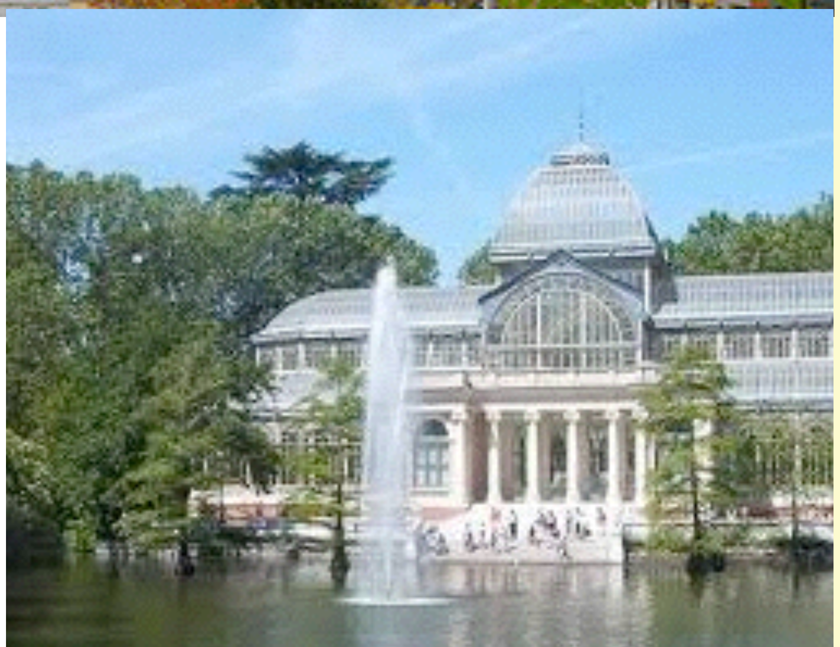
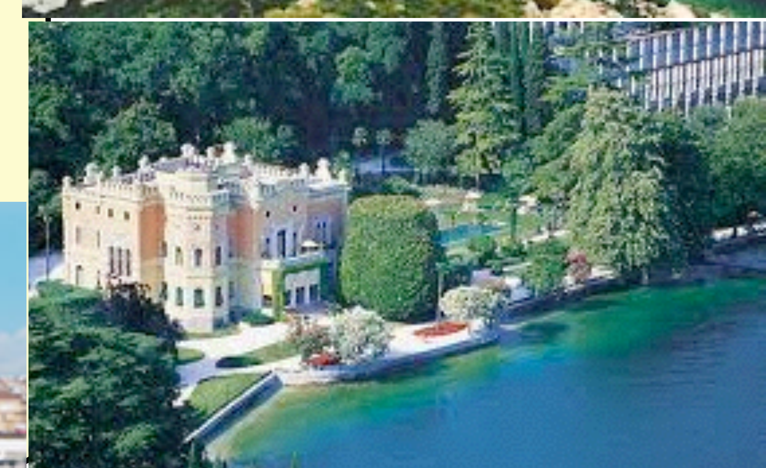
XIIth Quark Confinement and the Hadron Spectrum

Sunday 28 August 2016 - Saturday 03 September 2016

This is the XII edition of an enterprise started in 1994





Petersburg (Russia) 201

Munich(Germany)2012

Madrid (Spain) 2010

Mainz (Germany) 2008

Açores (Portugal) 2006

Sardinia (Italy) 2004

Gargnano (Italy) 2002

Vienna (Austria) 2000

Lab (USA) 1998

Como (Italy) 1996 1994

Scientific Sessions of the conference

Section A: Vacuum Structure and Confinement

Mechanisms of quark confinement (vortices, monopoles, calorons...) and the structure of the vacuum in non-Abelian gauge theories. Chiral symmetry breaking, and the Dirac spectrum in the low-momentum region. Studies of ghost and gluon propagators. Confining strings and flux tubes, their effective actions. Renormalons and power corrections. Interface between perturbative and non-perturbative physics.

Conveners: D. Antonov (Heidelberg), M. Faber (TU Vienna), J. Greensite (San Francisco State U)

Focus Subsection: Emergent gauge fields and chiral fermions

Chiral Fermions and anomalous hydrodynamic effects in condensed matter systems, quantum simulators of QCD, topological phenomena in condensed matter systems.

Conveners: T. Schaefer (NC State U), V. Shevchenko (NRC Kurchatov I.)

Section B: Light Quarks

Chiral and soft collinear effective theories; sum rules; lattice; Schwinger-Dyson equations; masses of light quarks; light-quark loops; phenomenology of light-hadron form factors, spectra and decays; structure functions and generalized parton distributions; exotics and glueballs; experiments.

Conveners: J. Goity (Hampton U.), B. Ketzer (Bonn U.), H. Sazdjian (IPN Orsay), N. G. Stefanis (Ruhr U. Bochum), H. Wittig (JGU Mainz)

Section C: Heavy Quarks

Heavy-light mesons, heavy quarkonia, heavy baryons, heavy exotics and related topics: phenomenology of spectra, decays, and production; effective theories for heavy quarks (HQET, NRQCD, pNRQCD, vNRQCD, SCET); sum rules for heavy hadrons; lattice calculations of heavy hadrons; heavy-quark masses determination; experiments.

Conveners: G. Bodwin (Argonne NL), P. Pakhlov (ITEP, Moscow), J. Soto (U. Barcelona), A. Vairo (TU Munich)

Section D: Deconfinement

QCD at finite temperature; quark-gluon plasma detection and characteristics; jet quenching; transportation coefficients; lattice QCD and phases of quark matter; QCD vacuum and strong fields; heavy-ion experiments.

Conveners: C. Allton (Swansea U.), E. Iancu (CEA/DSM/Saclay), M. Janik (WUT), P. Petreczky (BNL), A. Vuorinen (U. Helsinki), Y. Foka (GSI)

Section E: QCD and New Physics

Physics beyond the Standard Model with hadronic physics precision experimental data and precision calculations.

Conveners: W. Detmold (MIT), M. Gersabeck (U. Manchester), F. J. Llanes-Estrada (UC Madrid), E. Mereghetti (Los Alamos NL), J. Portoles (IFIC, Valencia)

Section F: Nuclear and Astroparticle Physics

Nuclear matter; nuclear forces; quark matter; neutron and compact stars.

Conveners: M. Alford (Washington U. in St.Louis), D. Blaschke (U. Wroclaw), T. Cohen (U. Maryland), L. Fabbietti (TU Munich), A. Schmitt (U Southampton)

Section G: Strongly Coupled Theories

Hints on the confinement/deconfinement mechanisms from supersymmetric and string theories; strongly coupled theories beyond the Standard Model; applications of nonperturbative methods of QCD to other fields.

Conveners: D. Espriu (U. Barcelona), Z. Fodor (BU Wuppertal), E. Kiritsis (APC and U. Crete), F. Sannino (CP3-Origins), A. Weiler (TU Munich)

Poster Section: with wine tasting (N. Isgur)

Convener: M. Creutz(BNL)

Two new sections at this edition:

Future Perspectives, Upgrades, Instrumentation

Probing QCD and facilities, future experiments, planned upgrades, performance studies, simulation and analysis methods, instrumentation and new technologies

Conveners: L. Musa (CERN), S. Leontsinis (U. Colorado), P. Di Nezza (INFN Frascati), C. Sturm (GSI)

Statistical Methods for Physics Analysis in the XXI Century

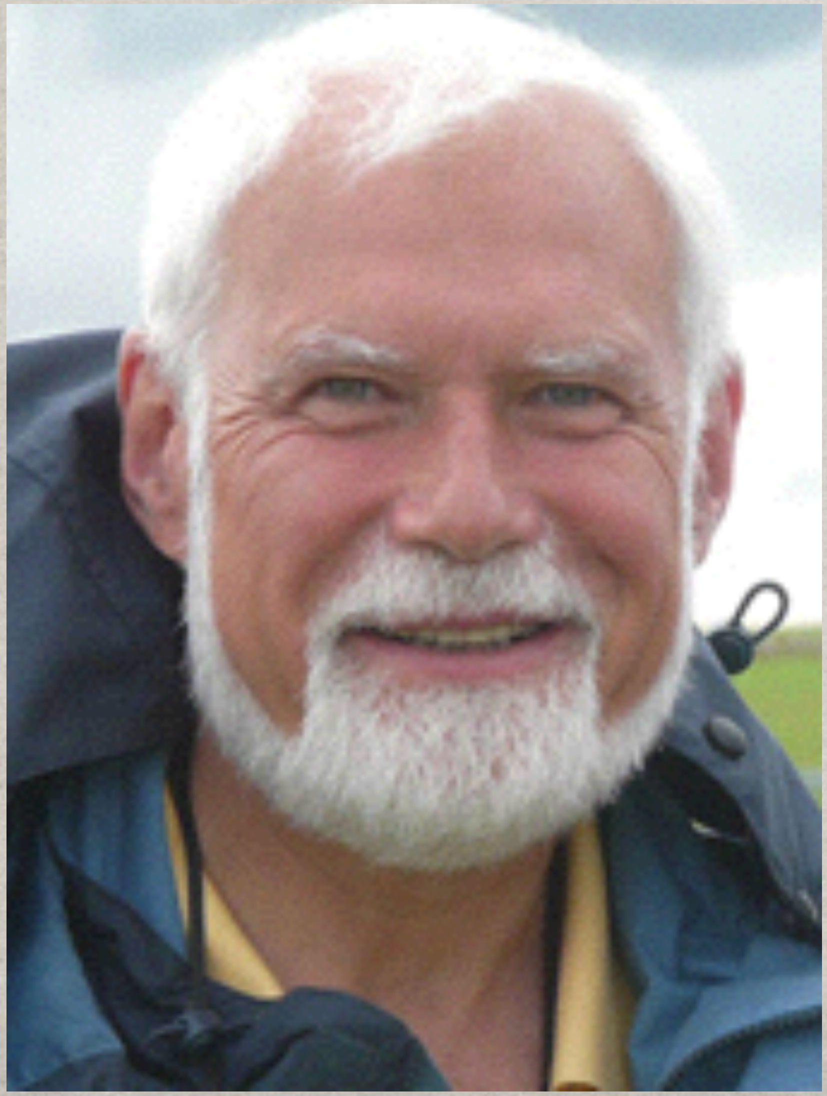
Machine learning techniques; data fitting and extraction of signals; new developents in unfolding methods; averaging and combination of results

Conveners: T. Dorigo (INFN, Italy)

The conference has been a **great mixing** of people, approaches, methods, cultures, tools, ideas… in the best tradition of this series !

It is more than 20 years that i organise the scientific program of the conference (in collaboration with loc, IAC, conveners..)

and the quark confinement has become a community seeing generations of physicists coming in young, becoming old or dying in it, and in fact at each edition we mourn our dear passed away



We dedicated Conf12 to the memory of Michael Mueller-Preussker and we had a commemorative talk by Andre Sternbeck "QCD propagators and vertices from lattice QCD"

QCD propagators and vertices from lattice QCD
(in memory of Michael Müller-Preußker)

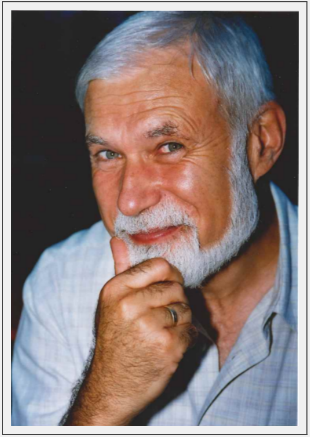
André Sternbeck

Friedrich-Schiller-Universität Jena, Germany

XIIth Quark Confinement and the Hadron Spectrum
Thessaloniki (Greece)

29 August to 3 September 2016

Michael Müller-Preußker



September 26, 1946 — October 12, 2015

(Potsdam, Germany) (Vladivostok, Russia)

(Eichwalde/Berlin, Germany)

Michael's Vita

Education

1965: Abitur (university entrance degree)

1973: Promotion (PhD), Humboldt-University Berlin

"Postdoc" phase

1972 – 1993: Research Assistant at Humboldt-University Berlin
("Assistent" and "Oberassistent")

1978 – 1983: Visiting Researcher at the JINR Dubna, Russia

1990 – 1991: Visiting Professor at Bielefeld University, Germany

1991 – 1992: Senior Scientist at Humboldt-University Berlin

Professor at Humboldt-University Berlin

1993 – 2011: Head of Research group
"Phenomenology / Lattice Gauge Theory"

2011 – 2015: Senior-Professor at Humboldt-University Berlin

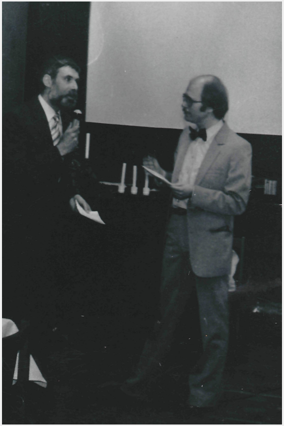
2012 – 2014: Chairman of the Physical Society Berlin (PGzB)

Research topics

A) Topology (since 1979)

- Many studies of semi-classical solutions of QCD (instantons, dyons, monopoles, calorons)

  ○ **On the Phase Transition in the {Yang-Mills} Instanton Gas**
  Ilgenfritz, Kazakov, Müller-Preussker (1979), PLB87 (1979) 242
  ...
  ○ **First Evidence for the Existence of Instantons in the Quantized SU(2) Lattice Vacuum**, Ilgenfritz, Laursen, Schierholz, Müller-Preussker, Schiller, NPB268(1986)693
  ...
  ○ **The Density of monopoles in SU(2) lattice gauge theory**
  Bornyakov, Ilgenfritz, Laursen, Mitrjushkin, Müller-Preussker, van der Sijs, Zadorozhnyi, PLB261(1991)116
  ...
  ○ **On the topological content of SU(2) gauge fields below T(c)**
  Ilgenfritz, Martemyanov, Müller-Preussker, Shcheredin, Veselov
  PRD66(2002)074503
  ...
  ○ **Dyons near the transition temperature in lattice QCD**
  Bornyakov, Ilgenfritz, Martemyanov, Müller-Preussker, PRD93(2016)074508



Political sketch at a festivity of the German community in Dubna
Courtesy by I. Müller-Preußker

- Reason to start with **lattice** calculations in the 80's with E.-M. Ilgenfritz (122 joint publications ... of 212 total)
- Collaborators: Bornyakov, Bruckmann, Ilgenfritz, Gattringer, Martemyanov, ...

Research topics

B) Gauge fixing and Propagators/Vertices (since 1990)

- Gauge fixing and Gribov problem on the lattice
- Maximal abelian, Landau and Coulomb gauge
- Compact lattice QED, pure $SU(2)$, $SU(3)$ YM theory, QCD
- Propagators and vertex functions

- **The Density of monopoles in SU(2) lattice gauge theory**
  Bornyakov, Ilgenfritz, Laursen, Mitrjushkin, Müller-Preussker, van der Sijs, Zadorozhnyi, PLB261(1991)116
- **Dirac sheets and gauge fixing in U(1) lattice gauge theory**
  Bornyakov, Mitrjushkin, M. Müller-Preussker, Pahl, PLB371(1993)596

...

- **Landau gauge gluon and ghost propagators from lattice QCD with $N_f = 2$ twisted mass fermions at finite temperature**, Aouane, Burger, Ilgenfritz, Müller-Preussker, Sternbeck, PRD87(2013)114502
- **Landau gauge ghost propagator and running coupling in SU(2) lattice gauge theory**
  Bornyakov, Ilgenfritz, Litwinski, Mitrjushkin, M. Müller-Preussker, PRD92(2015)074505

...

2^{nd} prize of the JINR award 2015
(Category: Best articles/cycles of papers in Theoretical Physics)

Lattice studies of Landau gauge gluon and ghost propagators in QCD
Bogolubsky, Bornyakov, Ilgenfritz, Mitrjushkin, Müller-Preussker and Sternbeck

Research topics

C) QCD thermodynamics (since 2006)

- QCD with twisted-mass fermions at finite T (tmfT-Collaboration)
  - **Phase structure of thermal lattice QCD with Nf=2 twisted mass Wilson fermions**
    Ilgenfritz, Jansen, Lombardo, Müller-Preussker, Petschlies, Philipsen, Zeidlewicz PRD80(2009)094502
  - **Thermal QCD transition with two flavors of twisted mass fermions**
    Burger, Ilgenfritz, Kirchner, Lombardo, Müller-Preussker, Philipsen, Urbach, Zeidlewicz, PRD87(2013)074508
  - **Equation of state of quark-gluon matter from lattice QCD with two flavors of twisted mass Wilson fermions**, Burger, Ilgenfritz, Lombardo, Müller-Preussker, PRD91(2015)074504
  - Recent years: $N_f = 2{+}1{+}1$ (few conference proceedings)

- Two-color QCD
  - **Two-Color QCD with Non-zero Chiral Chemical Potential**
    Braguta, Goy, Ilgenfritz, Kotov, Molochkov, Müller-Preussker, Petersson, JHEP1506(2015)094
  - **Magnetic catalysis (and inverse catalysis) at finite temperature in two-color lattice QCD**
    Ilgenfritz, Müller-Preussker, Petersson, Schreiber, PRD89(2014)054512
  - **Two-color QCD with staggered fermions at finite temperature under the influence of a magnetic field**,
    Ilgenfritz, Kalinowski, Müller-Preussker, Petersson, Schreiber PRD85(2012)114504

Research topics

D) Miscellaneous

- Spin and gauge Higgs models
- Quasi Monte Carlo methods
- ...

Focus of this talk

- Michael gave himself an overview on topology in memory of Pierre van Baal (Lattice 2014)
- I will focus on our joint lattice studies (2003–2015) on topic B)

"Gauge-Fixing, Propagators and Vertex functions"

Note:
I apologize in advance that I cannot review all developments in the field but will concentrate on the lattice studies Michael was involved.

This shall not disregard the value of other studies.

Why studying gauge-fixed propagators on the lattice?

Lattice QCD practitioners

- Often skeptical at first on the usefulness
- Advantage of lattice: gauge-invariant approach to QCD

Michael's view

- Gauge-fixed propagators contain information on confinement and χSB
  - Interesting on its own (perhaps an academic/theoretical question)
- Beside lattice, there are other methods to address QCD
  - Continuum functional methods: DSE, FRGE, bound-state equations
  - Lattice calculations can help to improve them
  - Interplay between functional methods and lattice very important & stimulating

How it started for us in 2002

- E.-M. Ilgenfritz brought the idea to study low-momentum behavior of the $SU(3)$ gluon and ghost propagators from his visit in Tübingen
- Michael experienced with gauge-fixing and I with HPC

Low-momentum regime of gluon and ghost propagators in Landau gauge

Power-law behavior for $p \to 0$

(von Smekal, Hauck and Alkofer (1997))

$$D_{\mu\nu} = \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right) \frac{Z(p^2)}{p^2}, \qquad Z(p^2) \propto (p^2)^{2\cdot 0.595}$$

$$G = \frac{J(p^2)}{p^2}, \qquad J(p^2) \propto (p^2)^{-0.595}$$

Coupling constant for $p \to 0$

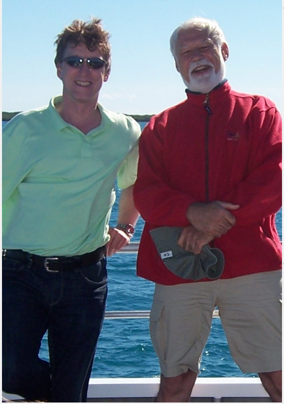
(today aka "Minimal MOM" or "ghost-gluon coupling")

$$\alpha_s(p^2) = \frac{g_0^2}{4\pi} Z(p^2) J^2(p^2) \xrightarrow{p^2 \to 0} \alpha_c > 0$$

would nicely fit to

- Kugo-Ojima confinement criterion
- Gribov-Zwanziger confinement scenario

Can one see this on the lattice?



(Australia, 2008, courtesy by L. von Smekal)

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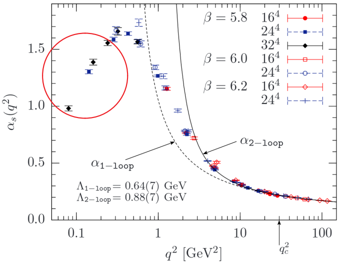

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Can one see this on the lattice? *No!*

- Furui and H. Nakajima PRD69(2004)074505, PRD70(2004)094504
- *A.S.*, Ilgenfritz, Müller-Preussker, Schiller PRD72(2005)014507

Low-momentum regime of gluon and ghost propagators in Landau gauge

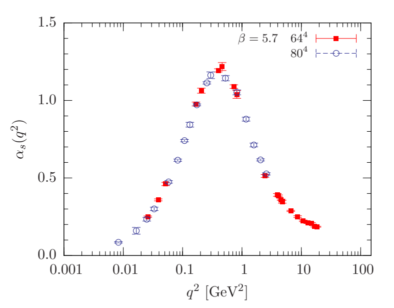
Reason for failure?

- Finite-volume effect? No!
- Gribov copy effect?

Run for biggest lattice (Lattice 2007)

$SU(2) : 128^4$	Cucchieri, Mendes PoS LAT2007,297
$SU(2) : 112^4$	A.S., von Smekal, et al PoS LAT2007,340
$SU(3) : 80^4$	Bogolubsky, Ilgenfritz, Müller-Preussker, A.S. PoS LAT2007,290

Bogolubsky, Ilgenfritz, Müller-Preussker, A.S., PLB676(2009)69



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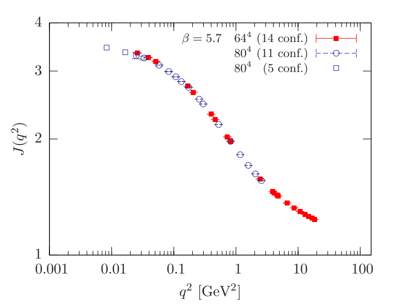

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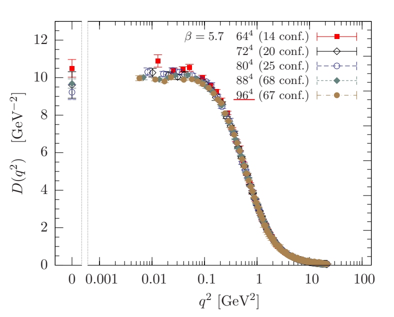


Impact of Gribov problem on gluon and ghost propagators

Alternative view

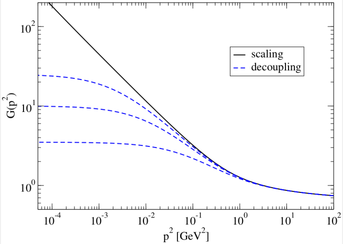
- Gluon and ghost propagators are finite at $p = 0$, as seen on the lattice

  - Boucaud, Leroy, Le Yaouanc, Micheli, Pene, Rodriguez-Quintero, JHEP0806(2008)099
  - Aguilar, D. Binosi and J. Papavassiliou, PRD78(2008)025010
  - Dudal, Sorella, Vandersickel, Verschelde, PRD77(2008)071501

Proposal for solution to puzzle

Fischer, Maas, Pawlowski, Ann.Phys324(2009)2408

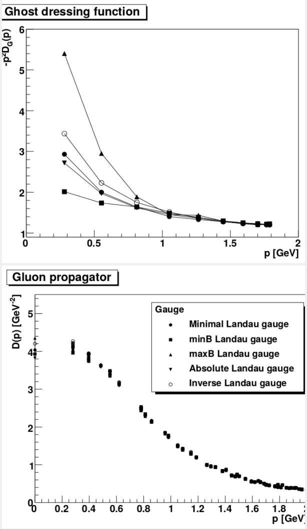
- Solved gluon-ghost DSEs and FRGEs
- Solution depends on the value $J(0)$ (fixes Gribov ambiguity)
- Family of decoupling and one scaling solution



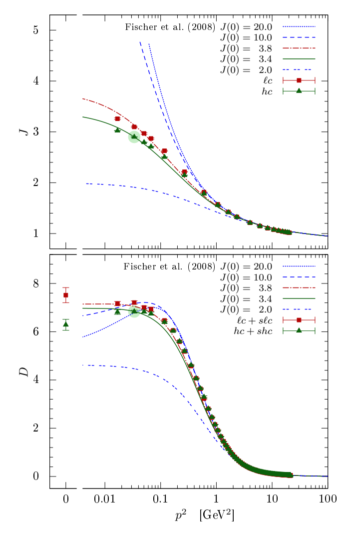
Lattice evidence for different decoupling solutions

SU(2) YM theory in Landau gauge

Maas, PLB689(2010)107



A.S. and Müller-Preussker, PLB726(2013)396



Greens function of QCD in Landau gauge from the lattice

Infrared behavior of gluon and ghost propagators

- More or less understood, some questions remain
- After all, it is an "academic question"

Most important: intensive scientific exchange

- between functional methods and lattice
- very stimulating for both sides
- **not restricted to infrared behavior**

St.Goar 2011

A) Gluon propagators at finite T

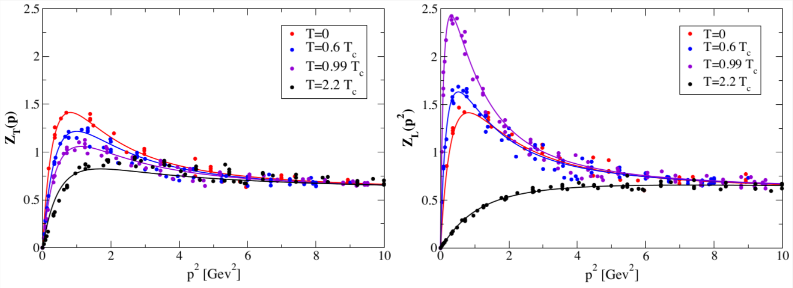
Dedicated lattice study of gluon propagator (2010–2013)

- **Landau gauge gluon and ghost propagators at finite temperature from quenched lattice QCD** Aouane, Bornyakov, Ilgenfritz, Mitrjushkin, Müller-Preussker, Sternbeck, PRD85(2012)034501
- **Landau gauge gluon and ghost propagators from lattice QCD with $N_f = 2$ twisted mass fermions at finite temperature**, Aouane, Burger, Ilgenfritz, Müller-Preussker, Sternbeck, PRD87(2013)114502

DSE study of $(T - \mu)$ phase diagram

- Input and cross-check for solution of gluon DSE
- Fischer, Luecker, PLB 718(2013)1036:

(Input)



B) Greens functions for hadron physics calculations

Research in hadron physics

- Successful but not restricted to lattice QCD
- Other nonperturbative frameworks exist (for better or for worse)

Bound-state equations

- Bethe-Salpether equations: Mesonic systems ($q\bar{q}$)
- Faddeev/ quark-diquark equations: Baryonic systems (qqq)
- no restriction to Euclidean metric (makes it simpler)
  - for lattice QCD Euclidean metric mandatory
    (can calculate static quantities: masses, etc. or equilibrium properties)
- **Conf 12**: G. Eichmann showed what is possible already

B) Greens functions for hadron physics calculations

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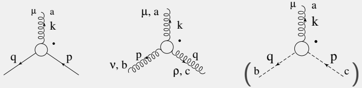
- **Conf 12**: G. Eichmann showed what is possible already
- **Input**: nonperturbative n-point Green's functions (in a gauge)
  - typically taken from numerical solutions of their Dyson-Schwinger equations
  - Note: Greens function enter in a certain gauge, but physical content obtained from BSEs (masses, decay constants) is gauge independent
- **Main problem**: truncation of system of equations required

Input from lattice QCD

Greens function from lattice QCD

- Nonperturbative structure of n-point functions in a certain gauge (Landau gauge) are needed to improve truncations / cross-check results
- Lattice QCD can provide these nonperturbative + untruncated
  - 2-point: quark, gluon (and ghost) propagators 
  - 3-point: quark–anti-quark–gluon, 3-gluon, (ghost-ghost-gluon)
  - 4-point: 4-gluon vertex, . . .
  - 5-point: . . .

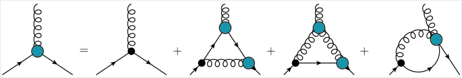


- Already: 2-point functions are used as input to DSE studies

Most desired 3-point functions (quenched + unquenched)

- Quark-gluon Vertex and Triple-Gluon Vertex
- Improved truncations of quark-DSE

full quark DSE



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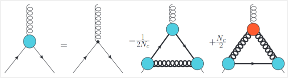
truncated



Two projects we started with Michael in 2014

Data taken, data analysis in progress

Triple-Gluon Vertex

with Balduf (MSc. student)

- Transversal tensor structure
- Quenched vs. unquenched, quark mass dependence
- Infrared behavior ("Zero-crossing"), i.e., $|p| \approx 0.1 \ldots 1$ GeV

Quark-Gluon Vertex

with Kızılersü, Oliveira, Silva, Skullerud, Williams

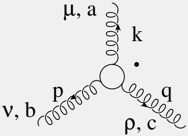
- Transversal tensor structure
- Quenched vs. unquenched, quark mass dependence

Acknowledgements

- $N_f = 2$ configurations provided by RQCD collaboration (Regensburg)
- Gauge-fixing and calculation of propagators at the HLRN (Germany)

Triple-Gluon-Vertex in Landau gauge

$$\boldsymbol{\Gamma_{\mu\nu\lambda}(p,q)} = \sum_{i=1,\ldots,14} f_i(p,q)\, P^{(i)}_{\mu\nu\lambda}(p,q)$$



- Perturbation theory: f_i known up to three-loop order (Gracey)
- Nonperturbative structure mostly unknown (few DSE and lattice results)

1) Projection on lattice tree-level form

$$G_1(p,q) = \frac{\Gamma^{(0)}_{\mu\nu\rho}}{\Gamma^{(0)}_{\mu\nu\rho}} \frac{G_{\mu\nu\rho}(p,q,p-q)}{D_{\mu\lambda}(p)D_{\nu\sigma}(q)D_{\rho\omega}(p-q)\Gamma^{(0)}_{\lambda\sigma\omega}}$$

2) Tensor structure of transversely projected triple-gluon vertex

Eichmann et al., PRD89(2014)105014

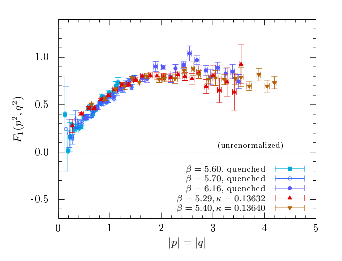
$$\Gamma^T_{\mu\nu\rho}(p,q) = \sum_{i=1}^{4} F_i(\mathcal{S}_0, \mathcal{S}_1, \mathcal{S}_2)\, \tau^{\mu\nu\rho}_{i\perp}(p_1,p_2,p_3)$$

$$P^{(1)} = \delta_{\mu\nu} p_\lambda, \quad P^{(2)} = \delta_{\nu\lambda} p_\mu, \ \ldots, \quad P^{(5)} = \delta_{\nu\lambda} q_\mu, \ \ldots, \quad P^{(9)} = \frac{1}{\mu^2} q_\mu p_\nu q_\lambda, \ \ldots$$

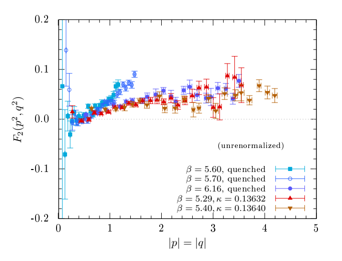
First lattice results for transverse tensor structure

in collaboration with Balduf, and Michael (data is still preliminary)

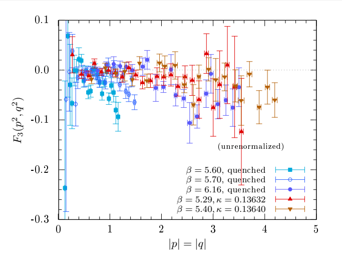
F$_1$



F$_2$



F$_3$



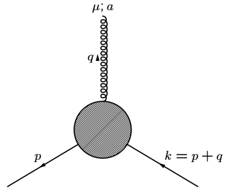
DSE study of triple-gluon vertex

[Eichmann et al. (2014)]

- Leading form factor is F_1
- $F_{i=2,3,4} \approx 0$ for all momenta

We can confirm that!

Quark-Gluon vertex in Landau gauge



Quark-Gluon Green's function

$$G_\mu^{\bar\psi\psi A} = \Gamma_\lambda^{\bar\psi\psi A}(p,q) \cdot S(p) \cdot D_{\mu\lambda}(q) \cdot S(p+q)$$

- Up to now: only lattice data for quenched QCD

Ball-Chiu parametrization

$$\Gamma_\mu^{\bar\psi\psi A}(p,q) = \Gamma_\mu^{ST}(p,q) + \Gamma_\mu^{T}(p,q)$$

with $\Gamma_\mu^{ST}(p,q) = \sum_{i=1\ldots4} \lambda_i(p^2,q^2) L_{i\mu}(p,q)$ satisfies Slavnov-Taylor identities

$\Gamma_\mu^{T}(p,q) = \sum_{i=1\ldots8} \tau_i(p^2,q^2) T_{i\mu}(p,q)$ is transverse ($q_\mu \Gamma_\mu^T = 0$).

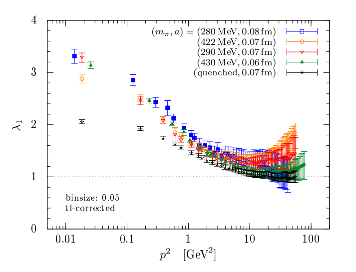
$$L_{1\mu}(p,q) = \gamma_\mu, \quad L_{2\mu}(p,q) = -\gamma_\mu(2p_\mu + q_\mu), \ldots,$$
$$T_{1\mu}(p,q) = i[p_\mu q^2 - q_\mu(p \cdot q)], \ldots$$

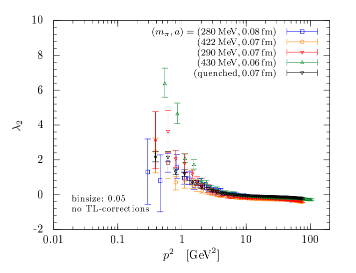
Lattice results for a few form factors

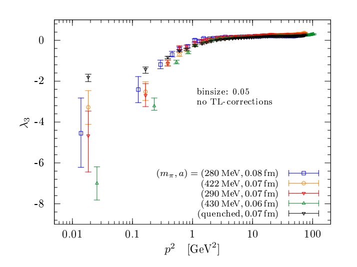
in collaboration with Kızılersü, Oliveira, Silva, Skullerud, Williams, and Michael (data is still preliminary)

For now: soft-gluon kinematic

- $\lambda_{i=1,2,3}(p, q=0) \neq 0$







Work in progress

- Taming discretization effects
- Other kinematics → $\tau_i(p, q)$
- larger lattices → smaller p^2

From QCD's n-point functions to nucleon resonances

Gernot Eichmann
University of Giessen, Germany

GE, Sanchis-Alepuz, Williams, Alkofer, Fischer, 1606.09602, Prog. Part. Nucl. Phys. (in press)

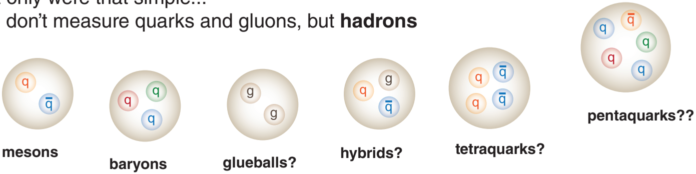
GE, Fischer, Sanchis-Alepuz, 1607.05748

XIIth Quark Confinement and the Hadron Spectrum
Thessaloniki, Greece
August 29, 2016

Introduction

QCD Lagrangian: $\mathcal{L} = \bar{\psi}\,(\partial\!\!\!/ + ig A\!\!\!/ + m)\,\psi + \frac{1}{4}\,F^{a}_{\mu\nu}\,F^{\mu\nu}_{a}$

- if it only were that simple...
  we don't measure quarks and gluons, but **hadrons**

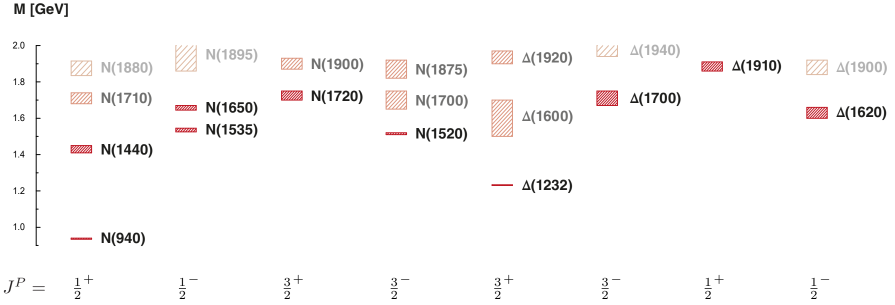


- origin of **mass generation** and **confinement?**

	u	d	s	c	b	t
Current mass [GeV]	**0.003**	**0.005**	**0.1**	**1**	**4**	**175**
„Constituent" mass [GeV]	**0.35**	**0.35**	**0.5**	**1.5**	**4.5**	**175**

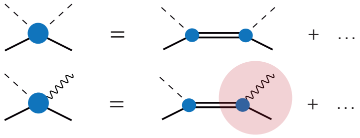
- need to understand **spectrum and interactions!**

Light baryon spectrum



Experimentally extracted from πN scattering, meson photo- and electroproduction

- Nature of **Roper** (level ordering)?
- Three-quark vs. **quark-diquark?**
- "Quark core" vs. meson-baryon **coupled channel effects?**
- **Hybrid baryons?**



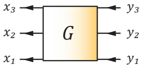
extraction of **transition form factors**

Bethe-Salpeter

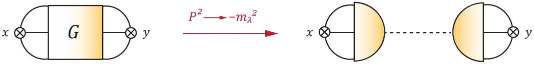
Extract baryon poles from (gauge-invariant) two-point correlators:

$$G(x-y) = \langle 0\,|\,T\,\underbrace{[\Gamma_{\alpha\beta\gamma}\,\psi_\alpha\,\psi_\beta\,\psi_\gamma]\,(x)}_{J(x)}\,\underbrace{[\bar\Gamma_{\rho\sigma\tau}\,\bar\psi_\rho\,\bar\psi_\sigma\,\bar\psi_\tau]\,(y)}_{\bar J(y)}\,|\,0\,\rangle \;=\; \int \mathcal{D}[\psi,\bar\psi,A]\,e^{-S}\,J(x)\,\bar J(y)$$

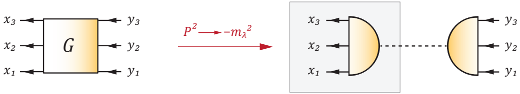
$$= \lim_{\substack{x_i \to x \\ y_i \to y}} \Gamma_{\alpha\beta\gamma}\,\bar\Gamma_{\rho\sigma\tau}\,\langle 0\,|\,T\,\psi_\alpha(x_1)\,\psi_\beta(x_2)\,\psi_\gamma(x_3)\,\bar\psi_\rho(y_1)\,\bar\psi_\sigma(y_2)\,\bar\psi_\tau(y_3)\,|\,0\,\rangle$$



$=$



Alternative: extract **gauge-invariant** baryon poles from **gauge-dependent** quark 6-point function:

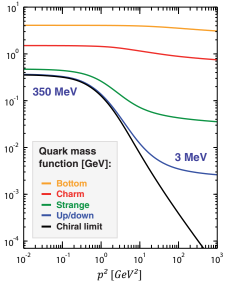


Bethe-Salpeter wave function:
residue at pole, contains all information about baryon

QCD's n-point functions

- **Quark propagator**

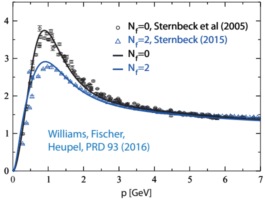
$A(p^2)\,(i\not{p} + M(p^2))$  $^{-1}$



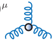
Dynamical chiral symmetry breaking generates 'constituent-quark masses'

- **Gluon propagator**

$\frac{D(p^2)}{p^2}\left(\delta^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}\right)$ 



- **Three-gluon vertex**

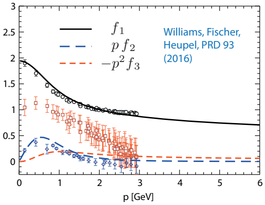
$F_1\,[\,\delta^{\mu\nu}(p_1-p_2)^\rho + \delta^{\nu\rho}(p_2-p_3)^\mu + \delta^{\rho\mu}(p_3-p_1)^\nu] + \dots$ 

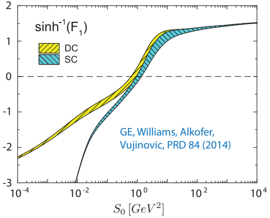
Agreement between lattice, DSE & FRG within reach

($\rightarrow$ **Sternbeck, Williams, Huber, Blum, Mitter, Cyrol, Campagnari, . . .**)

- **Quark-gluon vertex**

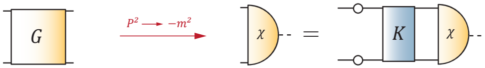
$f_1\,\gamma^\mu + f_2\,ip^\mu + f_3\,p^\mu\not{p} + \dots$ 



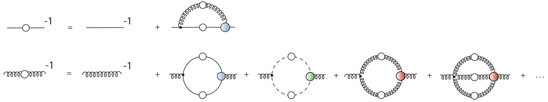


Bethe-Salpeter

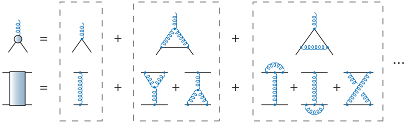
- Homogeneous **Bethe-Salpeter equation** for BS wave function:



- Depends on QCD's n-point functions as input, satisfy **DSEs = quantum equations of motion**

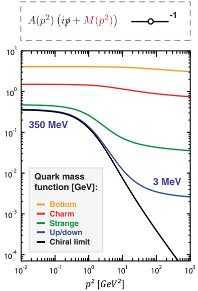


- Kernel can be derived in accordance with **chiral symmetry:**



→ **R. Williams**

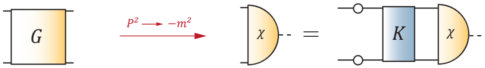
- **Quark propagator**



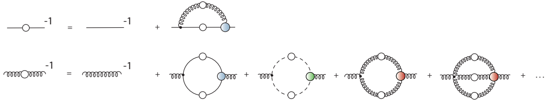
Dynamical chiral symmetry breaking generates 'constituent-quark masses'

Bethe-Salpeter

- Homogeneous **Bethe-Salpeter equation** for BS wave function:



- Depends on QCD's n-point functions as input, satisfy **DSEs = quantum equations of motion**



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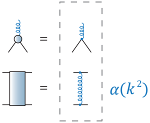
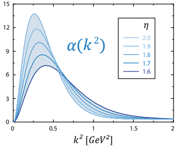




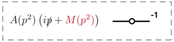
Rainbow-ladder:
effective gluon exchange

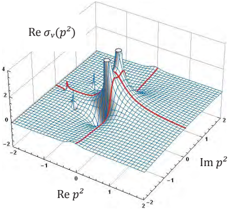
$$\alpha(k^2) = \alpha_{\text{IR}}\left(k^2/\Lambda^2, \eta\right) + \alpha_{\text{UV}}(k^2)$$

adjust scale Λ to observable,
keep width η as parameter

Maris, Tandy, PRC 60 (1999)

- **Quark propagator**

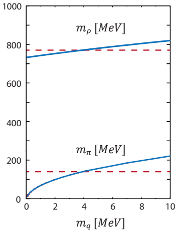




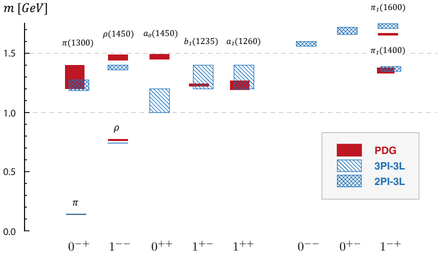
Calculated in **complex plane:** singularities pose restrictions (no physical threshold!)

Mesons

- Pion is **Goldstone boson:** $m_\pi{}^2 \sim m_q$



- **Light meson spectrum** beyond rainbow-ladder



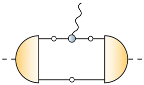
Williams, Fischer, Heupel, PRD 93 (2016)

GE, Sanchis-Alepuz, Williams, Alkofer, Fischer, 1606.09602

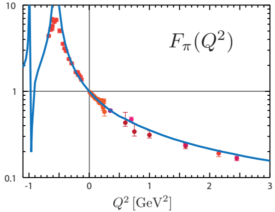
→ **C. Fischer**
R. Williams
T. Hilger

- **Pion electromagnetic form factor:**

Maris & Tandy, PRC 61 (2000), Chang, Cloet, Roberts, Schmidt, Tandy, PRL 111 (2013)



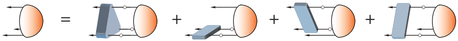
Timelike vector meson poles automatically generated in quark-photon vertex!



A. Krassnigg, Schladming 2010

Baryons

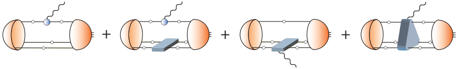
- Covariant Faddeev equation for **baryons:** keep 2-body interactions & rainbow-ladder, but no further approximations: $M_N = 0.94\,\text{GeV}$
  GE, Alkofer, Krassnigg, Nicmorus, PRL 104 (2010), GE, PRD 84 (2011)

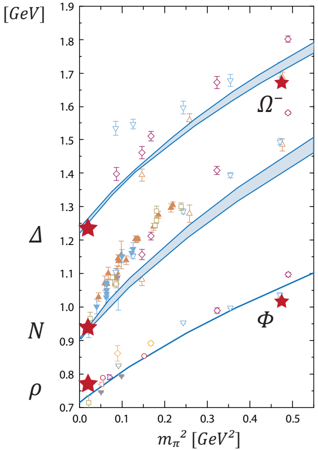


  Relativistic bound states:
  64 / 128 tensor structures for nucleon / Δ

- Octet & decuplet baryons, pion cloud effects, first steps beyond rainbow-ladder
  Sanchis-Alepuz, Fischer, PRD 90 (2014), Sanchis-Alepuz, Fischer, Kubrak, PLB 733 (2014), Sanchis-Alepuz, Williams PLB 749 (2015)

- **Baryon form factors:**
  nucleon and Δ FFs, $N\to\Delta\gamma$ transition
  GE, PRD 84 (2011), Sanchis-Alepuz, Williams, Alkofer, PRD 87 (2013), Alkofer, GE, Sanchis-Alepuz, Williams, Hyp. Int. 234 (2015)

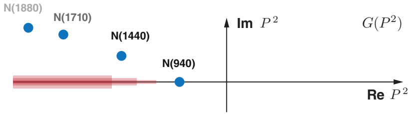




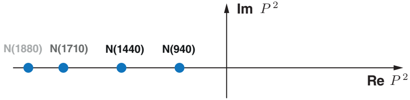
GE, Sanchis-Alepuz, Williams, Alkofer, Fischer, 1606.09602

Resonances?

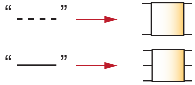
Branch cuts & widths generated by
meson-baryon interactions: Roper $\to N\pi$, etc.



Without them: **bound states without widths**

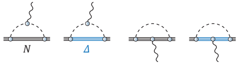


Difficult to implement at **quark-gluon level:**
complicated topologies beyond rainbow-ladder

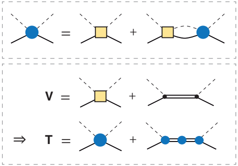


Different phenomenological pictures
how this could happen:

- **'pion-cloud effects'** affect masses and form factors in light-quark region



- **dynamical generation of resonances:** start with 'bare' seed, hadronic interactions produce new poles

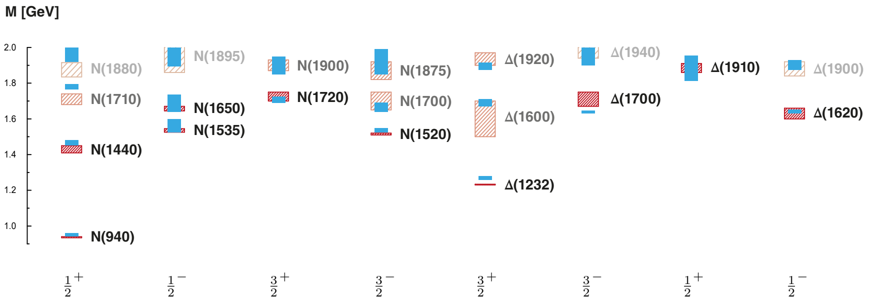


e.g.
Suzuki et al.,
PRL 104 (2010)

- Three-quark vs. five-quark / molecular components

Baryon spectrum II

Quark-diquark with reduced pseudoscalar + vector diquarks: GE, Fischer, Sanchis-Alepuz, 1607.05748

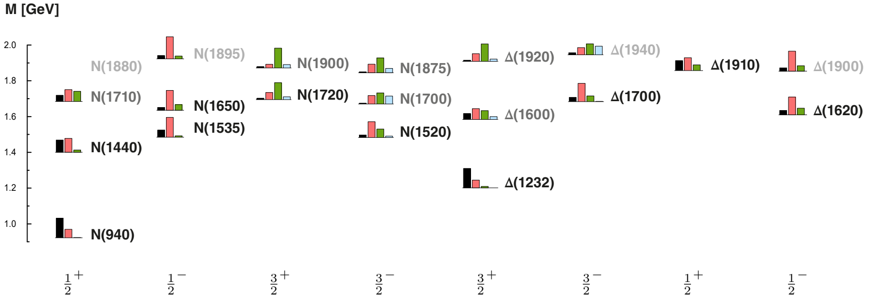


- **Quantitative agreement with experiment**
- N($\frac{1}{2}^+$) and Δ($\frac{3}{2}^+$) channels not affected, but remaining ones were polluted by ps + v diquarks
- Correct level ordering between **Roper and N(1535)**

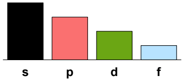
- Scale Λ set by f_π
- Current-quark mass set by m_π
- c adjusted to ρ–a_1 splitting
- η doesn't change much

Baryon spectrum II

Quark-diquark with reduced pseudoscalar + vector diquarks:



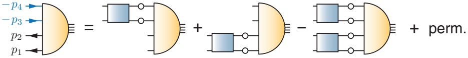
Partial-wave content:



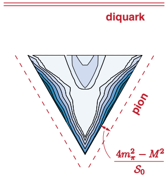
- N and Δ ground states dominated by **s waves,** negative-parity states typically by **p waves** (as expected)
- But 'quark-model forbidden' contributions are always present, e.g. **Roper: dominated by p waves** ⇒ **relativity is important!**

Tetraquarks *are* resonances

- **Light scalar mesons** σ, κ, a_0, f_0 as **tetraquarks:**
  solution of four-body equation reproduces mass pattern
  GE, Fischer, Heupel, PLB 753 (2016)

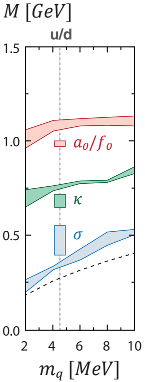


BSE dynamically generates **meson poles** in wave function,
drive σ mass from 1.5 GeV to ~350 MeV



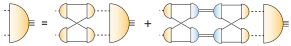
Four quarks rearrange
to **"meson molecule"**

Tetraquarks are "dynamically
generated **resonances**"
(but from the quark level!)



→ **C. Fischer**

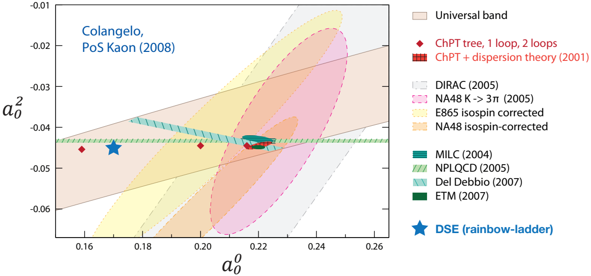
- Similar in **meson-meson / diquark-antidiquark** approximation
  (analogue of quark-diquark for baryons) Heupel, GE, Fischer, PLB 718 (2012)



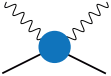
. . . and more

Scattering amplitudes from quark level:

- ***ππ* scattering**
  Bicudo et al., PRD 65 (2002),
  Cotanch, Maris, PRD 66 (2002)

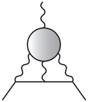


- **Nucleon Compton scattering**



GE, Fischer, PRD 85 (2012) & PRD 87 (2013), GE, FBS 57 (2016)

- **Hadronic light-by-light scattering**
  Goecke, Fischer, Williams, PLB 704 (2011),
  GE, Fischer, Heupel, PRD 92 (2015)



Summary

Progress with **Dyson-Schwinger, Bethe-Salpeter** and **Faddeev equations:**

- **Baryon spectrum** quantitatively reproduced
- **Quark-diquark** and **three-quark** spectrum very similar:

  Quark-diquark with **sc, av, ps, v** ~ three-quark **in RL**

  Quark diquark with **sc, av, ps, v** ~ three-quark **beyond RL?**

- Still "**bound states without widths**",
  because meson-baryon interactions difficult to implement at quark-gluon level.
  But:
  - would mainly shift poles into complex plane (?)
  - decay properties are calculable
  - tetraquarks are genuine resonances (even in RL!)

- For a recent review see:
  GE, Sanchis-Alepuz, Williams, Alkofer, Fischer, arXiv:1606.09602, Prog. Part. Nucl. Phys. (in press)

Thank you!

Chiral symmetry breaking in continuum QCD

Mario Mitter

Ruprecht-Karls-Universität Heidelberg

Thessaloniki, August 2016

Der Wissenschaftsfonds.

European Research Council
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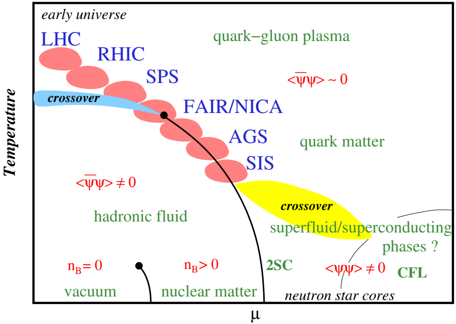
Bundesministerium für Bildung und Forschung

fQCD collaboration - QCD (phase diagram) with FRG:

J. Braun, L. Corell, A. K. Cyrol, L. Fister, W. J. Fu, M. Leonhardt, MM, J. M. Pawlowski, M. Pospiech, F. Rennecke, N. Strodthoff, N. Wink . . .



QCD with the FRG

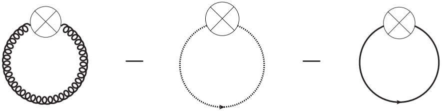
- use only perturbative QCD input
  - $\alpha_S(\Lambda = \mathcal{O}(10)\ \text{GeV})$
  - $m_q(\Lambda = \mathcal{O}(10)\ \text{GeV})$

QCD with the FRG

- use only perturbative QCD input
  - $\alpha_S(\Lambda = \mathcal{O}(10)\ \text{GeV})$
  - $m_q(\Lambda = \mathcal{O}(10)\ \text{GeV})$

- Wetterich equation with initial condition $S[\Phi] = \Gamma_\Lambda[\Phi]$

$$\partial_k \Gamma_k[A, \bar{c}, c, \bar{q}, q] = \frac{1}{2}$$



$\Rightarrow$ effective action $\Gamma[\Phi] = \lim_{k \to 0} \Gamma_k[\Phi]$

QCD with the FRG

- use only perturbative QCD input
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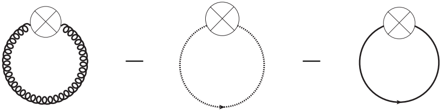


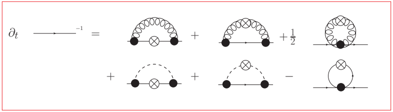
$$\Rightarrow \text{effective action } \Gamma[\Phi] = \lim_{k \to 0} \Gamma_k[\Phi]$$

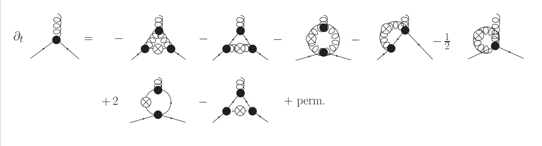
- ∂_k: integration of momentum shells controlled by regulator
- full field-dependent equation with $(\Gamma^{(2)}[\Phi])^{-1}$ on rhs
- gauge-fixed approach (Landau gauge): ghosts appear

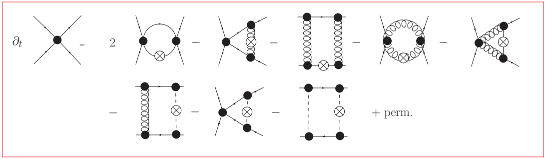
Vertex Expansion

[MM, Strodthoff, Pawlowski, 2014],

[Cyrol, Fister, MM, Strodthoff, Pawlowski, 2016]







Vertex Expansion

[MM, Strodthoff, Pawlowski, 2014],

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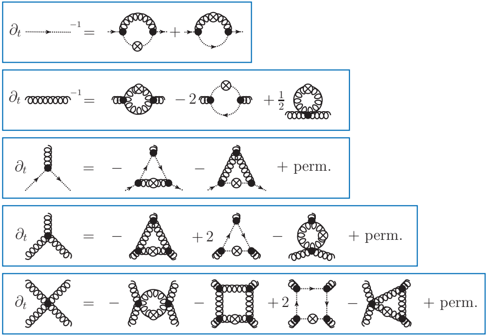

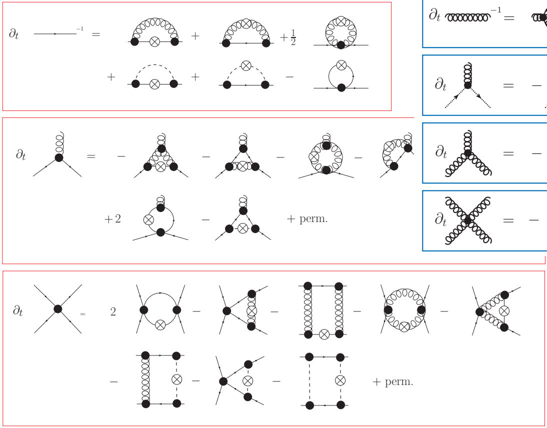

Vertex Expansion

[MM, Strodthoff, Pawlowski, 2014],

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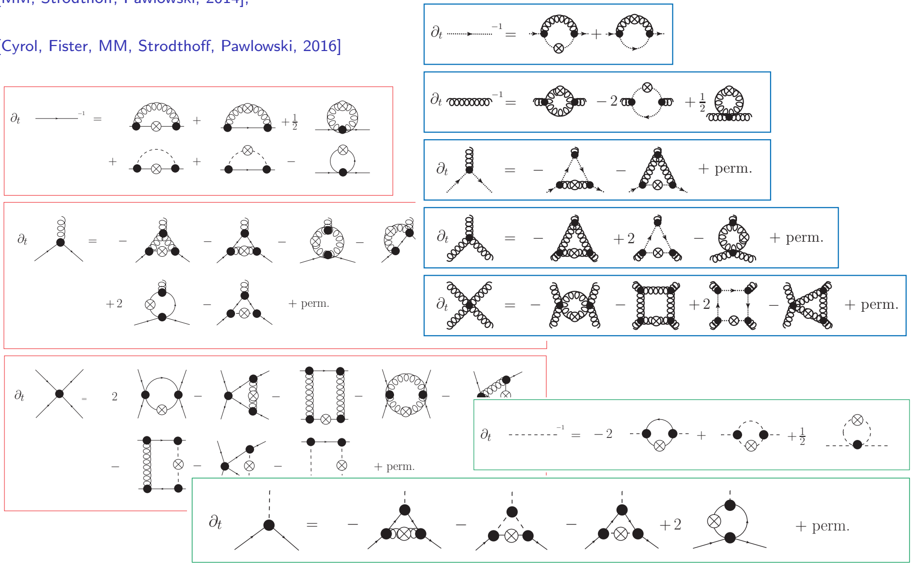
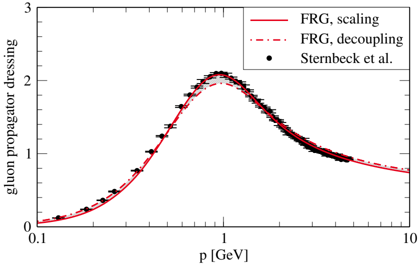
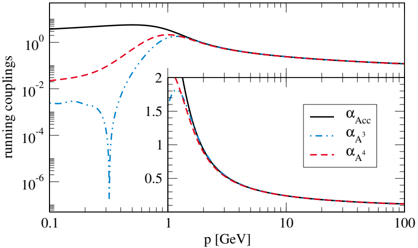


YM theory

[Cyrol, Fister, MM, Pawlowski, Strodthoff, 2016]

- $\Gamma^{(2)}_{AA}(p) \propto Z_A(p)\, p^2 \; \left(\delta^{\mu\nu} - p^\mu p^\nu / p^2\right)$
- running couplings





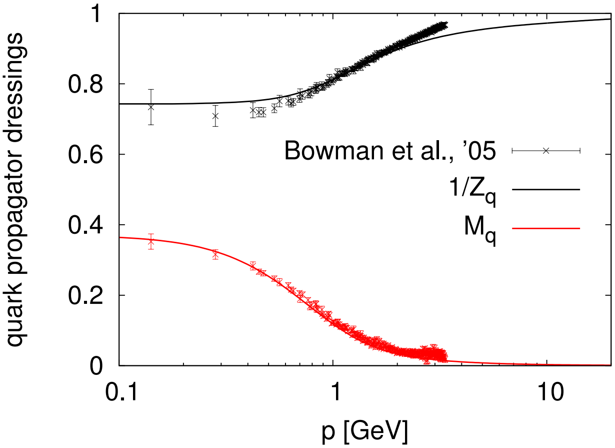
- band: family of decoupling solutions bounded by scaling solution
- more details ⇒ Talk Anton K. Cyrol, Thursday 6pm

lattice data: A. Sternbeck, E. M. Ilgenfritz, M. Muller-Preussker, A. Schiller, and I. L. Bogolubsky, PoS LAT2006, 076.

Quark propagator

[MM, Pawlowski, Strodthoff, 2014]

- $\Gamma^{(2)}_{\bar{q}q}(p) \propto Z_q(p)\,(\not{p} + M(p))$



- FRG vs. lattice: bare mass, quenched, scale set via gluon propagator

Summary and Outlook

QCD with functional RG

- vertex expansion
- sole input $\alpha_S(\Lambda = \mathcal{O}(10)\text{ GeV})$ and $m_q(\Lambda = \mathcal{O}(10)\text{ GeV})$
- good agreement with lattice correlators

Outlook

- QCD phase diagram:
  order parameters, equation of state and fluct. of cons. charges
- bound-state properties (form factors,PDA...)
- more checks on convergence of vertex expansion

Poster: "fQCD: QCD with the Functional RG" dedicated to the memory of Michael Müller-Preußker

On spectral functions and transport coefficients in QCD

Jan M. Pawlowski

Universität Heidelberg & ExtreMe Matter Institute

Thessaloniki, September 1st 2016

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European Research Council
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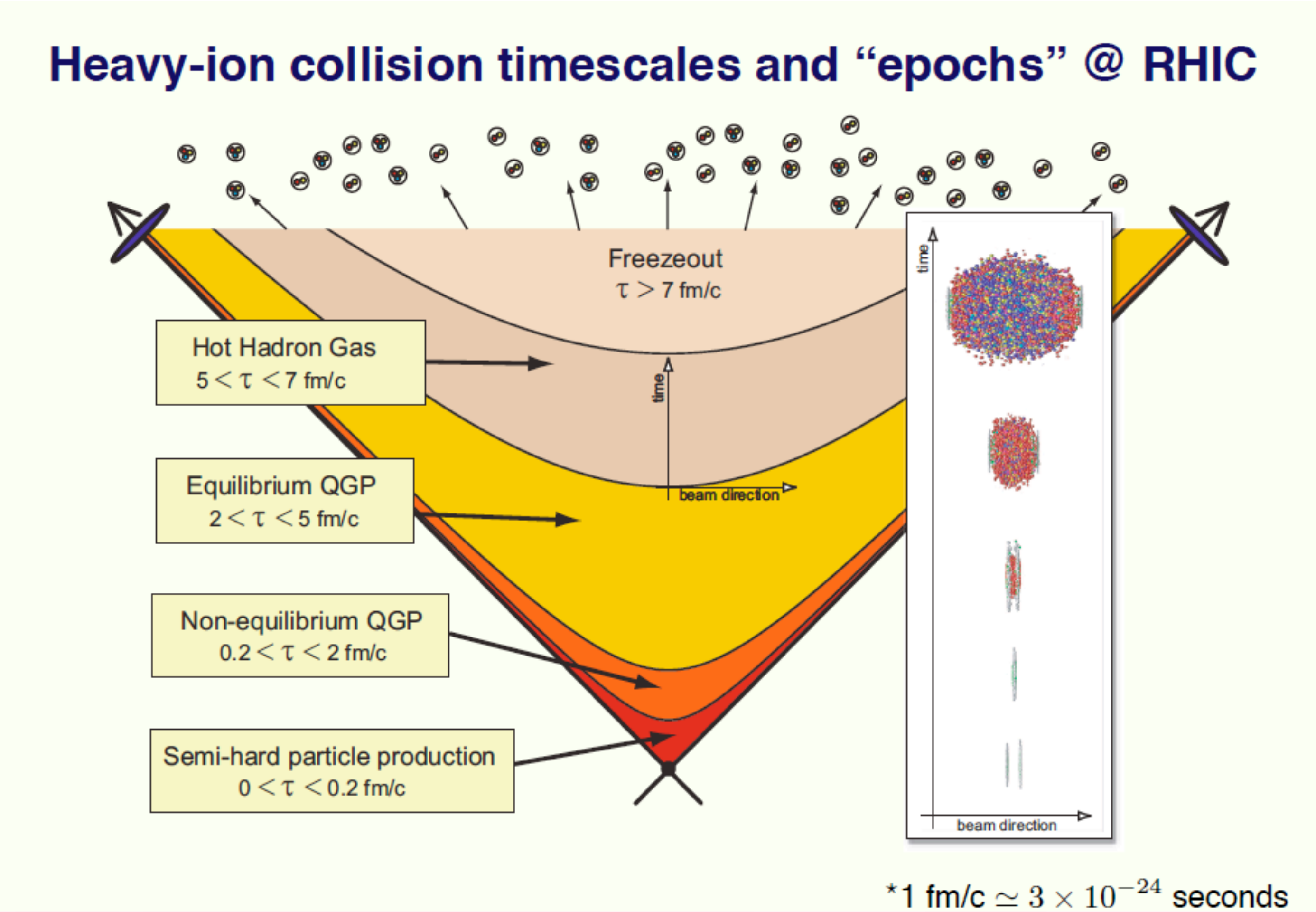
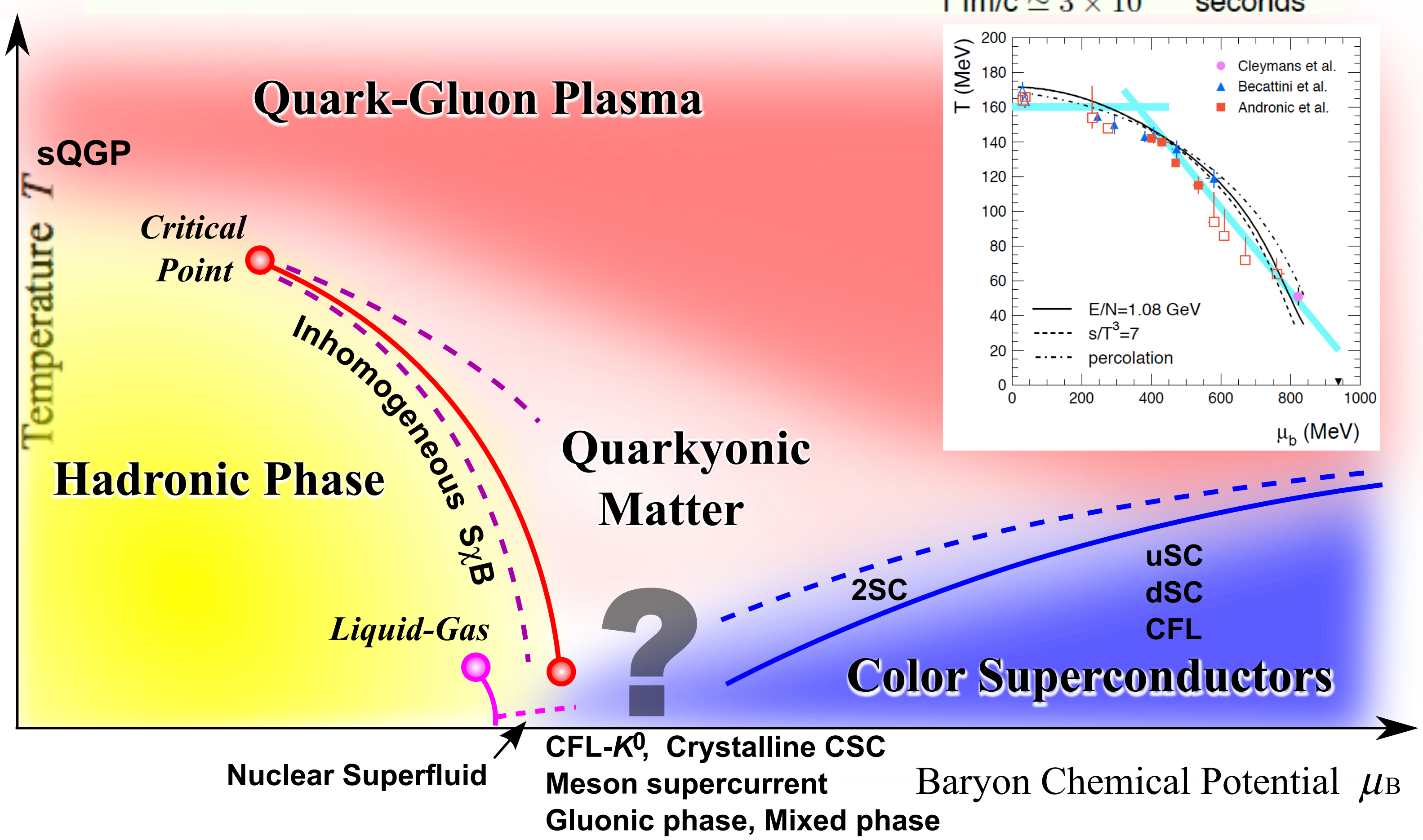
Outline

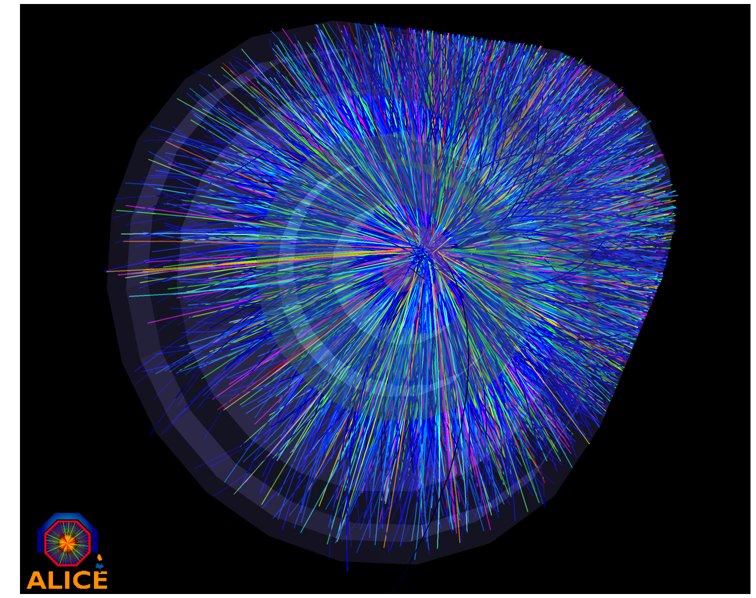
- Introduction
- Single particle spectral functions
- Spectral functions & transport coefficients
- Summary & outlook

Heavy ion collisions

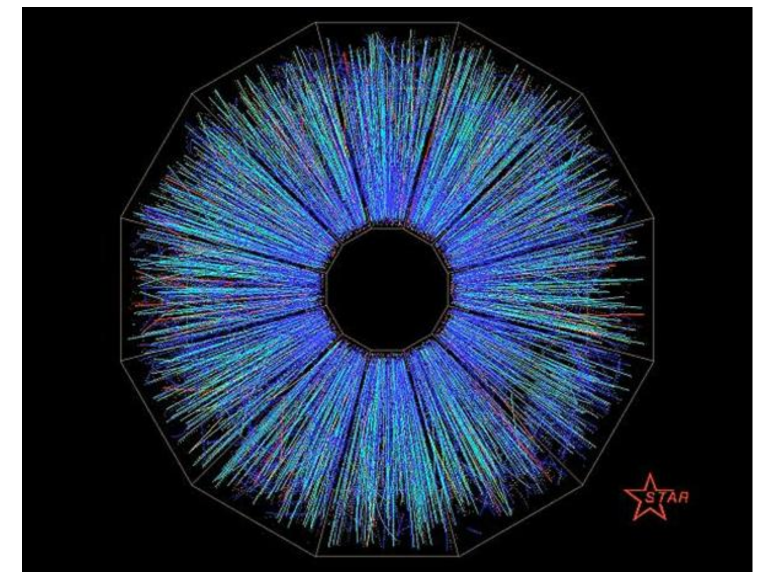




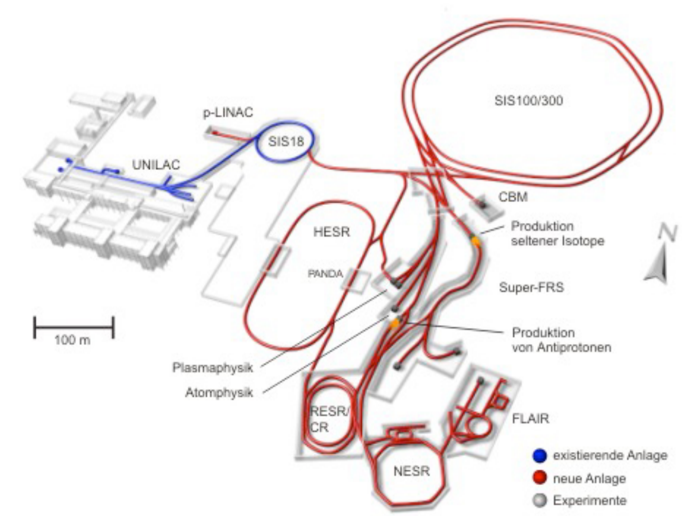
LHC



RHIC



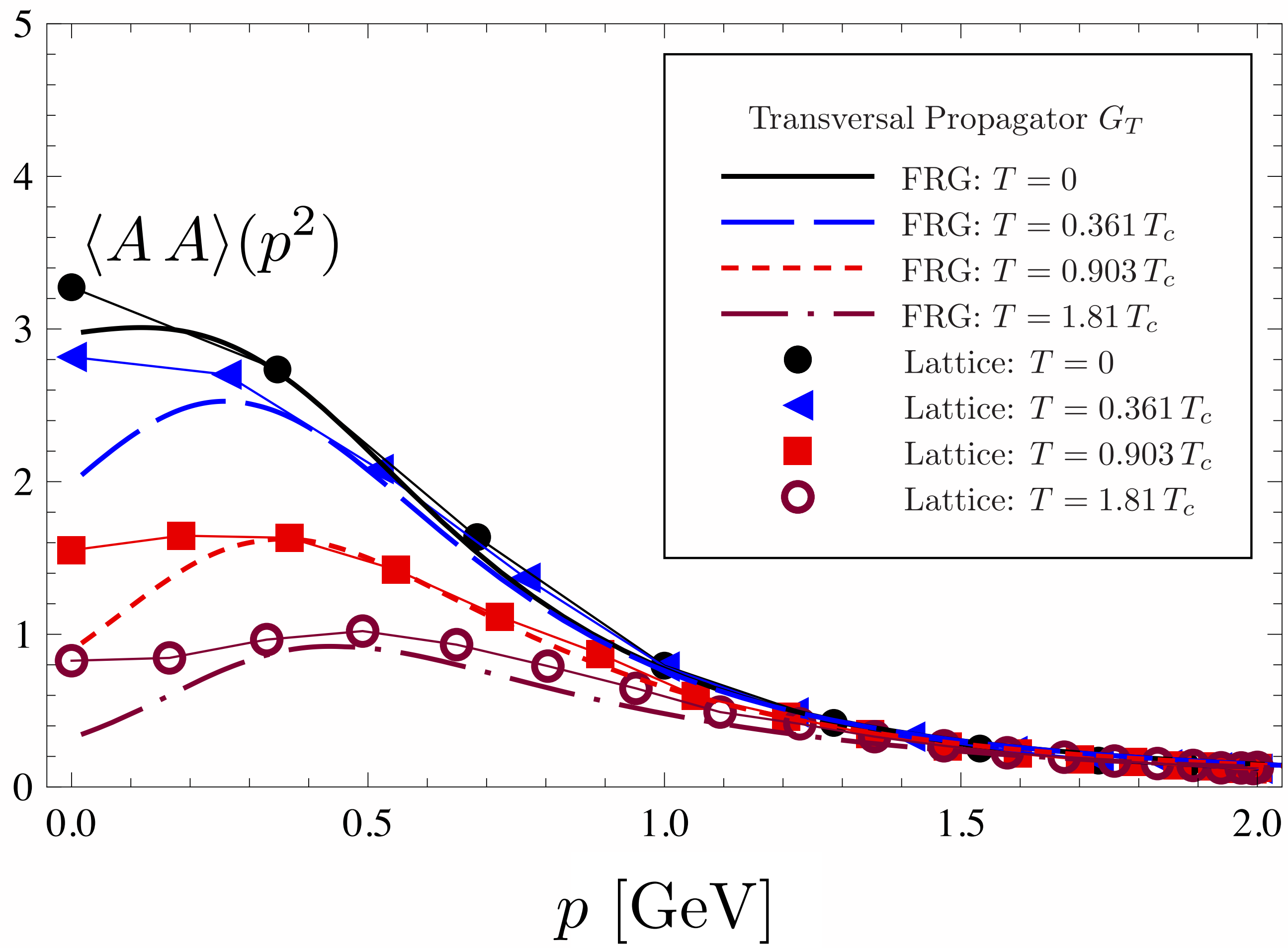
FAIR

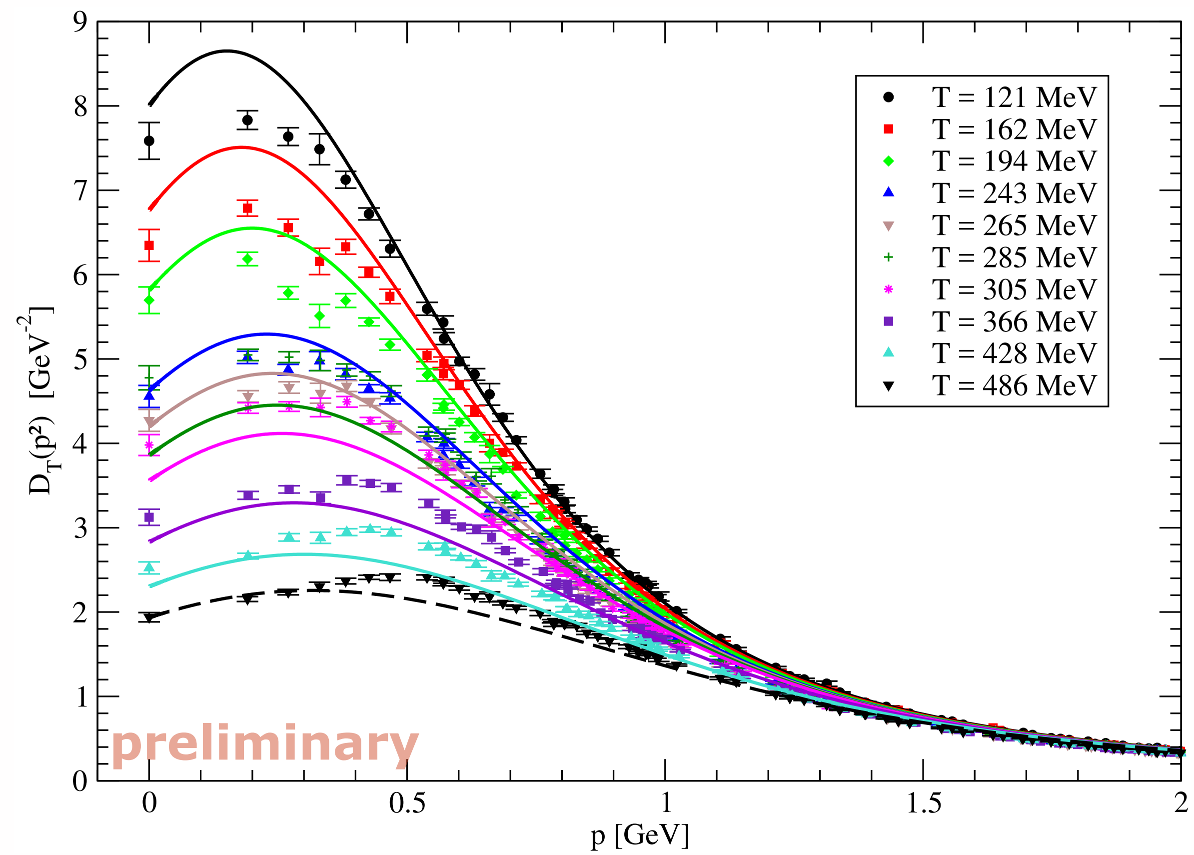


NICA

Euclidean gluon propagator

Yang-Mills propagators, finite T





Fister, JMP, arXiv:1112.5440

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

Cyrol, Mitter, JMP, Strodthoff, in preparation

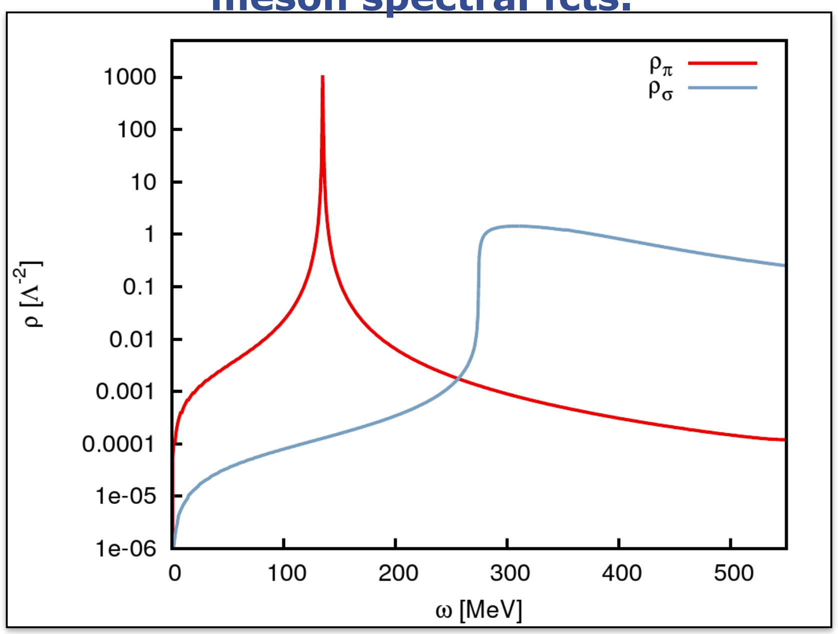
Lattice: Silva, Oliviera, Bicudo, Cardoso, PRD89 (2014) 7, 074503

see talks of A. Cyrol (FRG), M. Huber (DSE)

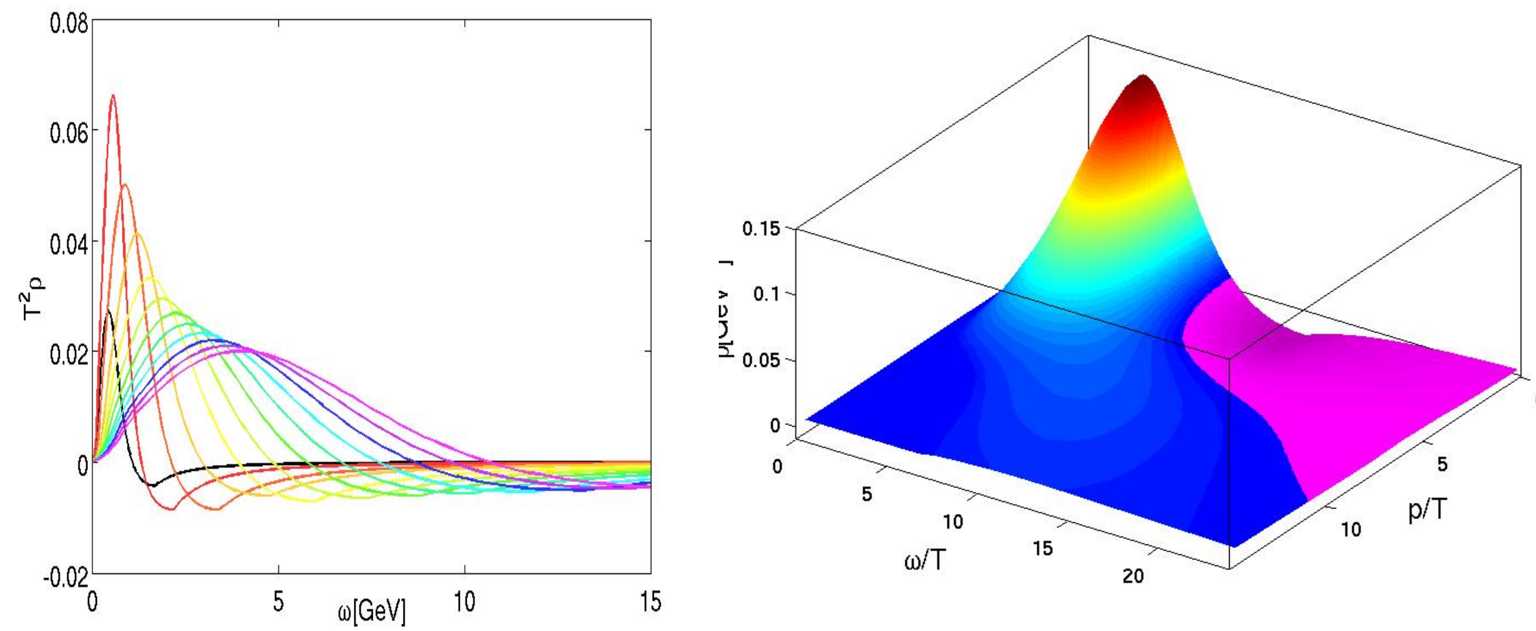
Summary & Outlook

▪ Spectral functions & transport coefficients

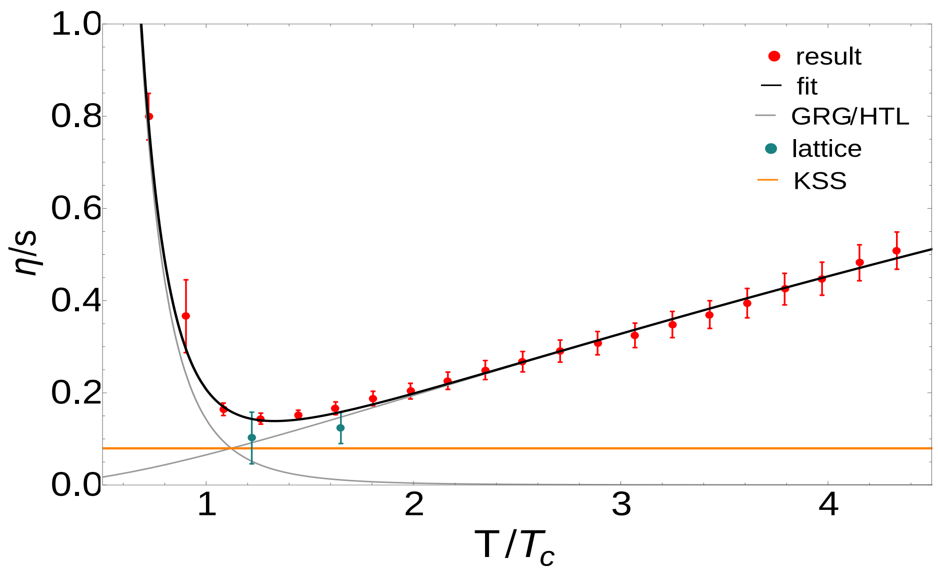
meson spectral fcts.



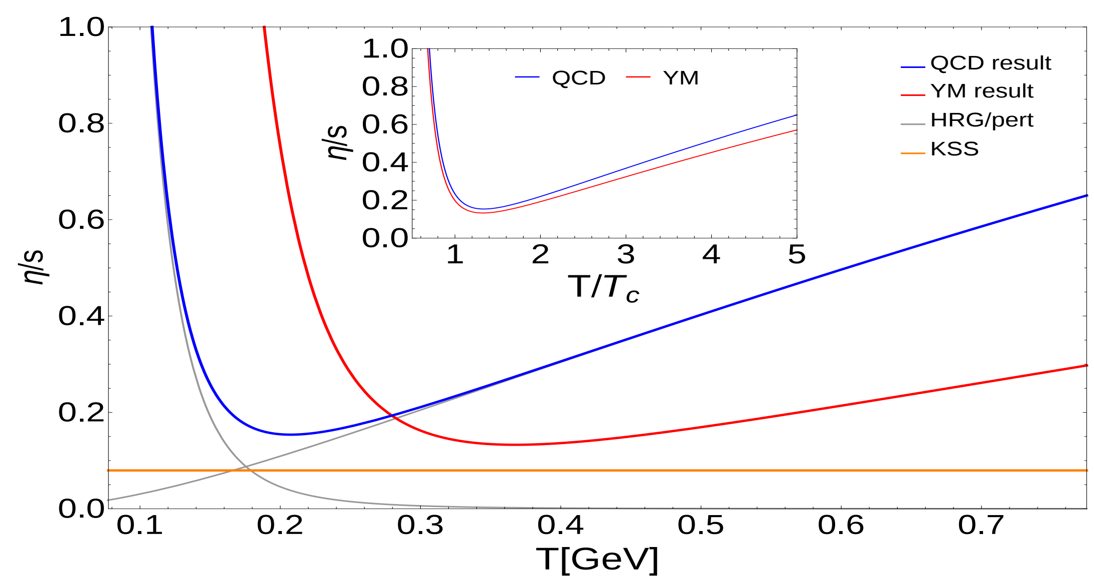
gluon spectral fcts.



glue viscosity/entropy



QCD estimate for eta/s



Summary & Outlook

- Single particle spectral functions

- transport coefficients

- direct computation of real time correlation functions in QCD

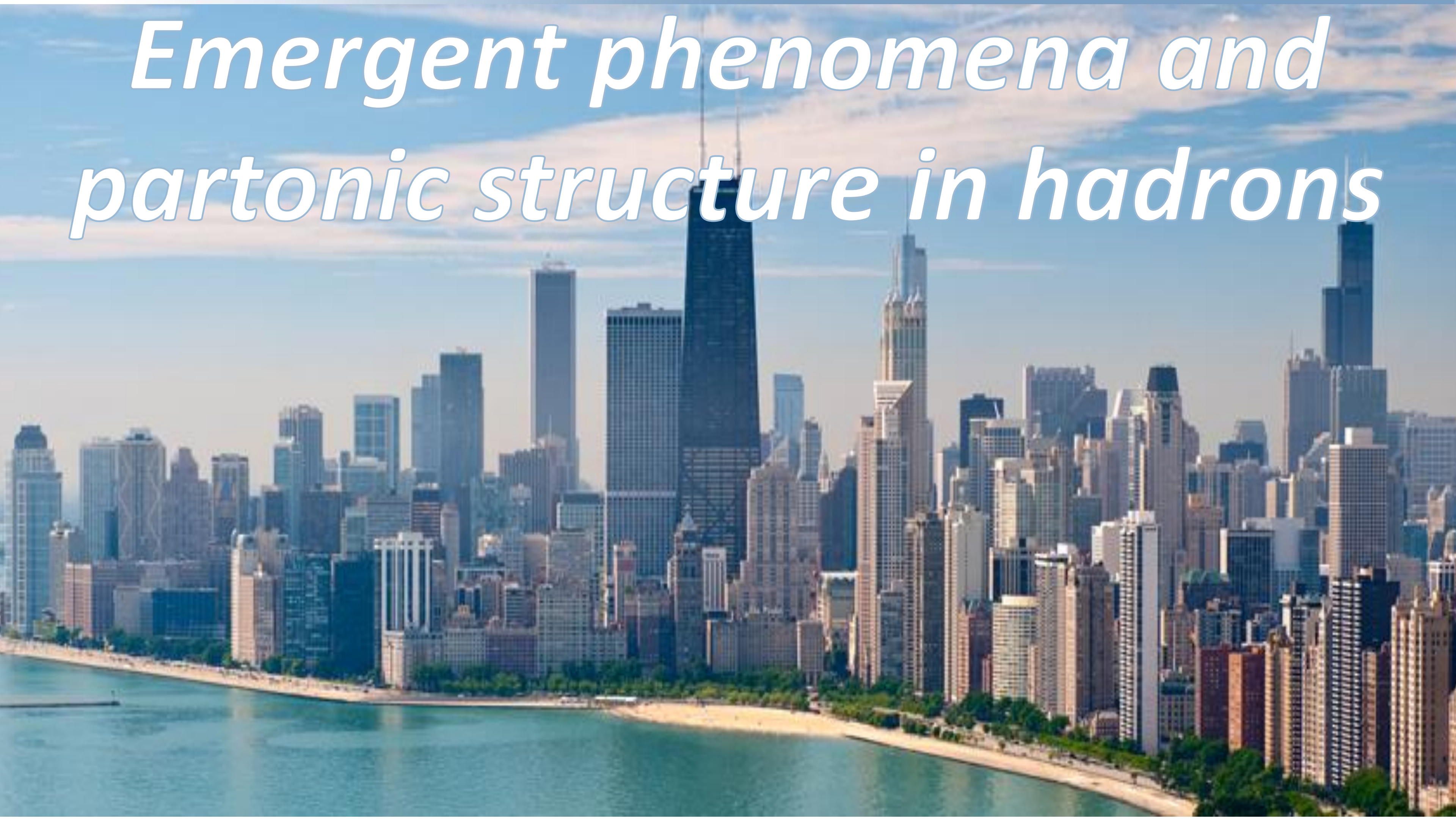
- bulk viscosity, relaxation time, ...

- Hadronic properties

  - glue balls, hadron spectrum & in medium modifications

  - low energy constants

Emergent phenomena and partonic structure in hadrons



Craig Roberts, Physics Division

Collaborators: 2013-Present

Students, Postdocs, Profs.

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2. *Jing CHEN (Peking U.)*
3. *Bo-Lin LI (Nanjing U.)*
4. *Ya LU (Nanjing U.)*
5. *Khépani RAYA (U Michoácan);*
6. *Chien-Yeah SENG (UM-Amherst) ;*
7. *Kun-lun WANG (PKU);*
8. *Chen CHEN (UNESP, São Paulo);*
9. *Zhu-Fang CUI (Nanjing U.) ;*
10. *J. Javier COBOS-MARTINEZ (U Michoácan);*
11. *Minghui DING (Nankai U.) ;*
12. *Fei GAO (Peking U.) ;*
13. *L. Xiomara Gutiérrez-Guerrero (Sonora U.);*
14. *Cédric MEZRAG (ANL, Irfu Saclay) ;*
15. *Mario PITSCHMANN (Vienna);*
16. *Si-xue QIN (ANL, U. Frankfurt am Main, PKU);*
17. *Eduardo ROJAS (Antioquia U.)*
18. *Jorge SEGOVIA (TU-Munich, ANL);*
19. *Chao SHI (ANL, Nanjing U.)*
20. *Shu-Sheng XU (Nanjing U.)*
21. Adnan Bashir (U Michoácan);
22. Daniele Binosi (ECT*)
23. Stan Brodsky (SLAC);
24. Lei Chang (Nankai U.) ;
25. Ian Cloët (ANL) ;
26. Bruno El-Bennich (São Paulo);
27. Roy Holt (ANL);
28. Tanja Horn (Catholic U. America)
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34. Jose Rodriguez Qintero (U. Huelva) ;
35. Franck Sabatié (CEA, Saclay);
36. Sebastian Schmidt (IAS-FZJ & JARA);
37. Peter Tandy (KSU);
38. Tony Thomas (U.Adelaide) ;
39. Shaolong WAN (USTC) ;
40. Hong-Shi ZONG (Nanjing U)

CLAY MATHEMATICS INSTITUTE

142 MILLENNIUM PRIZE PROBLEMS

YANG–MILLS EXISTENCE AND MASS GAP. *Prove that for any compact simple gauge group G, a non-trivial quantum Yang–Mills theory exists on* $\mathbb{R}^4$ *and has a mass gap* $\Delta > 0$. *Existence includes establishing axiomatic properties at least as strong as those cited in* [**45, 35**].

Confinement?

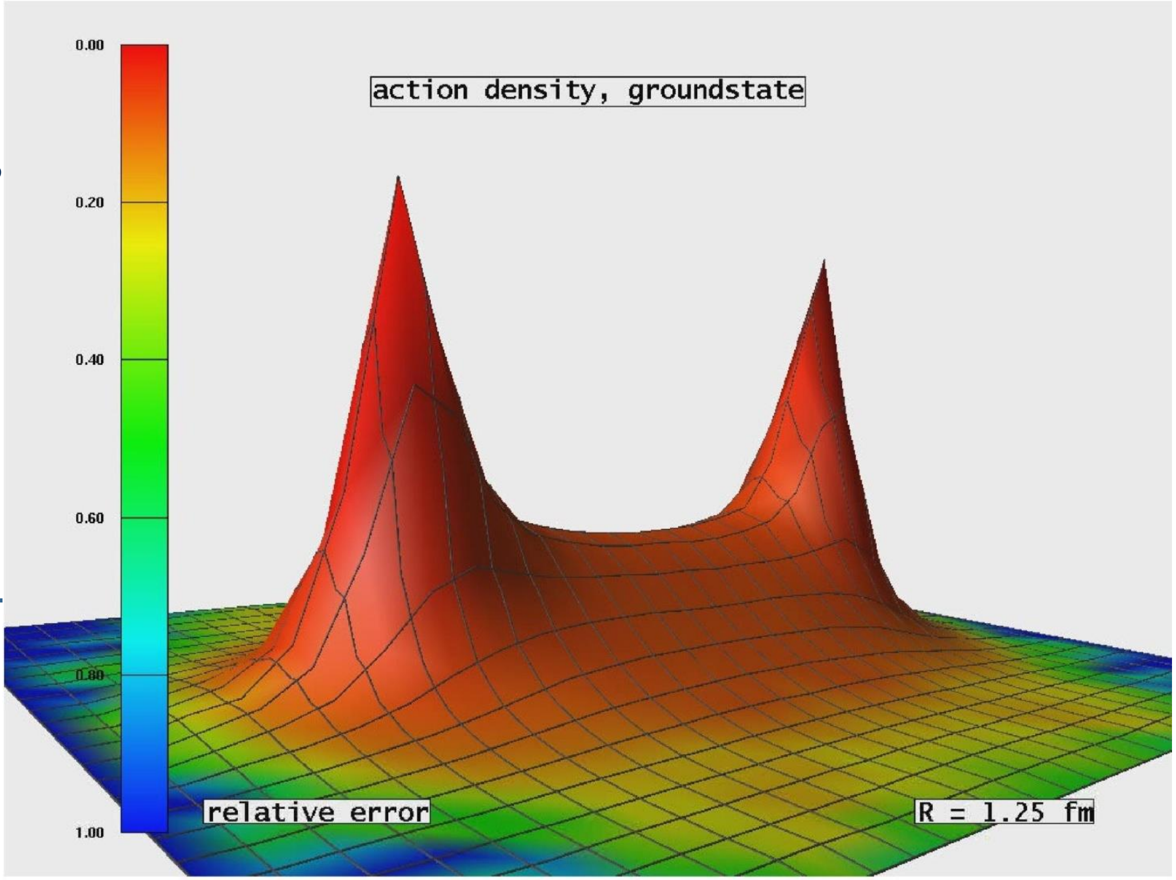
Light quarks & Confinement

- Folklore … *Hall-D Conceptual Design Report(5)*

"The color field lines between a quark and an anti-quark form flux tubes.

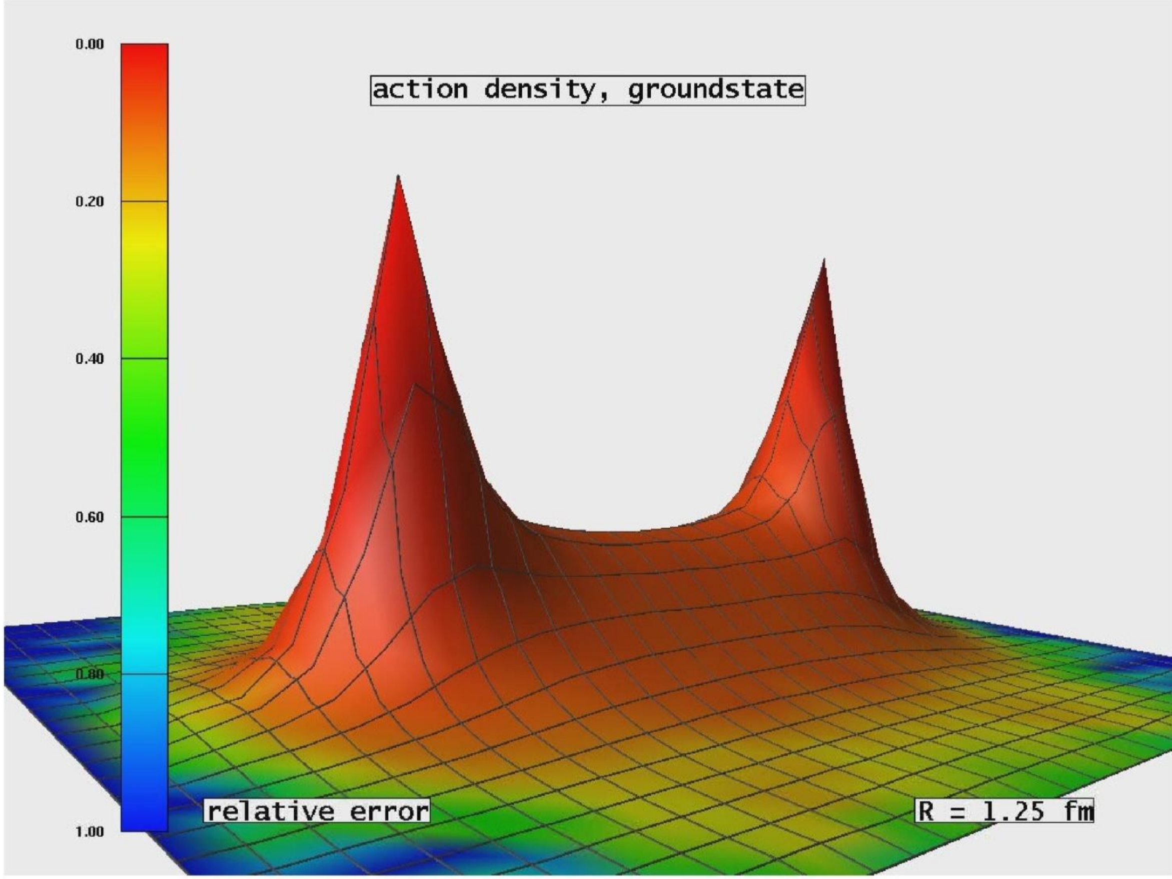
A unit area placed midway between the quarks and perpendicular to the line connecting them intercepts a constant number of field lines, independent of the distance between the quarks.

This leads to a constant force between the quarks – and a large force at that, equal to about 16 metric tons."



Light quarks & Confinement

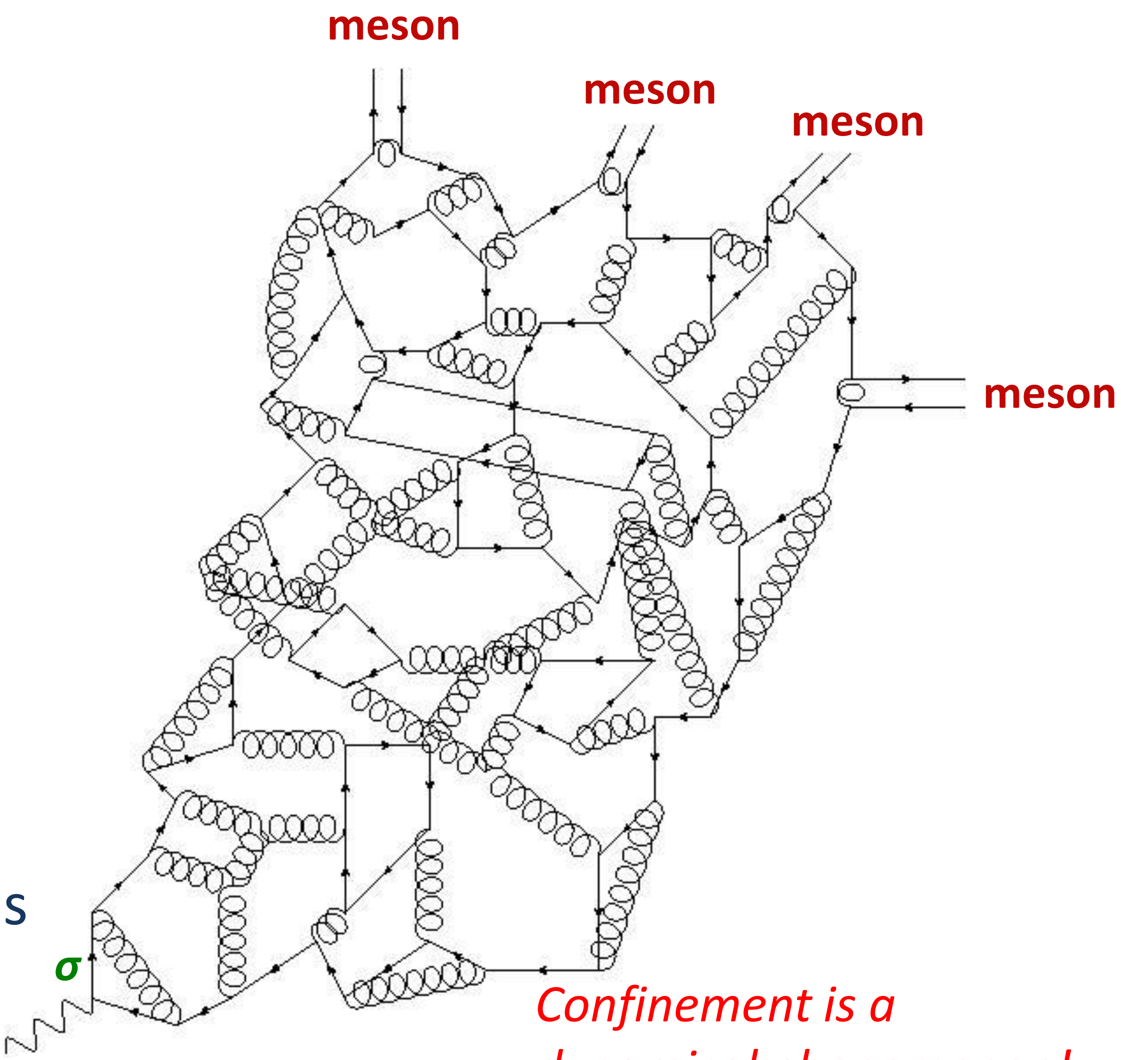
- In the presence of light quarks, *pair creation seems to occur non-localized and instantaneously*
- No flux tube in a theory with light-quarks.
- ***Flux-tube is not the correct paradigm for confinement in hadron physics***



Test: compute fragmentation functions & TMDs ⇒ compare with data

Quark Fragmentation

- A quark begins to propagate
- But after each "step" of length ***σ***, on average, an interaction occurs, so that the quark *loses* its identity, sharing it with other partons
- Finally, a cloud of partons is produced, which coalesces into colour-singlet final states



Confinement is a dynamical phenomenon!

Confinement from Center Vortices

a review of old and new results

Jeff Greensite
San Francisco State University

QCHS 12
Thessaloniki, Greece

August 2016

Old (and very old) work, reviewed in

- *The confinement problem in lattice gauge theory*, Prog. Part. Nucl. Phys. 51 (2003) 1, hep-lat/0301023.
- *An introduction to the confinement problem*, Springer Lect.Notes Phys. 821 (2011).
- Michael Engelhardt, *Lattice 2004 plenary*, Nucl.Phys.Proc.Suppl. 140 (2005) 92-105, hep-lat/0409023.

Newer work:

- Center vortices and chiral symmetry breaking *(Leinweber, Kamleh, and Trewartha)*
- Double-winding loops and implications for monopole/dyon confinement mechanisms *(Höllwieser & J.G)*

Motivation II

Focus on large vacuum fluctuations at all (large) scales: Confinement as the phase of magnetic disorder.

Which means:

- Wilson loop area law for all sufficiently large Wilson loops.
- Non-zero asymptotic string tension.

Defined in this way, confined and non-confined phases are distinguished by a symmetry, where

Confinement is the phase of unbroken center symmetry

Examples:

- gauge theories with Higgs fields in the adjoint representation
- the finite temperature deconfinement transition for pure gauge theories
- “string breaking:" matter fields which break center symmetry explicitly

Order parameters:

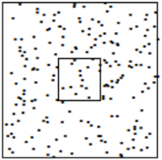
- Polyakov lines: $\langle P \rangle = 0$ in the confined phase.
- 't Hooft loops $B(C)$ are center vortex creation operators, which are "dual" to Wilson loops operators. They have a perimeter-law falloff in the confined phase.
- Center vortex free energy. Impose twisted boundary conditions to define the partition function Z_V, the vortex is oriented in the $L_z - L_t$ plane. Then

$$F_v = -\log \frac{Z_v}{Z_0} \quad , \quad \text{confinement if:} \quad F_v = L_z L_t e^{-\rho L_x L_y}$$

(Tomboulis and Jaffe (1985))

Confinement from Center Vortices

N vortices pierce a plane of area L^2 at random locations. The probability that n vortices will fall inside a loop of area A is



$$P_N(n) = \left(\begin{array}{c} N \\ n \end{array} \right) \left(\frac{A}{L^2}\right)^n \left(1 - \frac{A}{L^2}\right)^{N-n}$$

In SU(2) each vortex contributes a factor of -1, so

$$W(C) = \sum_{n=0}^{N} (-1)^n P_N(n) = \left(1 - \frac{2A}{L^2}\right)^N$$

Keep the vortex density $\rho = N/L^2$ fixed, taking $N, L \to \infty$, gives the Wilson loop area law falloff

$$W(C) = \lim_{N\to\infty} \left(1 - \frac{2\rho A}{N}\right)^N = e^{-2\rho A}$$

(The argument in this form is due to Engelhardt, Reinhardt et al. (1998).)

Chiral Symmetry Breaking

Some (relatively) new results from the Adelaide group (Kamleh, Leinweber, and Trewartha (2015)) in SU(3). They calculate the Landau gauge quark propagator using the overlap Dirac operator, for

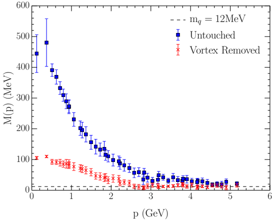
- full ("untouched")
- vortex-removed
- center projected ("vortex only") after some cooling steps

and fit to the form

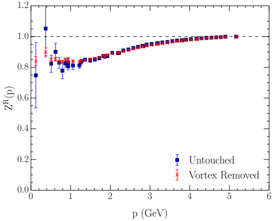
$$S(p) = \frac{Z(p)}{i\not{p} + M(p)}$$

It is found that after some smoothing, *the non-perturbative properties of full and vortex-only configurations are about the same!*

Here is what they find for full and vortex-removed:



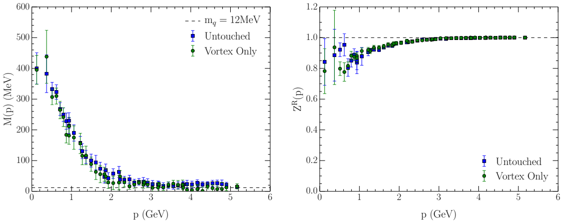
(a)



(b)

Figure : The mass (a) and renormalisation (b) functions on the original (untouched) (squares) and vortex-removed (crosses) configurations. Removal of the vortex structure from the gauge fields spoils dynamical mass generation and thus dynamical chiral symmetry breaking.

In contrast, cooled vortex-only looks about the same as full:



(a) (b)

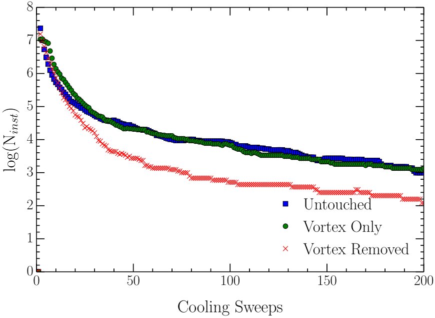
Figure : The mass(a) and renormalisation (b) functions on the original (untouched) (squares) and vortex-only (circles) configurations after 10 sweeps of three-loop $\mathcal{O}(a^4)$-improved cooling, at an input bare quark mass of 12 MeV.

String tensions also agree, and the hadron spectra are very similar.

Vortices and Instantons?

From Leinweber et al.:

"By examining the local maxima of the action density on vortex-only configurations during cooling, we find that after just 10 sweeps of cooling these local maxima stabilize, and begin to resemble classical instantons in shape and corresponding topological charge density at the center."



The authors speculate that center vortices contain the "seeds" of instantons, which are reproduced upon cooling.

The Adelaide group also computed low-lying hadron masses in vortex-only and vortex-removed ensembles. Results:

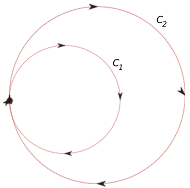
- The vortex-only spectrum is very similar to full QCD.
- The vortex-removed spectrum
  - shows chiral symmetry restoration for light quarks;
    pion is no longer a Goldstone boson.
  - is a weakly-interacting theory of constituent quarks at heavy quark masses.

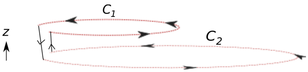
We consider, in SU(2) gauge theory, double-winding Wilson loops, coplanar and shifted:

computed according to

1. monopole/dyon plasma
2. dual superconductor
3. center vortex

theories of confinement.

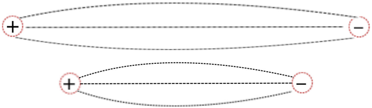




Loops C_1, C_2 have areas A_1, A_2 respectively.
Ignore, initially, effects of "W"-bosons. We will return to them.

double-winding II

In the dual superconductor, by the dual Meissner effect, there are two flux sheets bounded by C_1 and C_2. For loops in the RT-plane, there are two flux tubes in a time-slice.



This leads to a *sum-of-areas* falloff for the double-winding loop

$$W(C) \sim \exp[-\sigma(A_1 + A_2)]$$

In the case of a monopole or dyon plasma, following Polyakov and Diakonov-Petrov, there is a soliton spanning A_1 and another soliton spanning A_2. *This leads again to a sum-of-areas law.*

Intuitively: two current loops in a monopole plasma are screened by two monopole-antimonopole sheets along A_1 and A_2.

In particular, following Polyakov's classic calculation for U(1) gauge theory in D=3:

$$\langle W(C)\rangle = \frac{1}{Z_{mon}}\int D\chi(r)\ \exp\Big[-\frac{g^2}{4\pi}\int d^3r\ \Big(\frac{1}{2}(\partial_\mu(\chi-\eta_{S(C)})^2 - M^2\cos\chi(r)\Big)\Big]$$

where

$$-\partial^2\eta_{S(C)} = 2\pi\delta'(z)\theta_{S_2}(x,y) + 2\pi\delta'(z-\delta z)\theta_{S_1}(x,y)$$

and $\theta_{S_{1(2)}}(x,y) = 1$ if x, y lie in the minimal area of C_1 (C_2), and is zero otherwise. Assuming $\delta z \gg 1/M$, an approximate saddlepoint solution is the superposition

$$\begin{aligned}\chi &= \mathrm{sign}\, z\cdot 4\arctan(e^{-M|z|})\,\theta_{S_2}(x,y)\\ &\quad + \mathrm{sign}\,(z-\delta z)\cdot 4\arctan(e^{-M|z-\delta z|})\,\theta_{S_1}(x,y)\end{aligned}$$

leading to the sum-of-areas law.

In contrast, the prediction of the vortex mechanism is a *difference-of-areas* falloff

$$W(C) \sim \exp[-\sigma|A_2 - A_1|]$$

This is because a vortex only multiplies by a center element if it passes through the larger loop, but not the smaller loop

The numerical evidence is very clearly in favor of *difference-of-areas* falloff. (Roman Höllwieser and J.G., arXiv:1411.5091)

Conclusions: On the one hand...

Center vortices provide a plausible & well-motivated mechanism for

1. confinement
2. deconfinement
3. chiral symmetry breaking
4. generation of topological charge

It is not just a model. Center vortices are found in lattices generated by computer simulations, and

1. Vortex density scales according to asymptotic freedom.
2. Vortex-only configurations account (more-or-less accurately) for the observed asymptotic string tension, chiral symmetry breaking, instanton density, and hadron spectron.
3. i.e. smoothed vortex-only configurations are *almost identical*, in their non-perturbative properties, to full configurations.
4. Vortex-removed configurations are completely different (no confinement, no chiral sym breaking, etc.)

Conclusions: on the other hand...

1. This mechanism does not lend itself to analytical treatment.
2. A simple, effective theory of center vortices, having many of the features of infrared QCD, can be simulated numerically (Michael Engelhardt). But then it can be argued...
3. you might as well just simulate QCD.

For *solving* QCD, we have lattice Monte Carlo.

Understanding QCD may simply be a different problem.

Confinining properties of QCD in strong magnetic backgrounds

Massimo D'Elia

University of Pisa & INFN

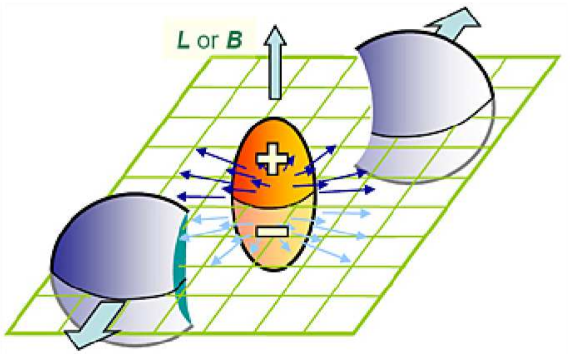
Based on arXiv:1607.08160, in collaboration with

C. Bonati, M. Mariti, M. Mesiti, F. Negro, A. Rucci and F. Sanfilippo

XII Quark Confinement and the Hadron Spectrum - Thessaloniki, 2 September 2016

QCD IN EXTERNAL MAGNETIC BACKGROUNDS

Quarks are subject to electroweak interactions, which in general induce small corrections to strong interaction dynamics. Exceptions are expected in the presence of strong e.m. backgrounds, a situation relevant to many contexts:

- **Large magnetic fields are expected in a class of neutron stars known as magnetars ($B \sim 10^{10}$ Tesla on the surface) (Duncan-Thompson, 1992).**
- **Large magnetic fields ($B \sim 10^{16}$ Tesla, $\sqrt{|e|B} \sim 1.5$ GeV), may have been produced at the cosmological electroweak phase transition (Vachaspati, 1991).**
- 

  in non-central heavy ion collisions, largest magnetic fields ever created in a laboratory (B up to 10^{15} Tesla at LHC) with a possible rich associated phenomenology (e.g., chiral magnetic effect)

Numerical QCD+QED studies go back to the early days of LQCD

- G. Martinelli, G. Parisi, R. Petronzio and F. Rapuano, Phys. Lett. B 116, 434 (1982).
- C. Bernard, T. Draper, K. Olynyk and M. Rushton, Phys. Rev. Lett. 49, 1076 (1982).

An e.m. background field a_μ modifies the covariant derivative as follows:

$$D_\mu = \partial_\mu + i\,g A^a_\mu T^a \quad \rightarrow \quad \partial_\mu + i\,g A^a_\mu T^a + i\,q a_\mu$$

in the lattice formulation:

$$D_\mu \psi \rightarrow \frac{1}{2a}\left(U_\mu(n) u_\mu(n) \psi(n+\hat{\mu}) - U^\dagger_\mu(n-\hat{\mu}) u^*_\mu(n-\hat{\mu}) \psi(n-\hat{\mu})\right)$$

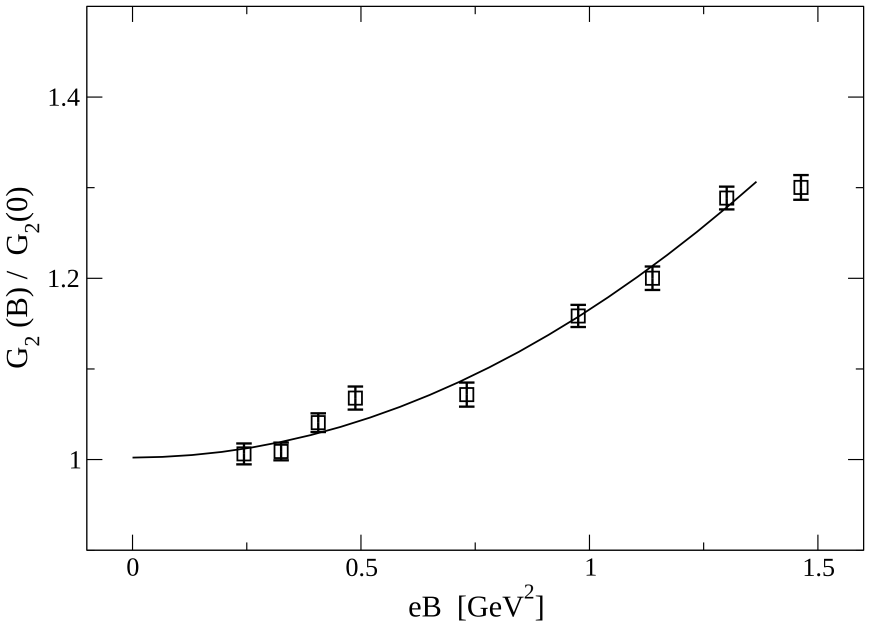
$U_\mu \in SU(3) \qquad \mathbf{u}_\mu \simeq \exp(\mathbf{i}\,\mathbf{q}\,\mathbf{a}_\mu(\mathbf{n})) \in \mathbf{U(1)}$

- $F^{(em)}_{ij} \neq 0 \implies$ **non-zero magnetic fiel (no sign problem)**
- $F^{(em)}_{0i} \neq 0 \implies$ **non-zero imaginary electric field (sign problem for real e. f.)**
- **Uniform background field are quantized in the presence of periodic boundary conditions**

Recent years have seen an increasing activity in the lattice study of QCD in magnetic backgrounds (with significant contributions coming from two friends that we miss, Michael Müller-Preussker and Misha Polikarpov) An incomplete summary of results:

Magnetic catalysis (increase of chiral symmetry breaking) of the QCD vacuum has been extensively verified (P. V. Buividovich et al. 2010; MD, F. Negro, 2011; G. S. Bali et al. 2012; E.-M. Ilgenfritz et al., 2012, 2014)

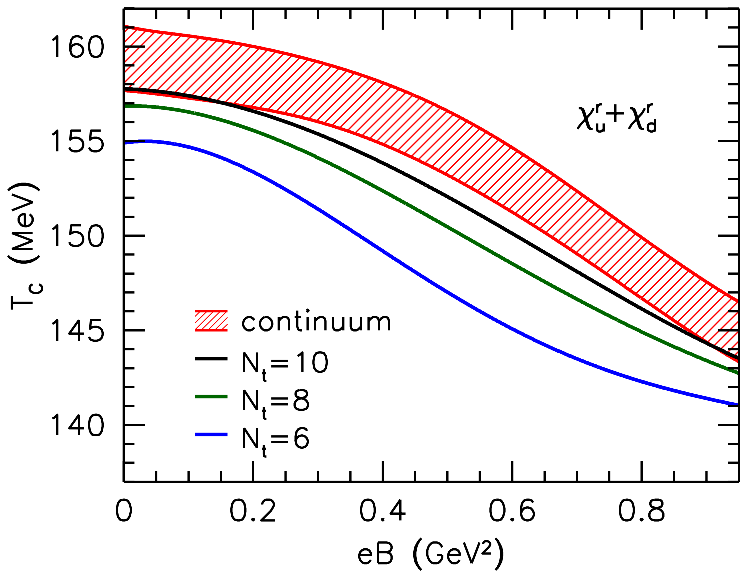
A large effect on gluon fields manifests in anisotropies of gauge observable and in an increase of the gluon condensate as a function of B (gluon magnetic catalysis) (M. Ilgenfritz et al, arXiv:1203.3360; G. Bali et al., arXiv:1303.1328; MD, M. Mesiti, E. Meggiolaro and F. Negro, arXiv:1510.07012)



from arXiv:1510.07012

The magnetic field has strong effects also on QCD thermodynamics and leads to a decrease of the pseudo-critical temperature (inverse magnetic catalysis)

G. S. Bali et al., arXiv:1111.4956

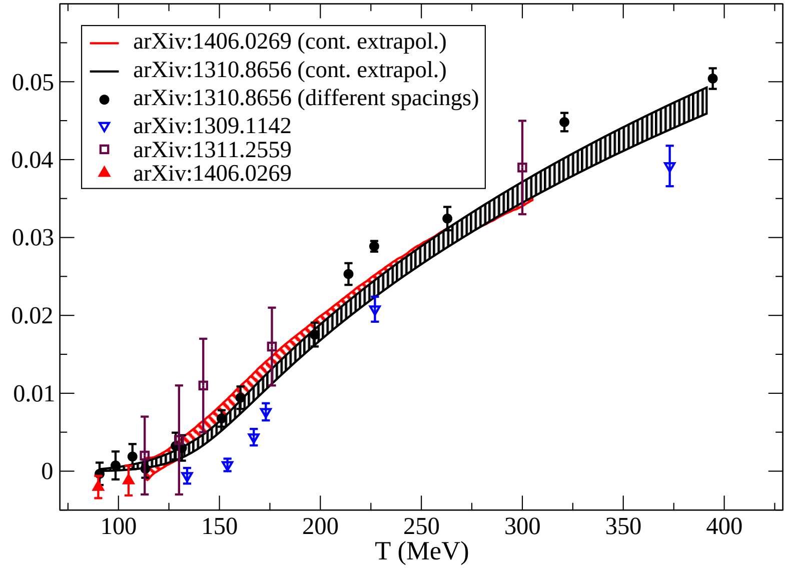


The thermal QCD medium becomes strongly paramagnetic right above T_c

C. Bonati et al., arXiv:1307.8063, arXiv:1310.8656;

L. Levkova and C. DeTar, arXiv:1309.1142;

G. S. Bali et al., arXiv:1406.0269



magnetic susceptibility

Focus of this talk:

Effects of the magnetic field on the static quark potential

- A previous study has shown that the quark-antiquark potential becomes anisotropic, with a string tension smaller (larger) in the direction parallel to $\vec{B}$

  (C. Bonati et al., arXiv:1403.6094)

- The issue is interesting both by itself and for possible phenomenological consequences, e.g. for heavy quark bound states.

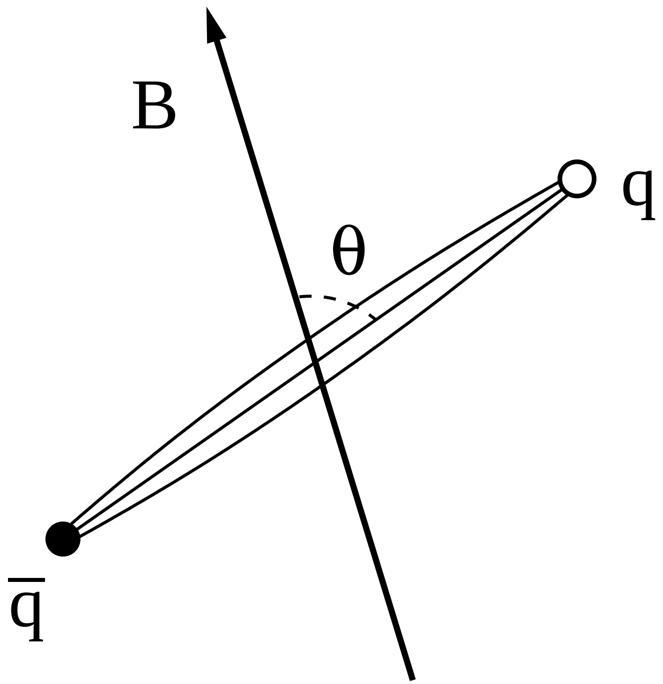
In this talk I discuss results reported in arXiv:1607.08160 (C. Bonati et al.), which try to achieve the following goals:

- A complete determination of the angular dependence of the potential
- An extrapolation to the continuum limit
- An extension to finite temperature

For non-zero background field $\vec{B}$, we want to study the potential not just for parallel or orthogonal directions, but for generic orientations.

In principle, one can either rotate the spatial side of the Wilson loop, or rotate $\vec{B}$ and perform new simulations.

Rotating the loop on the lattice introduces new cusps and renormalization effects, so we chose the second solution



Each component of the field gets quantized in the presence of spatial periodic b.c.

$$eB_x = 6\pi b_x/(a^2 N_z N_y)\,; \quad b_x \in \mathbb{Z}$$

$$eB_y = 6\pi b_y/(a^2 N_x N_z)\,; \quad b_y \in \mathbb{Z}$$

$$eB_z = 6\pi b_z/(a^2 N_x N_y)\,; \quad b_z \in \mathbb{Z}$$

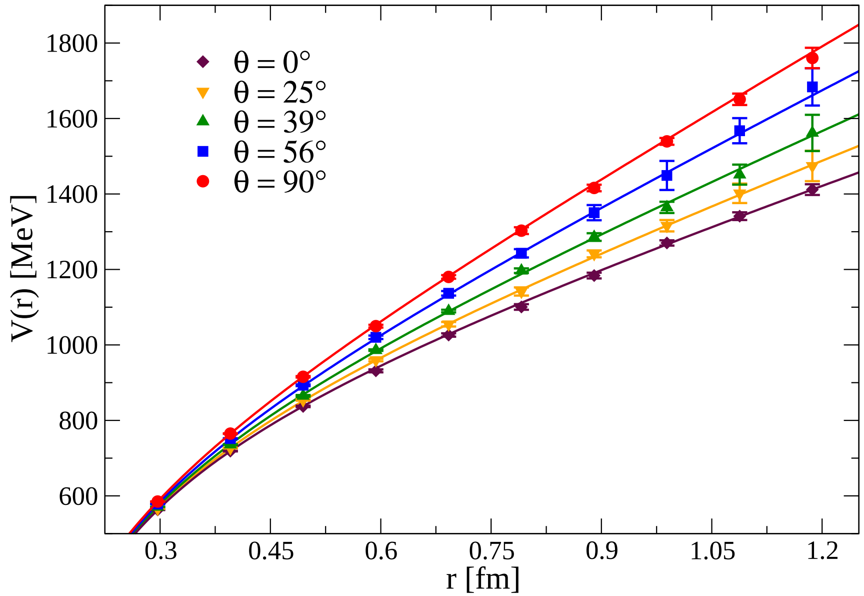
we performed different simulations at fixed $B_x^2 + B_y^2 + B_z^2$ and different $\vec{B}$ orientations

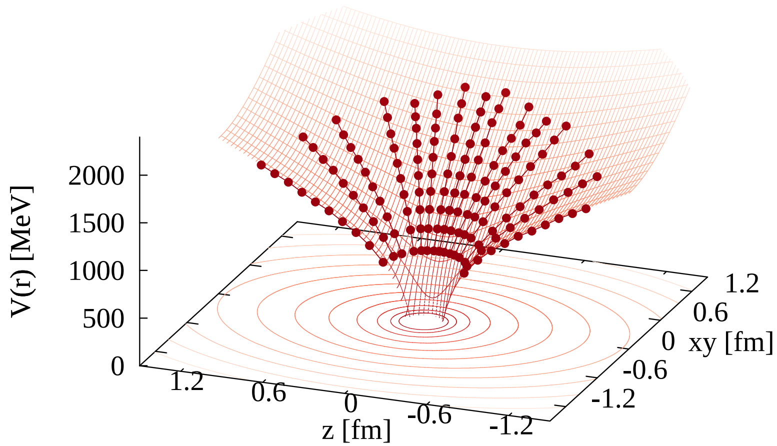
RESULTS

- **full angular dependence studied at just two lattice spacings, $a \simeq 0.1, 0.15$ fm and for $eB \sim 1$ GeV^2. Results shown for $a \sim 0.1$ fm**

- **At fixed r, the potential is an increasing function of the angle and reaches a maximum for orthogonal directions**

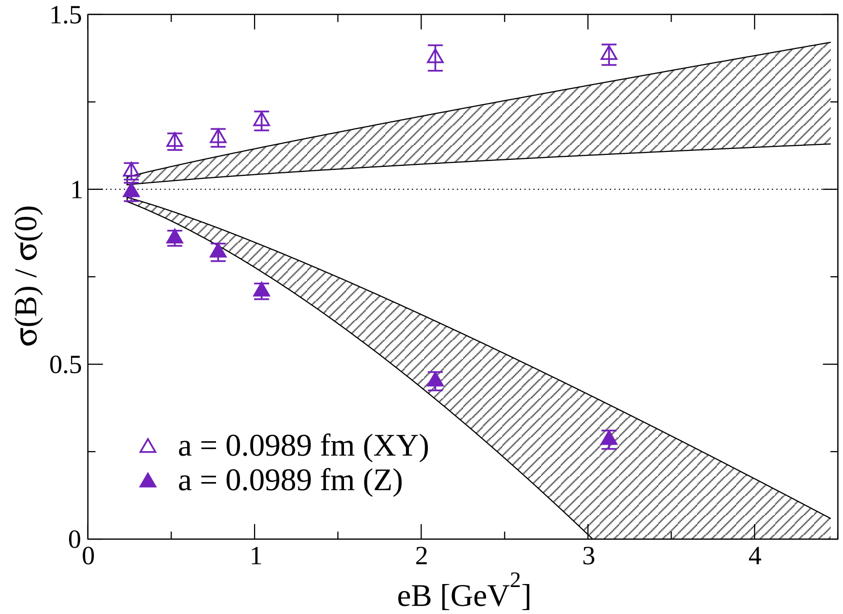
- **Our ansatz works well ($\chi^2/d.o.f. \sim 1$) with only the first term in the expansion $c_2 \neq 0$ (quadrupole-like deformation)**





The continuum extrapolated results for σ predict a vanishing longitudinal string tension for $eB \sim 4$ GeV^2

This is outside the range explored for the continuum extrapolation, $eB \lesssim 1$ GeV^2.
Can we trust the prediction?



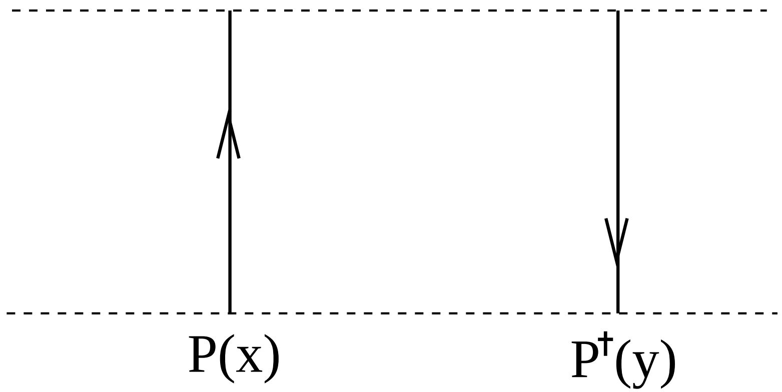
Cut-off effects are large for $eB \gtrsim 1/a^2$. We could extend to larger B just on the finest lattice spacing.

The decrease of $\sigma_{\|}$ is steady, even if it somewhat undershoots the continuum band extrapolated to large B.
Simulations at finer lattice spacings should clarify the issue in the future.

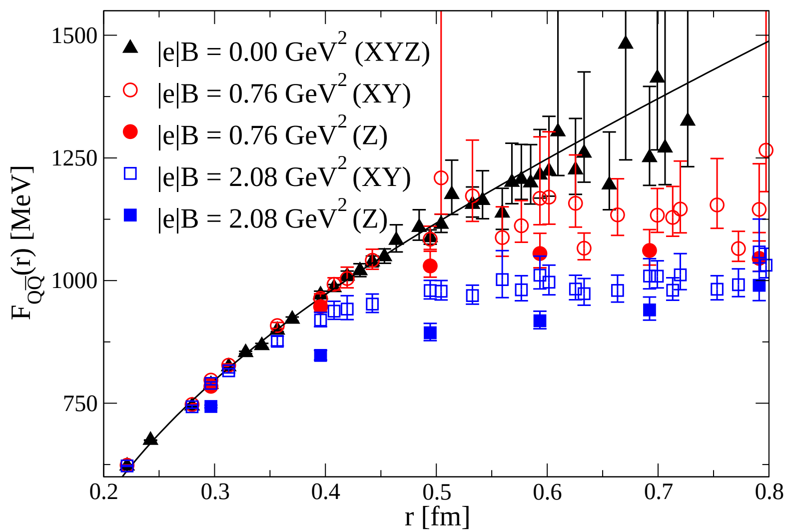
Finite T results

At finite T, the quark-antiquark potential is measured from Polyakov loop correlators

$$\langle \mathrm{Tr} P(\vec{x})\, \mathrm{Tr} P^{\dagger}(\vec{y}) \rangle \sim \exp\left(-\frac{F_{\bar{q}q}(r,T)}{T} \right)$$



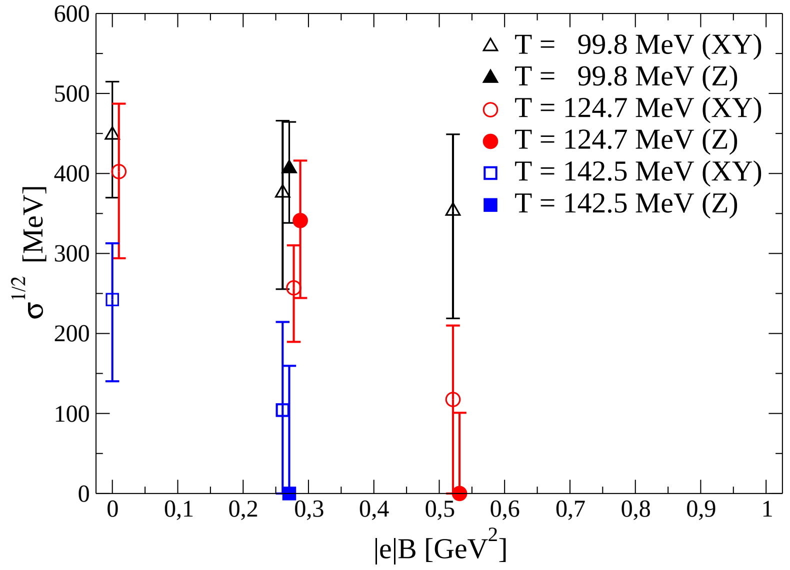
Results at $T \sim 100$ MeV on a $N_t = 20$ lattice



Although a small anisotropy is still visible, the main effect of B seems to suppress the potential in all directions

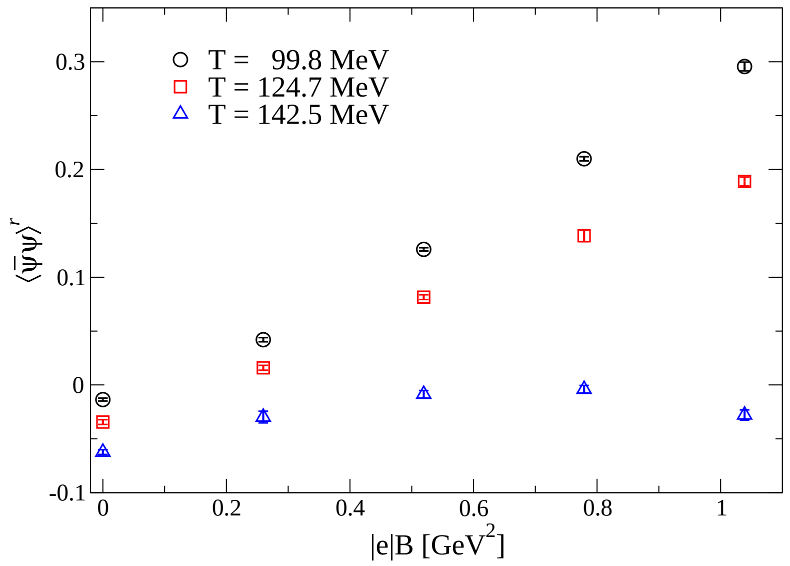
The string tension tends to disappear

A fit to the Cornell potential works in a limited range of distances and permits to obtain a determination of σ, which shows a steady decrease in all directions.



We can call this effect deconfinement catalysis

It is interesting to notice that this happens before (in temperature) inverse magnetic catalysis is visible in the chiral condensate



Is the decrease of T_c as a function of B related to a change in the confining properties?

CONCLUSIONS

- **The magnetic field leads to a quadrupole-like deformation of the static quark-antiquark potential**

- **Most of the effect seems related to a modification of the string tension**

- **We have hints that $\sigma_{||}$ could vanish in the vacuum for eB of the order of 10 GeV. Future simulations on finer lattice spacings could confirm this possibility.**

- **At finite T, the main effect is a general suppression of the potential leading to a precocious loss of confining properties: deconfinement catalysis.**
  That could be important for heavy ion physics in the thermal medium, think for instance of J/ψ suppression and related issues.

Recent progress in understanding deconfinement and chiral restoration phase transitions

Edward Shuryak

Stony Brook University

Confinement 12
Thessaloniki
Aug.2016

Outline

General comments: Three complementary views on hadronic matter, deconfinement and chiral restoration phase transitions

- **Instanton-dyons and their ensembles in QCD-like theories**
- **analytic (mean field) approach for dense ensemble (T<Tc) (1503.03058, 1503.09148 with Lui and Zahed)**
- **numerical studies at all densities: deconfinement (1504.03341 with Larsen) and chiral restoration (Nc=Nf=2)**
- **both transitions so strongly depend on quark periodicity phases that it nearly uniquely fixes the mechanism (1605.07474 with Larsen)**

Confining Dyon-Anti-Dyon Coulomb Liquid Model I

Yizhuang Liu,* Edward Shuryak,† and Ismail Zahed‡
Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA

(Dated: April 9, 2015)

We revisit the dyon-anti-dyon liquid model for the Yang-Mills confining vacuum discussed by Diakonov and Petrov, by retaining the effects of the classical interactions mediated by the streamline between the dyons and anti-dyons. In the SU(2) case the model describes a 4-component strongly interacting Coulomb liquid in the center symmetric phase. We show that in the linearized screening approximation the streamline interactions yield Debye-Huckel type corrections to the bulk parameters such as the pressure and densities, but do not alter significantly the large distance behavior of the correlation functions in leading order. The static scalar and charged structure factors are consistent with a plasma of a dyon-anti-dyon liquid with a Coulomb parameter $\Gamma_{D\bar{D}} \approx 1$ in the dyon-anti-dyon channel. Heavy quarks are still linearly confined and the large spatial Wilson loops still exhibit area laws in leading order. The t′ Hooft loop is shown to be 1 modulo Coulomb corrections.

$$
\begin{aligned}
\mathcal{Z}_{D\bar{D}}[T] \quad &\equiv \sum_{[K]} \prod_{i_L=1}^{K_L} \prod_{i_M=1}^{K_M} \prod_{i_{\bar{L}}=1}^{K_{\bar{L}}} \prod_{i_{\bar{M}}=1}^{K_{\bar{M}}} \\
&\times \int \frac{f d^3x_{Li_L}}{K_L!} \frac{f d^3x_{Mi_M}}{K_M!} \frac{f d^3y_{\bar{L}i_{\bar{L}}}}{K_{\bar{L}}!} \frac{f d^3y_{\bar{M}i_{\bar{M}}}}{K_{\bar{M}}!} \\
&\times \det(G[x]) \det(G[y])\; e^{-V_{D\bar{D}}(x-y)} \qquad (10)
\end{aligned}
$$

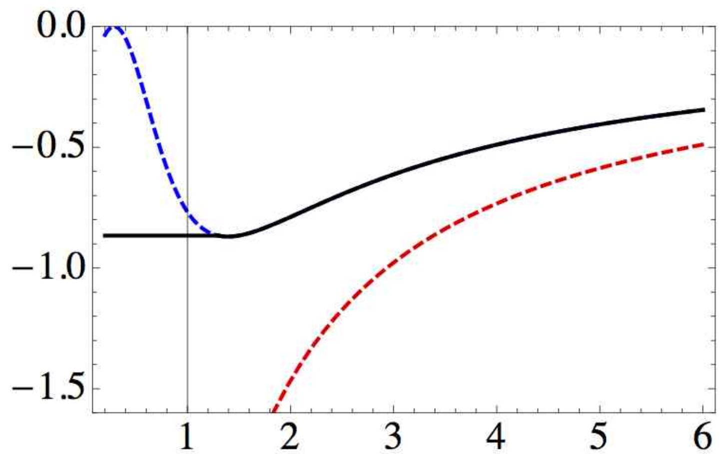
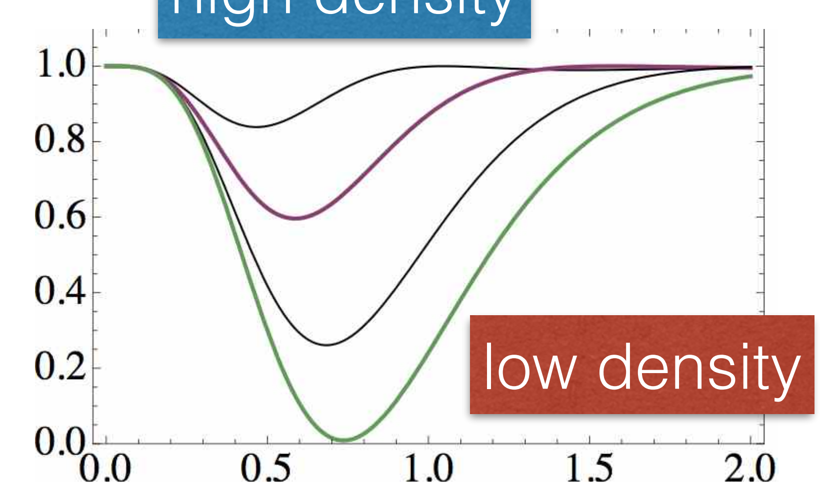


FIG. 1: (Color online) Black solid line is the SU(2) $D\bar{D}$ (dimensionless) potential versus the distance r (in units of $1/T$). Upper (blue) dashed line is the parameterization proposed in Ref.[22], the lower (red) (dashed) line is the Coulomb asymptotics.

$$
\ln Z_{1L}/V_3 = -\mathcal{V} - \frac{1}{2}\int \frac{d^3p}{(2\pi)^3} \ln\left|1 - \frac{V^2(p)}{16}\frac{p^8M^4}{(p^2+M^2)^4}\right| \qquad (30)
$$

with $V(p)$ the Fourier transform of (12)

$$
V(p) = \frac{4\pi}{p^2}\int_0^\infty dr \sin r\, V_{D\bar{D}}(r/p) \qquad (31)
$$



Mean field theory can only be used at high enough dyon density or T<Tc

Summary

Instanton-dyon ensembles:
in QCD-like theories the deconfinement
and chiral transitions
are driven just by sufficiently large dyon density
=> quasicritical Tdec and Tchir are about the same

Confinement 2016, Thessaloniki, Greece

The Chiral Magnetic Effect:

from quark-gluon plasma to Dirac/Weyl semimetals

D. Kharzeev

Stony Brook University

RIKEN BNL Research Center

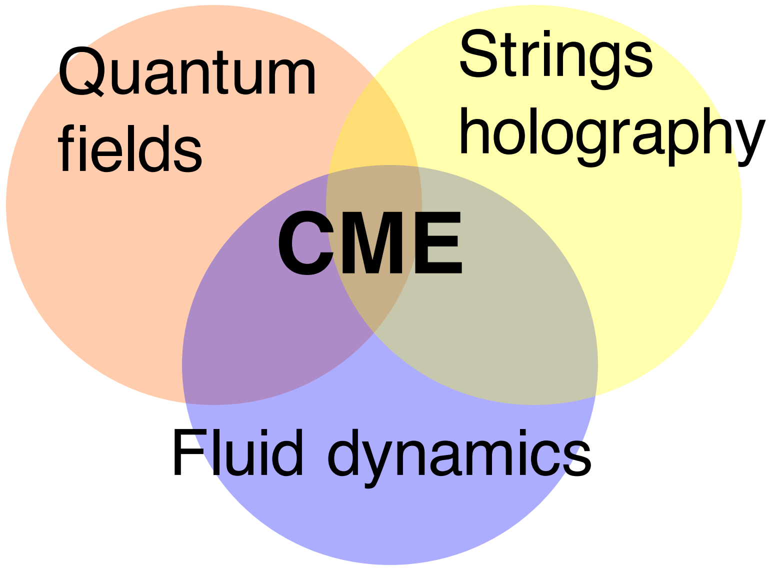
BROOKHAVEN NATIONAL LABORATORY

Summary

Nuclear physics

Particle physics

Cosmology



Astrophysics

Condensed matter physics

Real-world applications

Panel Discussion
Confinement and Anomalous Transport in Condensed Matter Systems: What can we learn?

C. Diamantini, D. Kharzeev, T. Sulejmanpasic

T. Schäfer, V. Shevchenko

Background

Experimentalists have achieved extraordinary control over designer many body systems

Cold Fermi/Bose gases with tuneable interactions

Cold atoms in optical lattices with tuneable geometry and hopping

Gauge fields from Aharonov Bohm phases

Designer Dirac/Weyl cones, topologically protected surface states

Possible impacts

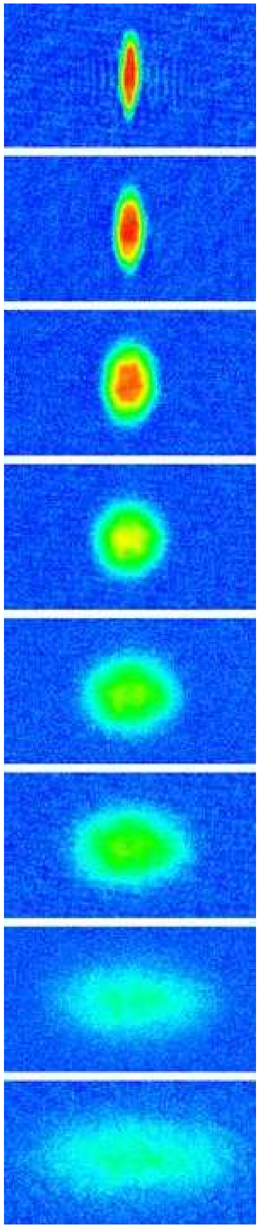
Study analog systems for bulk phenomena: Low viscosity flow, anomalous transport. Study universal effects: η/s, CME coefficient.

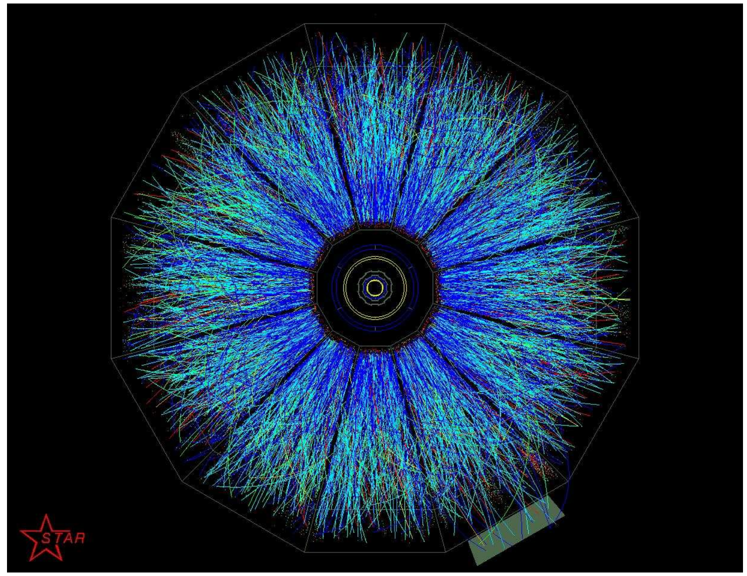
Study microscopic objects in controlled settings: Strings, Wilson lines, branes, monopoles. Study dynamics. Look for universality.

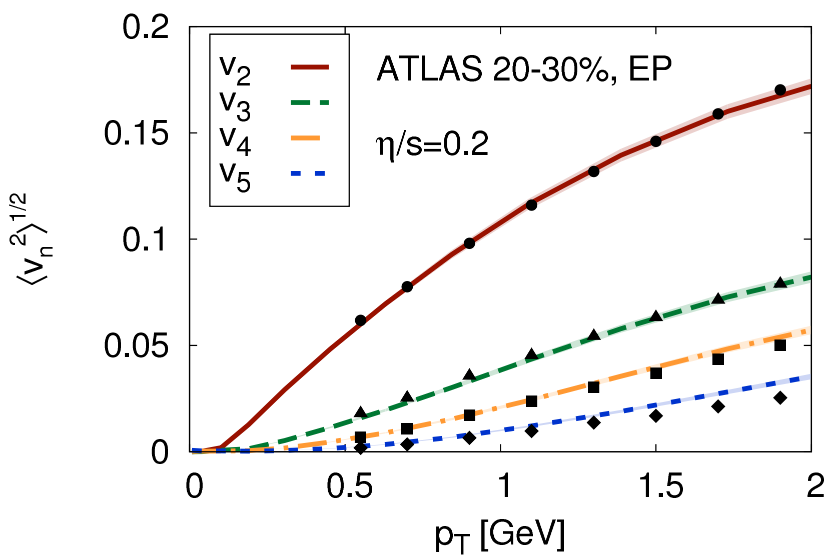
(The far future) Real time simulations of QCD in optical lattices, cavity QED, or trapped ion quantum computers. Real time dynamics, finite baryon density.

(The near future) String breaking, Schwinger mechanism, etc in abelian lattice systems.

Example I: Flow and η/s

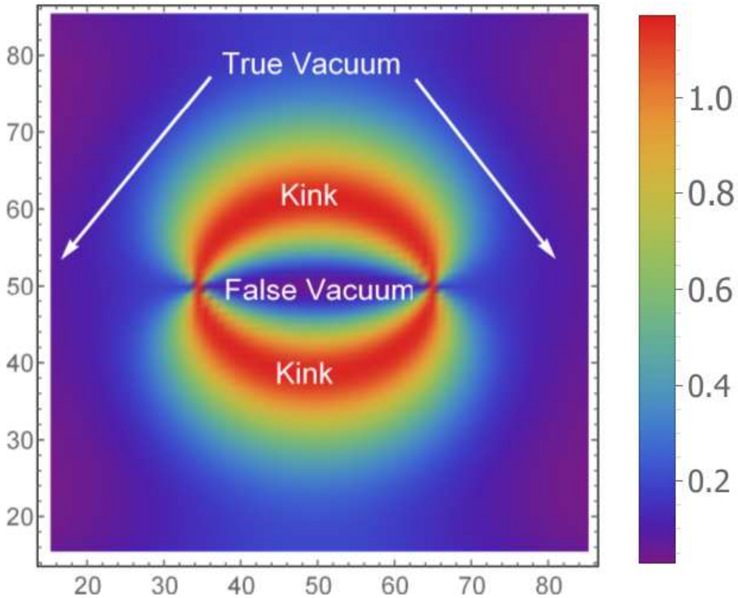




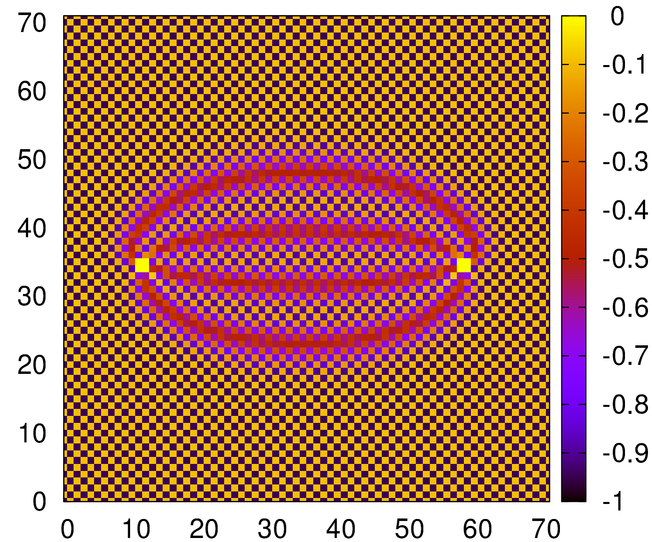


O'Hara et al. (2002), Gale et al. (2013)

Example II: Strings



SUSY QCD string



String in quantum link model

Poppitz & Sulejmanpasic

U.-J. Wiese

Confinement, August 31, 2016

Can we understand QCD better by studying analog materials?

Round table discussion

D. Kharzeev

Dirac semimetals (DSM) are 3D materials with chiral quasi-particles and strong effective coupling:

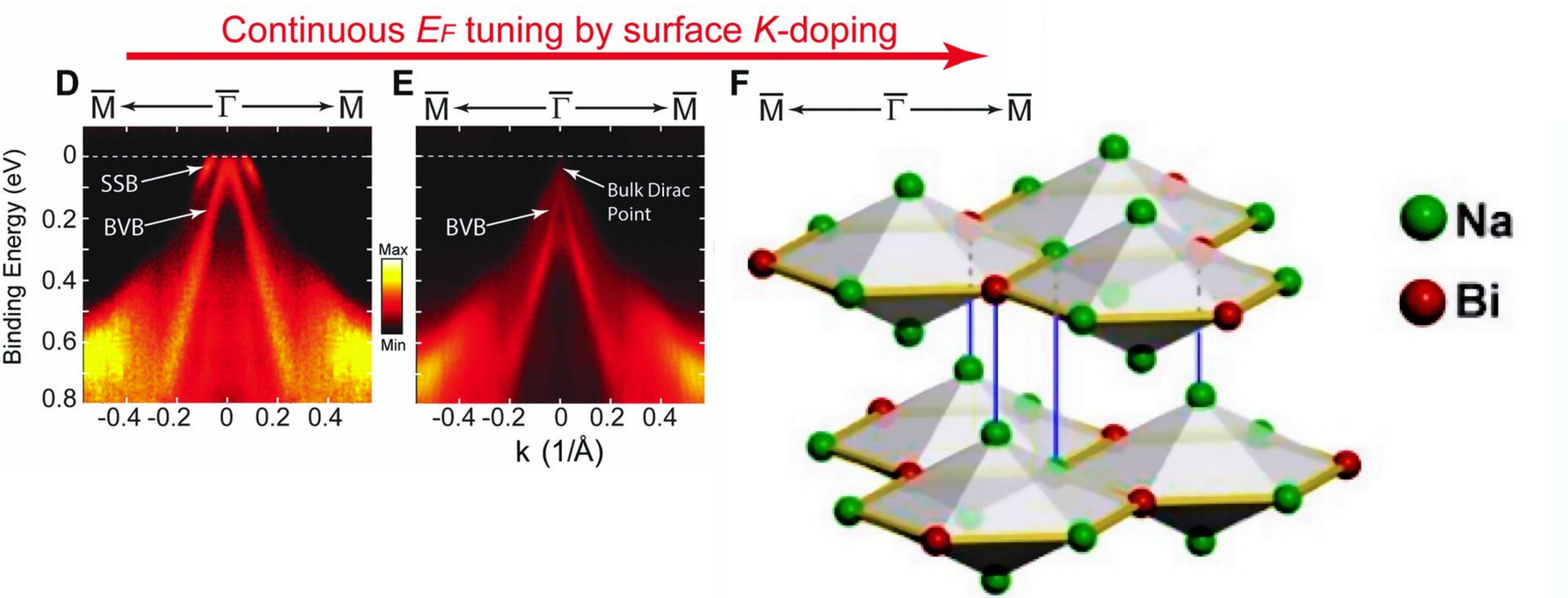
$$E = v_F k \qquad\qquad \alpha = \frac{e^2}{\hbar\, v_F}$$

Phase transition possible to an insulating gapped phase (excitonic condensate formation) –

analog of a chirally broken phase with a quark condensate!

Can tune doping (chemical potential), temperature, magnetic field, strain, etc –
new testing ground for theoretical methods in QCD

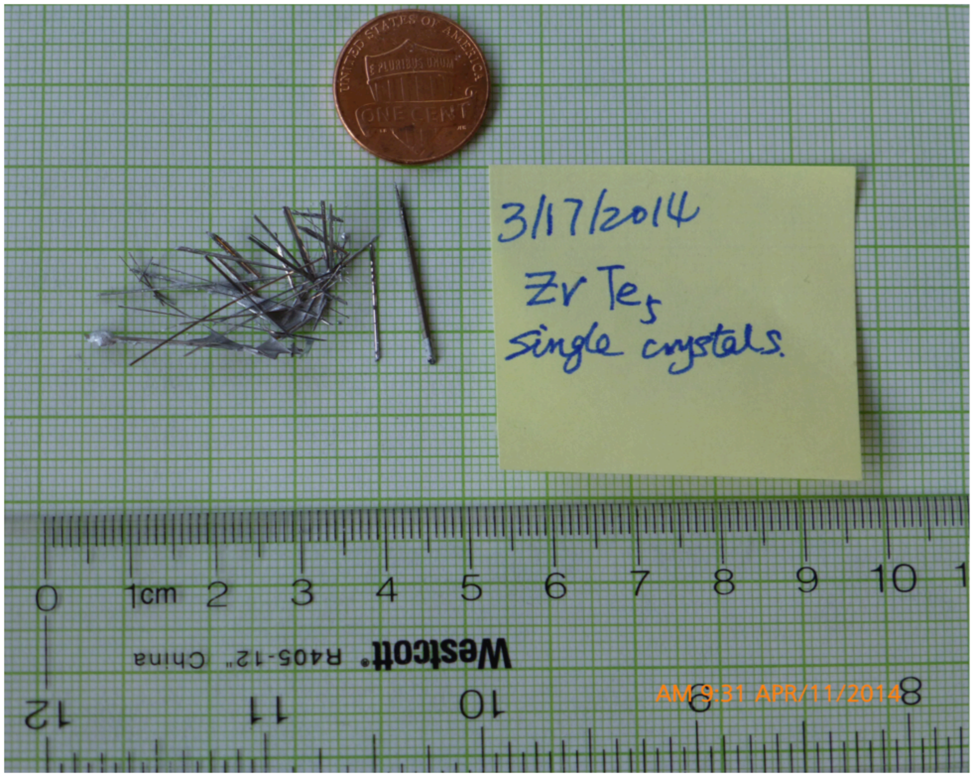
The discovery of Dirac semimetals – 3D chiral materials

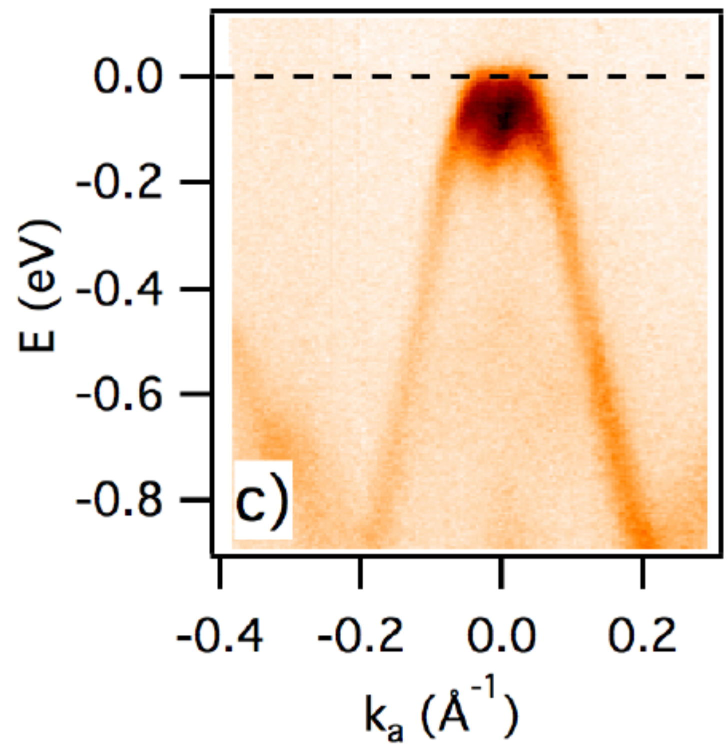


Z.K.Liu et al., Science 343 p.864 (**Feb 21, 2014**)

Observation of the chiral magnetic effect in $ZrTe_5$

Qiang Li,[1] Dmitri E. Kharzeev,[2,3] Cheng Zhang,[1] Yuan Huang,[4] I. Pletikosić,[1,5] A. V. Fedorov,[6] R. D. Zhong,[1] J. A. Schneeloch,[1] G. D. Gu,[1] and T. Valla[1]

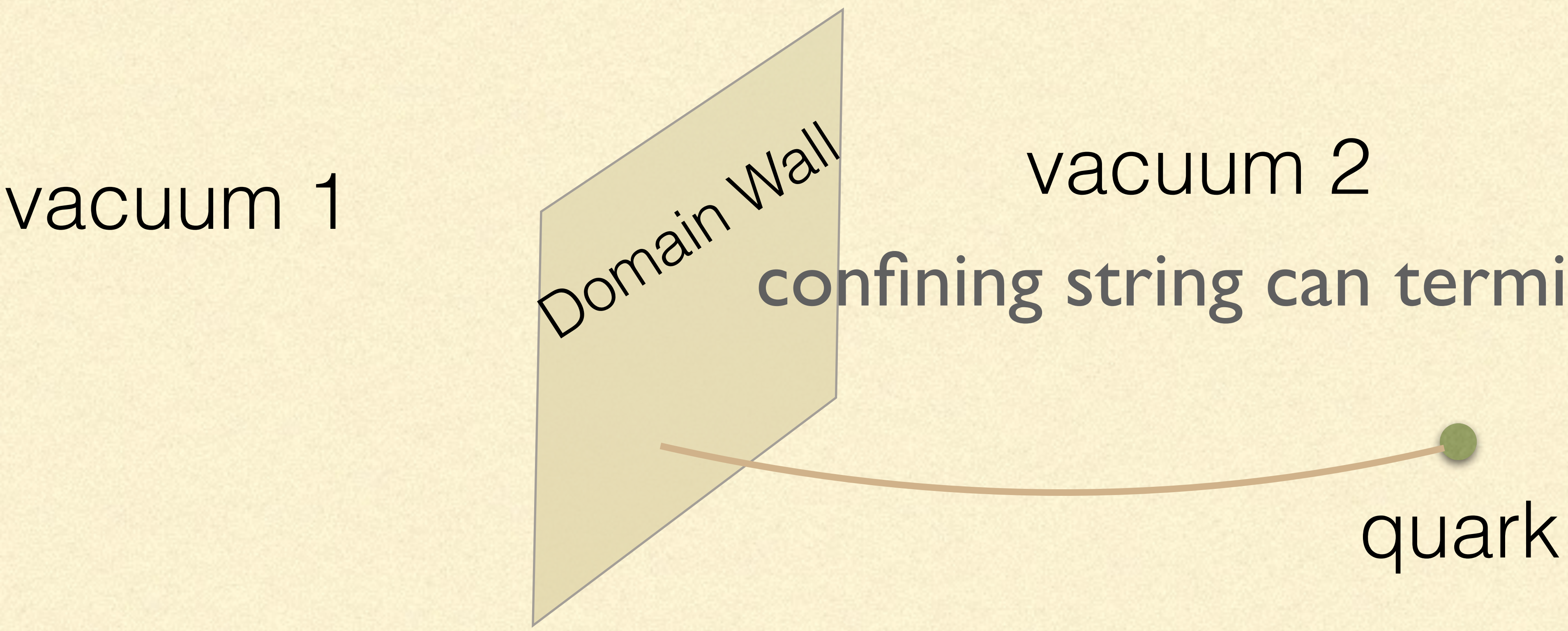




arXiv:1412.6543 (December 2014); Nature Physics **12**, 550 (2016)

Super Yang-Mills softly broken to $\mathcal{N}$=1,2

For SU(2) the picture is: there are two degenerate vacua

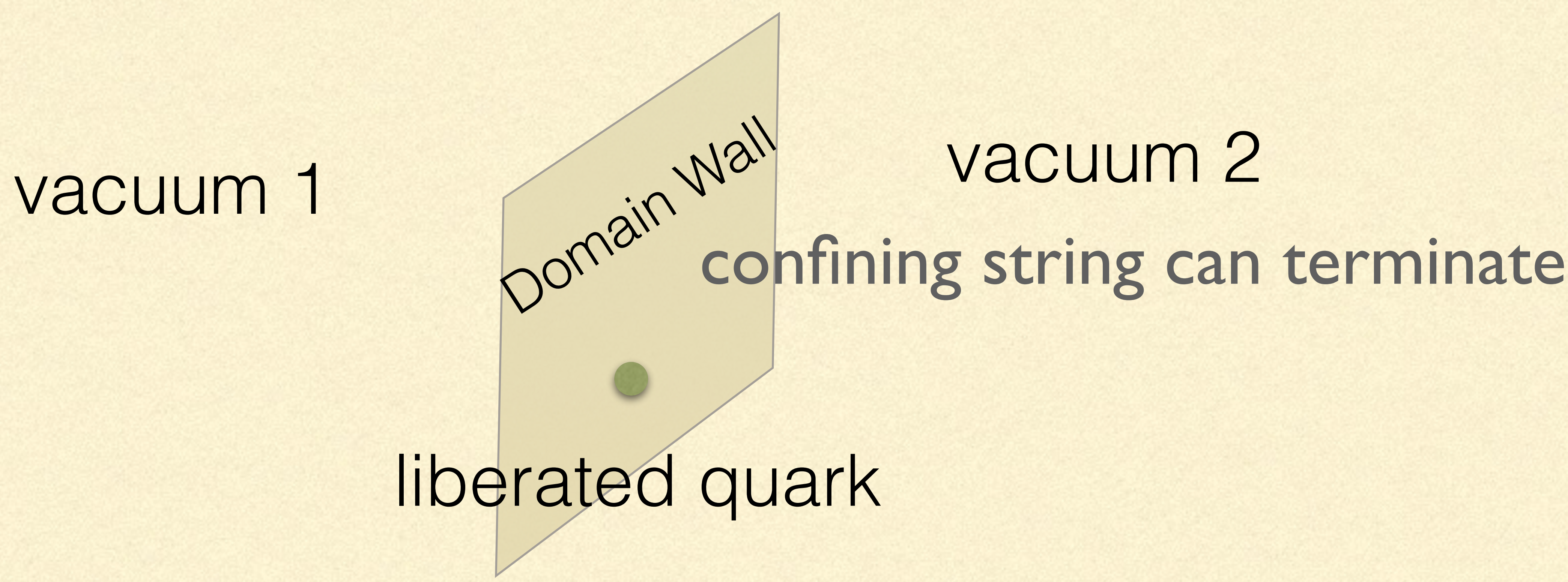


Due to S.-J. Rey 1998

Explored by Witten in M-theory construction of $\mathcal{N}$=1 SYM

Super Yang-Mills softly broken to $\mathcal{N}$=1,2

For SU(2) the picture is: there are two degenerate vacua

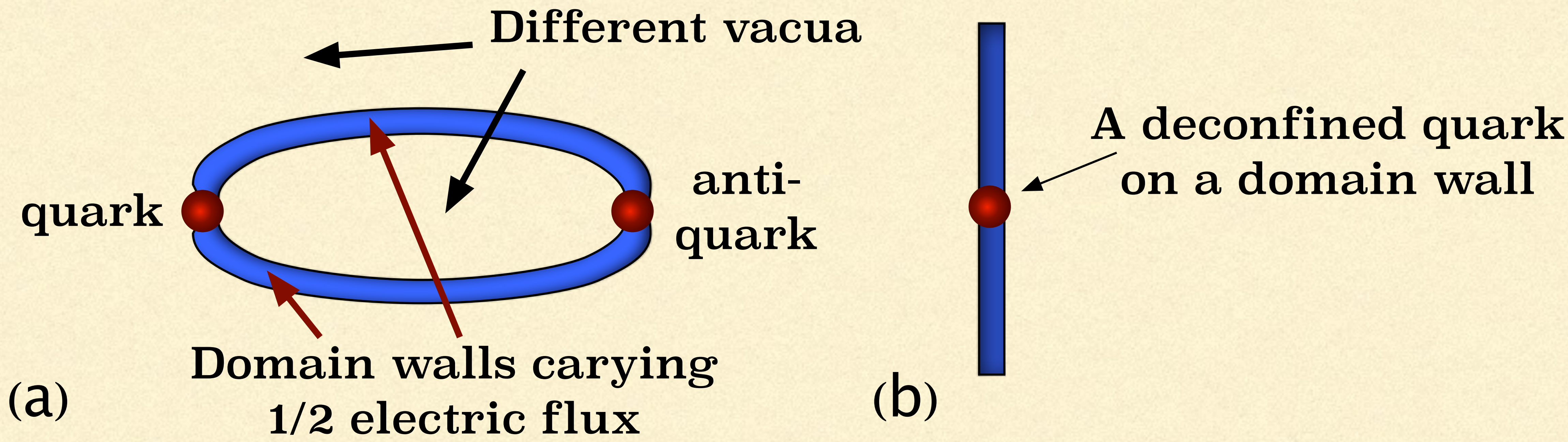


Due to S.-J. Rey 1998

Explored by Witten in M-theory construction of $\mathcal{N}$=1 SYM

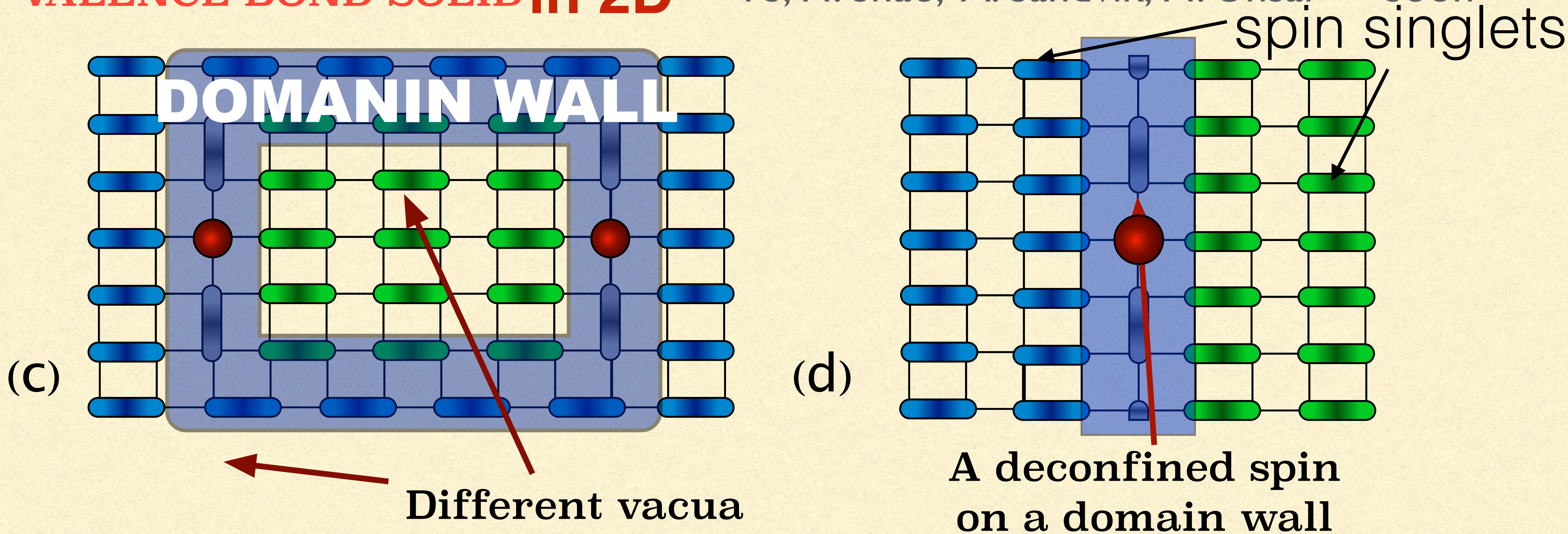
Poppitz, Anber, TS Phys.Rev. D92 (2015) no.2, 021701

GAUGE THEORY on $\mathbb{R}^3 \times S^1$ (Unsal, Yaffe, Shifman, Poppitz, etc. 2008-present)



VALENCE BOND SOLID in 2D

TS, H. Shao, A. Sandvik, M. Unsal — Soon



Collectivity in small systems

- The **deconfined** quark-gluon plasma formed in nucleus-nucleus collisions at RHIC and the LHC is best described as a fluid.
- But the phenomena leading to this conclusion have then been observed, to some extent, in proton-nucleus, and even high-multiplicity proton-proton collisions.
- *Are the underlying mechanisms identical in all systems?*
- *Can we describe small systems as fluids?*

Round table: Collectivity in Small Systems

Experimental Overview

Wei Li (Rice University)

XII Quark Confinement and the Hadron Spectrum
Aug. 29 – Sep. 3, 2016

Why colliding ultra-relativistic heavy ions?

"In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions.

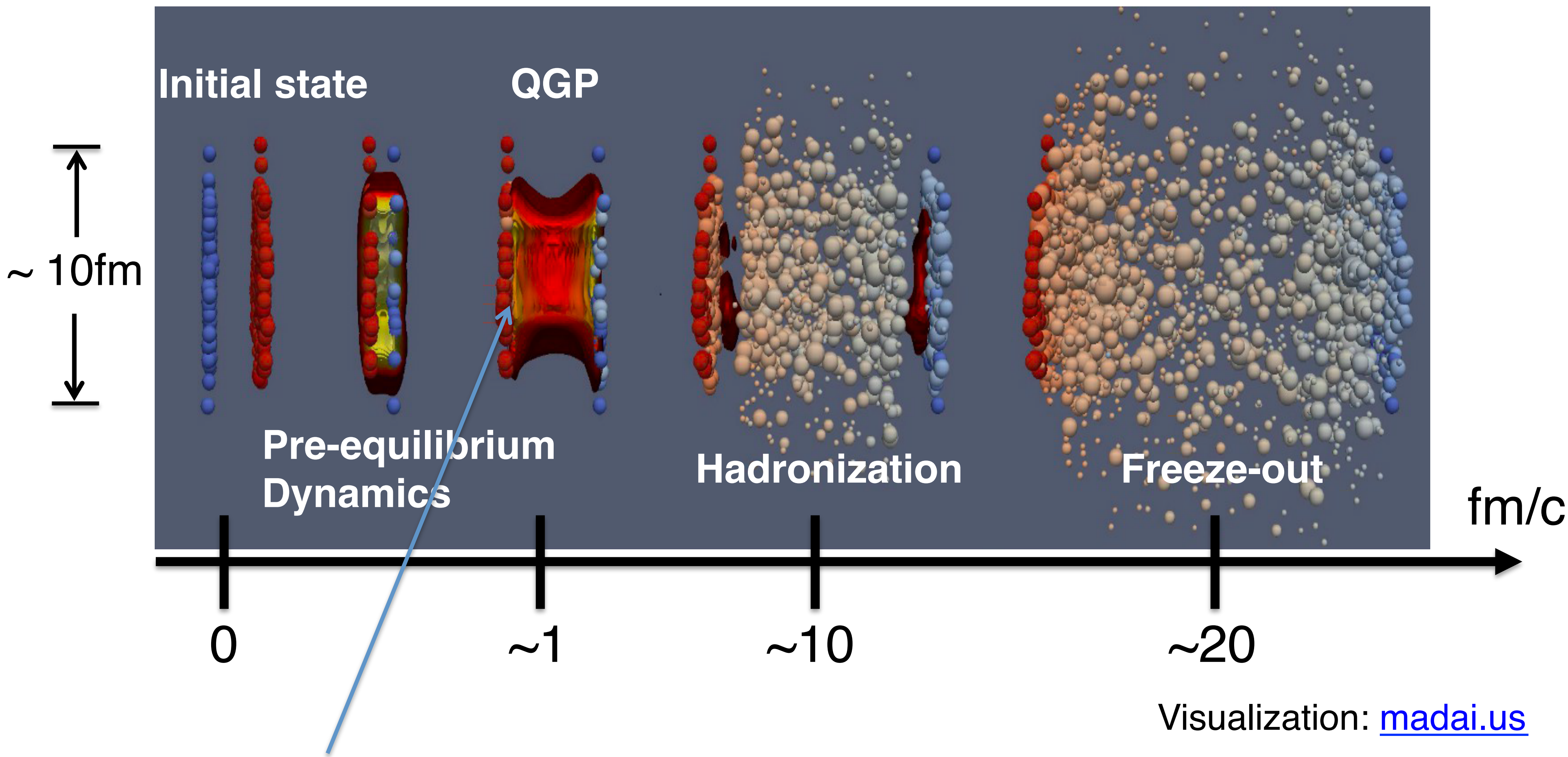
(e.g. pp, ep, e^+e^-)

In order to study the question of 'vacuum', we must turn to a different direction; we should investigate some 'bulk' phenomena by distributing high energy over a relatively large volume."

(AA)

Prof. T.D. Lee, Rev. Mod. Phys. *47*, 267(1975).

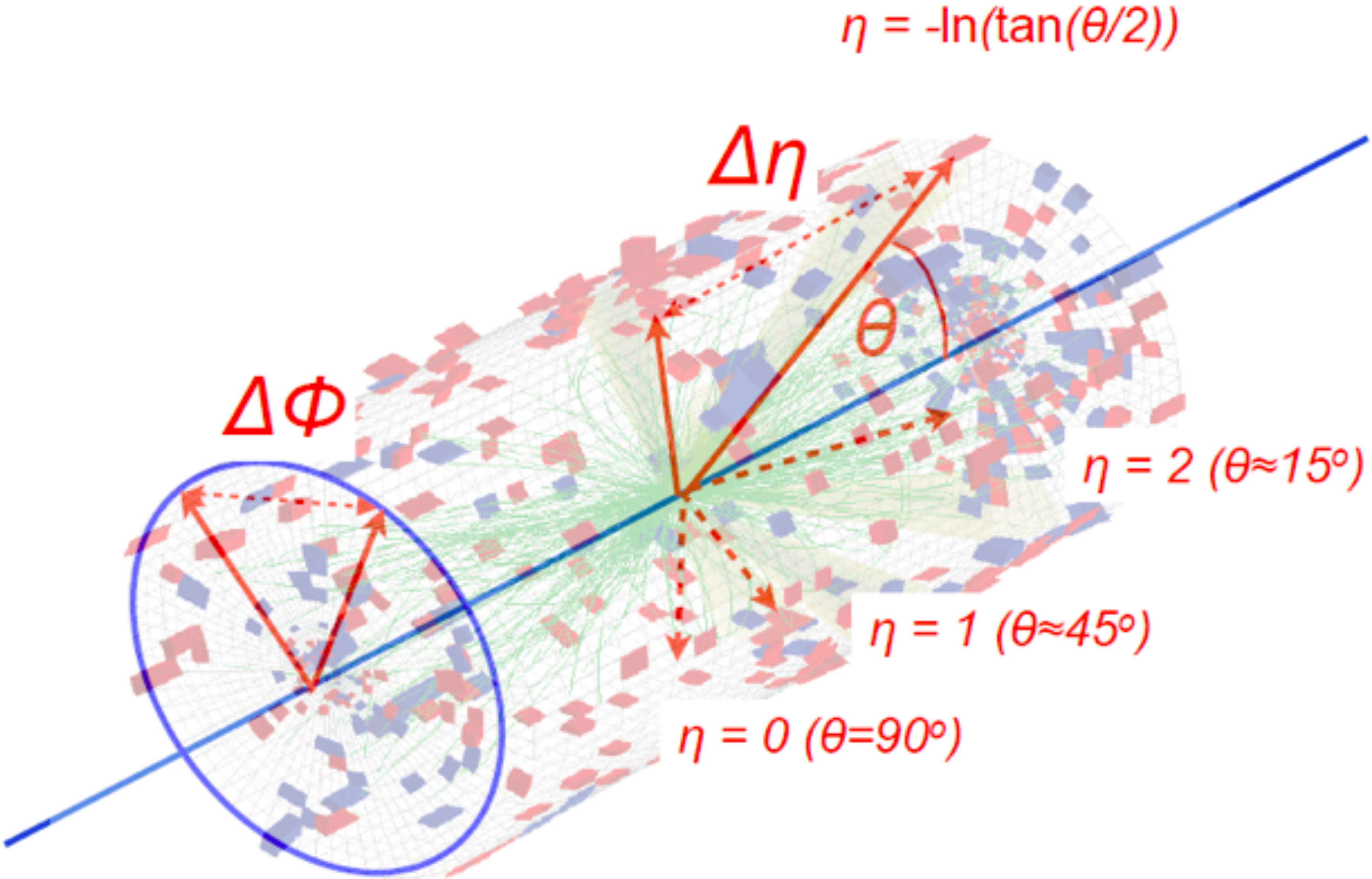
Standard paradigm of a heavy-ion collision



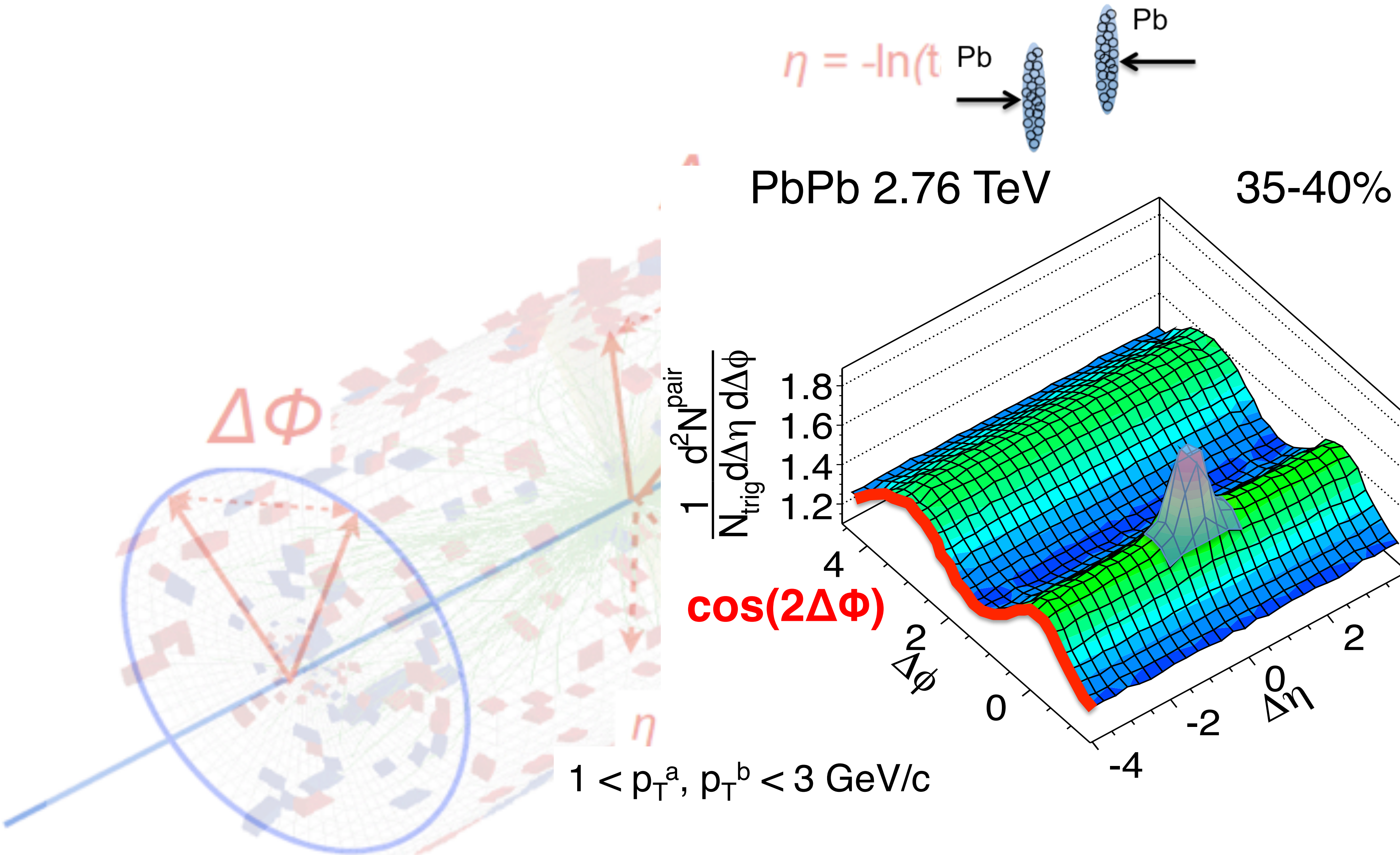
Visualization: madai.us

Discovery of a high temperature, thermalized medium with quark and gluon degree of freedom

Flow, two-particle correlations, ridge …



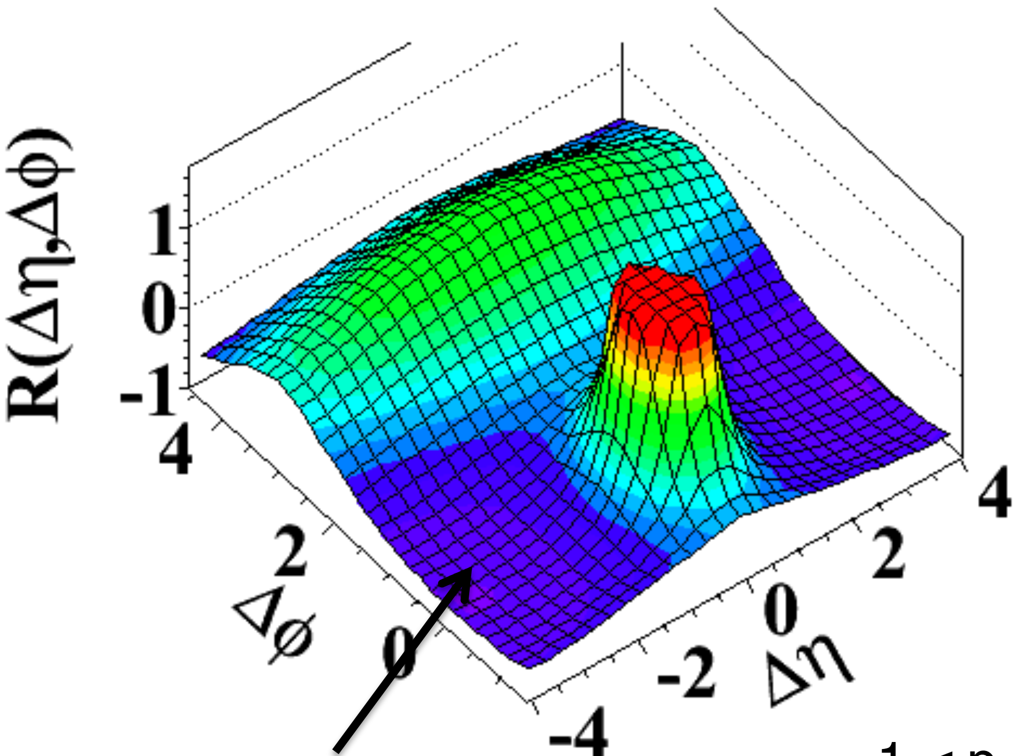
Flow, two-particle correlations, ridge …



Breaking news in 2010!

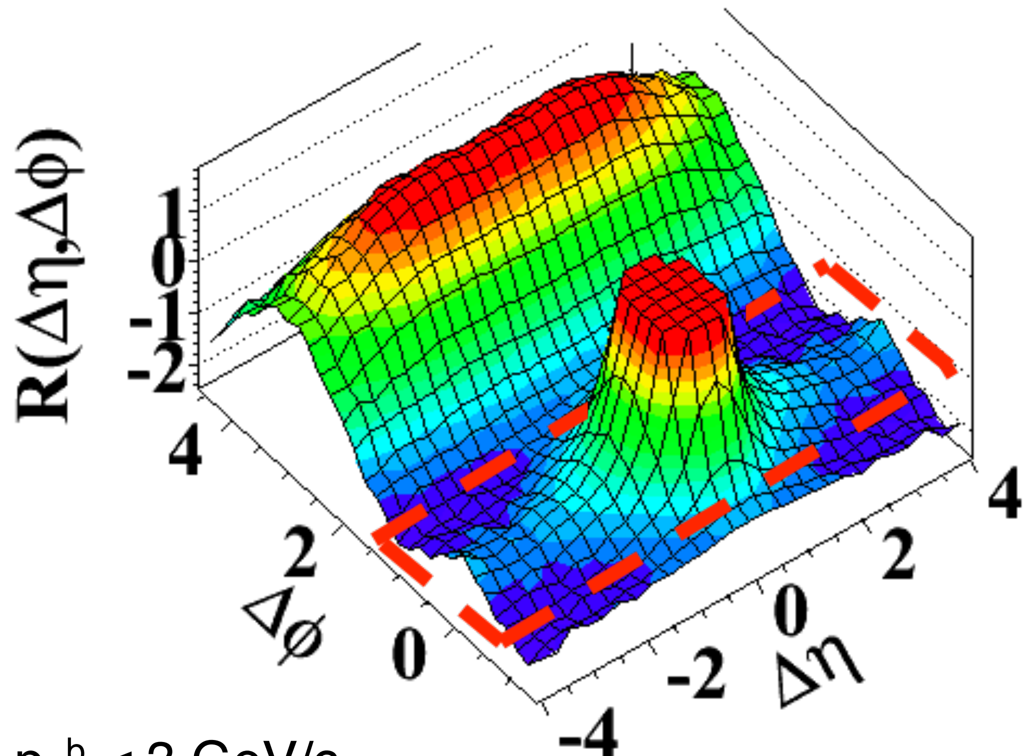
High-multiplicity pp events

pp 7 TeV, MinBias **$<N_{trk} \sim 15>$**



Nothing at ΔΦ ~ 0, |Δη|>2
(Near-side)

pp 7 TeV, **N_{trk}>110**

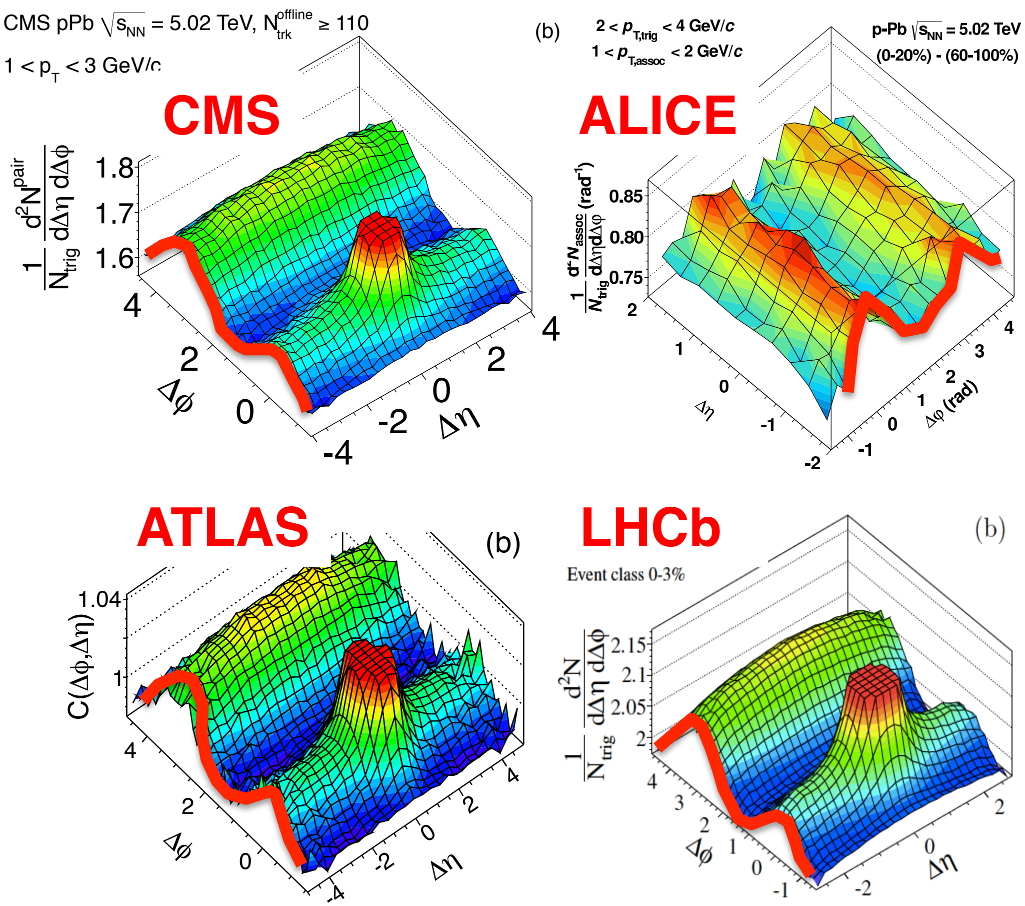


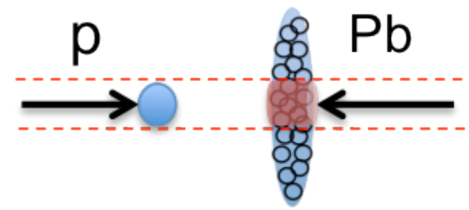
$1 < p_T^a, p_T^b < 3$ GeV/c

CMS, JHEP 09 (2010) 091

Near-side ridge

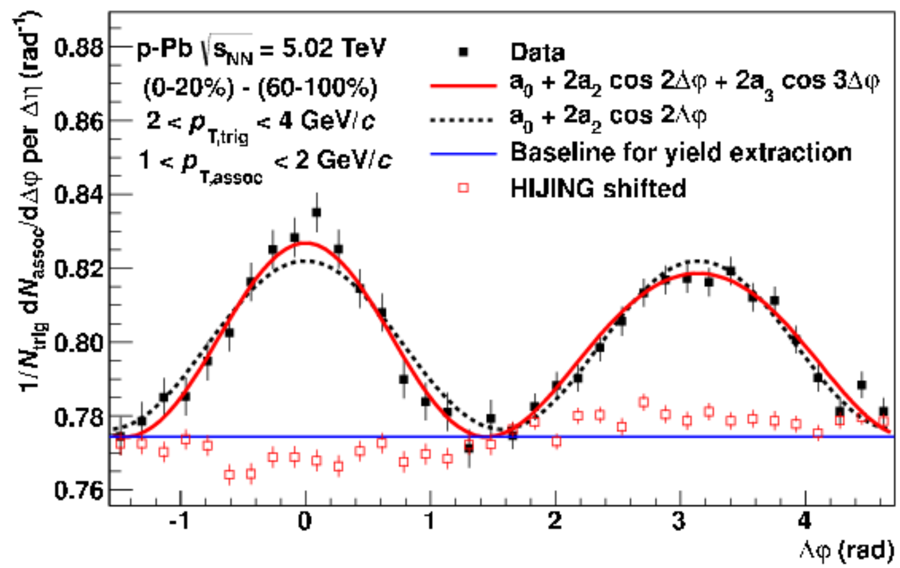
“Ridge” tsunami in pPb at the LHC





in 2012

“Flow” analysis



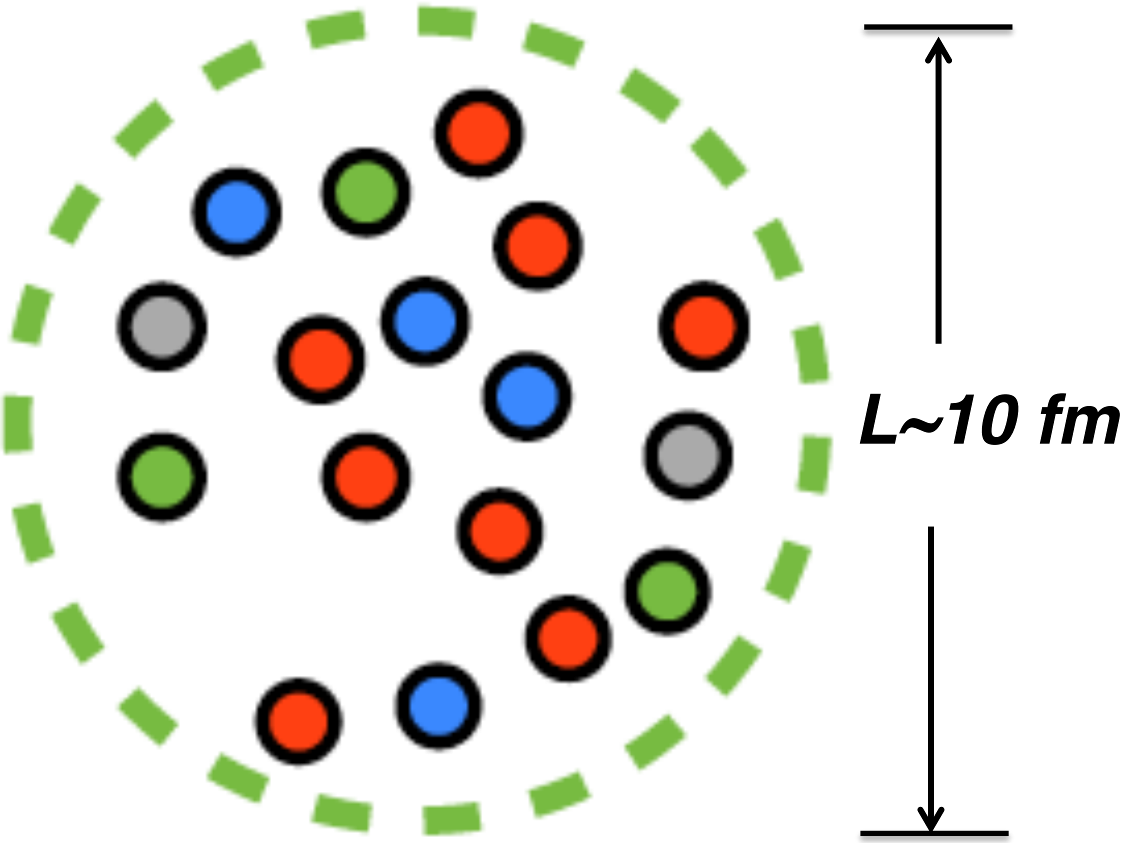
Collective phenomena and QGP fluid in small systems (L ~ 1fm)?!

How small a QGP fluid can be?

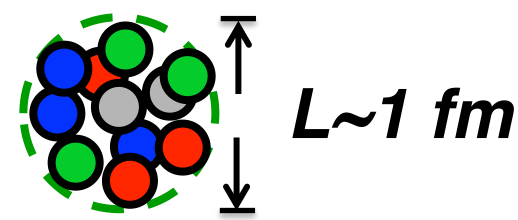
Hydrodynamic applies when:

$$L >> \lambda_{m.f.p.}$$

AA



What if making it denser by increasing N_{trk}?



Summary of current status

Almost all signatures of “flow” phenomena now commonly observed in all hadronic systems (pp, pA, AA), at sufficiently high multiplicities.

Some questions:

✧ Is QGP fluid created in small systems like pp?

✧ Is there a smallest scale of QCD fluid-like system?

✧ What’s still needed (experimentally) to reach a definitive conclusion?

✧ If everything flows, do we learn anything new about QGP from small systems?

Domain wall network as QCD vacuum: confinement, chiral symmetry, hadronization

Sergei Nedelko

Bogoliubov Laboratory of Theoretical Physics, JINR

XIIth Quark Confinement and the Hadron Spectrum,
Thessaloniki, August 29 - September 3, 2016

September 2, 2016

The character of background fields B has yet to be identified by the dynamics of fluctuations:

$$Z = N' \int_{\mathcal{B}} DB \int_{\Psi} D\psi D\bar\psi \int_{\mathcal{Q}} DQ \det[D(B)D(B+Q)]\delta[D(B)Q] \exp\{-S_{\rm QCD}[B+Q,\psi,\bar\psi]\}$$
$$= \int_{\mathcal{B}} DB \exp\{-S_{\rm eff}[B]\}$$

Global minima of $S_{\rm eff}[B]$ – field configurations that are dominant in the thermodynamic limit $V \to \infty$. Homogeneous Abelian (anti-)self-dual fields are of particular interest.

$$B_\mu = -\frac{1}{2} n B_{\mu\nu} x_\nu, \ \tilde B_{\mu\nu} = \pm B_{\mu\nu}$$
$$n = T^3 \ \cos\xi + T^8 \ \sin\xi.$$

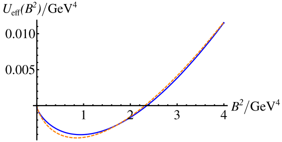
H. Pagels, and E. Tomboulis, Nucl. Phys. B 143 (1978) 485
P. Minkowski, Nucl. Phys. B177 (1981) 203
H. Leutwyler, Nucl. Phys. B 179 (1981) 129

$$G\left(z^2\right) \sim \frac{e^{-Bz^2}}{z^2}, \quad \tilde G\left(p^2\right) \sim \frac{1}{p^2}\left(1 - e^{-p^2/B}\right)$$

H. Leutwyler, Phys. Lett. B 96 (1980) 154

Gluon propagator ⇒ Regge trajectories

G.V. Efimov, and S.N. Nedelko, Phys. Rev. D 51 (1995)



A. Eichhorn, H. Gies and J. M. Pawlowski, Phys. Rev. D 83, 045014 (2011)

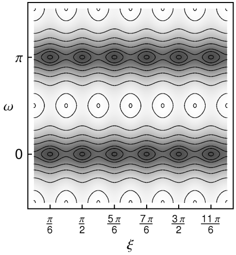
U_{eff} possesses 12 degenerate discrete minima:

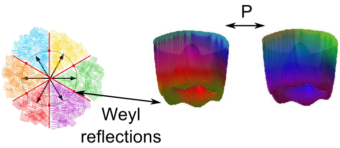
$$B_\mu = -\frac{1}{2} n_k B_{\mu\nu} x_\nu, \; \tilde{B}_{\mu\nu} = \pm B_{\mu\nu},$$

matrix n_k belongs to the Cartan subalgebra of $su(3)$

$$n_k = T^3 \; \cos\left(\xi_k\right) + T^8 \; \sin\left(\xi_k\right), \quad \xi_k = \frac{2k+1}{6}\pi, \; k = 0, 1, \ldots, 5,$$

$$\vec{E}\vec{H} = B^2 \cos(\omega)$$





The general kink configuration can be parametrized as

$$\zeta(\mu_i, \eta^i_\nu x_\nu - q^i) = \frac{2}{\pi} \arctan \exp(\mu_i(\eta^i_\nu x_\nu - q^i)).$$

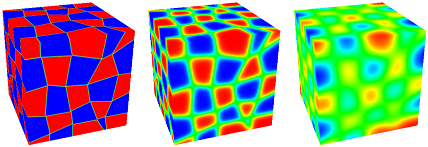
A single lump in two, three and four dimensions is given by

$$\omega(x) = \pi \prod_{i=1}^{k} \zeta(\mu_i, \eta^i_\nu x_\nu - q^i).$$

for $k = 4, 6, 8$, respectively. The general kink network is then given by the additive superposition of lumps

$$\omega = \pi \sum_{j=1}^{\infty} \prod_{i=1}^{k} \zeta(\mu_{ij}, \eta^{ij}_\nu x_\nu - q^{ij})$$

S.N., V.E. Voronin, Eur.Phys.J. A51 (2015) 4



$\langle F^2 \rangle = B^2$
$\langle |F\widetilde{F}| \rangle = B^2$

$\langle F^2 \rangle = B^2$
$\langle |F\widetilde{F}| \rangle \ll B^2$

What could stabilize a finite mean size of the domains?

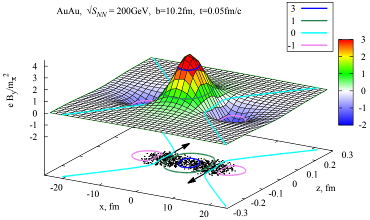
Lower dimensional defects?

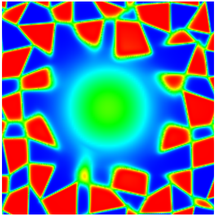
Quark (quasi-)zero modes?

"Polarization of QCD vacuum by the strong electromagnetic fields"

- **Relativistic heavy ion collisions - strong electromagnetic fields**

V. Skokov, A. Y. Illarionov and V. Toneev, Int. J. Mod. Phys. A **24** *(2009) 5925*
V. Voronyuk, V. D. Toneev, W. Cassing, E. L. Bratkovskaya,
V. P. Konchakovski and S. A. Voloshin, Phys. Rev C 84 (2011)

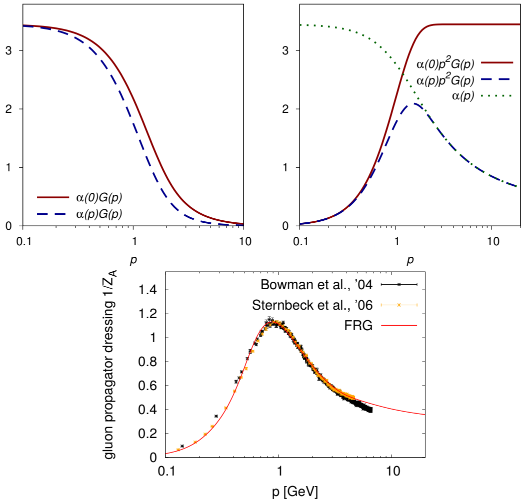




Strong electro-magnetic field plays catalyzing role for deconfinement and anisotropies!

B.V. Galilo and S.N. Nedelko, Phys. Rev. D84 (2011) 094017.
M. D'Elia, M. Mariti and F. Negro, Phys. Rev. Lett. **110**, 082002 (2013)
G. S. Bali, F. Bruckmann, G. Endrodi, F. Gruber and A. Schaefer, JHEP **1304**, 130 (2013)

Preliminary



Functional RG, DSE, Lattice QCD

Preliminary

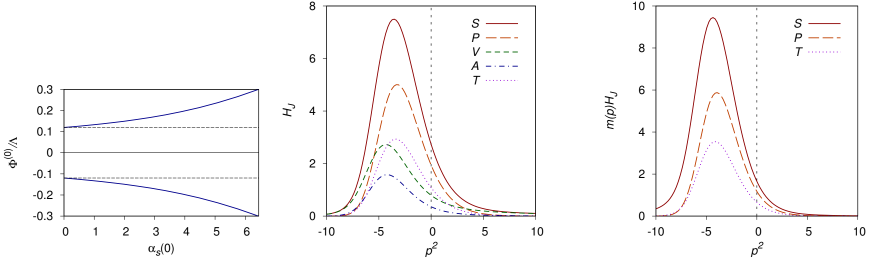


Figure : Scalar quark condensate (LHS). Momentum dependence of the scalar (solid line), pseudoscalar (long dash), vector (dash), axial (dash dot) and tensor (dot) form factors (central plot) in the quark propagator (4), and scalar, pseudoscalar and tensor form factors (RHS plot) multiplied by the quark mass.

$$\Lambda^2 \Phi^{(0)}_{\mathcal{Q}_1} = \sum_{k=1}^{\infty} \frac{g^k}{k} \sum_{\mathcal{Q}_1 \dots \mathcal{Q}_k} \Phi^{(0)}_{\mathcal{Q}_2} \dots \Phi^{(0)}_{\mathcal{Q}_k} \Gamma^{(k)}_{\mathcal{Q}_1 \dots \mathcal{Q}_k},$$

$$m(p) = \bar{m}(0) F_{00}(p^2), \quad F_{00}(p) = \left[1 - \exp\left(-\frac{p^2}{\Lambda^2}\right)\right] \frac{\Lambda^2}{p^2}, \quad \bar{m}(0) = \frac{1}{3} g \Phi^{(0)}, \tag{3}$$

$$\tilde{H}(p) = \frac{m}{2v\Lambda^2} \mathcal{H}_S(p^2) \mp \gamma_5 \frac{m}{2v\Lambda^2} \mathcal{H}_P(p^2) + \gamma_\alpha \frac{p_\alpha}{2v\Lambda^2} \mathcal{H}_V(p^2) \pm i\gamma_5\gamma_\alpha \frac{f_{\alpha\beta} p_\beta}{2v\Lambda^2} \mathcal{H}_A(p^2) \tag{4}$$