



On QCD correlation functions at finite temperature



Jan M. Pawlowski

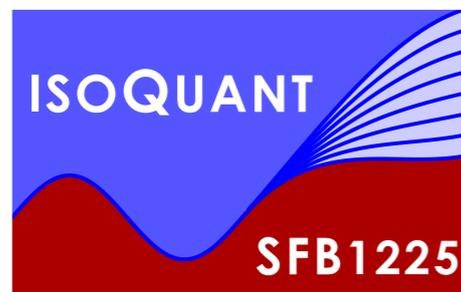
Universität Heidelberg & ExtreMe Matter Institute

Paris, November 9th 2017



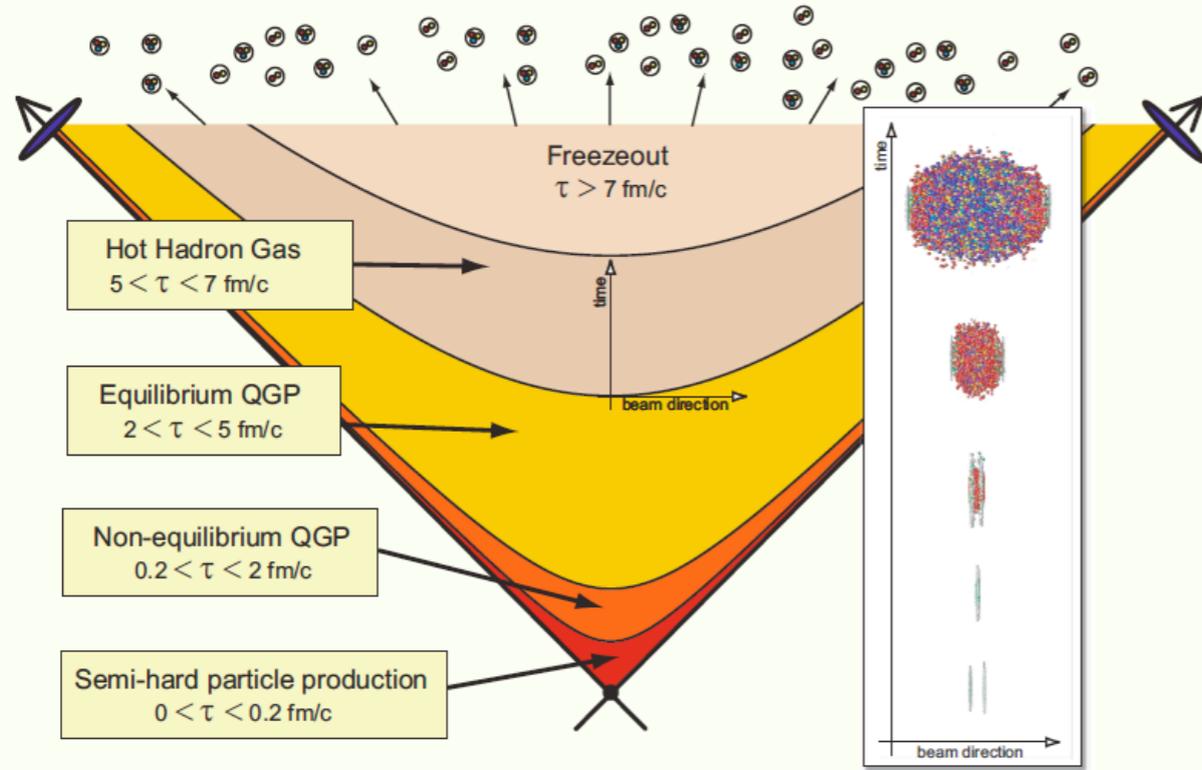
GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung



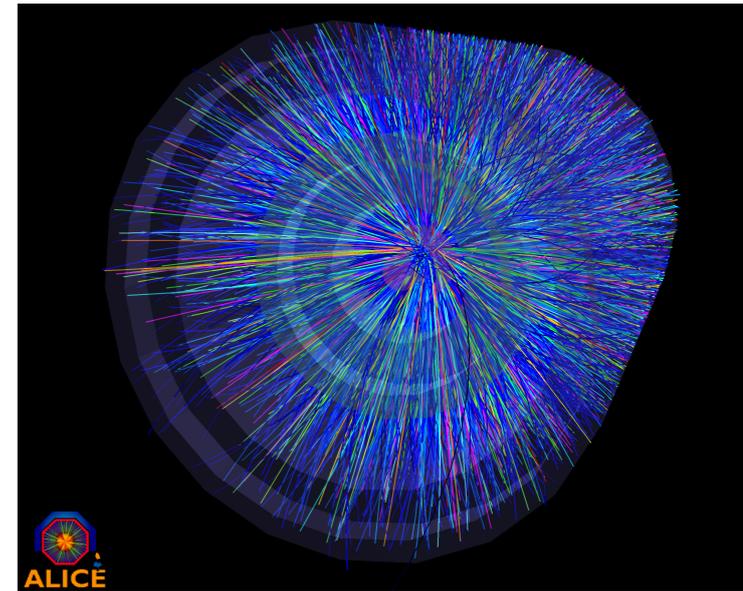
Heavy ion collisions

Heavy-ion collision timescales and “epochs” @ RHIC

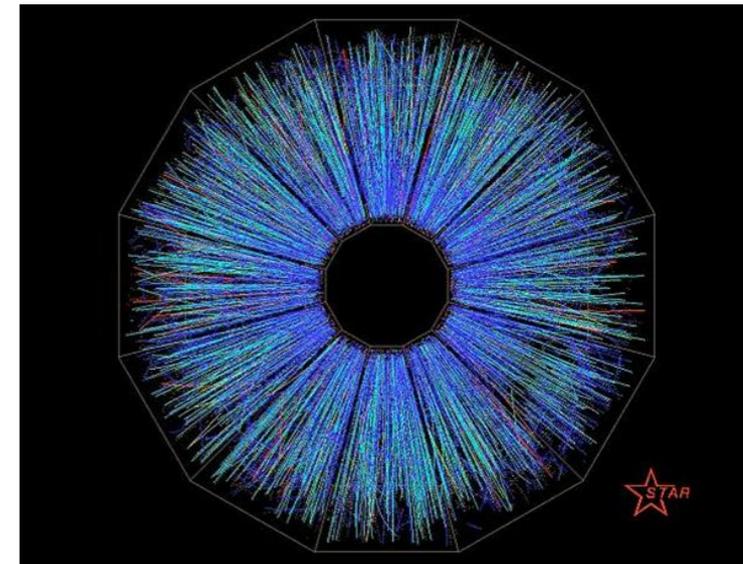


*1 fm/c $\simeq 3 \times 10^{-24}$ seconds

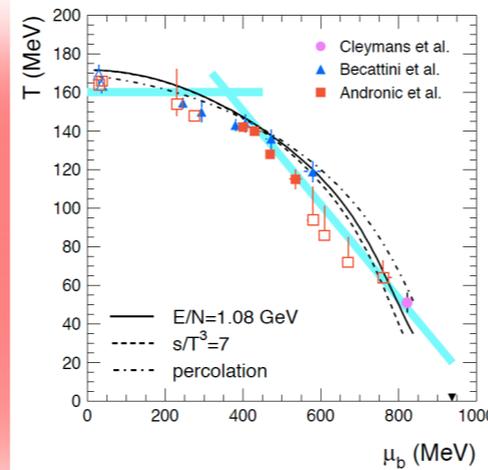
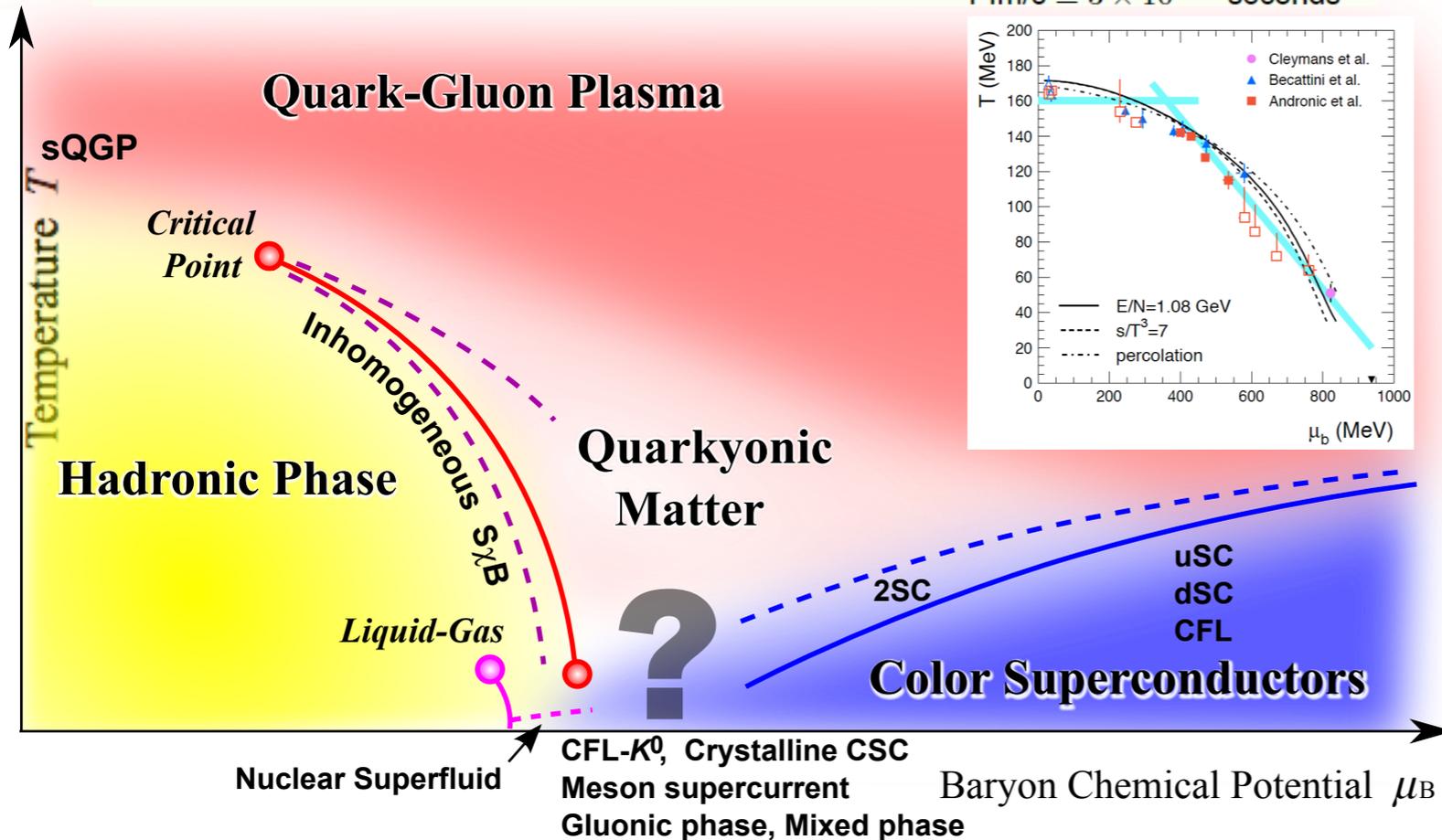
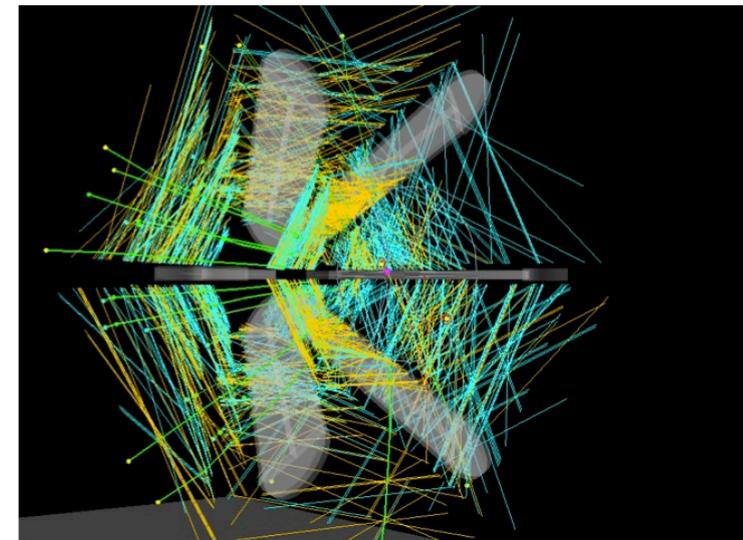
LHC



RHIC

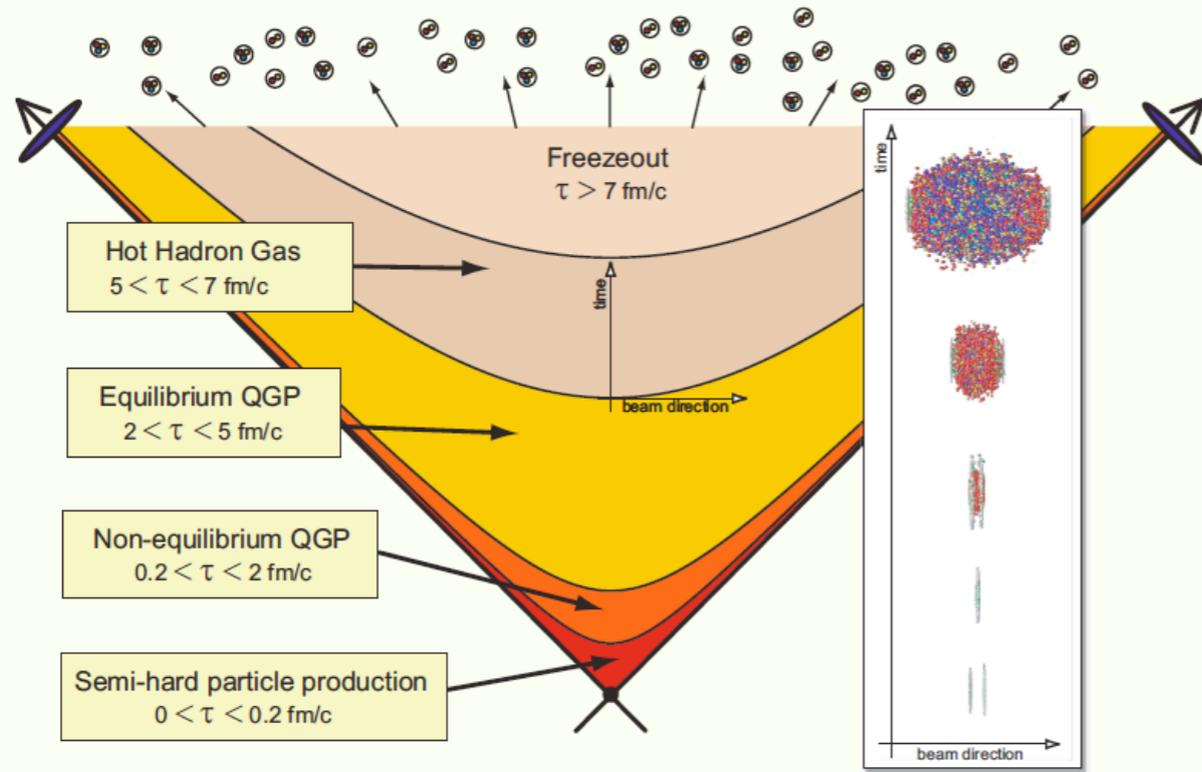


HADES



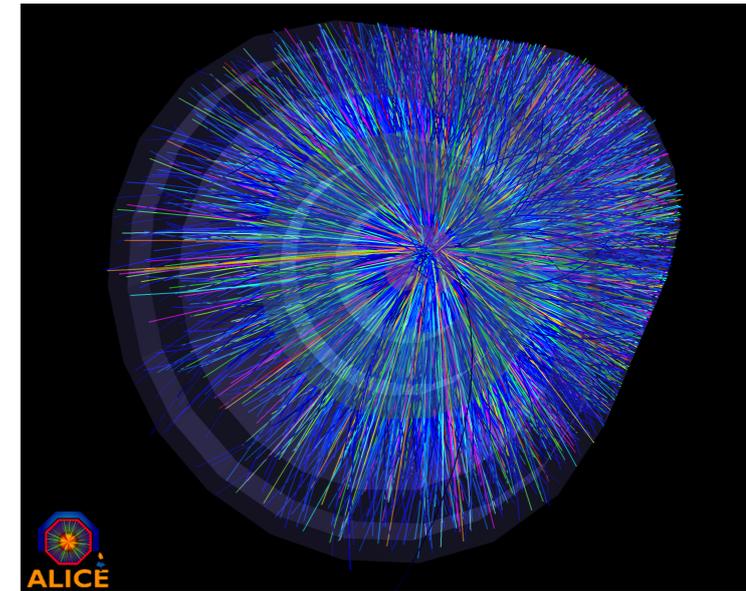
Heavy ion collisions

Heavy-ion collision timescales and “epochs” @ RHIC

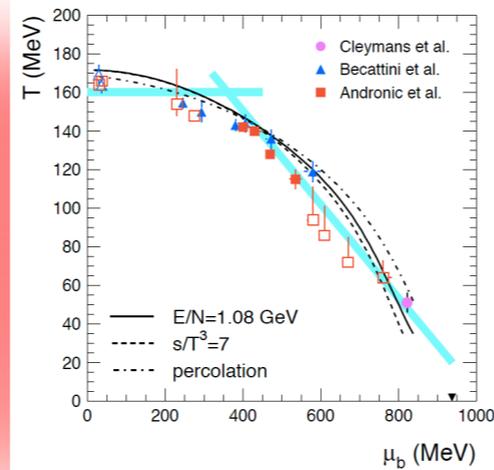
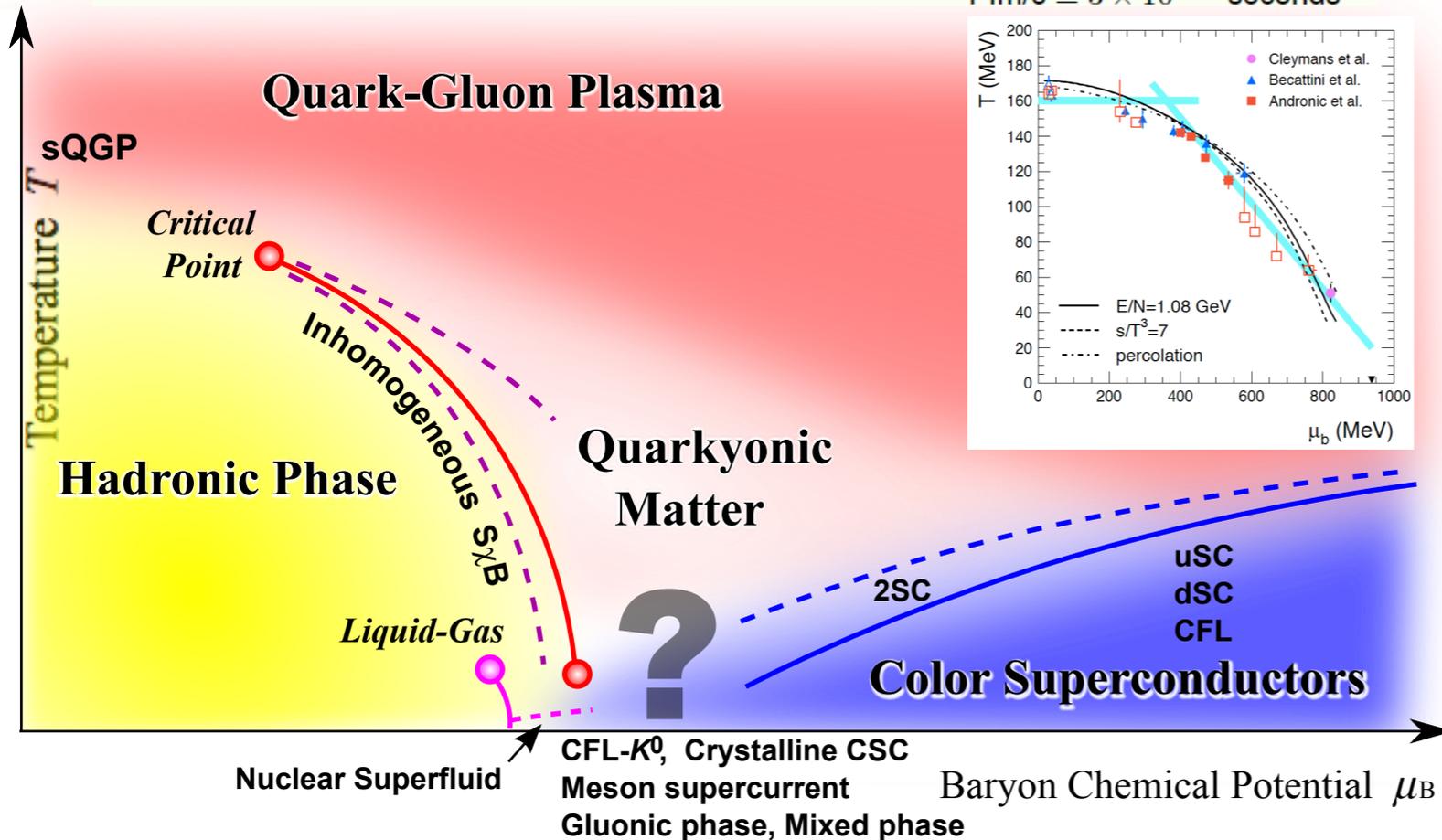
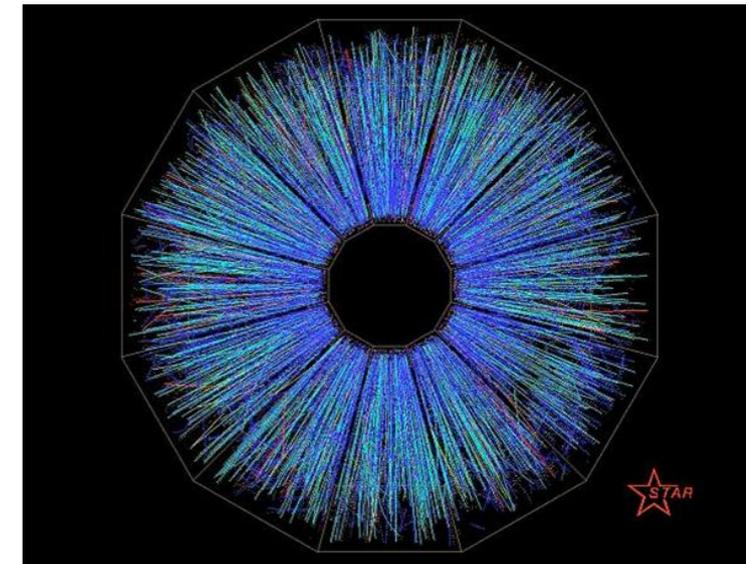


*1 fm/c $\simeq 3 \times 10^{-24}$ seconds

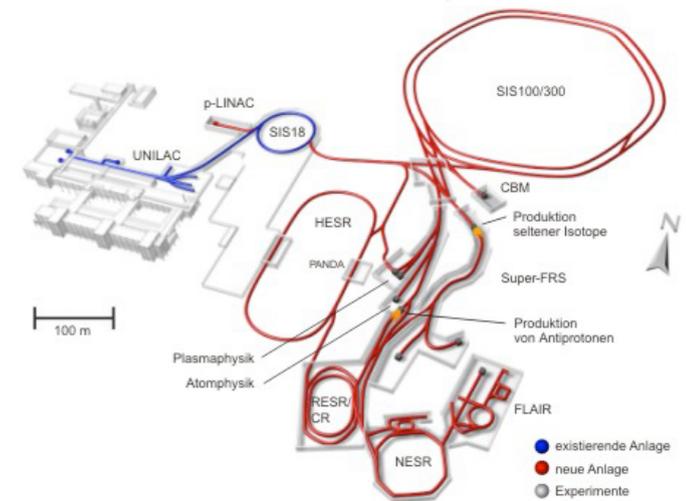
LHC



RHIC



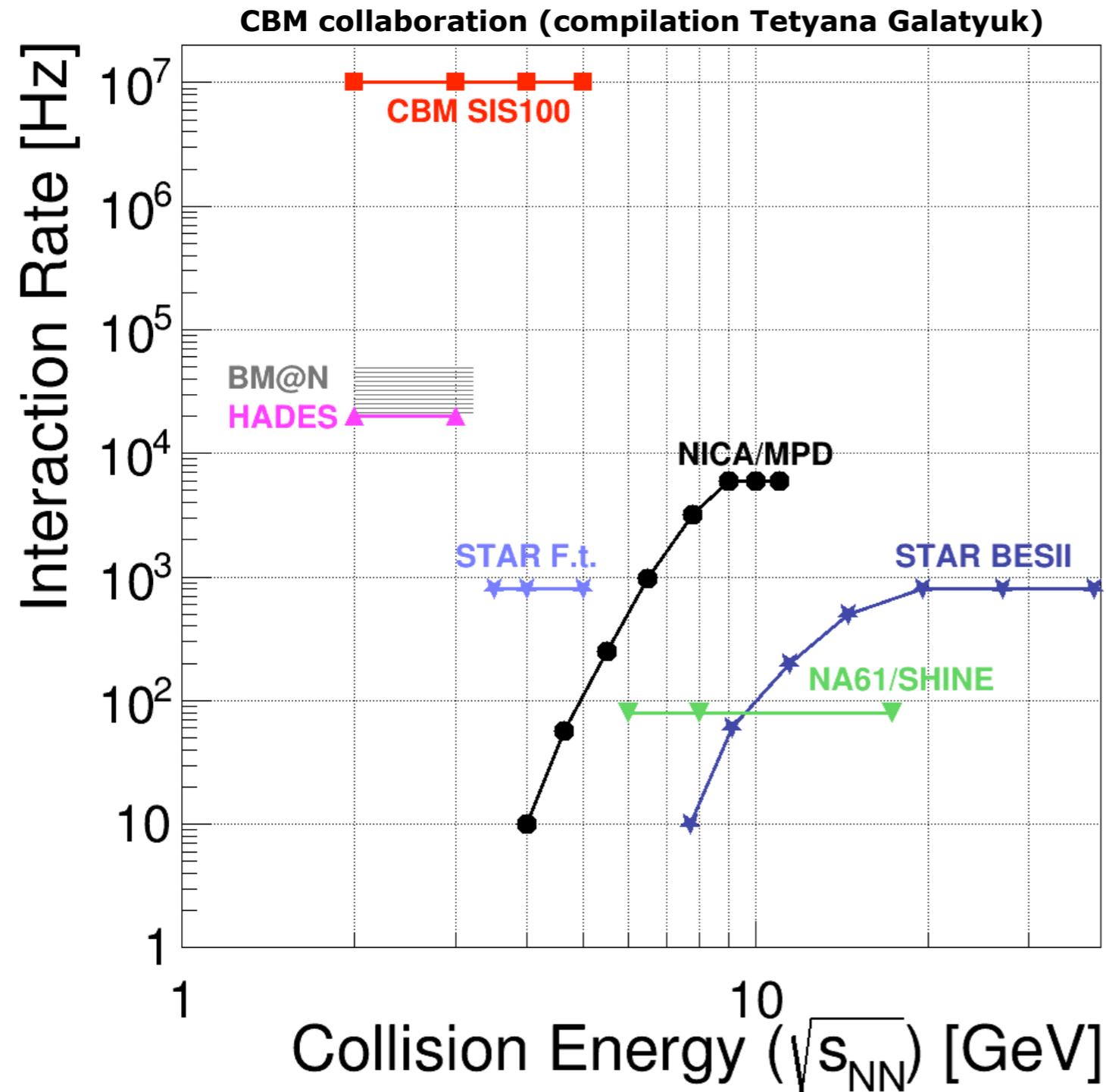
FAIR



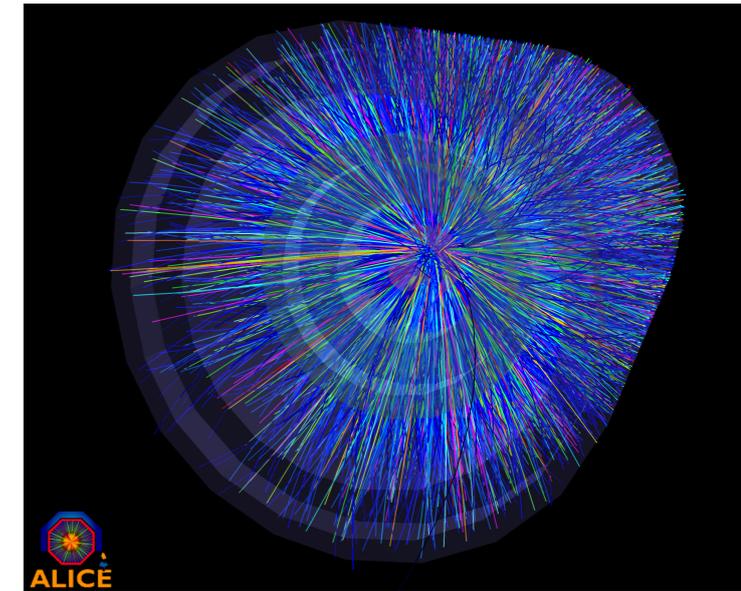
NICA

● existierende Anlage
● neue Anlage
● Experimente

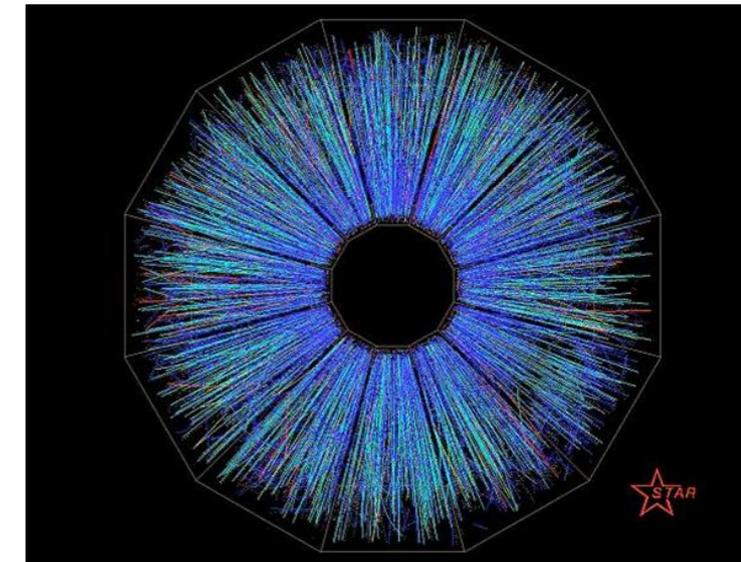
Heavy ion collisions



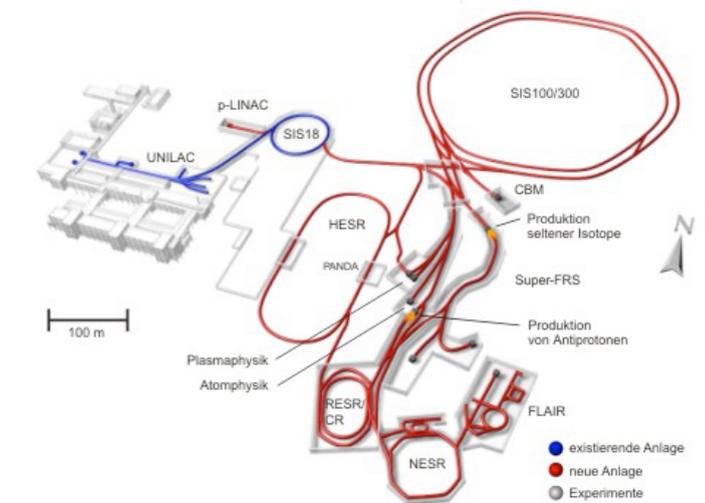
LHC



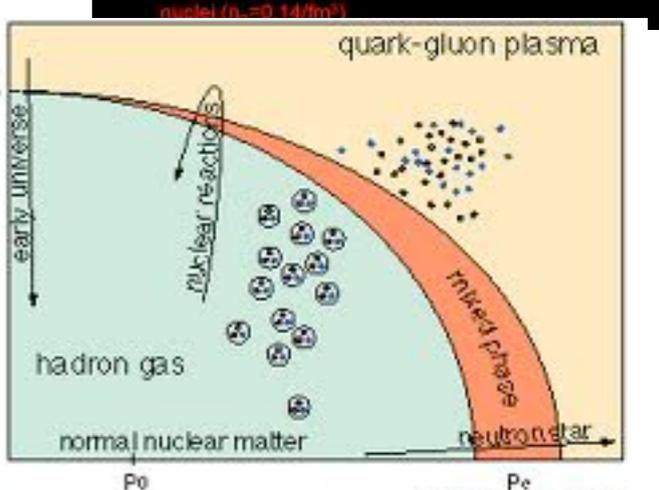
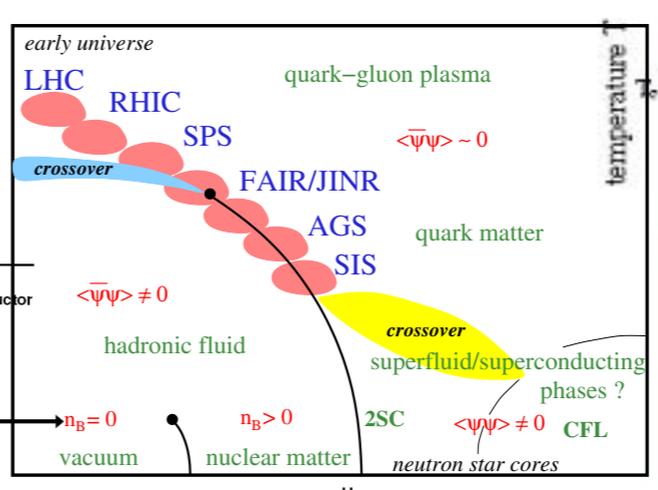
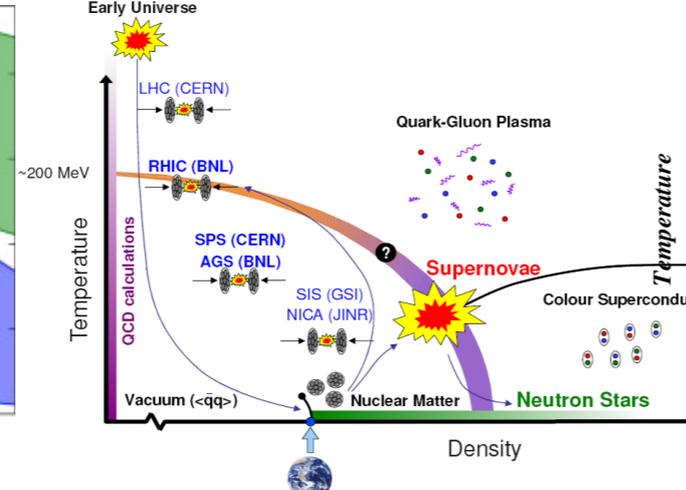
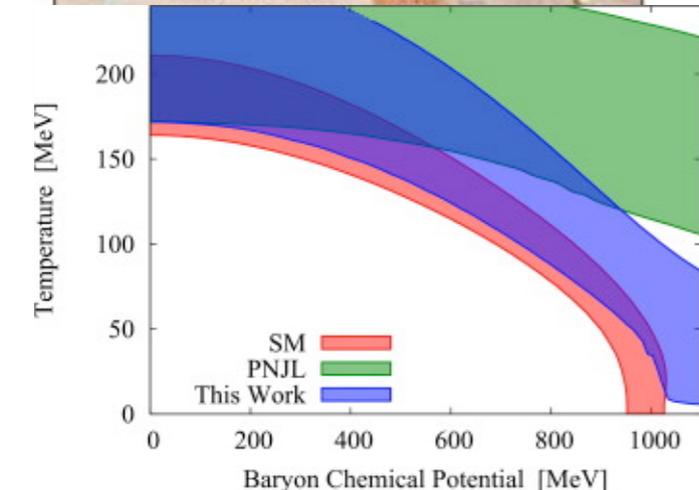
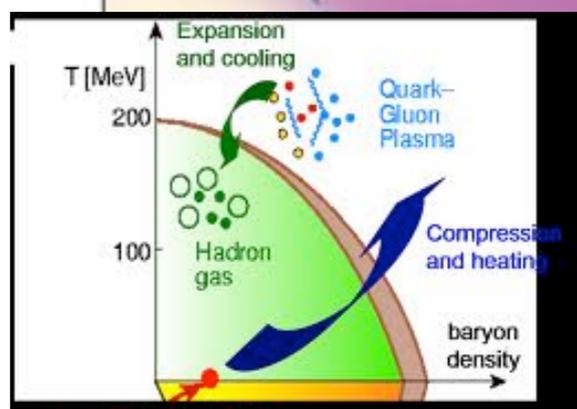
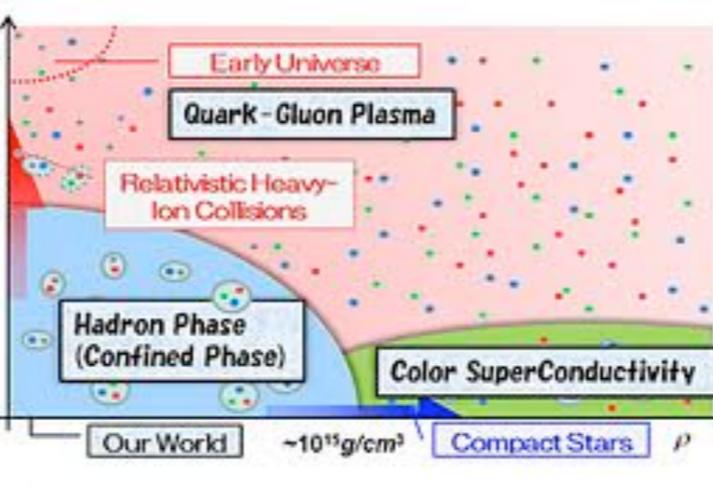
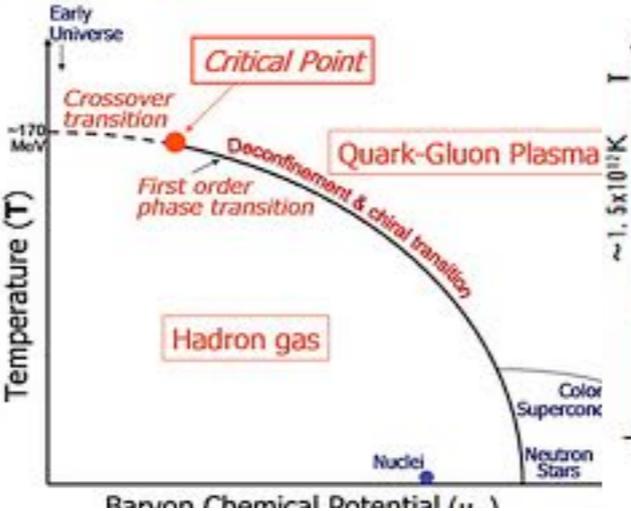
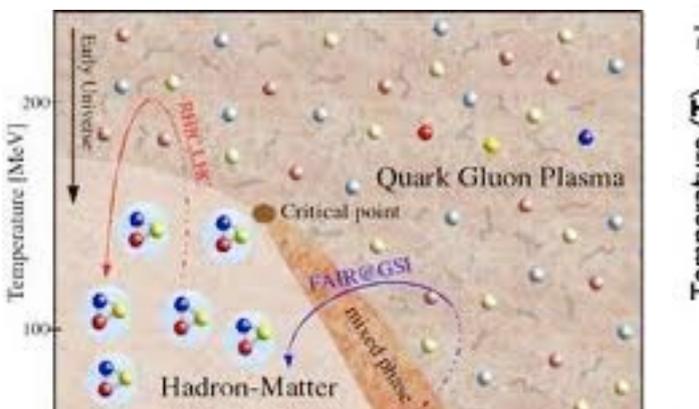
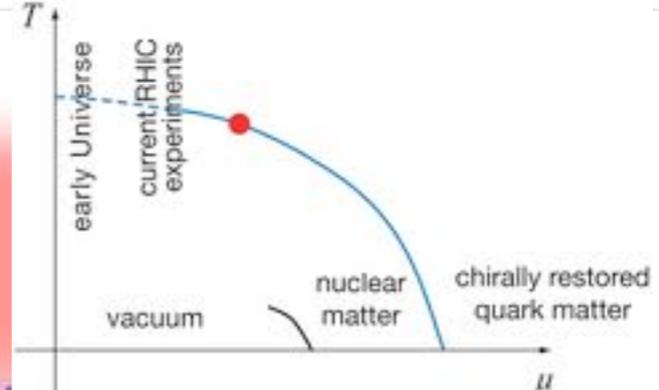
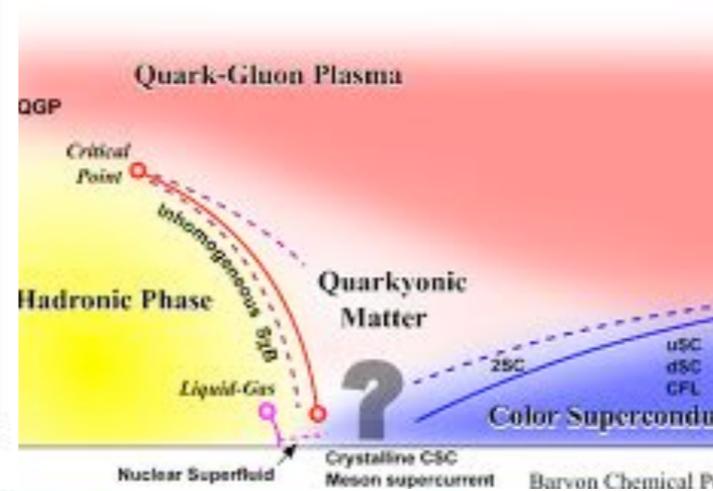
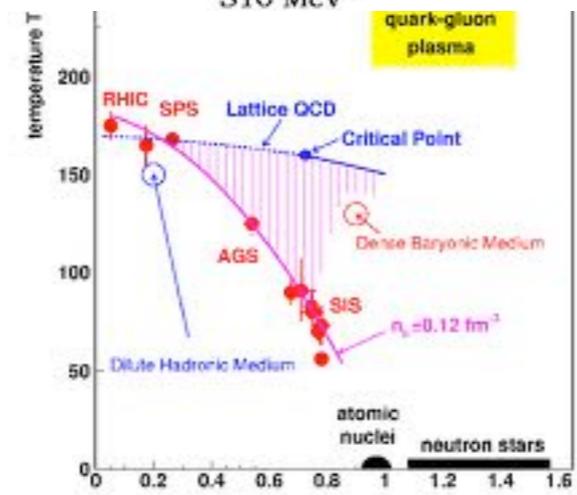
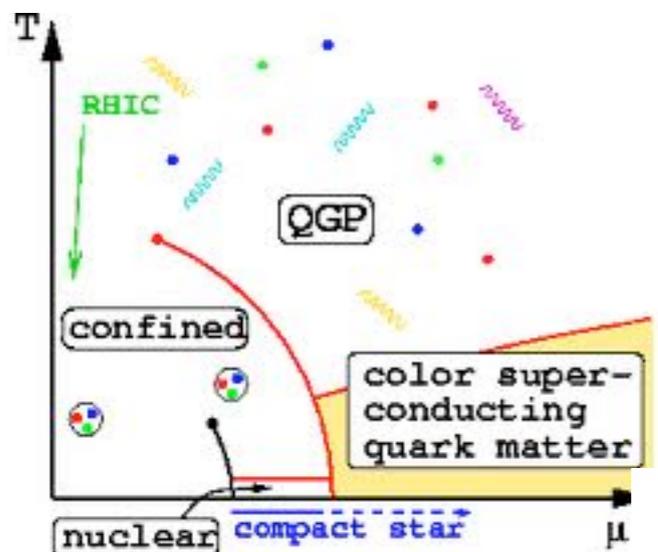
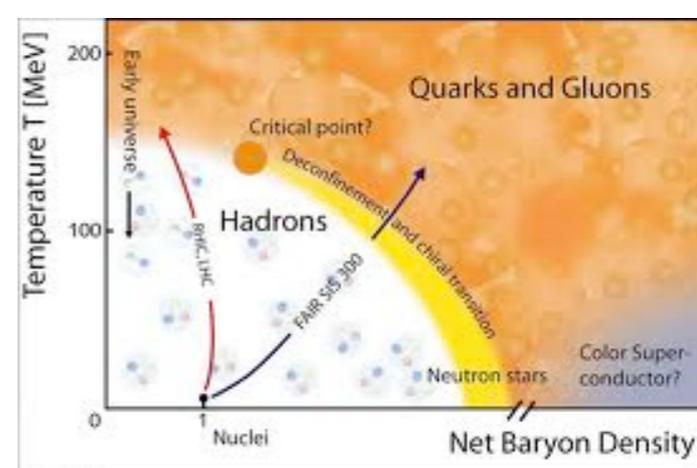
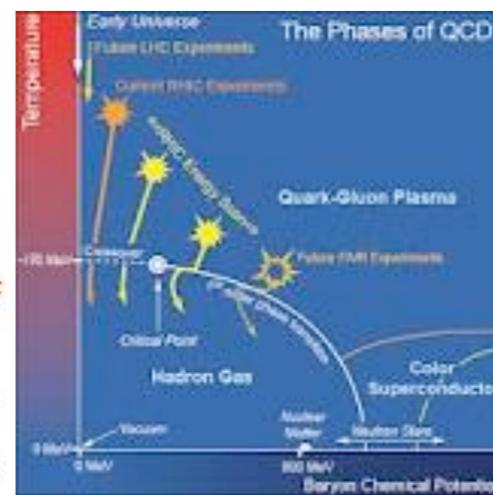
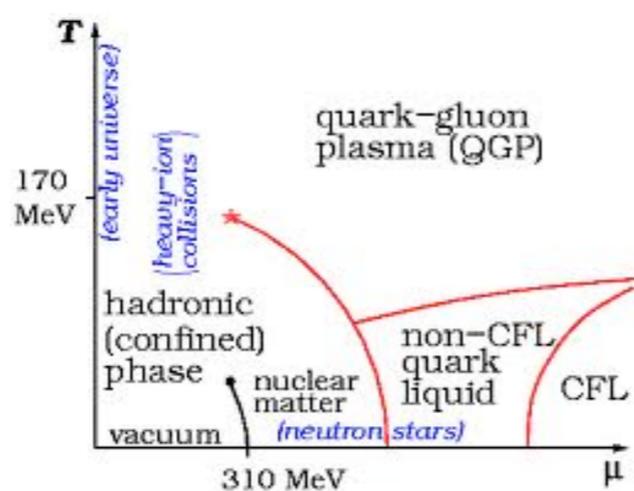
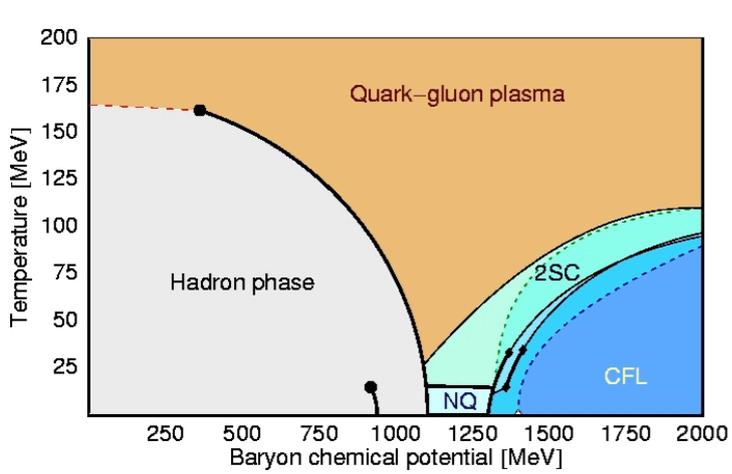
RHIC



FAIR

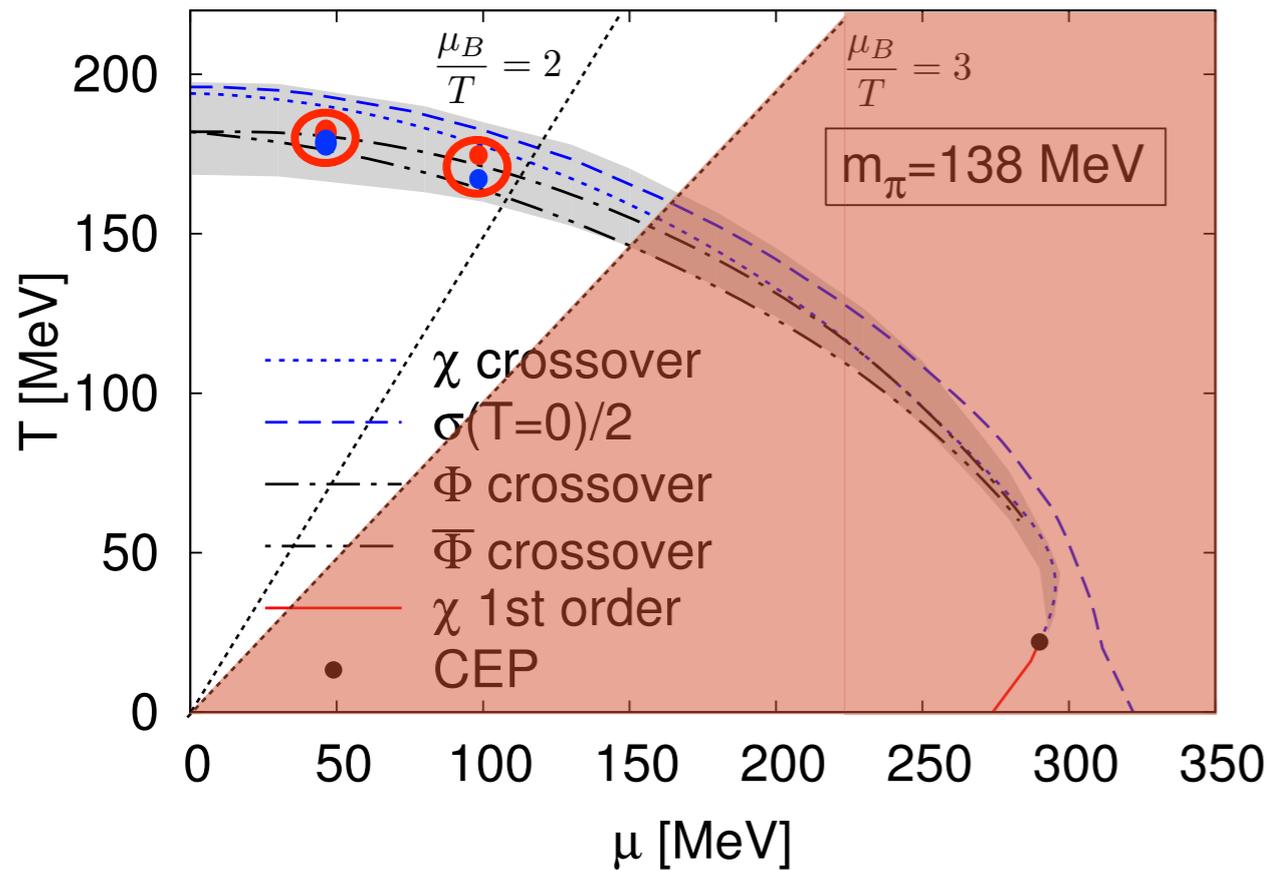


NICA



fQCD: motivation

Phase diagram of quantised 2-flavor PQM-model



Herbst, JMP, Schaefer, PLB 696 (2011) 58-67
PRD 88 (2013) 1, 014007

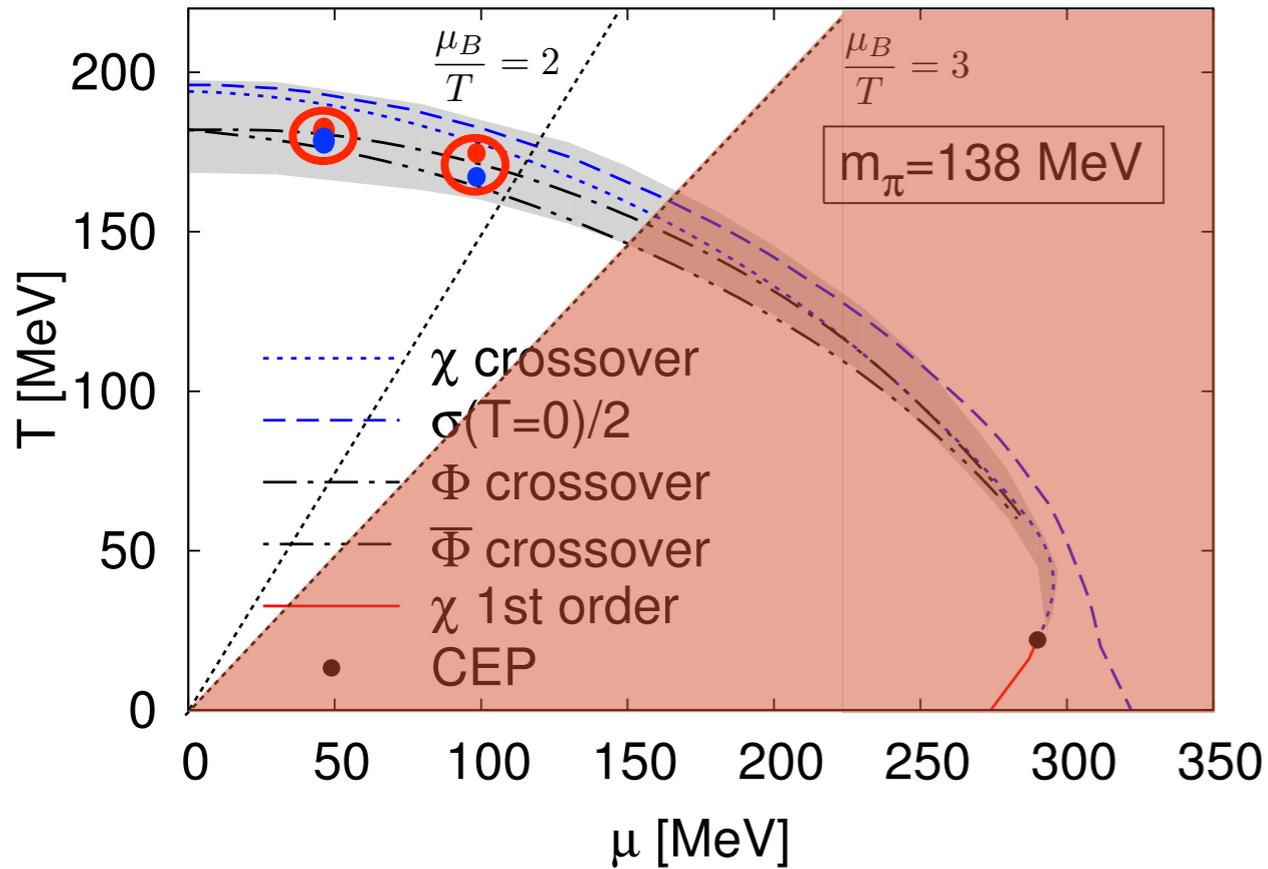
 FRG QCD results at finite density
Haas, Braun, JMP '09, unpublished

Extension of FRG QCD results at imaginary chemical potential

Braun, Haas, Marhauser, JMP, PRL 106 (2011) 022002

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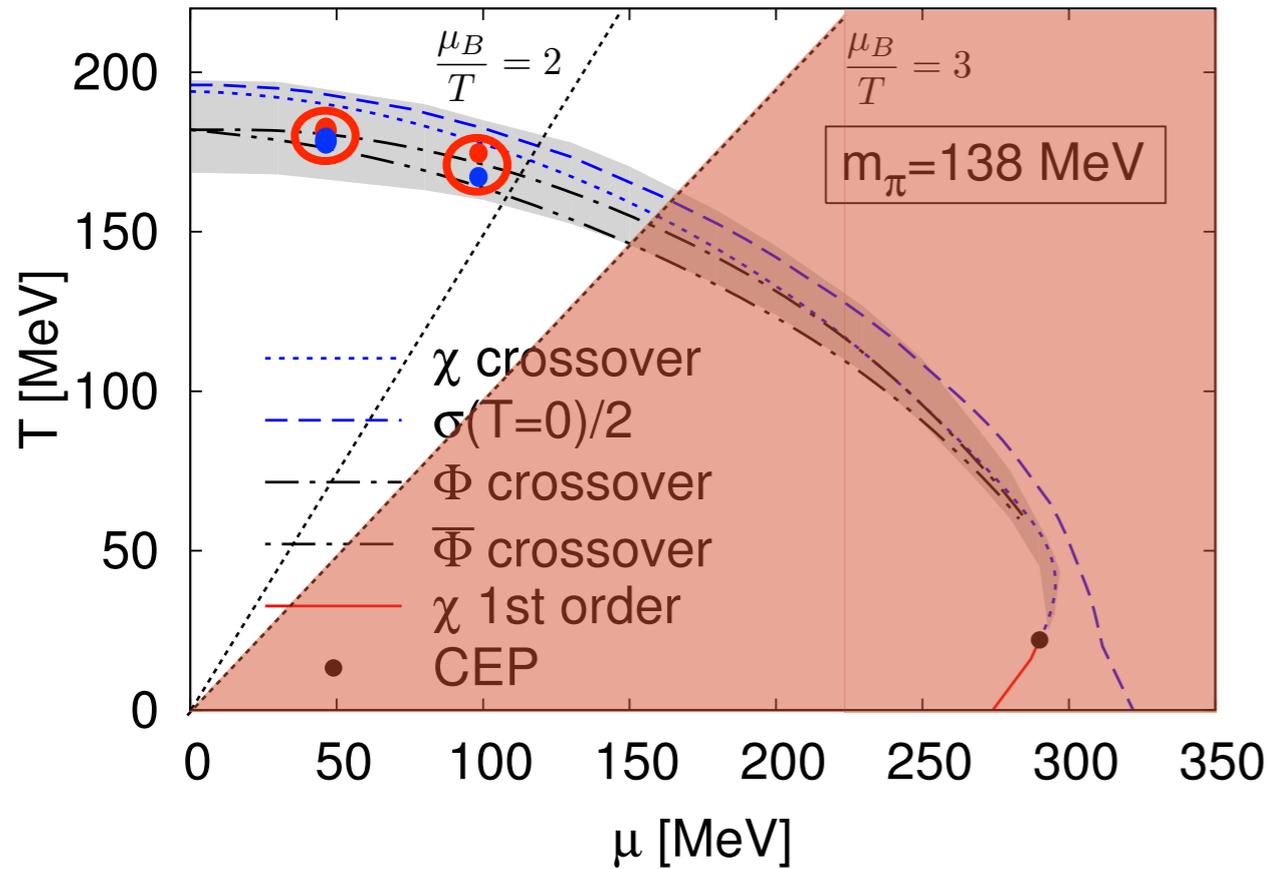
Braun, Haas, Marhauser, JMP, PRL 106 (2011) 022002

Qualitative sensitivity to approximations at sufficiently large density

Competing orders!?

fQCD: motivation

Phase diagram of quantised 2-flavor PQM-model

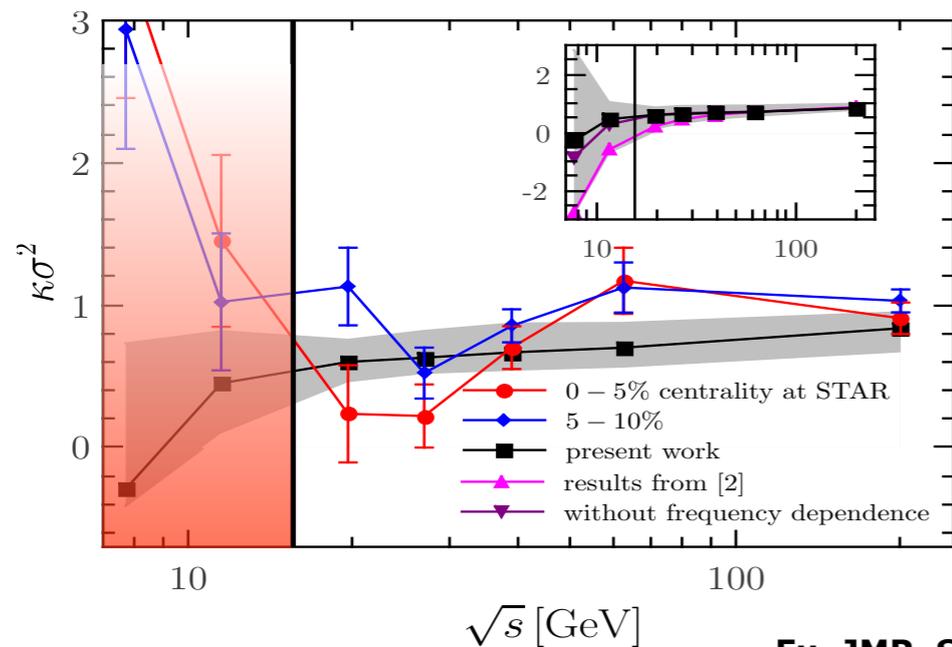


Herbst, JMP, Schaefer, PLB 696 (2011) 58-67
PRD 88 (2013) 1, 014007

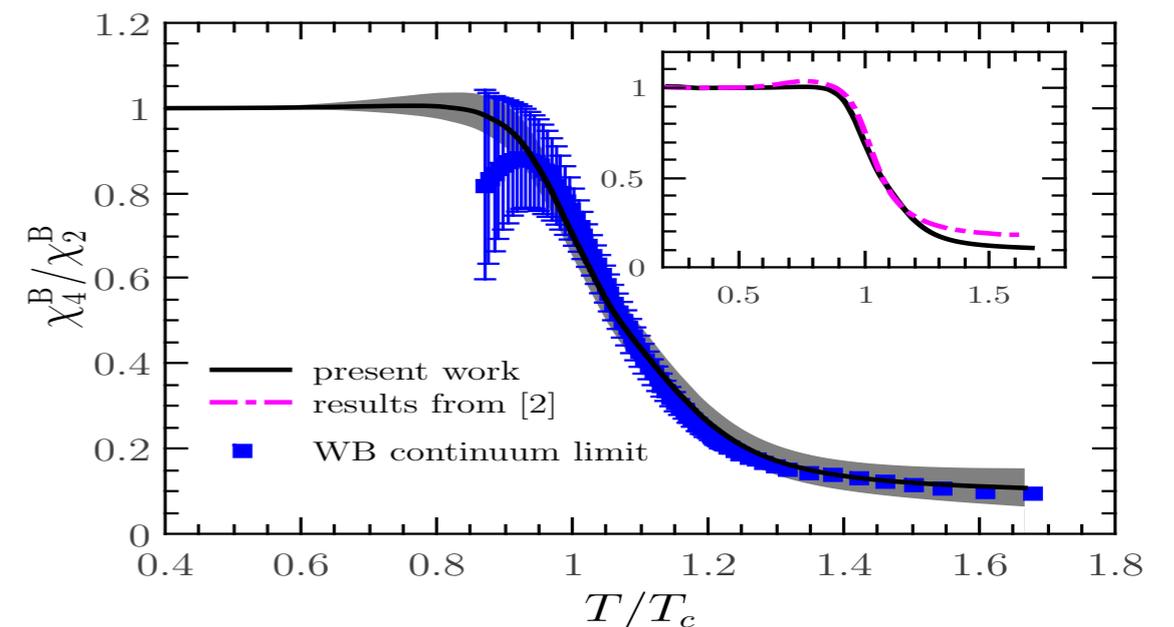
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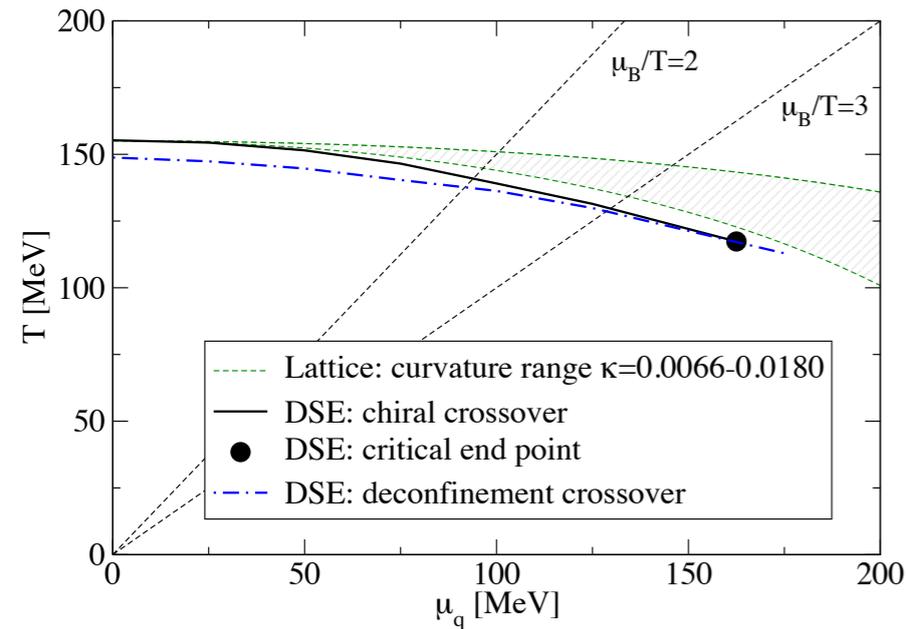


Fu, JMP, Schaefer, Rennecke, PRD 94 (2016) 11, 116020



Phase structure at finite density

Phase diagram of 2+1 flavor QCD



Kaczmarek et al. '11
 Endrodi, Fodor, Katz, Szabo '11
 Cea, Cosmai, Papa '14

Fischer, Fister, Luecker, JMP, PLB732 (2014)

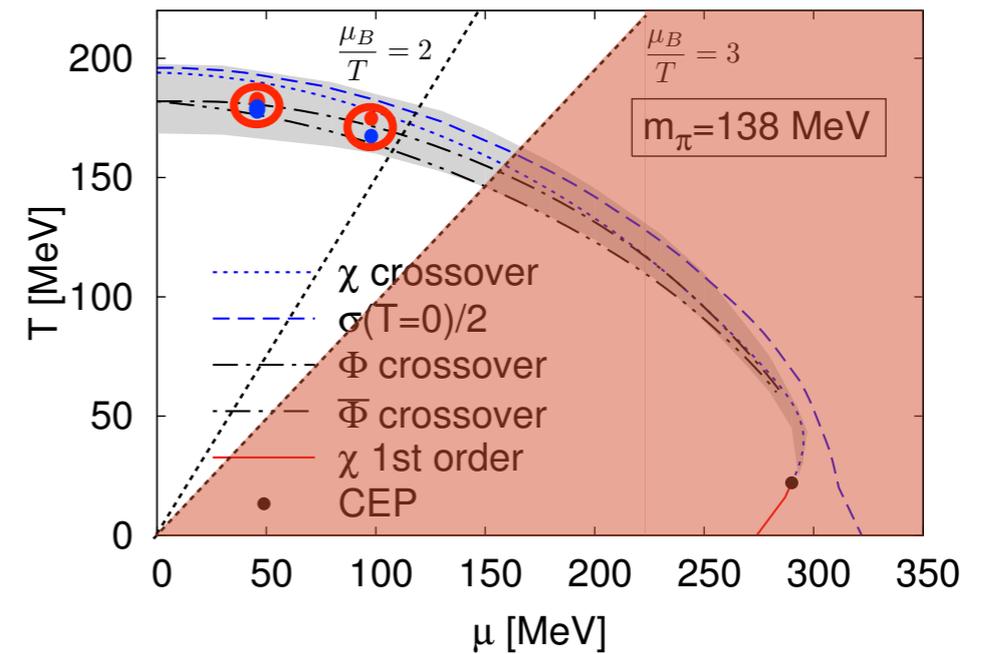
Fischer, Luecker, Welzbacher, PRD 90 (2014) 034022

Eichmann, Fischer, Welzbacher, PRD 93 (2014) 034013

Chiral phase structure

Qin, Chang, Chen, Liu, Roberts, PRL 106 (2011) 172301

Phase diagram of QCD-enhanced 2-flavor PQM-model



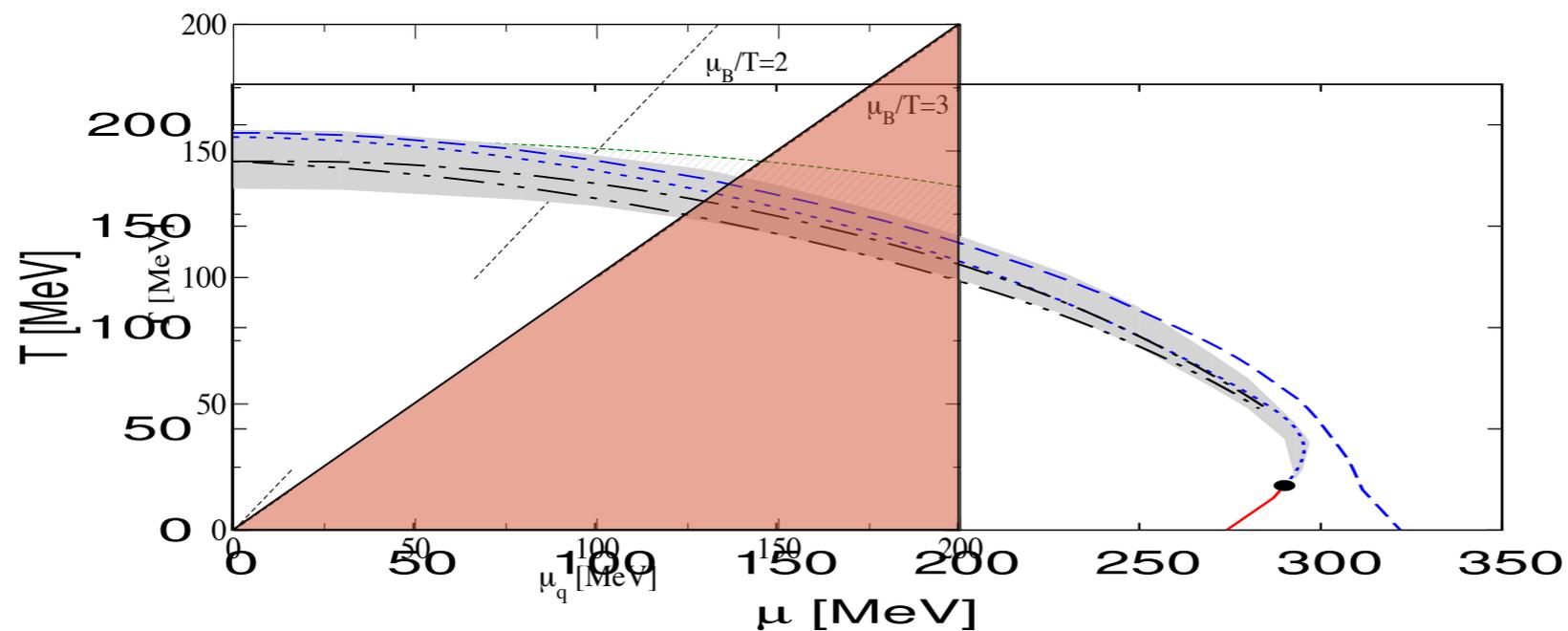
Herbst, JMP, Schaefer, PLB 696 (2011) 58-67
 PRD 88 (2013) 1, 014007



FRG QCD results at finite density

Haas, Braun, JMP '09, unpublished

Comparison with 2 flavor vs 2+1 flavor scale matching of T_c



Outline

- Motivation

- Functional RG for QCD

- Finite temperature correlation functions

- Confinement

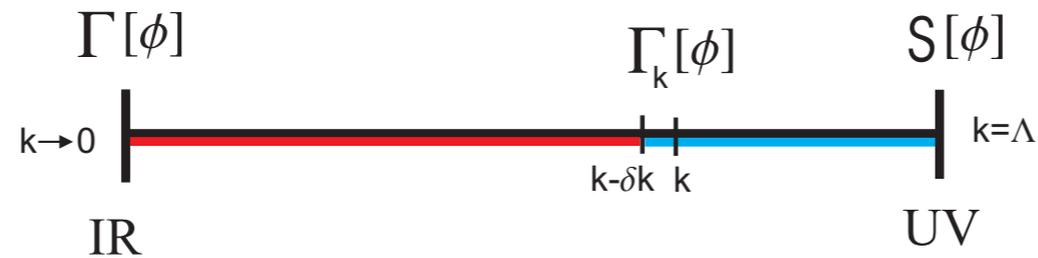
- Some remarks on confinement+chiral symmetry breaking, thermodynamics & transport

- Summary

Functional RG for QCD

JMP, AIP Conf.Proc. 1343 (2011)
Nucl.Phys. A931 (2014) 113

free energy at momentum scale k



ab initio

$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \left(\text{glue quantum fluctuations} - \text{quark quantum fluctuations} + \frac{1}{2} \text{hadronic quantum fluctuations} \right)$$

free energy/
grand potential

glue quantum fluctuations

quark quantum fluctuations

hadronic quantum fluctuations

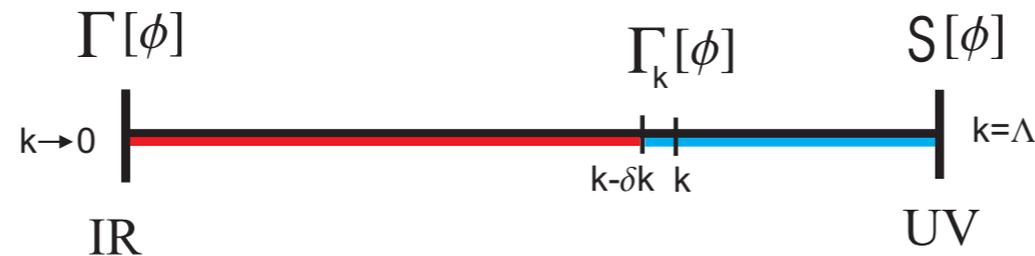
RG-scale k : $t = \ln k$

closed form

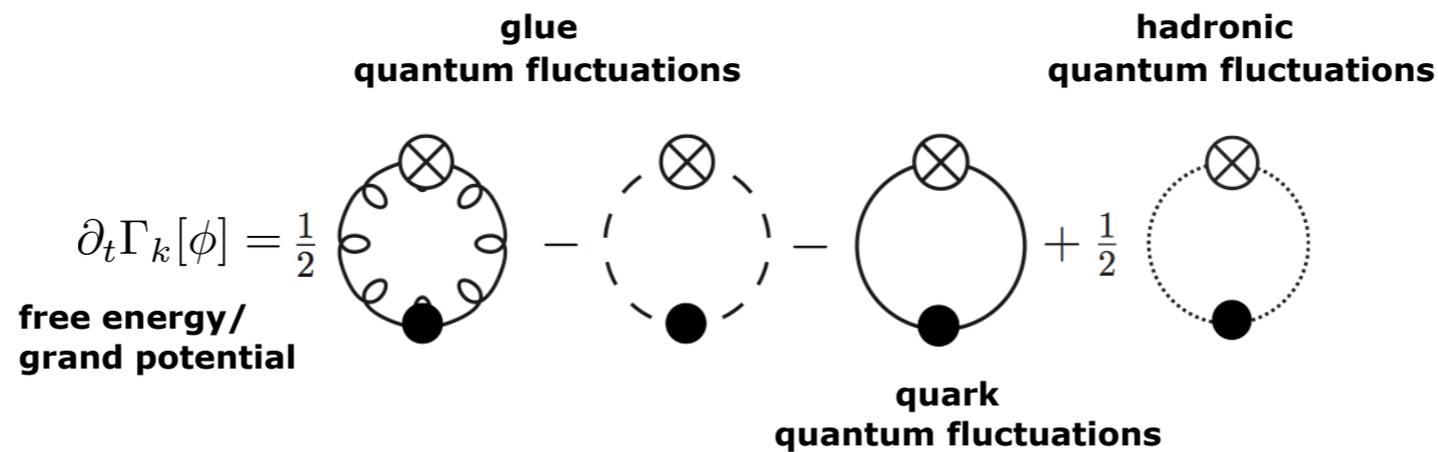
Functional RG for QCD

JMP, AIP Conf.Proc. 1343 (2011)
Nucl.Phys. A931 (2014) 113

free energy at momentum scale k



ab initio



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

properties

- access to physics 
- numerically tractable, also at real time
no sign problem
systematic error control via closed form
- low energy models naturally incorporated

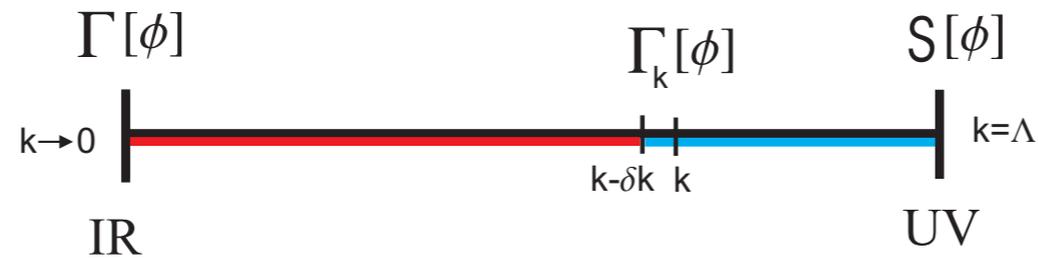
closed form



Functional RG for QCD

JMP, AIP Conf.Proc. 1343 (2011)
Nucl.Phys. A931 (2014) 113

free energy at momentum scale k



ab initio

glue quantum fluctuations
hadronic quantum fluctuations

$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \left(\text{glue loop} - \text{ghost loop} - \text{quark loop} \right) + \frac{1}{2} \left(\text{hadronic loop} \right)$$

free energy/ grand potential
quark quantum fluctuations

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

closed form

functional DSE :

$$\frac{\delta(\Gamma - S)}{\delta A_0} = \frac{1}{2} \left(\text{glue loop} - \text{ghost loop} - \text{quark loop} \right) - \frac{1}{6} \left(\text{glue loop} + \text{ghost loop} \right) + \dots$$

A_0 : background field

Functional RG for QCD

fQCD collaboration: J. Braun, L. Corell, A. Cyrol, W.-j. Fu, M. Leonhardt, M. Mitter, JMP, M. Pospiech, F. Rennecke, N. Wink

Heidelberg, Dalian, Darmstadt

Agenda

QCD at finite T & μ

Phase structure

Fluctuations

Phenomenology

Real time correlation functions

Hadron spectrum & decays

Transport coefficients

Dynamics

Selection of papers

quenched QCD:

Cyrol, Fister, Mitter, JMP, Strodthoff, PRD 94 (2016) 054005

unquenched QCD:

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

Cyrol, Mitter, JMP, Strodthoff, arXiv:1706.06326

vector mesons: Rennecke, PRD 92 (2015) 076012

pure glue:

Mitter, JMP, Strodthoff, PRD 91 (2015) 054035

finite T: Cyrol, Mitter, JMP, Strodthoff, arXiv:1708.03482

finite density: *fluctuations:* Fu, JMP, Schaefer, Rennecke, PRD 94 (2016) 11, 116020

phase structure: Braun, Leonhardt, Pospiech, PRD 96 (2017) 7, 076003

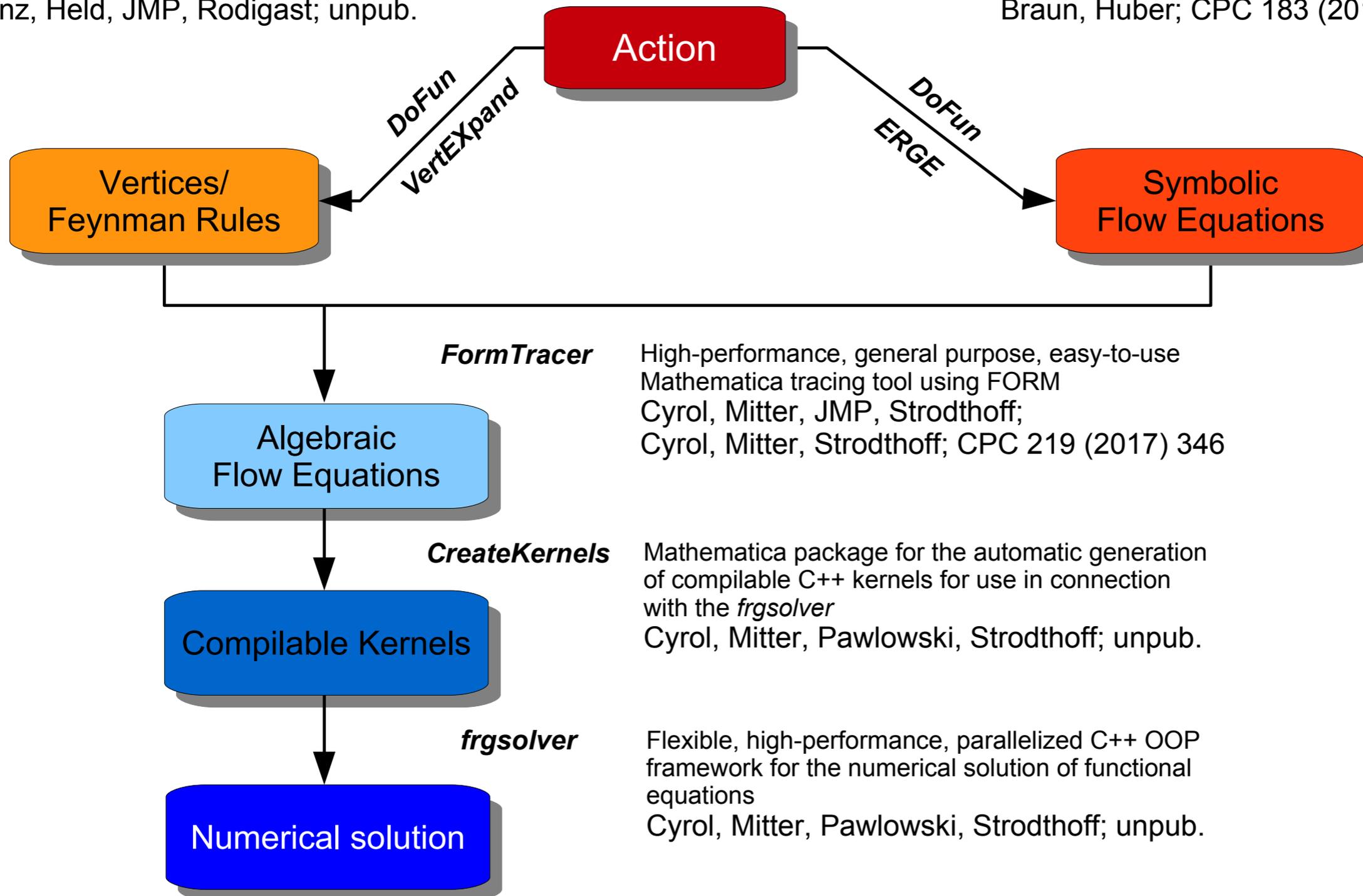
fOCD: workflow

VertEXpand

Mathematica package for the derivation of vertices from a given action using FORM
Denz, Held, JMP, Rodigast; unpub.

DoFun

Mathematica package for the derivation of functional equations
Braun, Huber; CPC 183 (2012) 1290



FormTracer

High-performance, general purpose, easy-to-use
Mathematica tracing tool using FORM
Cyrol, Mitter, JMP, Strodthoff;
Cyrol, Mitter, Strodthoff; CPC 219 (2017) 346

CreateKernels

Mathematica package for the automatic generation
of compilable C++ kernels for use in connection
with the *frgsolver*
Cyrol, Mitter, Pawlowski, Strodthoff; unpub.

frgsolver

Flexible, high-performance, parallelized C++ OOP
framework for the numerical solution of functional
equations
Cyrol, Mitter, Pawlowski, Strodthoff; unpub.

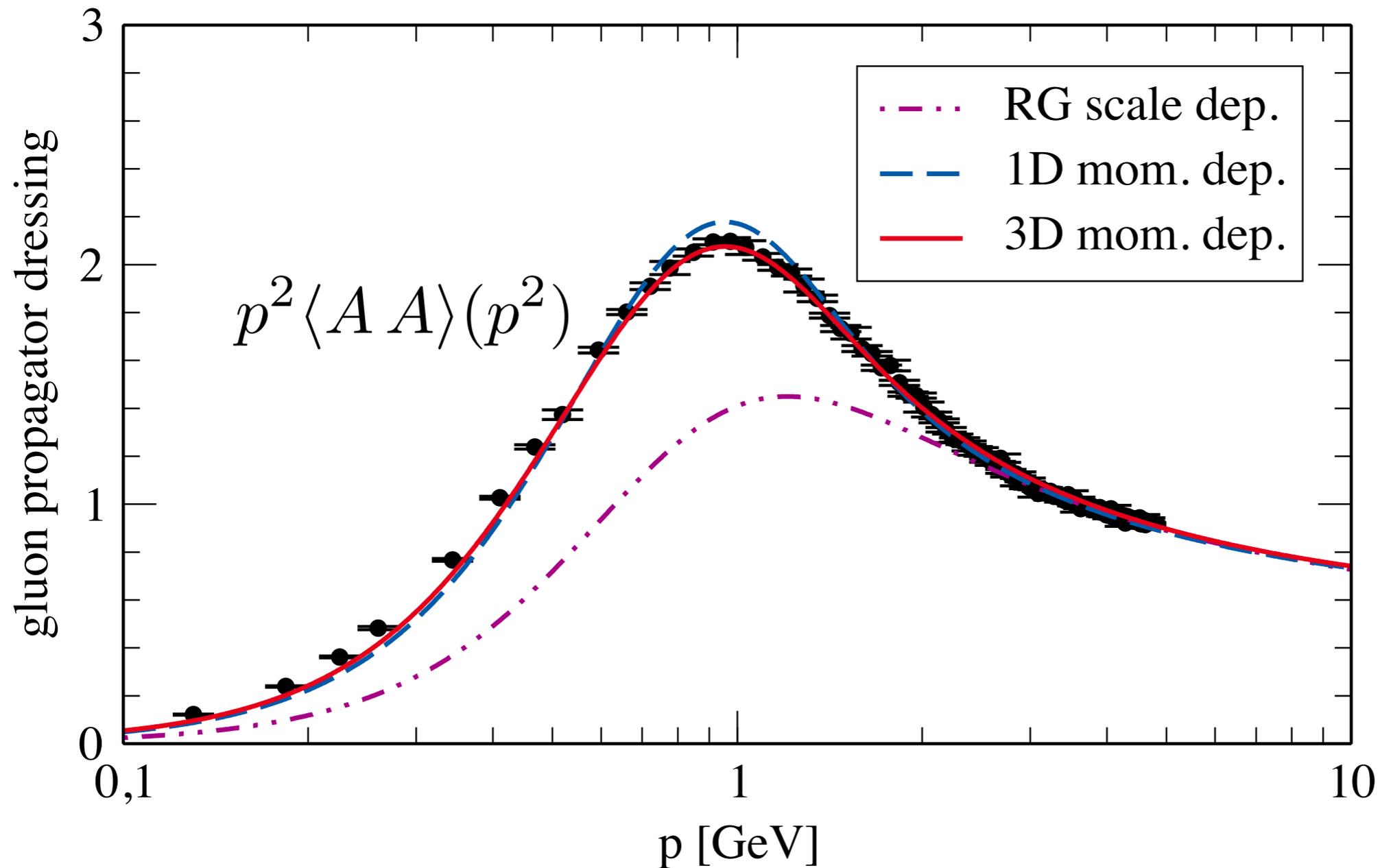
GEFÖRDERT VOM



YM-theory: Euclidean gluon propagator

see talk of Mario Mitter

Functional Renormalisation



Lattice: Sternbeck, Ilgenfritz, Müller-Preussker, Schiller, Bogolubsky, PoS LAT2006, 076

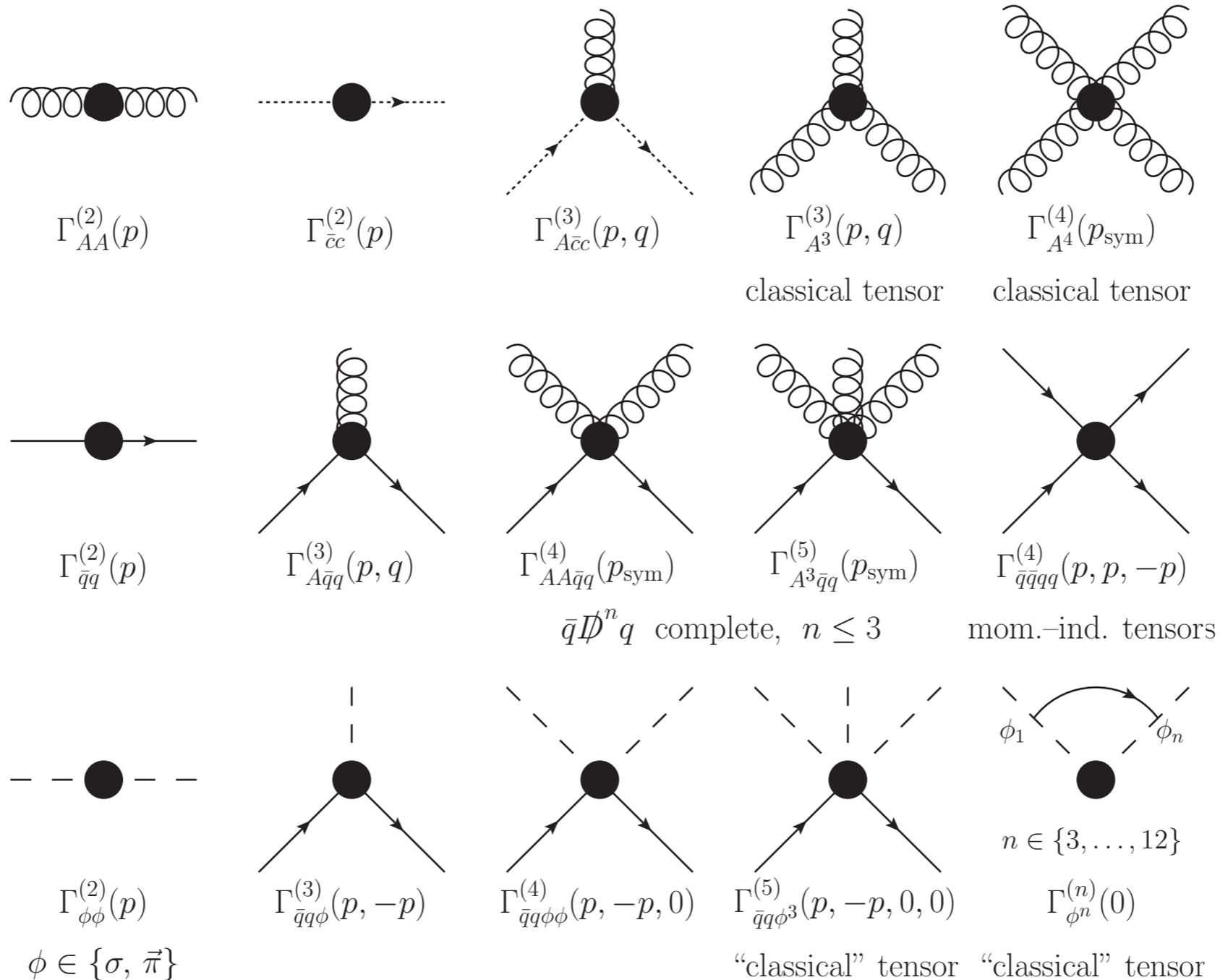
Aiming at apparent convergence

up to date pinch technique:
Aguilar, Binosi, Papavassiliou, PRD 89 (2014) 085032

up to date DSE:
Cyrol, Huber, Smekal, EPJ C75 (2015) 102

Cyrol, Fister, Mitter, JMP, Strodthoff, PRD 94 (2016) 054005

QCD: current set of correlation functions



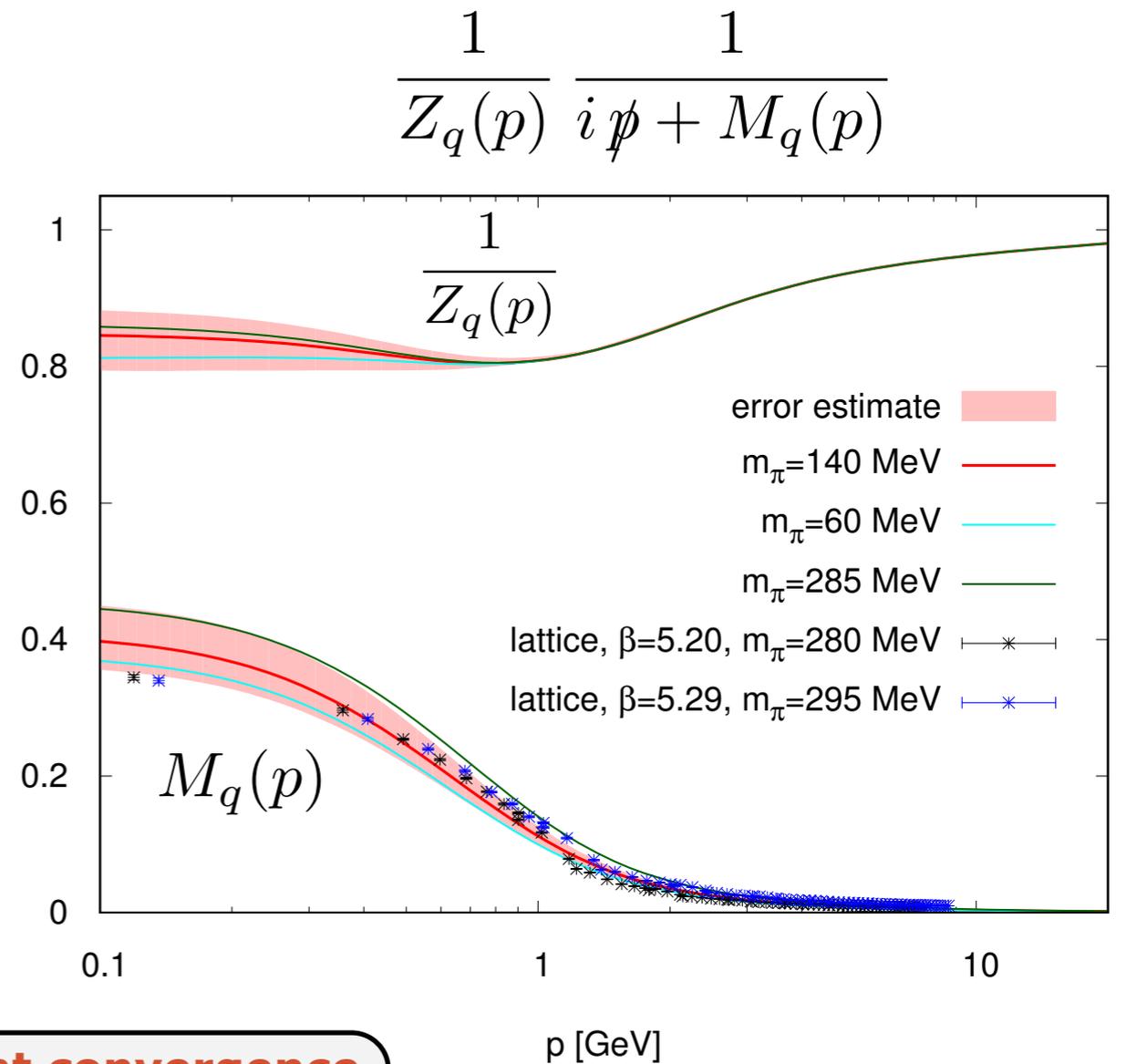
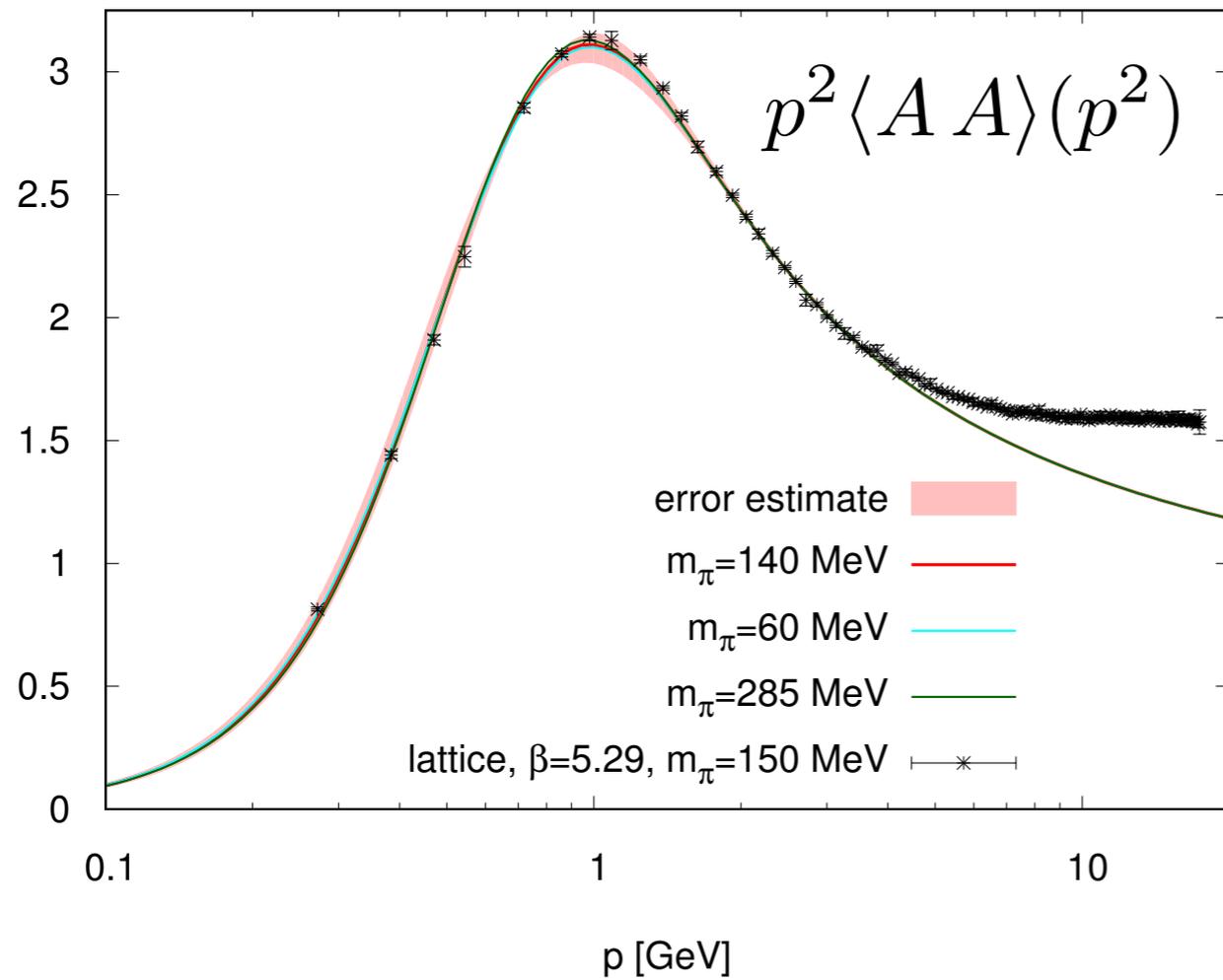
Aiming at apparent convergence

Cyrol, Mitter, JMP, Strodthoff, arXiv:1706.06326, arXiv:1708.03482

Cyrol, Fister, Mitter, JMP, Strodthoff, PRD 94 (2016) 054005

Mitter, JMP, Strodthoff, PRD 91 (2015) 054035

QCD: Euclidean propagators

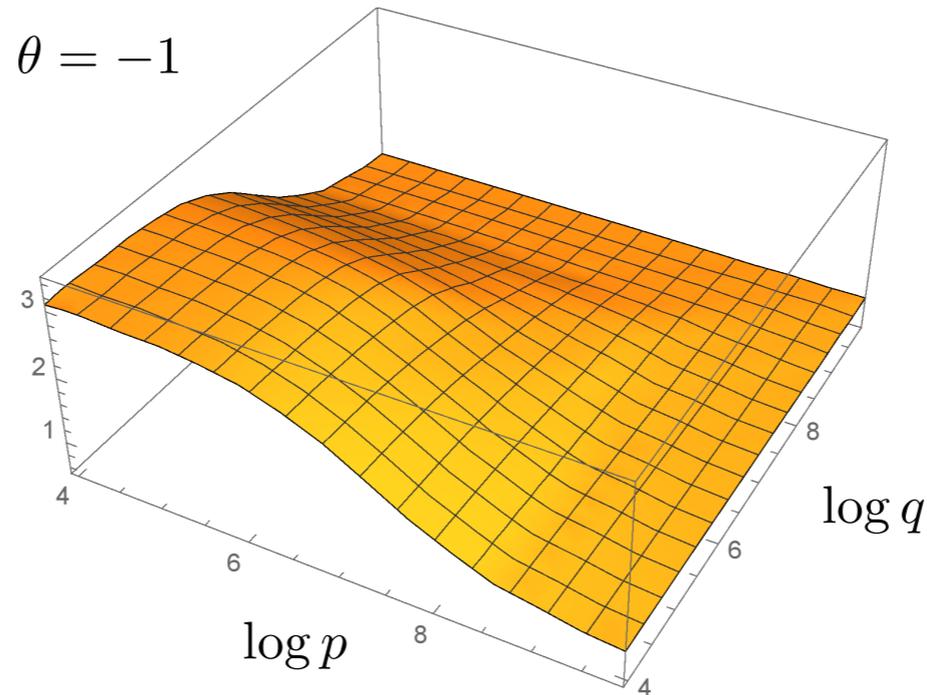


Aiming at apparent convergence

Quark-gluon vertex

$$\theta = \frac{p \cdot q}{\sqrt{p^2 q^2}}$$

p, q in MeV



$$\lambda_1(p, q)$$

Selection of up-to-date 1st principles works:

FunMethods:

Williams, EPJ A51 (2015) 57
 Sanchis-Alepuz, Williams, PLB 749 (2015) 592
 Williams, Fischer, Heupel, PRD 93 (2016) 034026

Aguilar, Binosi, Ibanez, Papavassiliou, PRD 89 (2014) 065027
 Binosi, Chang, Papavassiliou, Qin, Roberts, PRD 95 (2017) 031501
 Aguilar, Cardona, Ferreira, Papavassiliou, PRD 96 (2017) 014029

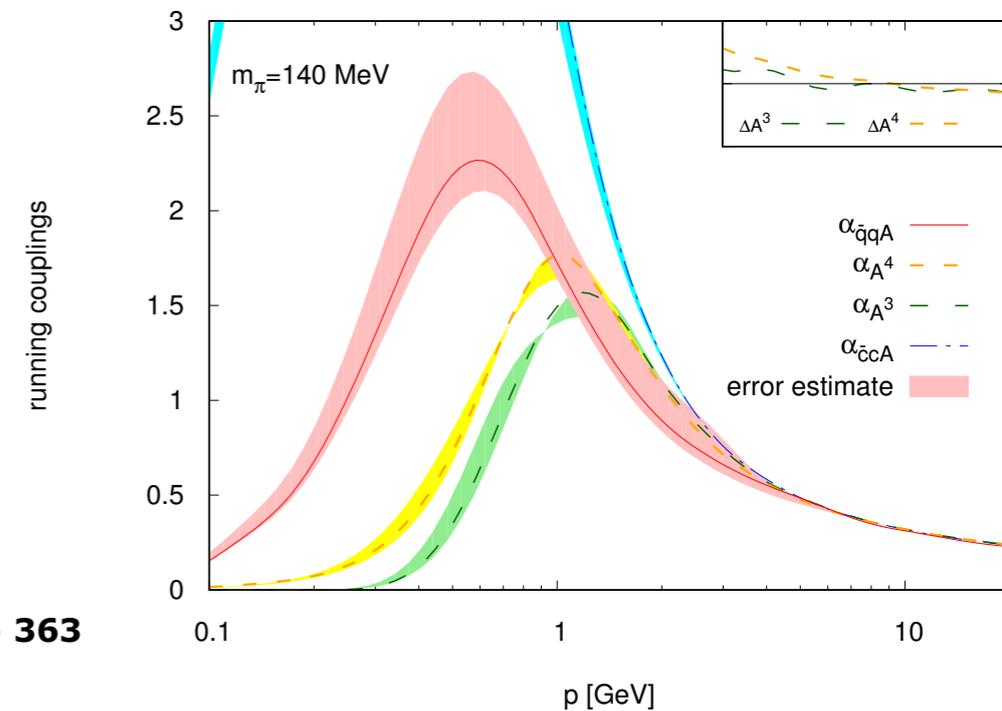
Mitter, JMP, Strodthoff, PRD 91 (2015) 054035

Pelaez, Tissier, Wschebor, PRD 92 (2015) 045012

Eichmann, Sanchis-Alepuz, Williams, Alkofer, Fischer, PPNP 91 (2016) 1

lattice: Oliveira, Kizilersü, Silva, Skullerud, Sternbeck, Williams, APP Suppl. 9 (2016) 363

Beware of BRST



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- Functional RG for QCD

- Finite temperature correlation functions

- Confinement

- Some remarks on confinement+chiral symmetry breaking, thermodynamics & transport

- Summary

YM-theory: gluonic correlation functions

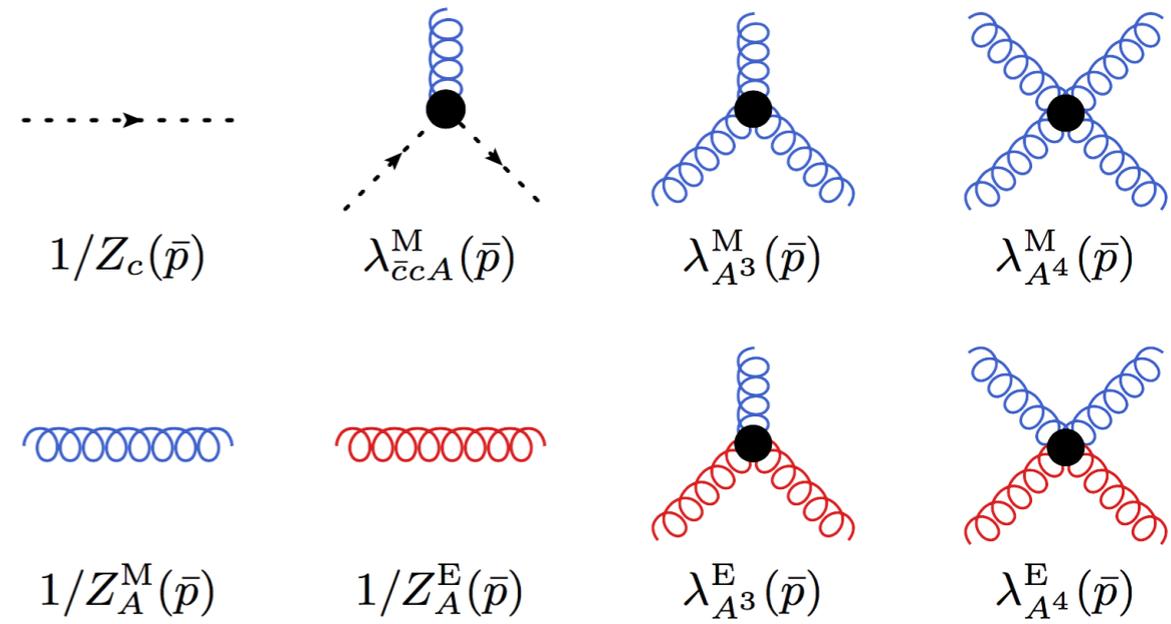
$$\partial_t \text{---}^{-1} = \text{---} \circlearrowleft + \text{---} \circlearrowright$$

$$\partial_t \text{---}^{-1} = \text{---} \circlearrowleft - 2 \text{---} \circlearrowright + \frac{1}{2} \text{---} \circlearrowleft$$

$$\partial_t \text{---} = - \text{---} \text{---} - \text{---} \text{---} + \text{perm.}$$

$$\partial_t \text{---} = - \text{---} \text{---} + 2 \text{---} \text{---} - \text{---} \text{---} + \text{perm.}$$

$$\partial_t \text{---} = - \text{---} \text{---} - \text{---} \text{---} + 2 \text{---} \text{---} - \text{---} \text{---} + \text{perm.}$$

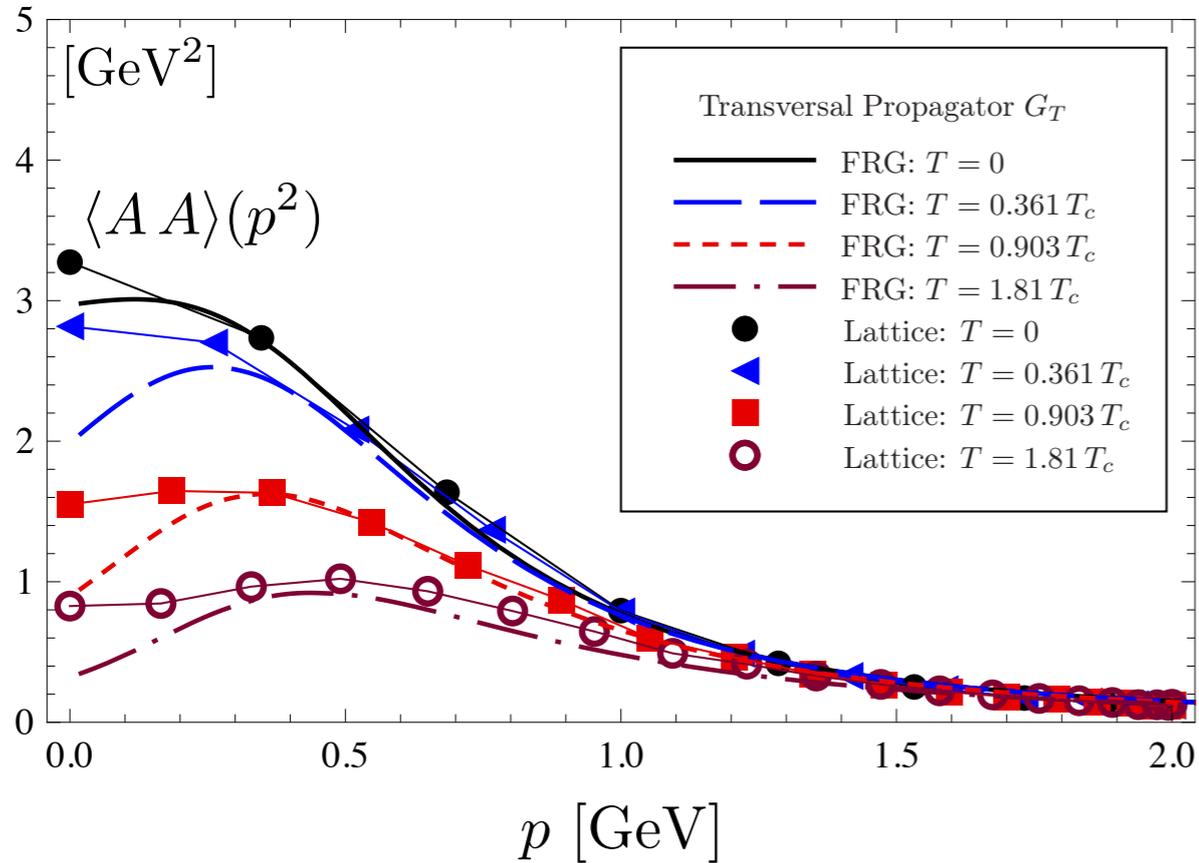


Aiming at apparent convergence

Euclidean gluon propagator at finite T

Yang-Mills propagators, finite T

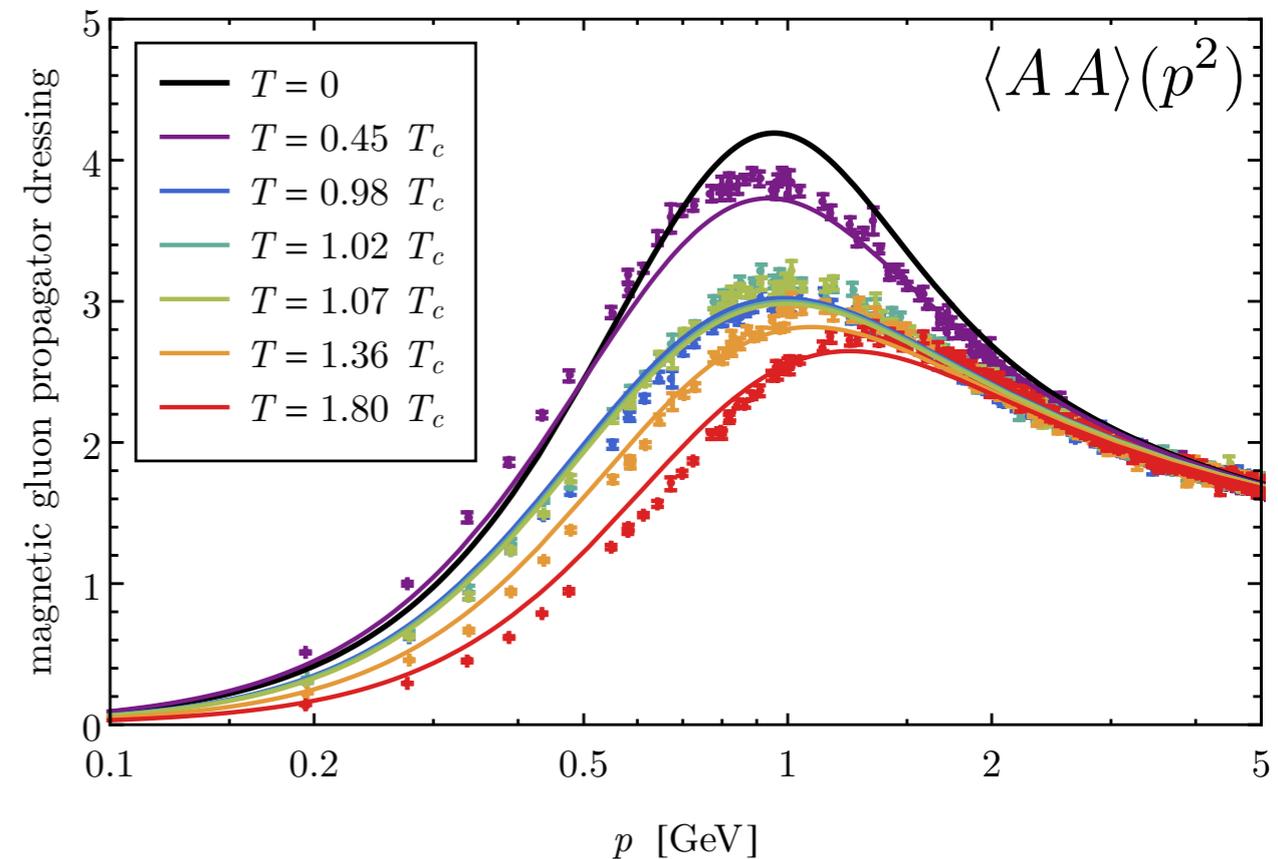
chromo-magnetic propagator



Fister, JMP, arXiv:1112.5440

Lattice: Maas, JMP, Smekal, Spielmann, PRD 85 (2012) 034037

CF model: Reinos, Serreau, Tissier, Tresmontant, PRD 95 (2017) 045014



Lattice: Silva, Oliveira, Bicudo, Cardoso, PRD89 (2014) 7, 074503

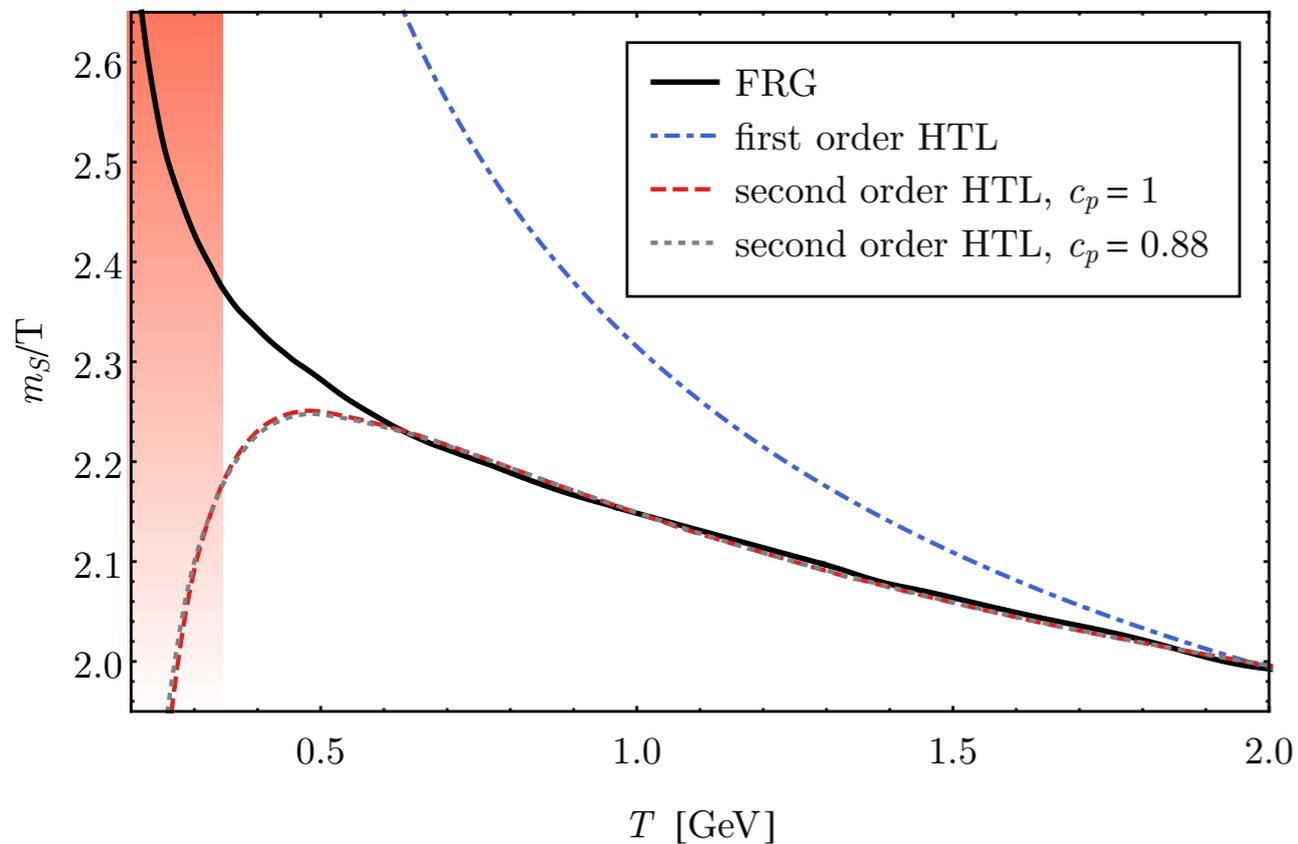
only possible with scaling solution

Cyrol, Fister, Mitter, JMP, Strodthoff, arXiv:1708.03482

Euclidean gluon propagator at finite T

Yang-Mills propagators, finite T

Debye mass (chromo-electric)

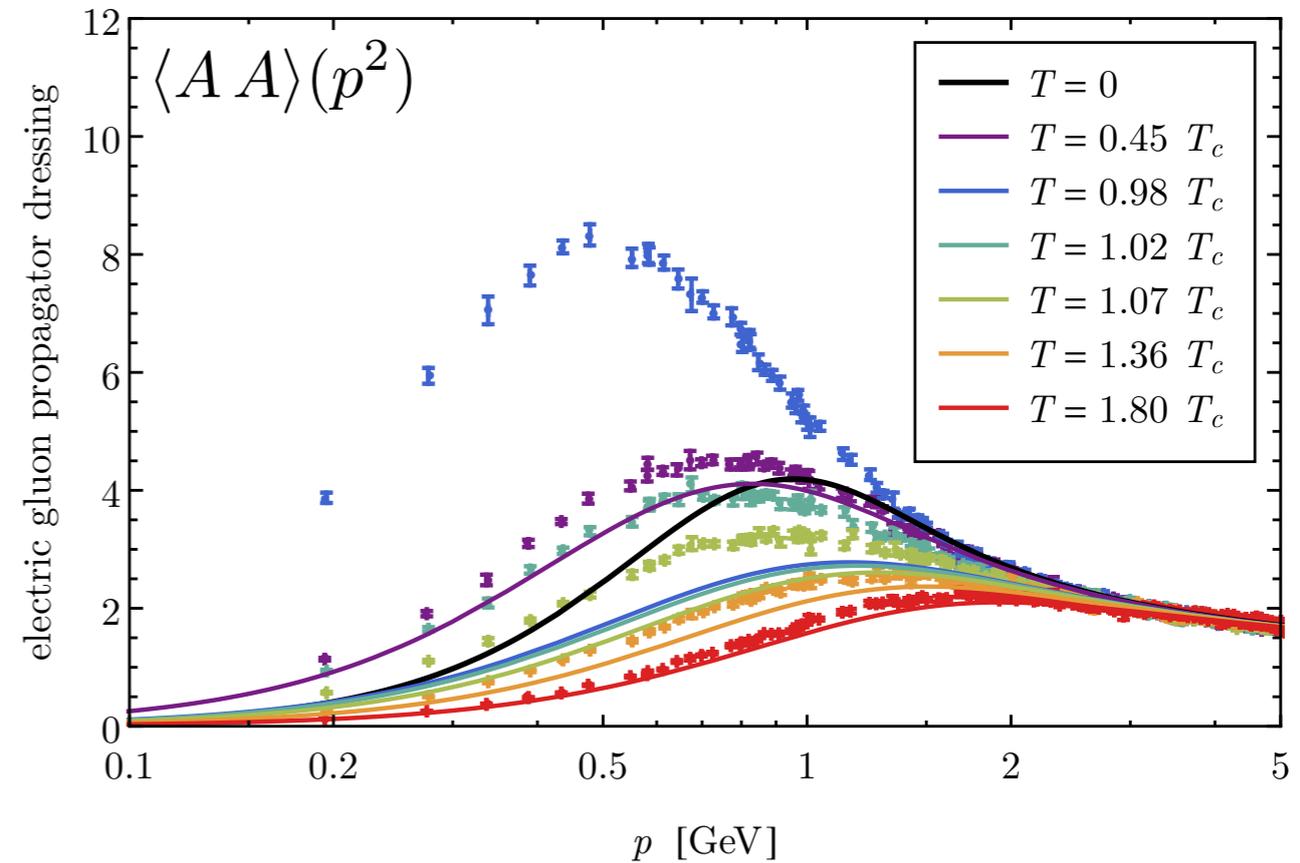


$$\langle A_0 \rangle \neq 0$$

Lattice: Maas, JMP, Smekal, Spielmann, PRD 85 (2012) 034037

CF model: Reinos, Serreau, Tissier, Tresmontant, PRD 95 (2017) 045014

chromo-electric propagator



Lattice: Silva, Oliveira, Bicudo, Cardoso, PRD89 (2014) 7, 074503

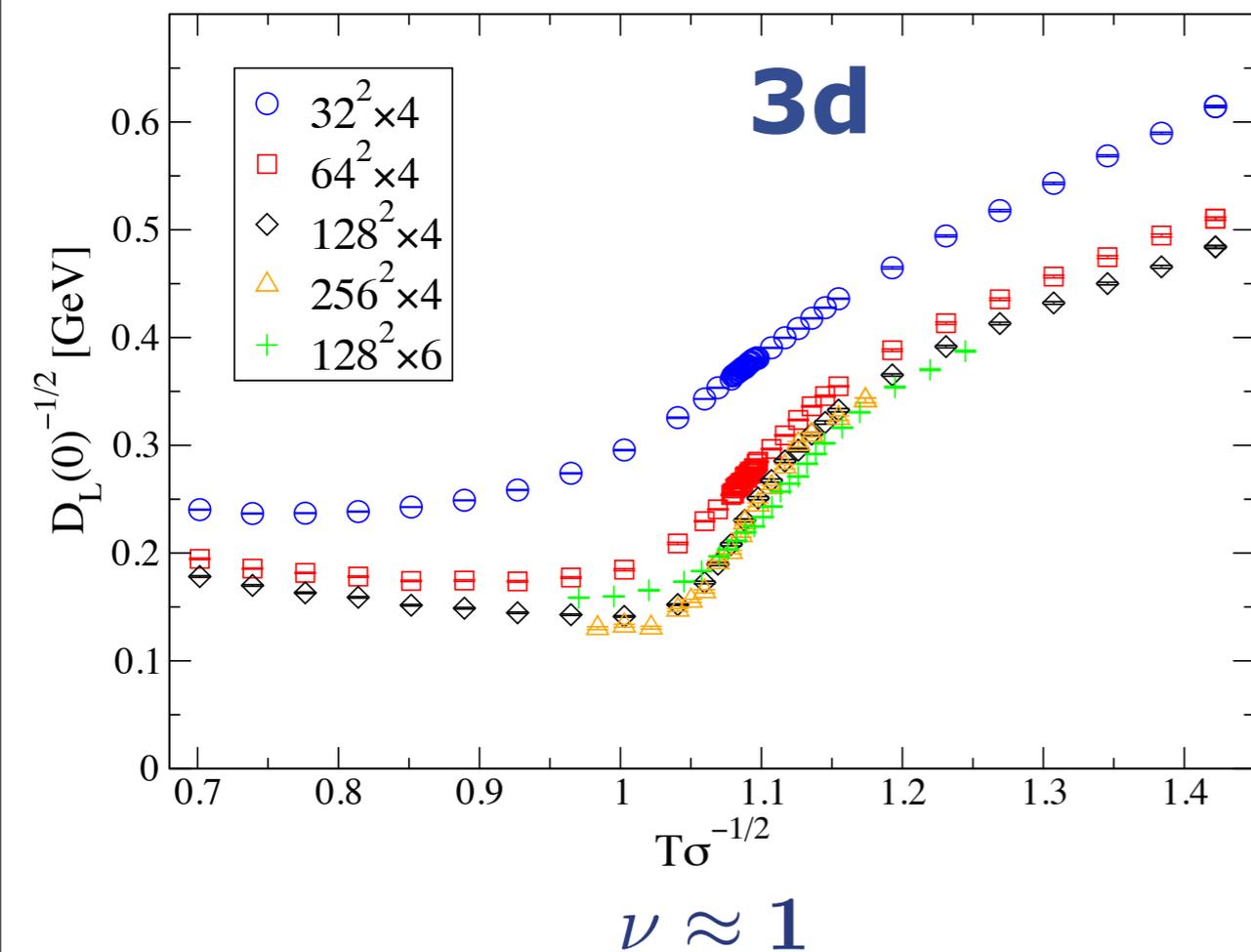
only possible with scaling solution

Cyrol, Fister, Mitter, JMP, Strodthoff, arXiv:1708.03482

Confinement

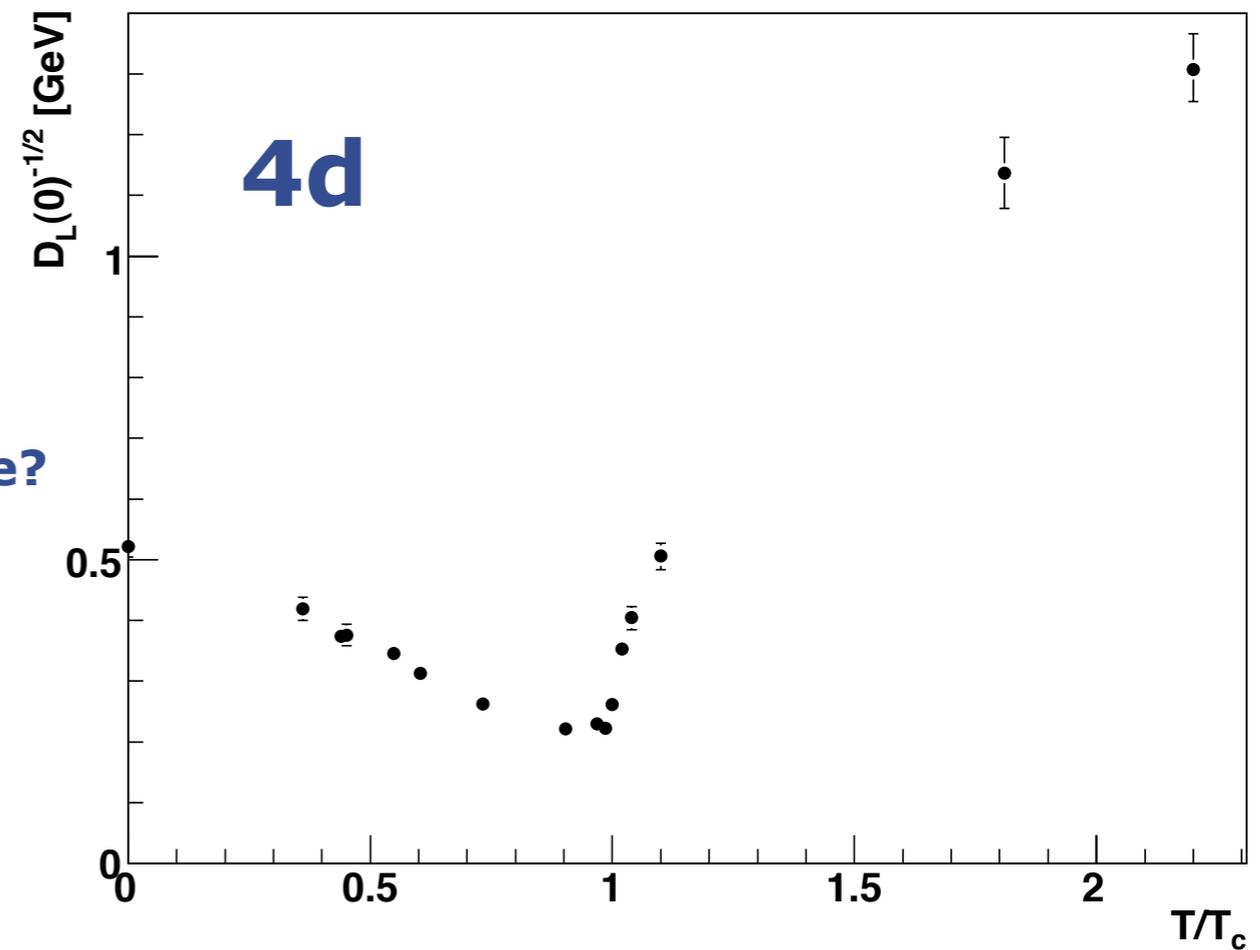
Chromo-electric propagator

Maas, JMP, Spielmann, von Smekal '11



$$D_L(0) = \langle A A \rangle_T(0)$$

Electric screening mass for SU(2)



$\nu \approx 0.68$

critical scaling in Landau gauge props on the lattice?

$$D_L(0)^{-1/2} \propto |T - T_c|^\nu + \dots$$

FRG

$$D_L(0)^{-1/2} \propto V''[A_0] + \dots$$

global gauge fixing

Outline

- Motivation

- Functional RG for QCD

- Finite temperature correlation functions

- Confinement

- Some remarks on confinement+chiral symmetry breaking, thermodynamics & transport

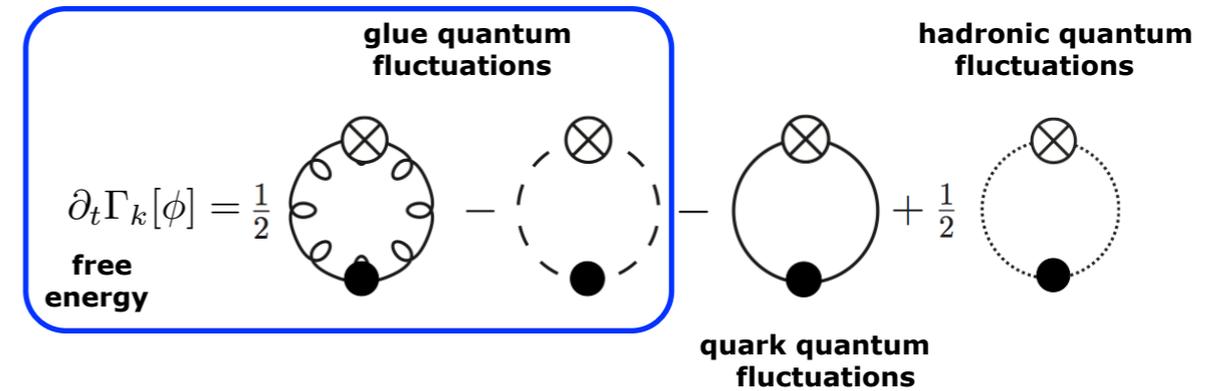
- Summary

Confinement

FRG: Braun, Gies, JMP, PLB 684 (2010) 262

FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

$$L[A_0] = \frac{1}{N_c} \text{tr} \mathcal{P} e^{ig \int_0^\beta \mathbf{A}_0(\mathbf{x})}$$



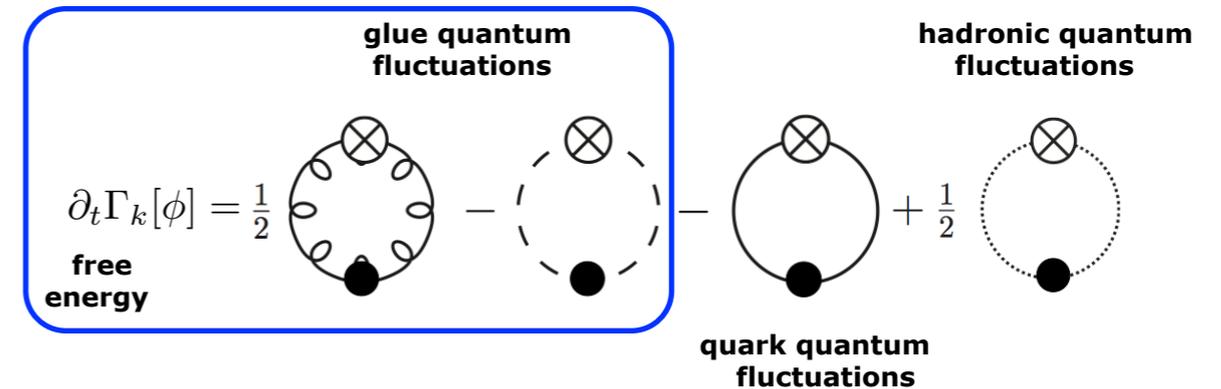
Positivity violation of the gluon spectral function \neq confinement

Confinement

FRG: Braun, Gies, JMP, PLB 684 (2010) 262

FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

$$L[A_0] = \frac{1}{N_c} \text{tr} \mathcal{P} e^{ig \int_0^\beta A_0(\mathbf{x})}$$



Background field formalism

Split: $A = \bar{A} + a$

Background gauge: $\bar{D}_\mu a_\mu = 0$

Gauge invariant Effective Action: $\Gamma[\bar{A}] = \Gamma[\bar{A}, a = 0]$

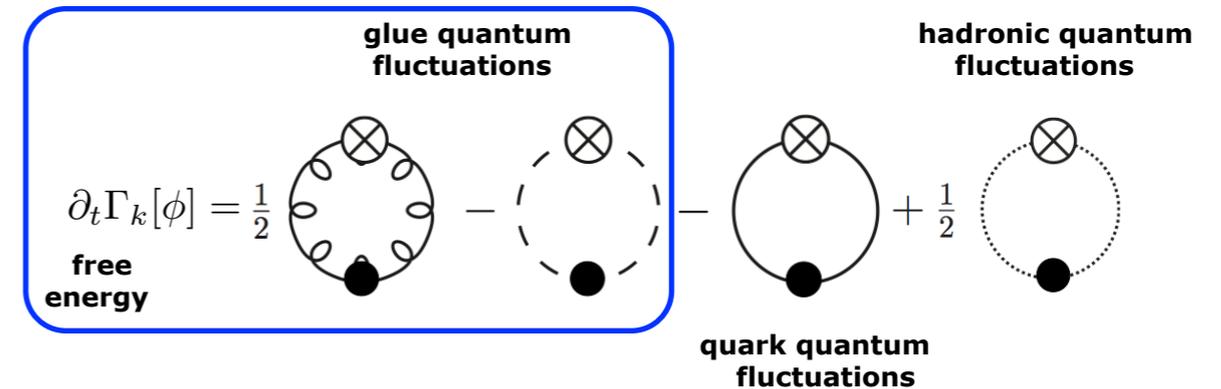
Cornerstone of background field formalism

Confinement

FRG: Braun, Gies, JMP, PLB 684 (2010) 262

FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

$$L[A_0] = \frac{1}{N_c} \text{tr} \mathcal{P} e^{ig \int_0^\beta \mathbf{A}_0(\mathbf{x})}$$



Background field formalism

Split: $A = \bar{A} + a$

Background gauge: $\bar{D}_\mu a_\mu = 0$

Gauge invariant Effective Action: $\Gamma[\bar{A}] = \Gamma[\bar{A}, a = 0]$

Finite Temperature \rightarrow Gauge invariant Effective Potential: $V_{\text{eff}}[\bar{A}] = \frac{1}{\mathcal{V}_{1+3}} \Gamma[\bar{A}_0, a = 0]$

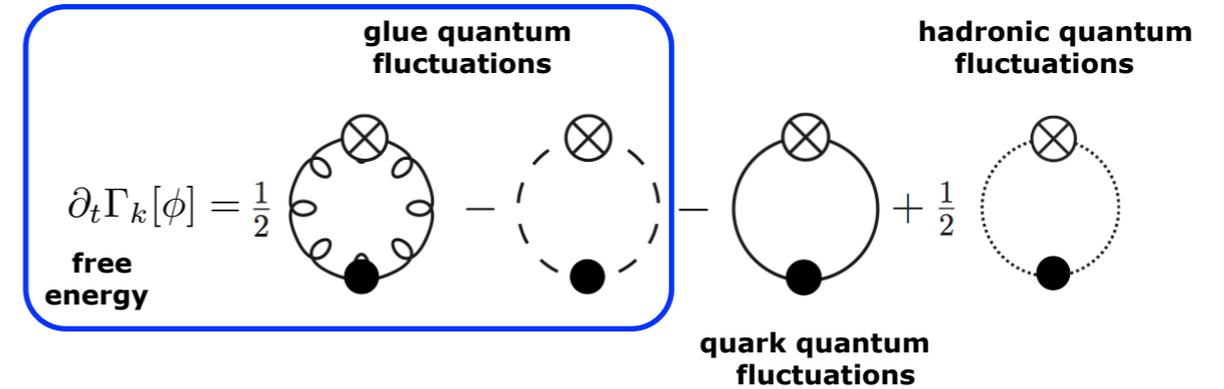
Effective potential carries center symmetry $\rightarrow \langle \bar{A}_0 \rangle$ Order parameter for confinement

Confinement

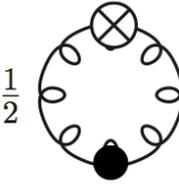
FRG: Braun, Gies, JMP, PLB 684 (2010) 262

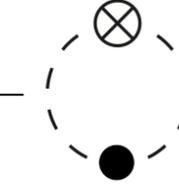
FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

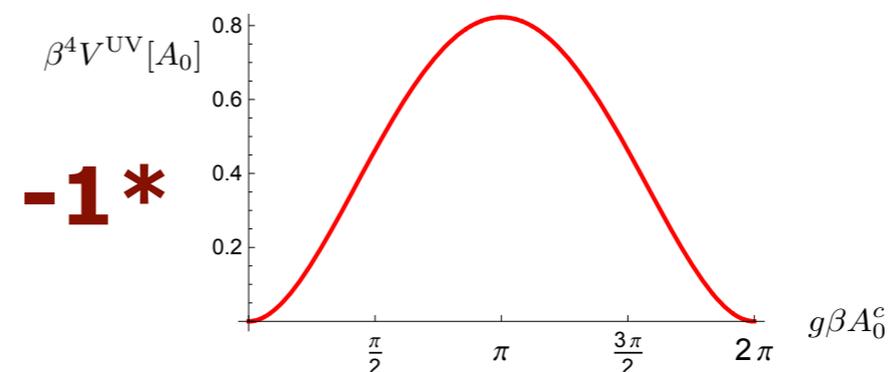
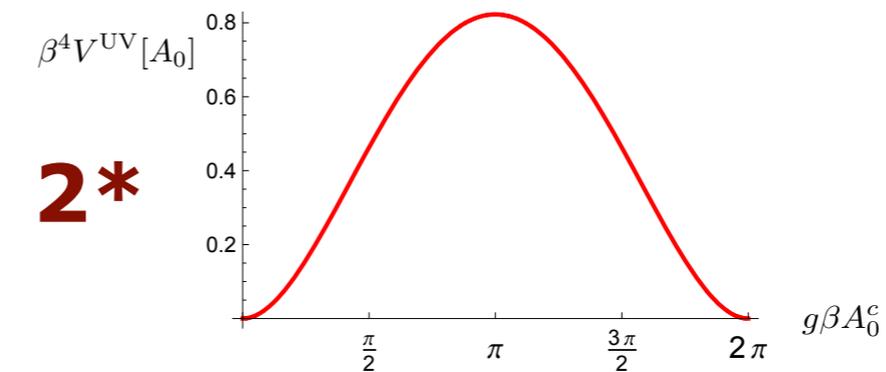
$$L[A_0] = \frac{1}{N_c} \text{tr} \mathcal{P} e^{ig \int_0^\beta A_0(\mathbf{x})}$$



Perturbation theory

$\frac{1}{2}$  **+ sign: deconfining**

$-$  **- sign: confining**



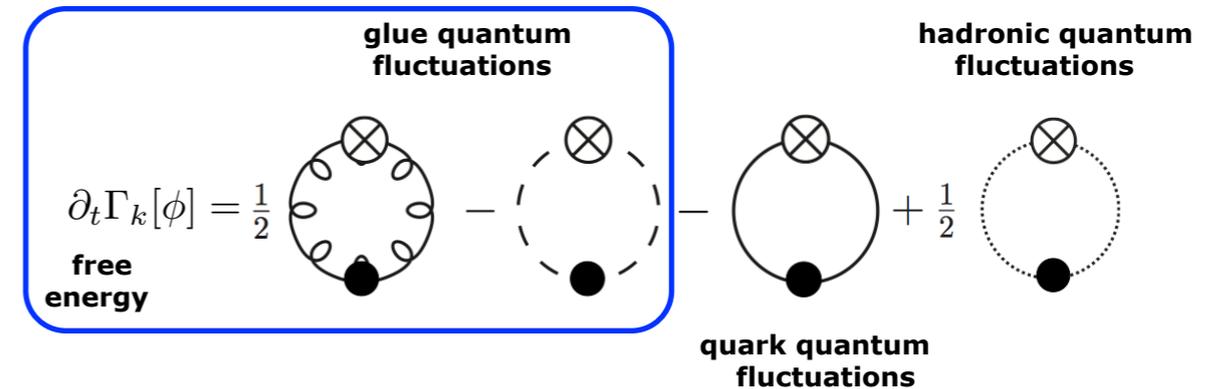
SU(2)

Confinement

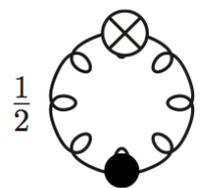
FRG: Braun, Gies, JMP, PLB 684 (2010) 262

FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

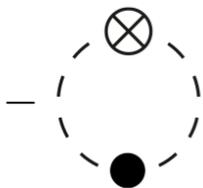
$$L[A_0] = \frac{1}{N_c} \text{tr} \mathcal{P} e^{ig \int_0^\beta A_0(\mathbf{x})}$$



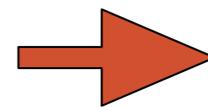
Confinement criterion



+ sign: deconfining



- sign: confining



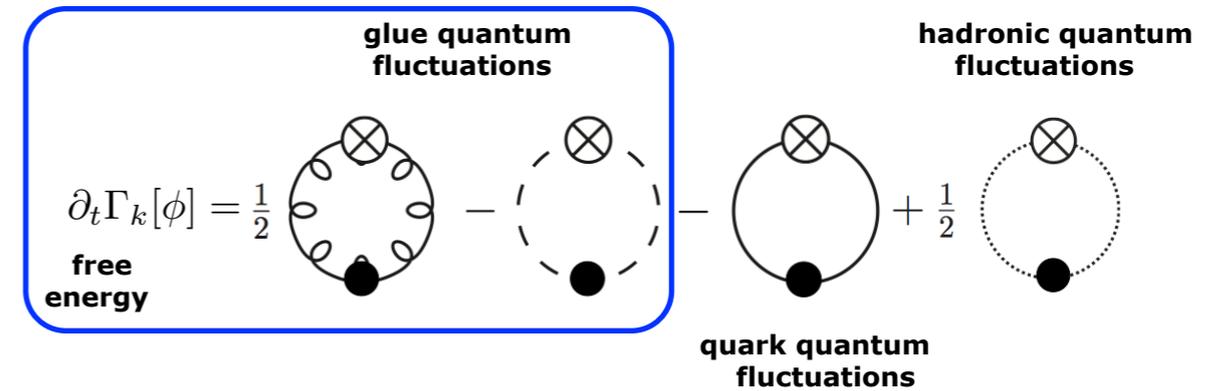
**Glueon propagator gapped
relative to
ghost propagator**

Confinement

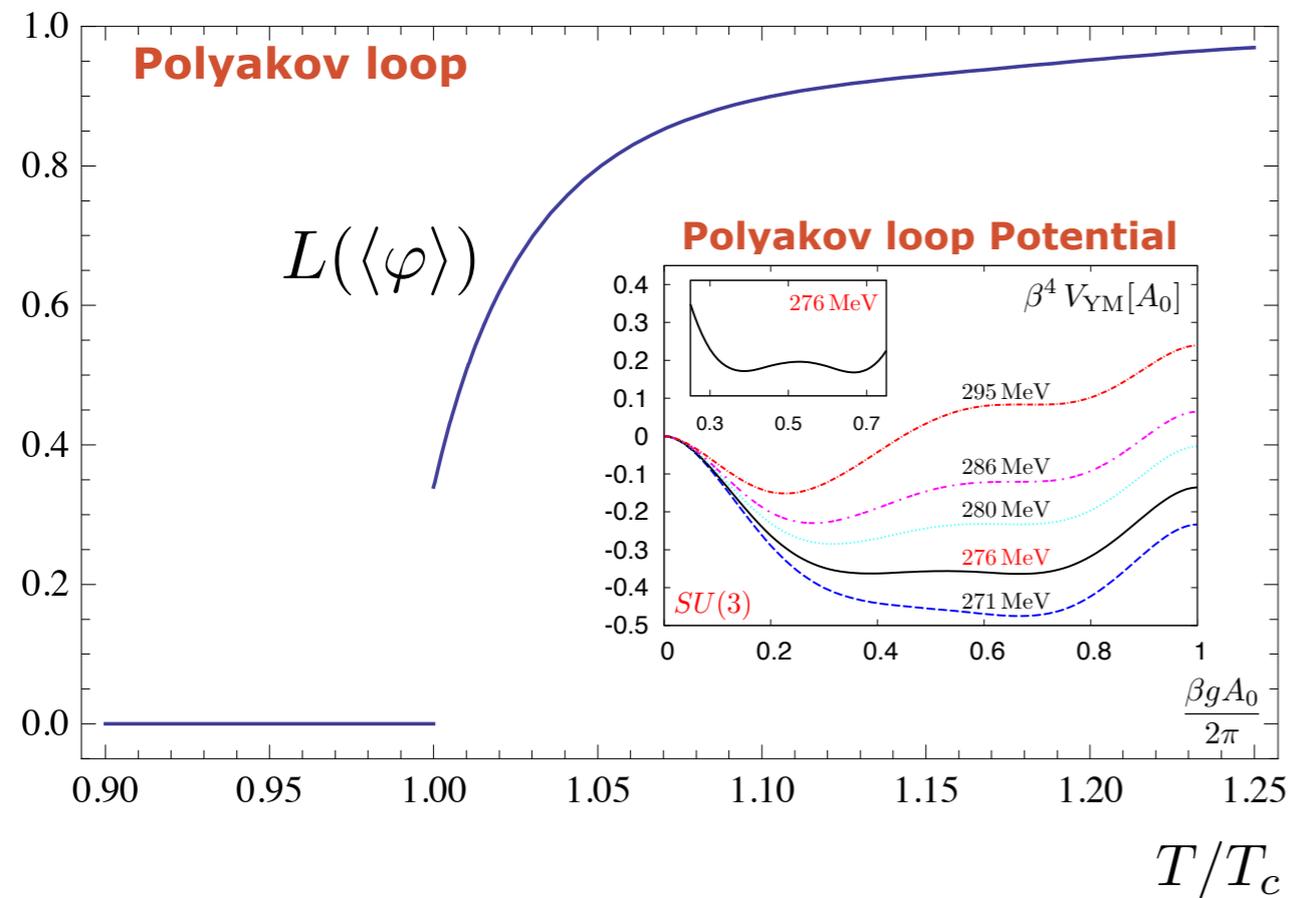
FRG: Braun, Gies, JMP, PLB 684 (2010) 262

FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

$$L[A_0] = \frac{1}{N_c} \text{tr} \mathcal{P} e^{i g \int_0^\beta A_0(x)}$$



$$\mathcal{P} e^{i g \int_0^\beta A_0(x)} = e^{i\varphi}$$



$$T_c / \sqrt{\sigma} = 0.658 \pm 0.023$$

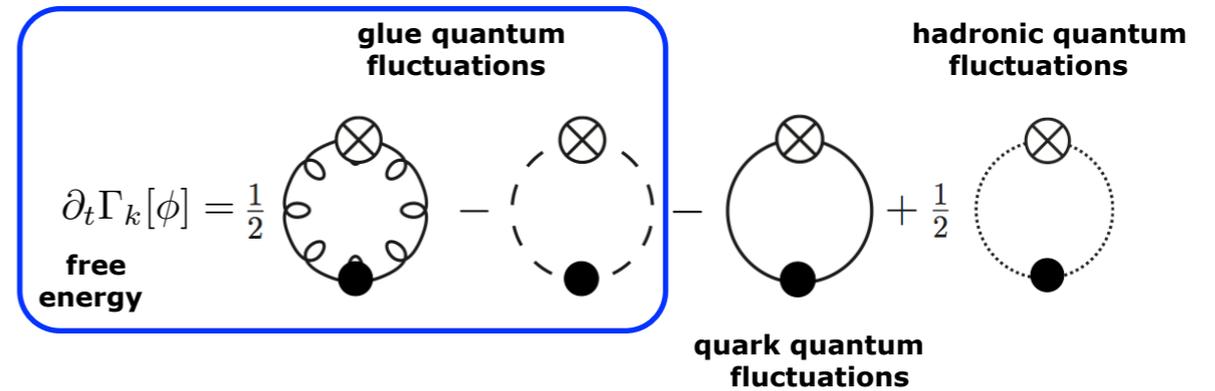
$$\text{lattice : } T_c / \sqrt{\sigma} = 0.646$$

Confinement

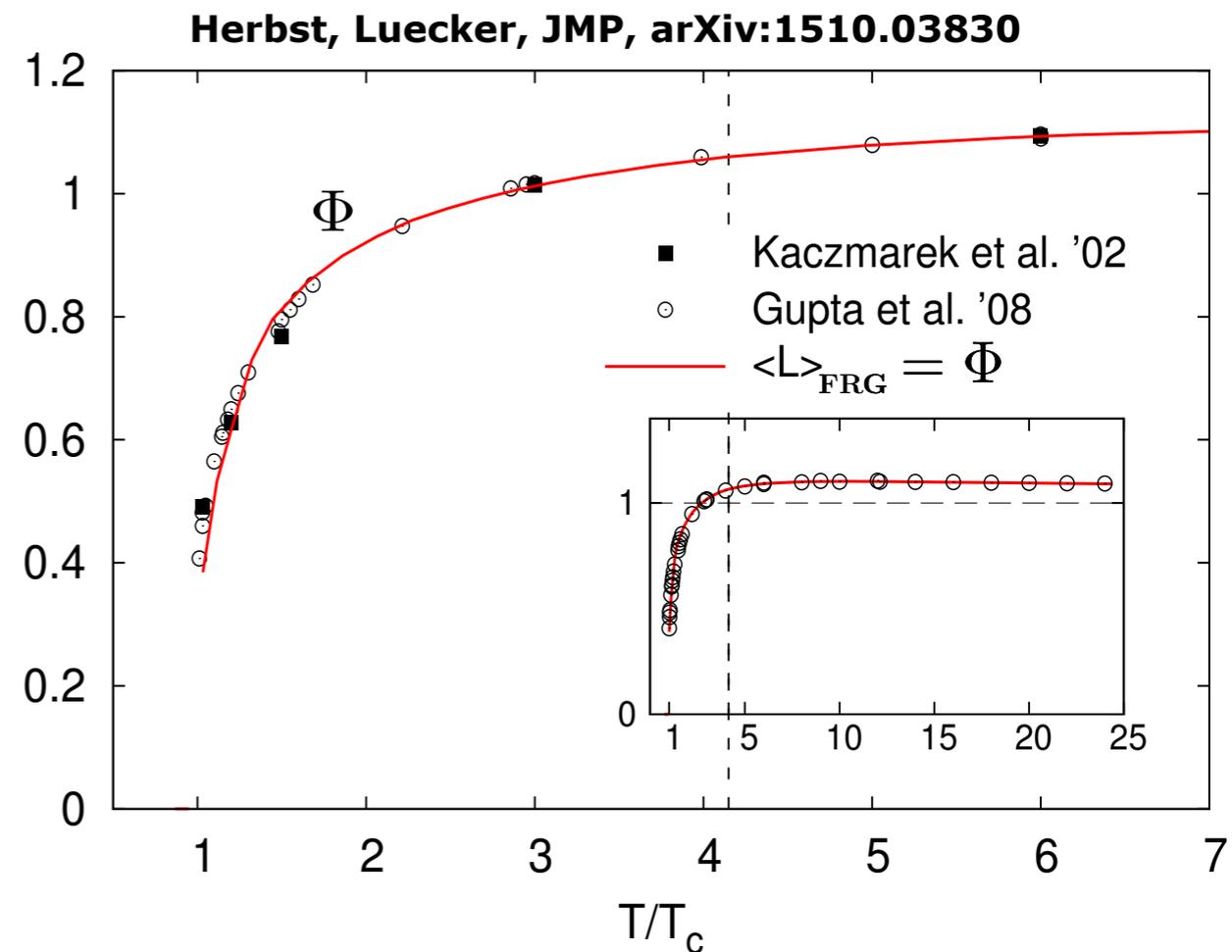
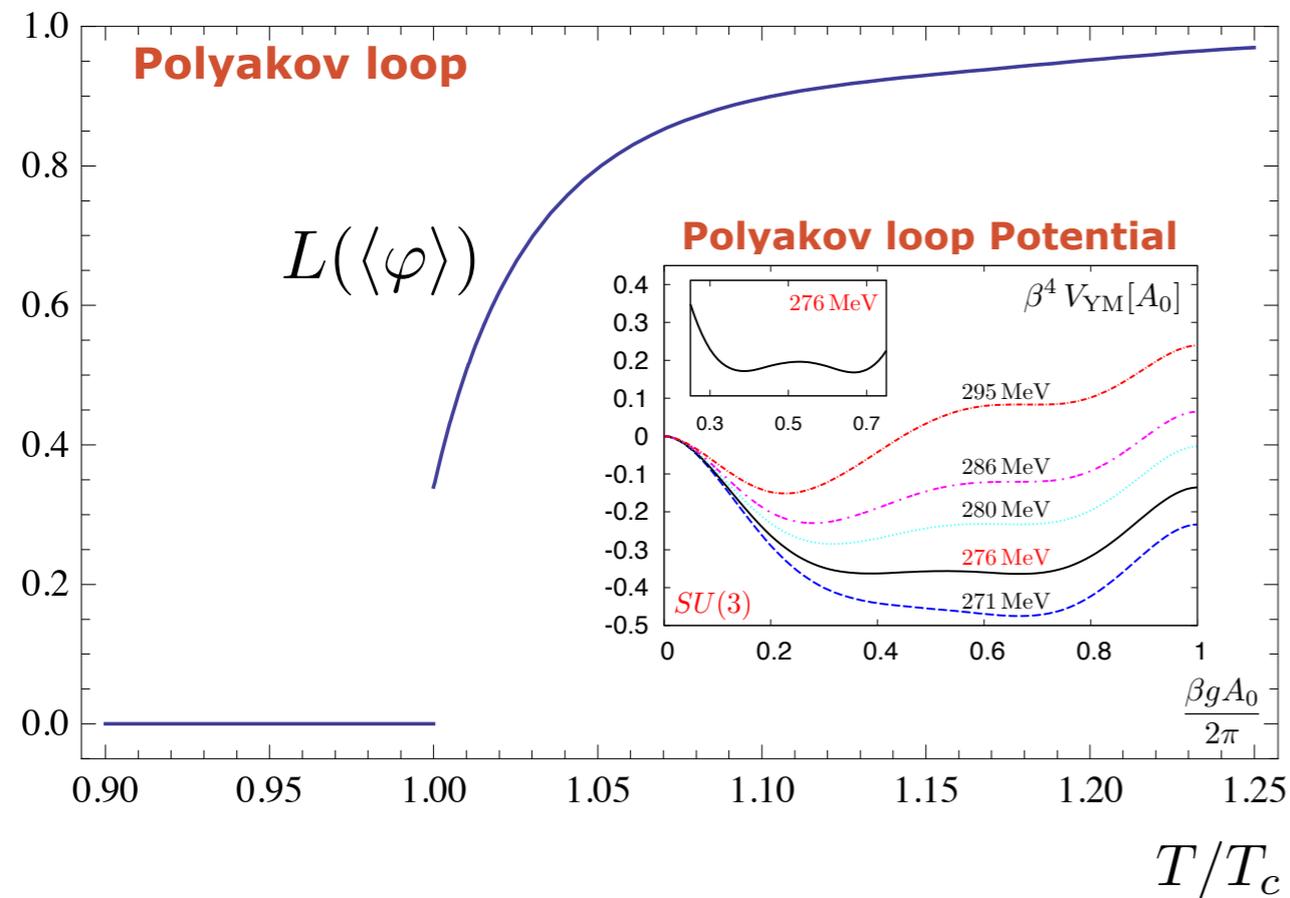
FRG: Braun, Gies, JMP, PLB 684 (2010) 262

FRG, DSE, 2PI: Fister, JMP, PRD 88 (2013) 045010

$$L[A_0] = \frac{1}{N_c} \text{tr} \mathcal{P} e^{i g \int_0^\beta A_0(x)}$$



$$\mathcal{P} e^{i g \int_0^\beta A_0(x)} = e^{i\varphi}$$



Confinement

Herbst, Luecker, JMP, arXiv:1510.03830

Flow equation for the Polyakov loop expectation value

$$\partial_t \langle L[A_0] \rangle = - \frac{1}{2} \left(\frac{\delta^2 \langle L[A_0] \rangle}{\delta A^2} - \frac{\delta^2 \langle L[A_0] \rangle}{\delta c \delta \bar{c}} \right)$$

Flow equation for composite operators

JMP, AP 322 (2007) 2831

Igarashi, Itoh, Sonoda, PTP Suppl. 181 (2010) 1

Pagani, PRD 94 (2016) 045001

Parameterisation

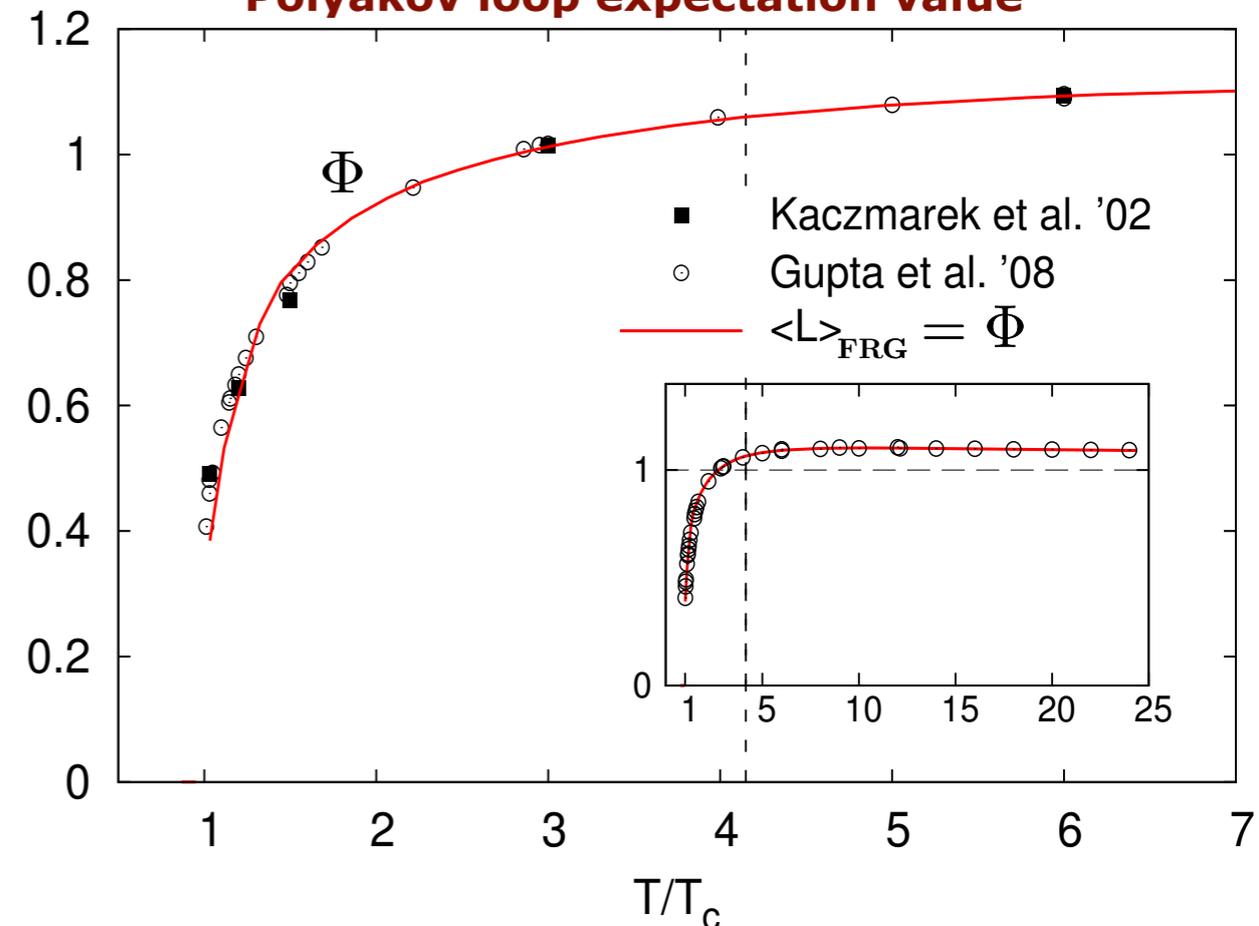
$$\langle L[A_0] \rangle = Z_L[\bar{A}, \phi] \cdot L[A_0]$$

with $\phi = (a_\mu, c, \bar{c})$

Flow for Polyakov loop wave function

$$\partial_t Z_L[\bar{A}, \phi] = \text{Flow}_{Z_L}[\bar{A}; Z_L, G_A, G_c, L[A_0]]$$

Polyakov loop expectation value



Outline

- Motivation

- Functional RG for QCD

- Finite temperature correlation functions

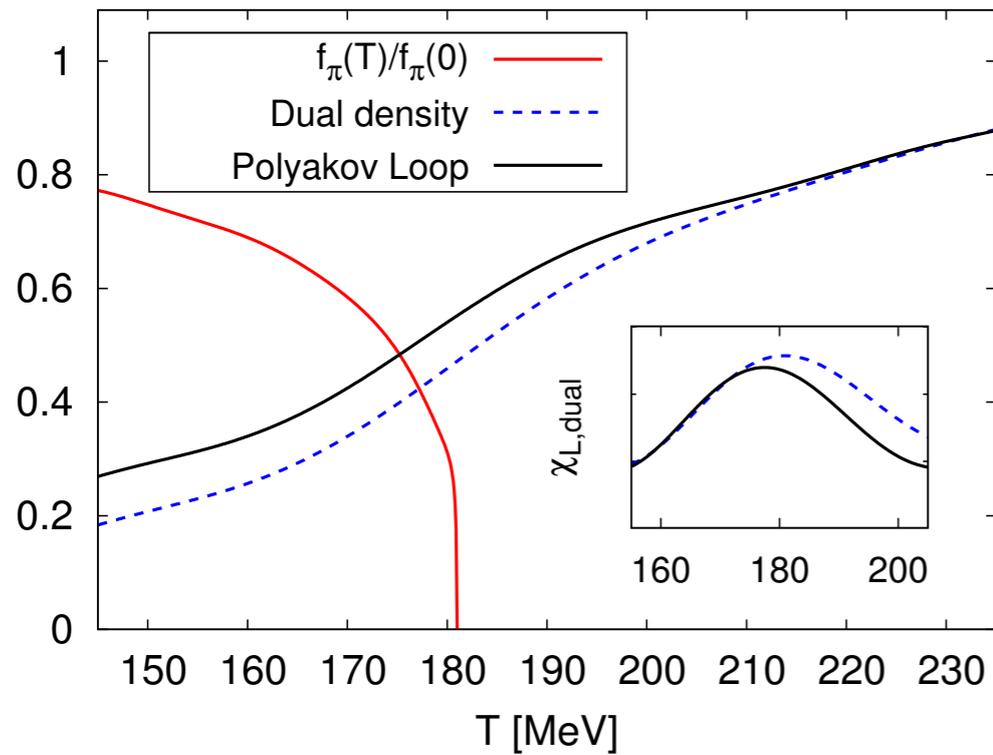
- Confinement

- Some remarks on confinement+chiral symmetry breaking, thermodynamics & transport

- Summary

Confinement & chiral symmetry breaking

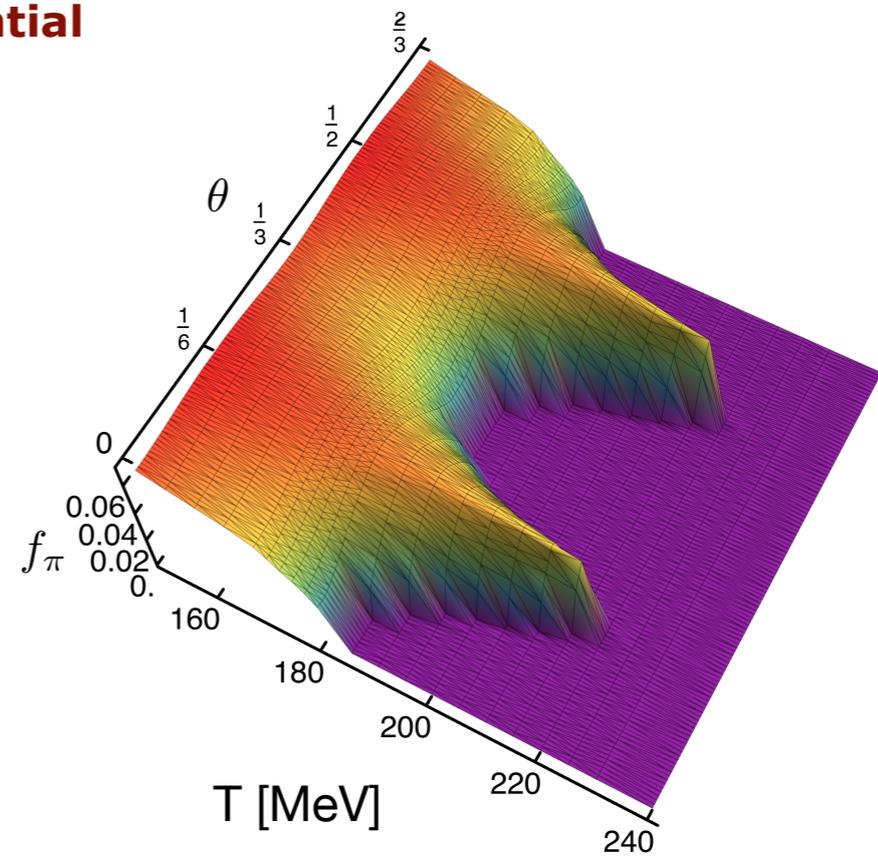
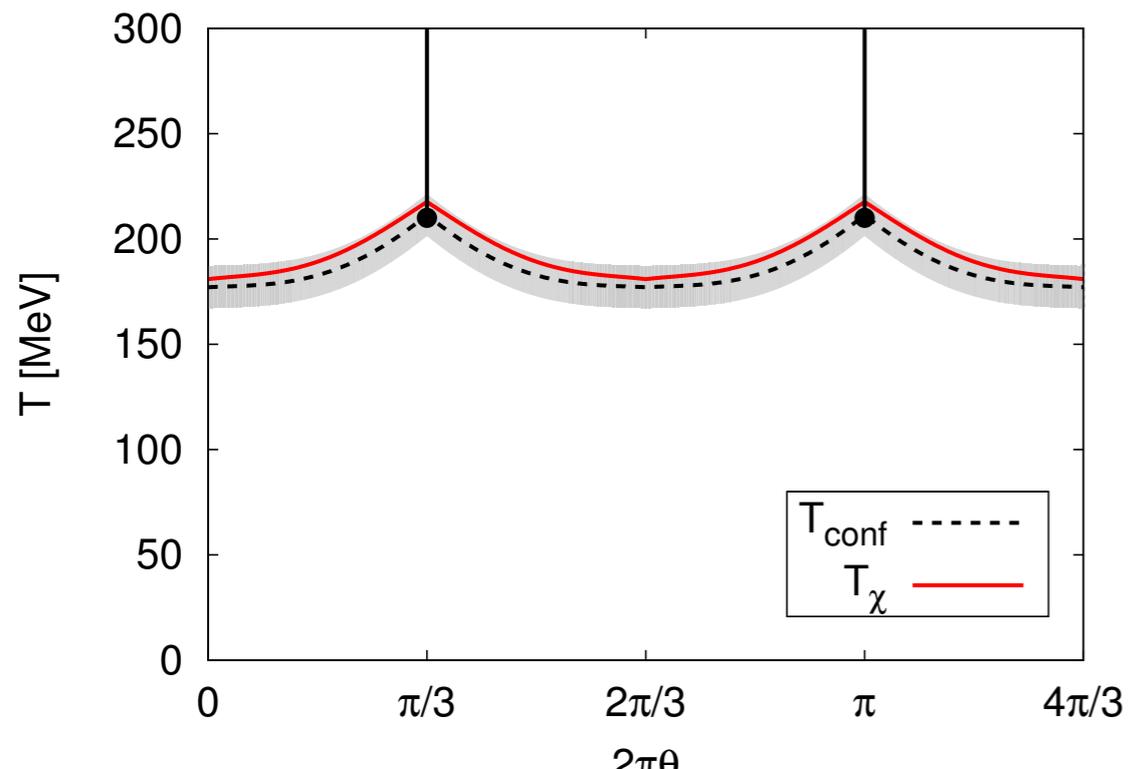
Phase structure in the chiral limit



Braun, Haas, Marhauser, JMP, PRL 106 (2011)

gone full circle

Phase structure at imaginary chemical potential

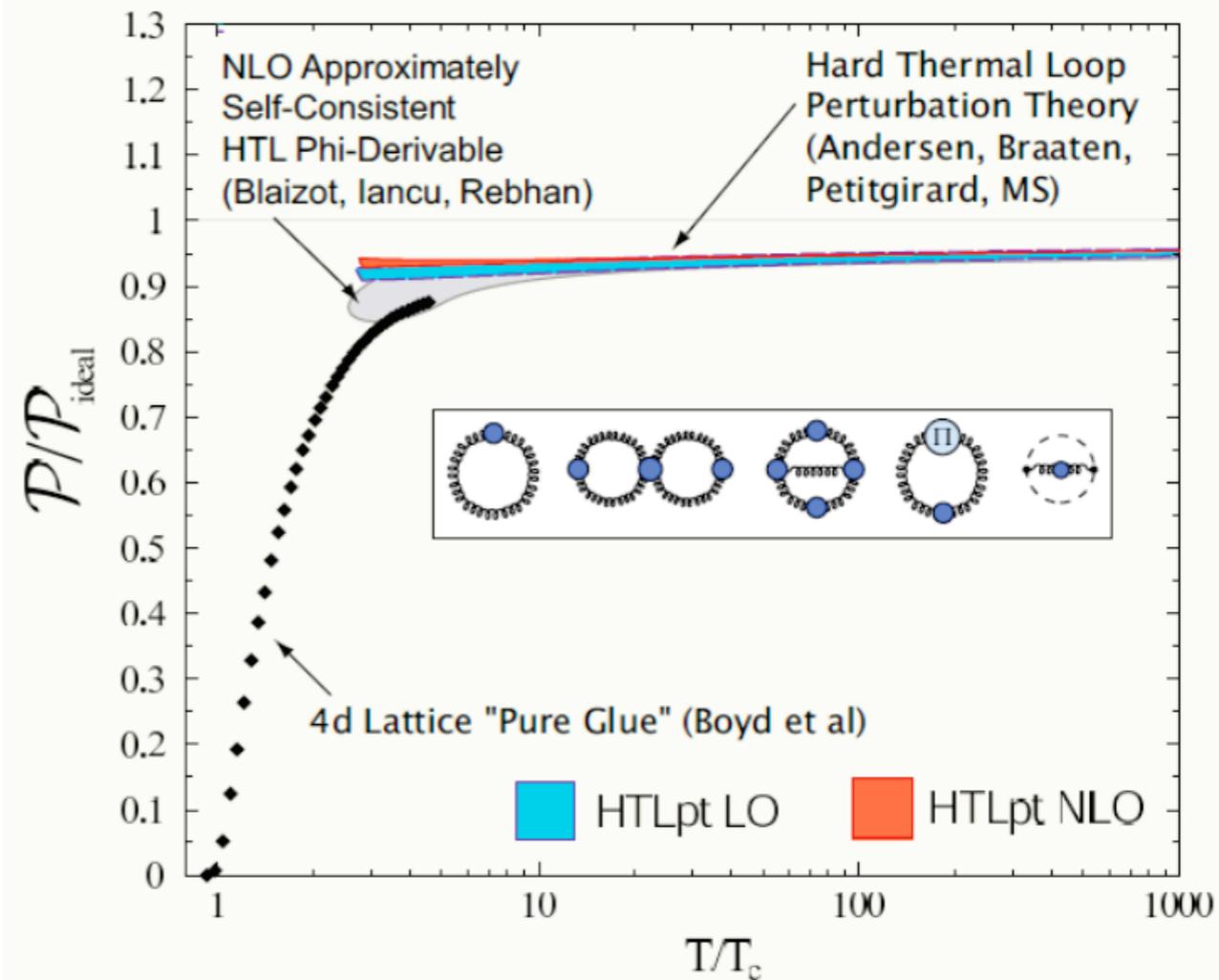
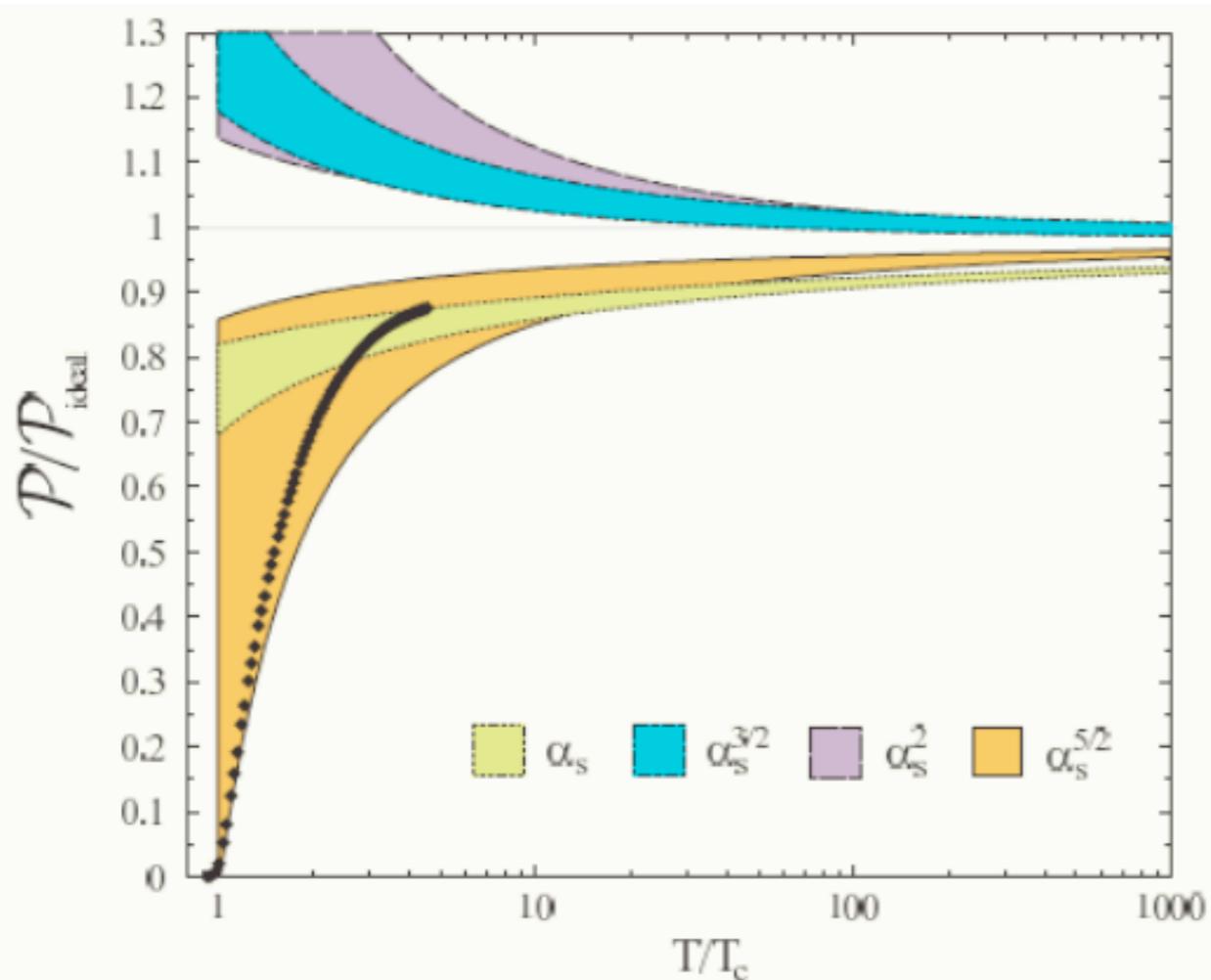


Confinement & Thermodynamics

from overview lectures at ERG 12

'The FRG approach to gauge theories & applications to QCD'

Confinement & Thermodynamics

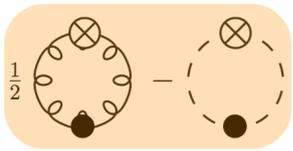


Strickland

$$-p(T; \bar{A}) = \int_{\Lambda}^0 \frac{dk}{k} \left\{ \left(\text{Diagram 1} \right) \Big|_T - \left(\text{Diagram 2} \right) \Big|_{T=0} \right\} \Big|_{\bar{A}}$$

Fister, JMP

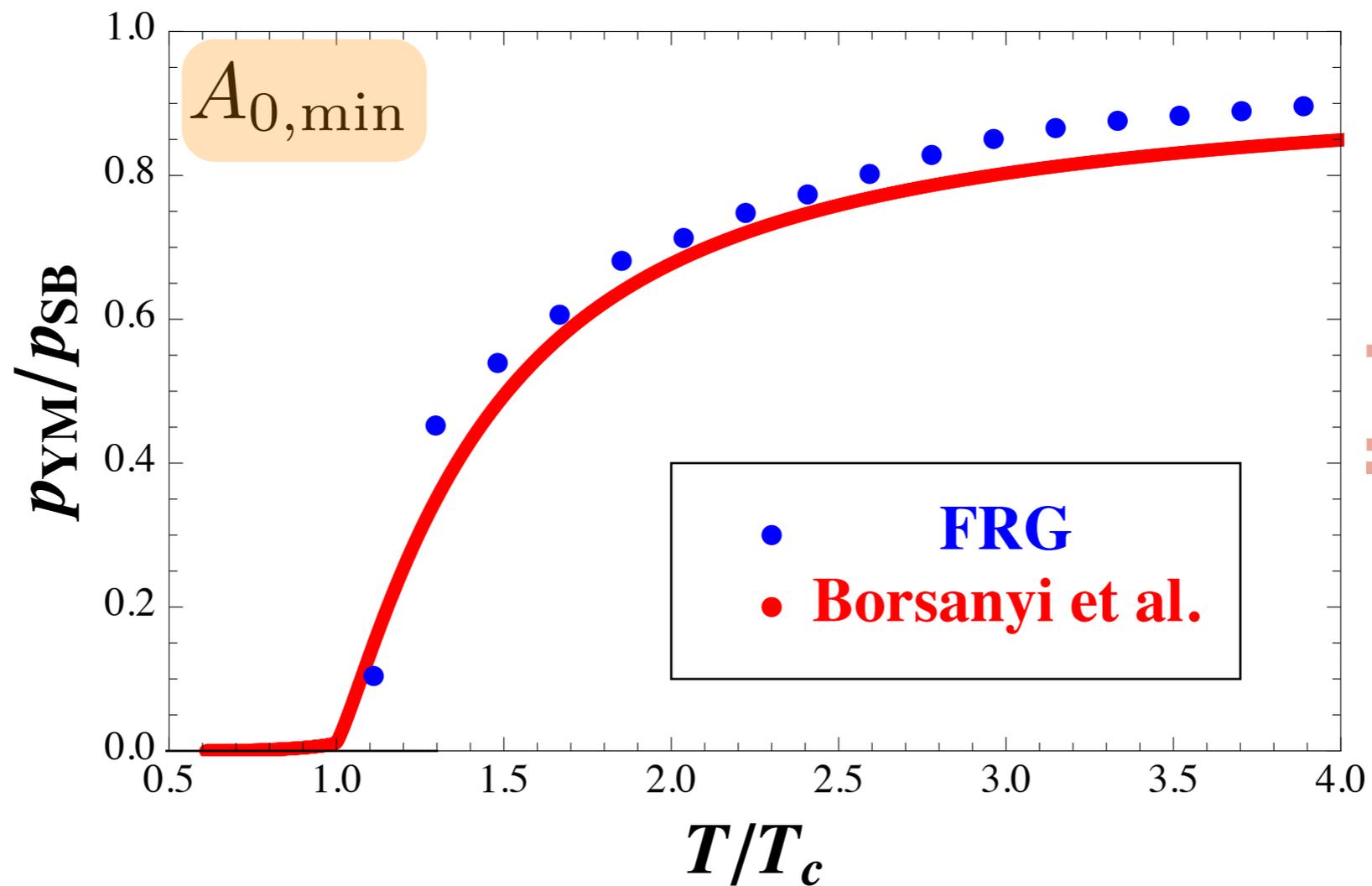
Confinement & Thermodynamics



$$-p(T; \bar{A}) = \int_{\Lambda} \frac{dk}{k} \left\{ \left. \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \right|_{T=0} - \left. \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \right|_{T} \right\} \Big|_{\bar{A}}$$

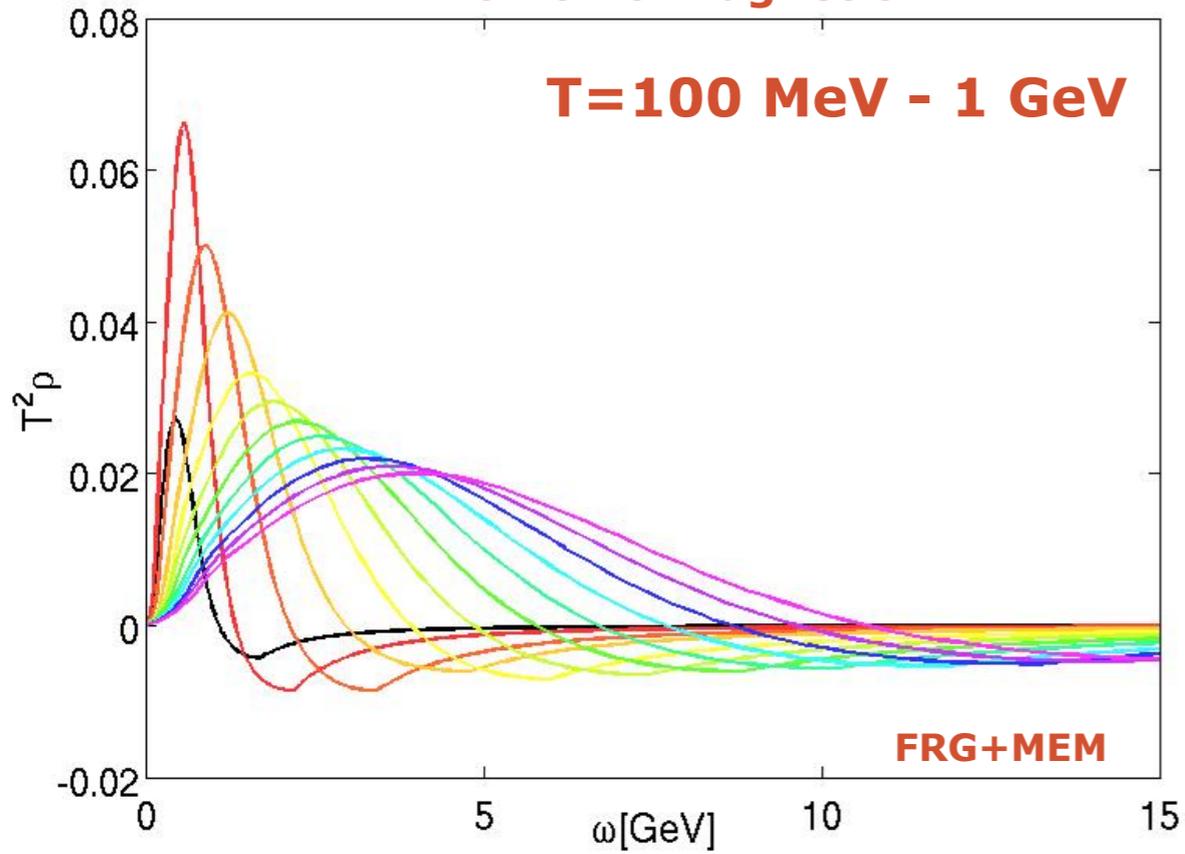
$\int_p G_{T,k} \partial_t R_k$
 $\int_p G_{T=0,k} \partial_t R_k$

see talk of L.Fister



Single particle spectral functions

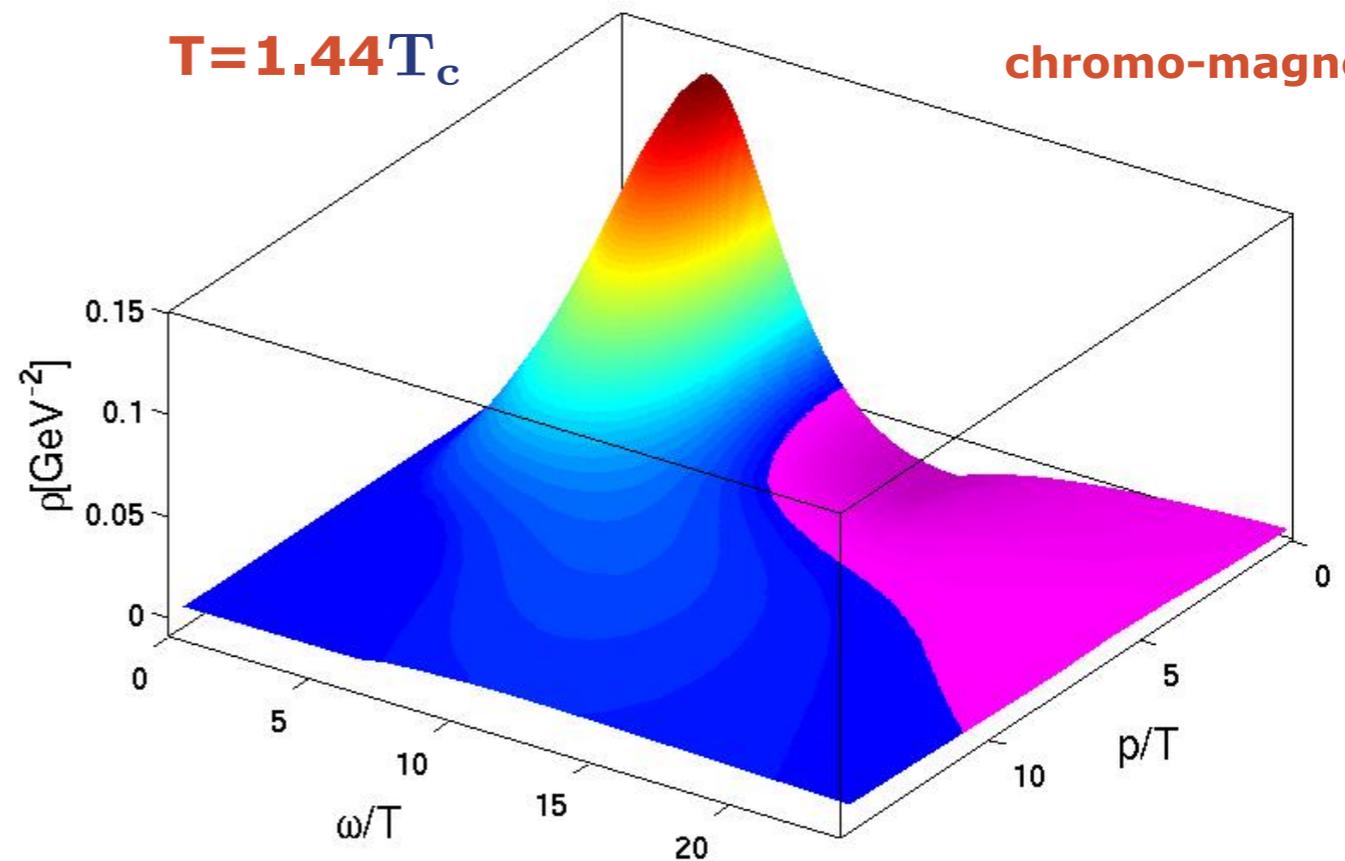
chromo-magnetic



$$\rho(p) = 2 \text{Im} \langle A A \rangle_{\text{ret}}(p)$$

T=1.44 T_c

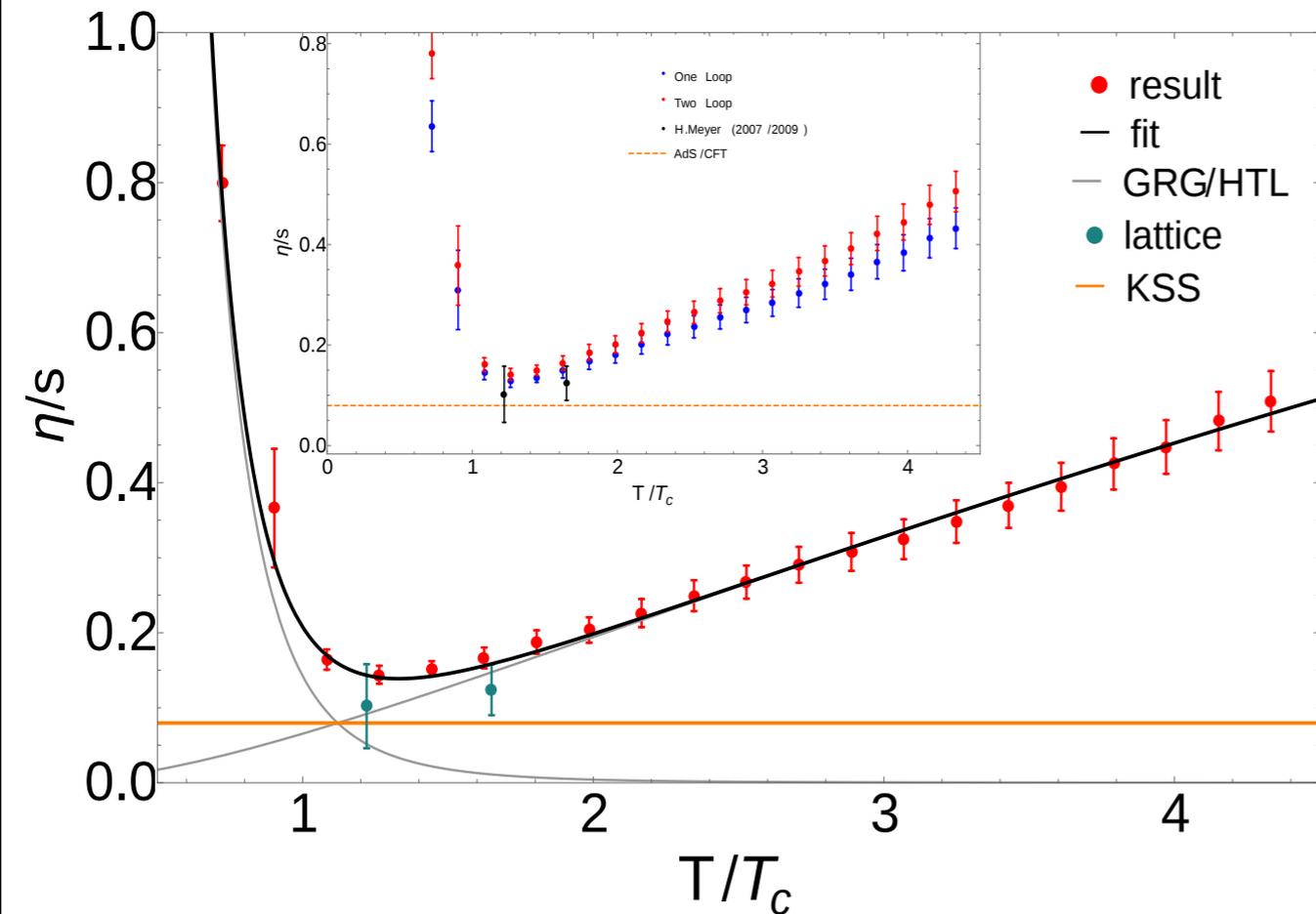
chromo-magnetic



Transport

QCD - estimate for viscosity over entropy ratio

viscosity over entropy ratio



$$\gamma_{\text{grg}} \approx 5$$

$$\gamma_{\text{qgp}} \approx 1.6$$

pure glue

$$a_{\text{qgp}} \approx 0.15$$

$$a_{\text{hrg}} \approx 0.14$$

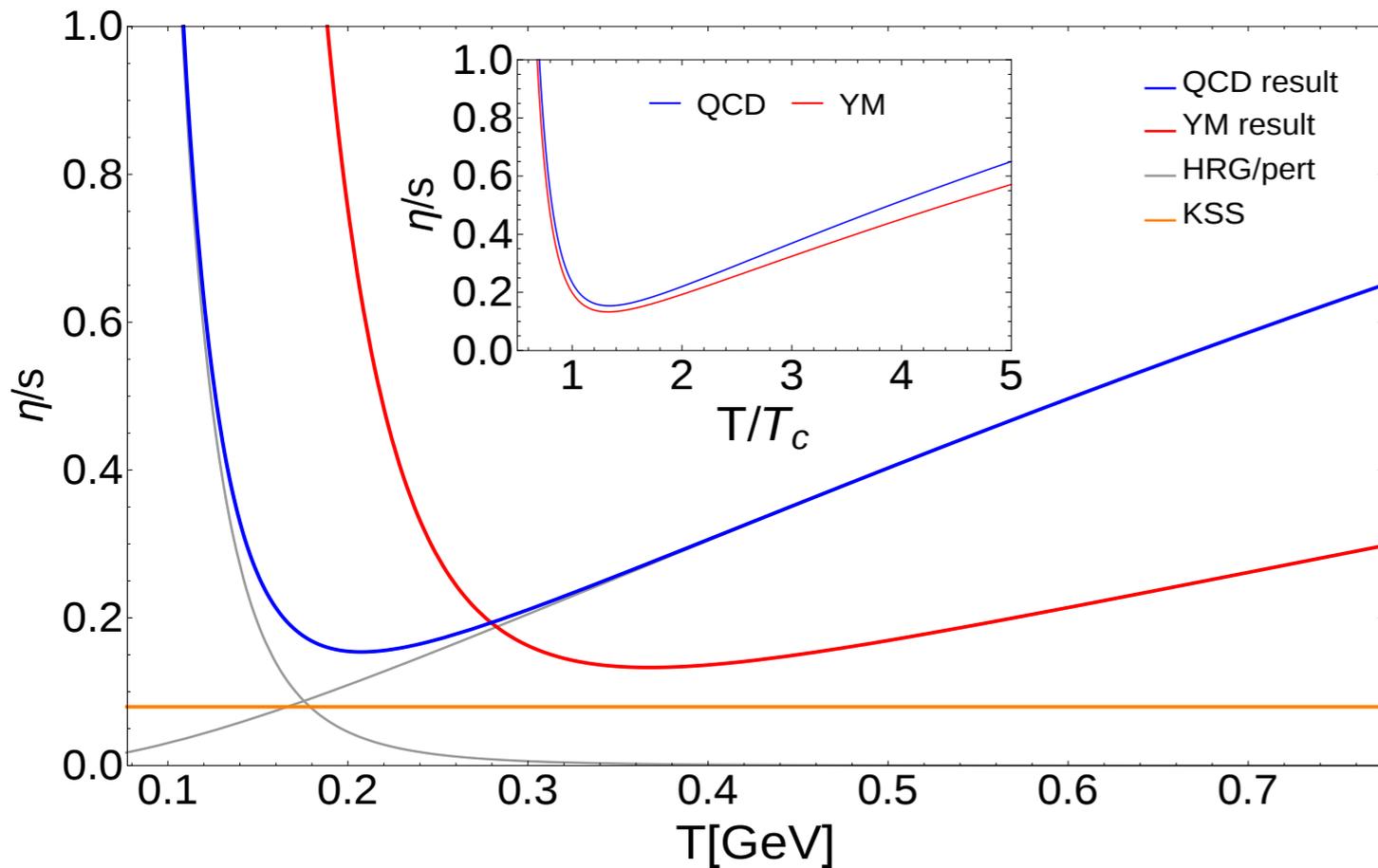
$$c \approx 0.66$$

$$\frac{\eta}{s}(T) = \frac{a_{\text{qgp}}}{\alpha_s^{\gamma_{\text{qgp}}}(cT/T_c)} + \frac{a_{\text{grg}}}{(T/T_c)^{\gamma_{\text{grg}}}}$$

Transport

QCD - estimate for viscosity over entropy ratio

viscosity over entropy ratio



$$a_{\text{qgp}} \approx 0.2$$

$$a_{\text{hrg}} \approx 0.16$$

$$c \approx 0.79$$

QCD

$$\gamma_{\text{grg}} \approx 5$$

$$\gamma_{\text{qgp}} \approx 1.6$$

pure glue

$$a_{\text{qgp}} \approx 0.15$$

$$a_{\text{hrg}} \approx 0.14$$

$$c \approx 0.66$$

$$\frac{\eta}{s}(T) = \frac{a_{\text{qgp}}}{\alpha_s^{\gamma_{\text{qgp}}}(cT/T_c)} + \frac{a_{\text{grg}}}{(T/T_c)^{\gamma_{\text{grg}}}}$$

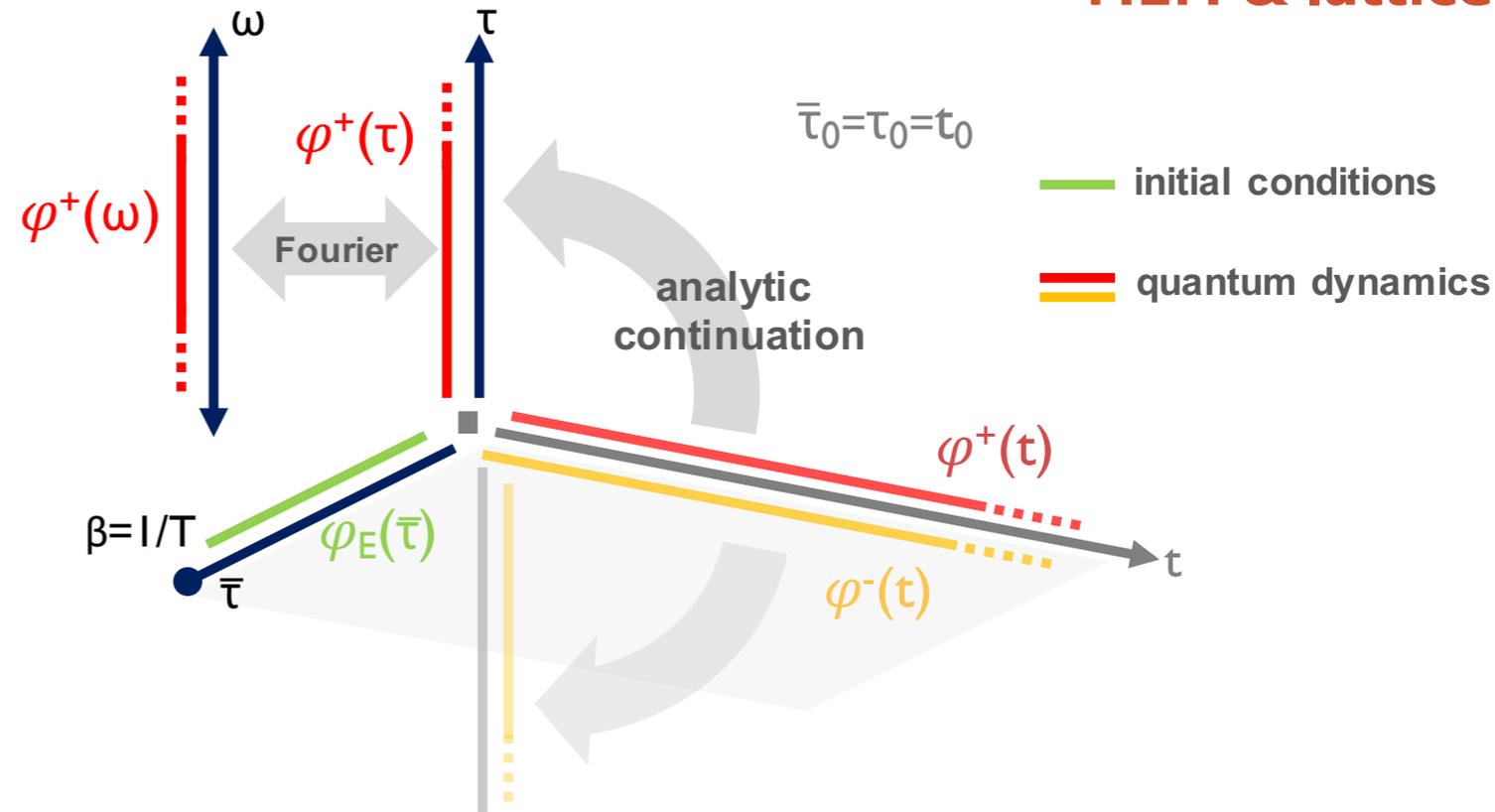
thermal spectral functions on the lattice

MEM & lattice

$$\underbrace{\int [d\varphi_0^+][d\varphi_0^-] \langle \varphi_0^+ | e^{-\beta \hat{H}} | \varphi_0^- \rangle}_{\text{initial conditions}} \underbrace{\int_{\varphi_0^+}^{\varphi_0^-} \mathcal{D}\varphi e^{iS_M[\varphi^+] - iS_M[\varphi^-]}}_{\text{quantum dynamics}}$$

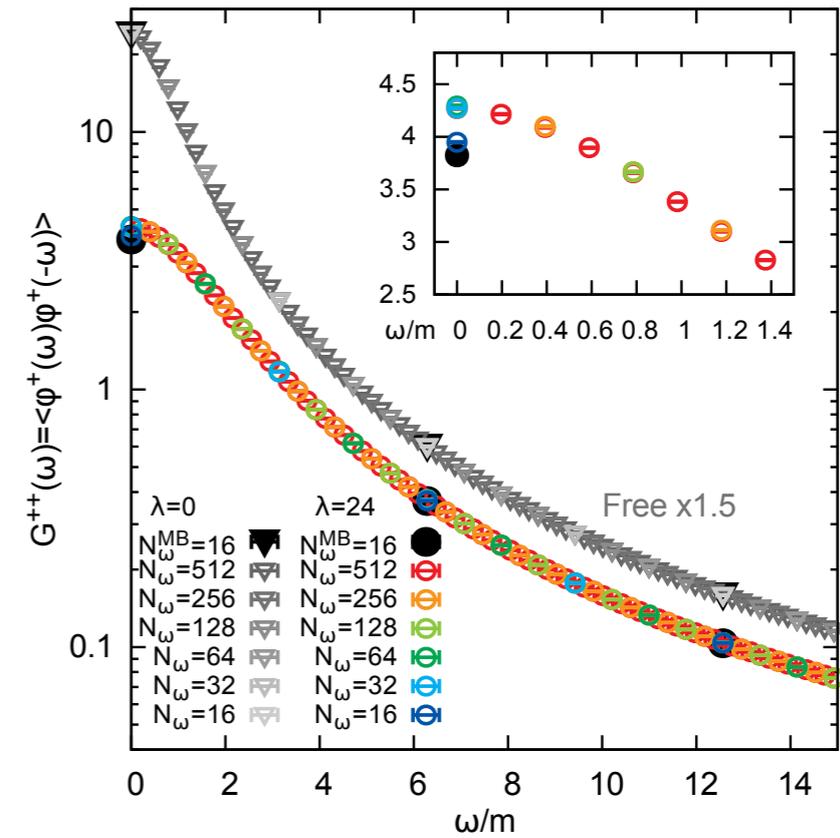
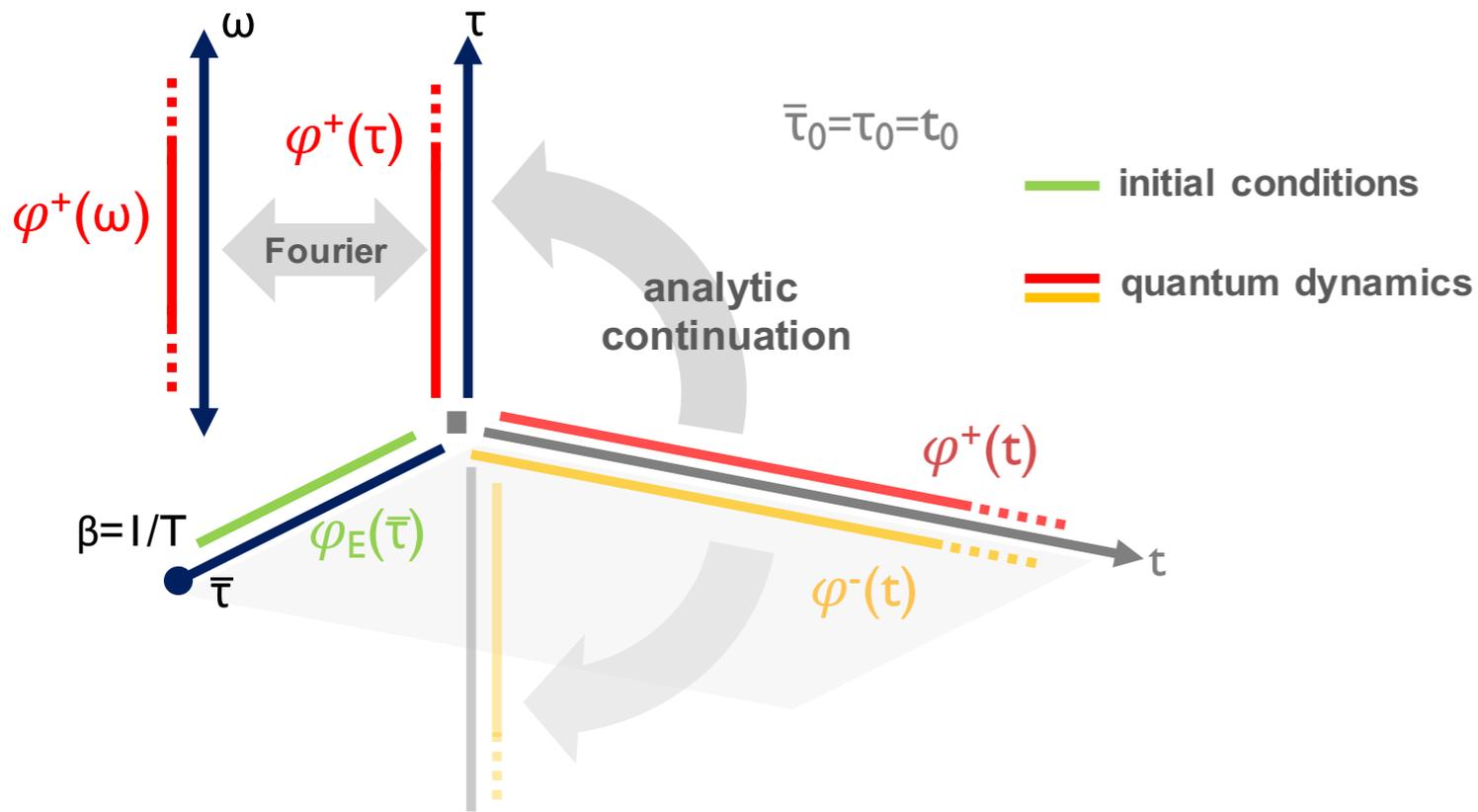
Stochastic quantisation

$$\partial_{t_5} \varphi^+(\omega_l) = -\frac{\delta S_0}{\delta \varphi^+(\omega_l)} - \frac{\delta S_E^{\text{int}}}{\delta \varphi^+(\tau_j)} \frac{\delta \varphi^+(\tau_j)}{\delta \varphi^+(\omega_l)} + \eta(\omega_l)$$

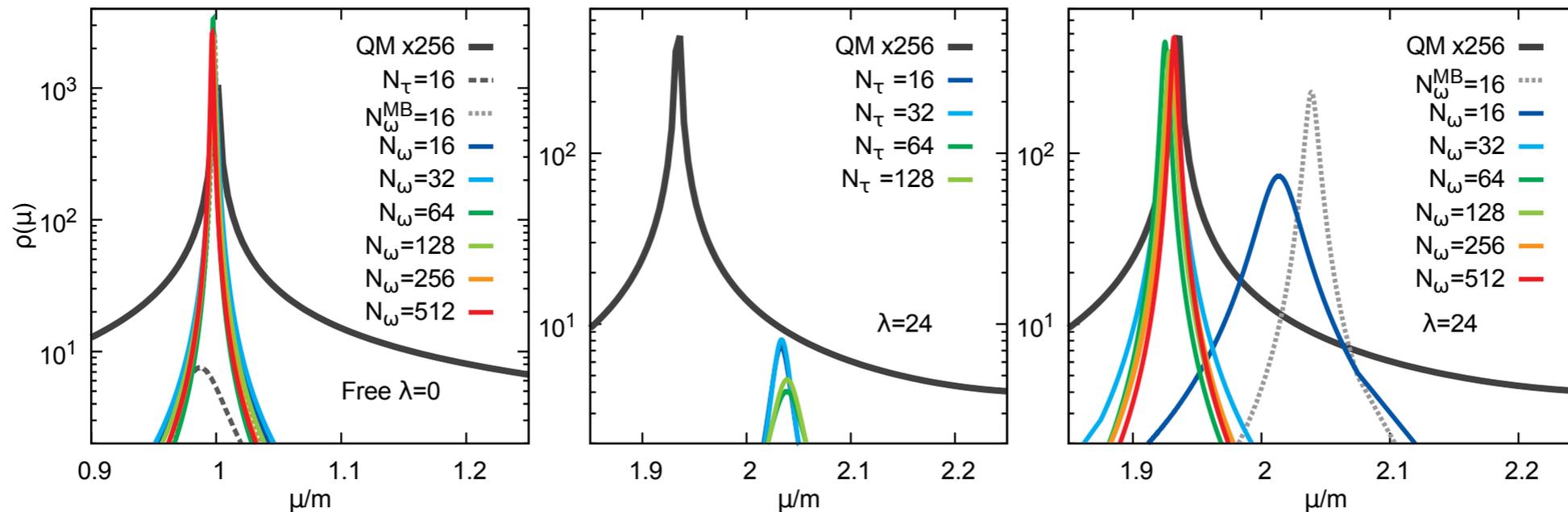


thermal spectral functions on the lattice

MEM & lattice



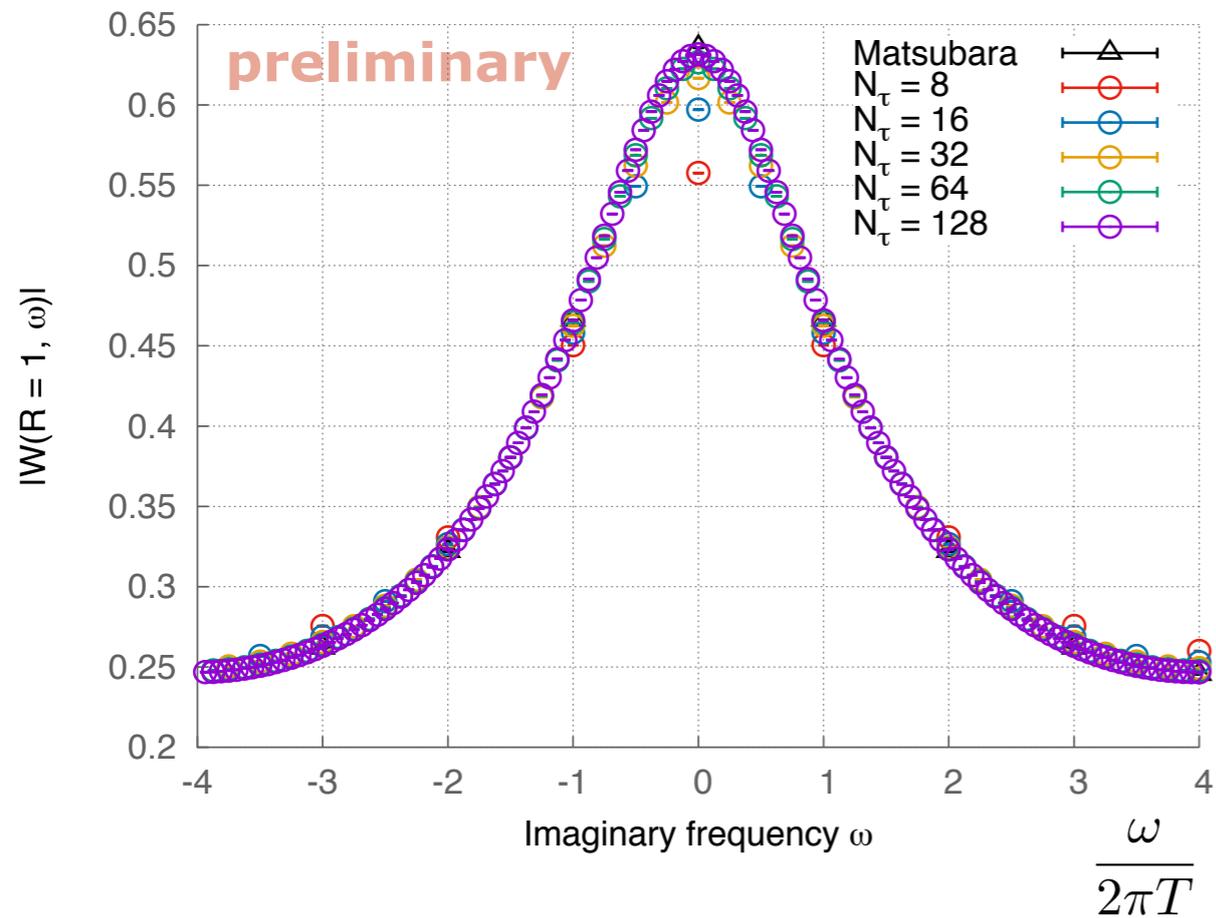
Test case: 1+0 dimensional scalar theory



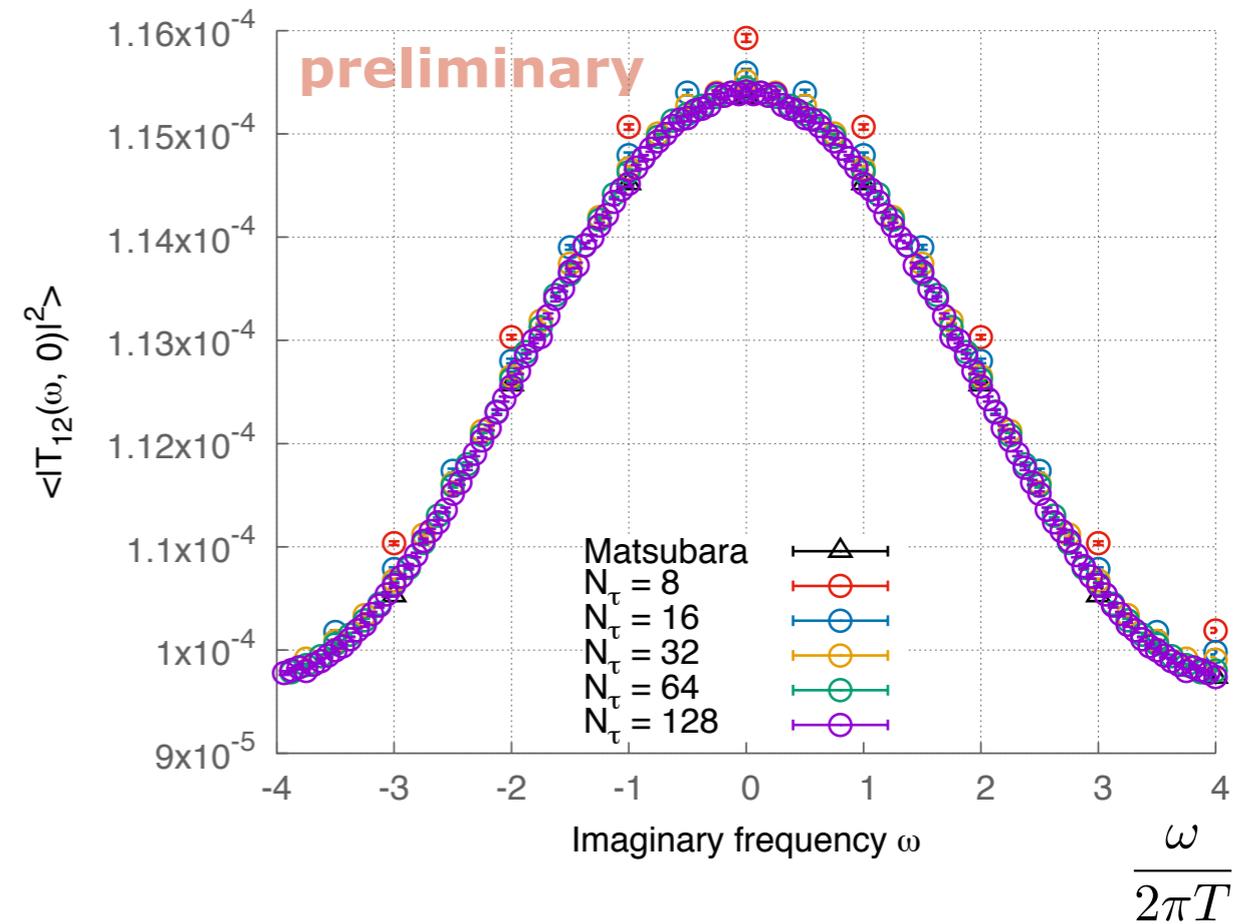
3+1-dimensional SU(2) gauge theory

MEM & lattice

Wilson loop in frequency space

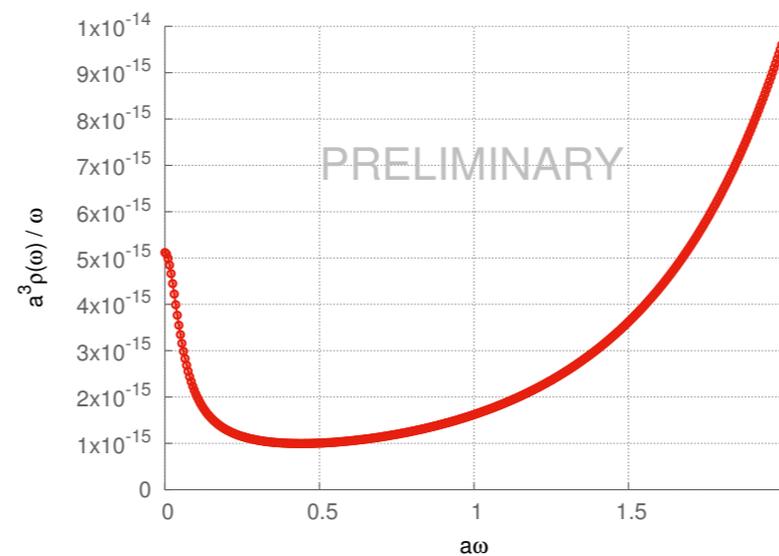


correlator of energy-momentum tensor



spectral function of EMT-correlator

fresh from the computer

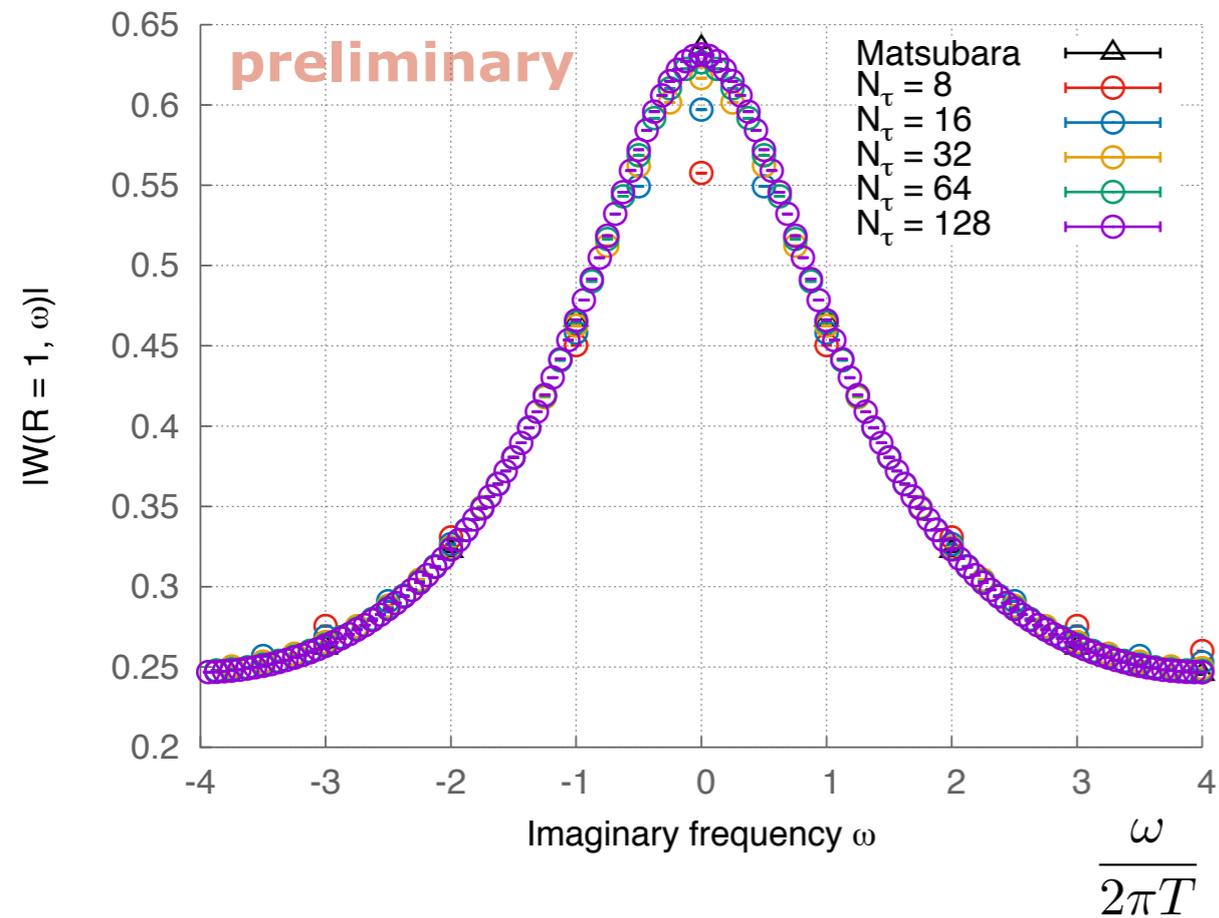


JMP, Rothkopf, Ziegler, work in progress

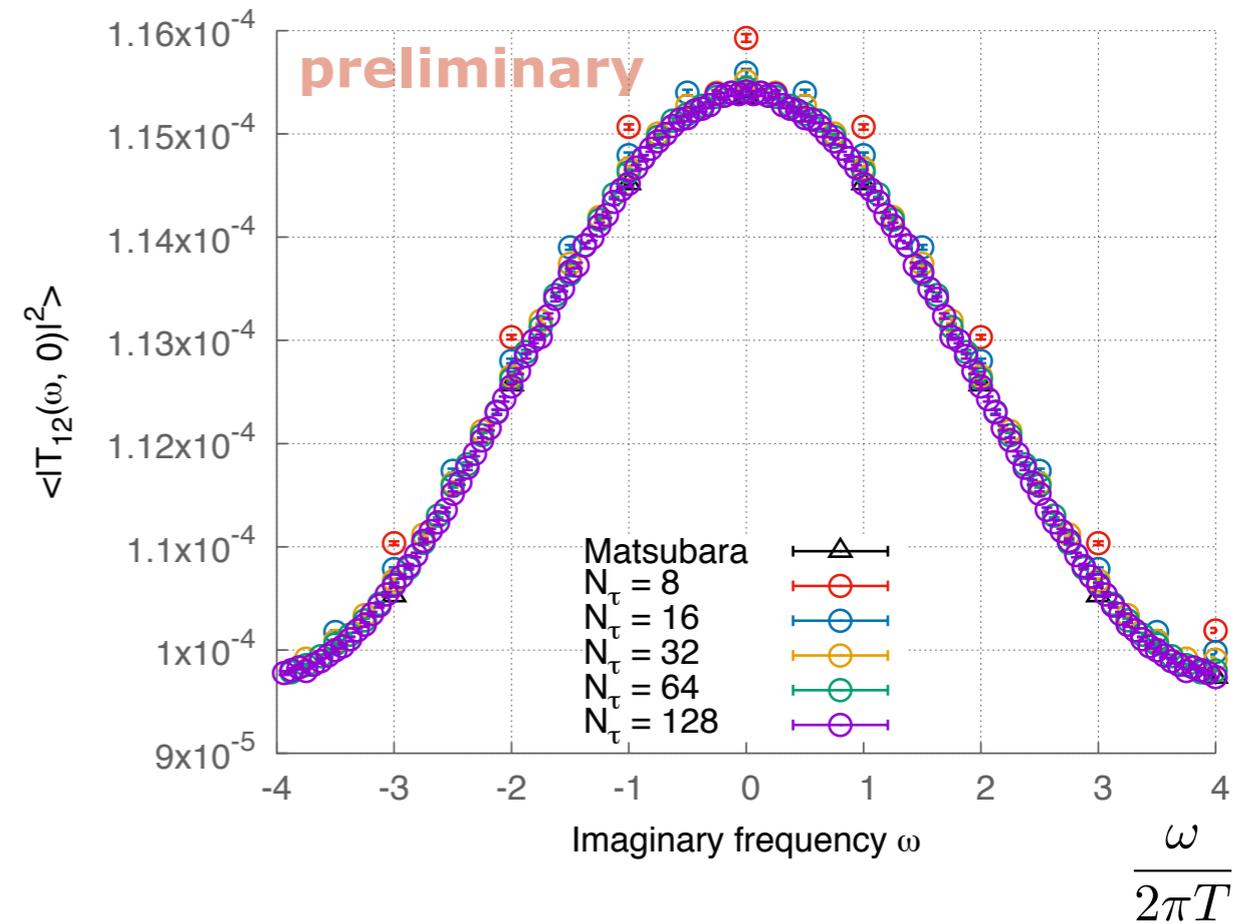
3+1-dimensional SU(2) gauge theory

MEM & lattice

Wilson loop in frequency space



correlator of energy-momentum tensor



MEM-type

Rothkopf, PRD 95 (2017) 5, 056016
Ilgenfritz, JMP, Rothkopf, Trunin; arXiv:1701.08610
Fischer, JMP, Rothkopf, Welzbacher, arXiv:1705.03207

JMP, Rothkopf, Ziegler, work in progress

Outline

● Motivation

● Functional RG for QCD

● Finite temperature correlation functions

● Confinement

● Some remarks on confinement+chiral symmetry breaking & thermodynamics

● Summary

Summary

- **Physics at finite density requires quantitative precision**
- **Systematic expansion scheme & apparent convergence**
- **Scaling, decoupling, irregularities and all that**
see talk of Mario Mitter
- **Finite temperature correlation function in Yang-Mills**
systematics requires scaling
- **Quark confinement & confinement criterion**
- **Expectation value of Polyakov loop**
- **Confinement & chiral symmetry breaking at finite T**
full circle: finite density