FRG-QCD: Status and Prospects

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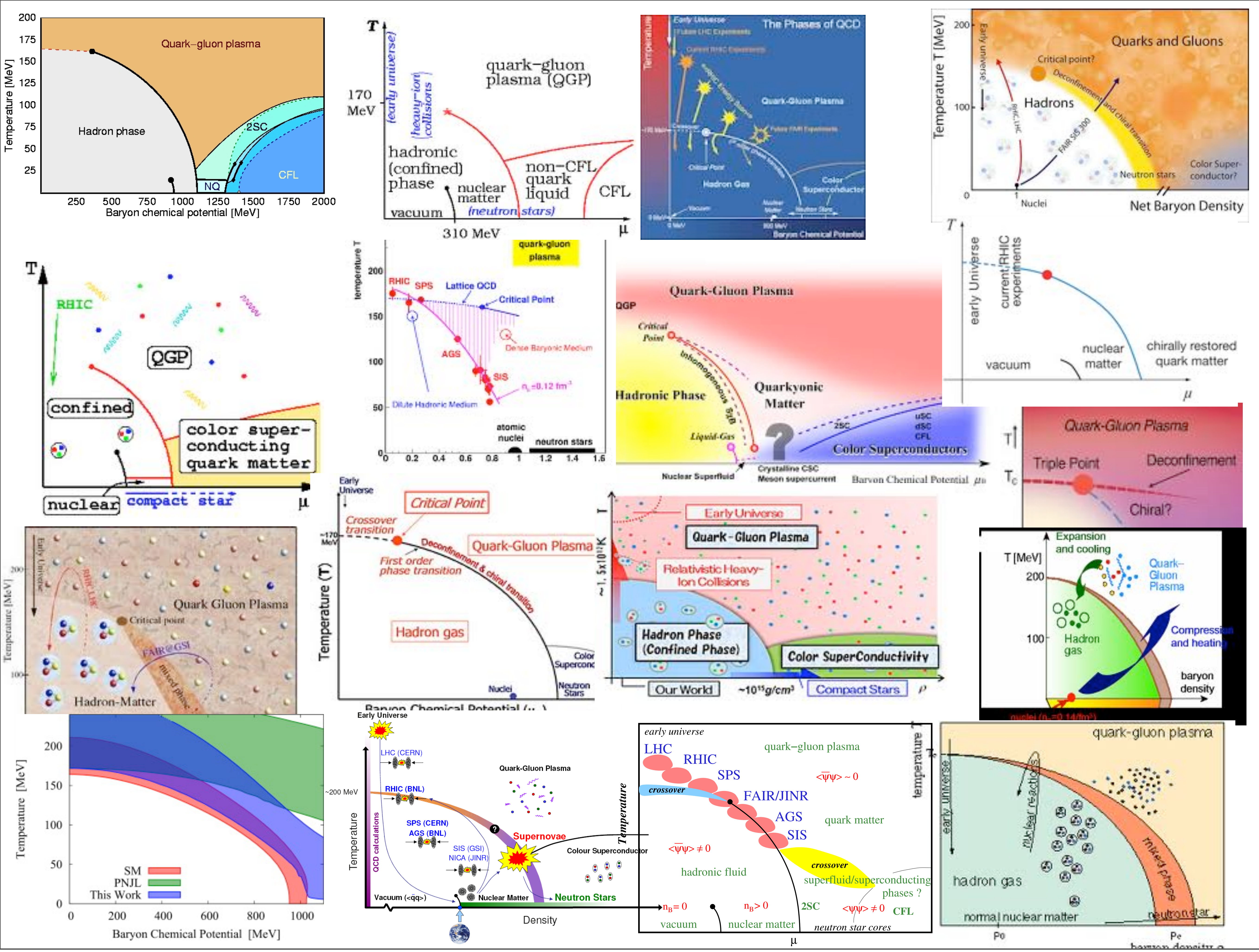
Universität Heidelberg & ExtreMe Matter Institute

Lefkada, September 23rd 2014



Quark–gluon plasma
Hadron phase
2SC
CFL
NQ
Temperature [MeV]
Baryon chemical potential [MeV]
quark–gluon plasma (QGP)
170 MeV
early universe
heavy-ion collisions
hadronic (confined) phase
nuclear matter
non-CFL quark liquid
CFL
vacuum
(neutron stars)
310 MeV
The Phases of QCD
Early Universe
Quark-Gluon Plasma
Critical Point
Hadron Gas
Color Superconductor
Nuclear Matter
Neutron Stars
Baryon Chemical Potential
Temperature
Quarks and Gluons
Critical point?
Hadrons
Deconfinement and chiral transition
Color Super-conductor?
Neutron stars
Nuclei
Net Baryon Density
Temperature T [MeV]
RHIC
QGP
confined
color super-conducting quark matter
nuclear
compact star
quark-gluon plasma
temperature T
RHIC
SPS
Lattice QCD
Critical Point
AGS
SIS
Dense Baryonic Medium
Dilute Hadronic Medium
atomic nuclei
neutron stars
Quark-Gluon Plasma
QGP
Critical Point
Hadronic Phase
Quarkyonic Matter
Liquid-Gas
2SC
uSC
dSC
CFL
Color Superconductors
Nuclear Superfluid
Crystalline CSC
Meson supercurrent
Baryon Chemical Potential
early Universe
current RHIC experiments
vacuum
nuclear matter
chirally restored quark matter
Quark-Gluon Plasma
Triple Point
Deconfinement
Chiral?
Early Universe
Quark Gluon Plasma
Critical point
FAIR@GSI
mixed phase
Hadron-Matter
Temperature [MeV]
Early Universe
Critical Point
Crossover transition
Deconfinement & chiral transition
Quark-Gluon Plasma
First order phase transition
Hadron gas
Color Superconductor
Nuclei
Neutron Stars
Temperature (T)
Baryon Chemical Potential
Early Universe
Quark - Gluon Plasma
Relativistic Heavy-Ion Collisions
Hadron Phase (Confined Phase)
Color SuperConductivity
Our World
~10^{15}g/cm³
Compact Stars
Expansion and cooling
T [MeV]
Quark–Gluon Plasma
Hadron gas
Compression and heating
baryon density
SM
PNJL
This Work
Temperature [MeV]
Baryon Chemical Potential [MeV]
Early Universe
LHC (CERN)
RHIC (BNL)
SPS (CERN)
AGS (BNL)
SIS (GSI)
NICA (JINR)
Quark-Gluon Plasma
Supernovae
Colour Superconductor
QCD calculations
Vacuum (<qq>)
Nuclear Matter
Neutron Stars
Density
Temperature
early universe
LHC
RHIC
SPS
FAIR/JINR
AGS
SIS
crossover
quark–gluon plasma
quark matter
hadronic fluid
superfluid/superconducting phases ?
2SC
CFL
vacuum
nuclear matter
neutron star cores
temperature T
quark-gluon plasma
early universe
nuclear reactions
hadron gas
mixed phase
normal nuclear matter
neutron star
baryon density

FRG-QCD Talks

L. Fister 'Correlation functions in Yang-Mills theory' cancelled by Air France

M. Mitter '<u>QCD and dynamical hadronisation</u>'

N. Strodthoff '<u>Spectral functions</u>'

F. Rennecke '<u>The chiral phase transition of QCD</u>'

FRG-QCD collaboration: J. Braun, L. Fister, T.K. Herbst, M. Mitter, JMP, F. Rennecke, N. Strodthoff

TARDIS, ERGE

DoFun

Braun, Huber, Comput.Phys.Commun. 183 (2012) 1290-1320

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Related Talks

M. Huber	'Yang-Mills correlation functions from Dyson-Schwinger equations'
A. Juricic	'Probing the QCD phase diagram with generalised quark susceptibilities'
K. Kamikado	'Magnetic susceptibility of the strongly interacting matter'
N. Khan	'The role of fluctuations in the QCD phase diagram'
J. Luecker	'Polyakov loop potential from functional methods'
S. Mao	'The Deconfinement phase transition in the Friedberg-Lee model'
N. Mueller	'QCD in magnetic fields'
S. Rechenberger	'Chiral dynamics in external magnetic fields'
B.J. Schaefer	'Phase structure, thermodynamics and fluctuations in QCD'
P. Springer	'Dynamical locking of chiral and deconfinement phase transitions'
W. Weise	'Chiral nuclear thermodynamics'
M. Yamada	'Beyond LPA for dynamical chiral symmetry breaking'

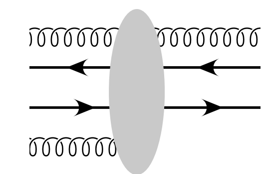
Outline

- Functional Methods for QCD
- Confinement & Chiral Symmetry Breaking
- Phase Structure and Transport
- Outlook

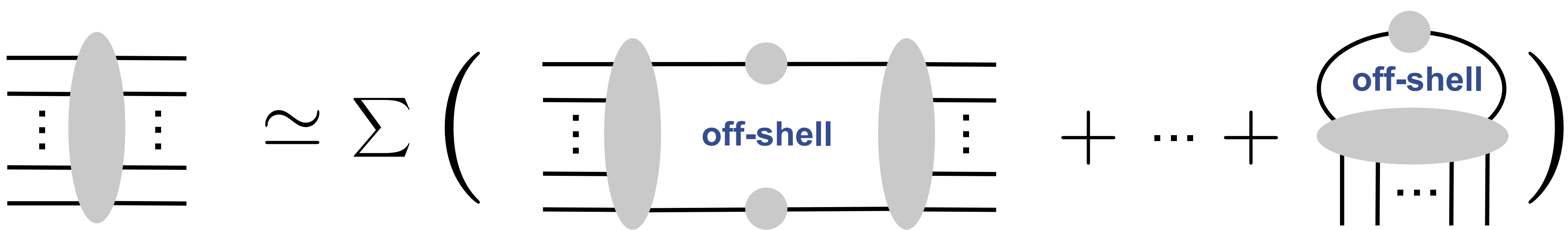
Functional Methods for QCD

quark-gluon correlations

$$\langle q(x_1) \cdots \bar{q}(x_{2n})\, A_\mu(y_1) \cdots A_\mu(y_m) \rangle$$



functional relations

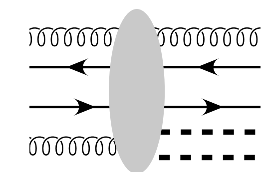


scattering amplitude/
vertex functions

Functional Methods for QCD

quark-gluon-hadron correlations

$$\langle q(x_1)\cdots\bar{q}(x_{2n})\,A_\mu(y_1)\cdots A_\mu(y_m)\,h(z_1)\cdots h(z_l)\rangle$$



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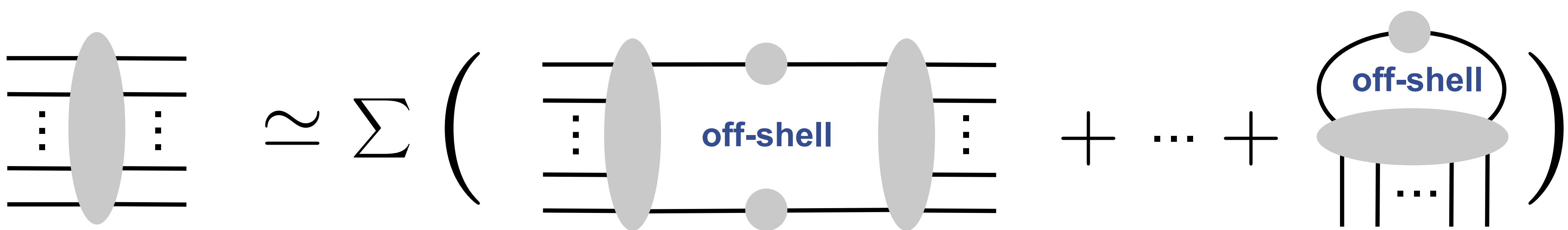

scattering amplitude/
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Functional renormalisation group equations

Dyson-Schwinger equations

2PI/nPI hierarchies

⋮

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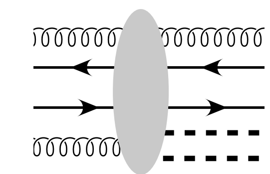

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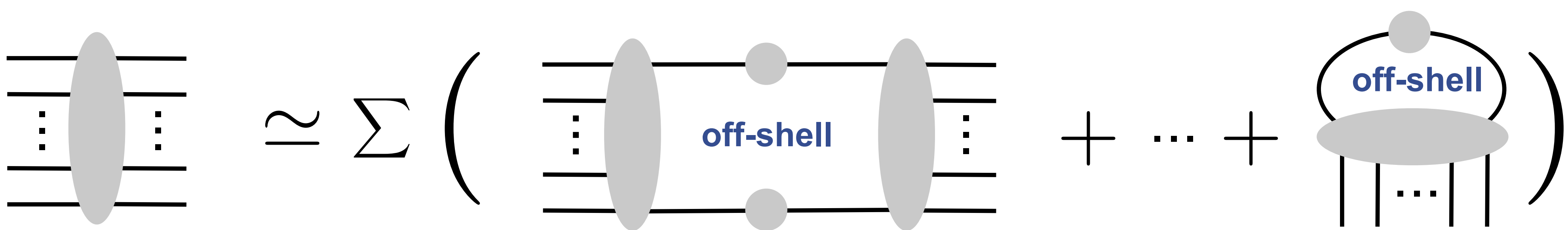

scattering amplitude/
vertex functions

properties

- access to physics mechanisms
- numerically tractable
  no sign problem
  systematic error control via closed form
- low energy models naturally encorporated

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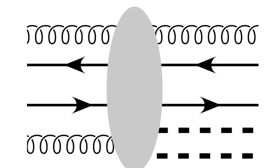

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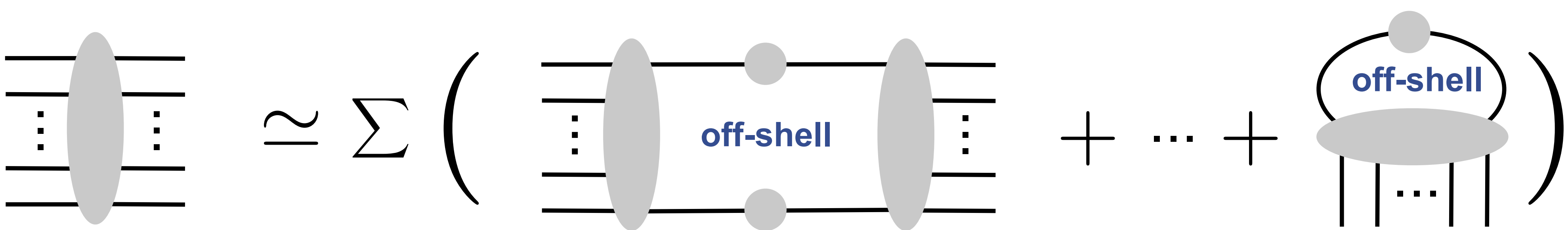

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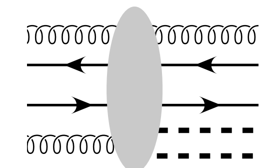

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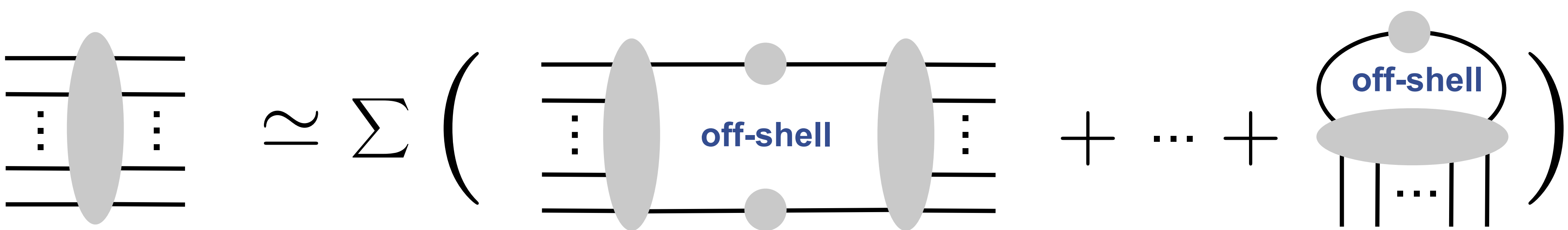

scattering amplitude/
vertex functions

e.g. lattice input on rhs

e.g. volume flucs., finite density,
dynamics, ...

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FunMethods complementary to lattice

Functional Methods for QCD

Scales

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- **explicit mass scales of QCD:**
  - **current quark masses:** $\left.\dfrac{\mathbf{m}_{\mathbf{q},\mathrm{current}}}{\Lambda_{\mathrm{QCD}}}\right|_{\mathrm{light\ quarks}} \approx \mathbf{10^{-2}}$ $\mathbf{m}_{\pi} \approx \mathbf{140}\,\mathrm{MeV}$

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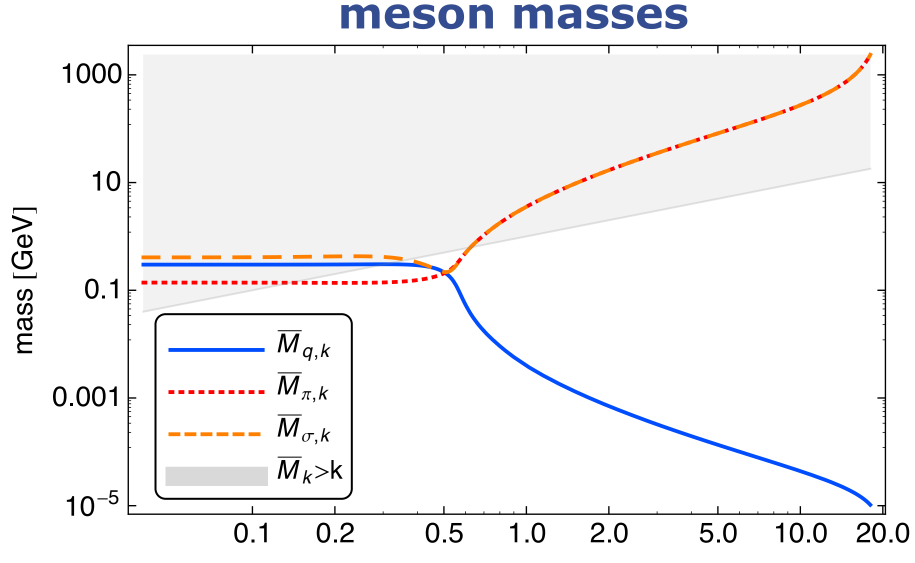
meson masses



see talk of F. Rennecke

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see talk of W. Weise

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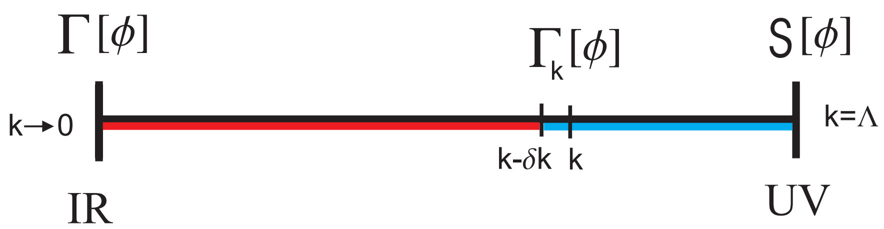
best done with a combination of imaginary and real time flows

Functional Methods for QCD

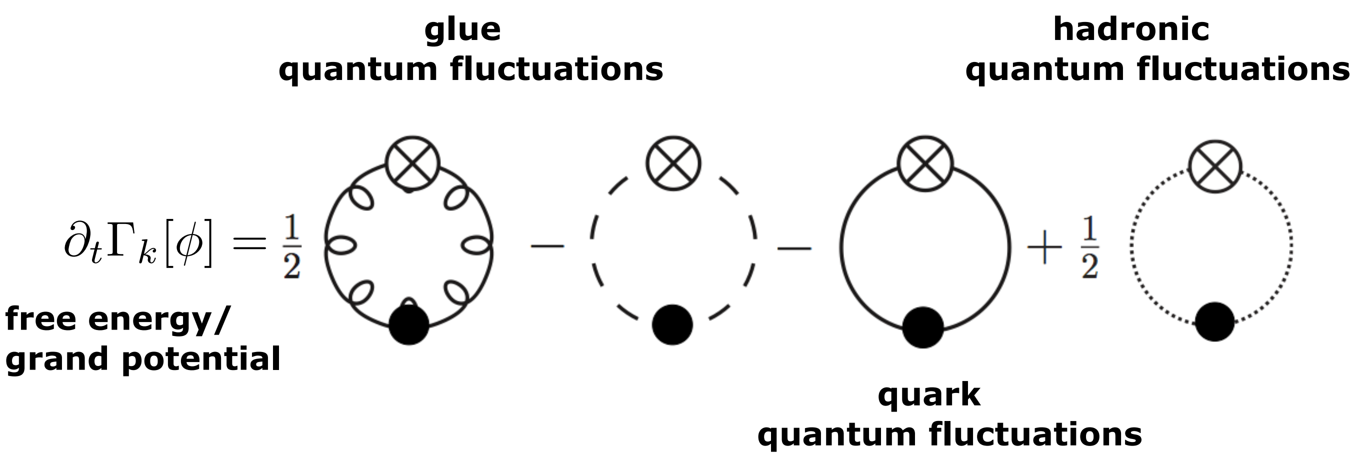
Functional RG

JMP, AIP Conf.Proc. 1343 (2011)

free energy at momentum scale k



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



ERG12 QCD survey

JMP, Aussois '12

ERG14 QCD survey

B.J. Schaefer, Lefkada '14

Phase diagram survey

JMP, Schladming '13

EoS & phase diagram

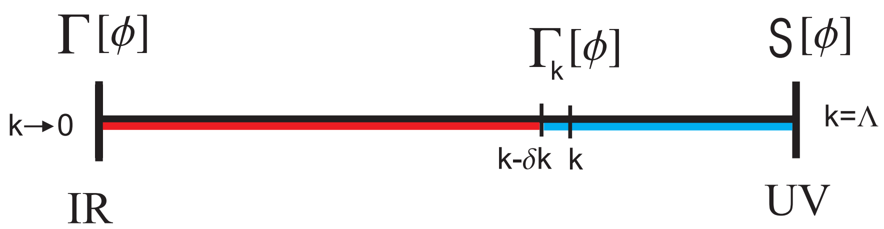
JMP, Quark Matter2014

Functional Methods for QCD

Functional RG

JMP, AIP Conf.Proc. 1343 (2011)

free energy at momentum scale k



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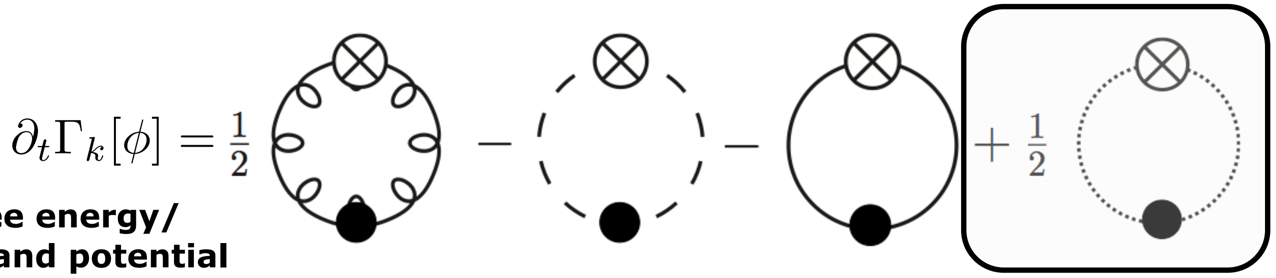
JMP, Aussois '12

ERG14 QCD survey

B.J. Schaefer, Lefkada '14

glue
quantum fluctuations

hadronic
quantum fluctuations



free energy/
grand potential

quark
quantum fluctuations

Phase diagram survey

JMP, Schladming '13

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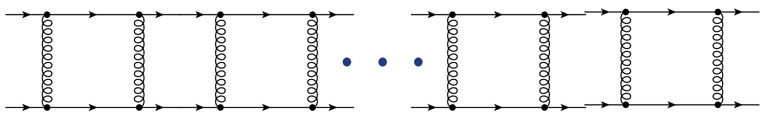
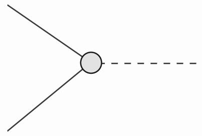
JMP, Quark Matter2014



Dynamical hadronisation



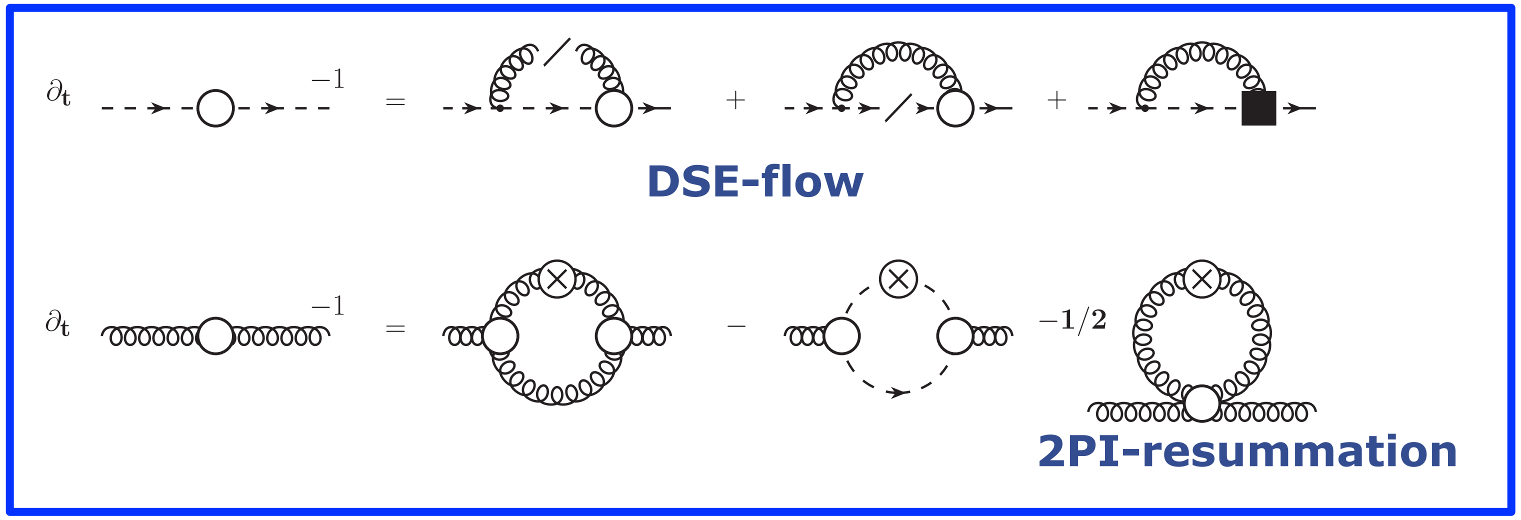
dynamical

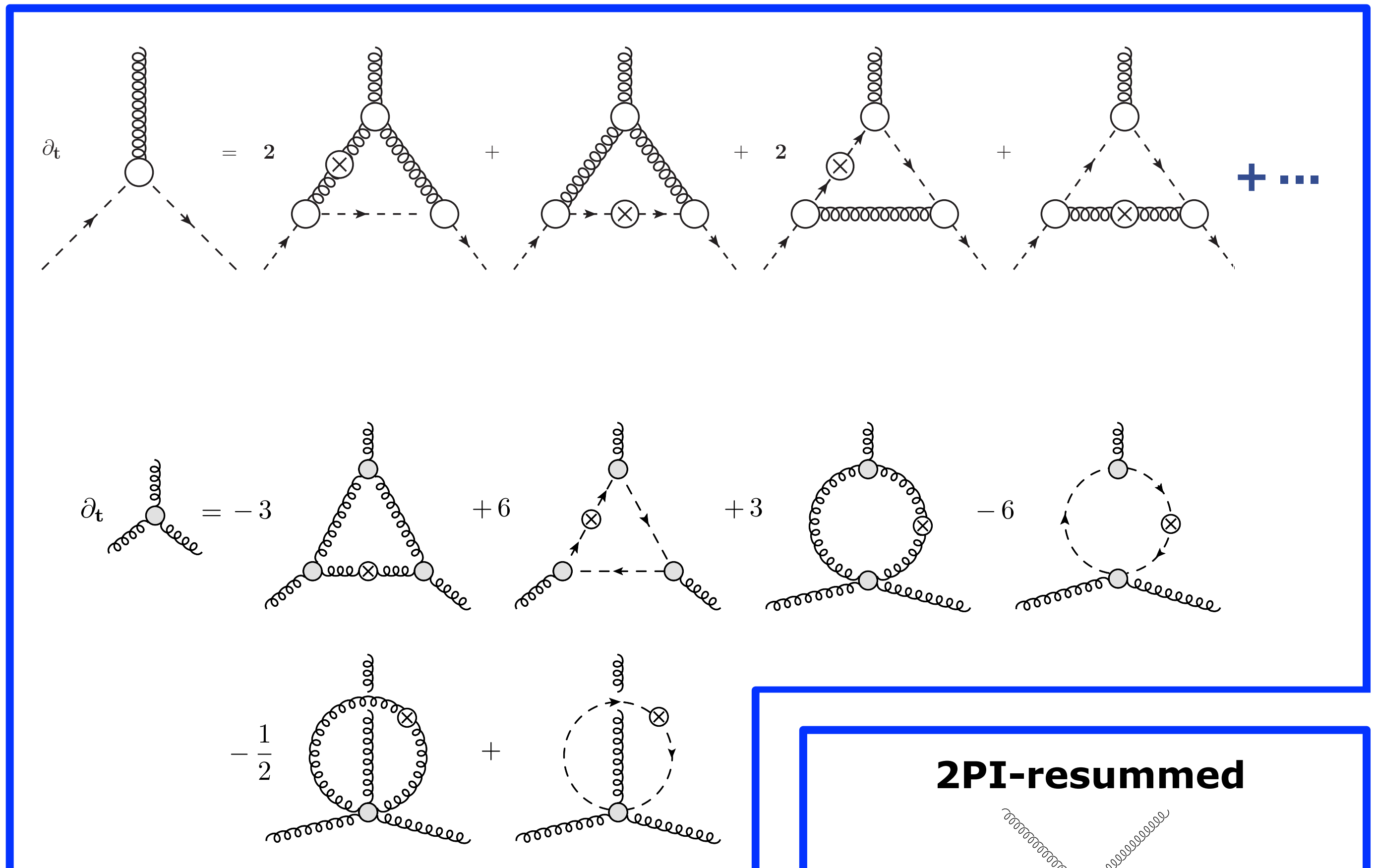
Gies, Wetterich '01
JMP '05
Flörchinger, Wetterich '09

Functional Methods for QCD

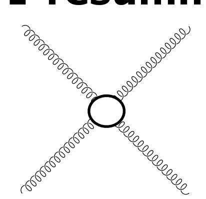
Yang-Mills theory

Yang-Mills

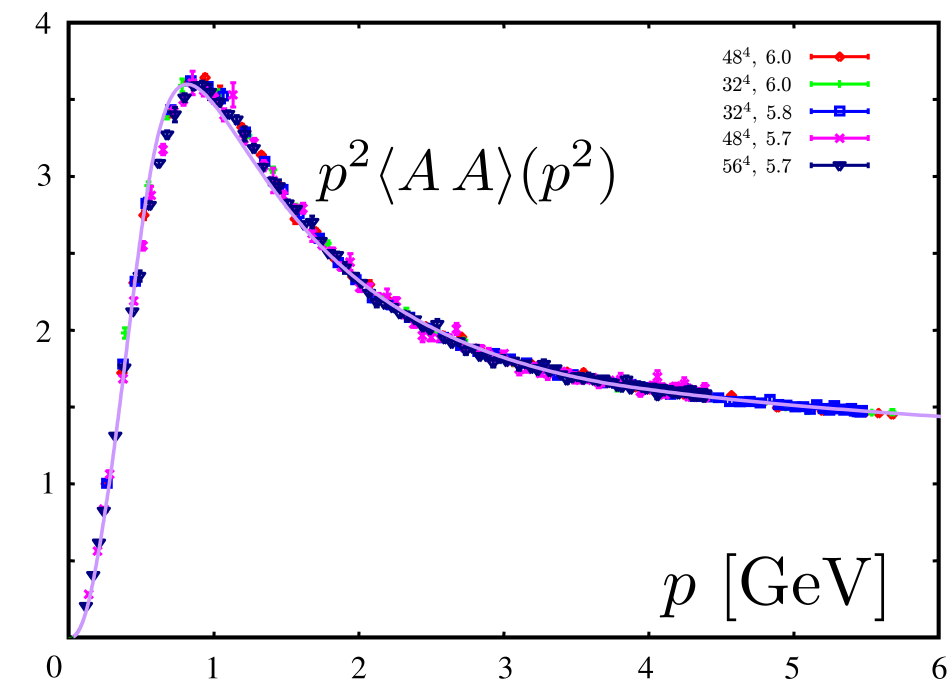




2PI-resummed



Yang-Mills propagators



FRG: Fischer, Maas, JMP, Annals Phys. 324 (2009) 2408

lattice: Sternbeck et al, PoS LAT2006 (2006) 076

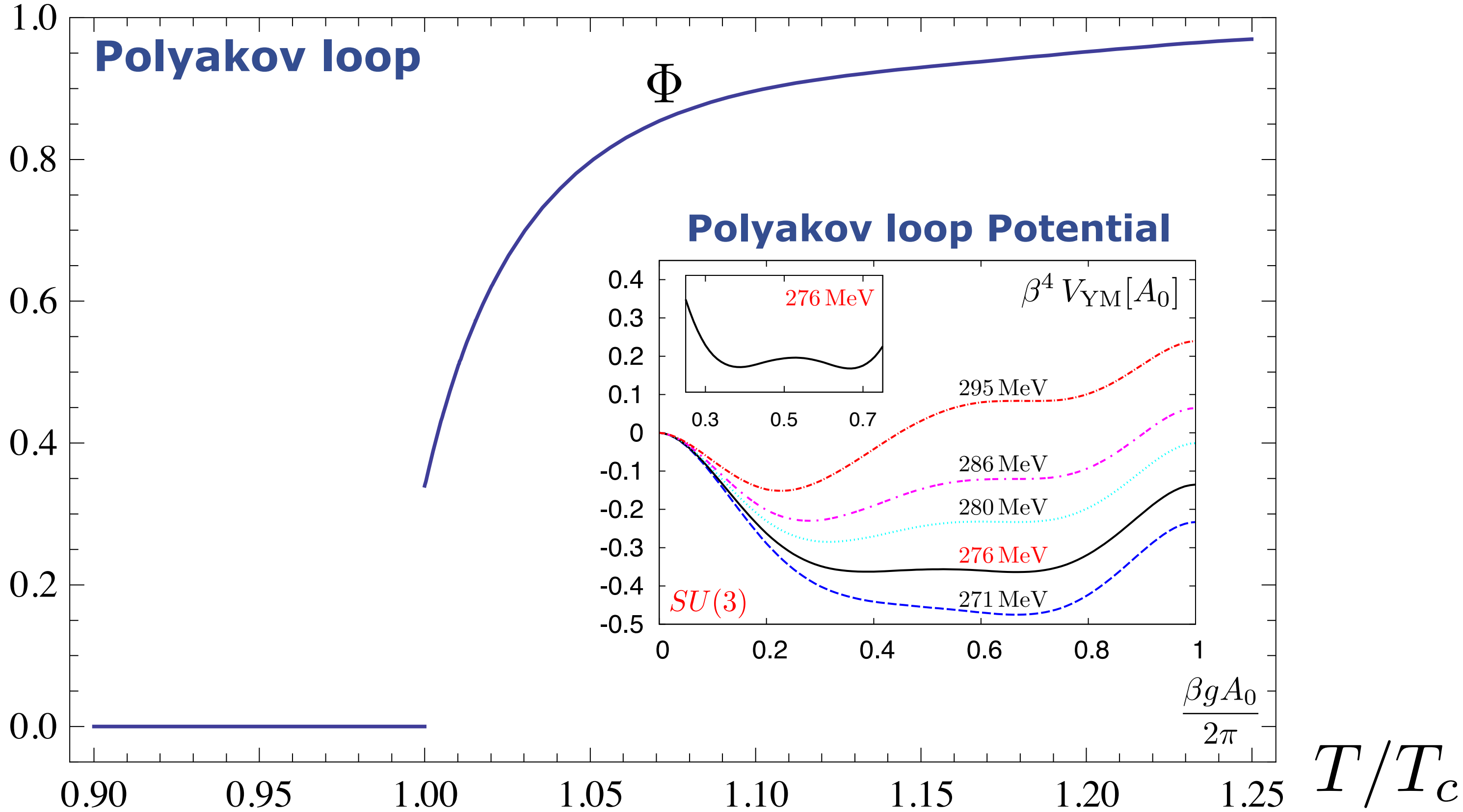
see talks of L. Fister, M. Huber

Functional Methods for QCD

Confinement

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

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



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

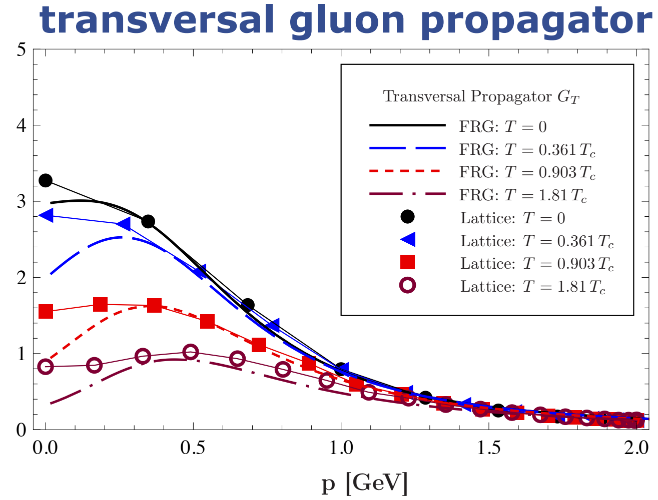
$$\text{lattice} : T_c/\sqrt{\sigma} = 0.646$$

see talk of L. Fister

$$\Phi[A_0] = \frac{1}{3}(1 + 2\cos\frac{1}{2}\beta g A_0)$$

- **from the full propagators**
- **gauge independence**
- **confinement criteria**

transversal gluon propagator



Fister, JMP, arXiv:1112.5440

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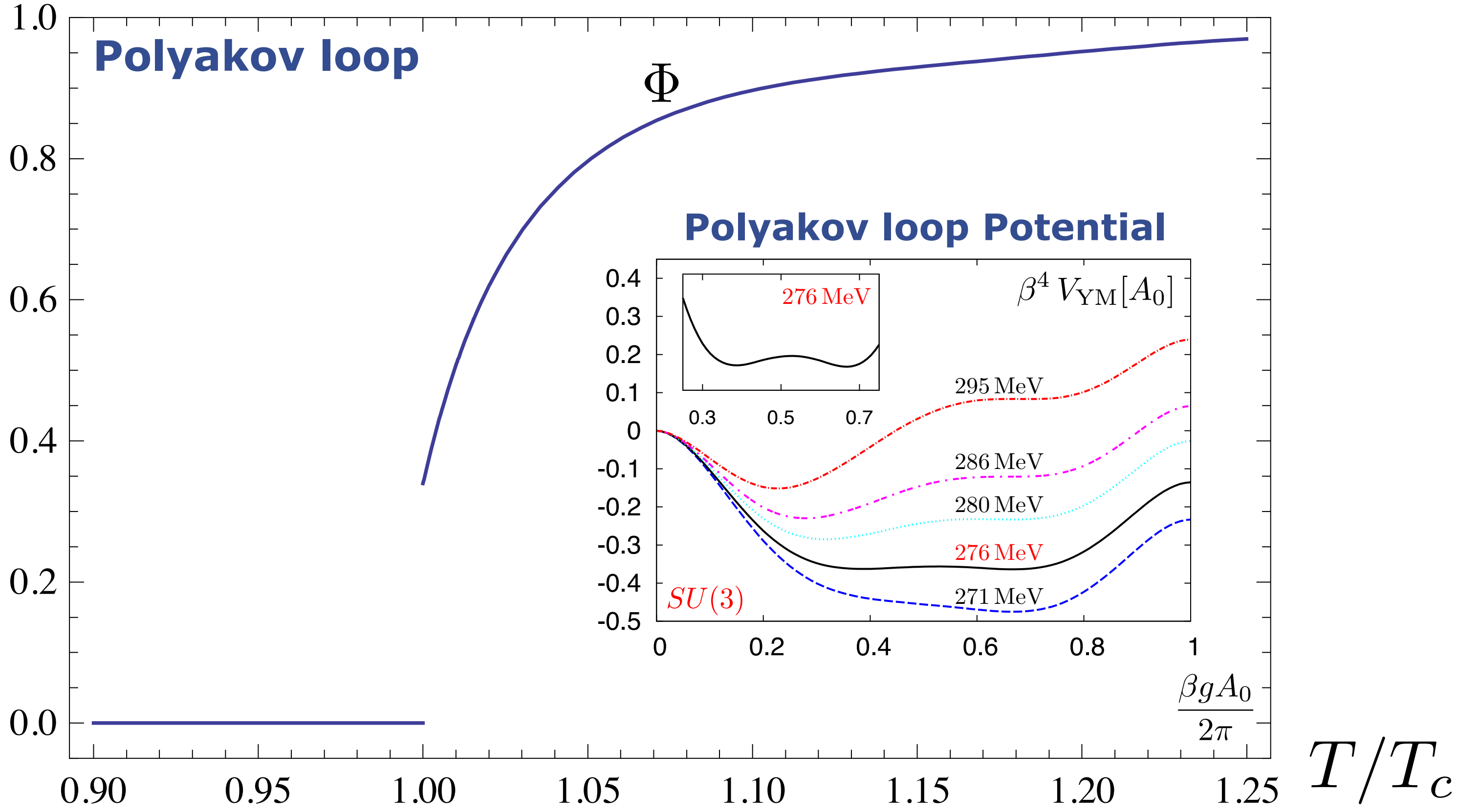

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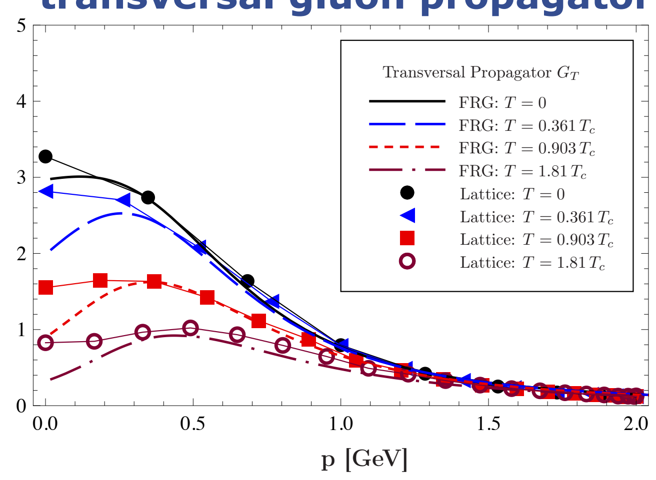

Fister, JMP, arXiv:1112.5440

confinement

gluon propagator
gapped relative to
ghost propagator

Braun, Gies, JMP '07
Marhauser, JMP '08
Fister, JMP '13

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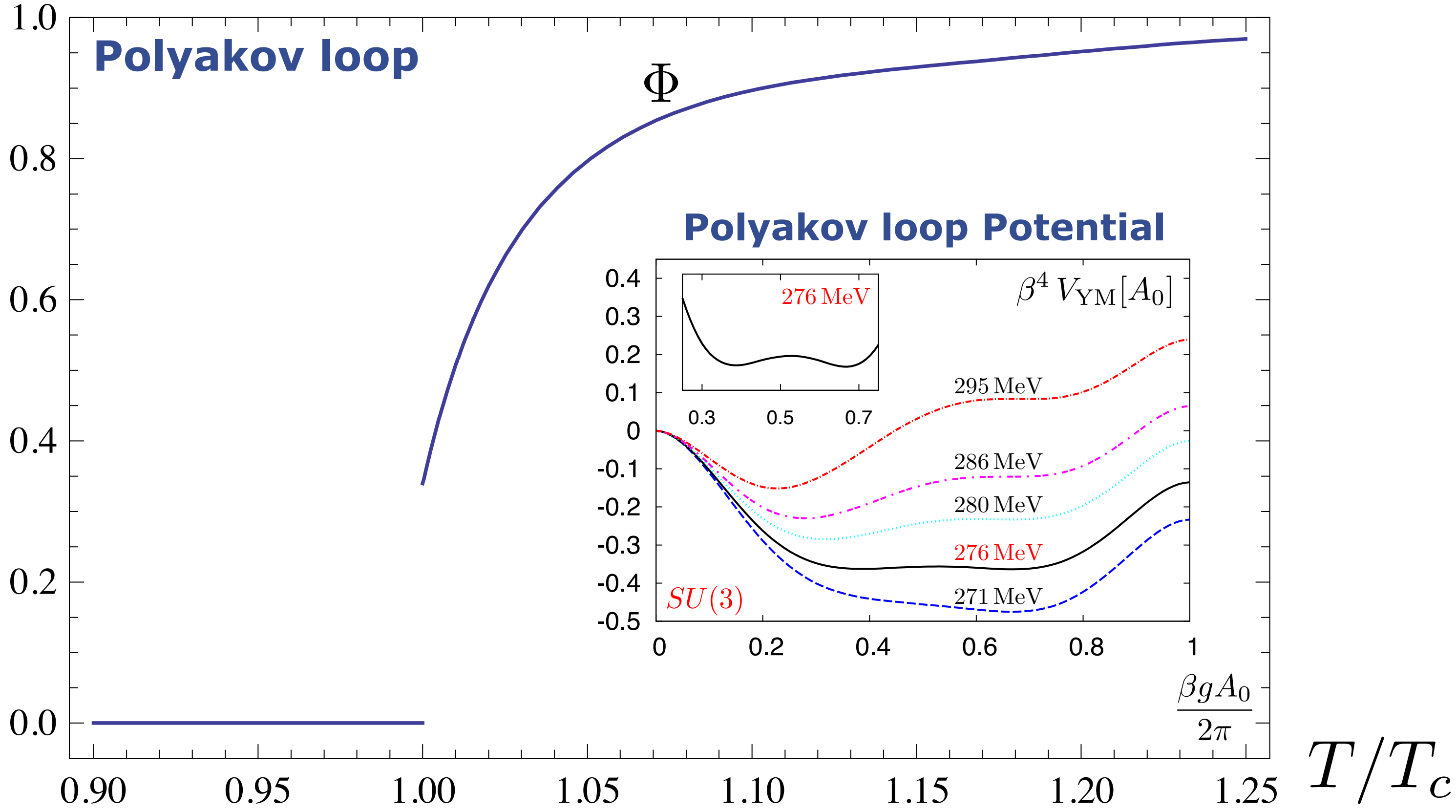
FRG: **Braun, Gies, JMP, PLB 684 (2010) 262**

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



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

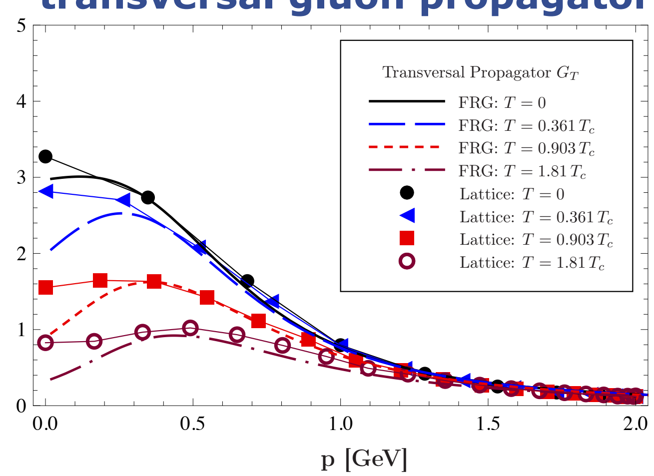
$$\text{lattice}: T_c/\sqrt{\sigma} = 0.646$$

see talk of L. Fister

$$\Phi[A_0] = \frac{1}{3}(1 + 2\cos\frac{1}{2}\beta g A_0)$$

- **from the full propagators**
- **gauge independence**
- **confinement criteria**

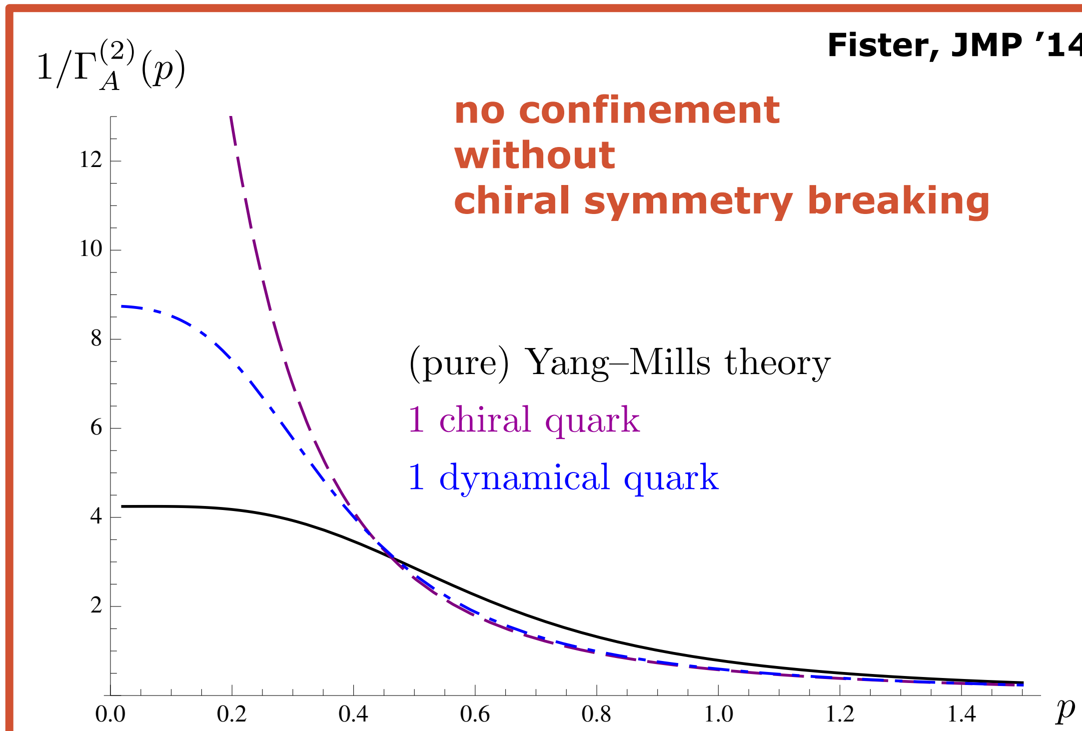
transversal gluon propagator



Fister, JMP, arXiv:1112.5440

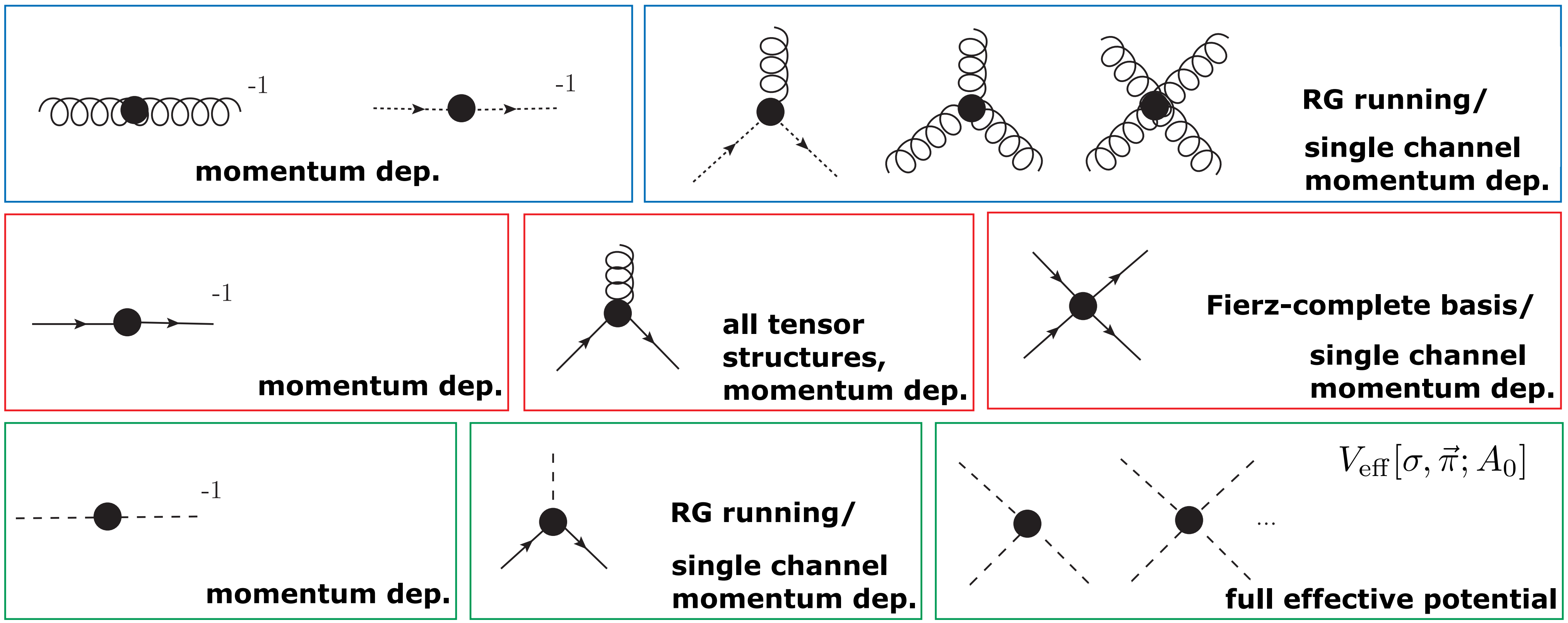
Fister, JMP '14

no confinement without chiral symmetry breaking



Functional Methods for QCD

present best approximation

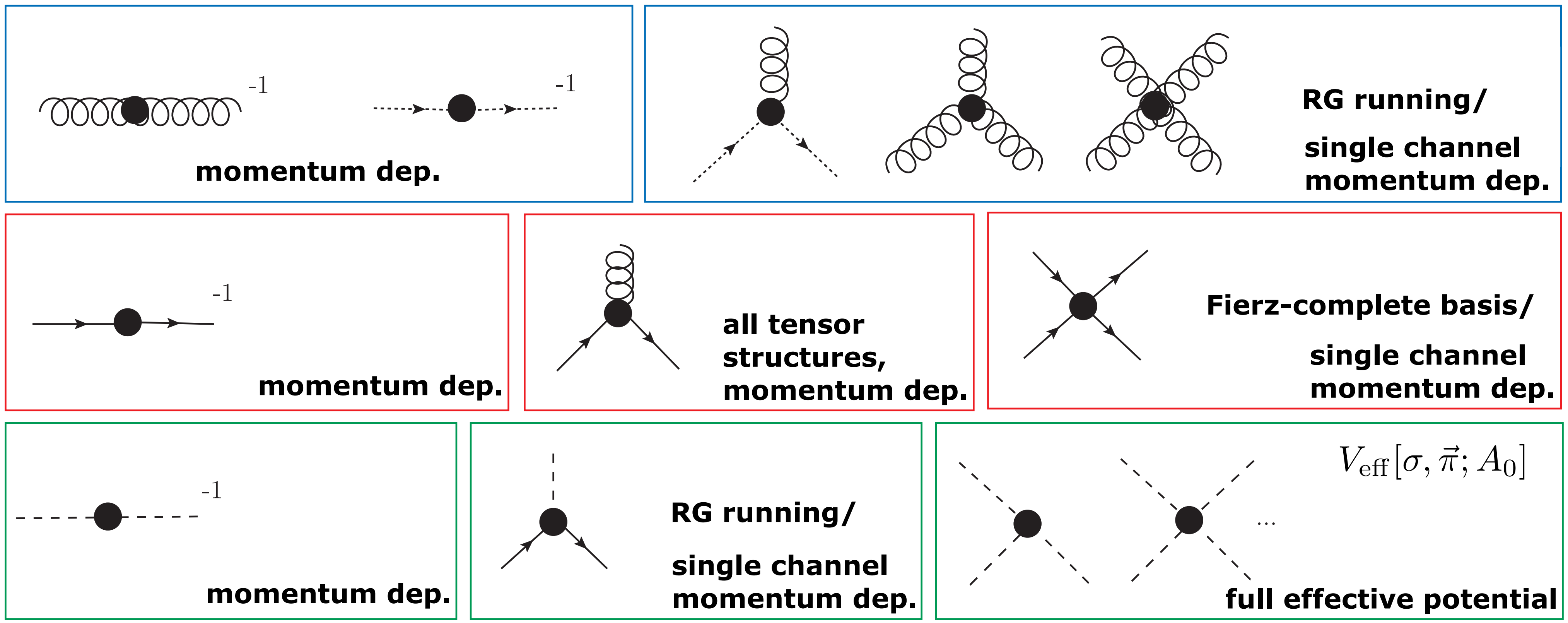


see talk of M. Mitter

FRG-QCD: Braun, Fister, Herbst, Mitter, JMP, Rennecke, Strodthoff

Functional Methods for QCD

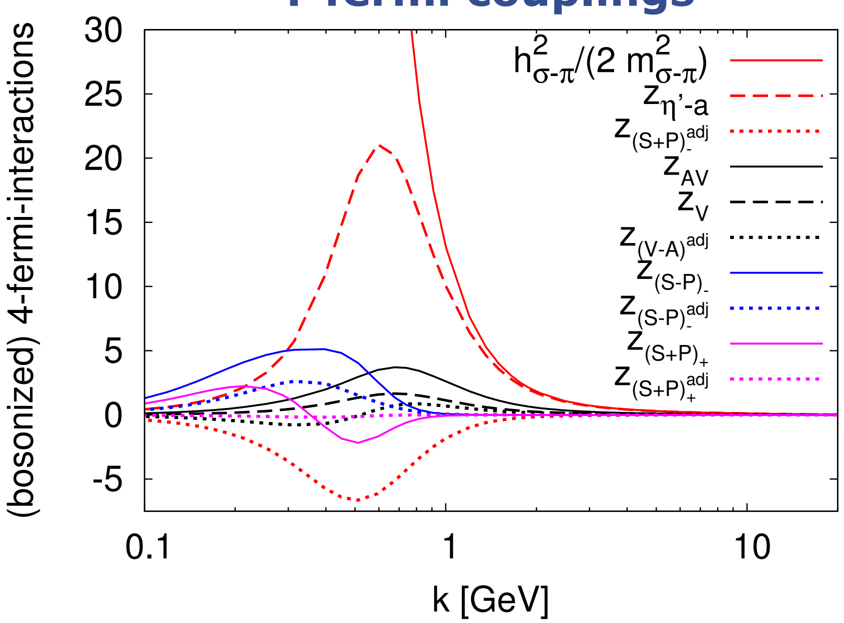
chiral symmetry breaking



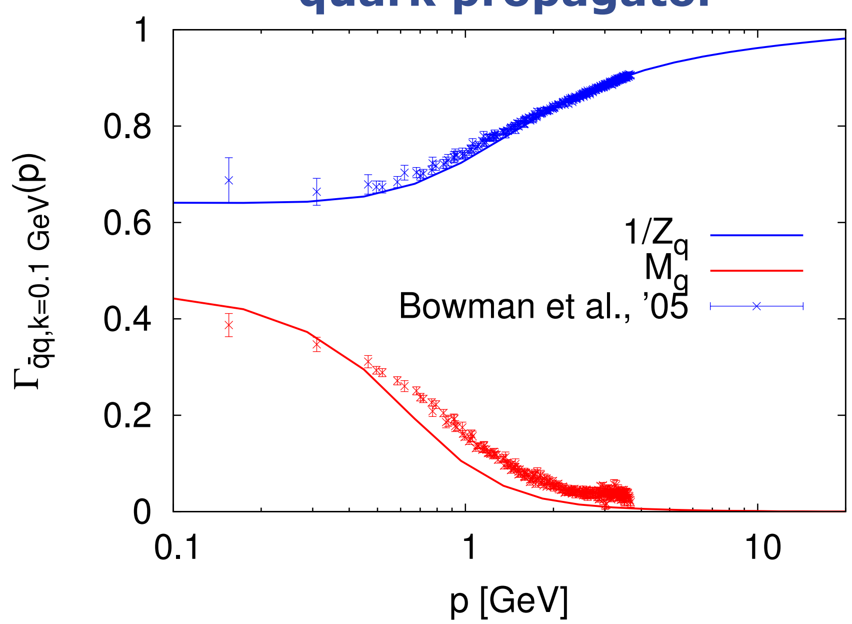
see talk of M. Mitter

FRG-quenched QCD vs lattice-quenced QCD

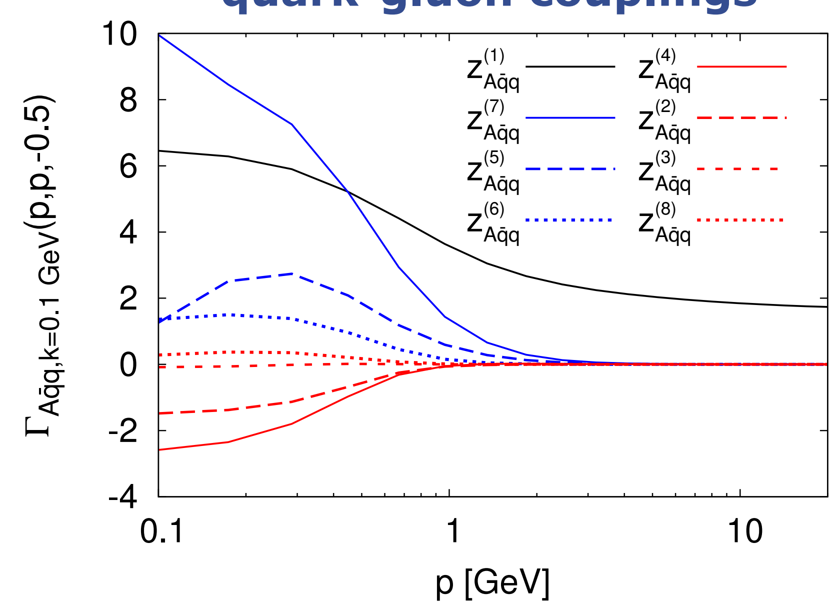
4-fermi couplings



quark propagator



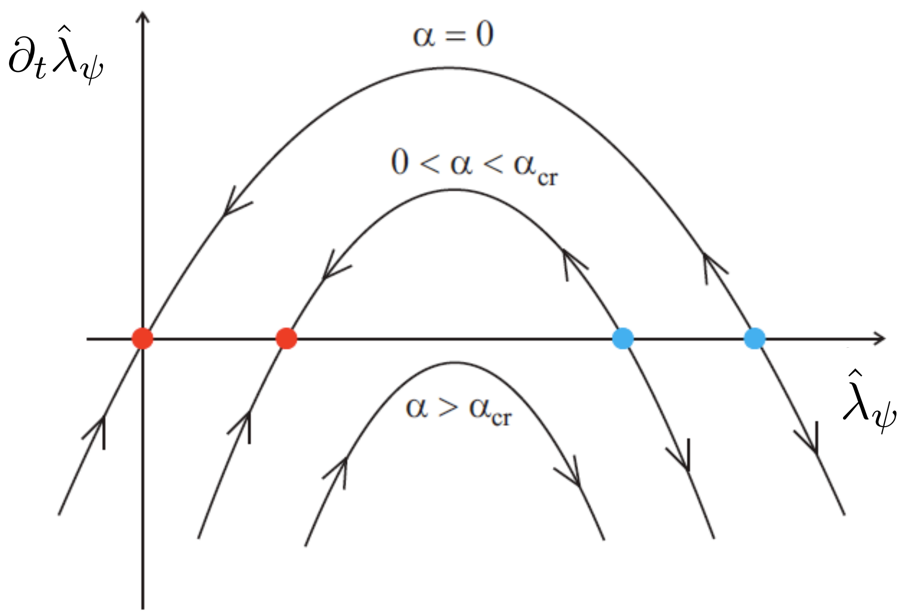
quark-gluon couplings

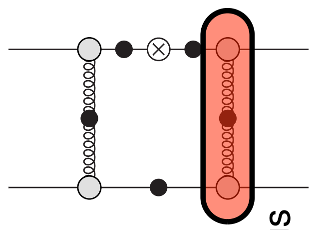


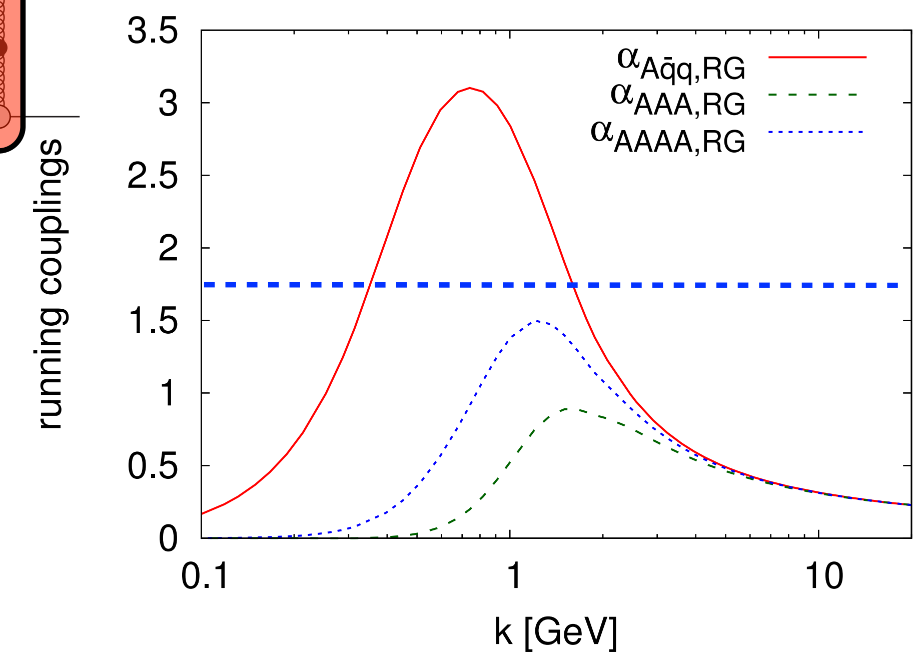
Mitter, JMP, Strodthoff, in preparation

Functional Methods for QCD

chiral symmetry breaking



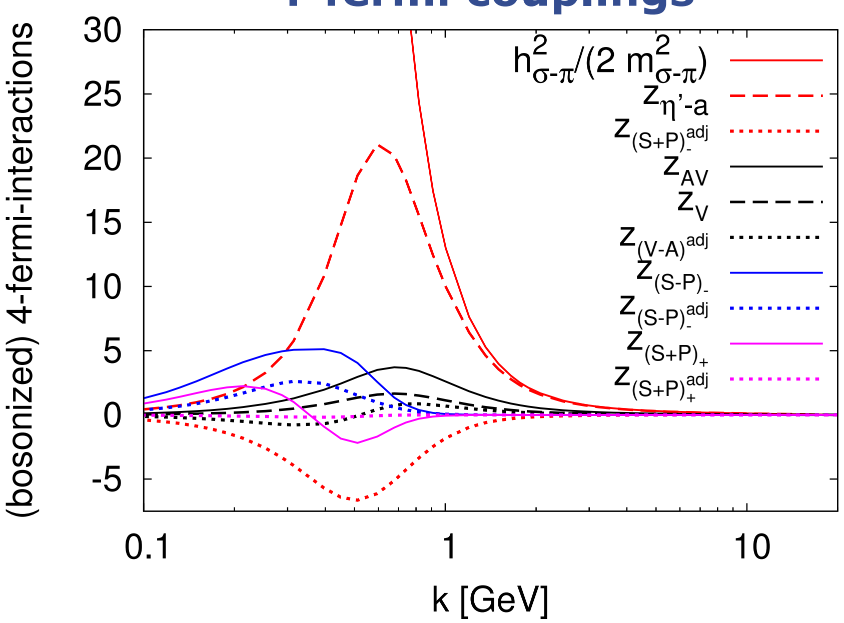




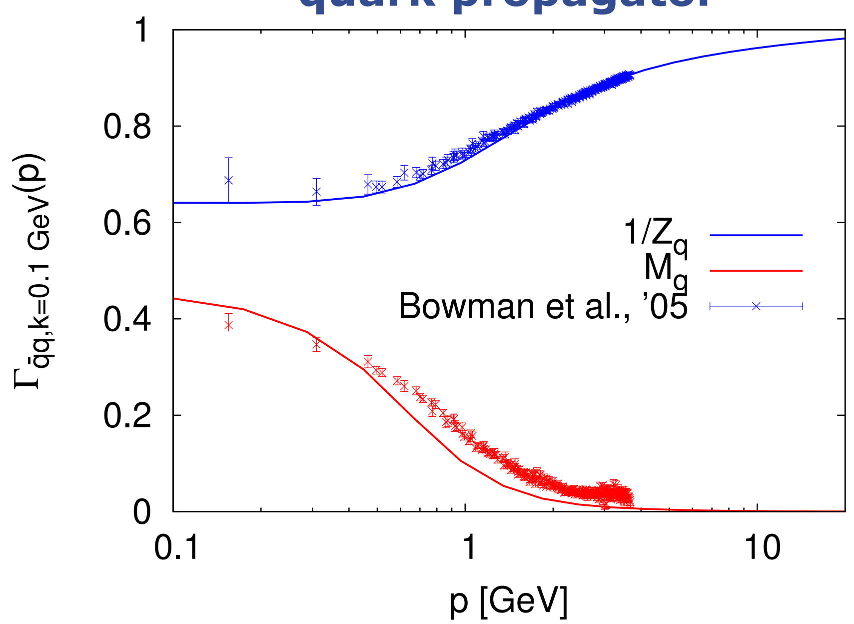
mag. catalysis vs inverse mag. catalysis: see talk of S. Rechenberger

FRG-quenched QCD vs lattice-quenced QCD

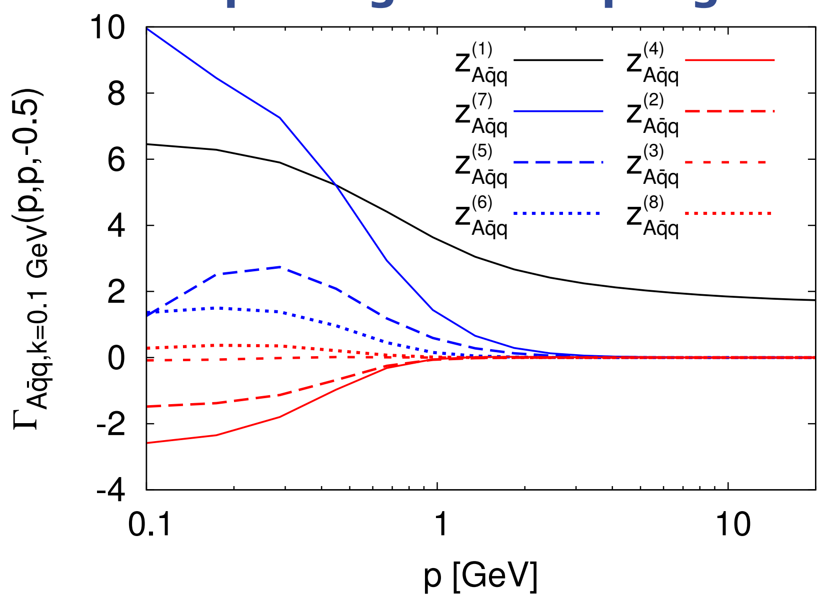
4-fermi couplings



quark propagator



quark-gluon couplings



Mitter, JMP, Strodthoff, in preparation

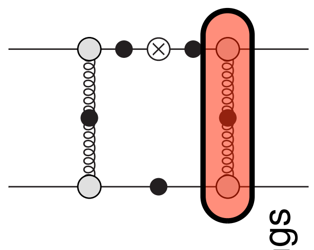
Functional Methods for QCD

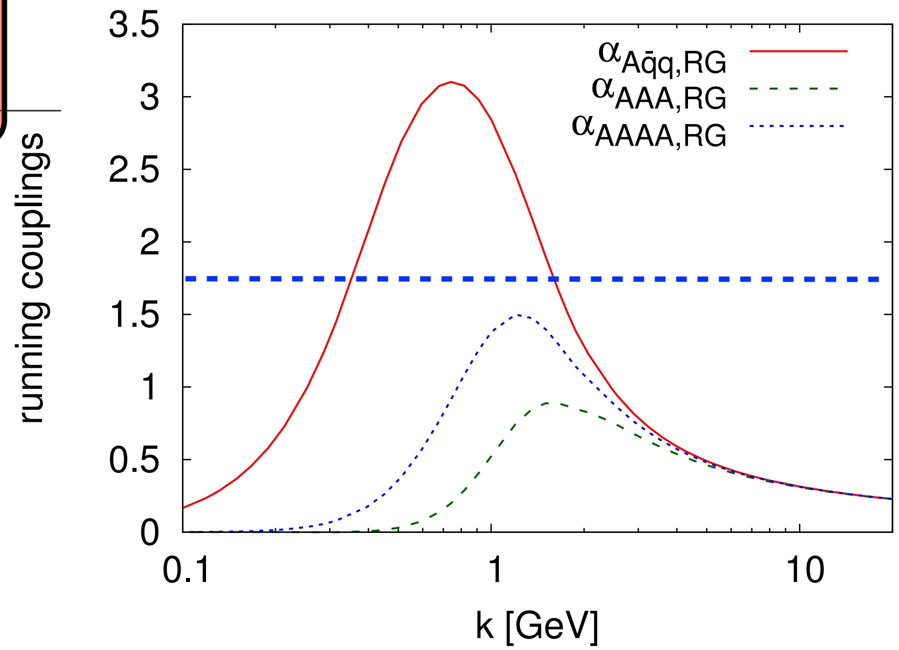
chiral symmetry breaking

dynamical correlation of confinement
and
chiral symmetry breaking

confinement	chiral symmetry breaking
gluon propagator gapped relative to ghost propagator	gluon propagator not gapped too much

Fister, Mitter, JMP, Strodthoff '14

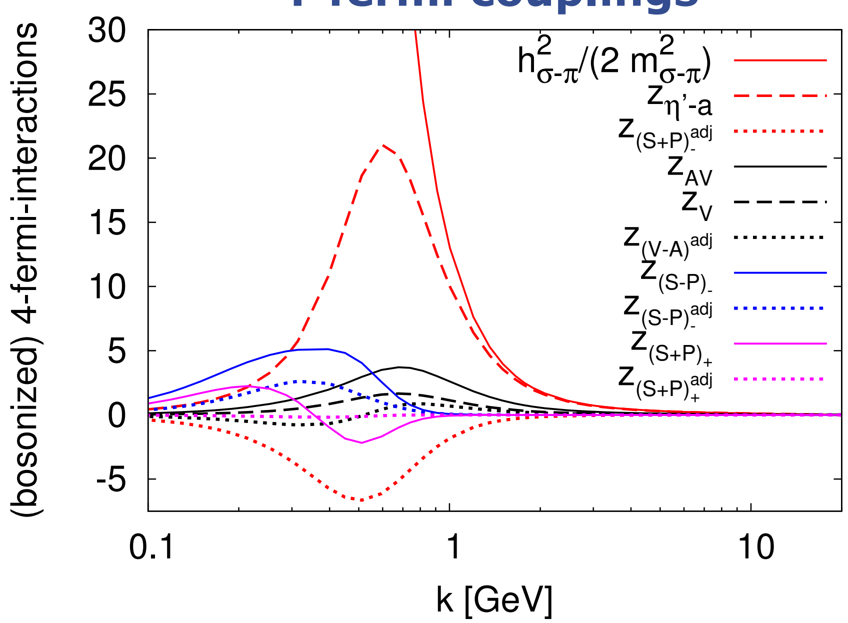




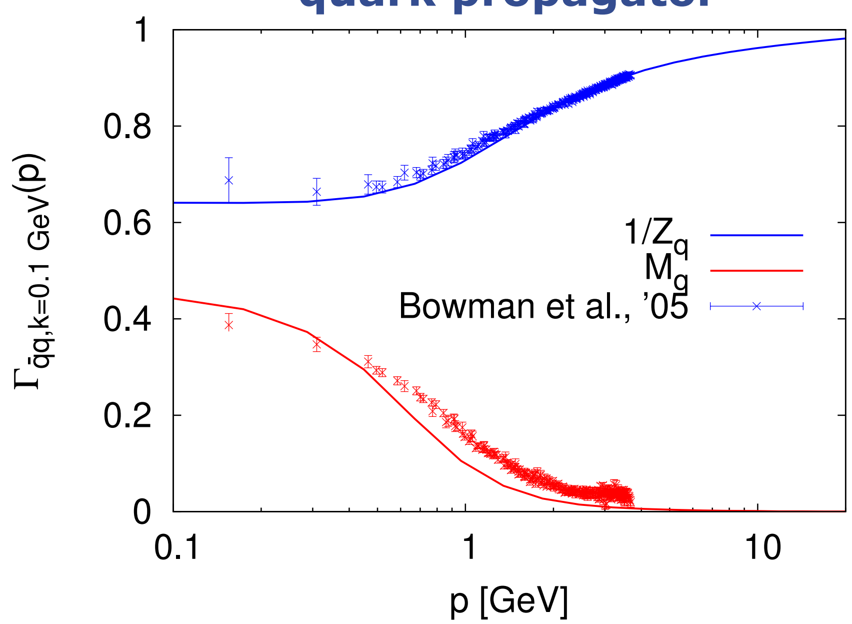
dynamical locking at finite T: see talk of P. Springer

FRG-quenched QCD vs lattice-quenced QCD

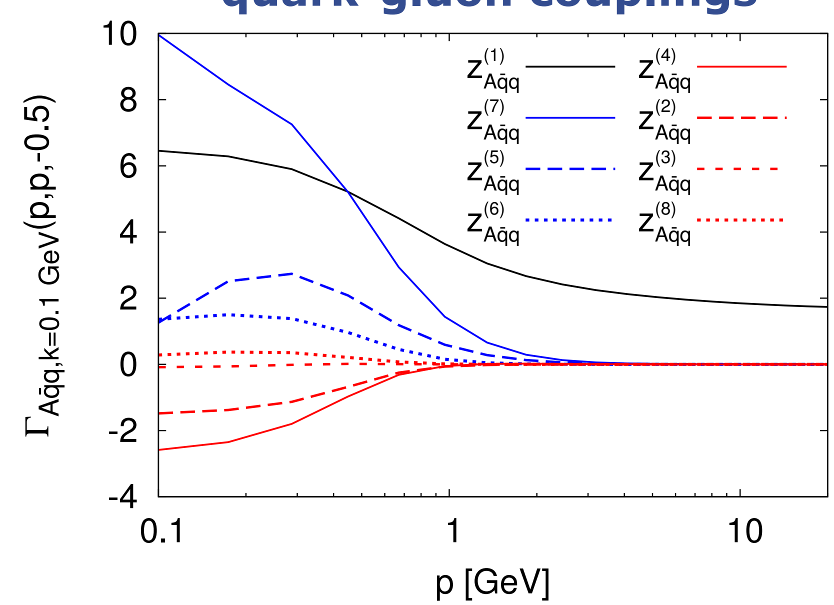
4-fermi couplings



quark propagator

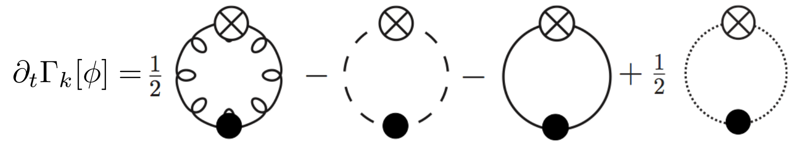


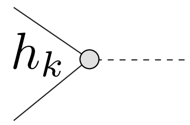
quark-gluon couplings



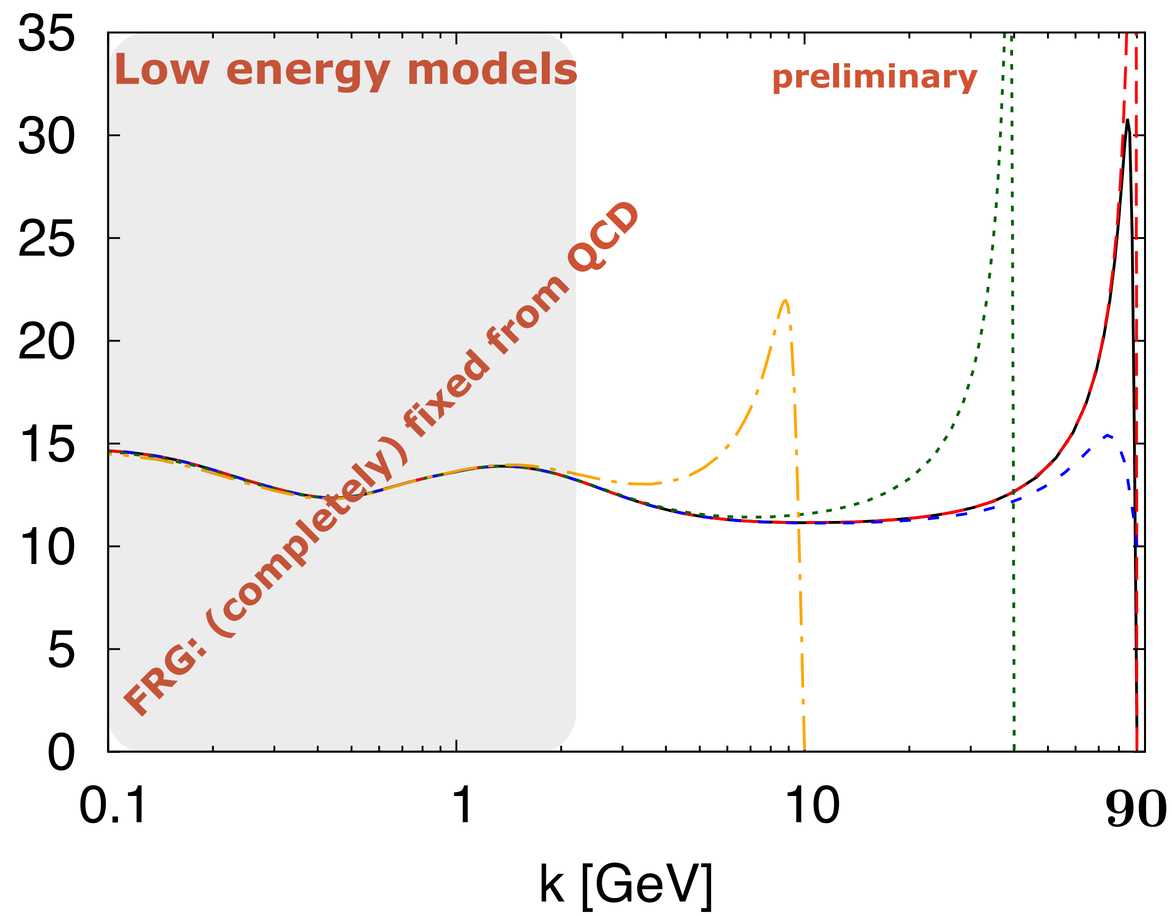
Mitter, JMP, Strodthoff, in preparation

QCD





quark-meson coupling

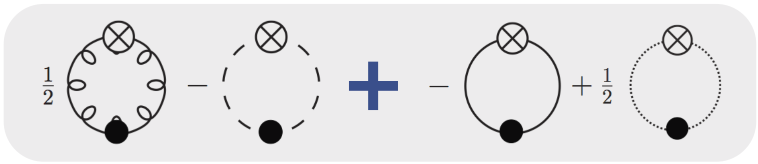


FRG-QCD: Braun, Fister, Herbst, Mitter, JMP, Rennecke, Strodthoff

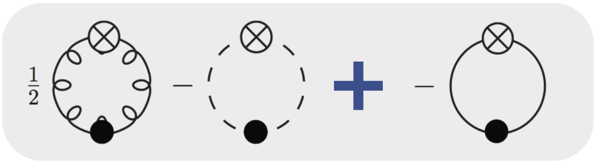
see talks of F. Rennecke, M. Mitter

Model results on the phase structure of QCD

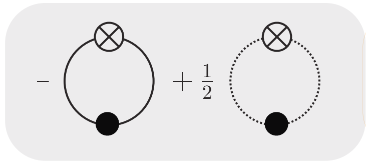
PQM-model



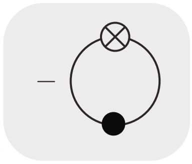
PNJL-model



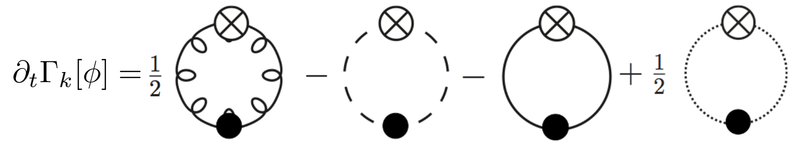
QM-model



NJL-model

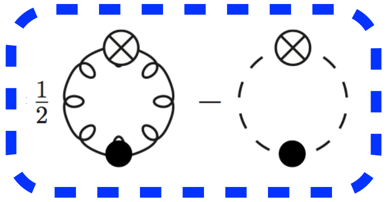


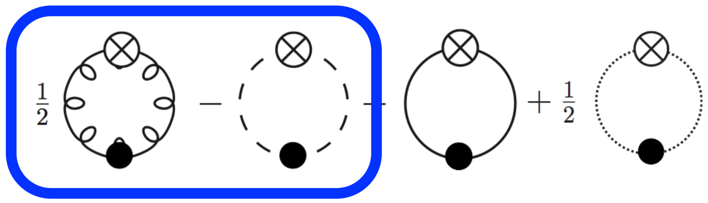
QCD



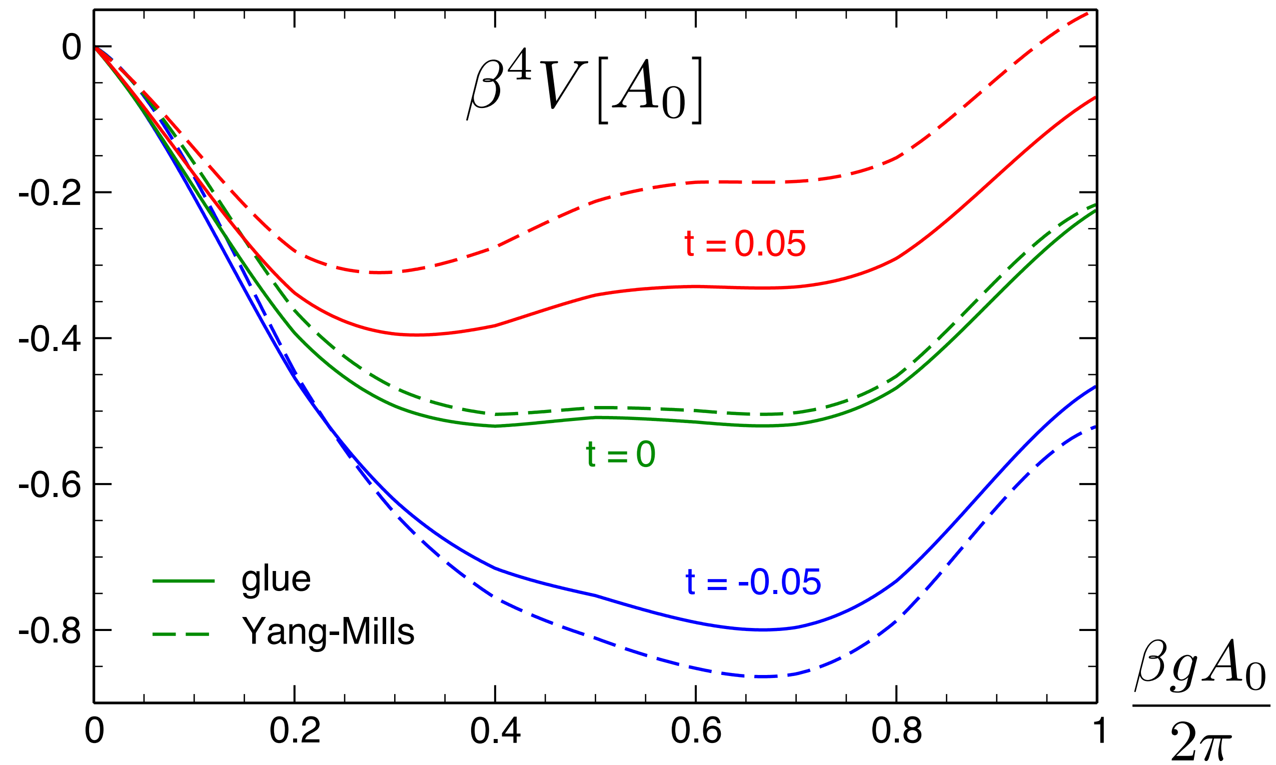
Polyakov loop potential in full QCD

Yang-Mills





glue

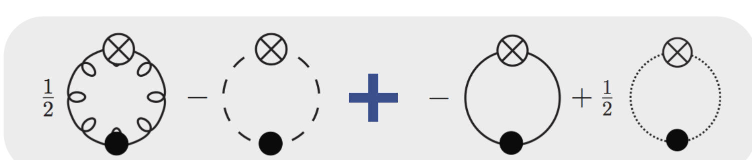


see talk of B.J. Schaefer

JMP, AIP Conf.Proc. 1343 (2011)
Haas, Stiele et al, Phys.Rev. D87 (2013) 076004

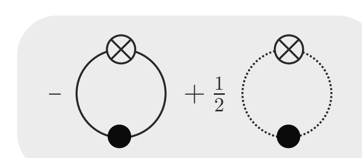
Model results on the phase structure of QCD

PQM-model

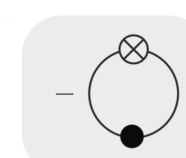


PNJL-model

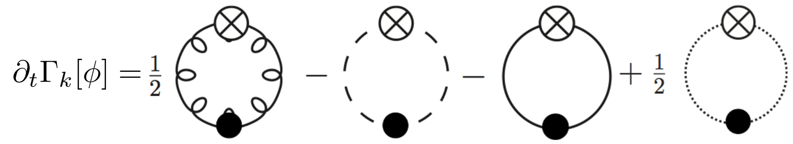
QM-model



NJL-model

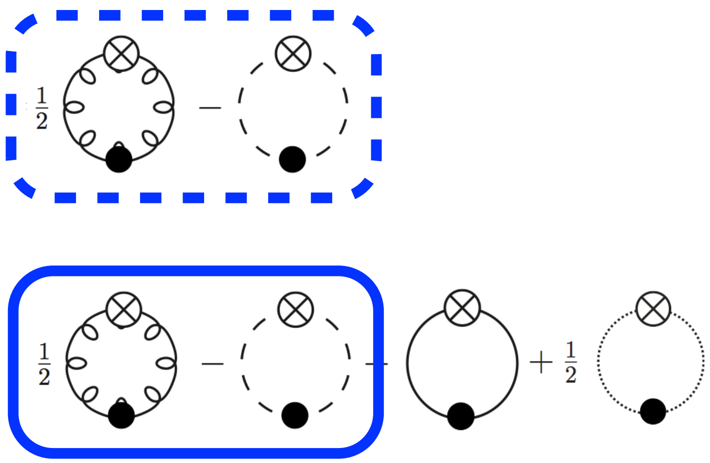


QCD

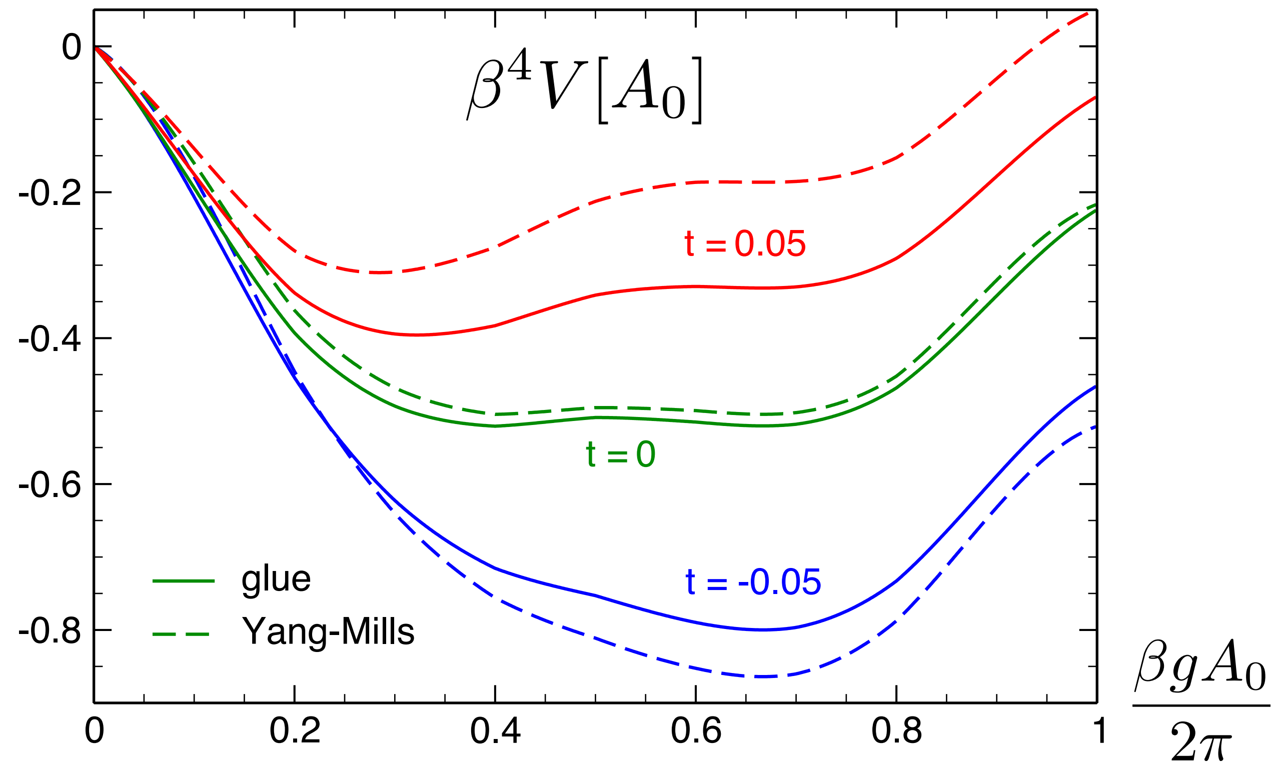


Polyakov loop potential in full QCD

Yang-Mills



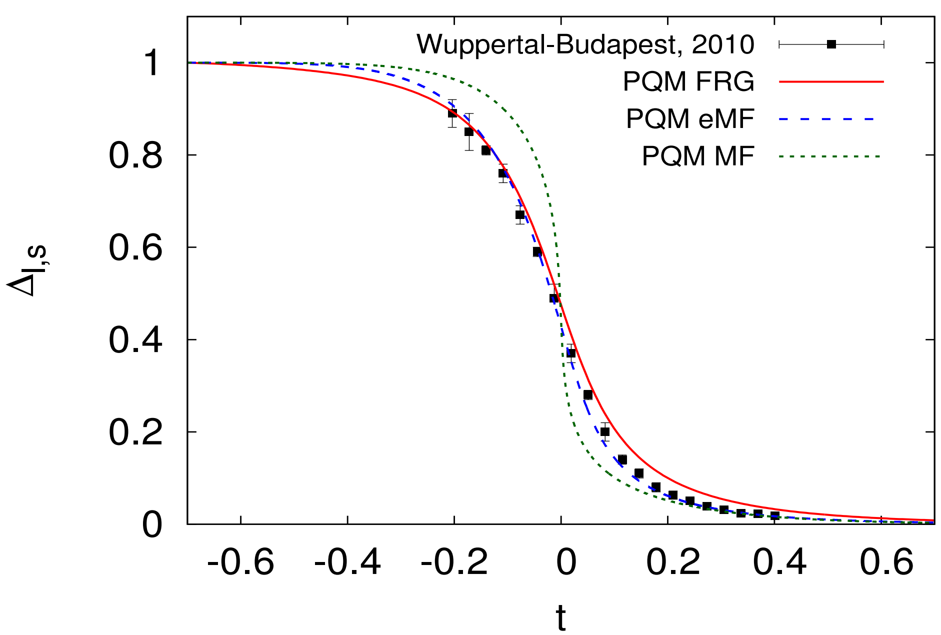
glue



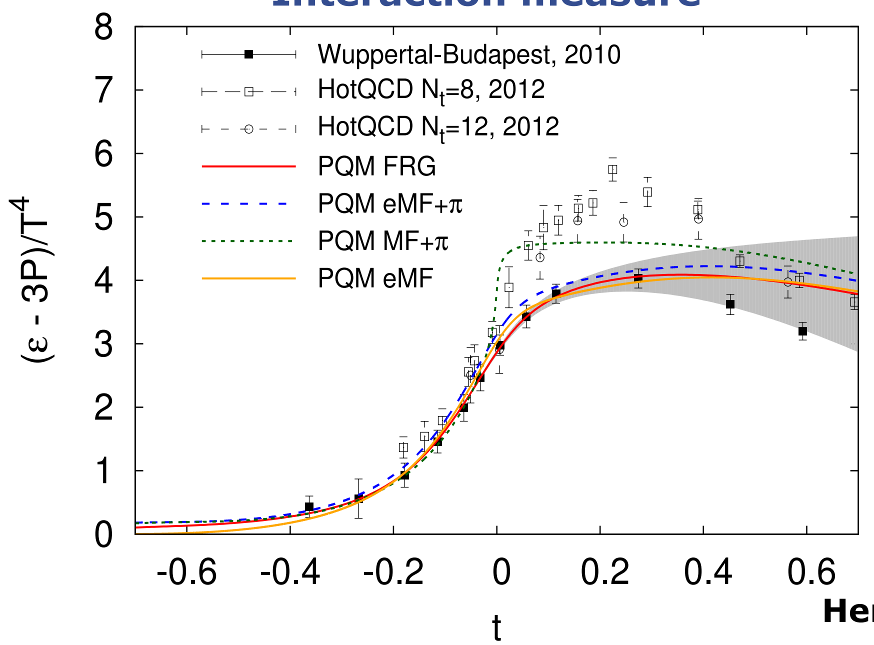
JMP, AIP Conf.Proc. 1343 (2011)
Haas, Stiele et al, Phys.Rev. D87 (2013) 076004

2+1 flavor Polyakov-loop - enhanced QM-model

reduced chiral condensate



Interaction measure



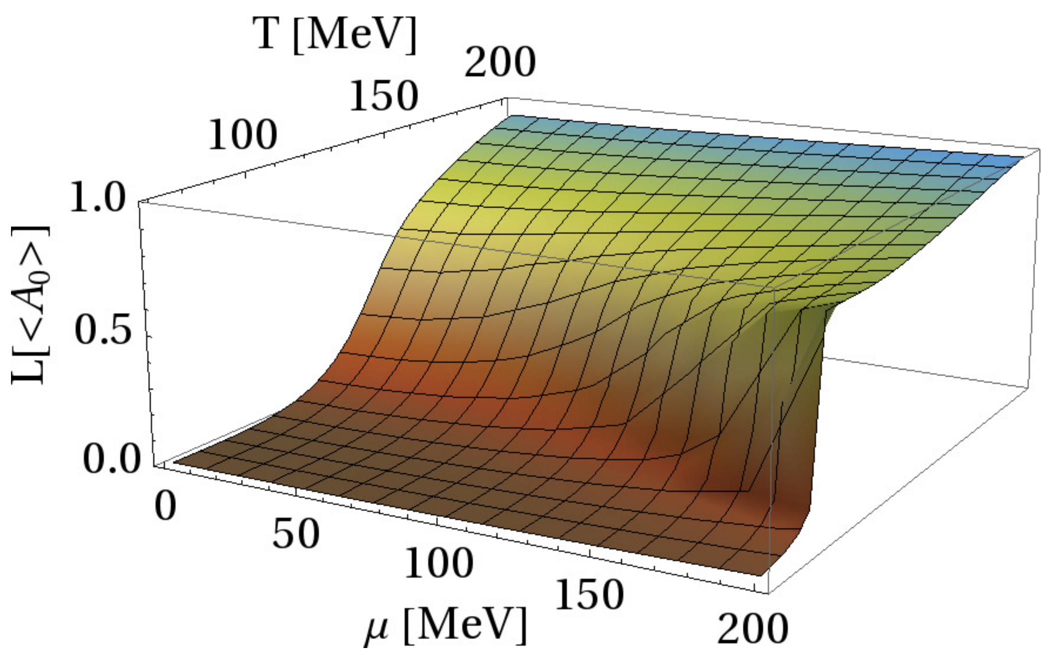
see talk of M. Mitter

Shaded area:
systematic error estimate
due to low initial scale 1 GeV

Herbst, Mitter et al, PLB 731 (2014) 248-256

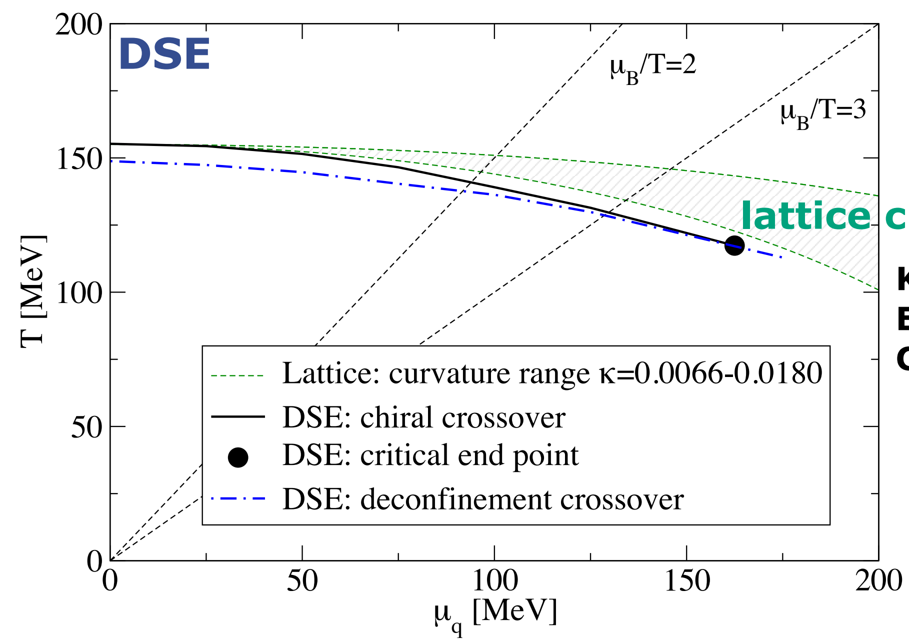
Phase structure at finite density

Polyakov loop at finite density



see talk of J. Luecker

Phase diagram of 2+1 flavor QCD



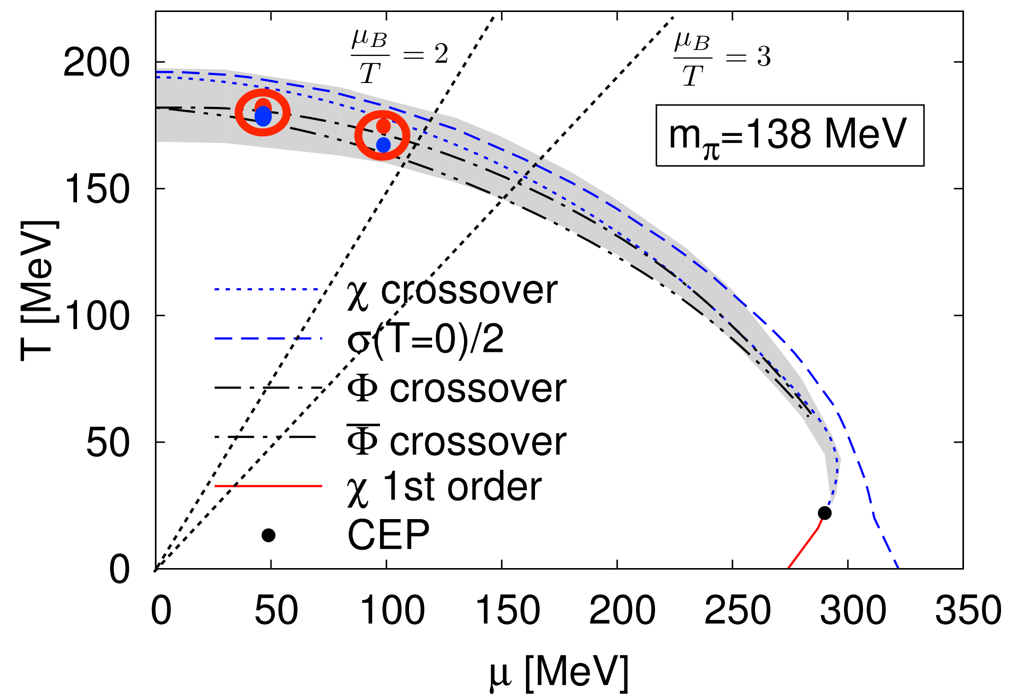
lattice curvature

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

Fischer, Luecker, PLB 718 (2013) 1036

Fischer, Fister, Luecker, JMP, PLB732 (2014) 248

Phase diagram of quantised PQM-model



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

FRG QCD results at finite density

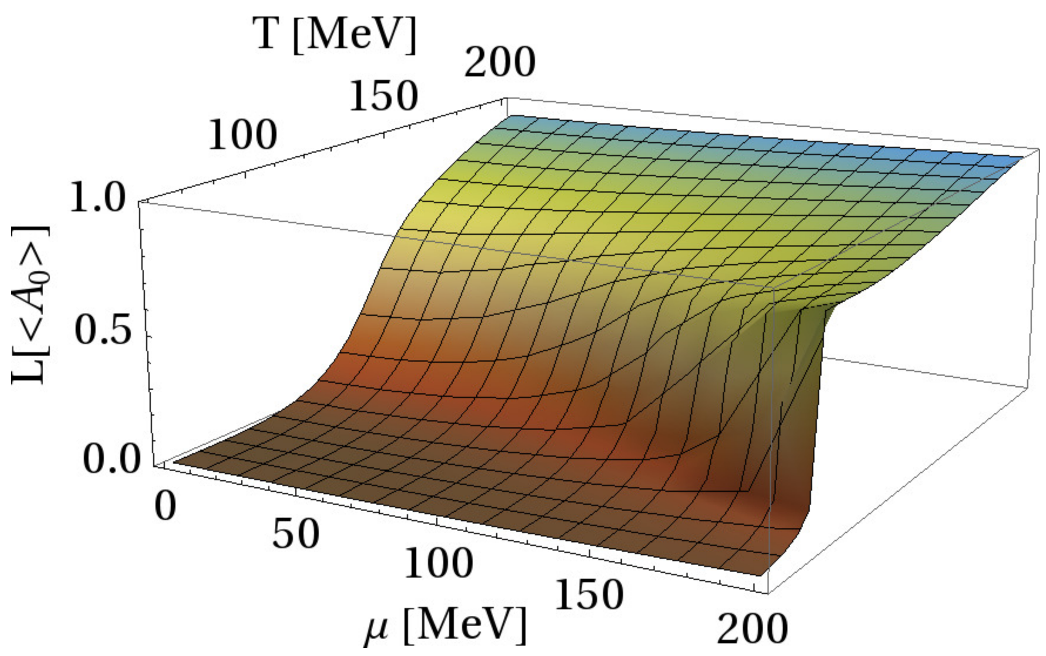
Haas, Braun, JMP '09, unpublished

Critical point unlikely for

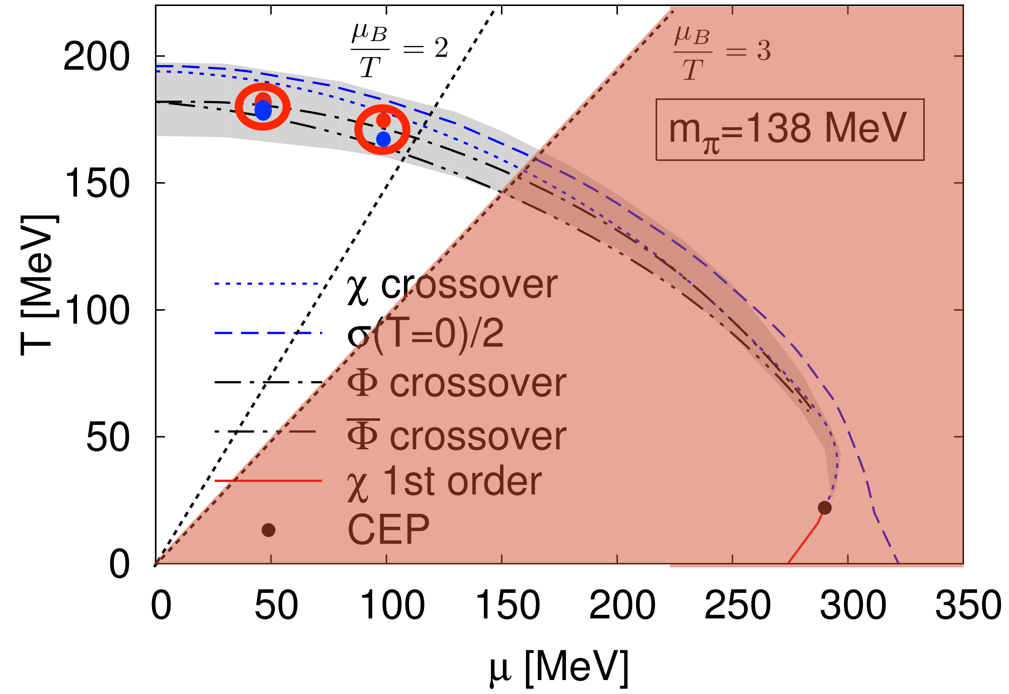
$$\frac{\mu_B}{T} < 2$$

Phase structure at finite density

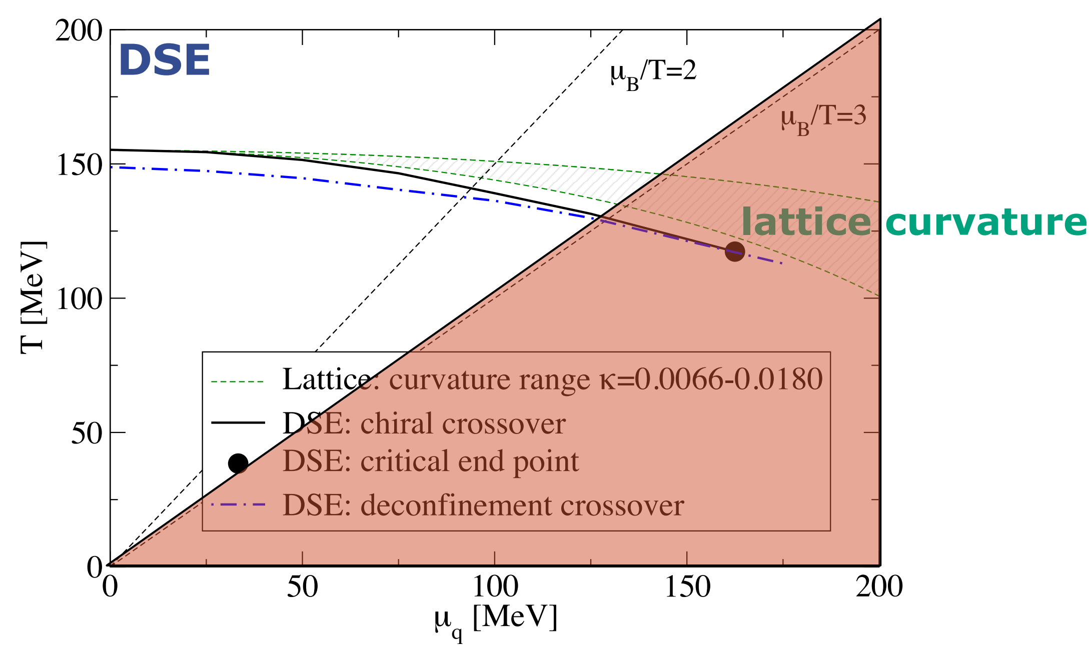
Polyakov loop at finite density



Phase diagram of quantised PQM-model



Phase diagram of 2+1 flavor QCD

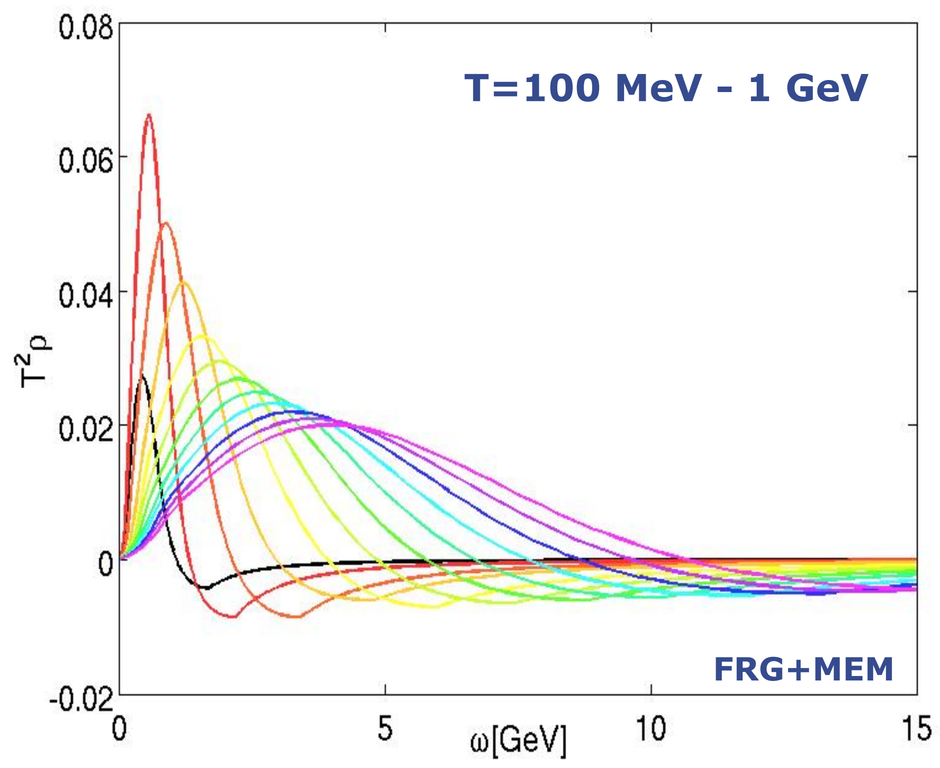


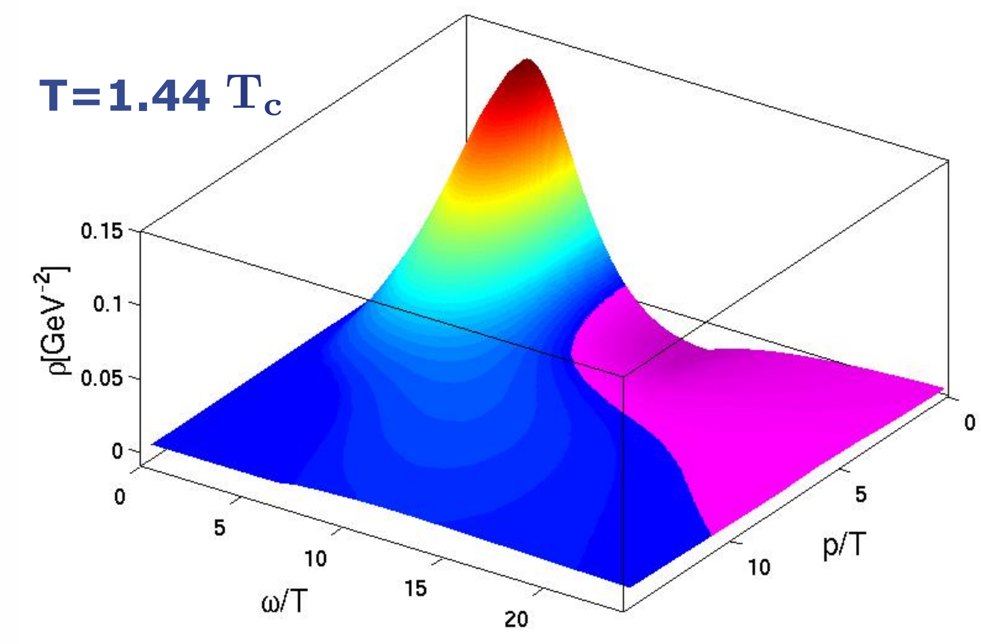
FRG-QCD with mesons, diquarks & baryons

finite mu and real frequencies

Viscosity in pure glue

transversal gluon spectral function

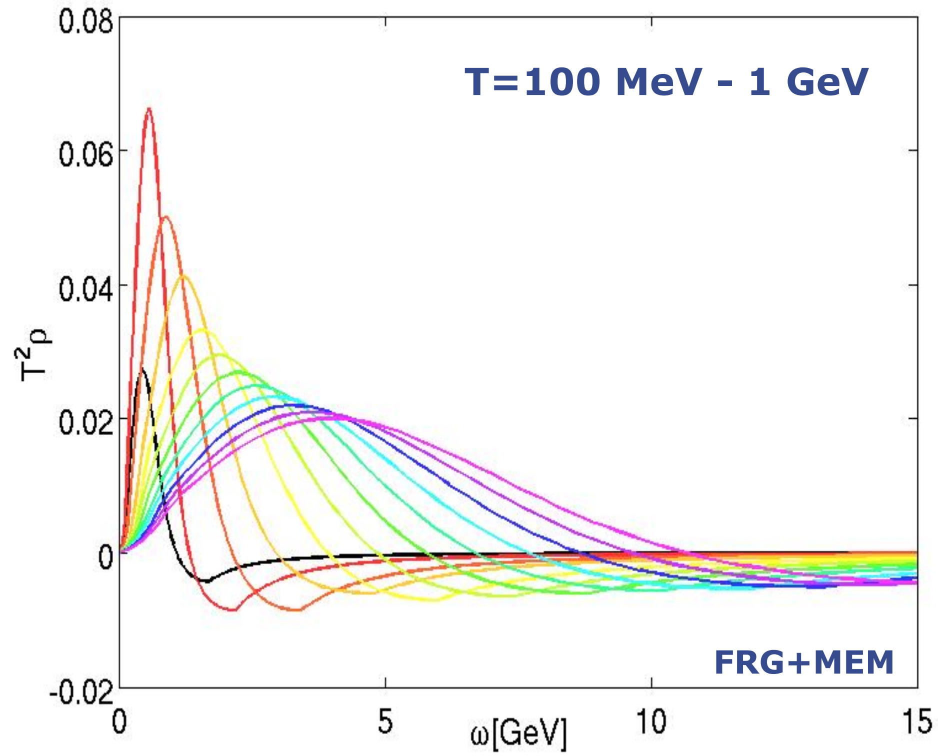


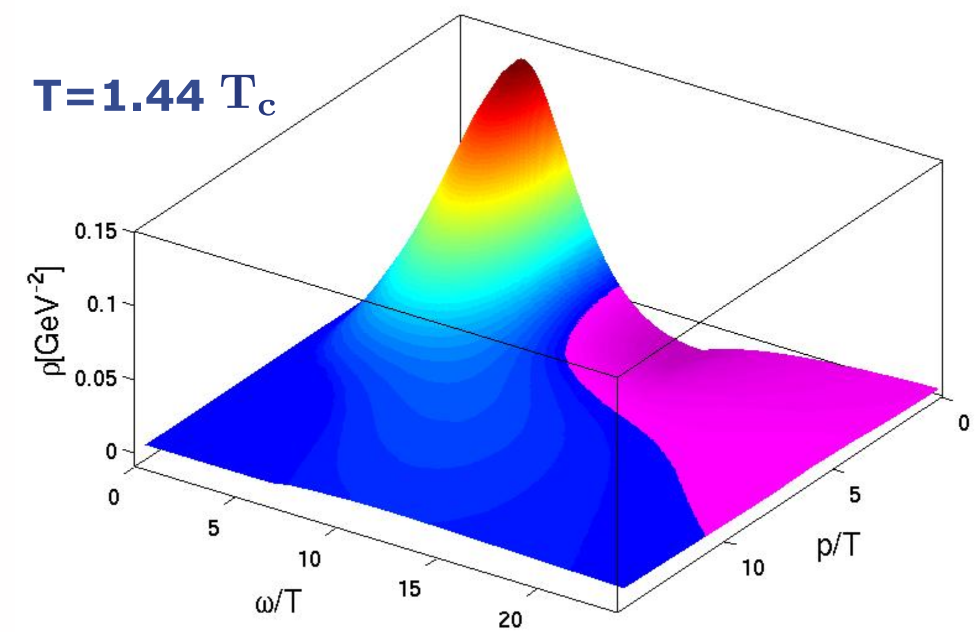


see talk of N. Strodthoff

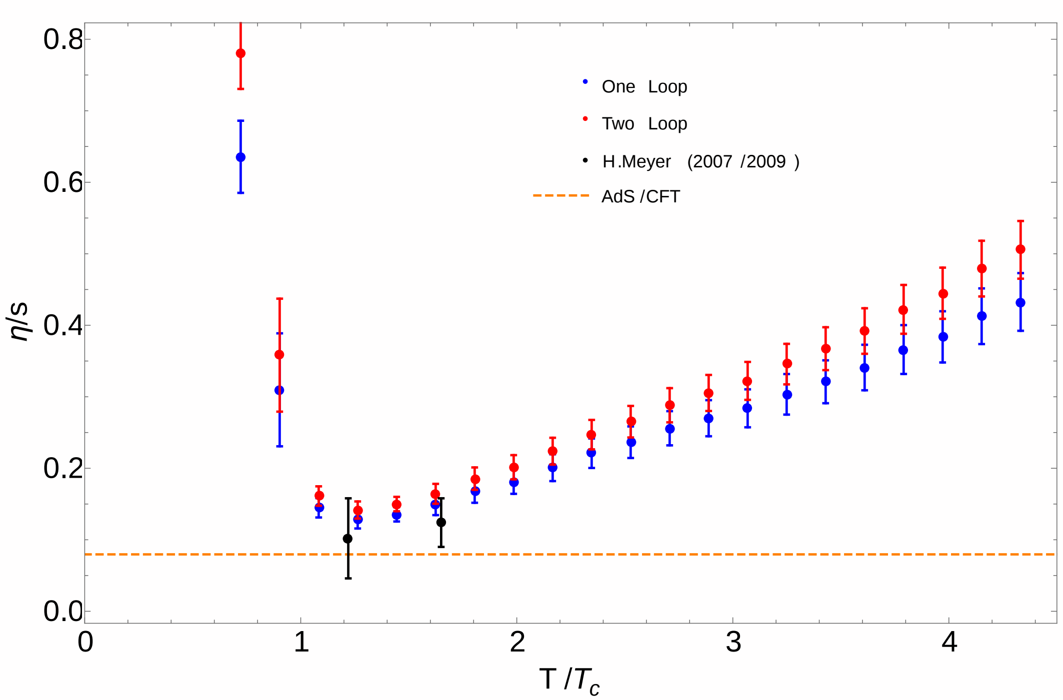
Viscosity in pure glue

transversal gluon spectral function





see talk of N. Strodthoff

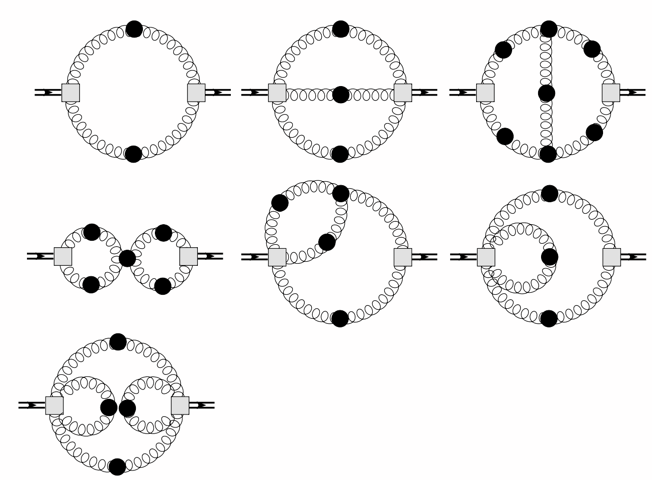


Kubo relation

$$\eta = \frac{1}{20}\,\frac{d}{d\omega}\bigg|_{\omega=0}\rho_{\pi\pi}(\omega,0)$$

3-loop exact functional relation

2-loop terms



M. Haas, Fister, JMP, arXiv:1308.4960
Christiansen, Haas, JMP, Strodthoff, in preparation

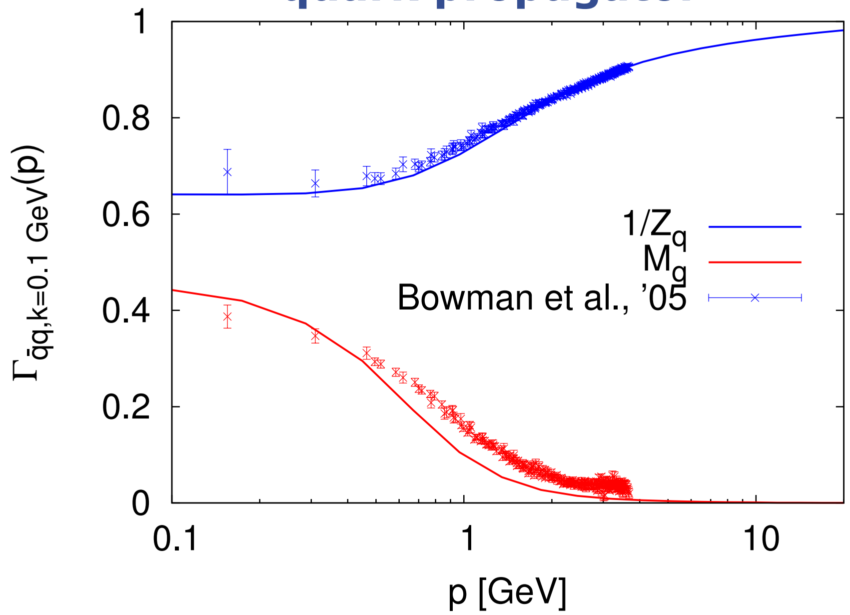
Summary & Outlook

Summary & Outlook

- **Chiral Symmetry Breaking and Confinement**

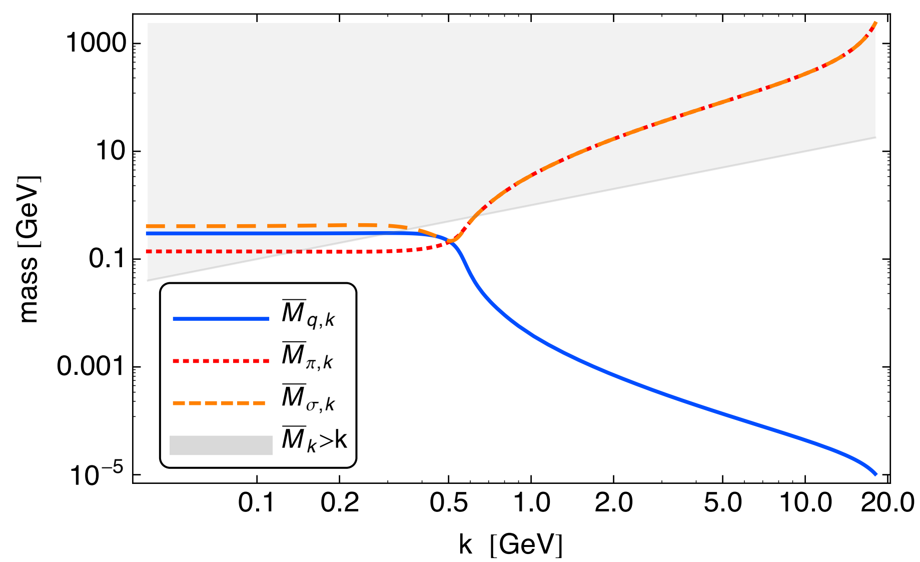
see talk of M. Mitter

quark propagator



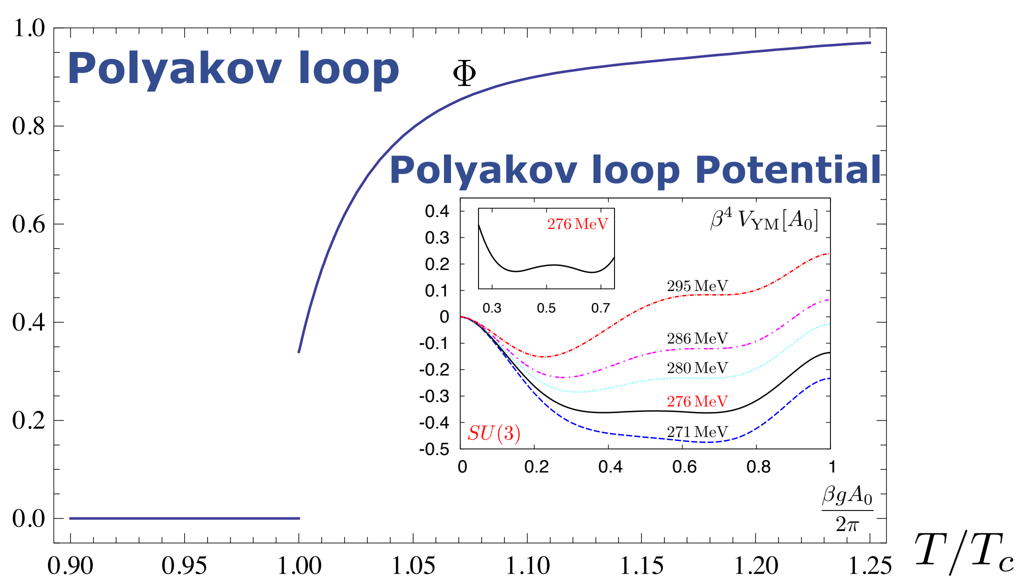
see talk of F. Rennecke

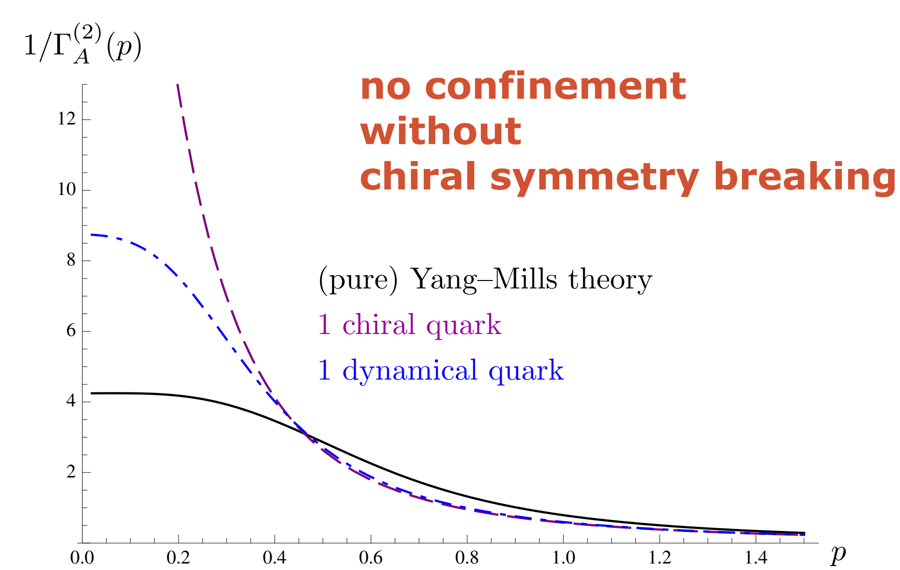
meson masses



see talk of L. Fister

gluon propagator



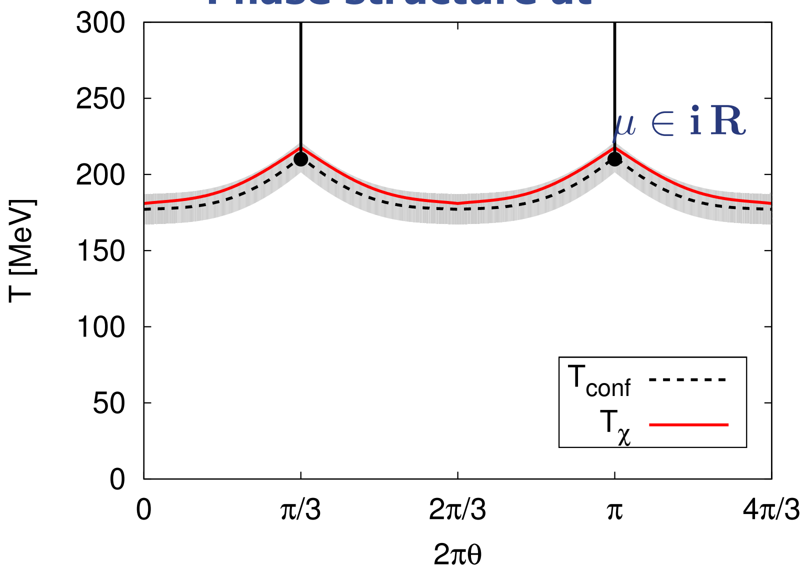


Summary & Outlook

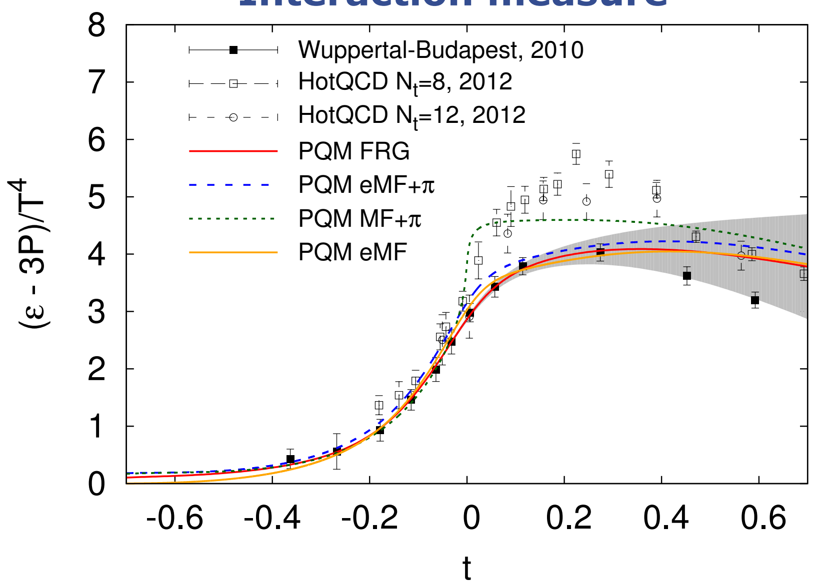
▪ Phase structure and Transport

see talks of M. Mitter
B.-J. Schaefer

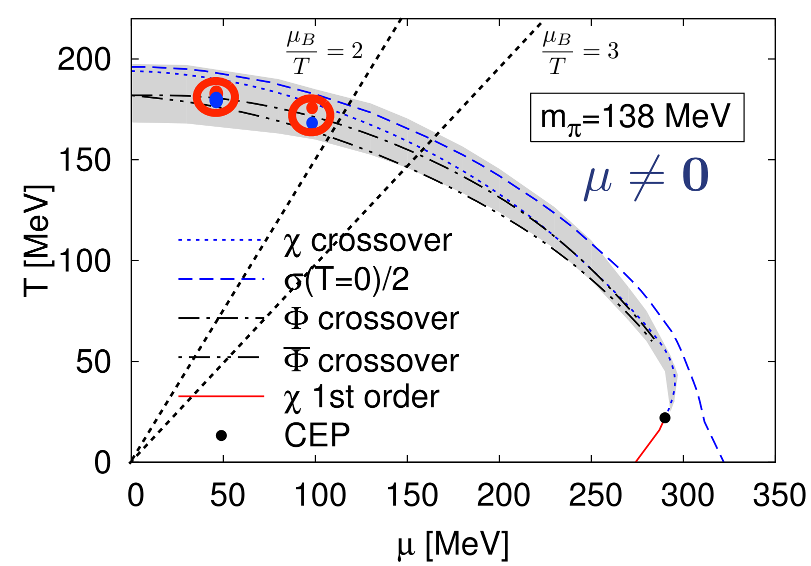
Phase structure at



Interaction measure

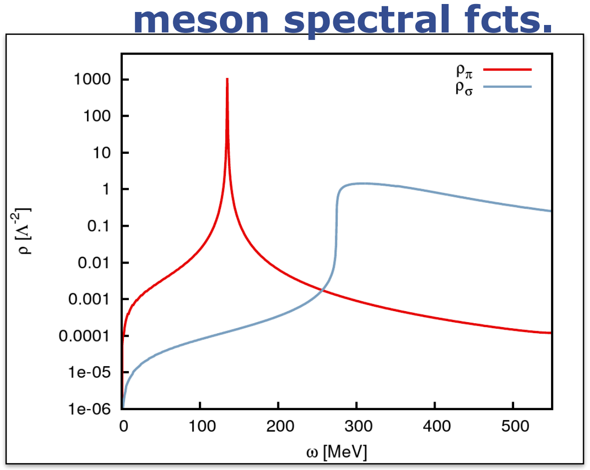


Phase structure at

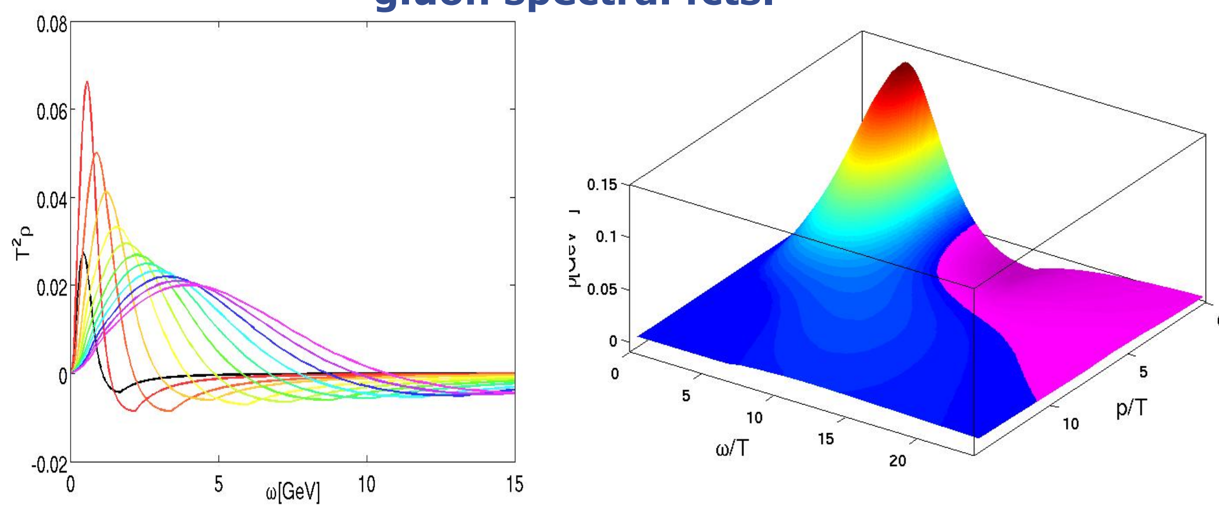


see talks of L. Fister
N. Strodthoff

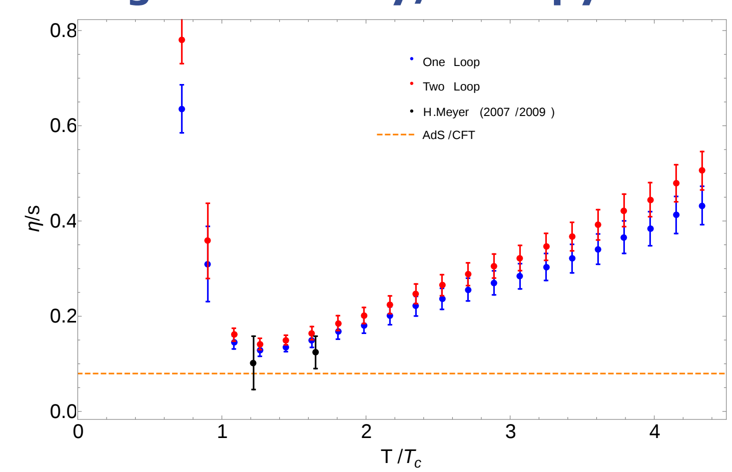
meson spectral fcts.



gluon spectral fcts.



glue viscosity/entropy



Summary & Outlook

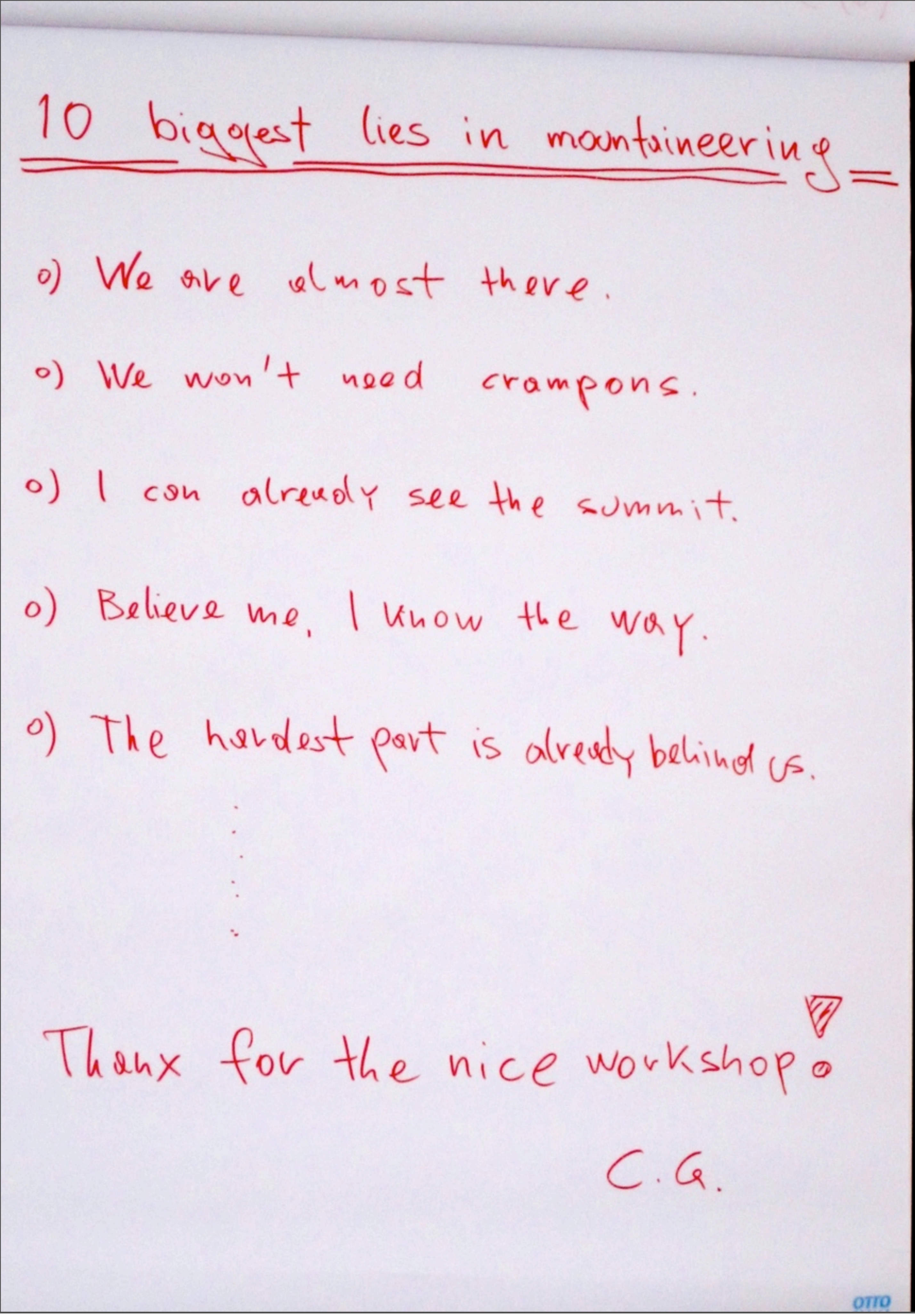
- Chiral Symmetry Breaking and Confinement

- Phase Structure and Transport

- Towards quantitative precision

- Baryons, high density regime, dynamics

- Hadronic properties
  - hadron spectrum & in medium modifications
  - low energy constants



final word of caution

- **Original application: sign-problem**

- **General appplication: Evaluate systematic error**

10 biggest lies in mountaineering =

o) We are almost there.

o) We won't need crampons.

o) I can already see the summit.

o) Believe me, I know the way.

o) The hardest part is already behind us.

⋮

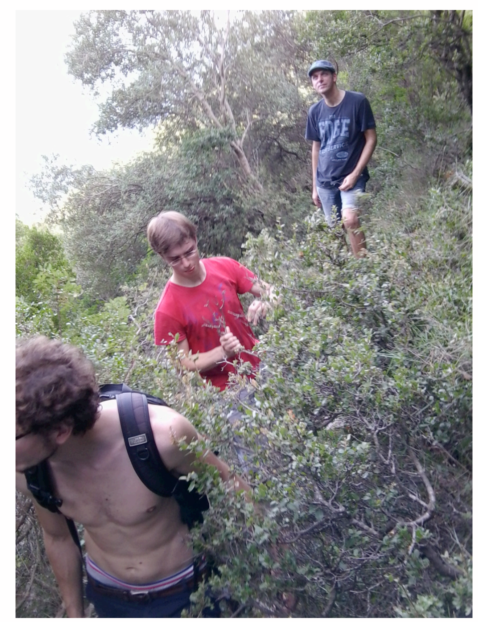
Thanx for the nice workshop!

C. G.

final word of caution

- **Original application: sign-problem**

- **General appplication: Evaluate systematic error**



Thanx to Holger, Jan, Manuel, Dietrich

...of course we have seen the summit!

...several of them......