NPSTRONG

Hadron Physics: *a World of Colour*

From quarks to hadrons and nuclei

Jornadas LIP 2020

IF INVESTIGADOR FCT

LIP

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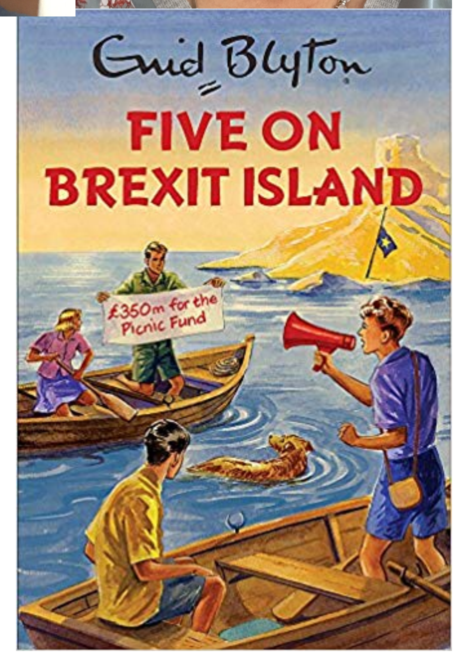
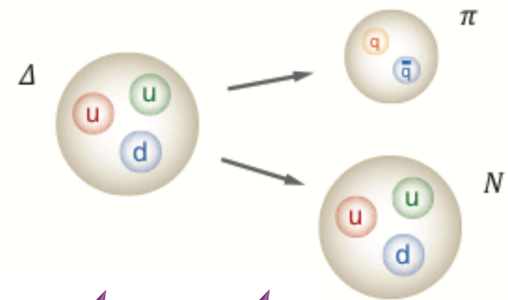


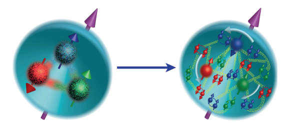
https://www.youtube.com/user/projetoMEFT

Our Interests

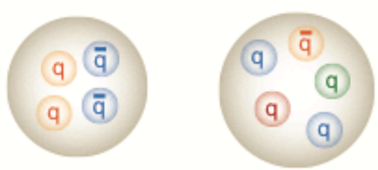
- **Resonances:** most hadrons decay into other hadrons ↔ poles in complex plane



- **Hadron structure calculations:** form factors, PDFs, GPDs, ...

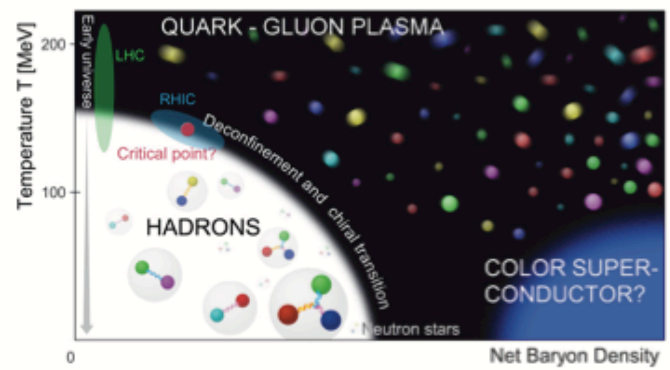


- **Exotic hadrons & multiquark states:** tetraquarks, pentaquarks, nuclei?



- **QCD contributions to BSM searches:** muon anomalous magnetic moment, ...

- **QCD under extreme conditions:** early universe, exotic phases, hadrons at large T and μ



Some open questions

Emergence of mass

Emergence of mass in Hadrons:

u	d	s	c	b	t
0.003	0.005	0.1	1	4	175
0.35	0.35	0.5	1.5	4.5	175

[GeV]

Bare quark

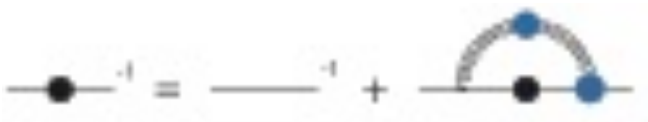
Dressed quark

Higgs

Emergence of mass

$$\mathcal{L} = \bar{\psi}\,(\not{\partial} + i\,g\not{A} + m)\,\psi + \frac{1}{4}\,F^{\,a}_{\mu\nu}\,F^{\mu\nu}_{a}$$

A quark can interact with itself through the same mechanism as with another quark.



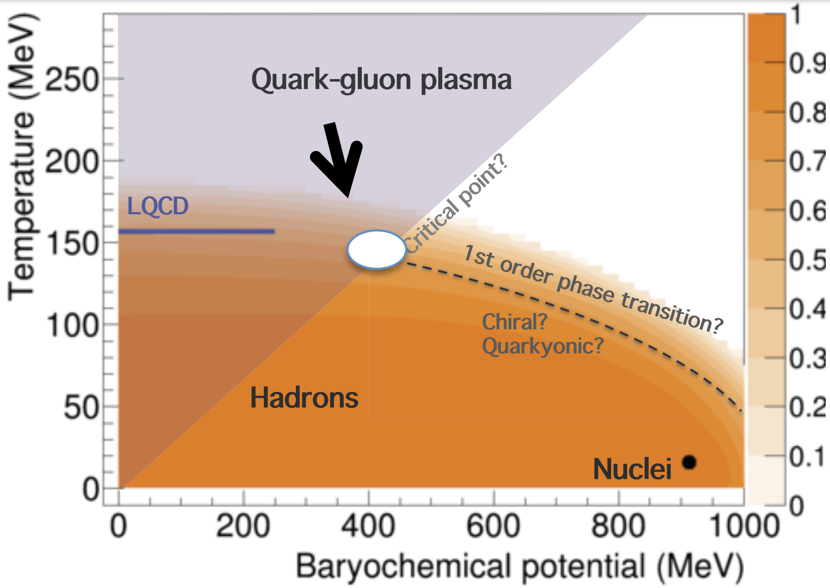
Mass becomes momentum dependent!

Bare quark

Dressed quark

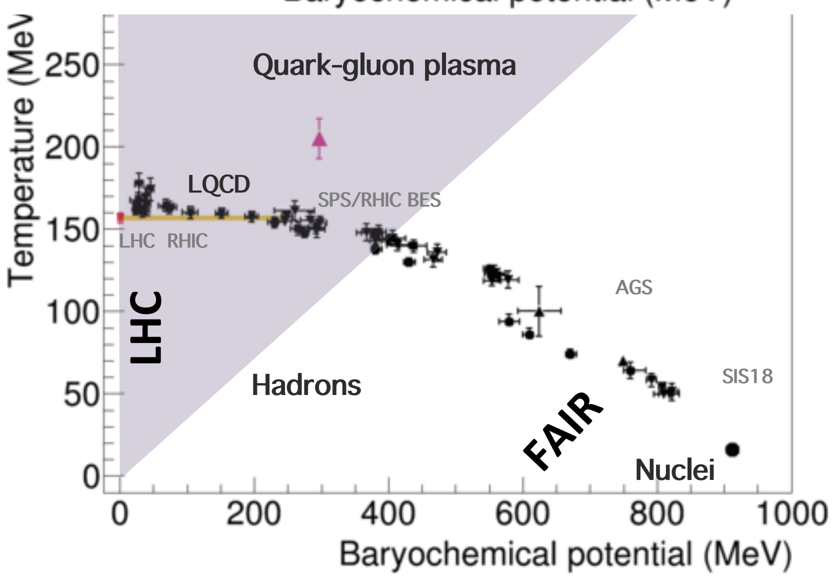
Higgs

QCD and the evolution of the Universe



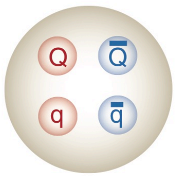
Is there critical endpoint in the QCD phase diagram?

How important are baryons for the phase transition?

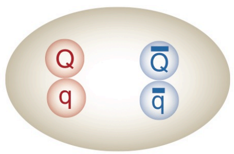


T. Galatyuk / Nuclear Physics A 982 (2019) 163–169

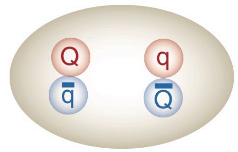
Hadron Structure from first principles



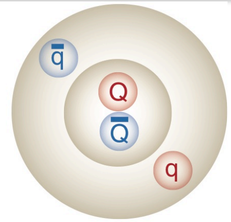
compact tetraquark



diquark-antidiquark

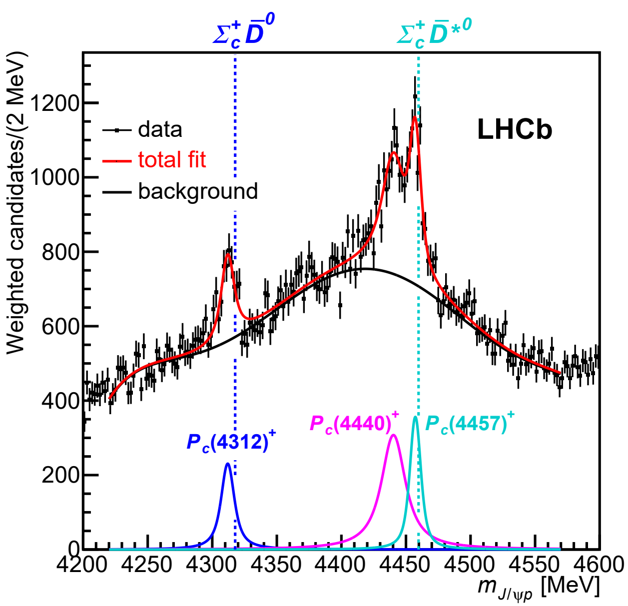


meson molecule

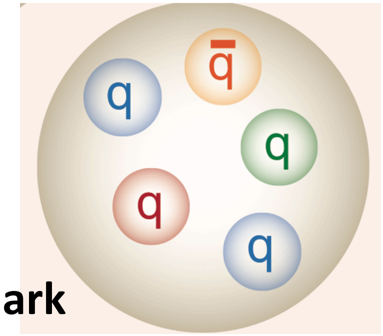


'hadro-quarkonium'

Can we understand exotic hadron structures?

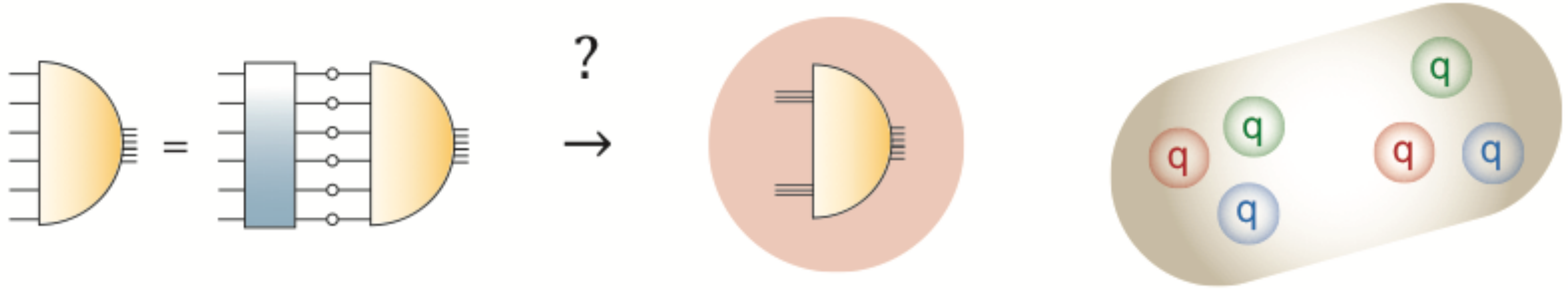


Aaij et al., Phys. Rev. Lett. 112 (2019) 222001

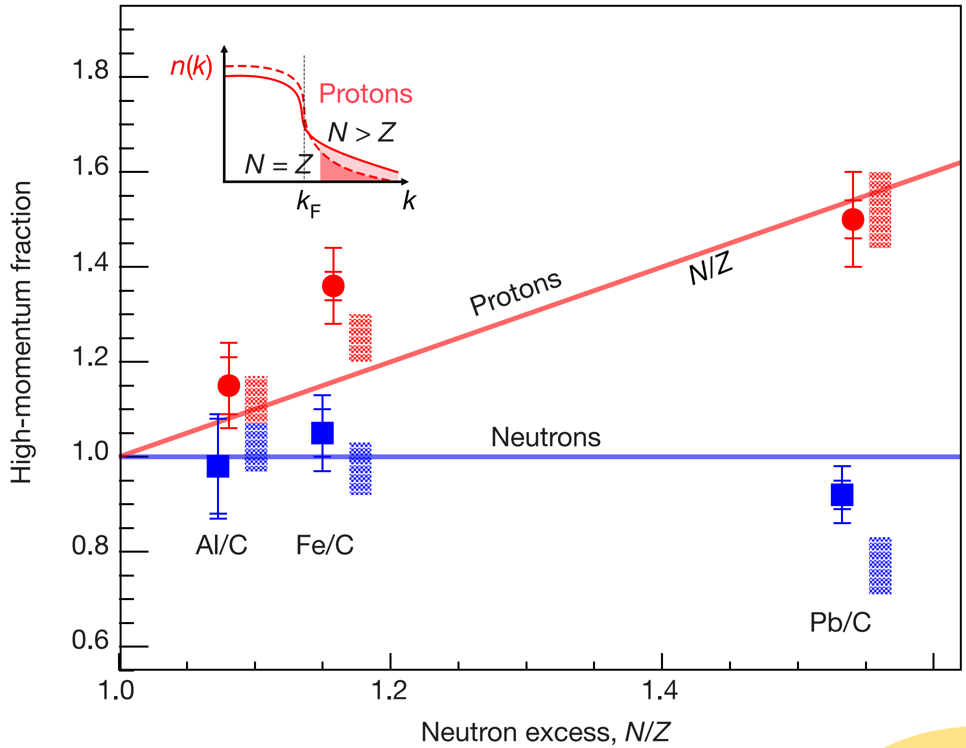


Pentaquark

Nuclear Interaction from first principles



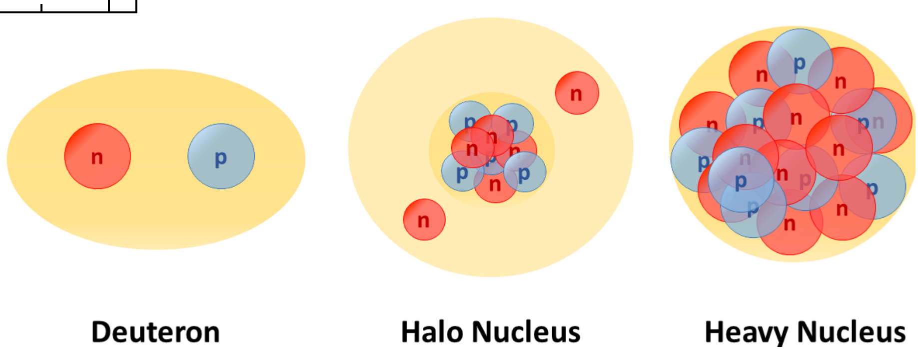
Adding neutrons to a nucleus increases the fraction of high-momentum protons



What are the consequences for

- Neutron stars?
- Dissociation of Borromean drip-line nuclei such as ^{17}Ne?
- General clusterization phenomena?
- …

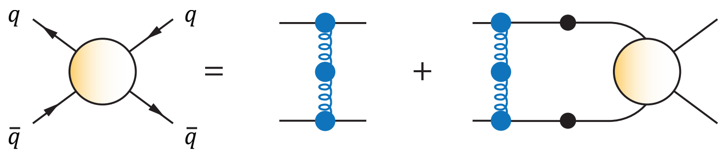
CLAS Collaboration, Nature 560 (2018) no.7720, 617-621

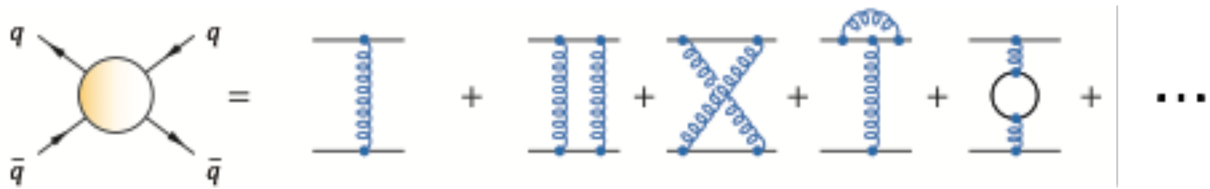


Theory Tool Kit

Dyson-Schwinger Methods

QCD cannot be solved perturbatively in the low energy limit.





Dyson-Schwinger Methods

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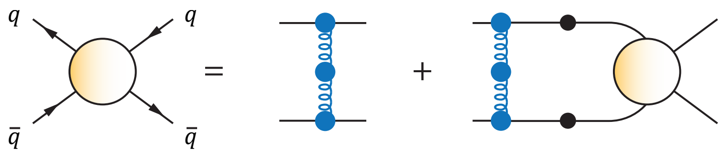
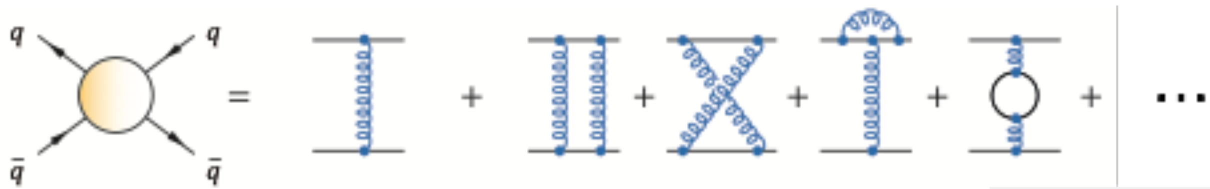
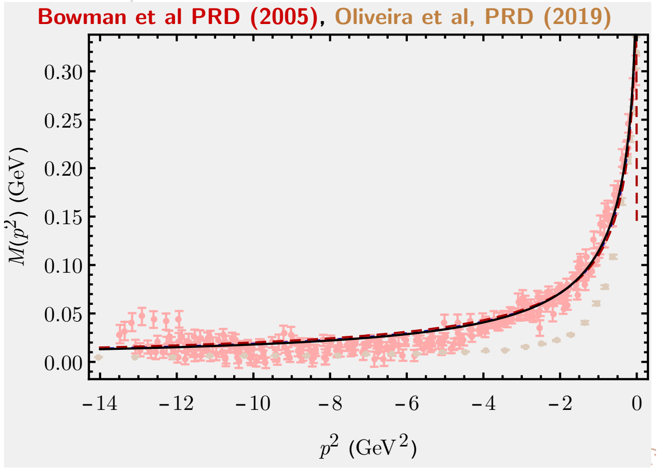




- Control of model dependence

combine synergies with lattice
(variable pion mass as tool)



Elmar P. Biernat e al
Phys.Rev. D98 (2018) 11, 114033

Dyson-Schwinger Methods

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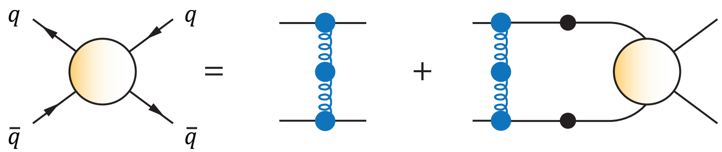
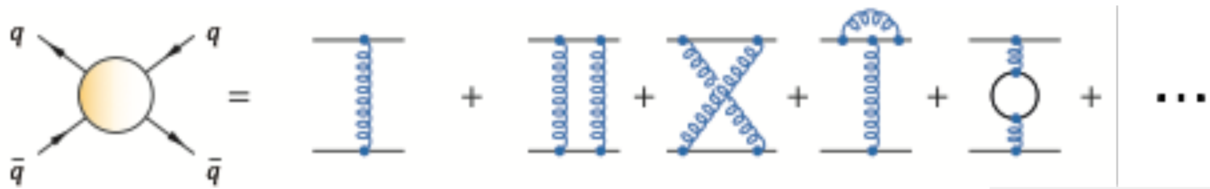


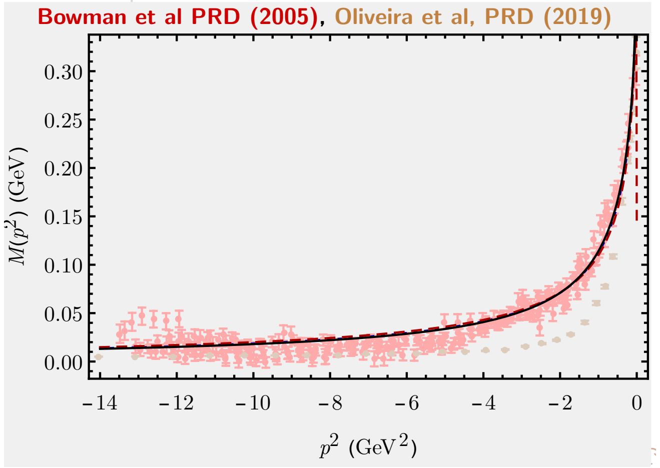


- Control of model dependence

combine synergies with lattice
(variable pion mass as tool)

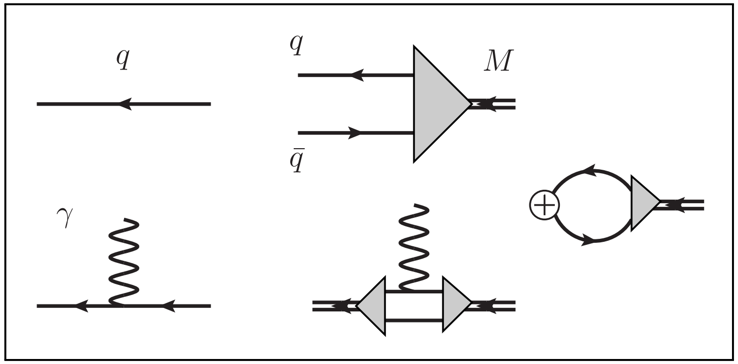
- Estimate theory uncertainty

compare results from different methods

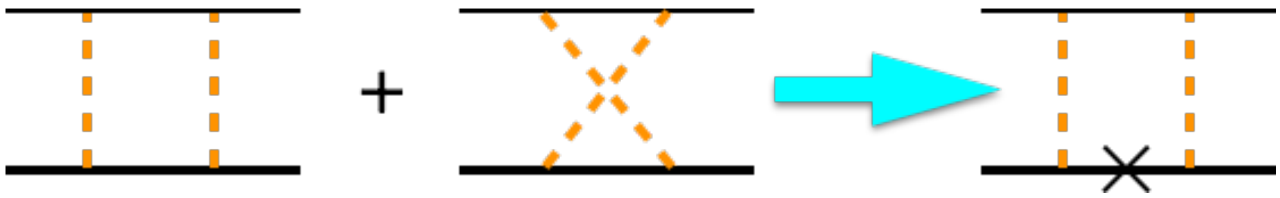


Elmar P. Biernat e al
Phys.Rev. D98 (2018) 11, 114033

CST© Covariant Spectator Theory



- Two-body CST equation effectively sums ladder and crossed-ladder exchange diagrams, due to cancelations.

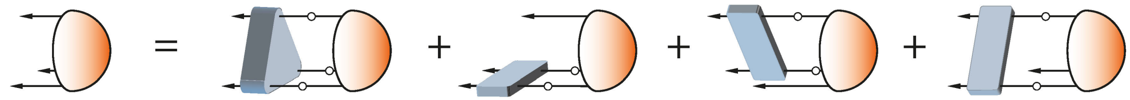


- Smooth non-relativistic limit.

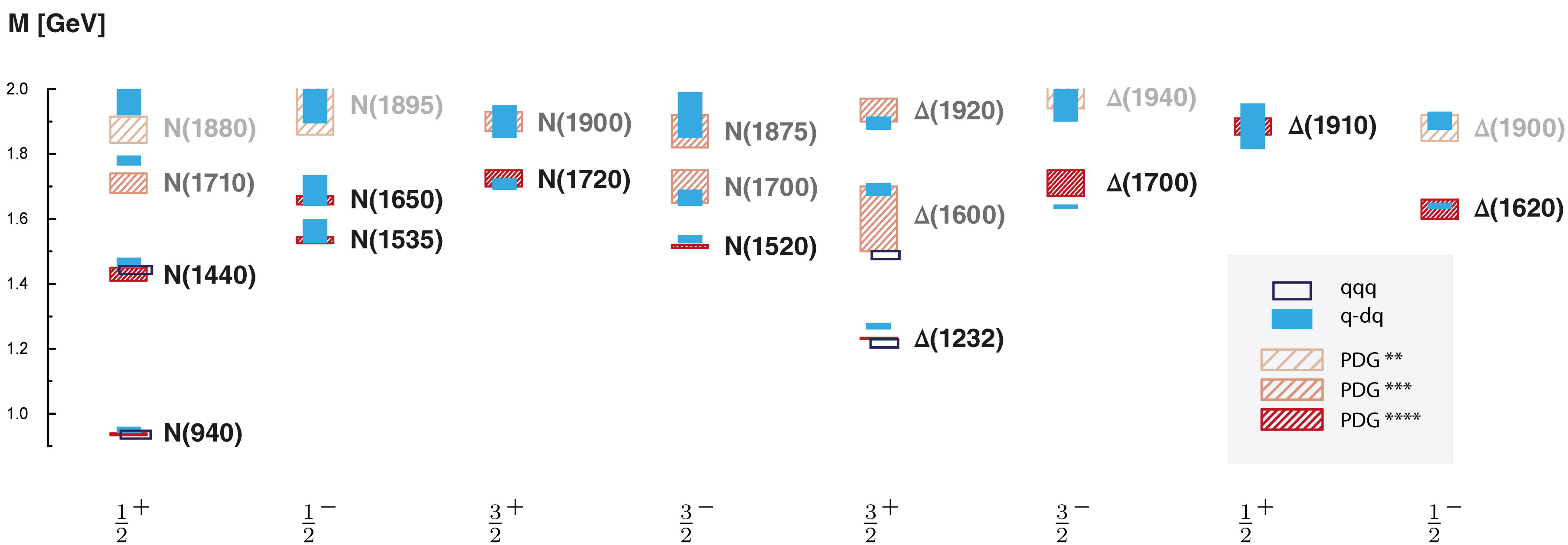
Some Highlights on Results

Light baryons

Bethe-Salpeter equation for baryons: GE, Sanchis-Alepuz, Williams, Alkofer, Fischer,



Light baryon spectrum (DSE-RL'): GE, Fischer, Sanchis-Alepuz, PRD 94 (2016)



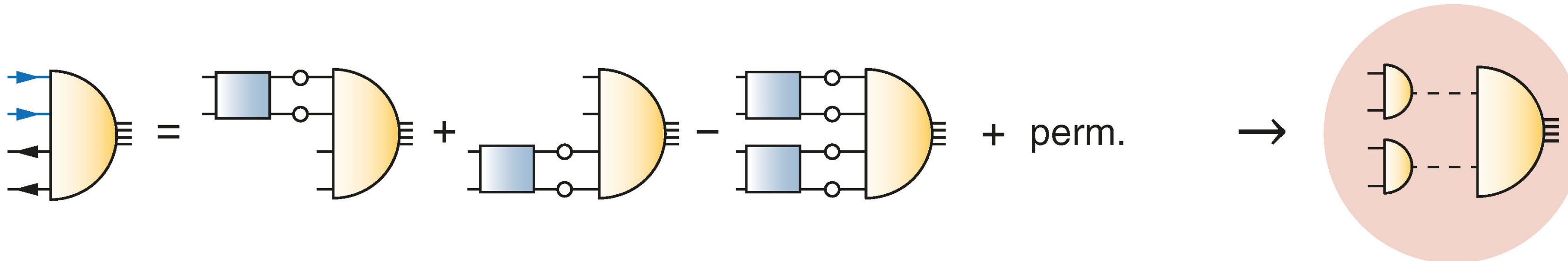
- Spectrum in 1:1 agreement with experiment
- Correct level ordering (without coupled-channel effects...)
- Three-body agrees with quark-diquark where applicable

2 parameters,
1 scale, $m_{u,d,s}$

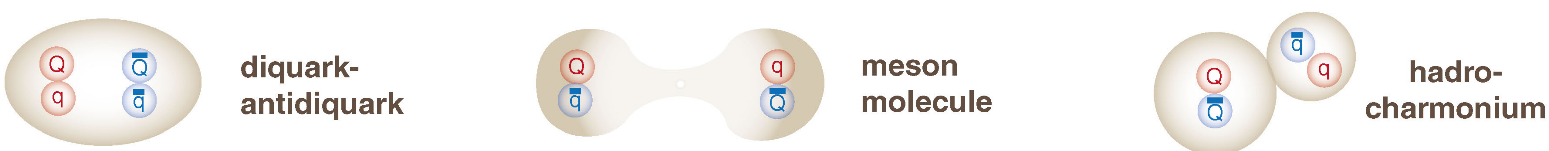
Tetraquarks are resonances

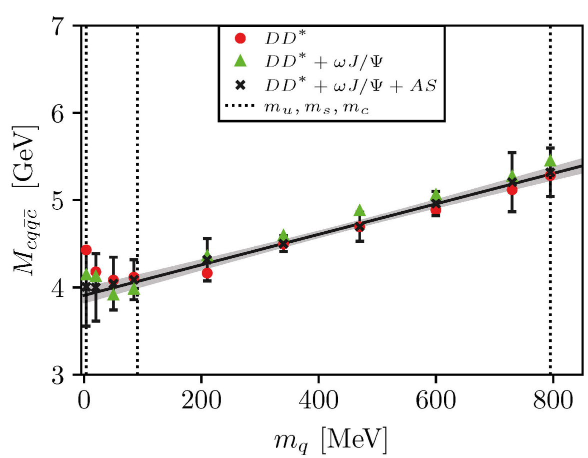
BSE dynamically generates **meson poles** in BS amplitude

GE, Fischer, Heupel, PLB 753 (2016)



X(3872): Can we distinguish different **tetraquark subclusters?**





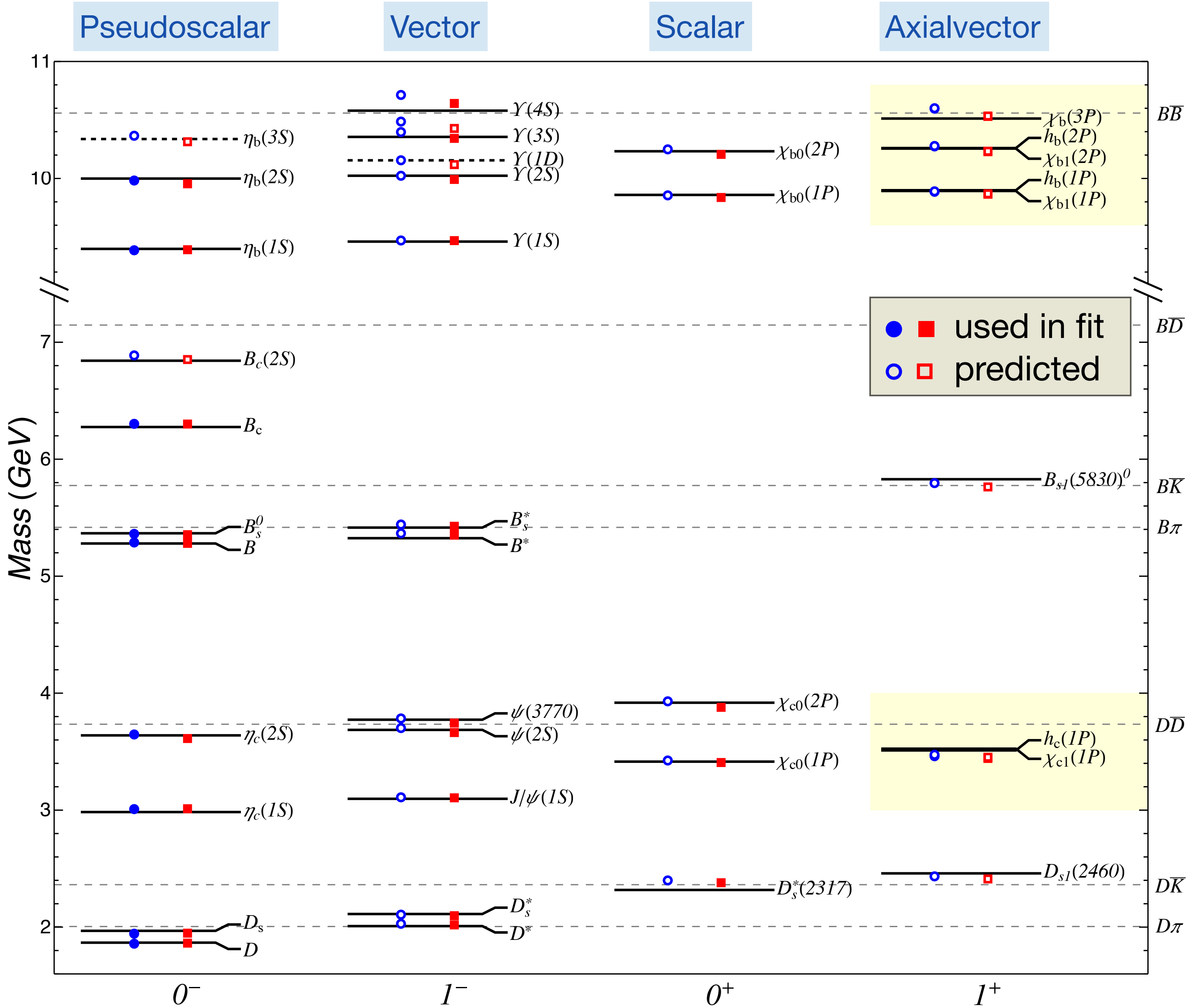
X(3872) dominated by DD*

Wallbott, GE, Fischer, PRD 100 (2019)

CST

Sofia Leitão, Alfred Stadler, TP, Elmar P. Biernat,
Heavy-light and quarkonia spectrum Phys. Lett. B, 764, 10, 2017

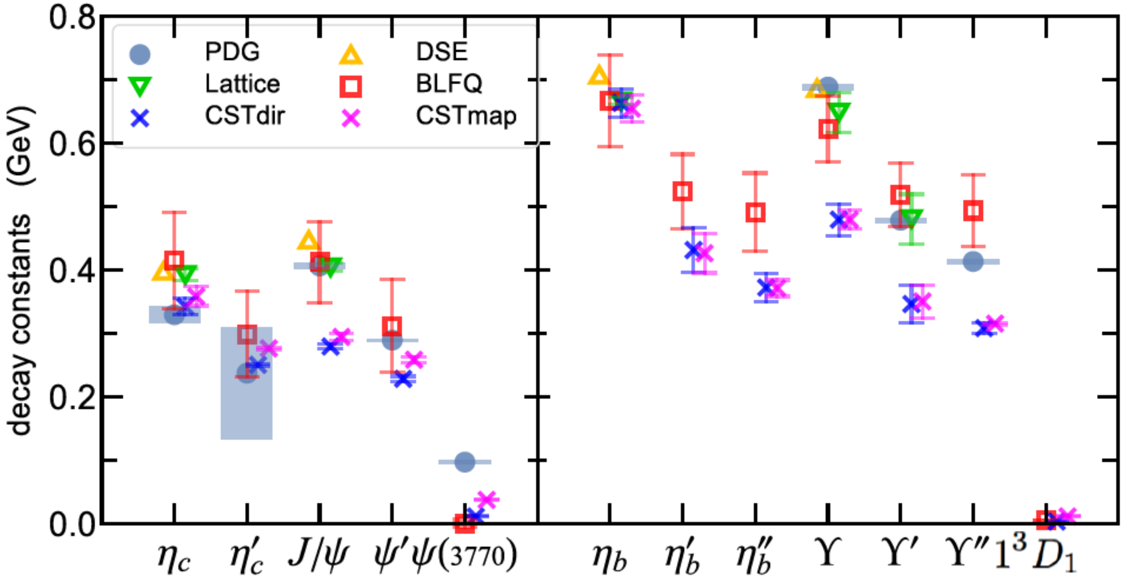
Blue:
model P1
fitted to 9
0^-(P) only

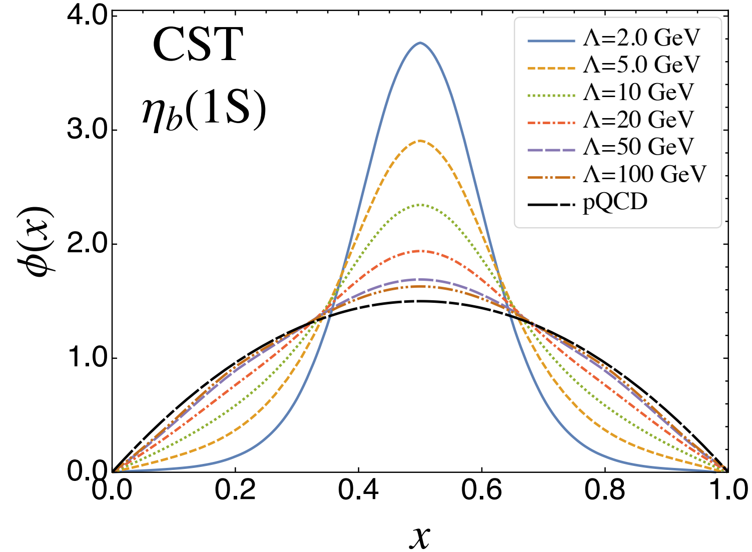


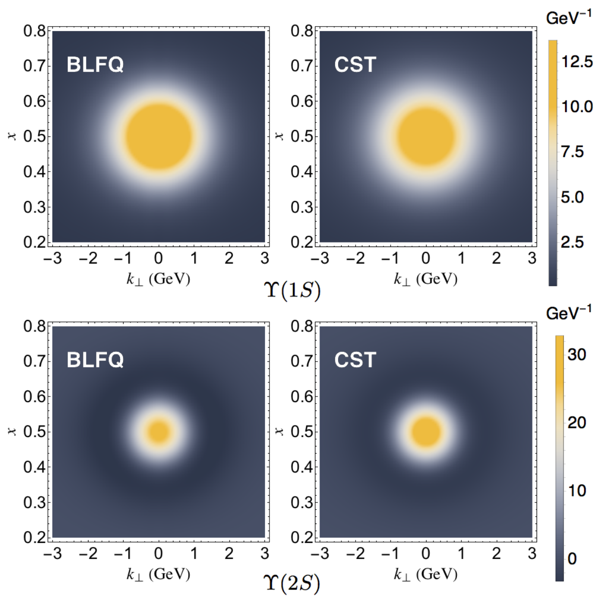
Red:
model PSV2
fitted to 25
P+S+V

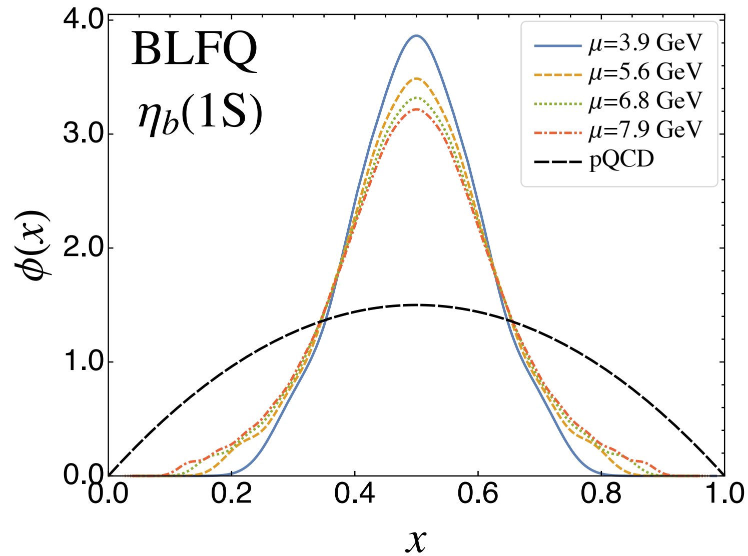
Comparison of two Minkowski-space approaches (CST and BLFQ) heavy quarkonia

Sofia Leitão, Yang Li, Pieter Maris, M.T. Peña, Alfred Stadler, James P. Vary, Elmar P. Biernat, Eur.Phys.J C (2017) 77





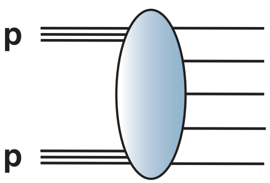




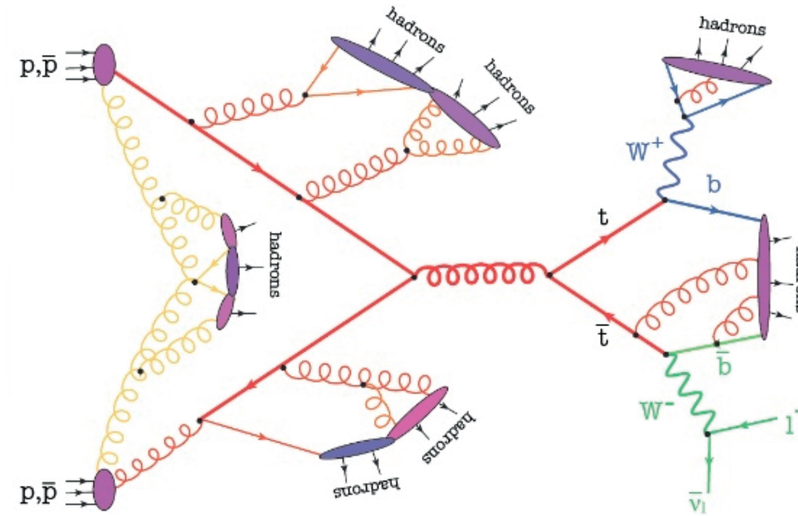
Connection to Experiments

Connection to experiment(s)

- $pp \to X, \; pA \to X, \; AA \to X, \ldots$

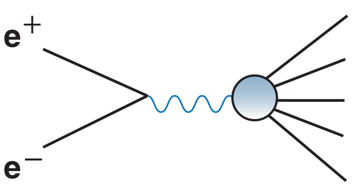


LHC (CERN)
RHIC (BNL)
GSI/FAIR (Germany)
. . .



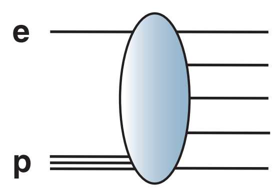
K. Hamilton

- $e^+e^- \leftrightarrow X$



BES III,
Belle,
BaBar,
. . .

- $ep \to X$



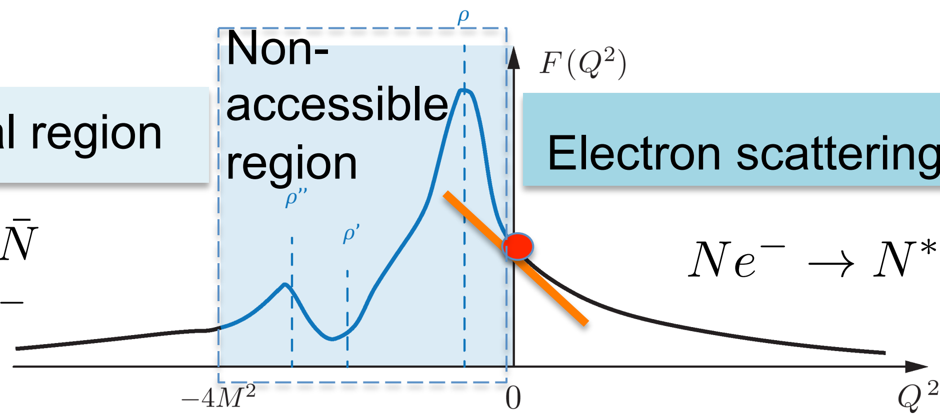
Jefferson Lab (USA)
COMPASS (CERN)
MAMI & ELSA (Germany)
EIC (USA)
. . .

Timelike: $Q^2<0$ | Spacelike: $Q^2>0$

Timelike physical region

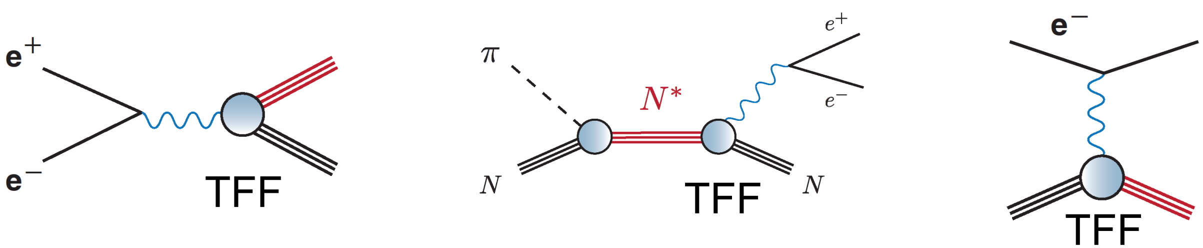
Electron scattering

$$e^+e^- \to N\bar{N}$$
$$N\bar{N} \to e^+e^-$$



$$Ne^- \to N^*e^-$$

$$Q^2 = -q^2$$



BES III, BELLE II

FAIR/GSI
HADES

JLab/CLAS:
most world data

Courtesy of
Gernot Eichmann

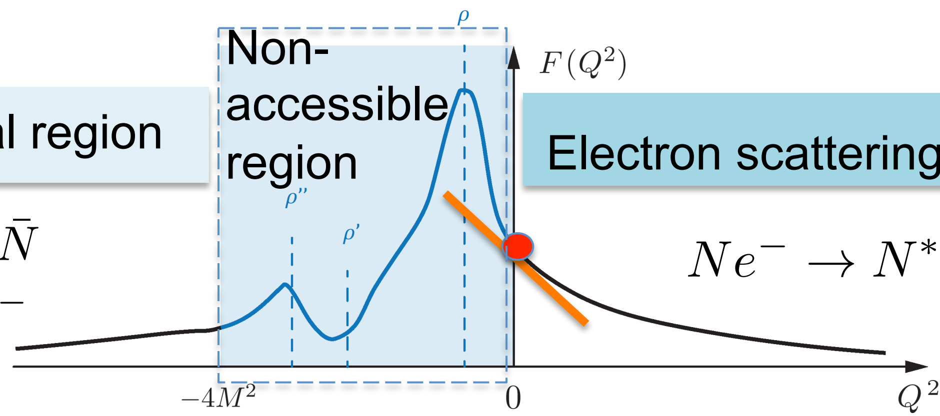
Crossing the boundaries between different Experiments to explore baryon resonances

Timelike: $Q^2<0$	Spacelike: $Q^2>0$

Timelike physical region

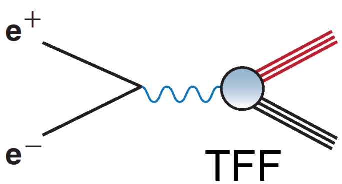
Electron scattering

$$e^+e^- \to N\bar{N}$$
$$N\bar{N} \to e^+e^-$$

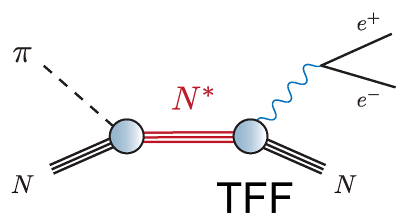


$$Ne^- \to N^*e^-$$

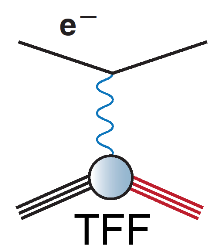
$$Q^2 = -q^2$$



BES III, BELLE II



FAIR/GSI
HADES

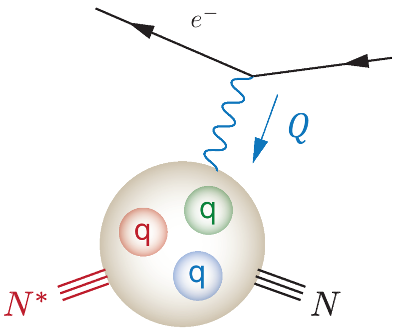


JLab/CLAS:
most world data

Results have to match at the photon point.

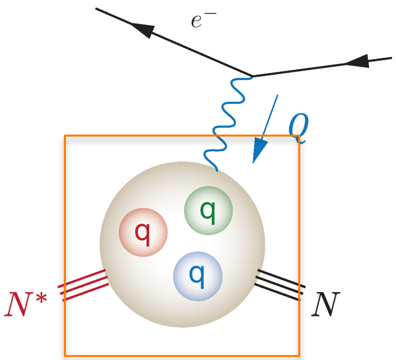
.

Transition form factors



Baryon resonances
transition form factors

Transition form factors



Baryon resonances
transition form factors

CLAS: Aznauryan et al., Phys. Rev. C 80 (2009)

MAID: Drechsel, Kamalov, Tiator, EPJ A 34 (2009)

See Gernot Eichmann and Gilberto Ramalho
Phys. Rev. D 98, 093007 (2018)

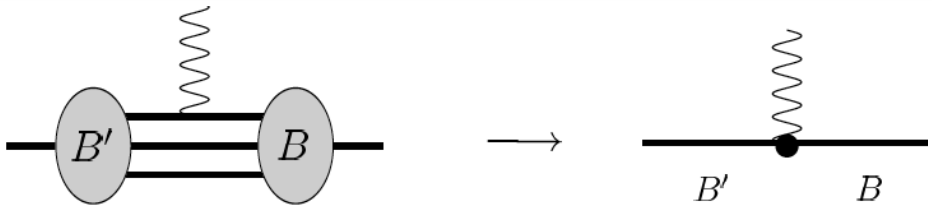
Spacelike form factors:

- Structure information: shape of charge distribution,…
- qqq excitation vs. hybrid, ...

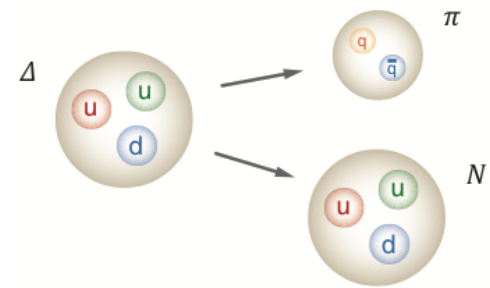
Timelike form factors:

- Particle production channels: vector mesons at small q^2
- In-medium dilepton production

Resonances as Pentaquarks seen in Form Factors

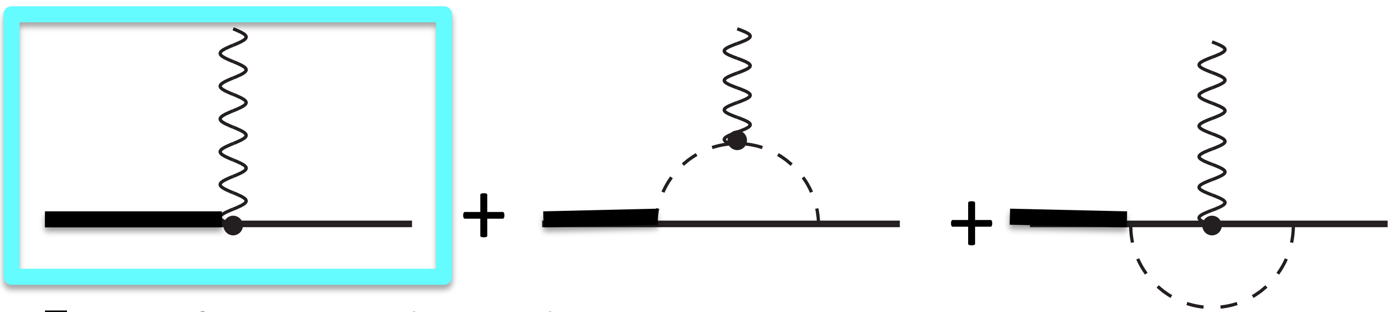


For low Q^2 : add coupling with pion in flight.



Bare quark component

Pion cloud



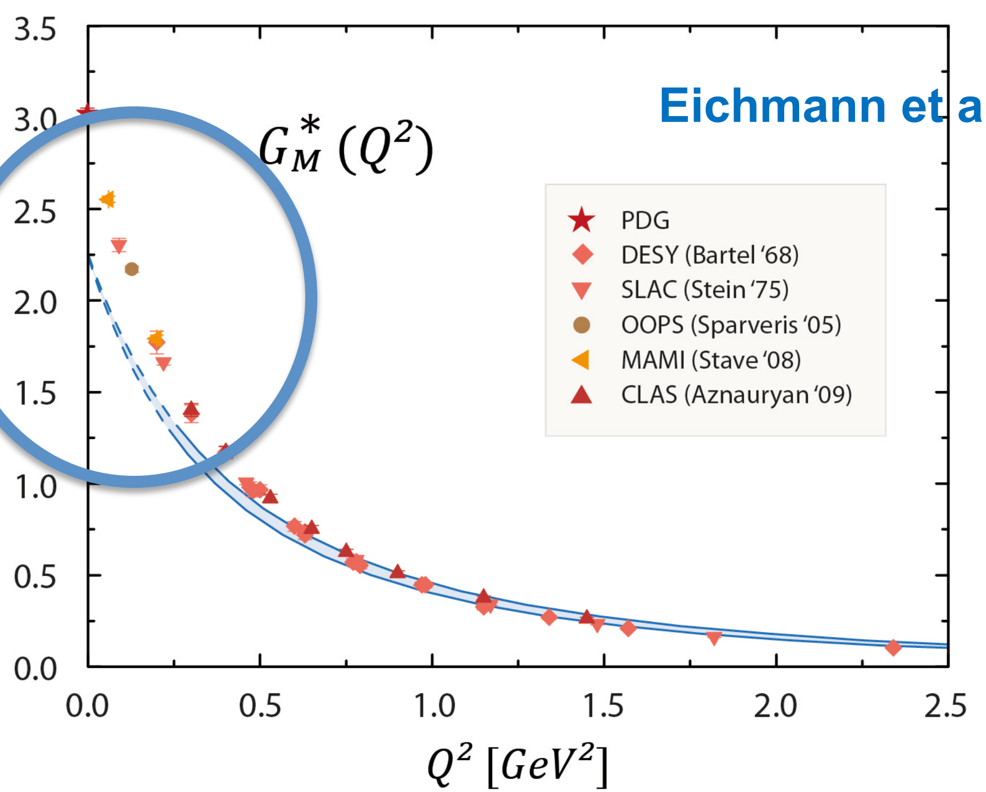
$q\bar{q}$ pairs from a single quark included in dressing

Pion cloud component supressed for high Q^2 $\dfrac{1}{Q^8}$

Signature of Pion Cloud is Model independent feature

$$\gamma N \to \Delta$$

Missing strength of G_M at the origin is an universal feature.
In a dynamical quark calculation:



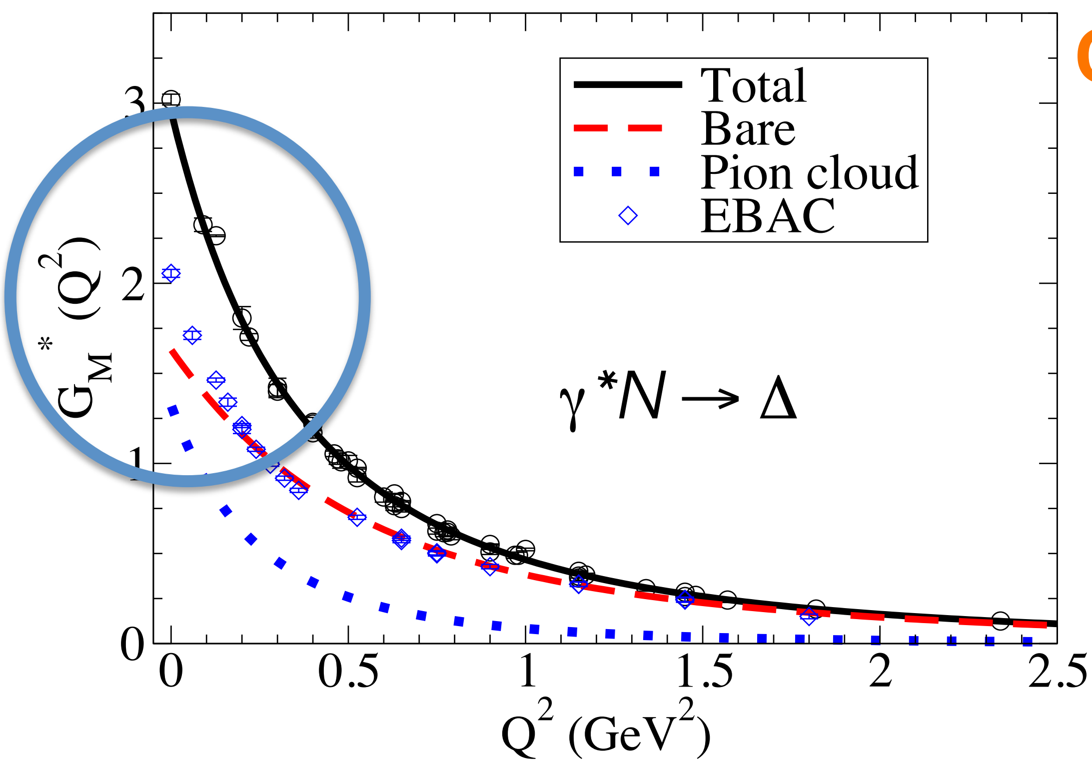
Eichmann et al., Prog. Part. Nucl. Phys. 91 (2016)

Effect of vicinity of the mass pole of the Delta to the pion-nucleon threshold.

Signature of pion cloud is Model independent feature

$$\gamma N \to \Delta$$

Missing strength of G_M at the origin is an universal feature.
In CST quark-diquark model:



CST© 2009

Bare quark-diquark core model:

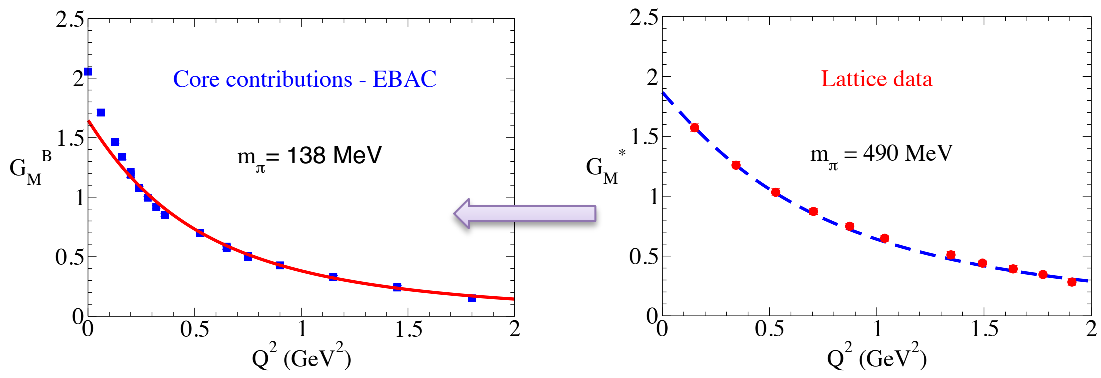
- dominates large Q^2 region.

Connection to Lattice QCD

In lattice pion mass regime, no pion cloud and only quark core contributions.

CST model constrained by LQCD data.

Then one can extract pion cloud indirectly from data.



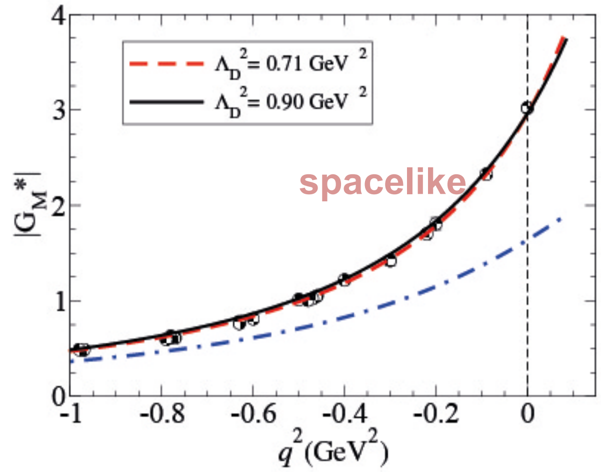
G. Ramalho and M. T. Peña, Phys. Rev. D 80, 013008 (2009)

Control of model dependence

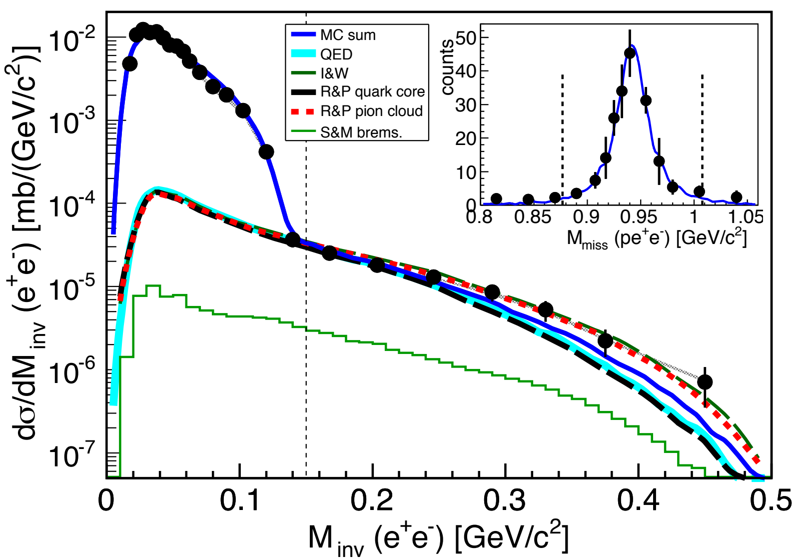
Crossing the boundaries

Δ(1232) Dalitz decay

Ramalho, Pena, Weil, Van Hees, Mosel, Phys.Rev. C93 (2016)



HADES Collaboration, Phys.Rev. C95 (2017)



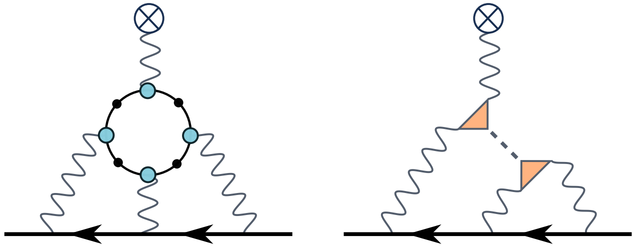
Dilepton mass spectrum including pion cloud

Consolidate...
and Innovate

New tracks:

- NN interaction from quark-gluon dynamics
- Hybrid mesons
- Higher mass N* excitations (HADES/FAIR)

- QCD contributions to BSM searches



Optimize the coupling between theory and experiment;
fostering interdisciplinary collaborations,

Main Message

Dyson-**S**chwinger dynamical quark calculations

- predict baryon spectrum and light mesons spectrum in agreement with experiment
- support quark-diquark picture for baryons
- allow to establish dynamic generation of tetraquarks;
- pentaquarks in the way

Covariant **S**pectator calculations

- gives a quark-diquark model which describes different resonance states

Δ(1232), N*(1440), N*(1535), **N*(1520)**, baryon octet, dilepton mass spectrum.

- is consistent with experimental data at high Q^2.
- also supports quark-diquark picture for baryons
- description of meson spectrum from fitting PS sector only, showing

that spin-dependent forces are correctly predicted through covariance.

Recent results

Description of meson spectrum from fitting PS sector only.
(Spin-dependent forces correctly predicted through covariance.)

Sofia Leitão, Alfred Stadler, TP, Elmar P. Biernat, Phys. Lett. B, 764, 10, 2017

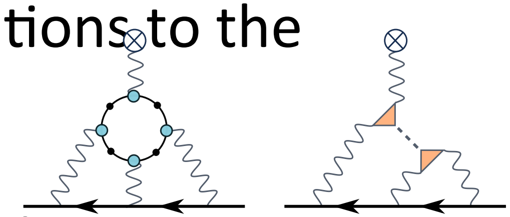
Results hyperon timelike form factors for future e^+e^- experiment

G. Ramalho, TP, Phys. Rev. D 1, 014014 (2020) B, 764, 10, 2017

Nucleon resonance contributions to nucleon Compton scattering,`
where experimental data exists

Gernot Eichmann, G. Ramalho, Phys.Rev. D98 (2018) 9, 093007

Pseudoscalar meson pole and pion box contributions to the
anomalous magnetic moment of the muon



Gernot Eichmann et al. Phys.Lett. B797 (2019) 134855

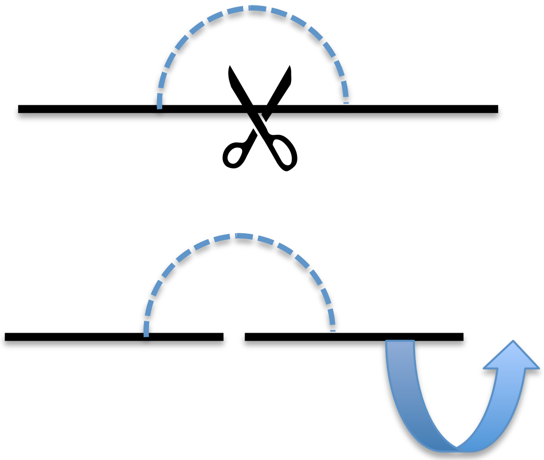
X(3872) as a four-quark state in a DS/BS approach

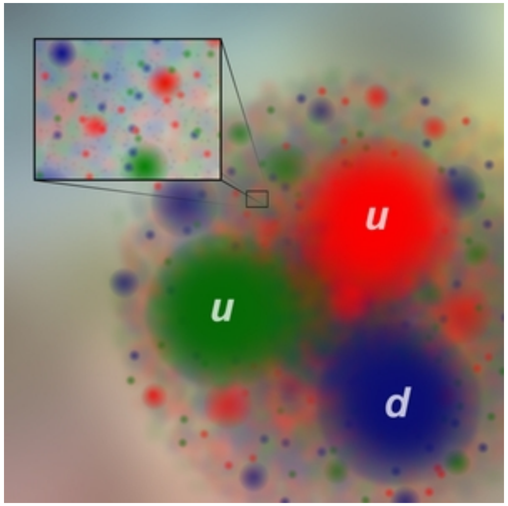
P. Wallbott, Gernot Eichmann, Christian S. Fischer, Phys.Rev. D100 (2019) 14033

Proof of gauge independence of the constituent quark mass
equation and identification of the appropriate gauge of CST.

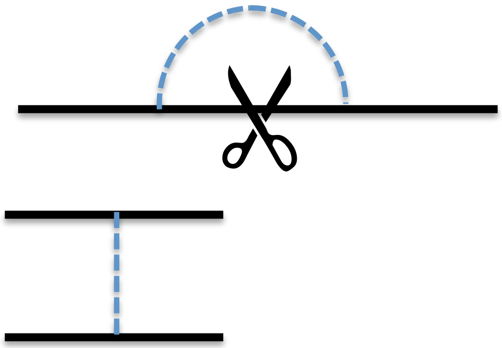
Elmar P. Biernat e al Phys.Rev. D98 (2018) 11, 114033

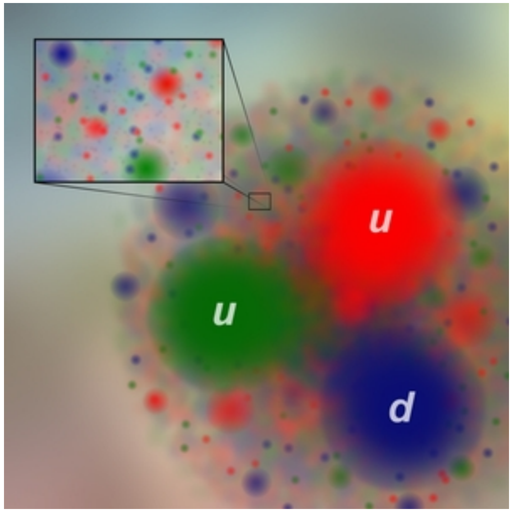
DSE and **CST©**: quark self-interaction is consistent with quark-anti-quark interaction





DSE and **CST©**: quark self-interaction is consistent with quark-anti-quark interaction

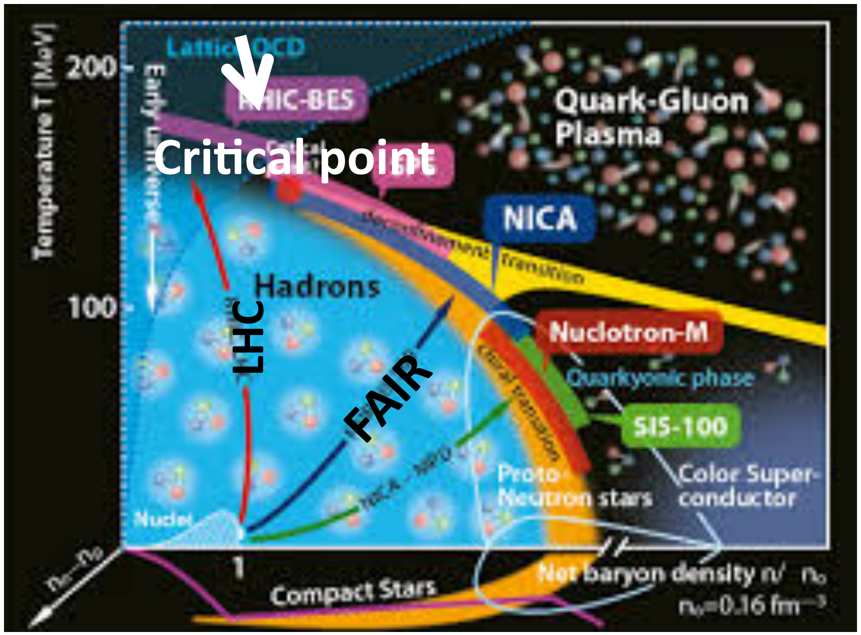




Two-body equation for bound state is consistent with one-body equation for self-energy, in the chiral limit.

Necessary for dynamical chiral symmetry breaking.

Big Questions



Is there critical endpoint in the QCD phase diagram?

How important are baryons for the phase transition?

The Gap and the Scope

- How do excess neutrons in neutron-rich nuclei form such close-proximity pairs?

- Is the tensor force indispensable for light nuclei to be bound or stable against breakup?

- What is the nature of the repulsive core of the nuclear interaction?

The project

- operates at the level of the nuclear interaction and its relation to low-energy QCD

- reaches out into nuclear astrophysics.

Benefits of JRA

- The teams cover all these methods.
- Strengthens international & interdisciplinary collaborations.
- Optimizes the connections between theory and experiment.
- Postdoc position strengthen existing connections.

- Computer programs can be made accessible.
- OPEN repositories of reports available online.
- Opportunity for attracting students and organize joint training programs.

Connections to Experiment

- **R3B@FAIR**

  (p,2p) reactions with radioactive beams
  high-energy protons.

  ^{15}O (2p, gamma)^{17}Ne

- **LNS@Catania**

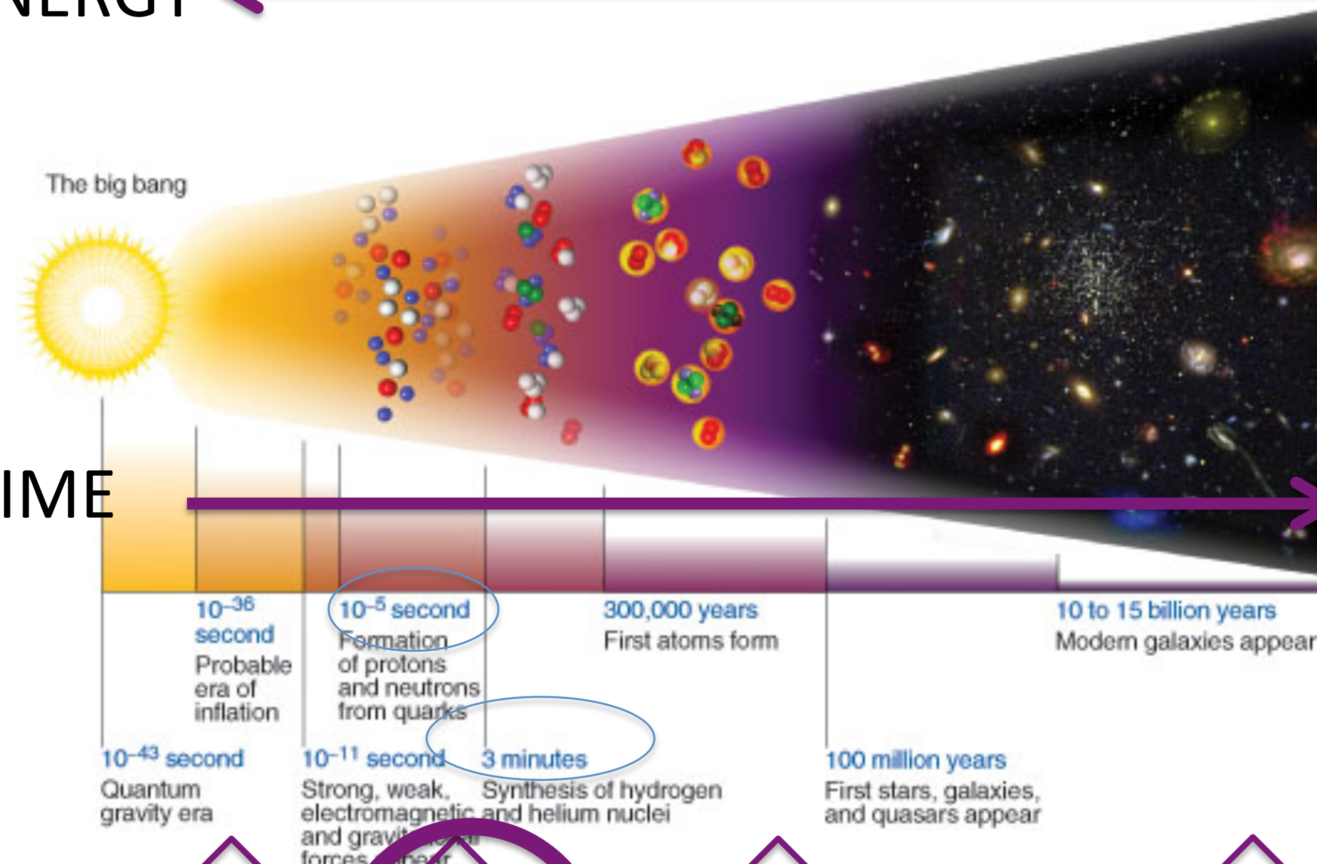
  Charge exchange reactions

- ...Task Force for Experimental activities

Natural Coupling: "**TheoS**" JRA for Theory of ENSAR2
US Analogue: "**FRIB** Theory Alliance"

Connections to Programs at Experimental Facilities

ENERGY



TIME

Active Collaborations
JLab
HADES/GSI
Giessen U
Iowa State U

Brazil (Rio Grande do Sul)

CERN

JLAB; FAIR

Radioactive Ion Beams

Nuclear Astrophysics

So far:

Light nuclear bound states (deuteron, 3N), 3N Forces

High precision NN force models with few number of parameters

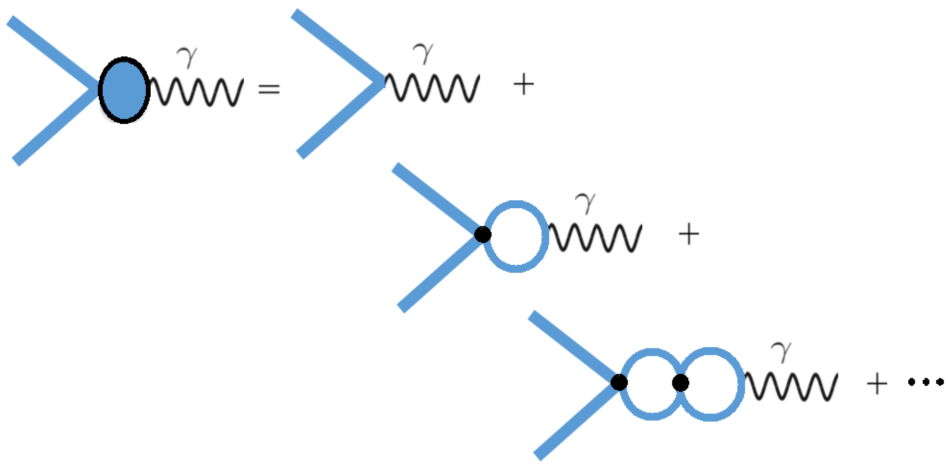
Elastic electromagnetic form factors with consistent gauge-invariant currents

Our Focus now:

Meson and Baryon properties with **functional methods (DS/BS and CST)**

Multiquark systems.

VMD as link to LQCD



$$\Gamma_\mu(p,Q) = \quad \gamma_\mu \quad +$$

$$\int \frac{d^4q}{(2\pi)^4} K(p,q,Q) S(q+\eta Q) \Gamma_\mu(q,Q) S(q-\eta Q)$$

VMD as link to LQCD

- VMD enables link to LQCD:

in the electromagnetic current the vector meson mass is taken as a function of the running pion mass.

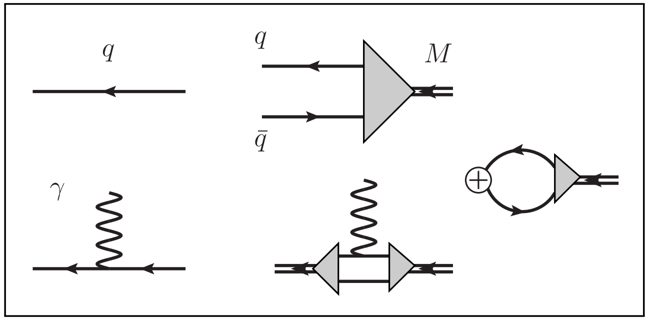
- Pion cloud contribution negligible for **large pion masses**:

and **bare** quark model could be calibrated to the **lattice data.**

- After that, in the limit of the physical pion mass value,

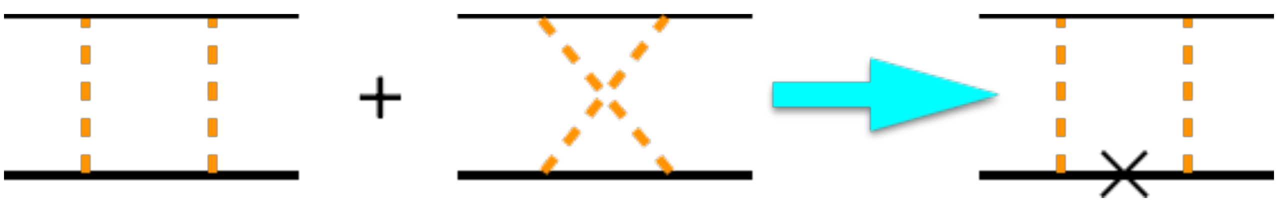
the **experimental data** is well described in the large Q^2 region.

CST© Covariant Spectator Theory



- Formulation in Minkowski space.

- Two-body CST equation effectively sums ladder and crossed-ladder exchange diagrams, due to cancelations.



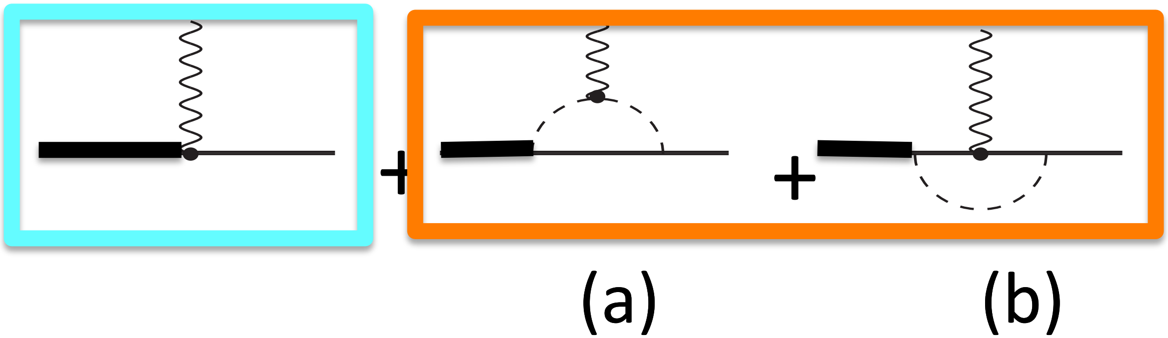
- Provides wave functions from covariant vertex with simple transformation properties under Lorentz boosts, appropriate angular momentum structures and smooth non-relativistic limit.

- Manifestly covariant, but only three-dimensional loop integrations.

$$\int_k = \int \frac{d^3\mathbf{k}}{2E_D(2\pi)^3}$$

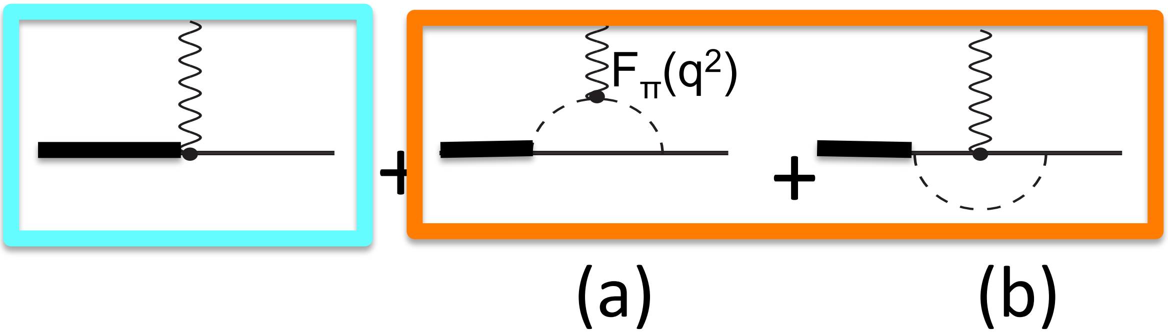
- Allows to implement confinement and dynamical chiral symmetry breaking.

Extension to Timelike



The residue of the pion from factor $F_\pi(q^2)$ at the timelike ρ pole is proportional to the $\rho \longrightarrow \pi\pi$ decay

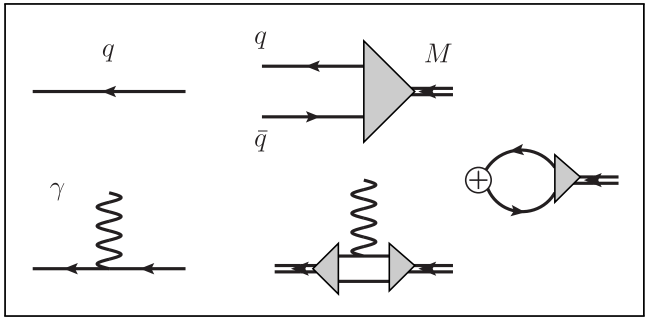
Extension to Timelike



The residue of the pion from factor $F_\pi(q^2)$ at the timelike ρ pole is proportional to the $\rho \longrightarrow \pi\pi$ decay

Diagram (a) related with pion electromagnetic form factor $F_\pi(q^2)$

CST© Covariant Spectator Theory



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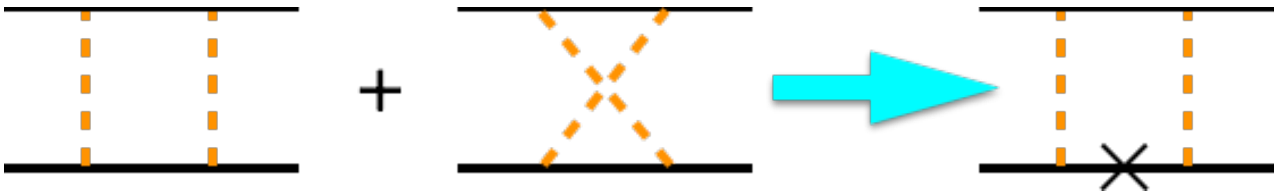

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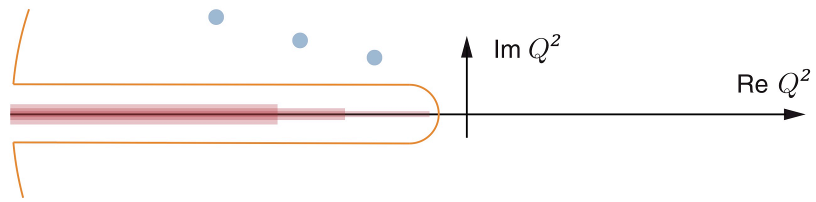
Theoretical toolkits

Timelike baryon transition form factors not yet within reach in lattice QCD: explore alternative methods, estimate theory uncertainty!

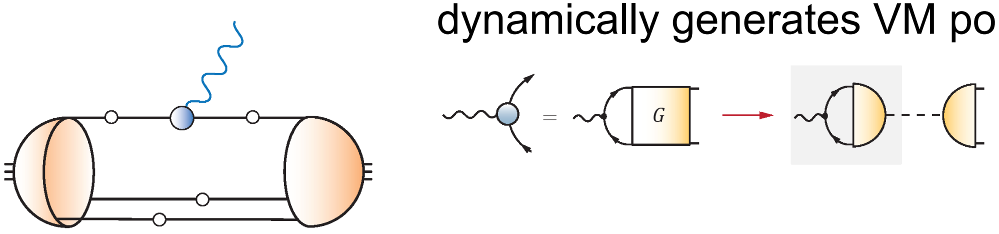
Figs courtesy of Gernot Eichmann

- **Analyticity**



→ Dispersion theory

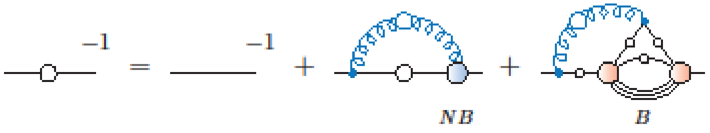
- **Dynamics**



Quark-photon coupling dynamically generates VM poles!

→ Dyson-Schwinger eqs.
→ Effective Lagrangian models
→ Quark models
→ Vector-meson dominance

- **Medium effects**



→ In-medium description of resonances!

Theoretical toolkits

Timelike baryon transition form factors not yet within reach in lattice QCD: explore alternative methods, estimate theory uncertainty!

Figs courtesy of
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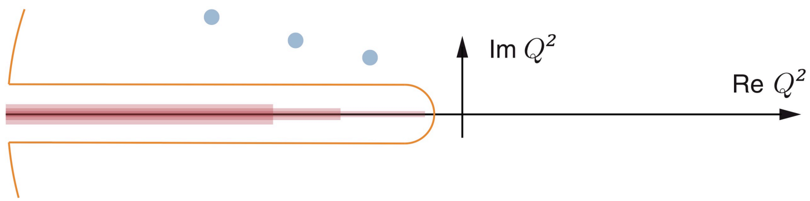

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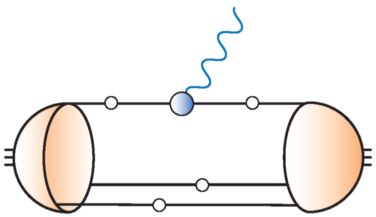

Quark-photon coupling
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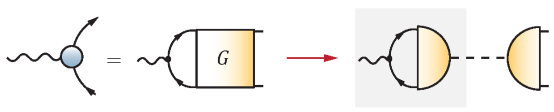

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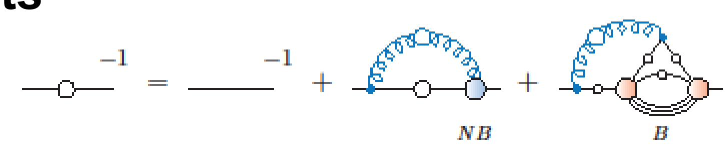
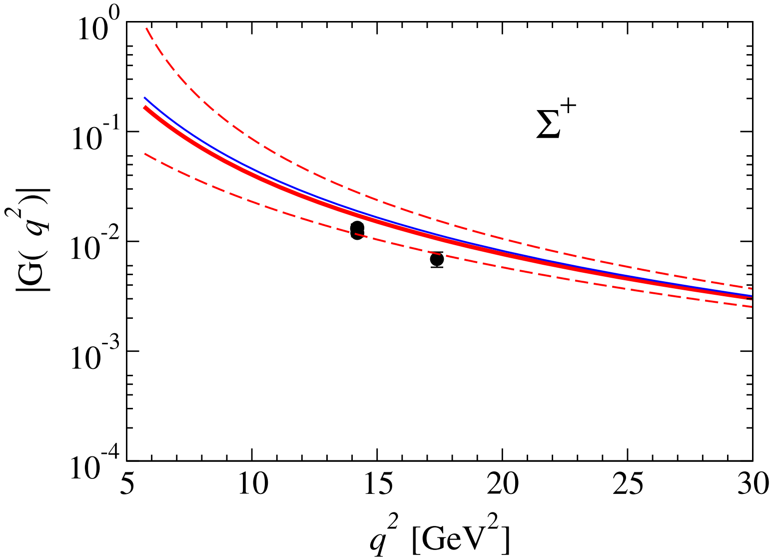
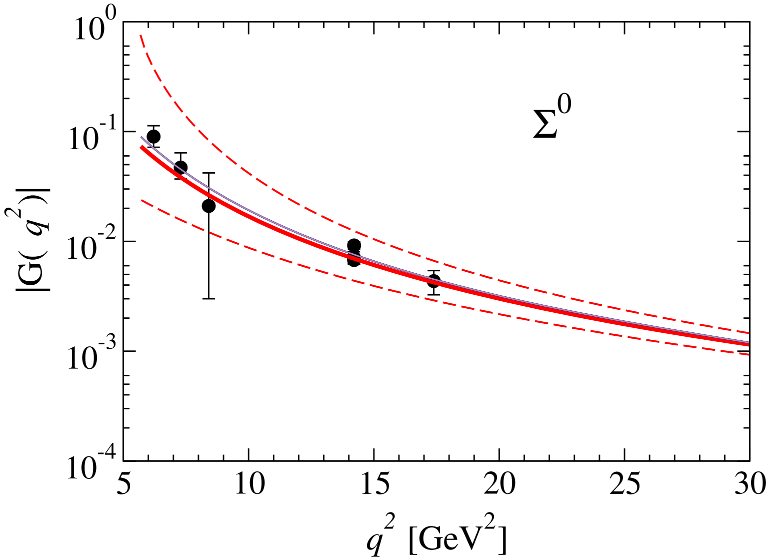


→ In-medium description of resonances!

Crossing the boundaries

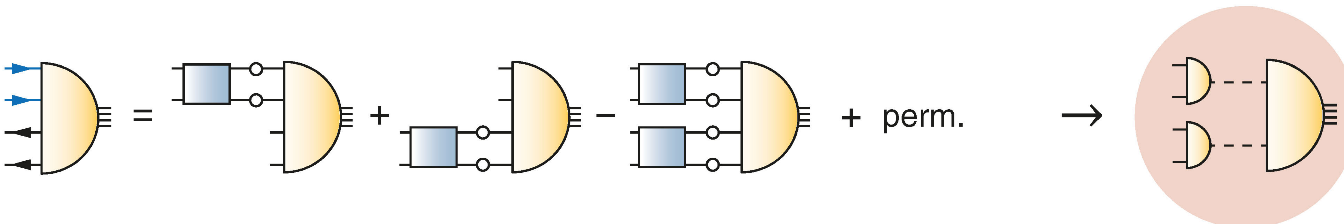


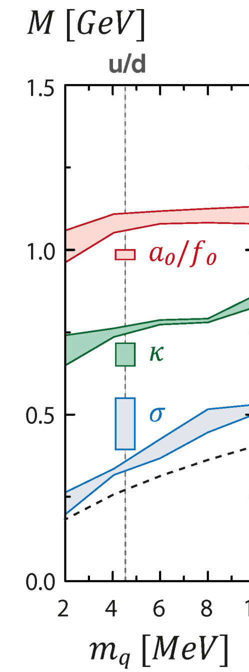


PHYSICAL REVIEW D **101,** 014014 (2020)

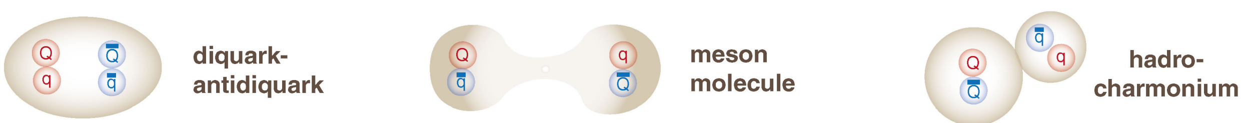
Tetraquarks are resonances

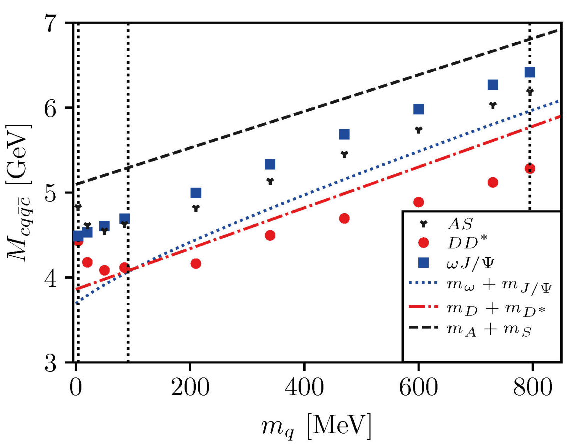
Light scalar mesons σ, κ, a_0, f_0 as **tetraquarks:**
BSE dynamically generates **meson poles** in BS amplitude
GE, Fischer, Heupel, PLB 753 (2016)

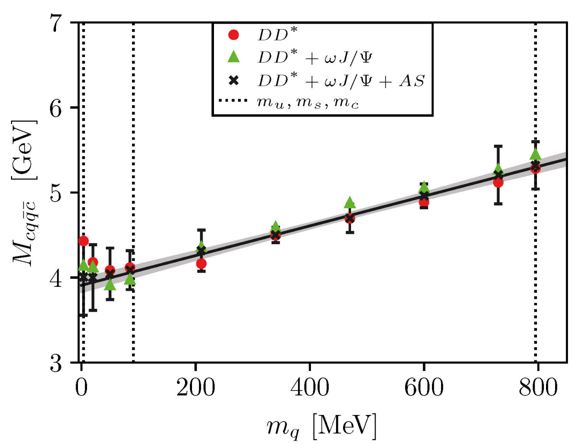




X(3872): Can we distinguish different **tetraquark subclusters?**

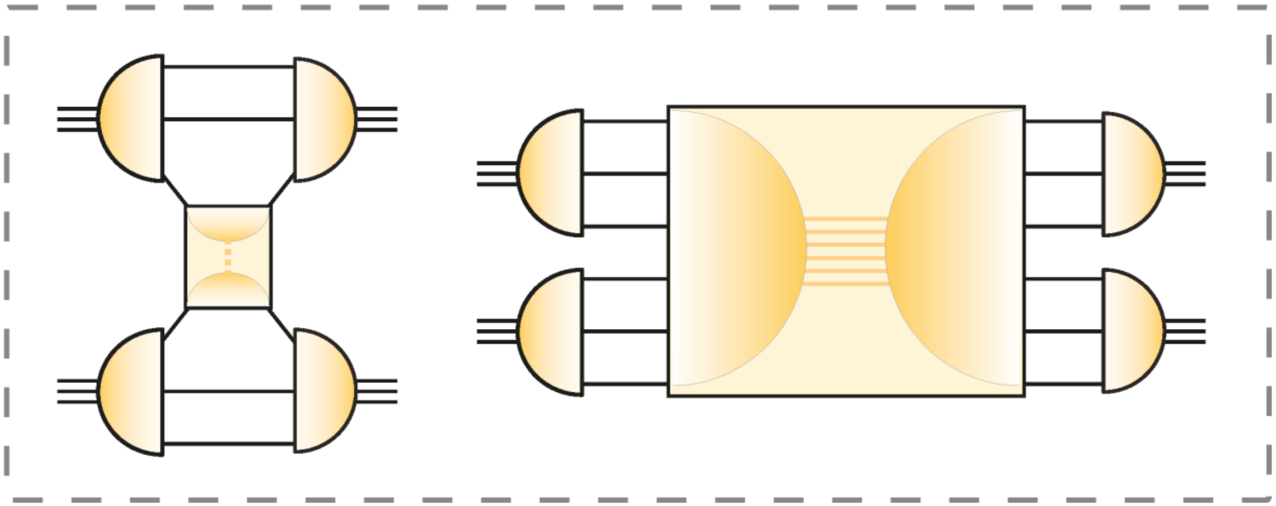






X(3872) dominated by DD*
Wallbott, GE, Fischer, PRD 100 (2019)

Nuclear Interaction from first principles



Meson exchange
and short-range
quark exchange

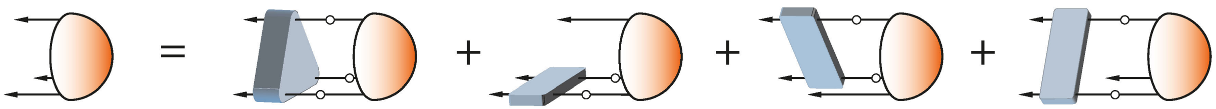
Dibaryon exchange:
Deuteron, …

Dyson-Schwinger and Bethe-Salpeter equations (DSEs/BSEs) (novel)

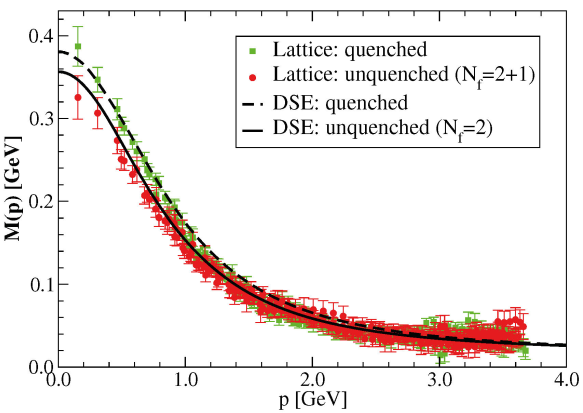
→ Deals with high-momentum transfer; can constrain Chiral EFT

Bound-state equations

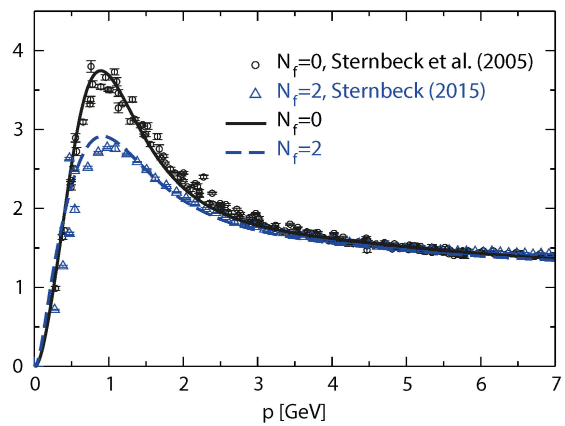
Bethe-Salpeter equation for baryons: GE, Sanchis-Alepuz, Williams, Alkofer, Fischer, PPNP 91 (2016), 1606.09602



Quark:



Gluon:



Quark-gluon vertex: