Introduction to Strong Interactions and the Hadronic Spectrum

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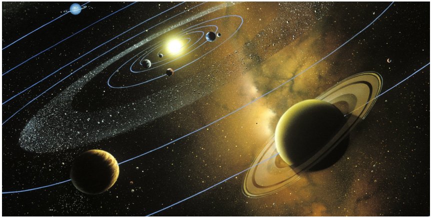
Overview of talk

- Some forces and scales of Nature.
- Strong interactions: from quark model to QCD.
- Theory toolbox: Dyson-Schwinger and Bethe-Salpeter equations.
- Model details and results.
- Conclusions and outlook.

Astronomic scales

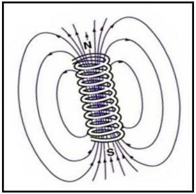
Interactions between stars, planets, galaxies . . . .

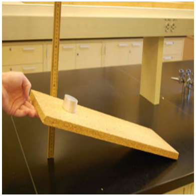
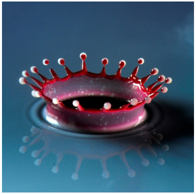


Responsible force: gravitation.
Applicable theories: Newtons theory, general relativity.

'Everyday' scales

Interactions between macroscopic objects, both charged and neutral.

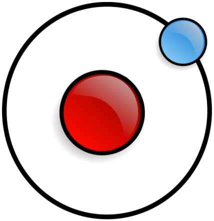


Responsible force: electromagnetic, and its residues.
Applicable theories: Maxwells electrodynamics, classical mechanics.

Atomic scales

Interactions between electrons and protons, bound into atoms.

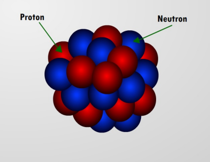


Responsible force: electromagnetic.

Applicable theories: Quantum mechanics, quantum electrodynamics.

Nuclear scales

Interactions between protons and neutrons.



Responsible force: strong nuclear interaction (not fundamental).

Hadron 'zoo' and the quark model

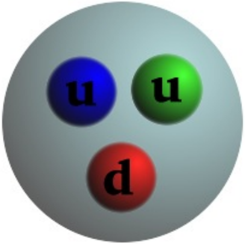
- Proton, neutron members of a family of hadrons.
- Hadron 'zoo' discovered in 50s and 60s.

  'If I could remember the names of these particles, I'd be a botanist.'
  E. Fermi

- Quark model as means of hadron classification $\rightarrow$
  hadron quantum numbers from quarks which 'make up' the hadron.
- For model inventors, unclear if quarks physically real or not.

Valence quarks

- Constituents which determine hadron quant. numbers.
- Fermions ($S = 1/2$), distinguished by
  1. Electric charge (+2/3, -1/3).
  2. 'Flavour', different masses (u,d,s,c,b,t).
  3. 'Color' (red, green, blue).
- All known hadrons color-neutral, 'white'.

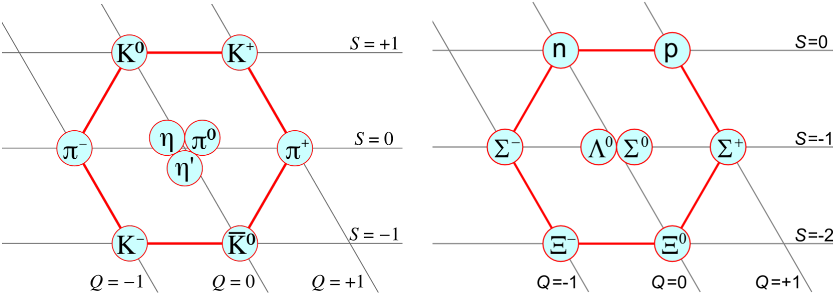


Quark model picture of a proton.

Hadrons in the quark model

Baryons (proton, neutron...) $\rightarrow$ three valence quarks, qqq.

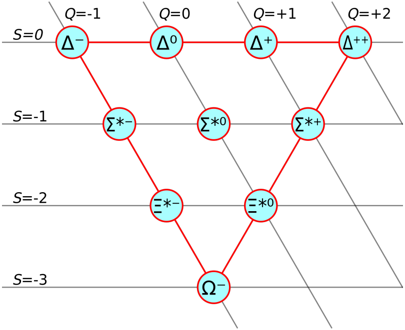
Mesons (pion, kaon...) $\rightarrow$ two valence quarks, $\bar{q}q$.



Pseudoscalar meson nonet (*left*) and baryon octet (*right*).

Triumph of the quark model

Ω^- baryon predicted before it was experimentally observed.

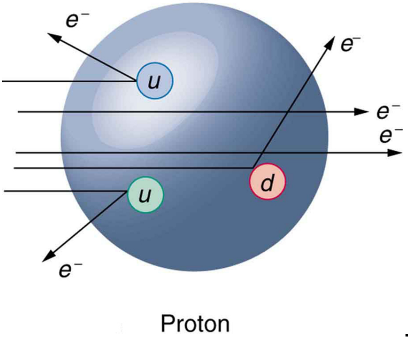


Baryon decuplet.

Cemented the success of the quark model.

Quarks as physical particles

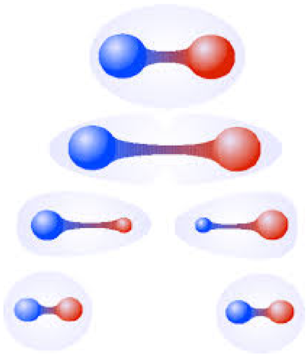
Scatering exps. in late 60s suggested quarks are more than mathematical trick.



However, no free quark was ever detected! (color confinement)

Simple picture of confinement

- Try pulling meson apart, separate quark and antiquark.
- The potential between quarks rises as separation increases.
- At one point it is energetically favourable to form new hadrons (hadronisation).



Current vs. constituent quarks

- Quarks confined, no direct measurement of mass.
- Split proton mass (≈ 1 GeV) threeway: $m_u^{const} \approx 350$ MeV.
- But high-energy scattering experiments see much different value:

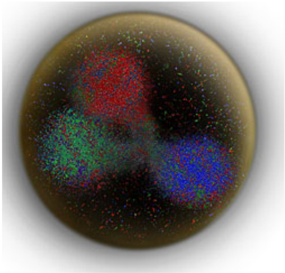
$$m_u^{curr} \approx 2 - 8 \text{ MeV} \tag{1}$$

- Where does the mass difference come from?

Origin of mass difference

- 'Extra mass' comes from virtual particles surrounding the 'bare' (current) quark.
- High-energy probe penetrates virtual particle cloud, 'sees' bare quark inside.

$$m_u^{const} = m_u^{curr} + m_{virt} \tag{2}$$



More realistic picture of nucleon structure.

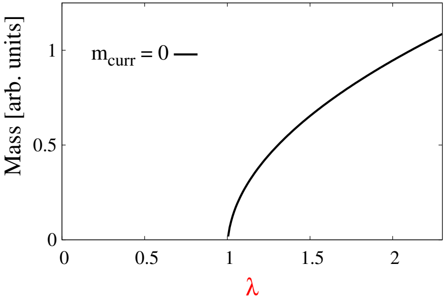
Unique features of the strong interaction

- Interaction among quarks enjoys two unique features:
  1. Color confinement
     No free colored objects detected, always bound inside hadrons.
  2. Dynamical mass generation
     Via interaction, big m_q^{const} generated from tiny m_q^{curr}.
- Is there a (field) theory which can describe these phenomena?

Nambu-Jona-Lasinio model

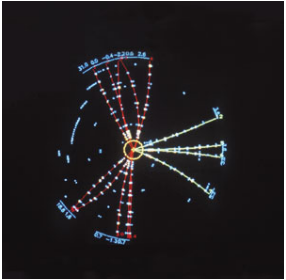
- Features dynamical mass generation, but not confinement.
- Mass generation as a 'critical phenomenon'.

$$\mathcal{L}_{\mathrm{NJL}} = \bar{\psi}(i\partial\!\!\!/ - m_{curr})\psi + \lambda(\bar{\psi}\psi)(\bar{\psi}\psi) \tag{3}$$



QCD and gluons

- Quantum Chromodynamics (QCD) is a theory of strong interaction.
- Quarks interact via 'color force', mediated by gluons
  $\rightarrow$ massless vector ($S = 1$) particles.
- Indirect experimental evidence for gluons (also confined).

.

Three-jet events as indirect evidence for gluons.

QCD Lagrangian

- Similar (deceptively) to QED, much richer.
- No analytic proof QCD is confining, only numerical simulations (Nobel prize ?).
- In principle, all hadronic states derivable from $\mathcal{L}_{\mathrm{QCD}}$.

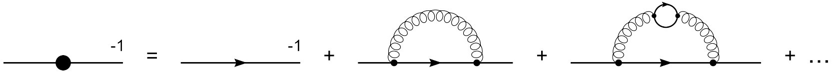
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_k (i \not{D}_{kj} - m_{curr}) \psi_j - G^a_{\mu\nu} G^{\mu\nu}_a \quad k, j, a \rightarrow \text{color} \tag{4}$$

Our aim

- Assuming that QCD is a correct theory, we ask:
  'How to get from $\mathcal{L}_{\text{QCD}}$ to the hadronic spectrum?'
  1. Masses.
  2. Decay constants.
  3. Form factors ...
- We choose Dyson-Schwinger/Bethe-Salpeter equations (DSEs/BSEs).

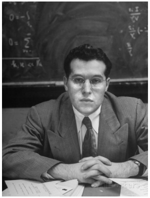
Greens functions

- Basic objects in QFTs are Greens functions.
- *n*-point Greens function: interactions of *n* 'particles'.
- Field theory analogues of correlation functions.
- E.g. a quark propagator: quark goes from A to B in all possible ways:



Dyson-Schwinger equations

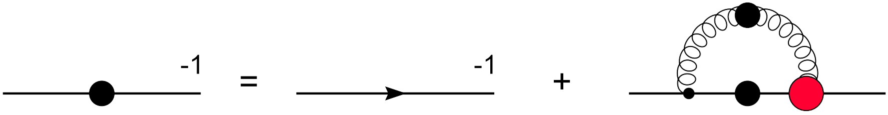
Freeeman Dyson (1923-)



Julian Schwinger (1918-1994)

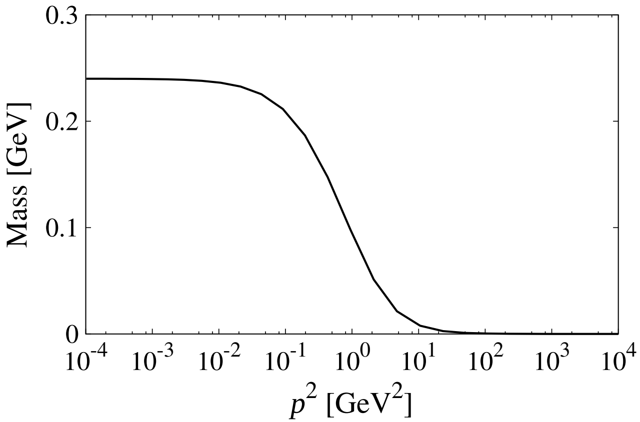
- DSEs connect various *n*-point Greens functions.
- Infinite tower of coupled, nonlinear integral equations.
- Continuous and relativistic formulation of a QFT. ✓
- All momentum regions (IR, mid, UV) equally accessible. ✓
- Practical calculations neccessitate truncations. ✗

Quark propagator DSE



- Exact equation, with full gluon propagator and quark-gluon vertex.
- Satisfy own DSEs, with higher-point Greens functions $\to \infty$ tower.
- Equation encodes dynamical generation of quark mass.

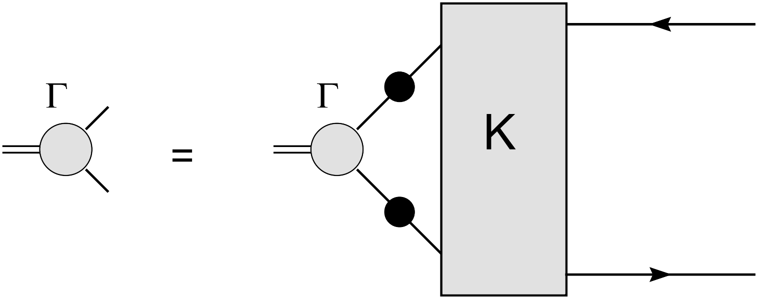
Quark mass function



Scale dependence of dynamical quark mass.

Bethe-Salpeter equation

Mesons described by a 2-body BSE:

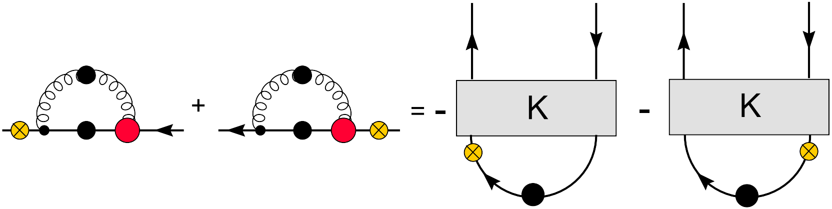


$K \rightarrow$ 4-point interaction kernel

K subsumes ∞ many interaction processes.

Constructing the BSE kernel

- BSE kernel connected to quark self-energy via axial Ward-Takahashi identity (axWTI):

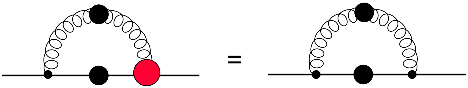


- Truncation of quark DSE determines the truncation of a BSE.

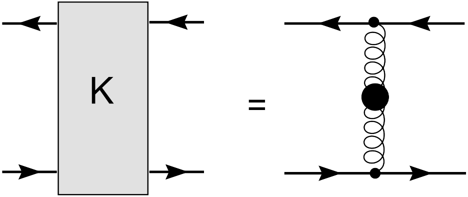
Rainbow-Ladder truncation

Simplest possible approximation:

- Rainbow in quark DSE



- Ladder in meson BSE



Gluon and QG vertex dressings → effective interaction, fit to hadronic observables.

Rainbow-Ladder results for light mesons

RL in QCD versus experiment, all units MeV

	f_π	m_π	f_ρ	m_ρ	m_σ	m_{b1}
RL result	131	138	154	758	645	912
Experiment	133	138	156	776	400-550	1230

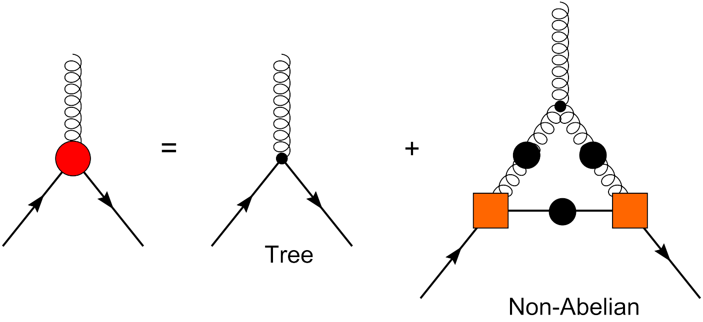
Fischer, Williams, PRL **103**, 2009

Alkofer, Watson, Weigel, PRD **65**, 2002

Going beyond the rainbow

- RL performs OK in QCD, but one can do better (σ, b_1)
  $\rightarrow$ a beyond rainbow-ladder (BRL) calculation neccessary.
- We choose BRL method based on diagrammatic expansion.
  Munczek, PRD **52**, 1995
  Bender, Roberts, von Smekal, PLB **380**, 1996
- Non-diagrammatic BRL methods also available.
  Chang, Roberts, PRD **103**, 2009
  Heupel, Goecke, Fischer, EPJA **50**, 2014

Truncated QG vertex DSE



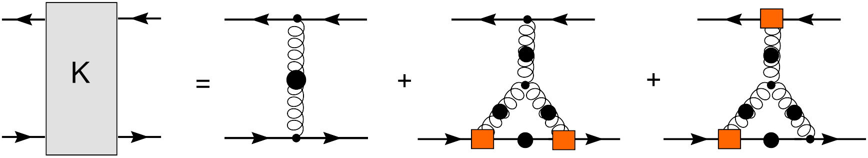
- Not a self-consistent solution of QG vertex DSE!

  S-C solution in FRG approach: Mitter, Pawlowski, Strodthoff, PRD **91**, 2015

- Internal QG vertices modeled (BSE kernel construction).

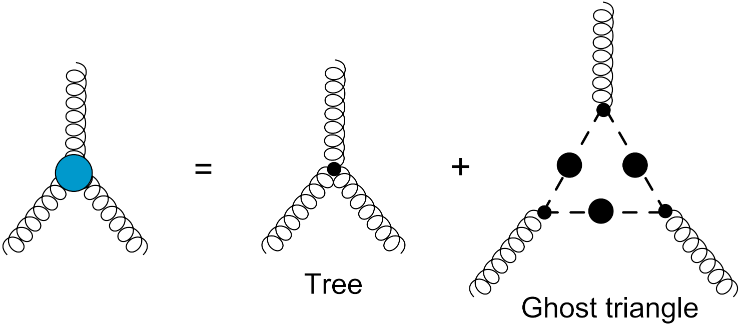
  R. Williams, arXiv: 1404.2545

Truncated BSE kernel



Dressing the three-gluon vertex

Assess model dependence: dress the three-gluon vertex.



Truncated DSE for three-gluon vertex.

Eichmann, Williams, Alkofer, MV, PRD **89**, 2014

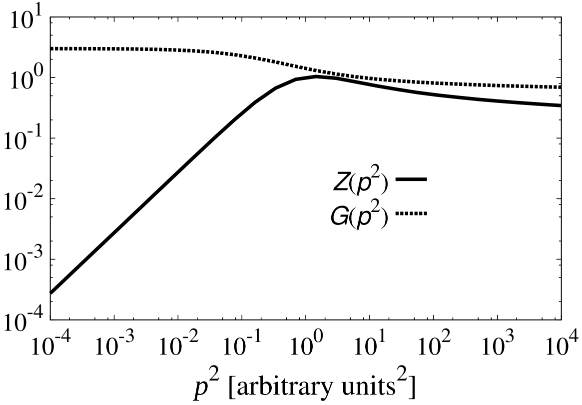
Blum, Huber, Mitter, von Smekal, PRD **89**, 2014

Aguilar, Binosi, Ibanez, Papavassiliou, PRD **89**, 2014

Ghost and gluon dressing functions

data by C. S. Fischer

Scale set *a posteriori* by demanding $f_\pi = 93$ MeV.



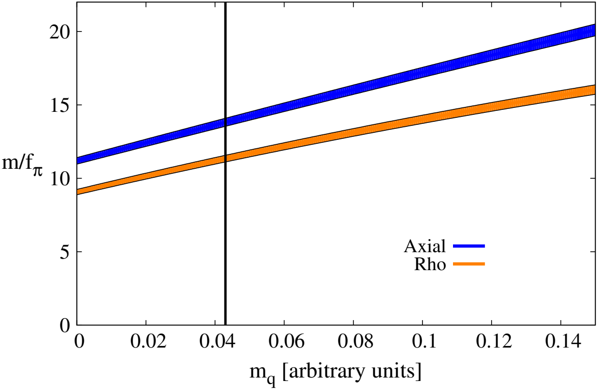
BRL results

Meson masses in rainbow-ladder (RL) and beyond rainbow-ladder (BRL) truncations, versus experiment. All units are in MeV.

J^{PC}	RL	BRL, bare 3g vertex	BRL, dressed 3g vertex	Exp.
0^{-+}	138	139(2)	139(2)	138
0^{++}	645	526(10)	502(10)	400-550
1^{--}	758	858(14)	890(14)	776
1^{++}	912	1090(16)	1170(16)	1230

Massive current quarks

$J = 1$ meson masses as a function of current quark mass.



MV, R. Williams, EPJC **75**, 2015

Conclusions

- QCD seems to be a correct theory of strong interaction.
- Hadrons are colorless bound states of quarks, described by relativistic bound state equations.
- Rainbow-Ladder will generally not do good enough:
  1. Limited interaction structure.
  2. Weak connection to underlying gauge sector.
- BRL results fare better in comparison to experiments.
- Results robust w.r.t. dressing of three-gluon vertex
  $\rightarrow$ influence of additional diagrams/Greens functions.

Outlook

- Additional 'robustness' checks:
  unquenched gluons, scale setting, three-gluon vertex . . .
- Truncation is systematically improvable
  $\rightarrow$ higher-loop contributions in QG vertex DSE.
- Calculate other observables, e.g. form factors, decay widths.
- Apply similar methods to other strongly interacting theories:
  (nearly) conformal dynamics $\rightarrow$ Technicolor phenomenology.

THANK YOU FOR YOUR ATTENTION!