Argonne NATIONAL LABORATORY

Exposing the valence-quark structure of the pion and nucleon

Craig Roberts, Physics Division

U.S. DEPARTMENT OF ENERGY

Students, Postdocs, Asst. Profs.

Collaborators: 2012-Present

1. Shi CHAO (Nanjing U) ;
2. Ming-hui DING (PKU);
3. Fei GAO (PKU) ;
4. S. HERNÁNDEZ (U Michoácan);
5. Cédric MEZRAG (CEA, Saclay) ;
6. Khépani RAYA (U Michoácan);
7. Chien-Yeah SENG (UM-Amherst) ;
8. Kun-lun WANG (PKU);
9. Shu-sheng XU (Nanjing U) ;
10. Chen CHEN (USTC);
11. J. Javier COBOS-MARTINEZ (U.Sonora);
12. Mario PITSCHMANN (Vienna);
13. Si-xue QIN (ANL, U. Frankfurt am Main, PKU);
14. Jorge SEGOVIA (Salamanca);
15. David WILSON (ODU);
16. Lei Chang (U. Adelaide) ;
17. Ian Cloet (ANL) ;
18. Bruno El-Bennich (São Paulo);
19. Adnan BASHIR (U Michoácan);
20. Daniele BINOSI (ECT*)
21. Stan BRODSKY (SLAC);
22. Roy HOLT (ANL);
23. G. Krein (São Paulo IFT)
24. Yu-xin LIU (PKU);
25. Hervé MOUTARDE (CEA, Saclay) ;
26. Joannis PAPAVASILLIOU (U.Valencia)
27. Michael RAMSEY-MUSOLF (UM-Amherst) ;
28. Alfredo RAYA (U Michoácan);
29. Jose RODRIGUEZ QINTERO (U. Huelva) ;
30. Sebastian SCHMIDT (IAS-FZJ & JARA);
31. Robert SHROCK (Stony Brook);
32. Peter TANDY (KSU);
33. Tony THOMAS (U.Adelaide) ;
34. Shaolong WAN (USTC) ;
35. Hong-Shi ZONG (Nanjing U)

Key Questions

- What is confinement?
- Where is the mass of the nucleon?
- Where is the nucleon's magnetic moment?
- *What is the nucleon?*
- *What is a hadron?*
- …

Examples of

Emergent Phenomena in QCD,

the strong-interaction sector of

the Standard Model

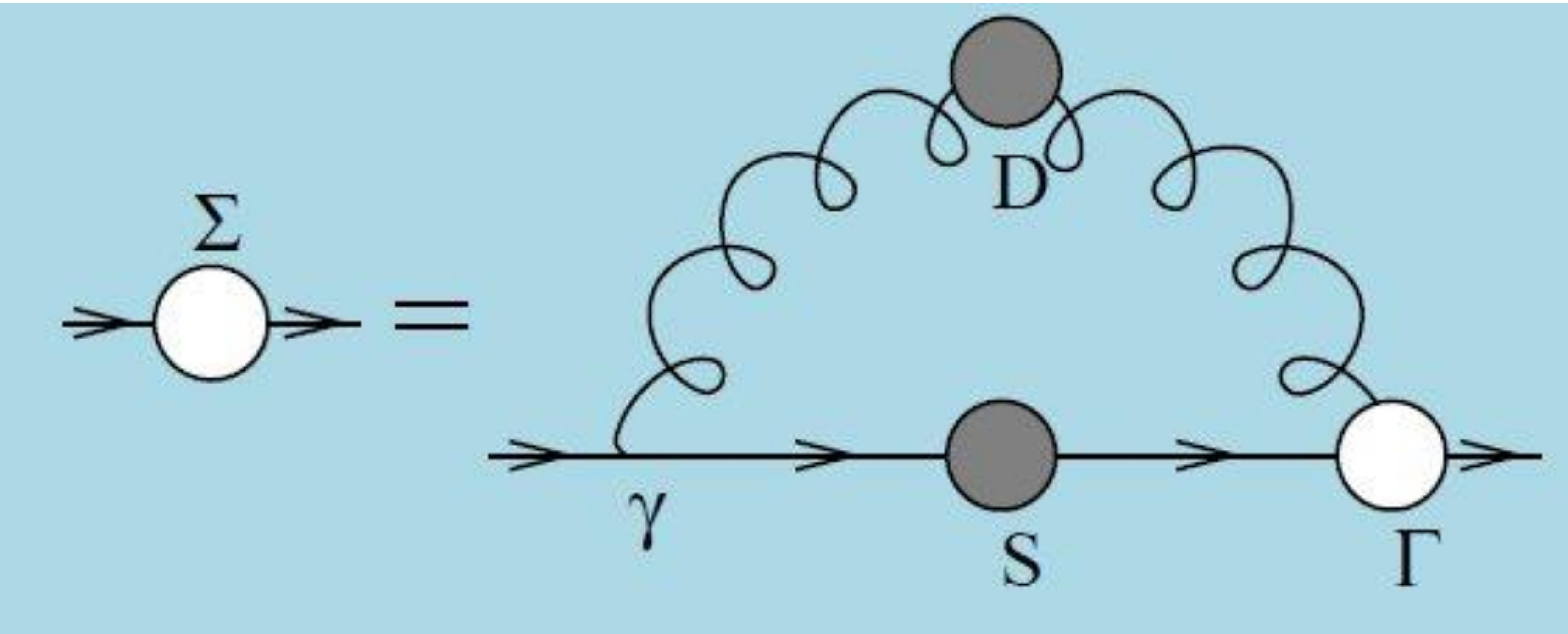
Significant Progress

- Novel understanding of gluon and quark confinement and its consequences is emerging from quantum field theory
- Arriving at a clear picture of how hadron masses emerge dynamically in a universe with light quarks

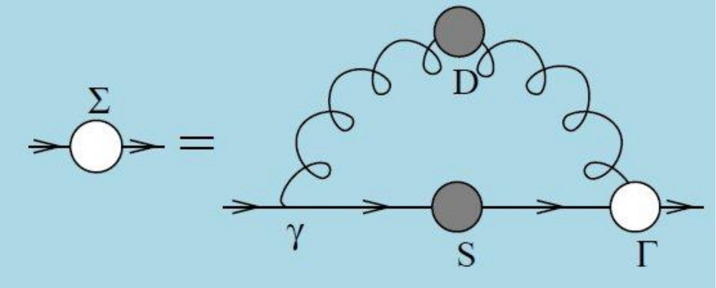
  Dynamical Chiral Symmetry Breaking (DCSB)

- Realistic computations of ground-state hadron wave functions with a direct connection to QCD are now available
  - Quark-quark correlations are crucial in hadron structure
  - Accumulating empirical evidence in support of this prediction

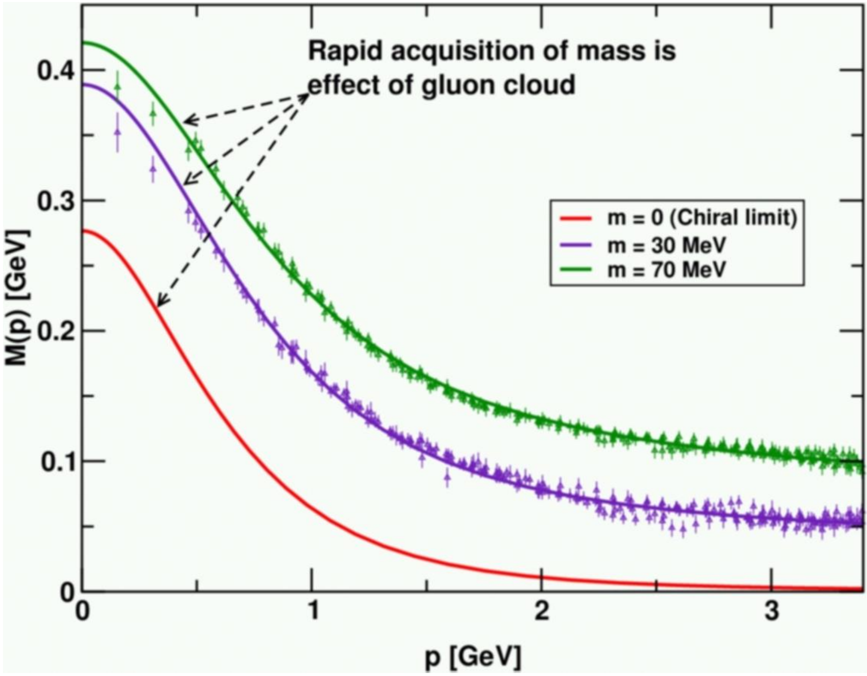
$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$



Quark Gap Equation



Dynamical Chiral Symmetry Breaking



- ***DCSB is a fact in QCD***
  - ***Dynamical***, not spontaneous
    - Add nothing to *QCD* ,

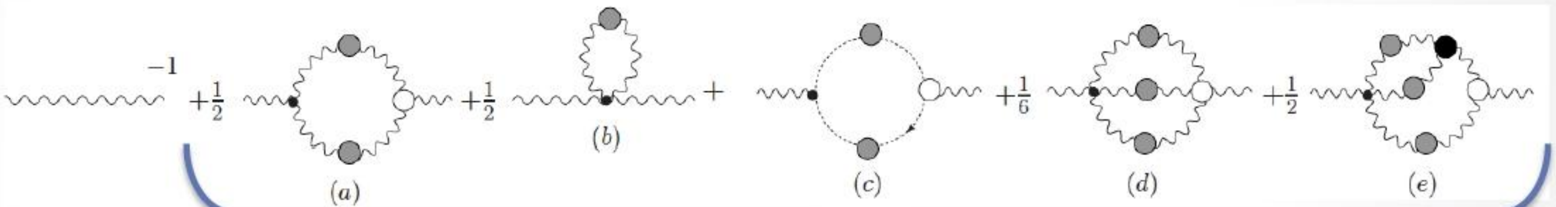
      No Higgs field, nothing!

      Effect achieved purely through quark+gluon dynamics.
  - It's the most important mass generating mechanism for visible matter in the Universe.
    - Responsible for ≈98% of the proton's mass.
    - Higgs mechanism is (*almost*) irrelevant to light-quarks.

Non-perturbative comparison of QCD effective charges, A.C. Aguilar, D. Binosi, J. Papavassiliou and J. Rodriguez-Quintero, Phys. Rev. D80 (2009) 085018

Gluons, too, have a gap equation

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



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

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

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

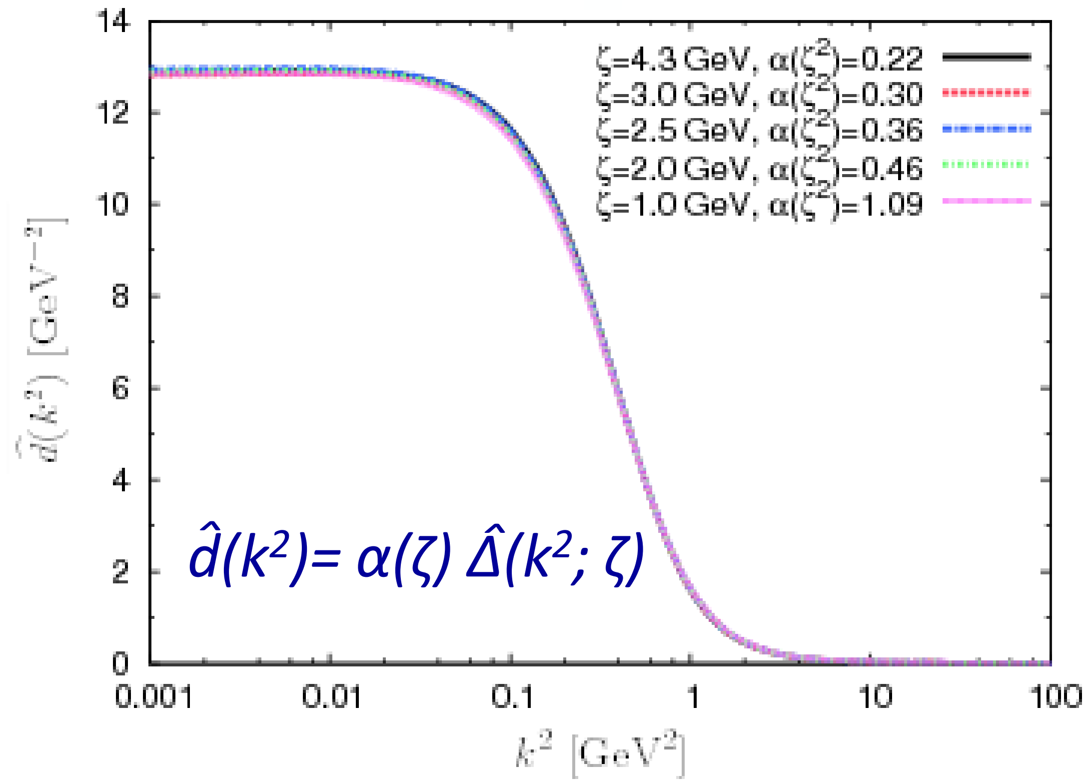
- Pinch-technique + background field method … reordering of diagrammatic summations in the self-energy – $\Pi_{\mu\nu}$ – ensures that subclusters are individually transverse and gluon-loop and ghost-loop contributions are separately transverse
- STIs → WGTIs
- Enables systematic analysis and evaluation of truncations and straightforward comparison of results with those of lQCD

Bridging a gap between continuum-QCD and ab initio predictions of hadron observables, D. Binosi, L. Chang, J.Papavassiliou, C.D. Roberts, arXiv:1412.4782 [nucl-th], Phys. Lett. B742 (2015) 183-188

RGI Running Interaction

- Input to the DSE analysis = lQCD result for the ghost dressing function at a given renormalisation scale, ζ
- Solve ghost gap equation self-consistently such that $\alpha_S(\zeta)$ reproduces lQCD result
- Gluon-ghost vertex in ghost gap equation is computed from its own DSE in the one-loop dressed approximation.
- Continuum- and lattice-QCD solutions agree on solution for the gluon self energy

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



Bridging a gap between continuum-QCD and ab initio predictions of hadron observables, D. Binosi, L. Chang, J.Papavassiliou, C.D. Roberts, arXiv:1412.4782 [nucl-th], Phys. Lett. B742 (2015) 183-188

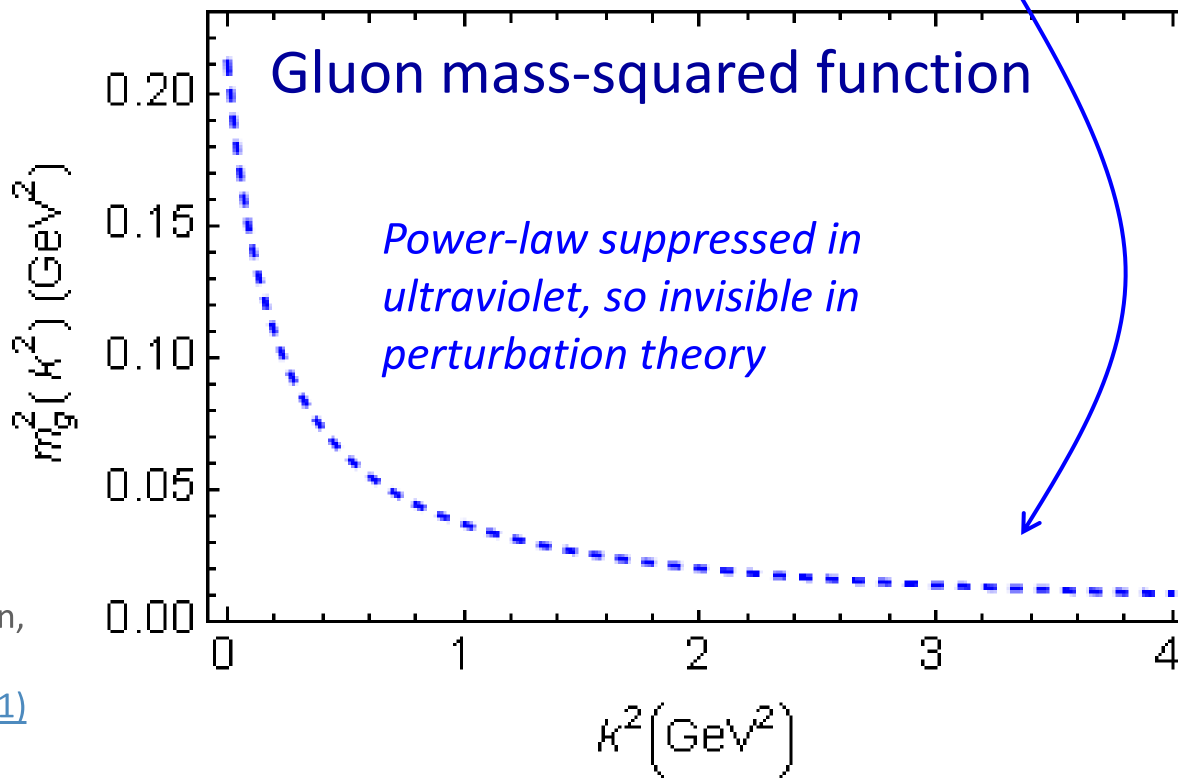
In QCD: Gluons also become massive!

- Running gluon mass

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

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

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



Interaction model for the gap equation, S.-x.Qin, L.Chang, Y-x.Liu, C.D.Roberts and D. J. Wilson, 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
  - Must play a role in gluon saturation ...
    In fact, perhaps it's a harbinger of gluon saturation?

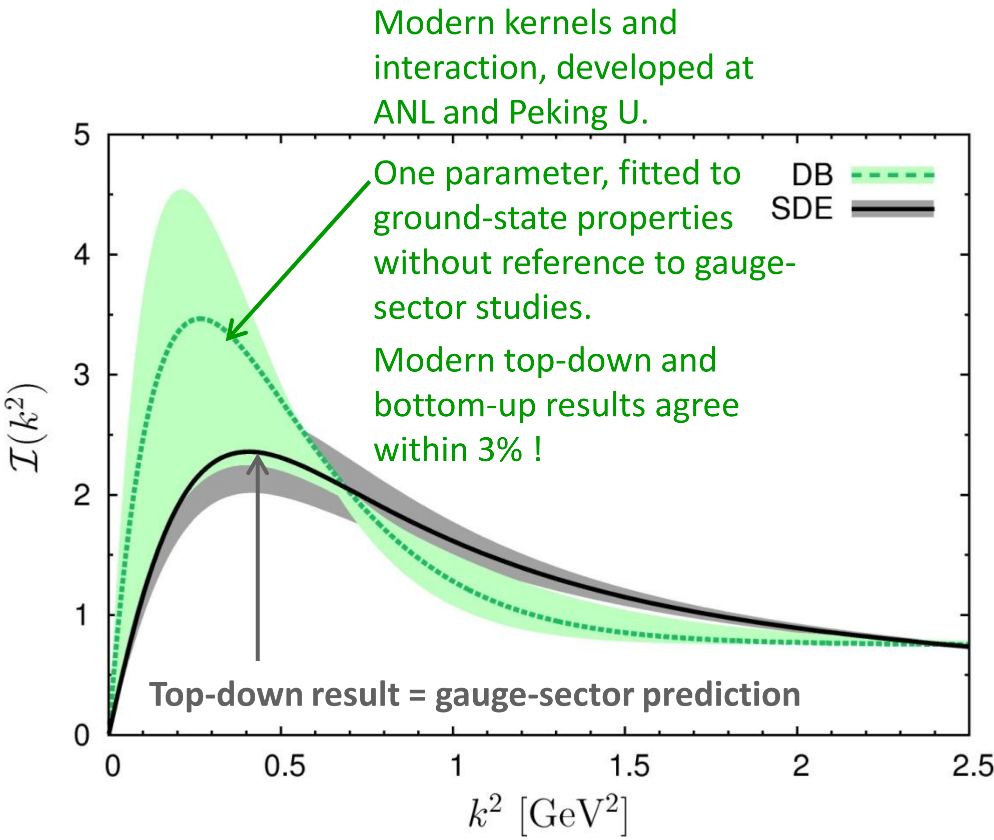
Electron Ion Collider: The Next QCD Frontier

Bridging a gap between continuum-QCD
& ab initio *predictions of hadron observables*

D. Binosi (Italy), L. Chang (Australia), J. Papavassiliou (Spain),
C. D. Roberts (US), arXiv:1412.4782 [nucl-th], *Phys. Lett. B* ***742*** *(2015) 183*

Top down & Bottom up

- *Top-down approach* – ab initio *computation of the interaction via direct analysis of the gauge-sector gap equations*
- *Bottom-up scheme – infer interaction by fitting data within a well-defined truncation of the matter sector DSEs that are relevant to bound-state properties.*
- *Serendipitous collaboration, conceived at one-week ECT* Workshop on* DSEs in Mathematics and Physics*, has united these two approaches*



– Interaction predicted by modern analyses of QCD's gauge sector coincides with that required to describe ground-state observables using the sophisticated matter-sector ANL-PKU DSE truncation

Bridging a gap between continuum-QCD & ab initio *predictions of hadron observables*

D. Binosi (Italy), L. Chang (Australia), J. Papavassiliou (Spain),
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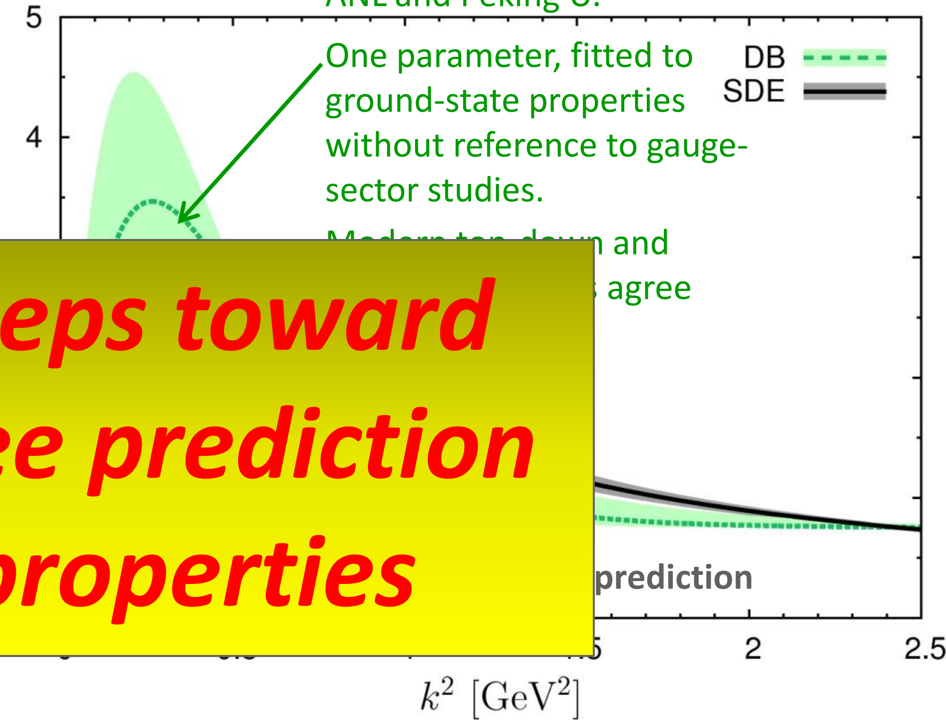
Top down & Bottom up

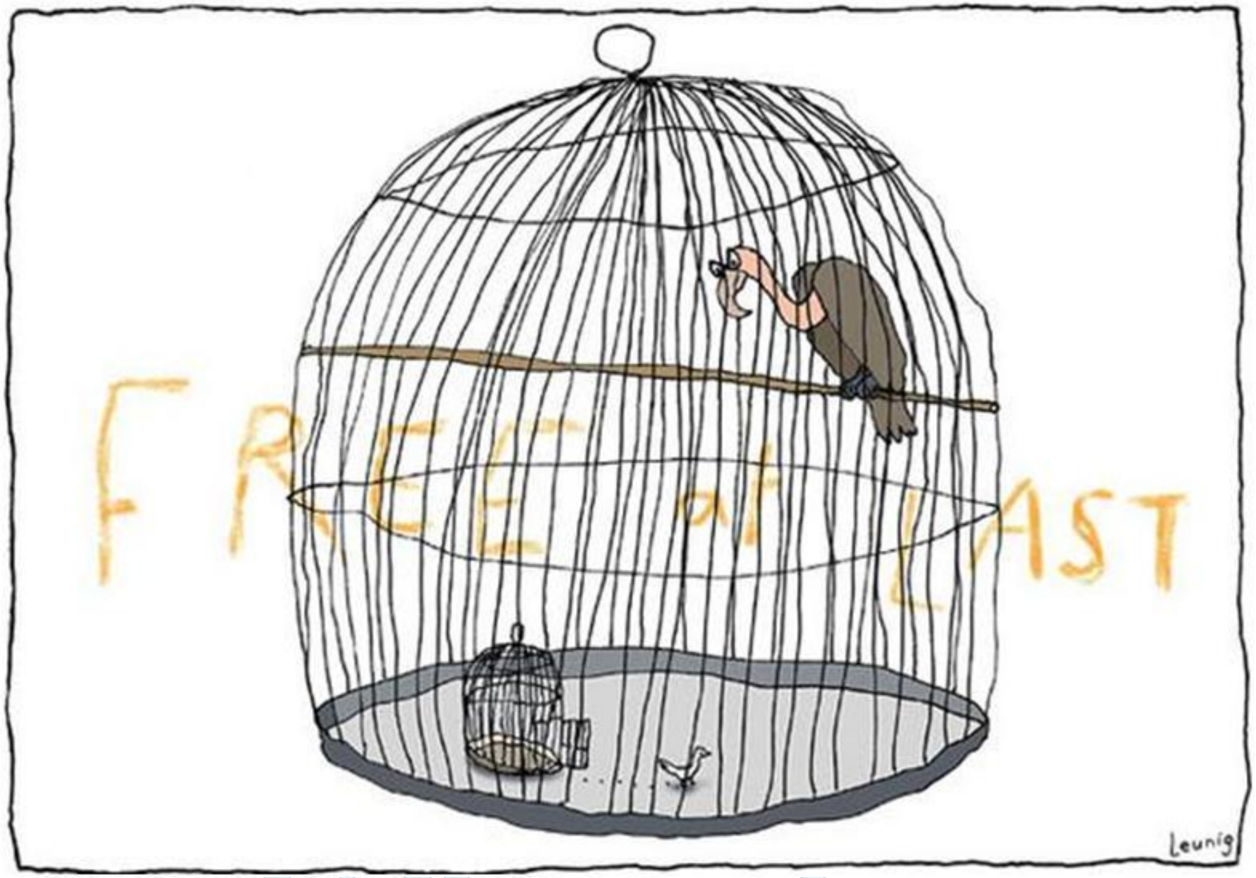
- *Top-down approach* – ab initio *computation of the interaction via direct analysis of the gauge-sector gap equations*
- *Bottom-up scheme – infer interaction by fitting* … *truncation* … *that are r*… *propertie*…
- *Serendipit*… *at one-we*… in Mathematics and Physics, *has united these two approaches*

Modern kernels and interaction, developed at ANL and Peking U.

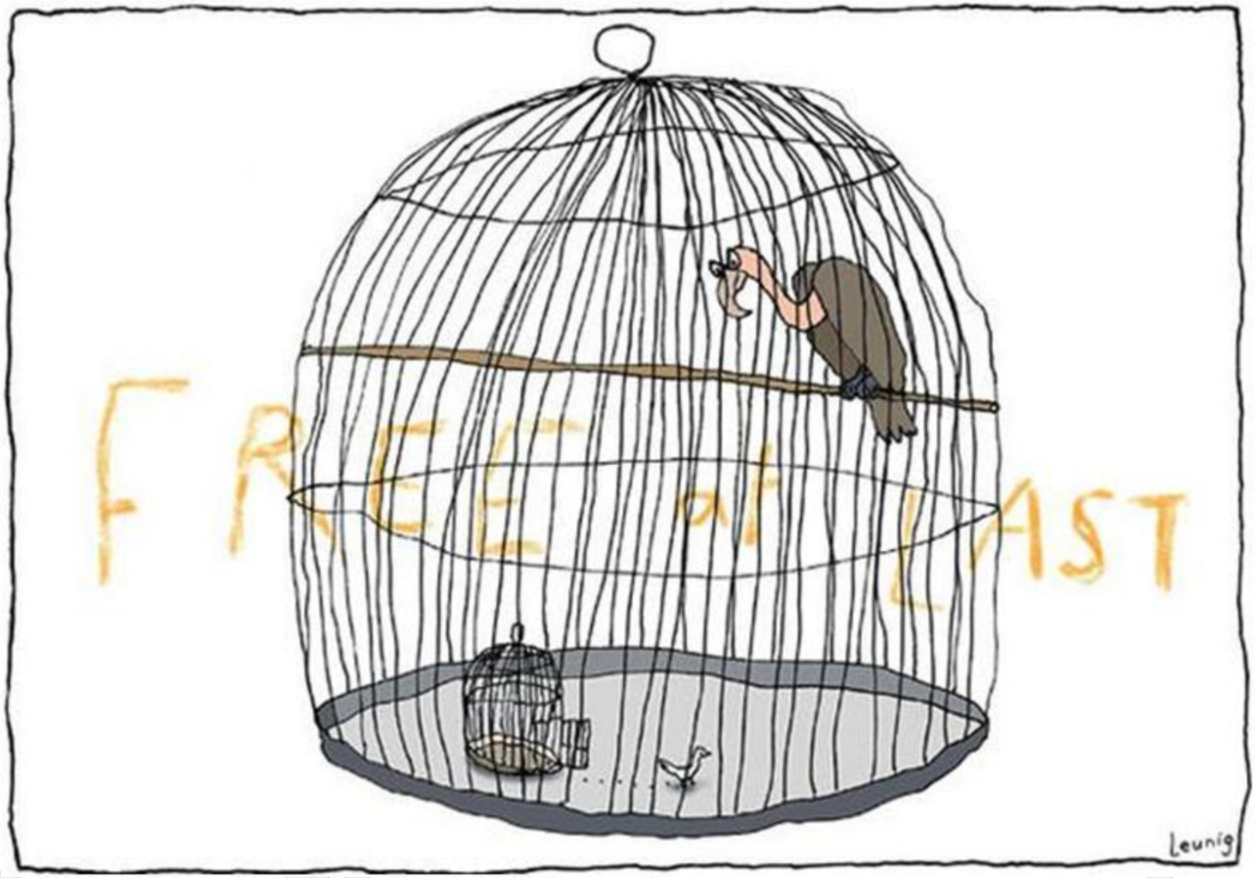


Significant steps toward parameter-free prediction of hadron properties

– Interaction predicted by modern analyses of QCD's gauge sector coincides with that required to describe ground-state observables using the sophisticated matter-sector ANL-PKU DSE truncation



What is Confinement?

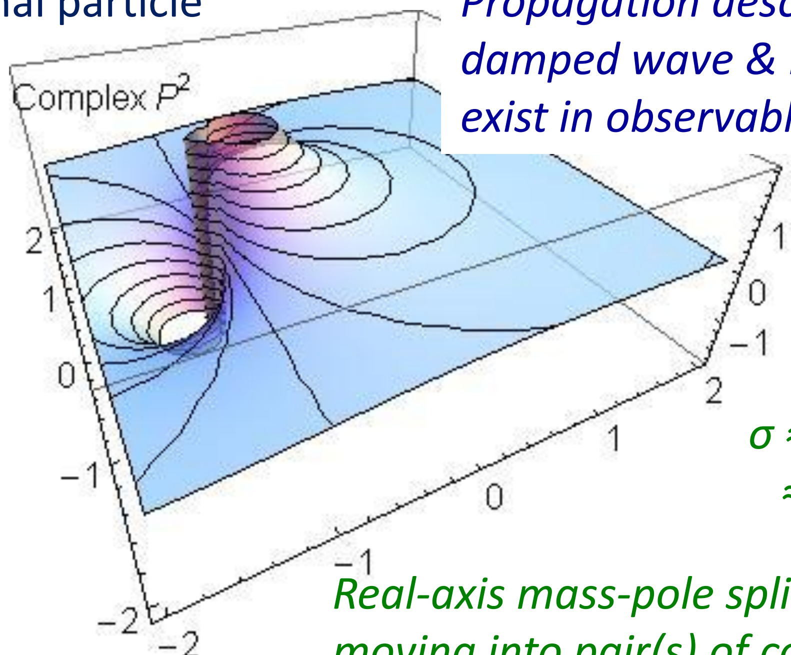


Confinement is dynamical!

Confinement

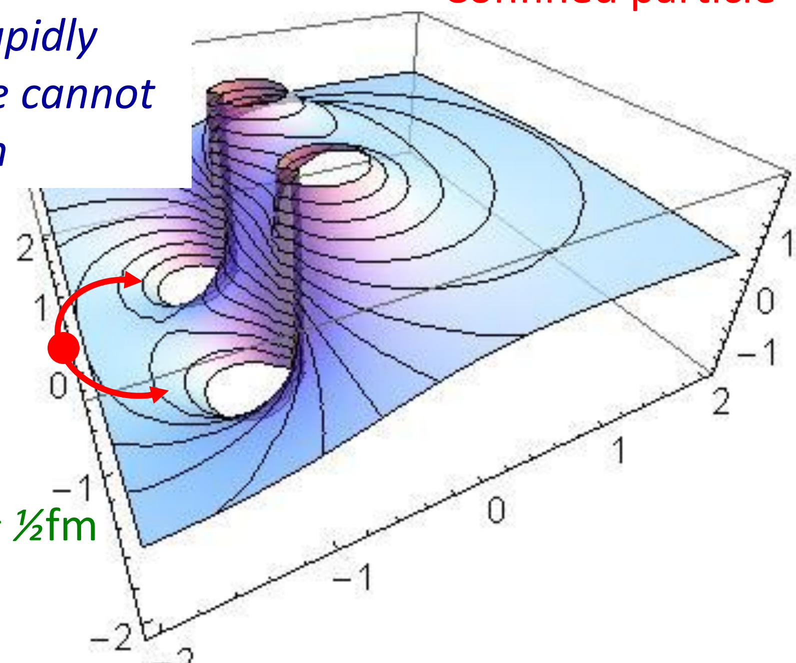
- QFT Paradigm:
  - Confinement is expressed through a *dramatic* change in the analytic structure of propagators for coloured states
  - It can be read from a plot of the dressed-propagator for a coloured state

Normal particle



Propagation described by rapidly damped wave & hence state cannot exist in observable spectrum

Confined particle



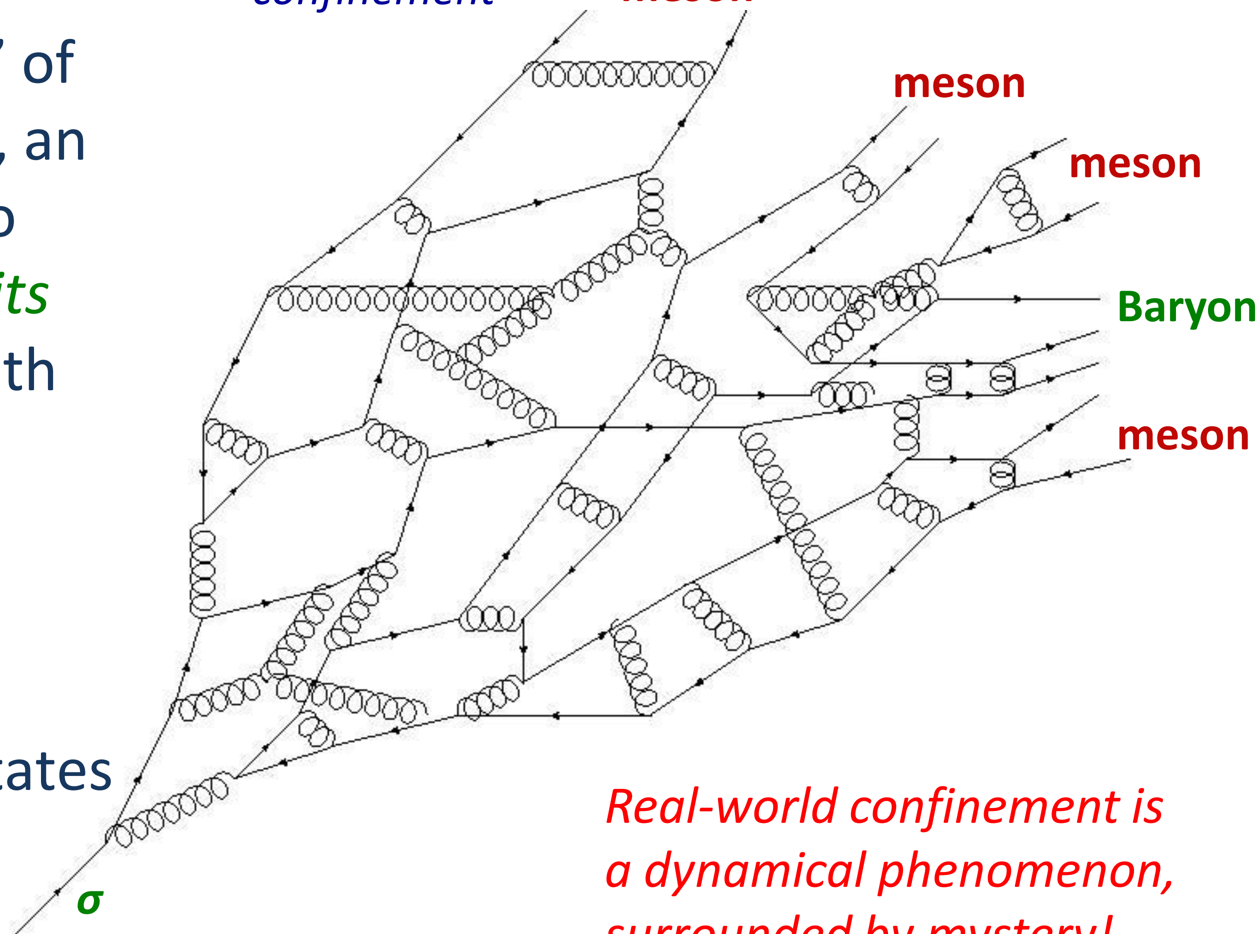
$\sigma \approx 1/Im(m)$
$\approx 1/2\Lambda_{QCD} \approx$ ½fm

Real-axis mass-pole splits,
moving into pair(s) of complex conjugate singularities, (or qualitatively analogous structures chracterised by a dynamically generated mass-scale)

Quark Fragmentation

- A quark begins to propagate in spacetime
- 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

An EIC will enable "3D" measurements relating to fragmentation and insight into real-world confinement



Real-world confinement is a dynamical phenomenon, surrounded by mystery!

Symmetry preserving analyses in continuum QCD

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

- 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**

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

The most fundamental expression of Goldstone's Theorem and DCSB

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

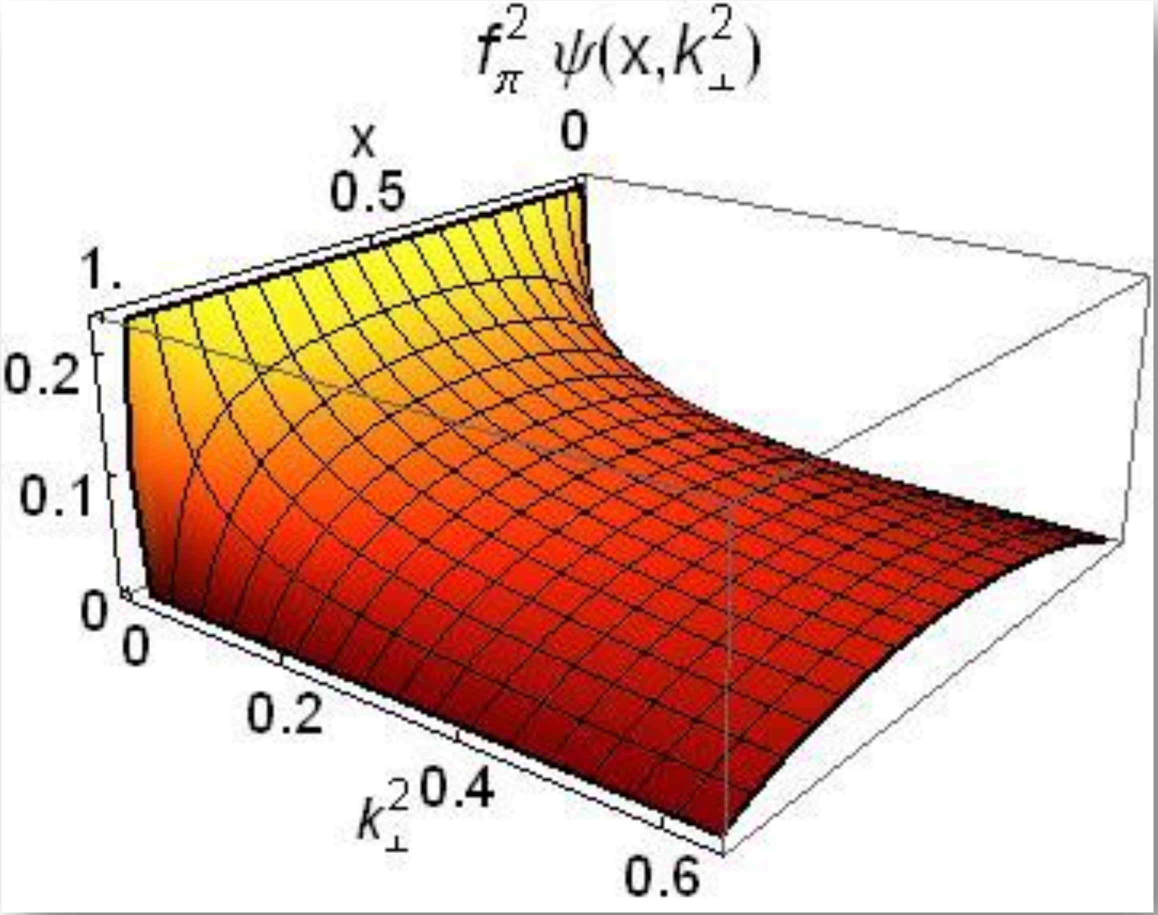
Enigma of mass

This identity is why the 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.



Pion's Wave Function

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

- Last two years, methods have been developed that enable direct computation of meson light-front wave functions
- $\varphi_\pi(x)$ = 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 rainbow-ladder DSE kernel, simplest symmetry preserving form; and the best DCSB-improved kernel that is currently available, which precisely matches gauge sector prediction

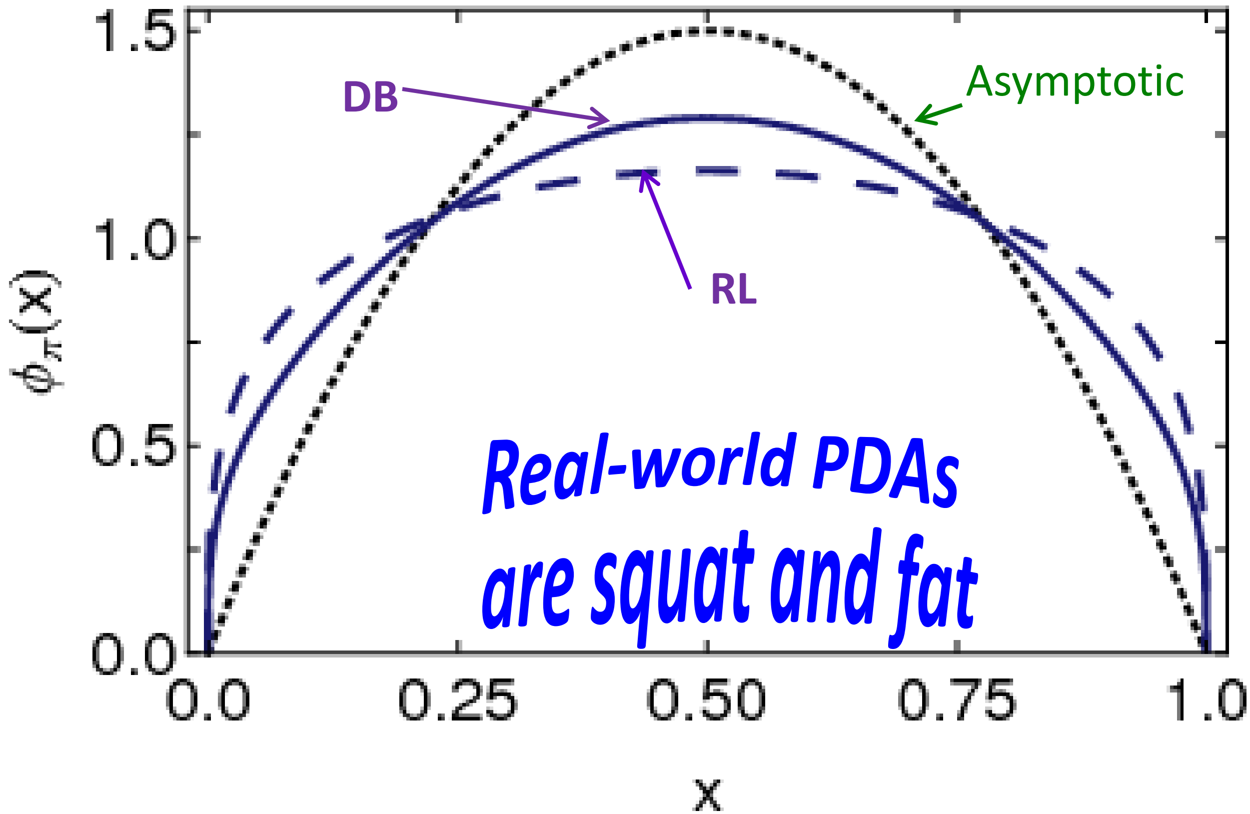
$$x^\alpha (1-x)^\alpha, \text{ with } \alpha \approx 0.5$$

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:

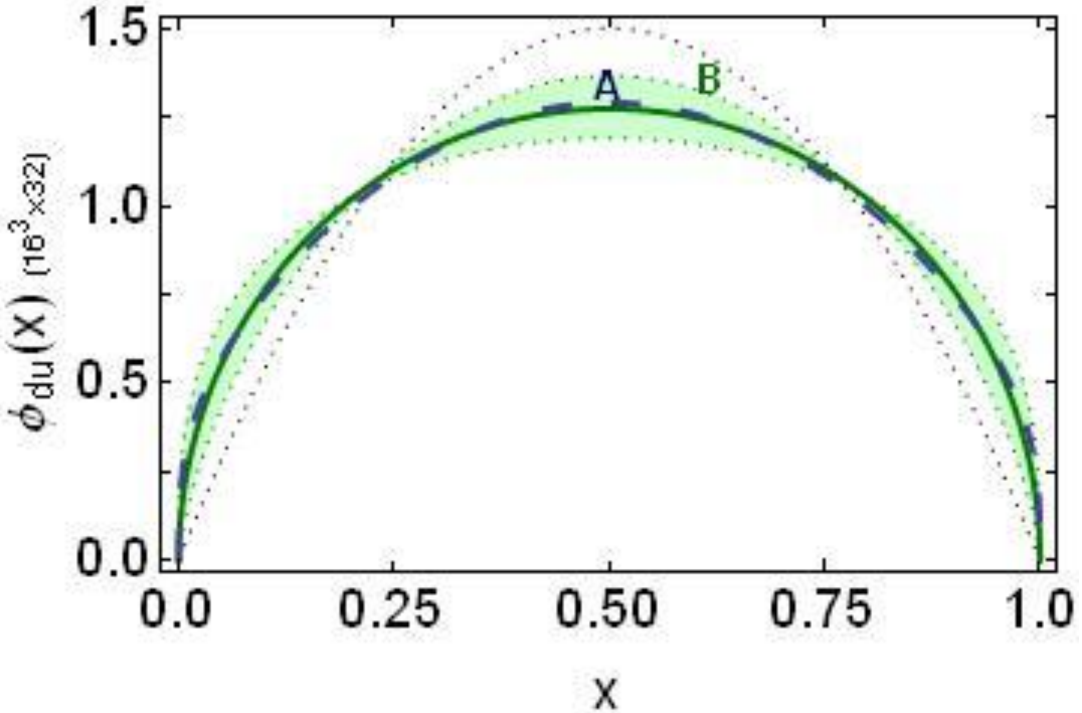
marked broadening of $\varphi_\pi(x)$, which owes to DCSB



Distribution amplitudes of light-quark mesons from lattice QCD,
J. Segovia, *et al.*, arXiv:1311.1390 [nucl-th] , Phys. Lett. B **731** (2014) pp. 13-18

Lattice-QCD & Pion's valence-quark Distribution Amplitude

- Isolated dotted curve = conformal QCD
- Green curve & band = result inferred from the single pion moment computed in lattice-QCD
- Blue dashed curve = DSE prediction obtained with DB kernel
- Precise agreement between DSE prediction & informed analysis of lQCD result



Explanation and Prediction of Observables using Continuum Strong QCD, Ian C. Cloët and Craig D. Roberts, arXiv:1310.2651 [nucl-th], Prog. Part. Nucl. Phys. **77** (2014) pp. 1–69 [on-line]

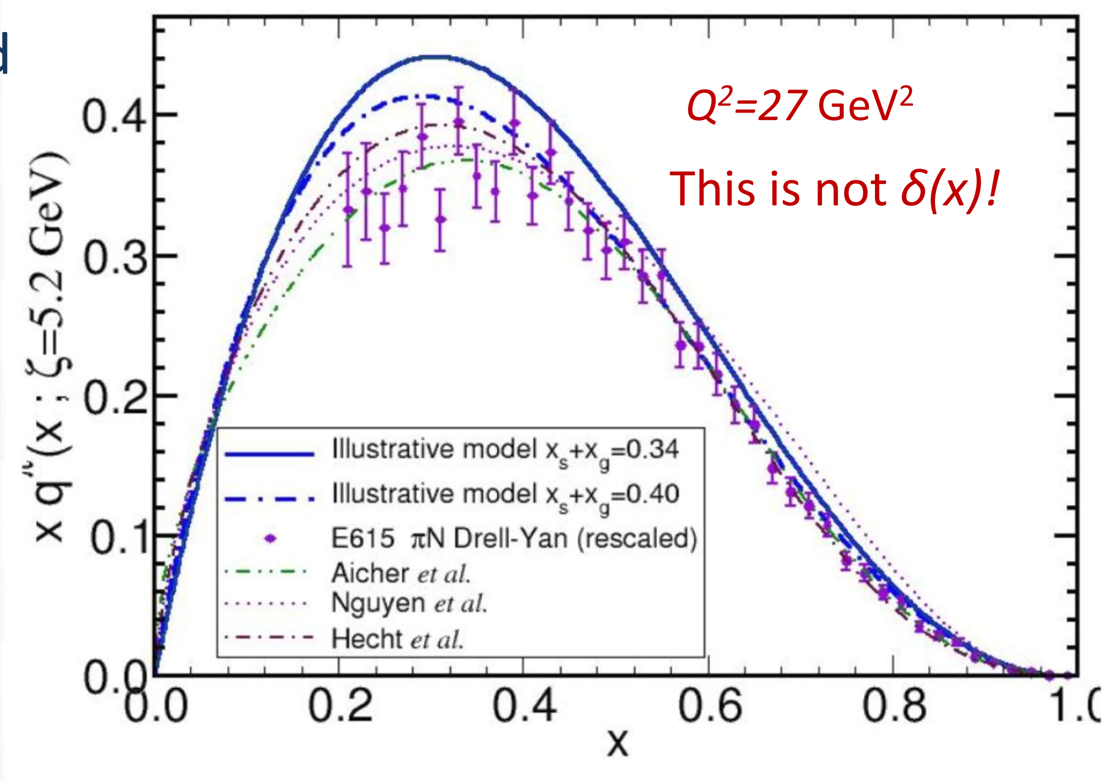
When is asymptotic PDA valid?

- PDA is a wave function
  ∴ not directly observable
  but PDF is.
- $\varphi_\pi^{asy}(x)$ can only be a good approximation to the pion's PDA when it is accurate to write

$$u_v^\pi(x) \approx \delta(x)$$

  for the pion's valence-quark distribution function.
- This is far from valid at currently accessible scales

Basic features of the pion valence-quark distribution function, L. Chang et al., Phys. Lett. B 737 (2014) pp. 23–29



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When is asymptotic PDA valid?

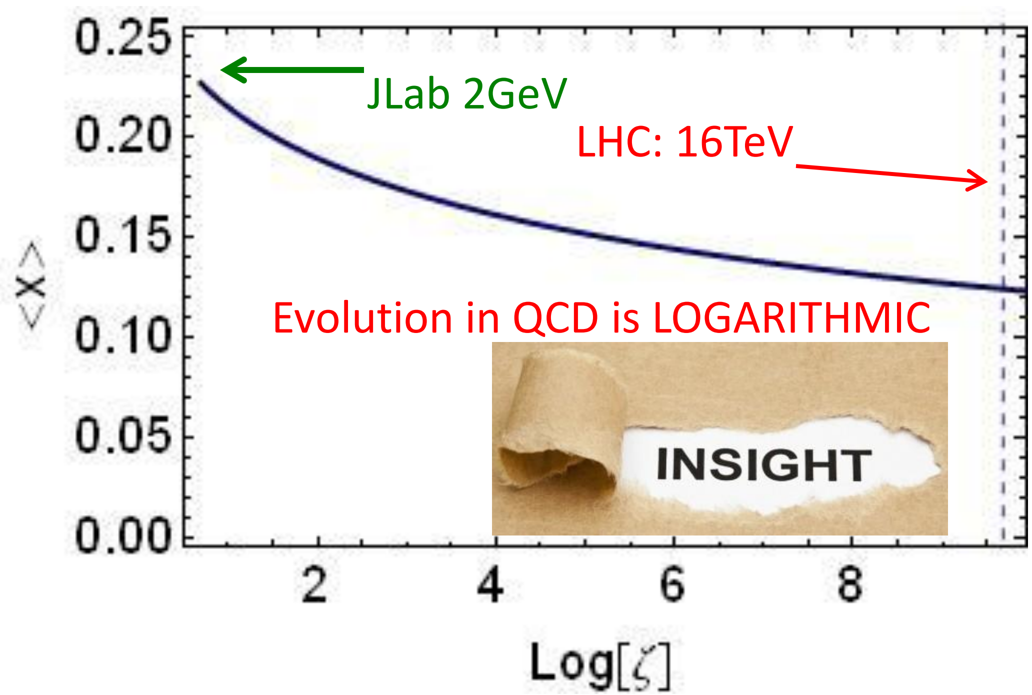
- When is asymptopia reached?
- If $u_v^\pi(x) \approx \delta(x)$, then

  $$<x> = \int_0^1 dx\, x\, u_v^\pi(x) = 0;$$

  i.e., the light-front momentum fraction carried by valence-quarks is ZERO

  ∴ Asymptopia is reached when $<x>$ is "small"
- As usual, the computed valence-quark distribution produces ($\pi = u+d_{bar}$)

  $$2<x>_{2GeV} = 44\%$$
- When is $<x>$ small?



- NLO evolution of PDF, computation of $<x>$.
- Even at LHC energies, light-front fraction of the π momentum:

  $<x>_{\text{dressed valence-quarks}} = 21\%$

  $<x>_{\text{glue}} = 54\%$, $<x>_{\text{sea-quarks}} = 25\%$

Lepage & Brodsky, Phys. Lett. B **87** (1979) 359-365;
Phys. Rev. D **22** (1980) 2157-2198.
Efremov & Radyushkin, Phys. Lett. B **94** (1980) 245-250

PDAs & Hard Exclusive Processes

- In the theory of strong interactions, the cross-sections for many *hard* exclusive hadronic reactions can be expressed in terms of the PDAs of the hadrons involved
- Example: pseudoscalar-meson elastic electromagnetic form factor

$$\exists Q_0 > \Lambda_{QCD} \,|\, Q^2 F_P(Q^2) \overset{Q^2>Q_0^2}{\approx} 16\pi\alpha_s(Q^2) f_P^2 w_\varphi^2,$$

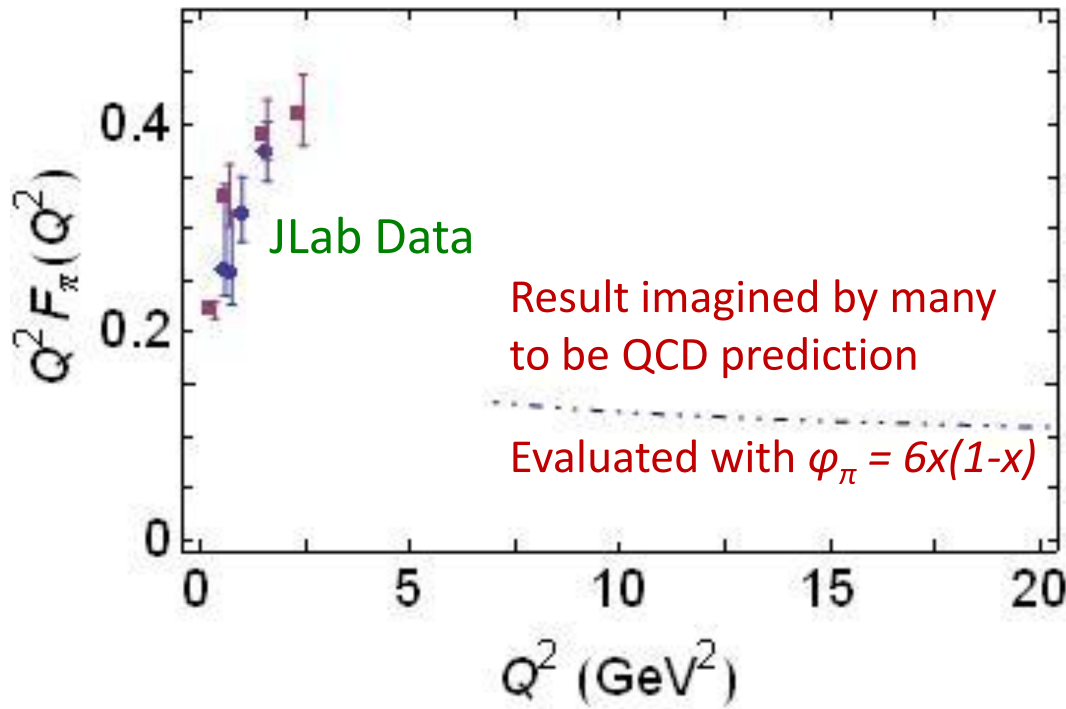
$$w_\varphi = \frac{1}{3}\int_0^1 dx\, \frac{1}{x}\varphi^P(x),$$

- $\alpha_S(Q^2)$ is the strong running coupling,
- $\varphi_\pi(u)$ is the meson's twist-two valence-quark PDA
- f_P is the meson's leptonic decay constant

It was promised that JLab would verify this fundamental prediction

Pion electromagnetic form factor

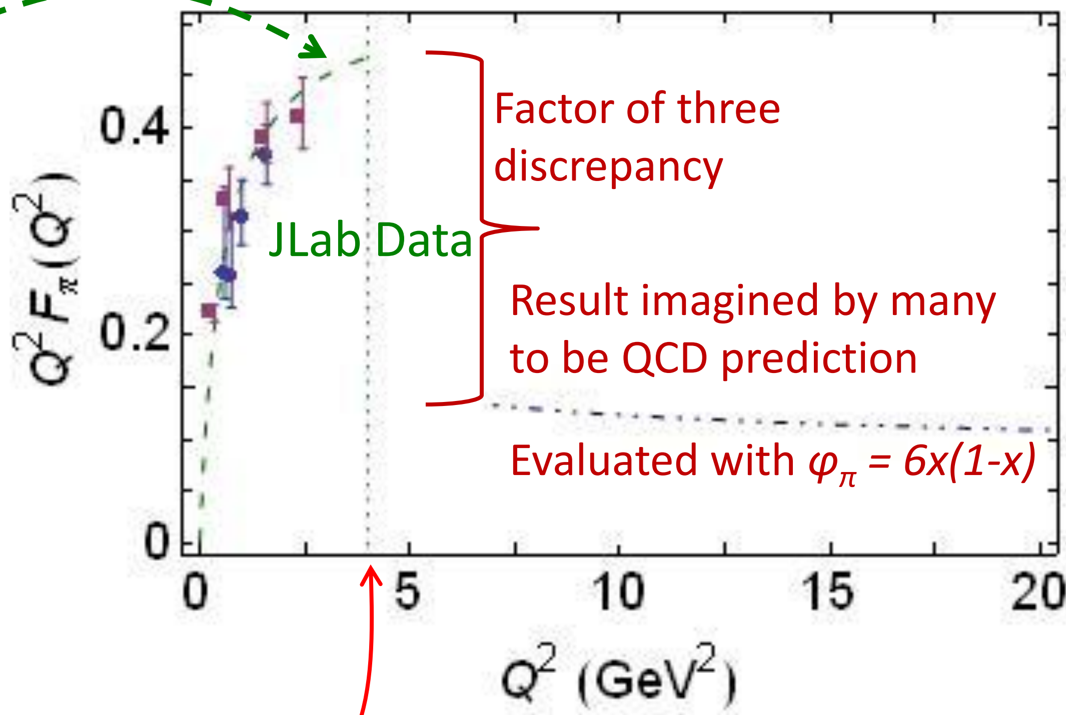
- In 2001 – seven years after beginning operations, Jefferson Lab provided the first high precision pion electroproduction data for F_π between Q^2 values of 0.6 and 1.6 (GeV/c)^2.



- 2006 & 2007 – new result, at $Q^2=2.45$ (GeV/c)^2
- Authors of the publications stated: "still far from the transition to the Q^2 region where the pion looks like a simple quark-antiquark pair"
  - disappointment and surprise

Pion electromagnetic form factor

- Year 2000 *prediction* for $F_\pi(Q^2)$
  - *P.Maris & P.C. Tandy, Phys.Rev. C62 (2000) 055204*
- Problem … used brute-force computational method … unable to compute for Q^2>4GeV^2

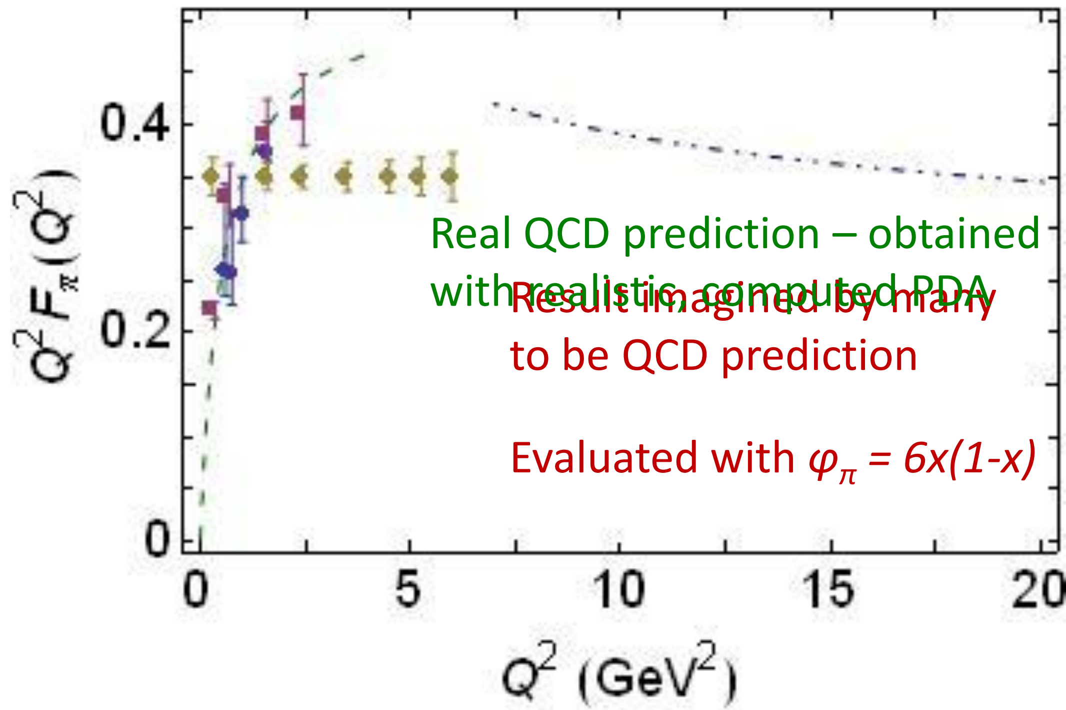


- Shape of prediction suggested to many that one might *never* see parton model scaling and QCD scaling violations

New Algorithm
New Insights

Pion electromagnetic form factor

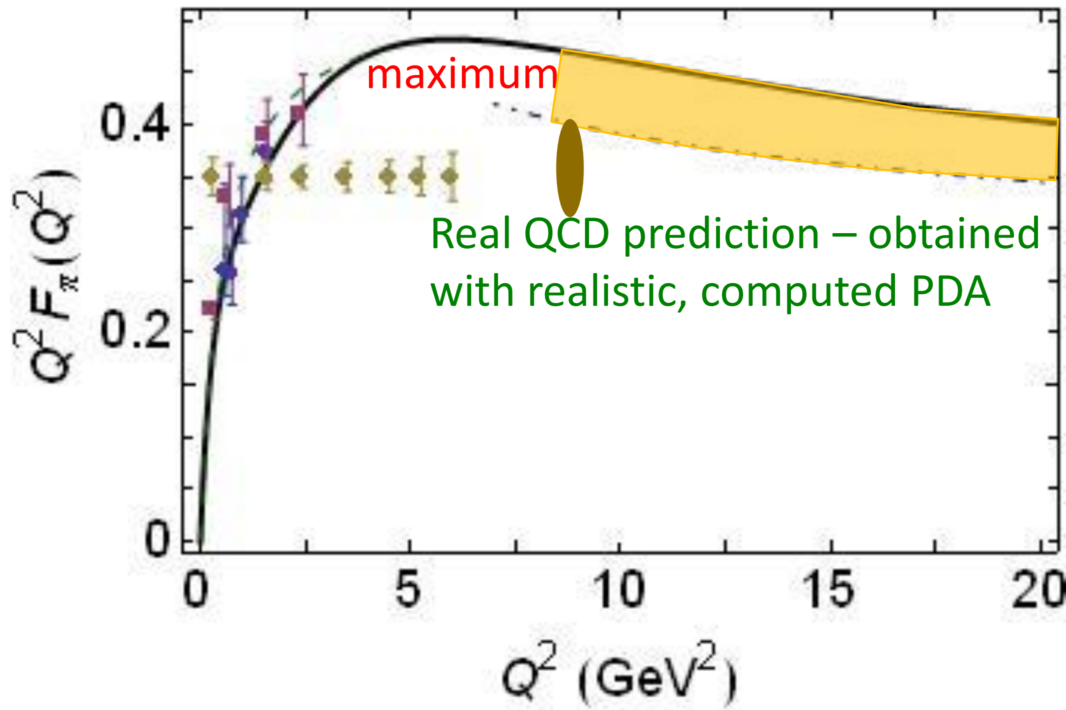
- Solution – Part 1
  - Compare data with the real QCD prediction; i.e. the result calculated using the broad pion PDA predicted by modern analyses of continuum QCD



Pion electromagnetic form factor

- Solution – Part 1
  - Compare data with the real QCD prediction; i.e. the result calculated using the broad pion PDA predicted by modern analyses of continuum QCD
- Solution – Part 2
  - Algorithm used to compute the PDA can also be employed to compute $F_\pi(Q^2)$ directly, to arbitrarily large Q^2

Agreement within 15%

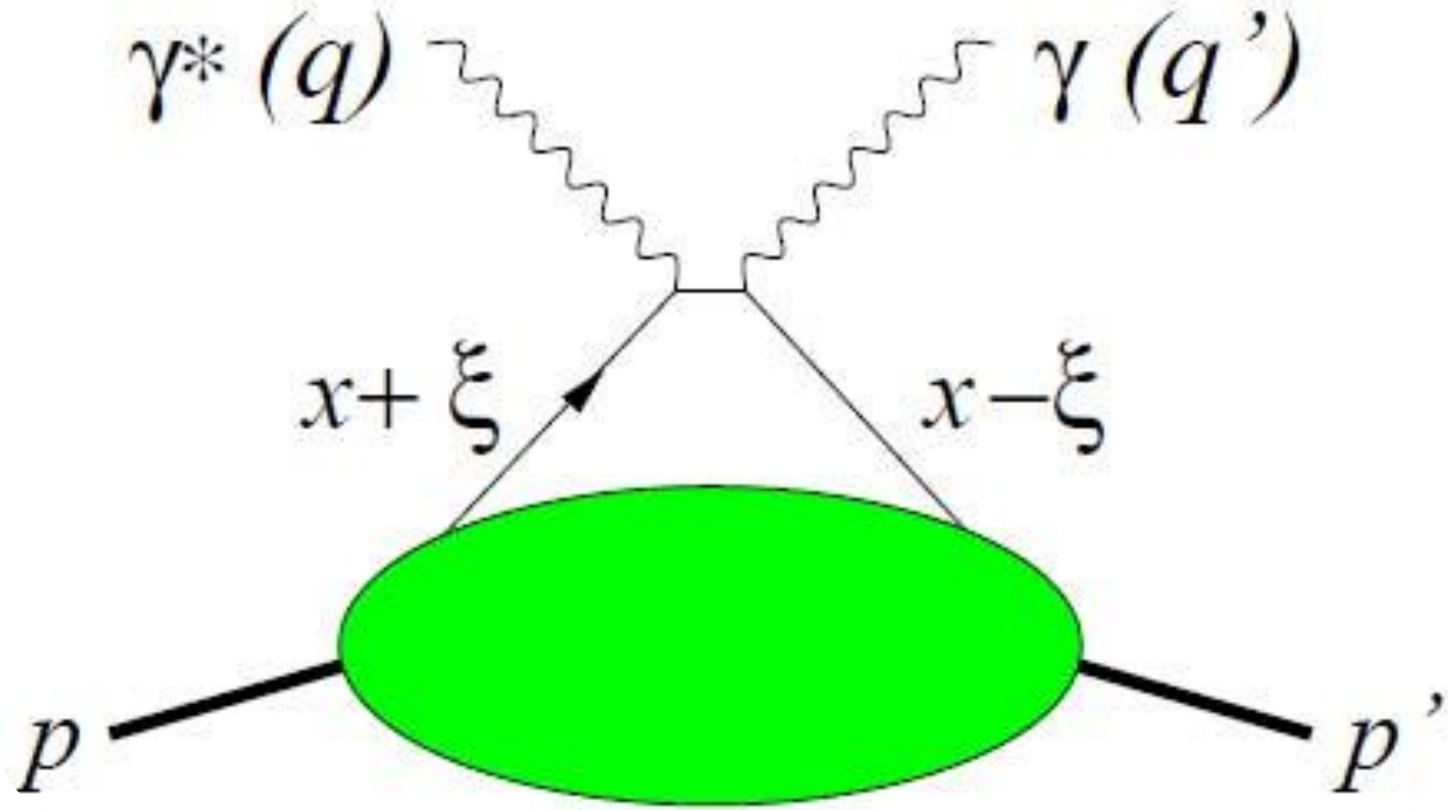


- Predictions:
  - JLab will see maximum
  - Experiments to 8GeV^2 will see parton model scaling and QCD scaling violations for the *first time* in a hadron form factor

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)

Implications

- Verify the theory of factorisation in hard exclusive processes, with dominance of hard contributions to the pion form factor for $Q^2>8$GeV^2.
- Notwithstanding that, normalisation of $F_\pi(Q^2)$ is fixed by a pion wave-function whose dilation with respect to $\varphi_\pi^{asy}(x)=6x(1-x)$ is a definitive signature of DCSB
  - ***Empirical measurement of the strength of DCSB in the Standard Model – the origin of visible mass***
- Paves the way for a dramatic reassessment of pictures of proton & neutron structure, which is already well underway



GPDs & TMDs

GPDs - unify & extend

- GPDs unify PDFs and elastic form factors, and extend both into a new domain

Returning to the definition in Eq. (2), it is plain that if one considers the forward limit: $\xi = 0, t = 0$, then x is Bjorken-x and the GPD reduces to a PDF; viz.,

$$H_\pi^q(x,0,0) = \begin{cases} q^\pi(x), & x > 0 \\ -\bar{q}^\pi(-x), & x < 0 \end{cases} . \tag{5}$$

Moreover, irrespective of the value of ξ, the electromagnetic pion form factor may be computed as

$$F_{\pi^+}(\Delta^2) = \int_{-1}^{1} dx \, [e_u H_{\pi^+}^u(x,\xi,-\Delta^2) + e_d H_{\pi^+}^d(x,\xi,-\Delta^2)] \tag{6}$$

$$=: e_u F_{\pi^+}^u(\Delta^2) + e_d F_{\pi^+}^d(\Delta^2) = F_{\pi^+}^u(\Delta^2)\,, \tag{7}$$

where $e_{u,d}$ are the quark electric charges in units of the positron charge and we have used Eq. (3) to show $F_{\pi^+}^d(\Delta^2) = -F_{\pi^+}^u(\Delta^2)$.

GPDs & TMDs

- Principal problem with phenomenology
  - If one wishes to use measured GPDs as a means by which to validate our basic perception of strong interactions in the Standard Model, then data fitting is inadequate.
- Instead, it is necessary to *compute* GPDs using a framework that possesses a direct connection with QCD.
- This observation is highlighted by experience drawn from the simpler case of the pion's valence-quark PDF (L. Chang *et al.*, Phys. Lett. B 737 (2014) pp. 23–29)
  - Data-based phenomenology contradicted QCD predictions
  - Many claimed QCD was challenged
  - Until nonperturbative continuum-QCD predictions appeared …
  - Data reanalysed … now the PDF is seen as a success for QCD

Pion *valence* -quark GPD

- GPD in impact parameter space:

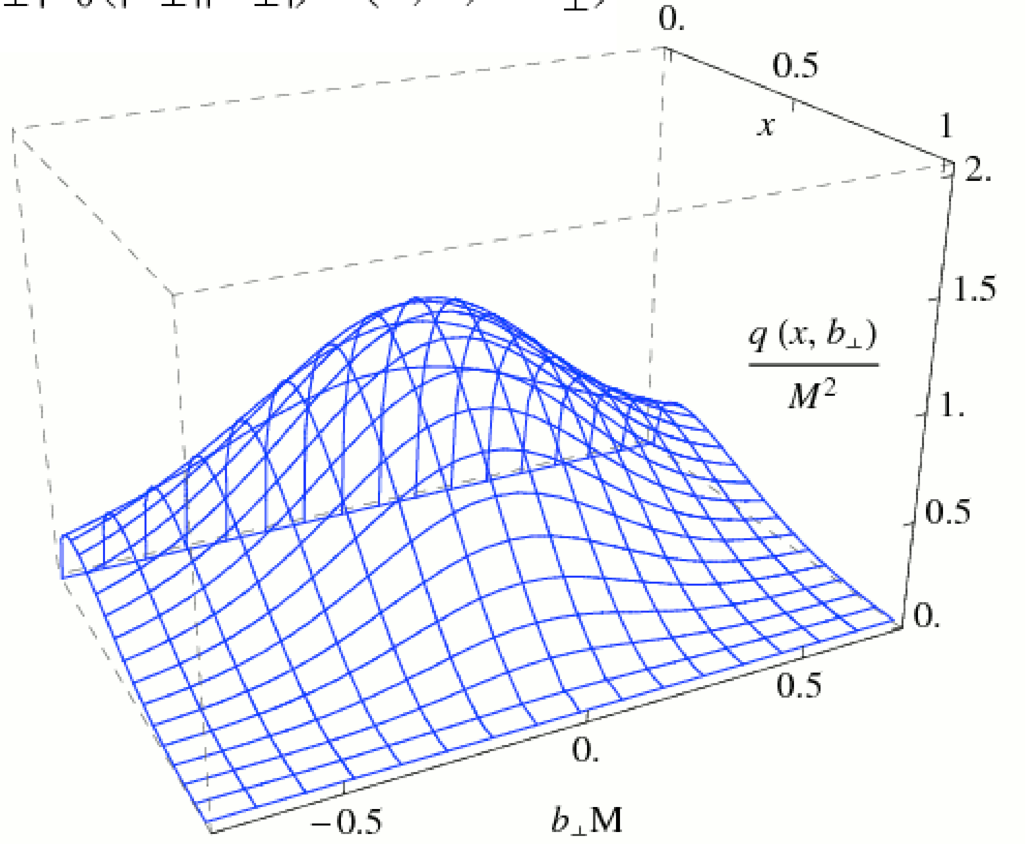
$$q_\pi(x, |\vec{b}_\perp|) = \int \frac{d|\Delta_\perp|}{2\pi} |\Delta_\perp| J_0(|\vec{b}_\perp||\vec{\Delta}_\perp|) H(x, 0, -\Delta_\perp^2)$$

- A true quantum mechanics density …

  … describes the probability of finding a parton within the light-front at a transverse position $|b_{perp}|$ from the hadron's centre of transverse momentum (CoTM)

- Computed result …

  … not a guess



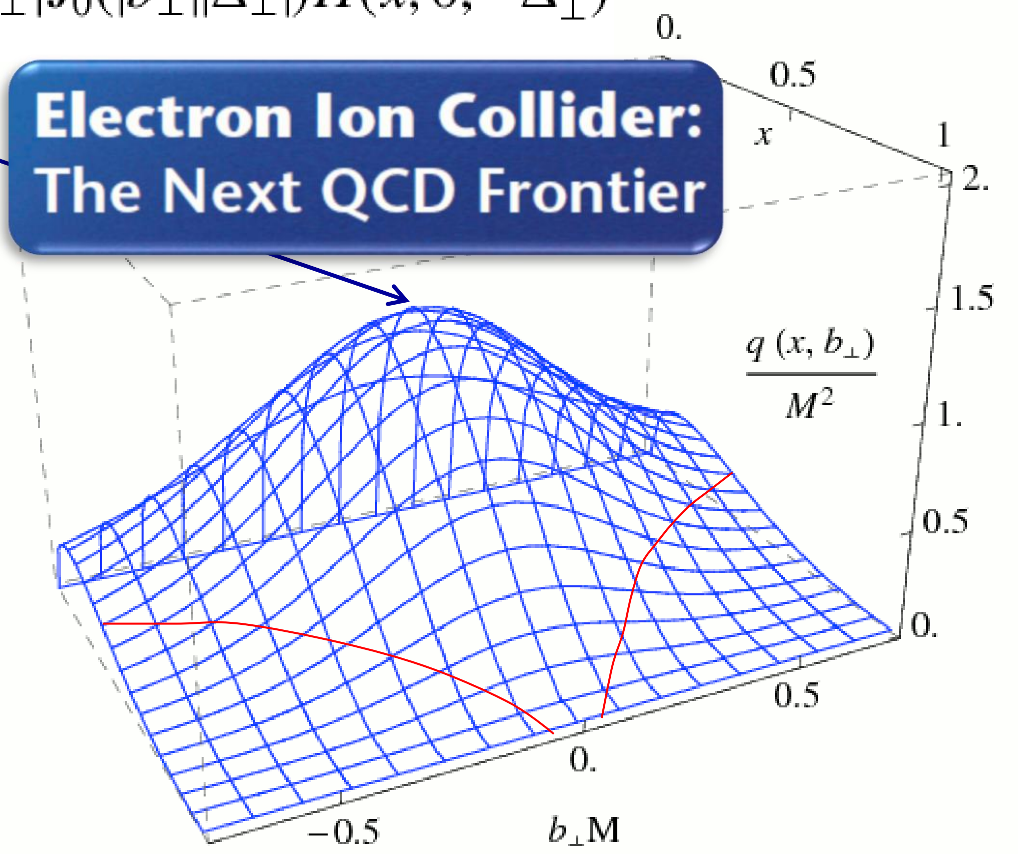
Sketching the pion's valence-quark generalised parton distribution,
C. Mezrag et al., arXiv:1411.6634 [nucl-th], PLB 741 (2015) pp. 190–196

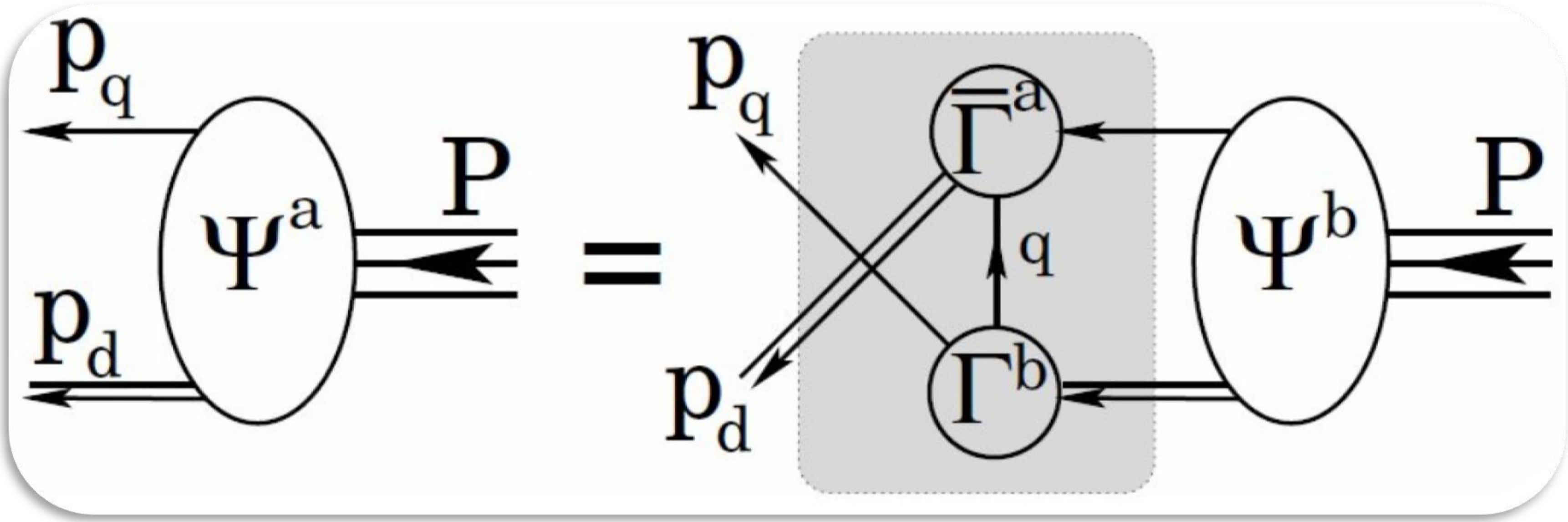
Pion *valence* -quark GPD

- GPD in impact parameter space:

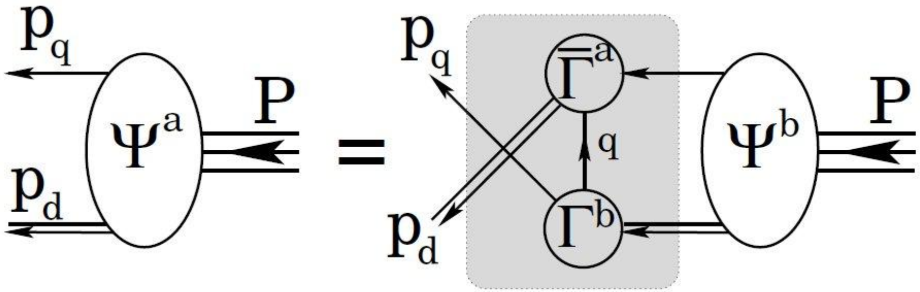
$$q_\pi(x, |\vec{b}_\perp|) = \int \frac{d|\Delta_\perp|}{2\pi} |\Delta_\perp| J_0(|\vec{b}_\perp||\vec{\Delta}_\perp|) H(x, 0, -\Delta_\perp^2)$$

- Peaked at *(x_V^m, $|b_{perp}|=0$)* … peak becomes sharper as resolving scale, ζ, increases
- Broad at *$|b_{perp}| = 0$,* becomes even broader as ζ increases
- Narrowing as x → 1 … *increasing ζ: x_V^m* → 0; GPD becomes even narrower … there can't be many partons carrying x≃1; i.e., all the hadron's light-front momentum



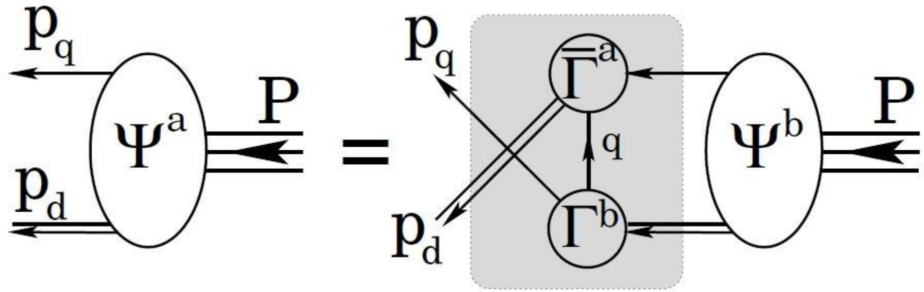


Baryon Bound-States



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***: *strong diquark correlations exist within baryons as a dynamical consequence of DCSB in QCD*
  - The same mechanism that produces an almost massless pion from two dynamically-massive quarks forces a strong correlation between two quarks in colour-antitriplet channels within a baryon
- Diquark correlations are not pointlike
  - Typically, $r_{0+} \sim r_\pi$ & $r_{1+} \sim r_\rho$ (actually 10% larger)
  - They have soft form factors



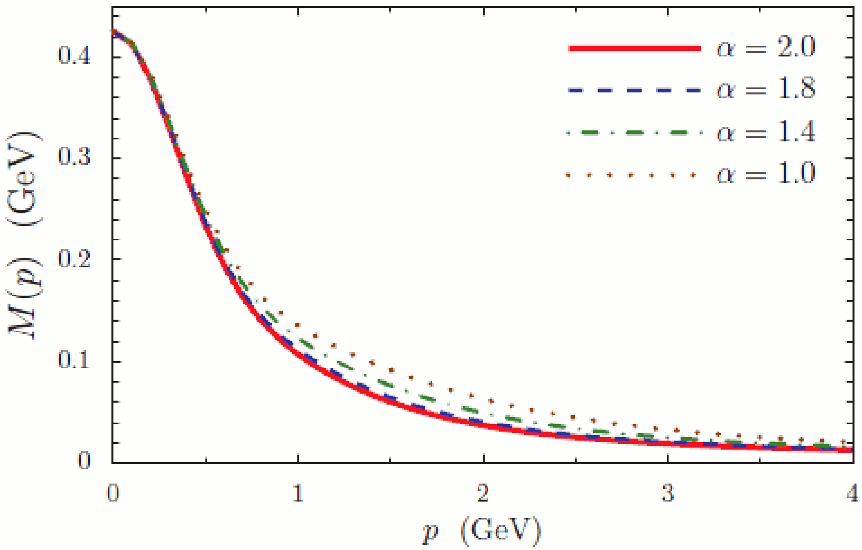
Baryon Structure

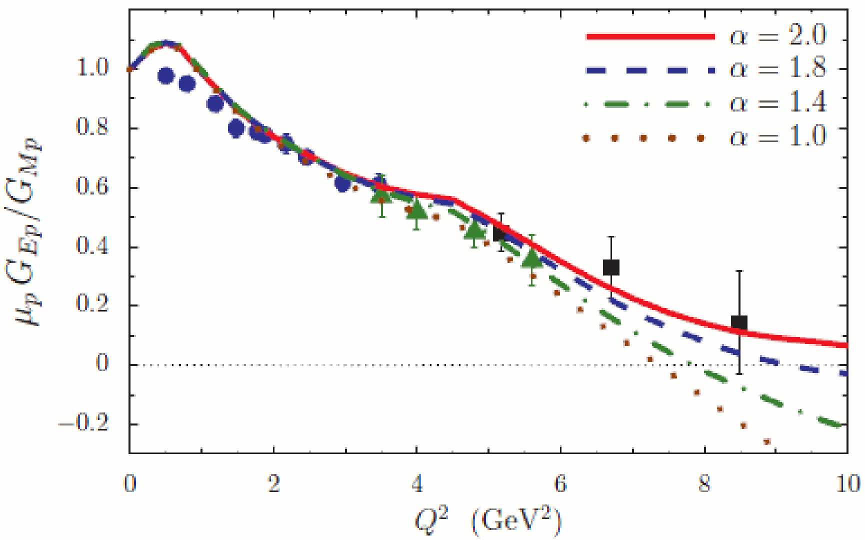
Nucleon wave function can be calculated ... prediction of nucleon properties is possible

- ... covariant Faddeev equation sums all possible ... interactions that can take place between three ...
- Con... readily expressed
- ***Prediction***: ... tions exist within baryons as ...
  - ...nism th... ssless pion from ... massive qua... tion ... rks in colour-antit... aryon
  - ...s are not pointlike
  - ... & $r_{1+} \sim r_\rho$ (actually 10% large...
  - They have soft form factors

I.C. Cloët, C.D. Roberts, A.W. Thomas: Revealing dressed-quarks via the proton's charge distribution, arXiv:1304.0855 [nucl-th], Phys. Rev. Lett. **111** (2013) 101803

Visible Impacts of DCSB



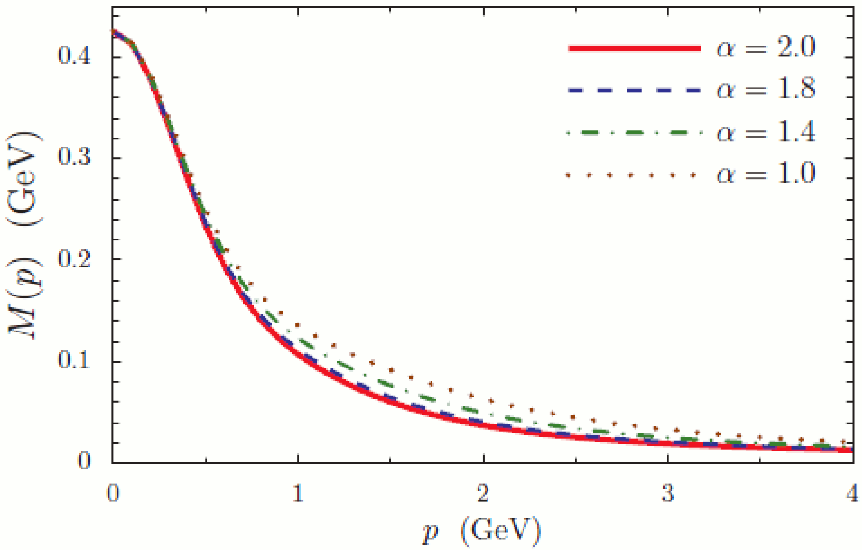


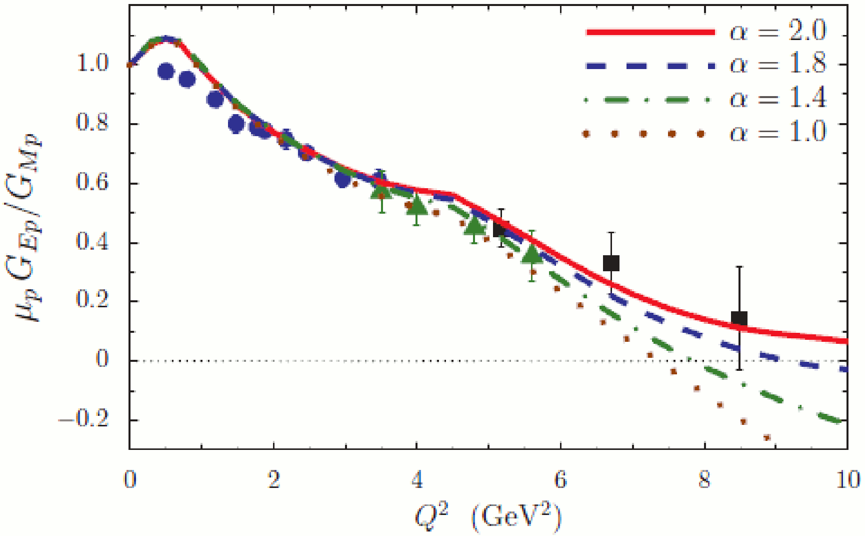
$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$

- Apparently small changes in M(p) within the domain 1<p(GeV)<3 have striking effect on the proton's electric form factor
- The possible existence and location of the zero is determined by behaviour of $Q^2F_2^p(Q^2)$, proton's Pauli form factor
- Like the pion's PDA, $Q^2F_2^p(Q^2)$ measures the rate at which dressed-quarks become parton-like:
  - ✓ $F_2^p=0$ for bare quark-partons
  - ✓ Therefore, G_E^p can't be zero on the bare-parton domain

I.C. Cloët, C.D. Roberts, A.W. Thomas: Revealing dressed-quarks via the proton's charge distribution,
arXiv:1304.0855 [nucl-th], Phys. Rev. Lett. **111** (2013) 101803

Visible Impacts of DCSB





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

- Follows that the
  - ✓ possible existence
  - ✓ and location

of a zero in the ratio of proton elastic form factors

$$[\mu_p G_{Ep}(Q^2)/G_{Mp}(Q^2)]$$

are a direct measure of the nature of the quark-quark interaction in the Standard Model.

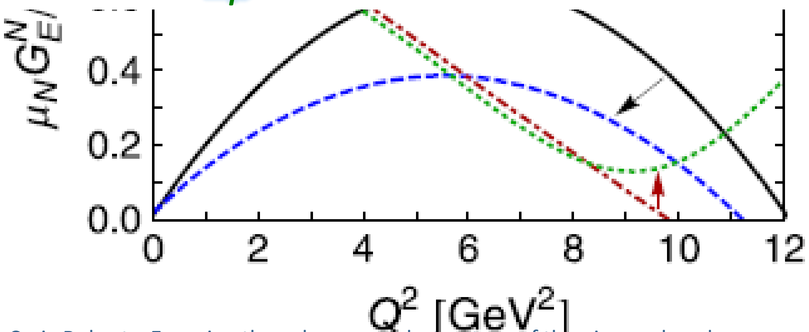
J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt: Nucleon and Δ Elastic and Transition Form Factors, arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) 1185 [on-line]

Electric Charge

- Proton: if one accelerates the rate at which the dressed-quark sheds its cloud of gluons to become a parton, then zero in G_{ep} is pushed to larger Q^2
- Opposite for neutron!
- Explained by presence of diquark correlations

Leads to *Prediction neutron:proton*

$G_{En}(Q^2) > G_{Ep}(Q^2)$ at $Q^2 > 4GeV^2$



- These features entail that at x≈ 5 the electric form factor of the neutral neutron will become larger than that of the unit-charge proton!
- JLab12 will probe this prediction

Phys. Rev. Lett. 106, 252003 (2011) [4 pages]

Flavor Decomposition of the Elastic Nucleon Electromagnetic Form Factors

Abstract | References | Citing Articles (11)

Download: PDF (200 kB) Buy this article **Export:** BibTeX or EndNote (RIS)

G. D. Cates[1], C. W. de Jager[2], S. Riordan[3], and B. Wojtsekhowski[2,*]
[1] *University of Virginia, Charlottesville, Virginia 22903, USA*
[2] *Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[3] *University of Massachusetts, Amherst, Massachusetts 01003, USA*

Received 8 March 2011; published 22 June 2011

Article Available via CHORUS Pilot
Download Accepted Manuscript

The *u*- and *d*-quark contributions to the elastic nucleon electromagnetic form factors have been determined by using experimental data on $G_E{}^n$, $G_M{}^n$, $G_E{}^p$, and $G_M{}^p$. Such a flavor separation of the form factors became possible up to negative four-momentum transfer squared Q^2=3.4 GeV^2 with recent data on $G_E{}^n$ from Hall A at Jefferson Lab. For Q^2 above 1 GeV^2, for both the *u* and the *d* quark, the ratio of the Pauli and Dirac form factors, F_2/F_1, was found to be almost constant in sharp contrast to the behavior of F_2/F_1 for the proton as a whole. Also, again for Q^2>1 GeV^2, both $F_2{}^d$ and $F_1{}^d$ are roughly proportional to $1/Q^4$, whereas the dropoff of $F_2{}^u$ and $F_1{}^u$ is more gradual.

URL: http://link.aps.org/doi/10.1103/PhysRevLett.106.252003
DOI: 10.1103/PhysRevLett.106.252003
PACS: 14.20.Dh, 13.40.Gp, 24.70.+s, 25.30.Bf

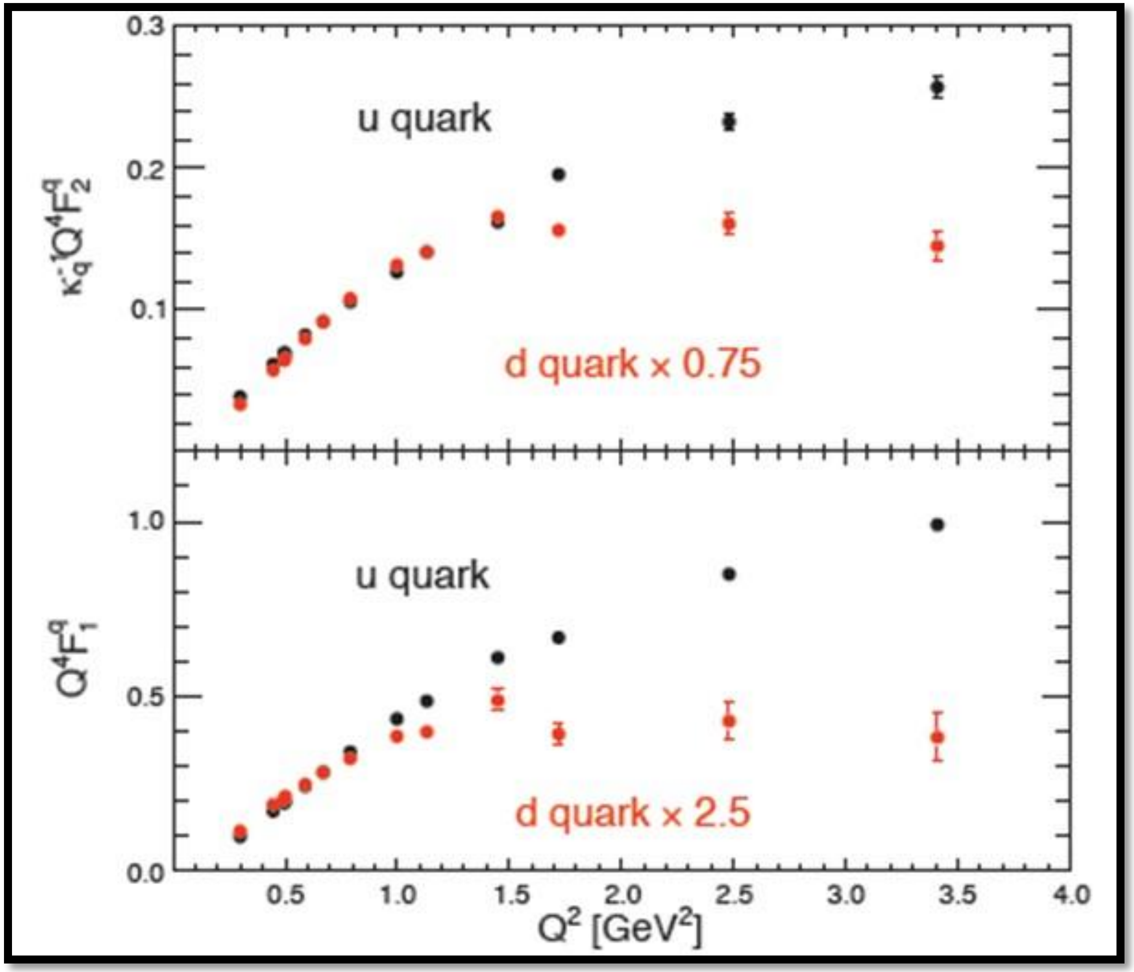
Discovering Diquarks

Flavor separation of proton form factors

$Q^4F_2^q/\kappa$

Cates, de Jager, Riordan, Wojtsekhowski, PRL 106 (2011) 252003

$Q^4 F_1^q$

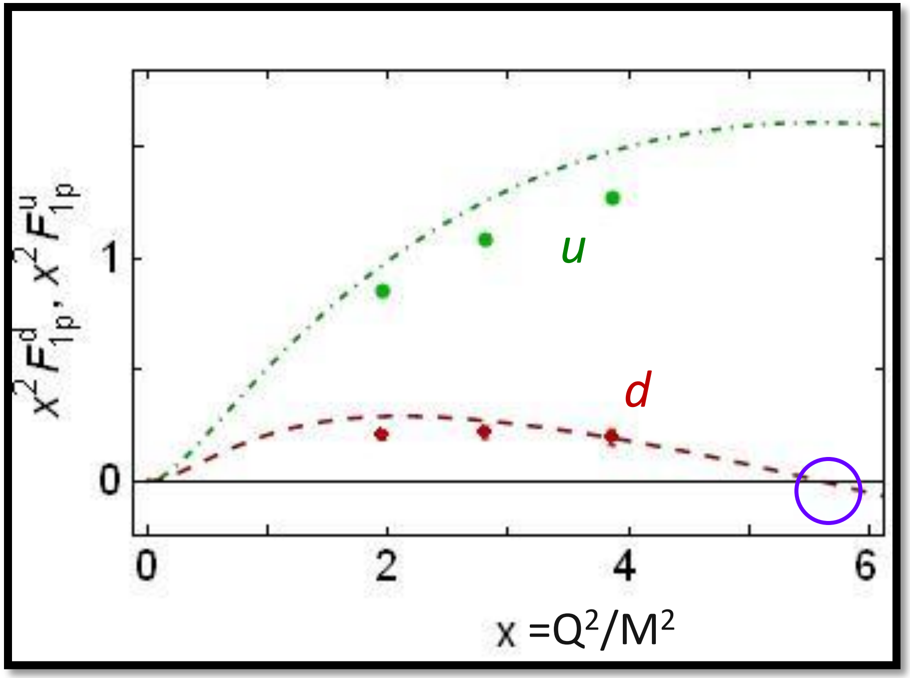


- Very different behavior for *u* & *d* quarks

  Means apparent scaling in proton F2/F1 is *purely accidental*

Cloët, Eichmann, El-Bennich, Klähn, Roberts, Few Body Syst. 46 (2009) pp.1-36
Wilson, Cloët, Chang, Roberts, PRC 85 (2012) 045205

Diquark correlations!

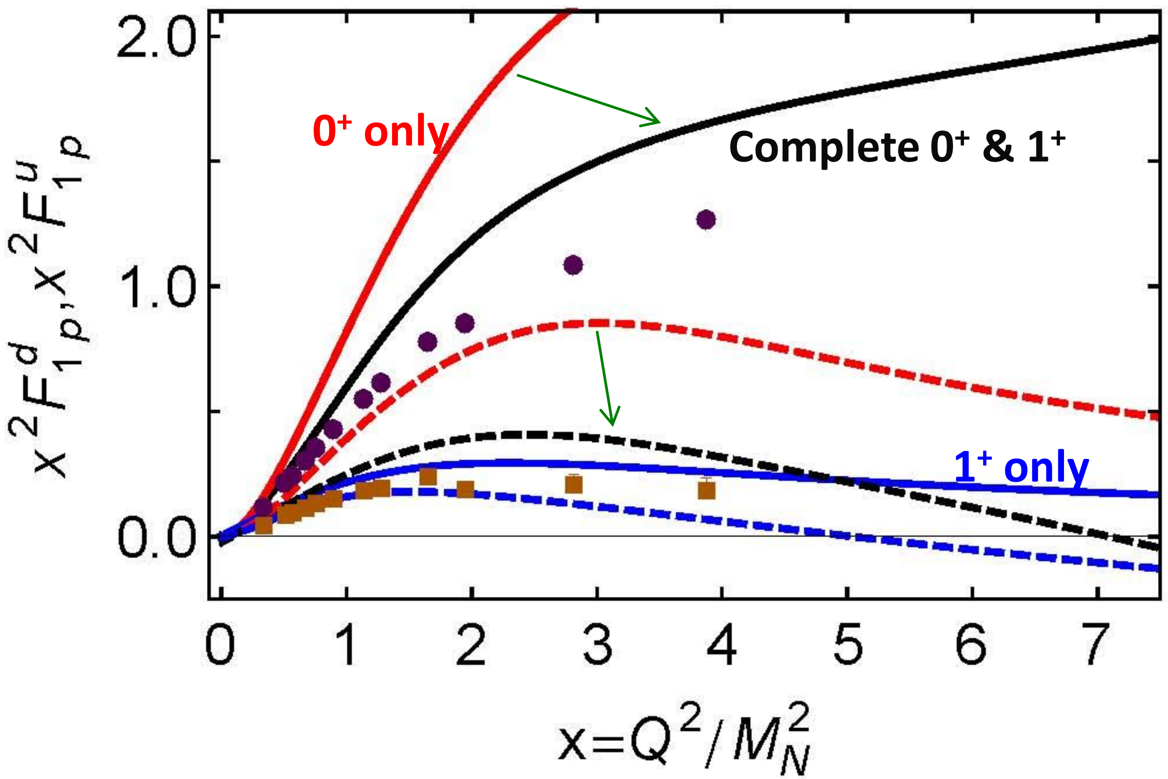


- Poincaré covariant Faddeev equation
  - Predicts scalar and axial-vector diquarks
- Proton's singly-represented *d*-quark more likely to be struck in association with *1^+* diquark than with *0^+*
  - form factor contributions involving *1^+* diquark are softer
- Doubly-represented *u*-quark is predominantly linked with harder *0^+* diquark contributions
- Interference produces zero in Dirac form factor of *d*-quark in proton
  - Location of the zero depends on the relative probability of finding 1^+ & 0^+ diquarks in proton
  - Correlated, e.g., with valence *d/u* ratio at x=1

J. Segovia, I.C. Cloët, C.D. Roberts, S.M. Schmidt:
Nucleon and Δ Elastic and Transition Form Factors,
arXiv:1408.2919 [nucl-th], Few Body Syst. **55** (2014) 1185 [on-line]

Diquark correlations

- u-quark = solid
- d-quark = dashed
- Plainly ,
  - presence of axial-vector diquark is crucial to agreement with data and is the origin of zero in F_1^d
  - scalar diquark alone
    - cannot describe data
    - does not produce a zero



J. Segovia et al., in progress

Far valence domain
$x \simeq 1$

Nucleon spin structure at very high-x
Craig D. Roberts, Roy J. Holt and Sebastian M. Schmidt
arXiv:1308.1236 [nucl-th], Phys. Lett. B 727 (2013) pp. 249–254

Far valence domain $x \simeq 1$

- Endpoint of the far valence domain: $x \simeq 1$, is especially significant
  - All familiar PDFs vanish at x=1; but ratios of any two need not
  - Under DGLAP evolution, the value of such a ratio is invariant.
- Thus, e.g.,
  - $\lim_{x\to 1} d_v(x)/u_v(x)$
    is unambiguous, scale invariant, nonperturbative feature of QCD.

  ∴ keen discriminator between frameworks
  that claim to explain nucleon structure.
- Furthermore, Bjorken-*x=1* corresponds strictly to the situation in which the invariant mass of the hadronic final state is precisely that of the target; viz., elastic scattering.

  ∴ Structure functions inferred experimentally on $x \simeq 1$
  are determined theoretically by target's elastic form factors.

I.C. Cloët, C.D. Roberts, *et al.*
arXiv:0812.0416 [nucl-th], Few Body Syst. 46 (2009) 1-36
D. J. Wilson, I. C. Cloët, L. Chang and C. D. Roberts
arXiv:1112.2212 [nucl-th], Phys. Rev. C**85** (2012) 025205 [21 pages]

Neutron Structure Function at high-*x*

- Valence-quark distributions at *x=1*
  - Fixed point under DGLAP evolution
  - Strong discriminator between theories

$$\left.\frac{d_v(x)}{u_v(x)}\right|_{x\to 1}, \quad \text{where} \quad \frac{d_v(x)}{u_v(x)} = \frac{4\frac{F_2^n(x)}{F_2^p(x)} - 1}{4 - \frac{F_2^n(x)}{F_2^p(x)}}$$

Measures relative strength of axial-vector/scalar diquarks in proton

- Algebraic formula

$$\left.\frac{d_v(x)}{u_v(x)}\right|_{x\to 1} = \frac{P_1^{p,d}}{P_1^{p,u}} = \frac{\frac{2}{3}P_1^{p,a} + \frac{1}{3}P_1^{p,m}}{P_1^{p,s} + \frac{1}{3}P_1^{p,a} + \frac{2}{3}P_1^{p,m}}$$

  - $P_1^{p,s}$ = contribution to the proton's charge arising from diagrams with a scalar diquark component in both the initial and final state
  - $P_1^{p,a}$ = kindred axial-vector diquark contribution
  - $P_1^{p,m}$ = contribution to the proton's charge arising from diagrams with a different diquark component in the initial and final state.

I.C. Cloët, C.D. Roberts, *et al.*
arXiv:0812.0416 [nucl-th], Few Body Syst. 46 (2009) 1-36
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Neutron Structure Function at high-*x*

Deep inelastic scattering – the Nobel-prize winning quark-discovery experiments

Reviews:
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- N. Isgur, PRD 59 (1999)
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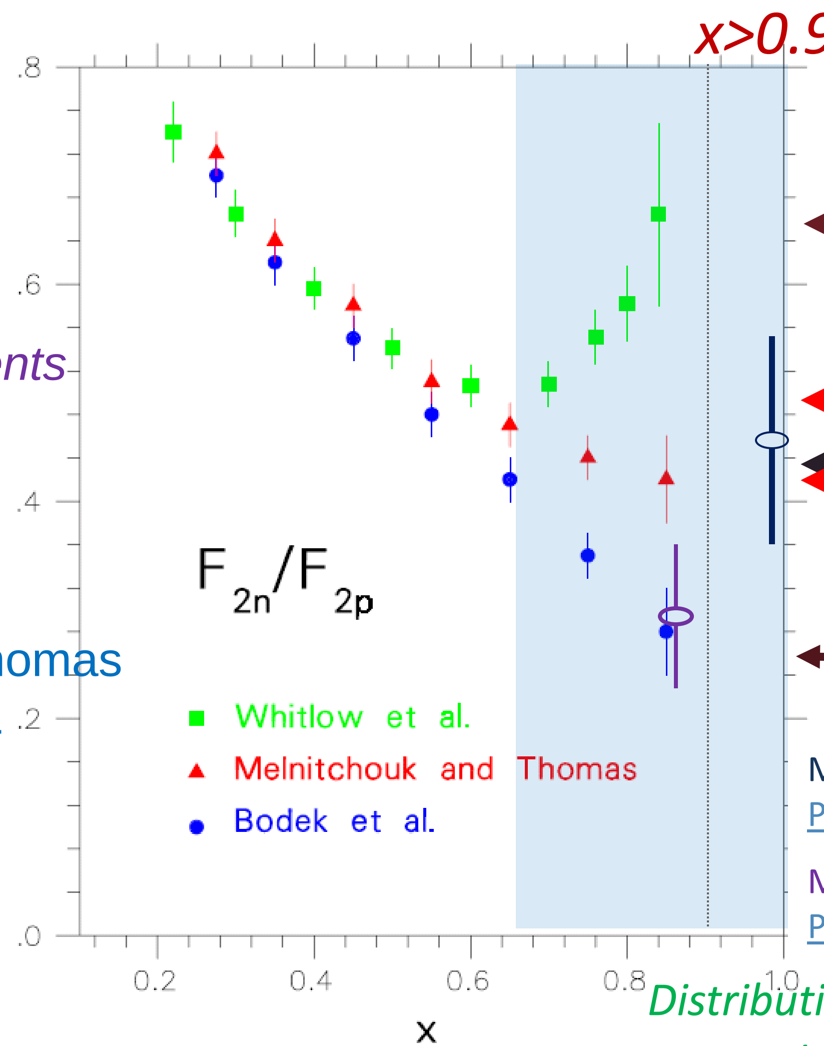

d/u=1/2
SU(6) symmetry

d/u=0.28
DSE: "realistic"

pQCD, uncorrelated *Ψ*

DSE: "contact"
d/u=0.18

0^+ qq only, *d/u=0*

Melnitchouk, Accardi *et al.*
Phys.Rev. D84 (2011) 117501

Melnitchouk, Arrington *et al.*
Phys.Rev.Lett. 108 (2012) 252001

Distribution of neutron's momentum amongst quarks on the valence-quark domain

I.C. Cloët, C.D. Roberts, *et al.*
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Neutron Structure Function at high-x

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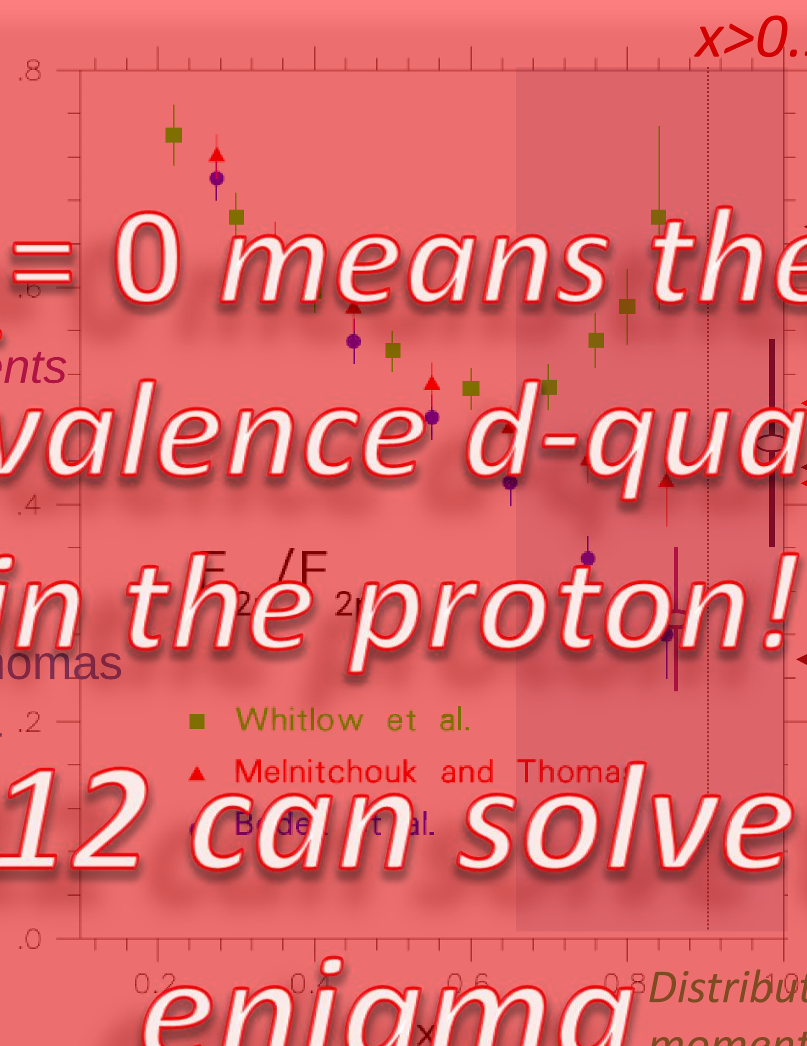

Melnitchouk, Accardi *et al.* Phys.Rev. D84 (2011) 117501

Melnitchouk, Arrington *et al.* Phys.Rev.Lett. 108 (2012) 252001

Distribution of neutron's momentum amongst quarks on the valence-quark domain

NB.
$d/u|_{x=1} = 0$ means there are no valence d-quarks in the proton!
JLab12 can solve this enigma

Physics Letters B 727 (2013) 249–254

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Nucleon spin structure at very high x

Craig D. Roberts [a,*], Roy J. Holt [a], Sebastian M. Schmidt [b]

[a] Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[b] Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, D-52425 Jülich, Germany

ARTICLE INFO

Article history:
Received 6 August 2013
Received in revised form 10 September 2013
Accepted 18 September 2013
Available online 25 September 2013
Editor: A. Ringwald

Keywords:
Continuum strong QCD
Diquark correlations
Dynamical chiral symmetry breaking
Dyson–Schwinger equations
Nucleon longitudinal spin asymmetries
Parton distribution functions
Valence quarks at very high x

ABSTRACT

Dyson–Schwinger equation treatments of the strong interaction show that the presence and importance of nonpointlike diquark correlations within the nucleon are a natural consequence of dynamical chiral symmetry breaking. Using this foundation, we deduce a collection of simple formulae, expressed in terms of diquark appearance and mixing probabilities, from which one may compute ratios of longitudinal-spin-dependent u- and d-quark parton distribution functions on the domain $x \simeq 1$. A comparison with predictions from other approaches plus a consideration of extant and planned experiments shows that the measurement of nucleon longitudinal spin asymmetries on $x \simeq 1$ can add considerably to our capacity for discriminating between contemporary pictures of nucleon structure.

Spin structure on $x \simeq 1$

Nucleon spin structure at very high-x
Craig D. Roberts, Roy J. Holt and Sebastian M. Schmidt
arXiv:1308.1236 [nucl-th], Phys. Lett. B 727 (2013) pp. 249–254

Quark helicity at large Bjorken-x

- Correlations
  between dressed-quarks within the proton
  have an enormous impact on nucleon spin structure

	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
DSE-1	0.49	0.28	−0.11	0.65	−0.26	0.17	0.59
DSE-2	0.41	0.18	−0.07	0.88	−0.33	0.34	0.88
$0^+_{[ud]}$	$\frac{1}{4}$	0	0	1	0	1	1
NJL	0.43	0.20	−0.06	0.80	−0.25	0.35	0.77
SU(6)	$\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{4}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	$\frac{5}{9}$
CQM	$\frac{1}{4}$	0	0	1	$-\frac{1}{3}$	1	1
pQCD	$\frac{3}{7}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	1

Nucleon spin structure at very high-x
Craig D. Roberts, Roy J. Holt and Sebastian M. Schmidt
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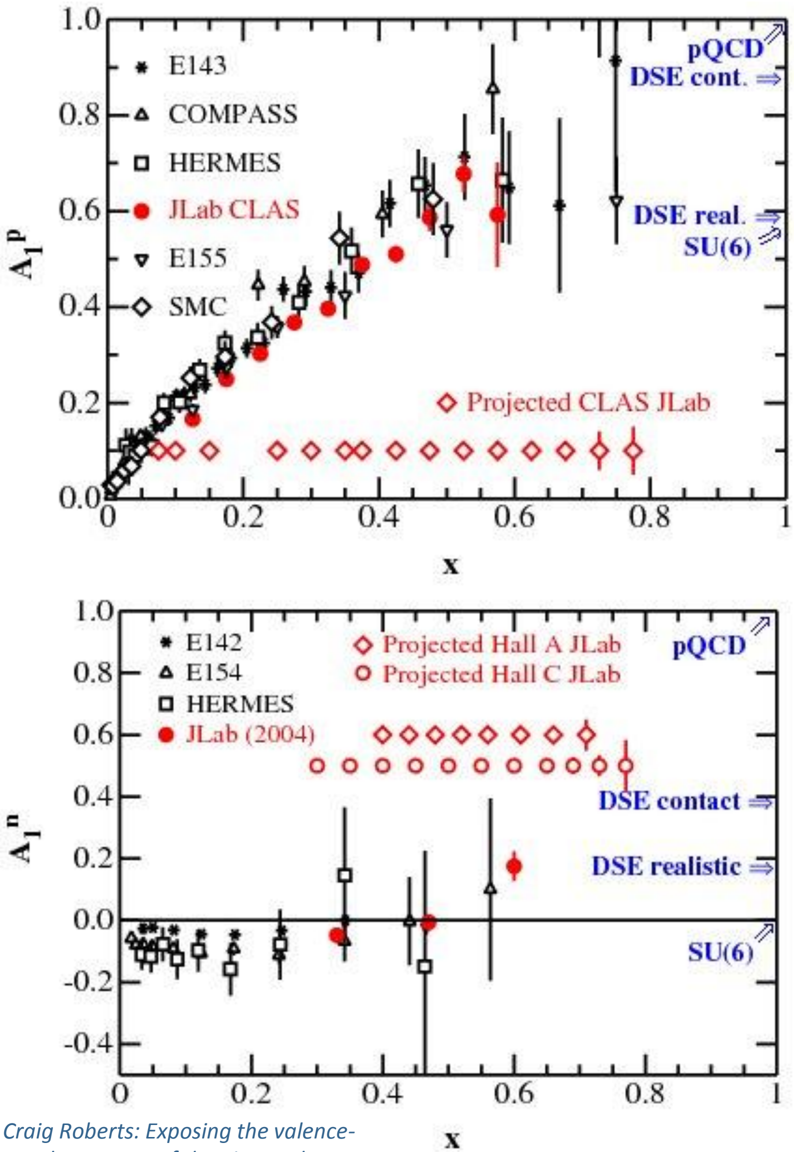
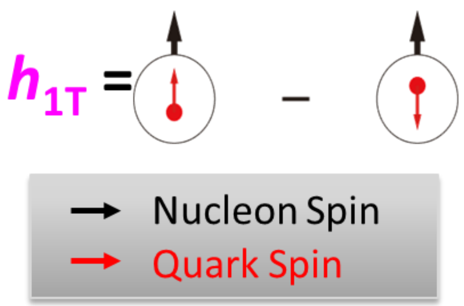
Quark helicity at large Bjorken-x



- Existing data cannot distinguish between modern pictures of nucleon structure
- Empirical results for nucleon longitudinal spin asymmetries on $x \simeq 1$ promise to add greatly to our capacity for discriminating between contemporary pictures of nucleon structure.

Direction of motion



TMDs … Transversity … Tensor Charge

$$\delta q = \int_0^1 dx\, \left(h_1^q(x) - h_1^{\bar{q}}(x)\right)$$

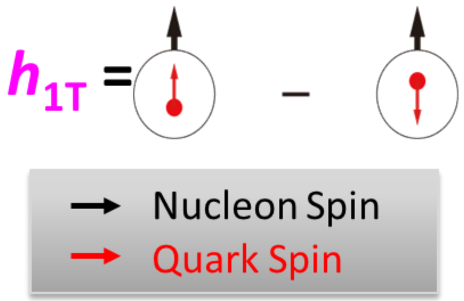
- Intrinsic, defining property of the nucleon

  … just as significant as axial-charge
- No gluon transversity distribution
- Value of tensor charge places constraints on some extensions of the Standard Model <PRD85 (2012) 054512>
- Current knowledge of transversity:

  SIDIS @HERMES, COMPASS, JLab
- Future SIDIS at JLab (SoLId), EIC, …

Electron Ion Collider: The Next QCD Frontier

Direction of motion

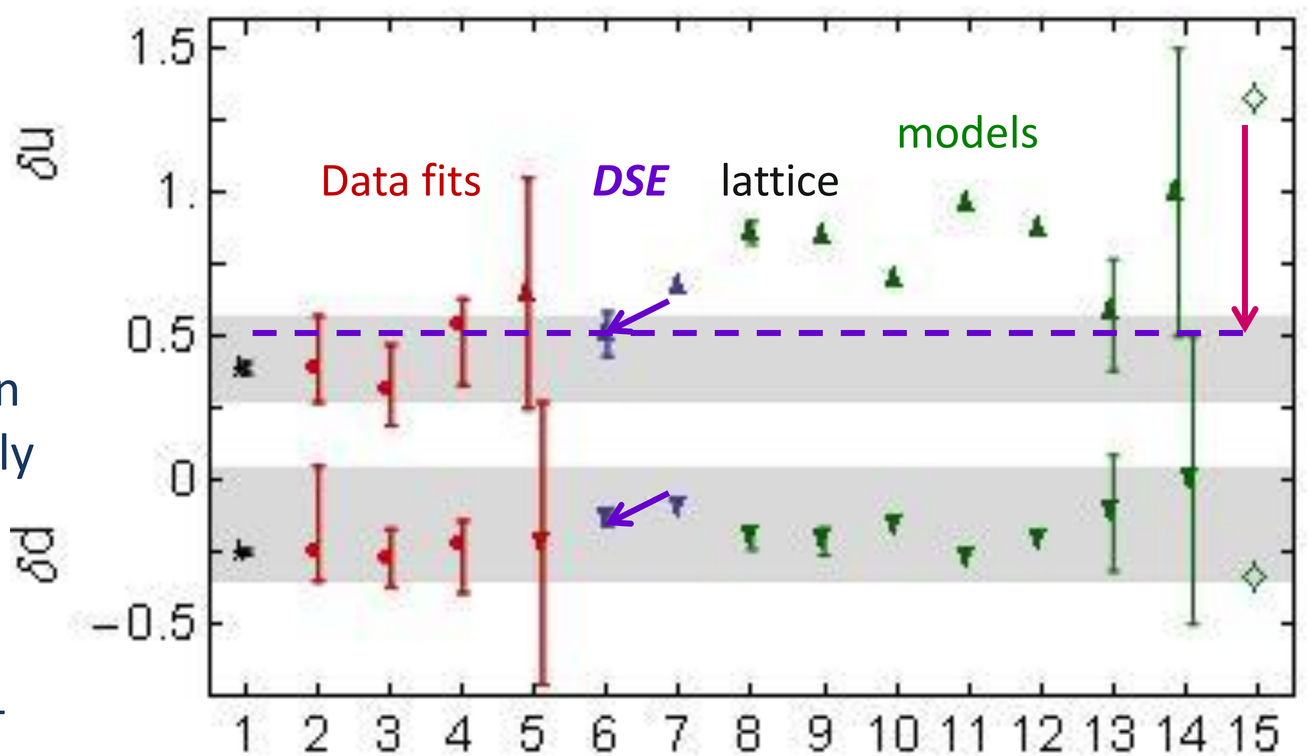


Pitschmann et al., arXiv:1411. 2052 – Nucleon tensor charges and electric dipole moments

TMDs …
Transversity … Tensor Charge

$$\delta q = \int_0^1 dx \left(h_1^q(x) - h_1^{\bar{q}}(x) \right)$$

- Presence of diquark correlations in the proton wave function suppresses δu by 50% cf. SU(6) quark model prediction
- Axial-vector correlation is crucial, e.g.: δd is only nonzero because the proton wave function contains axial-vector correlations; and axial-vector suppresses δu



Summary

- Conformal anomaly ... gluons and quarks acquire mass dynamically
- Top-down and bottom-up DSE analyses agree on RGI interaction in QCD ⇒ parameter-free prediction of meson properties
- DCSB ⇒ reliable predictions of pseudoscalar meson pion properties
- Prediction = PDAs are squat and fat, at all sensible scales
- Prediction = factorisation in hard scattering formalism will be verified in pion form factor at JLab
- Prediction = DCSB, diquark correlations & their many consequences, *e.g.*
  - zeros in G_{Ep}, G_{En}, F_{1d}
  - $G_{En} > G_{Ep}$ on $Q^2 > 5$ GeV^2
  - Far valence domain ... sensitive discriminator between pictures of nucleon
- Prediction = Nucleon tensor charge ... correlations within Faddeev amplitude are crucial ... connection with EDM of neutron and proton

Electron Ion Collider: The Next QCD Frontier

Future

- Strong self-interactions amongst gluons are a unique feature of QCD
  - Plausibly, they make QCD the only known nonperturbatively well-defined theory in Nature
- Gluon *cannibalism* produces nonperturbatively massive gauge bosons and dressed-quarks
  - It is responsible for 98% of the mass of visible matter in the Universe
- In this Universe, all readily accessible matter is defined by light quarks
  - Confinement is therefore a complex, dynamical phenomenon unrelated to static potentials in quantum mechanical models
- This is the Standard Model Frontier:
  - Predict
  - Measure
  - Explain

} All the phenomena driven by the gluons that bind us all

What is QCD?

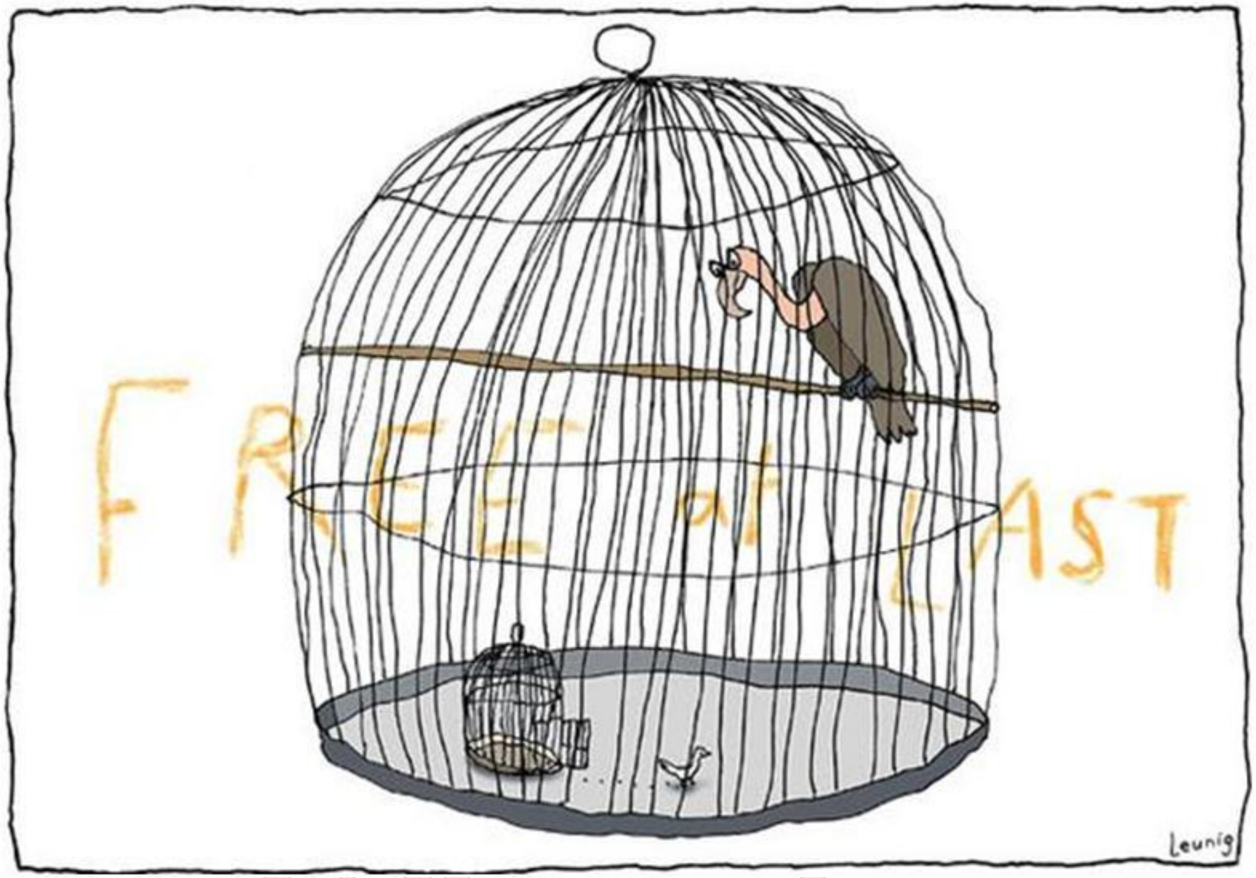
QCD is a *Theory*

(*not* an effective theory)

- Very likely a self-contained, nonperturbatively renormalisable and hence well defined Quantum Field Theory

  This is not true of QED – cannot be defined nonperturbatively
- No confirmed breakdown over an enormous energy domain:

  0 GeV < *E* < 8 TeV
- Increasingly probable that any extension of the Standard Model will be based on the paradigm established by QCD
  - Extended Technicolour: electroweak symmetry breaks via a fermion bilinear operator in a strongly-interacting non-Abelian theory. (Andersen *et al*. “Discovering Technicolor” Eur.Phys.J.Plus 126 (2011) 81)
  - Higgs sector of the SM becomes an effective description of a more fundamental fermionic theory, similar to the Ginzburg-Landau theory of superconductivity wikipedia.org/wiki/Technicolor_(physics)



What is Confinement?

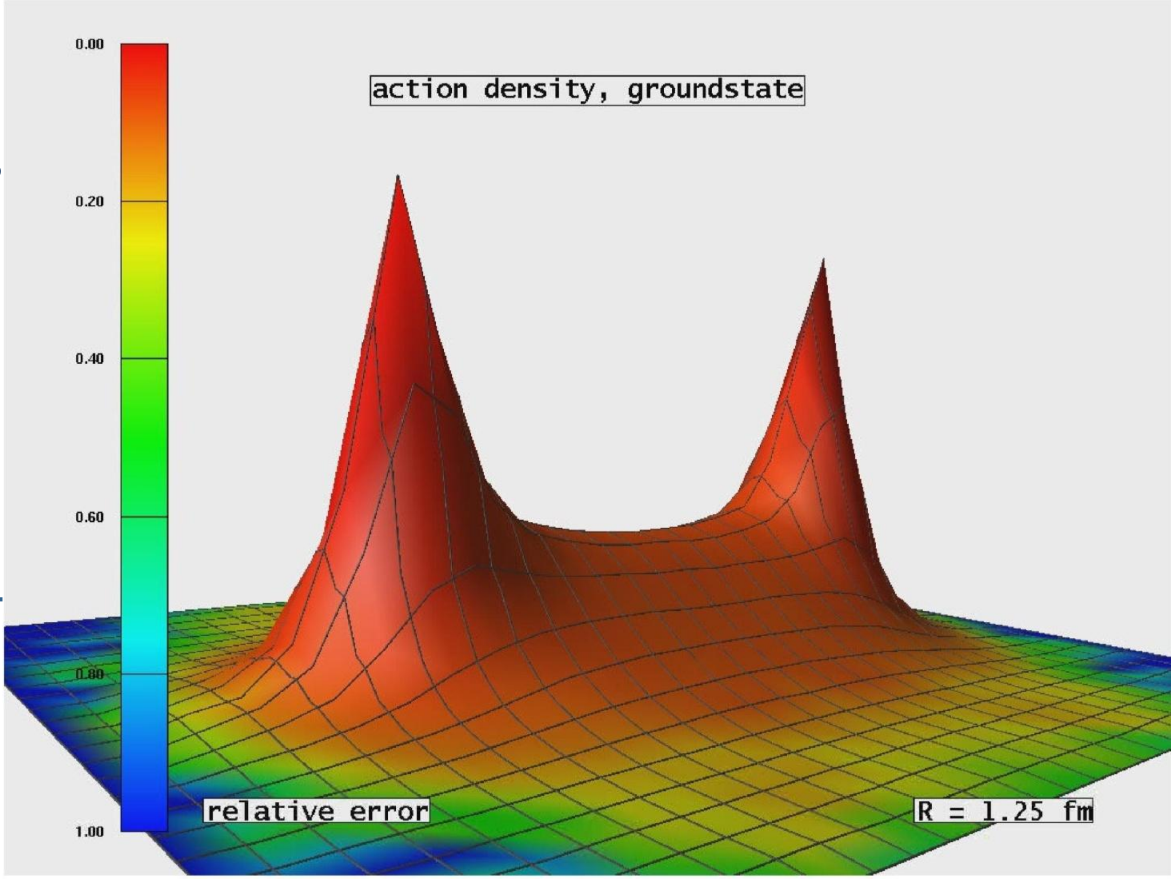
Light quarks & Confinement

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

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

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

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



Light quarks & Confinement

- Problem:

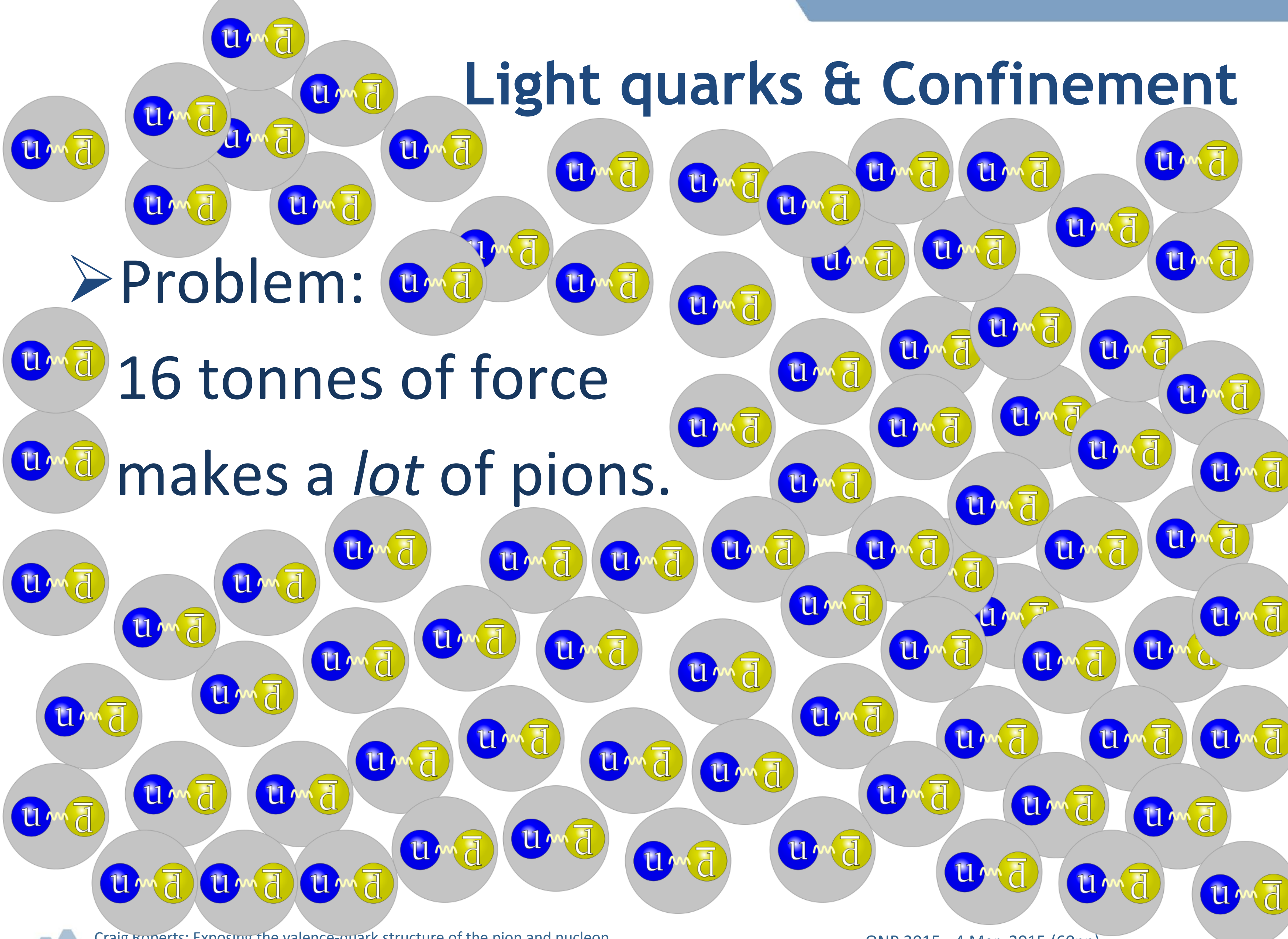
  Pions …

  They're unnaturally light

  so 16 tonnes of force

  makes a *lot* of them.

Light quarks & Confinement

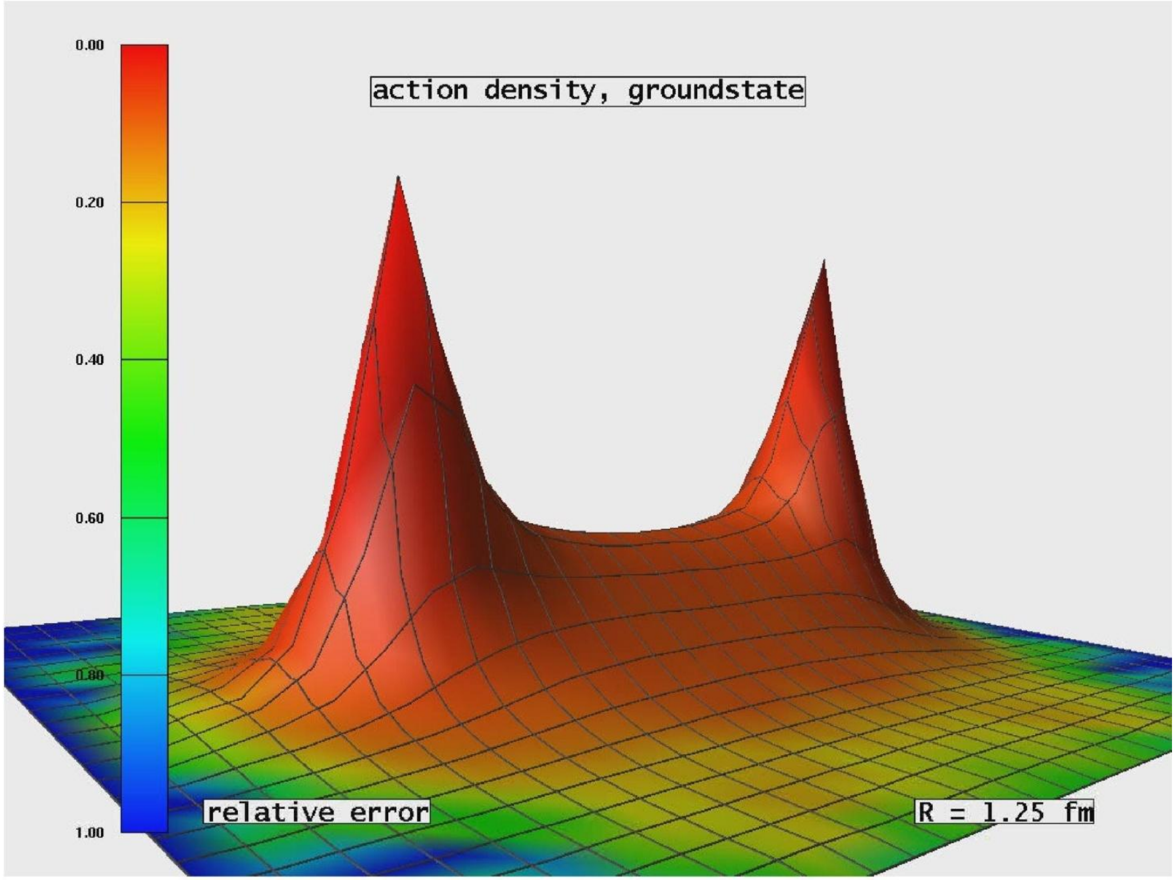


- Problem:

16 tonnes of force makes a *lot* of pions.

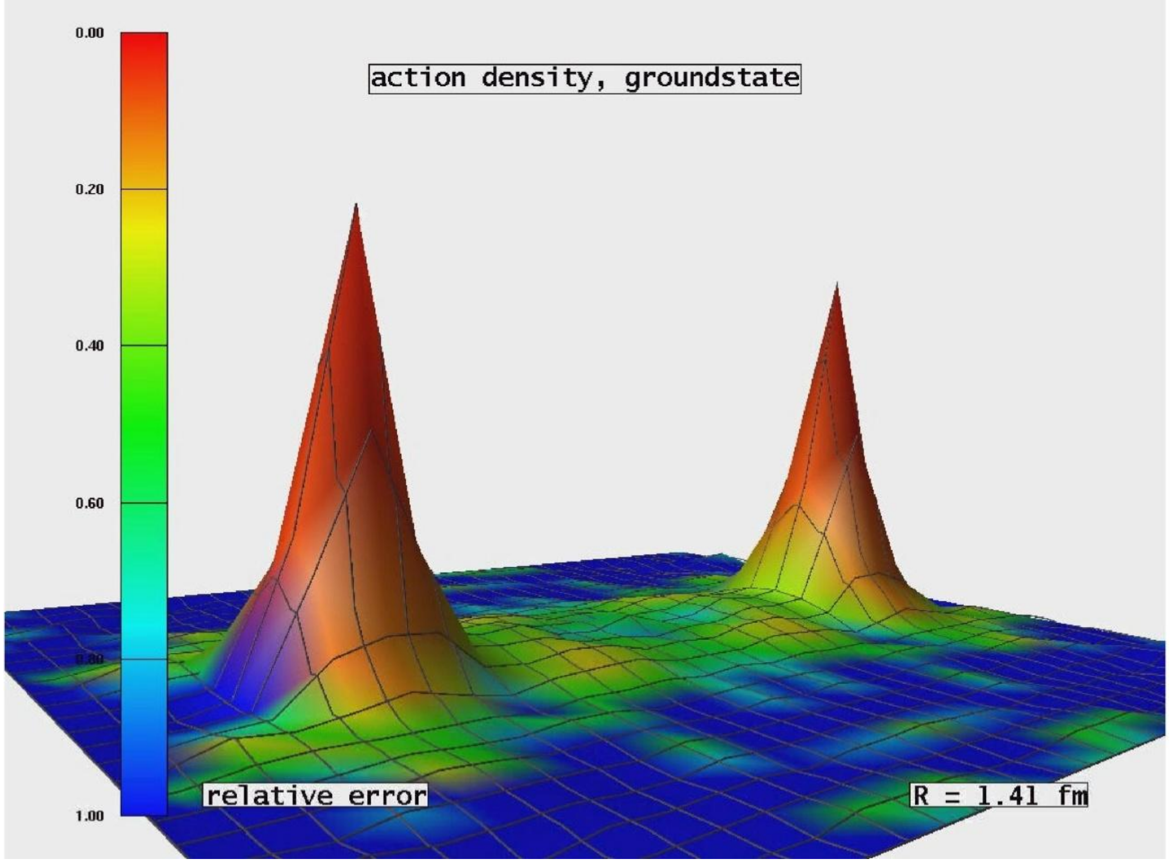
Light quarks & Confinement

- In the presence of light quarks, *pair creation seems to occur non-localized and instantaneously*



Light quarks & Confinement

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



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