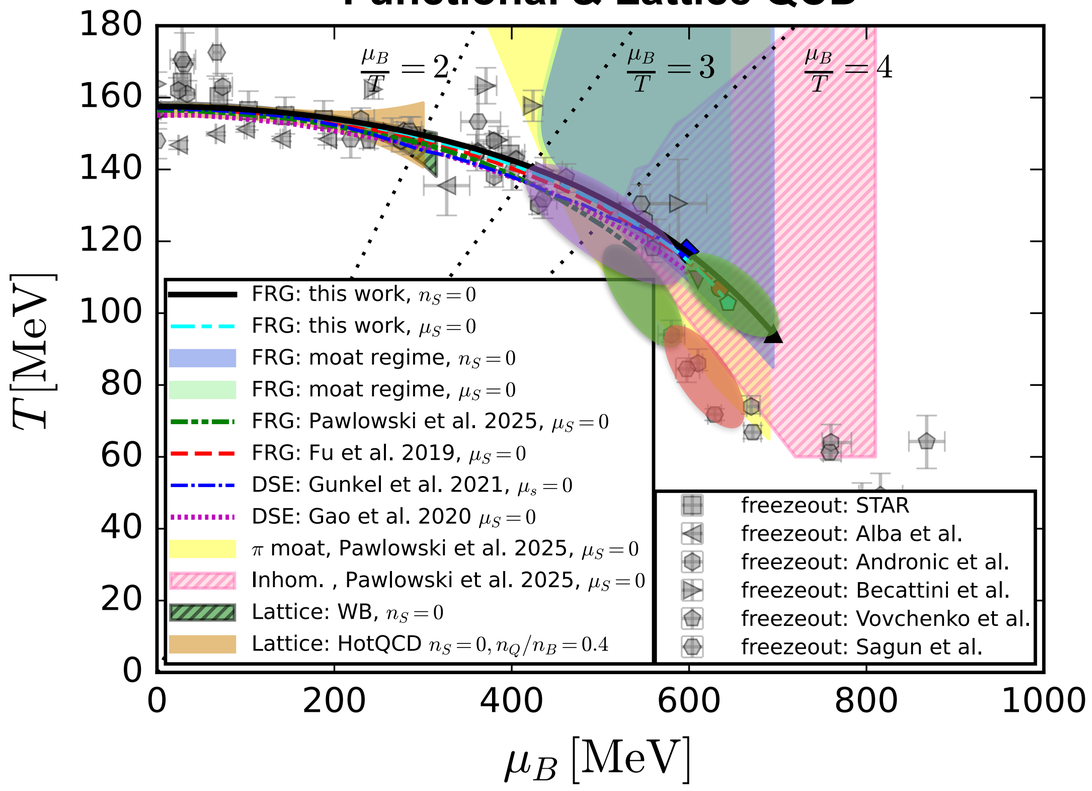
Galatyuk, A982 (2019) update 2025; CBM, EPJA 53 3 (2017) 60

Theoretical landscape

Onset of new phases on the chiral transition line (CEP)

Transition regime

Functional & Lattice QCD

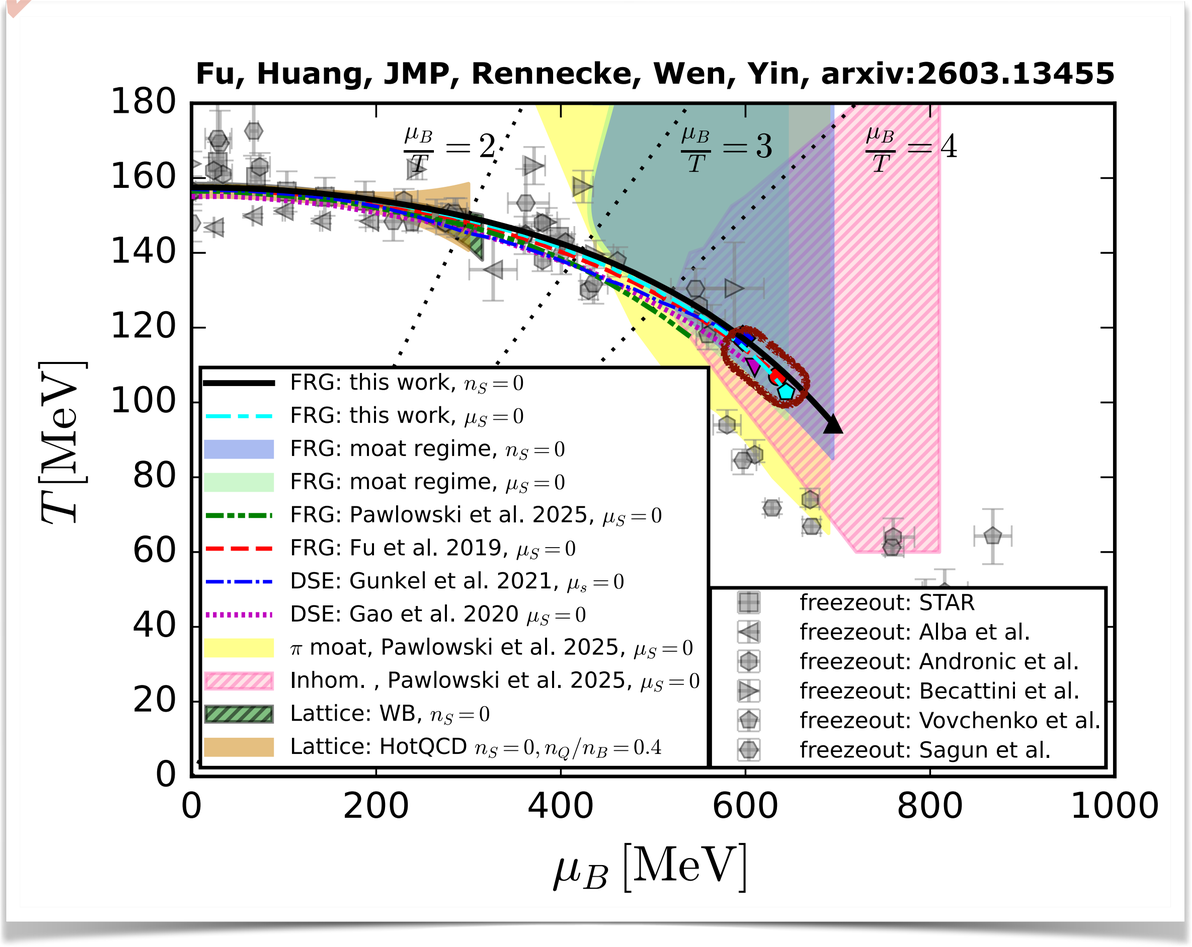


Fu, Huang, JMP, Rennecke, Wen, Yin, arxiv:2603.13455

Zooming in

Critical end point and new phases: where do we stand?

Quantitative functional QCD



$$\frac{\mu_B}{T} \lesssim 4.5$$

Functional QCD: CEP estimate

$$\mu_u = \mu_d = \mu_s$$

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

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

$$\mu_u = \mu_d \quad \mu_s = 0$$

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

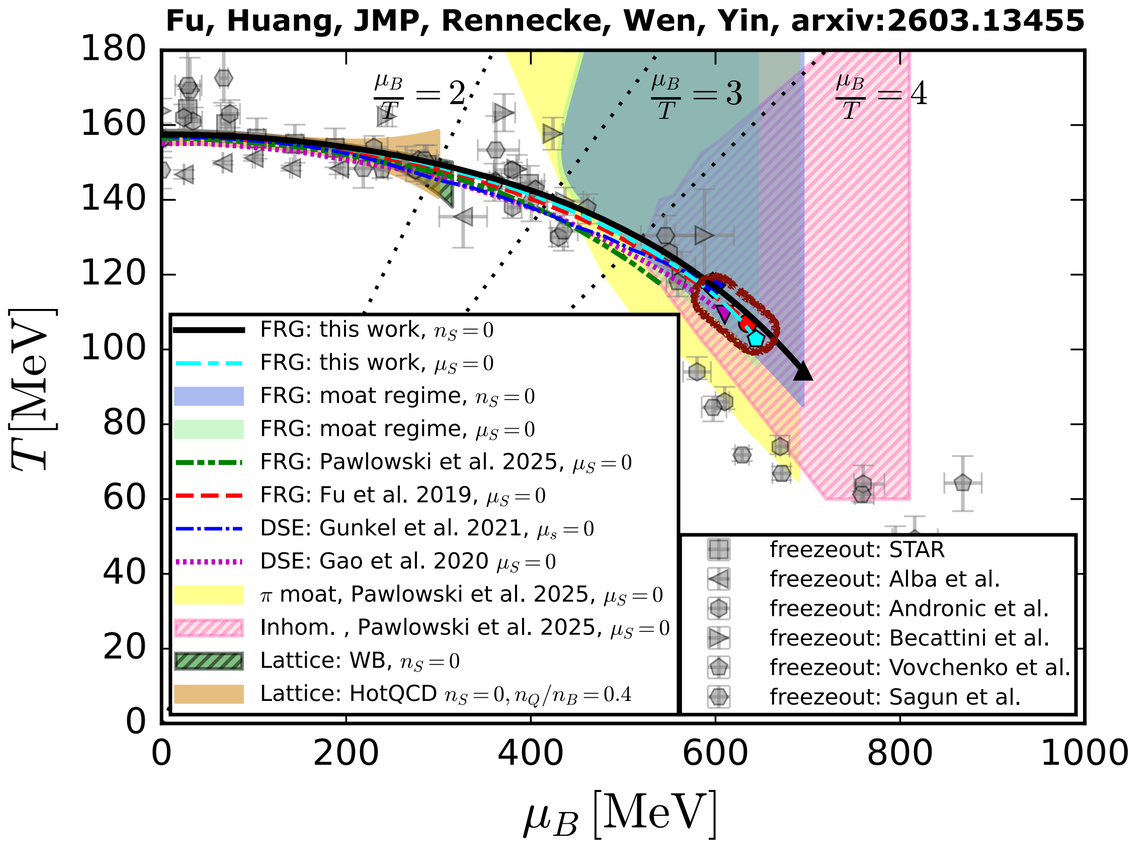
$$(T\,,\,\mu_B)_{\mathrm{CEP}} \sim (105-115\,,\,600-650)\ \mathrm{MeV}$$

Self-consistent Moat: JMP, Rennecke, Sattler, arxiv:2512.20510

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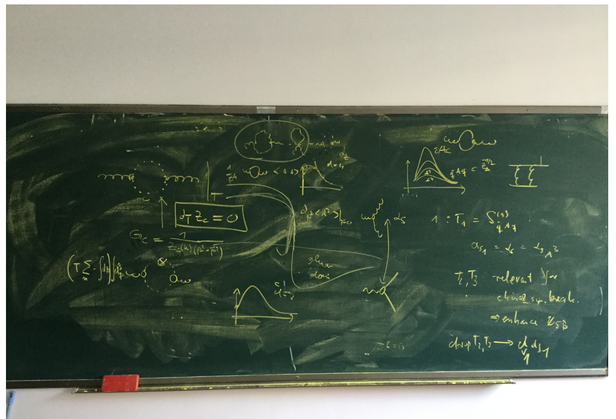
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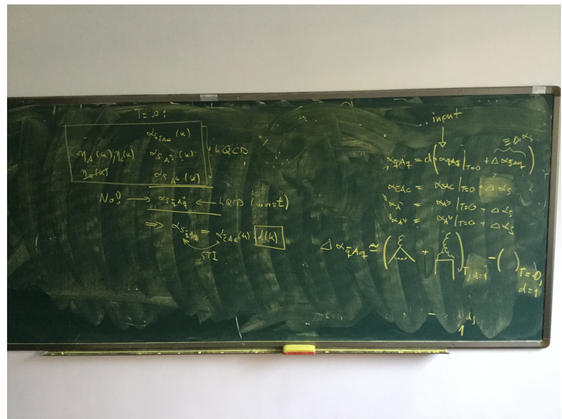
Gunkel, Fischer, PRD 104 (2021) 054022 (DSE)

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Dalian 2018: Wei-jie, Jan, Fabian & yellow chalk

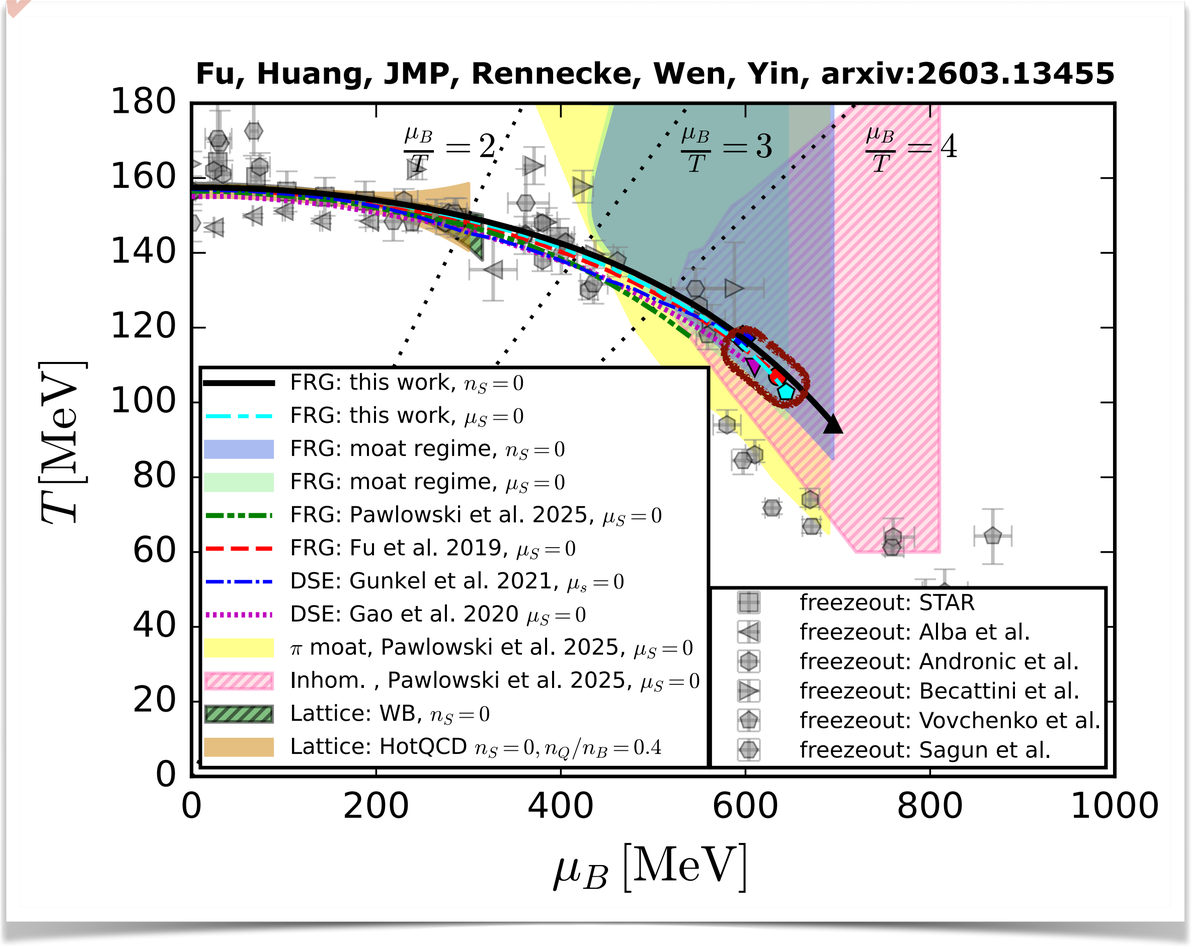




Zooming in

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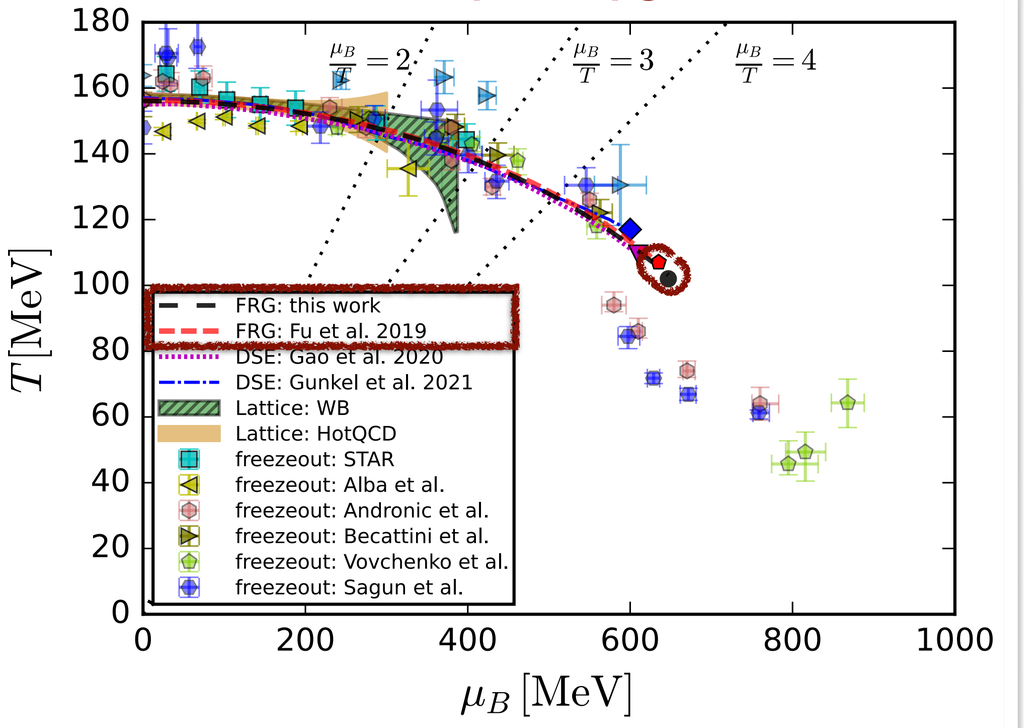
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fQCD **Fu, JMP, Rennecke, PRD 101 (2020) 054032 (fRG)**

Fierz-complete upgrade



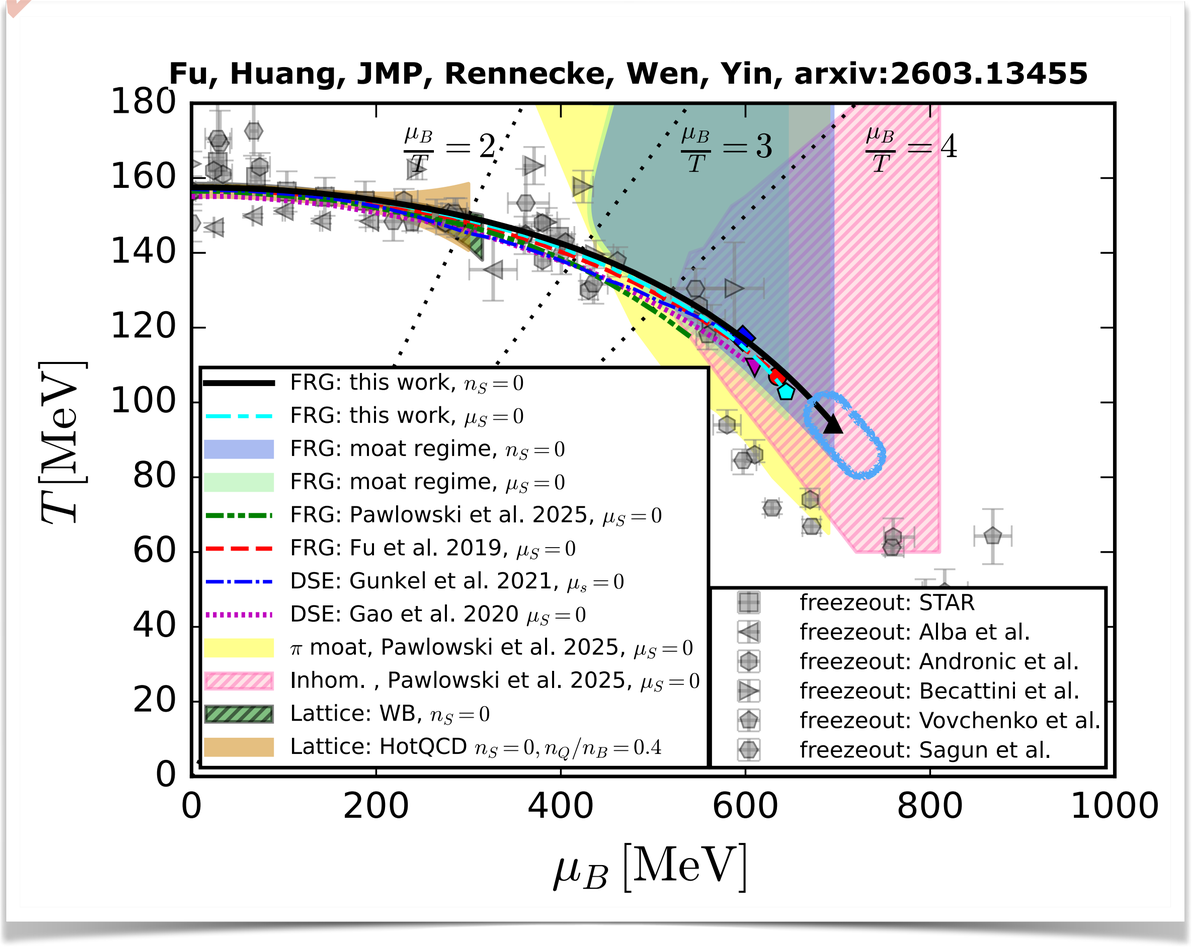
fQCD | **Self-consistent Moat: JMP, Rennecke, Sattler, arxiv:2512.20510**

fQCD **Wang, Zhou, Huang, Wen, Yin, Fu, arxiv:2607.07354**

Zooming in

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$$\frac{\mu_B}{T} \lesssim 4.5$$

Functional QCD: CEP estimate

Strangeness neutrality

$$(T\,,\,\mu_B)_{\mathrm{CEP}} = (92\,,\,696)\ \mathrm{MeV}$$

$$\frac{\kappa_{n_s=0}}{\kappa_{\mu_i=\mu_q}} = 0.897$$

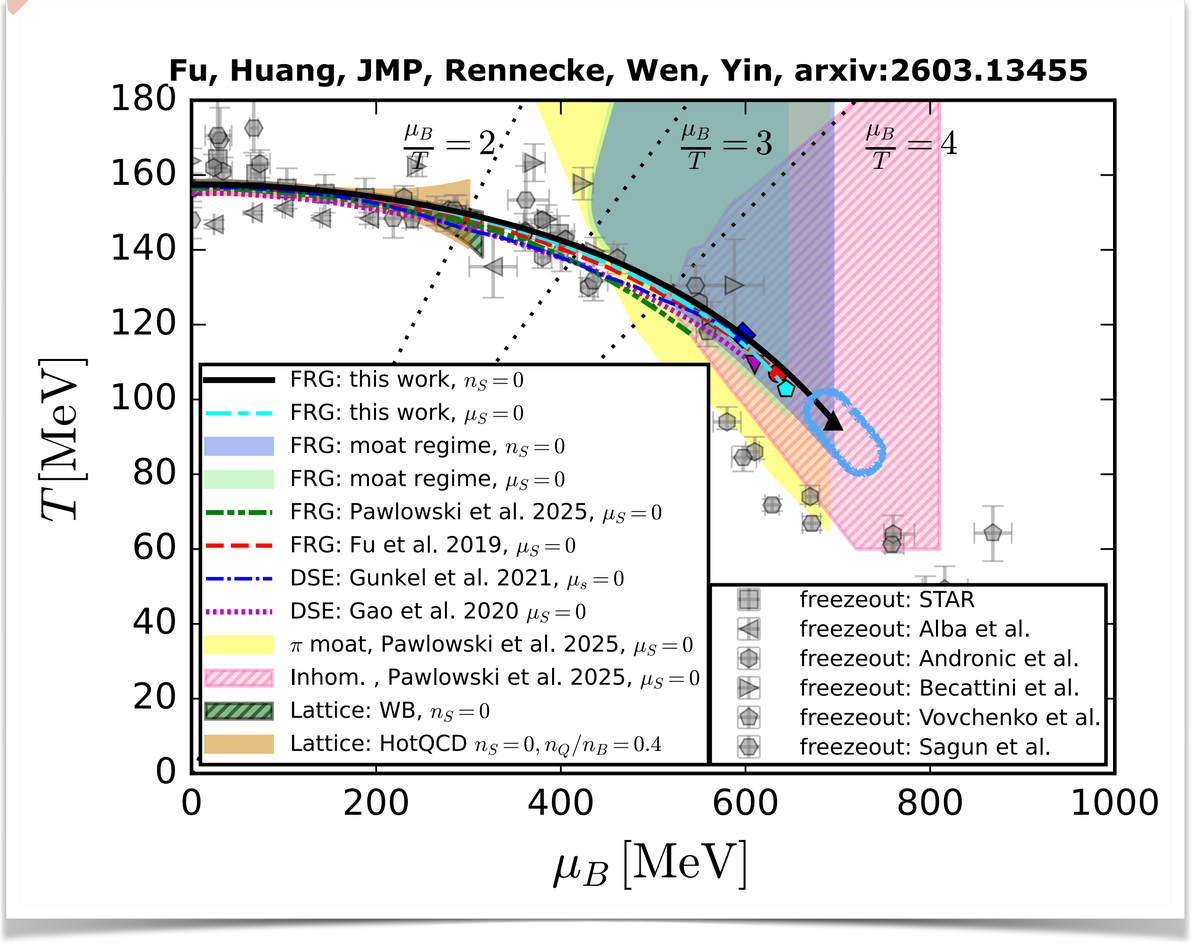
Self-consistent Moat: JMP, Rennecke, Sattler, arxiv:2512.20510

Fu, Huang, JMP, Rennecke, Wen, Yin, arxiv:2603.13455

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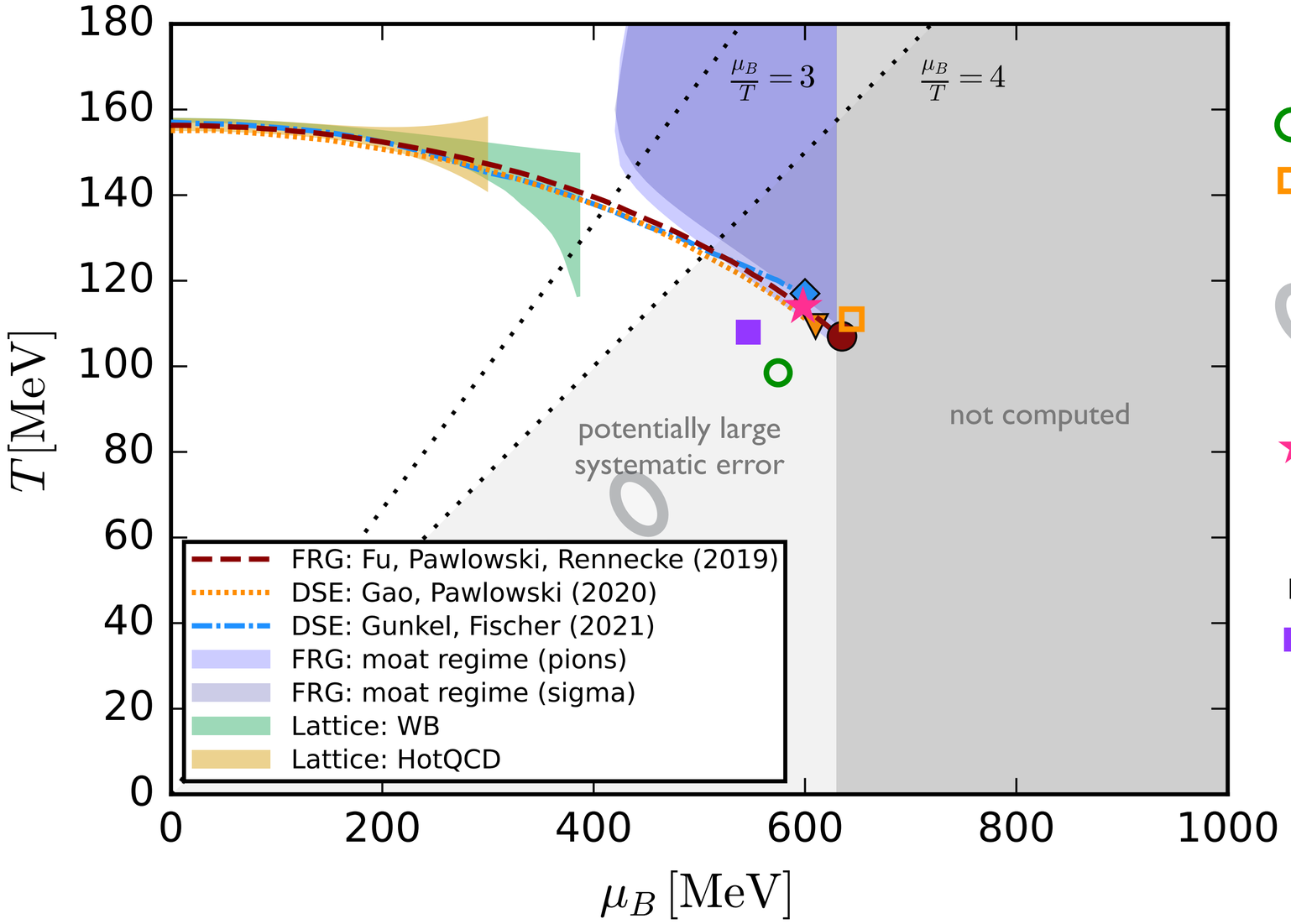
Self-consistent Moat: JMP, Rennecke, Sattler, arxiv:2512.20510

Fu, Huang, JMP, Rennecke, Wen, Yin, arxiv:2603.13455

QCD PHASE DIAGRAM & THE CEP

Modified from Fabian Rennecke's plenary talk @ QM 2025

FRG & DSE results ? corroborated ? by subsequent "extrapolations" of lattice data



Fu, Luo, JMP, Rennecke, Yin, PRD 111, L031502

using Yang-Lee edge singularities:

- conformal Padé [Basar, 2312.06952]
- multi-point Padé [Clarke et al., 2405.10196]
  $N_\tau = 6, 8$ results + continuum estimate
  [Schmidt, 2504.00629]
- **very recent lattice extrapolation (16^3 x 8)**
  [Adam et al, 2507.13254]

using thermodynamics:

- constant entropy density [Shah et al. 2410.16206]
  [Shah et al. 2601.08823]

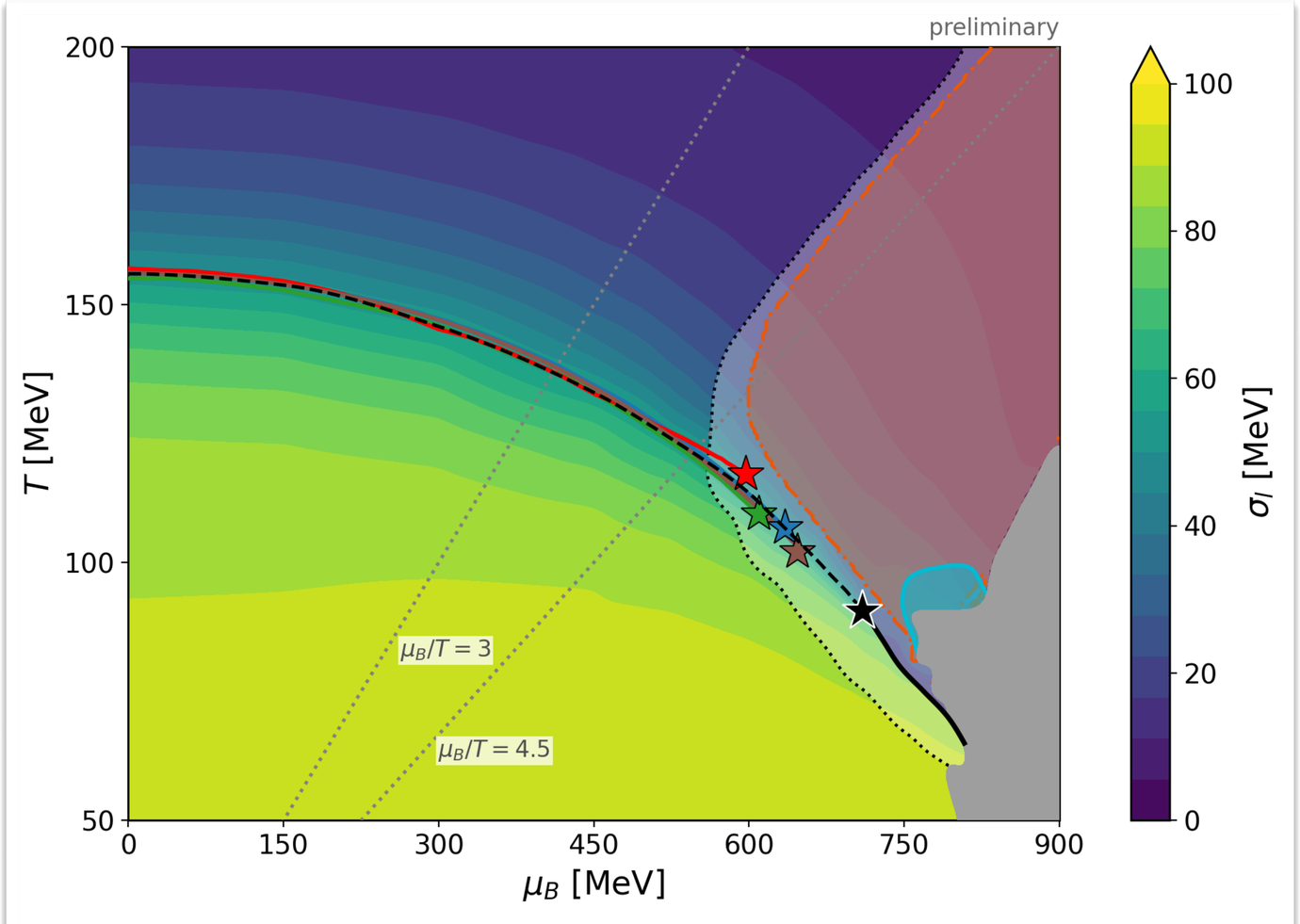
model-based extrapolation (tiny selection):

- holography [Hippert et al., 2309.00579]
  (agrees with [Cai et al., 2201.02004])

CEP location well constrained by now. And it's **in FAIR range!**

$\sqrt{s_{NN}} \approx 3.6 - 4.1\,\mathrm{GeV}$

Critical end point and new phases: where do we stand today?



The QCD moat and inhomogeneous phases

We stand in the moat!

Signatures of the moat

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

The moat and its physics

Pisarski, Rennecke, PRL 127 (2021) 152302

Chinese Moat



Wikipedia

German Moat



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

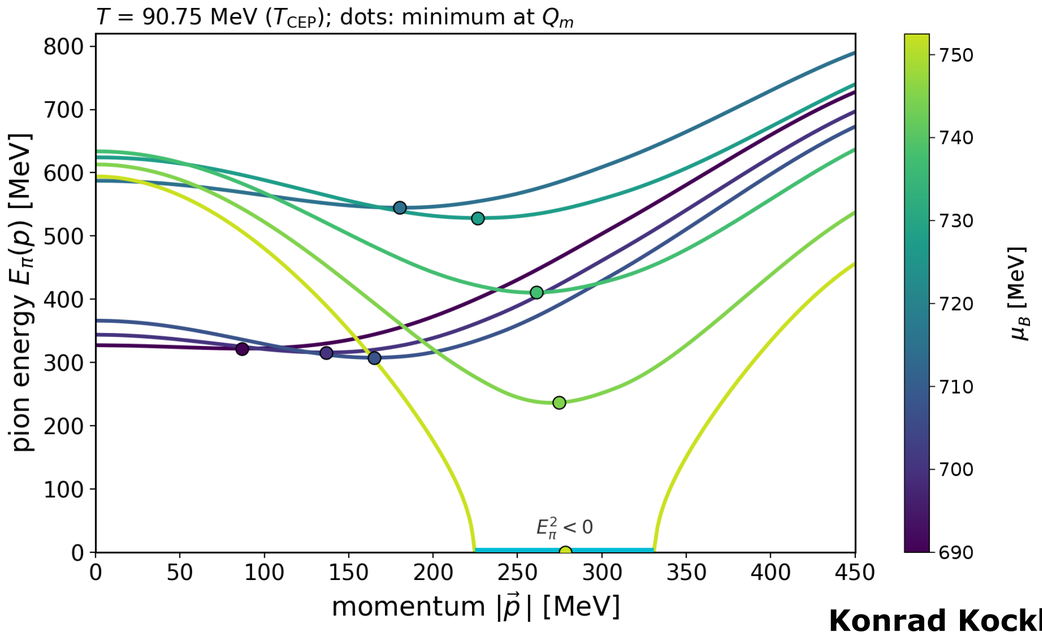
US Moat



Wikipedia

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Konrad Kockler, JMP, Rennecke, Sattler, in preparation

Chinese Moat



Wikipedia

German Moat



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

US Moat



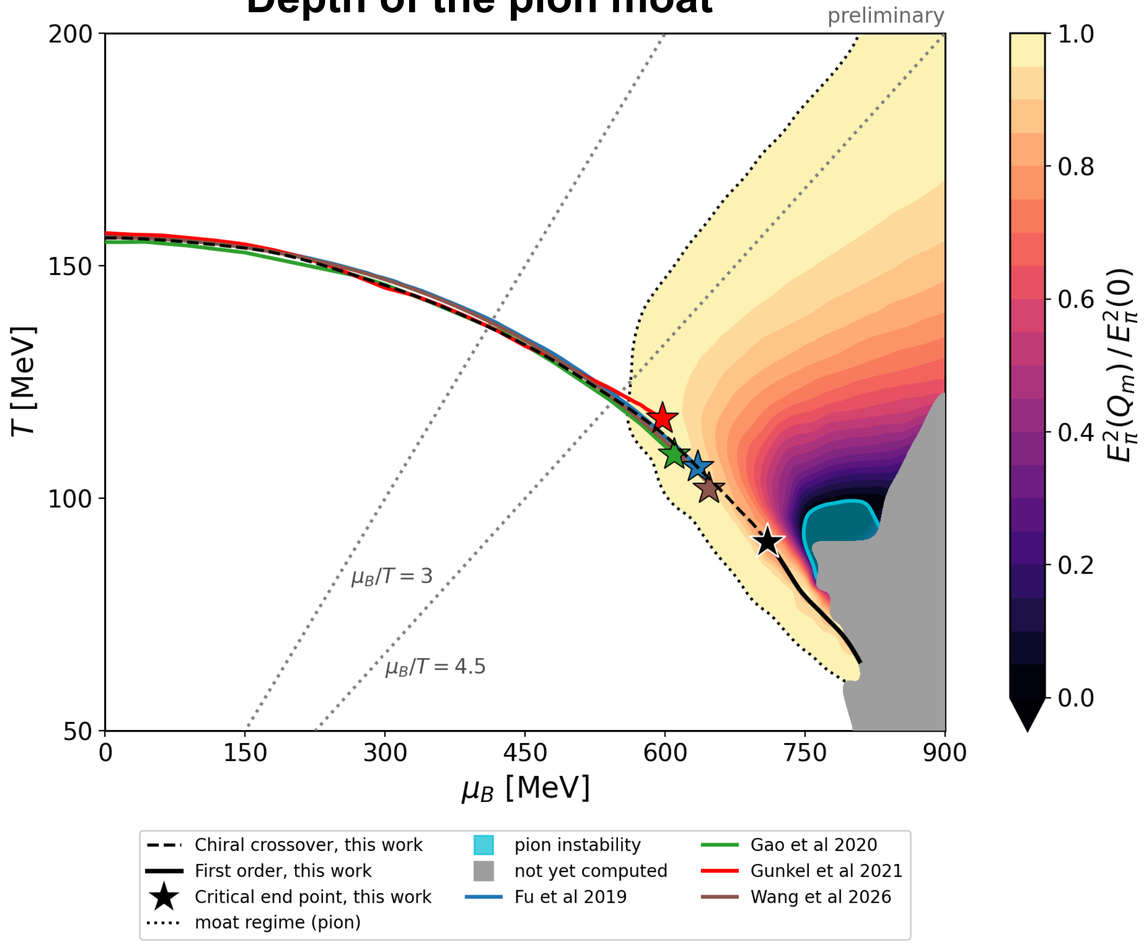
Wikipedia

The Moaty End Point (MEP)

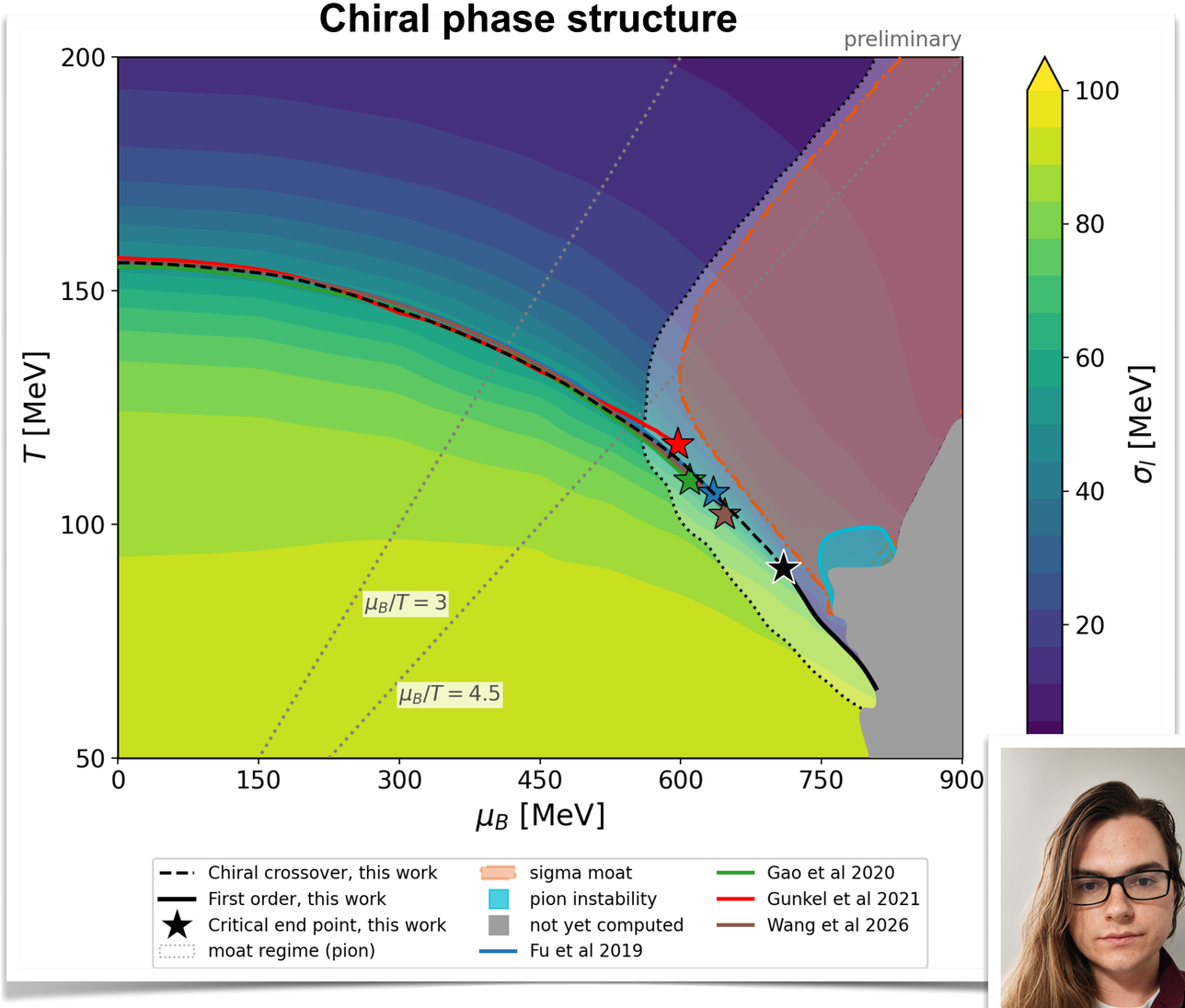
Zooming in
Preliminary



Depth of the pion moat



Chiral phase structure



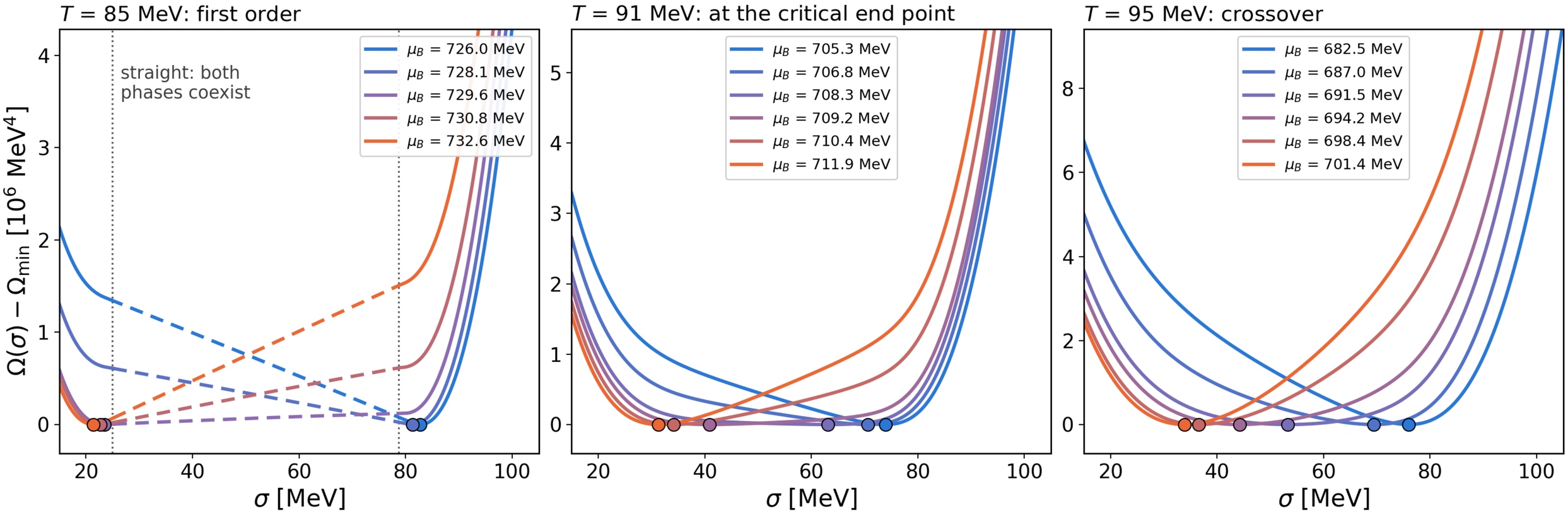
Konrad Kockler, JMP, Rennecke, Sattler, in preparation

Zooming in
Preliminary

The effective potential of the chiral condensate

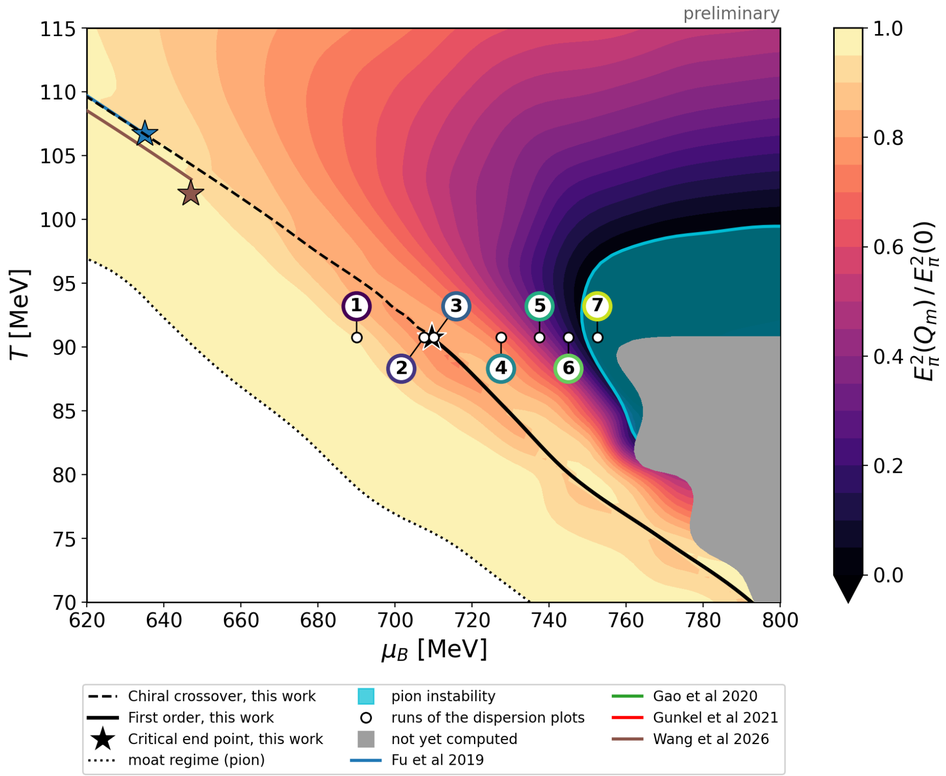
aka how to detect the MEP and 1st oder

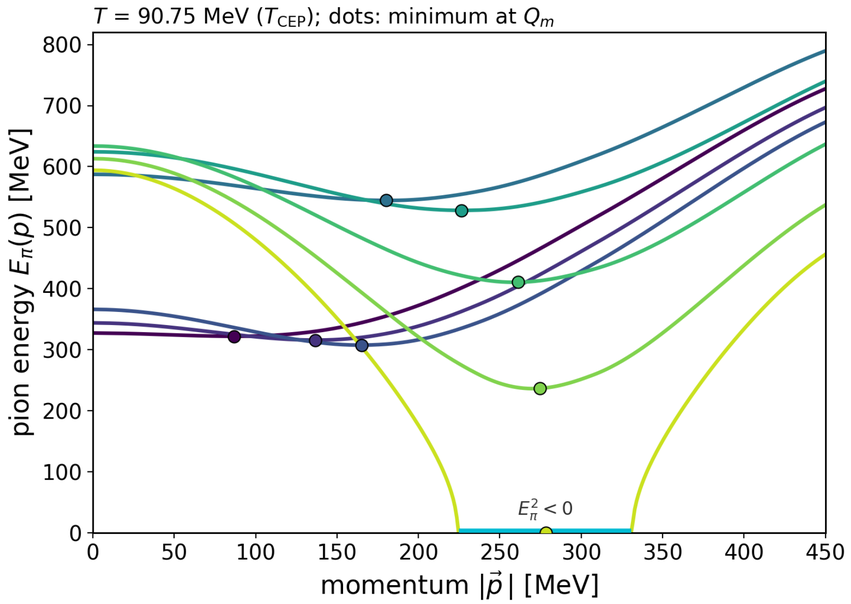
Effective potential at the end of the flow, k = 6.7 MeV; dashed: straight (flat) segment; dots: the minimum

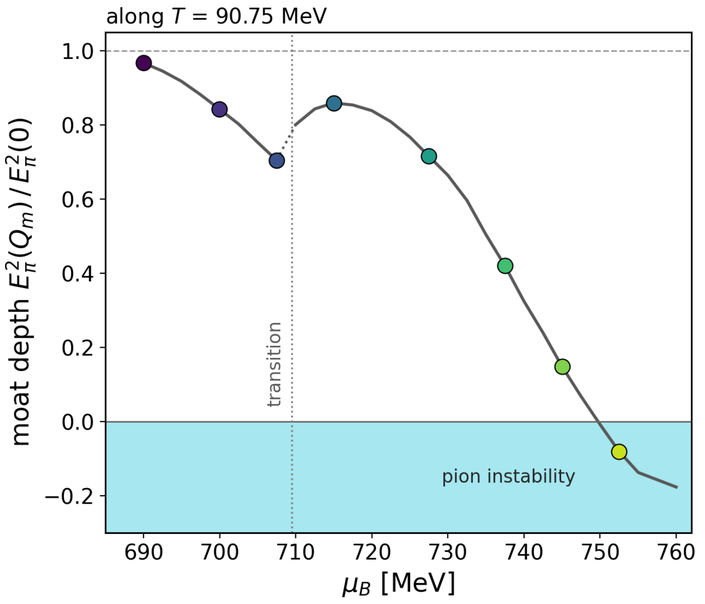


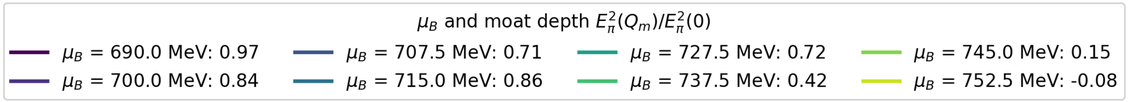
Zooming in
Preliminary

Pion correlations in the moat







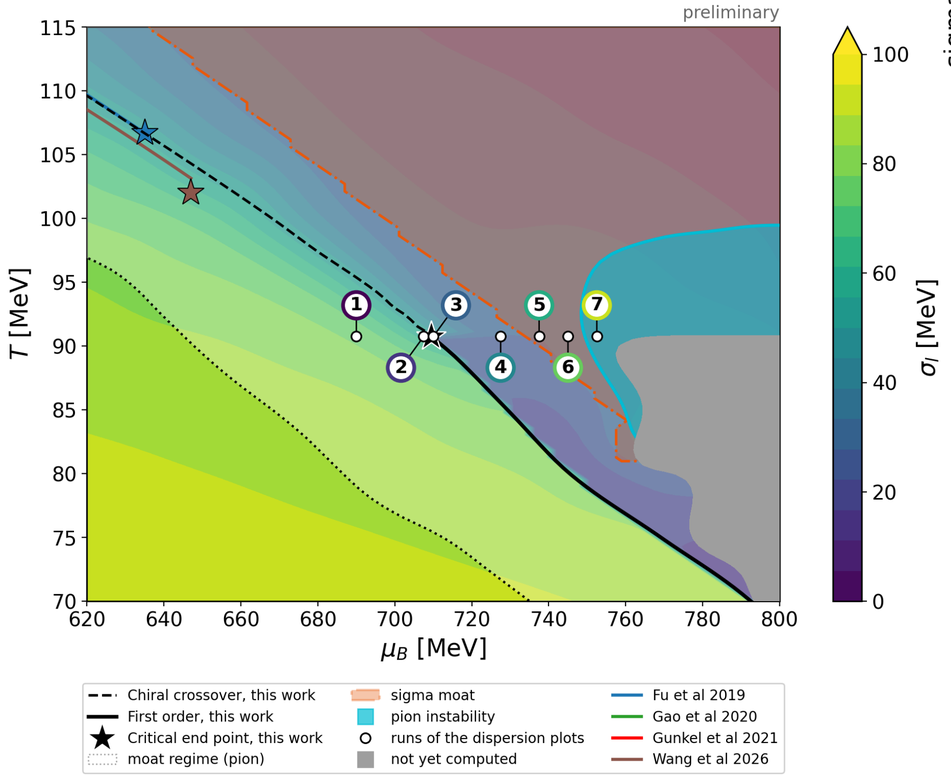


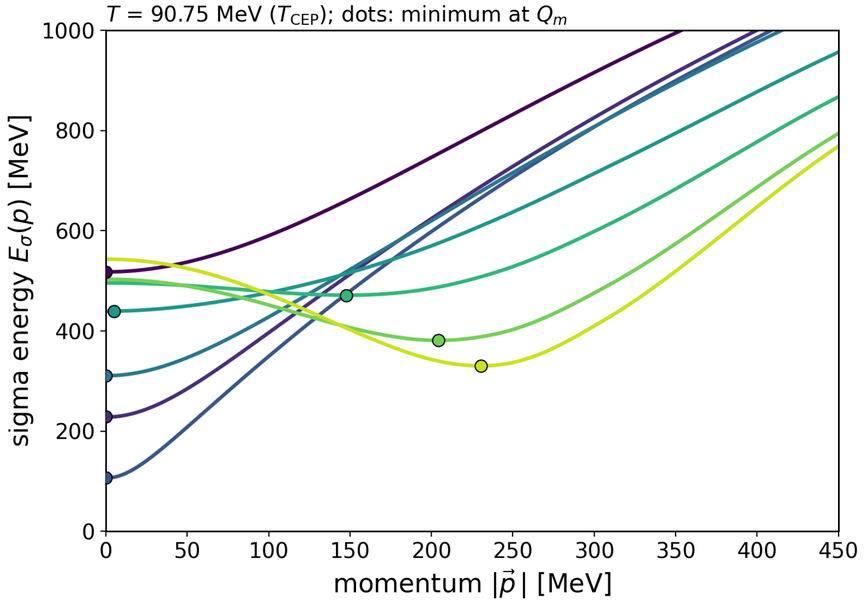


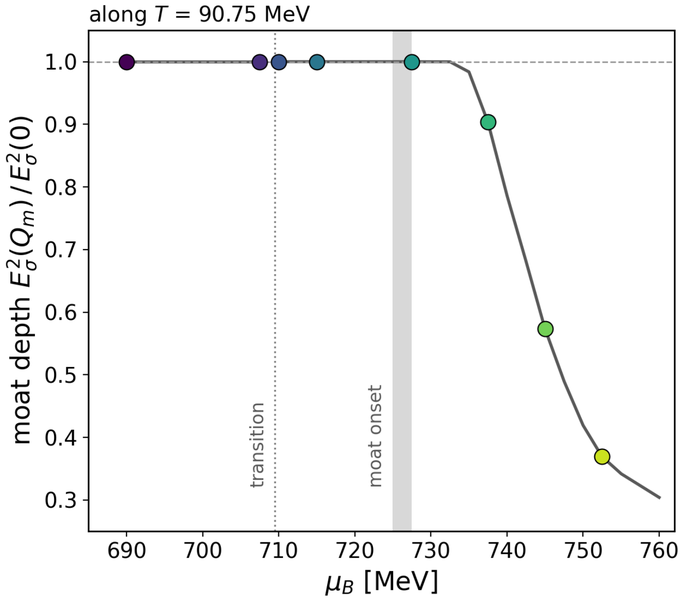
Konrad Kockler, JMP, Rennecke, Sattler, in preparation

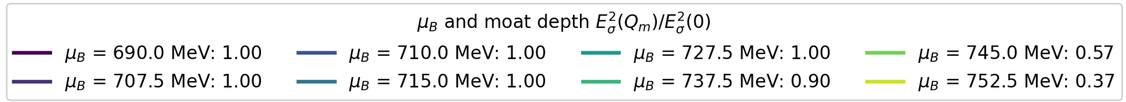
Scalar correlations in the mode

Zooming in
Preliminary









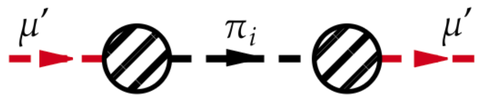


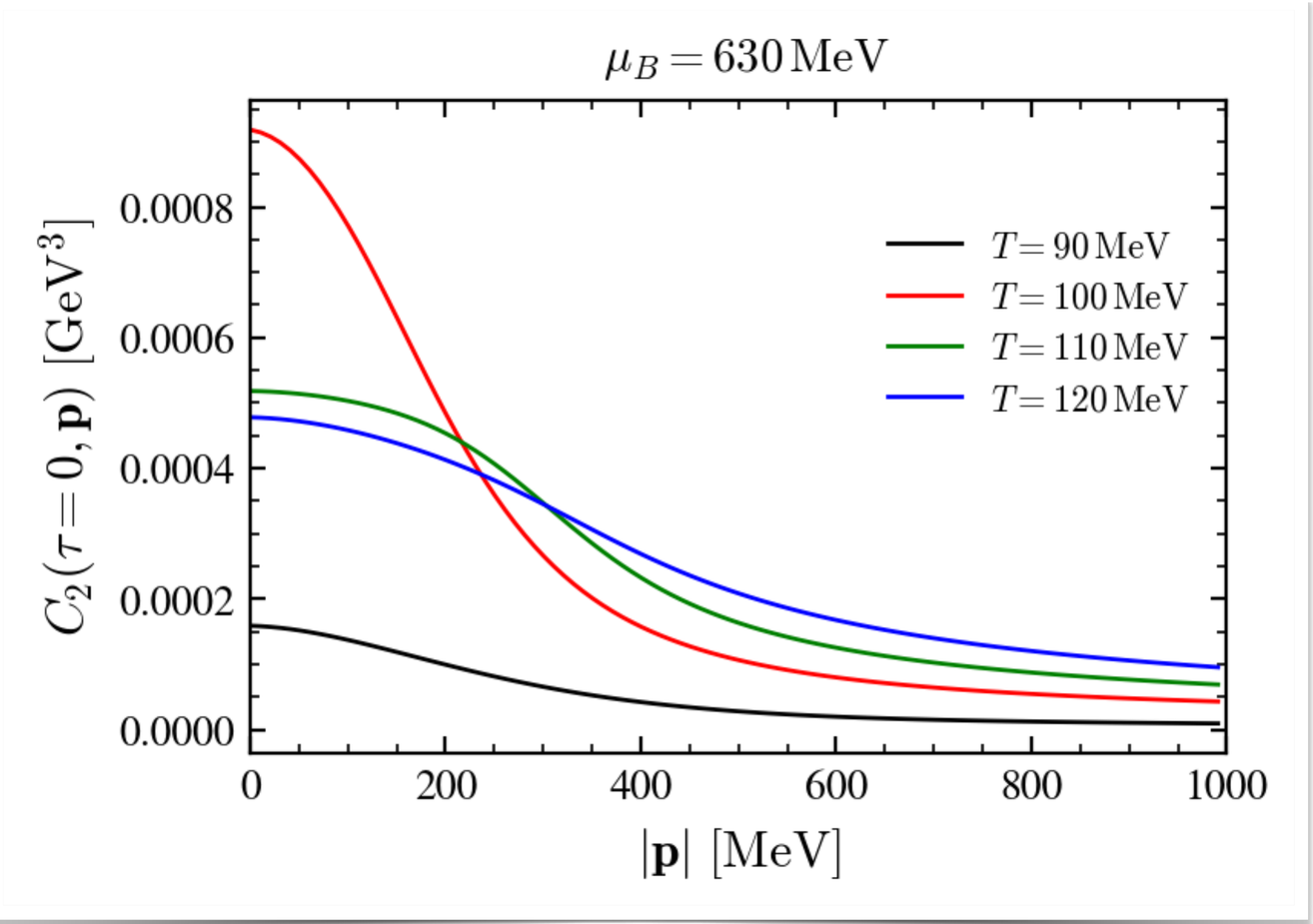
Konrad Kockler, JMP, Rennecke, Sattler, in preparation

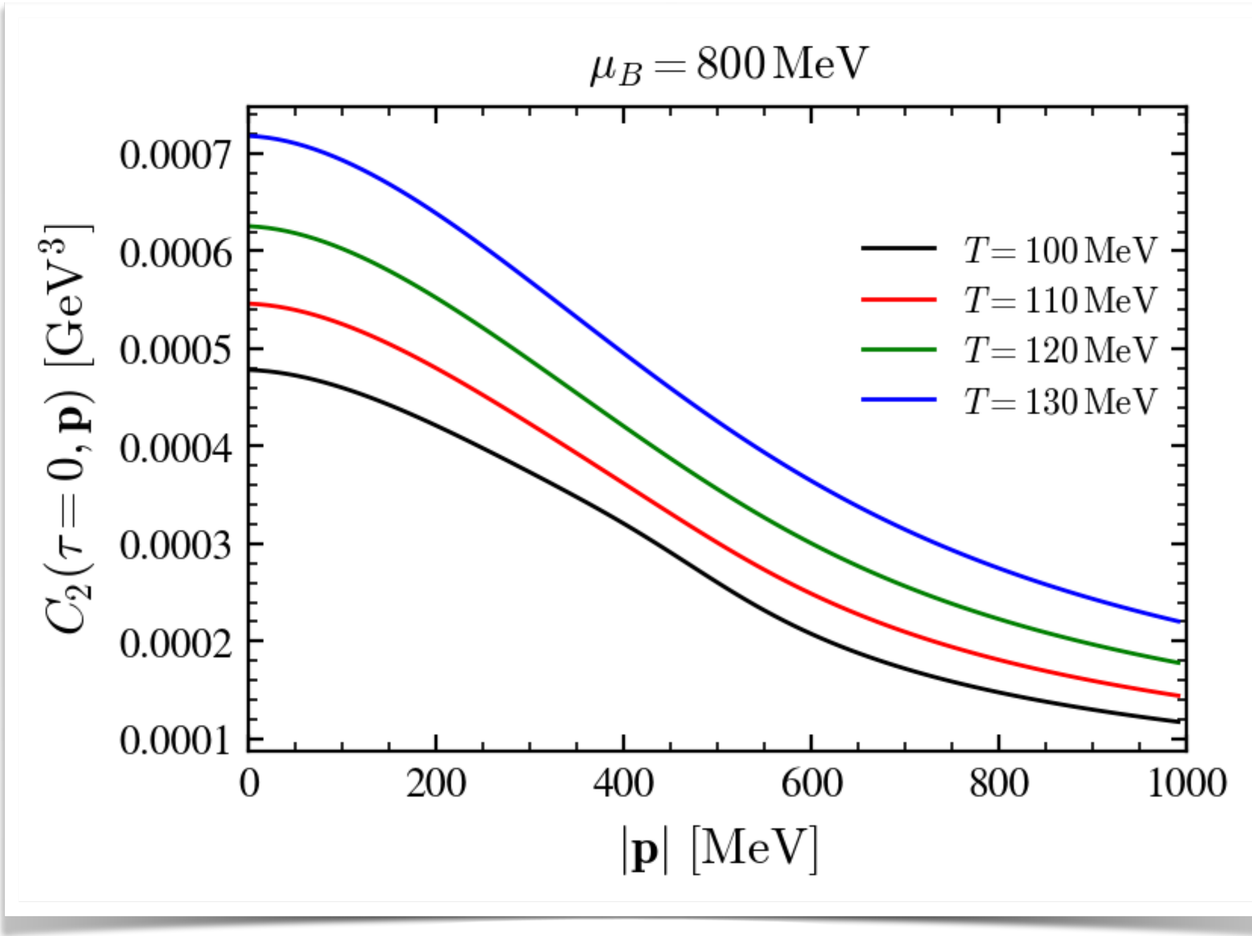
Zooming in
Preliminary

Disecting the moat with observables

Baryon density equal time correlations

$$C_2^{n_5} = -$$  $$+ \sum_i$$ 



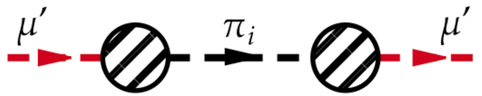


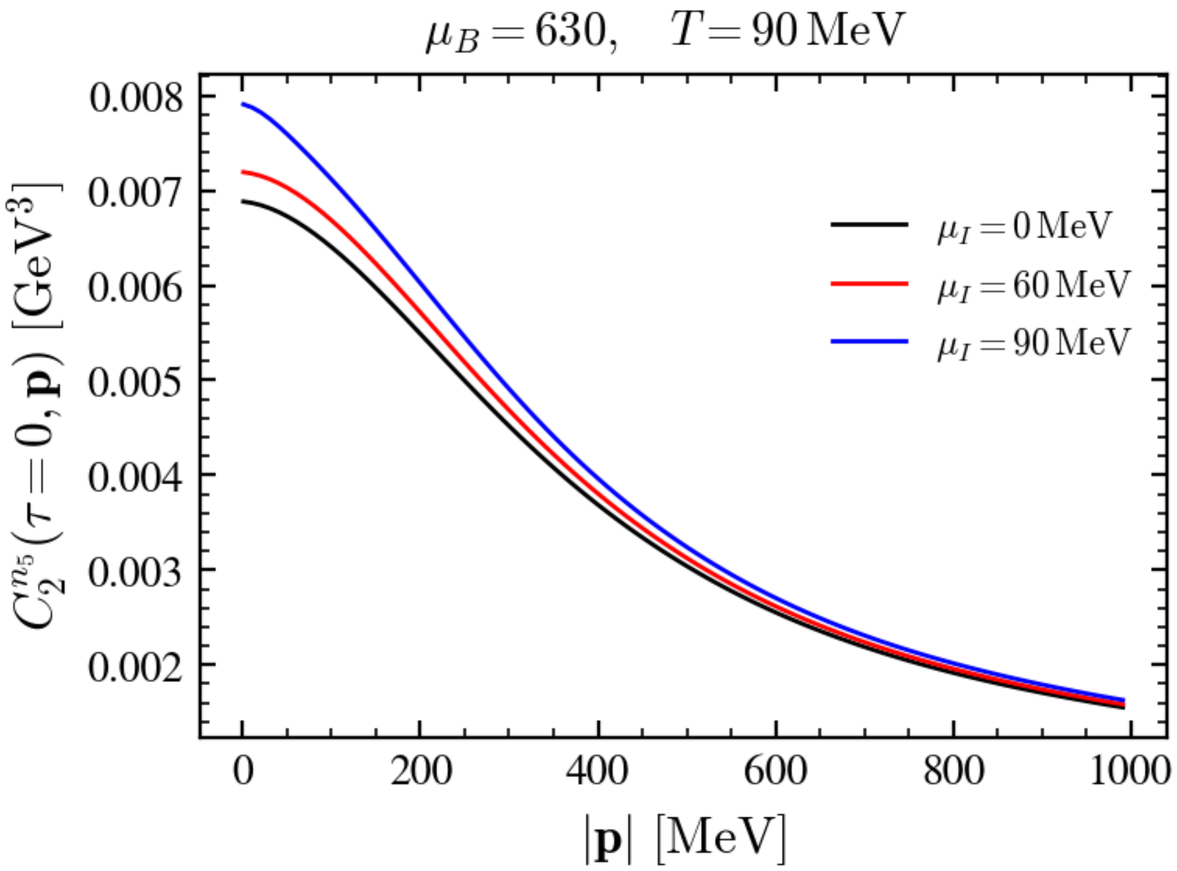
Jing Wu, Shen-nan Han, Shi Yin, Wei-jie Fu, in preparation

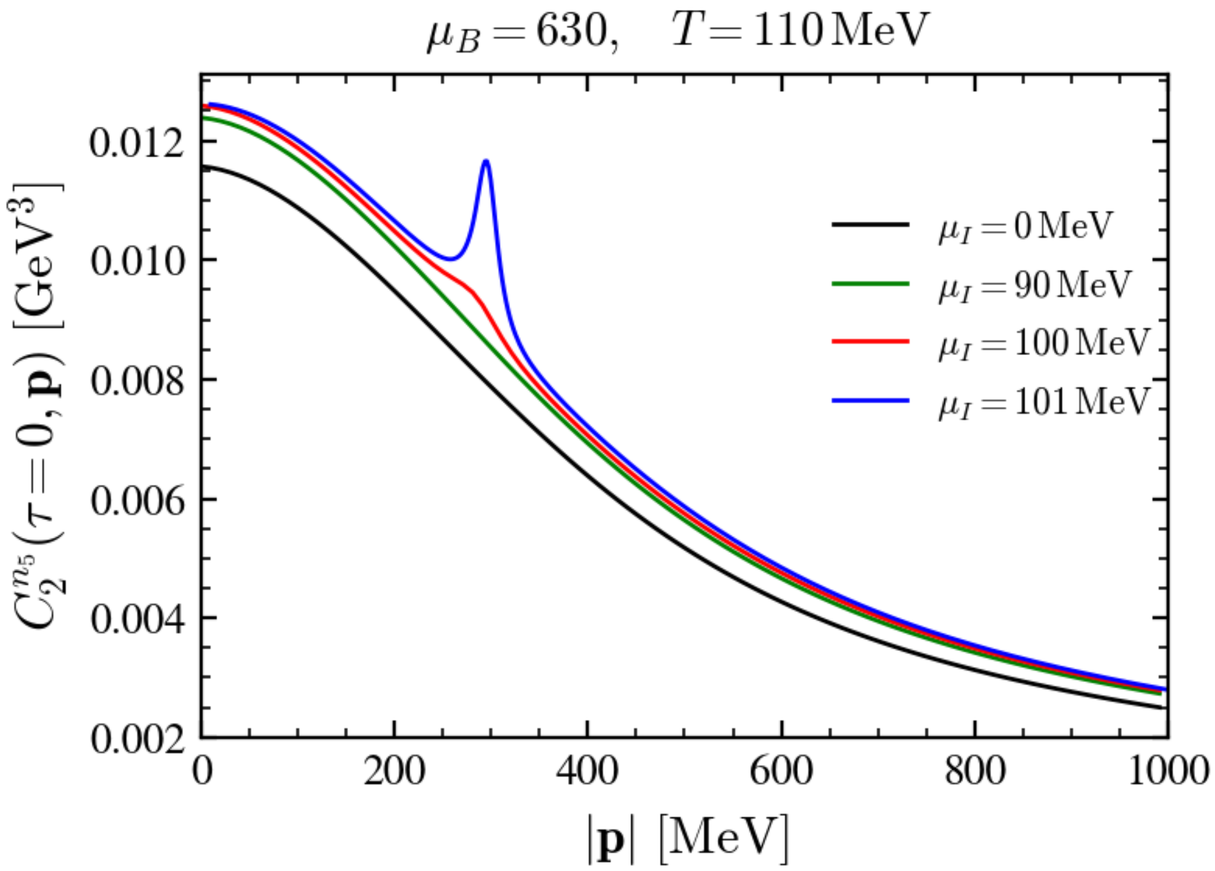
Zooming in
Preliminary

Disecting the moat with observables

Axial charge density equal time correlations

$$C_2^{n_5} = -$$  $$+ \sum_i$$ 

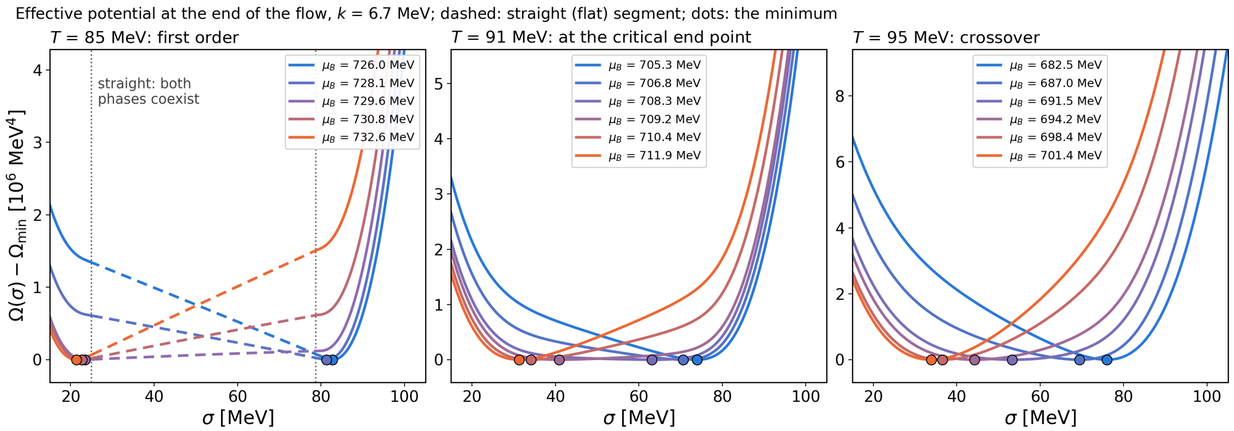


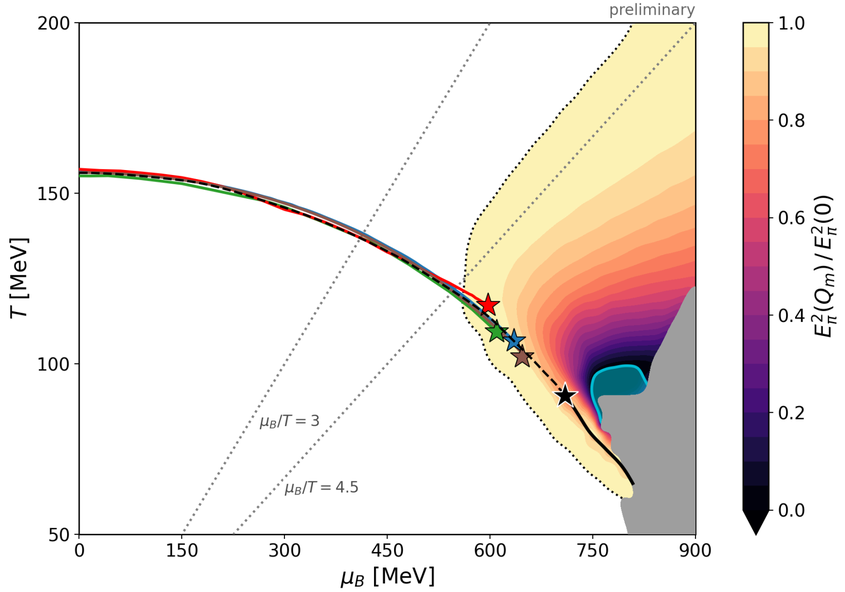


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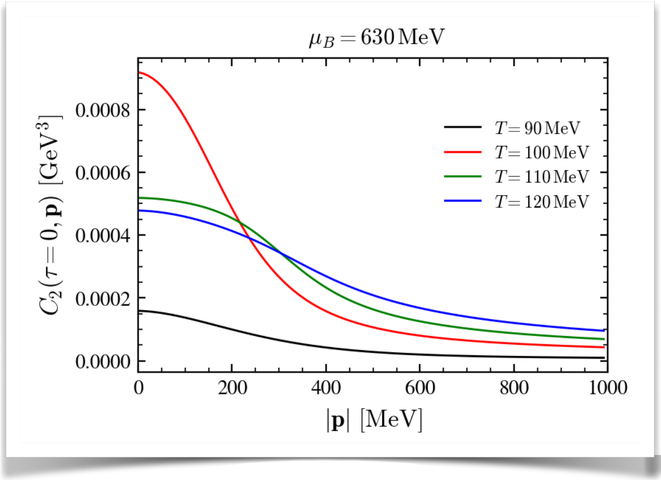
Summary

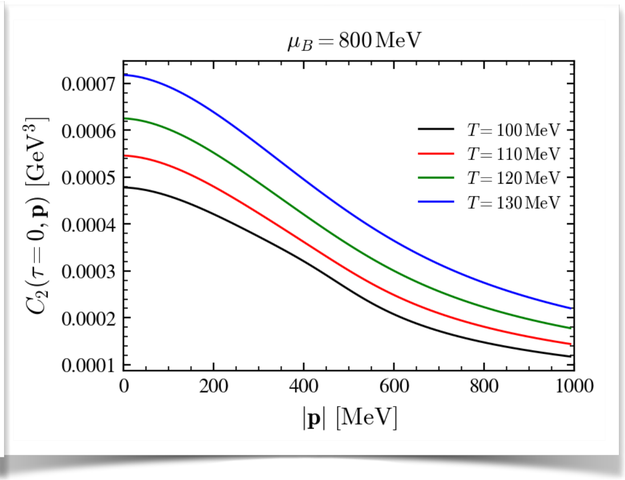
- **The QCD moat and the moat end point (MEP)**

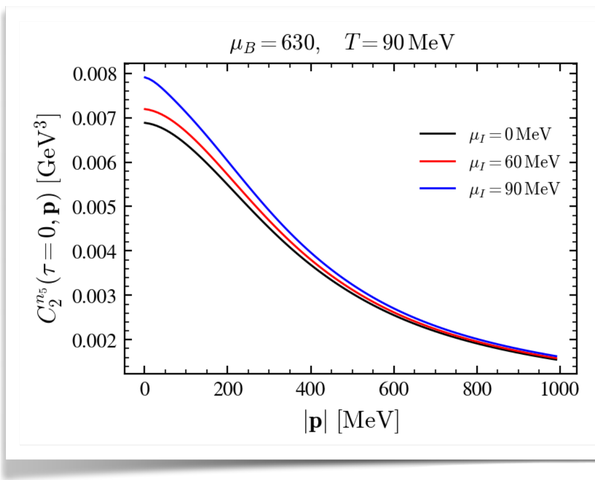


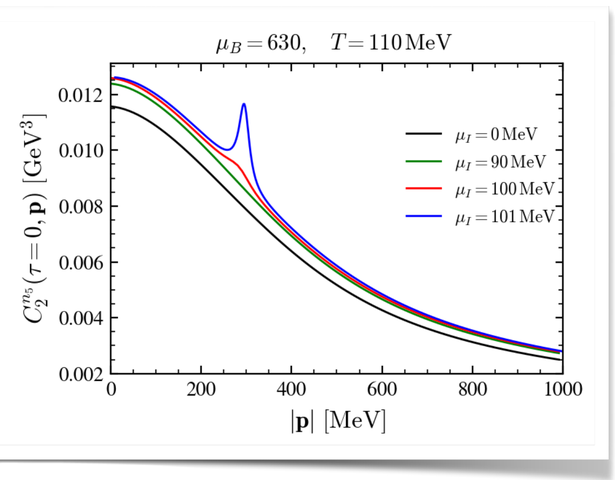


- **Discetion the moat with observables**











Backup

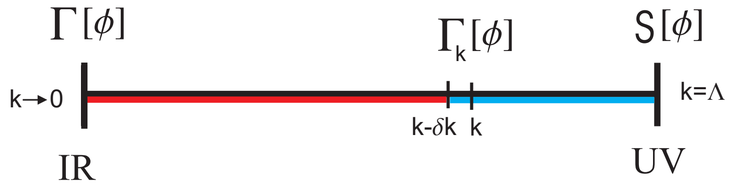
Phase structure from functional QCD: how to

Functional flows for QCD

Dupuis et al, Phys.Rept. (2021)

Fu, Commun.Theor.Phys. 74 (2022) 9, 097304

free energy at momentum



hadrons **quarks & gluons**

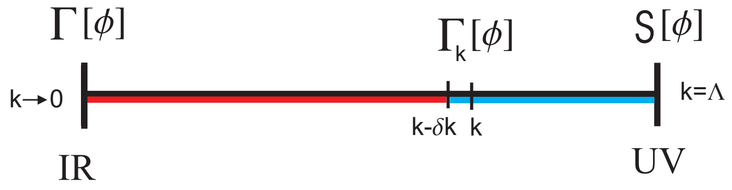
ab initio

Functional flows for QCD

Dupuis et al, Phys.Rept. (2021)

Fu, Commun.Theor.Phys. 74 (2022) 9, 097304

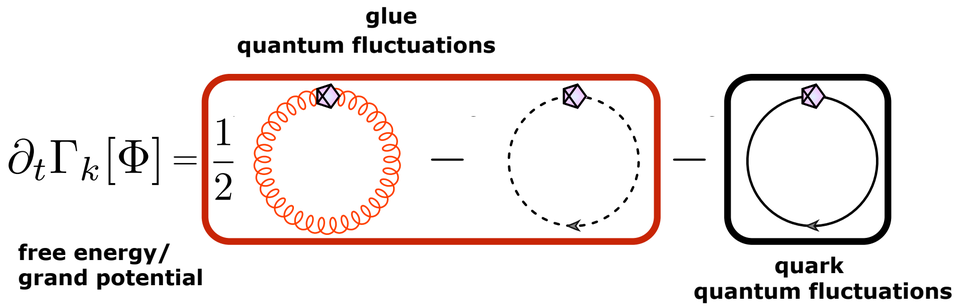
free energy at momentum



hadrons **quarks & gluons**

ab initio

functional RG:



$$\Phi = (A_\mu, c, \bar{c}, q, \bar{q})$$

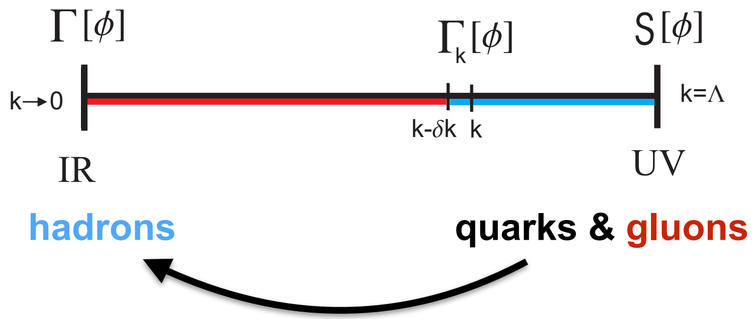
RG-scale k: $t = \ln k$

Functional flows for QCD

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free energy at momentum



ab initio

fRG approach with emergent composites/dynamical hadronisation

functional RG: $\left(\partial_t + \int_x \dot{\Phi}\frac{\delta}{\delta\Phi}\right)\Gamma_k[\Phi] = \frac{1}{2}$ — $-$ $+\frac{1}{2}$

glue quantum fluctuations

hadronic quantum fluctuations

free energy/ grand potential

quark quantum fluctuations

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

$\partial_t R =$ $\Gamma^{(n)} =$ n

$\left(\partial_t + 2\frac{\delta\dot{\Phi}}{\delta\Phi}\right) R =$ $G =$

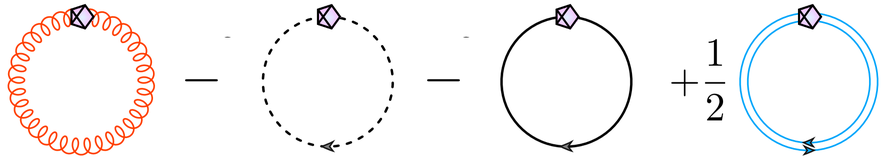
$$\Phi = (A_\mu, c, \bar{c}, q, \bar{q}, \phi)$$

ϕ **hadronic composites**

Flows for correlation functions

functional RG:

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



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

free energy/ grand potential

glue quantum fluctuations

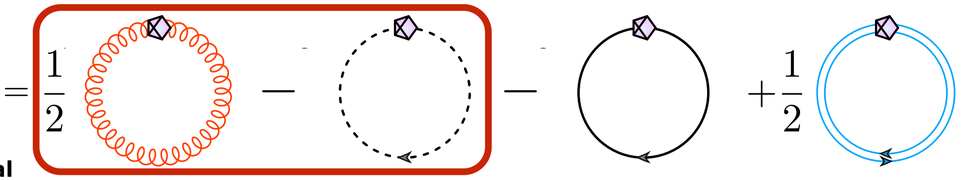
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gluon propagator

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

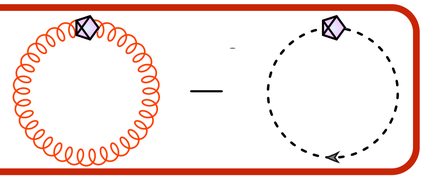
Correlation functions

Pure glue

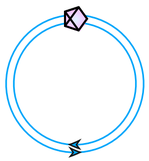
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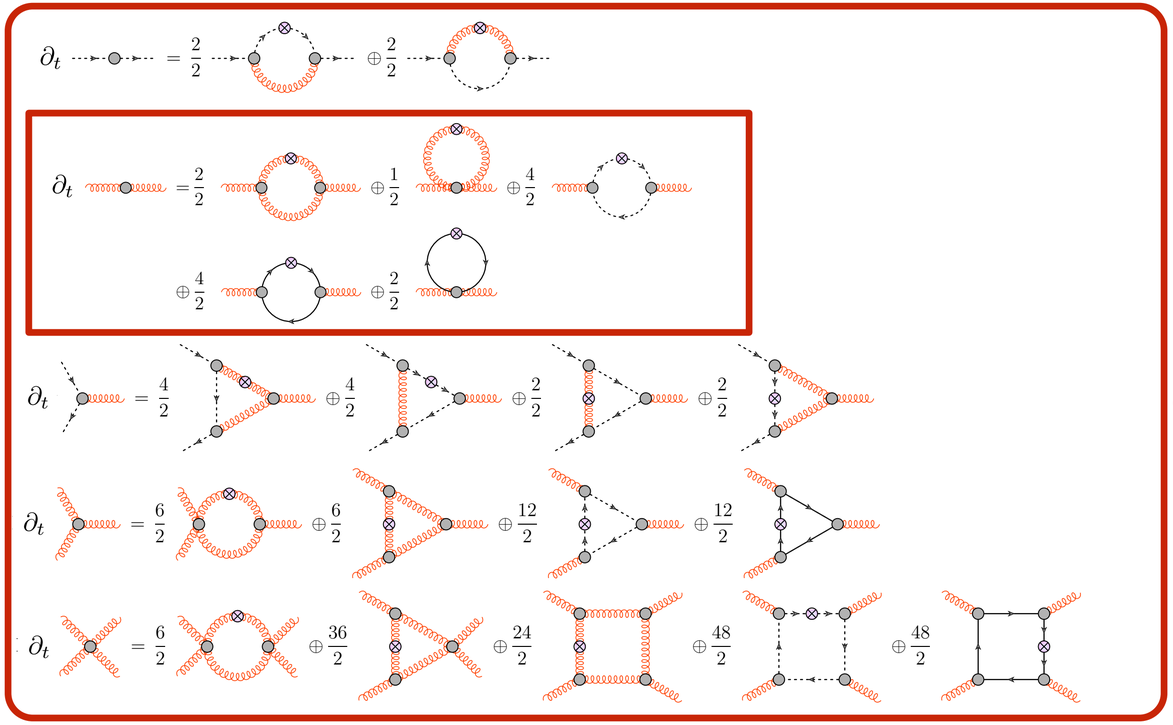
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··· 1-loop exact

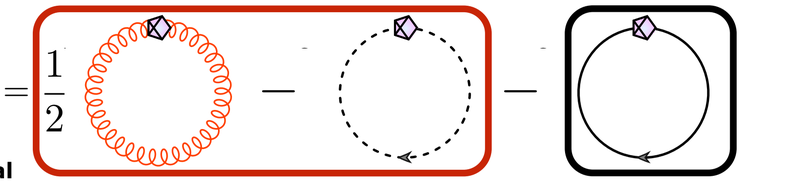
Flows for correlation functions

no hadronic composites

$$\phi = 0$$

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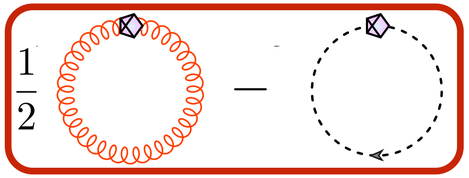
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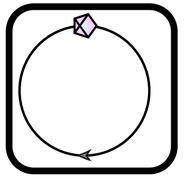
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$$-$$

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quark-gluon vertex

$$\langle q\bar{q}A_\mu \rangle(p_1, p_2)$$

Eight tranverse tensor structures

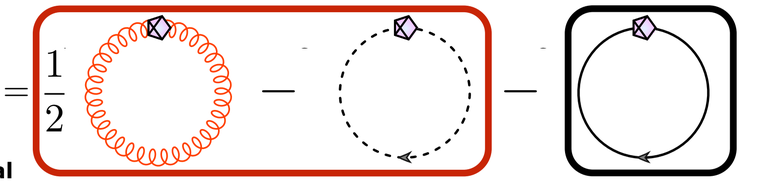
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Eight tranverse tensor structures

quark—anti-quark scattering

$$\langle q\bar{q}q\bar{q} \rangle (p_1, p_2, p_3)$$

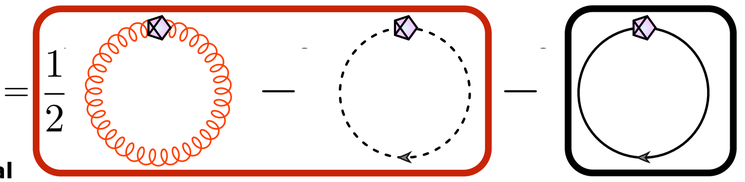
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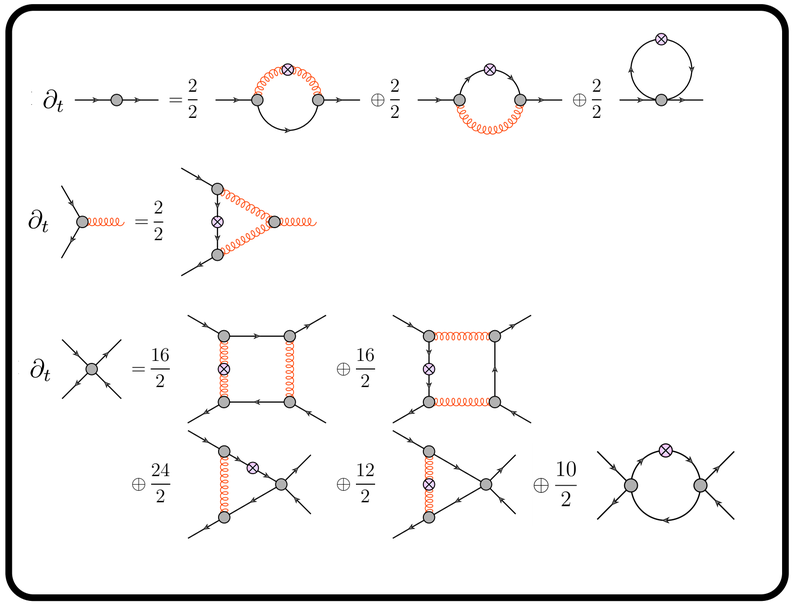
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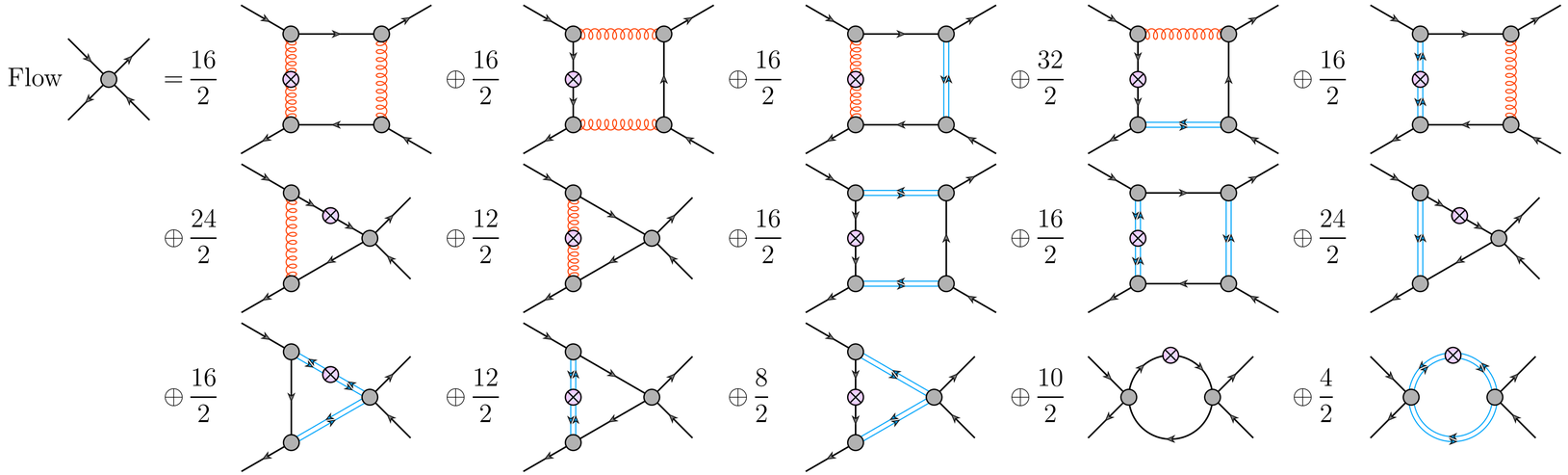
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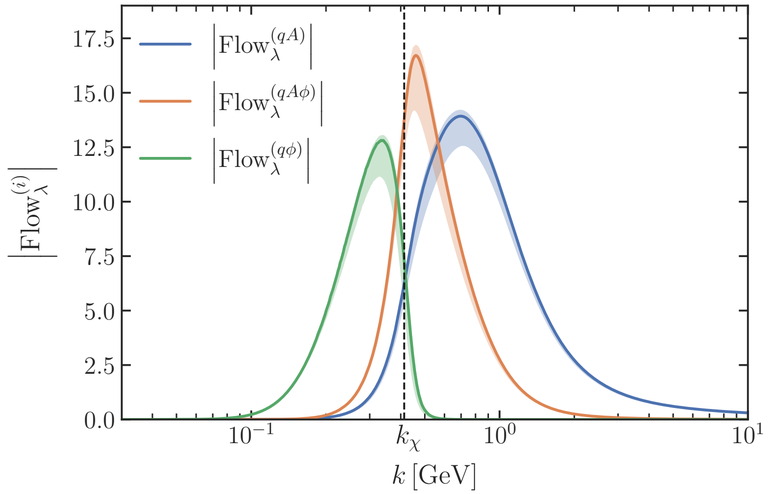


••• 1-loop exact

How to: systematic error estimates & the LEGO® principle

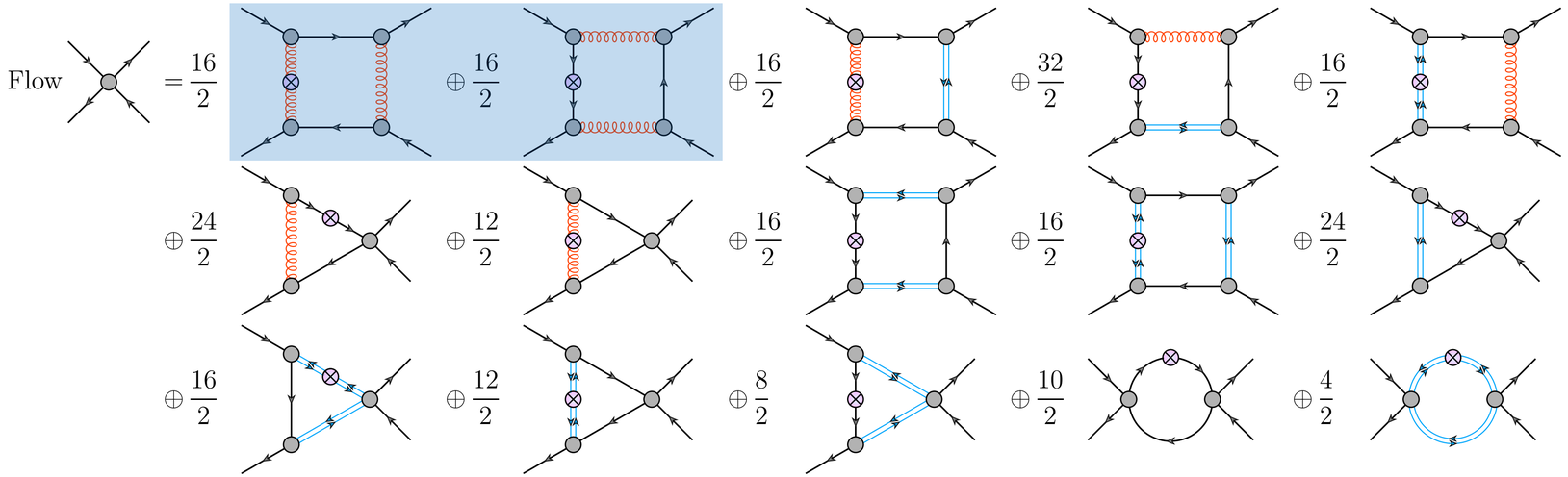


Example: 4-quark scattering vertex

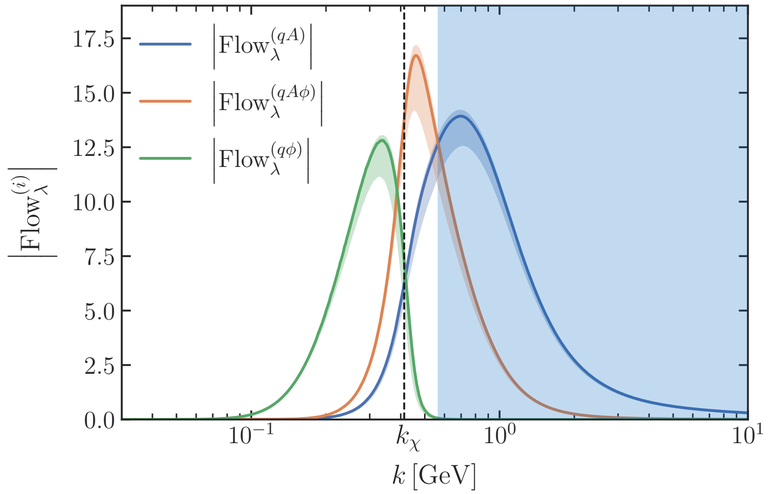


Ihssen, JMP, Sattler, Wink, 113 (2026) 9, 094038

How to: systematic error estimates & the LEGO® principle

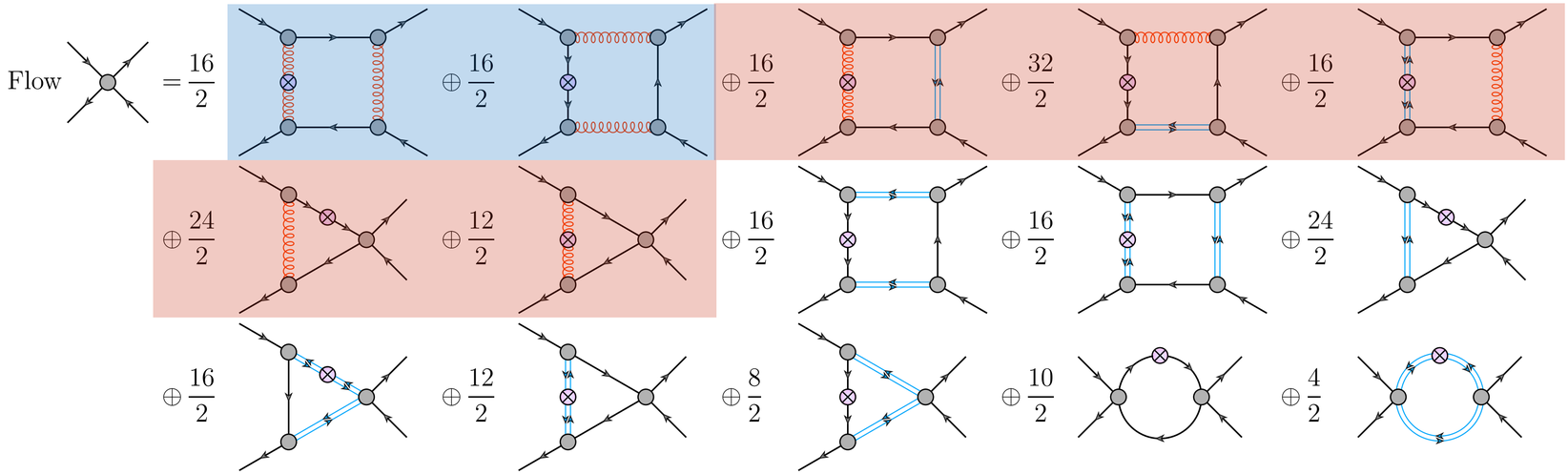


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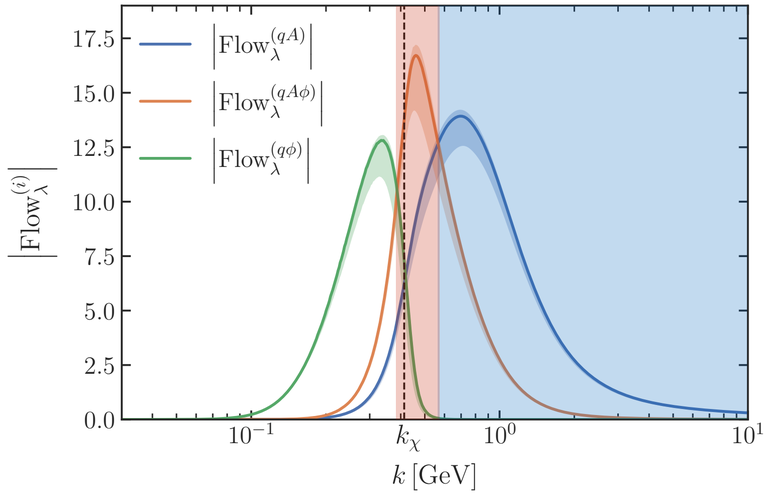


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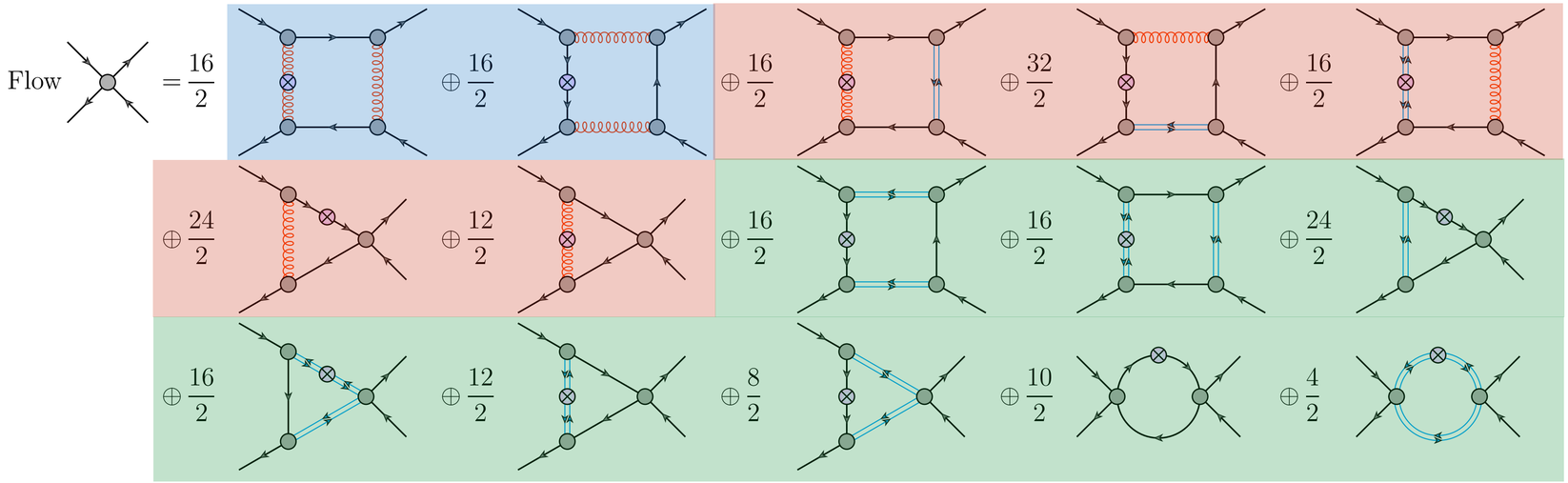


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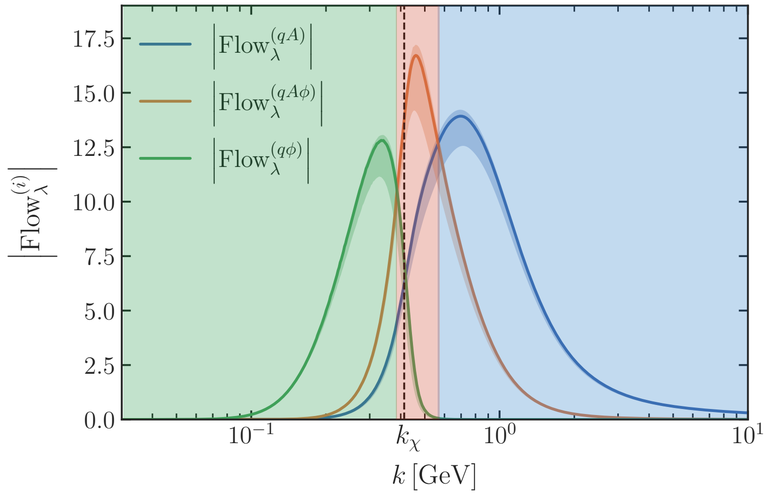


Ihssen, JMP, Sattler, Wink, 113 (2026) 9, 094038

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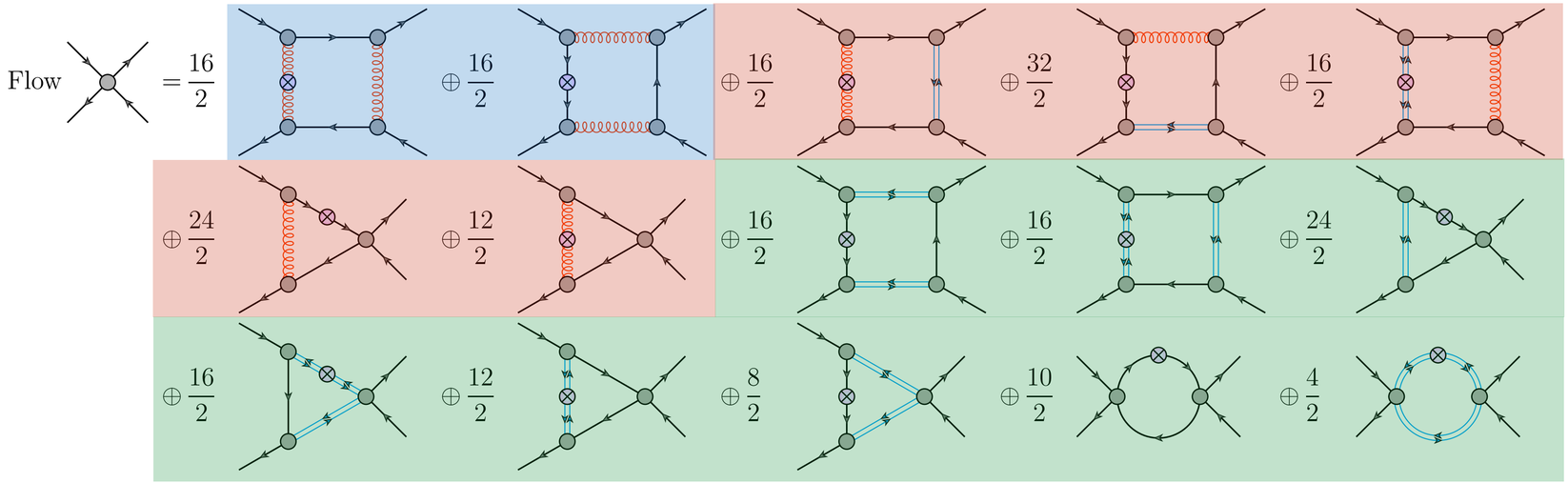


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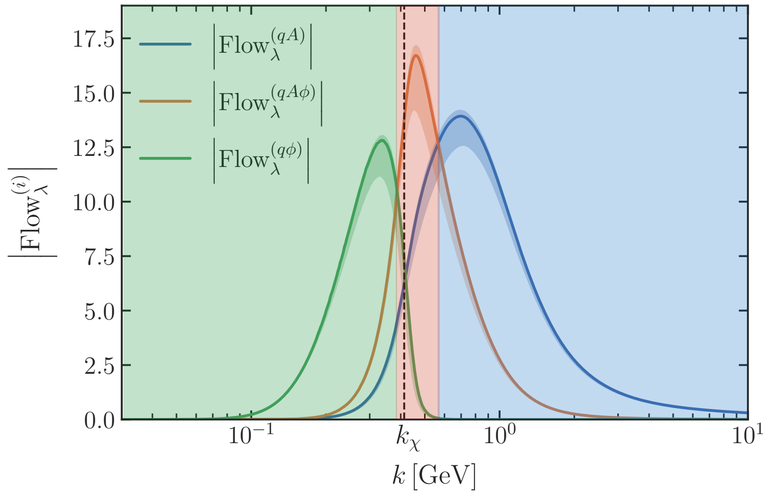


Ihssen, JMP, Sattler, Wink, 113 (2026) 9, 094038

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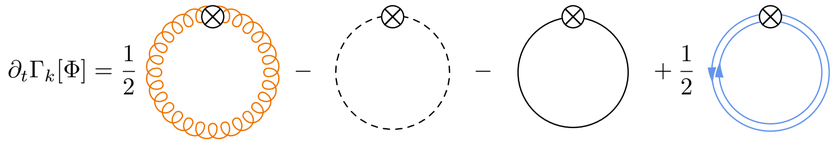
The unreasonable effectiveness of low energy effective theories



Access and combined use of error estimates from functional QCD & LEFTs

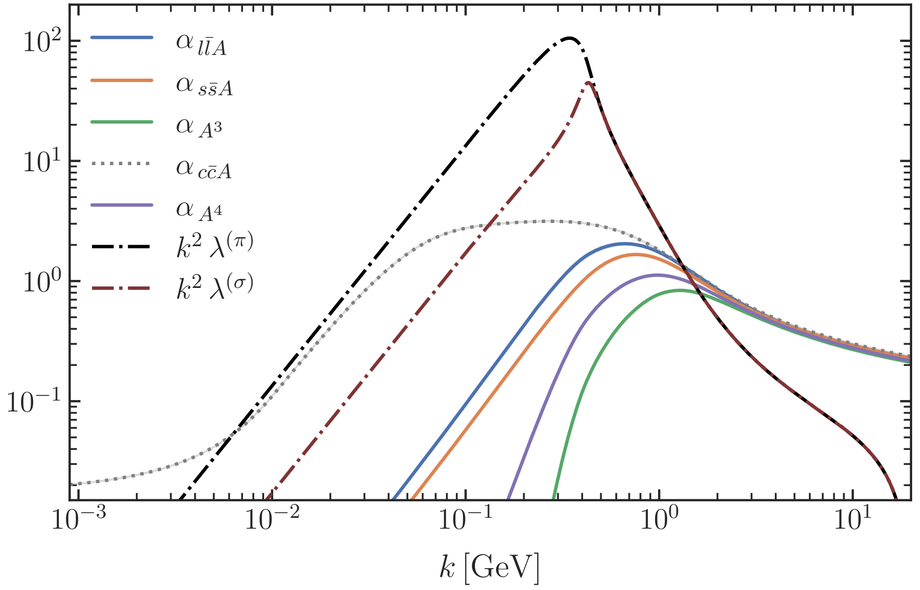
Ihssen, JMP, Sattler, Wink, 113 (2026) 9, 094038

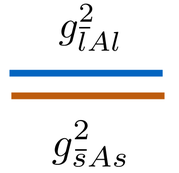
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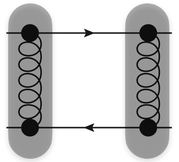


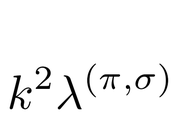
fQCD

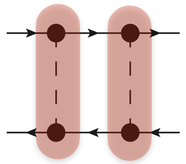
Sequential decoupling of gluon, quark, sigma, pion fluctuations







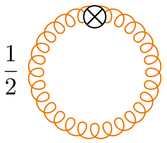
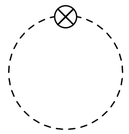
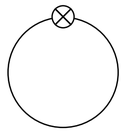
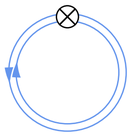




Vacuum: **Ihssen, JMP, Sattler, Wink, arXiv:2408.08413**

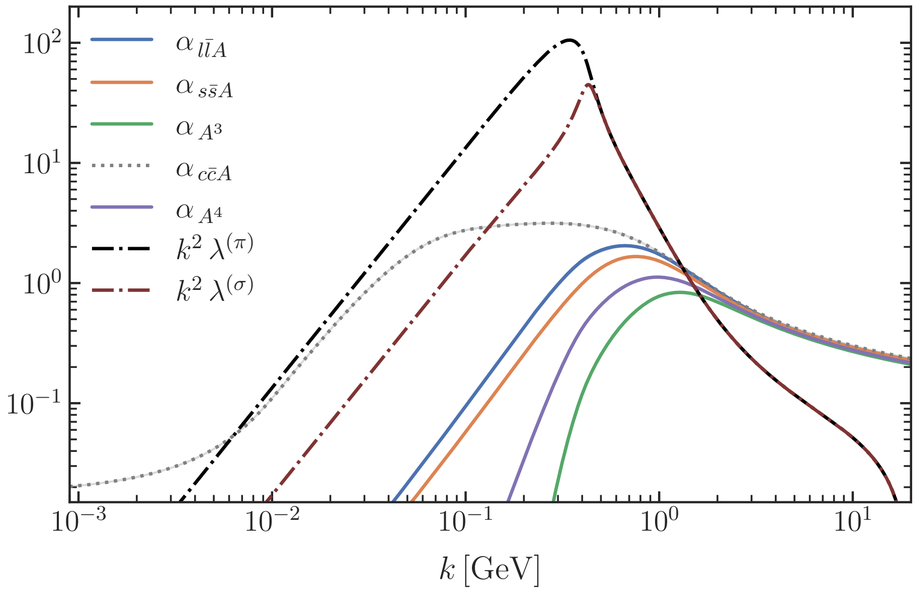
Phase structure: **Fu, JMP, Rennecke, PRD 101, (2020) 054032**

How to: the unreasonable effectiveness of low energy effective theories

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

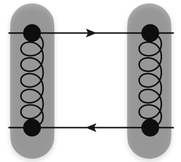
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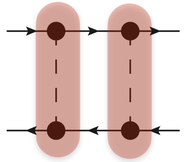


$g^2_{\bar{l}Al}$

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



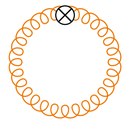
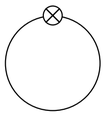
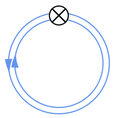
$k^2\lambda^{(\pi,\sigma)}$



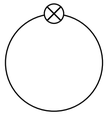
Vacuum: Ihssen, JMP, Sattler, Wink, arXiv:2408.08413

Phase structure: Fu, JMP, Rennecke, PRD 101, (2020) 054032

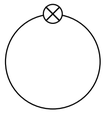
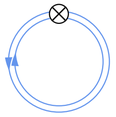
PQM-model

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

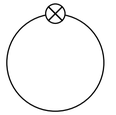
PNJL-model

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

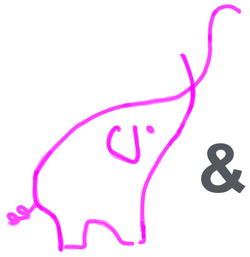
QM-model

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

NJL-model

$-$ 

QCD-assisted low energy effective theories



& functional QCD

Ripples of the CEP

aka

(Strong) signals of the ONP





Baryon vs proton fluctuations

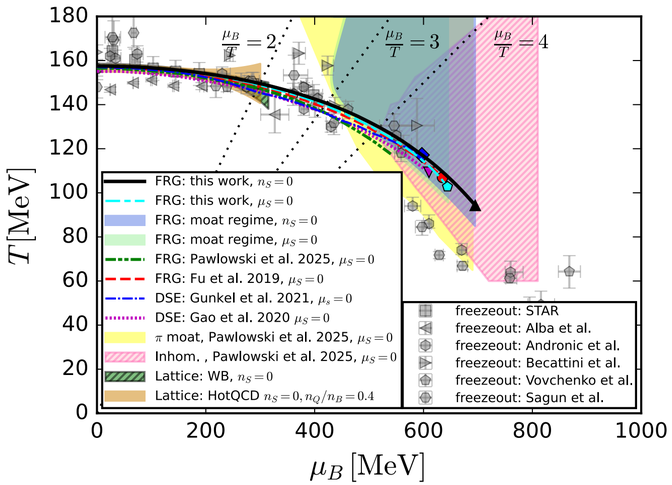
grand canonical vs canonical

Finite volume effects

QCD-assisted low energy effective theory

Direct functional QCD input

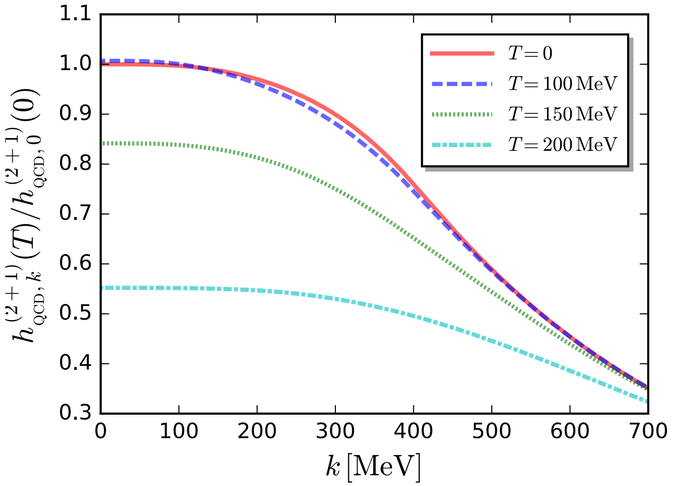
chiral phase structure



+



quark-antiquark — meson scattering



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

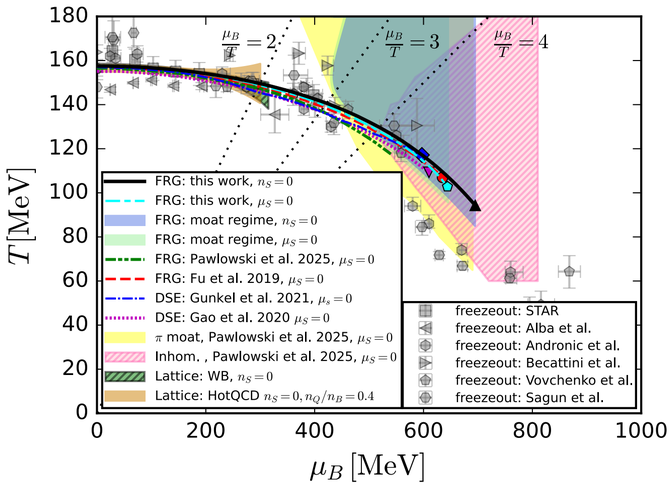
low energy quantum, thermal & density fluctuations via fRG (QCD-assisted PQM model)

Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

QCD-assisted low energy effective theory

Direct functional QCD input

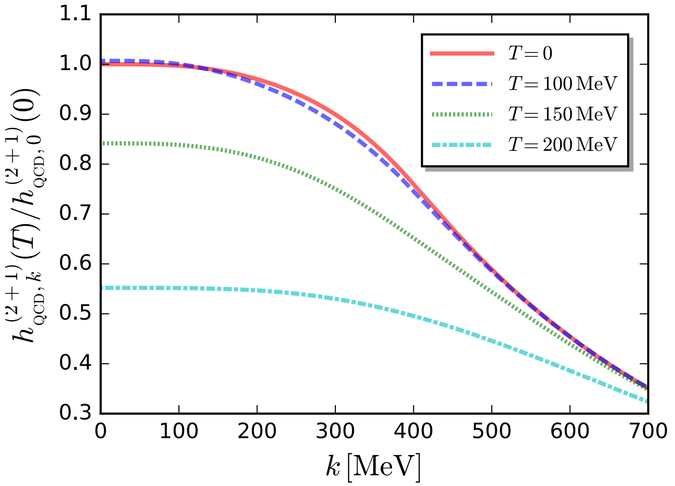
chiral phase structure



+



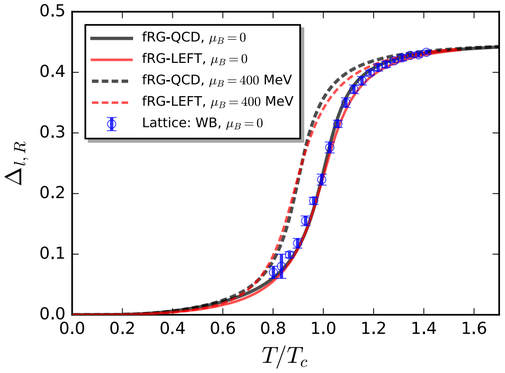
quark-antiquark — meson scattering



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

low energy quantum, thermal & density fluctuations via fRG (QCD-assisted PQM model)

renormalised chiral condensate

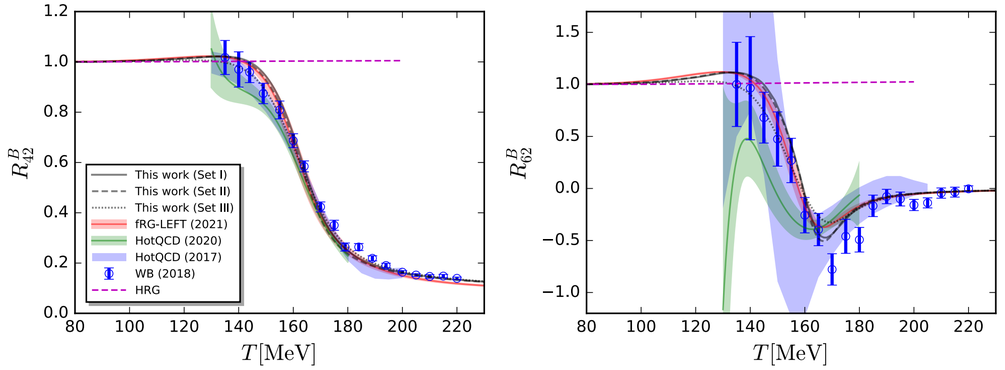


Benchmarks with lattice and functional QCD

at

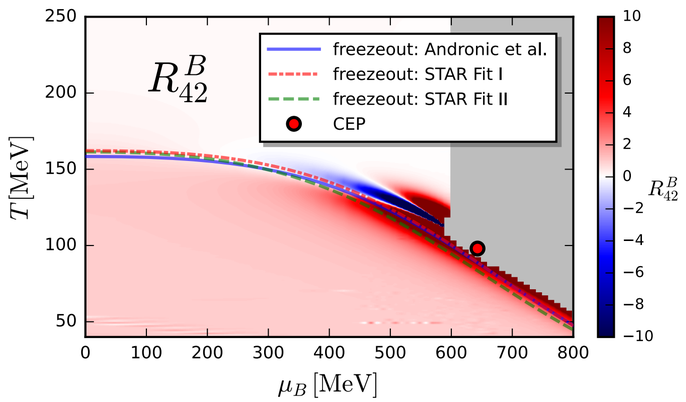
vanishing density and functional QCD at finite density

baryon number fluctuations



Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

Ripples of the critical point

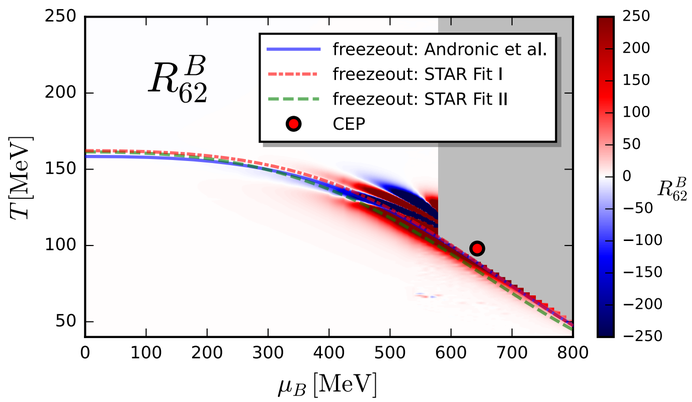


baryon number fluctuations in the phase structure

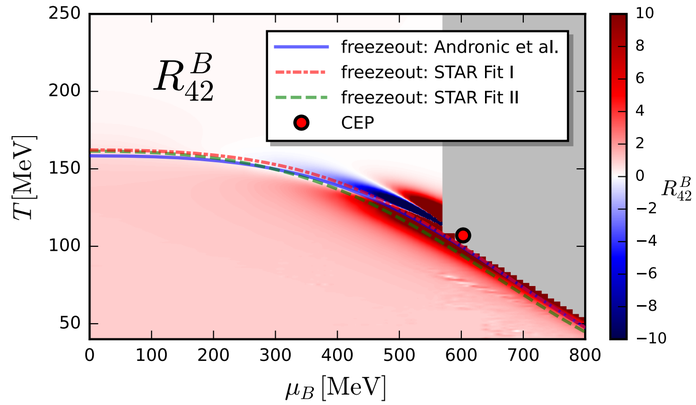
$$(T_{\mathrm{CEP}}, \mu_{B_{\mathrm{CEP}}}) = (98, 643)\,\mathrm{MeV}$$

Ride the

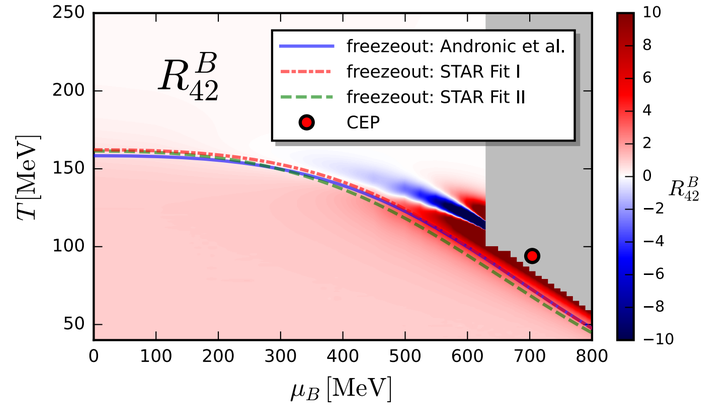




Variations of the CEP in the allowed estimate regime



$$(T_{\mathrm{CEP}}, \mu_{B_{\mathrm{CEP}}}) = (108, 604)\,\mathrm{MeV}$$



$$(T_{\mathrm{CEP}}, \mu_{B_{\mathrm{CEP}}}) = (94, 704)\,\mathrm{MeV}$$

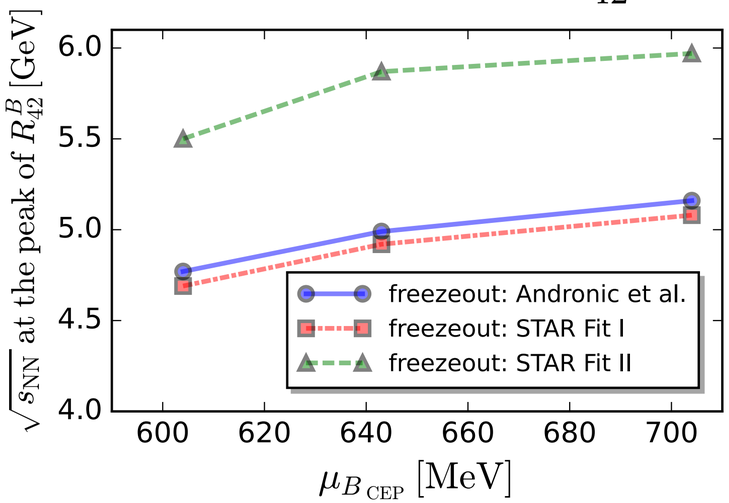
Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502



Ripples of the critical point at chemical freeze-out



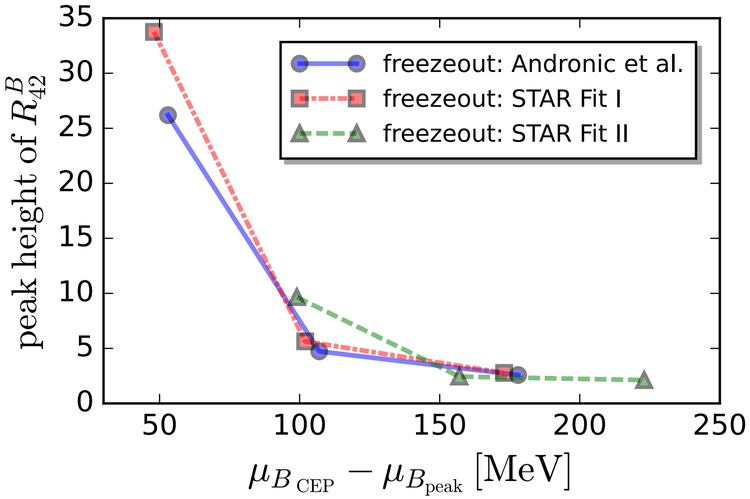
Location of the peak of R^B_{42}





Reconstructing the CEP

Height of the peak of R^B_{42}



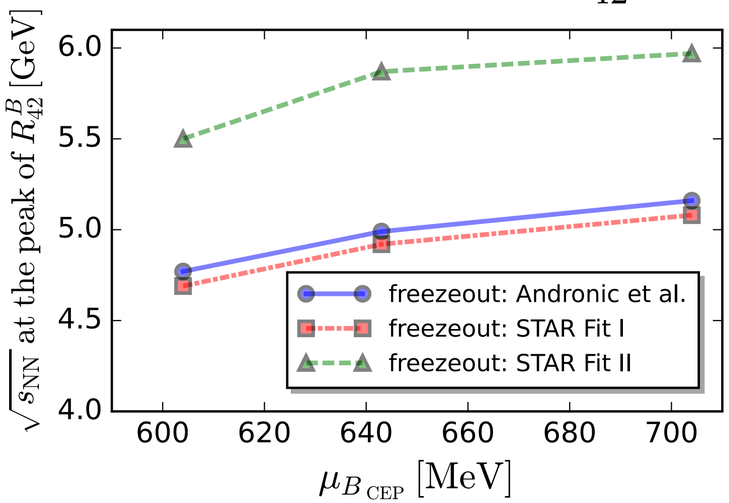
Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502



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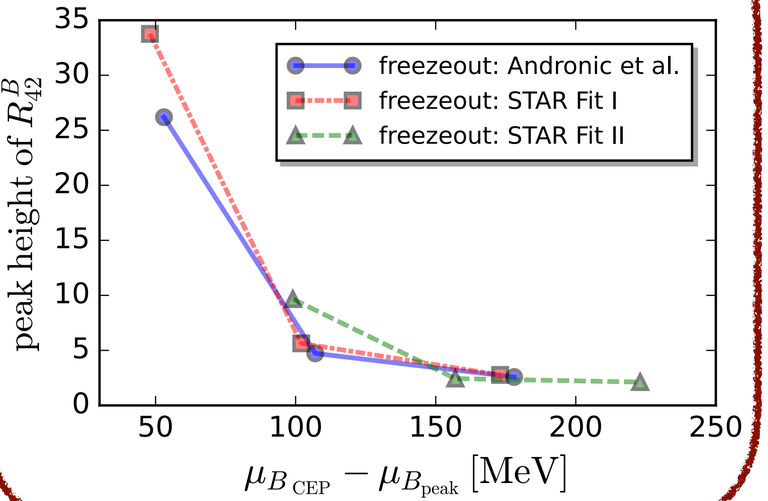
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Reconstructing the CEP

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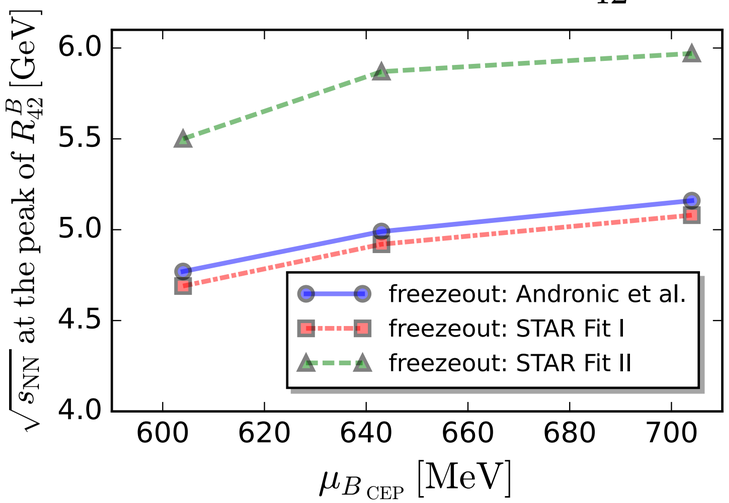
Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502



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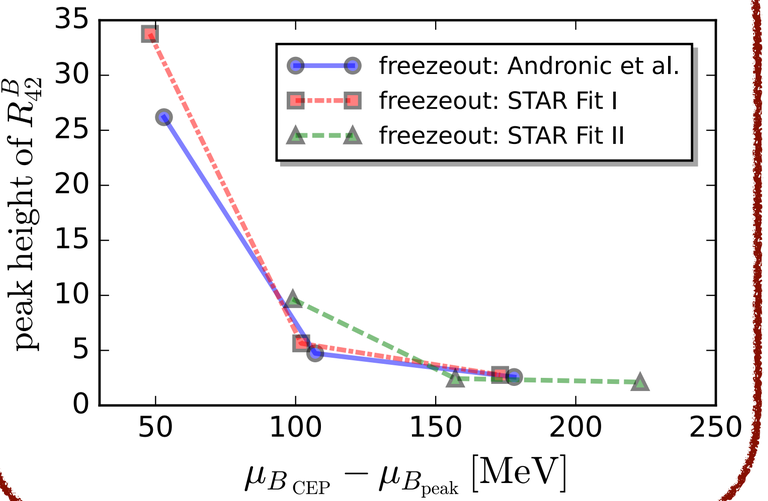
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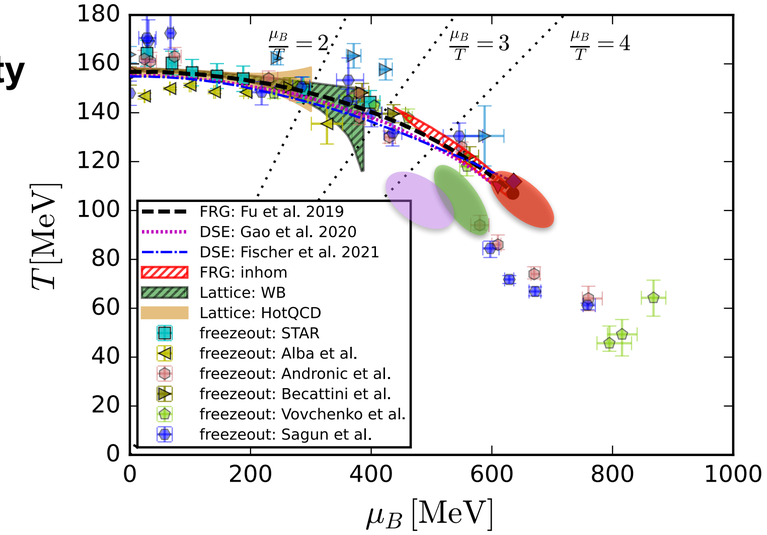
Unfolding the high density regime with new phases & physics

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

Fu, Luo, JMP, Rennecke, Wen, Yin, PRD 111, L031502

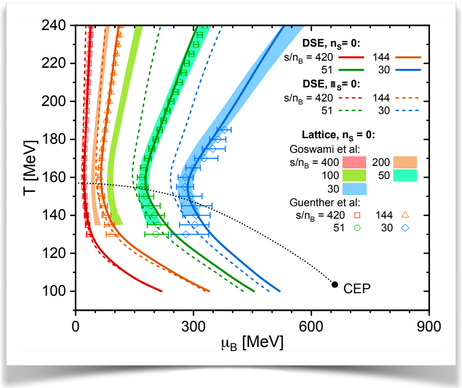
Summary

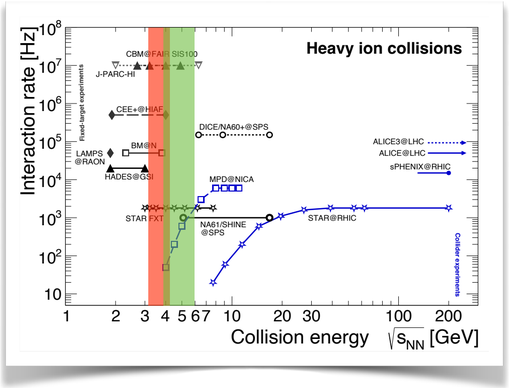
- **Functional QCD provides direct 1st principle results for the phase structure at finite density**
  - **Predictions:** $\frac{\mu_B}{T} \lesssim 4$
  - **Estimates:** $4 \lesssim \frac{\mu_B}{T} \lesssim 8$
- **Soft modes are commonplace, critical regimes are small**
- **Ripples of new phases aka of the critical end point**
  - **Explanation for the convergence of CEP locations of extrapolation approaches**
  - **Results & observables: EoS, fluctuations of conserved charges, tiny critical regime & onset of new phases; moat regime, ….**
  - **Peak height of kurtosis carries the location of the CEP**

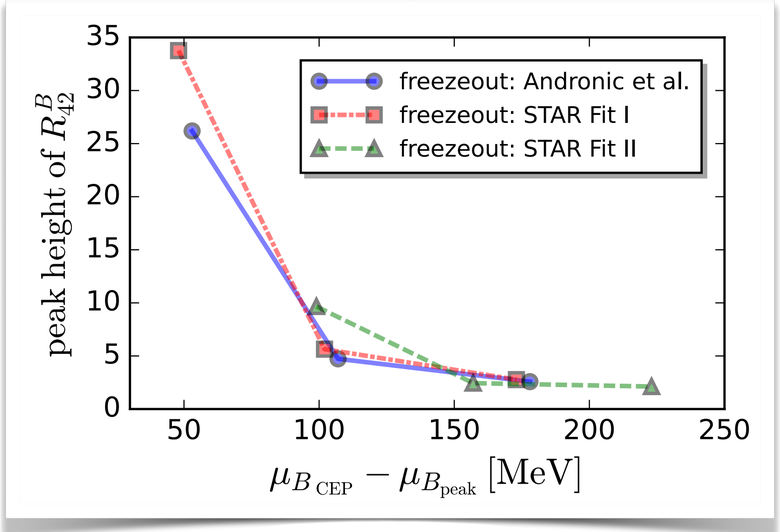


$$(\mu_B\,,\,T)_{\mathrm{CEP}} \sim (700\,,\,90)\ \mathrm{MeV}$$

Strangeness neutrality







Jump forward: Strong correlations above the chiral crossover

How to: Functional QCD, extrapolations & the minimal point of view





'… and now for something completely different…'

Extrapolations & von Neumann's Elephant

Extrapolations are ill-conditioned problems

Those are my interpretations, and if you don't like them…. well, I have others



'… and now for something completely different…'

Extrapolations & von Neumann's Elephant

Extrapolations are ill-conditioned problems

Those are my interpretations, and if you don't like them…. well, I have others

'There are two ways of doing calculations in theoretical physics.
One way is to have a clear physical picture of the process that you are calculating.
The other way is to have a precise and self-consistent mathematical formalism.
…You have neither'

Fermi to Dyson



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'*With four parameters I can fit an elephant,*
and with five I can make him wiggle his trunk'

Von Neumann



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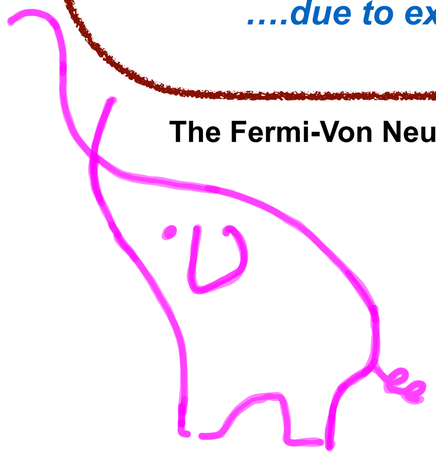
'*With four parameters I can fit an elephant,*
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Von Neumann

With four parameter models we can fit many data
but we cannot extrapolate without external information

In particular, extrapolations cannot predict the existence and location of the CEP without external information

The other way is to have a precise and self-consistent effective theory whose systematic error is under control ….due to external QCD information



The Fermi-Von Neumann QCD phase structure elephant



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Extrapolations & von Neumann's Elephant

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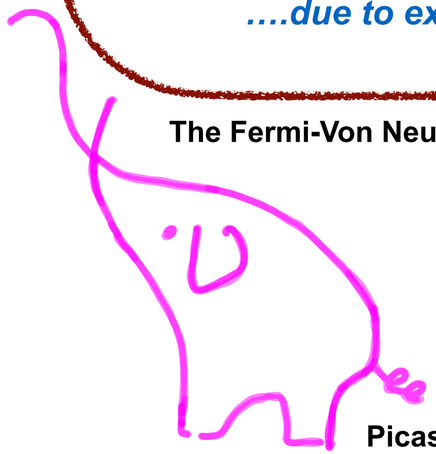
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Picasso-assisted Pawlowski elephant



'... and now for something completely different...'

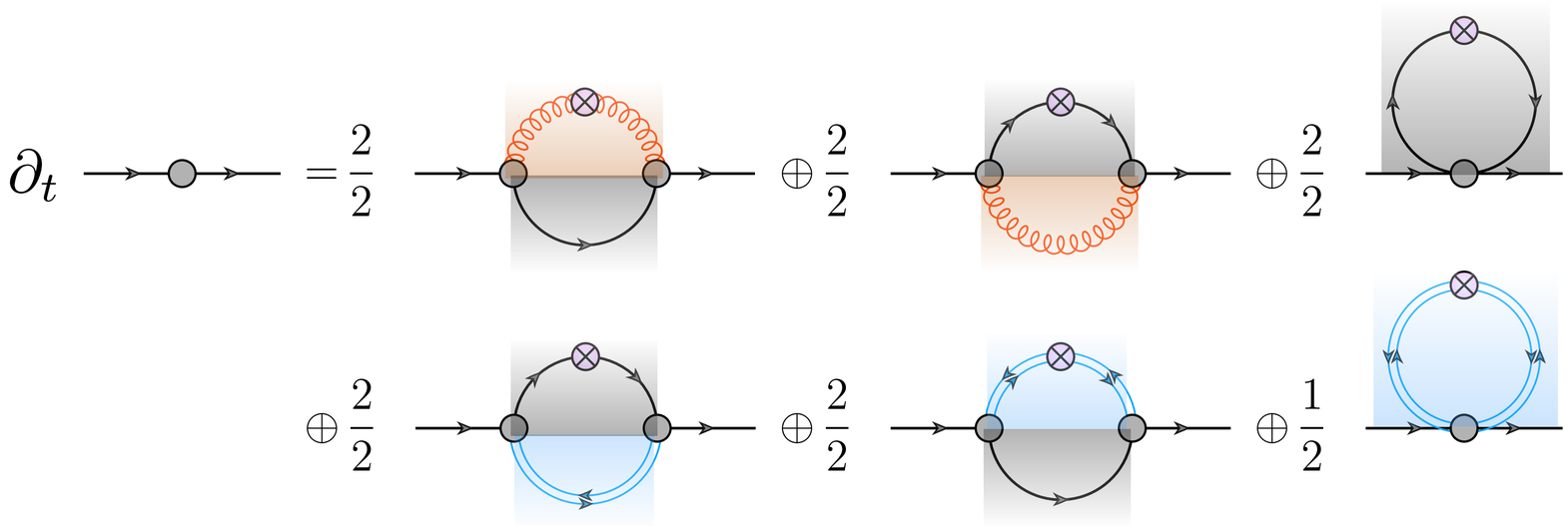
How to: direct computations (funQCD) vs extrapolations

To QCD or not to QCD….a minimal point of view

Those are my interpretations, and if you don't like them…. well, I have others

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

$$\partial_t \Big\langle q(x)\bar{q}(y)\Big\rangle^{-1}(\mu_B) = \text{Loop}\left[\Big\langle A_\mu(x)A_\nu(y)\Big\rangle(\mu_B), \Big\langle q(x)\bar{q}(y)\Big\rangle(\mu_B), \Big\langle \phi(x)\phi(y)\Big\rangle(\mu_B), \Big\langle q(x)A_\mu(y)\bar{q}(z)\Big\rangle(\mu_B), \cdots; \mu_B\right]$$





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How to: direct computations (funQCD) vs extrapolations

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Unique to functional QCD

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



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Unique to functional QCD

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

- **?Corroborated?**

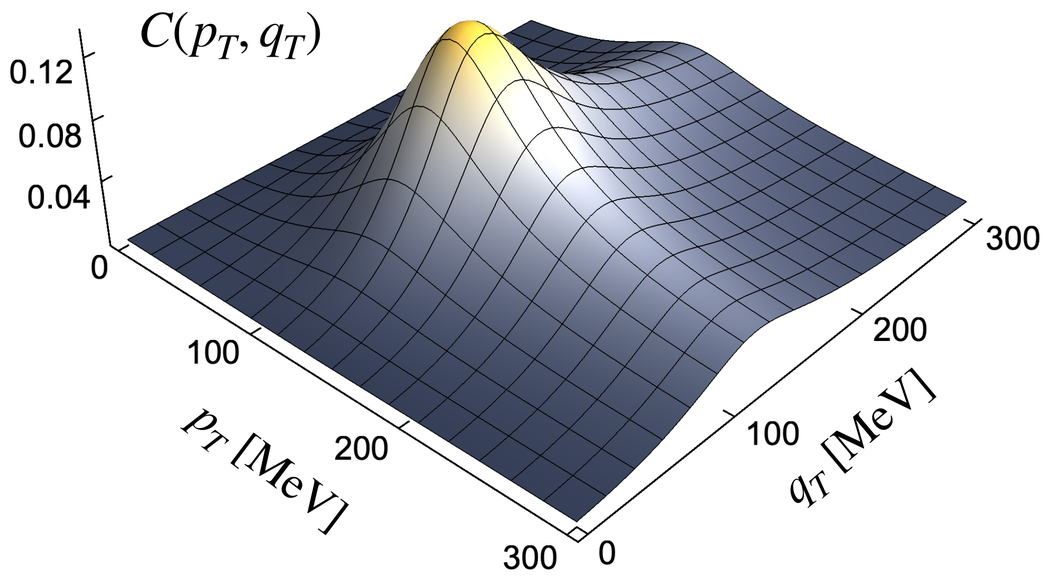
By definition, LEFTs (including extrapolations) cannot assess the existence or absence of emergent phenomena!

MORE TWO-PARTICLE CORRELATIONS

qualitative result appears to be generic

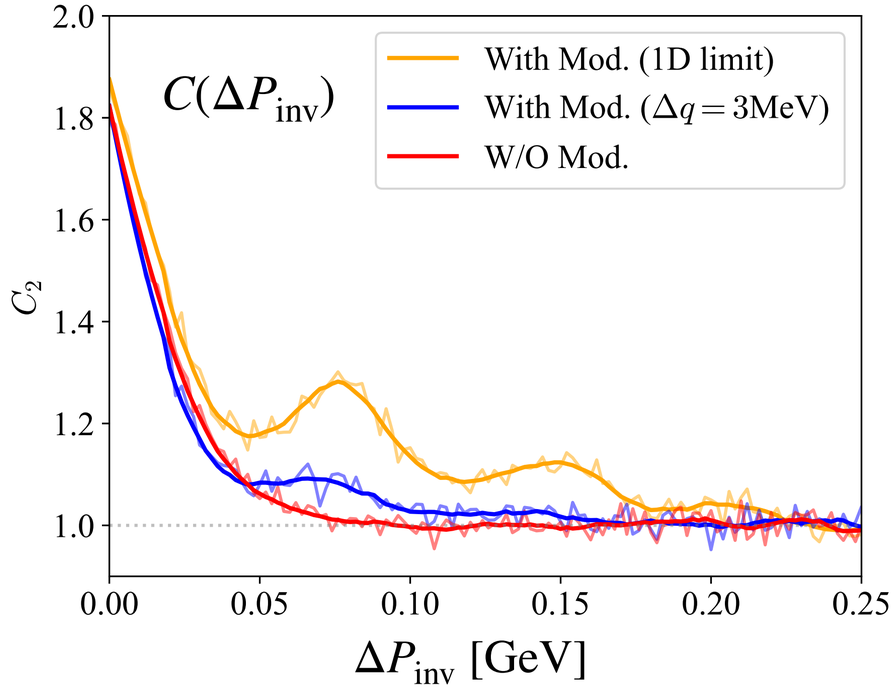
thermodynamic fluctuations in a moat regime

[Pisarski, FR; PRL 127 (2021)]



interference from primordial inhomogeneity (with AMPT transport)

[Fukushima et al.; PRC 109 (2023)]



→ peak position related to wavenumber of underlying spatial modulation

Slides Fabian

HANBURY-BROWN-TWISS CORRELATIONS

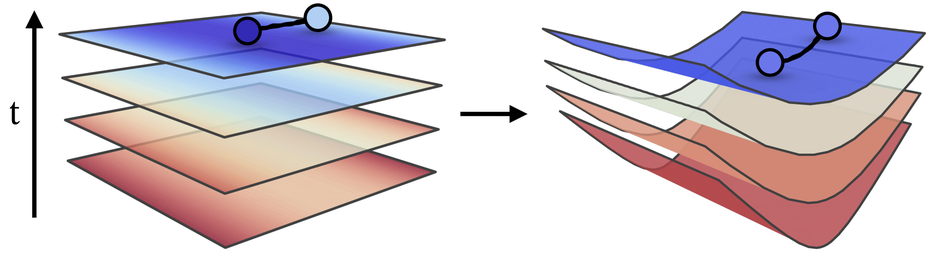
[FR, Pisarski, Rischke, PRD 107 (2023)]

Two-pion correlations from interference

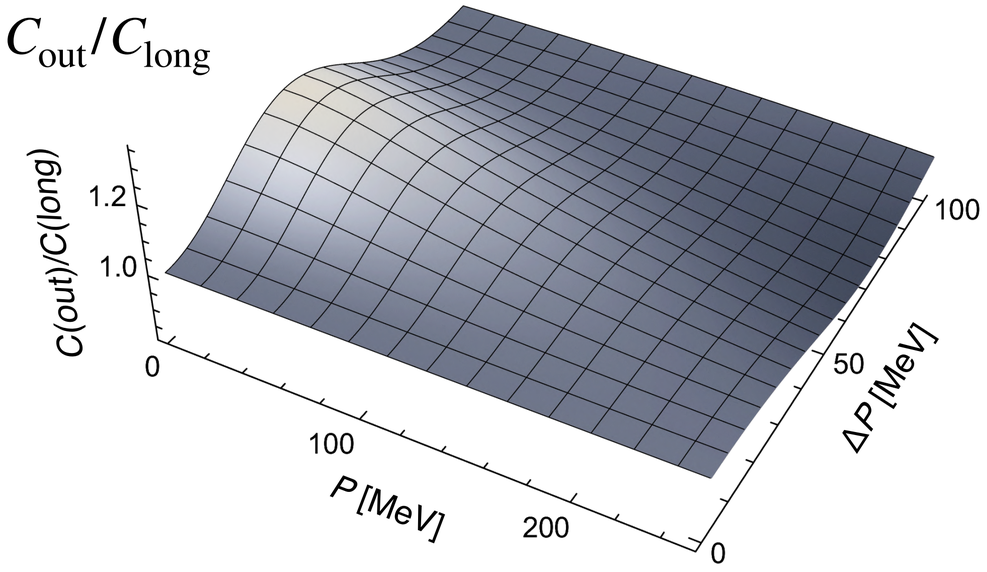
$$\langle \hat{N}_\pi \hat{N}_\pi \rangle \sim C(\mathbf{P}, \mathbf{\Delta P}) \sim \int d\Sigma_X \, DP_\parallel \, e^{-i\,\overline{\Delta P}\cdot X} f(X,P)\, \rho(X,P)$$

spectral function

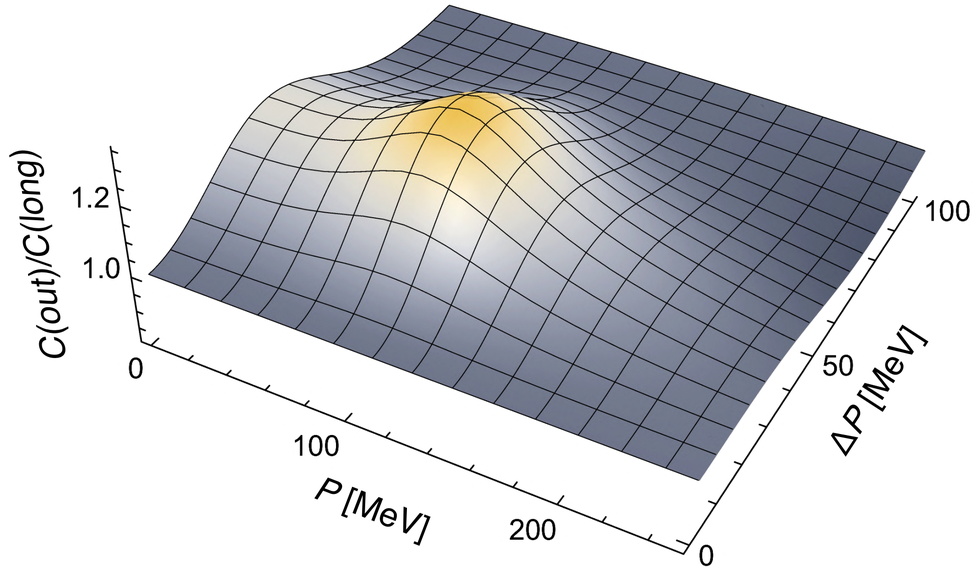
correlations on hypersurface with fixed T and μ_B



normal:



moat:



→ characteristic peak at nonzero average pair momentum

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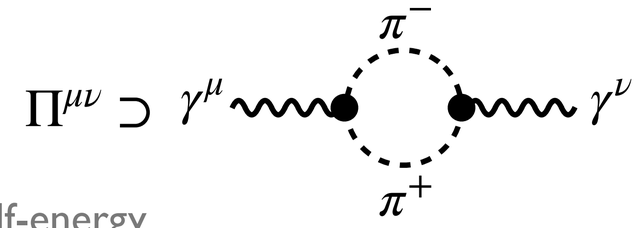
DILEPTON PRODUCTION

[Nussinov, Ogilvie, Pannullo, Pisarski, FR, Schindler, Winstel; PRL 135 (2024)]

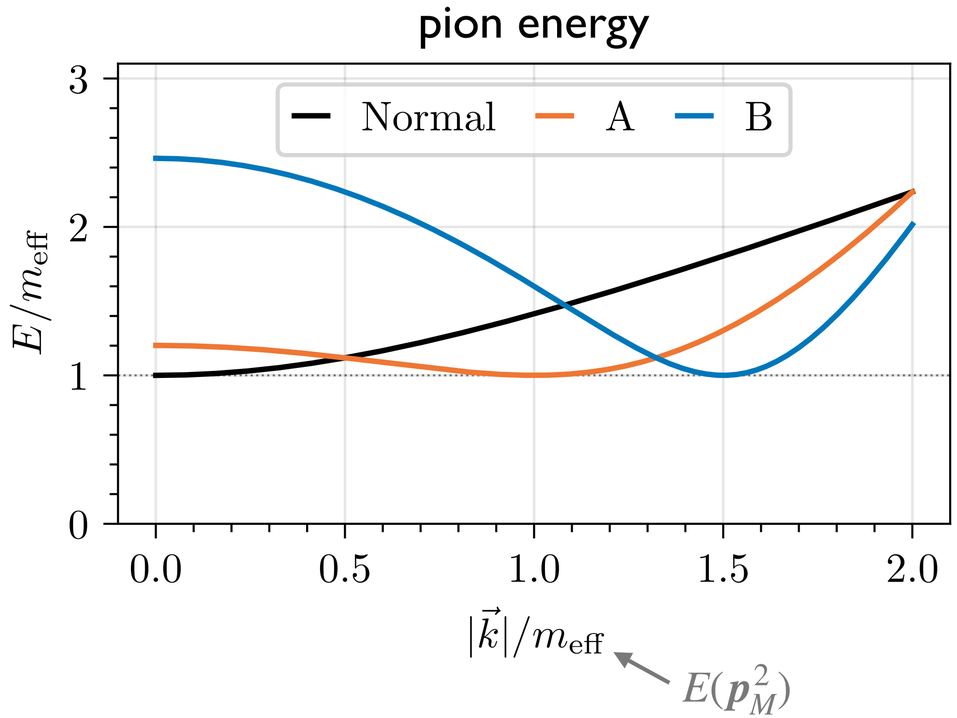
Contribution to the dilepton rate though pions/moatons:

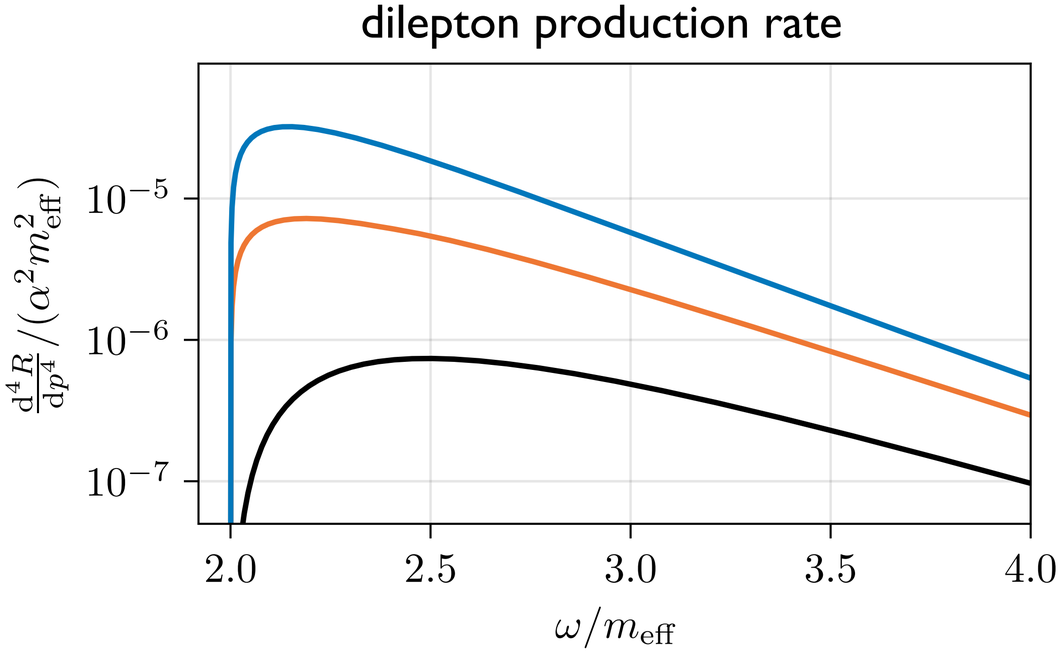
$$\frac{d^4R}{dp^4} \sim \mathrm{Im}\,\Pi^{\mu\nu}(p)$$

photon self-energy



For back-to-back dileptons ($p = 0$)





→ **enhanced dilepton rate at two-pion threshold**

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