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

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Origin of Visible Mass in the Universe

How did we get here?

The Nature of Things

- Looking at the known Universe, one could be awed by the many complex things it contains.
- Even the Earth itself is complicated enough to generate questions in the minds of we observers
- Basic amongst them are those which focus on our own existence and composition.
- Here, too, there are many levels to be explored, running right down to the nuclei at the core of every atom and molecule
- Even deeper, to the neutrons and protons (nucleons) that constitute those nuclei.
- Faced with all this, physicists nevertheless assume that a few simple mathematical rules should be sufficient to provide a complete explanation of everything we can now perceive, and which might become perceptible in future.
- This may be correct

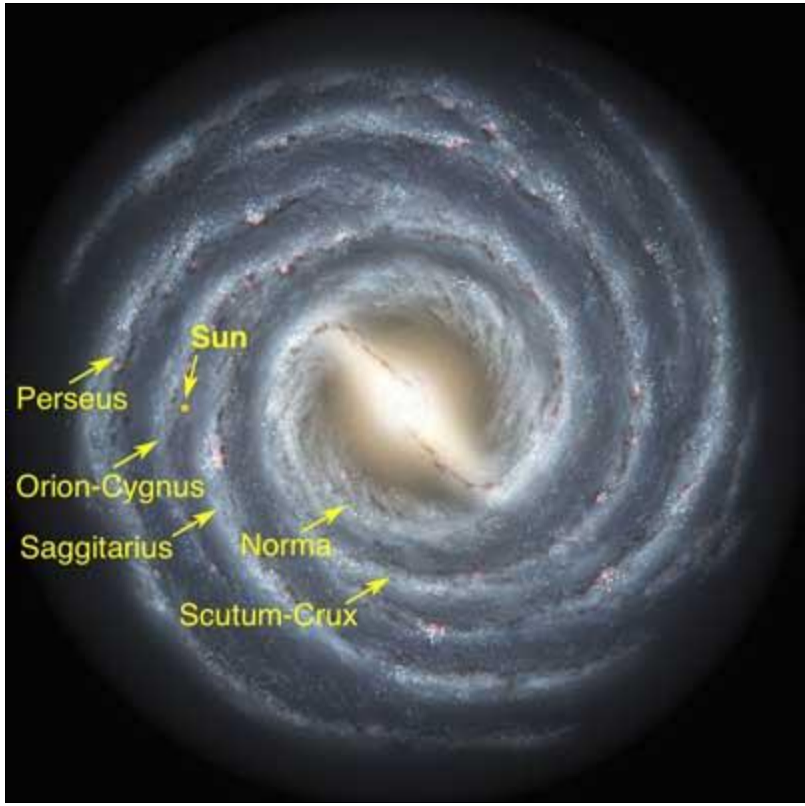
  Or it might be supreme arrogance = hubris

Emergent Phenomena in the Standard Model

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

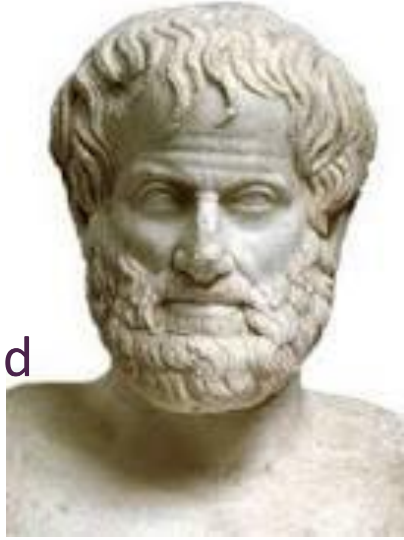
- Proton is massive
  - *i.e.*, the mass-scale for strong interactions – nucleus formation and nuclear structure – is vastly different to that of atomic physics
- Proton is absolutely stable
  - Despite being a composite object constituted from three valence quarks

Neither of these things is evident from just looking at the known/supposed Standard Laws of Nature



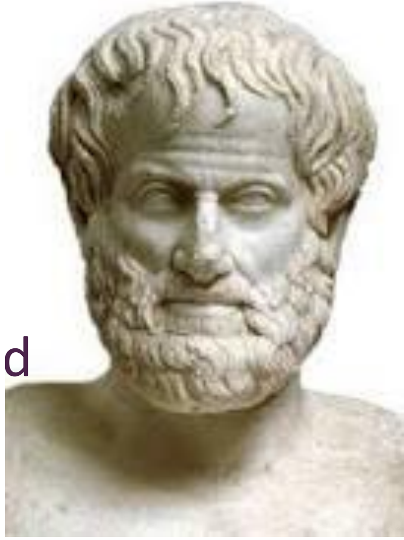
Emergence: low-level rules producing high-level phenomena, with enormous apparent complexity

Emergentism



- One might define emergent phenomena as those features of Nature which don't readily admit explanation solely in terms of known or conjectured rules.
- The concept is at least as old as Aristotle (384-322 BC), who argued that a compound item can have (emergent) properties in the whole which are not explicable merely through the independent actions of the item's constituent parts.
- Aristotle's view is often represented by the statement:
  "The whole is more than the sum of its parts".
- In this sense, *emergence* has its origins in the Greek "sunergos": "together" plus "working" = origin of our concept of synergy (协同效应), *viz*. things working together more effectively than could be anticipated from their independent actions in isolation.
- This perspective is typically contrasted with that described as *Reductionism*; namely, the view that everything in Nature can ultimately be viewed as no more complex in principle than,
  e.g. a (very good) watch, which is clearly a complex object; but, equally clearly, not more than the sum of its parts.

Emergentism



How does simplicity beget elegant complexity in the emergence of the most fundamental structures in Nature?

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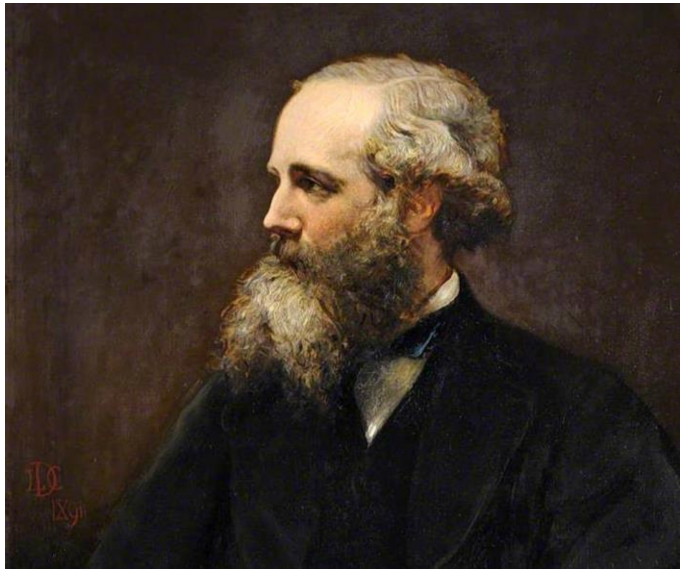
Three Great Unifications

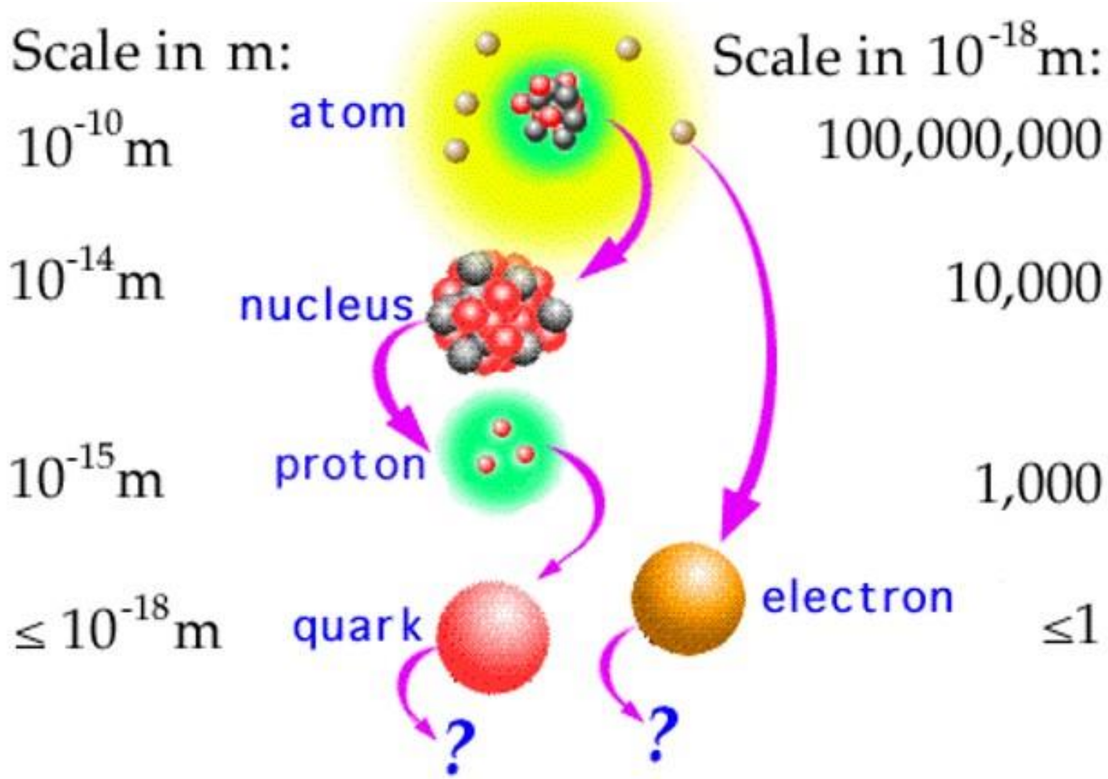
- ✓ "First Great Unification" – Isaac Newton – 350 years ago
  - ✓ Universal Law of Gravitation
  - ✓ Unified the understandings of the observable phenomena of gravity on Earth with the observable behaviour of celestial bodies in space
- ✓ "Second Great Unification" – 155 years ago – James Clerk Maxwell
  - ✓ Formulated the classical theory of electromagnetic radiation, unifying
    electricity + magnetism + light
    as different manifestations of the same phenomenon.



Great Unifications

- "Third Great Unification" – Standard Model of Particle Physics
- 1967 – S. Weinberg "A Model of Leptons"

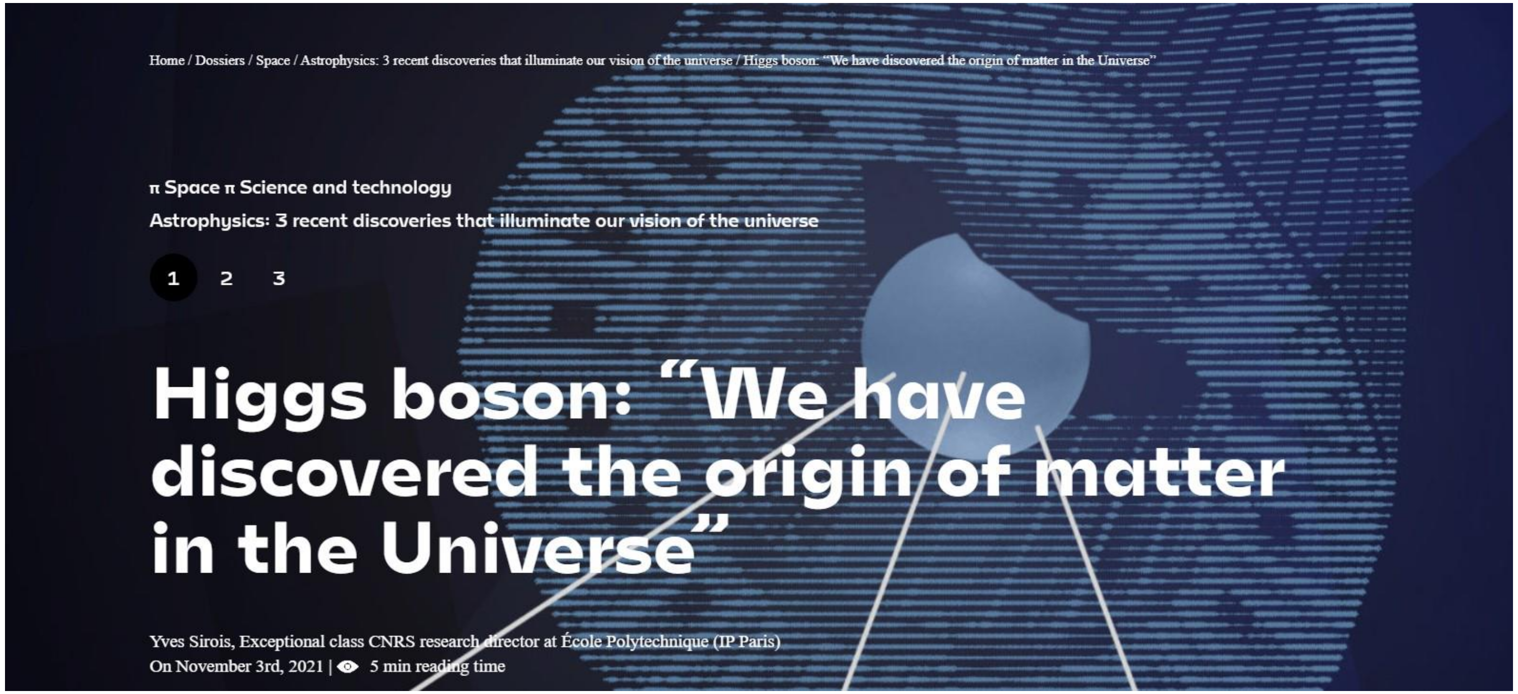
  ~ 13,800 citations
- "The most successful theory ever conceived …"
  - All particles predicted to exist have been found.
  - The masses of those particles lie within 1% of the theoretical values anticipated by the model.
  - 55 Nobel Prizes awarded for key developments and discoveries
- Description of all known fundamental physics except for gravity, and gravity is something that has no detectable effect when particles are studied a few at a time.



2013: Englert & Higgs

- 2012 – Higgs boson discovered at LHC

  With this discovery the Standard Model of Particle Physics became complete.
- 2013 – Nobel Prize in Physics was awarded to Peter Higgs and Francois Englert



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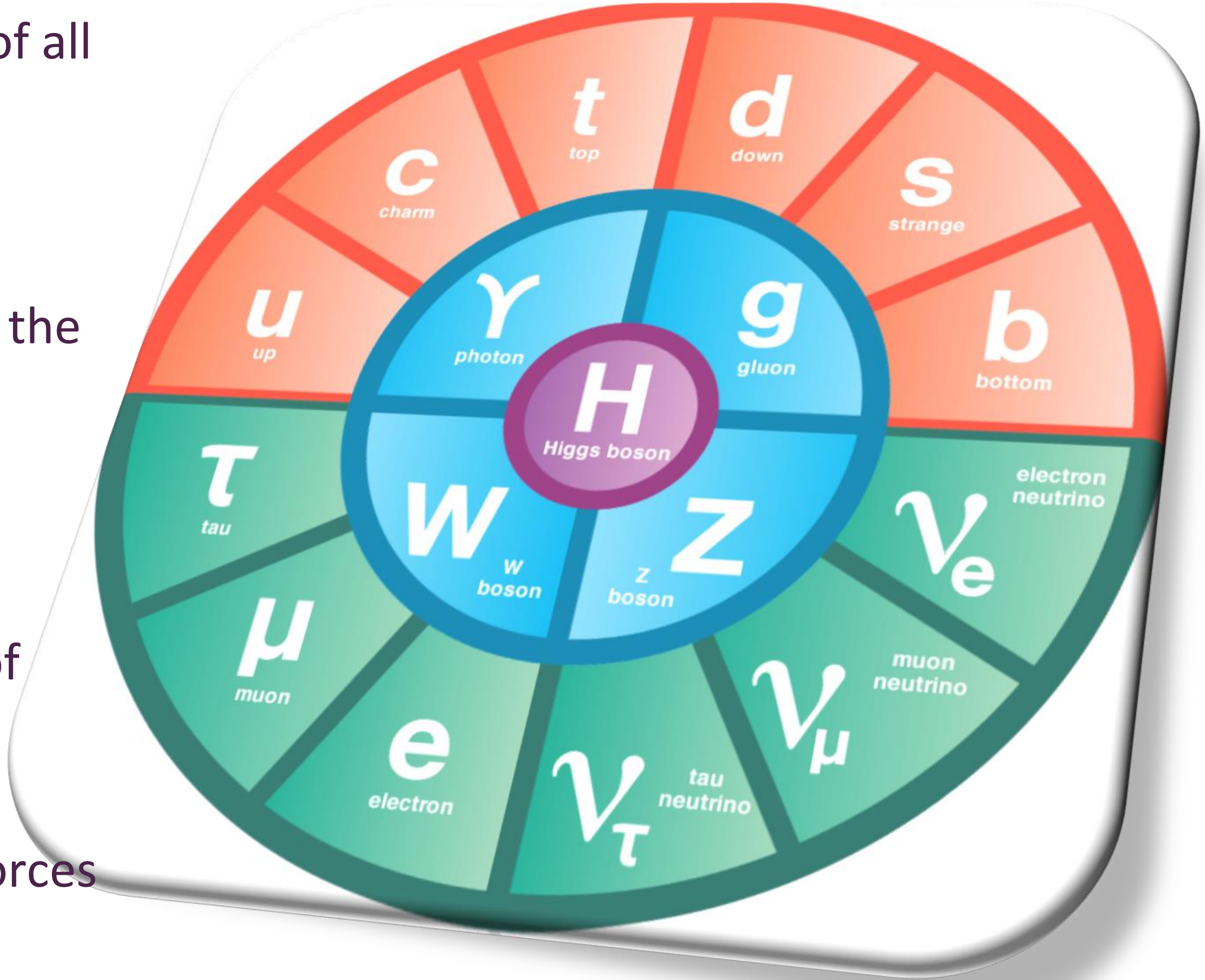
Where to now?

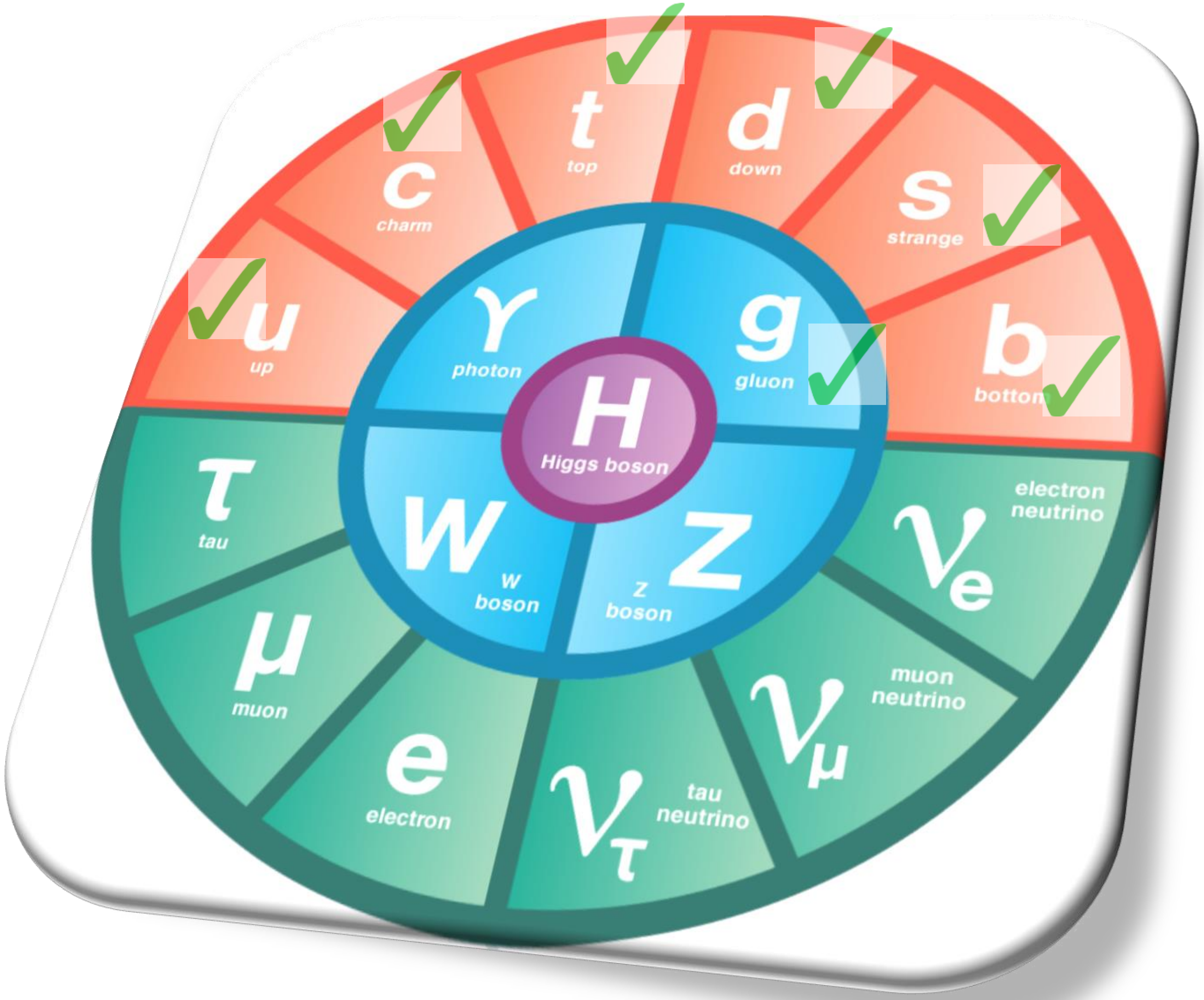
Standard Model of Particle Physics

- Standard Model (SM) offers a description of all known fundamental physics except gravity
- Gravity has no discernible effect when particles are studied a few at a time.
- Since LHC's discovery of the Higgs in 2012, the Higgs Boson has been promoted to the *Centre of Things*
- Standard Model has *17 particles and 19 parameters*, most of which relate to the Higgs and all of which must be determined through comparison with experiment
- SM supposedly describes most powerful forces in Nature
- Yet, somewhat unsatisfactory



Standard Model of Particle Physics

- Strong Interactions in the Standard Model are supposed to be described by quantum chromodynamics (QCD)
- Only two parameters are intrinsic to QCD
  - Higgs enters through current-quark masses
- One of them – θ_{QCD} – appears to be zero (exactly or almost) … know this because nucleon EDM is (as yet) unmeasurably small
- Just one parameter remains to be fixed
- Perhaps science has a chance of <u>*understanding*</u> QCD ∈ SM?



Strong Interactions in the Standard Model

THE DILEMMA OF ATTRIBUTION

Nobel Lecture, December 8, 2004

by

H. DAVID POLITZER

California Institute of Technology (Caltech), Pasadena, USA.

- The establishment by the mid-1970’s of QCD as the correct theory of the strong interactions completed what is now known prosaically as the Standard Model.
- It offers a description of all known fundamental physics except for gravity, and gravity is something that has no discernible effect when particles are studied a few at a time.
- However, the situation is a bit like the way that the Navier-Stokes equation accounts for the flow of water. The equations are at some level obviously correct, but there are only a few, limited circumstances in which their consequences can be worked out in any detail.
- Nevertheless, many leading physicists were inclined to conclude in the late 1970’s that the task of basic physics was nearly complete, and we’d soon be out of jobs.
- A famous example was the inaugural lecture of Stephen Hawking as Lucasian Professor of Mathematics, a chair first held by Isaac Barrow at Cambridge University. Hawking titled his lecture, “Is the End in Sight for Theoretical Physics?” And he argued strongly for “Yes”.

Emergence of Hadron Mass

- Standard Model of Particle Physics has one (widely) *known* mass-generating mechanism

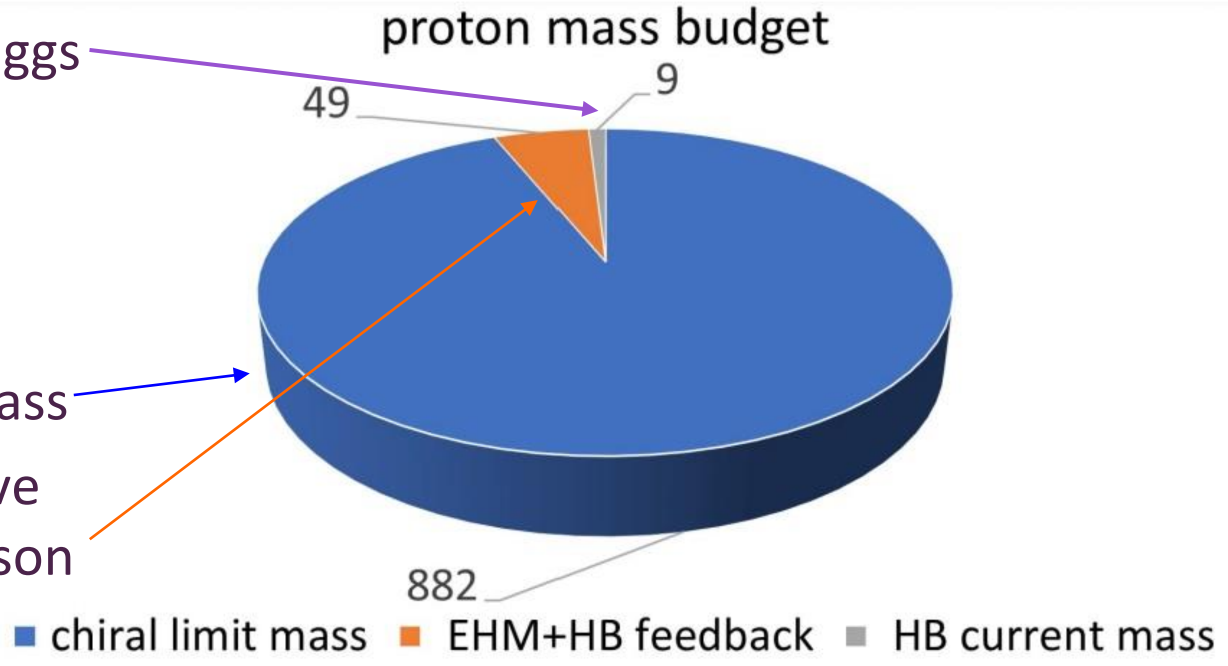
  = Higgs Boson … impacts are critical to evolution of Universe as we know it
- However, Higgs boson is alone responsible for just ~ 1% of the visible mass in the Universe
- Proton mass budget

  Only 9 MeV/939 MeV is directly from Higgs
- Evidently, Nature has another, ***very effective*** mechanism for producing mass:

  Emergent Hadron Mass (EHM)

  ✓ Alone, it produces 94% of the proton's mass

  ✓ Remaining 5% is generated by constructive interference between EHM and Higgs-boson



Emergence of Hadron Mass - Basic Questions

- What is the origin of EHM?
- Does it lie within the Standard Model, i.e., within QCD
- What are the connections with …
  - Gluon and quark confinement?
  - Dynamical chiral symmetry breaking (DCSB)?
  - Nambu-Goldstone modes = π & K?
- What is the role of Higgs in modulating observable properties of hadrons?
  - Critically, without Higgs mechanism of mass generation, π and K would be indistinguishable
- Whence mass?

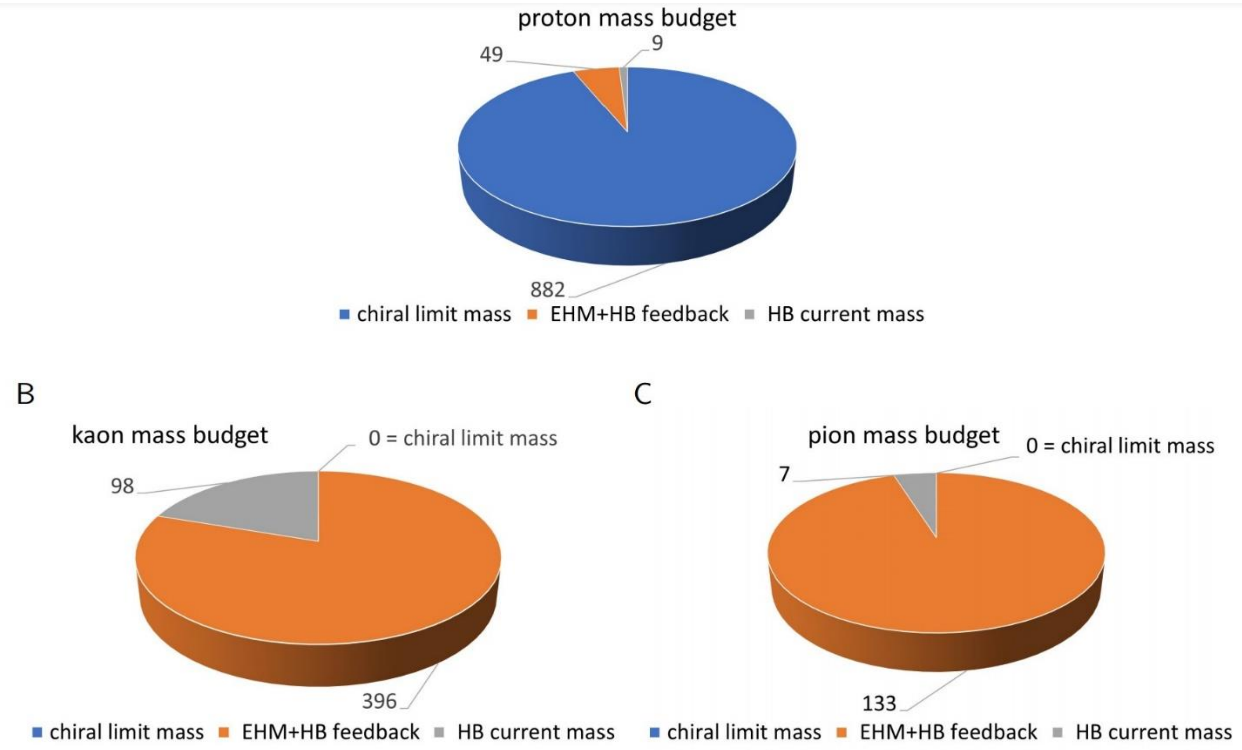


FIG. 1.1. Mass budgets for A – proton, B – kaon and C – pion, drawn using a Poincaré invariant decomposition. There are crucial differences. The proton's mass is large in the chiral limit, *i.e.* even in the absence of Higgs couplings into QCD. This nonzero chiral-limit component is an expression of emergent hadronic mass (EHM) in the SM. Conversely and yet still owing to EHM via its dynamical chiral symmetry breaking (DCSB) corollary, the kaon and pion are massless in the chiral limit – they are the SM's Nambu-Goldstone modes [24–27]. (See Eq. (2.22) below.) (Units MeV, separation at $\zeta = 2\,\text{GeV}$, produced using information from Refs. [8, 21–23].)

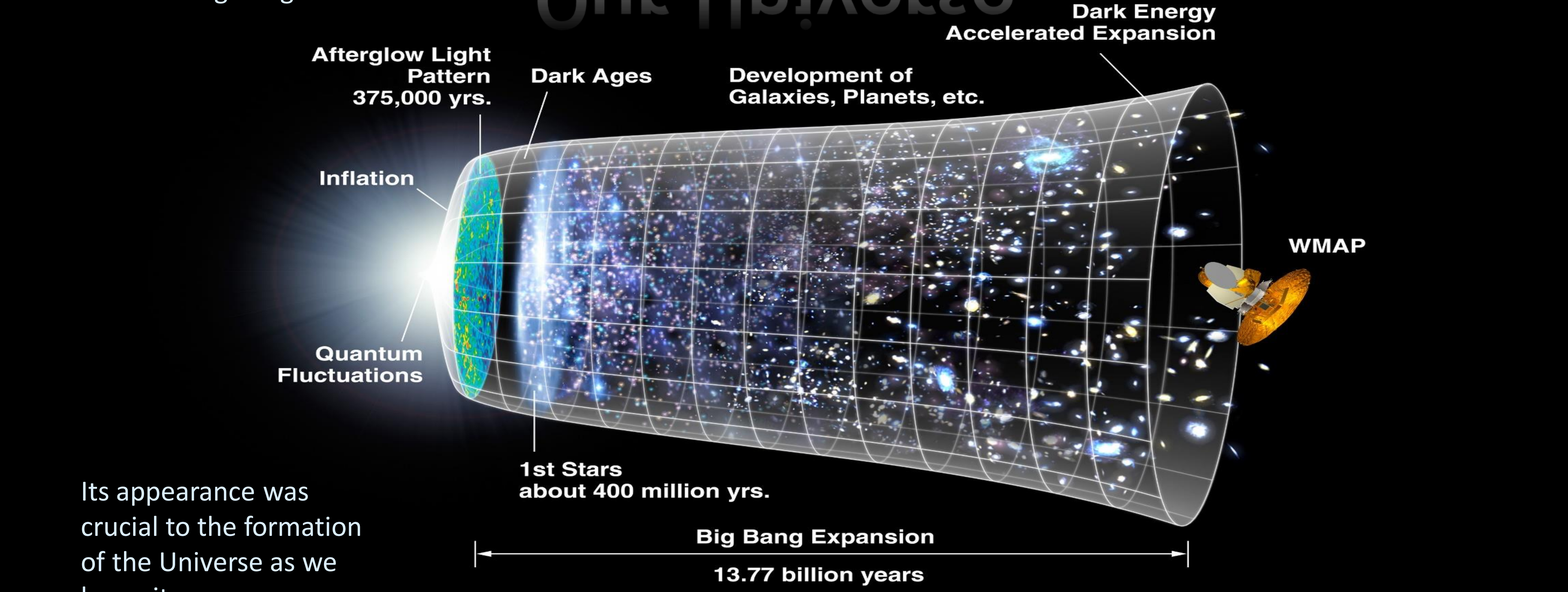
Visible Mass

- More than 98% of visible mass is contained within nuclei.
- First approximation:
  - atomic weights = sum of the masses of all the nucleons they contain.
- Each nucleon has a mass $m_N \sim 1$ GeV ≈ 2000 m_e
- Higgs boson produces m_e, but what produces m_N = remaining 1999 m_e?
- This question is basic to the whole of modern physics
  - **How can science explain the emergence of hadron mass (EHM)?**

Origin of Mass:
The Frontier of Physics

Our Universe

Mass originated 0.000001 second after the Big Bang

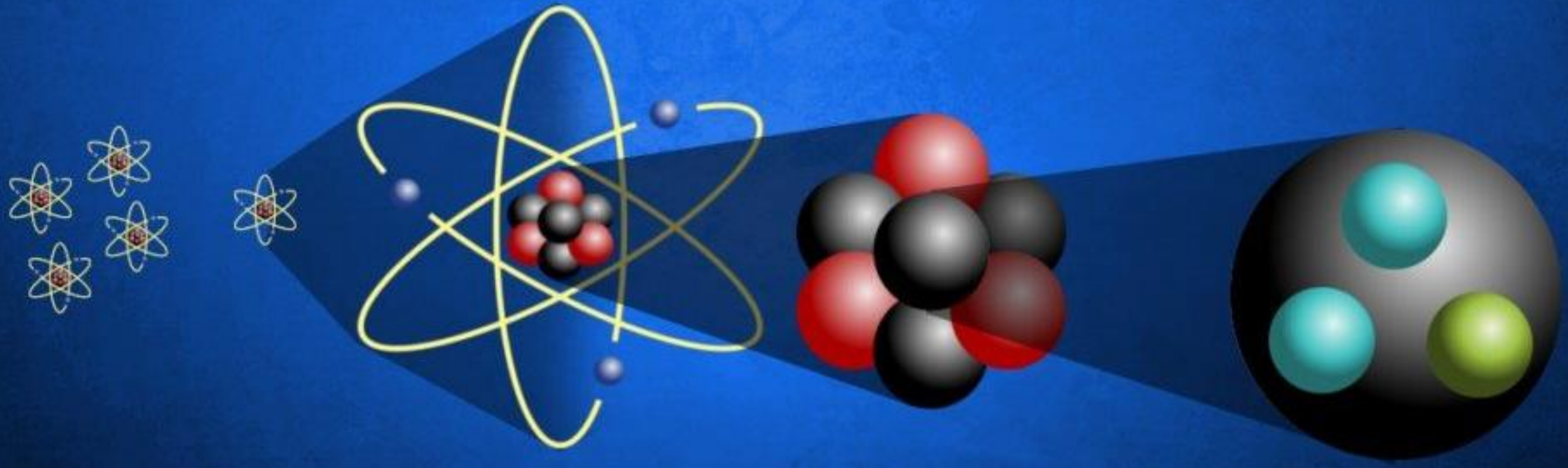


Its appearance was crucial to the formation of the Universe as we know it

2013: Englert & Higgs

- The most important chapter of the Standard Model is the least understood.
- Quantum Chromodynamics (QCD) is supposed to describe all nuclear physics
  - Matter = quarks
  - Gauge bosons = gluons
- Yet, fifty years after discovery of quarks, we are only just beginning to understand how QCD moulds the basic elements of nuclei:
  pions, neutrons, protons, etc.
- And there are controversies – as theory begins to predict quantities that hitherto were only inferred from measurements via phenomenological fits

Quarks? What are quarks?



And what are the gluons that bind them together inside the proton?

Revolutions in the Early 20th Century

- Quantum Mechanics & Special Relativity
  - Unification encountered many problems
- Nonrelativistically, all particles have mass

  But masslessness is possible in relativistic theories – Einstein's photon
- Antimatter is predicted by relativistic quantum mechanics – Dirac Equation
  - Antimatter = negative-energy matter … so, for any given system
    - It costs ZERO energy to create a virtual matter+antimatter pair
    - or 10 such pairs, or 100 pairs, … or infinitely many!
- Quantum mechanics is exactly solvable theory when number of particles is finite (~ 14, with today's computers and realistic Hamiltonians)
- Quantum mechanics is *unsolvable* when there are infinitely many particles
- Relativistic quantum mechanics requires existence of massless particles & antimatter but existence of either destroys relativistic quantum mechanics!

Solving the Problem with Antimatter

- There is only one way known to combine quantum mechanics and special relativity

Relativistic Quantum Field Theory

- 1st example: *Electromagnetism*
  - Quantum electrodynamics (QED), 1946-1950
  - Feynman, Schwinger, Tomonaga
    - Nobel Prize (1965):

      "for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles".

Solving the Problem with Antimatter

- There is only one way known to combine quantum mechanics and special relativity

Relativistic Quantum Field Theory

- 2nd example: Weak interaction
  - Radioactive decays, parity-violating decays, electron-neutrino scattering
  - Glashow, Salam, Weinberg - 1963-1973
    - Nobel Prize (1979):
    - *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including,* inter alia, *the prediction of the weak neutral current".*

Solving the Problem with Antimatter

- 3rd example:

  Strong interaction … all of nuclear physics and anything made from nuclei = basically everything that we can see and/or touch

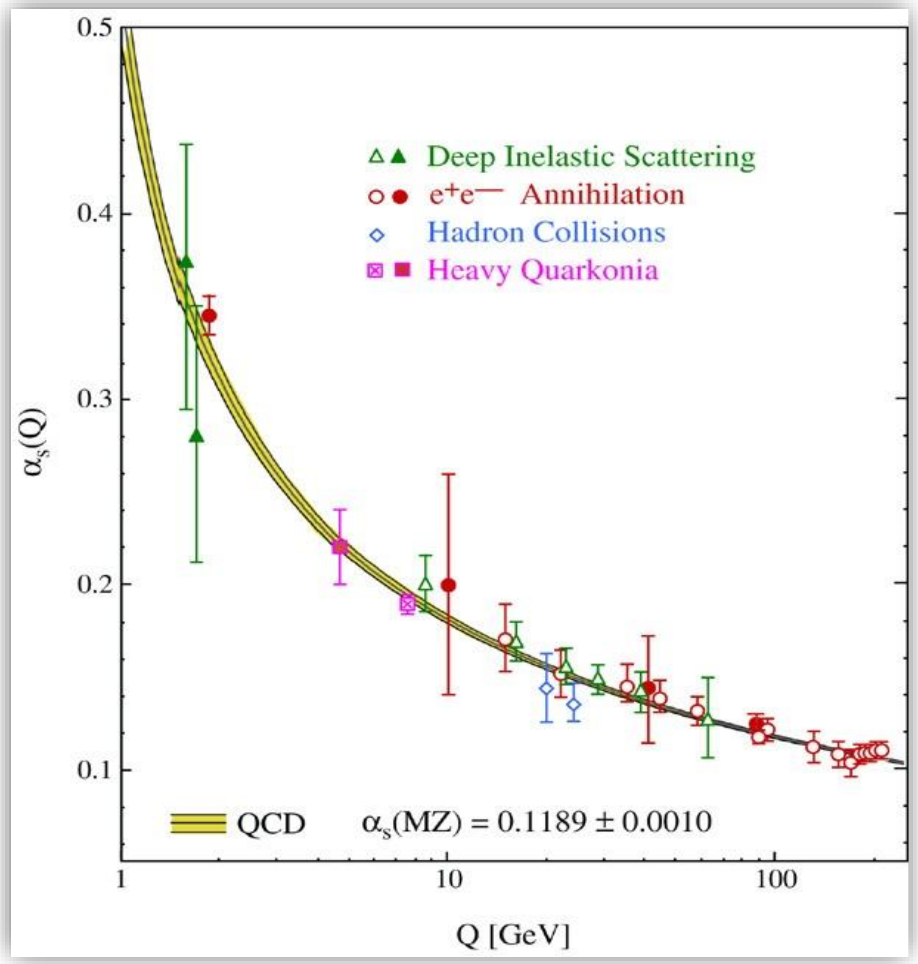
  – Existence and composition of the vast bulk of visible matter in the Universe:
    - proton, neutron
    - the forces that form them and bind them into nuclei
    - responsible for more than 98% of the visible matter in the Universe

  – Politzer, Gross and Wilczek – 1973-1974
    Quantum Chromodynamics – QCD
    - Nobel Prize (2004):

      "for the discovery of asymptotic freedom in the theory of the strong interaction".

This is where we live

⇐
What's happening out here?!



Asymptotic Freedom

Interaction becomes weaker as energy grows (charges get closer together)

QCD's Running Coupling

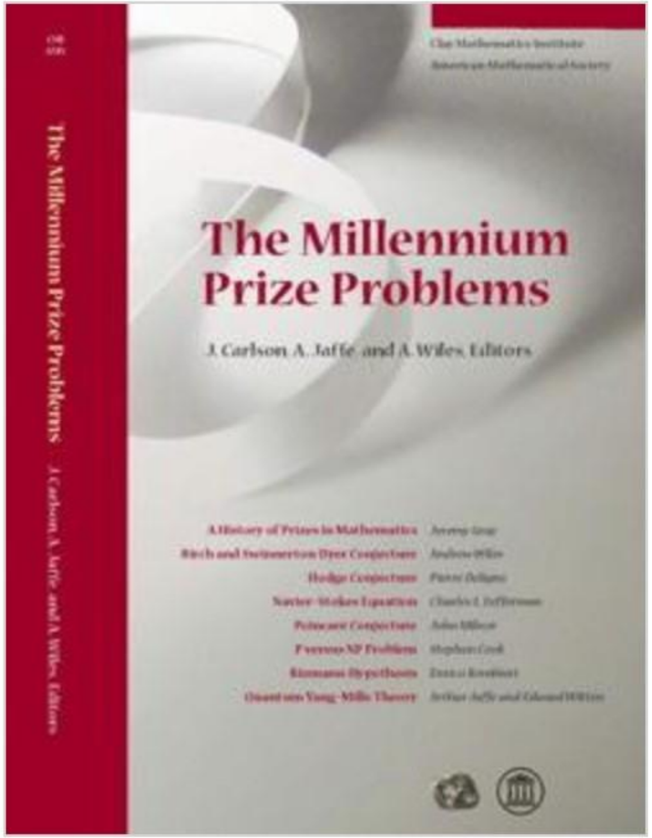
Quantum Chromodynamics

$$L = \frac{1}{4} G^a_{\mu\nu}(x) G^a_{\mu\nu}(x) + \bar{\psi}\left[\gamma \cdot \partial_x + m + ig\,\frac{\lambda^a}{2}\gamma \cdot A^a(x)\right]\psi(x)$$

$$G^a_{\mu\nu}(x) = \partial_\mu A^a_\nu(x) - \partial_\nu A^a_\mu(x) - f^{abc} A^b_\mu(x) A^c_\nu(x)$$

One line
Describes all properties of
the bulk of visible matter

The Millennium Prize Problems



On August 8, 1900, at the second International Congress of Mathematicians in Paris, David Hilbert delivered the famous lecture in which he described twenty-three problems that were to play an influential role in future mathematical research. A century later, on May 24, 2000, at a meeting at the Collège de France, the Clay Mathematics Institute announced the creation of a US$7 million prize fund for the solution of seven important classic problems that have resisted solution. The prize fund is divided equally among the seven problems. There is no time limit for their solution.

The Millennium Prize Problems were selected by the founding Scientific Advisory Board of CMI, Alain Connes, Arthur Jaffe, Andrew Wiles, and Edward Witten, after consultation with other leading mathematicians. Their aim was somewhat different than that of Hilbert: not to define new challenges, but to record some of the most difficult issues with which mathematicians were struggling at the turn of the second millennium; to recognize achievement in mathematics of historical dimension; to elevate in the consciousness of the general public the fact that in mathematics the frontier is still open and abounds in important unsolved problems; and to emphasize the importance of working toward a solution of the deepest, most difficult problems.

The Millennium Prize Problems gives the official description of each of the seven problems and the rules governing the prizes. It also contains an essay by Jeremy Gray on the history of prize problems in mathematics.

Excerpt from the top-10

The New York Times

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS | OPINION

10 Physics Questions to Ponder for a Millennium or Two

By George Johnson
Published: August 15, 2000

- ***Can we quantitatively understand quark and gluon confinement in quantum chromodynamics and the existence of a mass gap?***

  Quantum chromodynamics is the theory describing the strong nuclear force. Carried by gluons, it binds quarks into particles like protons and neutrons. Apparently, the tiny subparticles are permanently confined: one can't pull a quark or a gluon from a proton because the strong force gets stronger with distance and snaps them right back inside.

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Millennium prize of $1,000,000 for proving that $SU_c(3)$ gauge theory is mathematically well-defined, which will necessarily prove or disprove a confinement conjecture

142 MILLENNIUM PRIZE PROBLEMS

YANG–MILLS EXISTENCE AND MASS GAP. *Prove that for any compact simple gauge group G, a non-trivial quantum Yang–Mills theory exists on $\mathbb{R}^4$ and has a mass gap $\Delta > 0$. Existence includes establishing axiomatic properties at least as strong as those cited in* [**45, 35**].

5. Comments

An important consequence of the existence of a mass gap is clustering: Let $\vec{x} \in \mathbb{R}^3$ denote a point in space. We let H and $\vec{P}$ denote the energy and momentum, generators of time and space translation. For any positive constant $C < \Delta$ and for any local quantum field operator $\mathcal{O}(\vec{x}) = e^{-i\vec{P}\cdot\vec{x}}\mathcal{O}e^{i\vec{P}\cdot\vec{x}}$ such that $\langle\Omega, \mathcal{O}\Omega\rangle = 0$, one has

$$|\langle\Omega, \mathcal{O}(\vec{x})\mathcal{O}(\vec{y})\Omega\rangle| \leq \exp(-C|\vec{x} - \vec{y}|), \tag{2}$$

as long as $|\vec{x} - \vec{y}|$ is sufficiently large. Clustering is a locality property that, roughly speaking, may make it possible to apply mathematical results established on $\mathbb{R}^4$ to any 4-manifold, as argued at a heuristic level (for a supersymmetric extension of four-dimensional gauge theory) in [**49**]. Thus the mass gap not only has a physical significance (as explained in the introduction), but it may also be important in mathematical applications of four-dimensional quantum gauge theories to geometry. In addition the existence of a uniform gap for finite-volume approximations may play a fundamental role in the proof of existence of the infinite-volume limit.

There are many natural extensions of the Millennium problem. Among other things, one would like to prove the existence of an isolated one-particle state (an upper gap, in addition to the mass gap), to prove confinement, to

Confinement?

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Yang–Mills Existence and Mass Gap. *Prove that for any compact simple gauge group G, a non-trivial quantum Yang–Mills theory exists on $\mathbb{R}^4$ and has a mass gap $\Delta > 0$. Existence includes establishing axiomatic properties at least as strong as those cited in* [**45, 35**].

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$$(2) \qquad |\langle\Omega, \mathcal{O}(\vec{x})\mathcal{O}(\vec{y})\Omega\rangle| \leq \exp(-C|\vec{x} - \vec{y}|),$$

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Confinement?

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$$G^a_{\mu\nu}(x) = \partial_\mu A^a_\nu(x) - \partial_\nu A^a_\mu(x) - f^{abc} A^b_\mu(x) A^c_\nu(x)$$

- One-line Lagrangian – expressed in terms of gluon and quark partons
- Which are NOT the degrees-of-freedom measured in detectors

Questions

- What are the (asymptotic) detectable degrees-of-freedom?
- How are they built from the Lagrangian degrees-of-freedom?
- Is QCD really the theory of strong interactions?
- Is QCD really a theory? ⇒ Implications far beyond Standard Model

Quantum Chromodynamics

- QCD is the first place that humankind has fully experienced the collision between quantum mechanics and special relativity
- In attempting to match QCD with Nature, we confront the innumerable complexities of nonperturbative, nonlinear dynamics in relativistic quantum field theory, *e.g.*
  - the loss of particle number conservation
  - the frame and scale dependence of the explanations and interpretations of observable processes
  - and the evolving character of the relevant degrees-of-freedom
- Electroweak theory and phenomena are essentially perturbative, possessing none of this complexity

Strong Interactions in the Standard Model

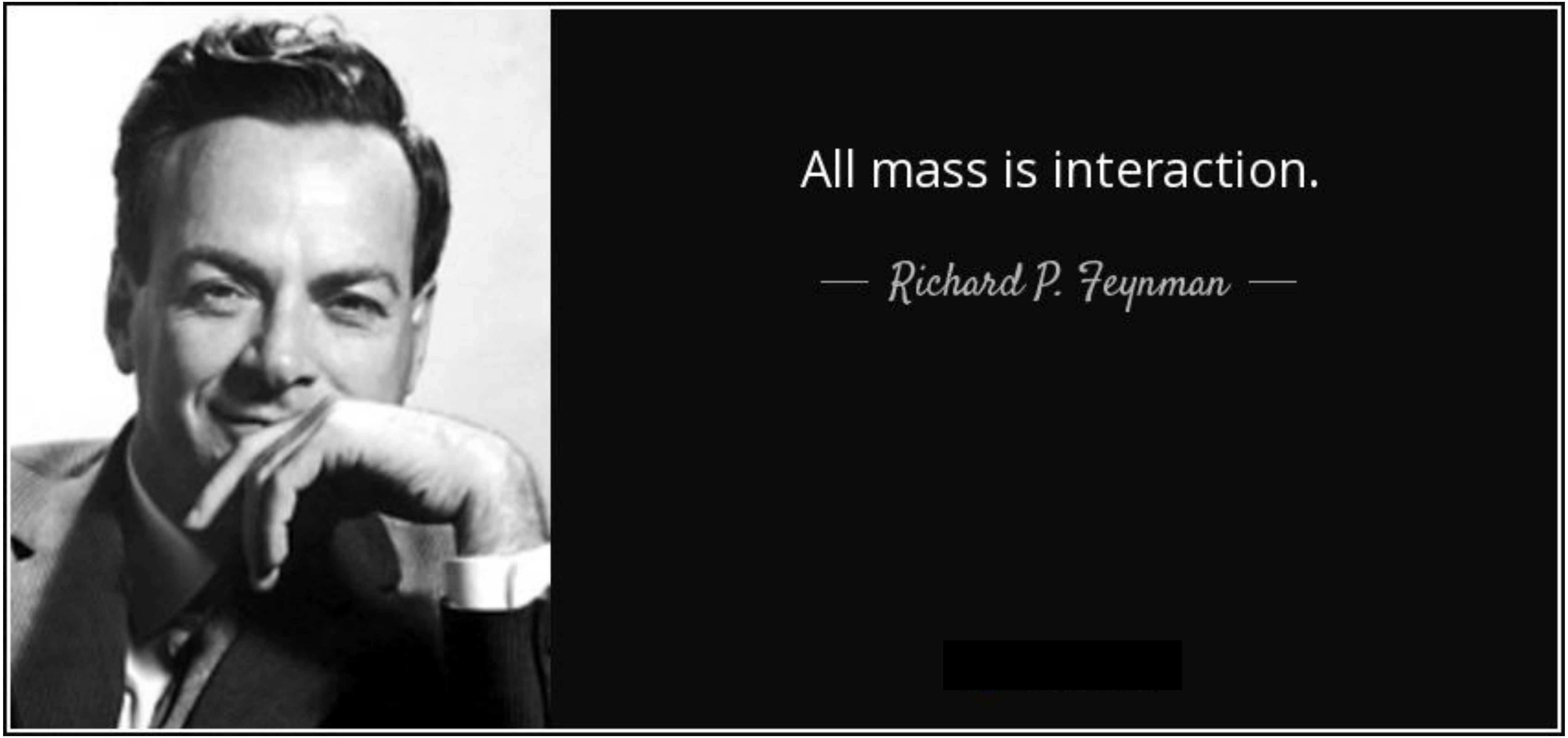
$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\, \delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

- Only apparent scale in chromodynamics is mass of the quark field
- Quark mass is said to be generated by Higgs boson.
- In connection with everyday matter, that mass is less-then 0.5% of the empirical scale for strong interactions,
  viz. more-than two orders-of-magnitude smaller
- Plainly, the Higgs-generated mass is very far removed from the natural scale for strongly-interacting matter
- *Nuclear physics mass-scale* – 1 GeV – is an *emergent feature of the Standard Model*
  - No amount of staring at $L_{\rm QCD}$ can reveal that scale
- Contrast with quantum electrodynamics, *e.g*. spectrum of hydrogen levels measured in units of m_e, which appears in $L_{\rm QED}$

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

Whence Mass?

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


All mass is interaction.
— Richard P. Feynman —
[redacted]

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

Trace Anomaly

- In a scale invariant theory

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

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

  … *dimensional transmutation*:

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

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

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

QCD β function … specifies how the coupling "runs"

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

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

Trace Anomaly

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

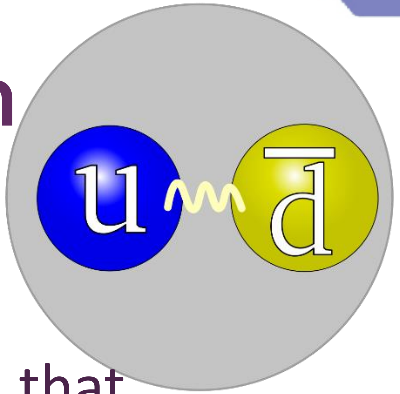
$$\langle p(P)|T_{\mu\nu}|p(P)\rangle = -P_\mu P_\nu$$
$$\langle p(P)|T_{\mu\mu}|p(P)\rangle = -P^2 = m_p^2$$
$$= \langle p(P)|\Theta_0|p(P)\rangle$$

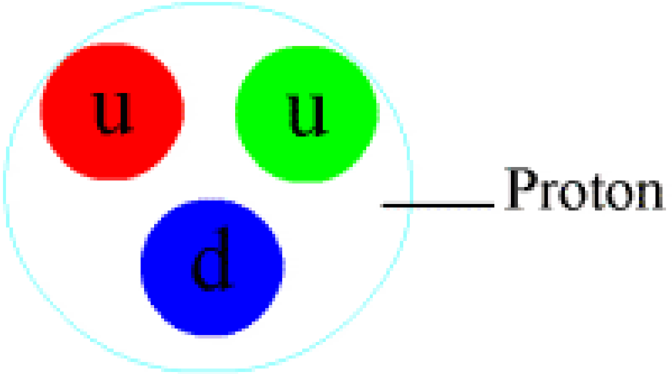
- In the chiral limit the entirety of the proton's mass is produced by the trace anomaly, Θ_0
  … In QCD, Θ_0 measures the strength of gluon self-interactions
  … so, from one perspective,
  m_p is (somehow) completely generated by glue.

The mass of visible matter is almost entirely produced by massless non-matter fields

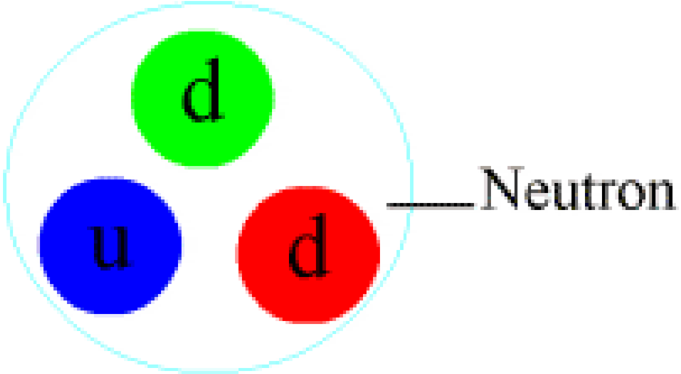
On the other hand …

Pion





- The pion is another one of the hadrons that was discovered as the standard model was being built
- Predicted by Yukawa in 1935
  - It had to exist, otherwise there was nothing that could hold neutrons and protons together inside a nucleus
- The pion, too, is crucial.
- It MUST be *unnaturally* light, otherwise the force it produces would act over a range that is too short to be useful in binding nuclei



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

Trace Anomaly

- In the chiral limit, pion is massless Nambu-Goldstone boson:

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

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

  It could only arise naturally because

  of some symmetry and/or symmetry-breaking pattern.

Whence "1" and yet "0" ?

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

- *No statement of the question*

  "How does the mass of the proton arise?"

  is complete without the additional clause

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

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

Whence "1" and yet "0" ?

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

- *No statement of the question*

  "How does the mass of the proton arise?"

  is complete without the additional clause

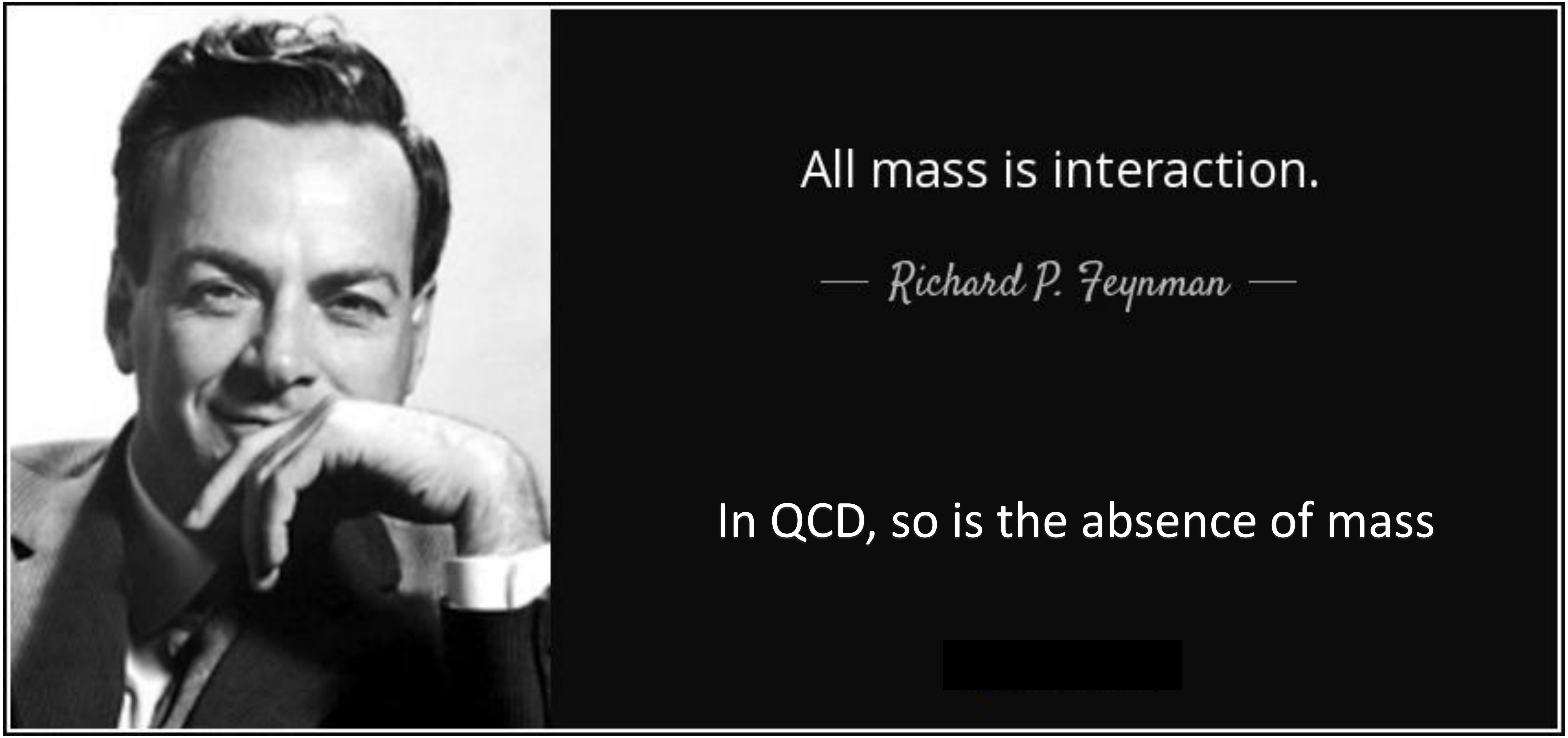
  "How does the pion remain **massless***?"*

- Modern Physics must

  Elucidate the entire array of Empirical Consequences

  of the Mechanism responsible

  so that the Standard Model can be Validated



In QCD, so is the absence of mass

G E N E S I S

GLUON

Particle Data Group

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

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

SU(3) color octet

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

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

gluon REFERENCES

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

GOOGLE

gauge boson mass

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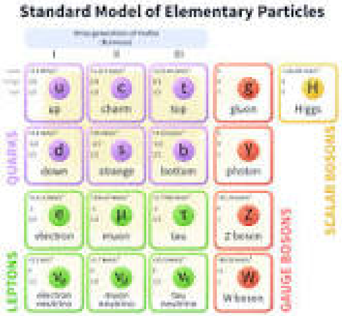
In particle physics, a **gauge boson** is a force carrier, a bosonic particle that carries any of the fundamental interactions of nature, commonly called forces. Elementary particles, whose interactions are described by a **gauge** theory, interact with each other by the exchange of **gauge bosons**—usually as virtual particles.

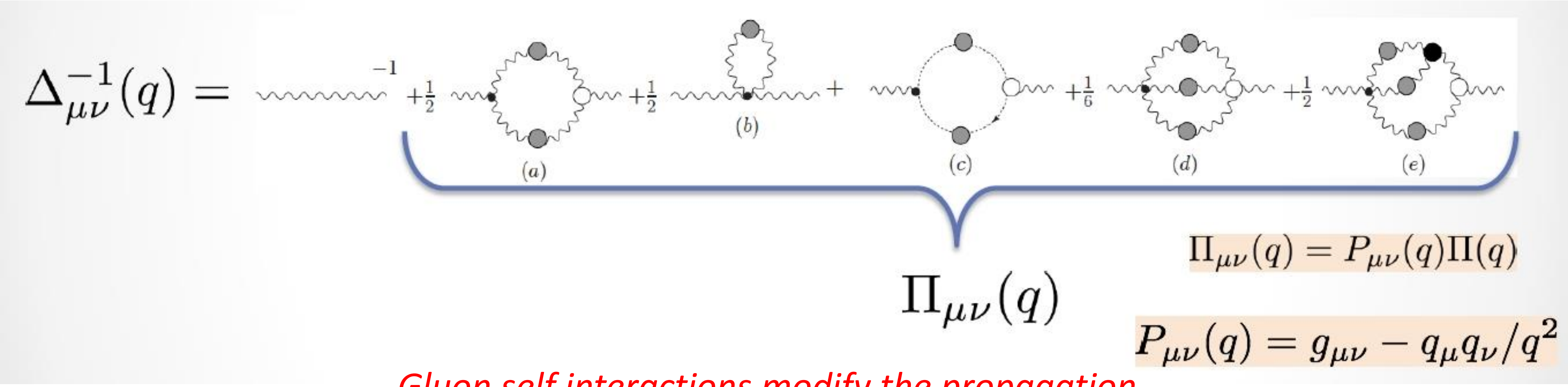


Gauge boson - Wikipedia
https://en.wikipedia.org/wiki/Gauge_boson

Do gluons have mass?

So far **gluons** appear massless, and if they **have mass** this would mean there is some sort of symmetry breaking or Higgs mechanism involved with QCD. So far there is no evidence of this, and theory **does** not make predictions of **gluon masses**. May 29, 2016

Every one of these assertions is wrong



Gluon self interactions modify the propagation characteristics of the gluon partons that define QCD.

They produce dressed gluons with a mathematical connection to the gluon partons, but with wildly different properties.

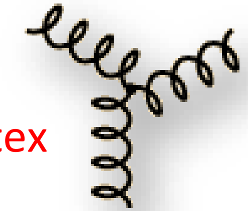
Gluon Dyson/Gap Equation

Modern Understanding Grew Slowly from *Ancient* Origins

- More than 40 years ago

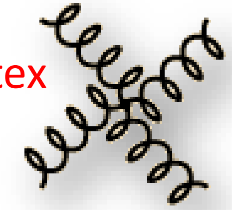
  Dynamical mass generation in continuum quantum chromodynamics,
  J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … ~ 1070 citations

3-gluon vertex

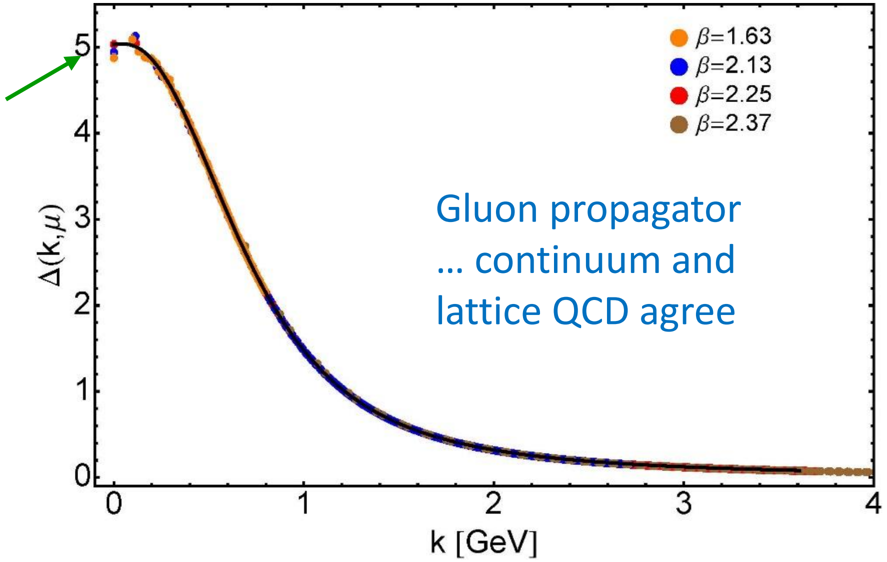


- Owing to strong self-interactions, gluon partons ⇒ gluon quasiparticles, described by a mass function that is large at infrared momenta

4-gluon vertex



$\frac{1}{m_g^2}$



Truly mass from nothing
An interacting theory, written in terms of massless gluon fields, produces dressed gluon fields that are characterised by a mass function that is large at infrared momenta

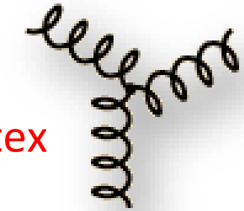
- ✓ *QCD fact*
- ✓ *Continuum theory and lattice simulations agree*
- ✓ *Empirical verification?*

Modern Understanding Grew Slowly from … Origins

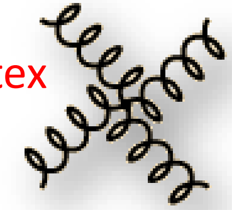
- More than 40 year…
  Dynamical mass ger… …mics,
  J.M. Cornwall, Phys.…
- Owing to strong se… …uasiparticles,
  described by a… …omenta

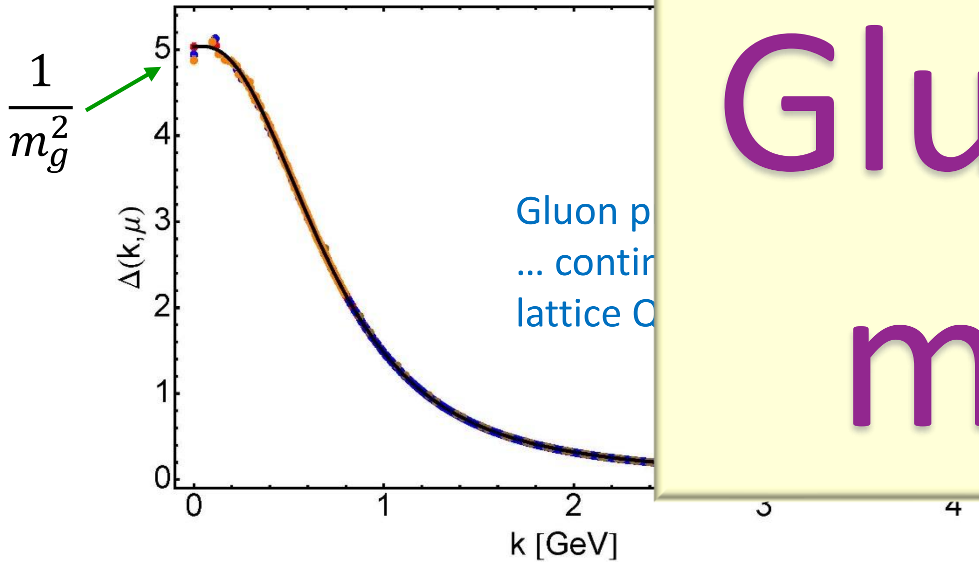
EHM means Gluons are massive

3-gluon vertex



4-gluon vertex

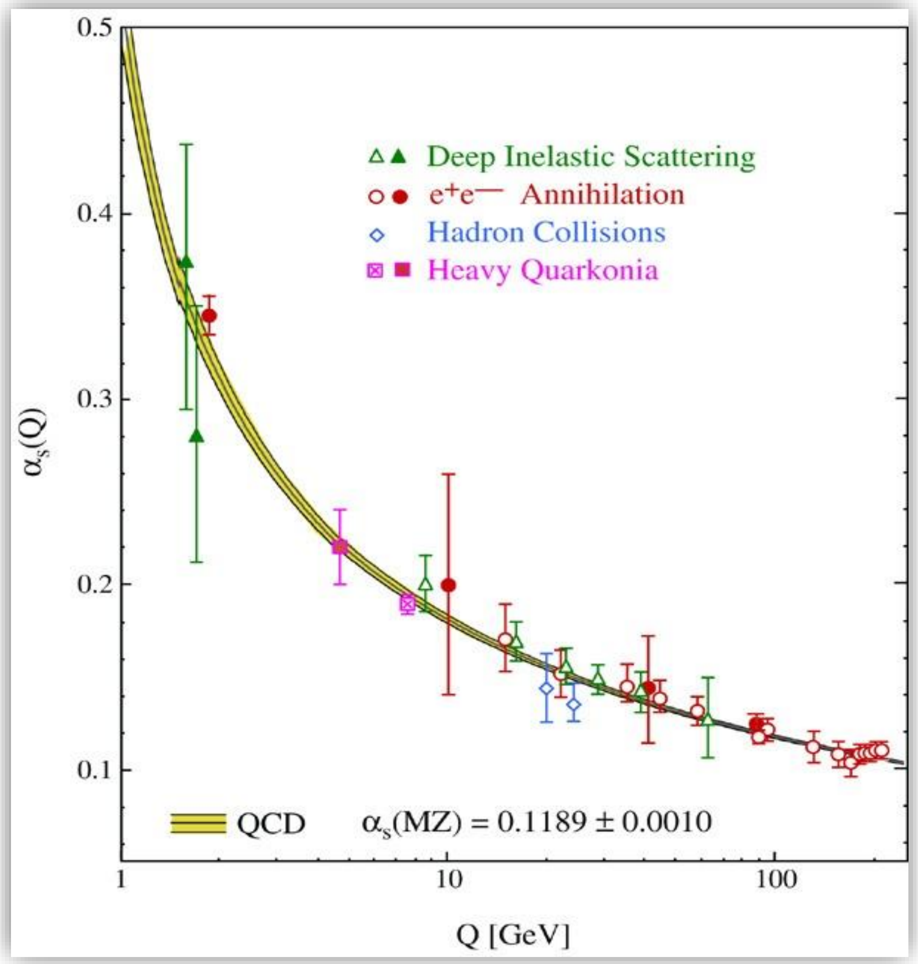




- ✓ *QCD fact*
- ✓ *Continuum theory and lattice simulations agree*
- ✓ *Empirical verification?*

This is where we live

⇐
What's happening out here?!

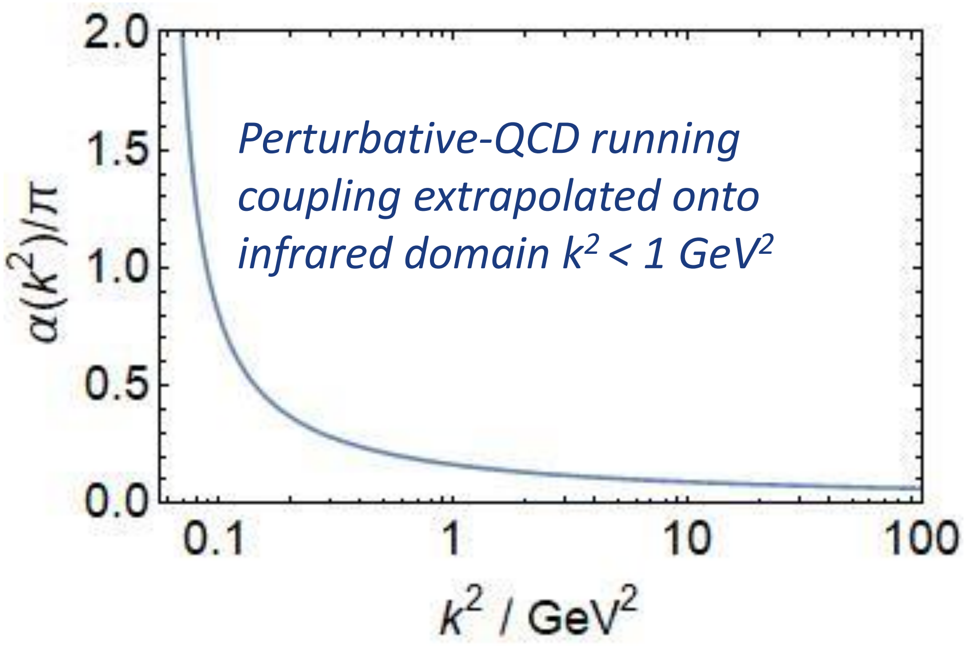


Asymptotic Freedom

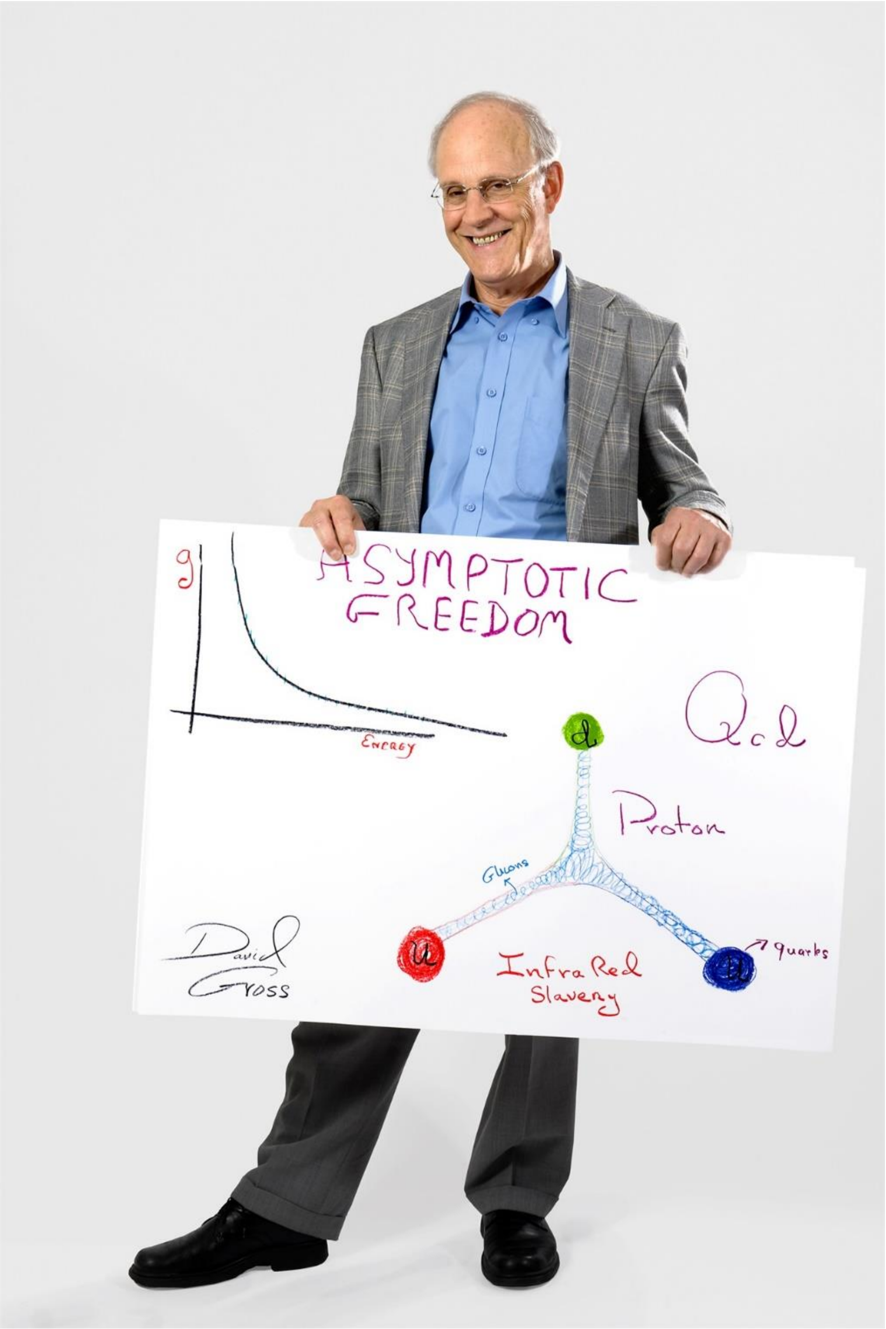
Interaction becomes weaker as energy grows (charges get closer together)

QCD's Running Coupling

"Asymptotic freedom comes with a flip side"



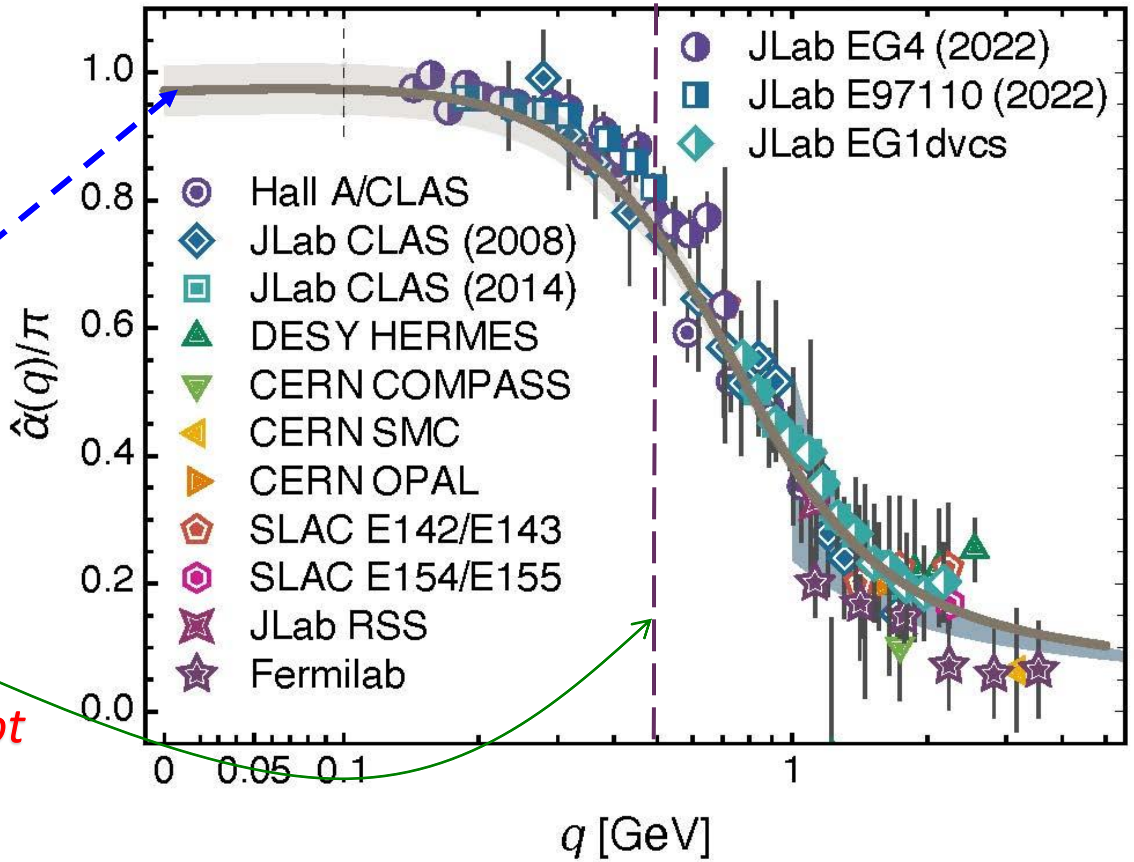
- "Imaginatively called infrared slavery"
- Coupling runs to infinity as k^2 runs to zero
- Many people interpret this as being synonymous with confinement
- Is this correct?



Effective charge from lattice QCD, *Zhu-Fang Cui, Jin-Li Zhang et al.*, *NJU-INP 014/19*, *arXiv:1912.08232 [hep-ph]*, *Chin. Phys. C 44 (2020) 083102/1-10*

Process independent effective charge = running coupling

- Modern theory enables unique QCD analogue of "Gell-Mann – Low" running charge to be rigorously defined and calculated
- Analysis of QCD's gauge sector yields a *parameter-free prediction*
- N.B. Qualitative change in $\hat{\alpha}_{PI}(k)$ at $k \approx ½\, m_p$
- No Landau Pole
  - *"Infrared Slavery" picture – linear potential – is not correct explanation of confinement*
- Below $k \sim \widehat{m}_0$, interactions become scale independent, just as they were in the Lagrangian; so, QCD becomes practically conformal again



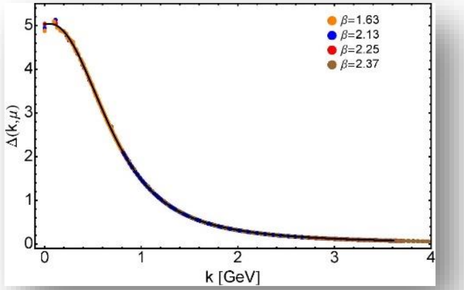
- ✓ *Process independent strong running coupling* Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7
- ✓ *Experimental determination of the QCD effective charge $\alpha_{g1}(Q)$.* A. Deur; V. Burkert; J.-P. Chen; W. Korsch, Particles 5 (2022) 171
- ✓ *QCD Running Couplings and Effective Charges,* Alexandre Deur, Stanley J. Brodsky and Craig D. Roberts, NJU-INP 071/23, e-Print: 2303.00723 [hep-ph]

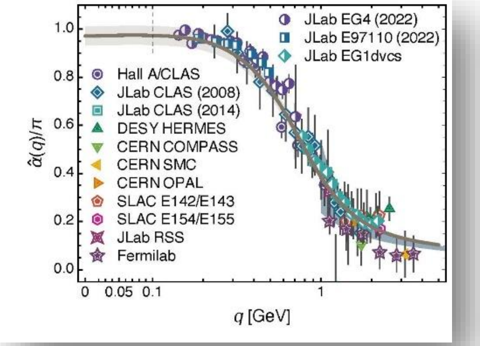
EHM Basics

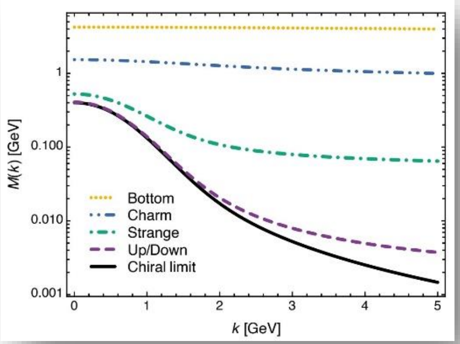
- Absent Higgs boson couplings, the Lagrangian of QCD is scale invariant
- Yet …
  - Massless gluons become massive
  - A momentum-dependent charge is produced
  - Massless quarks become massive
- EHM is expressed in
  EVERY strong interaction observable
- Challenge to Theory =

  Elucidate all observable consequences of these phenomena and highlight the paths to measuring them
- Challenge to Experiment =
  Test the theory predictions so that the boundaries of the Standard Model can finally be drawn

THREE PILLARS OF EHM







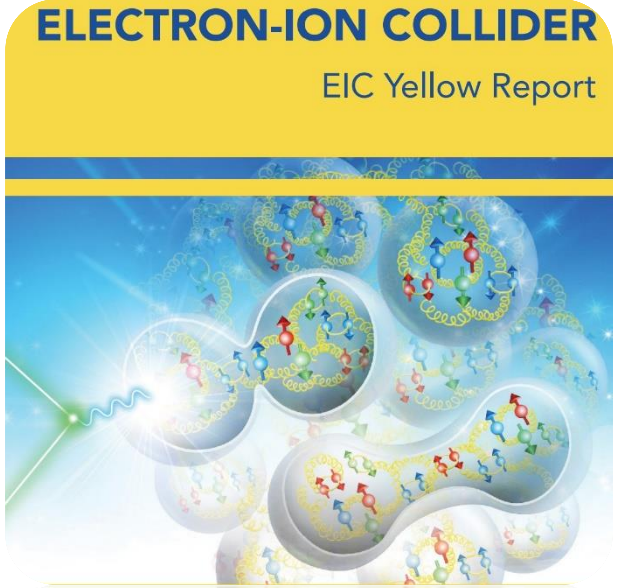
JLab Beam Energy (GeV)	Fraction EHM mapped (%)
6	≈ 35
12	≈ 50
22	≈ 90

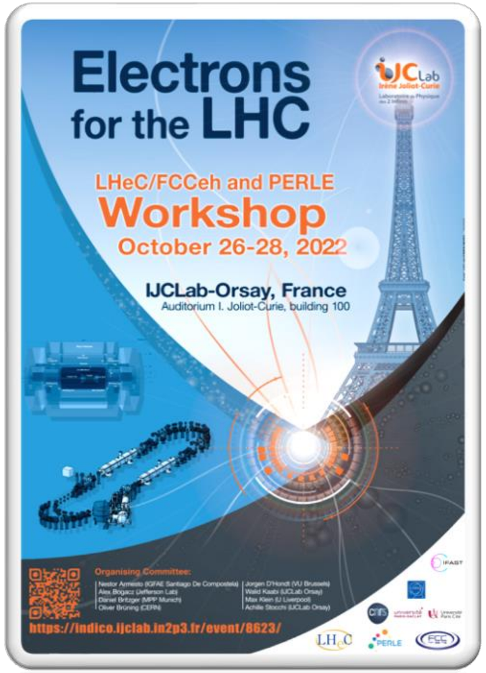
Focus of experiments at New Generation Facilities

AMBER

A new QCD facility at the M2 beam line of the CERN SPS

Jefferson Lab
Thomas Jefferson National Accelerator Facility





Exposing & 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 dawning
  High energy + high luminosity
  ⇒ science can move beyond the monomaniacal focus on the proton
- Precision studies of the structure of
  - Nature's most fundamental Nambu-Goldstone bosons (π & K) will become possible
  - 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.

AMBER @ CERN
EIC
EicC
JLab12 & JLab20+

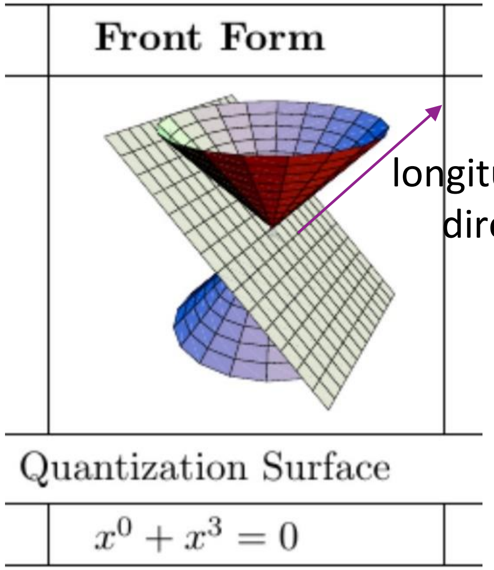
$$\Psi(x,t)$$

π & K DAs & Form Factors

Wave Functions of Nambu Goldstone Bosons

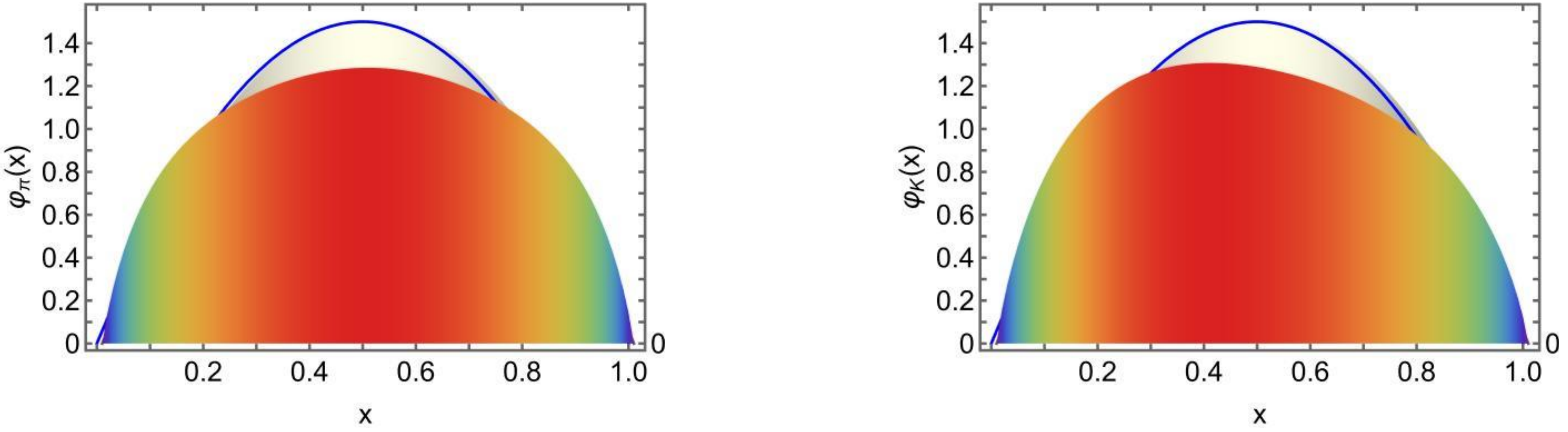
- Physics Goals:
  - Pion and kaon distribution amplitudes (DAs – $\varphi_{\pi,K}$)
  - Nearest thing in quantum field theory to Schrödinger wave function
  - Consequently, fundamental to understanding π and K structure.
- Scientific Context:
  - For 40 years, the *x*-dependence of the pion's dominant distribution amplitude (DA) has been controversial.
  - Modern theory ⇒ EHM expressed in *x*-dependence of $\varphi_{\pi,K}(x)$
  - $\varphi_{\pi}(x)$ is direct measure of dressed-quark running mass in chiral limit.
  - Kaon DA = asymmetric around midpoint of its domain of support (0<x<1)
    - Degree of asymmetry is signature of constructive interference between EHM and HB mass-generating mechanisms

DAs are 1D projection of hadron's light-front wave function, obtained by integration $\sim \int d^2k_\perp \Psi(x,k_\perp)$



Insights into the Emergence of Mass from Studies of Pion and Kaon Structure, Craig D. Roberts, David G. Richards, Tanja Horn and Lei Chang, NJU-INP 034/21, arXiv: 2102.01765 [hep-ph], Prog. Part. Nucl. Phys. **120** (2021) 103883/1-65

π & K DAs cf. asymptotic profile



- EHM generates broadening in both π & K
- EHM + Higgs-boson interference is responsible for skewing in kaon
  - HB-only ⇒ peak shifted to $\frac{m_u^{\mathrm{HB}}}{m_s^{\mathrm{HB}}} \times \frac{1}{2} \approx 0.02$ … *wrong*
  - Instead, EHM*HB for u and s quarks … $\frac{\mathrm{EHM}\ m_u \to M_u}{\mathrm{EHM}\ m_s \to M_s} \times \frac{1}{2} \approx 0.4$

Preprint no. NJU-INP 070/23

Empirical Determination of the Pion Mass Distribution

Y-Z. Xu ID,[1,2] K. Raya ID,[1] Z.-F. Cui ID,[3,4] C. D. Roberts ID,[3,4] and J. Rodríguez-Quintero ID,[1]

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(Dated: 2023 February 14)

phycui@nju.edu.cn (ZFC); cdroberts@nju.edu.cn (CDR); jose.rodriguez@dfaie.uhu.es (JRQ)

Existing pion+nucleus Drell-Yan and electron+pion scattering data are used to develop ensembles of model-independent representations of the pion generalised parton distribution (GPD). Therewith, one arrives at a data-driven prediction for the pion mass distribution form factor, θ_2. Compared with the pion elastic electromagnetic form factor, θ_2 is harder: the ratio of the radii derived from these two form factors is $r_\pi^{\theta_2}/r_\pi = 0.79(3)$. Our data-driven predictions for the pion GPD, related form factors and distributions should serve as valuable constraints on theories of pion structure.

π mass distribution

- Expectation value of the QCD energy-momentum tensor in the pion
  = pion gravitational current

$$\Lambda^{g}_{\mu\nu}(K,Q) = 2K_\mu K_\nu \theta_2^\pi(Q^2) + \tfrac{1}{2}[Q^2\delta_{\mu\nu} - Q_\mu Q_\nu]\theta_1^\pi(Q^2) + 2m_\pi^2\delta_{\mu\nu}\bar{c}^\pi(Q^2)$$

Zero owing to energy+momentum conservation

- Contract with $\delta_{\mu\nu}$: $\Lambda^{g}_{\mu\mu}(K,0) = 2m_\pi^2\theta_2^\pi(Q^2)$
  - $\theta_2^\pi(Q^2=0) = 1$ (canonical mass-normalisation)
  - $\theta_2^\pi(Q^2)$ measures mass distribution in π

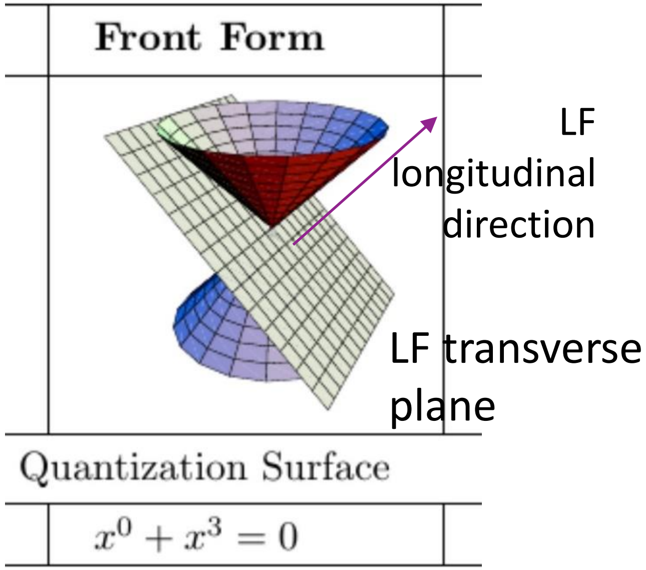
- θ_2^π can be obtained as the first Mellin moment of the pion GPD

$$\theta_2^\pi(\Delta^2) = \int_{-1}^{1} dx\, 2x\, H_\pi^u(x,0,-\Delta^2;\zeta_{\mathcal{H}})$$

Pion GPD

Generalised Parton Distributions

- “Standard” parton DFs
  - 1D picture – dependence of in-hadron parton properties on the light-front (LF) fraction, x, of the hadron’s total momentum
- Generalised parton distributions (GPDs)
  - Provide extension of 1D parton distribution functions into 3D images
  - Also describe hadron’s distributions of partons in plane perpendicular to bound-state's total momentum, *i.e.*, within the light front itself.



- Data relating to GPDs
  - deeply virtual Compton scattering
    - $\gamma^*(q)T(p) \to \gamma^*(q')T(p')$ – so long as at least one photon possesses large virtuality
  - deeply virtual meson production
    - $\gamma^*(q)T(p) \to M(q')T(p')$, where M is a meson
- GPDs connect DFs with hadron form factors because
  - any DF may be recovered as forward limit $(p' = p)$ of relevant GPD
  - any elastic form factor can be expressed via a GPD-based sum rule

GPD measurement … numerous experimental programmes – underway or planned at JLab, EIC, and EicC

Empirical determination of the pion mass distribution

- GPDs connect DFs with hadron form factors because
  - any DF may be recovered as forward limit $(p' = p)$ of relevant GPD
  - any elastic form factor can be expressed via a GPD-based sum rule
- Working solely with
  - existing pion + nucleus Drell-Yan data (CERN and FNAL – 1989)
    - two phenomenological fits to this data [Aicher:2010cb, Barry:2021osv] … use both
  - electron+pion scattering data
    - CERN – 1984, 1986
    - JLab 2000, 2006, 2007, 2008
- Used a χ^2-based selection procedure to develop ensembles of model-independent representations of the three-dimensional pointwise behaviour of the pion generalised parton distribution (GPD).
- These ensembles yield data-driven prediction for pion GPD

Pion Generalised Parton Distribution

- Pion GPDs, reconstructed from available analyses of relevant Drell-Yan and electron+pion scattering data
  - Different ensembles only marginally compatible, owing to differences between analyses in [Aicher:2010cb, Barry:2021osv]
  - Yet, both agree with lQCD based ensembles, within mutual uncertainties, because lQCD-constrained ensemble has large uncertainty – improvement of lQCD results needed
  - CSM prediction favours $u_A^\pi(x;\zeta_5)$ ensemble
- In all cases, support of the valence-quark GPD becomes increasingly concentrated in the neighbourhood $x \simeq 1$ with increasing Δ^2
  - Namely, greater probe momentum focuses attention on domain in which one valence-quark carries a large fraction of the pion's light-front momentum

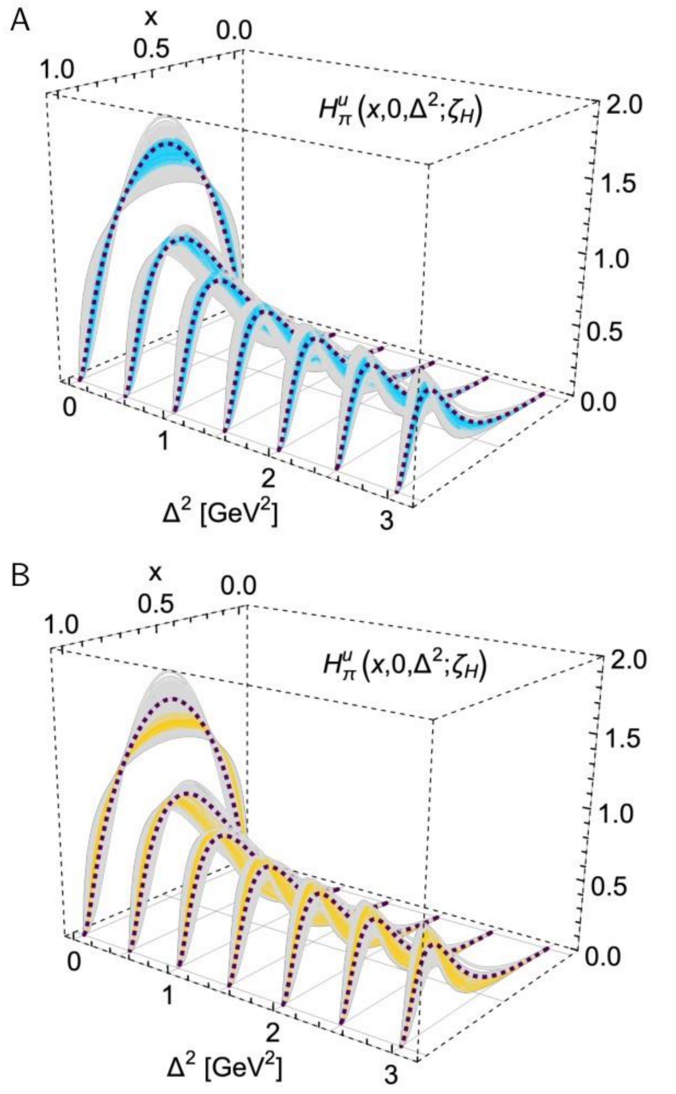


FIG. 3. Pion GPDs. *Panel A*. Working with DFs $u_A^\pi(x;\zeta_{\mathcal{H}})$ [63] – blue band. *Panel B*. Using DFs $u_B^\pi(x;\zeta_{\mathcal{H}})$ [54, Sec. 8] – orange band. Comparison curves, both panels: CSM prediction in Refs. [59, 72] – dashed purple curve; GPD ensemble generated from valence-quark DFs developed in Ref. [55], obtained from results computed using lattice Schwinger function methods [65–67] – grey band.

Revealing pion and kaon structure via generalised parton distributions, K. Raya, Z. –F. Cui (崔著钫) et al., NJU-INP 051/21, e-Print: 2109.11686 [hep-ph], Chin. Phys. C **46** (01) (2022) 013107/1-22

Pion charge distribution form factor

- 0^{th} Moment of pion GPD

$$F_\pi(\Delta^2) \equiv F_\pi^u(\Delta^2) = \int_{-1}^{1} dx\, H_\pi^u(x, 0, -\Delta^2; \zeta_H)$$
$$= \int_0^1 dx\, u^\pi(x;\zeta_H)\, \Phi^\pi(\Delta^2 x^2; \zeta_H)\,,$$

- All ensembles reproduce empirical $F_\pi(\Delta^2)$
  - Blue – based on $u_A^\pi(x;\zeta_5)$ ensembles
  - Orange – based on $u_B^\pi(x;\zeta_5)$ ensembles
- Comparison curves
  - dashed purple – CSM prediction for $F_\pi(\Delta^2)$
  - grey band – Ensemble of $F_\pi(\Delta^2)$ results developed from DFs based on results obtained using lattice-QCD
- Once again, data-driven results are in accord with modern theory predictions.

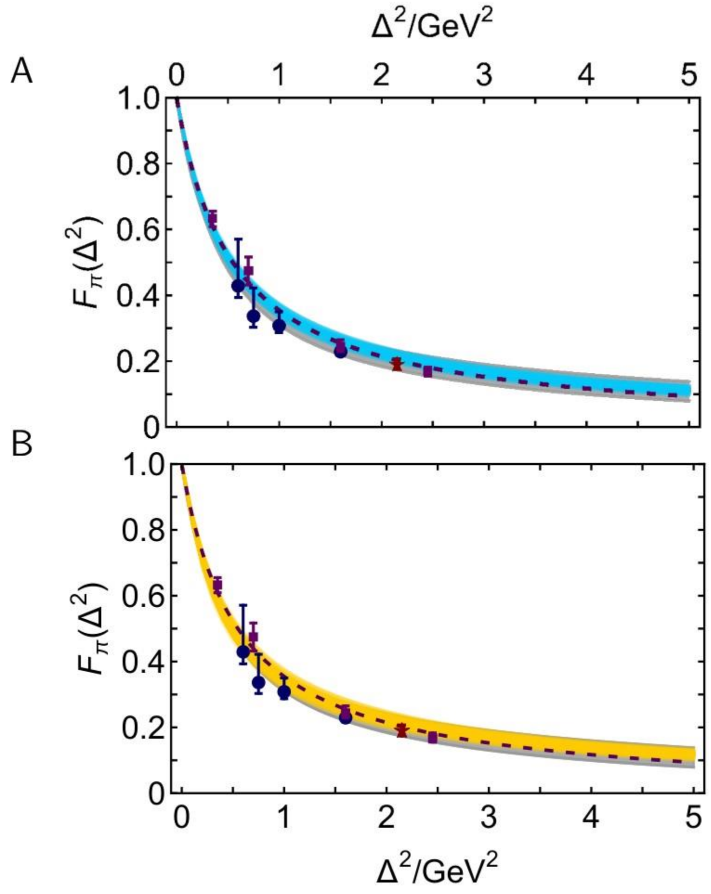


FIG. 2. Pion elastic electromagnetic form factor, $F_\pi(\Delta^2)$, obtained from Eq. (11) using the GPD ensembles generated via S4. *Panel A.* DFs $u_A^\pi(x;\zeta_\mathcal{H})$ [63] (blue band). *Panel B.* DFs $u_B^\pi(x;\zeta_\mathcal{H})$ [54, Sec. 8] (orange band). Comparison curves: dashed purple – $F_\pi(\Delta^2)$ calculated using CSMs [21, Sec. 4B], [45]; grey band – $F_\pi(\Delta^2)$ ensemble obtained with valence-quark DFs developed in Ref. [55] from results obtained using lattice Schwinger function methods [65–67]. The form factor data are from Refs. [36–40].

See, e.g., Sec. 4B in
📖 *Insights into the Emergence of Mass from Studies of Pion and Kaon Structure,*
C.D. Roberts, D.G. Richards, T. Horn and L. Chang,
NJU-INP 034/21, arXiv: 2102.01765 [hep-ph], Prog. Part. Nucl. Phys. **120** (2021) 103883/1-65

π mass distribution

$$\theta_2^\pi(\Delta^2) = \int_{-1}^{1} dx\, 2x\, H_\pi^u(x, 0, -\Delta^2; \zeta_{\mathcal{H}})$$

- Expressed as first Mellin-moment of the pion GPD
- Principal, dynamical coefficient in the expectation value of the QCD energy-momentum tensor in the pion

  = pion gravitational current

$$\Lambda^g_{\mu\nu}(K,Q) = 2K_\mu K_\nu \theta_2^\pi(Q^2) + \tfrac{1}{2}[Q^2\delta_{\mu\nu} - Q_\mu Q_\nu]\theta_1^\pi(Q^2)$$

- Plainly … $\theta_2(\Delta^2)$ is harder than the $F_\pi(\Delta^2)$

  i.e., the distribution of mass in the pion is more compact than the distribution of electric charge.

- *This is an empirical fact*

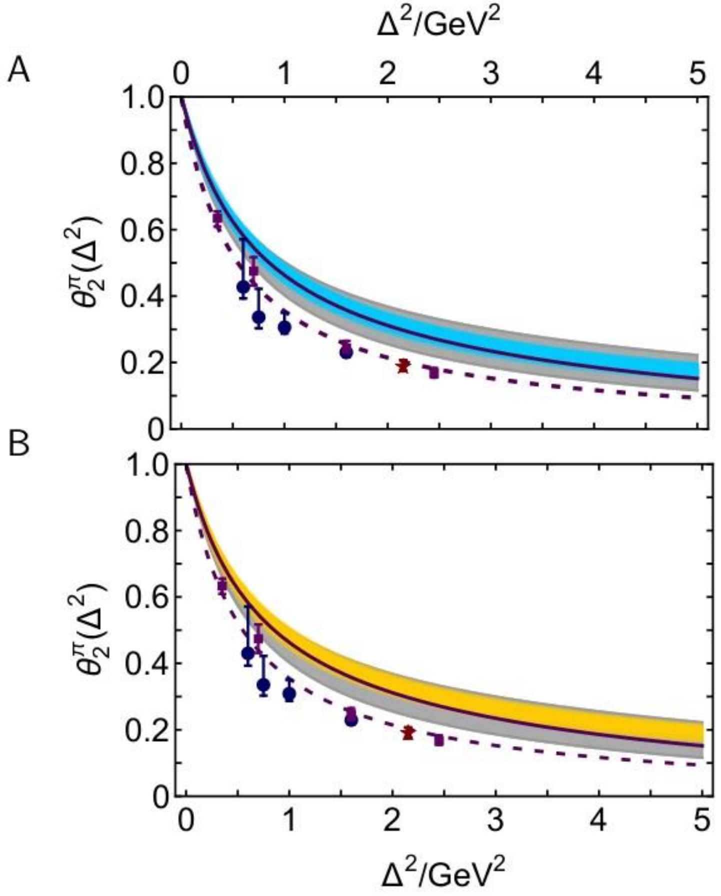


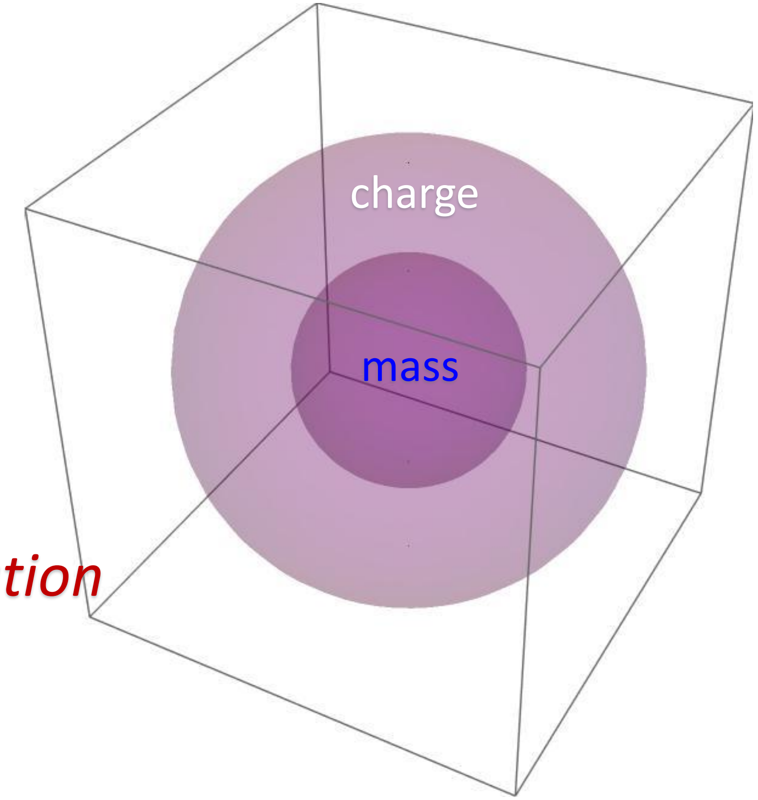
FIG. 4. Pion mass distribution form factor, $\theta_2^\pi(\Delta^2)$. *Panel A.* Developed from the $u_A^\pi(x;\zeta_{\mathcal{H}})$ ensemble [63] – blue band. *Panel B.* Developed from the $u_B^\pi(x;\zeta_{\mathcal{H}})$ ensemble [54, Sec. 8] – orange band. Comparison curves, both panels: CSM prediction for $\theta_2^\pi(\Delta^2)$ in Refs. [59, 72] – solid purple; GPD ensemble generated from valence-quark DFs developed in Ref. [55] using lQCD results [65–67] – grey band. In addition, each panel displays the CSM prediction for $F_\pi(\Delta^2)$ [21, Sec. 4B], [45] – dashed purple curve. The data are those for $F_\pi(\Delta^2)$ from Refs. [36–40], included so as to highlight the precision required to distinguish the mass and electromagnetic form factors.

π mass radius

	A	B	lQCD
$r_\pi^{\theta_2}$	0.518(16)	0.498(14)	0.512(21)

- Comparison value for charge radius: $r_\pi = 0.64(2)$
- Data-driven prediction: $\frac{r_\pi^{\theta_2}}{r_\pi} = 0.79(3)$
- Translates into spacetime volume ratio = $0.49(6)$

Pion mass distribution is concentrated within just 50% of the spacetime volume of the charge distribution



π mass distribution is harder

- Empirical fact is readily understood physically
- Pion wave function (hence, pion GPD) is independent of the probe.
  - It's the same whether 1 photon or 2 photons or graviton is the probing object.
- However, probe itself focuses on different features of the target constituents
  - Target quark carries same charge, irrespective of its momentum.
    - So, pion LFWF alone controls distribution of charge.
  - Gravitational interaction of target quark depends on its momentum.

    (The current = the energy momentum tensor)
    - Pion effective mass distribution therefore depends on interference between quark momentum growth and LFWF momentum suppression with increasing $\Delta^2 x^2$.
    - This pushes support to a larger momentum domain in the pion = smaller distance domain.

π mass distribution is harder

- The difference between mass and charge radii grows with strength of EHM-induced broadening of pion (DA) DF because …

  Broadening magnifies endpoint differences, accentuating low-x positive support in integrand

$$\theta_2(\Delta^2) - F_\pi(\Delta^2) = \int_0^1 dx\,(1-2x)u^\pi(x;\zeta_H)\Phi^\pi(\Delta^2 x^2;\zeta_H)$$

- This broadening is also manifested in $\Delta^2 x^2$-dependence of Φ^π
  - Broadening of DF is expression of smoothing in the momentum dependence of Φ^π

- "*Is there a specific aspect of the pion GPDs driven by the data which is responsible?*"
- Yes. EHM induced broadening of pion LFWF = GPD.

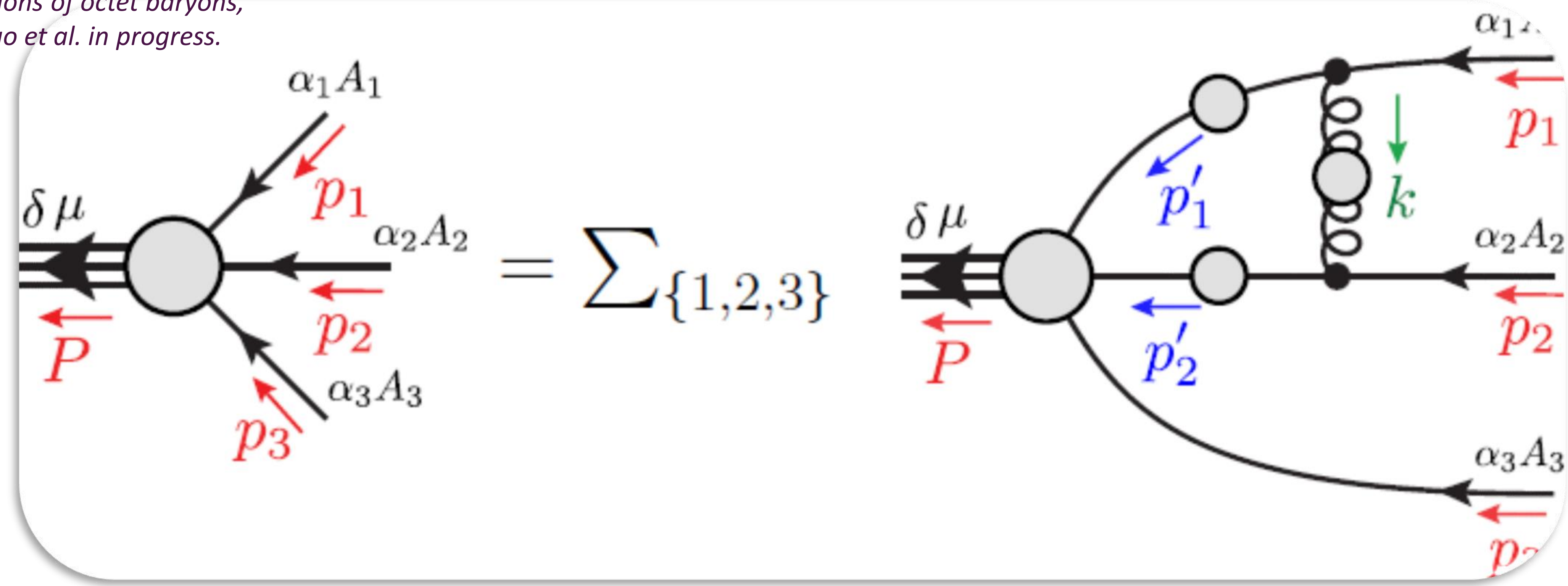
  Given GPD overlap representation, they're the same thing.

Data on large-momentum tail of $F_\pi(\Delta^2)$ and endpoint behaviour of $u^\pi(x;\zeta_H)$ will enable tighter constraints on mass-charge radii difference

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

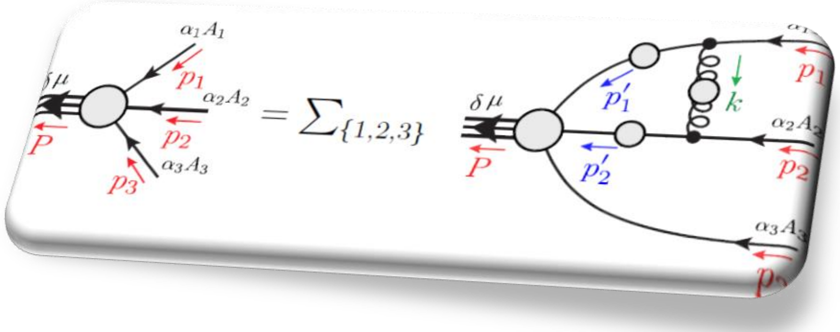
Poincaré-covariant analysis of heavy-quark baryons,
Si-Xue Qin *et al*. Phys.Rev. D 97 (2018) 114017/1-13

Weak transitions of octet baryons,
Zhao-Qian Yao et al. in progress.

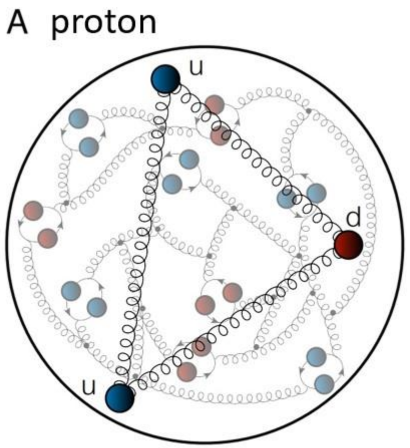


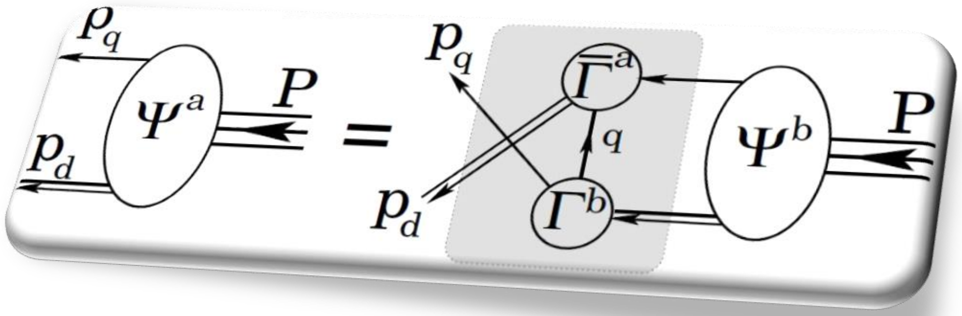
Faddeev Equation for Baryons

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



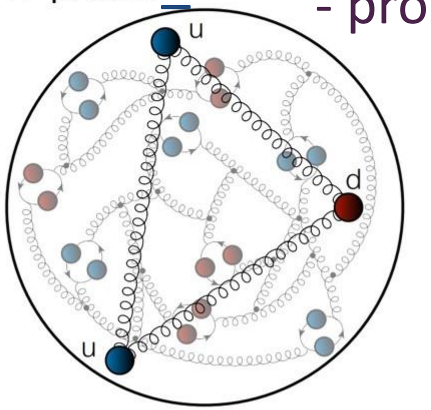


Solution delivers Poincaré-covariant proton wave function

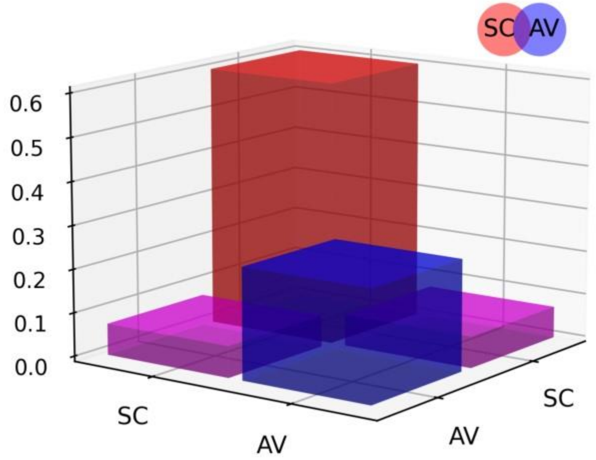
Structure of Baryons

- 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
- For many/most applications, diquark approximation to quark+quark scattering kernel is used
- ***Prediction***: owing to EHM phenomena, *strong diquark correlations exist within baryons*

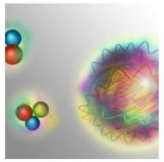
A proton



- 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



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] ✉

PHYSICAL REVIEW D **105**, 094022 (2022)

Nucleon axial-vector and pseudoscalar form factors and PCAC relations

Chen Chen (陈晨)[1,2,3,4,*], Christian S. Fischer[3,4,†] Craig D. Roberts[5,6,‡] and Jorge Segovia[7,6,§]
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[2]*Peng Huanwu Center for Fundamental Theory, Hefei, Anhui 230026, China*
[3]*Institut für Theoretische Physik, Justus-Liebig-Universität Gießen, D-35392 Gießen, Germany*
[4]*Helmholtz Forschungsakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung, Campus Gießen, D-35392 Gießen, Germany*
[5]*School of Physics, Nanjing University, Nanjing, Jiangsu 210093, China*
[6]*Institute for Nonperturbative Physics, Nanjing University, Nanjing, Jiangsu 210093, China*
[7]*Dpto. Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, E-41013 Sevilla, Spain*

Chen Chen solved a > 20-year problem in theoretical physics
= construction of axialvector current of nucleon described by realistic Poincaré-covariant wave function

Eur. Phys. J. A (2022) 58:206
https://doi.org/10.1140/epja/s10050-022-00848-x

THE EUROPEAN PHYSICAL JOURNAL A

Check for updates

Regular Article - Theoretical Physics

Nucleon axial form factor at large momentum transfers

Chen Chen[1,2,a], **Craig D. Roberts**[3,4,b]
[1] Interdisciplinary Center for Theoretical Study, University of Science and Technology of China, Hefei 230026, Anhui, China
[2] Peng Huanwu Center for Fundamental Theory, Hefei 230026, Anhui, China
[3] School of Physics, Nanjing University, Nanjing 210093, Jiangsu, China
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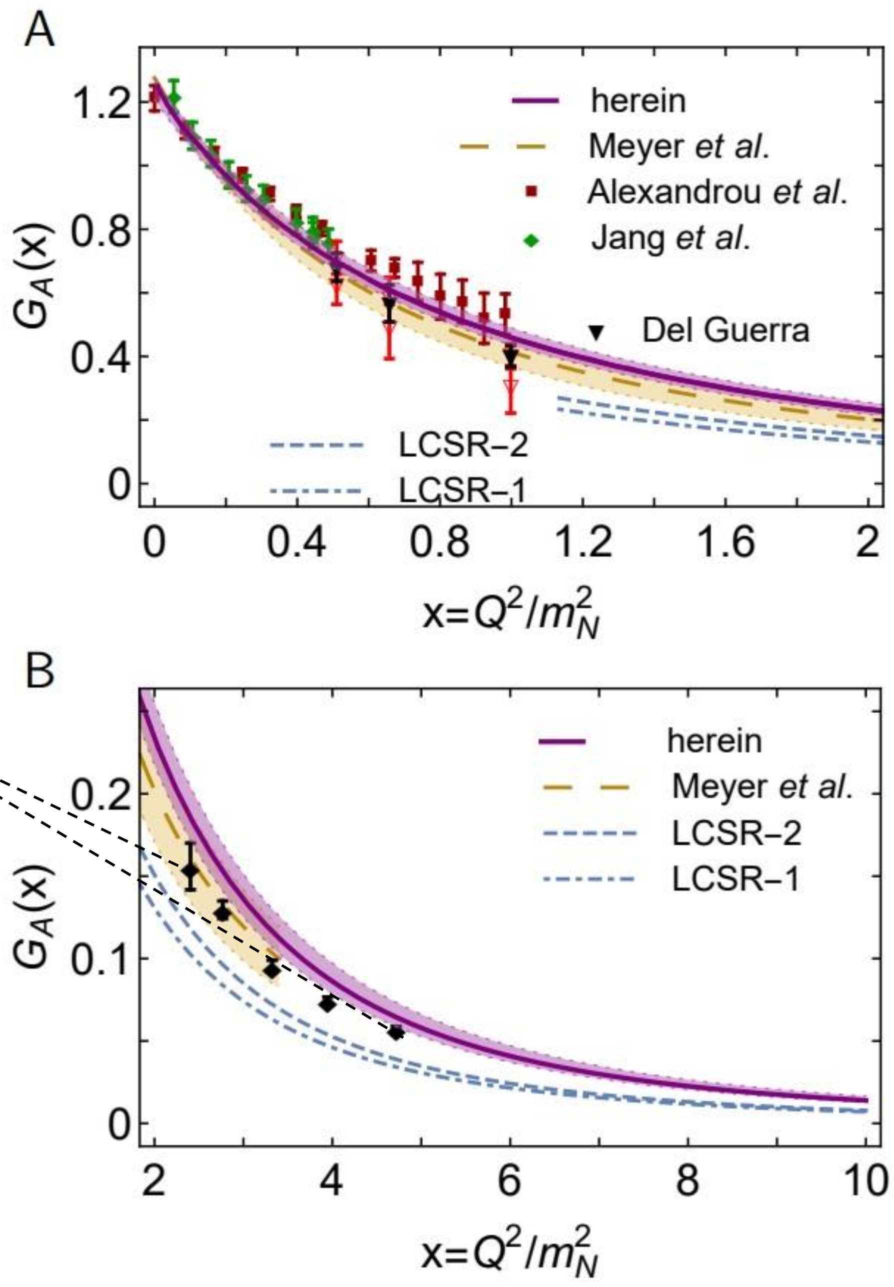
Received: 26 June 2022 / Accepted: 4 October 2022

Large Q^2 Nucleon Axial Form Factor

- Parameter-free CSM predictions to $Q^2 = 10\, m_p^2$
- One other calculation, *viz*. LCSRs using different models for proton DA ... Only available on $Q^2 > 1\, m_p^2$
- CSM prediction agrees with available data: small & large Q^2
- Large Q^2 data from CLAS [Park *et al*., Phys. Rev. C 85 (2012) 035208], threshold π electroproduction, $Q^2 \approx 5\, m_p^2$
  - ✓ This technique could be used to reach higher Q^2

✓ Regarding oft-used dipole *Ansatz*,
  - ✓ Fair representation of $G_A(x)$ on x ∈ [0, 3] = fitting domain
  - ✓ But outside fitted domain, quality of approximation deteriorates quickly
  - ✓ dipole overestimates true result by 56% at x = 10



Large Q^2 Nucleon Axial Form Factor

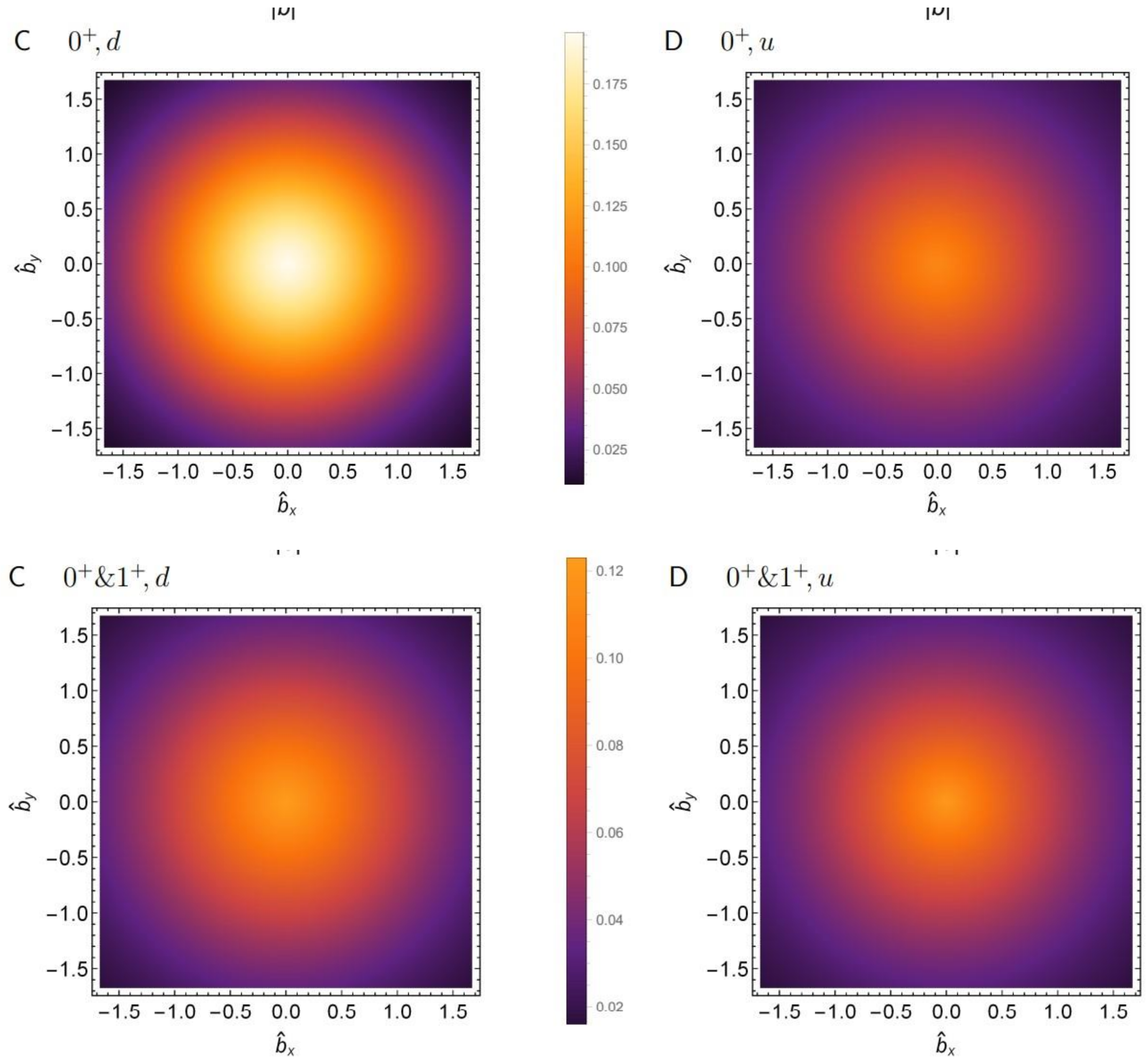
- Light-front transverse density profiles

- Omitting axialvector diquarks
  - ✓ magnitude of the d quark contribution to GA is just 10% of that from the u quark
  - ✓ d quark is also much more localized

$$r_{A_d}^{\perp} \approx 0.5\, r_{A_u}^{\perp}$$

- Working with realistic axialvector diquark fraction
  - ✓ d and u quark transverse profiles are quite similar

$$r_{A_d}^{\perp} \approx 0.9\, r_{A_u}^{\perp}$$



Proton Spin Structure

- Flavour separation of proton axial charge
- d-quark receives large contribution from probe+quark in presence of axialvector diquark
  - $\frac{g_A^d}{g_A^u} =^{0^+\&1^+} -0.32(2)$
  - $\frac{g_A^d}{g_A^u} =^{0^+ \text{ only}} -0.054(13)$

Table 1 Diagram and flavour separation of the proton axial charge: $g_A^u = G_A^u(0)$, $g_A^d = G_A^d(0)$; $g_A^u - g_A^d = 1.25(3)$. The listed uncertainties in the tabulated results reflect the impact of $\pm 5\%$ variations in the diquark masses in Eq. (3), *e.g.* $0.88 6_{\mp} \Rightarrow 0.88 \mp 0.06$.

	$\langle J\rangle_q^S$	$\langle J\rangle_q^A$	$\langle J\rangle_{qq}^{AA}$	$\langle J\rangle_{qq}^{\{SA\}}$	$\langle J\rangle_{ex}^{SS}$	$\langle J\rangle_{ex}^{\{SA\}}$	$\langle J\rangle_{ex}^{AA}$
g_A^u	$0.88 6_{\mp}$	$-0.08 0_{\pm}$	$0.03 0_{\pm}$	$0.08 0_{\mp}$	0	≈ 0	$0.03_{\pm 1}$
$-g_A^d$	0	$0.16 0_{\pm}$	0	$0.08 0_{\mp}$	$0.05 1_{\pm}$	≈ 0	$0.01_{\pm 0}$

Probability that scalar diquark only picture of proton is consistent with data = 1/7,100,000

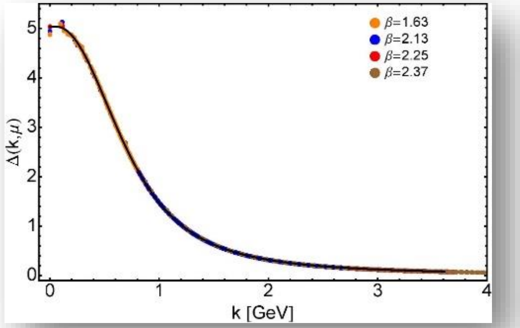
- Experiment: $\frac{g_A^d}{g_A^u} =^{0^+\&1^+} -0.27(4) \Leftarrow$ strong pointer to importance of AV correlation
- Hadron scale: $g_A^u + g_A^d\ (+g_A^s = 0) = 0.65(2) \Rightarrow$ quarks carry 65% of the proton spin
- Poincaré-covariant proton wave function: remaining 35% lodged with quark+diquark orbital angular momentum
- Extended to entire octet of ground-state baryons: dressed-quarks carry 50(7)% of proton spin at hadron scale

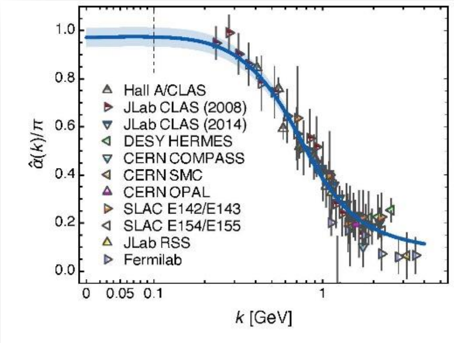
Contact interaction analysis of octet baryon axialvector and pseudoscalar form factors, Peng Cheng (程鹏), Fernando E. Serna, Zhao-Qian Yao (姚照千) et al., NJU-INP 063/22, e-Print: 2207.13811 [hep-ph], Phys. Rev. D **106**,(2022) 054031

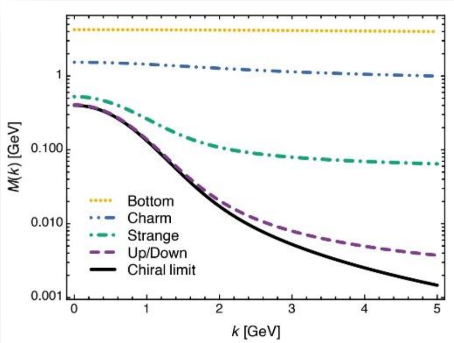
Synergy of Experiment, Phenomenology, Theory

- *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*
- *Understanding how QCD's simplicity explains the emergence of hadron mass and structure requires investment in a facility that can deliver precision data on much more than one of Nature's hadrons.*
- *An energy-upgraded Jlab complex is the only envisaged facility that 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.*

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







Grant no. 12135007

国家自然科学基金委员会
National Natural Science Foundation of China

Emergent Hadron Mass

- QCD is unique amongst known fundamental theories of natural phenomena
  - Degrees-of-freedom used to express the scale-free Lagrangian are not directly observable
  - Massless gauge bosons become massive, with no "human" interference
  - Gluon mass ensures a stable, infrared completion of the theory through appearance of a running coupling that saturates at infrared momenta, being everywhere finite
  - Massless fermions become massive, producing
    - Massive baryons and simultaneously Massless mesons
- Emergent features of QCD are expressed in every strong interaction observable
- They can also be revealed via

  EHM interference with Nature's other known source of mass = Higgs
- High energy and high luminosity facilities are the key to validating these concepts

  proving QCD to be 1st well-defined four-dimensional quantum field theory ever contemplated
- *This may open doors that lead far beyond the Standard Model*

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National Natural Science Foundation of China
NSFC

Emergent Hadron Mass

There are theories of many things,

But is there a theory of everything?

$$\mathcal{L}_{Nature} = ?$$

- QCD is uniq
  - Degrees ... ɔservable
  - Massles
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Thankyou