Exploring the phase structure and dynamics of QCD

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GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

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EMMI

Outline

- **Introduction**

- **Confinement & transport**

- **Chiral symmetry breaking & the phase structure**

- **Summary & outlook**

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- **Chiral symmetry breaking & the phase structure**
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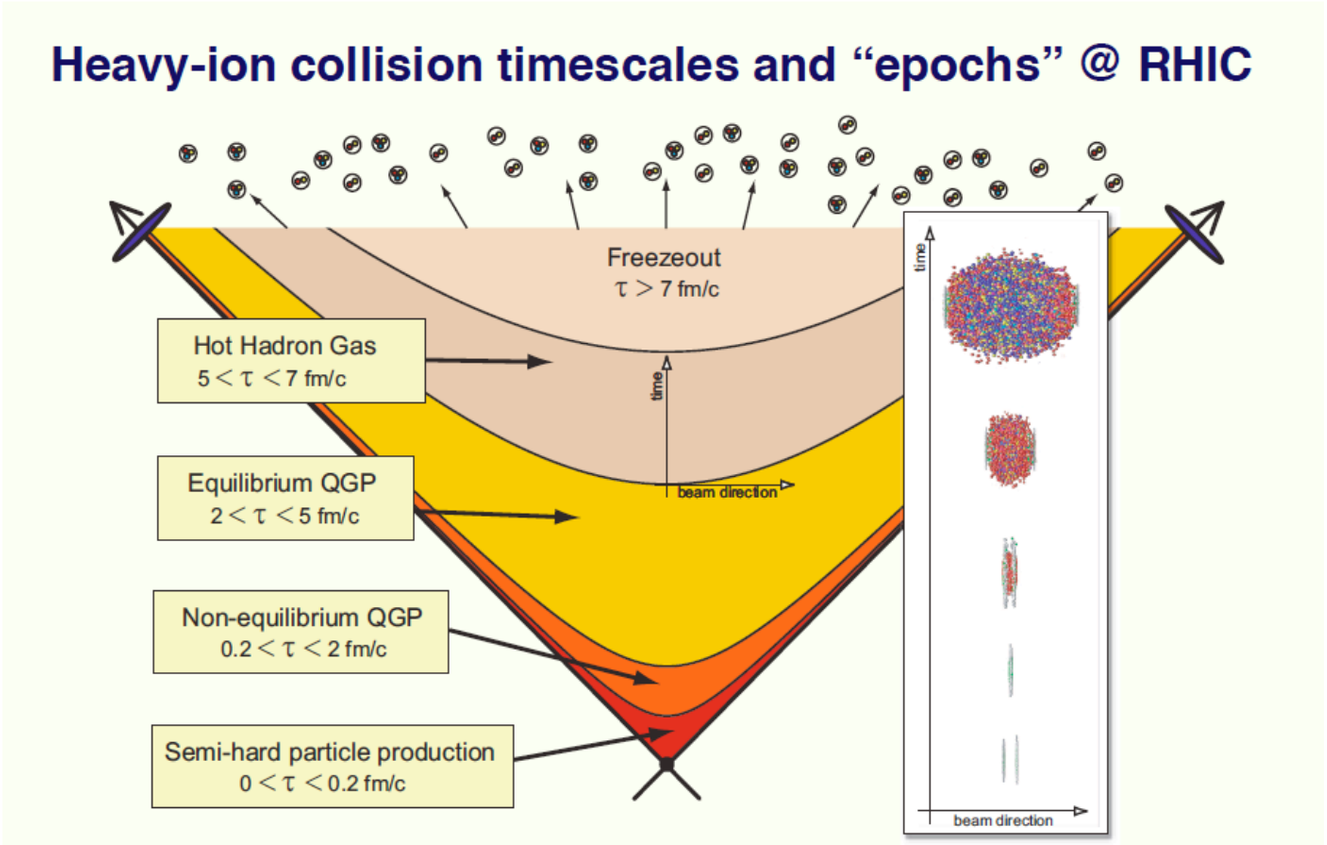
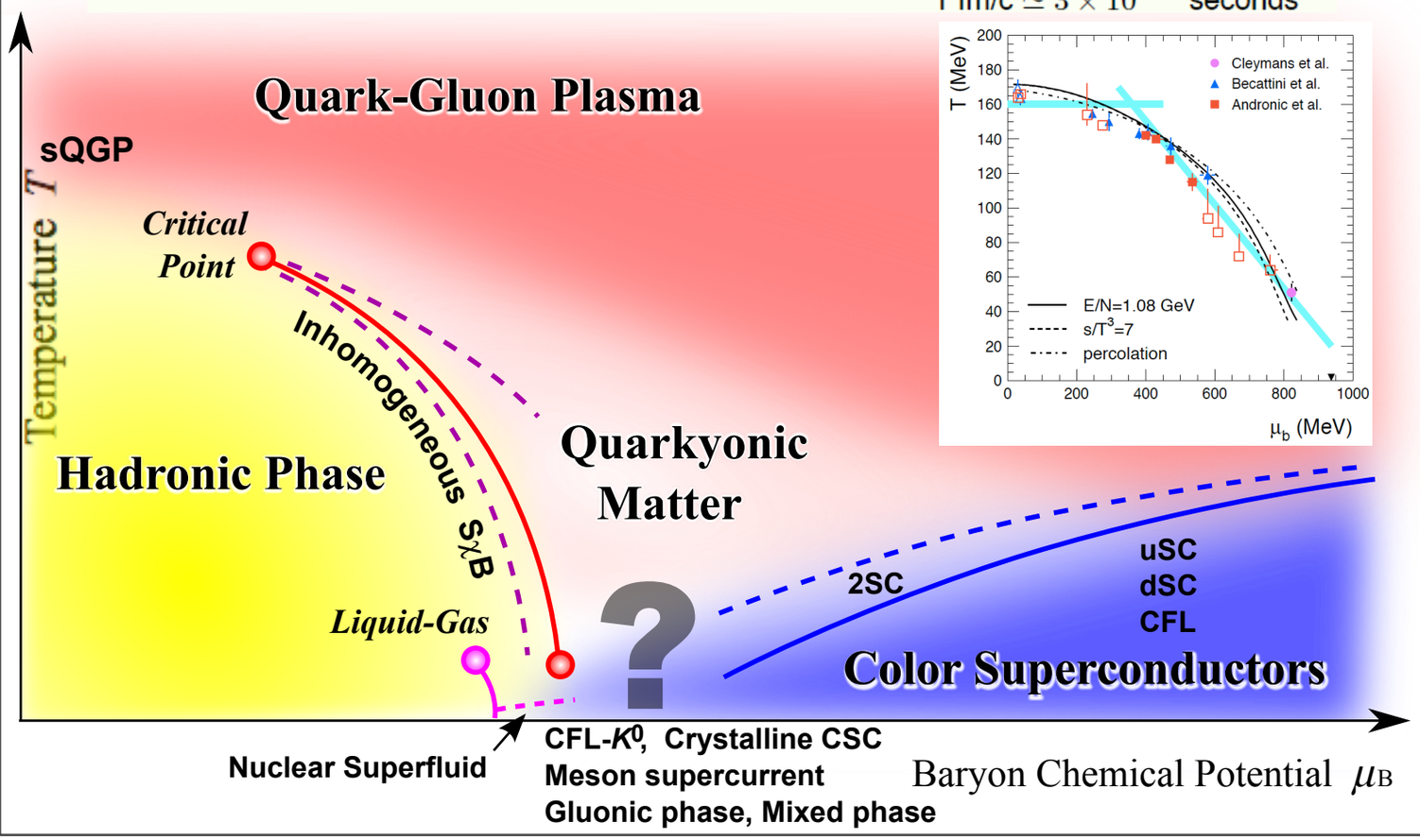
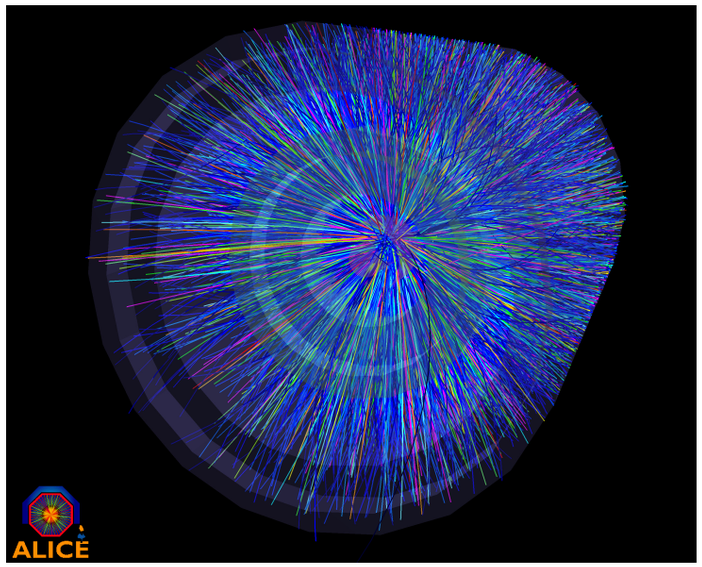
Heavy ion collisions

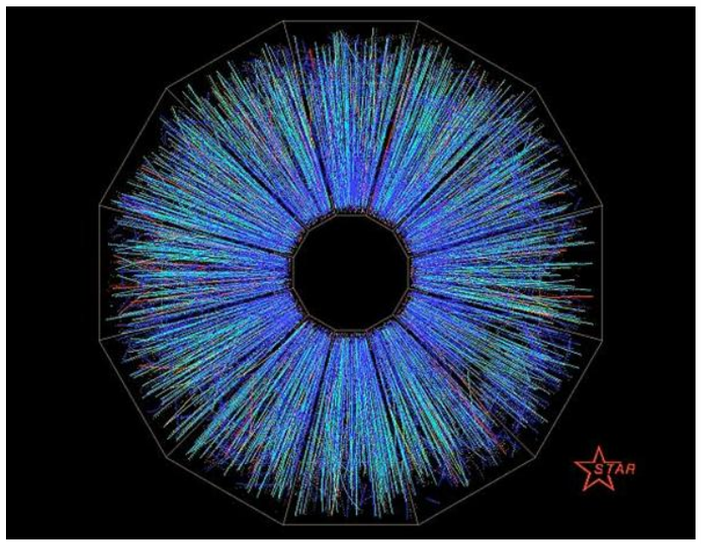




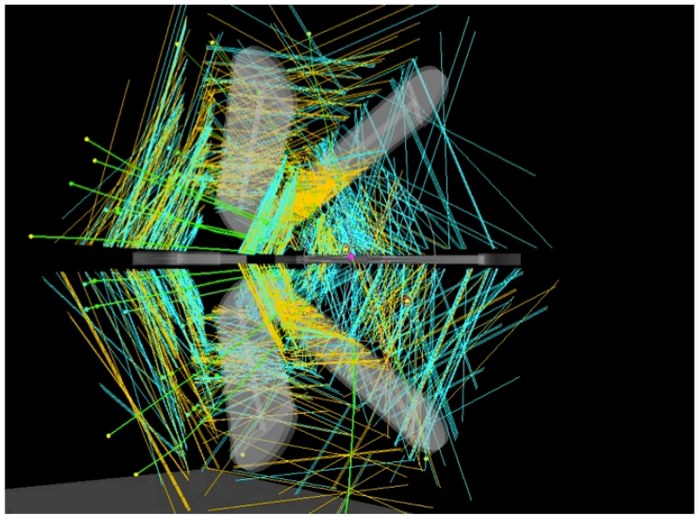
LHC



RHIC



GSI



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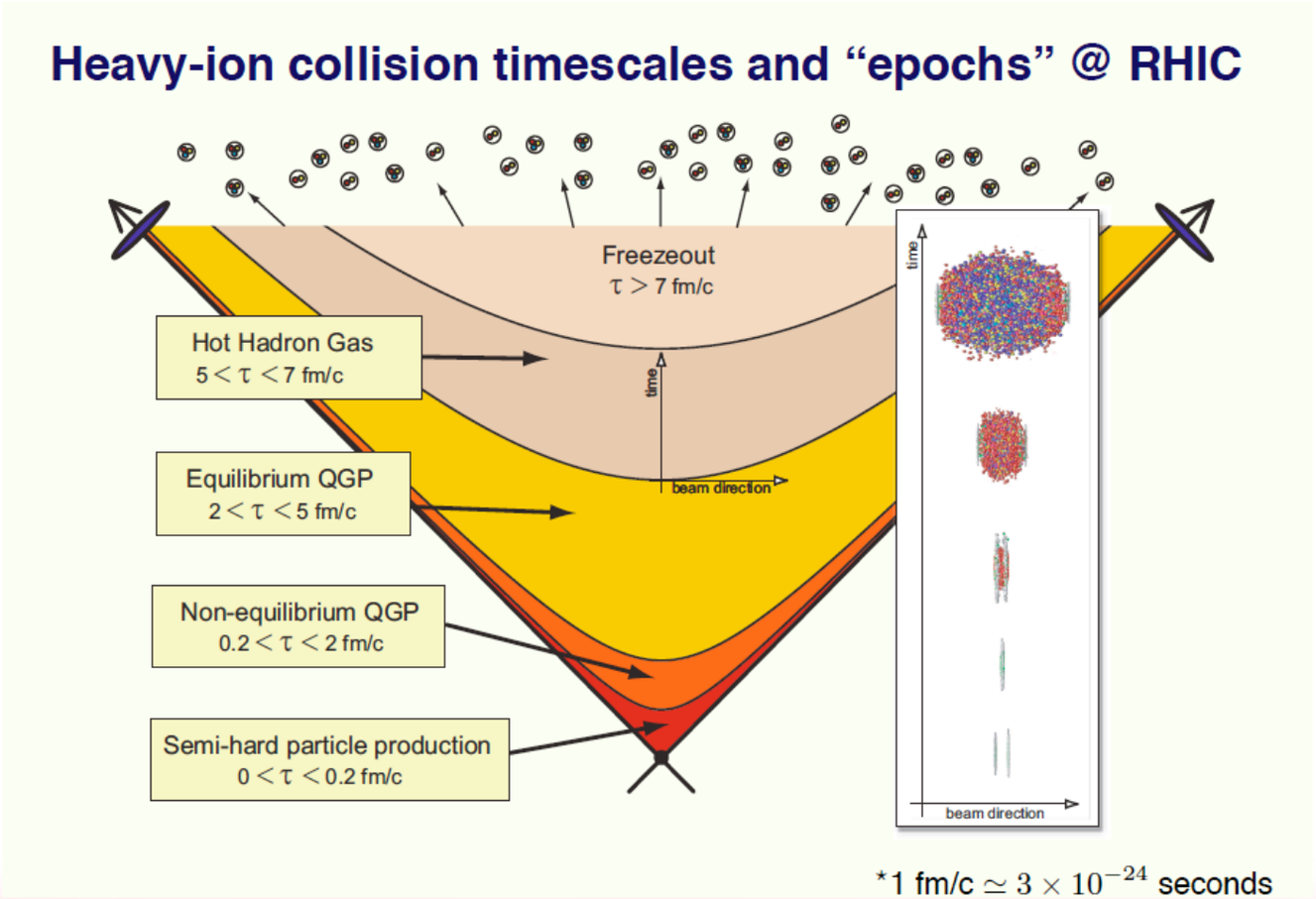

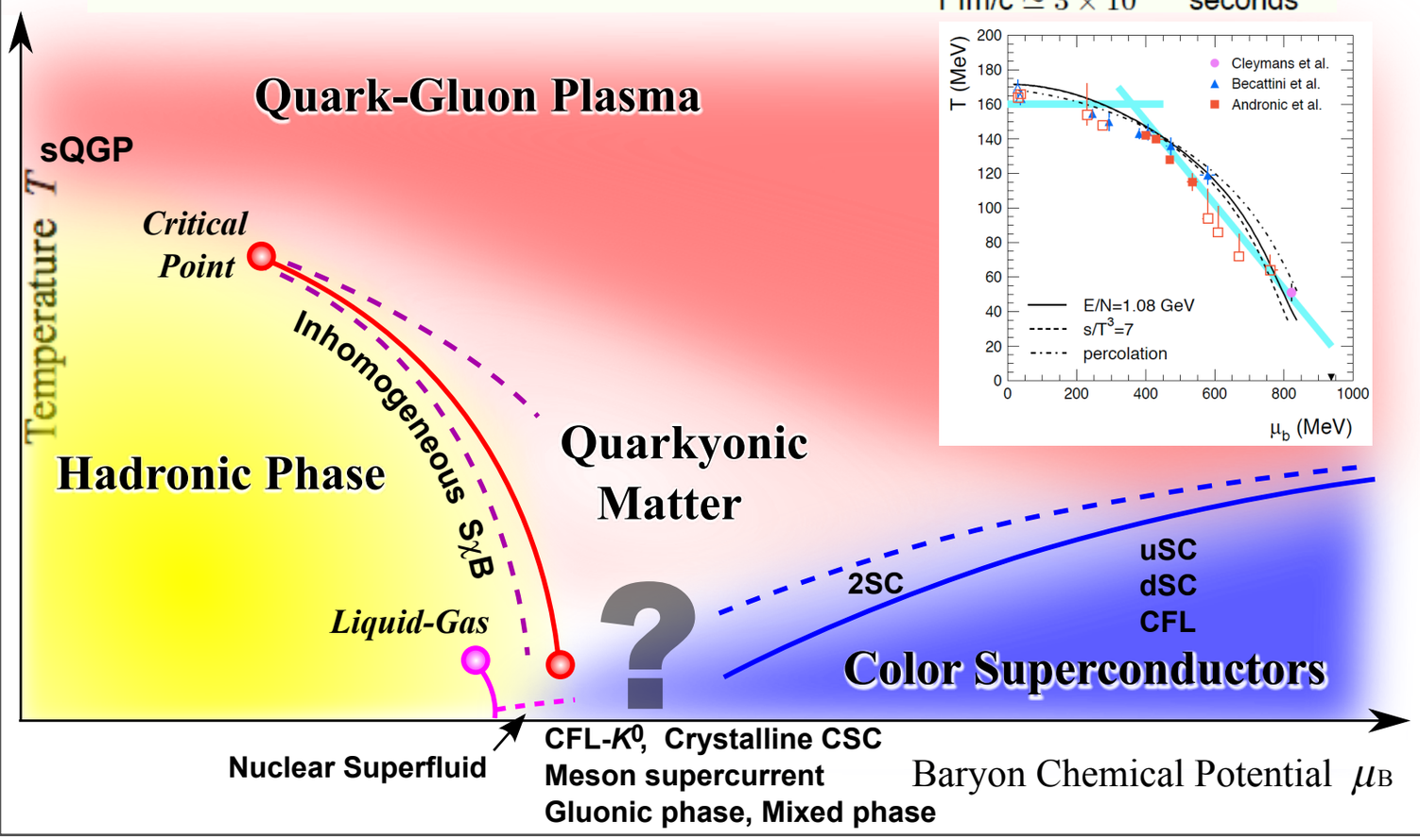

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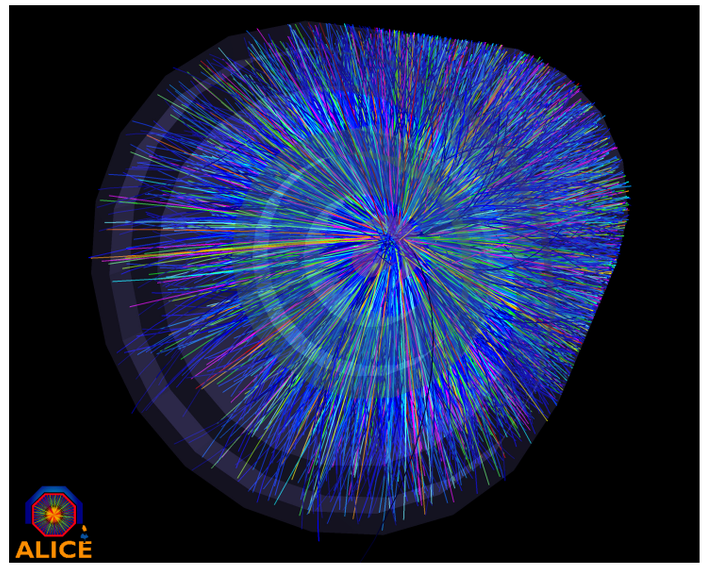

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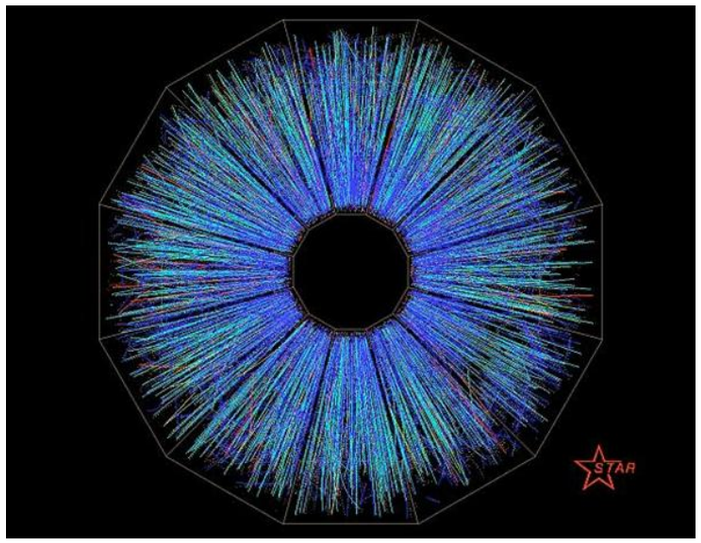
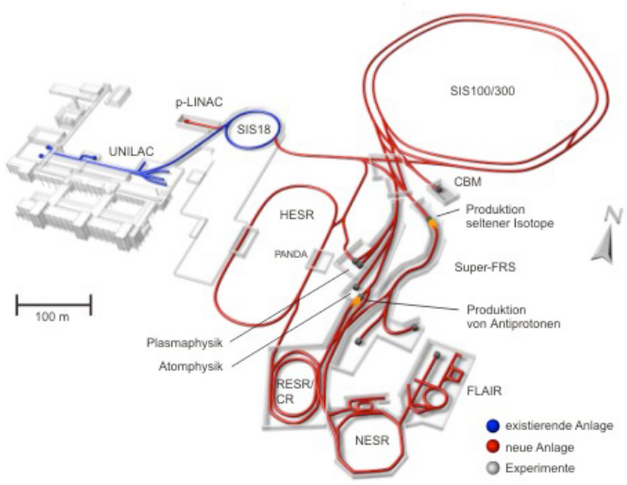
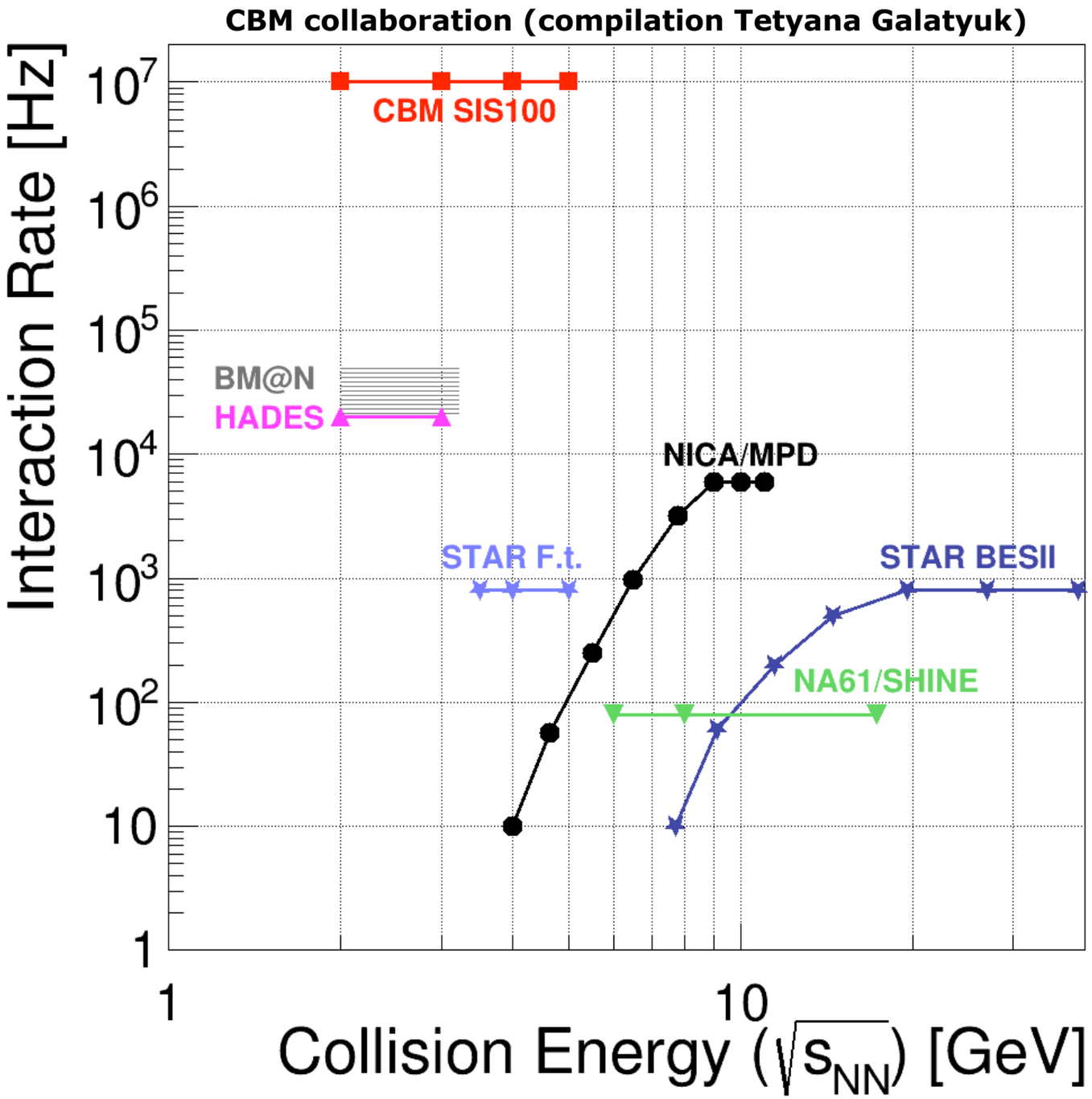


FAIR



NICA

Heavy ion collisions



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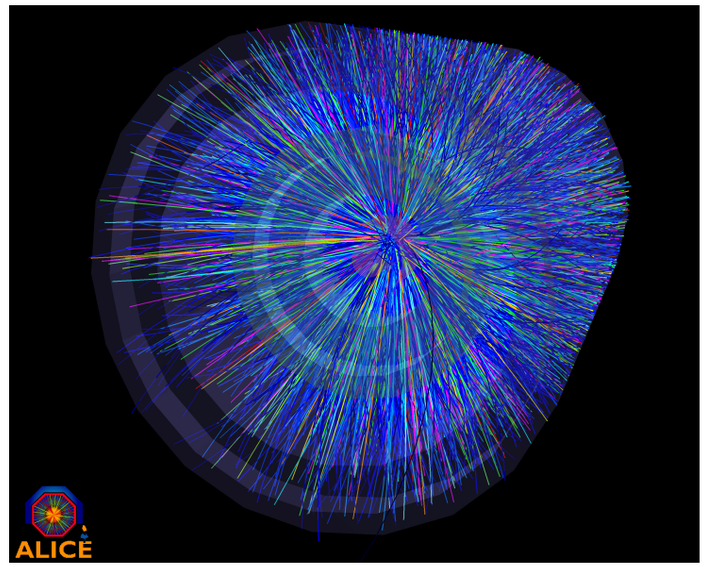

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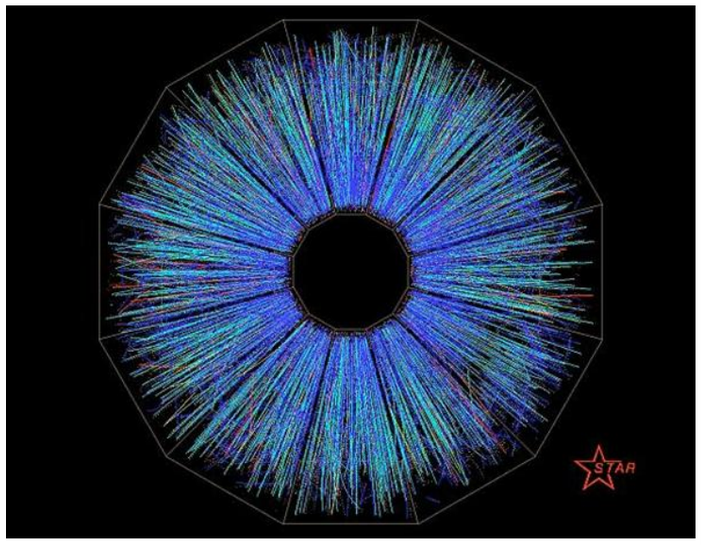

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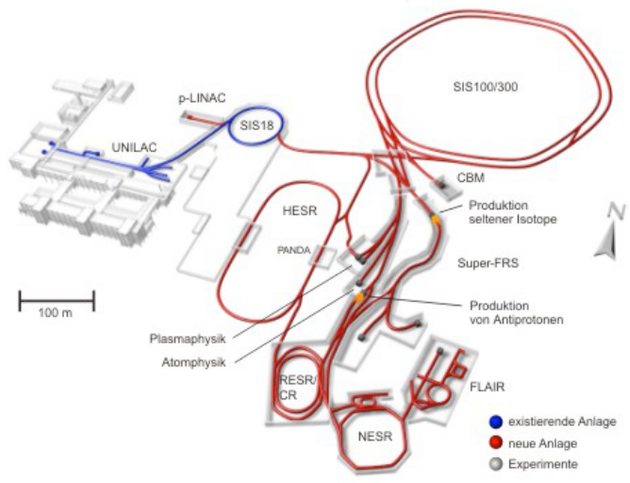

NICA

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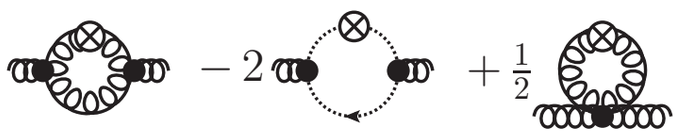
Gluonic correlation functions

Functional Renormalisation Group

$$\langle A\, A\rangle(p^2)$$

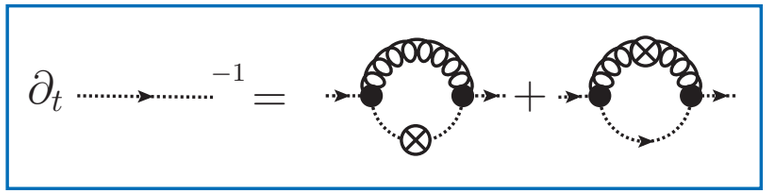
$$\partial_t \Gamma_{AA}^{-1} = \quad - 2 \quad + \frac{1}{2}$$

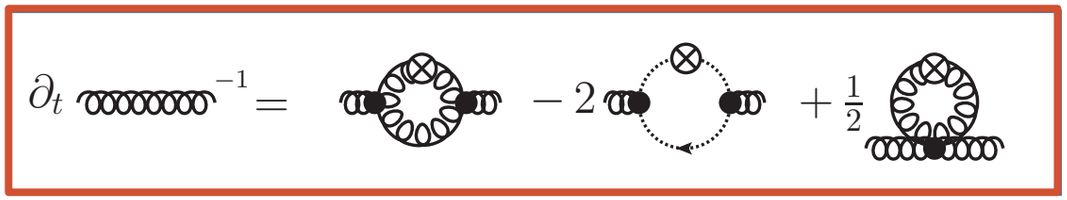


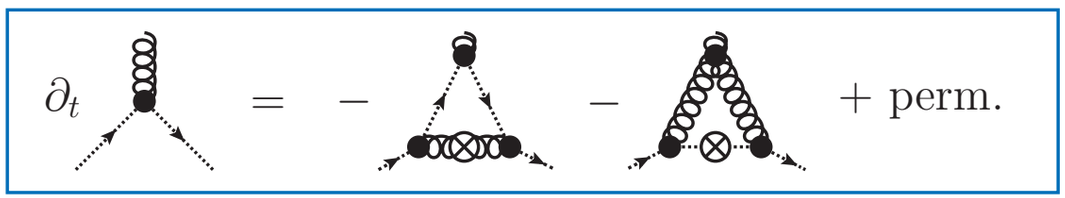
Cyrol, Fister, Mitter, JMP, Strodthoff, arXiv:1605.01856

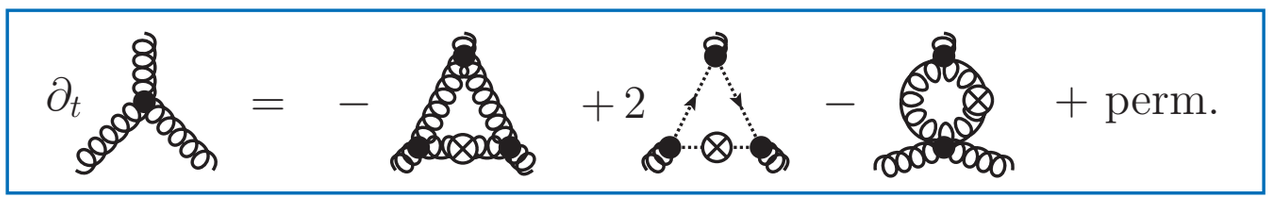
Gluonic correlation functions

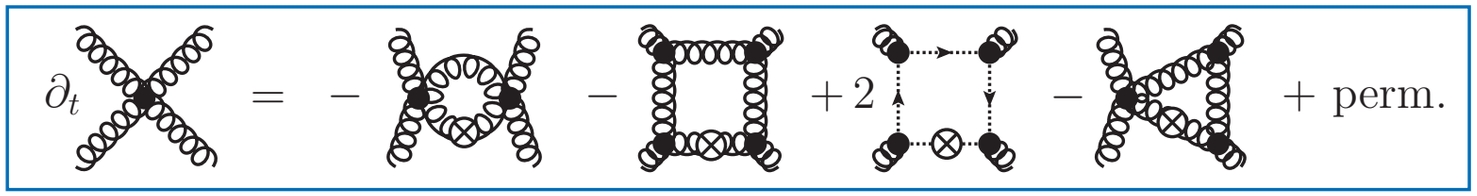
Functional Renormalisation Group

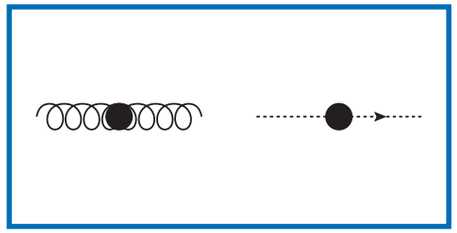




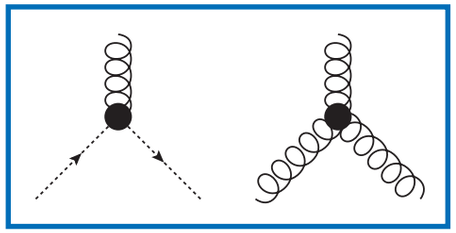




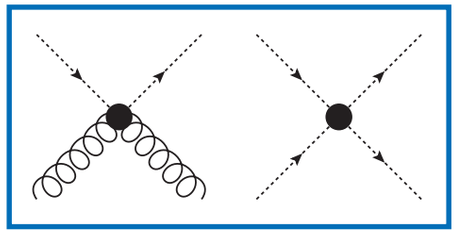




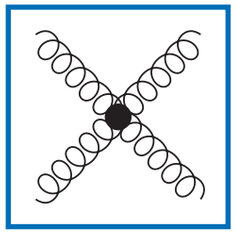
full. mom. dep.



full. mom. dep.
classical tensor structures



mom. dep. needed by tadpoles
full tensor basis



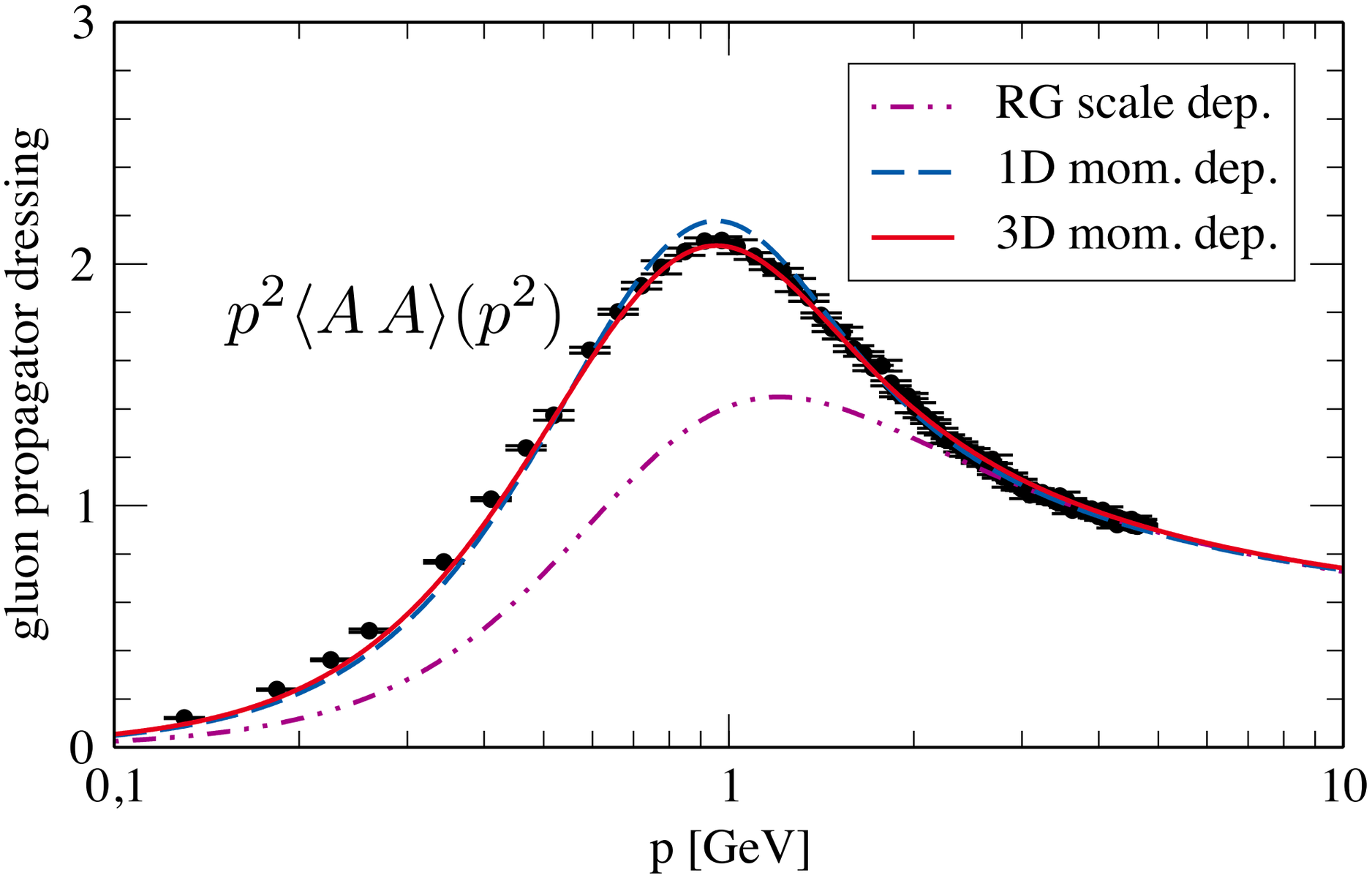
sym. point mom. dep. and
mom. dep. needed by tadpole
classical tensor structure

Aiming at apparent convergence

Cyrol, Fister, Mitter, JMP, Strodthoff, arXiv:1605.01856

Euclidean gluon propagator

Functional Renormalisation Group

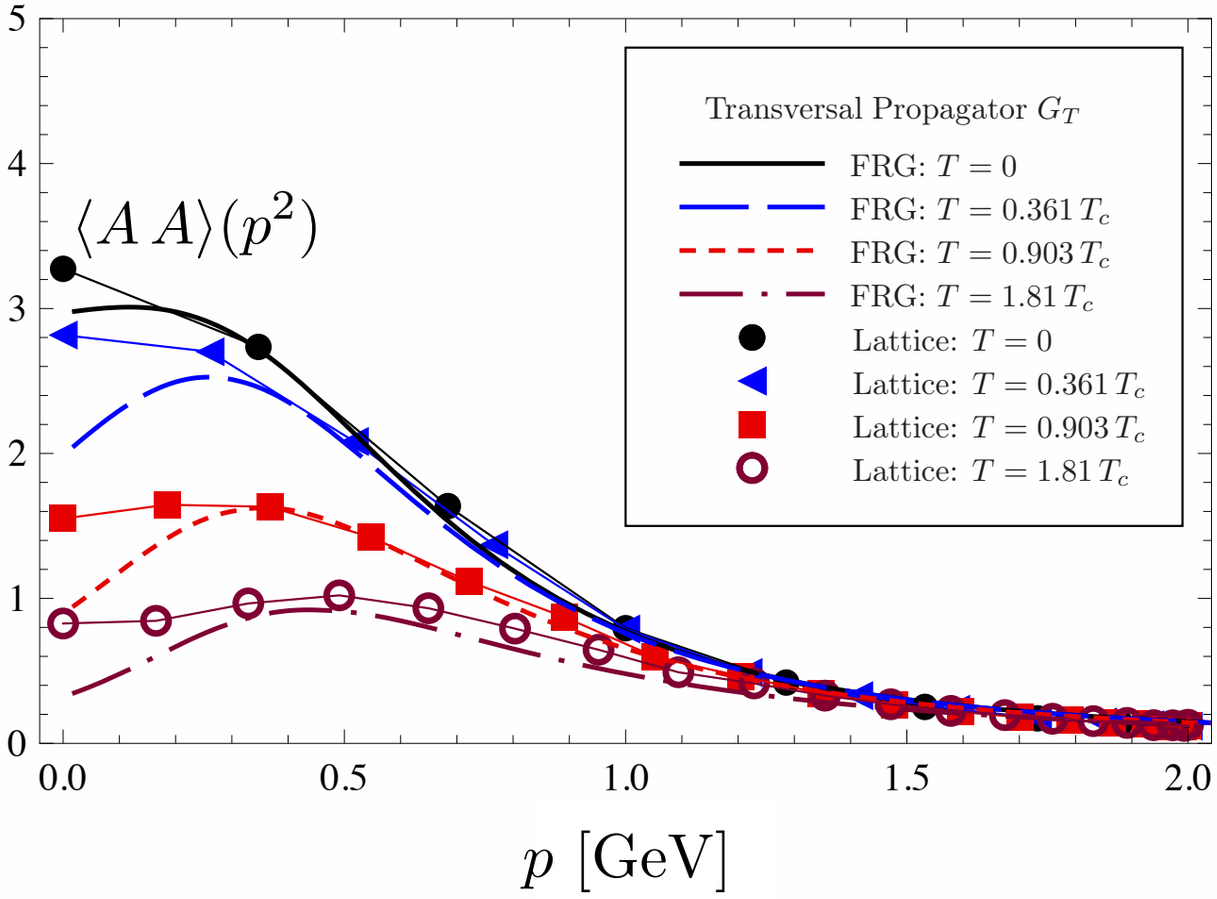


Aiming at apparent convergence

Cyrol, Fister, Mitter, JMP, Strodthoff, arXiv:1605.01856

Euclidean gluon propagator

Yang-Mills propagators, finite T



Fister, JMP, arXiv:1112.5440

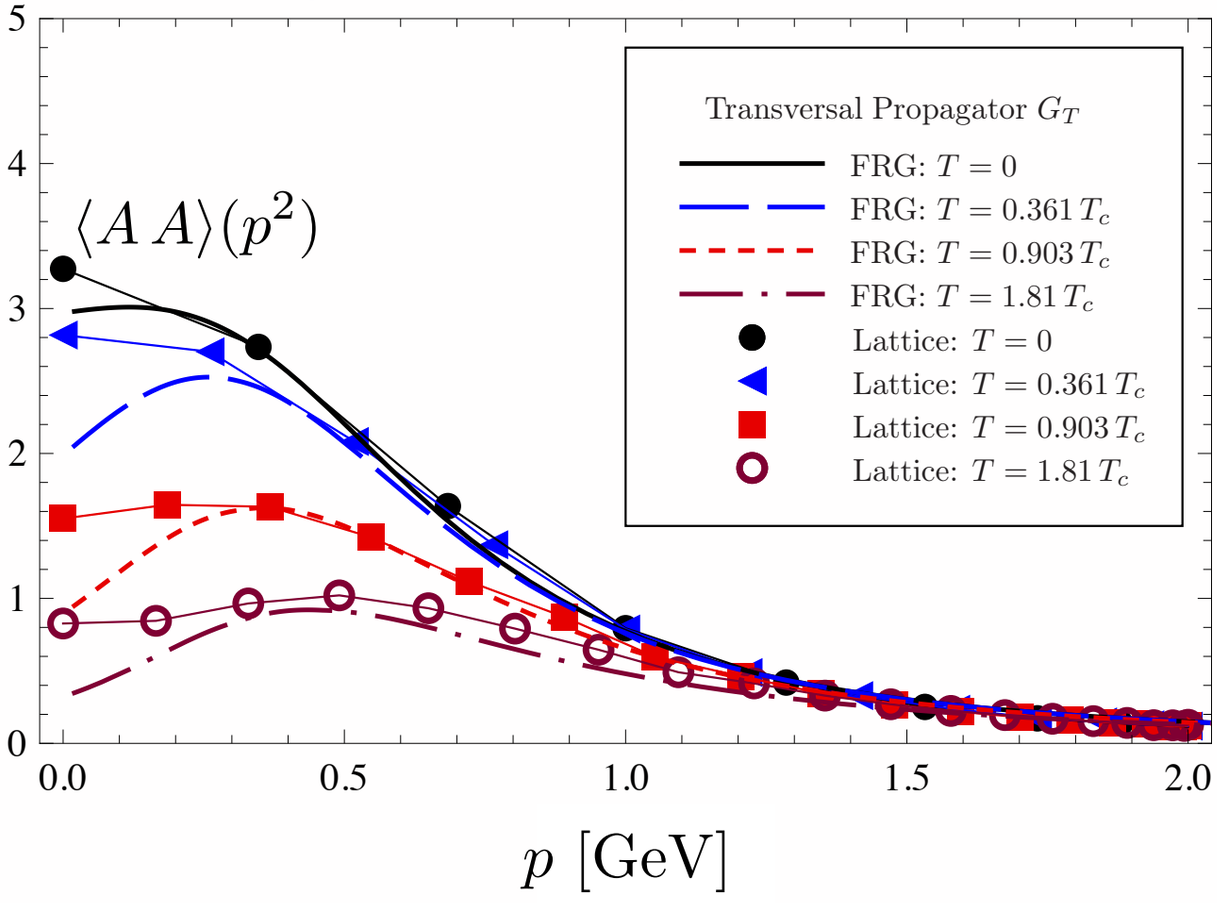
Lattice: Maas, JMP, Smekal, Spielmann, PRD 85 (2012) 034037

Approximations of infrared dynamics involved

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

Euclidean gluon propagator

Yang-Mills propagators, finite T



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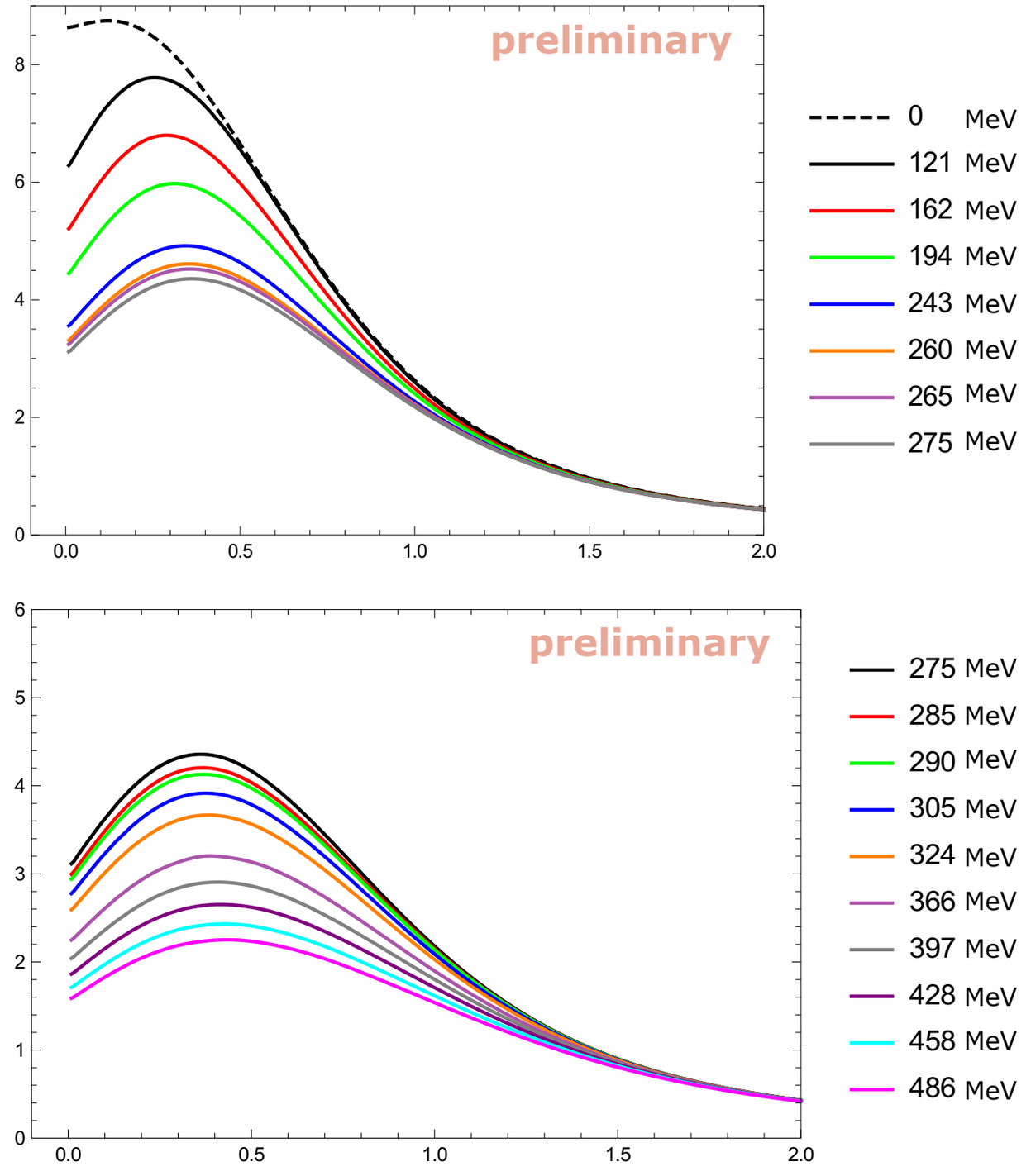


Approximations of infrared dynamics involved

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

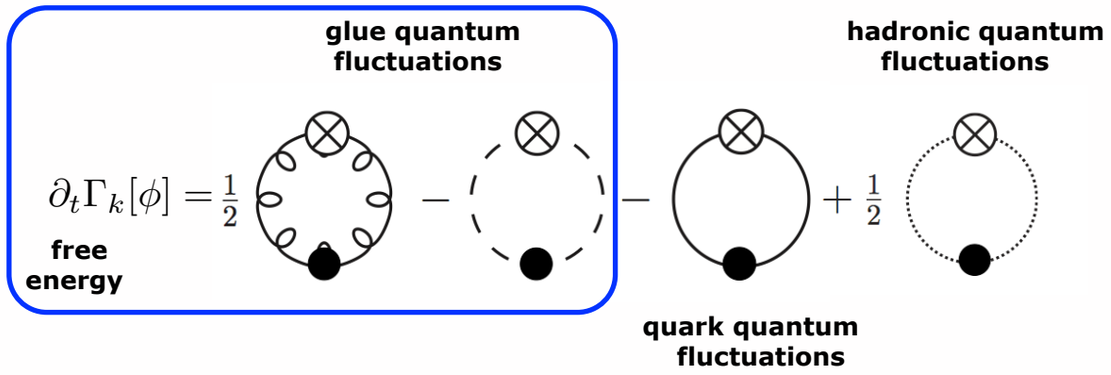
Cyrol, Mitter, JMP, Strodthoff, in preparation

Confinement

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

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

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

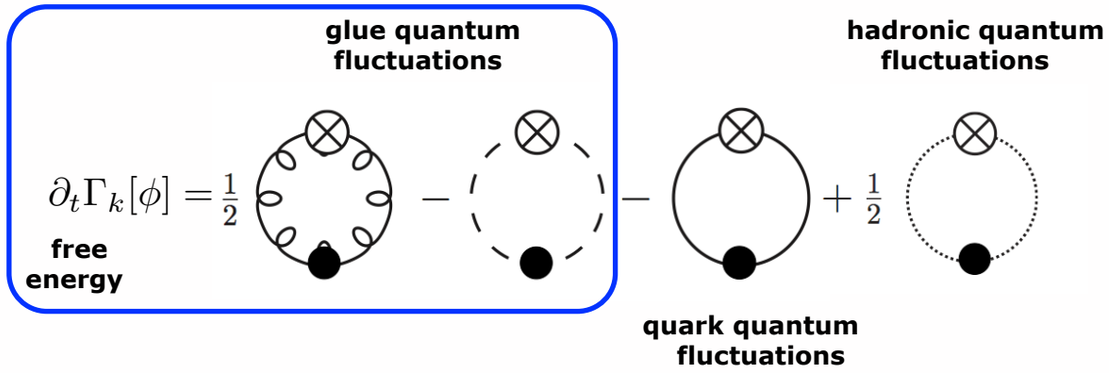


Confinement

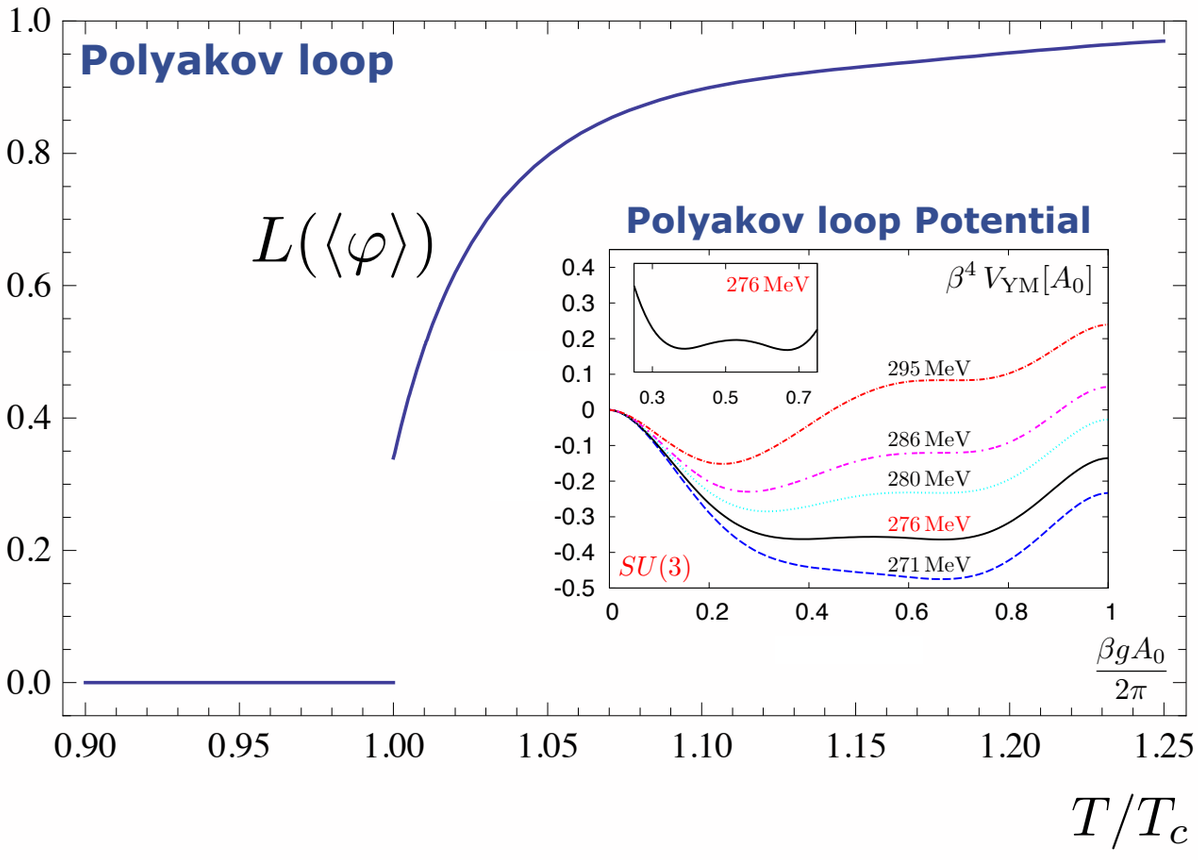
FRG: Braun, Gies, JMP, PLB 684 (2010) 262

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

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



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



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

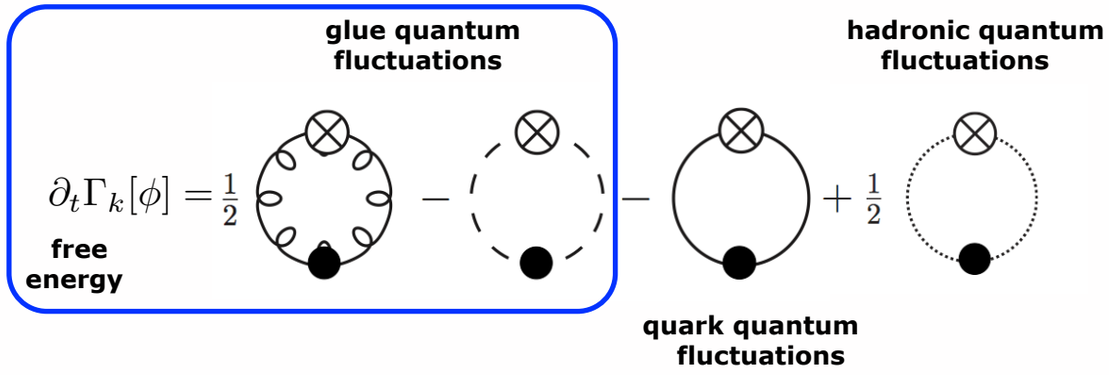
lattice : $T_c/\sqrt{\sigma} = 0.646$

Confinement

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

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

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



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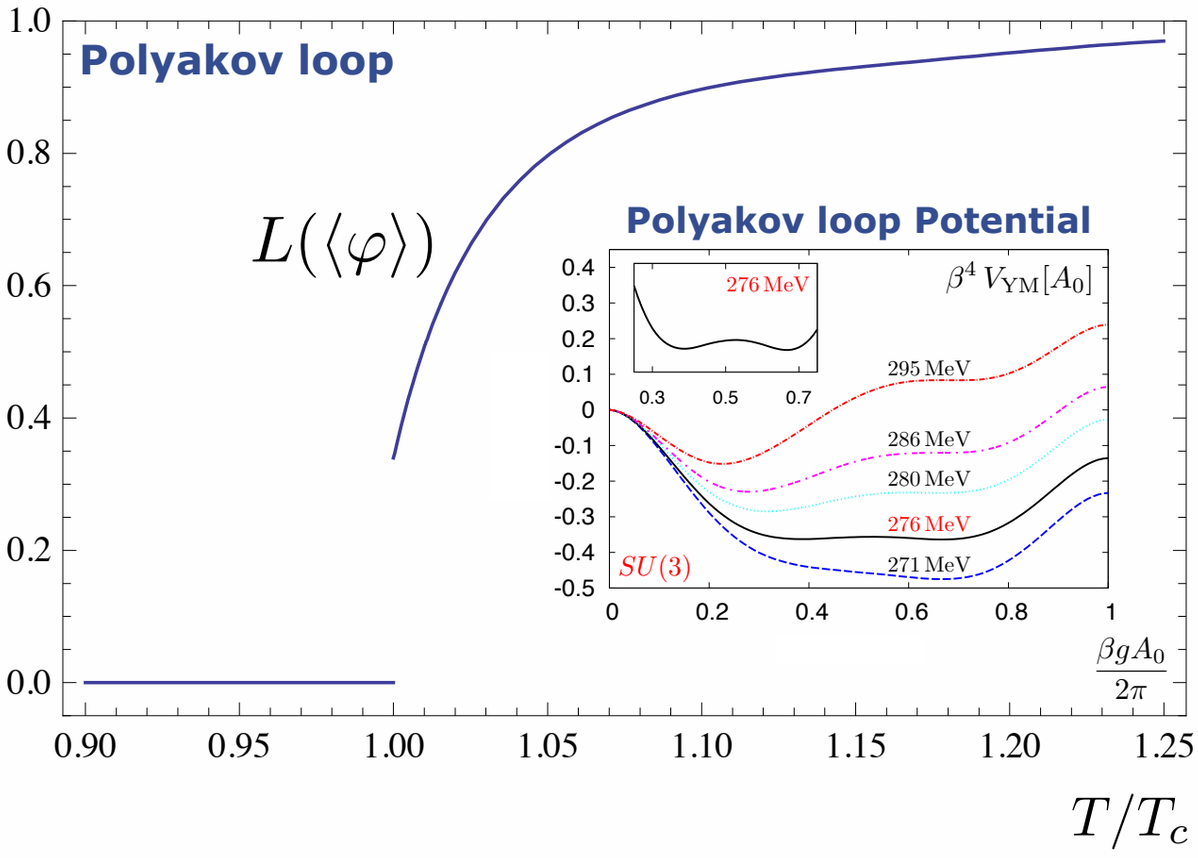
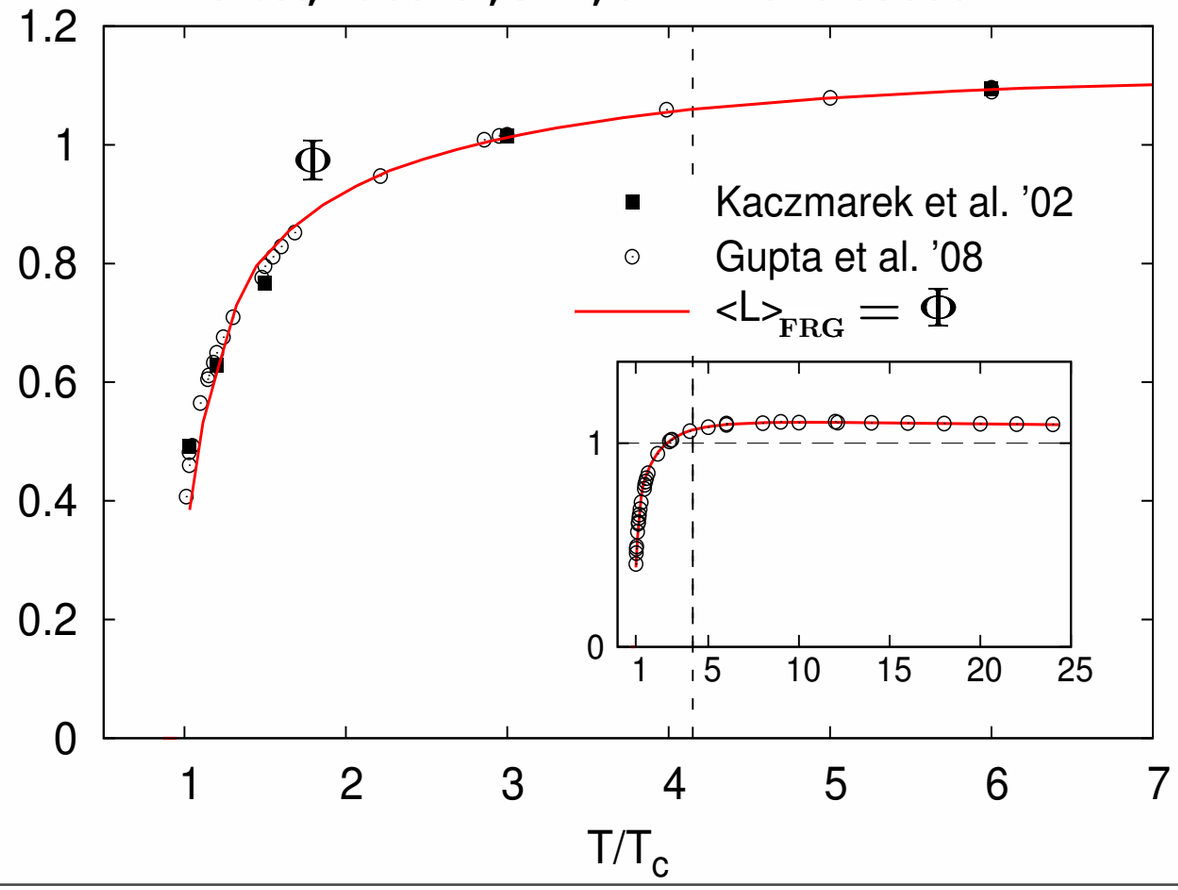


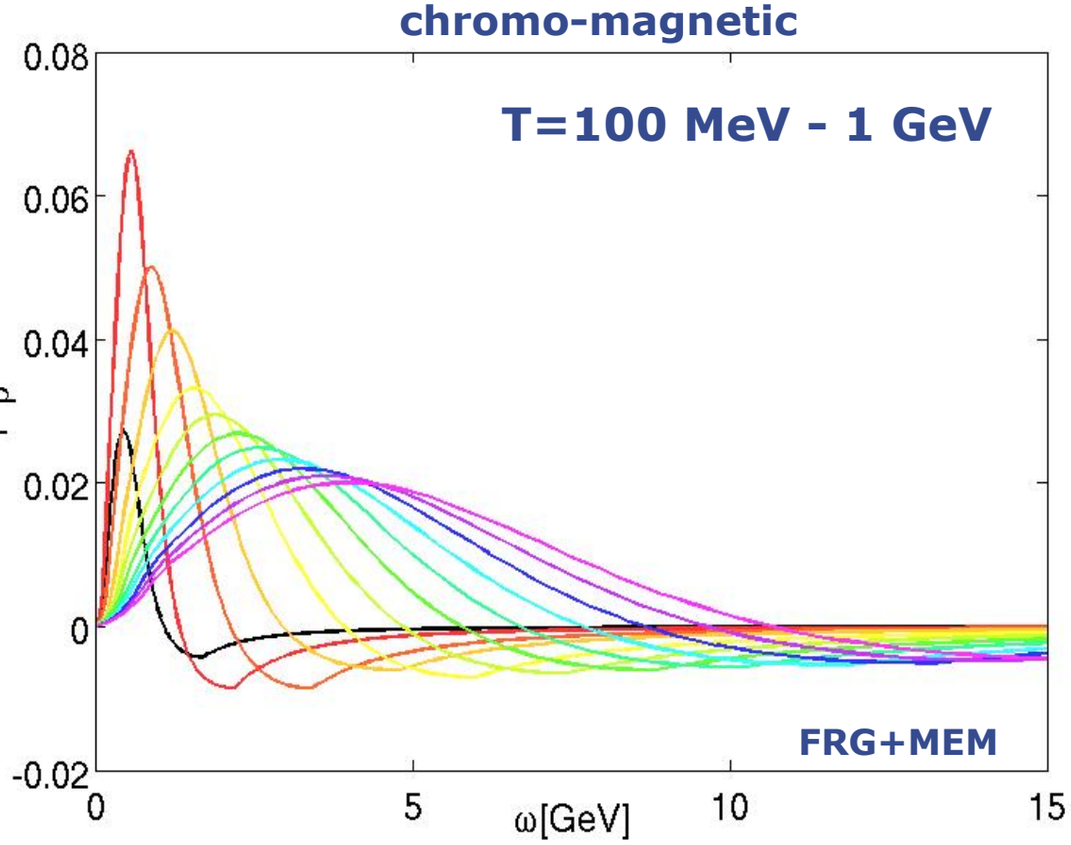
Herbst, Luecker, JMP, arXiv:1510.03830



Single particle spectral functions

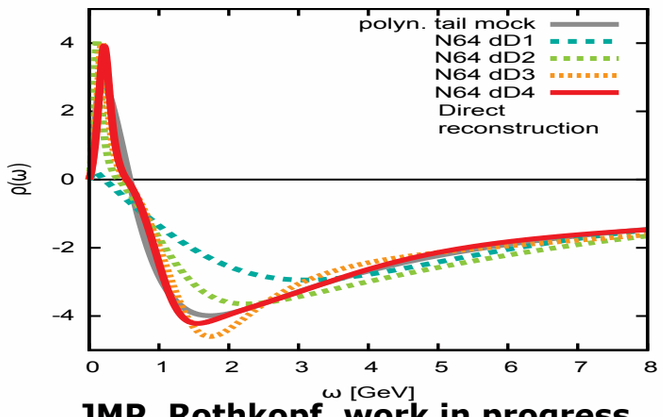
$$\rho(p) = 2\,\mathrm{Im}\langle A\,A\rangle_{\mathrm{ret}}(p)$$

Single particle spectral functions

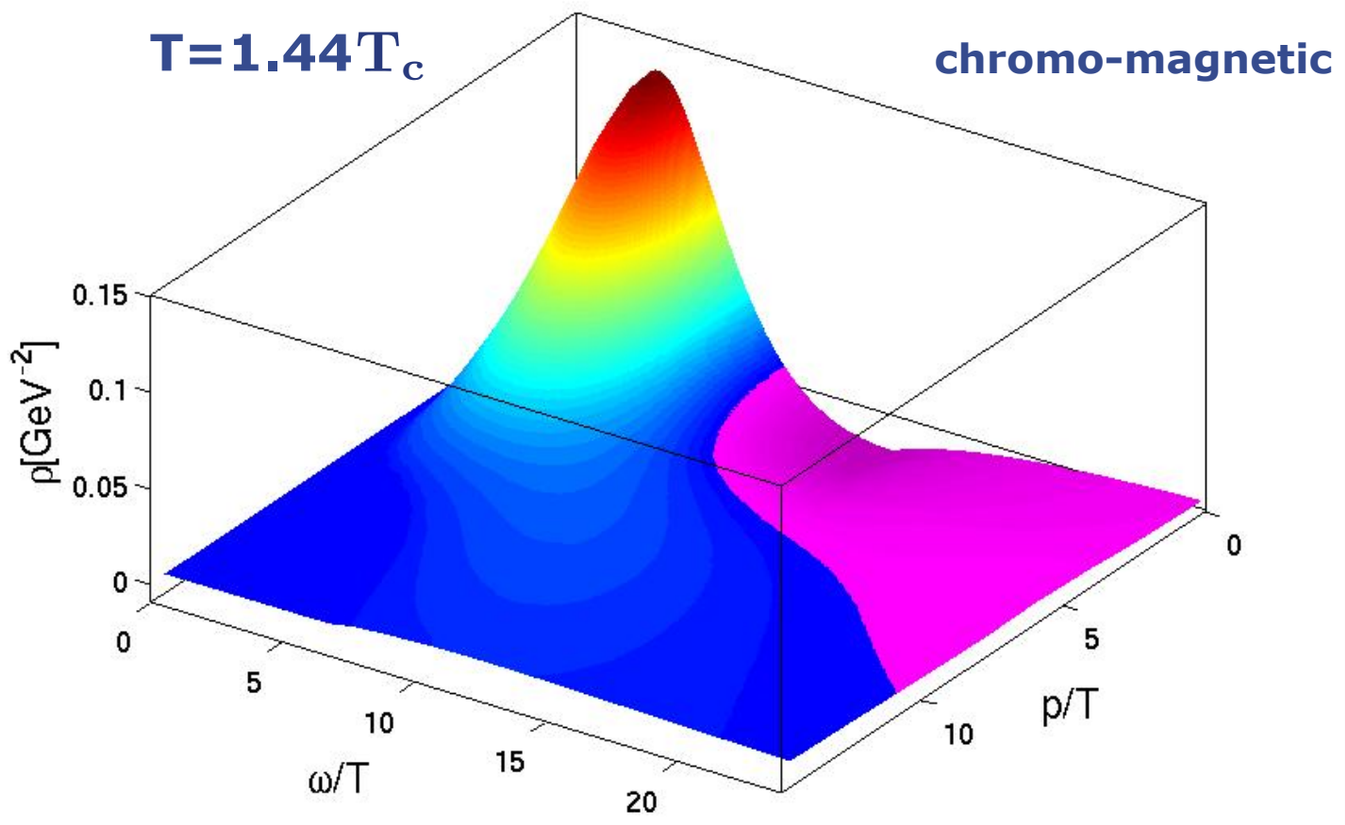


$$\rho(p) = 2\,\mathrm{Im}\langle A\,A\rangle_{\mathrm{ret}}(p)$$

Maximum Entropy Method

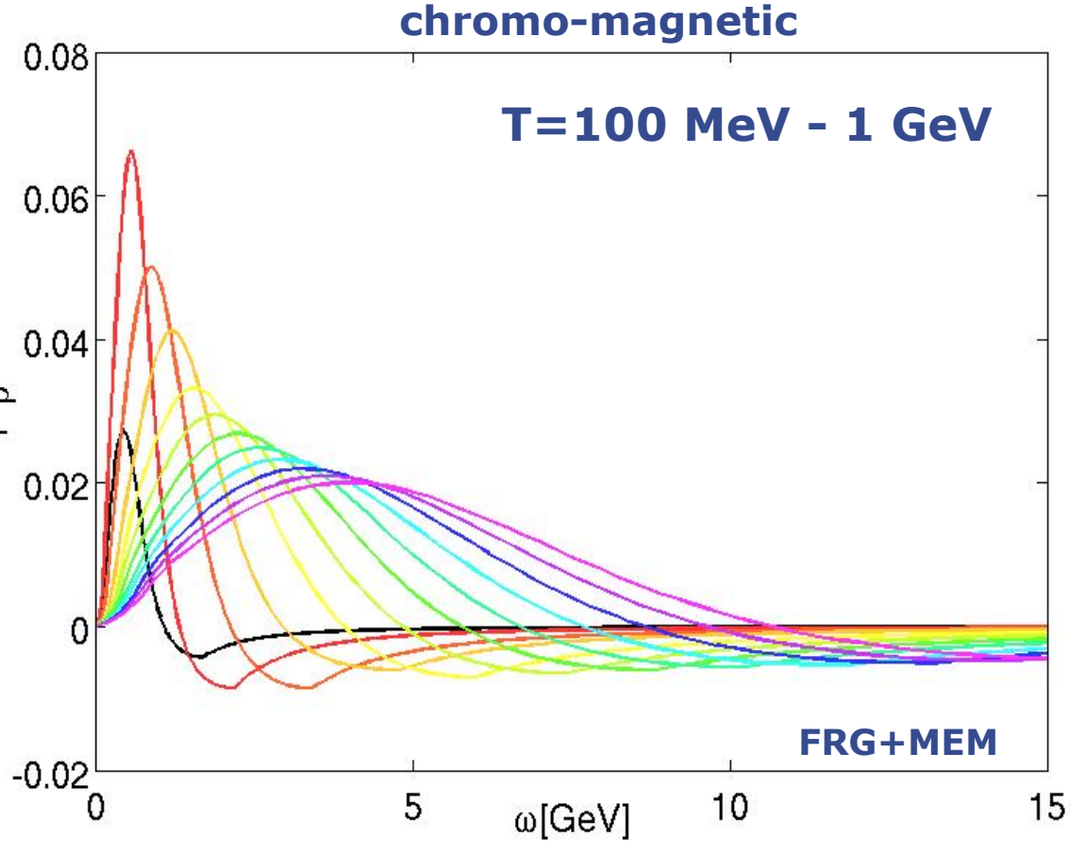


JMP, Rothkopf, work in progress



Haas, Fister, JMP, PRD 90 (2014) 9, 091501

Single particle spectral functions



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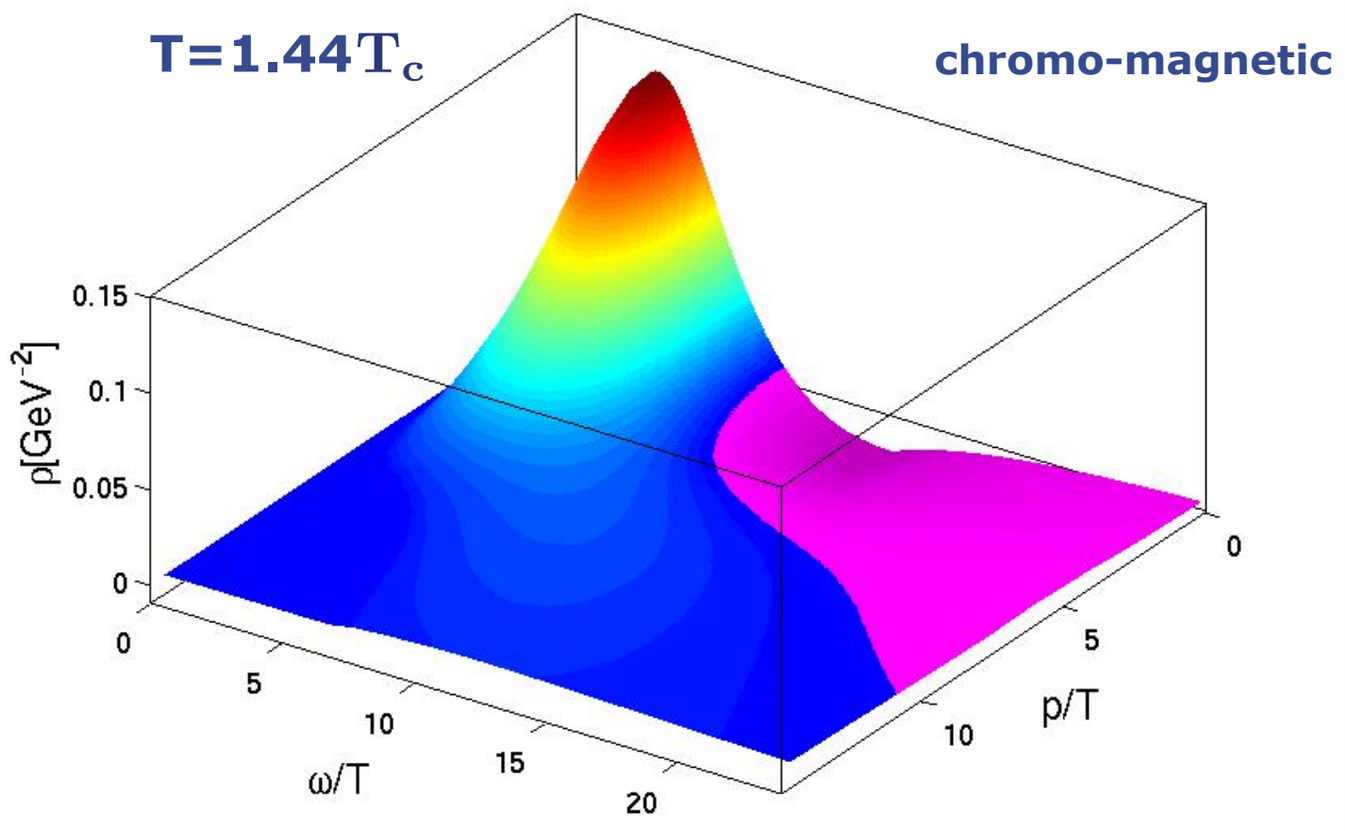


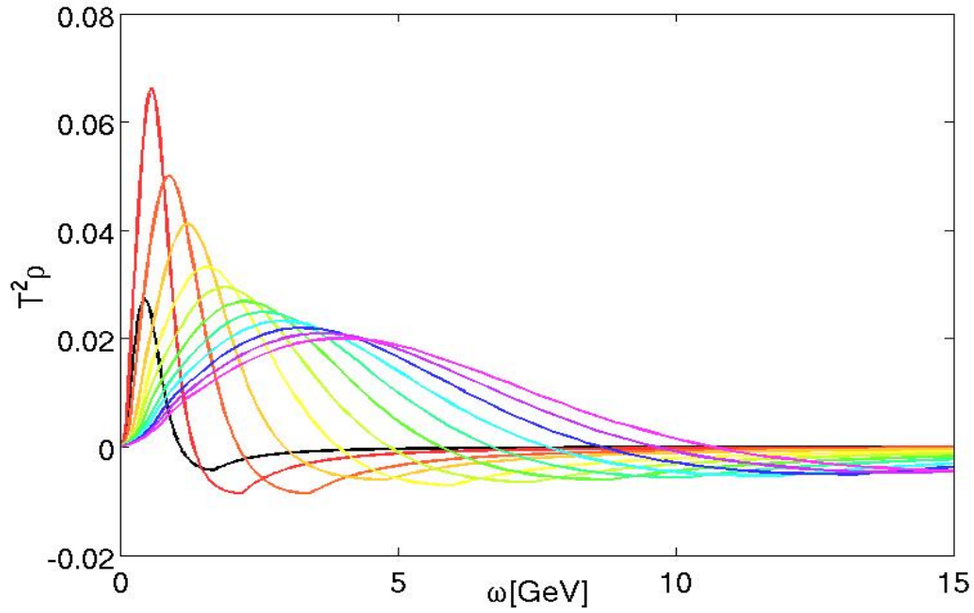
'Those are my methods (principles), and if you don't like them…well, I have others'

direct computation **Groucho Marx**

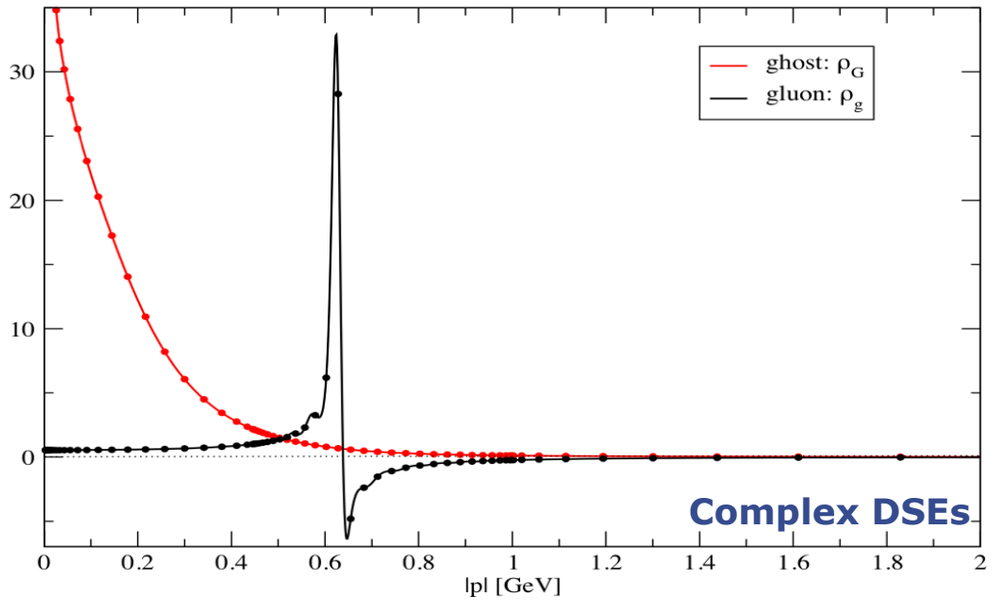
Haas, Fister, JMP, PRD 90 (2014) 9, 091501

Transport

gluon spectral functions

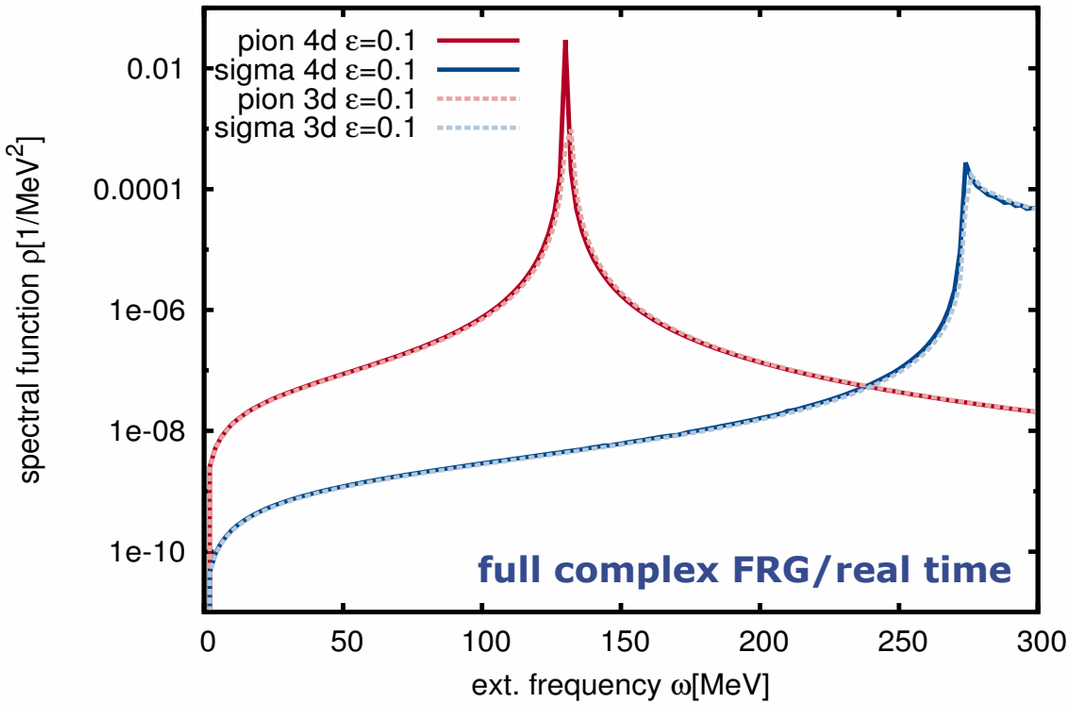


Haas, Fister, JMP, PRD 90 (2014) 9, 091501

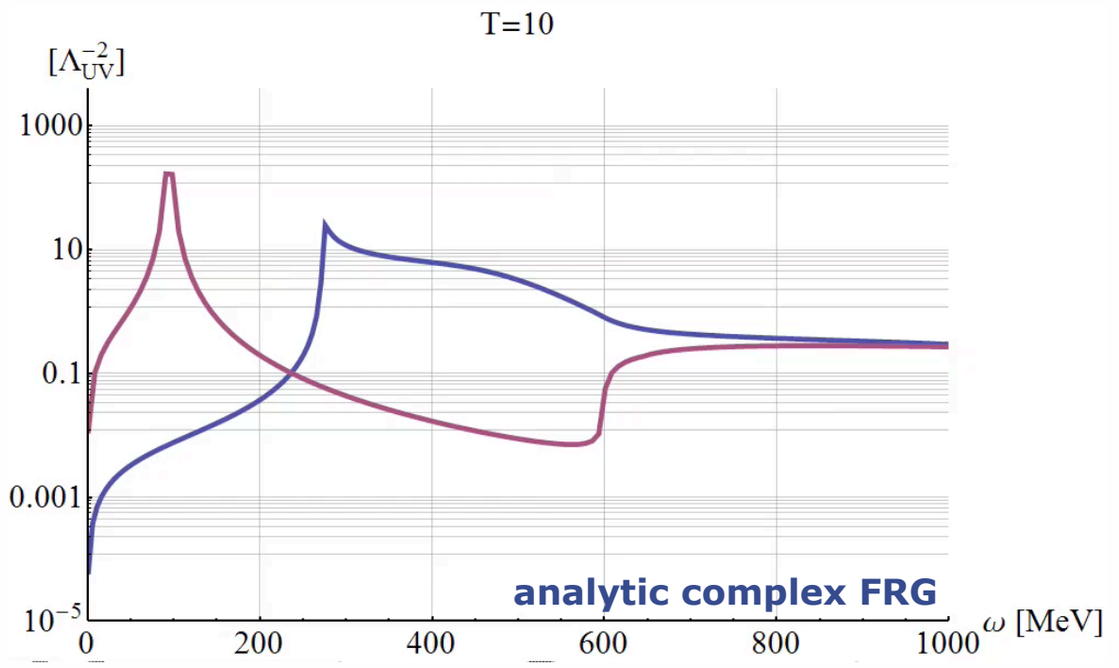


Strauss, Fischer, Kellermann, PRL 109 (2012) 252001

pion and sigma spectral functions



JMP, Strodthoff, PRD 92 (2015) 094009



Tripolt, Strodthoff, von Smekal, Wamach, PRD 89 (2014) 034010
Kamikado, Strodthoff, von Smekal, Wambach, EPJ C74 (2014) 2806

Transport

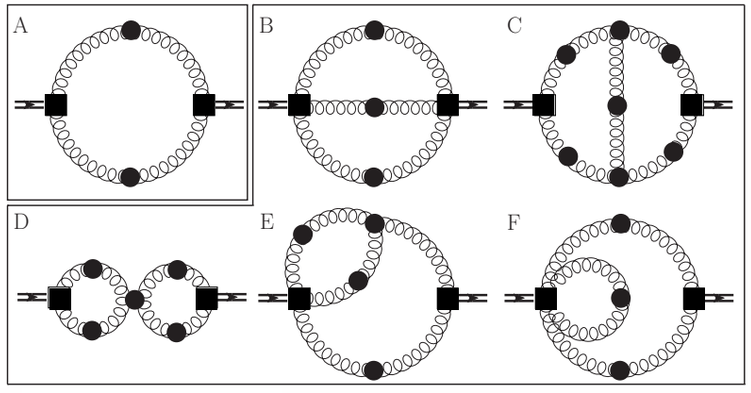
transport coefficients

Kubo relation

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

‘3-loop’ exact functional relation for $\rho_{\pi\pi}$

1 & 2-loop terms



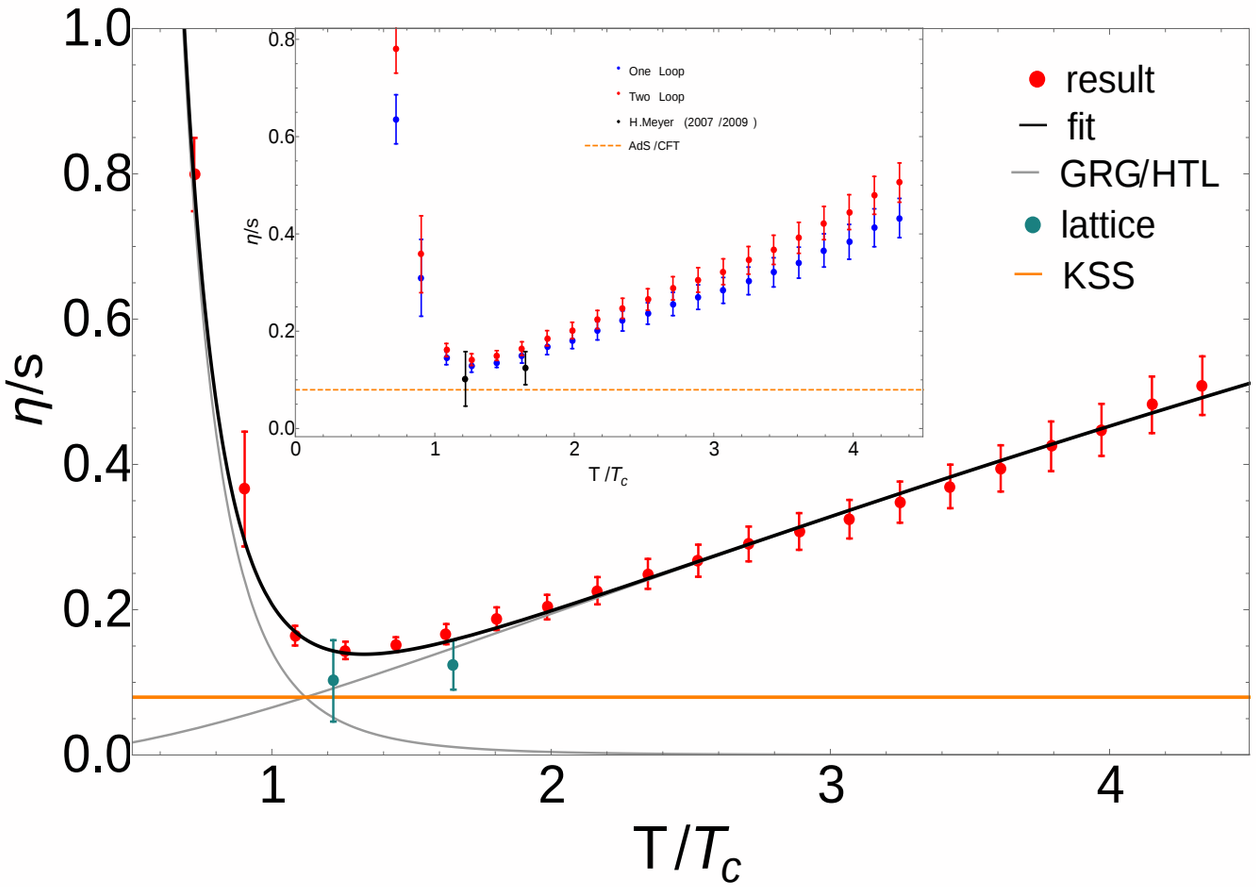
Haas, Fister, JMP, PRD 90 (2014) 9, 091501

Christiansen, Haas, JMP, Strodthoff, PRL 115 (2015) 11, 112002

Transport

transport coefficients

Yang-Mills viscosity over entropy ratio



Aiming at apparent convergence

Kubo relation

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

'3-loop' exact functional relation for $\rho_{\pi\pi}$

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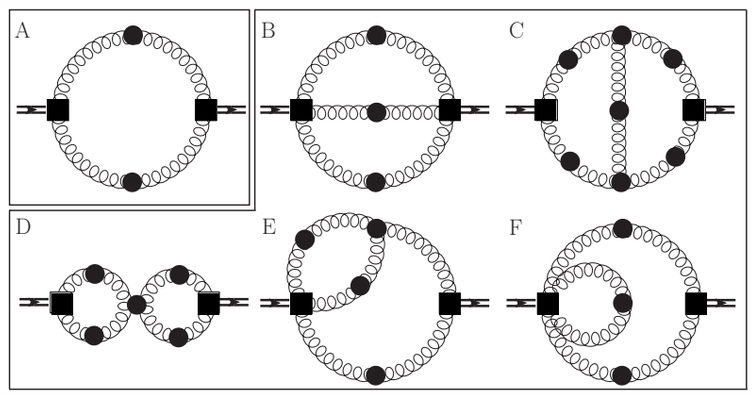


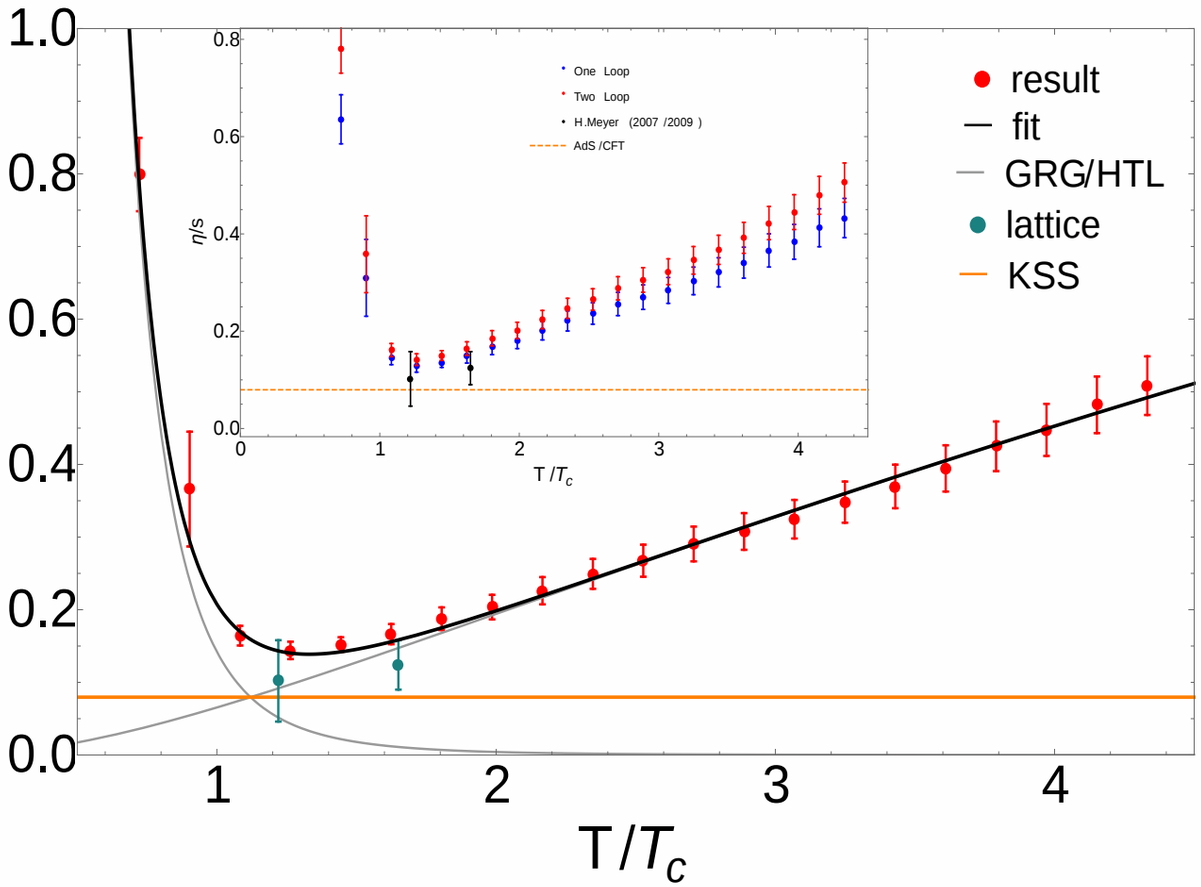
Haas, Fister, JMP, PRD 90 (2014) 9, 091501

Christiansen, Haas, JMP, Strodthoff, PRL 115 (2015) 11, 112002

Transport

QCD - estimate for viscosity over entropy ratio

viscosity over entropy ratio



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

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

pure glue

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

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

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

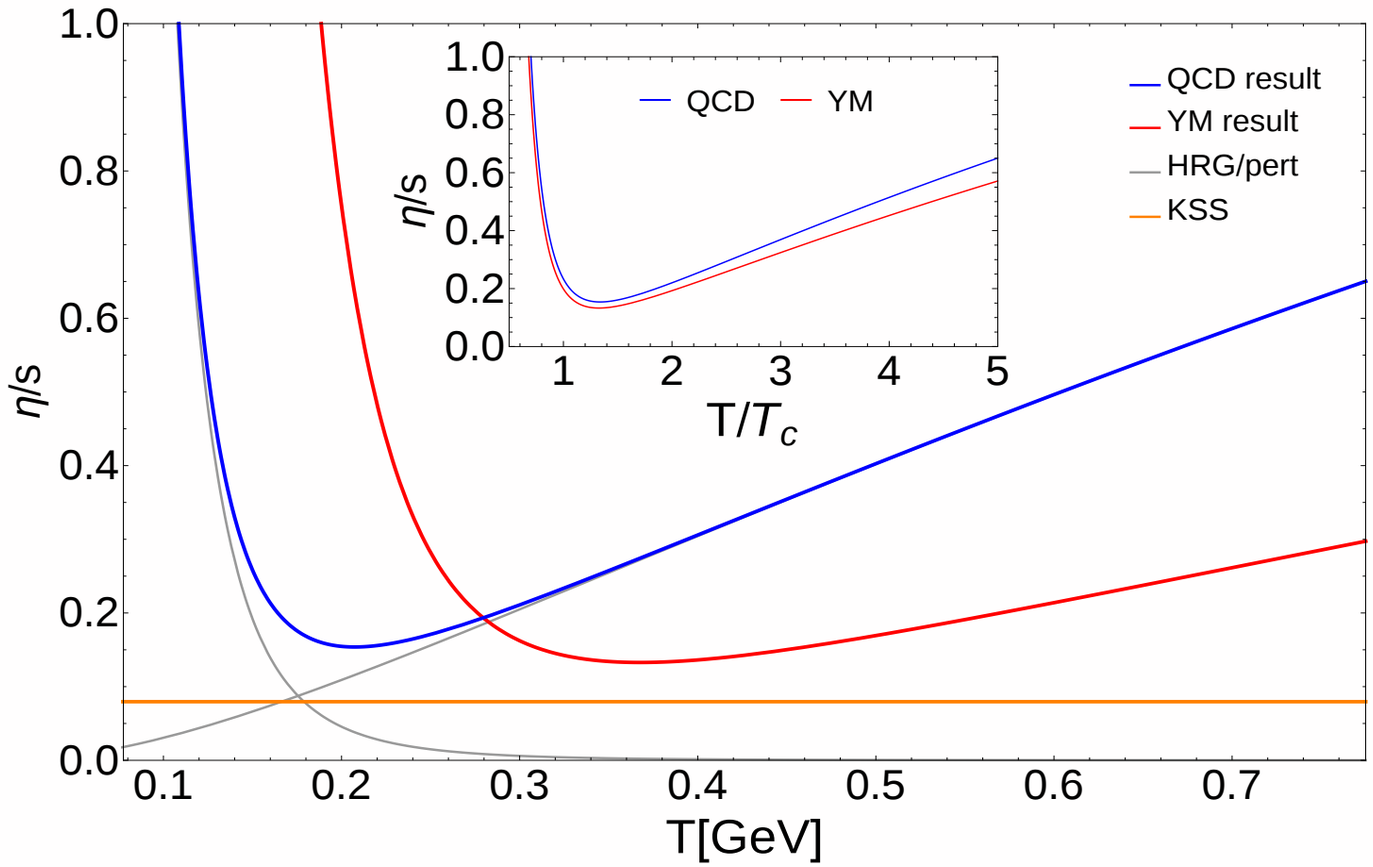
$$c \approx 0.66$$

Christiansen, Haas, JMP, Strodthoff, PRL 115 (2015) 11, 112002

Transport

QCD - estimate for viscosity over entropy ratio

viscosity over entropy ratio



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

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

$$c \approx 0.79$$

QCD

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

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

pure glue

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

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

$$c \approx 0.66$$

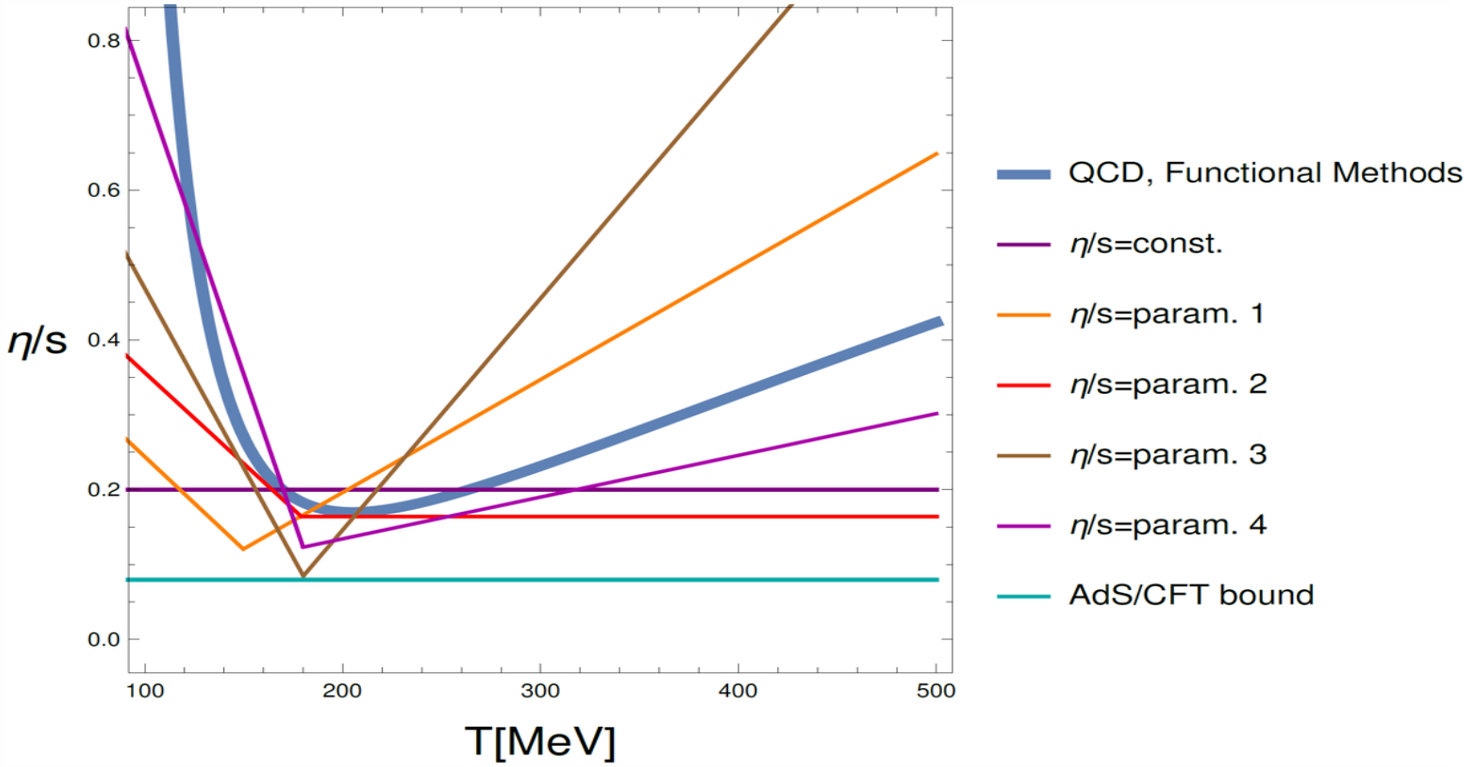
$$\frac{\eta}{s}(T) = \frac{a_{\rm qgp}}{\alpha_s^{\gamma_{\rm qgp}}(cT/T_c)} + \frac{a_{\rm grg}}{(T/T_c)^{\gamma_{\rm grg}}}$$

Christiansen, Haas, JMP, Strodthoff, PRL 115 (2015) 11, 112002

Transport

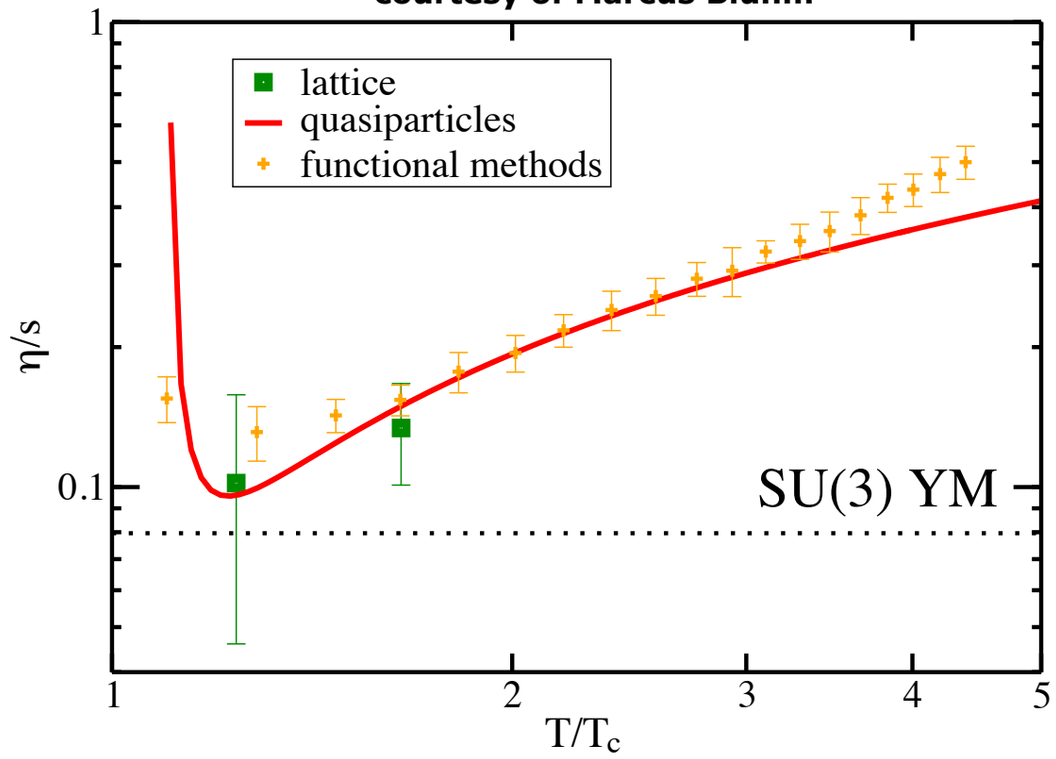
QCD transport & transport models

courtesy of Nicolai Christiansen



Niemi, Eskola, Paateleinen, PRC 93 (2016) 024907

courtesy of Marcus Bluhm

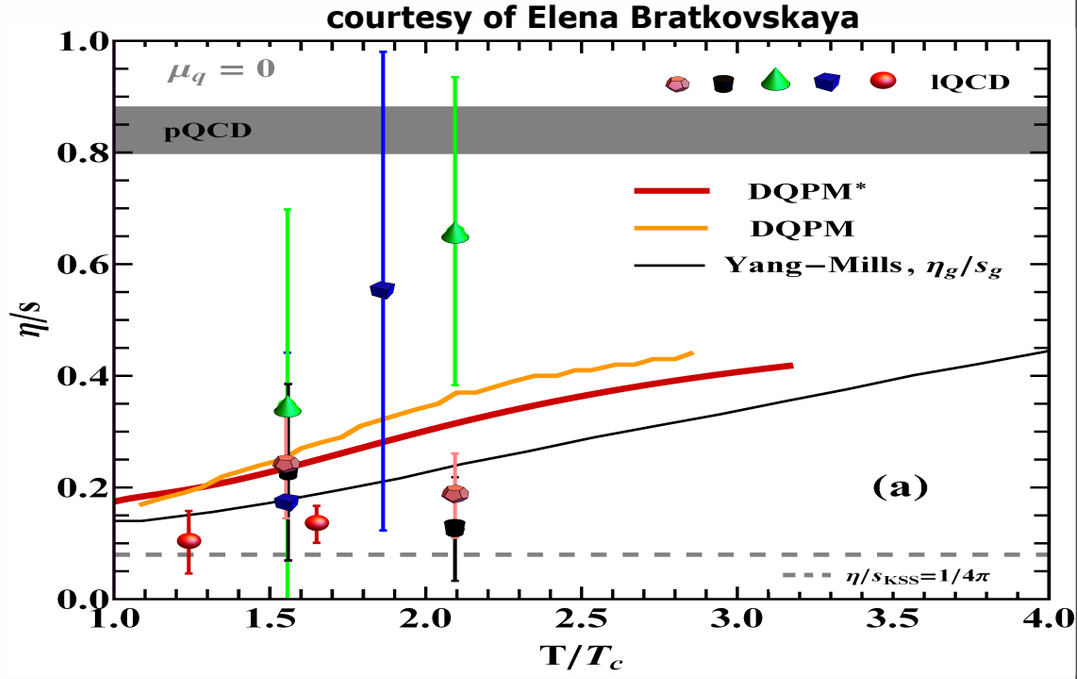


Bluhm, Kaempfer, Redlich, PRC 84 (2011) 025201

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

Christiansen, Haas, JMP, Strodthoff, PRL 115 (2015) 11, 112002

courtesy of Elena Bratkovskaya



Berrehrah, Cassing, Bratkovskaya, Steinert, PRC 93 (2016) 044914

Outline

- Introduction

- Confinement & transport

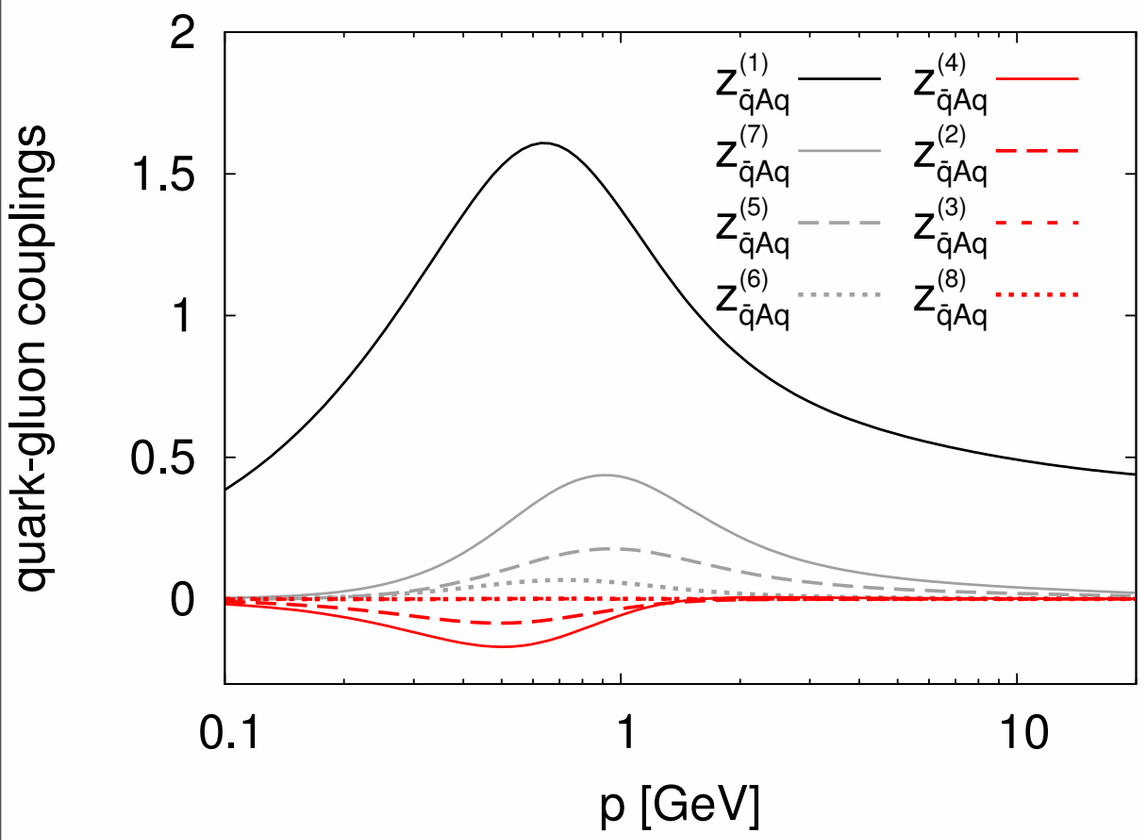
- Chiral symmetry breaking & the phase structure

- Summary & outlook

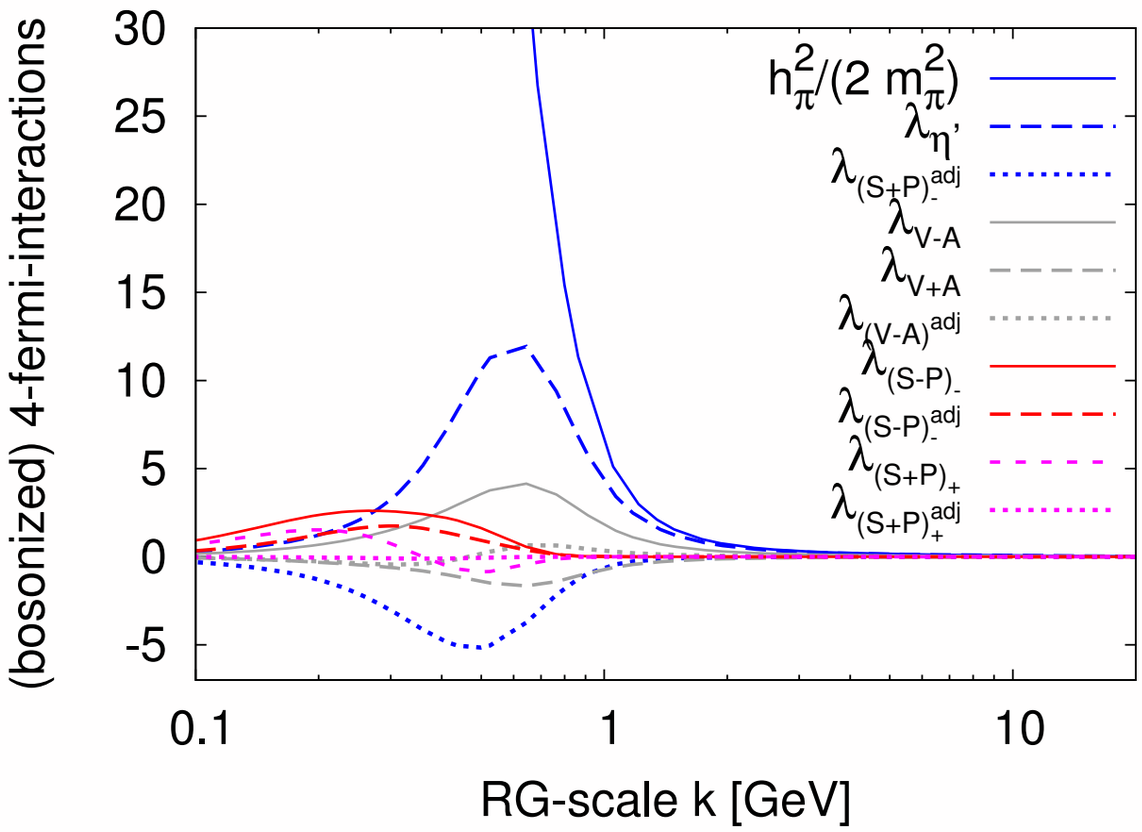
Chiral symmetry breaking

FRG-quenched QCD vs lattice-quenced QCD

quark-gluon vertex



four-fermi vertex



see also **Williams, Eur.Phys.J. A51 (2015) 5, 57**
Williams, Fischer, Heupel, PRD 93 (2016) 034026

$$\mathbf{N_f = 2}$$

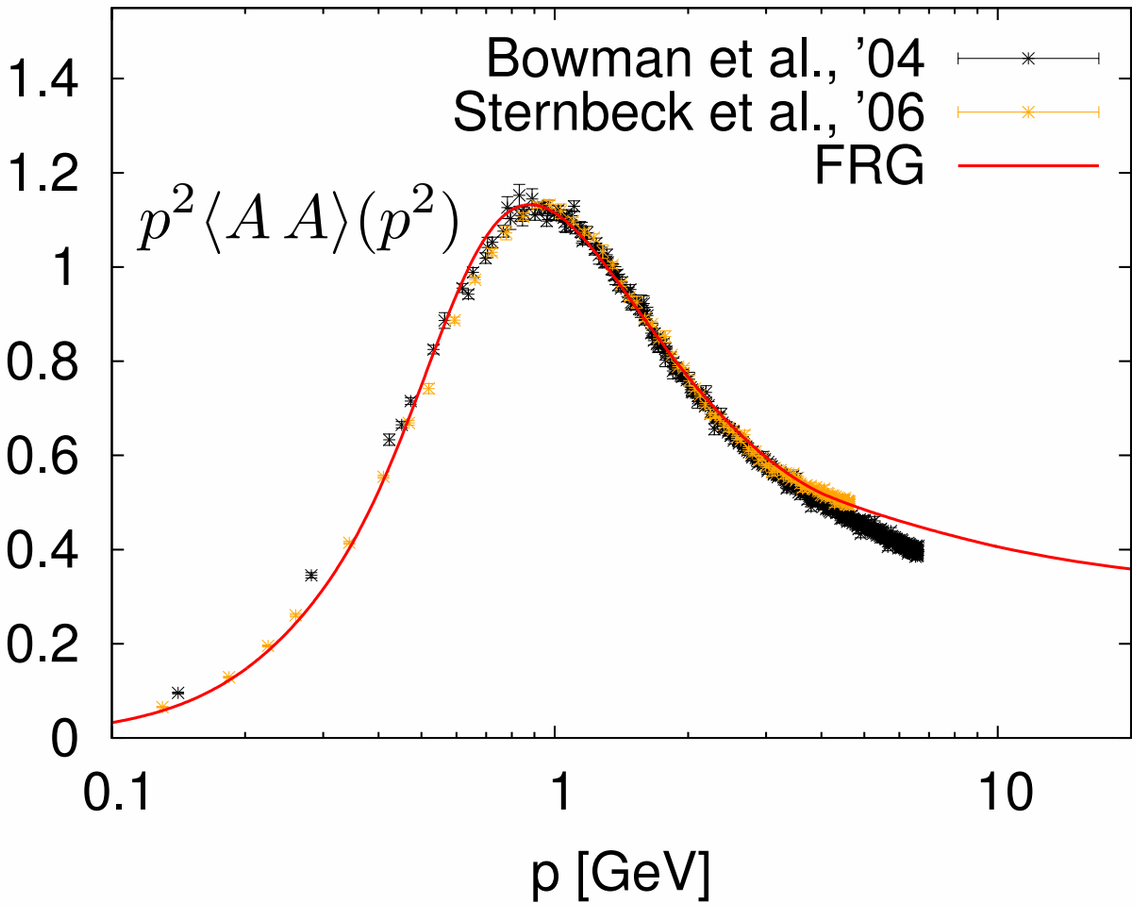
rapid convergence in covariant expansion scheme

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

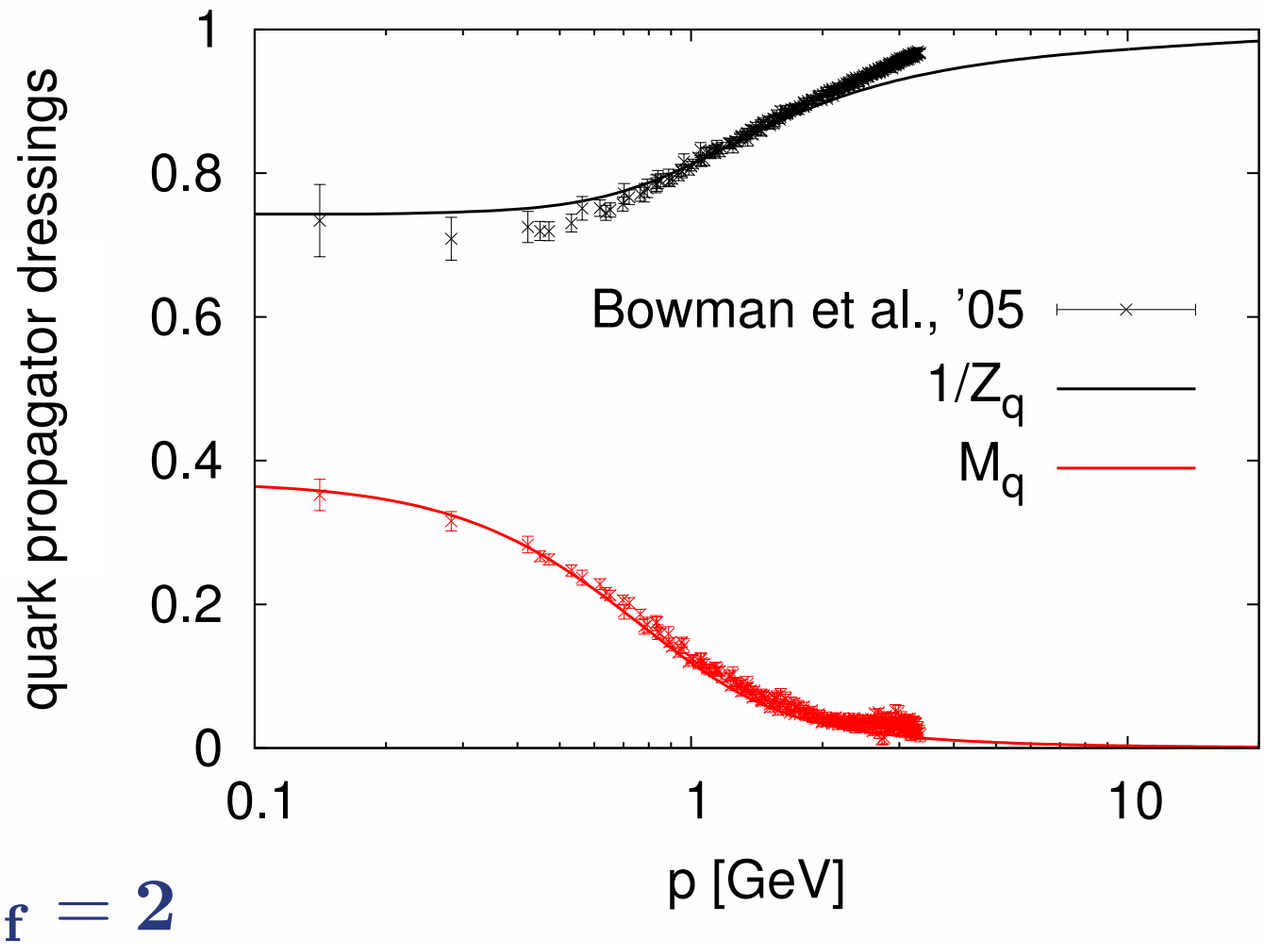
Chiral symmetry breaking

FRG-quenched QCD vs lattice-quenced QCD

quenched gluon dressing



quark propagator



$\mathbf{N_f = 2}$

rapid convergence in covariant expansion scheme

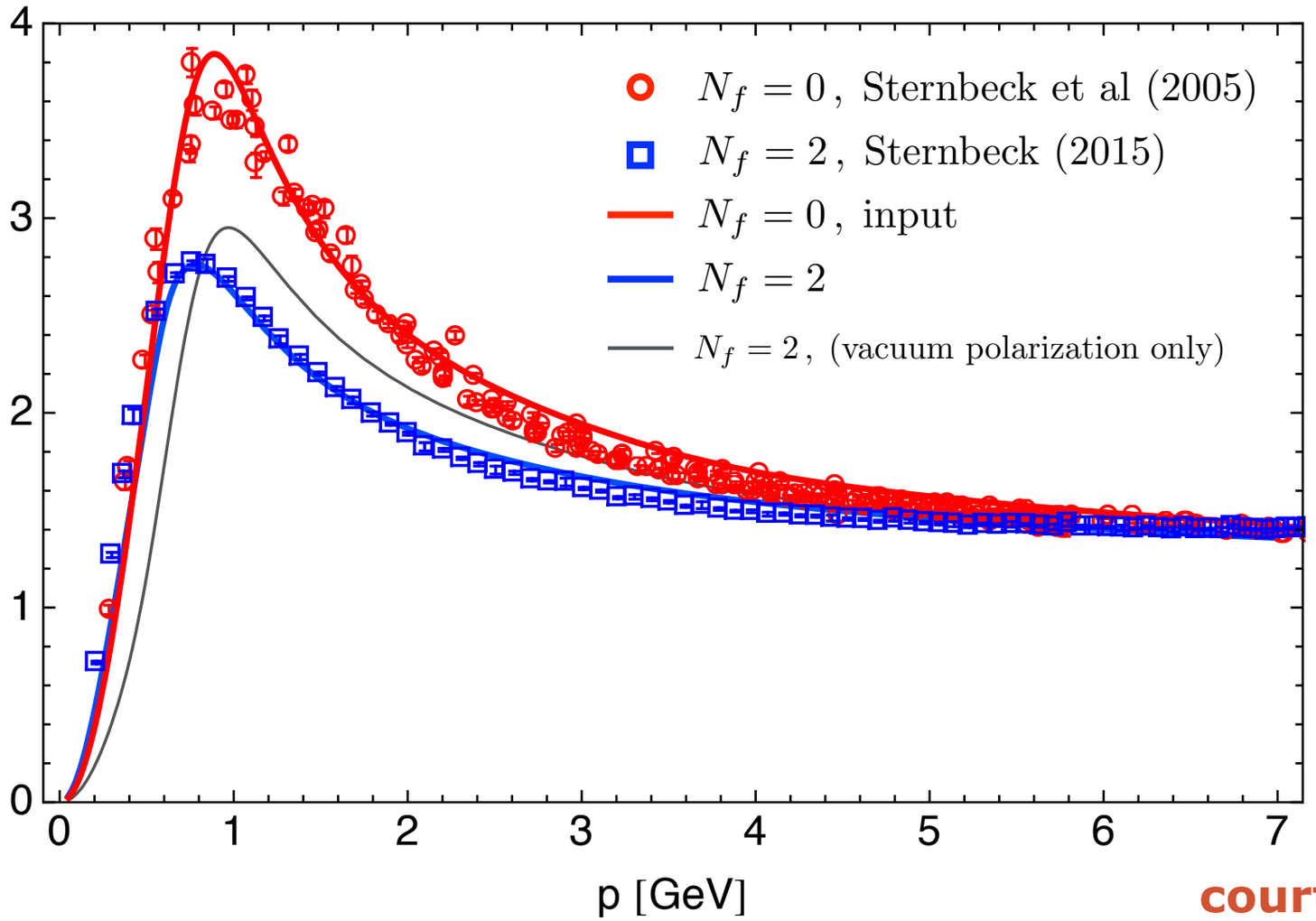
Mitter, JMP, Strodthoff, PRD 91 (2015) 054035

Chiral symmetry breaking

FRG-unquenched QCD vs lattice-unquenced QCD

unquenched gluon dressing

$p^2\langle A\,A\rangle(p^2)$



courtesy of F. Rennecke

$\mathbf{N_f = 2}$

Braun, Fister, Haas, JMP, Rennecke, arXiv:1412.1045

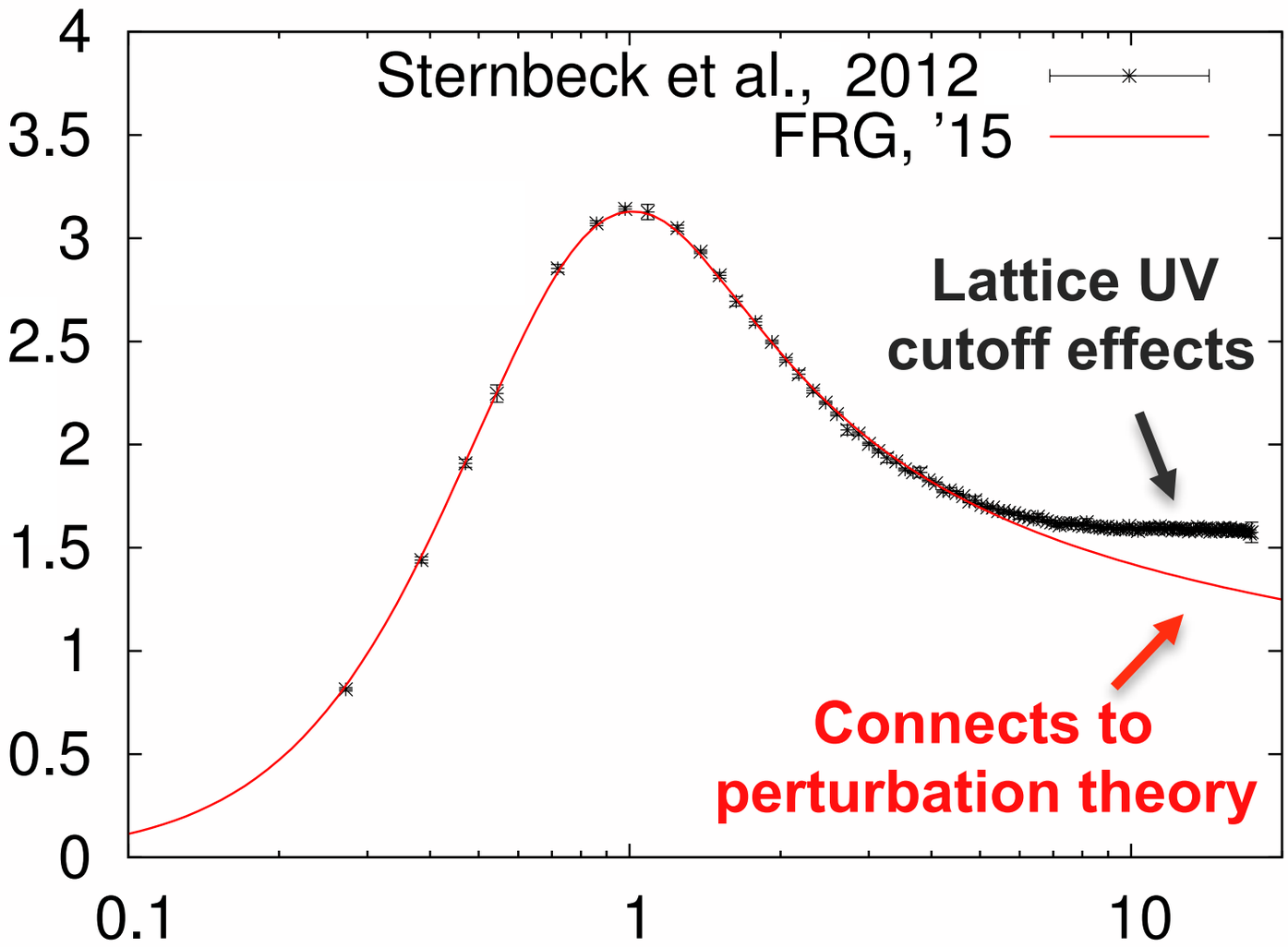
Rennecke, Phys.Rev. D92 (2015) 7, 076012

Chiral symmetry breaking

FRG-unquenched QCD vs lattice-unquenced QCD

unquenched gluon dressing

$p^2\langle A\,A\rangle(p^2)$

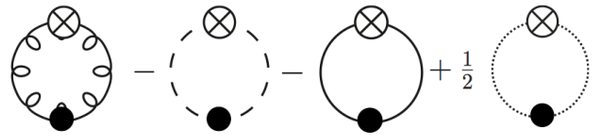


$\mathbf{N_f = 2}$

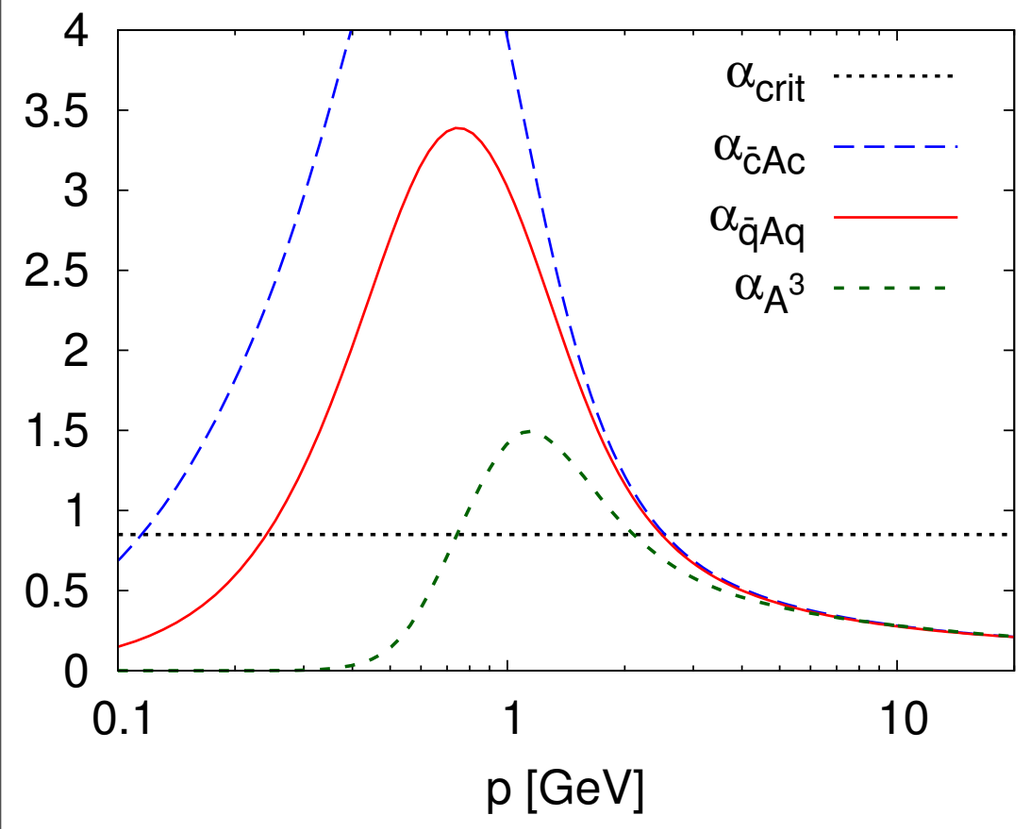
Aiming at apparent convergence

Cyrol, Mitter, JMP, Strodthoff, in prep.

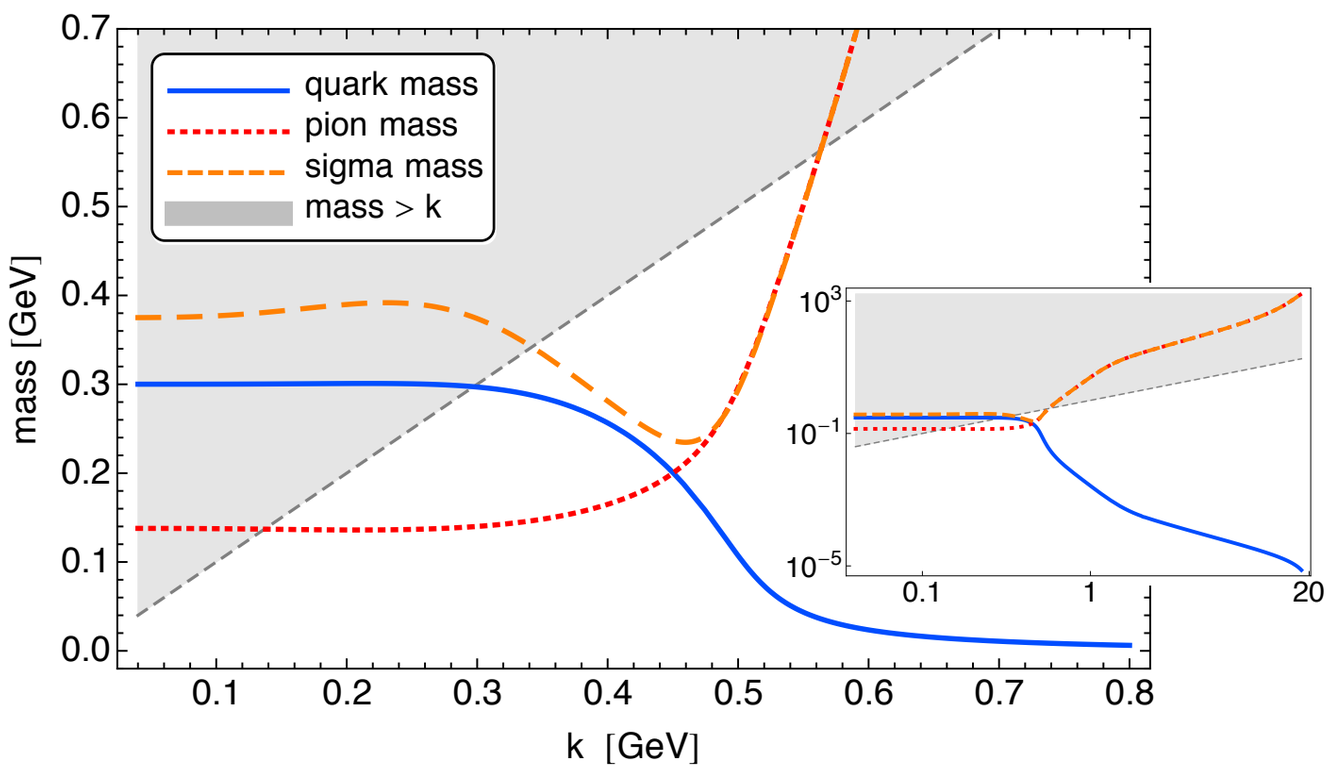
QCD

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

Sequential decoupling of gluon, quark, sigma, pion fluctuations



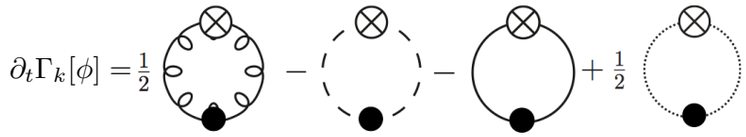
Mitter, JMP, Strodthoff, PRD 91 (2015) 054035



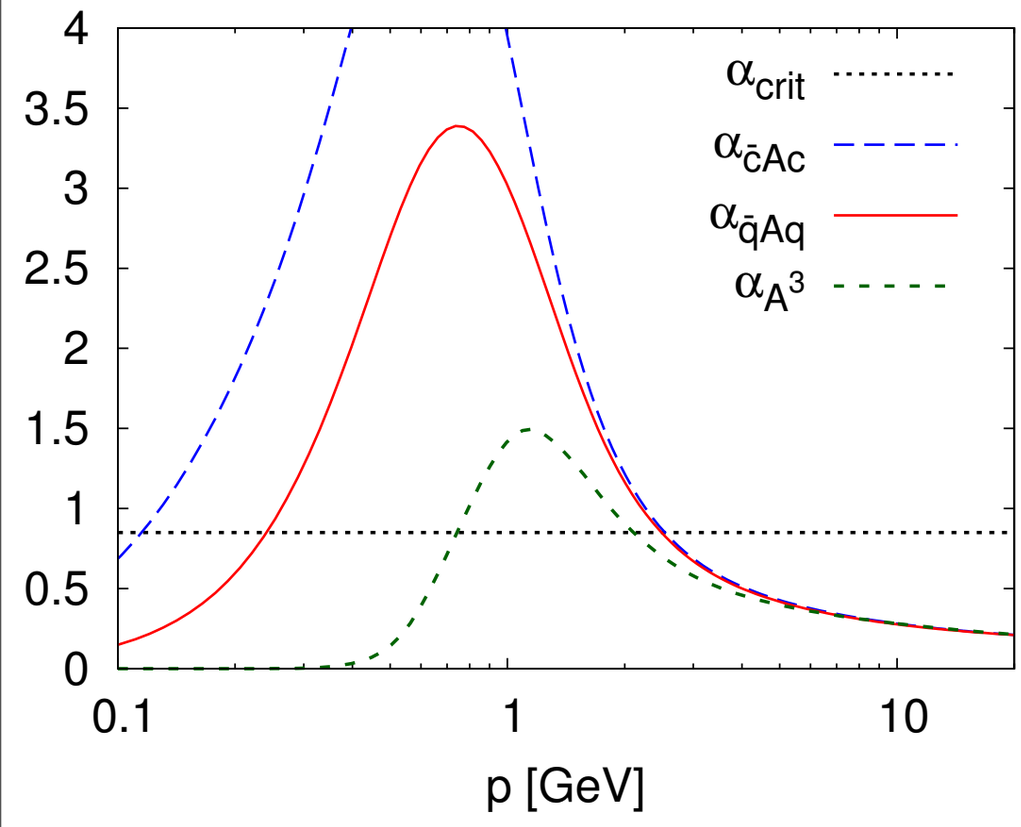
Braun, Fister, Haas, JMP, Rennecke, arXiv:1412.1045

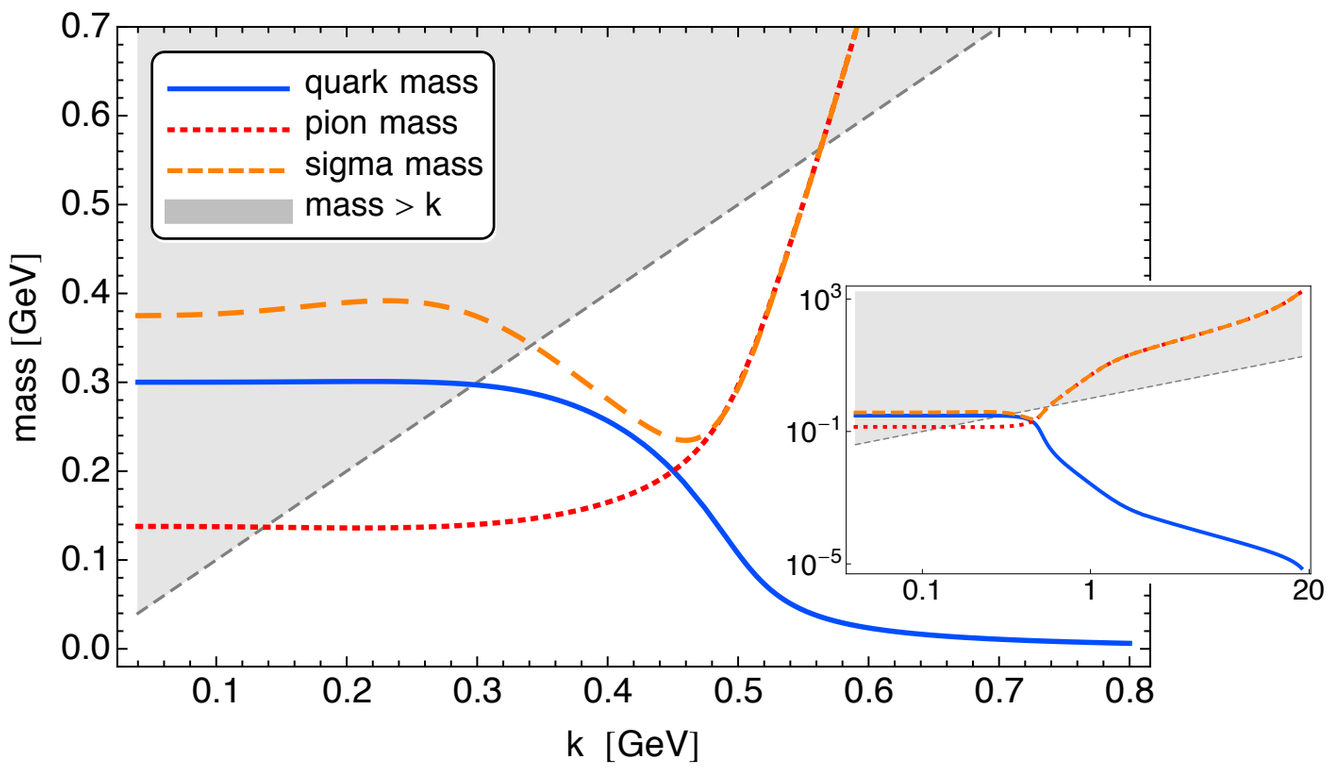
Rennecke, Phys.Rev. D92 (2015) 7, 076012

QCD

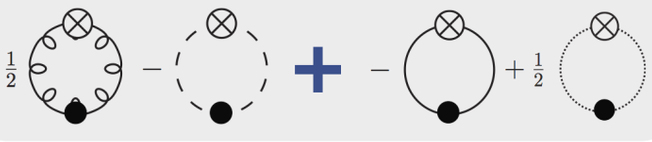


Sequential decoupling of gluon, quark, sigma, pion fluctuations

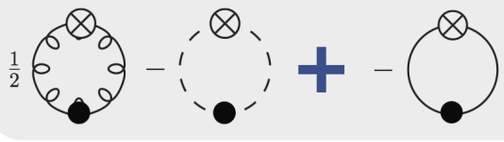




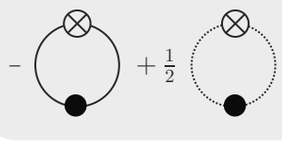
PQM-model



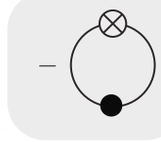
PNJL-model



QM-model

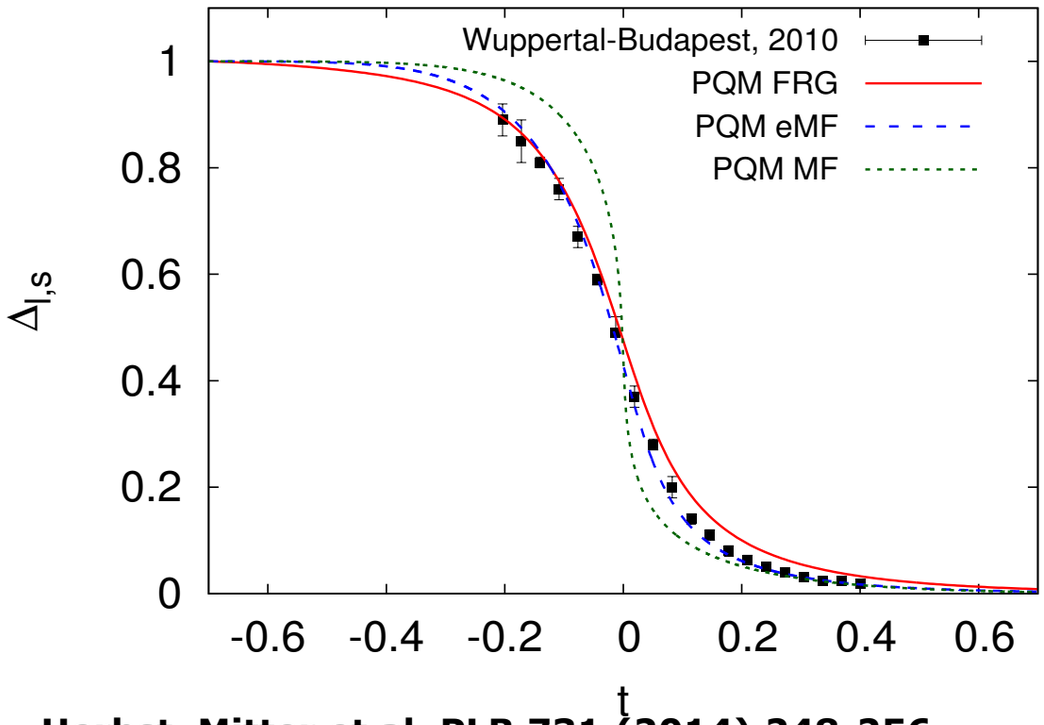


NJL-model



Thermodynamics and condensates

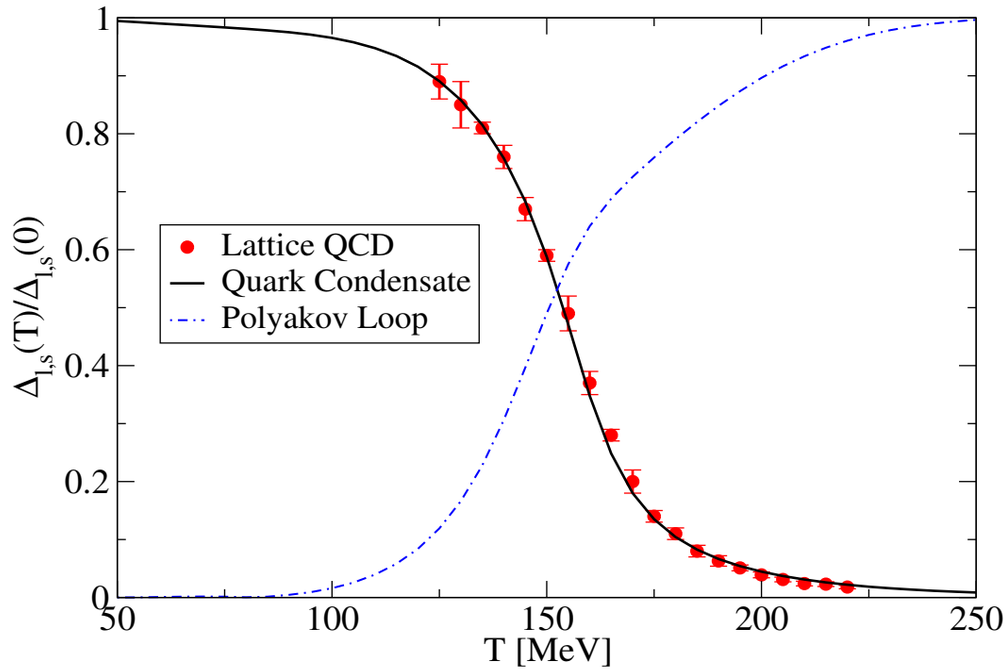
2+1 flavor QCD - enhanced PQM-model



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

2+1 flavor DSE

reduced chiral condensate



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

Fischer, Fister, Luecker, JMP, PLB 732 (2014) 273-277

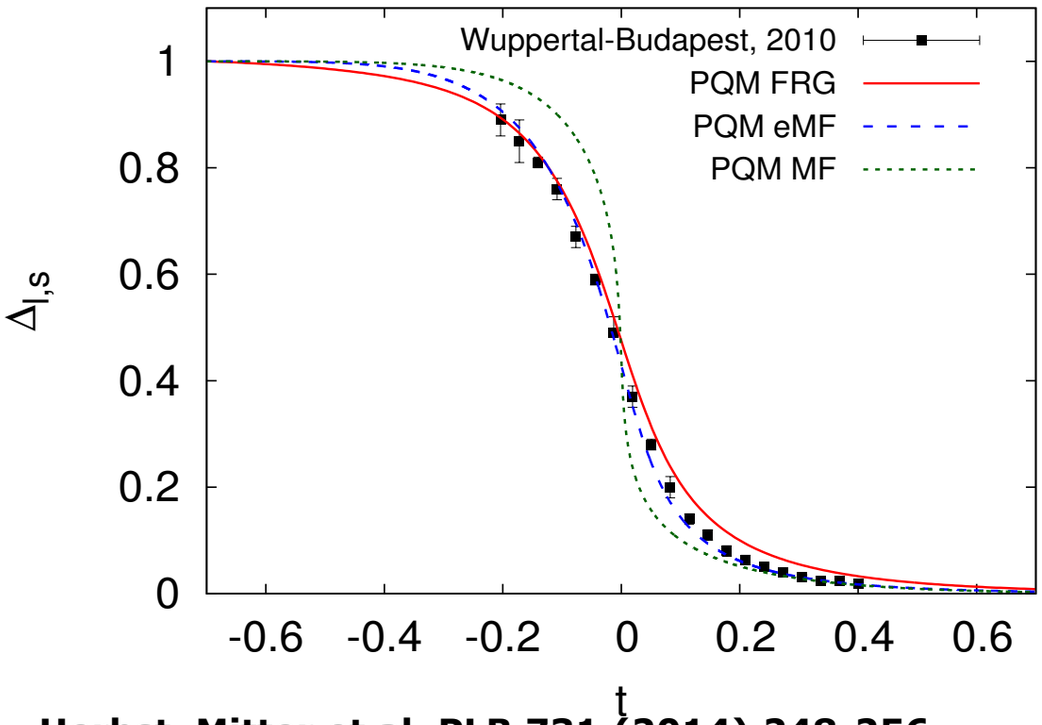
Glue potential from QCD-computation with FRG

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

Approximations of infrared dynamics involved

Thermodynamics and condensates

2+1 flavor QCD - enhanced PQM-model



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

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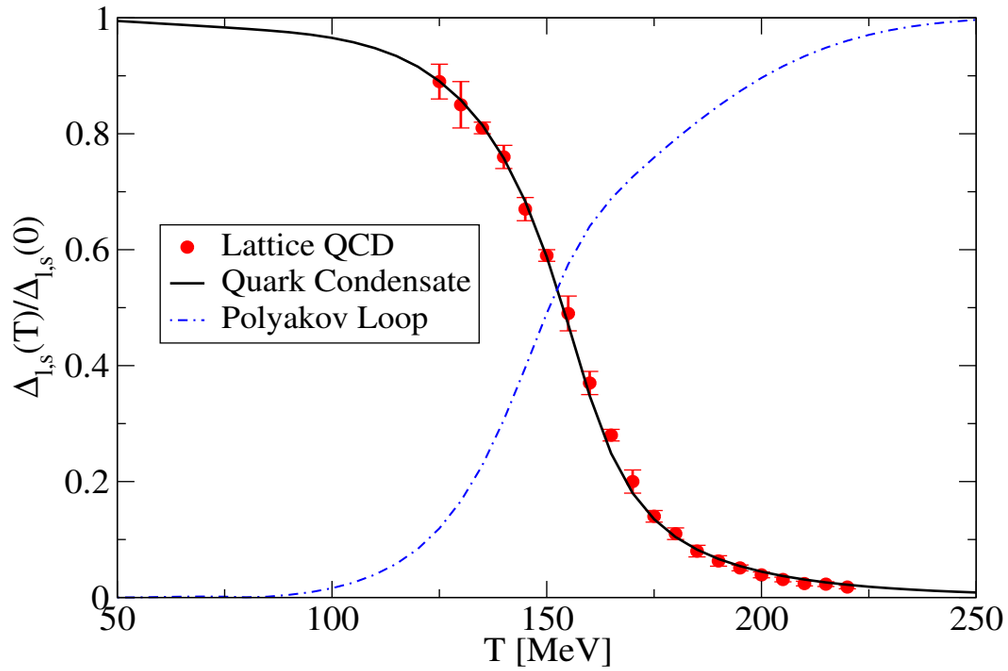
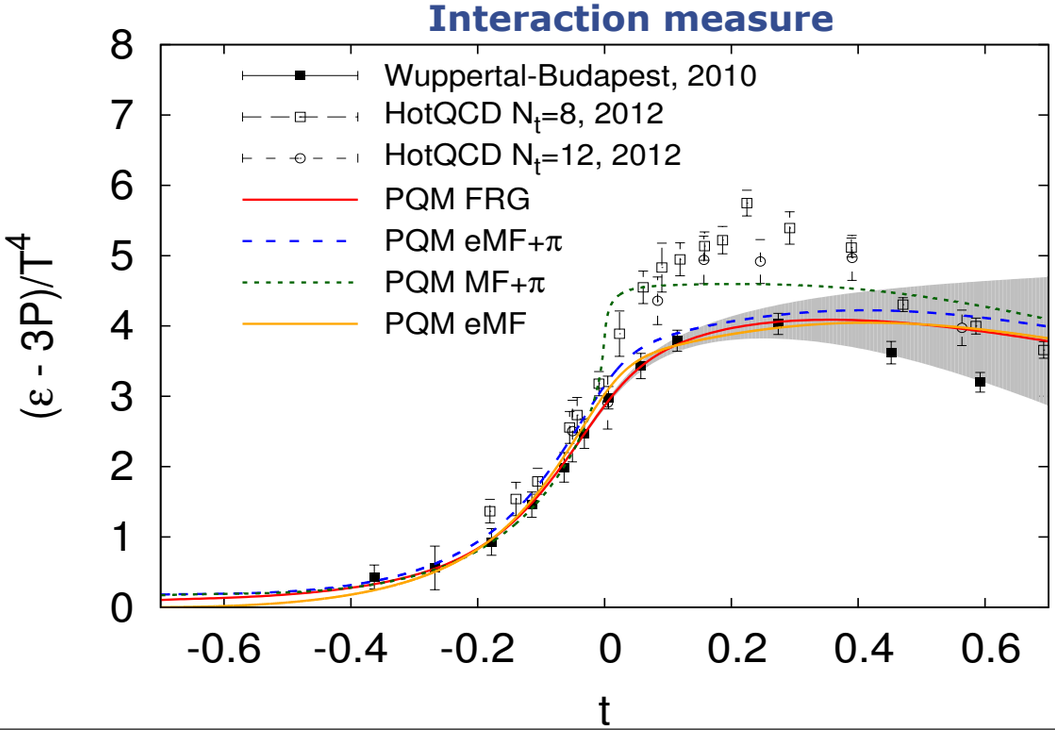


Fischer, Luecker, Welzbacher, PRD 90 (2014), 034022

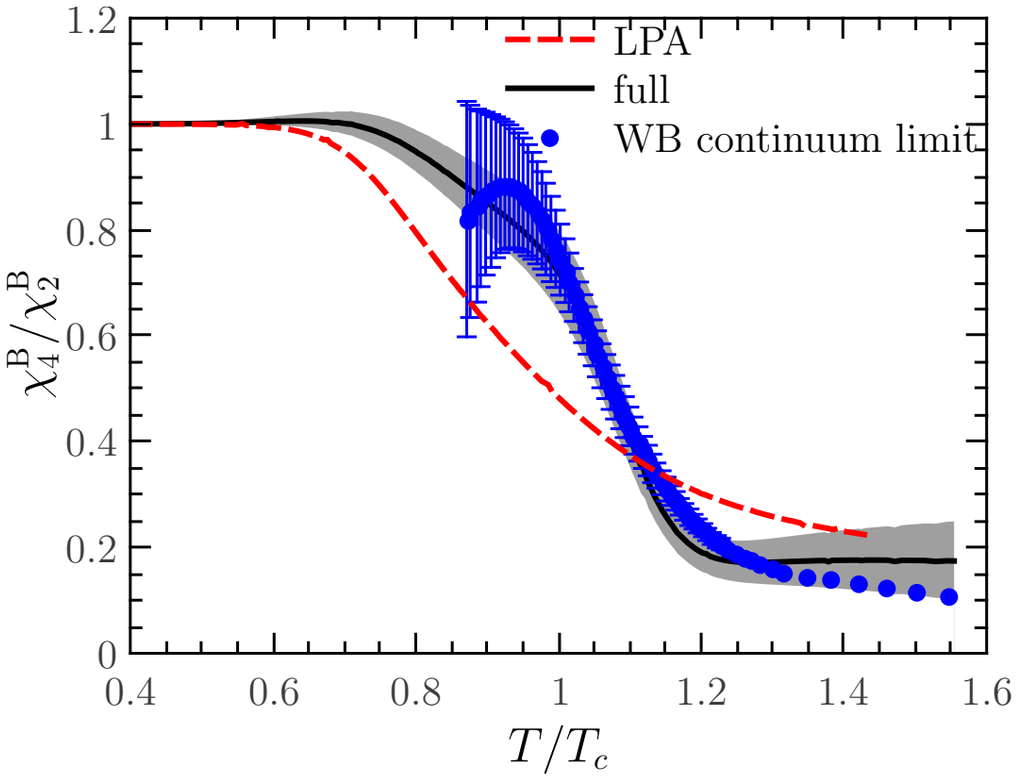
Fischer, Fister, Luecker, JMP, PLB 732 (2014) 273-277

Interaction measure



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

Fluctuations as a measure of confinement



Fu, JMP, PRD 92 (2015) 11, 116006

$$\chi_n^{\rm B} = \frac{\partial^n}{\partial(\mu_{\rm B}/T)^n}\frac{p}{T^4}$$

Skewness, Kurtosis

$$\sigma^2 = VT^3\chi_2^{\rm B} \qquad S = \frac{\chi_3^{\rm B}}{\chi_2^{\rm B}\sigma} \qquad \kappa = \frac{\chi_4^{\rm B}}{\chi_2^{\rm B}\sigma^2}$$

Karsch, Schaefer, Wagner, Wambach, PLB 698 (2011) 256

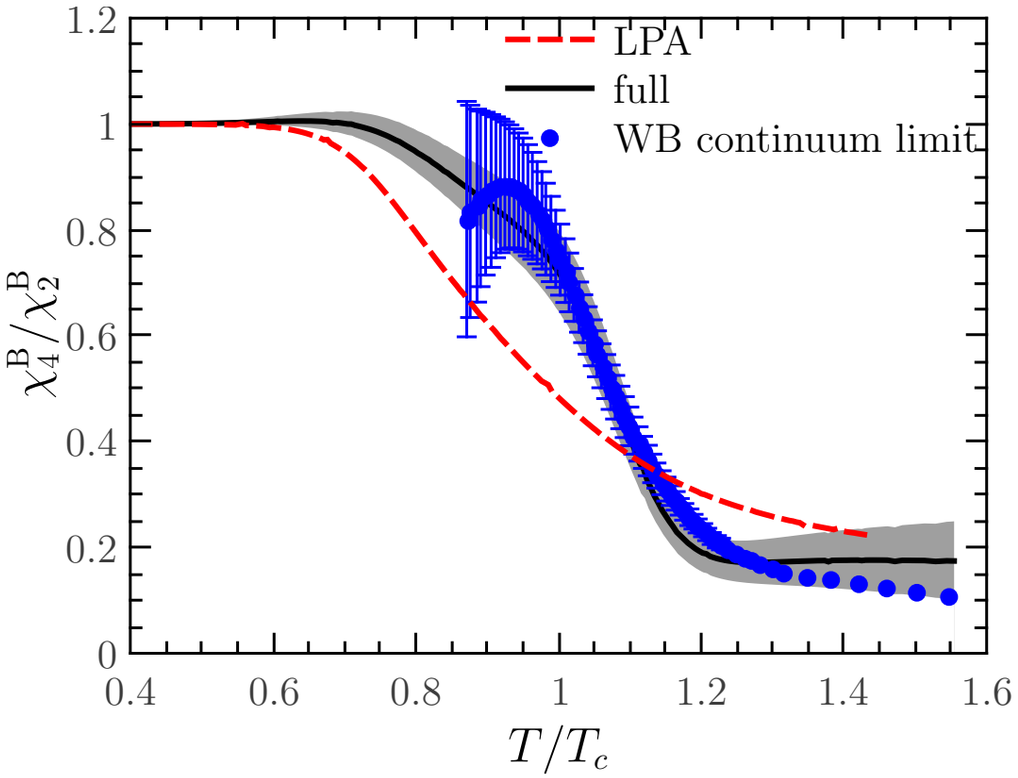
Friman, Karsch, Redlich, Skokov, EPJ C71 (2011) 1694

Schaefer, Wagner, PRD 85 (2012) 034027

Skokov, Friman, Redlich, PRC 88 (2013) 034911

Almasi, Friman, Redlich, arXiv:1601.0078

Fluctuations as a measure of confinement



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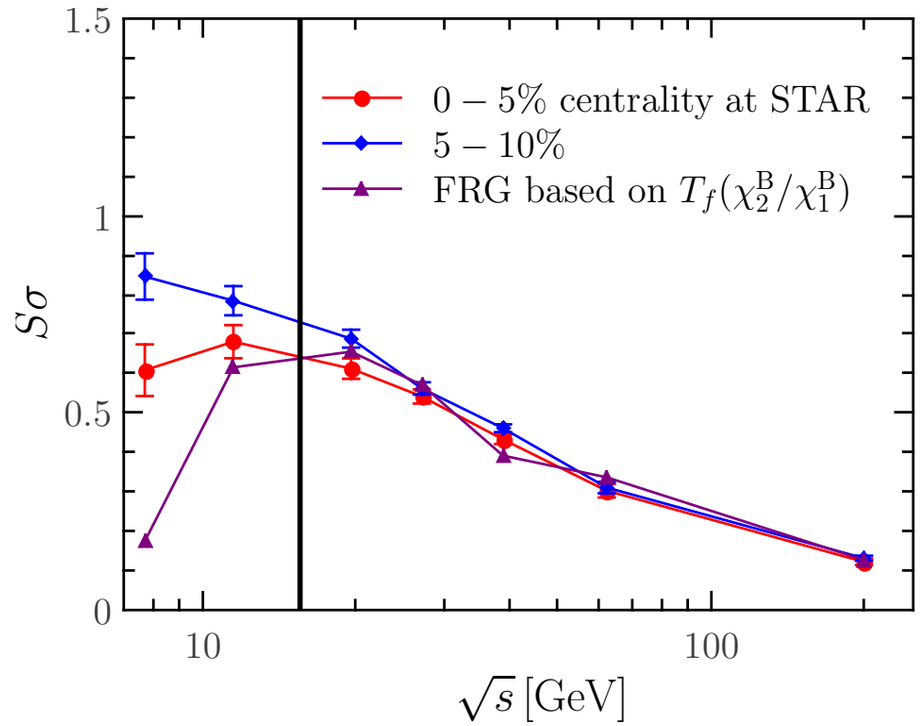
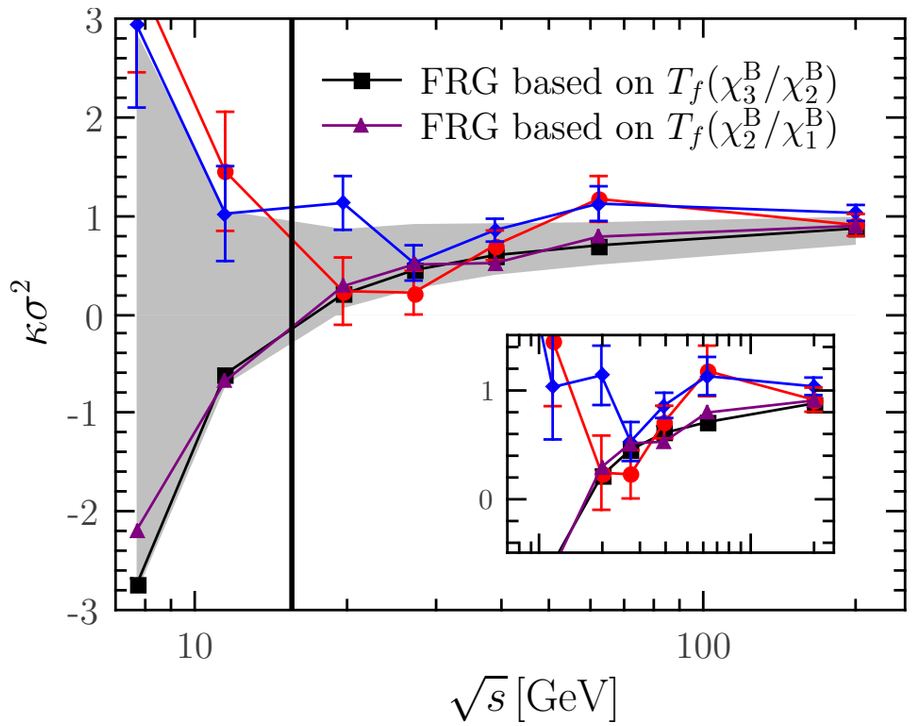
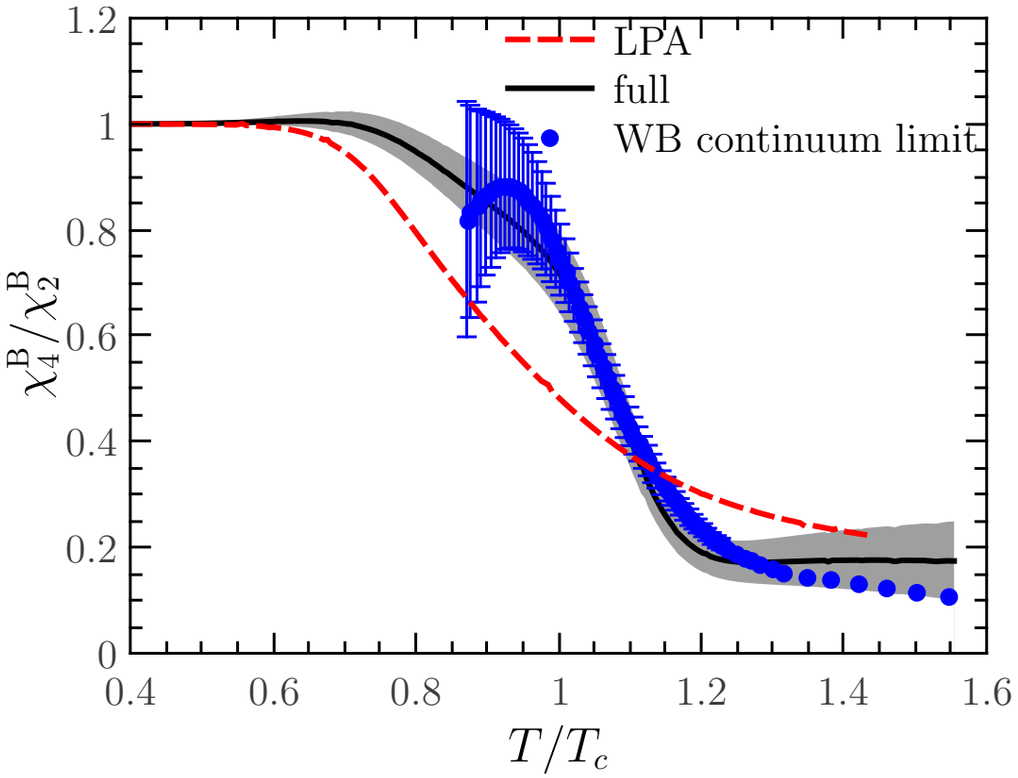




Fu, JMP, arXiv:1512.08461

Fluctuations as a measure of confinement



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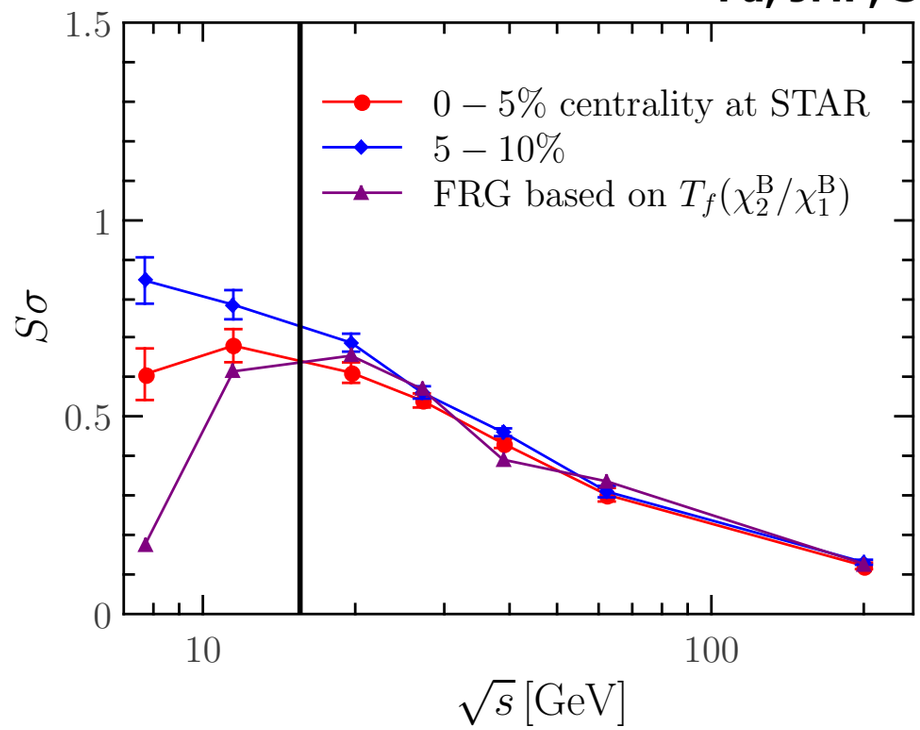
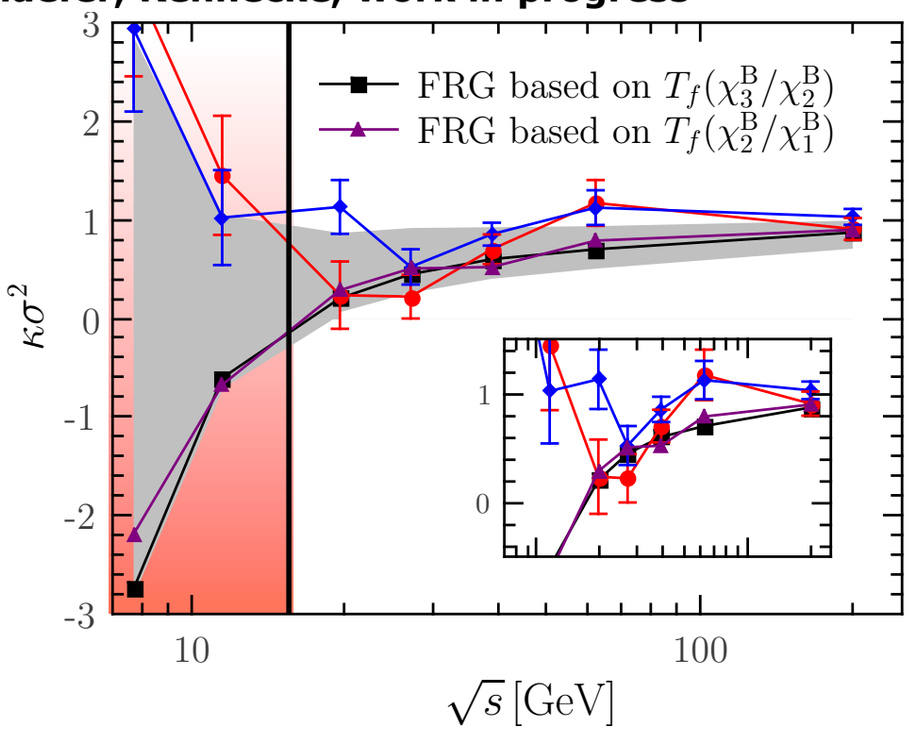
Fu, JMP, PRD 92 (2015) 11, 116006

Fu, JMP, Schaefer, Rennecke, work in progress

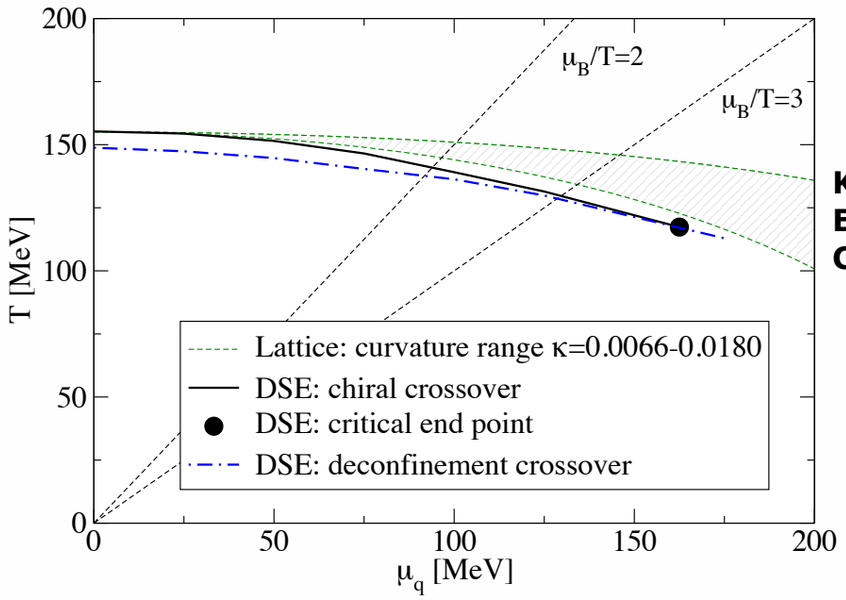




Fu, JMP, arXiv:1512.08461

Phase structure at finite density

Phase diagram of 2+1 flavor QCD



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

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

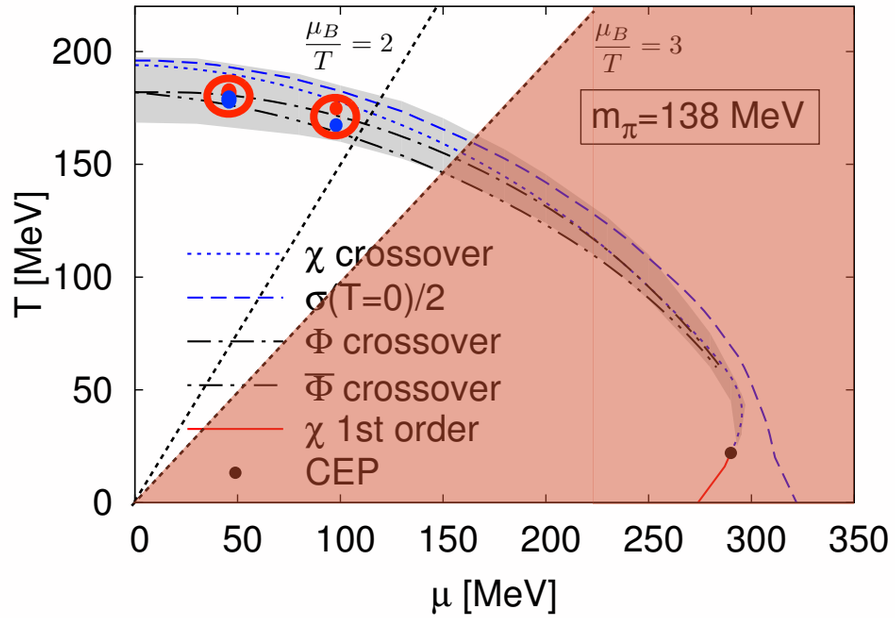
Fischer, Luecker, Welzbacher, PRD 90 (2014) 034022

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

Phase structure at finite density

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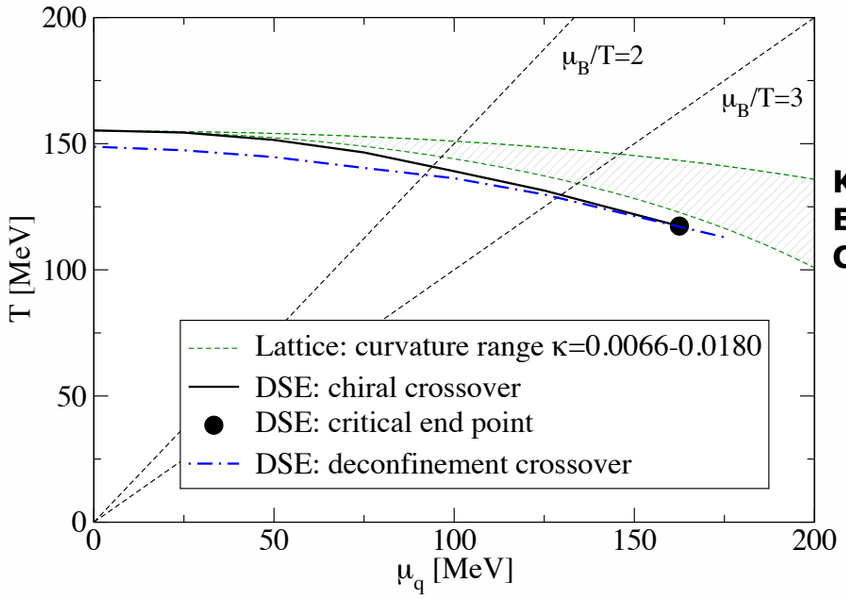

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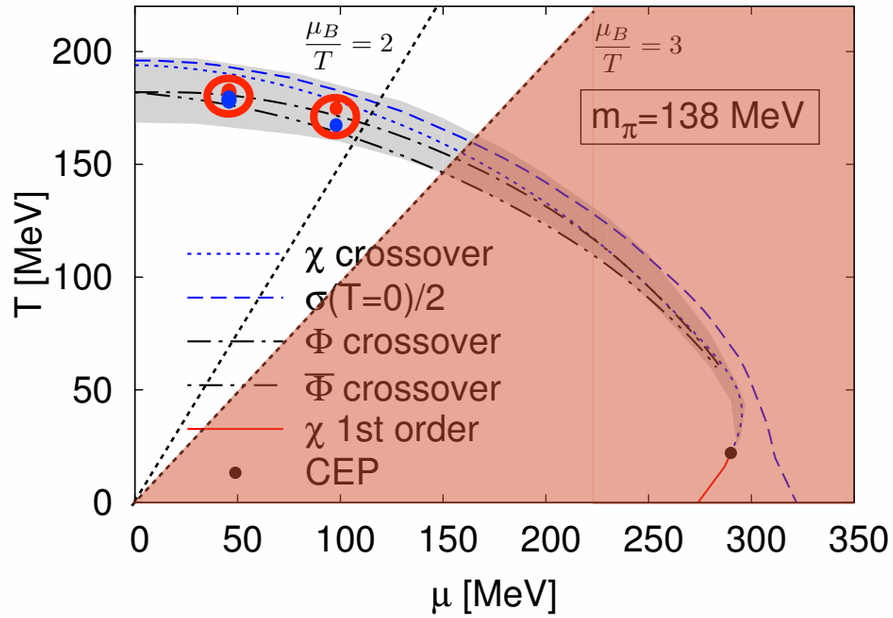

Herbst, JMP, Schaefer, PLB 696 (2011) 58-67
PRD 88 (2013) 1, 014007

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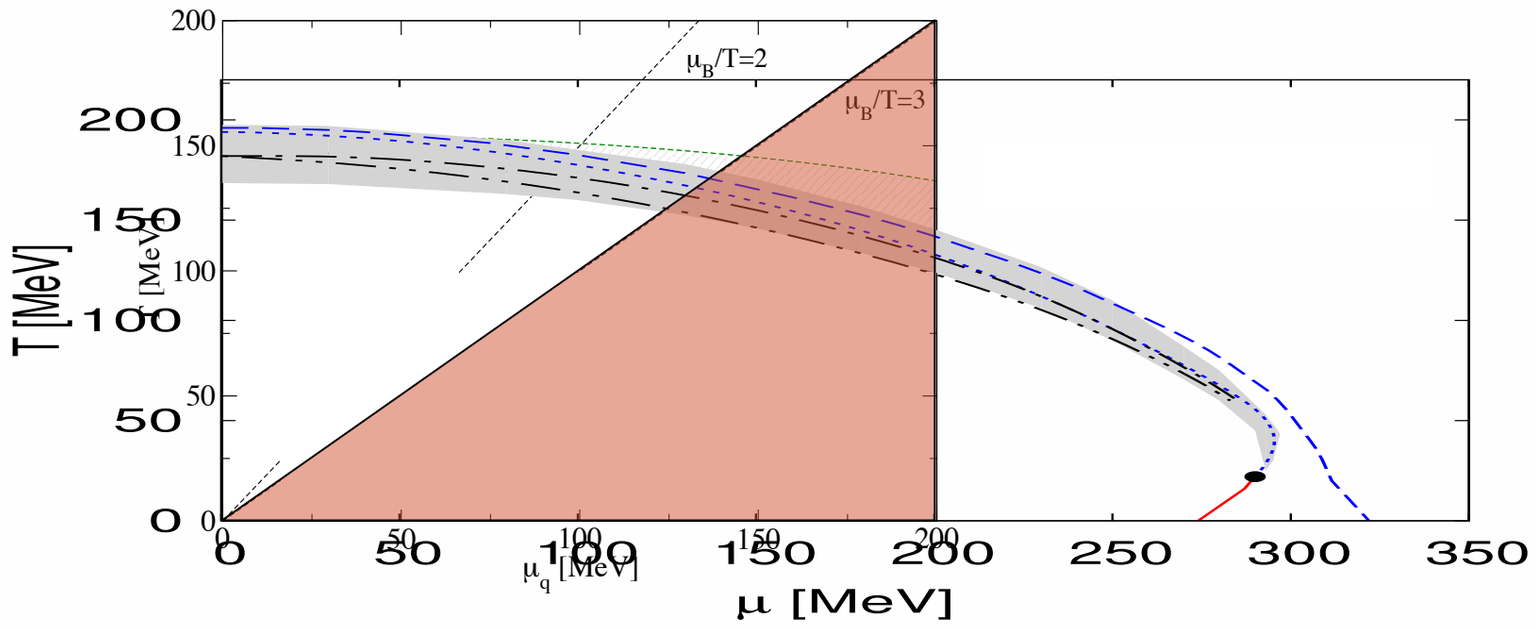
Haas, Braun, JMP '09, unpublished

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



Summary & Outlook

- **Chiral Symmetry Breaking and Confinement**

- **Phase Structure and Transport**

Summary & Outlook

- Chiral Symmetry Breaking and Confinement
- Phase Structure and Transport

- Towards quantitative precision
- Baryons, high density regime & CEP, dynamics
- Hadronic properties
  - hadron spectrum & in medium modifications
  - low energy constants