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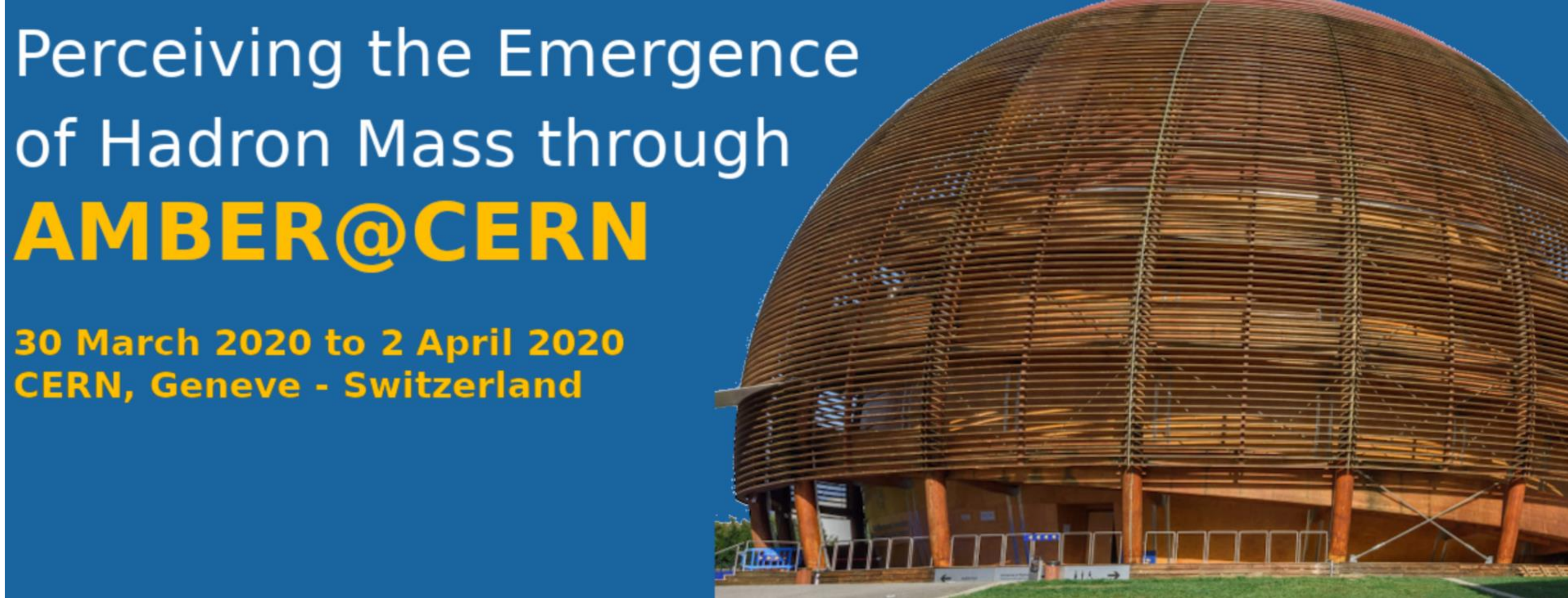
Measurable Expressions of EHM

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

Character of Mass



Perceiving the Emergence of Hadron Mass through
AMBER@CERN

30 March 2020 to 2 April 2020
CERN, Geneve - Switzerland

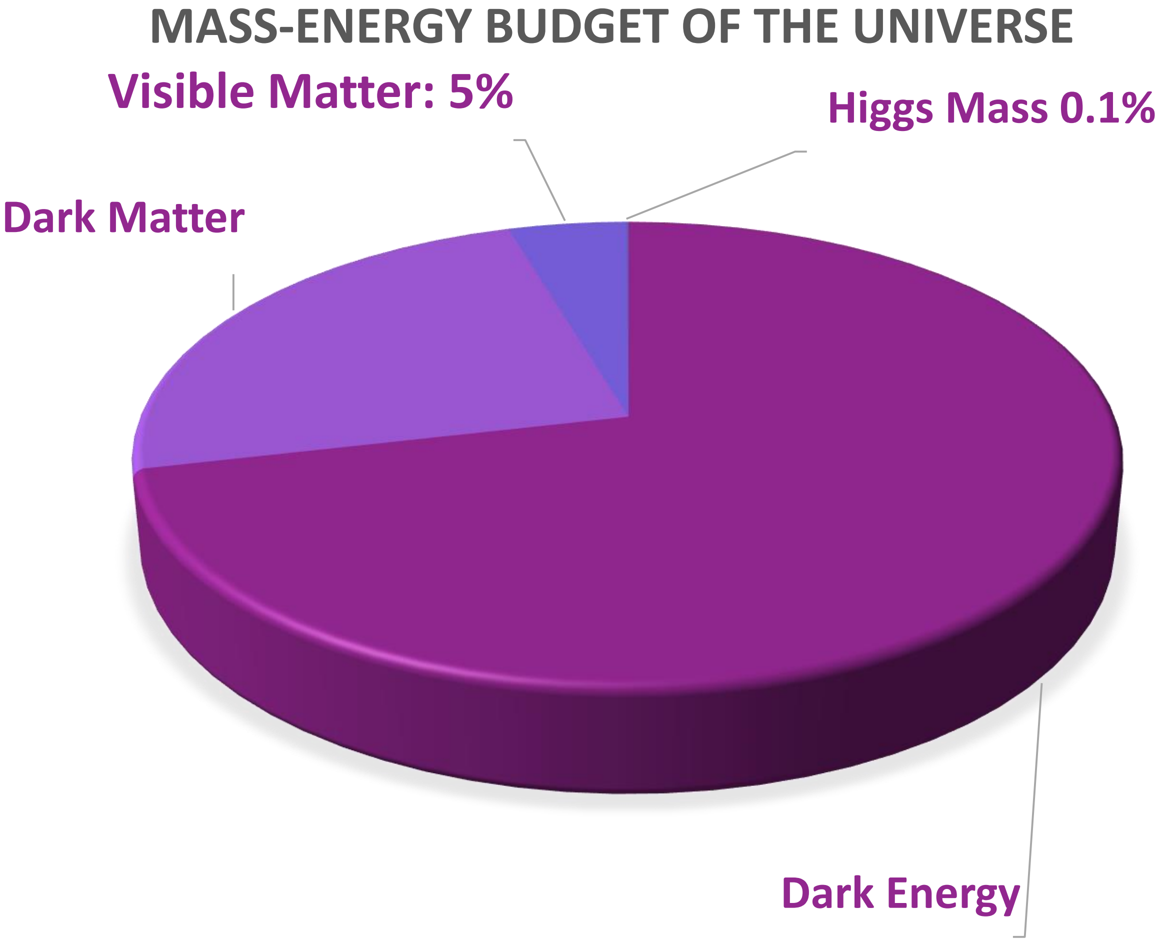
- Key question posed to modern science:
  - What is the origin of mass?
  - What are the consequences of the appearance of mass?
- Of course, when considering the source of mass, many people think of explicit mass, generated via the Higgs-mechanism
  - especially because the Higgs boson was discovered relatively recently at CERN (2012)
  - importance acknowledged by the Nobel Prize awarded to Englert and Higgs:
    - *for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles …*

Character of Mass

- Discovery of the Higgs was a watershed.
- However, it should be placed in context.
- Therefore, consider the mass-energy budget of the Universe
  - Dark energy = 71%
  - Dark Matter = 24%
  - Visible material = 5%
    - Higgs effect is just 0.1% of the visible matter
- Little is known about the first two

Science can say almost nothing about 95% of the mass-energy in the Universe.

- The explanation lies outside the Standard Model.



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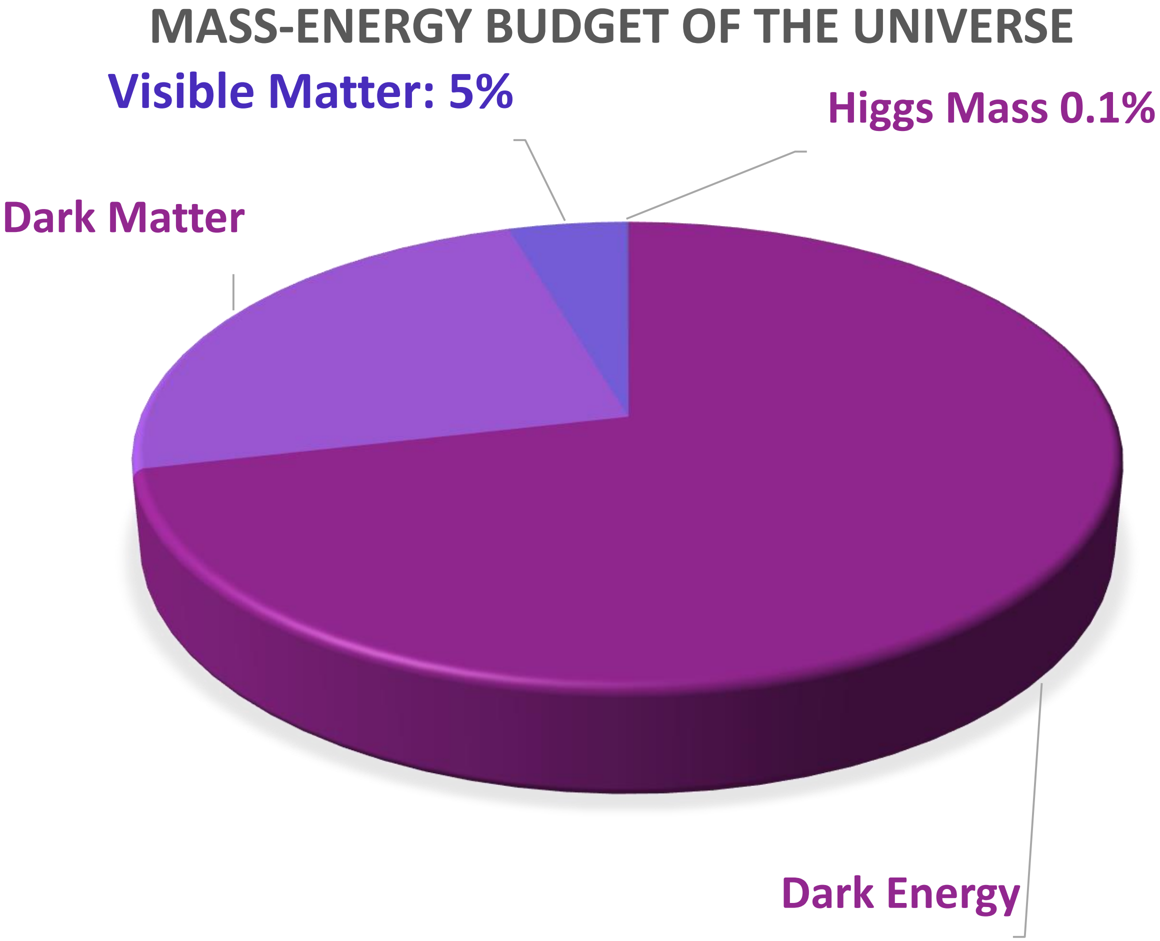
Character of Mass

- Little is known about Dark Energy and Dark Matter …

  Science can say almost nothing about 95% of the mass-energy in the Universe.
- On the other hand, the remaining 5% has forever been the source of everything tangible.
- Yet, amongst this 5%, less-than 0.1% is tied directly to the Higgs boson
- Hence, even concerning visible material, too much remains unknown.



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 the latter, but what produces m_N ?
- This question is the crux of modern physics
  - How can science explain the emergence of hadronic mass (EHM)?

Standard Model

- Strong interactions are described by quantum chromodynamics (QCD).
- QCD: hadrons are composites,
  - built from quarks and/or antiquarks (matter fields)
  - held together by forces produced by the exchange of gluons (gauge fields).
- These forces are unlike any previously encountered.
  - become very weak when two quarks are brought close together within a nucleon
  - but all experimental attempts to remove a single quark from within a nucleon and isolate it in a detector have failed.
- Seemingly, then, the forces become enormously strong as the separation between quarks is increased
- Modern science is encumbered with The Confinement Problem

confinement

Google Scholar: 25,000 mentions of quark confinement since 2000

Confinement Problem

- Modern science is encumbered with The Confinement Problem
- Confinement is crucial because it ensures absolute stability of the proton.
- In the absence of confinement:
  - protons in isolation could decay;
  - the hydrogen atom would be unstable;
  - nucleosynthesis would be a chance event, having no lasting consequences;
  - and without nuclei, there would be no stars and no living Universe.
- Without confinement, our Universe could not exist.

confinement

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Confinement Problem

- Modern science is encumbered with The Confinement Problem
- As the 21st Century began, the Clay Mathematics Institute established seven Millennium Prize Problems
  - Each represents one of the toughest challenges in mathematics.
  - The set contains the problem of confinement; and presenting a sound solution will win its discoverer $1,000,000
- Even with such motivation, today, almost fifty years after the discovery of quarks no rigorous solution has been found
- Confinement and EHM are inextricably linked
- Consequently, as science plans for the next thirty years, solving the problem of EHM has become a Grand Challenge

confinement

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Proton Size

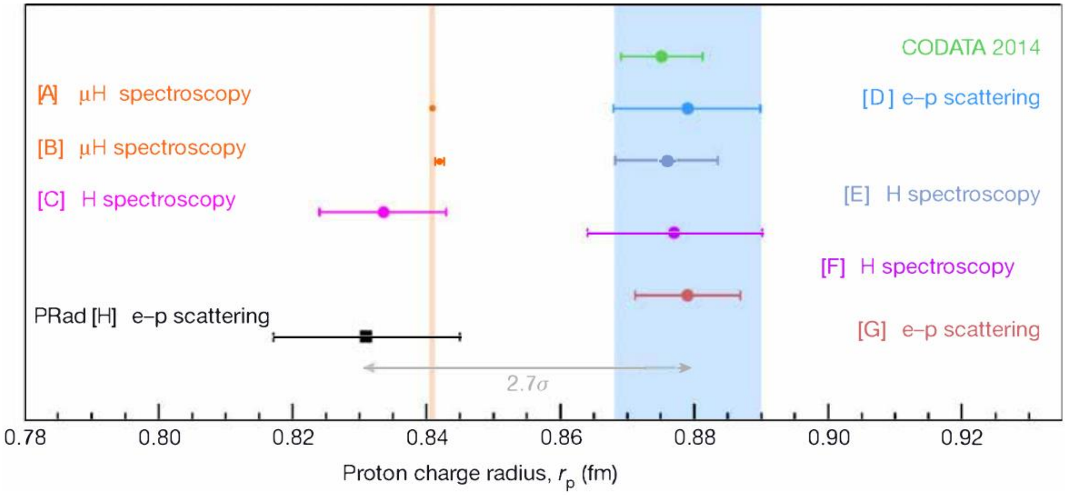

FIG. 1: Measurements of the proton charge radius using various techniques: CODATA = Ref. [24]; [A] = Ref. [25]; [B] = Ref. [26]; [C] = Ref. [27]; [D] = ep scattering average from Ref. [24]; [E] = H spectroscopy average from Ref. [24]; [F] = Ref. [28]; [G] = Ref. [29]; and [H] = Ref. [30]. Figure adapted from Ref. [30].

- Proton's mass correlated with its size
  - Hence, with attempts to explain the confinement of gluons and quarks.
- Today there is a puzzle over that size:
  - elastic electron scattering experiments and laser spectroscopy measurements are in marked disagreement.
- This discrepancy may point to physics beyond the Standard Model
- Or it could mean that low-Q^2 scattering is more subtle than previously thought.
- In either case, solving the puzzle is crucial
  - Will set a hard mark for the value of the proton radius as a rigorous test of quantitative strong interaction theory
- New experimental results are therefore of utmost priority.

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Proton Radius

- Meanwhile, also worth taking a fresh look at existing high-precision data
  - Especially since Prad published their result, which agrees with the muonic-H work
- Cui, Binosi, Roberts, Schmidt (2020):
  - Analysed all high-precision e-p scattering data obtained in the last 15 years [Xiong:2019umf, Bernauer:2010wm, Arrington:2007ux]
  - Used a statistical sampling approach based on the Schlessinger point method for the interpolation and extrapolation of smooth functions.
  - Crucial feature of this scheme = no specific functional form is assumed for the interpolator, *i.e*. produces a form-unbiased interpolation as the basis for a well-constrained extrapolation.

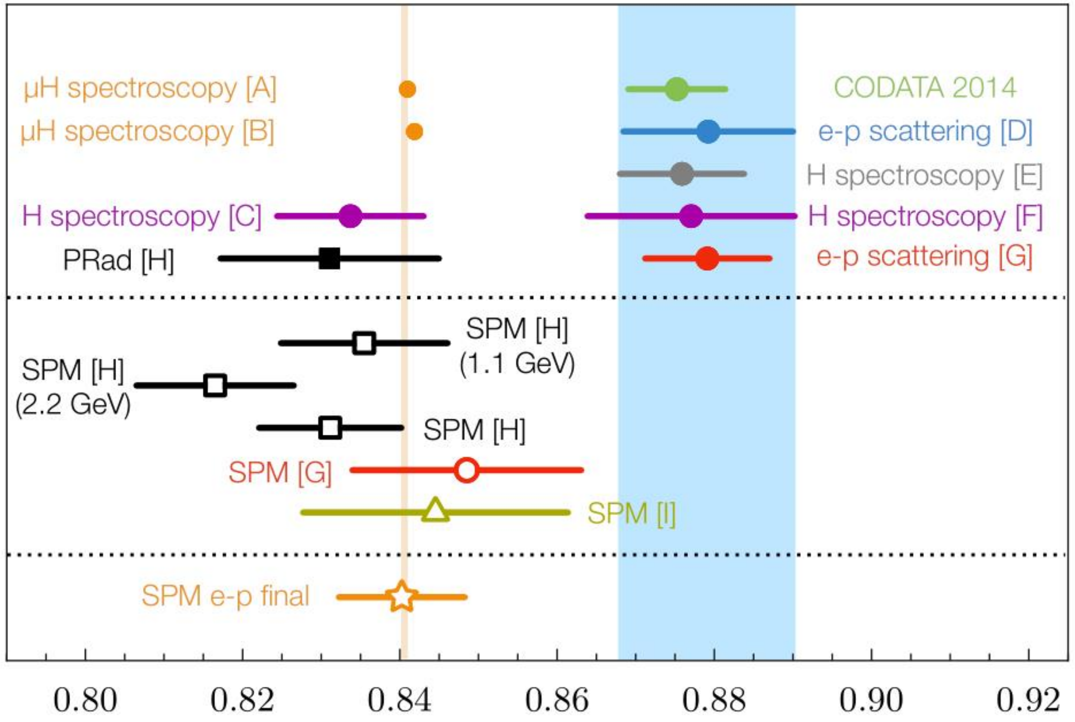


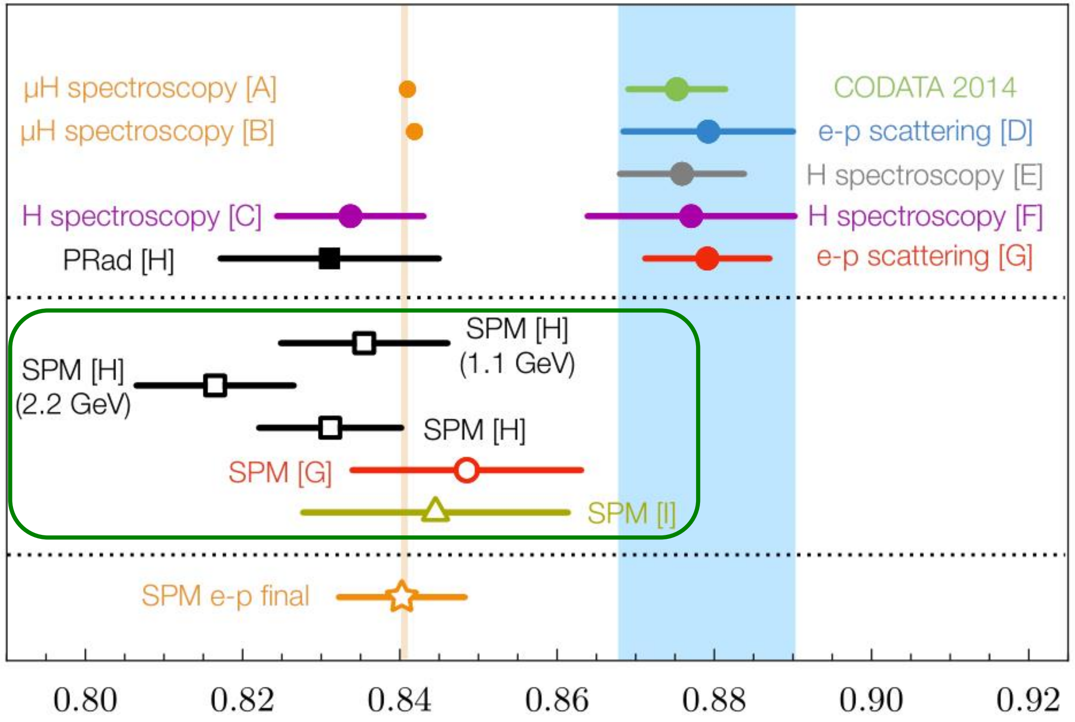
FIG. 1. *Top panel.* Reported empirical results for the proton radius obtained using various techniques: CODATA = Ref. [9]; [A] = Ref. [10]; [B] = Ref. [6]; [C] = Ref. [11]; [D] = *ep* scattering average from Ref. [9]; [E] = *H* spectroscopy average from Ref. [9]; [F] = Ref. [12]; [G] = Ref. [13]; and [H] = Ref. [14]. *Middle panel.* Results obtained from the data in Refs. [13, 14] and [I] = [15] using the Schlessinger Point Method (SPM) [16–18] as described herein. *Bottom panel.* "SPM *ep* final" = combined result from SPM extractions.

Proton Radius

- Cui, Binosi, Roberts, Schmidt (2020):
  - All data sets yielded consistent results, combined to yield – r_p = 0.840(8) fm
- Conclusion
  - There is no discrepancy between the proton radius obtained from ep scattering and that determined from the Lamb shift in muonic hydrogen

  r_p = 0.84136(39) [Antognini:1900ns, Pohl:2010zza]
  - or modern measurement of the 2S–4P transition-frequency in regular hydrogen

  r_p = 0.8335(95) [Beyer:2017gug]
- Analysis indicates that the explanation for the mismatch which spawned the “proton radius puzzle” lies in an underestimation of the bias introduced by the use of specific, limiting choices for the functions employed to fit and extrapolate ep scattering data



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QCD is full of surprises

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

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

- In appearance, QCD is simple.
- QCD is also unique.
- Fundamental theory with the capacity to sustain massless elementary degrees-of-freedom, *viz*. gluons and quarks;
  - Yet gluons and quarks are predicted to acquire mass dynamically
  - And nucleons and almost all other hadrons likewise
- Only massless systems in QCD = composite Nambu-Goldstone (NG) bosons, *e.g*. pions and kaons.
- Pions responsible for binding systems as diverse as atomic nuclei and neutron stars
- Energy associated with the gluons and quarks within the NG modes is not readily apparent.
- Stark contrast with all other “everyday” hadrons:
  - systems constituted from *u*, *d*, *s* quarks possess nuclear-size masses
  - masses far in excess of anything that can directly be tied to the Higgs boson

QCD is full of surprises

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- In trying to match QCD with Nature, one confronts the many complexities of strong, nonlinear dynamics in relativistic quantum field theory, *e.g.*:
  - loss of particle number conservation
  - frame and scale dependence of the explanations and interpretations of observable processes
  - evolving character of the relevant degrees-of-freedom
- Electroweak theory and phenomena are essentially perturbative; hence, possess little of this complexity.
- Science has never before encountered an interaction such as that at work in QCD.
- Understanding this interaction, explaining everything of which it is capable, can potentially change the way we look at the Universe.

QCD is full of surprises

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- Comparison with QED
  - One essential difference = circled term, describing gluon self-interactions.
- If QCD is correct, then this term must hold the answers to an enormous number of Nature's basic questions, e.g.:
  - what is the origin of visible mass?
  - how is mass distributed within atomic nuclei?
  - what carries the proton's spin?
  - how can the same degrees-of-freedom combine to ensure the pion is spinless?
- Nowhere are there more basic expressions of *emergence* in Nature

QCD is full of surprises

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

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

- Treated as a classical theory, chromodynamics is a non-Abelian local gauge field theory.
- Formulated in four spacetime dimensions, such theories do not possess any mass-scale in the absence of Lagrangian masses for the quarks.
  - There is no dynamics in a scale-invariant theory, only kinematics.
  - Bound states are therefore impossible
  - Accordingly, our Universe cannot exist.
- A Spontaneous breaking of symmetry - Higgs mechanism - does not solve this problem
  - m_N ≈ 100-times larger than Higgs-generated current-masses of the light *u*- and *d*-quarks, the valence constituents of nucleons

QCD is full of surprises

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

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

- On the other hand … NG bosons are (nearly) massless
- In these systems, the strong interaction’s $m_N \approx 1$ GeV mass-scale is hidden.
- Chiral limit, when Higgs-generated masses are omitted, NG modes are massless
  - Exactly massless … no fine tuning … no danger of tachyons
- In this case, perturbative QCD predicts that strong interactions cannot distinguish between quarks with negative or positive helicity – chiral symmetry
- Such a chiral symmetry would have numerous corollaries, *e.g.*
  - pion would be partnered with a scalar meson of equal mass.
- However, no such state is observed
- No consequences of this chiral symmetry found in Nature – symmetry broken by interactions.
- Dynamical chiral symmetry breaking (DCSB) ensures both
  - massless quarks in QCD's Lagrangian acquire large effective masses
  - interaction energy between those quarks cancels their masses exactly so that $m_\pi = 0$

QCD is full of surprises

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

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

- Restore the Higgs mechanism = add realistic current-quark masses
- DCSB is responsible for, *inter alia*:
  - physical size of the pion mass
    - $m_\pi \approx 0.15\ m_N$
  - large mass-splitting between pion and its valence-quark spin-flip partner, ρ-meson
    - $m_\rho > 5\ m_\pi$
  - neutron and proton possessing masses
    - $m_N \approx 1$ GeV
  - Interesting things also happen to the kaon
    - Like a pion, but with one light quark replaced by *s*-quark, K possesses a mass $m_K \approx 0.5$ GeV
    - Here a competition is taking place, between dynamical and Higgs-driven mass-generation.

Fundamental Mysteries

- These phenomena and features, their origins and corollaries, entail that the question
  - how did the Universe evolve?
- is inseparable from the questions
  - how does the $m_N \approx 1$ GeV mass-scale that characterises atomic nuclei appear?
  - why does it have the observed value?
  - and, enigmatically, why does the dynamical generation of m_N have seemingly no effect on the composite NG bosons in QCD?
    - *i.e*. whence the near-absence of the pion mass?

Confinement

- Confinement is one of the most fascinating aspects of QCD
- At issue is the definition.
- When communicating about confinement, a typical practitioner has a notion in mind; yet the perspectives of any two different practitioners are often distinct
  - e.g., [Wilson:1974sk, Gribov:1998kb, Cornwall:1981zr].
- The proof of one expression of confinement will be contained within demonstration that quantum $SU_c(3)$ gauge field theory is mathematically well-defined,
  - *i.e*. a solution to the “Millennium Problem” [Clay Mathematics Institute $1,000,000]
- However, that may be of limited utility because
  - Nature has provided light-quark degrees-of-freedom
  - They seemingly play a crucial role in the empirical realisation of confinement,
  - Perhaps because they enable screening of colour at low couplings [Gribov:1998kb].

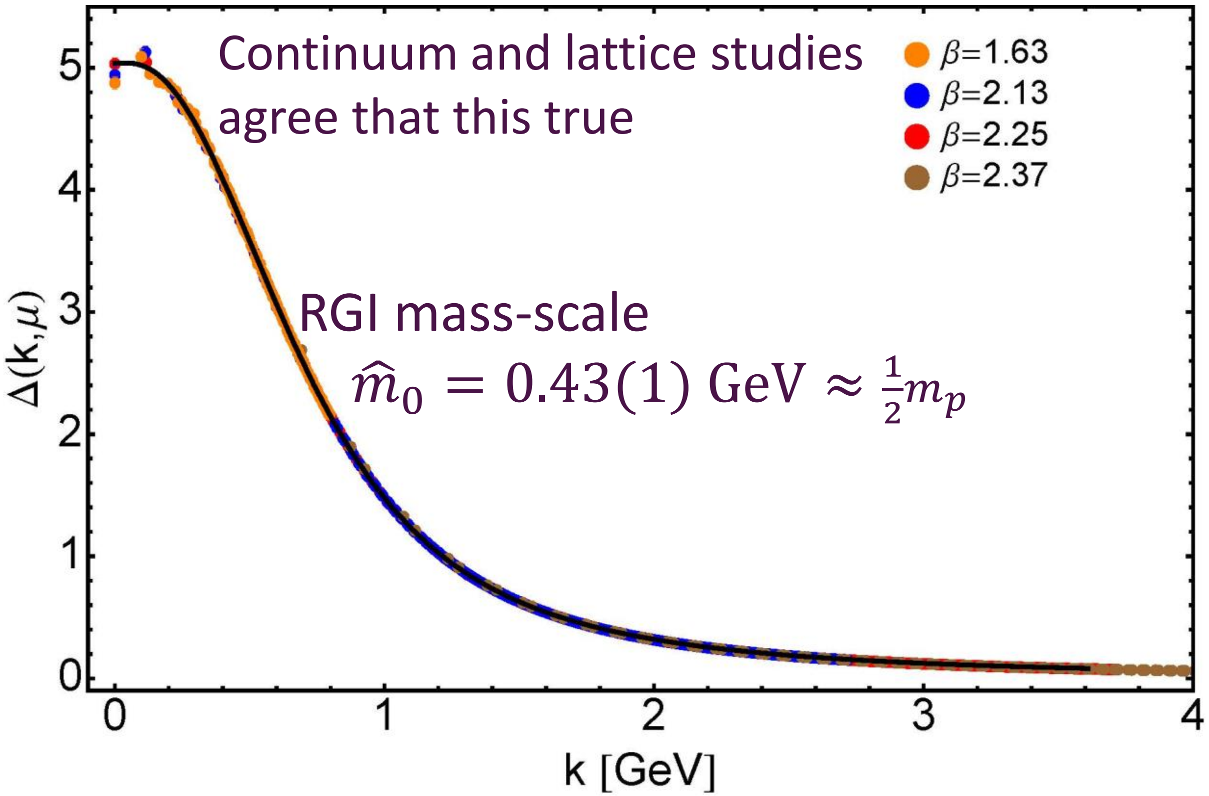
IR Behaviour of QCD

- ➢ Gluons are *supposed* to be massless …
  This is true in perturbation theory
- ➢ ***Not preserved non-perturbatively!***

  No symmetry in Nature protects four-transverse gluon modes …

  $q_\mu \, \Pi_{\mu\nu}(q) \equiv 0$
- ➢ Gluons acquire a running mass, which is large at infared momenta

  ⇒ Prediction: Gluon two-point function is nonzero and finite at $q^2 = 0$



Continuum and lattice studies agree that this true

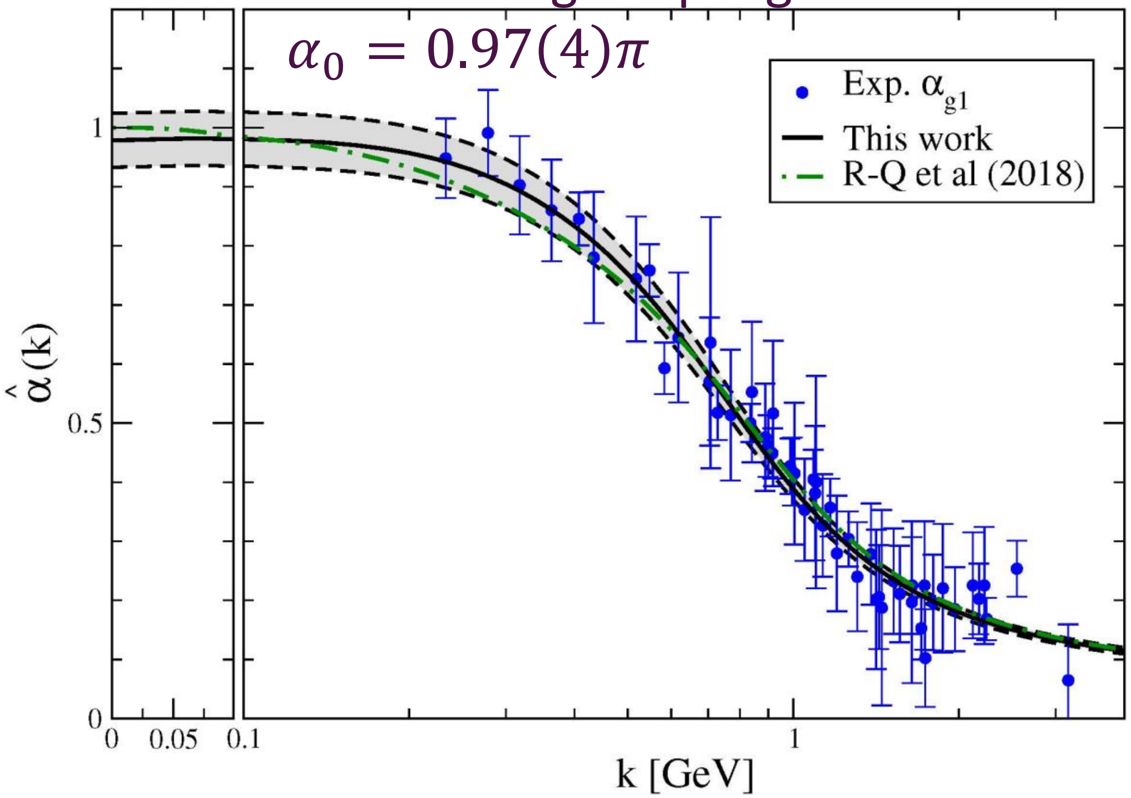
RGI mass-scale
$\hat{m}_0 = 0.43(1)\ \text{GeV} \approx \frac{1}{2} m_p$

Dynamical mass generation in continuum quantum chromodynamics
*J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … ~ 1000 citations … approach modernized and sketched results are confirmed*

RGI PI Effective Charge

- Gluon vacuum polarization can be translated into a RGI process independent effective charge for QCD
  - Use pinch technique and background field method
- Unique analogue of Gell-Mann – Low running coupling in QED
- Parameter-free prediction

RGI PI strong coupling



The QCD Running Coupling,
A. Deur, S. J. Brodsky and G. F. de Teramond, Prog. Part. Nucl. Phys. **90** (2016) 1-74

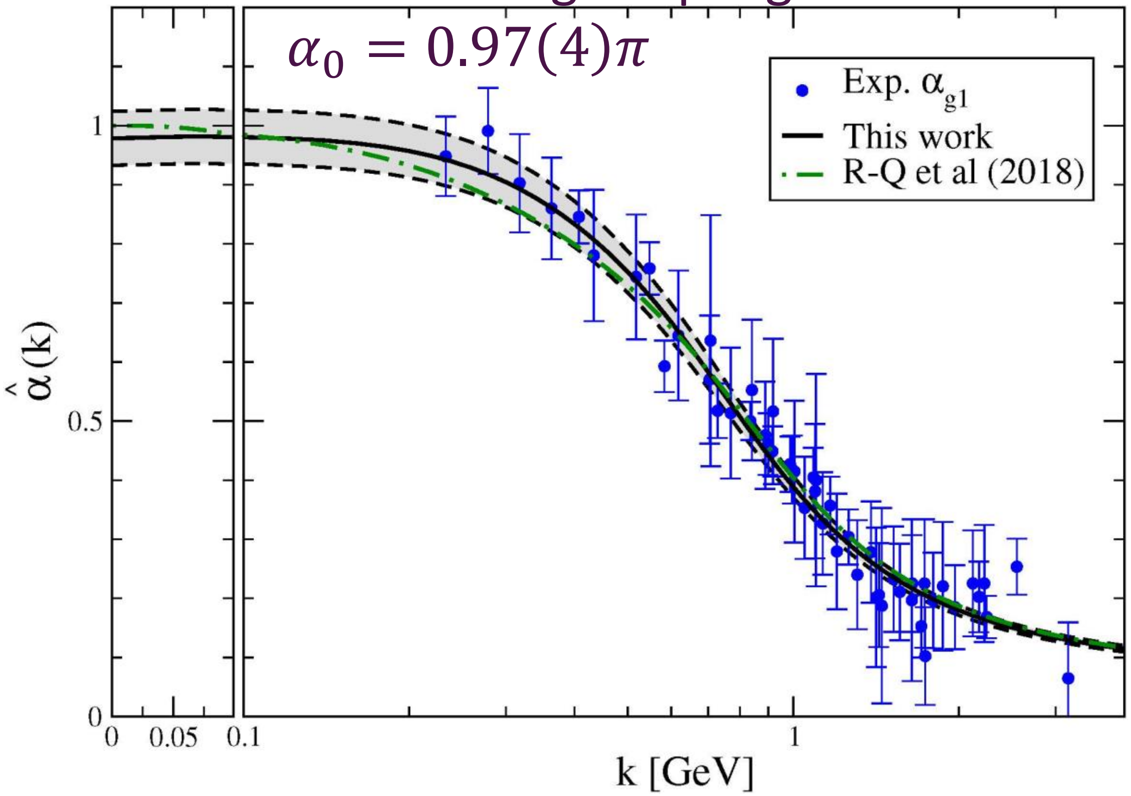
Process independent strong running coupling
Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7

Process-independent effective coupling. From QCD Green functions to phenomenology,
Jose Rodríguez-Quintero *et al.*, arXiv:1801.10164 [nucl-th]. Few Body Syst. **59** (2018) 121/1-9

Effective charge from lattice QCD, Zhu-Fang Cui, Jin-Li Zhang et al., NJU-INP 014/19, arXiv:1912.08232 [hep-ph]

RGI PI Effective Charge

- $\hat{\alpha}(k^2)$ is smooth and monotonically decreasing on $k^2 \geq 0$
- Known to unify a wide range of observables, *e.g.*
  - static properties
  - distribution amplitudes and functions
  - elastic and transition form factors



RGI PI strong coupling

$\alpha_0 = 0.97(4)\pi$

RGI PI Effective Charge

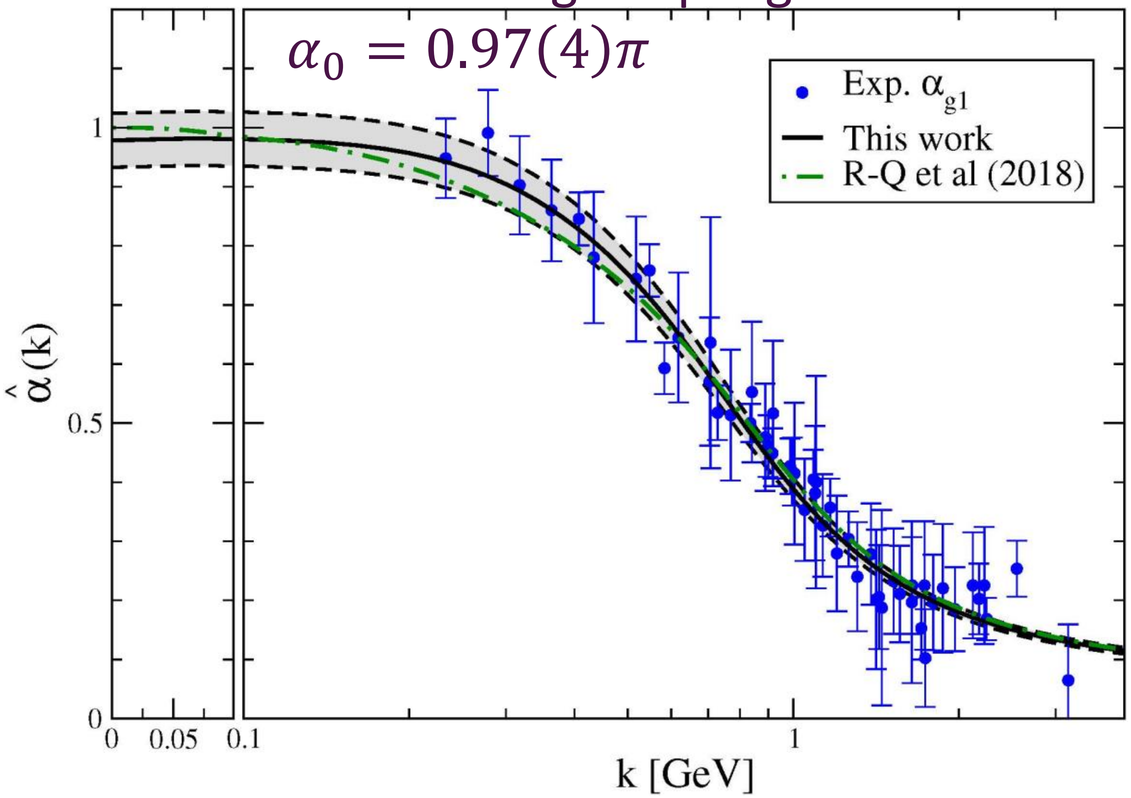
- Also, $\hat{\alpha}(k^2)$is:

i. pointwise (almost) identical to the process-dependent (PD) effective charge,α_{g_1}, defined via the Bjorken sum rule;

ii. capable of marking the boundary between soft and hard physics;

iii. that PD charge which, used at one-loop in the QCD evolution equations, delivers agreement between pion parton distribution functions calculated at the hadronic scale and experiment.

RGI PI strong coupling

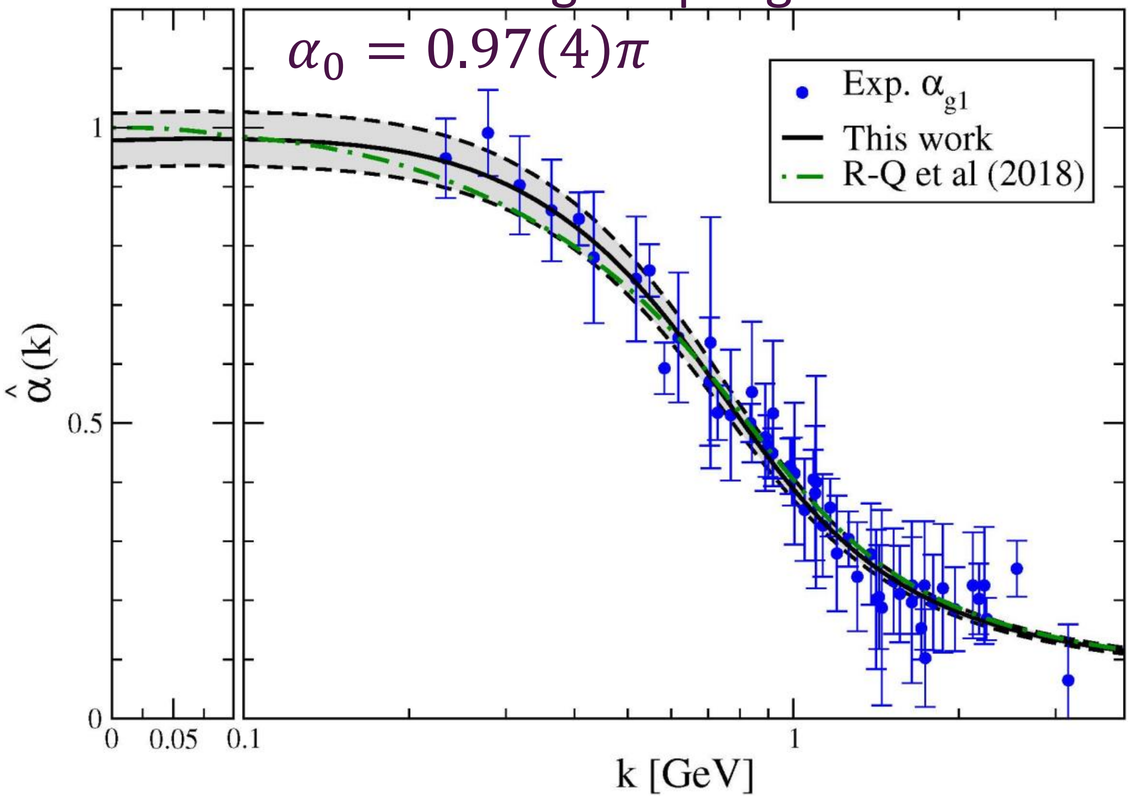


RGI PI Effective Charge

- In playing so many diverse roles, $\hat{\alpha}(k^2)$ is a strong candidate for that object which properly represents the interaction strength in QCD at any given momentum scale.
- Landau pole, a prominent feature of perturbation theory, is screened (eliminated) in QCD by the dynamical generation of a gluon mass-scale
- Theory possesses an infrared stable fixed point.

RGI PI strong coupling

$\alpha_0 = 0.97(4)\pi$



- Accordingly, with standard renormalisation theory ensuring that QCD's ultraviolet behaviour is under control, QCD emerges as a mathematically well-defined quantum field theory in four dimensions.

Craig Roberts. Measurable Expressions of EHM

Matter Sector

- Dynamical violation of scale invariance in QCD enables emergence of gluon mass
- What about the matter sector?
- Inspired by BCS theory, Nambu developed simple model … won him Nobel Prize
  - fermion & antifermion form a Cooper-like pair so long as coupling is strong enough
- Studied via Dyson's Gap Equation – describes emergence of quasiparticle in many body systems & quantum field theories are systems with infinitely many bodies

$$S^{-1}(p) = Z_2\,(i\gamma\cdot p + m^{\rm bm}) + \Sigma(p)\,,$$

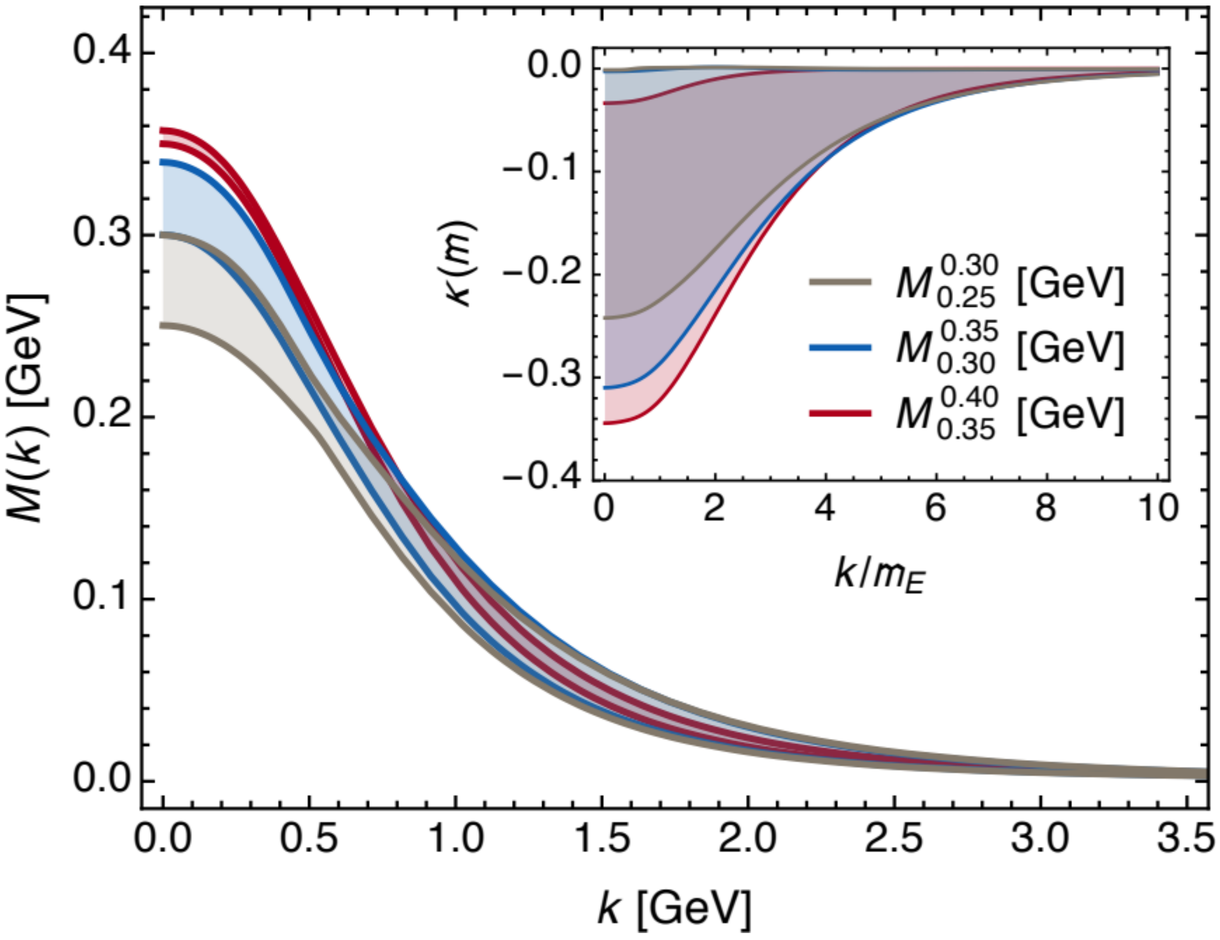
$$\Sigma(p) = Z_2 \int_{dq}^{\Lambda} 4\pi\hat{\alpha}(k^2)\mathcal{D}_{\mu\nu}(k)\gamma_\mu S(q)\hat{\Gamma}^a_\nu(q,p)\,,$$

- If and only if $\alpha_0 \geq 0.3\pi$, then this gap equation produces a nonzero fermion mass even in the absence of a Higgs coupling
- Dynamical chiral symmetry breaking – emergence of a fermion mass *from nothing*

Matter Sector

$\alpha_0 = 0.97\,\pi$

- Dressed-quark quasiparticles emerge
- Characterised by a running mass M(k)
  - Vanishes in ultraviolet, following the pattern predicted by Lane (1974) and Politzer (1976)
  - Large at infrared momenta, *i.e.* $M(0) \approx \frac{1}{3} m_p$
  - Just like constituent quark
- Dressed-quark is a bare parton at ultraviolet momenta
- But that parton carries a cloud of sea and glue with it in the infrared



Empirical Consequences of EHM

- QCD's interactions are universal … same in all hadrons
- However, expression need not be the same in all hadrons
- DCSB in chiral limit ensures SUM of different trace-anomaly operator-contributions cancel amongst each other to yield $m_\pi = 0$
  - Individual terms do not vanish separately
- In proton, no symmetry requires cancellations to be complete

  Thus, value of proton's mass is typical of the magnitude of scale breaking in one body sectors = dressed-gluon and -quark mass scales
- This “DCSB paradigm” provides basis for understanding why:
  - mass-scale for strong interactions is vastly different to that of electromagnetism
  - proton mass expresses that scale
  - pion is nevertheless unnaturally light

Pion mass – a decomposition?

- Rest frame decomposition of the trace anomaly has been used [Yang:2014qna] to separate the pion's mass into contributions from pieces defined as the
  - m_q-term,
  - H_A = trace-anomaly,
  - H_{KU} = quark E_K+E_U,
  - H_g = gluon energy
- Conclusion:

  "For the light PS mesons, the m_q-term is about 50% of the total mass. This implies that H_A contributes ~12% of the mass.

  The remaining contributions from H_g and H_{KU} are ~30% and ~8% respectively.

  It is interesting to observe that all these contributions are positive which suggests that they all approach zero at the chiral limit when the pion mass approaches zero."
- Unfortunately … none of this makes sense.

Pion mass - problems

- Rest frame decomposition in this form leads to a precarious position because
  1. Any conclusions are frame- and scale-dependent
  2. the gluons in the trace anomaly and in the kinetic and potential energy are seemingly being treated as separate entities, which, of course, they're not
  3. chiral limit – massless particle does not have a rest frame – no simple-minded limit of separate terms is meaningful
- No quantum mechanics picture of a bound-state's mass has all terms positive:
  - kinetic energy and mass terms are positive
  - binding energy is negative
- Gell-Mann – Oakes – Renner [GellMann:1968rz] … known for > 50 years:

Huge EHM enhancement factor $\approx 200\,(m_u + m_d)$

$$m_\pi^2 \propto m \times DCSB\ enhancement\ factor \quad \ldots \quad \text{explicitly, } m_\pi^2 = (m_u + m_d)\boxed{\frac{-\langle \bar{q}q\rangle}{f_\pi^2}}$$

If ALL of m_π^2 owes to the current-quark mass term in a Poincaré-invariance statement

Then what possible meaning can one associate with "rest frame" statement that only half m_π comes from the quark mass term, *i.e.* m_q-term produces 0.25 m_π^2 ?!

Decompositions of mass - Solution

- Avoid a Mass Crisis
- Stay away from decompositions whose definitions and interpretations are muddled by frame- and scale- dependence
- Cleanest statement of the origin of mass
  - There is a trace anomaly: $\Theta_0 = \beta(\alpha)\, ¼ G_{\mu\nu} G_{\mu\nu} = T_{\rho\rho}$
  - In the chiral limit

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

- Understand, explain and explicate how this dichotomy is resolved.

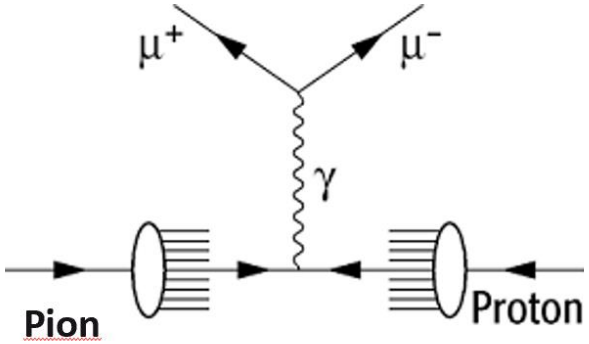
Empirical Consequences of EHM

- No significant mass-scale is possible unless one of similar size is expressed in the dressed-propagators of gluons and quarks.
- Follows that the mechanism(s) responsible for emergence of mass can be exposed by measurements sensitive to such dressing
- This potential is offered by many observables:
  - Spectra and static properties
  - Form factors, elastic and transition
  - All types of parton distributions
- Describe three (particularly clean) examples

QCD prediction of π valence-quark distributions

- Owing to absence of stable pion targets, the pion's valence-quark distribution functions have hitherto been measured via the Drell-Yan process:

$$\pi\, p \to \mu^+ \mu^- X$$

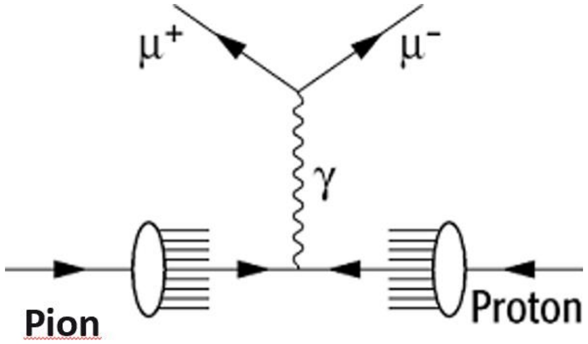


- Consider a theory in which quarks scatter via a vector-boson exchange interaction whose $k^2 >> m_G^2$ behaviour is $(1/k^2)^\beta$
- Then at a resolving scale ζ_H … $u_\pi(x;\zeta_H) \sim (1-x)^{2\beta}$

  Namely, the large-x behaviour of the quark distribution function is a direct measure of the momentum-dependence of the underlying interaction.
- In QCD, β=1 and hence

$$QCD: Q > \zeta_H \Rightarrow 2 \rightarrow 2+\gamma,\ \gamma > 0$$

$$^{QCD}u_\pi(x;\zeta_H) \sim (1-x)^2$$



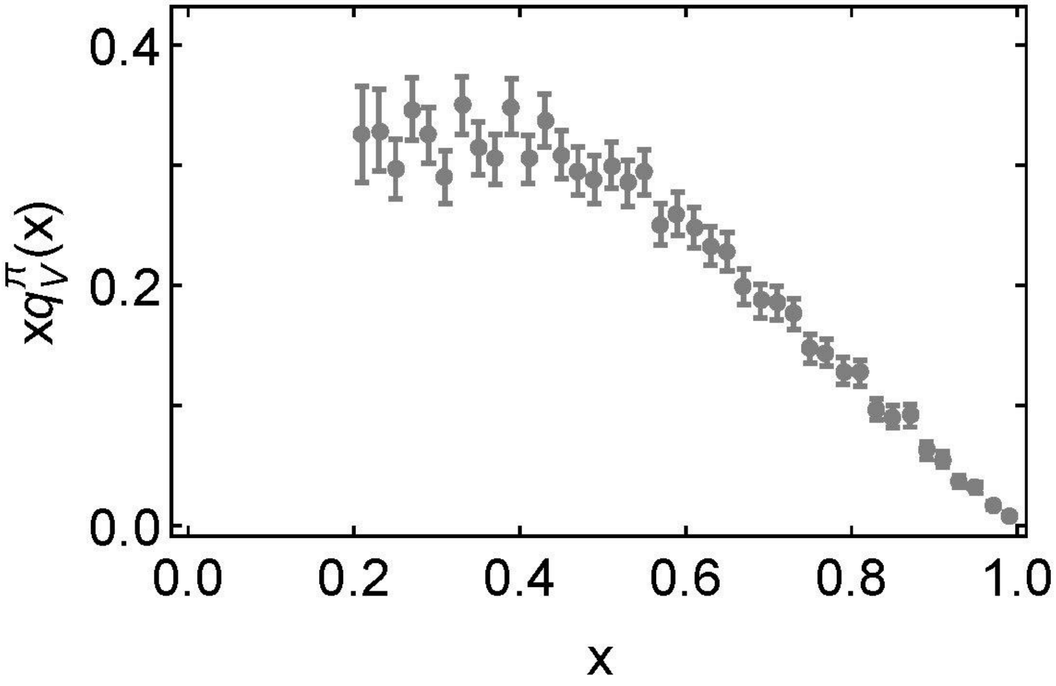
Empirical status of the Pion's valence-quark distributions

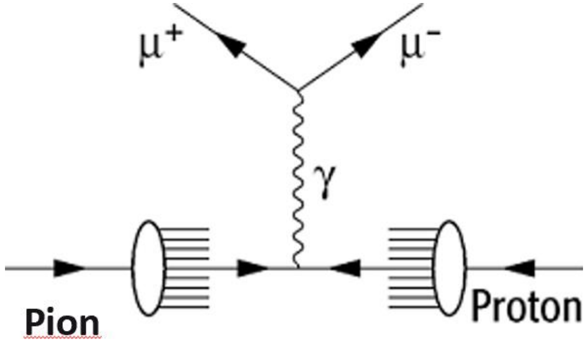
- Owing to absence of pion targets, the pion's valence-quark distribution functions have hitherto been measured via the Drell-Yan process:

  $\pi\, p \rightarrow \mu^+ \mu^- X$

- Three experiments:
  - CERN (1983 & 1985)
  - FNAL (1989).
- None more recent
- Conway *et al.*

  Phys. Rev. D **39**, 92 (1989)
  - Leading-order analysis of the Drell-Yan data
  - ~ 400 citations





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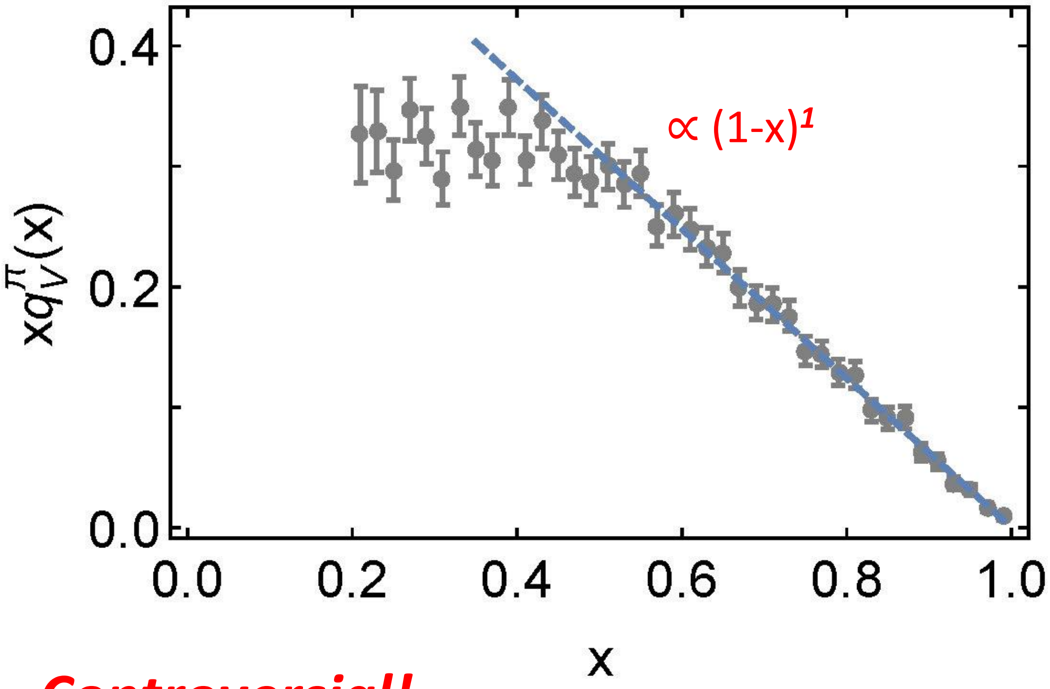
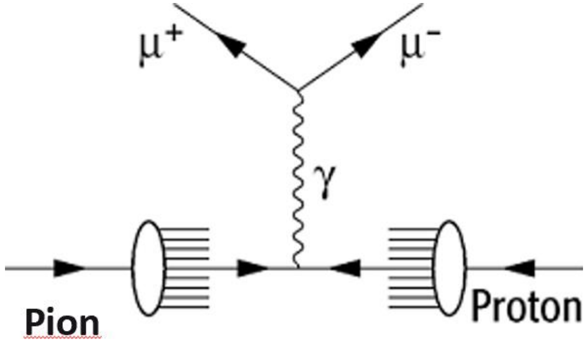
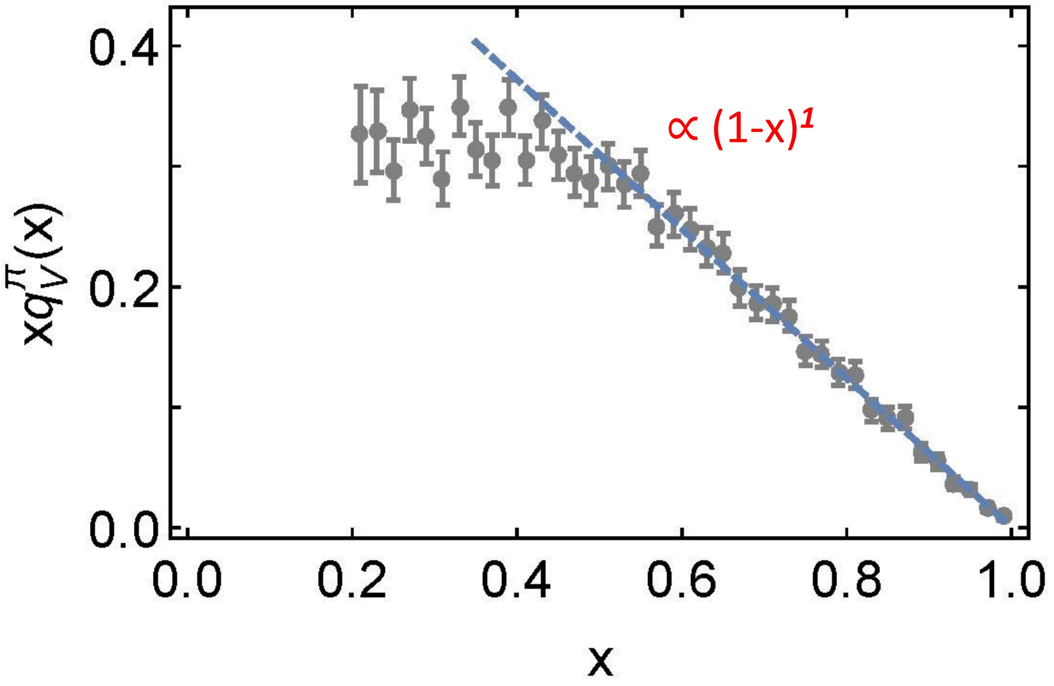


Factor of 2 discrepancy with QCD! ***Controversial!***



Empirical status of the Pion's valence-quark distributions

- Conway *et al.* Phys. Rev. D **39**, 92 (1989)
  - Leading-order analysis of Drell-Yan data
- Ensuing years, great deal of fog
- Perceptions ebbed and flowed
  - Is this data a fundamental challenge to Standard Model?

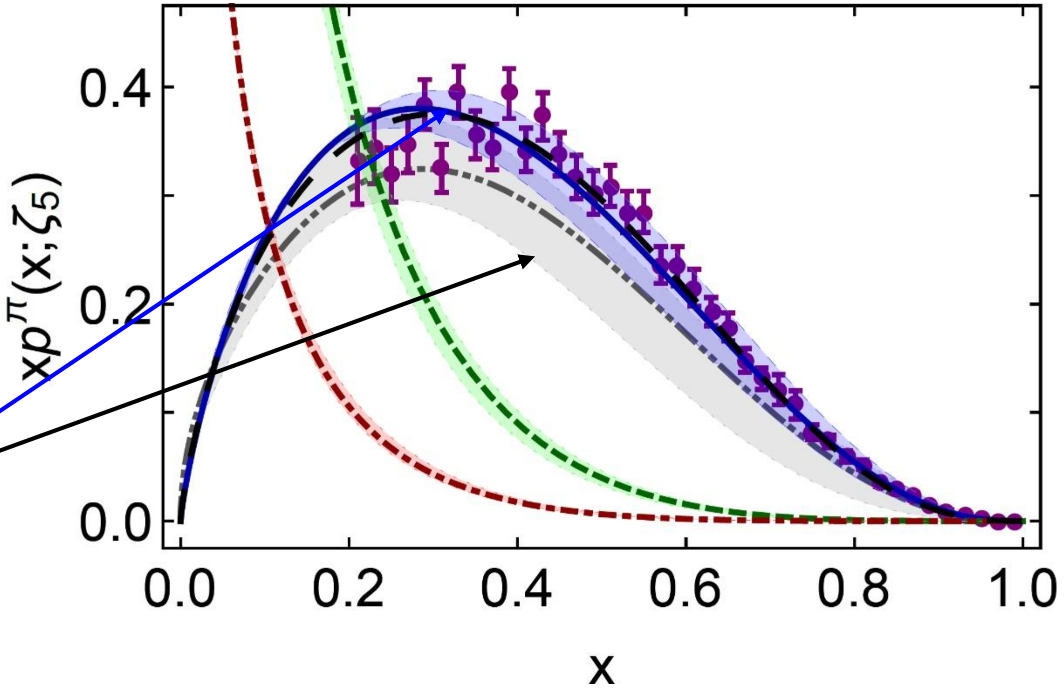


π valence-quark distributions
20 Years of Evolution → 2019

- Renewed pressure being applied by theory advances
- Novel lattice-QCD algorithms beginning to yield results for pointwise behaviour of $u^{\pi}(x;\zeta)$
- Developments in continuum-QCD have enabled 1st parameter-free predictions of valence, glue and sea distributions within the pion
  - Reveal that $u^{\pi}(x;\zeta)$is hardened by emergent mass
- Agreement between new continuum prediction for $u^{\pi}(x;\zeta)$ [Ding:2019lwe] and recent lattice-QCD result [Sufian:2019bol]
- Real strides being made toward understanding pion structure.
- Standard Model prediction is stronger than ever before
- *Now – after 30 years – new era dawning in which the ultimate experimental checks can be made*

$\beta^{\text{contm}}(\zeta_5) = 2.66(12)$

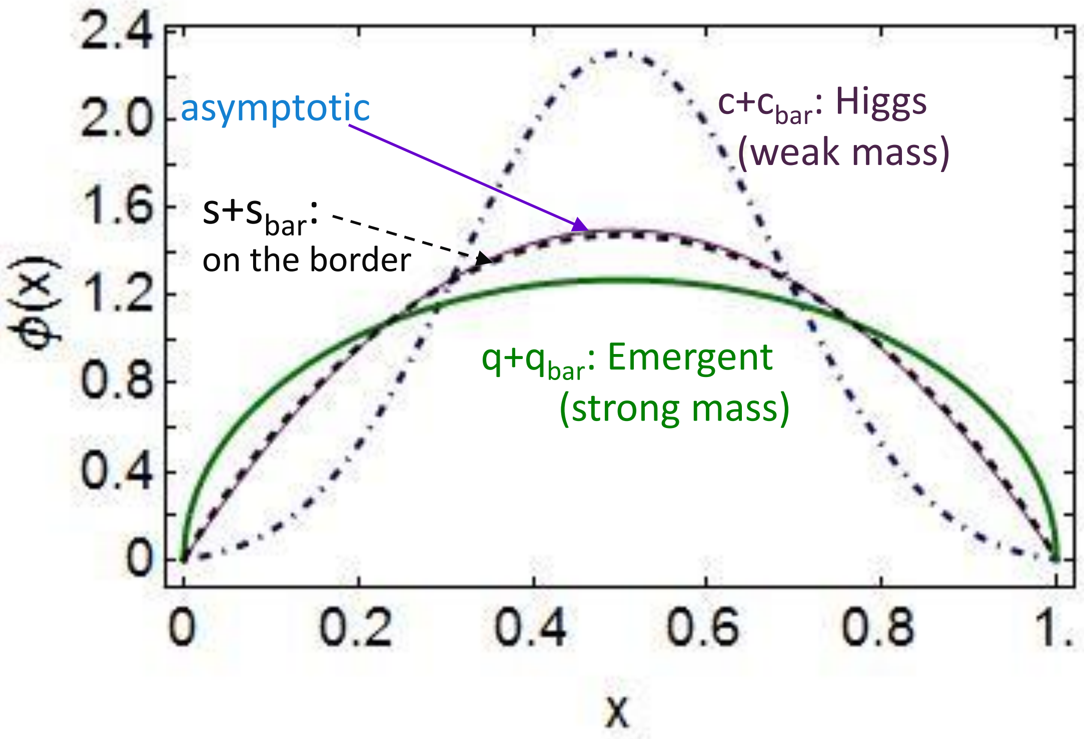
$\beta^{\text{lattice}}(\zeta_5) = 2.45(58)$



Parton distribution amplitudes of S-wave heavy-quarkonia
Minghui Ding, Fei Gao, Lei Chang, Yu-Xin Liu and Craig D. Roberts
arXiv:1511.04943 [nucl-th], Phys. Lett. B **753** (2016) pp. 330-335

Emergent Mass *vs.* Higgs Mechanism

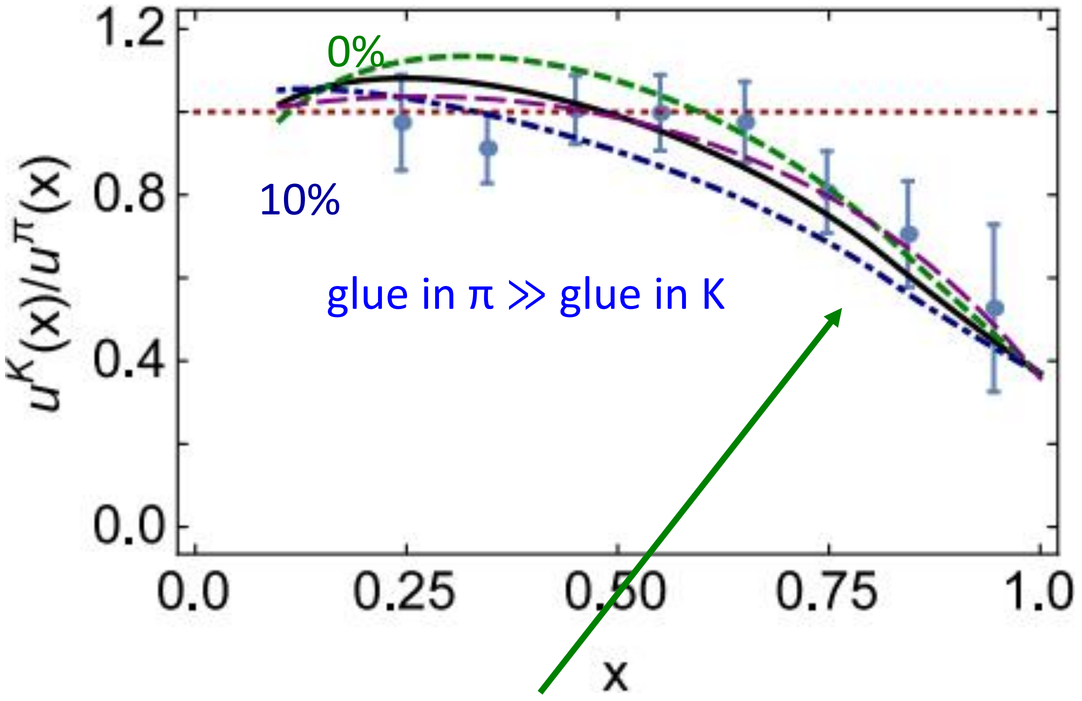
- When does Higgs mechanism begin to influence mass generation?
- limit $m_{\text{quark}} \to \infty$
  $\varphi(x) \to \delta(x-½)$
- limit $\text{m}_{\text{quark}} \to 0$
  $\varphi(x) \sim (8/\pi)\,[x(1-x)]^{½}$
- Transition boundary lies just above m_{strange}
- *Hence … Comparisons between distributions of truly light quarks and those describing strange quarks are ideally suited to exposing measurable signals of emergent mass in counterpoint to Higgs-driven effects*



Emergent Mass *vs.* Higgs Mechanism

- Striking example found in contrast between $u^{\pi}(x;\zeta)$ & $u^{K}(x;\zeta)$ at large *x*
- Significant disparity between these distributions would point to big difference between fractions of pion and kaon momentum carried by other bound state participants, particularly gluons.
- Prediction for ratio $u^{K}(x;\zeta)/\,u^{\pi}(x;\zeta)$ is available [Chen:2016sno].
- Confirms assessment:
  - gluon content of kaon at hadronic scale = 5 ± 5 %
  - Pion more-than 30%
- Persists to large resolving scales, e.g. at ζ=2 GeV,

$$\langle x\rangle_g^{\pi} \approx 1.5\, \langle x\rangle_g^{K}$$



- Difference in gluon content expressed clearly in large-x behaviour of

$$u^{K}(x;\zeta)/\,u^{\pi}(x;\zeta)$$

Craig Roberts. Measurable Expressions of EHM

Valence-quark distribution functions in the kaon and pion,
Chen Chen, Lei Chang *et al*.
arXiv:1602.01502 [nucl-th], Phys. Rev. D**93** (2016) 074021/1-11

π & K PDFs

- Empirical signal of almost-pure Nambu-Goldstone-boson character of pion
- Marking near perfect expression of

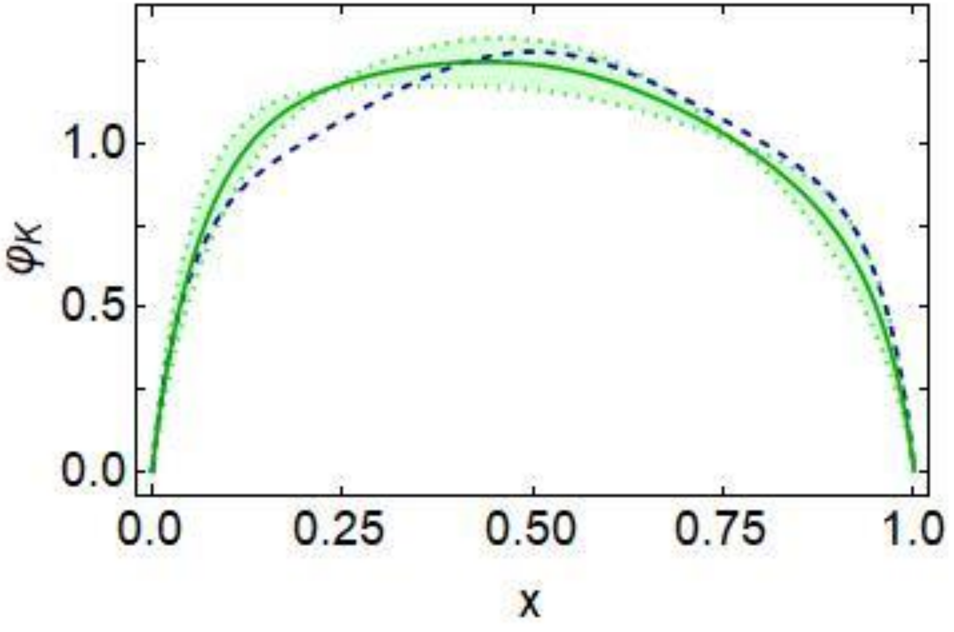
$$M_{\rm quark}^{\rm dressed} + M_{\rm antiquark}^{\rm dressed} + U_{\rm quark-antiquark\ interaction}^{\rm dressed} \overset{\rm chiral\ limit}{\equiv} 0$$

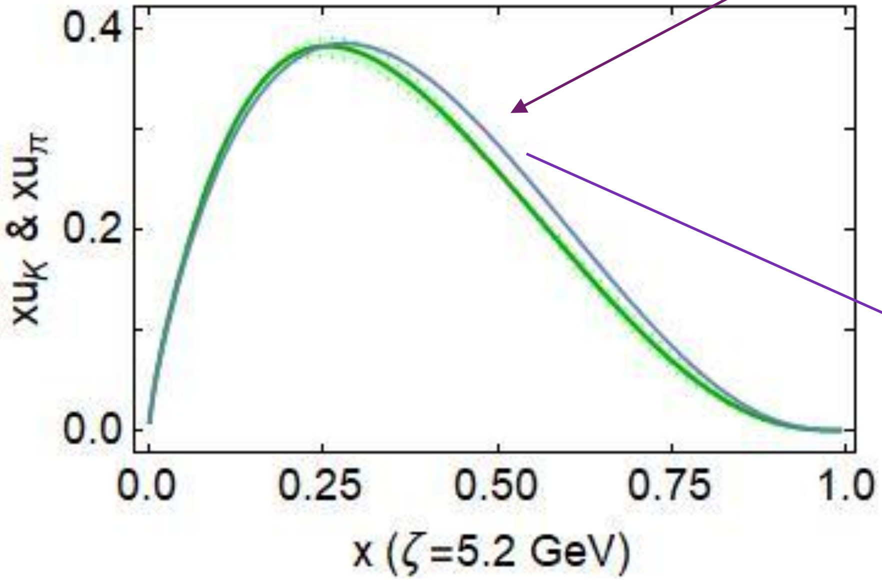
in the almost-massless pion

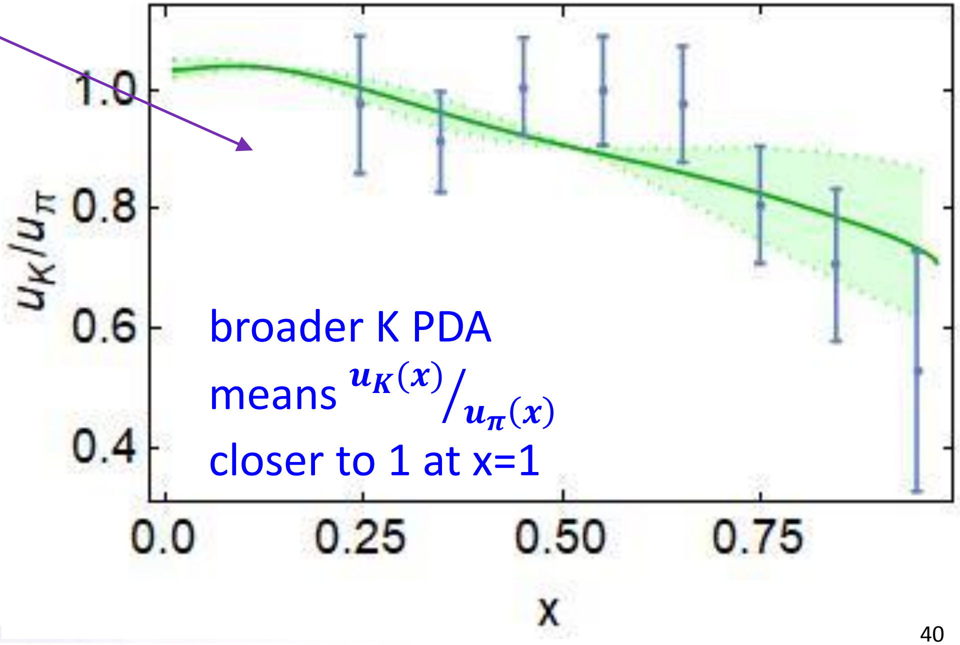
- Compared to incomplete cancellation in the strange-quark-containing kaon.
- Big Issue – ONE, however:
  - Only one forty-year-old measurement of $u^K(x;\zeta)/\ u^\pi(x;\zeta)$
  - CERN [Badier:1980jq].
- Big Issue – TWO …

$^{u_K(x)}/_{u_\pi(x)}$ Next Steps

- Existing continuum results for PDFs used simplest truncation of meson bound-state equations
- In-progress: use most sophisticated version of the q+q̄ scattering kernel
- Here work with CSM analysis of existing lQCD results for kaon PDA
- Use these inputs to illustrate sensitivity of $^{u_K(x)}/_{u_\pi(x)}$ to kaon wave function
- Pion's LFWF with best kernel is known
- Compute final kaon LFWF, then deliver prediction for ratio & sea and glue distributions in kaon







broader K PDA means $^{u_K(x)}/_{u_\pi(x)}$ closer to 1 at x=1

$\langle x\rangle_{glue}^{\pi}$ is 20% > $\langle x\rangle_{glue}^{K}$

π & K PDFs

- Cannot claim understanding of Standard Model until explanation is provided for emergence and structure of Nambu-Goldstone (NG) modes
- NG modes are far more complex than is typically thought.
  - Not pointlike;
  - Intimately connected with the origin of mass;
  - Probably play an essential part in any answer to the question of gluon and quark confinement in the *physical* Universe.
- Internal structure of NG modes is very complicated; and that structure provides the clearest window onto the emergence of mass in the Standard Model.
- Cleanest expression may be found in following statement
  - *The gluon content of Nature's only near-pure Nambu-Goldstone mode, the pion, is significantly larger than that in any other hadron*

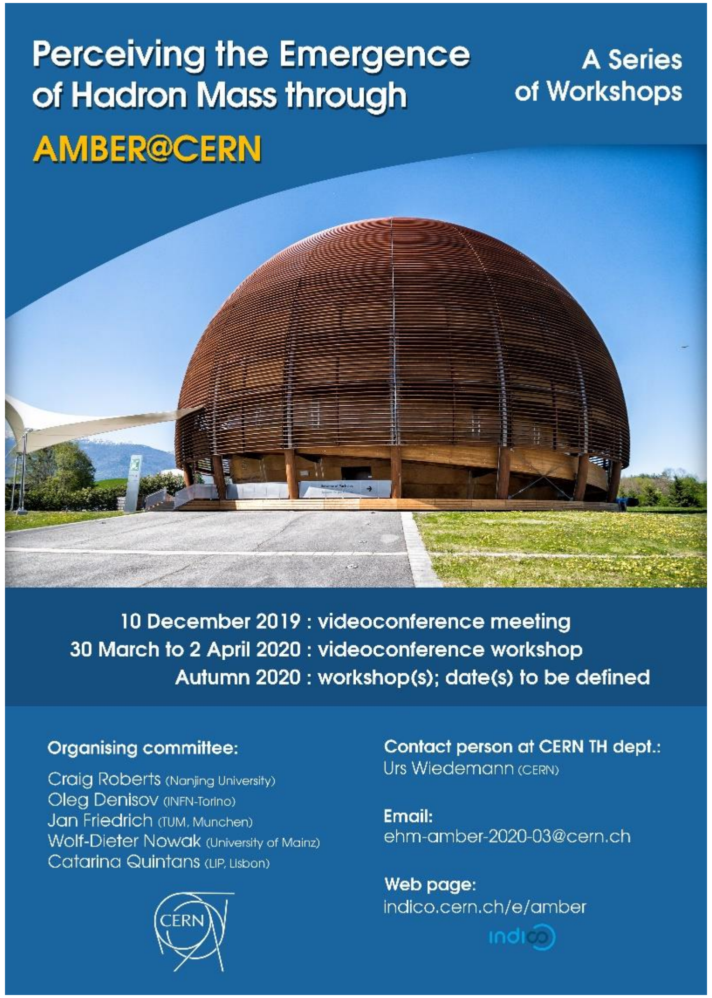
π & K PDFs

- Cleanest expression may be found in following statement
  - *The gluon content of Nature's only near-pure Nambu-Goldstone mode, the pion, is significantly larger than that in any other hadron*
- Observably expressed in $u^{\pi}(x;\zeta)$ & accentuated in $u^{K}(x;\zeta)/\,u^{\pi}(x;\zeta)$
- New-era experiments, capable of validating these predictions, are of highest priority.
- Why Validation?
  - Pion properties are critical to the formation of everything:
    - From nucleons, to nuclei, and on to neutron stars.
- A chapter of the Standard Model, for which Yukawa wrote the opening sentences more than eighty years ago, can be closed.
  - *Elucidation of structural details of the Standard Model's only NG modes*

Future

Thank you

- Challenge: <u>Explain</u> the Origin & Distribution of the Bulk of Visible Mass
- *Progress* and *Insights* being delivered by amalgam of
  - Experiment … Phenomenology …Theory
- Continued exploitation of synergies essential
  to capitalise on new opportunities provided by existing & planned facilities
- This Discussion … join theorists from high-energy nuclear & particle physics in dialogue with the experimentalists … address the Emergence of Hadron Mass
- Start collaborative effort between experimentalists proposing the new measurement campaigns, phenomenologists doing global data analyses, and hadron-structure theorists.
- Next Step … hopefully, a face-to-face meeting at CERN in Autumn.



Perceiving the Emergence of Hadron Mass through
AMBER@CERN

A Series of Workshops

10 December 2019 : videoconference meeting
30 March to 2 April 2020 : videoconference workshop
Autumn 2020 : workshop(s); date(s) to be defined

Organising committee:
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Oleg Denisov (INFN-Torino)
Jan Friedrich (TUM, Munchen)
Wolf-Dieter Nowak (University of Mainz)
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