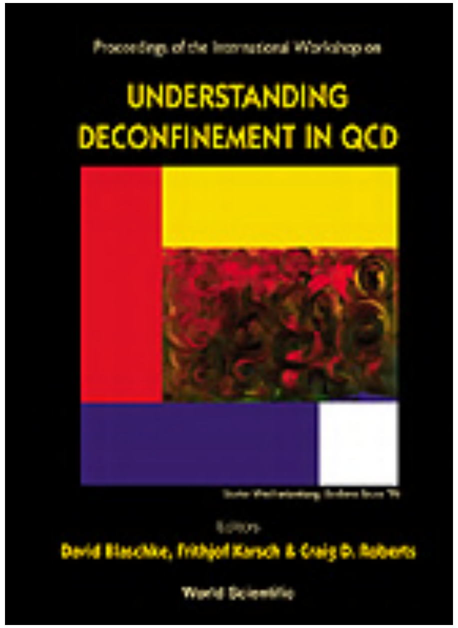
NANJING UNIVERSITY

Emergence of Mass in Hadronic Systems

Craig Roberts

David Blaschke

- 1995, Summer: David visited ANL following a Quark Matter meeting in CA
  - 24 years and counting
- 1995, September: CDR visits Rostock
  - Guest in David's apartment
  - Celebrates David's 36th birthday
- 1995, September: At David's 36th birthday party, CDR meets Almut, his future wife
- 1996, March: CDR visits Rostock to complete work on first joint publication
  - *Continuum study of deconfinement at finite temperature*, A. Bender, D. Blaschke, Yu. Kalinovsky and C. D. Roberts, nucl-th/9606006 Phys. Rev. Lett. **77**, pp. 3724 (1996)
- Now:
  - 10 joint publications
  - Organised quite a few conferences/workshops together



David's qualities

- Constructive
- Enthusiastic
- Optimistic
- Imaginative
- Collaboration Builder
- Adventurous
- Exceedingly Hospitable and Generous
- …
- Developed into a snappy dresser


HAPPY
BIRTHDAY

2013: Englert & Higgs

- ➢ The 2013 Nobel Prize in Physics was awarded to Peter Higgs and Francois Englert following discovery of the Higgs boson at the Large Hadron Collider.
- ➢ With this discovery the Standard Model of Particle Physics became complete.

Where to now?

2013: Englert & Higgs

- "The Higgs boson is often said to give mass to everything."
- "However, that is wrong. It only gives mass to some very simple particles, accounting for only one or two percent of the mass of more complex things …"
- *The vast majority of mass comes from the energy needed to hold quarks together inside hadrons*

confinement

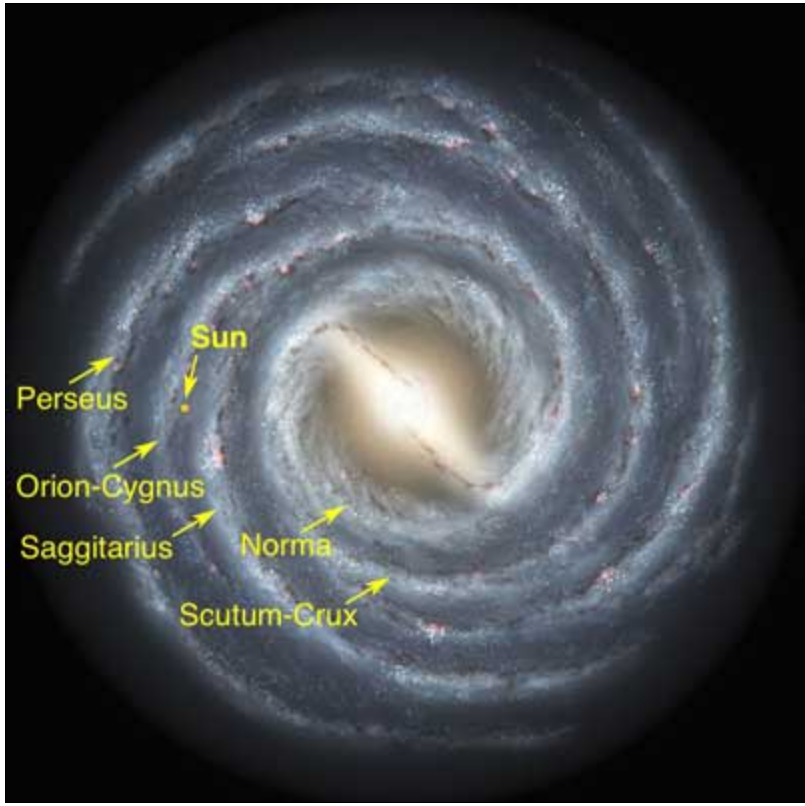
2013: Englert & Higgs

- The most important chapter of the Standard Model is the least understood.
- Quantum Chromodynamics (QCD) is that part of the Standard Model which is supposed to describe all of nuclear physics
  - Matter = quarks
  - Gauge bosons = gluons
- Yet, fifty years after the discovery of quarks, we are only just beginning to understand how QCD moulds the basic bricks for nuclei: pions, neutrons, protons, etc.

Emergent Phenomena in the Standard Model

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

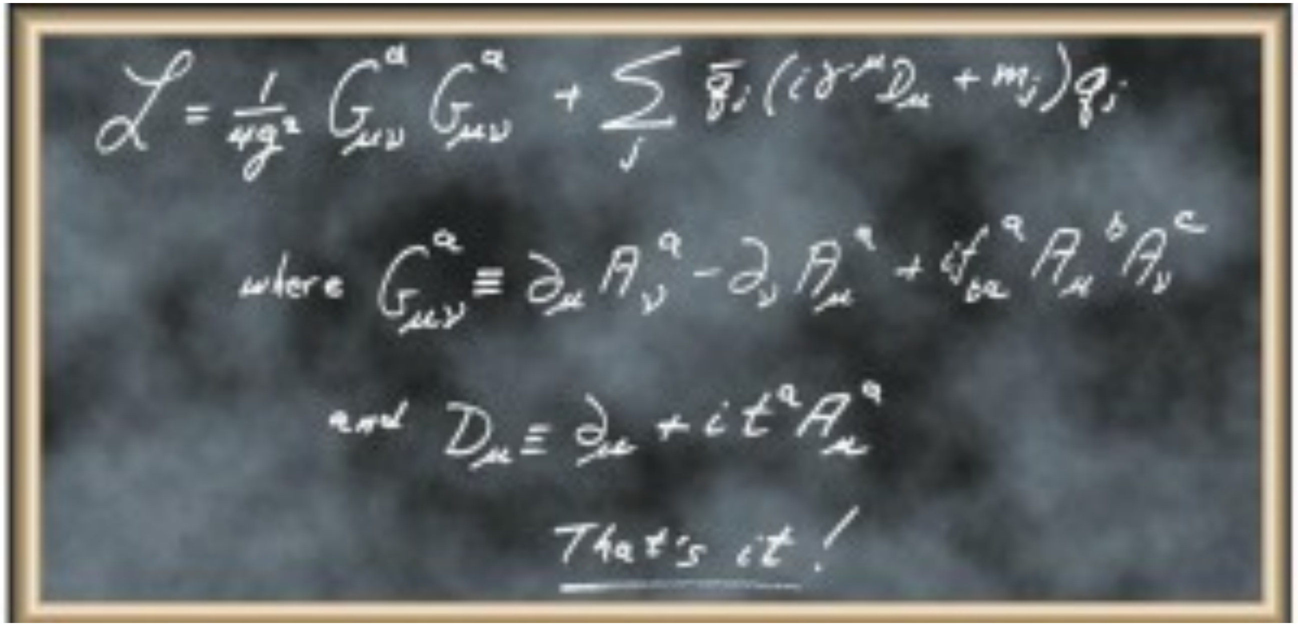
- ➢ Proton is massive
  - *i.e.* the mass-scale for strong interactions is vastly different to that of electromagnetism
- ➢ Proton is absolutely stable
  - Despite being a composite object constituted from three valence quarks
- ➢ Pion is unnaturally light (not massless, but lepton-like mass)
  - Despite being a strongly interacting composite object built from a valence-quark and valence antiquark



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

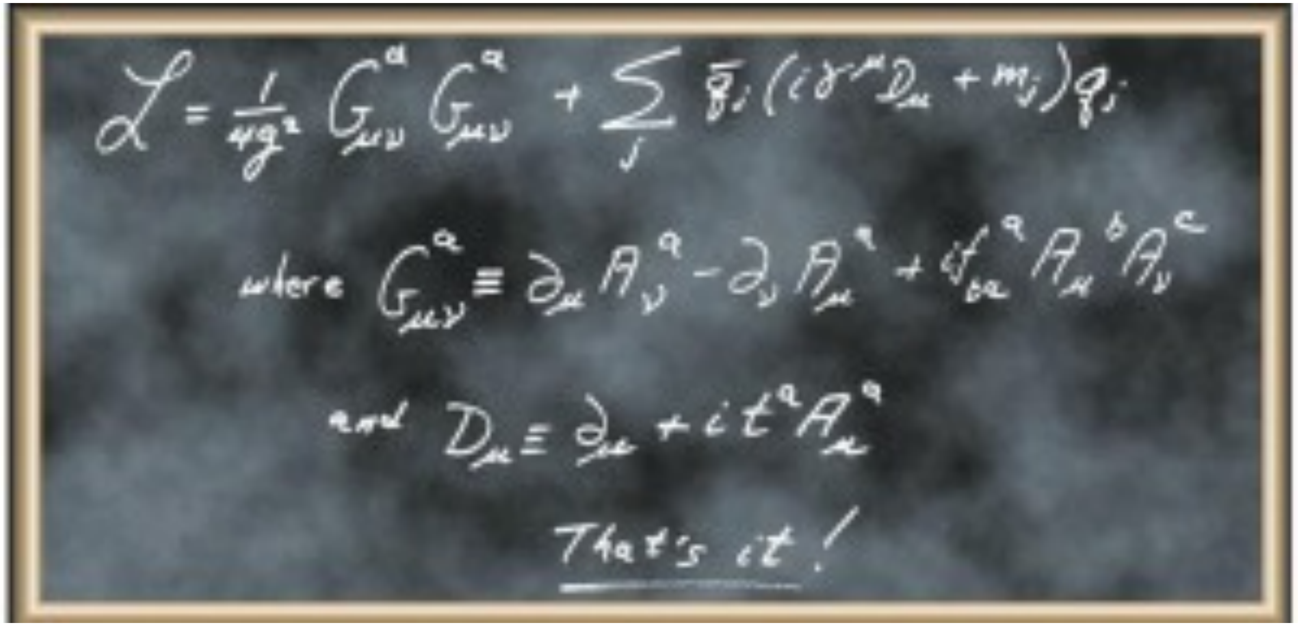
F. Wilczek, QCD Made Simple
Physics Today **53N8** 22-28, (2000)

Quantum Chromodynamics



- Quite possibly, the most remarkable theory we have ever invented
- One line and two definitions are responsible for the
  origin, mass and size of (almost) all visible matter!

Quantum Chromodynamics



- Quite possibly, the most remarkable theory we have ever invented
- One line and two definitions are responsible for the origin, mass and size of (almost) all visible matter!

Strong Interactions in the Standard Model

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

- 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 $L_{\rm QED}$

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

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?*

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

Trace Anomaly

- In a scale invariant theory Poincaré invariance entails

  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, L(m=0)

  $\Rightarrow \partial_\mu D_\mu = \delta L/\delta\sigma = \alpha\beta(\alpha)\, dL/d\alpha = \boxed{\beta(\alpha)\, \tfrac{1}{4} G_{\mu\nu} G_{\mu\nu} = T_{\rho\rho} =: \Theta_0}$

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

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

Trace Anomaly

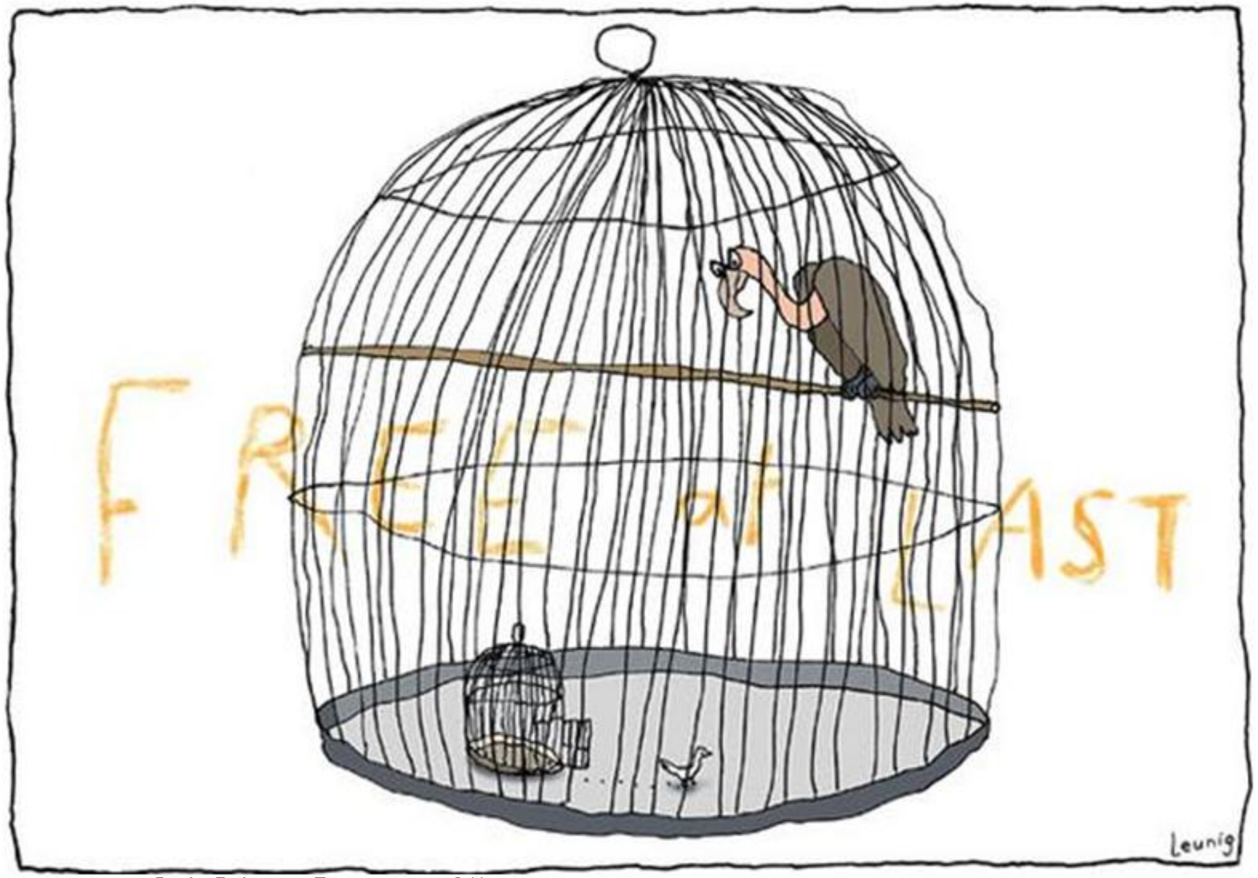
- Knowing that a trace anomaly exists does not deliver a great deal
  … Indicates only that a mass-scale must exist
- Key Question:
  - Can one compute and/or understand the magnitude of that scale?
- One can certainly *measure* the magnitude … consider proton:

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

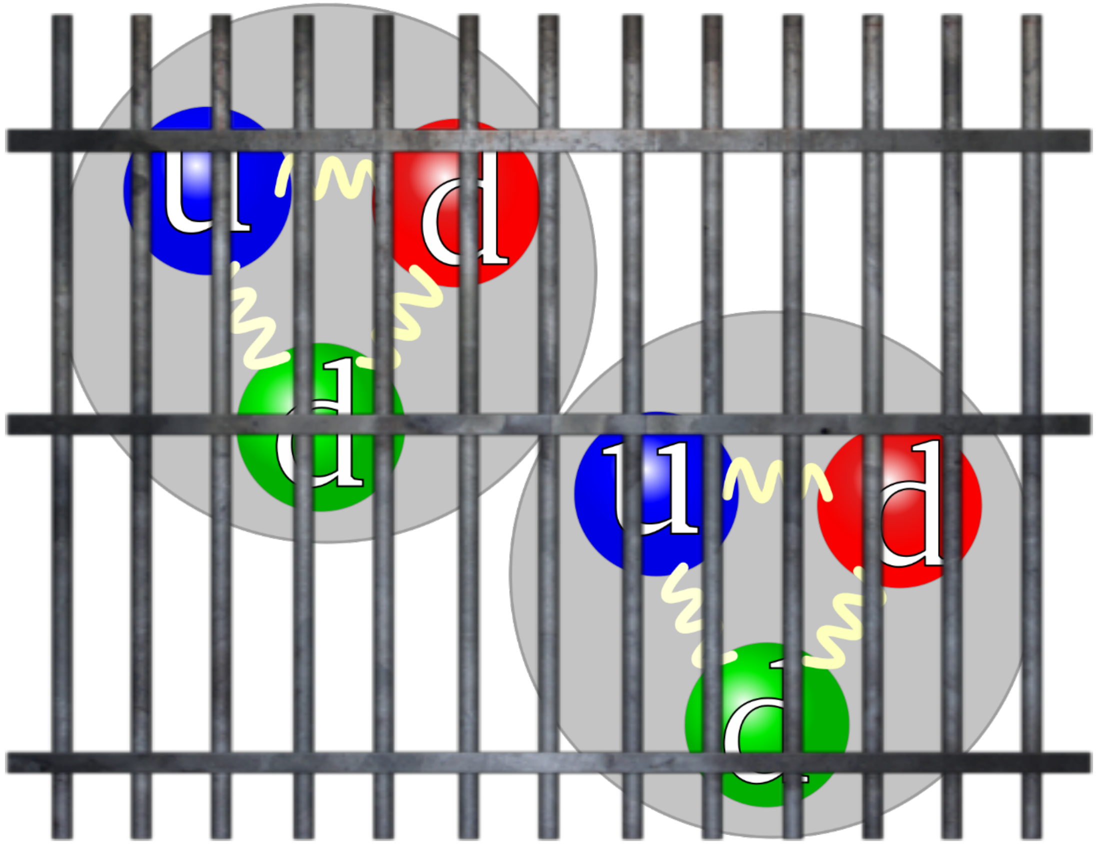
- In the chiral li … aly, Θ_0
  … In QCD, Θ_0 measures the strength of gluon self-interactions
  … so, from one perspective, m_p is (somehow) completely generated by glue.

Confinement & Origin of Mass

➢ *The vast majority of mass comes from the energy needed to hold quarks together inside nuclei*



Craig Roberts. Emergence of Mass



On the other hand …

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

Trace Anomaly

- In the chiral limit

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

- *Might* mean that the scale anomaly vanishes trivially in the pion state, *i.e.* gluons contribute nothing to the pion mass.
- But that is 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 chiral-limit 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

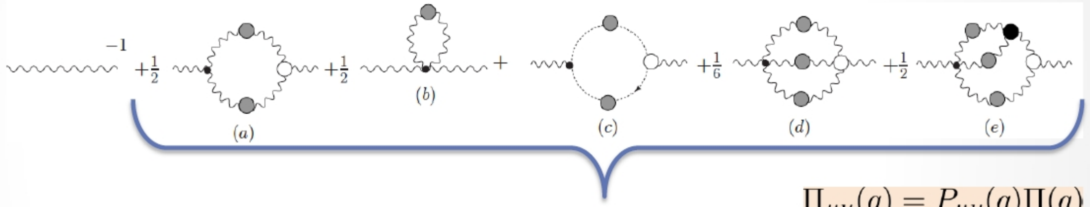
  *"How does the pion remain **massless**?"*

- Modern Physics must
  Elucidate the Entire Array of Empirical Consequences
  of the Mechanism responsible
  so that the Standard Model can be Validated

ıs

Ideas: Old & New

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



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

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

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

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 …

$$q\mu\,\Pi\mu\nu(q) \equiv 0$$

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

g **or gluon**

$$I(J^P) = 0(1^-)$$

SU(3) color octet

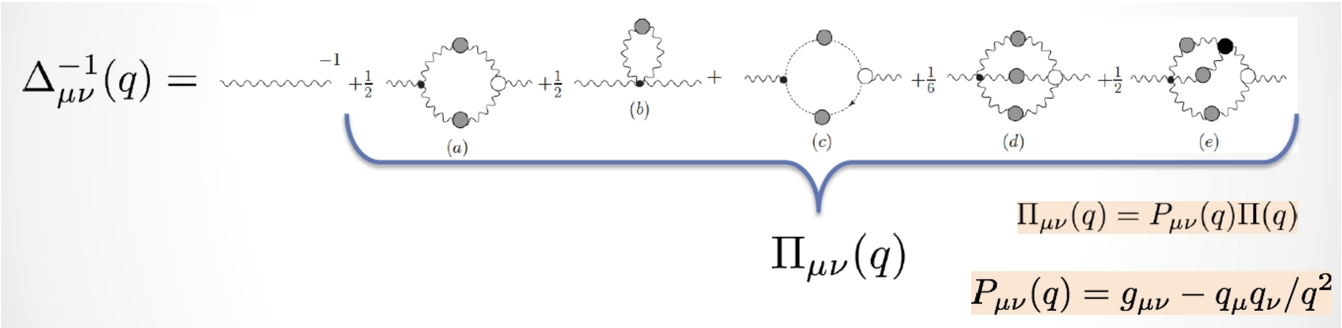
$\boxed{\text{Mass } m \neq 0.}$ Theoretical value. A mass as large as a few MeV may not be precluded, see YNDURAIN 95.

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.)

IR Behaviour of QCD



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

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

- ➢ Running gluon mass

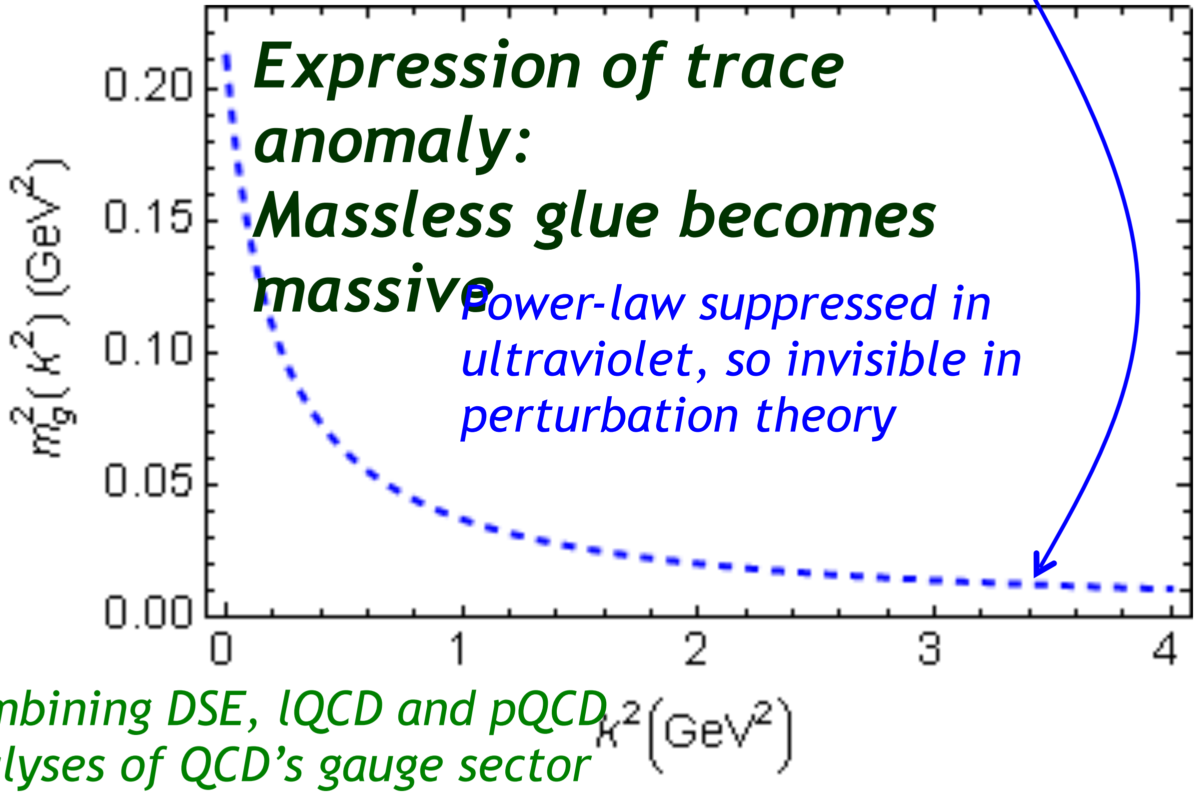
$$d(k^2) = \frac{\alpha(\zeta)}{k^2 + m_g^2(k^2;\zeta)}$$

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

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

$\mu_g \approx ½\, m_p$

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



Expression of trace anomaly:
Massless glue becomes massive

Power-law suppressed in ultraviolet, so invisible in perturbation theory

Combining DSE, lQCD and pQCD analyses of QCD's gauge sector

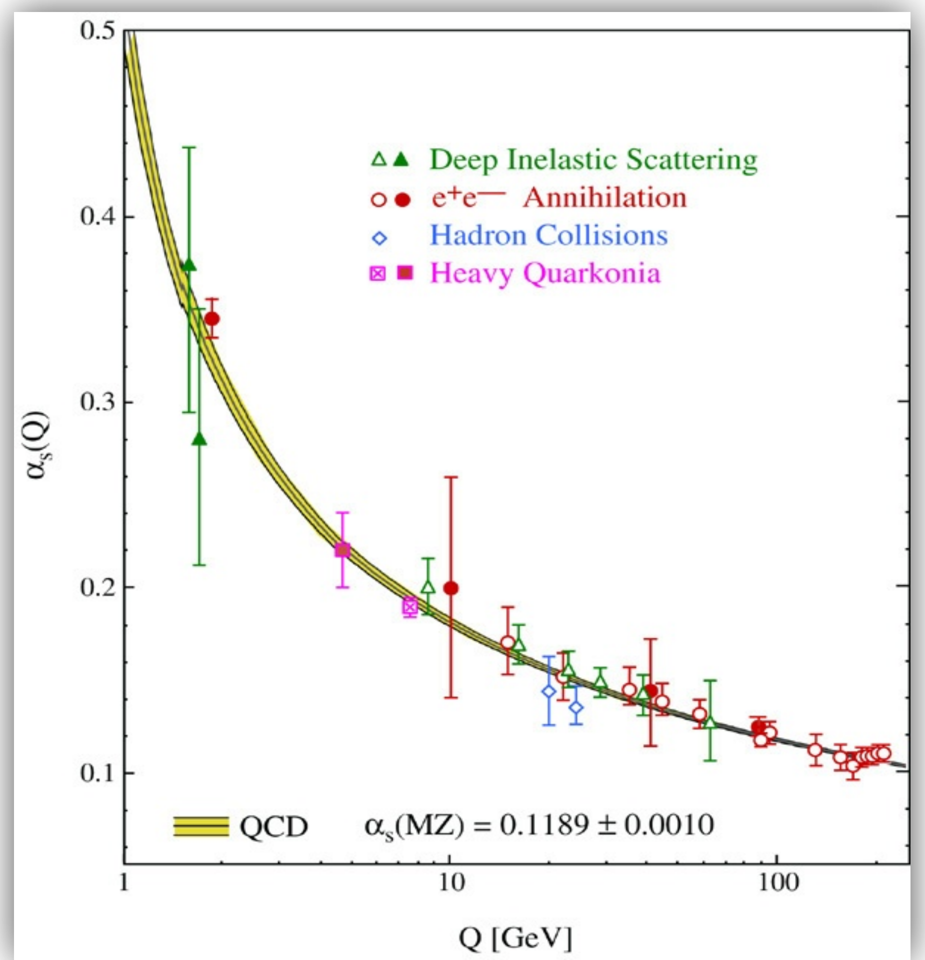
Dynamical mass generation in continuum quantum chromodynamics
J.M. Cornwall, Phys. Rev. D ***26*** *(1981) 1453*

The Gluon Mass Generation Mechanism: A Concise Primer
A.C. Aguilar, D. Binosi, J. Papavassiliou, Front. Phys. **11** (2016) 111203

This is where we live

⇐

What's happening out here?!



QCD's Running Coupling

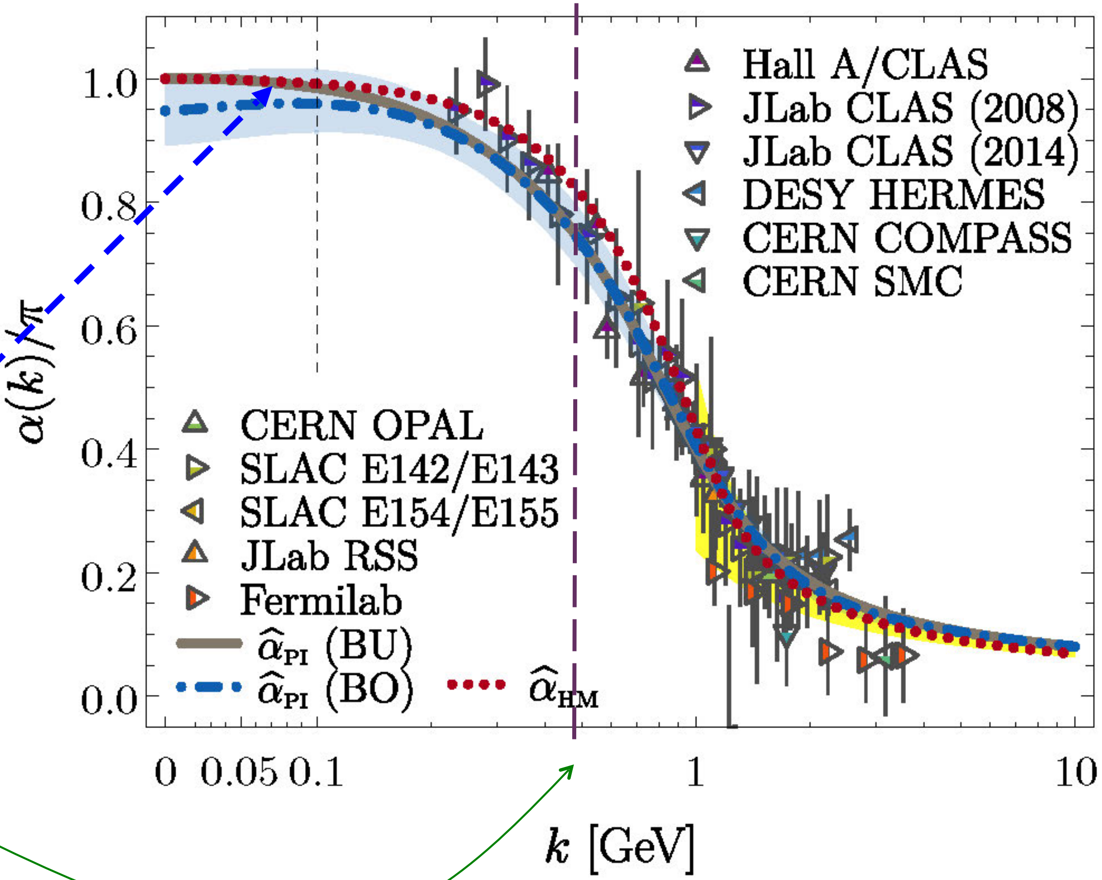
The QCD Running Coupling,
A. Deur, S. J. Brodsky and G. F. de Teramond, Prog. Part. Nucl. Phys. **90** (2016) 1-74
Process independent strong running coupling
Daniele Binosi *et al*., arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7
Process-independent effective coupling. From QCD Green functions to phenomenology,
Jose Rodríguez-Quintero *et al*., arXiv:1801.10164 [nucl-th]. Few Body Syst. **59** (2018) 121/1-9

Process-independent effective-charge in QCD

- Modern continuum & lattice methods for analysing gauge sector enable

  "Gell-Mann – Low"

  running charge to be defined in QCD
- Combined continuum and lattice analysis of QCD's gauge sector yields a *parameter-free prediction*
- N.B. Qualitative change in $\hat{\alpha}_{PI}(k)$ at $k \approx ½\, m_p$



Data = process dependent effective charge [Grunberg: 1982fw]:

α_{g1}, defined via Bjorken Sum Rule

Process independent strong running coupling
Binosi, Mezrag, Papavassiliou, Roberts, Rodriguez-Quintero
arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7
The QCD Running Coupling,
A. Deur, S. J. Brodsky and G. F. de Teramond,
Prog. Part. Nucl. Phys. **90** (2016) 1-74
Process-independent effective coupling. From QCD Green functions to phenomenology,
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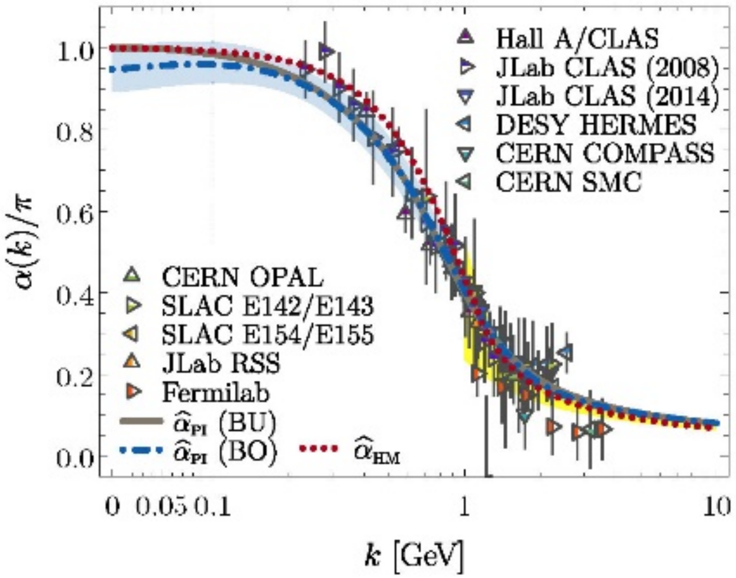
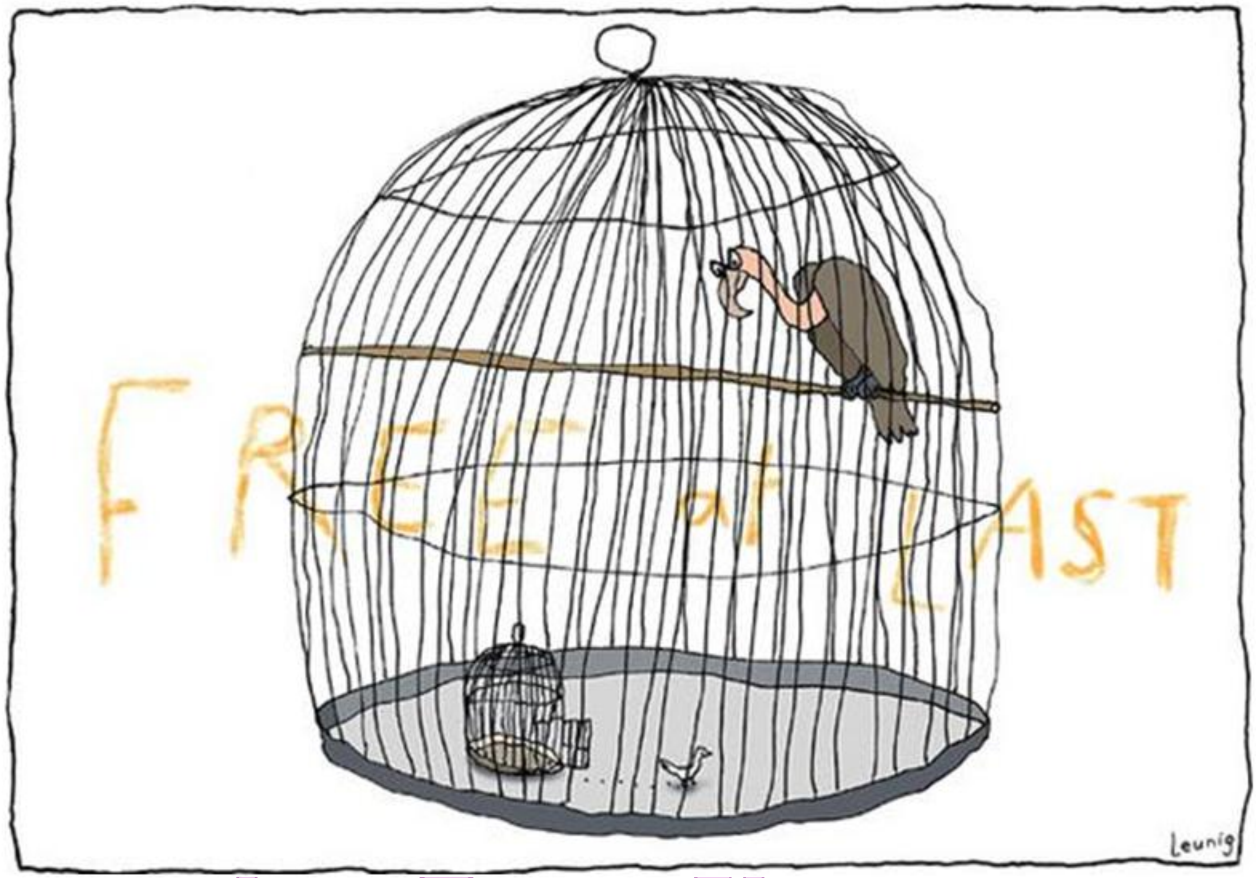
Process-independent effective-charge in QCD



- $\hat{\alpha}_{PI}$ is a new & unique type of effective charge
  - completely determined by the gauge-boson two-point function.
- $\hat{\alpha}_{PI}$ is
  - process-independent
  - unifies a vast array of observables
- $\hat{\alpha}_{PI}$ possesses an infrared saturation point
  - Nonperturbative analysis demonstrating absence of a Landau pole in QCD
- QCD is IR finite, owing to dynamical generation of gluon mass-scale
- Asymptotic freedom ⇒ QCD is well-defined at UV momenta
- ***QCD is therefore unique amongst known 4D quantum field theories***
  - ***Potentially, defined & internally consistent at all momenta***

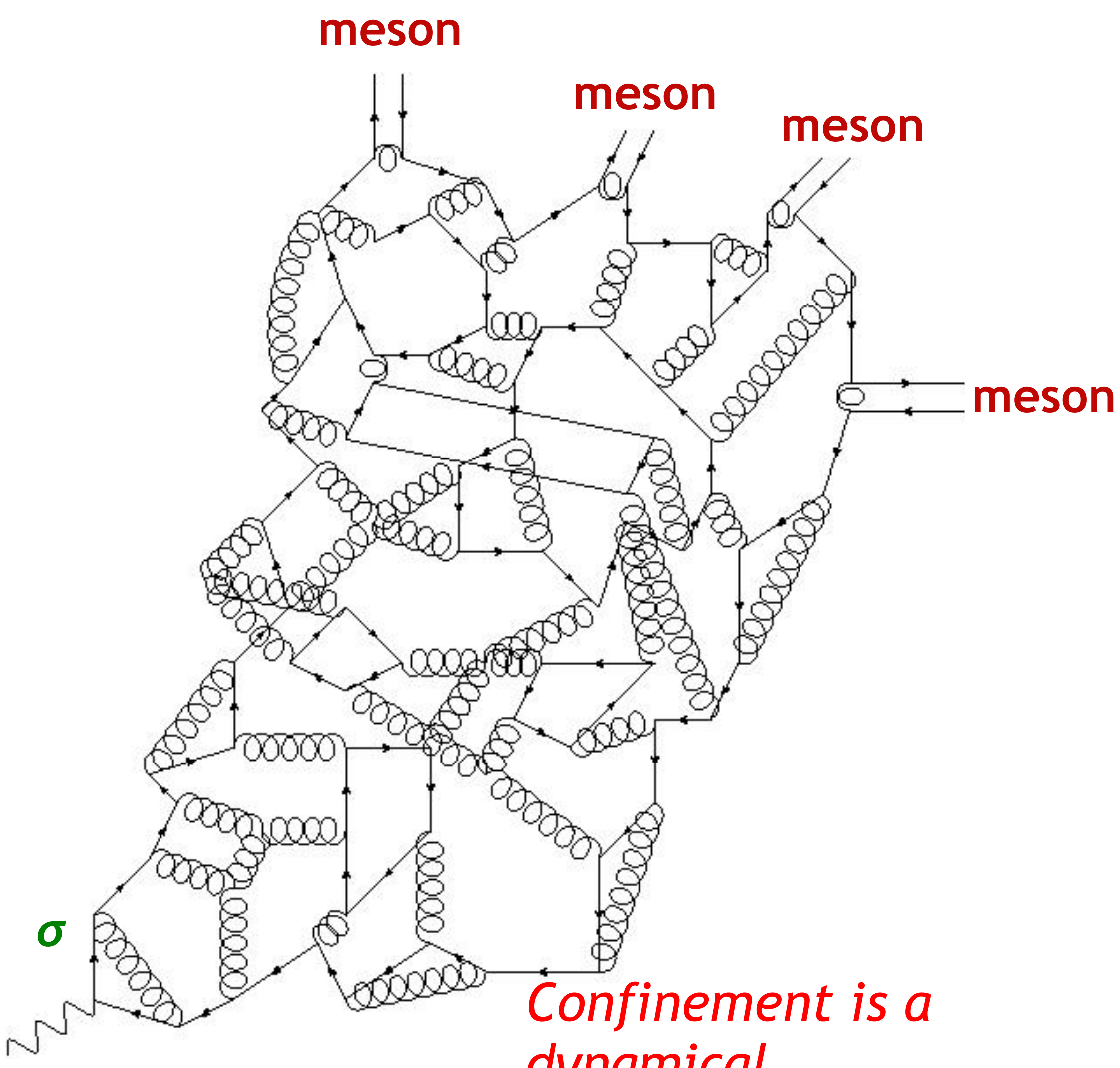


What is Confinement?

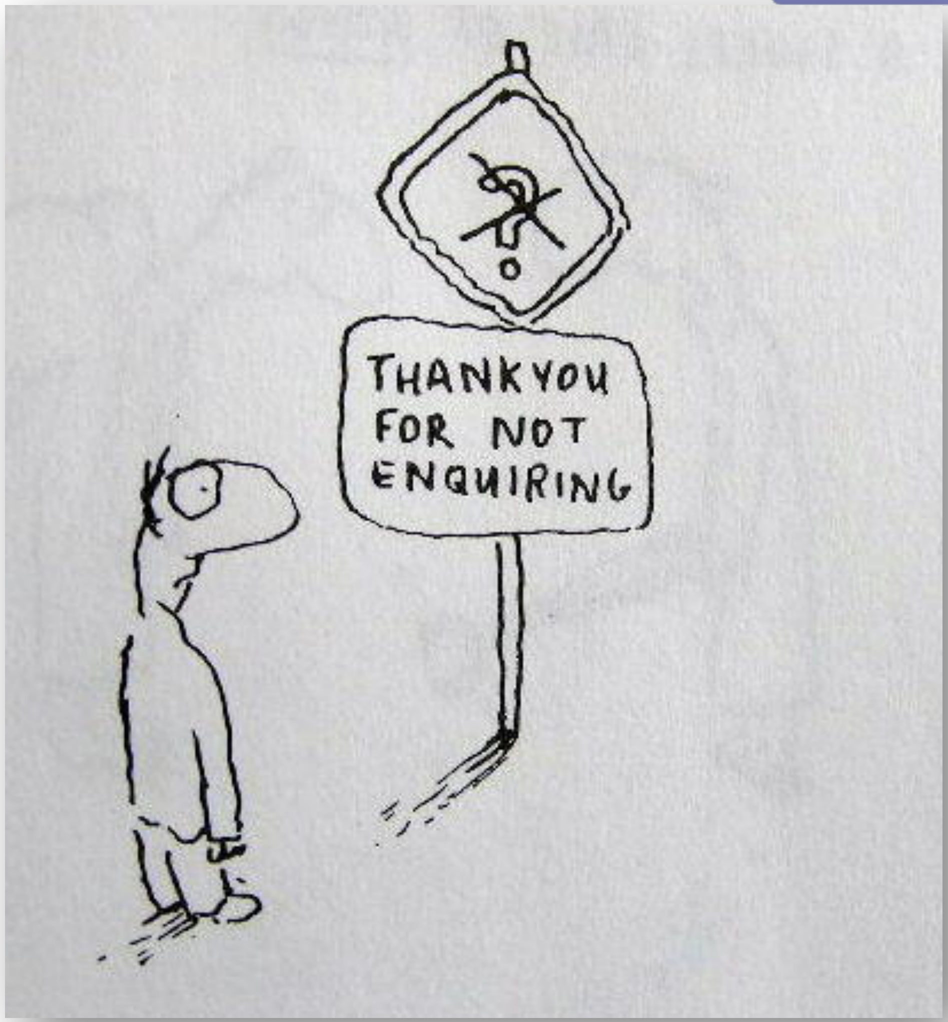
Confinement is dynamical!

Quark Fragmentation

- A quark begins to propagate
- But after each "step" of length $\sigma \approx 1/m_g$, on average, an interaction occurs, so that the quark *loses* its identity, sharing it with other partons
- Finally, a cloud of partons is produced, which coalesces into colour-singlet final states



Confinement is a dynamical phenomenon!



Enigma of Mass

Maris, Roberts and Tandy
nucl-th/9707003, Phys.Lett. B**420** (1998) 267-273

Pion's Goldberger -Treiman relation

- Pion's Bethe-Salpeter amplitude
  Solution of the Bethe-Salpeter equation

$$\Gamma_{\pi^j}(k;P) = \tau^{\pi^j}\gamma_5\left[iE_\pi(k;P)+\gamma\cdot P F_\pi(k;P) + \gamma\cdot k\, k\cdot P\, G_\pi(k;P)+\sigma_{\mu\nu}\,k_\mu P_\nu\, H_\pi(k;P)\right]$$

- Dressed-quark propagator

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

- Axial-vector Ward-Takahashi identity entails

$$f_\pi E_\pi(k;P=0) = B(k^2)$$

Owing to DCSB & Exact in Chiral QCD

***Miracle*: two body problem solved, almost completely, once solution of one body problem is known**

Rudimentary version of this relation is apparent in Nambu's Nobel Prize work

Model independent
Gauge independent
Scheme independent

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

The most fundamental expression of Goldstone's Theorem and DCSB

Rudimentary version of this relation is apparent in Nambu's Nobel Prize work

Model independent
Gauge independent
Scheme independent

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

NG Pion exists if, and only if, mass emerges dynamically

Rudimentary version of this relation is apparent in Nambu's Nobel Prize work

Model independent
Gauge independent
Scheme independent

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

Correlations are strong if, and only if, emergent mass is large

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

Whence "0" ?

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

Whence "0" ?

The answer is algebraic

Pion masslessness

*Munczek, H. J., Phys. Rev. D **52** (1995) pp. 4736-4740*
*Bender, A., Roberts, C.D. and von Smekal, L., Phys. Lett. B **380** (1996) pp. 7-12*
*Maris, P. , Roberts, C.D. and Tandy, P.C., Phys. Lett. B **420** (1998) pp. 267-273*
Binosi, Chang, Papavassiliou, Qin, Roberts, Phys. Rev. D 93 (2016) 096010/1-7

- Obtain a coupled set of gap- and Bethe-Salpeter equations
  - Bethe-Salpeter Kernel:
    - valence-quarks with a momentum-dependent running mass produced by self-interacting gluons, which have given themselves a running mass
    - Interactions of arbitrary but enumerable complexity involving these “basis vectors”
  - Chiral limit:
    - Algebraic proof
      - at any & each finite order in symmetry-preserving construction of kernels for
        - » the gap (quark dressing)
        - » and Bethe-Salpeter (bound-state) equations,
      - there is a precise cancellation between
        - » mass-generating effect of dressing the valence-quarks
        - » and attraction introduced by the scattering events
    - Cancellation guarantees that
      - simple system, which began massless,
      - becomes a complex system, with
        - » a nontrivial bound-state wave function
        - » attached to a pole in the scattering matrix, which remains at $P^2=0$ …
    - Interacting, bound system remains massless!

Pion masslessness

Munczek, H. J., Phys. Rev. D **52** (1995) pp. 4736-4740
Bender, A., Roberts, C.D. and von Smekal, L., Phys. Lett. B **380** (1996) pp. 7-12
Maris, P. , Roberts, C.D. and Tandy, P.C., Phys. Lett. B **420** (1998) pp. 267-273
Binosi, Chang, Papavassiliou, Qin, Roberts, Phys. Rev. D 93 (2016) 096010/1-7

- Obtain a coupled set of gap- and Bethe-Salpeter equations
  - Bethe-S
    - val ... ven themselves a run
    - Int
  - Chiral
    - Alg
    - Ca
  - becomes a c
    - a nont
    - attach
  - Interacting, bound

Quantum field theory statement:
In the pseudsocalar channel, the dynamically generated mass of the two fermions is precisely cancelled by the attractive interactions between them -

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

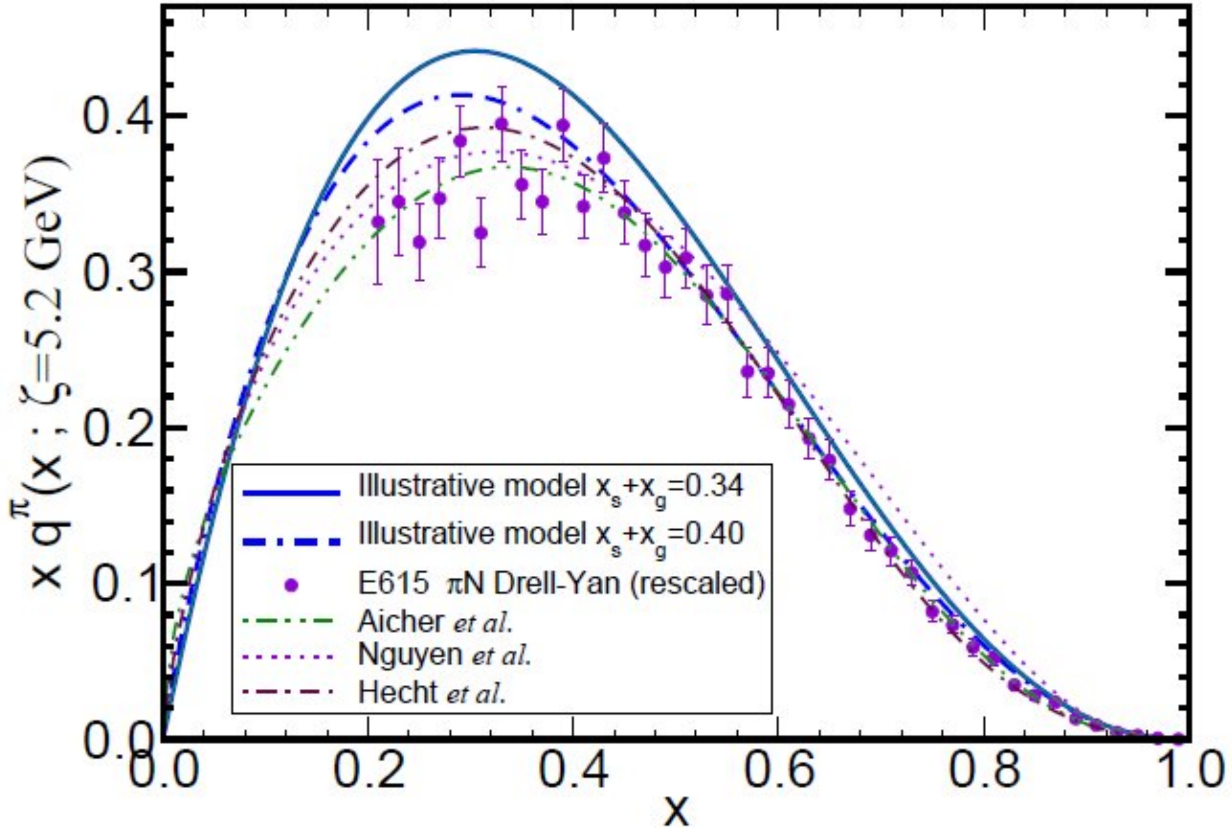
$$\Rightarrow 2 M_q + U_g \equiv$$

Empirical Consequences of Emergent Mass

- QCD's interactions are universal … same in all hadrons

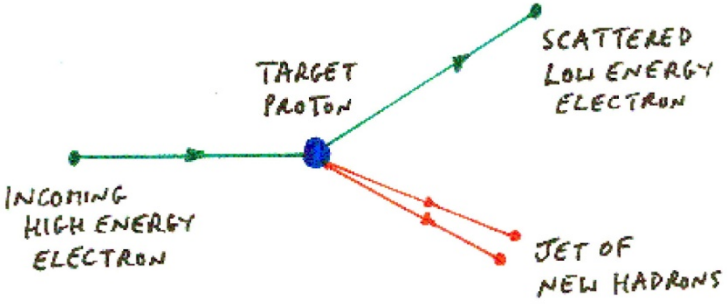
  Hence, similar cancellations must take place within the proton
- However, in the proton, no symmetry requires cancellations to be complete

  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
- 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 … Three (particularly clean) Examples



π & K Valence-quark Distribution Functions

Deep inelastic processes

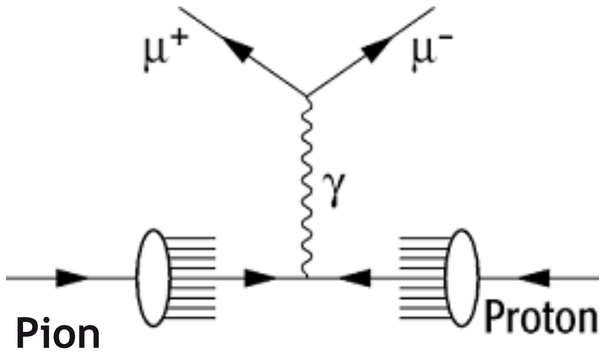


- Quark discovery experiment at SLAC
  (1966-1978, Nobel Prize in 1990)
- Completely different to elastic scattering
  - *Blow the target to pieces instead of keeping only those events where it remains intact.*
- Cross-section serves as measurement of the momentum-fraction probability distribution for quarks and gluons within the target hadron: $q(x)$, $g(x)$

Probability that a quark/gluon within the target will carry a fraction x of the bound-state's light-front momentum

Distribution Functions of the Nucleon and Pion in the Valence Region,
Roy J. Holt and Craig D. Roberts,
arXiv:1002.4666 [nucl-th], Rev. Mod. Phys. **82** (2010) pp. 2991-3044

Parton momentum and helicity distributions in the nucleon
P. Jimenez-Delgado, W. Melnitchouk and J.F. Owens
arXiv:1306.6515, J.Phys. G **40** (2013) 093102



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:

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

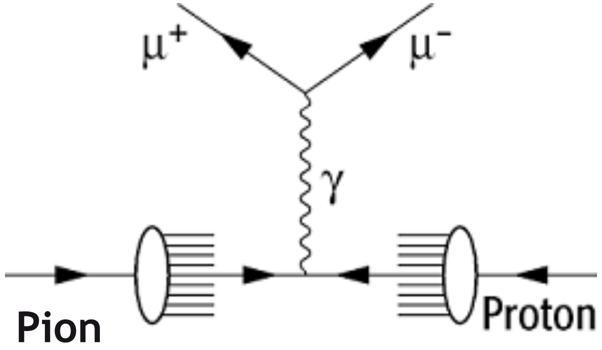
- Consider a theory in which quarks scatter via a vector-boson exchange interaction whose $k^2 >> m_G^2$ behaviour is $(1/k^2)^\beta$
- Then at a resolving scale ζ_H … $u_\pi(x; \zeta_H) \sim (1-x)^{2\beta}$

  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

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

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



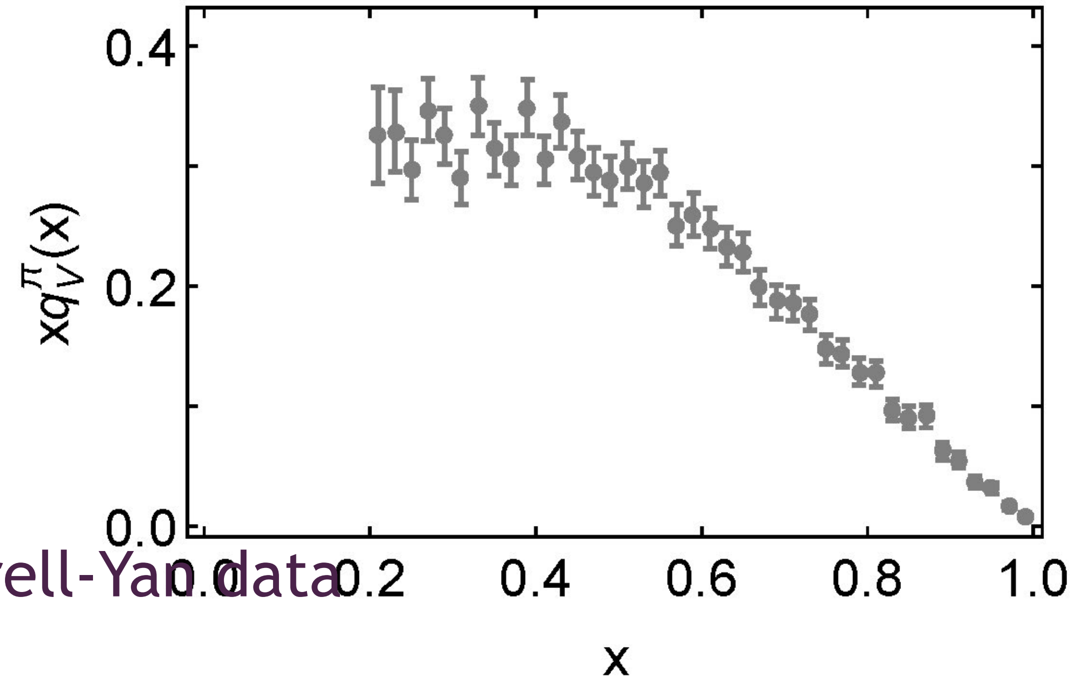
Empirical status of the Pion's valence-quark distributions

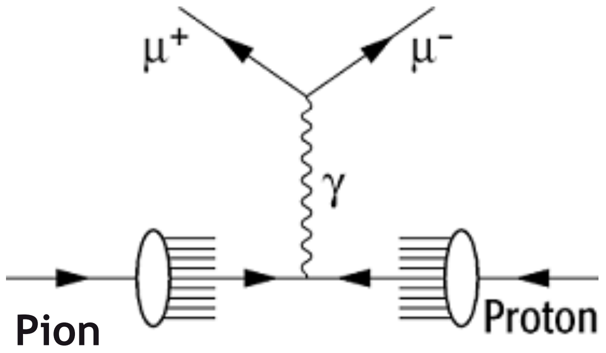
- Owing to absence of pion targets, the pion's valence-quark distribution functions have hitherto been measured via the Drell-Yan process:

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

- 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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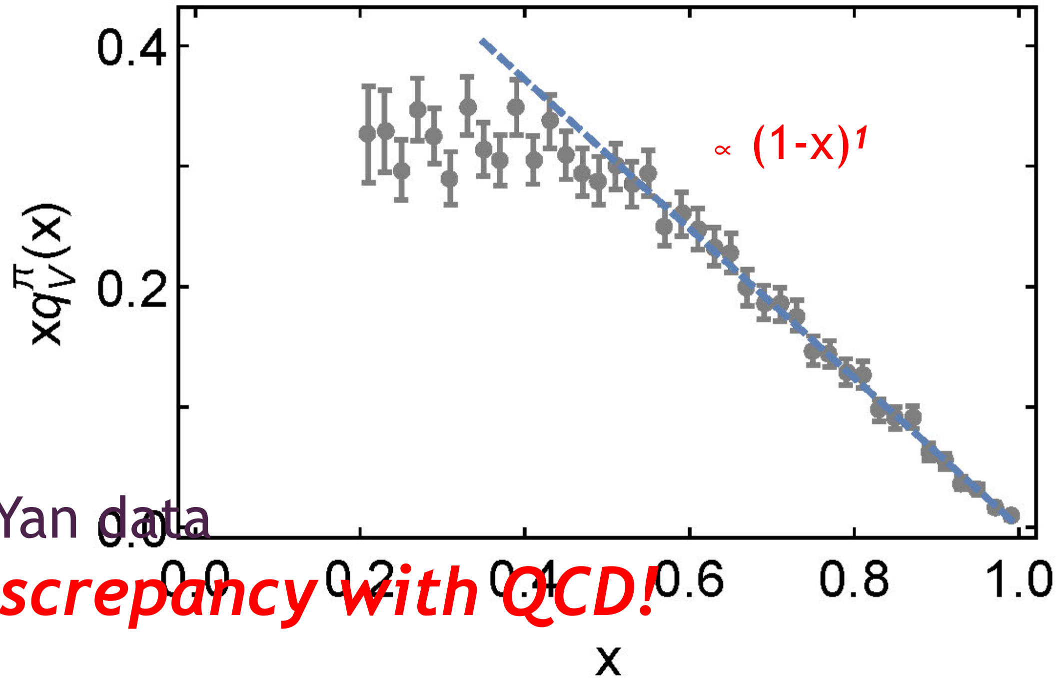
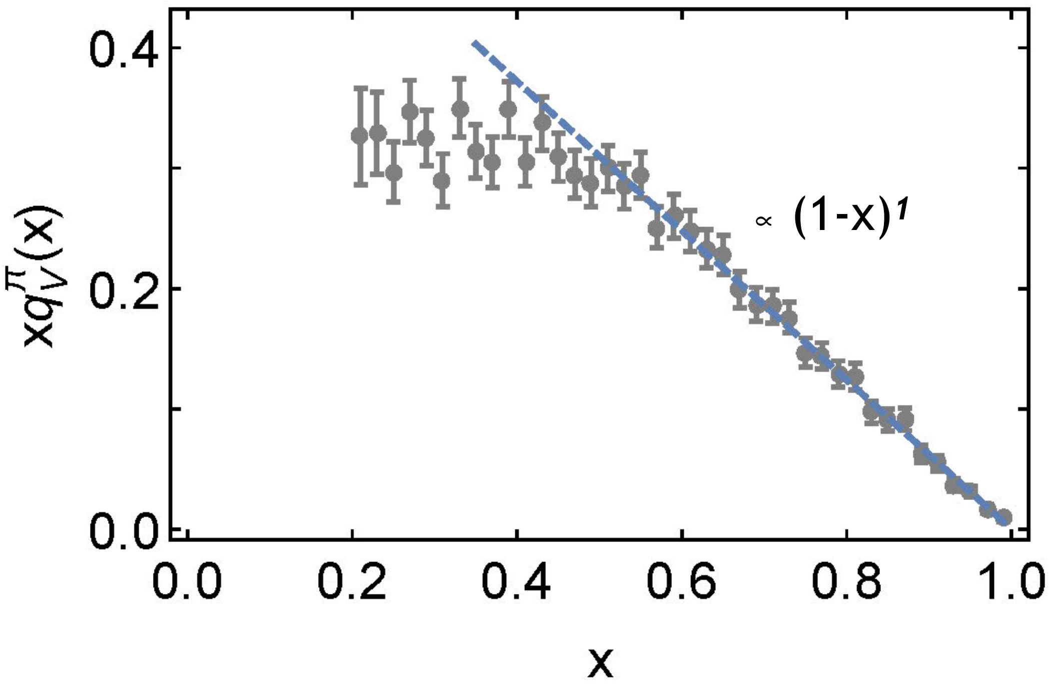
  - Leading-order analysis of the Drell-Yan data
- ***Factor of 2 discrepancy with QCD!***

Controversial!



π valence-quark distributions
20 Years of Evolution

- 1989 … 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?

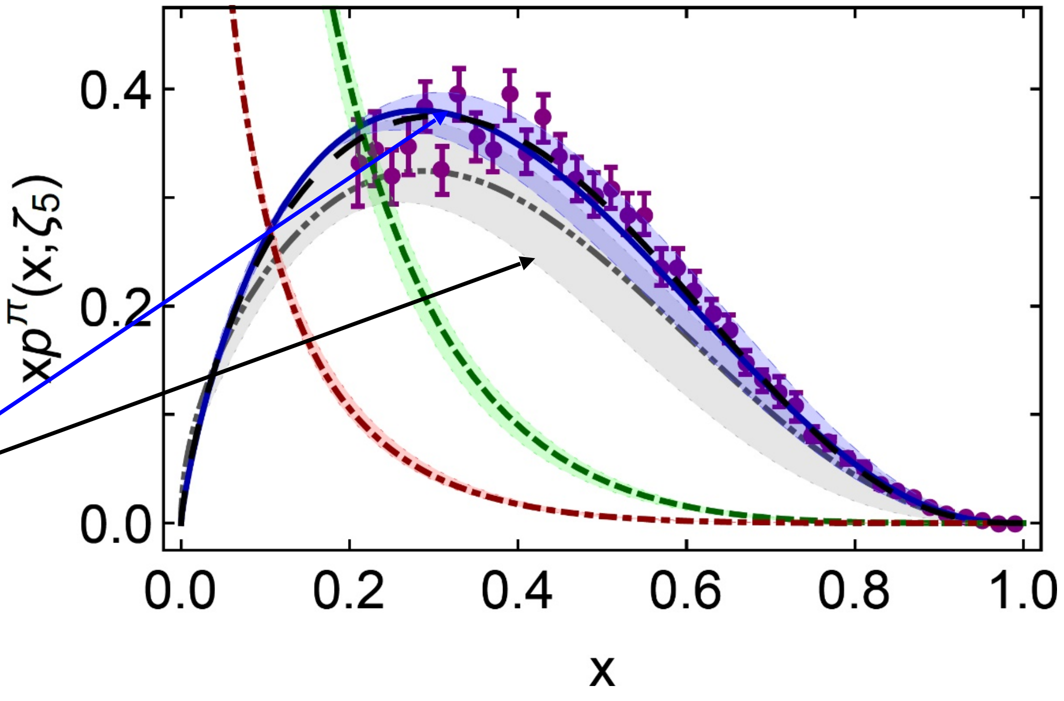


π valence-quark distributions
20 Years of Evolution → 2019

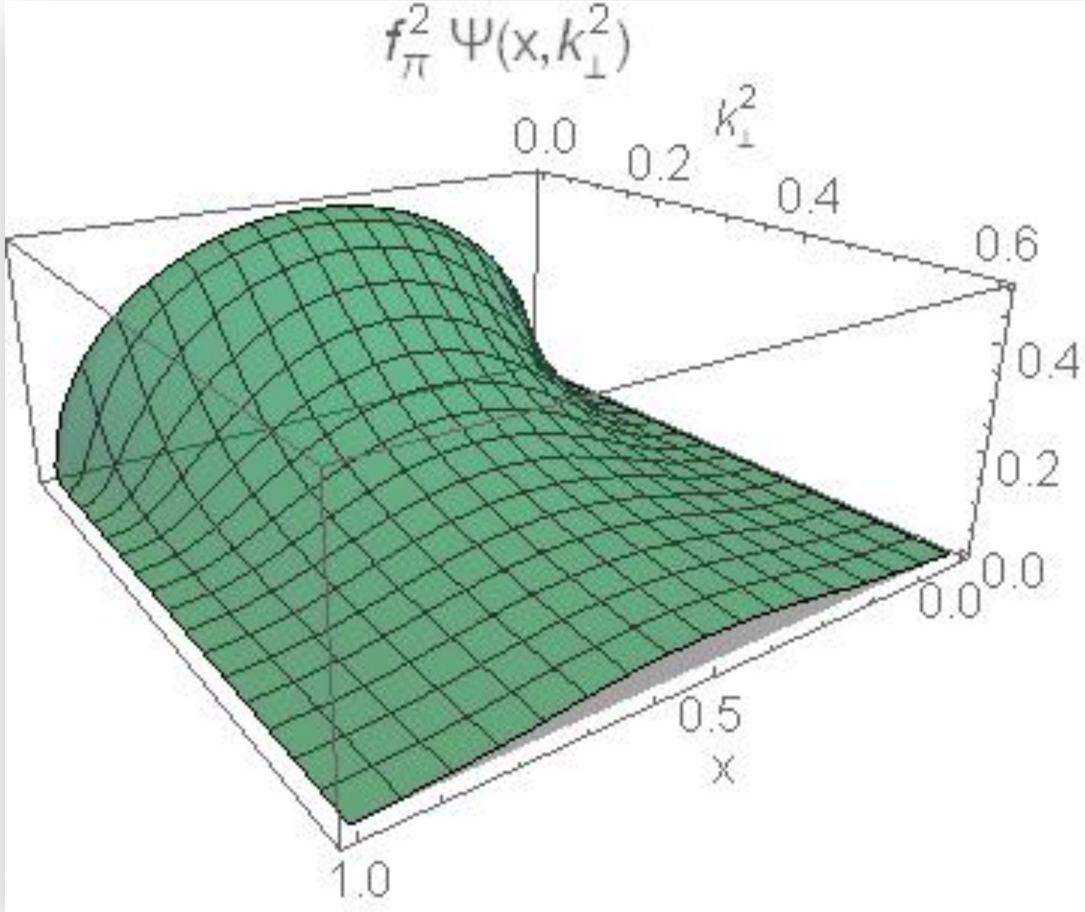
- Renewed pressure being applied by theory advances
- Novel lattice-QCD algorithms beginning to yield results for pointwise behaviour of $u\pi(x;\zeta)$
- Developments in continuum-QCD have enabled 1st parameter-free predictions of valence, glue and sea distributions within the pion
  - Reveal that $u\pi(x;\zeta)$ 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

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

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



Now – after 30 years – new era dawning in which the ultimate experimental checks can be made



Meson Wave Functions

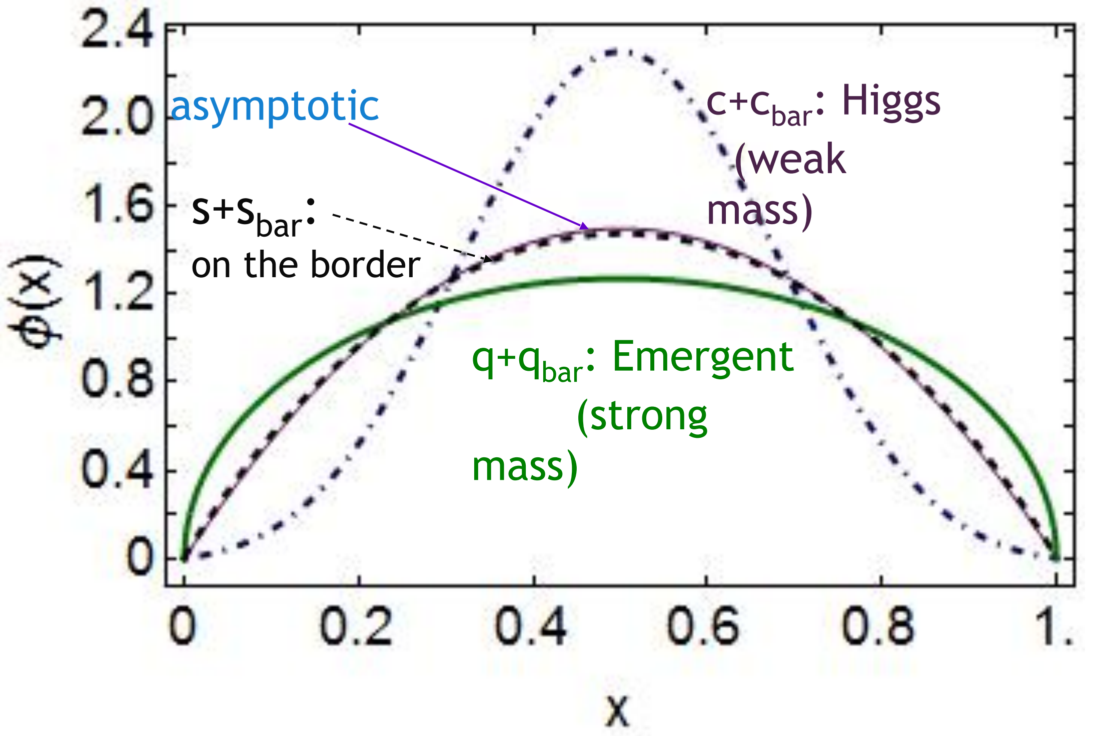
Parton distribution amplitudes of S-wave heavy-quarkonia
Minghui Ding, Fei Gao, Lei Chang, Yu-Xin Liu and Craig D. Roberts
arXiv:1511.04943 [nucl-th], Phys. Lett. B **753** (2016) pp. 330-335

Emergent Mass *vs*. Higgs Mechanism

- When does Higgs mechanism begin to influence mass generation?
- limit $m_{quark} \to \infty$

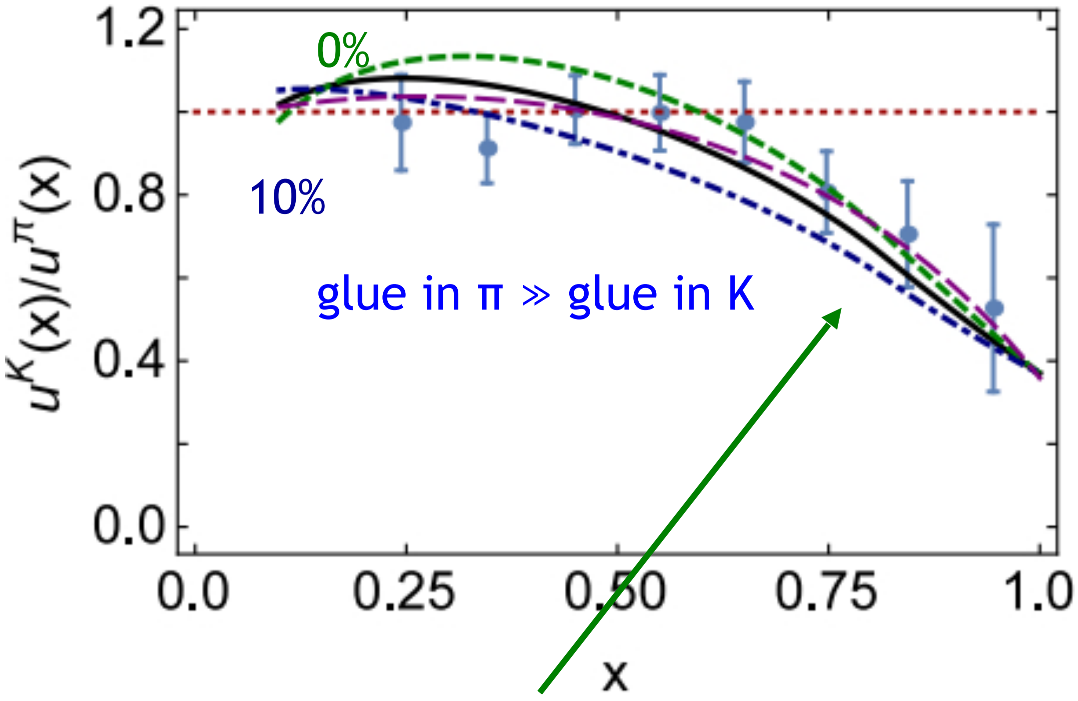
  $\varphi(x) \to \delta(x-½)$
- limit $m_{quark} \to 0$

  $\varphi(x) \sim (8/\pi)\,[x(1-x)]^{½}$
- 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 $u\pi(x;\zeta)$ & $uK(x;\zeta)$ 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 $uK(x;\zeta)/\ u\pi(x;\zeta)$ 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

$$uK(x;\zeta)/\ u\pi(x;\zeta)$$

π & K PDFs

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

$$M^{\text{dressed}}_{\text{quark}} + M^{\text{dressed}}_{\text{antiquark}} + U^{\text{dressed}}_{\text{quark}-\text{antiquark interaction}} \overset{\text{chiral limit}}{\equiv} 0$$

  in the almost-massless pion
- Compared to incomplete cancellation in the strange-quark-containing kaon.
- Big Issue, however:
  - Only one forty-year-old measurement of $uK(x;\zeta)$/ u
  - CERN [Badier:1980jq].

π & K PDFs

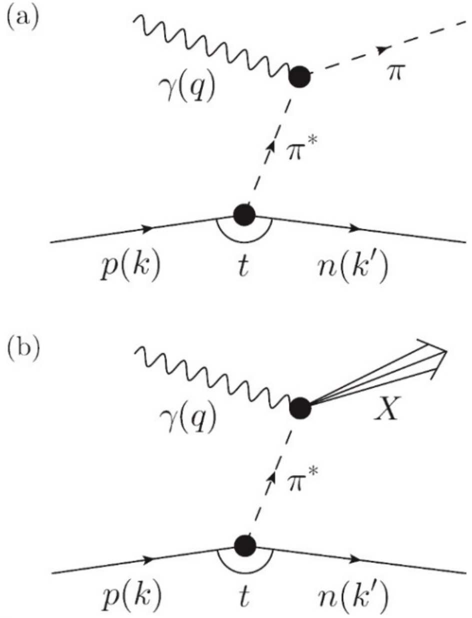
- ➢ Cannot claim understanding of Standard Model until explanation is provided for <u>emergence</u> and <u>structure</u> of Nambu-Goldstone (NG) modes
- ➢ NG modes are far more complex than is typically thought.
  - Not pointlike;
  - Intimately connected with the origin of mass;
  - Probably play an 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 is found in following statement
  - *The gluon content of Nature's only near-pure Nambu-Goldstone mode, the pion, is far greater than that in any other hadron*

π & K PDFs

- Cleanest expression is found in following statement
  - *The gluon content of Nature's only near-pure Nambu-Goldstone mode, the pion, is far greater 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*

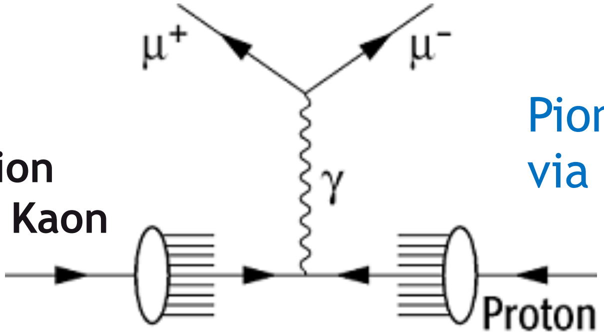
Approved & Planned Experiments

- JLab 12 … Tagged Deep Inelastic Scattering
  - Pion and Kaon PDFs at large *x*
  - Sullivan Process …
    - $\gamma + p \to n + X$
    - $\gamma + p \to \Lambda + X$
  - *Approved* … R. A. Montgomery *et al.*, AIP Conf. Proc. **1819** (2017) 030004



Craig Roberts. Emergence of Mass

- *Letter of Intent: A New QCD facility at the M2 beam line of the CERN SPS* (COMPASS++/AMBER), B. Adams, arXiv:1808.00848 [hep-ex]



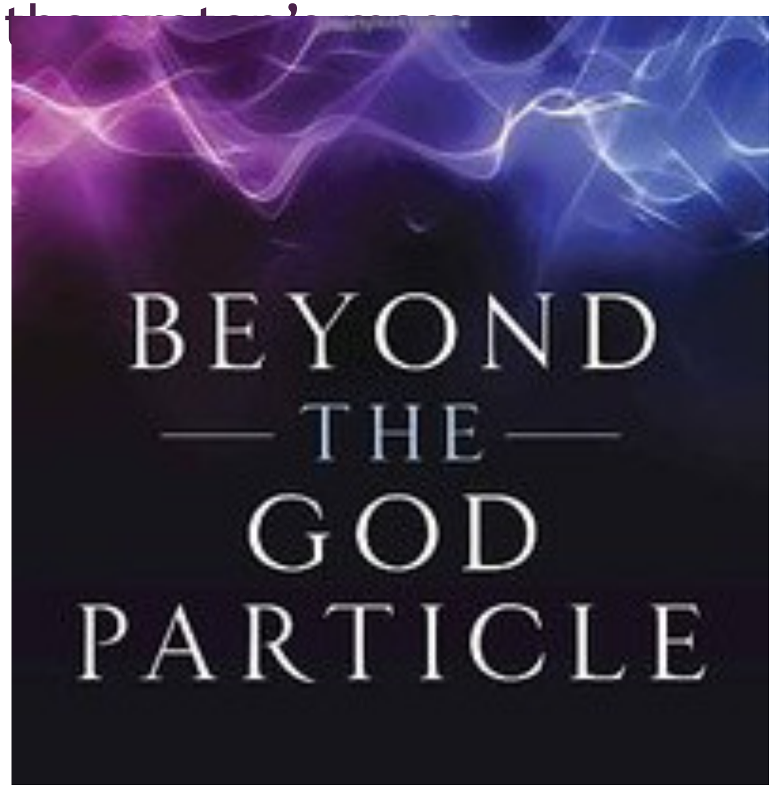
Pion and kaon PDFs via Drell-Yan reaction

- *Pion and Kaon Structure at the EIC*, A. C. Aguilar *et al.*, arXiv:1907.08218 [nucl-ex]
  - 5 key experiments:
    i. pion and kaon PDFs;
    ii. pion and kaon GPDs;
    iii. open charm production;
    iv. pion form factor to 35 GeV^2;
    v. pion and kaon fragmentation functions

Epilogue

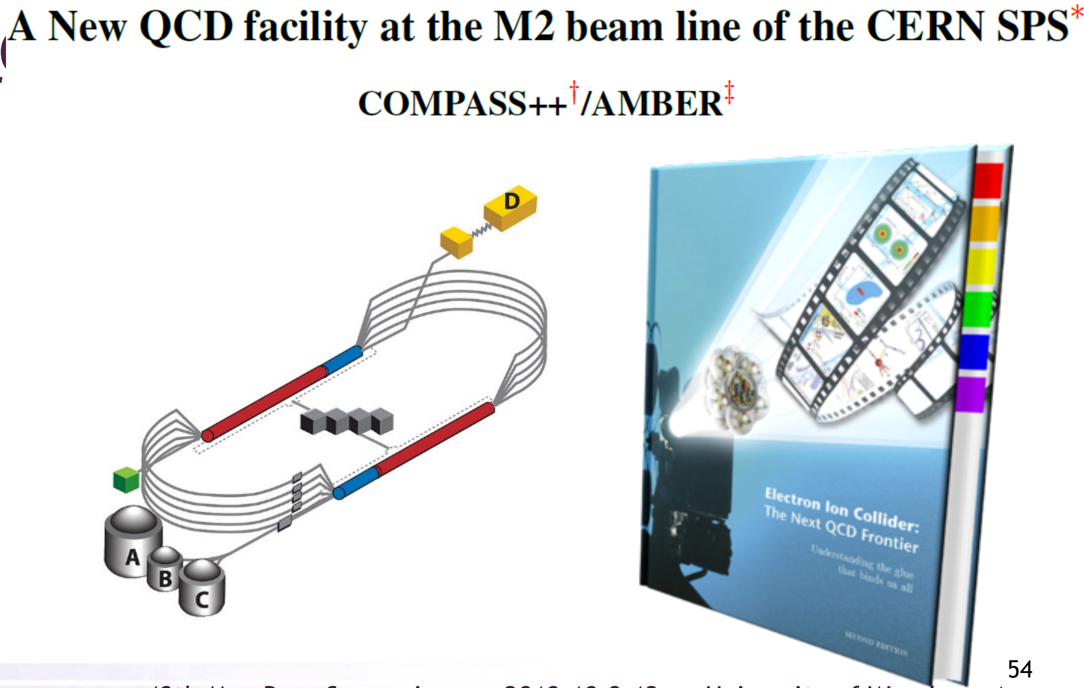
Epilogue

- LHC has NOT found the “God Particle” … the Higgs boson is NOT the origin of mass
  - Higgs-boson only produces a little bit of mass
  - Higgs-generated light-quark mass-scales explain neither
    nor the pion’s (*near*-) masslessness
- Strong interaction sector of the Standard Model,
  i.e. QCD, is the key to understanding the
  origin, existence and properties
  of the vast bulk of all known matter



Epilogue

- Challenge: <u>Explain</u> the Origin & Distribution of the Bulk of Visible Mass
- Current Paradigm: Quantum Chromodynamics
- QCD is plausibly a mathematically well-defined quantum field theory,
  The only one we've ever produced
  - Consequently, it potentially defines a new paradigm for developing Beyond-SM theories
- Challenge is to reveal the content of strong-Q
- *Progress* and *Insights*
  being delivered by amalgam of
  - Experiment … Phenomenology …Theory
- Continued exploitation of synergies essential
  to capitalise on new opportunities provid
  by existing & planned facilities



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Thankyou!

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