NANJING UNIVERSITY

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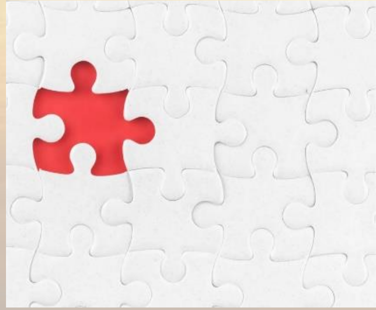
The Importance of Transition Form Factors for a Complete Understanding of QCD

Charting EHM

- Proton was discovered 100 years ago … It is stable; hence, an ideal target in experiments
- But just as studying the hydrogen atom ground state didn't give us QED,
  focusing on the ground state of only one form of hadron matter will not solve QCD
- New era is dawning … high energy + high luminosity
  ⇒ Science can move beyond the focus on the proton
- Precision studies of the structure of
  - Baryon excited states
    - ✓ Baryons are the most fundamental three-body systems in Nature
    - ✓ If we don't understand how QCD, a Poincaré-invariant quantum field theory, builds each of the baryons in the complete spectrum, then we don't understand Nature.
- EHM is not immutable
  - its manifestations are manifold
  - experience ⇒ each hadron reveals different facets
  - One piece does not complete a puzzle



AMBER @ CERN
EIC
EicC & SCT & CEPC
JLab12 & JLab20+

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Nucleon Resonances

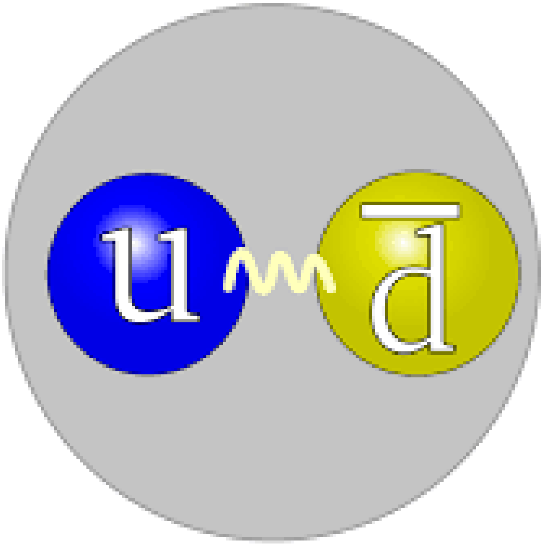
- Ground state is just one isolated member of a set of Hamiltonian eigenvectors with infinitely many elements
- Many Hamiltonians can possess practically equivalent ground states yet lead to excited-state spectra that are vastly different.
- Masses alone, as infrared-dominated quantities, contain relatively little information
  - Example: Faddeev equation with contact *cf*. realistic interaction produce equivalent ground-state spectra
- Different Hamiltonians may adequately reproduce known hadron spectra
- But these same Hamiltonians can yield predictions that disagree markedly when used to compute structural properties.
- Such properties—like wave functions and the Q^2-dependence of elastic and transition form factors—possess the greatest discriminating power.
- Intense study – experiment + phenomenology + theory – of the structure of nucleon resonances is a critical complement to that of ground-state nucleons and mesons because it is capable of revealing additional novel and unique features of strong QCD.

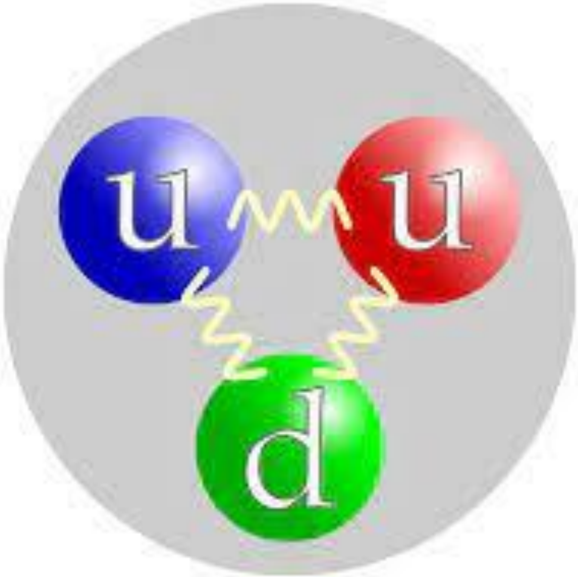
Structure of Baryons

- The most important lessons to be learnt in modern hadron physics are …

  This is NOT a baryon

- *This is NOT a meson*



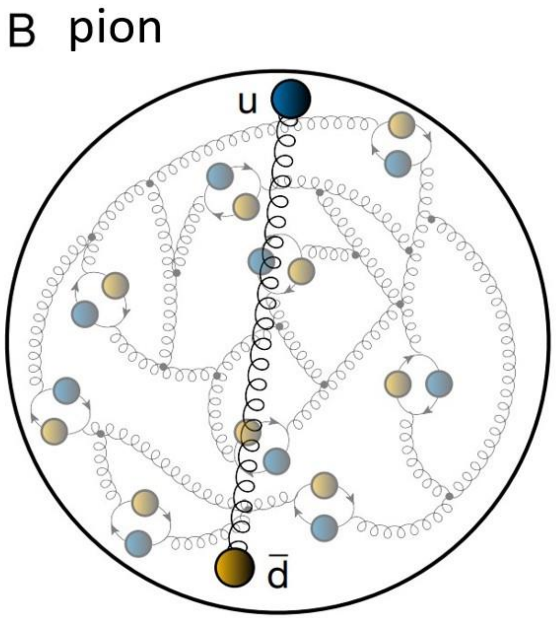


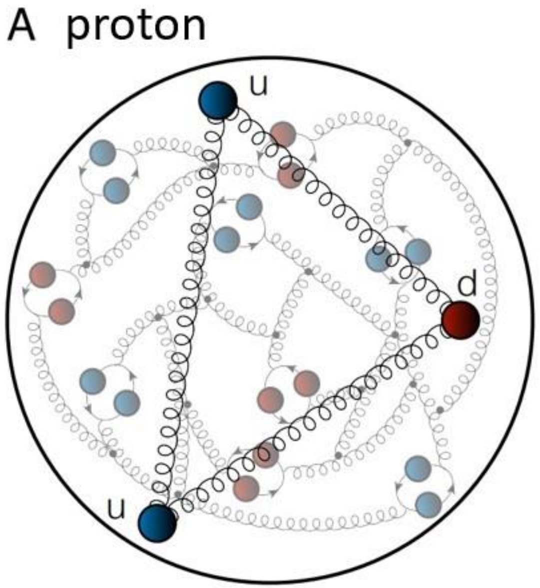
Three "constituent" quarks "confined" within some three-dimensional volume by an instantaneous potential

Structure of Baryons

- The most important lessons to be learnt in modern hadron physics are …

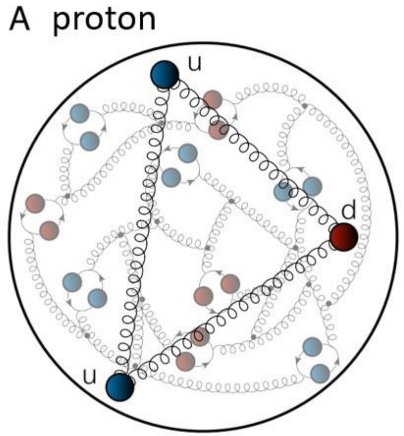
  This IS a baryon
- *This IS a meson*





A few "valence" quark partons and/or antiquark partons, and infinitely many sea and glue partons confined by spacetime-dependent nonperturbative, nonlinear dynamics

Baryon Structure



- Poincaré covariance ⇒ irrespective of quark model assignments $n^{2s+1}\ell_J$, every hadron contains orbital angular momentum, *e.g.*,
  - π contains two S-wave components and two P-wave components
  - Few systems are simply radial excitations of another
- No separation of J into $L + S$ is Poincaré invariant
  - Consequently, *e.g.*, negative parity states are <u>not</u> simply orbital angular momentum excitations of positive parity ground states
- In quantum field theory, there is no direct connection between parity and orbital angular momentum
  - Parity is a Poincaré invariant quantum number
  - L is not Poincaré invariant = value depends on the observer's frame of reference
- QCD structure of hadrons – mesons and baryons – is far richer than can be produced by quark models, relativized or not
  - ✓ *Baryons are the most fundamental three-body systems in Nature*
  - ✓ *If we don't understand how QCD, a <u>Poincaré-invariant quantum field theory</u>, builds each of the baryons in the complete spectrum, then we don't understand Nature.*

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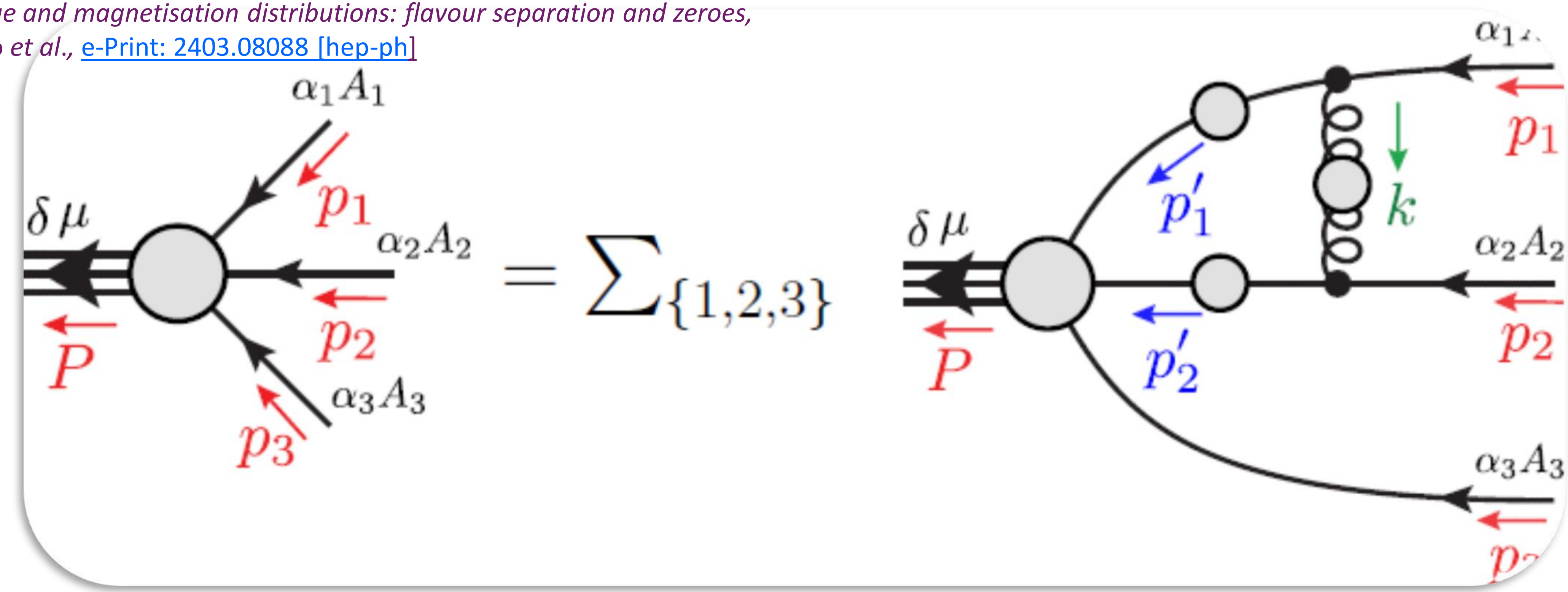
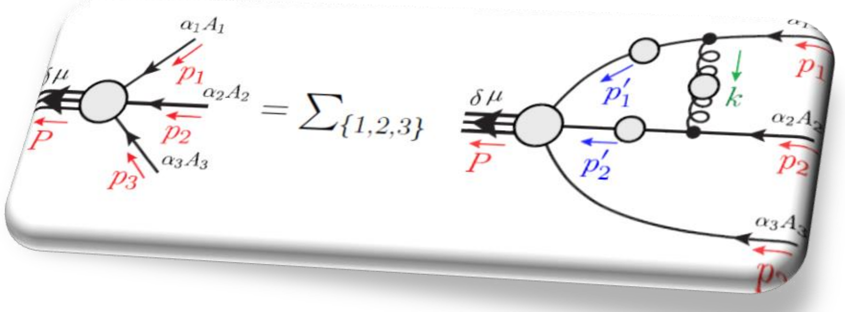
Nucleon mass from a covariant three-quark Faddeev equation
G. Eichmann *et al*., Phys. Rev. Lett. 104 (2010) 201601
Nucleon charge and magnetisation distributions: flavour separation and zeroes,
Zhao-Qian Yao *et al*., e-Print: 2403.08088 [hep-ph]

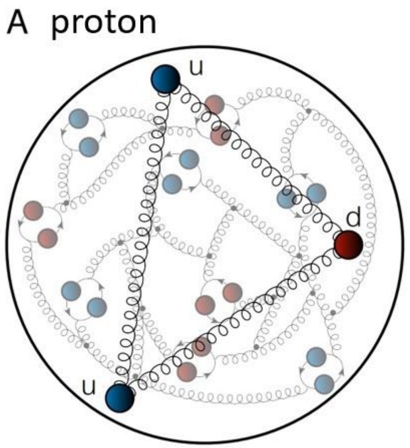


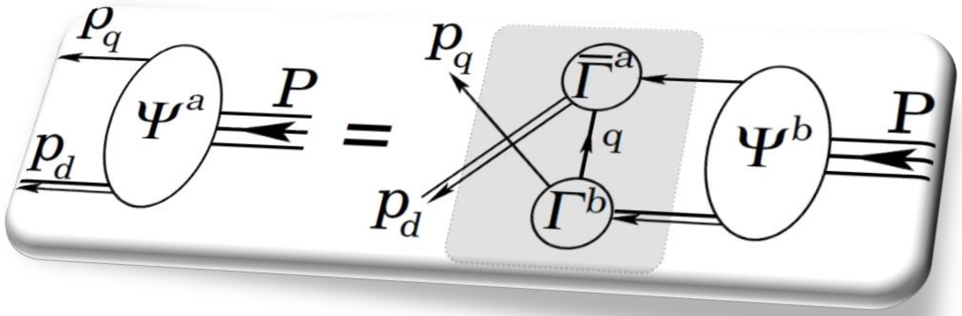
Faddeev Equation for Baryons



Structure of Baryons

- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but numerical challenges remain



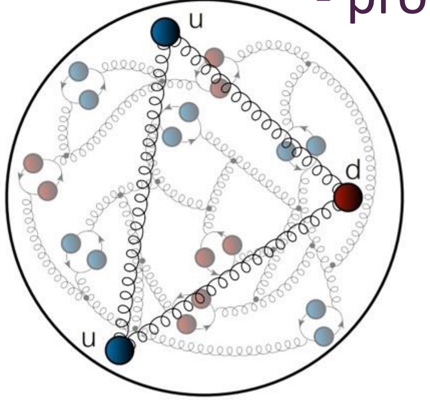


Solution delivers Poincaré-covariant proton wave function

Structure of Baryons

- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but numerical challenges remain – algorithms and numerical analysis
- For many/most applications, diquark approximation to quark+quark scattering kernel is used
- ***Prediction***: owing to EHM phenomena, *strong diquark correlations exist within baryons*

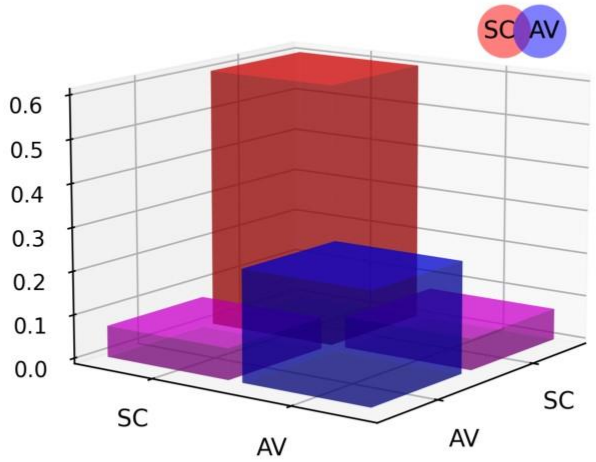
A proton



- proton and neutron … both scalar and axial-vector diquarks are present

✓ CSM prediction = presence of axialvector (AV) diquark correlation in the proton

✓ AV Responsible for ≈ 40% of proton charge



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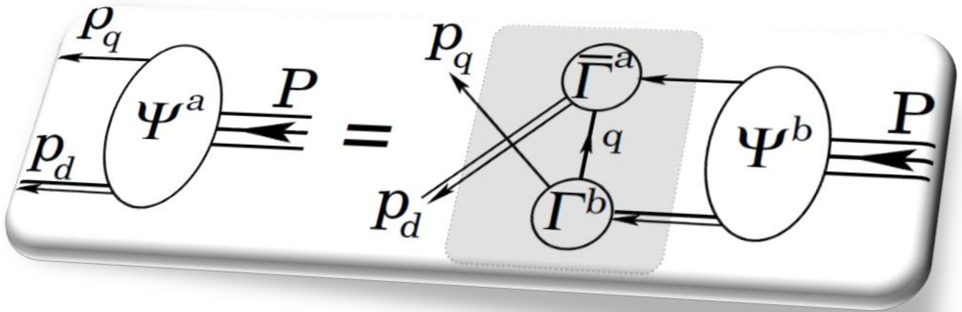
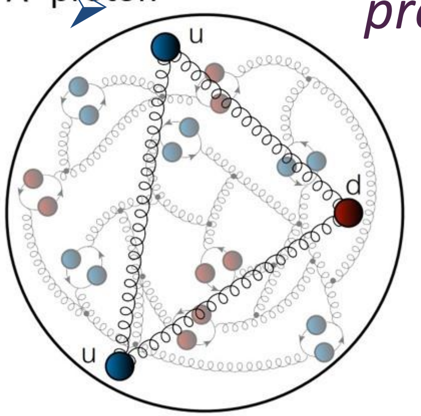
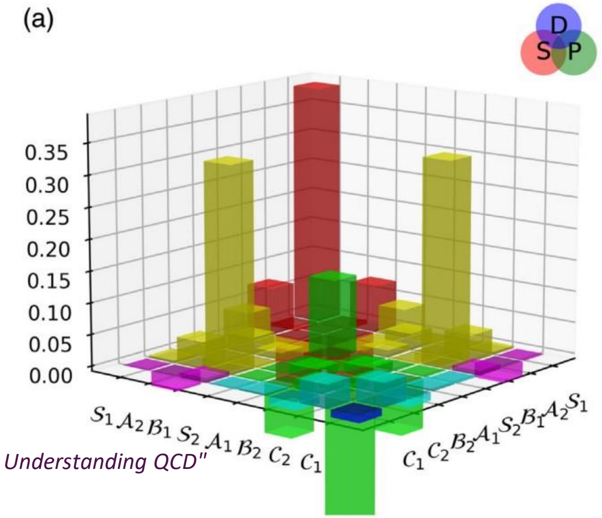


Structure of Baryons

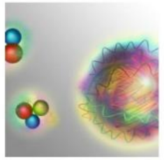
Solution delivers Poincaré-covariant proton wave function

- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but numerical challenges remain
- For many/most applications, diquark approximation to quark+quark scattering kernel is used
- ***Prediction***: owing to EHM phenomena*:*
- *proton wave function is not just S-wave, but contains strong P-wave contributions*





- ✓ CSM prediction = canonical normalization dominated by $S \otimes S$, but receives large $S \otimes P$ and $P \otimes P$ contributions
- ✓ Non-$S \otimes S$ make-up 60% of proton charge



23 September 2019 — 27 September 2019

DIQUARK CORRELATIONS IN HADRON PHYSICS: ORIGIN, IMPACT AND EVIDENCE

Modern experimental facilities, new theoretical techniques for the continuum bound-state problem and progress with lattice-regularized QCD have provided strong indications that soft quarkquark (diquark) correlations play a crucial role in hadron physics.

More info

Diquarks - Facts

- Theory predicts experimental observables that would constitute unambiguous measurable signals for the presence of diquark correlations.
- Some connect with spectroscopy of exotics
  - ✓ tetraquarks and pentaquarks
- Numerous observables connected with structure of conventional hadrons, e.g.
  - ✓ existence of zeros in *d*-quark contribution to proton Dirac and Pauli form factors
  - ✓ Q^2-dependence of nucleon-to-resonance transition form factors
  - ✓ x-dependence of proton structure functions
  - ✓ deep inelastic scattering on nuclear targets (nDIS) … proton production described by direct knockout of diquarks, which subsequently form into new protons

ELSEVIER

Progress in Particle and Nuclear Physics

Volume 116, January 2021, 103835

Review

Diquark correlations in hadron physics: Origin, impact and evidence

M.Yu. Barabanov [1], M.A. Bedolla [2], W.K. Brooks [3], G.D. Cates [4], C. Chen [5], Y. Chen [6, 7], E. Cisbani [8], M. Ding [9], G. Eichmann [10, 11], R. Ent [12], J. Ferretti [13] ✉, R.W. Gothe [14], T. Horn [15, 12], S. Liuti [4], C. Mezrag [16], A. Pilloni [9], A.J.R. Puckett [17], C.D. Roberts [18, 19] ✉ … B.B. Wojtsekhowski [12] ✉

Baryon Structure

- Spectrum of Baryons
- Where comparisons between Models and Continuum and Lattice studies are possible, spectra are largely in agreement
  - Are there missing resonances or not?
  - Continuum and Lattice seem to suggest not
  - Pointlike diquarks are disfavoured
    - composite diquark approaches produce 3-body spectrum
- Structural details, as revealed by elastic and transition form factors, provide a real test of any picture
- Many Hamiltonians can produce a similar spectrum
  … but different Hamiltonians typically produce
  vastly different pictures of hadron internal structure
- Existing form factor information + comparison with phenomenology and theory suggests Nucleon resonances have complex structure:
  - formed from quark core, exposed at larger Q^2,
  - with meson + baryon FSIs playing a significant role at low Q^2

Gather all pieces of the puzzle … Reveal the source of Nature's basic mass-scale

Synergy of Experiment, Phenomenology, Theory

- *Drawing detailed map of the proton is important because proton is Nature's only absolutely stable bound state.*
  - ✓ *However, while QCD is the proton, the proton is not QCD*
- *Strong interaction theory is maturing*
  - ✓ *Expanding array of parameter-free predictions for the proton – yes*
  - ✓ *And all the other hadrons whose properties express the full meaning of QCD*
- *Structure of baryons, e.g., Q^2-dependence of nucleon resonance transition form factors*
  - ✓ *Spectrum is insufficient – many approaches give same spectrum, but form factors discriminate between pictures.*
- *Understanding how QCD's simplicity explains the emergence of hadron mass and structure requires investment in facilities that can deliver precision data on much more than one of Nature's hadrons.*
- *JLab, JLab22, EIC, EicC, could …*
  - ✓ *Deliver precise structure data on a wide range of hadrons with distinctly different quantum numbers*
  - ✓ *Thereby move Science into a new realm of understanding.*