NANJING UNIVERSITY

Craig Roberts … http://inp.nju.edu.cn/

Strong Interactions and the Emergence of Mass

2013: Englert & Higgs

- The 2013 Nobel Prize in Physics was awarded to Peter Higgs and Francois Englert following discovery of the Higgs boson at the Large Hadron Collider.
- With this discovery the Standard Model of Particle Physics became complete.

Where to now?

2013: Englert & Higgs

- "The Higgs boson is often said to give mass to everything."
- "However, that is wrong. It only gives mass to some very simple particles, accounting for only one or two percent of the mass of more complex things …"
- *The vast majority of mass comes from the energy needed to hold quarks together inside hadrons*

confinement

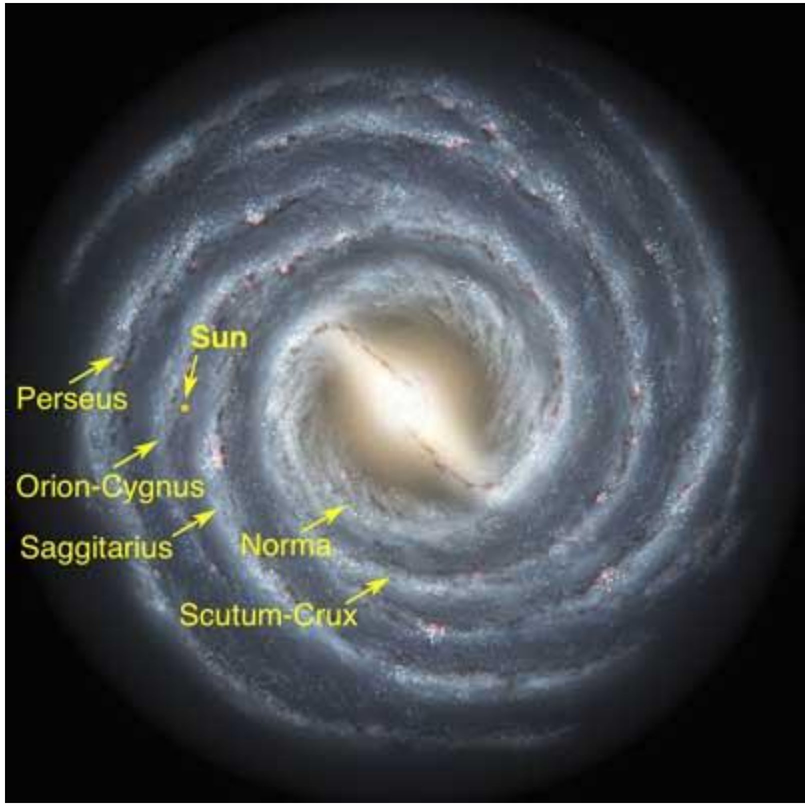
2013: Englert & Higgs

- The most important chapter of the Standard Model is the least understood.
- Quantum Chromodynamics (QCD) is that part of the Standard Model which is supposed to describe all of nuclear physics
  - Matter = quarks
  - Gauge bosons = gluons
- Yet, fifty years after the discovery of quarks, we are only just beginning to understand how QCD moulds the basic bricks for nuclei: pions, neutrons, protons, etc.

Emergent Phenomena in the Standard Model

Existence of our Universe depends critically on the following empirical facts:

- Proton is massive
  - *i.e*. the mass-scale for strong interactions is vastly different to that of electromagnetism
- Proton is absolutely stable
  - Despite being a composite object constituted from three valence quarks
- Pion is unnaturally light (not massless, but lepton-like mass)
  - Despite being a strongly interacting composite object built from a valence-quark and valence antiquark



Emergence: low-level rules producing high-level phenomena, with enormous apparent complexity

F. Wilczek, [QCD Made Simple](#)
Physics Today **53N8** 22-28, (2000)

Quantum Chromodynamics

- Quite possibly, the most remarkable theory we have ever invented
- One line and two definitions are responsible for the
  <u>origin</u>, <u>mass</u> and <u>size</u> of (almost) all visible matter!

F. Wilczek, QCD Made Simple
Physics Today **53N8** 22-28, (2000)

Quantum Chromodynamics

- Quite possibly, the most remarkable theory we have ever invented
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Strong Interactions in the Standard Model

$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\, \delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

- Only apparent scale in chromodynamics is mass of the quark field
- Quark mass is said to be generated by Higgs boson.
- In connection with everyday matter, that mass is less-then 0.5% of the empirical scale for strong interactions,

  viz. more-than two orders-of-magnitude smaller
- Plainly, the Higgs-generated mass is very far removed from the natural scale for strongly-interacting matter
- *Nuclear physics mass-scale* – 1 GeV – is an *emergent feature of the Standard Model*
  - No amount of staring at $L_{\rm QCD}$ can reveal that scale
- Contrast with quantum electrodynamics, *e.g*. spectrum of hydrogen levels measured in units of m_e, which appears in $L_{\rm QED}$

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - \qquad \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Whence Mass?

- Classical chromodynamics … non-Abelian local gauge theory
- Remove the current mass … there's no energy scale left
- *No dynamics in a scale-invariant theory*; only kinematics … the theory looks the same at all length-scales … there can be no isolated clumps of anything
  … *hence bound-states are impossible*.
- *Our Universe can't exist*
- *Higgs boson doesn't solve this problem* …
  - normal matter is constituted from light-quarks
  - the mass of protons and neutrons, the kernels of all visible matter, are 100-times larger than anything the Higgs can produce
- *Where did it all begin? … becomes … Where did it all come from?*

$$T_{\mu\mu} = \frac{1}{4}\beta(\alpha(\zeta))G^{a}_{\mu\nu}G^{a}_{\mu\nu}$$

Trace Anomaly

- In a scale invariant theory Poincaré invariance entails

  the *energy-momentum tensor must be traceless:* $T_{\mu\mu} \equiv 0$

- Regularisation and renormalisation of (ultraviolet) divergences in Quantum Chromodynamics introduces a mass-scale

  … *dimensional transmutation*:

  Lagrangian's *constants* (couplings and masses) become dependent on a mass-scale, ζ

- $\alpha \to \alpha(\zeta)$ in QCD's (massless) Lagrangian density, $\mathbf{L}(\mathbf{m}\ \ \mathbf{0})$

  $\Rightarrow \partial_\mu \mathbf{D}_\mu = \delta\mathbf{L}/\delta\sigma = \alpha\beta(\alpha)\, d\mathbf{L}/d\alpha = \boxed{\beta(\alpha)\, \tfrac{1}{4} G_{\mu\nu} G_{\mu\nu} = T_{\rho\rho} =: \Theta_0}$

  Trace anomaly

  QCD β function … specifies how the coupling "runs"

Quantisation of renormalisable four-dimensional theory forces nonzero value for trace of energy-momentum tensor

$$T_{\mu\mu} = \frac{1}{4}\beta(\alpha(\zeta))G^a_{\mu\nu}G^a_{\mu\nu}$$

Trace Anomaly

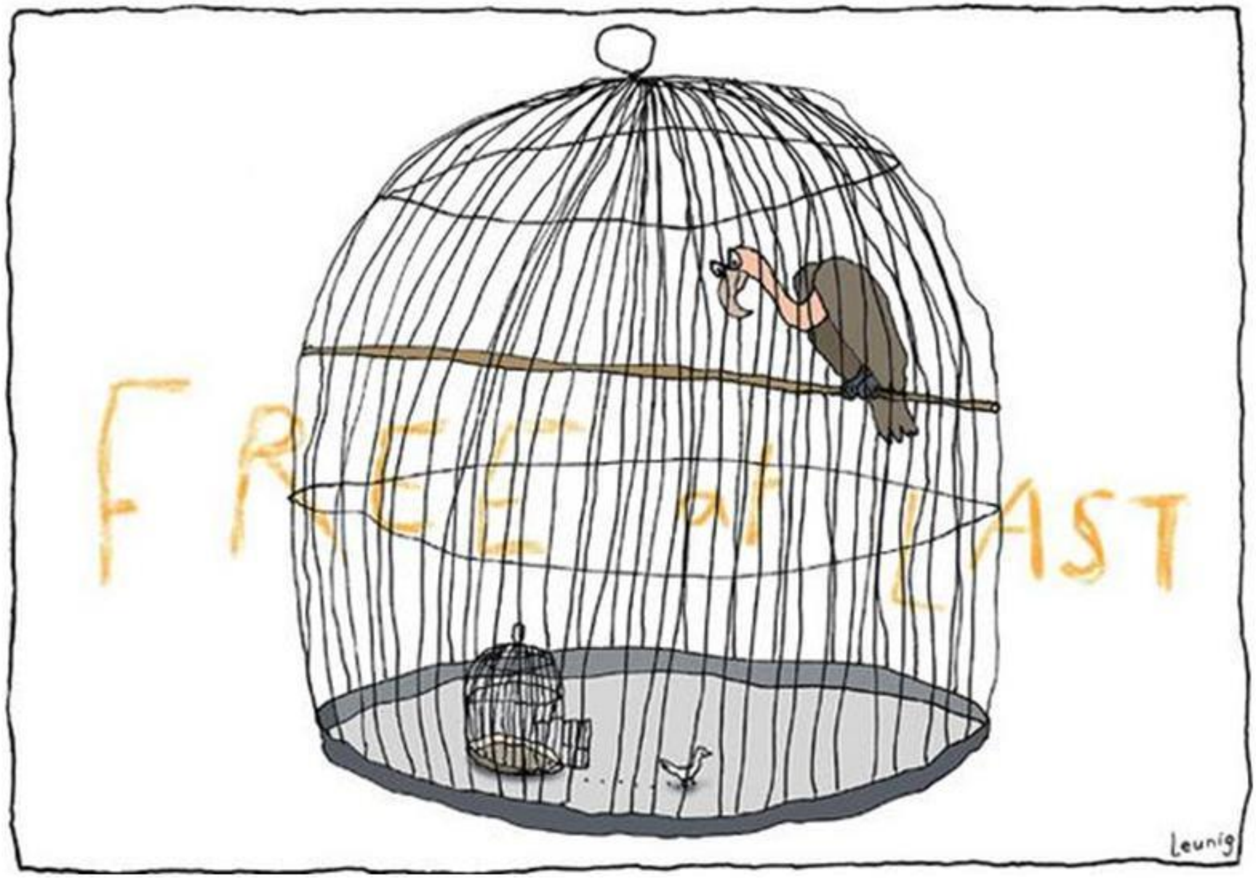
- Knowing that a trace anomaly exists does not deliver a great deal
  … Indicates only that a mass-scale must exist
- Key Question:
  - Can one compute and/or understand the magnitude of that scale?
- One can certainly *measure* the magnitude … consider proton:

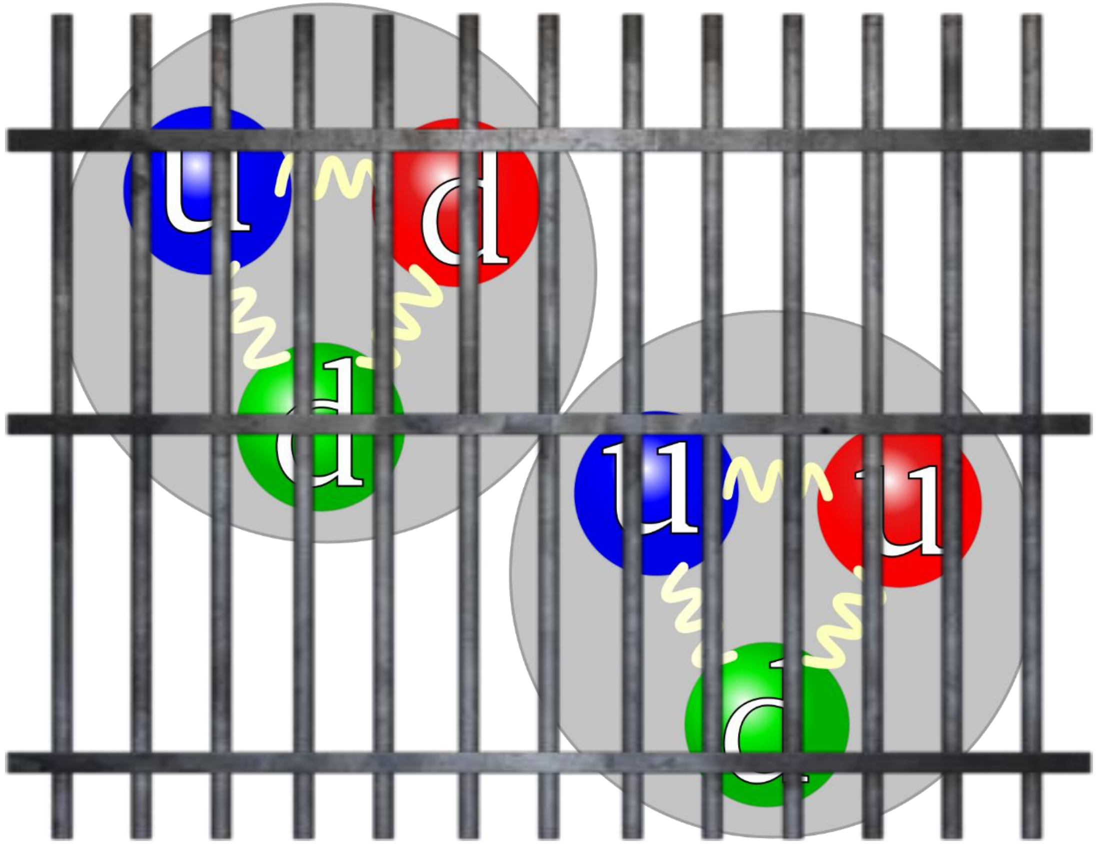
$$\langle p(P)|T_{\mu\nu}|p(P)\rangle = -P_\mu P_\nu$$
$$\langle p(P)|T_{\mu\mu}|p(P)\rangle = -P^2 = m_p^2$$
$$= \langle p(P)|\Theta_0|p(P)\rangle$$

- In the chiral limit the entirety of the proton's mass is produced by the trace anomaly, Θ_0
  … In QCD, Θ_0 measures the strength of gluon self-interactions
  … so, from one perspective, m_p is (somehow) completely generated by glue.

Confinement & Origin of Mass

- *The vast majority of mass comes from the energy needed to hold quarks together inside nuclei*





Craig Roberts. Strong Interactions and the Emergence of Mass

On the other hand …

$$T_{\mu\mu} = \frac{1}{4}\beta(\alpha(\zeta))G^a_{\mu\nu}G^a_{\mu\nu}$$

Trace Anomaly

- In the chiral limit

$$\langle \pi(q)|T_{\mu\nu}|\pi(q)\rangle = -q_\mu q_\nu \;\; \Rightarrow \langle \pi(q)|\Theta_0|\pi(q)\rangle = 0$$

- *Might* mean that the scale anomaly vanishes trivially in the pion state, *i.e*. gluons contribute nothing to the pion mass.
- But that is difficult way to obtain "zero"!
- Easier to imagine that "zero" owes to cancellations between different operator contributions to the expectation value of Θ_0.
- Of course, such precise cancellation should not be an accident.

  It could only arise naturally because

  of some symmetry and/or symmetry-breaking pattern.

Whence "1" and yet "0" ?

$$\langle p(P)|\Theta_0|p(P)\rangle = m_p^2\,, \quad \langle \pi(q)|\Theta_0|\pi(q)\rangle = 0$$

- *No statement of the question*

  "How does the mass of the proton arise?"

  is complete without the additional clause

  "How does the pion remain **massless***?"*

- Natural visible-matter mass-scale must emerge simultaneously with apparent preservation of scale invariance in related systems
  - Expectation value of Θ_0 in chiral-limit pion is always zero, irrespective of the size of the natural mass-scale for strong interactions = m_p

Whence "1" and yet "0" ?

$$\langle p(P)|\Theta_0|p(P)\rangle = m_p^2\,, \quad \langle \pi(q)|\Theta_0|\pi(q)\rangle = 0$$

- *No statement of the question*

  "How does the mass of the proton arise?"

  is complete without the additional clause

  "How does the pion remain **massless***?"*

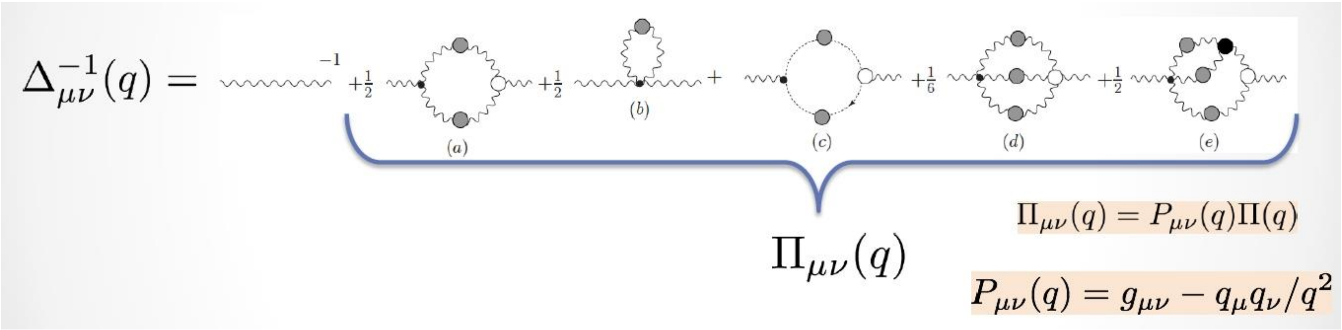
- Modern Physics must

  Elucidate the Entire Array of Empirical Consequences

  of the Mechanism responsible

  so that the Standard Model can be Validated

Ideas: Old & New



IR Behaviour of QCD

- Gluons are *supposed* to be massless
- This is true in perturbation theory
- ***Not preserved non-perturbatively!***

No symmetry in Nature protects

four-transverse gluon modes …

$$q_\mu \, \Pi_{\mu\nu}(q) \equiv 0$$

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

g or gluon $\qquad I(J^P) = 0(1^-)$

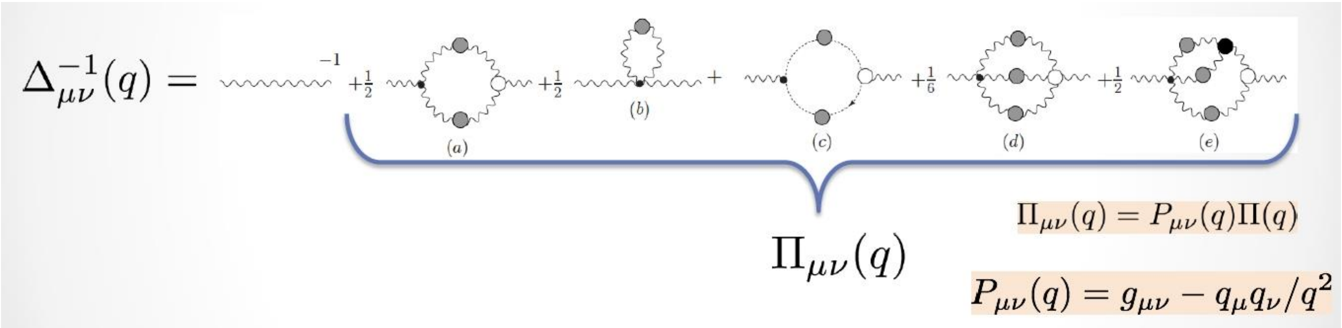
SU(3) color octet

Mass $m \neq 0$. Theoretical value. A mass as large as a few MeV may not be precluded, see YNDURAIN 95.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	ABREU	92E	DLPH	Spin 1, not 0
	ALEXANDER	91H	OPAL	Spin 1, not 0
	BEHREND	82D	CELL	Spin 1, not 0
	BERGER	80D	PLUT	Spin 1, not 0
	BRANDELIK	80C	TASS	Spin 1, not 0

gluon REFERENCES

YNDURAIN	95	PL B345 524	F.J. Yndurain	(MADU)
ABREU	92E	PL B274 498	P. Abreu *et al.*	(DELPHI Collab.)
ALEXANDER	91H	ZPHY C52 543	G. Alexander *et al.*	(OPAL Collab.)
BEHREND	82D	PL B110 329	H.J. Behrend *et al.*	(CELLO Collab.)
BERGER	80D	PL B97 459	C. Berger *et al.*	(PLUTO Collab.)
BRANDELIK	80C	PL B97 453	R. Brandelik *et al.*	(TASSO Collab.)



IR Behaviour of QCD

- Running gluon mass

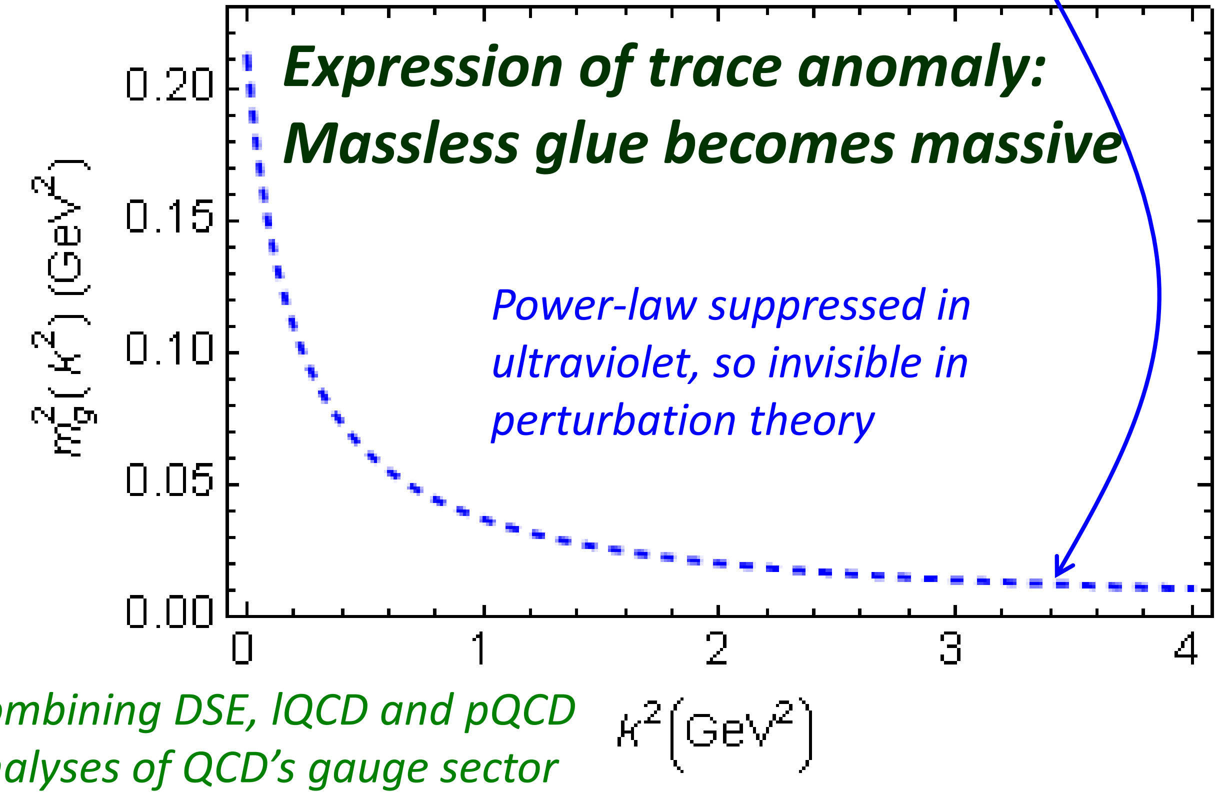
$$d(k^2) = \frac{\alpha(\zeta)}{k^2 + m_g^2(k^2;\zeta)}$$

$$\alpha_s(0) = 2.77 \approx 0.9\pi\,,\ m_g^2(0) = (0.46\,\text{GeV})^2$$

- Gluons are ***cannibals*** – a particle species whose members become massive by eating each other!

$\mu_g \approx ½\, m_p$

$$m_g^2(k^2) \approx \frac{\mu_g^4}{\mu_g^2 + k^2}$$



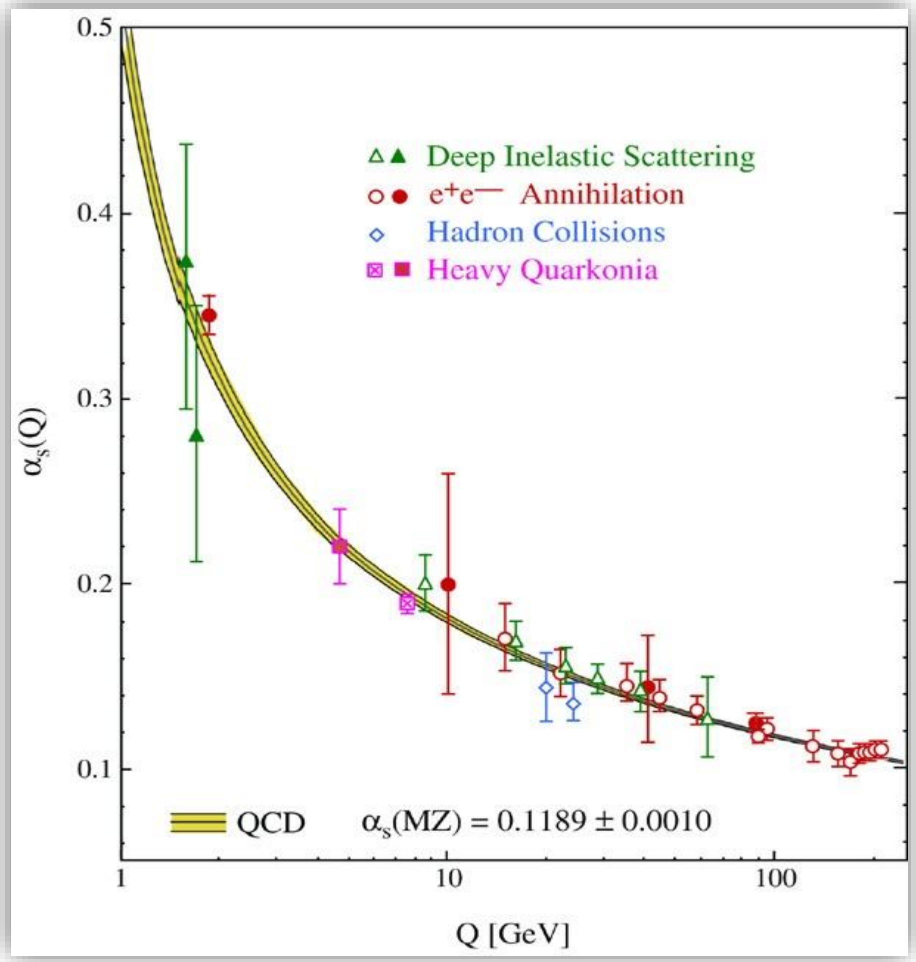
Combining DSE, lQCD and pQCD analyses of QCD's gauge sector

Dynamical mass generation in continuum quantum chromodynamics
*J.M. Cornwall, Phys. Rev. D **26** (1981) 1453*

The Gluon Mass Generation Mechanism: A Concise Primer
A.C. Aguilar, D. Binosi, J. Papavassiliou, Front. Phys. **11** (2016) 111203

This is where we live

⇐
What's happening out here?!

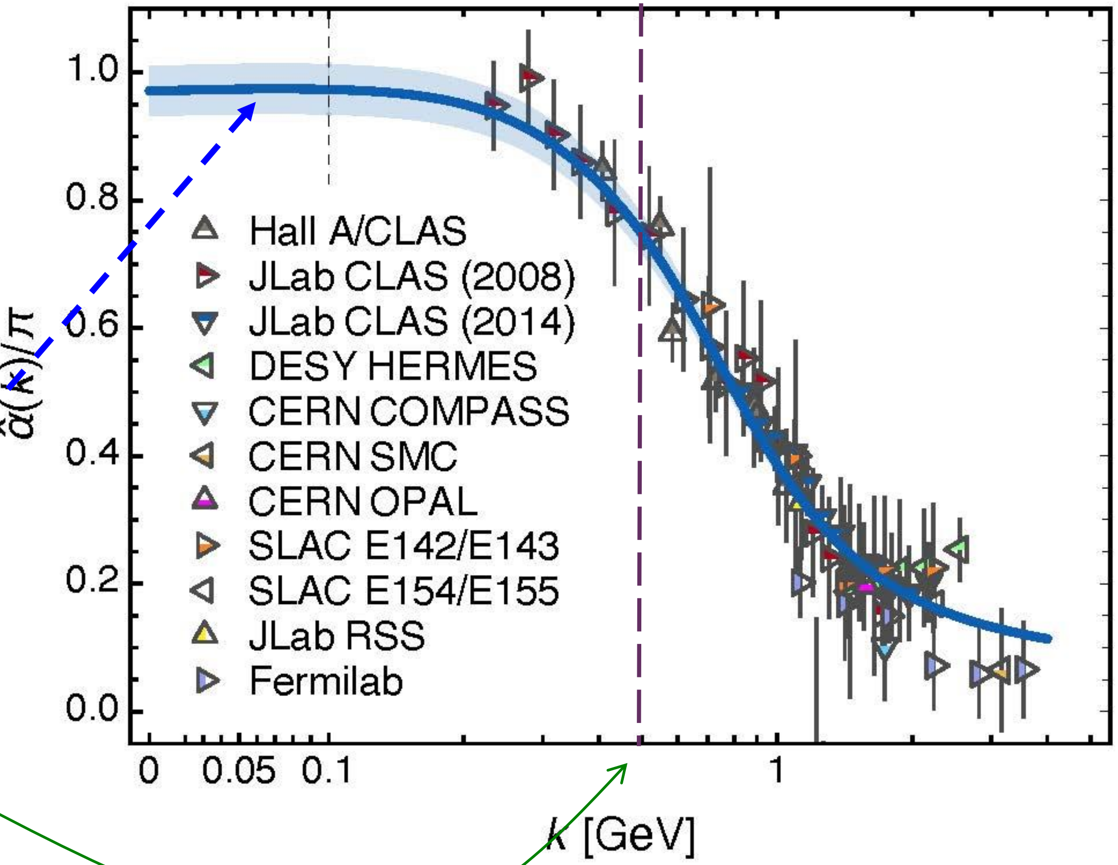


QCD's Running Coupling

The QCD Running Coupling,
A. Deur, S. J. Brodsky and G. F. de Teramond, Prog. Part. Nucl. Phys. **90** (2016) 1-74
Process independent strong running coupling
Daniele Binosi *et al*., arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7
Effective charge from lattice QCD, Zhu-Fang Cui et al., NJU-INP 014/19, arXiv:1912.08232 [hep-ph], Chin. Phys. C **44** (2020) 083102/1-10

Process-independent effective-charge in QCD

- Modern continuum & lattice methods for analysing gauge sector enable "Gell-Mann – Low" running charge to be defined in QCD
- Combined continuum and lattice analysis of QCD's gauge sector yields a *parameter-free prediction*
- N.B. Qualitative change in $\hat{\alpha}_{PI}(k)$ at $k \approx ½\, m_p$



Data = process dependent effective charge [Grunberg:1982fw]: α_{g1}, defined via Bjorken Sum Rule

The QCD Running Coupling,
A. Deur, S. J. Brodsky and G. F. de Teramond, Prog. Part. Nucl. Phys. **90** (2016) 1-74
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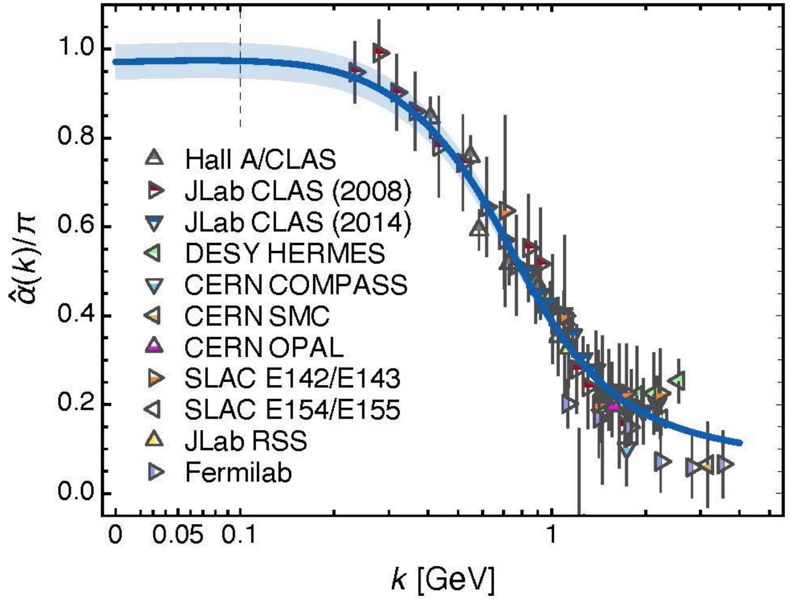
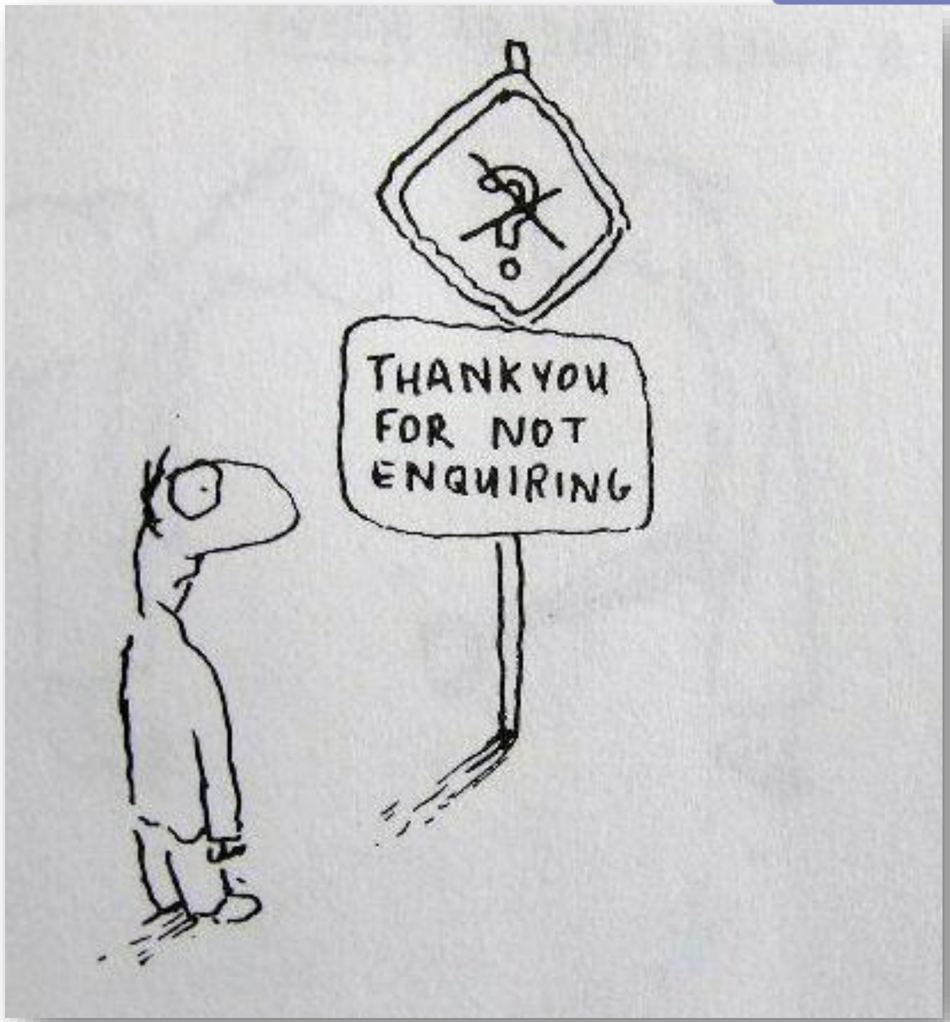


- $\hat{\alpha}_{PI}$ is a new & unique type of effective charge
  - completely determined by the gauge-boson two-point function.
- $\hat{\alpha}_{PI}$ is
  - process-independent
  - unifies a vast array of observables
- $\hat{\alpha}_{PI}$ possesses an infrared saturation point
  - Nonperturbative analysis demonstrating absence of a Landau pole in QCD
- QCD is IR finite, owing to dynamical generation of gluon mass-scale
- Asymptotic freedom ⇒ QCD is well-defined at UV momenta
- ***QCD is therefore unique amongst known 4D quantum field theories***
  - ***Potentially, defined & internally consistent at all momenta***



Enigma of Mass

Maris, Roberts and Tandy
nucl-th/9707003, Phys.Lett. B**420** (1998) 267-273

Pion's Goldberger -Treiman relation

- Pion's Bethe-Salpeter amplitude
  Solution of the Bethe-Salpeter equation

$$\Gamma_{\pi^j}(k;P) = \tau^{\pi^j}\gamma_5\left[iE_\pi(k;P) + \gamma\cdot P F_\pi(k;P) + \gamma\cdot k\, k\cdot P\, G_\pi(k;P) + \sigma_{\mu\nu}\, k_\mu P_\nu\, H_\pi(k;P)\right]$$

- Dressed-quark propagator

$$S(p) = \frac{1}{i\gamma\cdot p\, A(p^2) + B(p^2)}$$

- Axial-vector Ward-Takahashi identity entails

$$f_\pi E_\pi(k;P=0) = B(k^2)$$

Owing to DCSB & Exact in Chiral QCD

Miracle: **two body problem solved, almost completely, once solution of one body problem is known**

Rudimentary version of this relation is apparent in Nambu's Nobel Prize work

Model independent
Gauge independent
Scheme independent

$$f_\pi E_\pi(p^2) = B(p^2)$$

The most fundamental expression of Goldstone's Theorem and DCSB

Rudimentary version of this relation is apparent in Nambu's Nobel Prize work

Model independent
Gauge independent
Scheme independent

$$f_\pi E_\pi(p^2) = B(p^2)$$

Pion exists if, and only if, mass emerges dynamically

Rudimentary version of this relation is apparent in Nambu's Nobel Prize work

Model independent
Gauge independent
Scheme independent

$$f_\pi E_\pi(p^2) = B(p^2)$$

π-nucleon coupling is strong if, and only if, emergent mass is large

$$\langle p(P)|\Theta_0|p(P)\rangle = m_p^2\,, \quad \langle \pi(q)|\Theta_0|\pi(q)\rangle = 0$$

Whence "0" ?

$$\langle p(P)|\Theta_0|p(P)\rangle = m_p^2\,, \quad \langle \pi(q)|\Theta_0|\pi(q)\rangle = 0$$

Whence "0" ?

The answer is algebraic

*Munczek, H. J., Phys. Rev. D **52** (1995) pp. 4736-4740*
*Bender, A., Roberts, C.D. and von Smekal, L., Phys. Lett. B **380** (1996) pp. 7-12*
*Maris, P. , Roberts, C.D. and Tandy, P.C., Phys. Lett. B **420** (1998) pp. 267-273*
*Binosi, Chang, Papavassiliou, Qin, Roberts, Phys. Rev. D **93** (2016) 096010/1-7*

Pion masslessness

- Obtain a coupled set of gap- and Bethe-Salpeter equations
  - Bethe-Salpeter Kernel:
    - valence-quarks with a momentum-dependent running mass produced by self-interacting gluons, which have given themselves a running mass
    - Interactions of arbitrary but enumerable complexity involving these “basis vectors”
  - Chiral limit:
    - Algebraic proof
      - at any & each finite order in symmetry-preserving construction of kernels for
        - » the gap (quark dressing)
        - » and Bethe-Salpeter (bound-state) equations,
      - there is a precise cancellation between
        - » mass-generating effect of dressing the valence-quarks
        - » and attraction introduced by the scattering events
    - Cancellation guarantees that
      - simple system, which began massless,
      - becomes a complex system, with
        - » a nontrivial bound-state wave function
        - » attached to a pole in the scattering matrix, which remains at $P^2=0$ …
    - Interacting, bound system remains massless!

Munczek, H. J., Phys. Rev. D ***52*** *(1995) pp. 4736-4740*
Bender, A., Roberts, C.D. and von Smekal, L., Phys. Lett. B ***380*** *(1996) pp. 7-12*
Maris, P. , Roberts, C.D. and Tandy, P.C., Phys. Lett. B ***420*** *(1998) pp. 267-273*
Binosi, Chang, Papavassiliou, Qin, Roberts, Phys. Rev. D ***93*** *(2016) 096010/1-7*

Pion masslessness

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    - Interacting, bound system remains massless!

<u>Quantum field theory statement:</u>

In the pseudsocalar channel, the dynamically generated mass of the two fermions is <u>precisely</u> cancelled by the attractive interactions between them – iff –

$$f_\pi E_\pi(p^2) = B(p^2)$$

$$\Rightarrow 2\, M_q + U_g \equiv 0$$

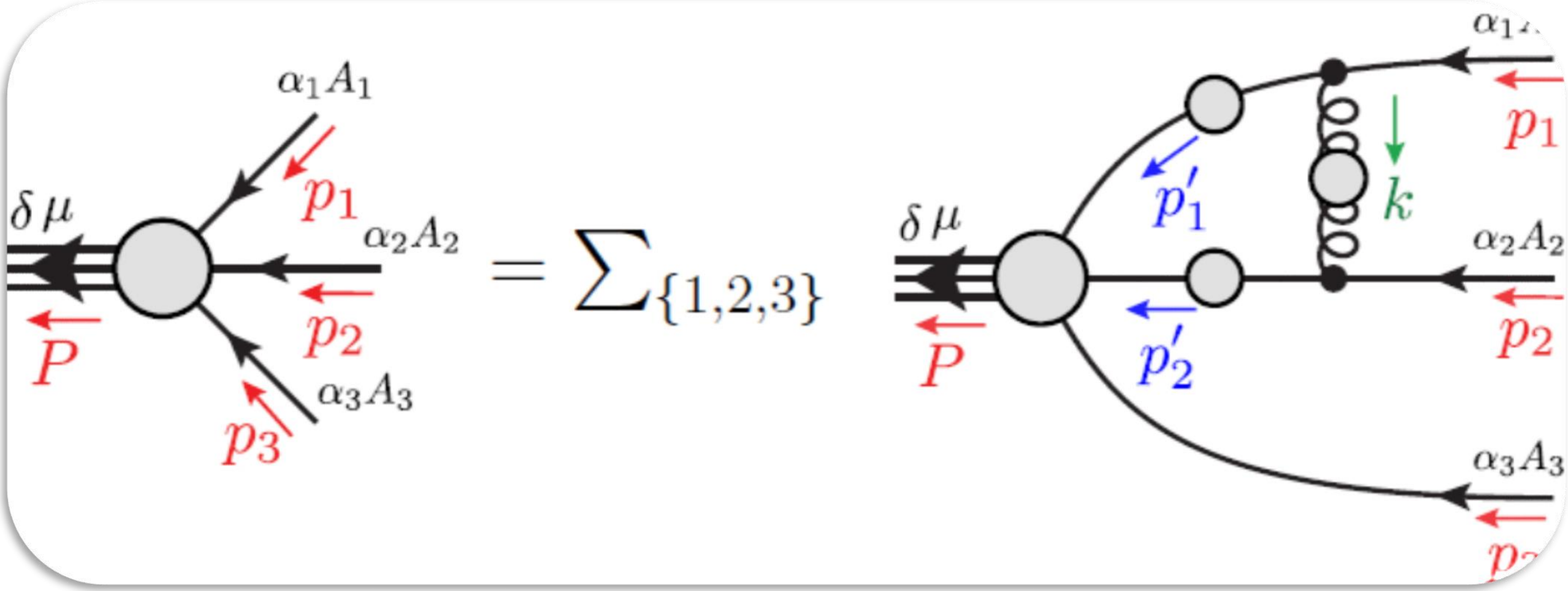
Empirical Consequences of Emergent Mass

- QCD's interactions are universal … same in all hadrons

  Hence, similar cancellations <u>must</u> take place within the proton
- However, in the proton, no symmetry requires cancellations to be complete

  Thus, value of proton's mass is typical of the magnitude of scale breaking in one body sectors = dressed-gluon and -quark mass scales
- This "DCSB paradigm" provides basis for understanding why:
  - mass-scale for strong interactions is vastly different to that of electromagnetism
  - proton mass expresses that scale
  - pion is nevertheless unnaturally light
- No significant mass-scale is possible unless one of similar size is expressed in the dressed-propagators of gluons and quarks.
- Follows that the mechanism(s) responsible for emergence of mass can be exposed by measurements sensitive to such dressing
- This potential is offered by many observables … Three Examples

Nucleon mass from a covariant three-quark Faddeev equation
G. Eichmann *et al*., Phys. Rev. Lett. 104 (2010) 201601



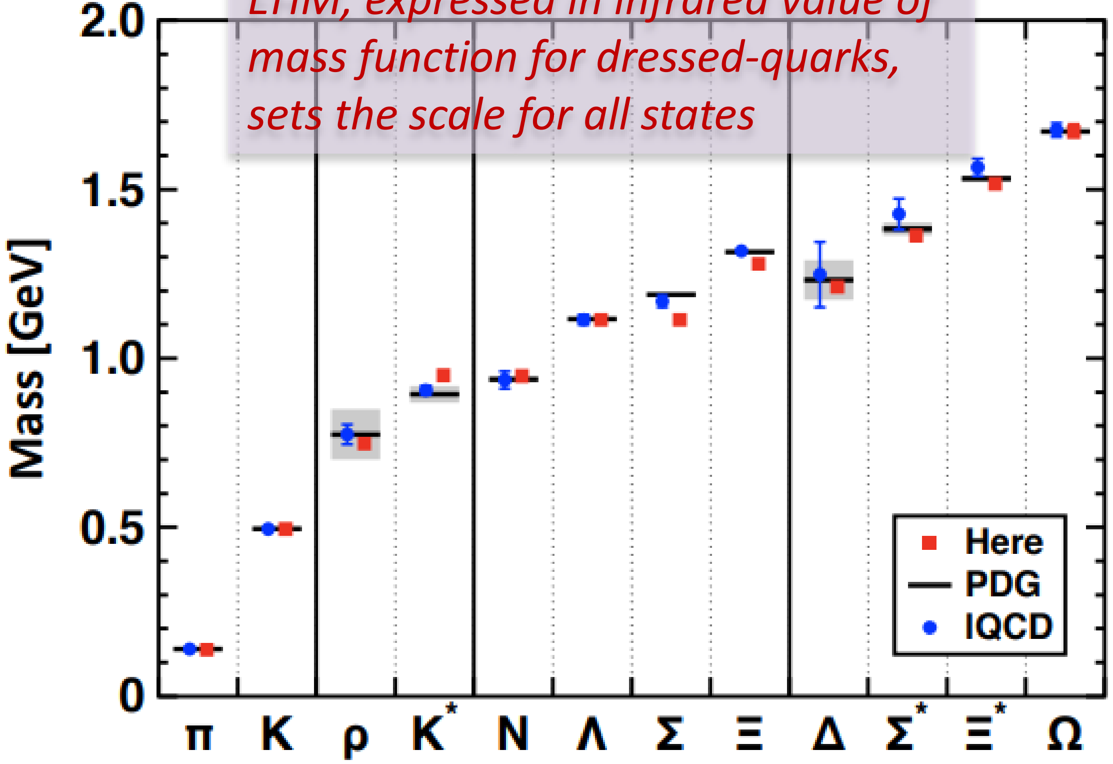
Faddeev Equation for Baryons

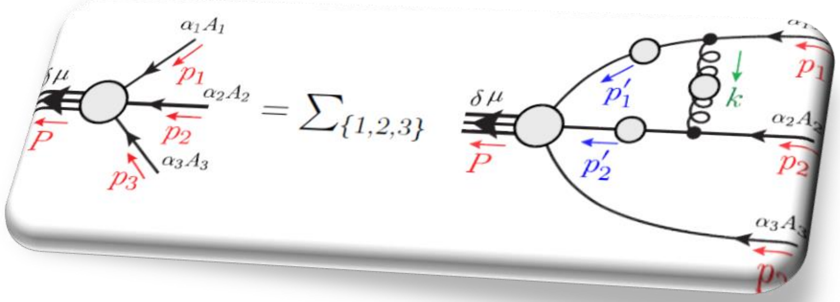
BARYON SPECTRUM

i. *Spectrum of light- and heavy-baryons*, Si-Xue Qin, C. D. Roberts and S.M. Schmidt, arXiv:1902.00026 [nucl-th], Few Body Syst. **60** (2019) 26/1-18
(Contribution to a Special Issue dedicated to Ludwig Faddeev.)

- ✓ Symmetry-preserving truncation of the strong-interaction bound-state equations = gap- and Faddeev-equations
- ✓ Calculate spectrum of
  - ✓ ground-state J=1/2$^+$, 3/2$^+$ (qq'q'') -baryons, q,q',q''∈{u,d,s,c,b} ,
  - ✓ their first positive-parity excitations
  - ✓ parity partners.
- ✓ Using two parameters (RL), description of the known spectrum of 39 such states is obtained
  - ✓ with a mean-absolute-relative-difference between calculation and experiment of 3.6(2.7)%.
- ✓ The framework is subsequently used to predict the masses of 90 states not yet seen empirically.

EHM, expressed in infrared value of mass function for dressed-quarks, sets the scale for all states





Structure of Baryons

- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but numerical challenges remain
- ***Prediction***: owing to *DCSB in QCD, strong diquark correlations exist within baryons*

Diquark Correlations in Hadron Physics: Origin, Impact and Evidence

M.Yu. Barabanov (Dubna, JINR), M.A. Bedolla (Chiapas Autonoma U.), W.K. Brooks (Santa Maria U., Valparaiso), G.D. Cates (Virginia U.), C. Chen (Giessen U.) Show All(27)

Aug 17, 2020

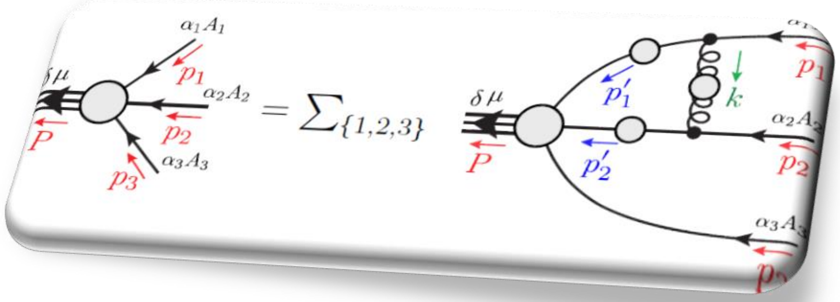
113 pages

e-Print: 2008.07630 [hep-ph]

Report number: NJU-INP 024/20

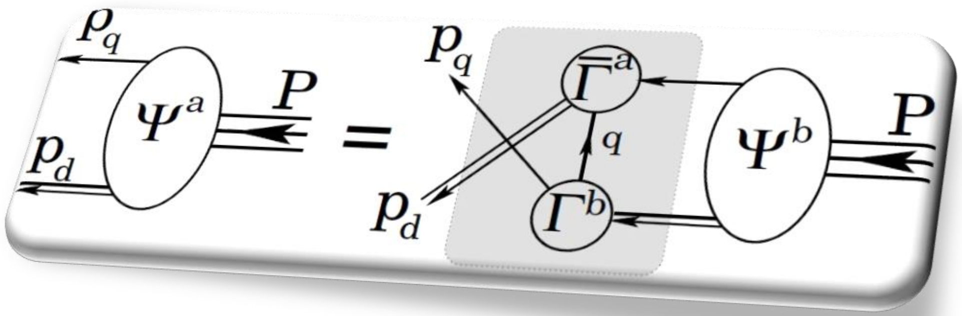
View in: HAL Archives Ouvertes, ADS Abstract Service

Prog. Part. Nucl. Phys. (in press)



Structure of Baryons

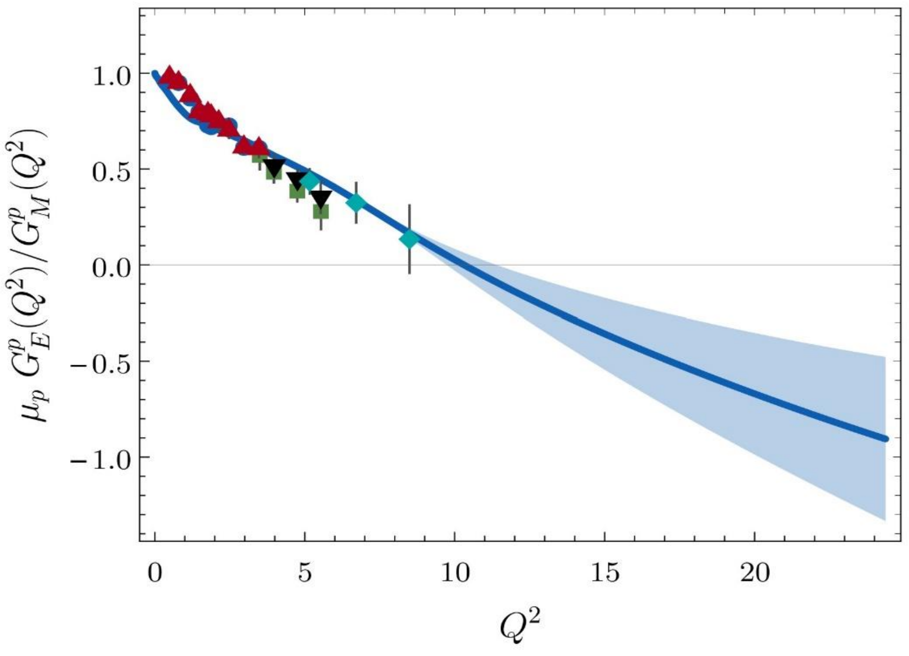
- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but numerical challenges remain
- ***Prediction***: owing to *DCSB in QCD, strong diquark correlations exist within baryons*
- For many/most applications, diquark approximation to quark+quark scattering kernel is used
- Confinement and DCSB are readily expressed
- Diquark correlations are not pointlike
  - Typically, $r_{0+} \sim r_\pi$ & $r_{1+} \sim r_\rho$ (actually 10% larger)
  - They have soft form factors



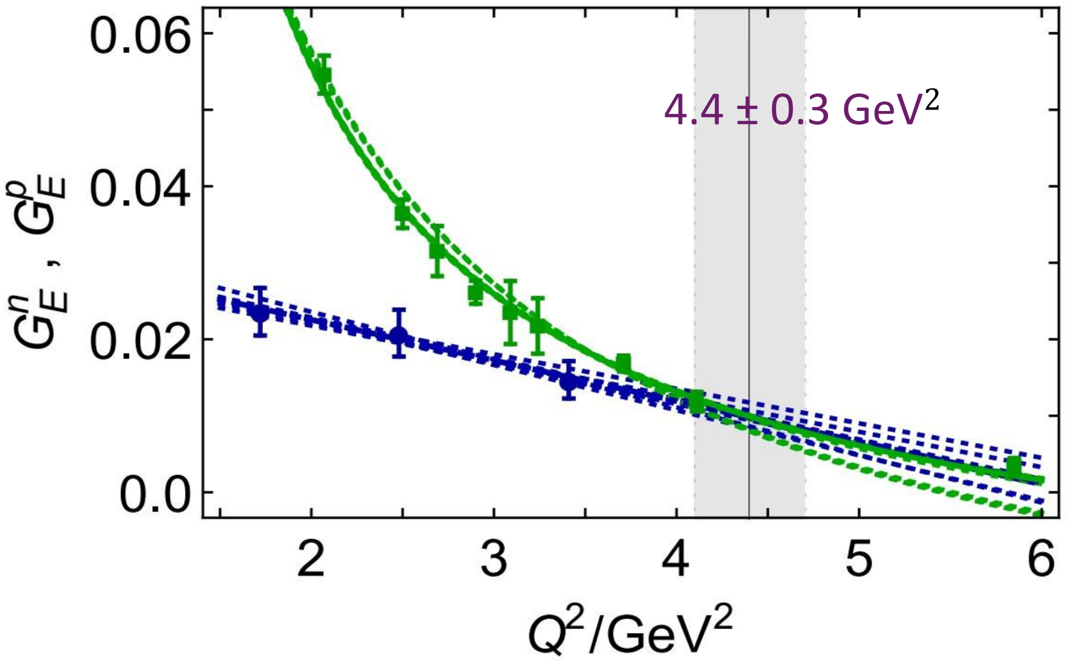
Ground States are *Easy*.

Empirical Consequences of Emergent Mass, Craig D. Roberts, NJU-INP 021/20, arXiv:2009.04011 [hep-ph], Symmetry (2020) **12**(9), 1468/1-35
Invited article for a special issue in "Symmetry" devoted to "Chiral Symmetry in Physics", Dubravko Klabucar (ed.)

- Strong-QCD theory makes an array of predictions relating to the emergence of mass
- Calculations connect these features with observables for nucleon ground-states.
  - Outcome = predictions of EHM consequences to be tested at new-era facilities



Existence & then location of zero in proton's elastic electric form factor are consequences of EHM expressed in dressed-quark anomalous magnetic moment



Almost linear decrease in G_p^E ⇒ there is a Q^2 for which the electric charge form factor of the charge=0 neutron is larger than that of the charge=1 proton

Ground States are *Easy*. Equally, Ground States are Insufficient

Evgeny Isupov (Moscow State University Skobeltsyn Institute of Nuclear Physics)
Advances in N* physics with CLAS/CLAS12
16 Oct 2020, 16:35

"Enough with the low-hanging fruit. How about some slow-moving meat?"

Ground States are *Easy*. Equally, Ground States are Insufficient

- Strong-QCD theory makes an array of predictions relating to the emergence of mass
- Calculations connect these features with observables for nucleon ground-states.
  - Outcome = predictions of EHM consequences to be tested at new-era facilities
- Ground state is one member of Hamiltonian eigenvectors set with infinitely many elements
  - Many Hamiltonians produce effectively identical ground states, but their excitation spectra are vastly different.
- And spectra alone are not enough.
  - Many Hamiltonians produce effectively equivalent spectra
- Structural properties
  - Q^2 dependence of elastic & transition form factors possess greatest discriminating power
  - With many Hamiltonians tuned to fit elastic form factors, transition form factors become hugely important
  - Only detailed study of baryon resonances can reveal how <u>*spectrum*</u> emerges from QCD

This means using realistic wave functions & currents … computed by whatever reliable means are available

Roper resonance: Toward a solution to the fifty-year puzzle,
Volker D. Burkert and Craig D. Roberts, arXiv:1710.02549 [nucl-ex],
Rev. Mod. Phys. 91 (2019) 011003/1-18

Structure of the nucleon's low-lying excitations, Chen Chen et al.,
arXiv:1711.03142 [nucl-th], Phys. Rev. D **97** (2018) 034016/1-13

Structure of the nucleon's low-lying excitations

- Unified understanding of the four lightest (I = ½; J = ½$^{\pm}$) baryon isospin-doublets
- Proton/neutron
  - (I = ½; J = ½$^{+}$) ground state
  - *u* + *u* + *d* valence-quarks
- Roper resonance
  - Nucleon's first positive-parity excitation
    - well-defined dressed-quark core
    - augmented by a meson cloud
      - reduces Roper's core mass by ≈ 20%
      - contributes materially to electroproduction transition form factors at low-Q^2

Structure of the nucleon's low-lying excitations, Chen Chen et al.,
arXiv:1711.03142 [nucl-th], Phys. Rev. D **97** (2018) 034016/1-13

Structure of the nucleon's low-lying excitations

- Regarding N(1535) ½ $^-$ and N(1650) ½ $^-$, an analogous picture ought to be correct.

  However, new questions arise.
- In constituent-quark models, typical to describe these states as P-wave baryons, *i.e.* quantum mechanical systems with one unit of constituent-quark orbital angular momentum, L
- Classify them as members of the (70; 1_1^-) supermultiplet of SU(3) ⊗ O(3):
  - lighter state: L = 1, constituent-quark total spin S = ½ … coupled to J = L+S = ½
  - heavier state: L = 1, S = 3/2 and J = L + S = ½
- ***But*** in relativistic quantum field theory, L and S are not good quantum numbers.
- Moreover, even if they were, owing to the loss of particle number conservation, it is not clear *a priori* just with which degrees-of-freedom L, S should be connected.
- This issue is related to the fact that the constituent-quarks used in building quantum mechanical models have no known mathematical connection with the degrees-of-freedom featuring in QCD
- Plainly, much still to learn about the

  nature of the nucleon's parity partner and its excitations.

Structure of the nucleon's low-lying excitations

- Quark+Diquark Faddeev amplitude for proton
  - 8 terms … Rest frame: 3 S-wave ⊕ 4 P-wave ⊕ 1 D-wave
- Intrinsic orbital angular momentum within the four lightest
  ($I = ½$; $J = ½^{\pm}$) baryon isospin-doublets
- Evidently … ground-states are S-wave
  Parity partners are primarily P-wave in character
- Presence of (small) D-wave component
  indicates all these states possess intrinsic quadrupole deformation = Q^0
- However …

$$Q = \frac{3J_z^2 - J(J+1)}{(J+1)(2J+3)} Q^0$$

- Q = spectroscopic quadrupole moment & difference between Q^0 and Q represents the averaging of the nonspherical charge distribution due to its rotational motion as seen in the laboratory/rest- frame.
- Q = 0 for J = ½ … no measurable quadrupole moment of J = ½ particle <u>in isolation</u>

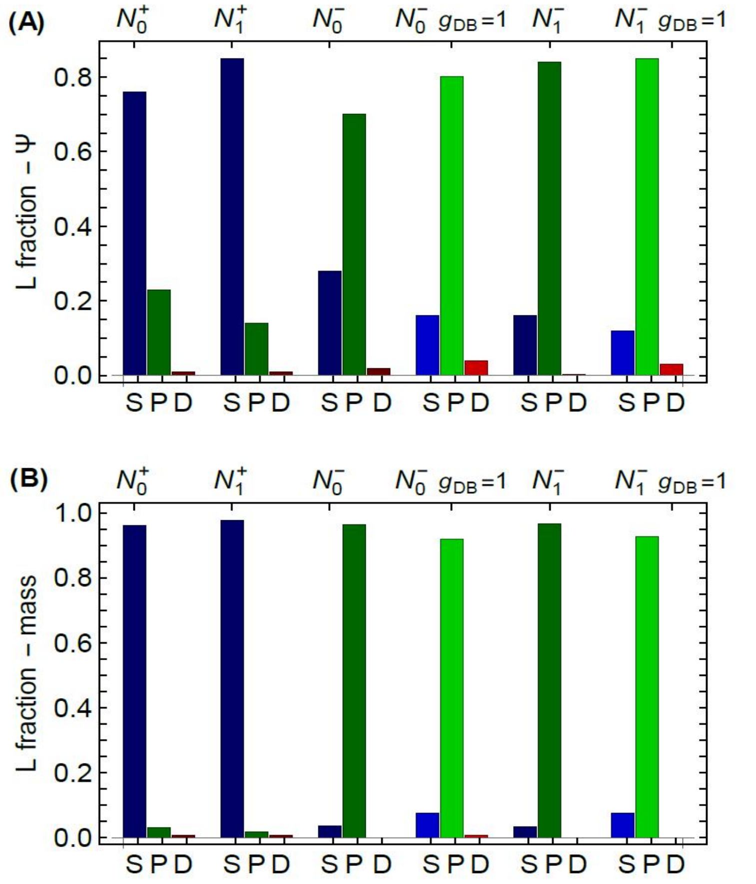


FIG. 2. *Upper panel* – (A) Baryon rest-frame quark-diquark orbital angular momentum fractions, as defined in Eqs. (17). *Lower panel* – (B) Relative contribution of various quark-diquark orbital angular momentum components to the mass of a given baryon. In both panels, the results were computed with $g_{DB} = 0.43$, except for the identified bar-triplets with lighter shading, for which $g_{DB} = 1$. Legend: N_0^+ is the ground-state nucleon, $N_1^+ = N(1440)\,1/2^+$, $N_0^- = N(1535)\,1/2^-$, $N_1^- = N(1650)\,1/2^-$.

Structure of the nucleon's low-lying excitations

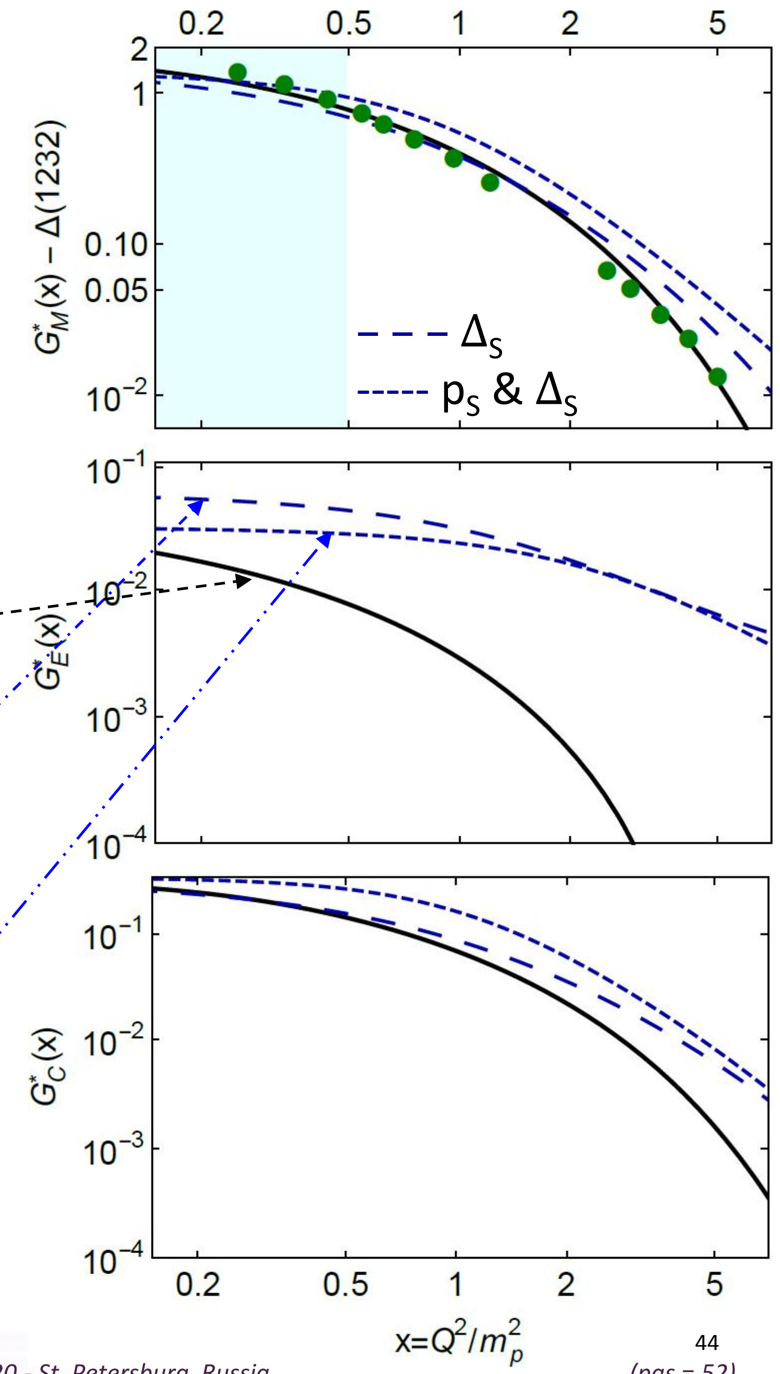
- Quark+Diquark Faddeev amplitude for proton's spin-flip excitation = $\Delta(1232)\ 3/2^+$
  - 8 terms … Rest frame: 1 S-wave $\oplus$ 3 P-wave $\oplus$ 3 D-wave $\oplus$ 1 F-wave
- Observe deformation of ground state proton and excited state $\Delta(1232)\ 3/2^+$ by measuring

  $\gamma* + p \to \Delta(1232)$

  Q^2-dependence of the electroproduction transition form factors
- Three Poincaré-invariant form factors
  - G_M (magnetic = dominant) & G_E (electric) & G_C (Coulomb)
  - $G_E = 0 = G_C$ with SU(6) spin-flavour symmetric wave functions
  - G_E & G_C are sensitive to deformation of the final and initial states
- JLab … $\gamma* + p \to \Delta(1232)$ are now available for $0 < Q^2 < 8\ GeV^2$

Transition form factors: γ∗ + p → Δ(1232)

- Top panel: Magnetic dipole γ∗ + p → Δ(1232) form factor compared with contemporary data.
- Middle panel: Electric quadrupole transition form factor.
- Bottom panel: Coulomb quadrupole transition form factor.
- In all panels:
  - ✓ solid (black) curve, complete result;
  - ✓ long-dashed (blue) curve, result obtained when only those components of the Δ(1232) wave function are retained which correspond to S-waves in the rest frame;
  - ✓ dashed (blue) curve, obtained when both the proton and Δ(1232) are reduced to S-wave states.



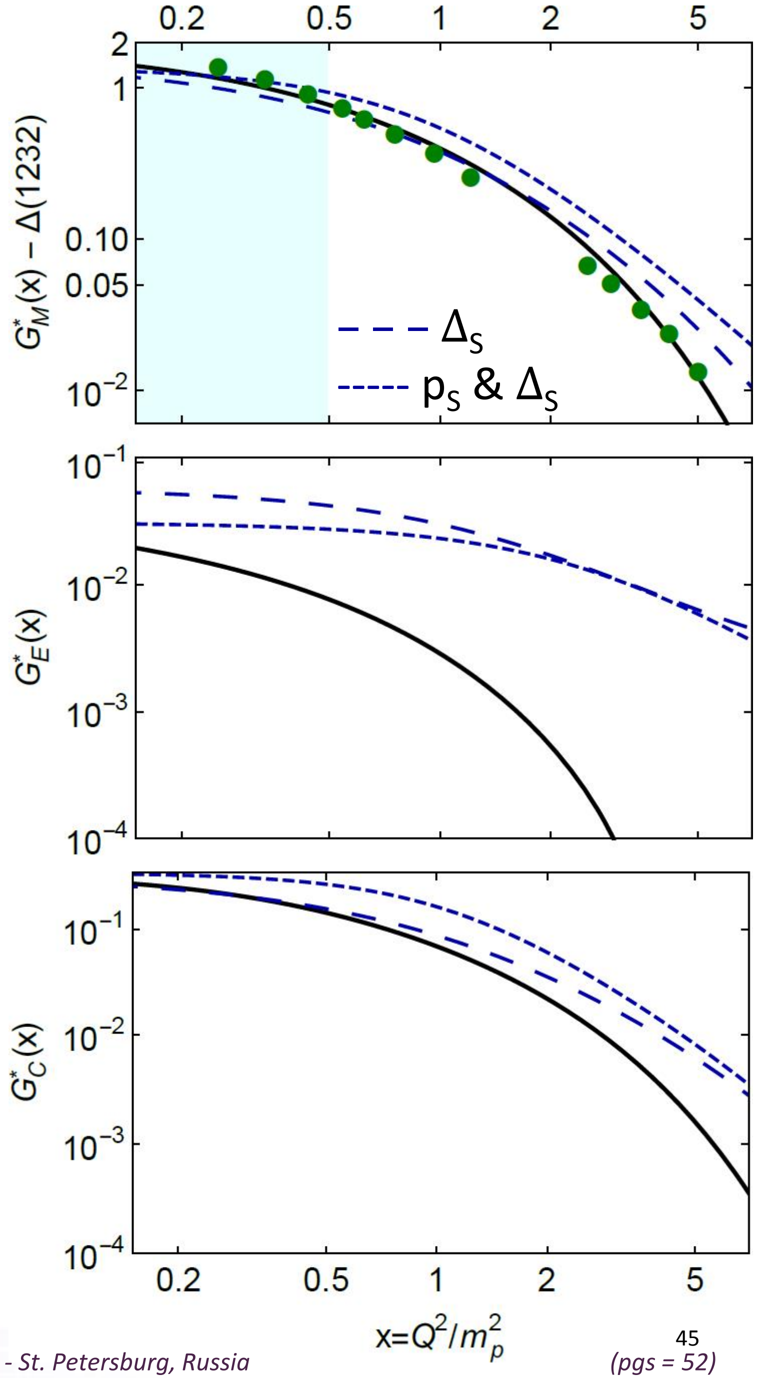
N* @ MSU & JLab
Moscow State University, Skobeltsyn Nuclear Physics Institute (Prof. B. Ishkhanov: reaction models, data taking and interpretation; Prof. I. Obukhovsky: quark models of N* structure)
Dr. V.I. Mokeev extraction of transition form factors, leading effort on-ground at JLab

Transition form factors: γ∗ + p → Δ(1232)

- The role played by higher partial waves in the wave functions increases with momentum transfer (something also observed in meson form factors), here generating destructive interference
  - ✓ agreement with data on G_M^* is impossible without the higher partial waves
  - ✓ effect of these components is very large in G_E^*

    (The complete result for G_E^* exhibits a zero at $x \approx 4$, which is absent in the S-wave-only result(s).)
- Explanation of data requires intrinsic deformation of

  BOTH proton and Δ(1232)



N* @ MSU & JLab
Moscow State University Group (Prof B. Ishkhanov - reaction models and data interpretation)
Skobeltsyn Nuclear Physics Institute (Prof. I. T. Obukhovsky - N* structure theory)
SS V. I. Mokeev - extraction of transition form factors, leading effort on-ground at JLab

Transition form factors: $\gamma* + p \to \Delta(1600)$

- Roper resonance:
  - Nucleon's first positive-parity excitation is lighter than first negative-parity excitation
- Similar pattern found with J=3/2 baryons
- Namely, contradicting quark-model predictions, the 1st positive-parity excitation,

  $\Delta(1600)\ 3/2^+$

  lies below the negative parity $\Delta(1700)\ 3/2^-$,

  with splitting approximately same as that in the nucleon sector.
- This being the case, and given the Roper-resonance example,
  elucidating the nature of the $\Delta(1600)\ 3/2^+$ will require both:
  - i. data on its electroproduction form factors which extends well beyond the meson-cloud domain
  - ii. predictions for these form factors to compare with that data.
- The data exist; and can be analysed with this aim understood.
- Theoretical predictions are now also available

Real predictions confronted by new data analysis = stringent test of EHM picture of baryon structure

To Nuclear Physics

J. Draayer & team (LSU & SURA)
V. I. Mokeev + CLAS12 (JLab & MSU)
NJU-INP & international collaboration

- Combine contemporary progress on the continuum bound-state problem in QCD with advances in *ab initio* approaches for studying the structure of atomic nuclei
  - Are baryons in their intrinsic frame spherical or deformed?
    All signs indicate deformed, some more than others
  - Can one define and compute meson-nucleon coupling constants and form factors?
    Unification of nucleon structure and shape with nucleon-nucleon interactions
- How do the QCD-driven interactions between nucleons within nuclei generate the structure and dynamic deformation of atomic nuclei?
  First step = reduction in number of free-parameters in nucleon-nucleon potentials
  Possibly ⇒ parameter-free predictions of nuclear properties
- Drive toward QCD-connected predictions for structure of light- and medium-mass nuclei
  Testable predictions for observables at low-energy nuclear physics facilities

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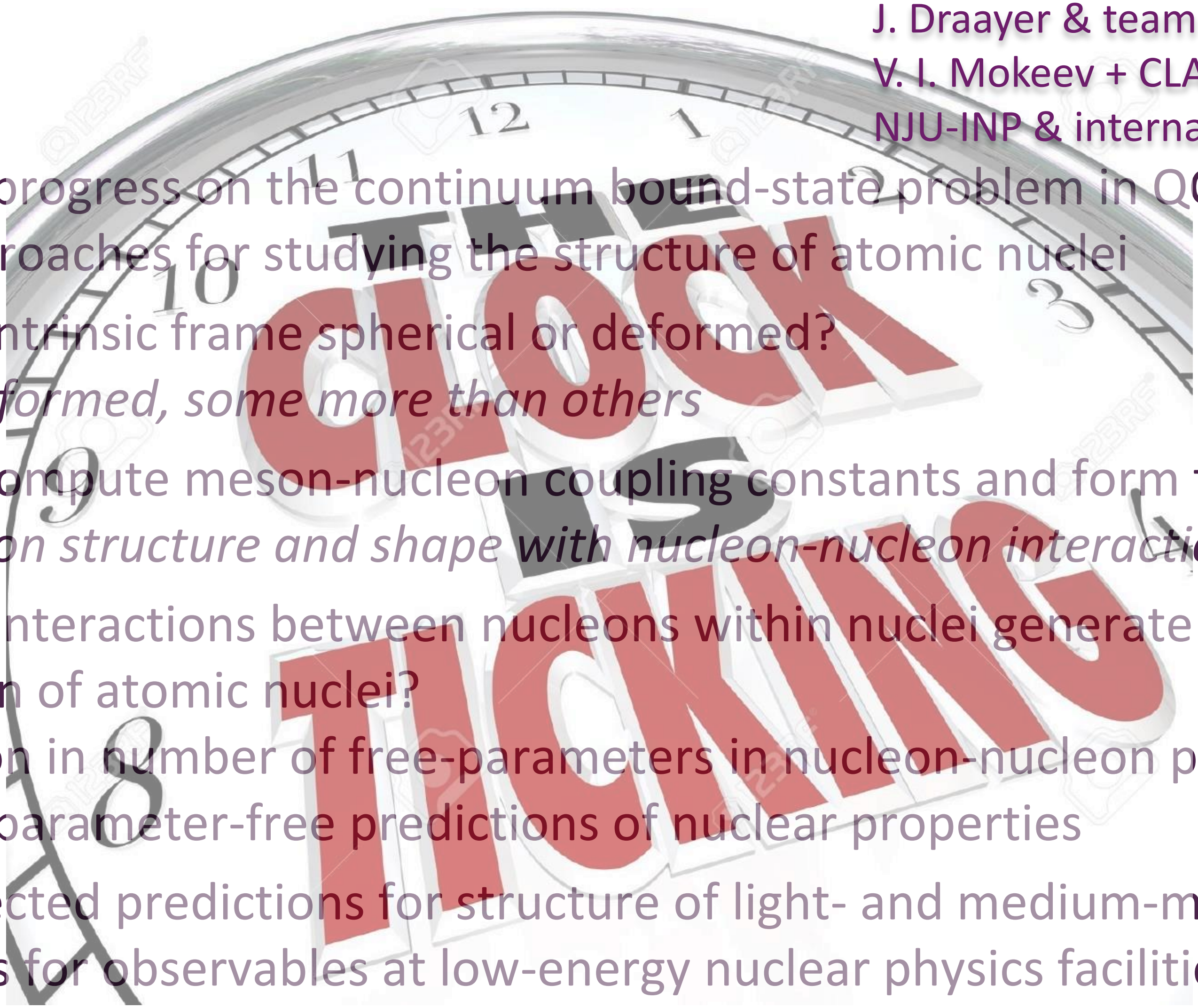

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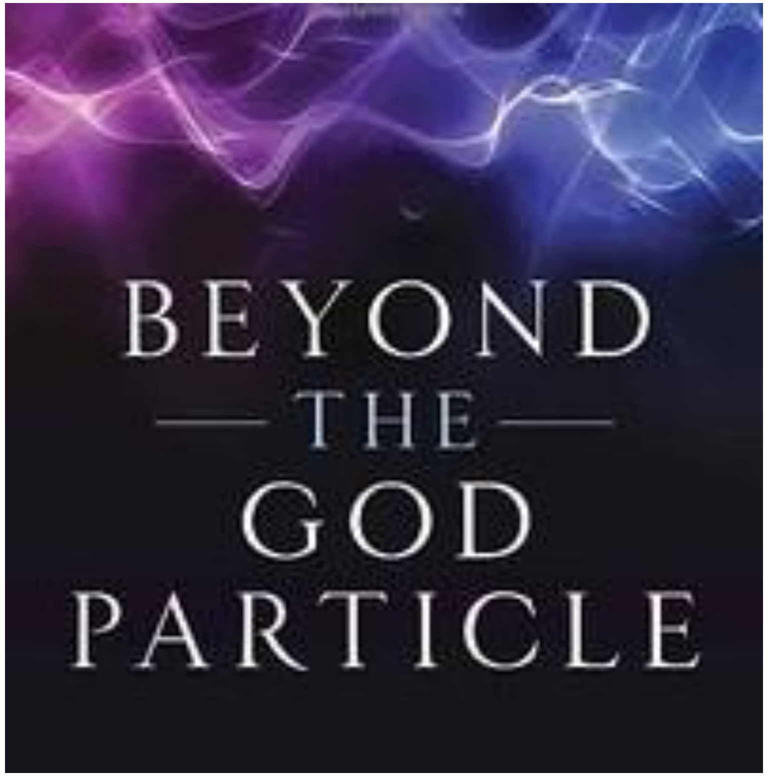
  Possibly ⇒ parameter-free predictions of nuclear properties
- Drive toward QCD-connected predictions for structure of light- and medium-mass nuclei
  Testable predictions for observables at low-energy nuclear physics facilities
- Goal = Unification of QCD and Nuclear Physics … Ambitious, certainly. Achievable, possibly.
  Time scale = 10 – 20 years, depending on resources allocated

Strong QCD from Hadron Structure Experiments, S. J. Brodsky *et al.*, NJU-INP 015/20, arXiv:2006.06802 [hep-ph], Int. J. Mod. Phys. E (*in press*)

Epilogue

Epilogue

- LHC has NOT found the "God Particle" … the Higgs boson is NOT the origin of mass
  - Higgs-boson only produces a little bit of mass
  - Higgs-generated light-quark mass-scales explain neither the proton's mass nor the pion's (*near*-) masslessness
- Strong interaction sector of the Standard Model, *i.e*. QCD, is the key to understanding the origin, existence and properties of the vast bulk of all known matter

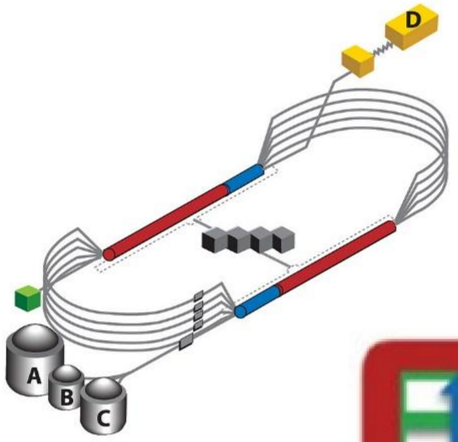


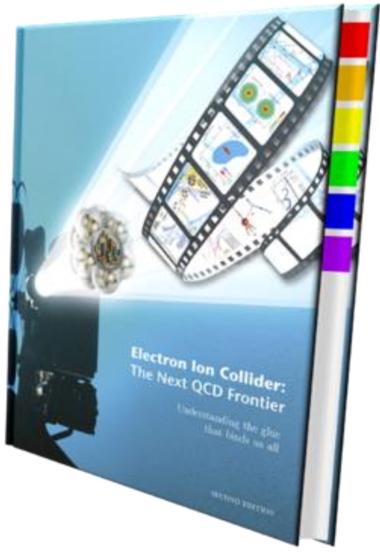
Epilogue

- Challenge: <u>Explain</u> the Origin & Distribution of the Bulk of Visible Mass
- Current Paradigm: Quantum Chromodynamics
- QCD is plausibly a mathematically well-defined quantum field theory,
  The only one we've ever produced
  - Consequently, it potentially defines a new paradigm for developing Beyond-SM theories
- Challenges are to reveal the content of strong-QCD and unify QCD with Nuclear Physics
- *Progress* and *Insights* being delivered by amalgam of
  - Experiment … Phenomenology …Theory
- Continued exploitation of synergies essential to capitalise on new opportunities provided by existing & planned facilities

A New QCD facility at the M2 beam line of the CERN SPS*

COMPASS++†/AMBER‡





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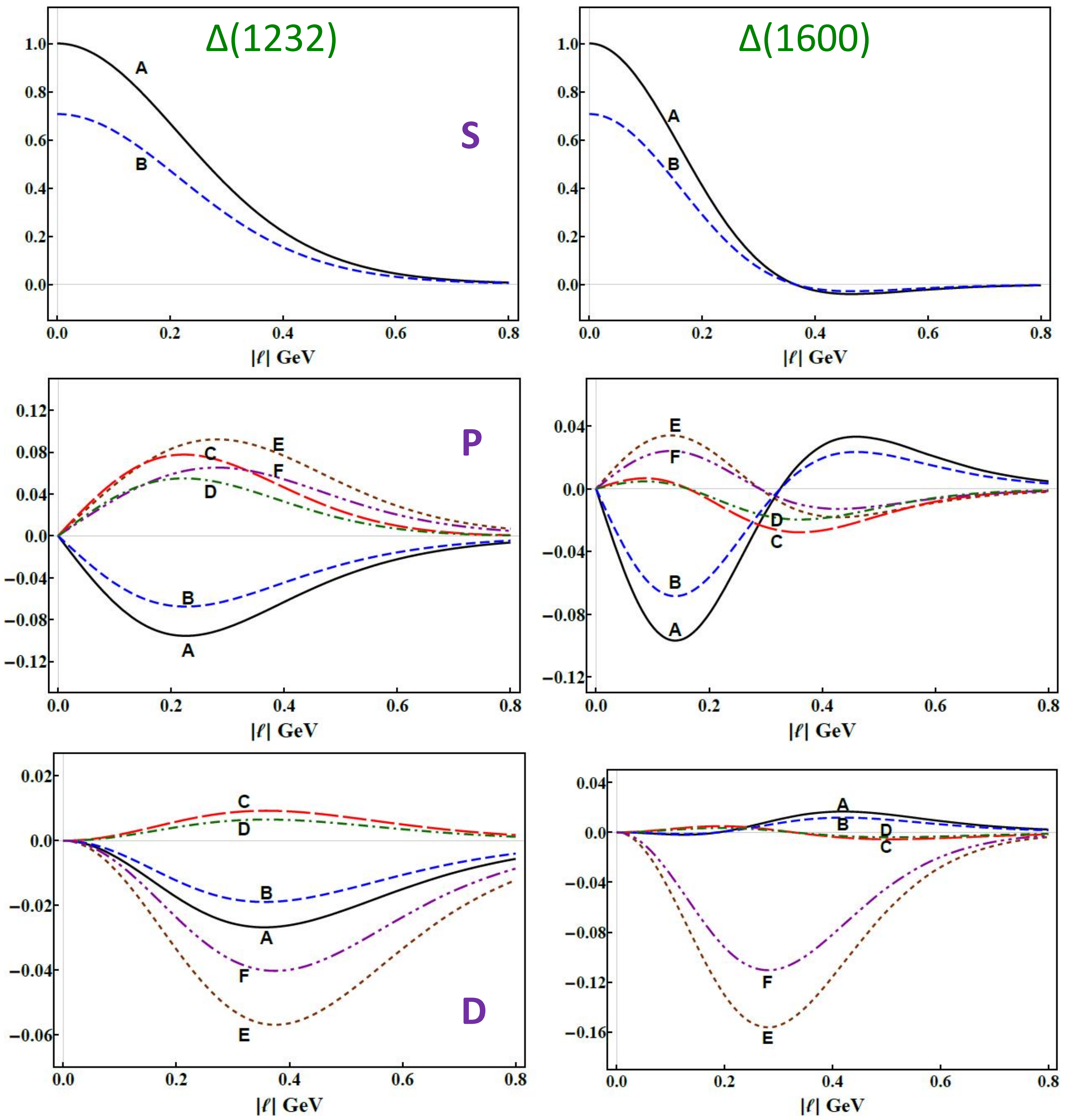
39. … and many more …

Poincaré-covariant wave functions Δ(1232) & Δ(1600)

- Δ-Baryon ground-state and positive-parity excitation are primarily S-wave in character: the magnitudes of the curves in the top row are greater than those in the other rows.
- NB – A: ground-state mass is almost insensitive to non-S-wave components
- NB – B: Ground-state (elastic FF) quadrupole-moment is large in magnitude and negative ⇒ oblate deformation
- NB – C: 1st positive-parity excitation, P-wave components generate a little repulsion, some attraction is provided by D-waves, and F-waves have no impact.
- NB – D: Evidently, some S-wave strength is shifted into P- and D-wave contributions within 1st positive-parity excitation



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- Top panel: Magnetic dipole $\gamma* + p \rightarrow \Delta(1232)$ form factor compared with contemporary data [84].
- Middle panel: Electric quadrupole transition form factor.
- Bottom panel: Coulomb quadrupole transition form factor.
- In all panels:
  - ✓ solid (black) curve, complete result;
  - ✓ long-dashed (blue) curve, result obtained when $\Delta(1600)$ is reduced to S-wave state;
  - ✓ dashed (blue) curve, both the proton and $\Delta(1600)$ are reduced to S-wave states;
  - ✓ dotted (green) curve, obtained by enhancing proton's axial-vector diquark content;
  - ✓ shaded (grey) band, light-front relativistic Hamiltonian dynamics (LFRHD);
  - ✓ dot-dashed (brown) curve, light-front relativistic quark model (LFRQM) with unmixed wave functions;
  - ✓ and dot-dot-dashed (orange) curve, LFRQM with configuration mixing.