Probing the origin of mass using hadron form factors

Craig Roberts, Physics Division

Hadron Form Factors

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

Hadron Form Factors

Why?

- Classical QCD … non-Abelian local gauge theory
- Remove the mass … there's no scale left
- *No dynamics in a scale-invariant theory*; only kinematics … the theory looks the same at all length-scales … there can be no 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?

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

Whence?

- Classical chromodynamics … non-Abelian local gauge theory
- Local gauge invariance; but there is no confinement without a mass-scale
  - Three quarks can still be colour-singlet
  - Colour rotations will keep them colour singlets
  - But they need have no proximity to one another
    … proximity is meaningless in a scale-invariant theory
- Whence mass … equivalent to whence a mass-scale … equivalent to whence a confinement scale
- *Understanding the origin and absence of mass in QCD is quite likely inseparable from the task of understanding confinement.*

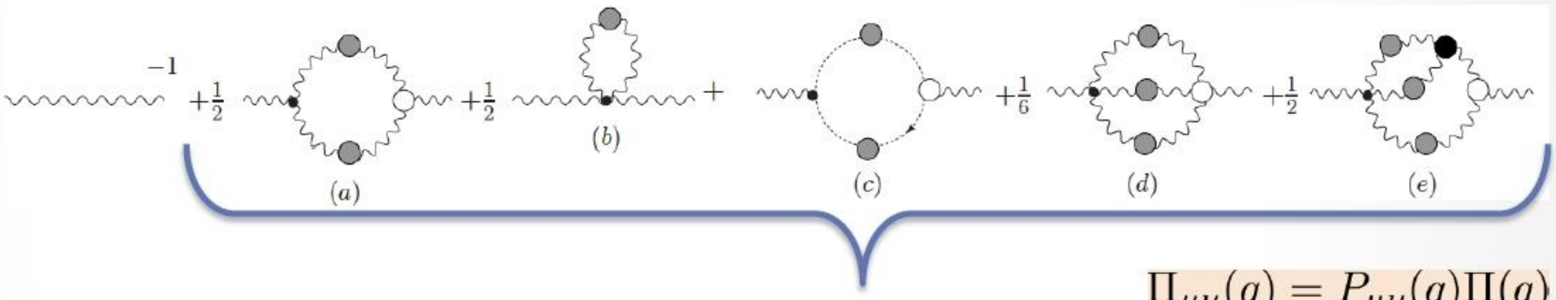
Existence alone of a scale anomaly answers neither question

Hadron Form Factors

- Scale-dependent probe of hadron internal structure
- Map the transition
  - from dressed quasiparticles in the confinement domain
  - to Feynman partons in the conformal limit
- Theoretically, full machinery of renormalisable quantum field theory is necessary to expose the signatures of this transition
  - Power laws and scaling ("easy")
  - Anomalous dimensions and scaling violations ("hard")

  Scaling violations *are* QCD
- Answers are <u>not</u> enough … Derivation is understanding
- Emergence of mass (confinement) is encoded in a reductive elucidation and explanation of the details of this transition

$$\Delta^{-1}_{\mu\nu}(q) =$$



$$\Pi_{\mu\nu}(q)$$

$$\Pi_{\mu\nu}(q) = P_{\mu\nu}(q)\Pi(q)$$

$$P_{\mu\nu}(q) = g_{\mu\nu} - q_\mu q_\nu / q^2$$

Gluon Gap Equation

Bridging a gap between continuum-QCD and ab initio predictions of hadron observables, D. Binosi *et al.*, arXiv:1412.4782 [nucl-th], Phys. Lett. B742 (2015) 183-188

In QCD: Gluons become massive!

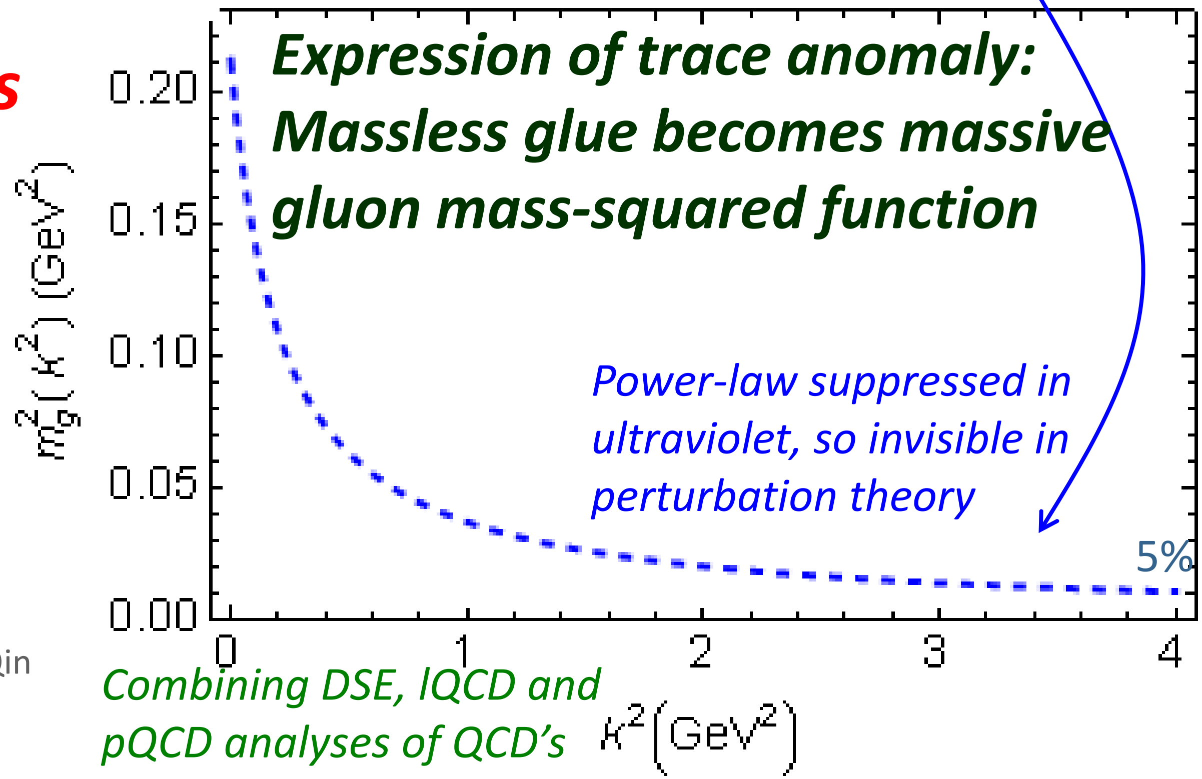
- Running gluon mass

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

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

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

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



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

Interaction model for the gap equation, S.-x.Qin *et al.*, arXiv:1108.0603 [nucl-th], Phys. Rev. C **84** (2011) 042202(R) [5 pages]

Massive Gauge Bosons!

- Gauge boson cannibalism

  … a new physics frontier … within the Standard Model
- Asymptotic freedom means
  … ultraviolet behaviour of QCD is controllable
- Dynamically generated masses for gluons and quarks means that QCD dynamically generates its own infrared cutoffs
  - Gluons and quarks with

    wavelength $\lambda > 2/\text{mass} \approx 1$ fm

    decouple from the dynamics … ***Confinement?!***
- How does that affect observables?
  - It will have an impact in any continuum study
  - Possibly (probably?) plays a role in gluon saturation ... In fact, could be a harbinger of gluon saturation?

Electron Ion Collider: The Next QCD Frontier

Confinement

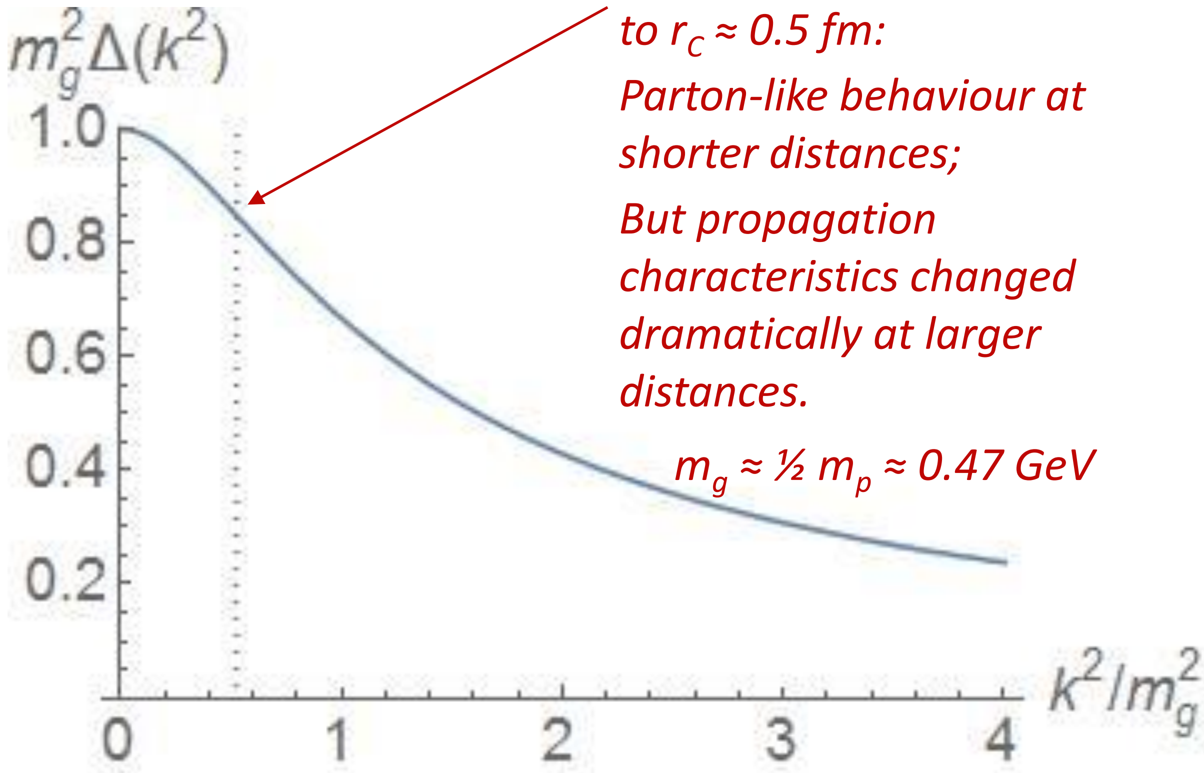
- All continuum and lattice solutions for Landau-gauge gluon & quark propagators exhibit an inflection point in k^2

⇒ Violate reflection positivity = sufficient for confinement

⇒ Such states have negative norm

⇒ All observable states of a physical Hamiltonian have positive norm

⇒ Negative norm states are not observable

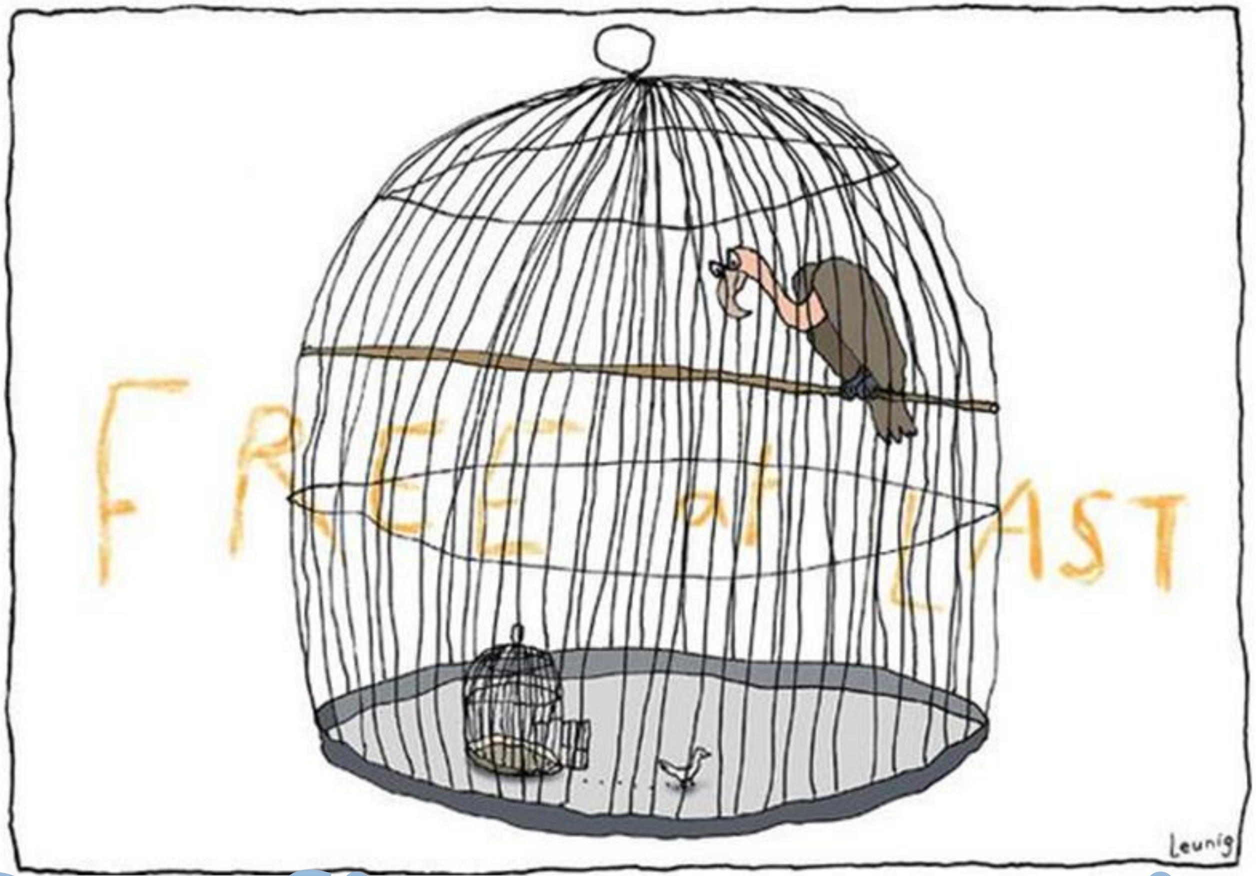


Inflexion point corresponds to $r_C \approx 0.5$ fm:

Parton-like behaviour at shorter distances;

But propagation characteristics changed dramatically at larger distances.

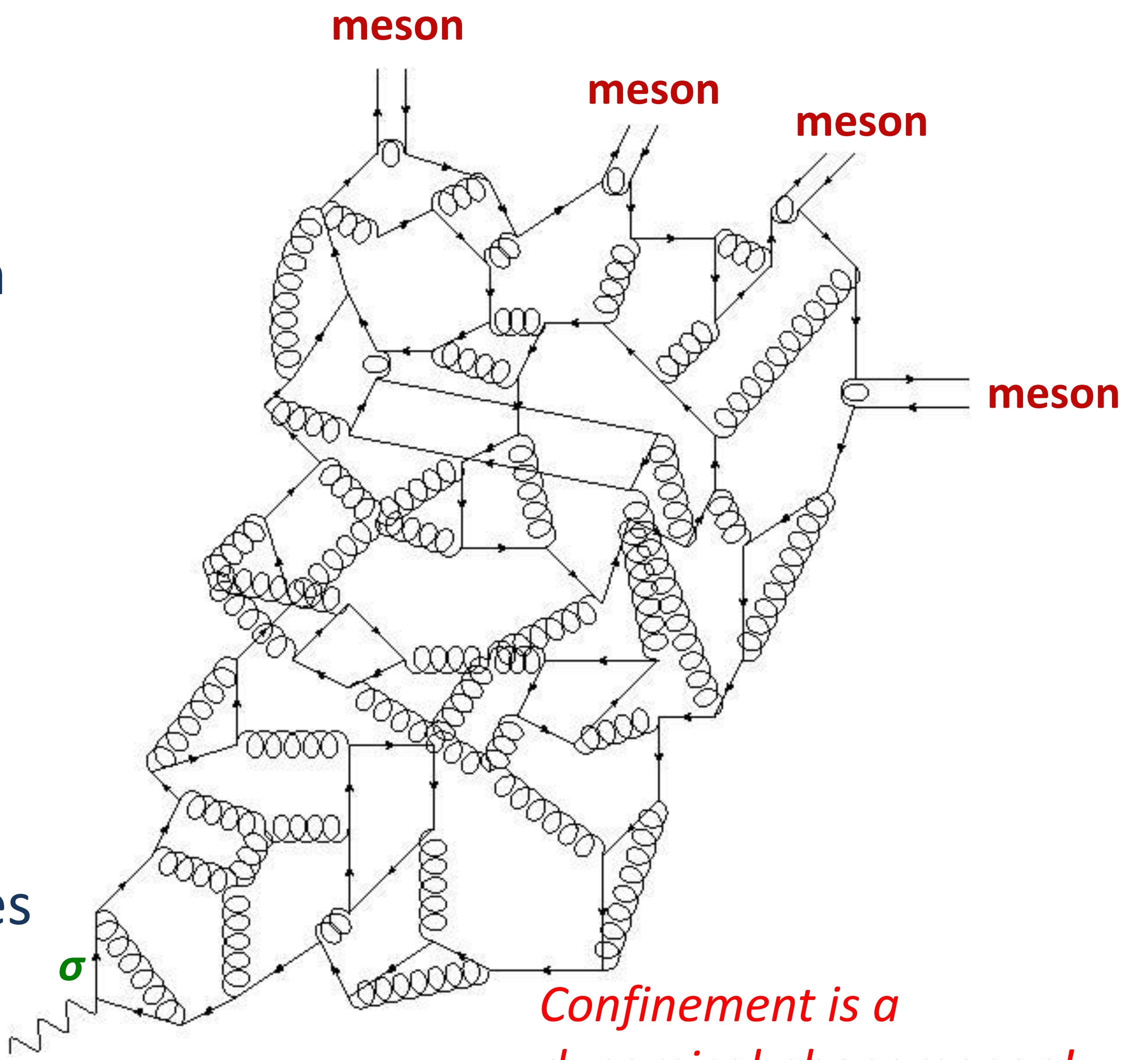
$m_g \approx ½\, m_p \approx 0.47$ GeV



Confinement is dynamical

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

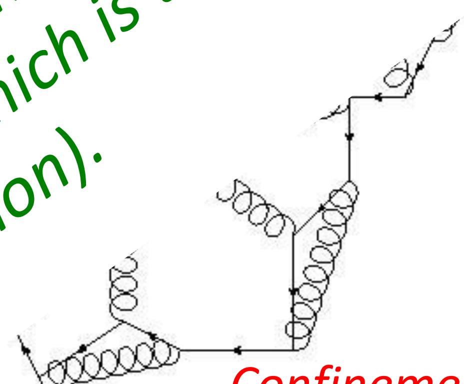


Confinement is a dynamical phenomenon!

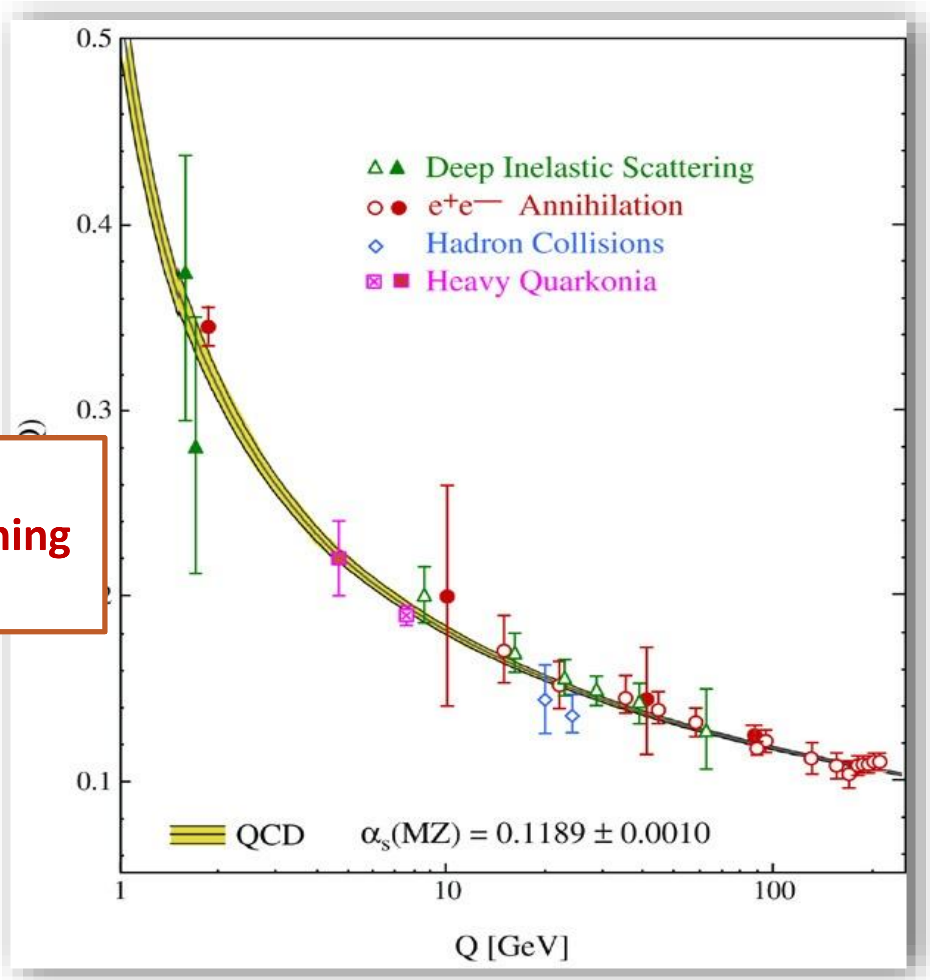
Quark Frag ation

- A quark begins to propagate
- But after each "step" of length ***σ***, on average, an interaction occurs, sc that the quark *lo* identity, shar other pa
- Fin par whic colour-

Confinement in hadron physics is largely a dynamical phenomenon, intimately connected with the fragmentation effect.
It is unlikely to be comprehended without simultaneously understanding dynamical chiral symmetry breaking, which is the origin of a near-zero mass hadron (pion).



Confinement is a dynamical phenomenon!

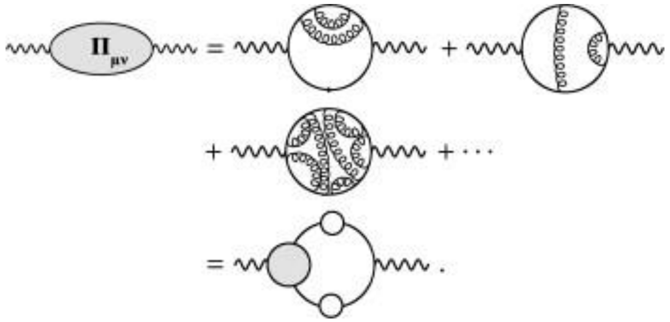


⇐
What's happening out here?!

QCD's Running Coupling

QED Running Coupling

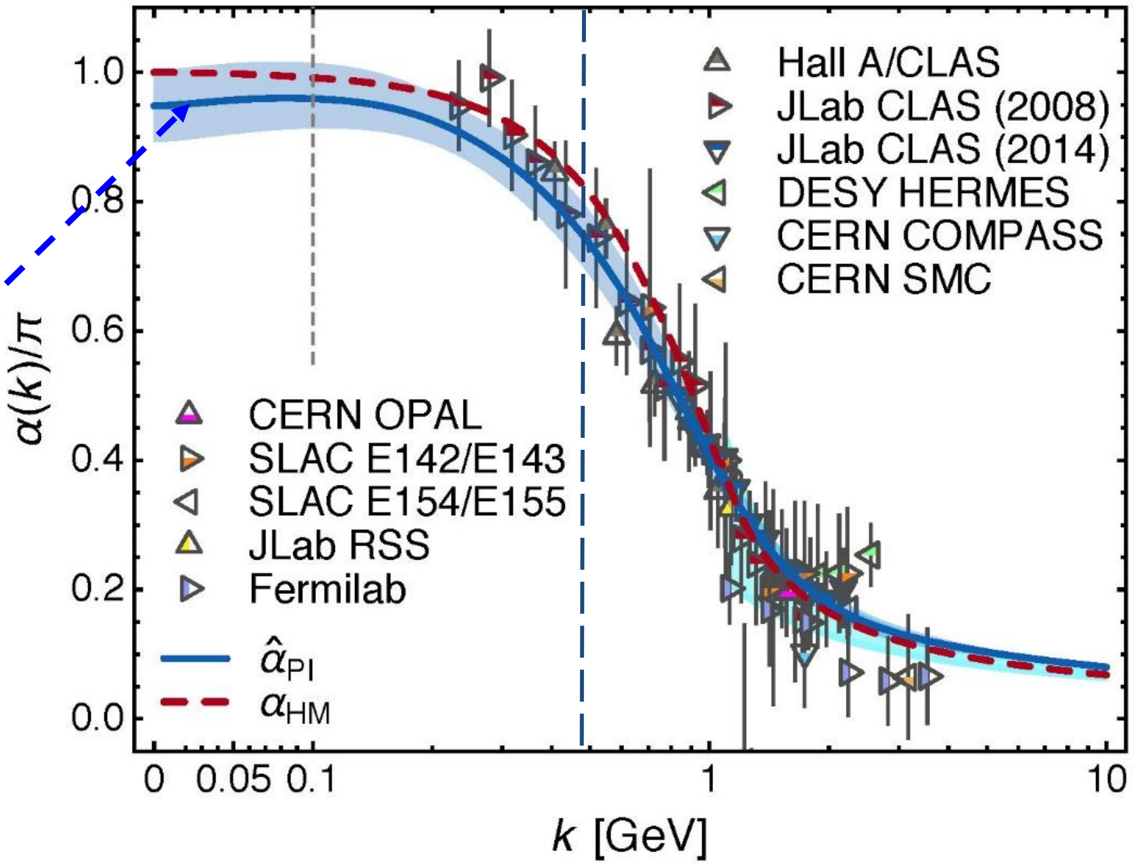
- Quantum gauge field theories in four spacetime dimensions,
  - Lagrangian couplings and masses come to depend on a mass scale
  - Can often be related to the energy or momentum at which a given process occurs.
- Archetype is QED, for which there is a sensible perturbation theory.
- QED, owing to the Ward identity:
  - a single running coupling
  - measures strength of the photon-charged-fermion vertex
  - can be obtained by summing the virtual processes that dress the bare photon, *viz*. by computing the photon vacuum polarisation.



- QED's running coupling is known to great accuracy and the running has been observed directly.

Process-independent effective-charge in QCD

- Modern continuum & lattice methods for analysing gauge sector enable analogous quantity to be defined in QCD
- Combined continuum and lattice analysis of QCD's gauge sector yields a parameter-free prediction
- Near precise agreement with the process-dependent effective charge defined via the Bjorken sum-rule
- N.B. Qualitative change in $\hat{\alpha}_{PI}(k)$ at $k \approx ½\, m_p$



QCD Effective Charge

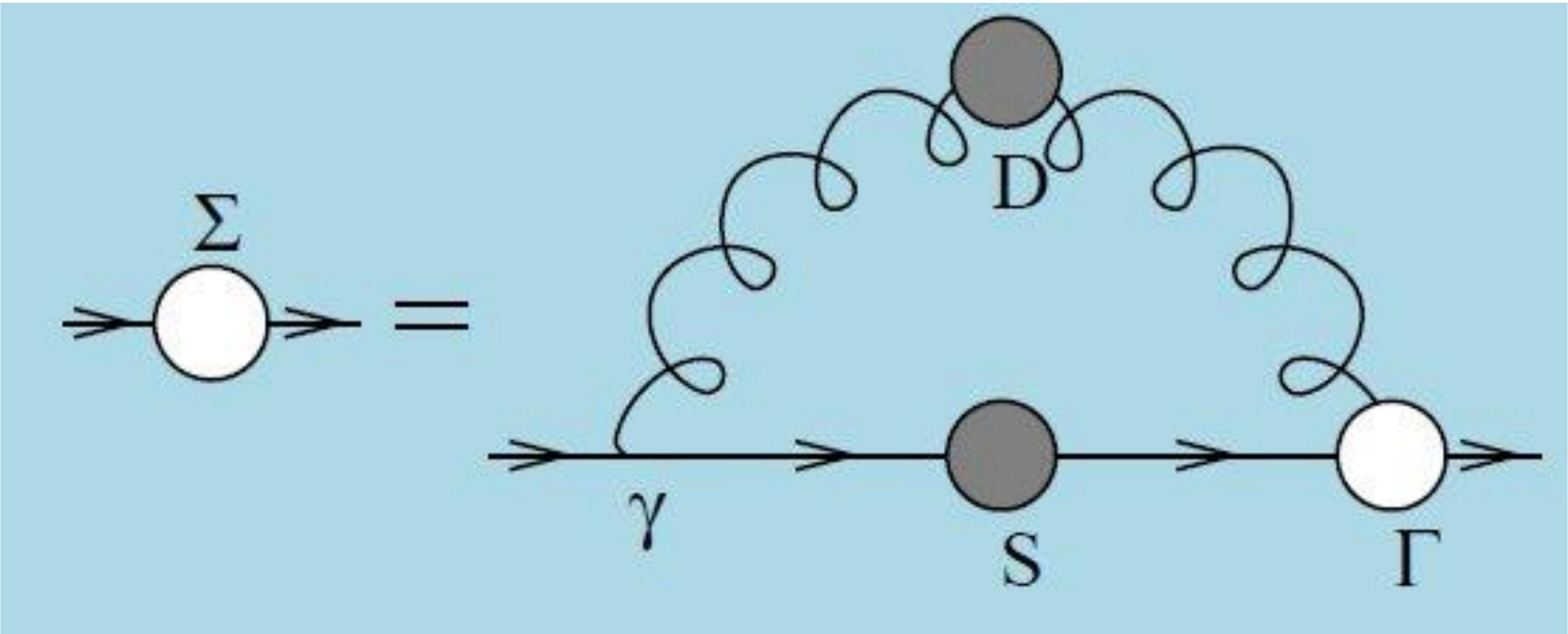
- $\hat{\alpha}_{PI}$ is a new type of effective charge
  - direct analogue of the Gell-Mann–Low effective coupling in QED, *i.e*. completely determined by the gauge-boson two-point function.
- Prediction for $\hat{\alpha}_{PI}$ is parameter-free
  - Draws best from continuum & lattice results for QCD's gauge sector
- Prediction for $\hat{\alpha}_{PI}$ smoothly unifies the nonperturbative and perturbative domains of the strong-interaction theory.
- $\hat{\alpha}_{PI}$ is
  - process-independent
  - known to unify a vast array of observables
- $\hat{\alpha}_{PI}$ possesses an infrared-stable fixed-point
  - Nonperturbative analysis demonstrating absence of a Landau pole in QCD
- QCD is IR finite, owing to dynamical generation of gluon mass-scale

QCD - a paradigm for extending the Standard Model?

- How do quantum field theories fail?
  - Ultraviolet and infrared divergences
- Asymptotic freedom ⇒ QCD is well-defined at UV momenta
- Dynamical generation of gluon mass function, large on $k^2 \simeq 0$,

  ⇒ the infrared domain of QCD is self-regularizing
- QCD is therefore unique amongst known four-dimensional quantum field theories
  - Potentially self-consistent
  - Defined & internally consistent at all momenta (e.g., no Landau pole)
- If all this is true, then QCD can serve as a basis for theories that take physics beyond the Standard Model

$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$

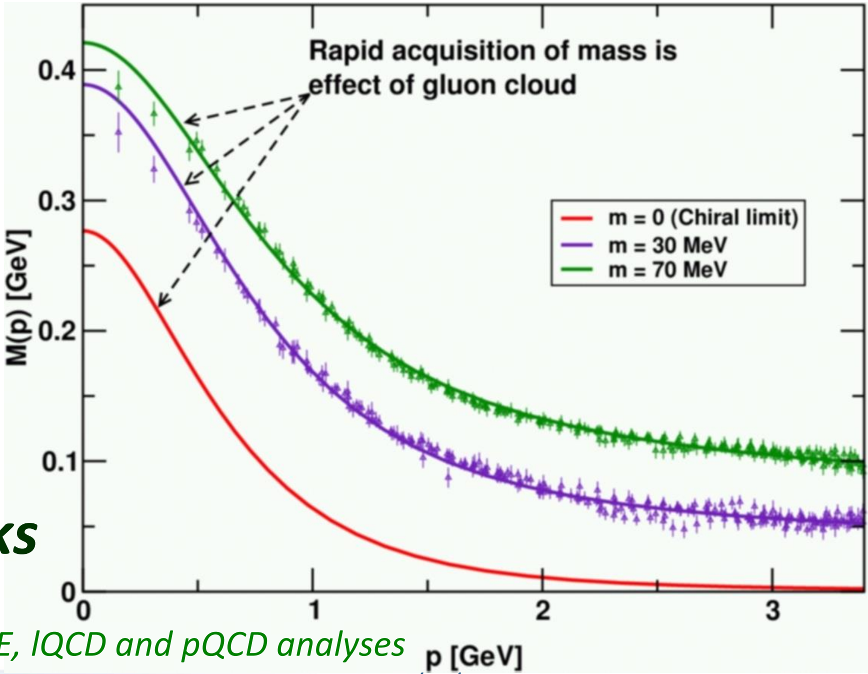


Quark Gap Equation

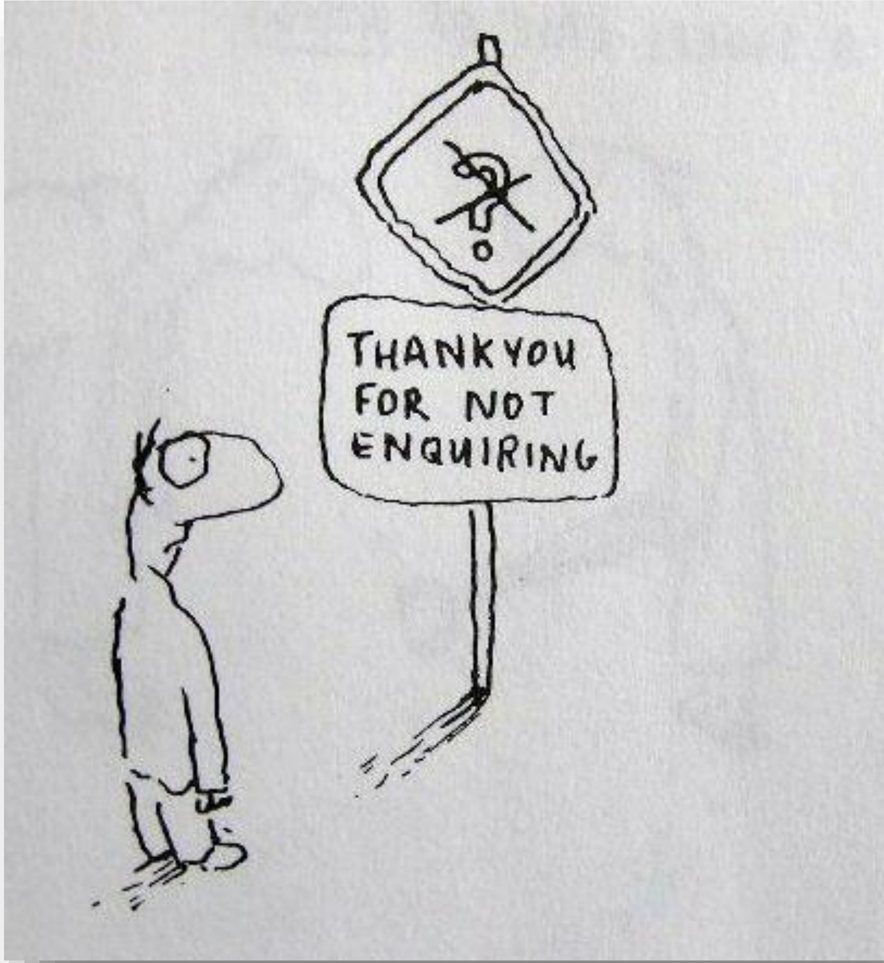
DCSB

- Dynamical chiral symmetry breaking (DCSB) is a key emergent phenomenon in QCD
- Expressed in hadron wave functions not in vacuum condensates
- Contemporary theory indicates that DCSB is responsible for more than 98% of the visible mass in the Universe; namely, given that classical massless-QCD is a conformally invariant theory, then DCSB is the origin of *mass from nothing*.
- ***Dynamical***, not spontaneous
  - Add nothing to *QCD* ,

    No Higgs field, nothing!
    Effect achieved purely through quark+gluon dynamics.
  - ✓ ***Trace anomaly: massless quarks become massive***



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



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

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

- 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

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

Pion exists if, and only if, mass is dynamically generated

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

Enigma of mass

This algebraic identity is why QCD's pion is massless in the chiral limit

- The quark level Goldberger-Treiman relation shows that DCSB has a very deep and far reaching impact on physics within the strong interaction sector of the Standard Model; viz.,

  Goldstone's theorem is fundamentally an expression of equivalence between the one-body problem and the two-body problem in the pseudoscalar channel.

- This emphasises that Goldstone's theorem has a pointwise expression in QCD
- Hence, pion properties are an almost direct measure of the dressed-quark mass function.
- Thus, enigmatically, the properties of the *massless* pion are the cleanest expression of the mechanism that is responsible for almost all the visible mass in the universe.

Observing *Mass*

Imaging dynamical chiral symmetry breaking: pion wave function on the light front, Lei Chang, et al., arXiv:1301.0324 [nucl-th], Phys. Rev. Lett. **110** (2013) 132001 (2013) [5 pages].

Pion's valence-quark Distribution Amplitude

- Methods have been developed that enable direct computation of the pion's light-front wave function
- $\varphi_\pi(x)$ = twist-two parton distribution amplitude = projection of the pion's Poincaré-covariant wave-function onto the light-front

$$\varphi_\pi(x) = Z_2 \mathrm{tr}_{CD} \int \frac{d^4k}{(2\pi)^4} \delta(n \cdot k - x n \cdot P)\, \gamma_5 \gamma \cdot n\, S(k) \Gamma_\pi(k;P) S(k-P)$$

- Results have been obtained with the DCSB-improved DSE kernel, which unifies matter & gauge sectors

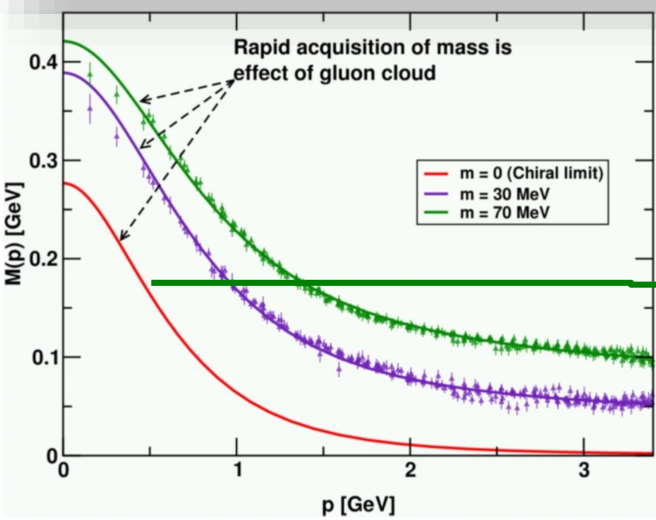
$$\varphi_\pi(x) \propto x^\alpha (1-x)^\alpha, \text{ with } \alpha \approx 0.5$$

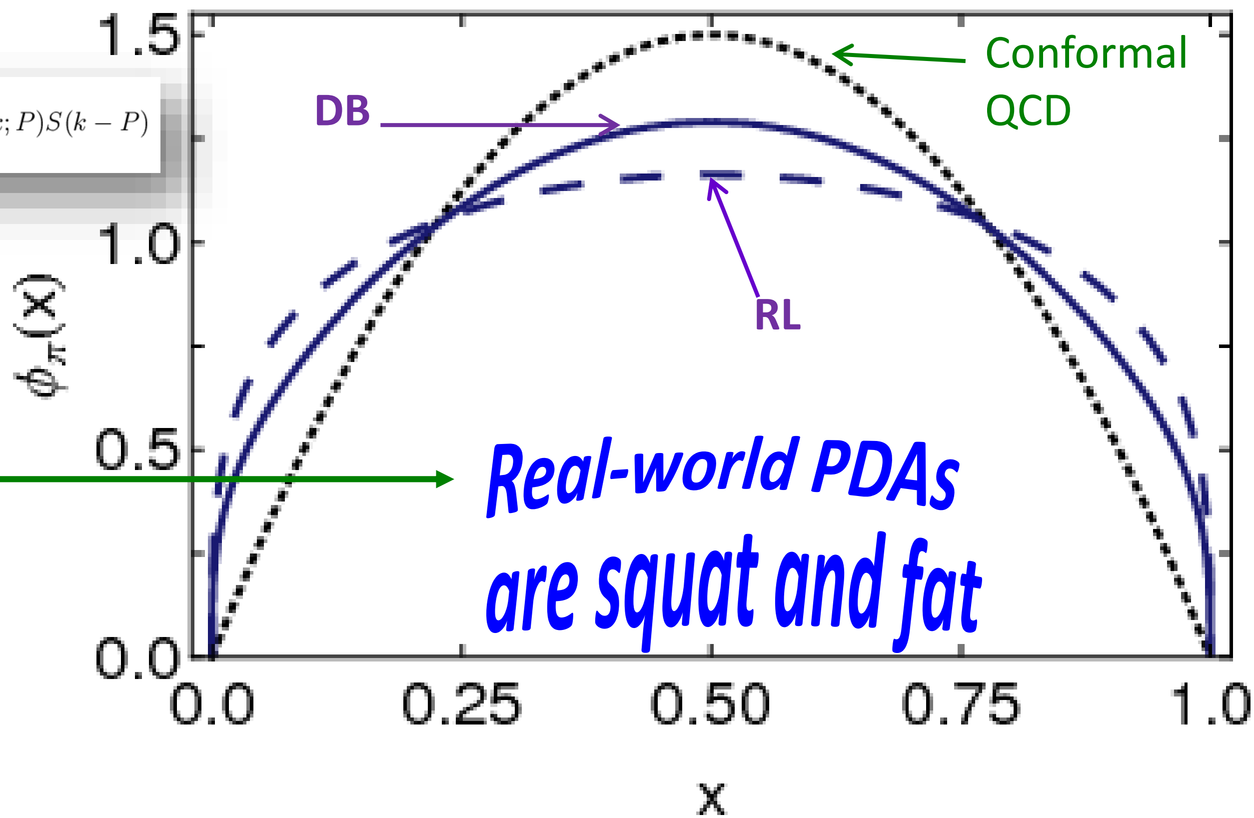
Imaging dynamical chiral symmetry breaking: pion wave function on the light front, Lei Chang, *et al.*, arXiv:1301.0324 [nucl-th], Phys. Rev. Lett. **110** (2013) 132001 (2013) [5 pages].

Pion's valence-quark Distribution Amplitude

- Continuum-QCD prediction:
  marked broadening of φ_π(x), which owes to DCSB

$$\varphi_\pi(x) = Z_2 \mathrm{tr}_{CD} \int \frac{d^4k}{(2\pi)^4} \delta(n\cdot k - x n\cdot P)\, \gamma_5 \gamma\cdot n\, S(k) \Gamma_\pi(k;P) S(k-P)$$

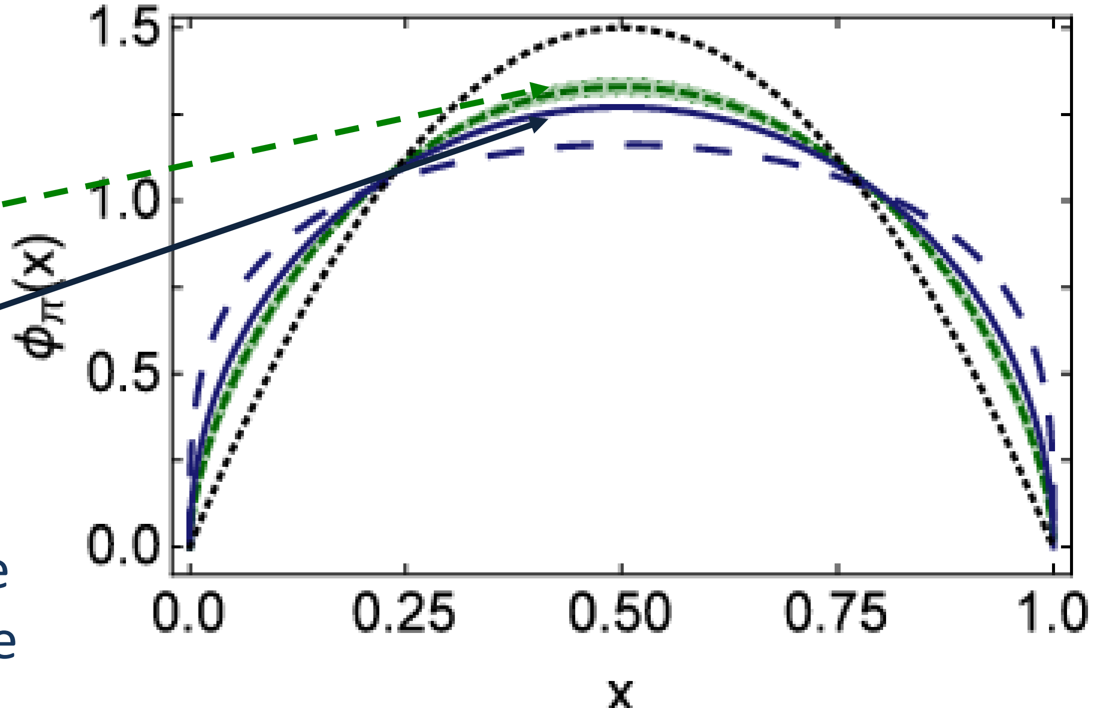




Flavour symmetry breaking in the kaon parton distribution amplitude, Chao Shi *et al.*, *arXiv:1406:3353 [nucl-th], Phys. Lett. B 738 (2014) pp. 512–518*

Lattice-QCD & Pion's valence-quark PDA

- Isolated dotted curve = conformal QCD
- Green curve & band = result inferred from the single pion moment computed in lattice-QCD
- Blue solid curve = DSE prediction obtained with DB kernel
- DSE & lQCD predictions are practically indistinguishable



- arXiv:1702.00008, *Pion Distribution Amplitude from Lattice QCD*
  Jian-Hui Zhang, Jiunn-Wei Chen, Xiangdong Ji, Luchang Jin, Huey-Wen Lin

Pion electromagnetic form factor at spacelike momenta
L. Chang, I. C. Cloët, C. D. Roberts, S. M. Schmidt and P. C. Tandy,
arXiv:1307.0026 [nucl-th], Phys. Rev. Lett. 111, 141802 (2013)

Pion's electromagnetic form factor

- PDA Broadening has enormous impact on understanding $F_\pi(Q^2)$

A: Internally-consistent DSE prediction

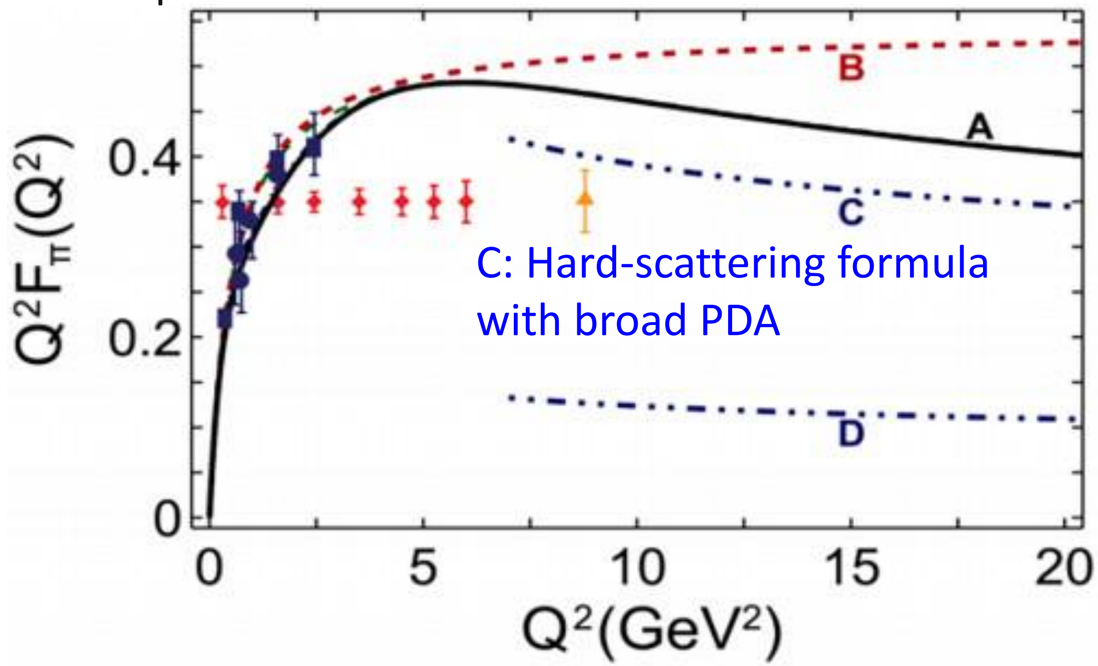
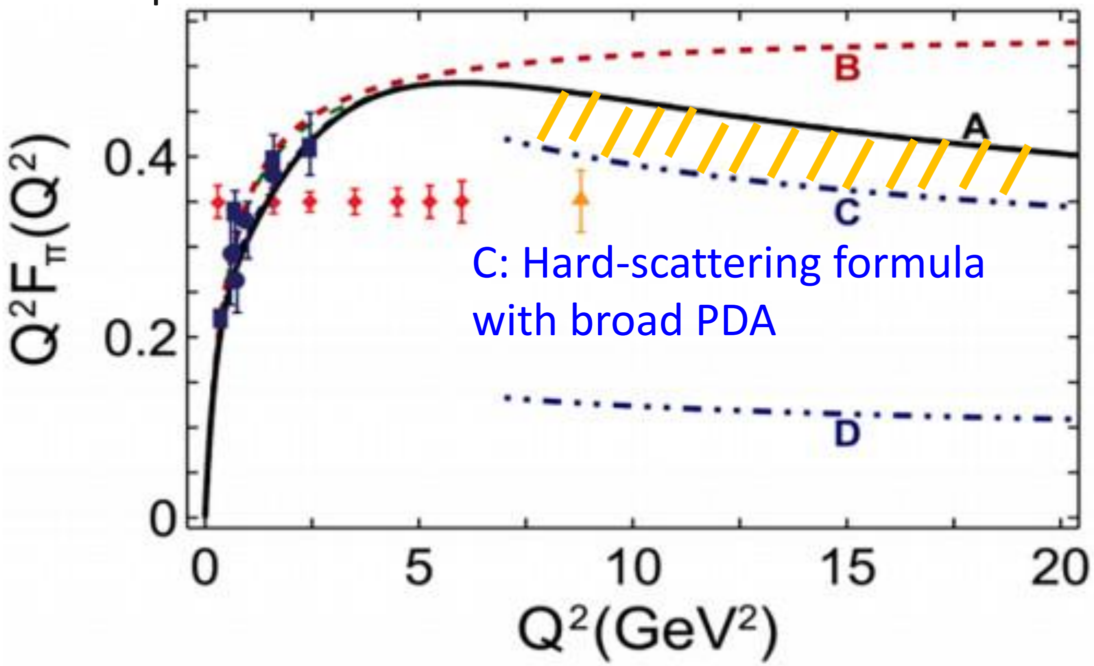


Figure 2.2: *Existing (dark blue) data and projected (red, orange) uncertainties for future data on the pion form factor. The solid curve (A) is the QCD-theory prediction bridging large and short distance scales. Curve B is set by the known long-distance scale—the pion radius. Curves C and D illustrate calculations based on a short-distance quark-gluon view.*

Pion's electromagnetic form factor

- PDA Broadening has enormous impact on understanding *$F_\pi(Q^2)$*
- Appears that JLab12 is within reach of first verification of a QCD hard-scattering formula

A: Internally-consistent DSE prediction



C: Hard-scattering formula with broad PDA

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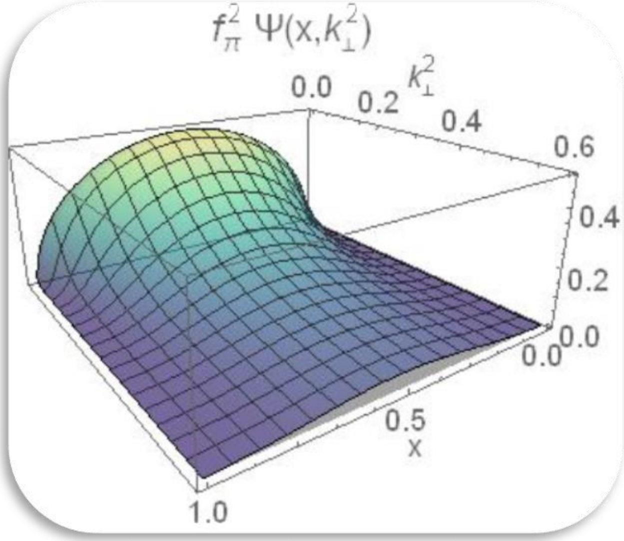
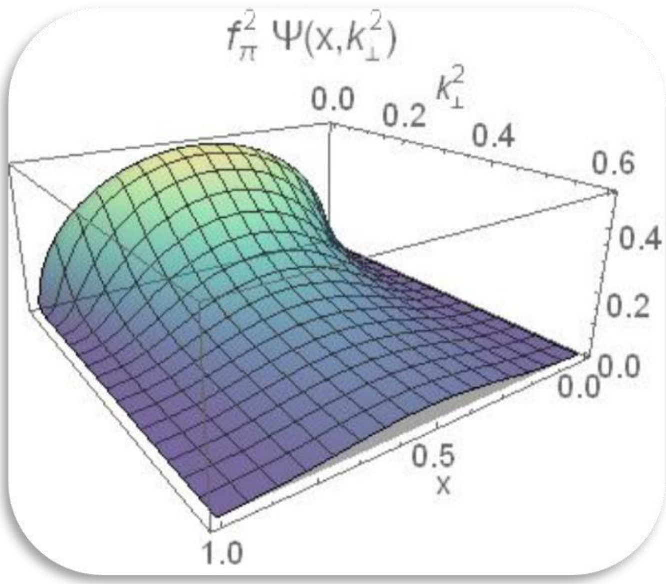
Validity of hard scattering formulae?

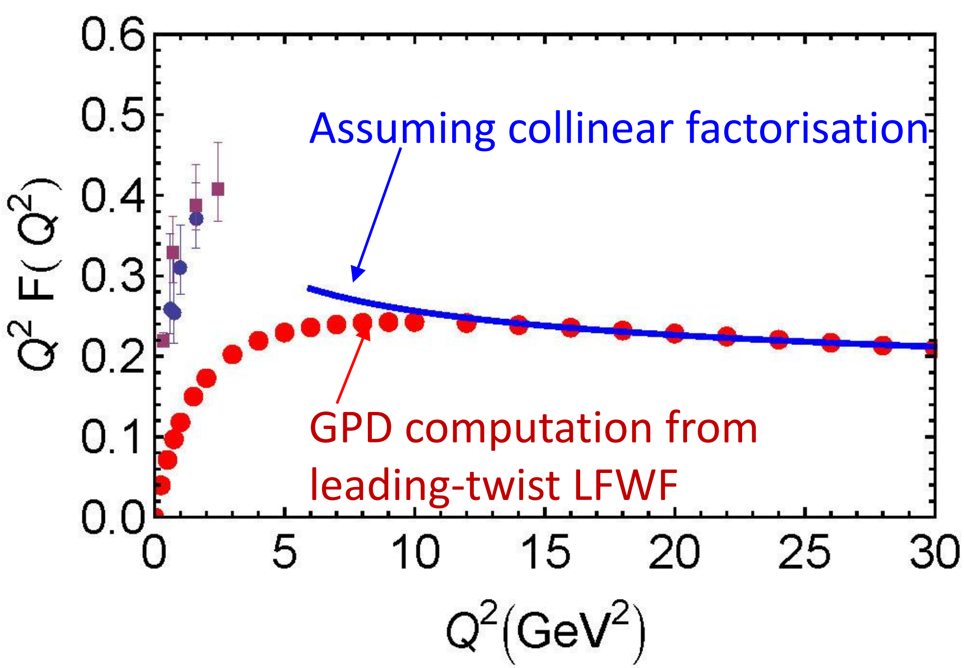
- Do endpoint singularities invalidate collinear factorisation at accessible scales?
- No … because the nonperturbatively-generated infrared gluon mass provides the infrared cut-off needed to screen this singularity
- Can be checked – once one has a pion light-front wave function:
  - GPD in overlap representation provides direct access to $F_\pi(Q^2)$
- Leading-twist valence-parton LFWF is available



Validity of hard scattering formulae?

- Leading-twist valence-parton light-front wave function
- Direct calculation of $F_\pi(Q^2)$ via overlap representation of GPD
- No assumption of validity of collinear factorisation
- Computational verification … good approximation on $Q^2 > 7$ GeV^2

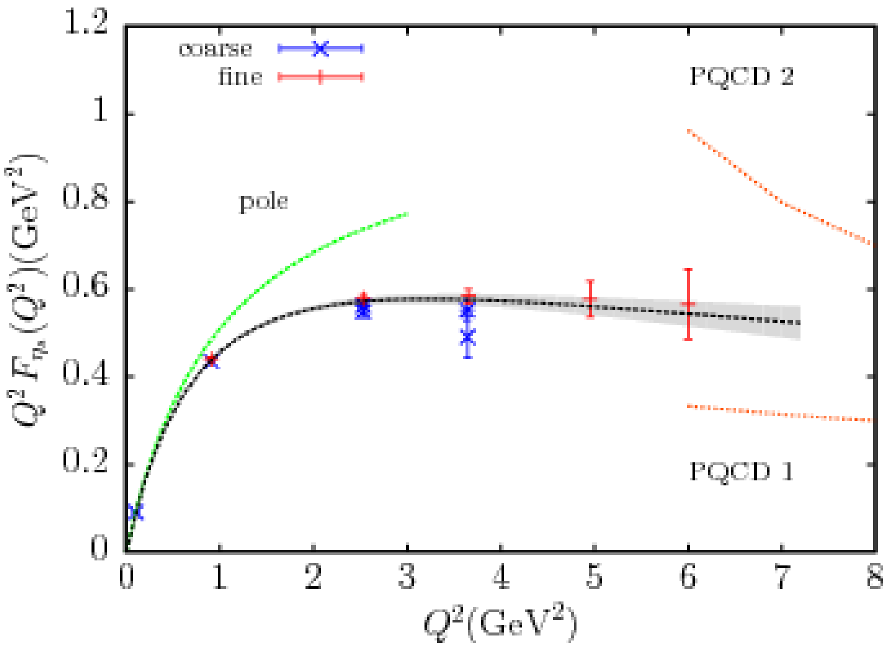




Pseudo-pion form factor

- J. Koponen *et al*.: arXiv:1701.04250 [hep-lat]

We give an accurate determination of the vector (electromagnetic) form factor, F(Q²), for a light meson up to squared momentum transfer Q² values of 6 GeV² for the first time from full lattice QCD, including u, d, s and c quarks in the sea at multiple values of the lattice spacing. Our results show good control of lattice discretisation and sea quark mass effects, indicating that higher Q² values could be reached in future with finer lattices. We study a pseudoscalar meson made of valence s quarks but the qualitative picture obtained applies also to the π meson, relevant to upcoming experiments at Jefferson Lab. We find that Q²F(Q²) becomes flat in the region between Q² of 2 GeV² and 6 GeV², with a value well above that of the asymptotic perturbative QCD expectation, but well below that of the vector-meson dominance pole form appropriate to low Q² values. Our calculations open the way for further lattice QCD analysis of high-Q² form factors to shed light on where the perturbative QCD result emerges.



To obtain a flatter curve in better agreement with our results would require a broader distribution amplitude and a higher scale for α_s for less evolution. Such curves have been obtained for the π in a recent Dyson-Schwinger approach [46], and it would be interesting to see if it can reproduce our results for the η_s. For this purpose we give the parameters for our continuum curve in the supplemental materials.

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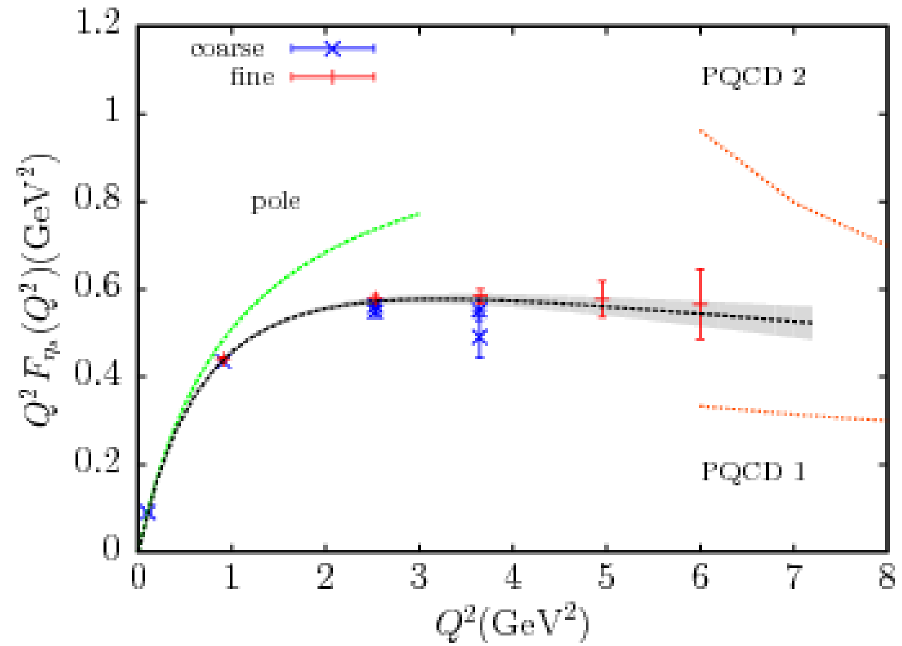

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	$m_{s\bar{s}}$	$f_{s\bar{s}}$
DSE 2004	0.69 GeV	0.13 GeV
Lattice 2017	0.6885(2)	0.1281(39)

Pseudo-pion form factor

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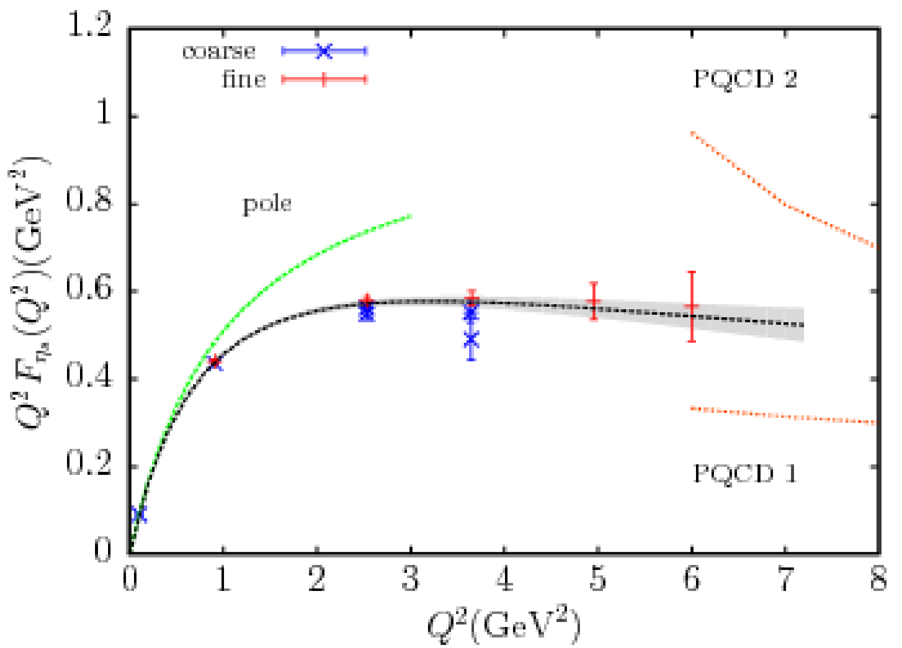
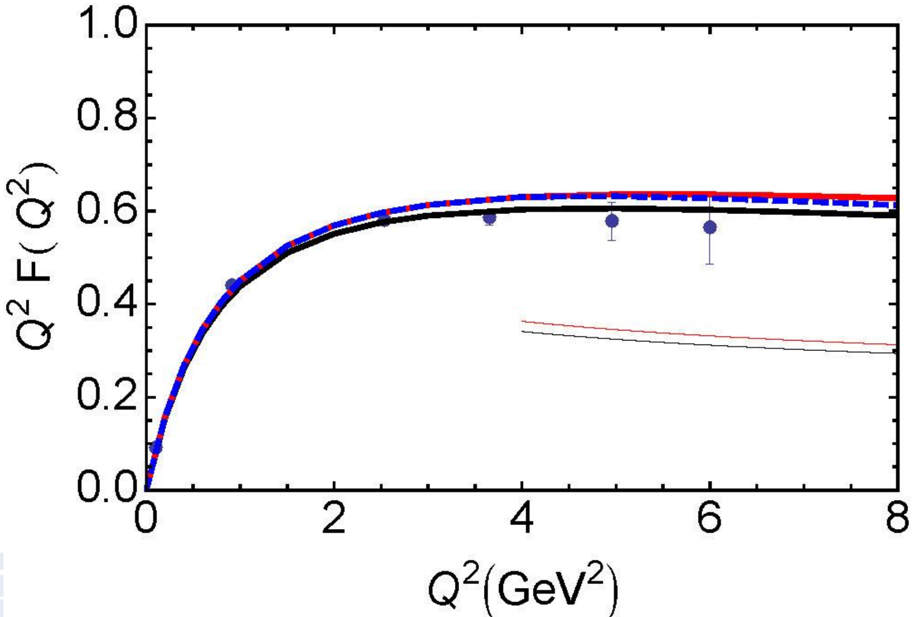


Preliminary DSE result for *s*-massive pseudo-π

… Internally consistent calculation, producing *s*-massive PDA ∝ $[x(1-x)]^{0.8}$

… Independent confirmation of reality and impact of dilated PDAs on meson form factors

… Move on to baryons



Kaon electromagnetic form factor

- Chiral limit
  - π & K are degenerate
  - Internal structure is identical

    QCD's Nambu-Goldstone modes
- But … in physical kaon, the Higgs mechanism plays a role
  - *s*-quark current mass is much greater than that of the *u*-quark

    $m_s \sim 25\, m_u$
  - Translates into IR difference in running masses

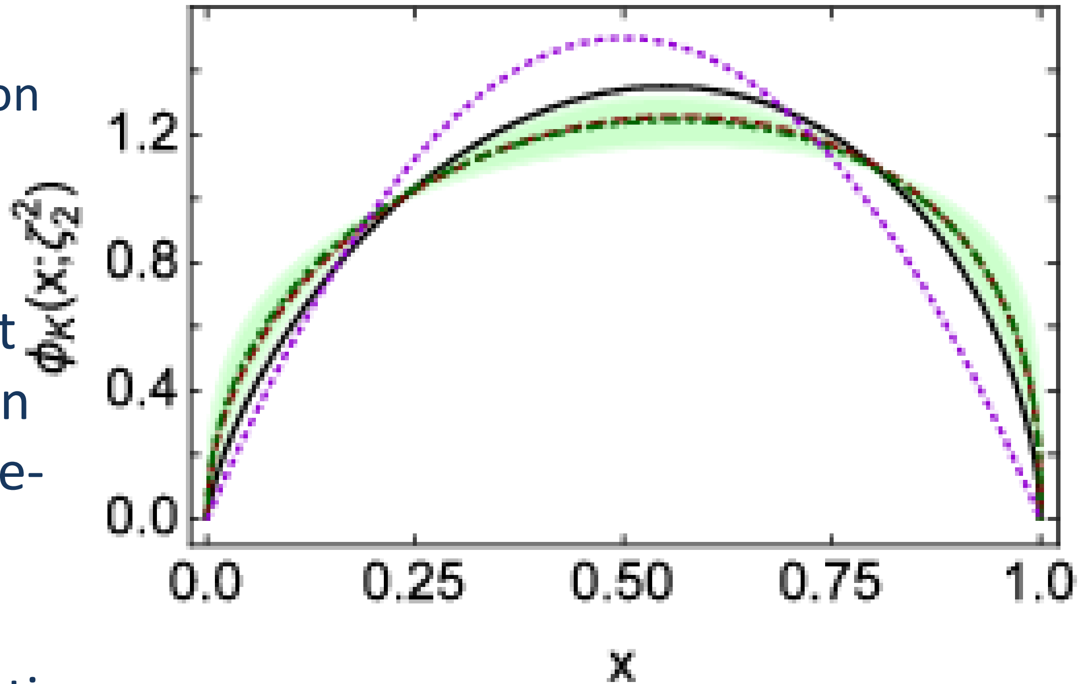
    $M_s(0) \sim 1.25\, M_u(0)$
- Comparison between π & K properties provides direct access to
  - interplay
  - feedback

  between strong and electroweak mass generating mechanisms

Kaon electromagnetic form factor

- Techniques developed for pion
  - PDA
  - Form factor

  also directly applicable to kaon
- Isolated dotted curve = conformal QCD
- Green curve & band = result inferred from the single pion moment computed in lattice-QCD
- Black solid and red dashed curves = band of DSE predictions
- Agreement between DSE & lQCD predictions, within errors



Flavour symmetry breaking in the kaon parton distribution amplitude, Chao Shi, Chen Chen, Lei Chang, Craig D. Roberts, Sebastian M. Schmidt and Hong-Shi Zong, arXiv:1406:3353 [nucl-th], Phys. Lett. B 738 (2014) pp. 512–518

Kaon electromagnetic form factor

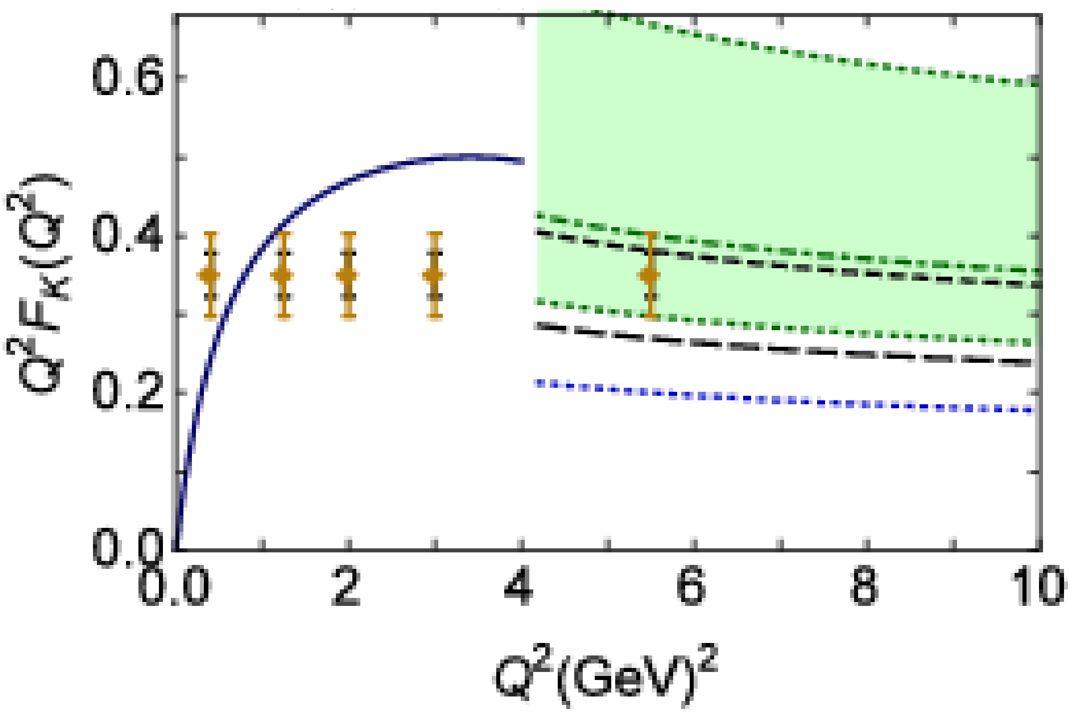
- Solid blue curve = DSE (Maris-Tandy 2000) prediction
- Hard-scattering formula
  - Short- and long-dashed curves = DSE prediction for PDA yields result within this area
  - Green band = broad, skewed lQCD PDA
- Skewing is not the issue: 12%-15%, DSE- and lattice-QCD agree
- It's extent of the broadening that generates the uncertainty
- JLab 12 has potential to settle the issue … Meantime, extend $F_\pi(Q^2)$ analysis on entire spacelike domain → $F_K(Q^2)$

$$\exists \bar{Q}_0 > \Lambda_{\rm QCD} \mid Q^2 F_K(Q^2) \overset{Q^2>\bar{Q}_0^2}{\approx} 16\pi\alpha_s(Q^2) f_K^2 w_K^2(Q^2)$$

with [41] $f_K = 0.110\,{\rm GeV}$ and, for the K^+:

$$w_K^2 = e_{\bar{s}} w_{\bar{s}}^2 + e_u w_u^2,$$

$$w_{\bar{s}} = \frac{1}{3}\int_0^1 dx\, \frac{1}{1-x}\,\varphi_K(x)\,, \quad w_u = \frac{1}{3}\int_0^1 dx\, \frac{1}{x}\,\varphi_K(x)$$



The pion: an enigma within the Standard Model
Tanja Horn and Craig D. Roberts
arXiv:1602.04016 [nucl-th], J. Phys. G **43** (2016) 073001/1-46

Kaon's electromagnetic form factor

- Solid blue curve = Maris-Tandy prediction
- Hard-scattering formula
  - Short- and long-dashed curves = DSE prediction for PDA yields result within this area
  - Green band = broad, skewed lQCD PDA
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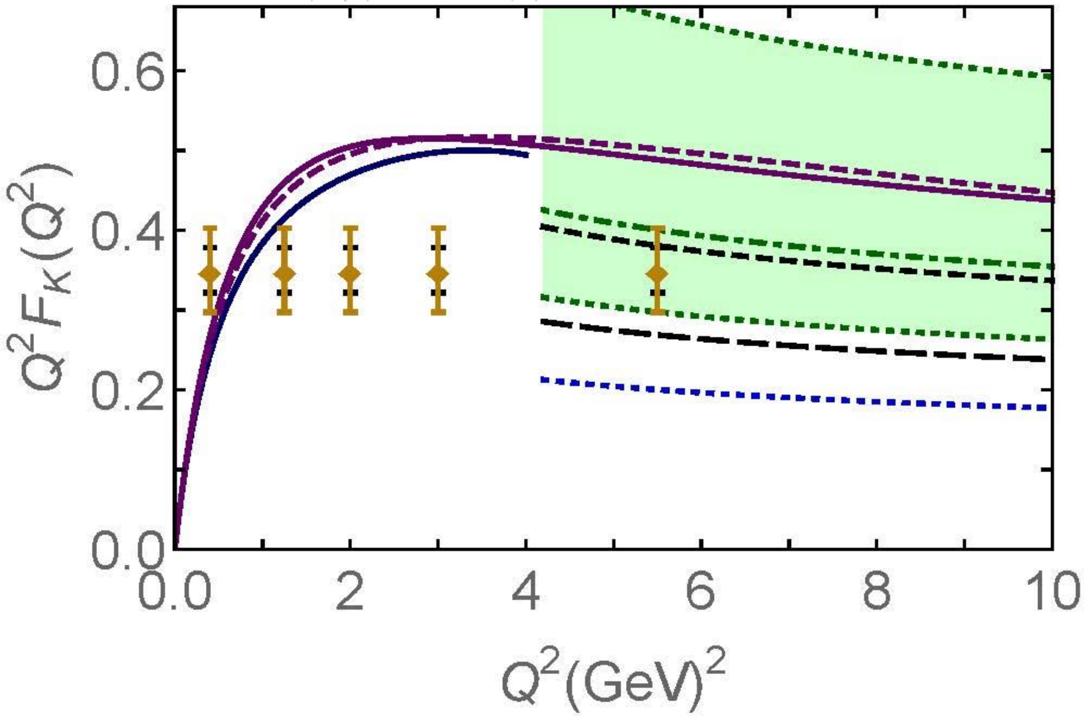


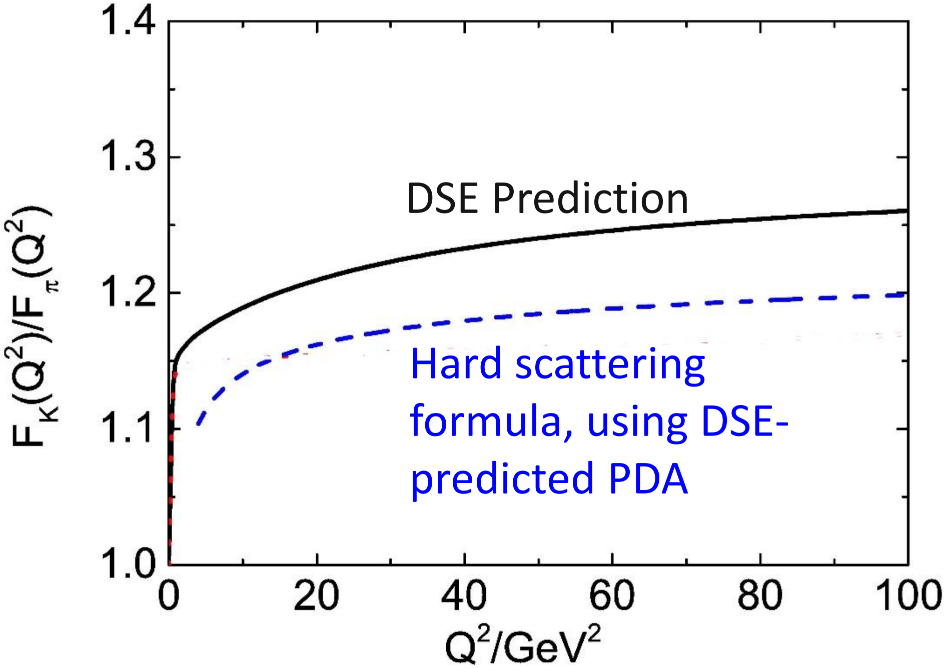
Kaon cf. pion form factor

- QCD prediction …

  as $Q^2 \to \infty$

  $F_K(Q^2)/F_\pi(Q^2) = f_K^2/f_\pi^2 = 1.4$
- Logarithmic approach to pQCD limit
- Direct calculation confirms validity of hard-scattering formula on $Q^2 > 8\ GeV^2$
- Q^2-evolution of
  - wave functions
  - interaction current

  essential to agreement between trends of direct calculation and hard scattering formula
  - Restore hard-gluons omitted in all truncations used heretofore



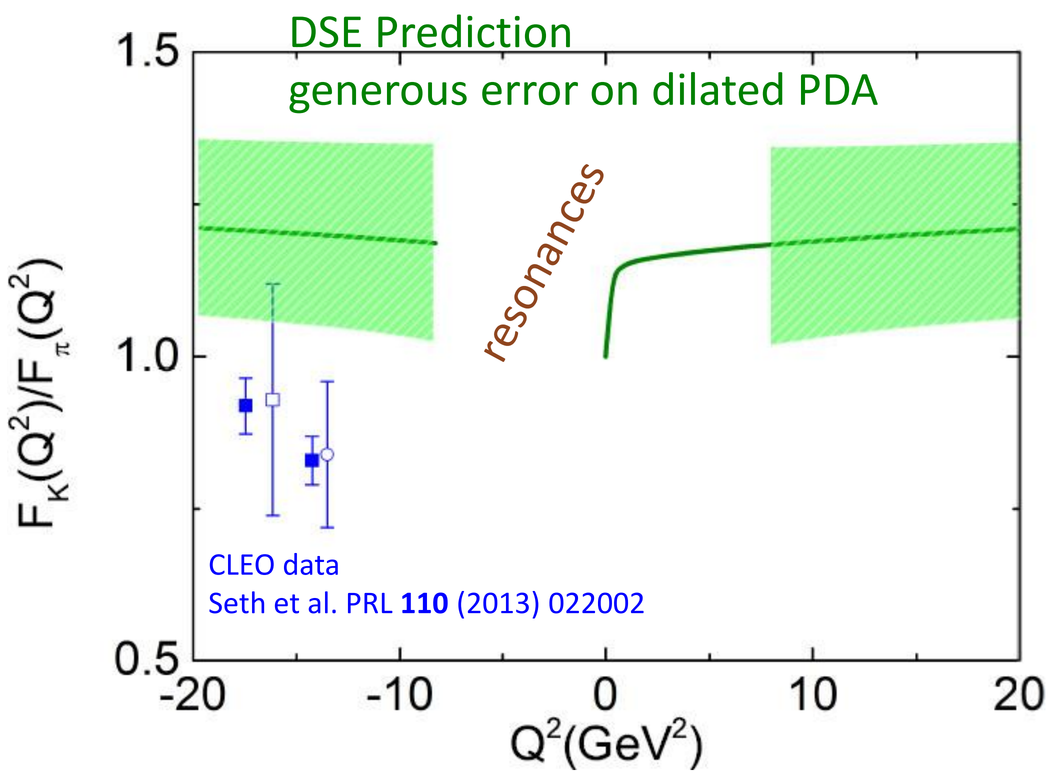
Models typically tuned to generate correct power law, but then produce wrong anomalous dimension

General defect of uneducated use of covariant framework, anticipated in Lepage-Brodsky Phys.Rev. D ***22*** *(1980) 2157 [p.2168]*

Remedied here, following Structure of the neutral pion and its electromagnetic transition form factor, *K. Raya, L. Chang, A. Bashir, J.J. Cobos-Martinez, L.X. Gutiérez-Guerrero, C.D. Roberts and P.C. Tandy, arXiv:1510.02799 [nucl-th] , Phys. Rev. D**93** (2016) 074017/1-9*

Kaon cf. pion form factor timelike

- Hard-scattering formulae are valid on $Q^2 > 8$ GeV^2
- At leading order in pQCD, spacelike and timelike form factors are identical
- Confidence in prediction at timelike momenta, using direct mapping of spacelike behaviour
- Data … problems?:
  - F_π = factor of 2 too-large compared with DSE maximum
  - F_K = factor of 1.5 too-large compared with DSE maximum
- Check normalisation
- Repeat experiments



Holt & Gilman, Rept. Prog. Phys. **75** (2012) 086301: "The prospect for improving the measurements in the time-like region is excellent because of the e^+e^- colliders in operation or recently in operation."

Kaon elastic form factor at all spacelike momenta,
Fei Gao, L. Chang, Y.-X. Liu and C. D. Roberts

Kaon form factor - flavour separation

$$\exists \bar{Q}_0 > \Lambda_{\rm QCD} \mid Q^2 F_K(Q^2) \overset{Q^2 > \bar{Q}_0^2}{\approx} 16\pi \alpha_s(Q^2) f_K^2 w_K^2(Q^2)$$

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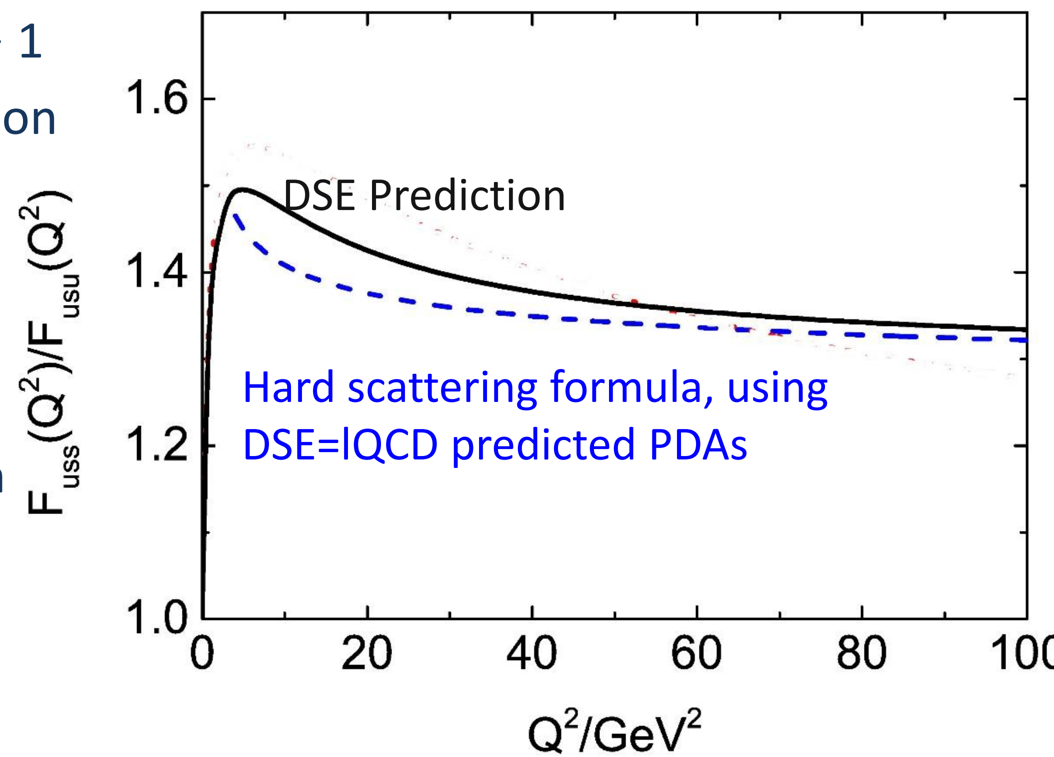
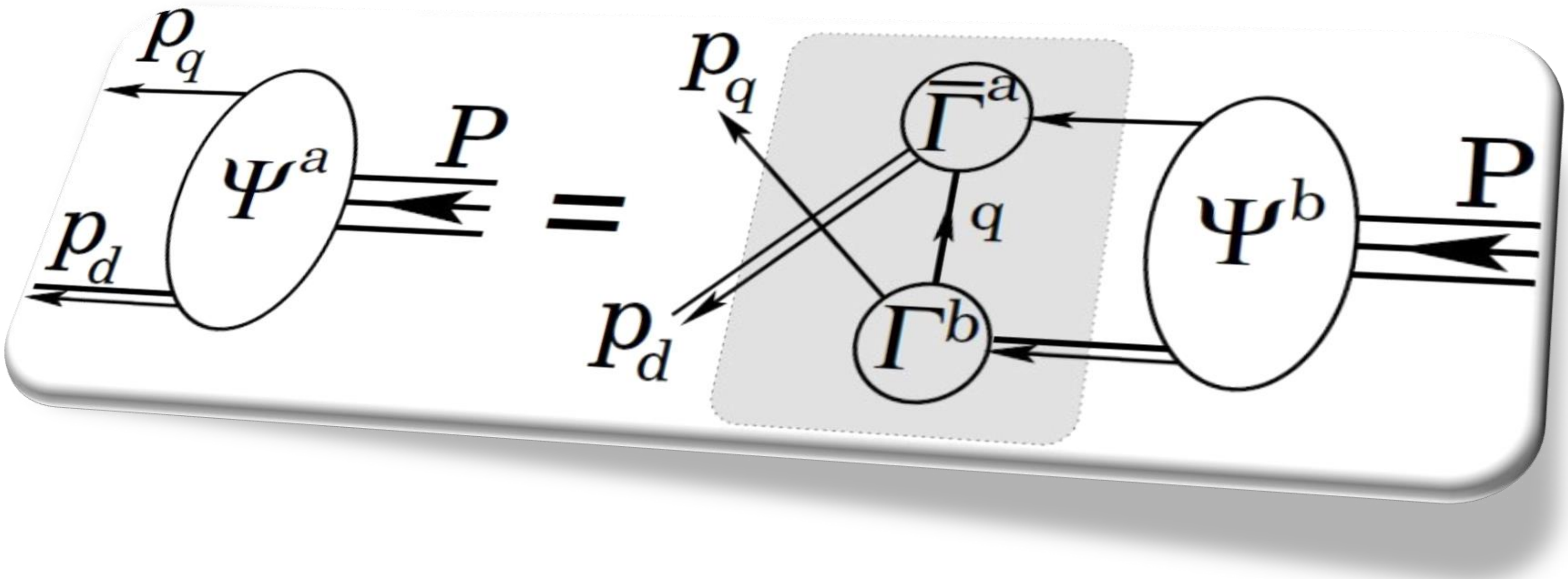
- Current conservation
  $F_{uss}(0) = F_{uus}(0)$
- Under evolution:
  $\varphi_K \to 6\,x\,(1-x) \Rightarrow \omega_{\bar{s}} \to \omega_u \Rightarrow$ Ratio $\to 1$
- Agreement between direct calculation and hard-scattering formula, using consistent PDA
- Ratio never exceeds 1.5 and

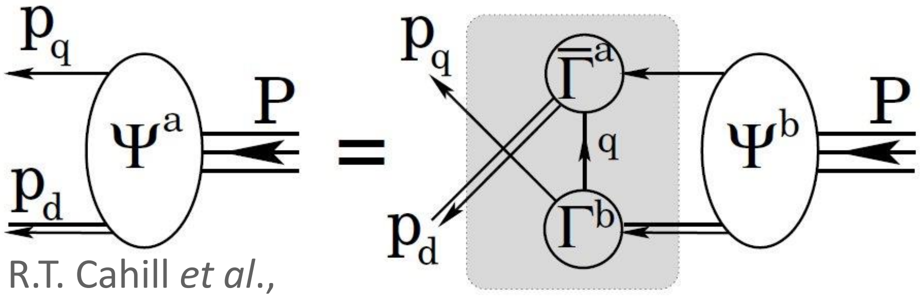
  Logarithmic approach to unity
- Typical signal of DCSB-dominance in flavour-symmetry breaking:
  - $M_s(0) \sim 1.25\, M_u(0)$
  - but this scale difference becomes irrelevant under evolution

$[\,\bar{s}\,\gamma\, s\, u_{spectator} \,/\, \bar{u}\,\gamma\, u\, s_{spectator}\,]^2 \leq 1.5$





Structure of Baryons



R.T. Cahill *et al.*,
Austral. J. Phys. 42 (1989) 129-145

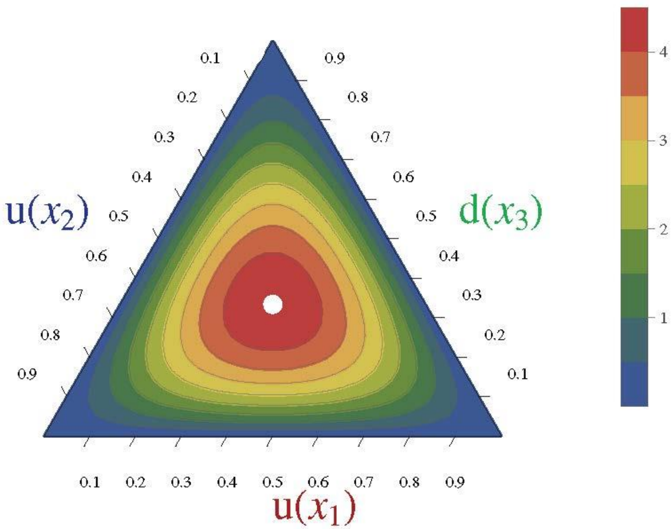
Baryon Structure

- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Confinement and DCSB are readily expressed
- ***Prediction***: owing to *DCSB in QCD, strong diquark correlations exist within baryons*
- Diquark correlations are not pointlike
  - Typically, $r_{0+} \sim r_\pi$ & $r_{1+} \sim r_\rho$ (actually 10% larger)
  - They have soft form factors

C. Mezrag, C. D. Roberts and J. Segovia,
Near completion

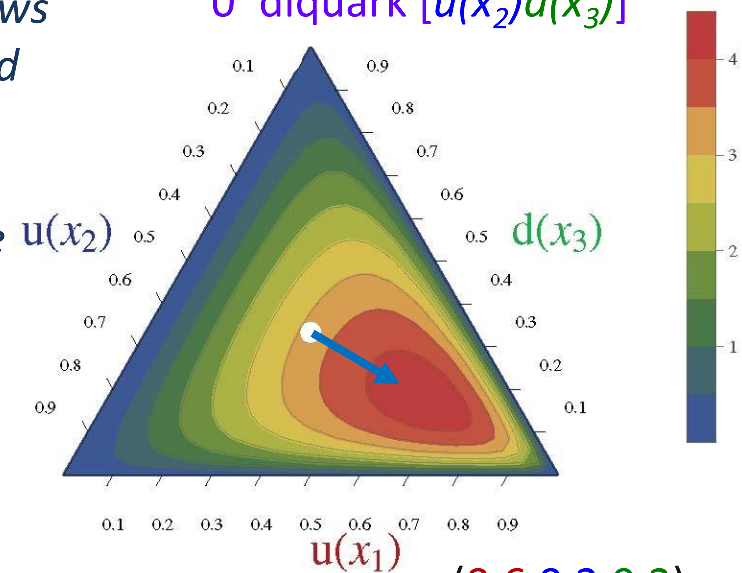
Nucleon Parton Distribution Amplitudes

➢ Computations underway. First results available.



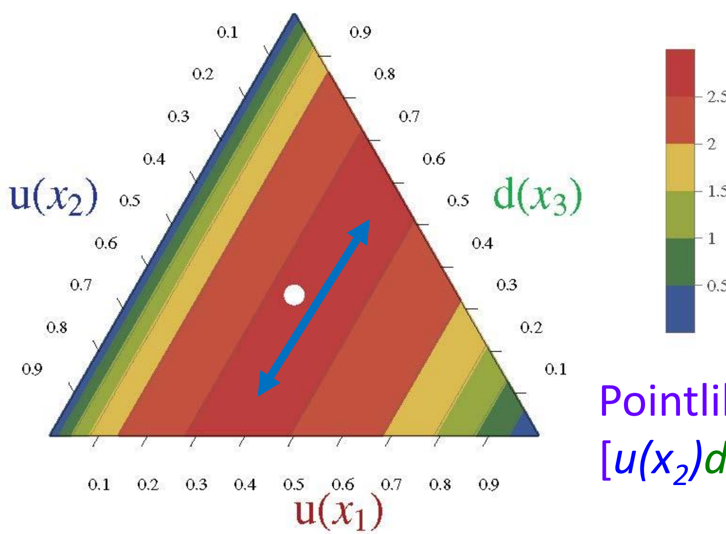
Diquark clustering skews the distribution toward the dressed-quark bystander, which therefore carries more of the proton's light-front momentum

Realistic, finite size (0.7fm) 0^+ diquark [$u(x_2)d(x_3)$]



(0.6,0.2,0.2)

conformal limit:
120 $x_1x_2x_3$
$\langle x_i \rangle = ⅓$ ... peak of the distribution



Pointlike 0^+ diquark [$u(x_2)d(x_3)$]

Light-cone distribution amplitudes of the nucleon and negative parity nucleon resonances from lattice QCD
V. M. Braun *et al.*, Phys. Rev. D 89 (2014) 094511

Light-cone distribution amplitudes of the baryon octet
G. S. Bali *et al*. JHEP 1602 (2016) 070

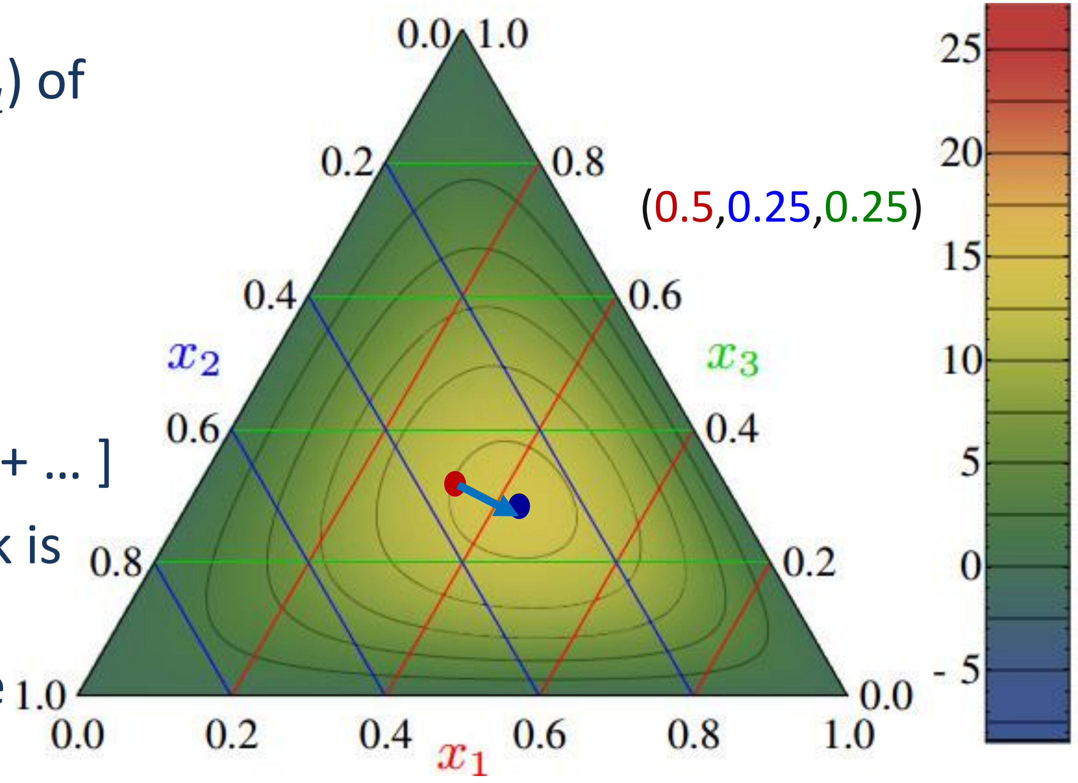
Nucleon PDAs & lQCD

- First lQCD results for n=0, 1 moments of the leading twist PDA of the nucleon are available
- Used to constrain strength (a_{11}) of the leading-order term in a conformal expansion of the nucleon's PDA:

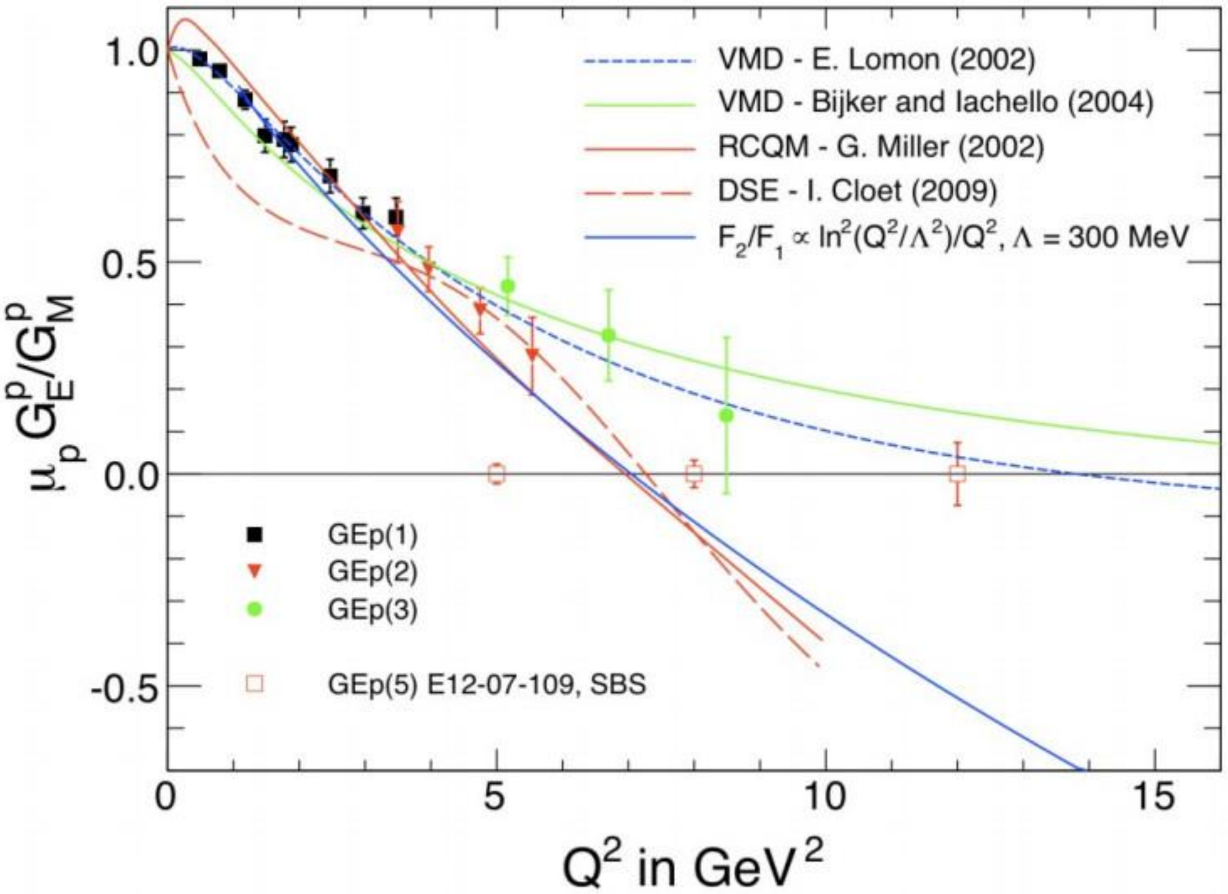
$\Phi(x_1,x_2,x_3)$

$= 120\, x_1\, x_2\, x_3\, [\, 1 + a_{11}\, P_{11}(x_1,x_2,x_3) + \ldots\,]$

- Shift in location of central peak is consistent with existence of diquark correlations within the nucleon



GEp5 Projected results



Nucleon Form Factors

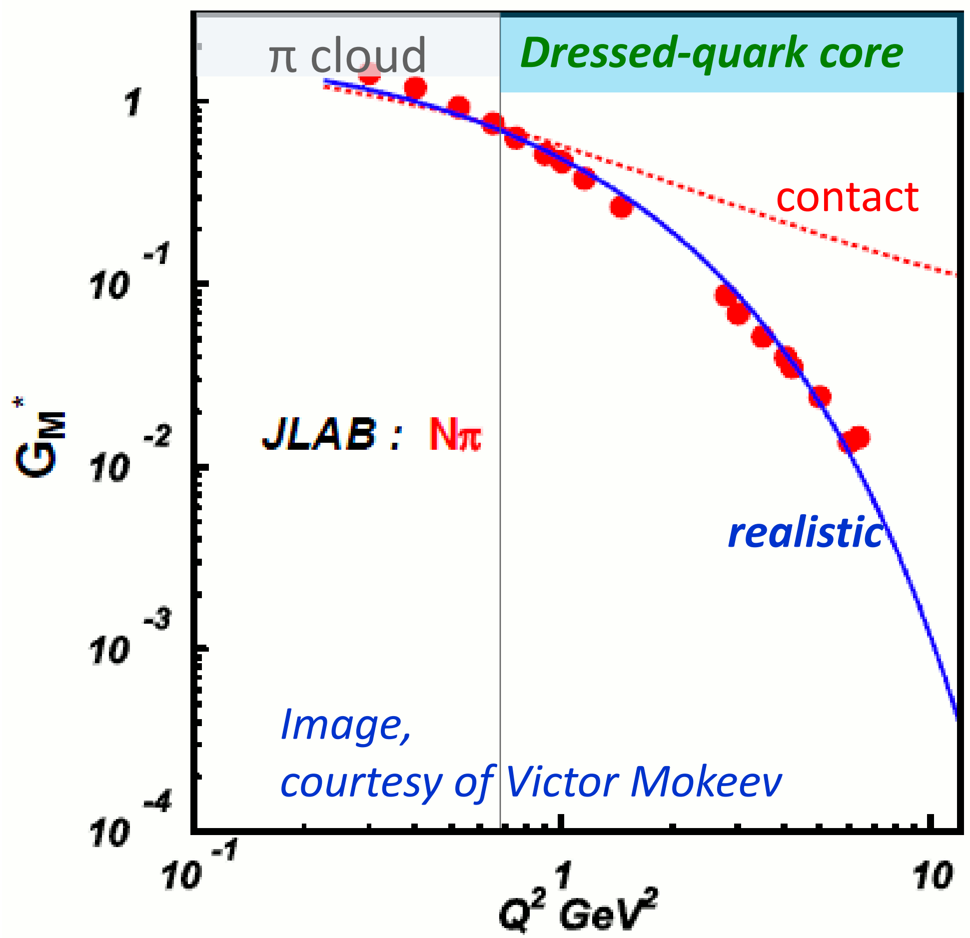
γ N → Resonance

- Prediction and measurement of ground-state elastic form factors is essential to increasing our understanding of strong-interaction … many surprising discoveries already
- However, alone, it is insufficient to explore and expose the infrared behaviour of the strong interaction
  - the hydrogen ground-state didn't give us QED
- There are numerous nucleon → resonance transition form factors.
  - The challenge of mapping their Q^2-dependence provides a vast array of novel ways to probe the infrared behaviour of the strong interaction, including the environment and energy sensitivity of correlations

J. Segovia, et al.: Nucleon and Δ Elastic and Transition Form Factors, arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) pp. 1185-1222 [on-line]

$\gamma N \rightarrow \Delta$

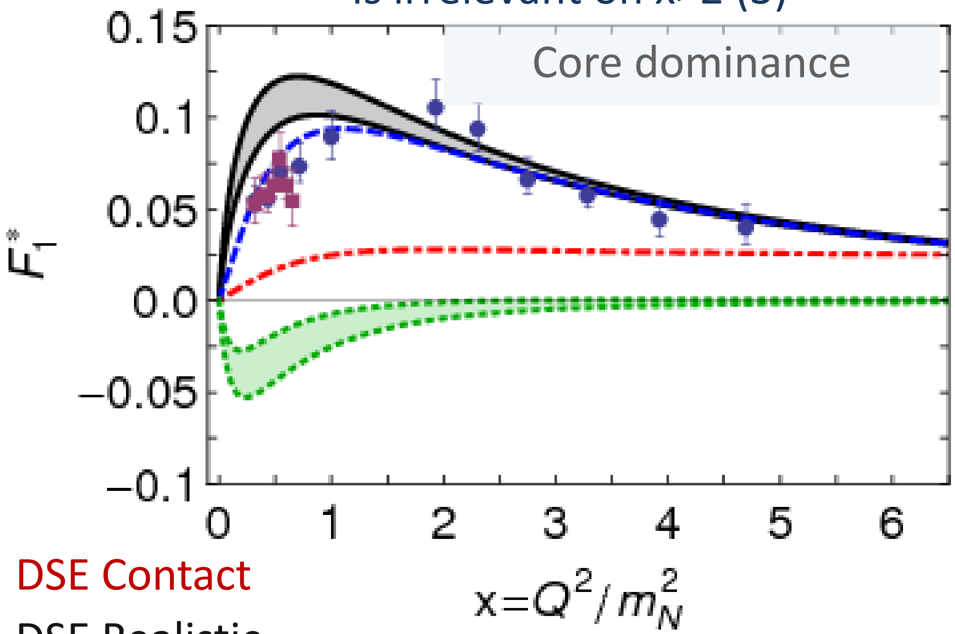
- Jones-Scadron convention – simplest direct link to helicity conservation in pQCD
- Single set of inputs …
  - dressed-quark mass function (***same as that which predicted meson properties***)
  - diquark amplitudes , masses, propagators
  - same current operator for elastic and transition form factors
- ***Prediction N→Δ transition is indistinguishable from data on $Q^2>0.7$ GeV^2***

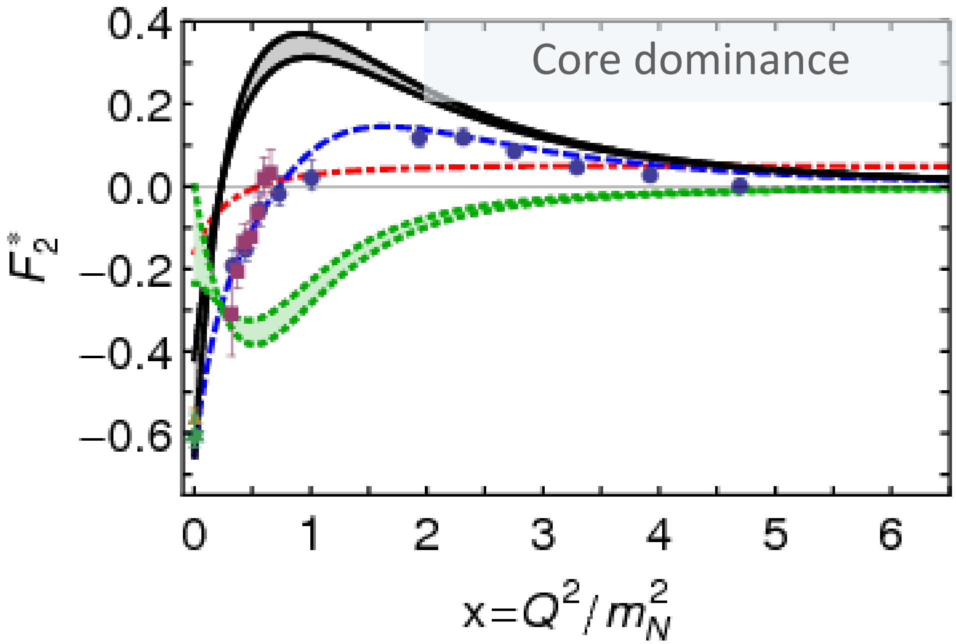


Completing the picture of the Roper resonance, Jorge Segovia *et al.*,,
arXiv:1504.04386 [nucl-th], Phys. Rev. Lett. **115** (2015) 171801

$\gamma N \to$ Roper

- Predicted transition form factors
  - Excellent agreement with data on *x>2 (3)*
  - Like $\gamma N \to \Delta$, room for meson cloud on *x<2* … appears likely that cloud
    - Is a negative contribution that depletes strength on *0<x<2*
    - Has nothing to do with existence of zero; but is influential in shifting the zero in F_2^* from *x=¼* to *x=1*
    - Is irrelevant on x>2 (3)





DSE Contact

DSE Realistic

Inferred meson-cloud contribution

Anticipated complete result

M. Dugger *et al.*, Phys. Rev. C79, 065206 (2009).
I. Aznauryan *et al.*, Phys. Rev. C80, 055203 (2009).
I. G. Aznauryan *et al.*, arXiv:1108.1125 [nucl-ex].
V. I. Mokeev *et al.*, Phys. Rev. C86 (2012) 035203

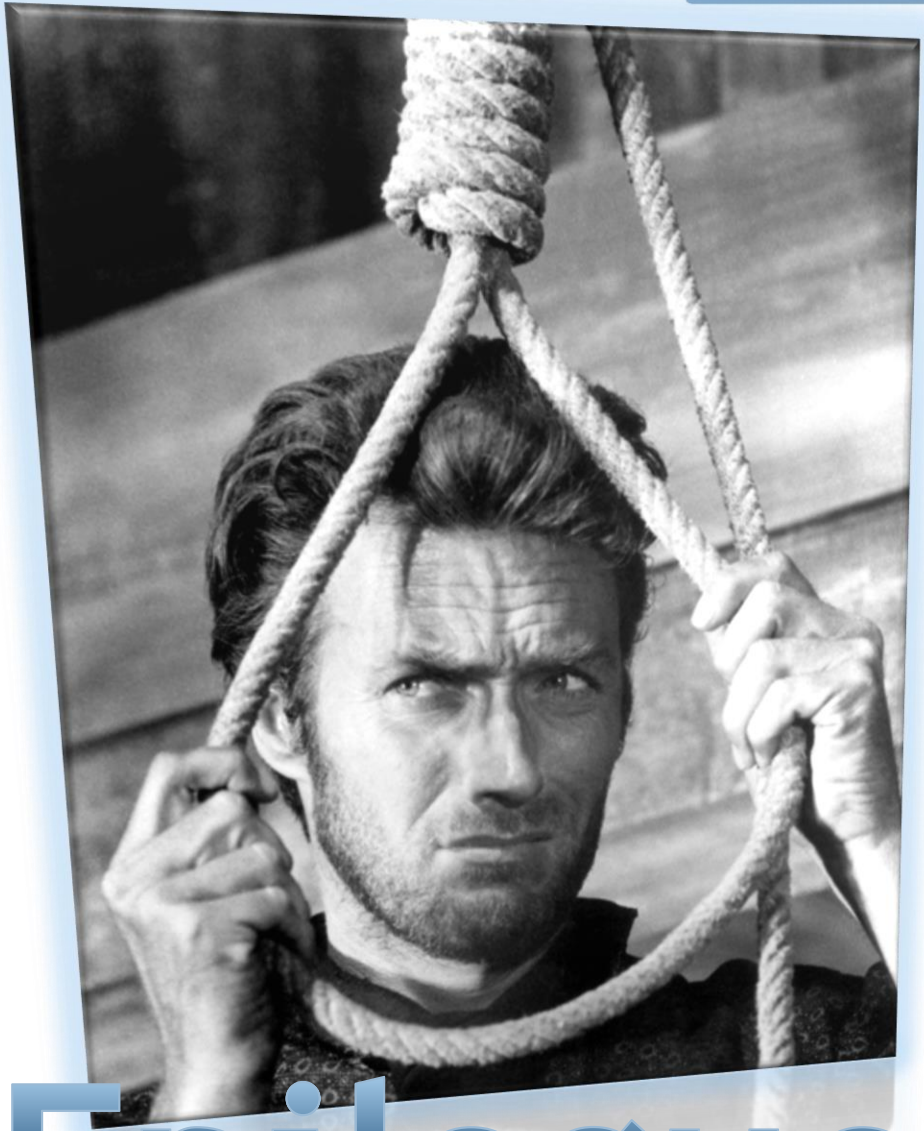
Nucleon and Δ elastic and transition form factors
Jorge Segovia *et al*., arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) pp. 1185-1222

Completing the picture of the Roper resonance
Jorge Segovia *et al*. arXiv:1504.04386 [nucl-th], Phys. Rev. Lett. **115** (2015) 171801

Dissecting nucleon transition electromagnetic form factors
Jorge Segovia and Craig D. Roberts, arXiv:1607.04405 [nucl-th], Phys. Rev. C **94** (2016) 042201(R)/1-6

Baryons

- Critical issues:
  - is there an environment sensitivity of DCSB and the dressed-quark mass function?
  - are quark-quark correlations an essential element in the structure of all baryons?
    - E.g. N*(1535)(1/2)- and N*(1520)(3/2)- must involve unnatural-parity diquarks = pseudoscalar and vector diquarks … Baryons possess far more complex internal structure than nucleon and Δ
- Existing feedback between experiment and theory ⇒ no environment sensitivity for the nucleon, Δ-baryon and Roper resonance:
  - DCSB in these systems is expressed in ways that can readily be predicted once its manifestation is understood in the pion, and this includes the generation of diquark correlations with the same character in each of these baryons.



Epilogue

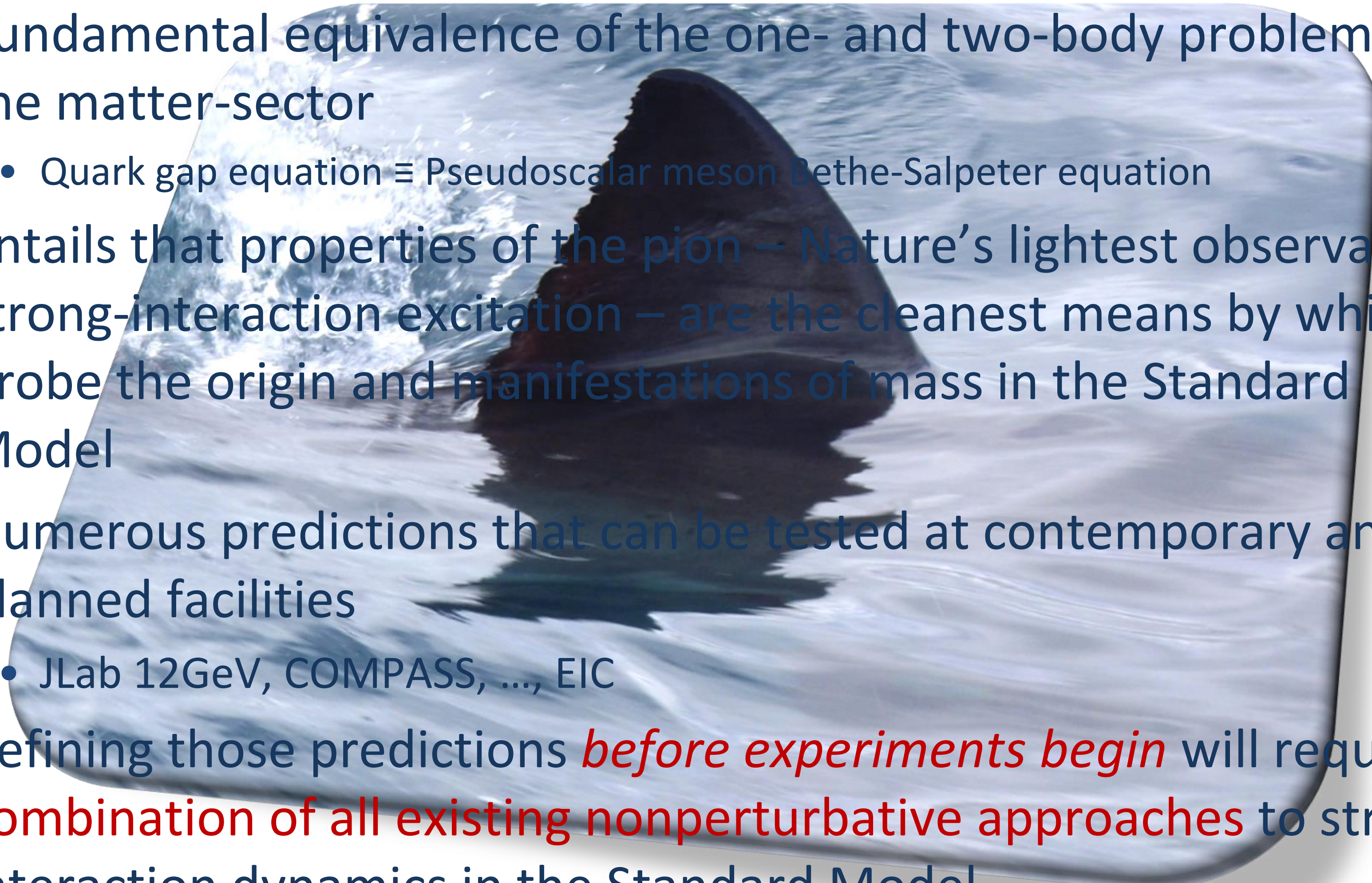
Epilogue

- Emergence:
  - Confinement and dynamical chiral symmetry breaking in the Standard Model
    - How are they related?
      - Role of the pion seems to be key in answering these questions
  - Conformal anomaly
    - Can have neither confinement nor DCSB if scale invariance of (classical) chromodynamics is not broken by quantisation
    - Know a mass-scale must exist, but only experience/experiment informs us of its value
    - Once size known, continuum and lattice-regularised *quantum* chromodynamics ⇒ *gluons and quarks acquire momentum-dependent masses*
      - Values are large in the infrared $m_g \propto 500$ MeV ≈ $m_p/2$ & $M_q \propto 350$ MeV ≈ $m_p/3$
      - Seem to be the foundation for DCSB
      - And can be argued to explain confinement as a dynamical phenomenon, tied to fragmentation functions

Epilogue

- Reductive explanation
  - Fundamental equivalence of the one- and two-body problems in the matter-sector
    - Quark gap equation ≡ Pseudoscalar meson Bethe-Salpeter equation
  - Entails that properties of the pion – Nature's lightest observable strong-interaction excitation – are the cleanest means by which to probe the origin and manifestations of mass in the Standard Model
  - Numerous predictions that can be tested at contemporary and planned facilities
    - JLab 12GeV, COMPASS, …, EIC
  - Refining those predictions *before experiments begin* will require combination of all existing nonperturbative approaches to strong interaction dynamics in the Standard Model

Epilogue



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Students, Postdocs, Profs.

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