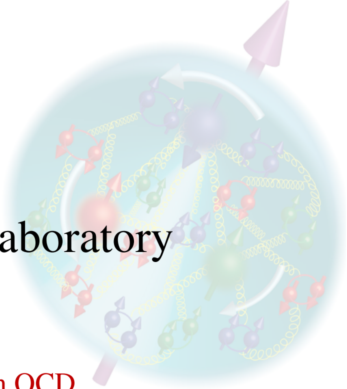
Continuum-based theory for QCD



Ian Cloët

Argonne National Laboratory

Joint Town Meetings on QCD

Temple University

September 13-15, 2014

U.S. DEPARTMENT OF ENERGY | Office of Science

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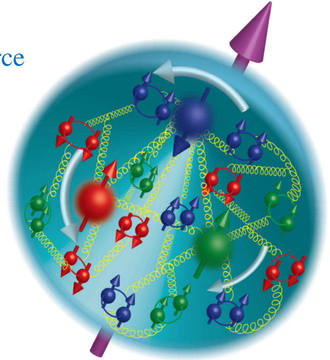
Roads to Discovery: 2014-2023

- Meson and baryon spectroscopy
  - the discovery of exotic or hybrid hadrons would force a dramatic reassessment of the distinction between the notions of matter fields and force fields



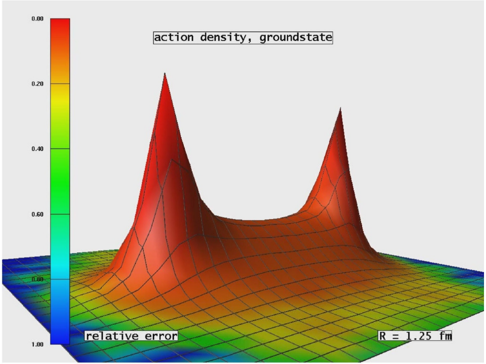
- Exploit opportunities provided by new data on nucleon elastic and transition form factors
  - chart infrared evolution of QCD's coupling and dressed-masses
  - reveal correlations that are key to nucleon structure
  - expose the facts or fallacies in modern descriptions of nucleon structure
- Precision experimental study of valence region, together with theoretical computation of distribution functions and distribution amplitudes
  - computation is critical – without computation no amount of data can reveal anything about the theory underlying strong interaction physics

Discover the meaning of *confinement* and its relation to *dynamical chiral symmetry breaking*

– origin of visible mass –

A Perspective on Confinement

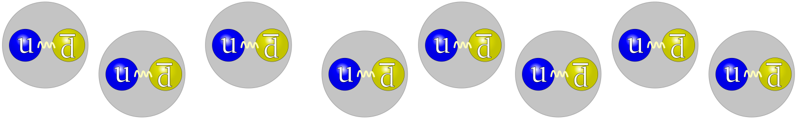
G. Bali *et al.*, PoS LAT2005 (2006) 308



- **Folklore:** “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.

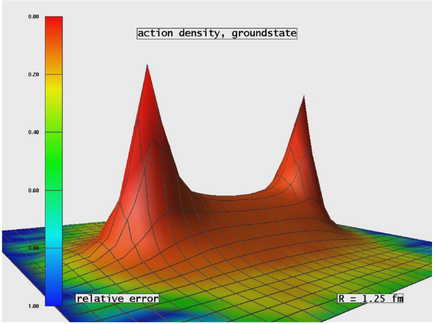
  This leads to a constant force between the quarks – and a large force at that, equal to about 16 metric tons.” **Hall-D CDR(5)**

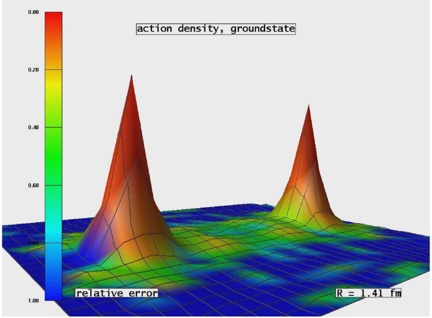
- **Problem:** in QCD 16 tonnes of force produces a lot of pions!



A Perspective on Confinement

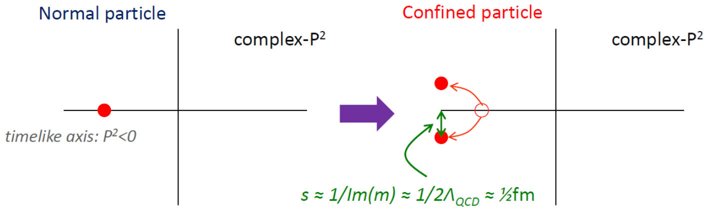
G. Bali *et al.*, PoS LAT2005 (2006) 308





- In the presence of *light quarks* the breaking of the string appears to be an instantaneous de-localized process
- *No flux tube in a theory with light quarks!*
- Paradigm for confinement in hadron physics must be different from the flux tube picture

Confinement in QCD with light-quarks

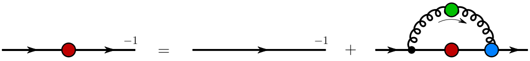


- *Confinement is expressed through a dramatic change in the analytic structure of propagators for coloured states*
- In the study of hadrons attention should turn from potential models toward the continuum bound-state problem in quantum field theory
- Such approaches offer the possibility of posing simultaneously the questions
  - What is confinement?
  - What is dynamical chiral symmetry breaking?
  - How are they related?
- Is it plausible that these two phenomena – so important in the Standard Model – can have different origins and fates?

Dynamical Chiral Symmetry Breaking

- DCSB is the most important mass generating mechanism for visible matter in the Universe
  - responsible for approximately 98% of the proton's mass
  - Higgs mechanism is (almost) irrelevant for light quarks

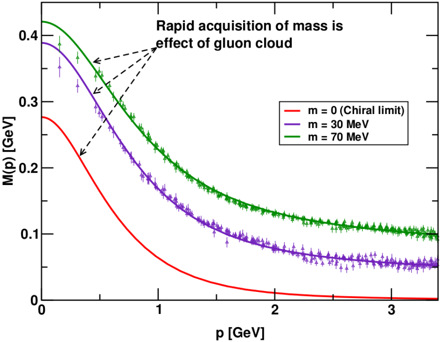
- QCD's quark propagator $\Longleftrightarrow$ QCD's gap equation



$$S(p) = \frac{Z(p^2)}{i\not{p} + M(p^2)}$$

- *Continuum- and Lattice-QCD are in agreement: the vast bulk of the light-quark mass comes from a cloud of gluons, dragged along by the quark as it propagates*

[Nuclear Science Advisory Committee: Long Range Plan (2007)]



The Pion

The Pion in QCD

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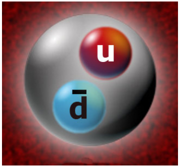


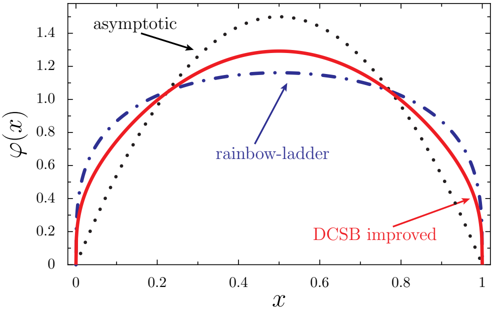
- The pion has a dichotomous nature it is both a bound state of a *dressed-quark* and a *dressed-antiquark* in QFT and the Goldstone mode associated with DCSB in QCD

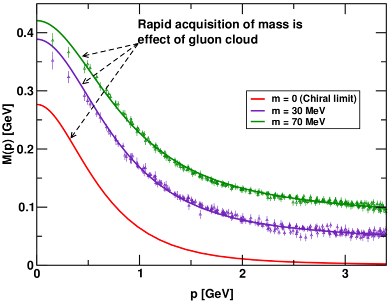
- In QFT the pion's wave function is given by the Bethe-Salpeter Equation

- A related quantity is the pion's parton distribution amplitude
  - $\varphi_\pi(x,\xi)$: *is a light-front probability amplitude that describes the momentum distribution of a quark and antiquark in the bound-state's valence Fock state*

- The pion PDA is an essentially nonperturbative quantity whose asymptotic form is known: $\varphi_\pi(x,\xi=\infty) = 6\,x\,(1-x)$
  - such PDAs are crucial because their form sets the normalization of elastic and transition form factors in hard exclusive processes; e.g., pion form factor

$$Q^2\,F_\pi(Q^2) \overset{Q^2\to\infty}{\longrightarrow} 16\,\pi\,f_\pi^2\,\alpha_s(Q^2) \qquad \Longleftrightarrow \qquad \varphi_\pi^{\text{asy}}(x) = 6\,x\,(1-x)$$





- The pion PDA exhibits a pronounced broadening compared with the asymptotic pion PDA – at any energy scale accessible to modern experiment
  - broading of the pion's PDA is directly linked to DCSB

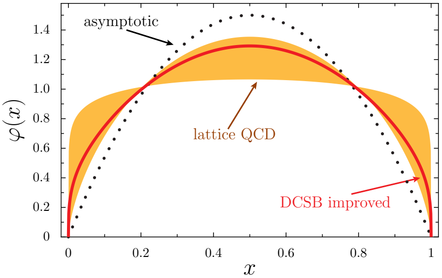
- Evidence pointing in this direction has been accumulating for some time:
  - Sum Rules: S. V. Mikhailov and A. V. Radyushkin, JETP Lett. **43**, 712 (1986)
  - Instantons: V. Y. Petrov, *et al.*, Phys. Rev. D **59**, 114018 (1999)
  - LCSR + lattice: V. M. Braun, M. Gockeler, *et al.*, Phys. Rev. D **74**, 074501 (2006)
  - AdS/QCD: S. J. Brodsky, F. G. Cao, *et al.*, Phys. Rev. D **84**, 075012 (2011)

Pion PDA: Continuum and Lattice QCD

- Contemporary lattice-QCD simulations can only access one nontrivial moment

$$\int_0^1 dx\,(2\,x-1)^2\varphi_\pi(x) = 0.27 \pm 0.04$$

[V. Braun *et al.*, Phys. Rev. D **74**, 074501 (2006)]

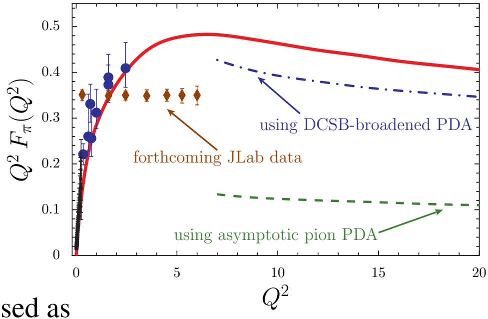


- Continuum QCD and Bayesian analysis demonstrate that maximum information can be obtained from the lattice moment by using a *generalized expansion* ($\alpha \neq 3/2$)

$$\varphi_\pi(x,Q^2) = N_\alpha\, x^{\alpha-1/2}(1-x)^{\alpha-1/2}\left[1+\sum\nolimits_{n=2,\,4,\ldots} a_n^\alpha(Q^2)\, C_n^\alpha(2x-1)\right]$$

- This approach reveals complete consistency between continuum- and lattice-QCD computations
  - at real-world energy scales, ground-state PDAs are broad and concave

- Direct, symmetry-preserving computation of pion form factor predicts maximum in $Q^2\, F_\pi(Q^2)$ at $Q^2 \approx 6\,\mathrm{GeV}^2$
  - magnitude of this product is determined by strength of DCSB at all accessible scales



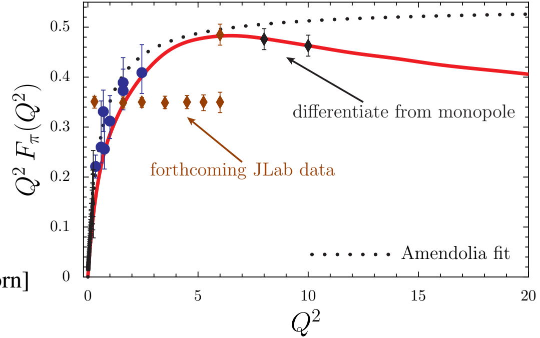
- The QCD prediction can be expressed as

$$Q^2 F_\pi(Q^2) \overset{Q^2 \gg \Lambda^2_{\rm QCD}}{\sim} 16\,\pi\, f_\pi^2\, \alpha_s(Q^2)\, w_\pi^2; \qquad w_\pi = \frac{1}{3}\int_0^1 dx\, \frac{1}{x}\, \varphi_\pi(x)$$

- Continuum-QCD methods have provided a new picture of the pion form factor; with excellent agreement between direct calculation and the hard scattering formula – when all elements are computed self-consistently
- *Continuum-QCD predicts that QCD power law behaviour – with QCD's scaling law violations – sets in at* $Q^2 \sim 8\,\mathrm{GeV}^2$

- To observe onset of perturbative power law behaviour – *to differentiate from a monopole* – optimistically need data at $8\,\mathrm{GeV}^2$ but likely also at $10\,\mathrm{GeV}^2$

[see talk by Tanja Horn]

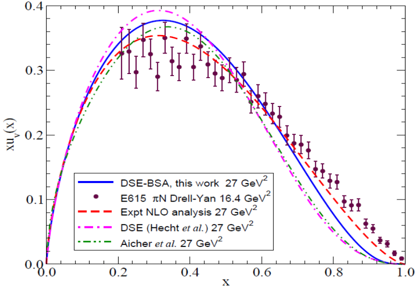


- Scaling predictions are valid for both spacelike and timelike momenta, and timelike data show promise as the means of verifying modern predictions

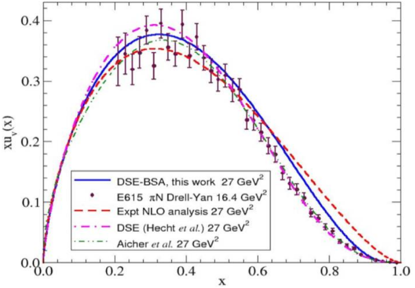
- By using DCSB-broadened PDAs for pion and kaon, existing data for $F_K(q^2)/F_\pi(q^2)$ at timelike $q^2 \approx 17\,\mathrm{GeV}^2$ begin to appear understandable
  [K. K. Seth, S. Dobbs, *et al.*, Phys. Lett. B 730 (2014) 332–335]
  [Chao Shi, Lei Chang, *et al.*, Phys. Lett. B (2014)]
  - however, questions remain about the separate normalization of F_π and F_K

Pion PDF

[J. S. Conway et al. (E615 Collaboration), Phys. Rev. D 39, 92 (1989)]



[M. Aicher, *et al.*, Phys. Rev. Lett. **105**, 252003 (2010)]



- Need for *QCD-based* calculation is emphasized by story of pion's valence quark distribution function:
  - 1989: $u_v^\pi \overset{x\to 1}{\sim} (1-x)^1$ – inferred from LO-Drell-Yan & disagrees with QCD
  - 2001: Dyson-Schwinger Equations (DSEs) predicts $u_v^\pi \overset{x\to 1}{\sim} (1-x)^2$ – argues that distribution inferred from data can't be correct
  - 2010: new NLO reanalysis – including soft-gluon resummation – inferred distribution agrees with DSE-QCD
- *Potentially important ramifications for nucleon PDF studies!*

Some Key References

- A. V. Radyushkin, *"Shape of Pion Distribution Amplitude,"* Phys. Rev. D **80**, 094009 (2009);
- S. J. Brodsky, F. G. Cao and G. F. de Teramond, *"Evolved QCD predictions for the meson-photon transition form factors,"* Phys. Rev. D **84**, 033001 (2011);
- L. Chang, I. C. Cloët, J. J. Cobos-Martinez, C. D. Roberts, *et al.*, *"Imaging dynamical chiral symmetry breaking: pion wave function on the . . .,"* Phys. Rev. Lett. **110**, no. 13, 132001 (2013);
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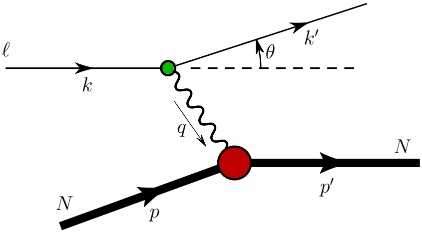
- L. Chang, I. C. Cloët, C. D. Roberts, S. M. Schmidt and P. C. Tandy, *"Pion electromagnetic form factor at spacelike momenta,"* Phys. Rev. Lett. **111**, no. 14, 141802 (2013);
- S. J. Brodsky, G. F. de Teramond, H. G. Dosch and J. Erlich, *"Light-Front Holographic QCD and Emerging Confinement,"* arXiv:1407.8131 [hep-ph].

Baryons

Nucleon Elastic Form Factors



- Provide vital information about the structure and composition of the most basic elements of nuclear physics
  - elastic scattering – therefore probes confinement at all energy scales
- Today accurate form factor measurements are creating a paradigm shift in our understanding of nucleon structure:
  - proton radius puzzle
  - $\mu_p \, G_{Ep}/G_{Mp}$ ratio and a possible zero in G_{Ep}
  - flavour decomposition and evidence for diquark correlations
  - meson-cloud effects
  - seeking verification of perturbative QCD scaling predictions and scaling violations in elastic form factors
  - etc

Proton G_E/G_M and DCSB

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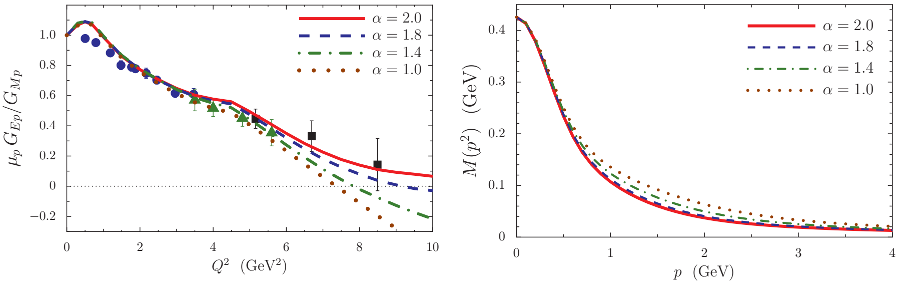
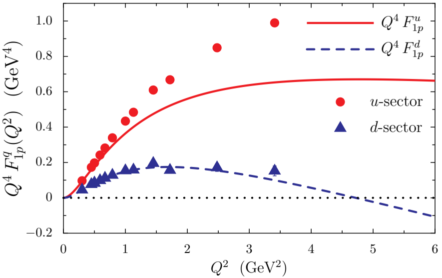
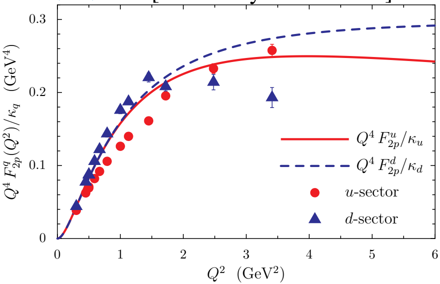


- Polarization transfer measurements of proton G_E/G_M from Jefferson Lab have drawn an enormous amount of attention
  - dispelled decades of perceived wisdom that distributions of charge and magnetization are the same
- Find that slight changes in $M(p)$ on the domain $1 \lesssim p \lesssim 3\,\text{GeV}$ have a striking effect on the G_E/G_M proton form factor ratio
- Strong indication that position of a zero is very sensitive to underlying dynamics and the nature of the transition from nonperturbative to perturbative QCD

Flavour separated proton form factors

[G. D. Cates, C. W. de Jager, *et al.*, Phys. Rev. Lett. **106**, 252003 (2011)] [see talk by Ron Gilman]



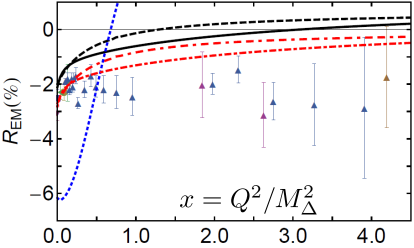


- Prima facie, these experimental results are remarkable
  - u and d quark sector form factors have very different scaling behaviour
- In the context of diquark correlations data straightforward to understand
  - e.g. in the proton the d quark is much more likely to be in a scalar diquark than the doubly-represented u quark; diquark $\Longrightarrow$ $1/Q^2$ suppression
  - ICC, Eichmann, *el al.*, Few Body Syst. **46**, 1 (2009);
    ICC and G. A. Miller, Phys. Rev. C **86**, 015208 (2012);
    J. O. Gonzalez-Hernandez, S. Liuti, *et al.*, Phys. Rev. C **88**, 065206 (2013)
- Future experiments will test for predicted zero in d-quark Dirac form factor

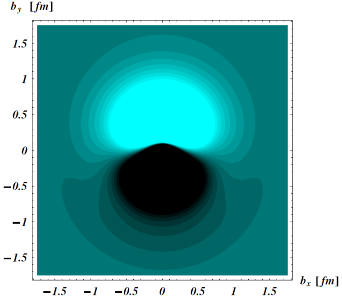
- Given the challenges posed by non-perturbative QCD it is insufficient to study hadron ground-states alone   [see talks by Gothe, Mokeev]

- Nucleon to resonance transition form factors provide a critical extension to elastic form factors – providing many more windows and different perspectives on quark-gluon dynamics
  - nucleon resonances are more sensitive to long-range effects in QCD than the properties of ground states . . . analogous to exotic and hybrid mesons
  - e.g. for $N \to \Delta$ it is found that $R_{EM} = -\frac{G_E^*}{G_M^*}$ is a particularly sensitive measure of *quark orbital angular momentum correlations* in the nucleon and Δ

- Internally consistent continuum-QCD studies all predict a zero in R_{EM}; an essential precursor to discovering pQCD [$R_{EM} \to 1$]; it *must* be found in experiment

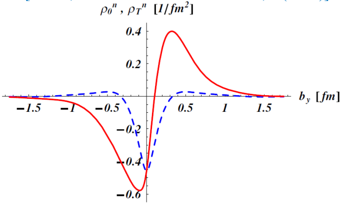


Transverse Charge Densities



Quark transverse charge density for a neutron polarized along the x-axis

[Carlson and Vanderhaeghen, Phys. Rev. Lett. **100**, 032004 (2008)]
[Miller, Ann. Rev. Nucl. Part. Sci. **60**, 1 (2010)]



- It is now recognized that care must be taken when interpreting a 3-D Fourier transform of a form factor as a charge or magnetization density
- A rigorous density can be defined via a 2-D Fourier transform
  - these hadronic transverse charge densities are quantities as seen in a reference frame moving with infinite momentum
- Numerous new physical insights for elastic and transition form factors
  - e.g. the negative central neutron charge density, caused by the dominance of d quarks at the center

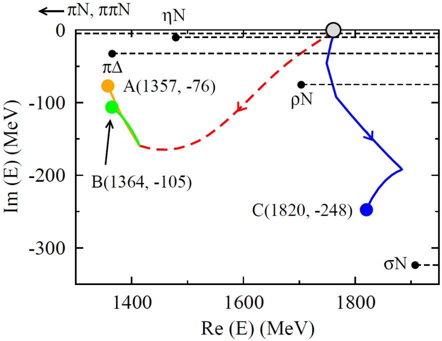
Baryon Spectroscopy

[see talk by Michael Doering]

Three poles, each seeded by a single dressed quark core:

Two poles associated with Roper resonance and the third with the next higher P_{11} resonance

[H. Kamano, *et al.*, Phys. Rev. C **88**, no. 3, 035209 (2013)]



- The Excited Baryon Analysis Center (EBAC), resolved a fifty-year puzzle by demonstrating that the Roper resonance is the proton's first radial excitation
  - its lower-than-expected mass owes to a dressed-quark core shielded by a dense cloud of pions and other mesons
    [Decadal Report on Nuclear Physics: Exploring the Heart of Matter]
- This Experiment/Theory collaborative effort has now evolved into *JLab Physics Analysis Center* (JPAC) [see Michael Pennington's talk]

Some Key References

- I. C. Cloët, G. Eichmann, B. El-Bennich, T. Klahn and C. D. Roberts, *"Survey of nucleon electromagnetic form factors,"* Few Body Syst. **46**, 1 (2009);
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- F. Gross, G. Ramalho and M. T. Pena, *"Covariant nucleon wave function with S, D, and P-state components,"* Phys. Rev. D **85**, 093005 (2012)
- H. Kamano, S. X. Nakamura, T.-S. H. Lee and T. Sato, *"Nucleon resonances within a dynamical coupled-channels model of* πN *and* γN *reactions,"* Phys. Rev. C **88**, no. 3, 035209 (2013);
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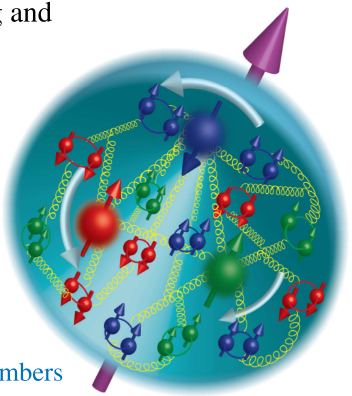
- I. C. Cloët, C. D. Roberts and A. W. Thomas, *"Revealing dressed-quarks via the proton's charge distribution,"* Phys. Rev. Lett. **111**, 101803 (2013);
- J. O. Gonzalez-Hernandez, S. Liuti, G. R. Goldstein and K. Kathuria, *"Interpretation of the Flavor Dependence of Nucleon Form Factors in a GPD Model,"* Phys. Rev. C **88**, 065206 (2013).

Parton Structure

Parton Structure

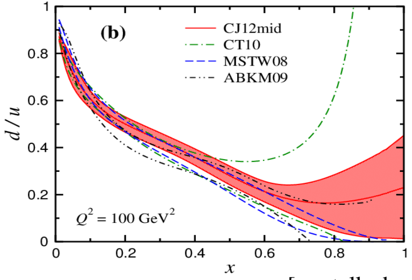
- Understanding hadron structure means charting and computing the distribution of this matter and energy within the hadron
  - mapping correlations and exposing their influence are the hallmark of nuclear physics
- Valence-quark structure of hadrons
  - definitive of a hadron – it's how one tells a proton from a neutron
  - expresses charge; flavour; baryon number; and other Poincaré-invariant macroscopic quantum numbers



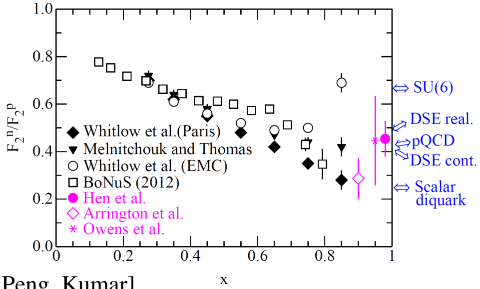
- Flavour content and asymmetry of sea-quark distributions
- The former and any non-trivial structure in the latter, are both essentially nonperturbative features of QCD
- Light front provides a link with quantum mechanics
  - if a probability interpretation is ever valid, it's on the light front

PDFs at $x \to 1$

[CTEQ-Jefferson Lab Collaboration]

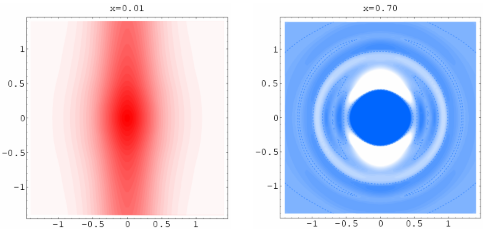


[C. D. Roberts, R. J. Holt and S. M. Schmidt, Phys. Lett. B **727**, 249 (2013)]



[see talks by Qiu, Peng, Kumar]

- Value of PDF ratios at $x = 1$ are fixed points of the evolution equations
  - hence they are very strong tests of nonperturbative dynamics
- For nucleon $x \to 1$ limit provides information on admixture of quark-quark correlations in nucleon wave function
- Existing data cannot discriminate between various scenarios, however a combination of polarized and unpolarized data on $x \gtrsim 0.8$ can



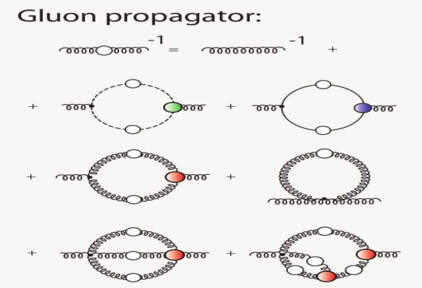
A model parametrization of the u-quark phase space charge distribution inside the nucleon

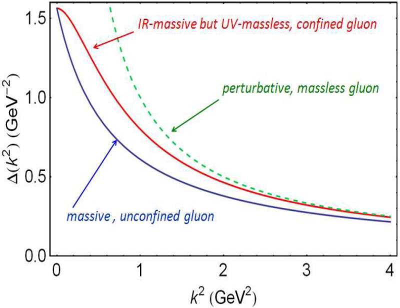
[A. V. Belitsky, X. -d. Ji & F. Yuan, PRD 69, 074014 (2004)]

[see talks by Qiu, Metz & Liuti]

- GPDs and TMDs encode an enormous amount of information about hadrons & certain hard processes
  - understanding these distributions is at forefront of hadron theory
- Information will be revealed by a very close collaboration between experiment and theory
  - these functions must be calculated in framework with well-defined connection to QCD
- This is a critical near-term goal for hadron theory – a closer connection with QCD is required and a greater US effort is needed

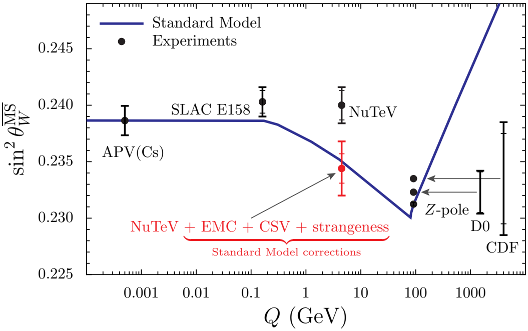
An Eye Toward an EIC





- Gluon satisfies its own gap equation & possesses a dynamically generated mass – which provides an infrared cutoff
  - role of gluons with wavelength larger than $1/m(0)$ is greatly suppressed
- Hadron structure at low Bjorken-x is dominated by gluons
  - features in this regime must reflect infra-red properties of gluon dressing function
  - QCD-connected computations certainly will
- For example, gluon saturation, if observed must be reflected in infra-red properties of QCD's gluon propagator

Beyond Standard Model



Fermilab press conference

"The predicted value was 0.2227. The value we found was 0.2277, a difference of 0.0050. It might not sound like much, but the room full of physicists fell silent when we first revealed the result"

"99.75% probability that the neutrinos are not behaving like other particles . . . only 1 in 400 chance that our measurement is consistent with prediction"

- NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$ [Zeller *et al.* PRL. **88**, 091802 (2002)]
- Standard Model: $\sin^2\theta_W = 0.2227 \pm 0.0004 \Leftrightarrow 3\sigma \Longrightarrow$ "NuTeV anomaly"
- At the time widely thought as evidence for physics beyond Stardard Model
- *However a decade of effort in hadron theory has likely provided a Standard Model explanation* [see talk by Wally Melnitchouk]
  - explained by nuclear effects + charge symmetry violation + strangeness

Some Key References

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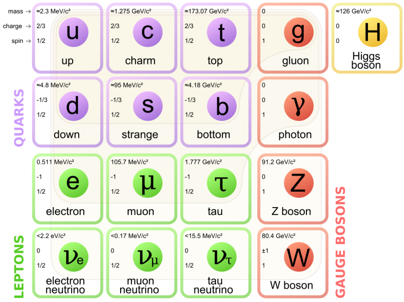
The Future

- QCD and Hadron Physics are unique:
  - must confront a fundamental theory in which the elementary degrees-of-freedom are confined and only hadrons reach detectors



- Continuum-QCD approaches are essential; they are at the forefront of guiding experiment and provide rapid feedback; thereby building intuition & understanding

- Hadron theory will guide and stimulate new endeavors – aimed at exposing the content of the Standard Model and to help discover what lies beyond

- A vibrant and balanced hadron theory program – interacting effectively with experiment – is crucial if the full potential of the nation’s investment in hadron physics is to be realized

- *This will ensure future investments have maximum discovery potential!*