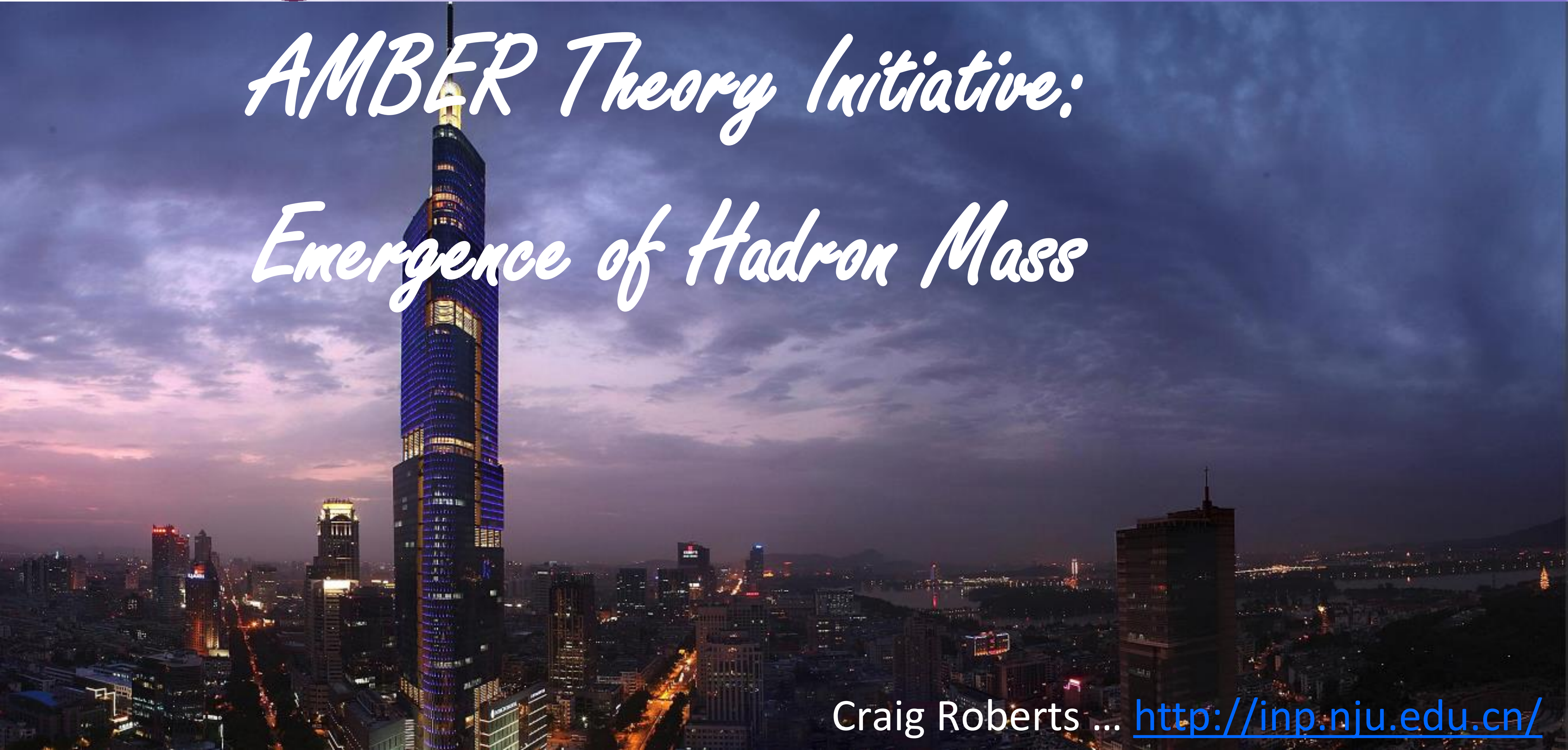
NANJING UNIVERSITY

# AMBER Theory Initiative: Emergence of Hadron Mass



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

# Physics Beyond Colliders: AMBER

- In the context of the Physics Beyond Colliders initiative at CERN, the AMBER collaboration submitted a Letter of Intent to the SPSC in order to establish a "New QCD facility at the M2 beam line of the CERN SPS“ … http://inspirehep.net/record/1684784?ln=en
- Extensive installation would make the Experimental Hall EHN2 the site for a great variety of measurements to address fundamental issues of strong interactions.
- The proposed measurements cover a wide range in the squared four-momentum transfer $Q^2$
  - at lowest values of $Q^2$ … determine proton charge radius through elastic muon-proton scattering
  - at intermediate $Q^2$ … perform hadron spectroscopy using dedicated meson beams
  - at high $Q^2$ … study the structure of hadrons via the Drell-Yan process
- Full proposal submitted to the SPSC in late September 2019
- Defended/Advocated at Physics Beyond Colliders Working Group Meeting in early-November
- In this context, the AMBER Collaboration seeks to build an international network of theorists whose research interests and output can assist the collaboration in advocating the programme and maximise the impact of the results

# Emergence of Hadron Mass

- Everything we see and use is built from atoms.
- Their properties are readily understood, using quantum mechanics augmented by quantum electrodynamics (QED) at higher energies.
- Within every atom, however, lies a compact nucleus, comprised of neutrons and protons; and the structure and arrangements of all these things is supposed to be described by quantum chromodynamics (QCD).
- Yet, fifty years after the discovery of quarks, science is only just beginning to grasp how QCD moulds the most elementary hadrons: pions, neutrons, protons, *etc*.
- It is far from understanding how QCD produces nuclei.

# Higgs Boson

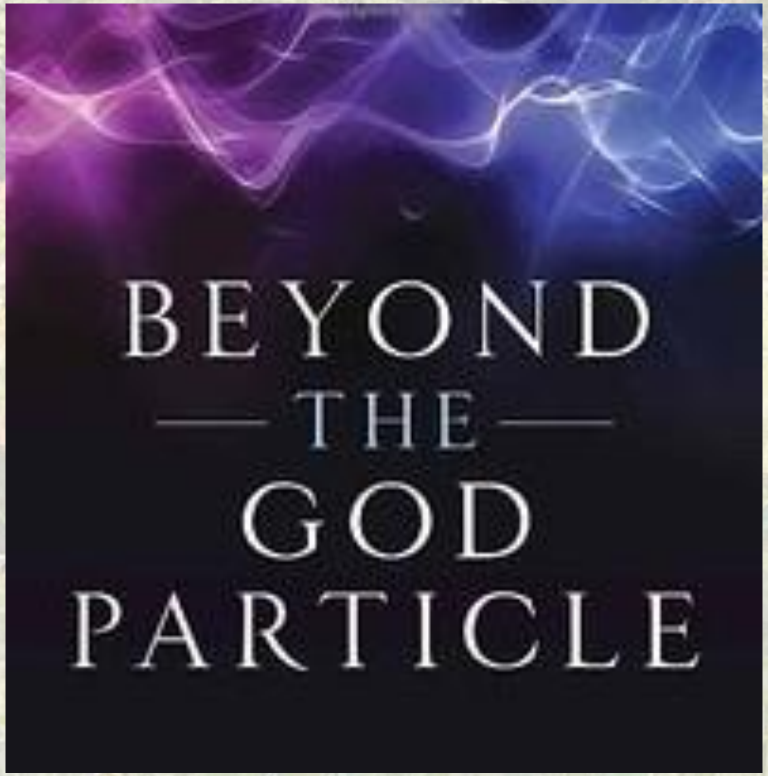
- Discovered in 2012 at the LHC
- Nobel Prize in Physics (2013) awarded to Peter Higgs and Francois Englert
- With this discovery, Standard Model of Particle Physics is complete
- Higgs is crucial for many things within the Standard Model & might also be essential in searching for physics beyond the Standard Model … But
- "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*


*Craig Roberts. Emergence of Hadron Mass*

# Strong QCD

- 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 the proton's mass
    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
- No single approach/experiment can solve this problem alone
- Success has required and is being delivered by amalgam of Experiment … Phenomenology …Theory



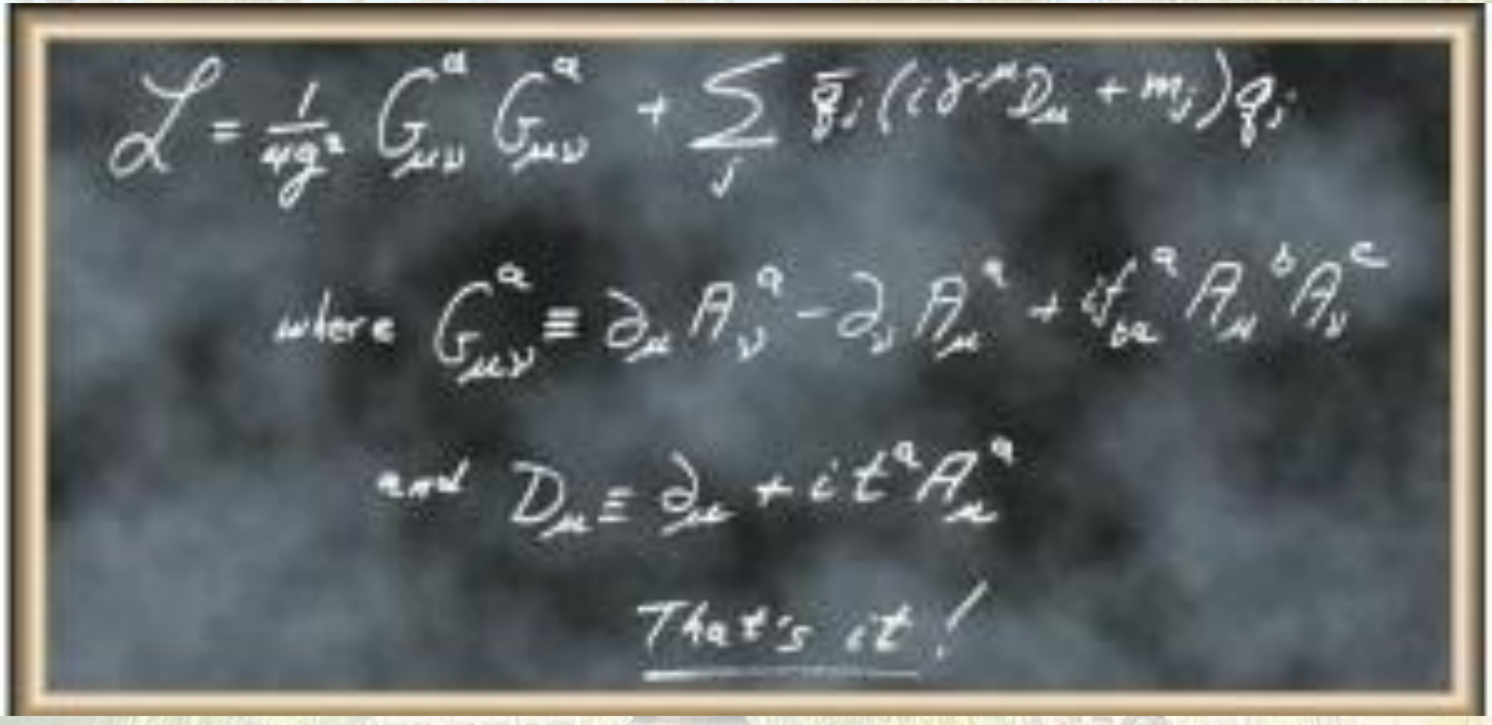
# Emergent Phenomena in the Standard Model

- 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)

# QCD




- 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

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

- 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 $L_{\rm QED}$

# Proton Size

- The proton's mass correlated with its proton's size
  - Hence, with attempts to explain the confinement of gluons and quarks.
- Today there is a puzzle over that size; namely,
  - 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.

# Nambu-Goldstone Modes

- Role of emergent mass is strikingly expressed in properties of SM's Nambu-Goldstone modes
- Their internal structure is complex

  & that structure provides the clearest window onto the emergence of mass.
- This is revealed by low-energy properties of the pion:
  - Charged-pion radius

    … in domain of emergent mass dominance, $r_\pi \, f_\pi \approx \text{constant}$
  - Neutral pion radius and two-photon transition form factors

    … strength of Abelian anomaly is intimately connected with character of emergent mass
  - Pion polarisabilities

    … reaction to pressure from e.m. probes constrained by size of emergent mass
- Successes of chiral perturbation theory

  … rest on dominance of emergent mass in light-quark sector

# Nambu-Goldstone Modes

- Role of emergent mass is strikingly expressed in properties of SM's Nambu-Goldstone modes
- Their internal structure is complex
  & that structure provides the clearest window onto the emergence of mass.
- Theory predicts that the gluon content within the pion – the only near-pure NG mode in Nature – is far greater than that in any other hadron.
- Can be observed directly in pion's valence-quark distribution function
  & highlighted in comparison between valence-quark distributions in π and much-heavier K.
- New-era experiments capable of validating these predictions are of highest priority.
- With validation, an entire chapter of the Standard Model – begun by Yukawa more than eighty years ago – can be completed and closed with elucidation of the structural details of the SM's only NG modes, whose existence and properties are critical to the formation of everything from nucleons, to nuclei, and on to neutron stars.
- No claim to have understood SM is supportable until explanation is provided for the emergence and structure of NG modes.

# Dark Mass

- Compelling contrast … the question of “invisible” or dark matter (DM)
  - Non-baryonic and electrically neutral
- Empirical evidence indicates that DM must constitute bulk of all matter in the Universe.
- It surrounds galaxies and other large structures, forming the major component of the Universe’s gravitational fabric
- However, origin and nature are completely unknown.
- Weakly interacting massive particles (WIMPs), cold thermal relics of the big bang, present a possible (the most appealing) solution to these puzzles
- Their discovery would herald a new age in physics
- Input that can shed light onto this “dark” arena would be highly prized.

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

# Proton Mass

- Turn off the Higgs couplings to light quarks and QCD is scale invariant
- 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, $\mathbf{L}(\mathbf{m}\ \ 0)$
  $\Rightarrow \partial_\mu \mathbf{D}_\mu = \delta\mathbf{L}/\delta\sigma = \alpha\beta(\alpha)\, d\mathbf{L}/d\alpha = \boxed{\beta(\alpha)\, \tfrac{1}{4} G_{\mu\nu} G_{\mu\nu} = T_{\rho\rho} =: \Theta_0}$

*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*

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

# Proton Mass

- 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:

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

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

$$= \langle p(P)|\Theta_0|p(P)\rangle$$

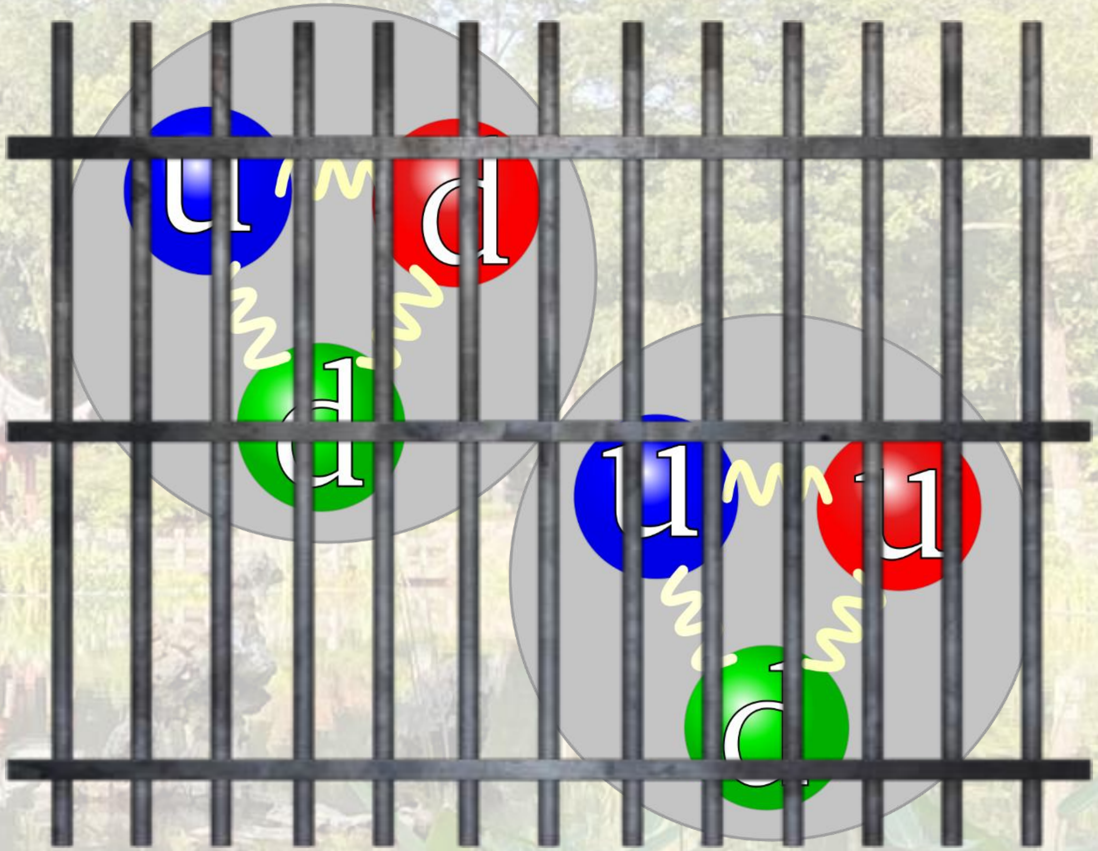
- In the chiral limit the entirety of the proton's mass is produced by the trace anomaly, $\Theta_0$
  … In QCD, $\Theta_0$ measures the strength of gluon self-interactions
  … so, from one perspective, $m_p$ is (somehow) completely generated by glue.

# Confinement & Origin of Mass

- *The vast majority of mass comes from the energy needed to hold quarks together inside nuclei*
- Restore Higgs mechanism

$$T_{\mu\mu} = \tfrac{1}{4}\beta(\alpha(\zeta))G^a_{\mu\nu}G^a_{\mu\nu} + [1+\gamma(\alpha(\zeta))]\sum_f m_f^\zeta \bar{q}_f q_f$$

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




- Poincaré-invariant statement:
  - ✓ Expectation value of $T_{\mu\mu}$ in proton gives all of $m_p^2$
  - ✓ All! Not some fraction thereof
- Continuum- and lattice-QCD ⇒ σ-term is 10% of $m_p^2$
- *Trace anomaly gives 90% of the proton's mass*

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

# What about the Pion Mass?

- In the chiral limit

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

- *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 $\Theta_0$.
- Of course, such precise cancellation should not be an accident.

  It could only arise naturally because

  of some symmetry and/or symmetry-breaking pattern.

$$T_{\mu\mu} = \frac{1}{4}\beta(\alpha(\zeta))G^a_{\mu\nu}G^a_{\mu\nu} + [1+\gamma(\alpha(\zeta))]\sum_f m_f^\zeta\, \bar{q}_f q_f$$

# What about the Pion Mass?

- Restore Higgs coupling: $m_\pi^2 = (m_u + m_d)\dfrac{-\langle \bar{q}q\rangle}{f_\pi^2}$
- Poincaré-invariant statement:
  - Entirety of the pion mass-squared owes to the current-quark mass term in the QCD Lagrangian.
- This result is 50 years old
- Shocking that modern practitioners are today claiming that only 50% of the pion's mass is generated by the current-quark mass term
- Much confusion is being generated by rest-frame decomposition of hadron masses
  - Related to confusion between energy and momentum
  - & Differences between partons, which are not frame independent.
- In quantum field theory:

  E & p are not independent and particle number is NOT conserved

# Resolve Dichotomy

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

- *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 $\Theta_0$ in chiral-limit pion is always zero, irrespective of the size of the natural mass-scale for strong interactions = $m_p$

# Resolve Dichotomy

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

- *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***?"*

AMBER Programme

Aims at Elucidating Key Consequences

of the Mechanism responsible

so that the Standard Model can be Validated

# 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].

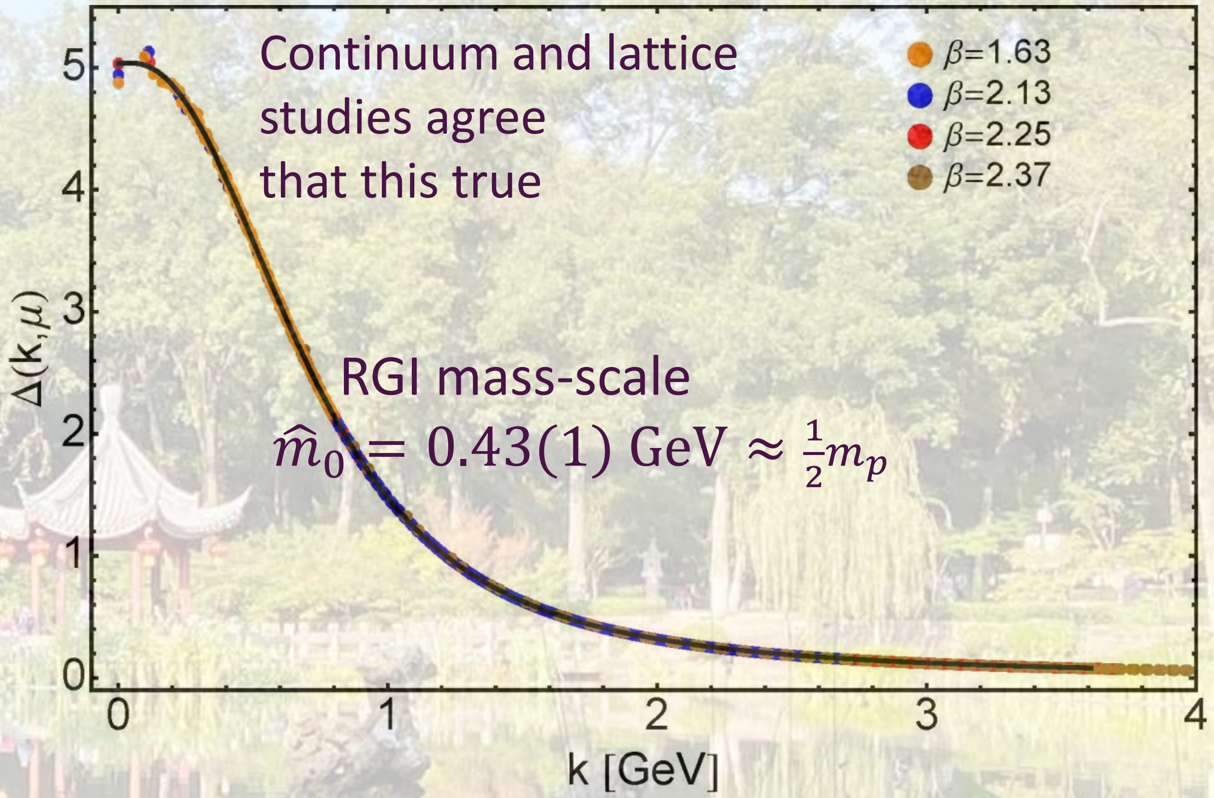
# IR Behaviour of QCD

- 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 $q^2 = 0$



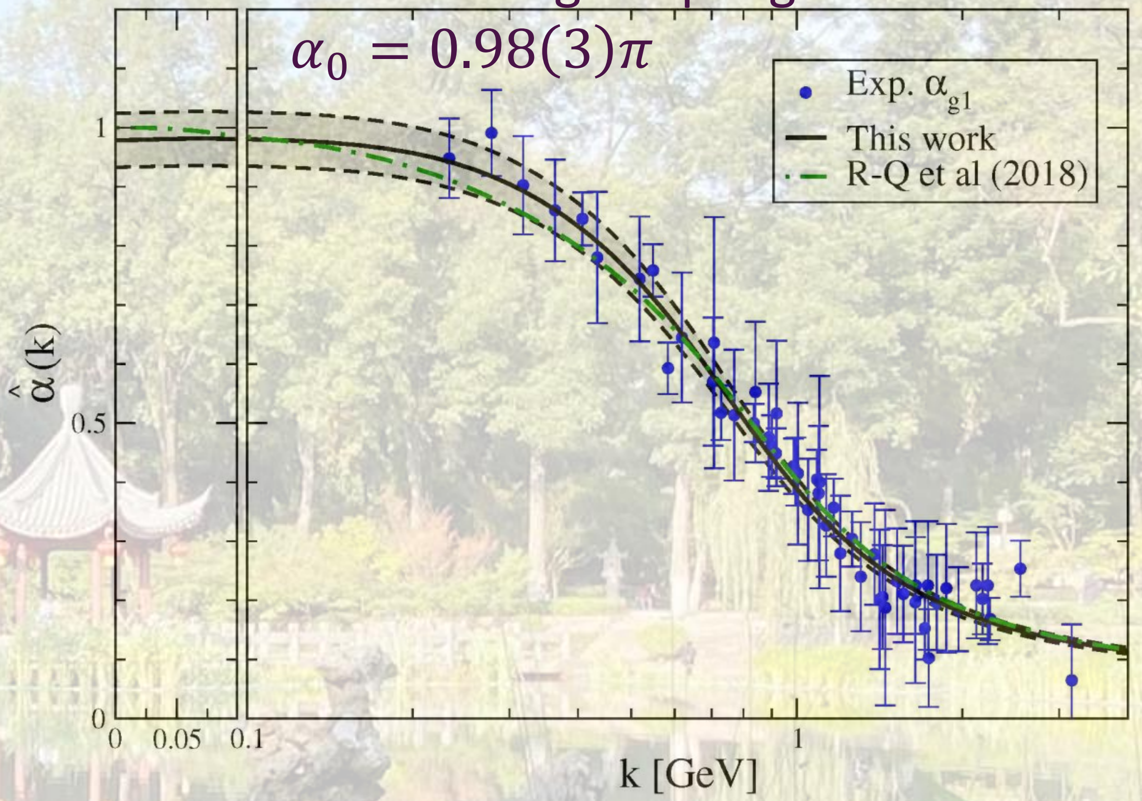

*Dynamical mass generation in continuum quantum chromodynamics*
*J.M. Cornwall, Phys. Rev. D* ***26*** *(1981) 1453 … ~ 1000 citations … approach modernized and sketched results are confirmed*

# 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

$\alpha_0 = 0.98(3)\pi$




*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

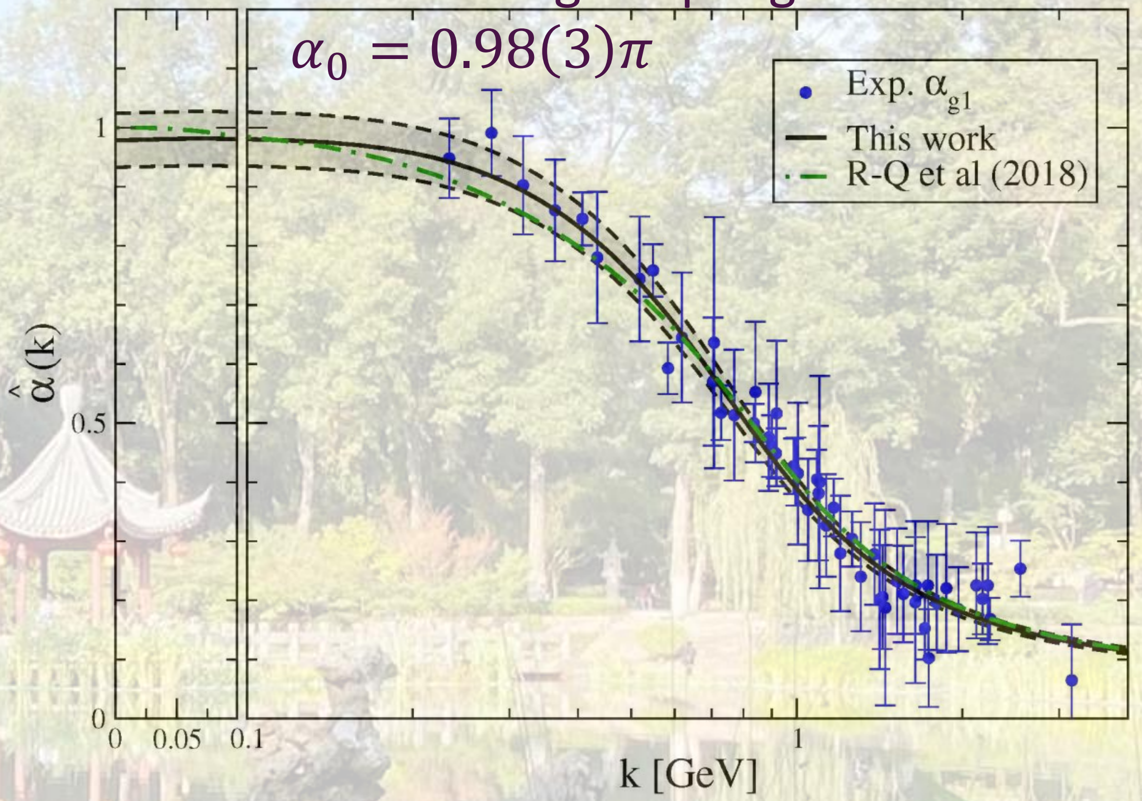
*Process-independent effective coupling. From QCD Green functions to phenomenology,*
Jose Rodríguez-Quintero *et al.*, arXiv:1801.10164 [nucl-th]. Few Body Syst. **59** (2018) 121/1-9

# 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

$\alpha_0 = 0.98(3)\pi$



# RGI PI Effective Charge

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

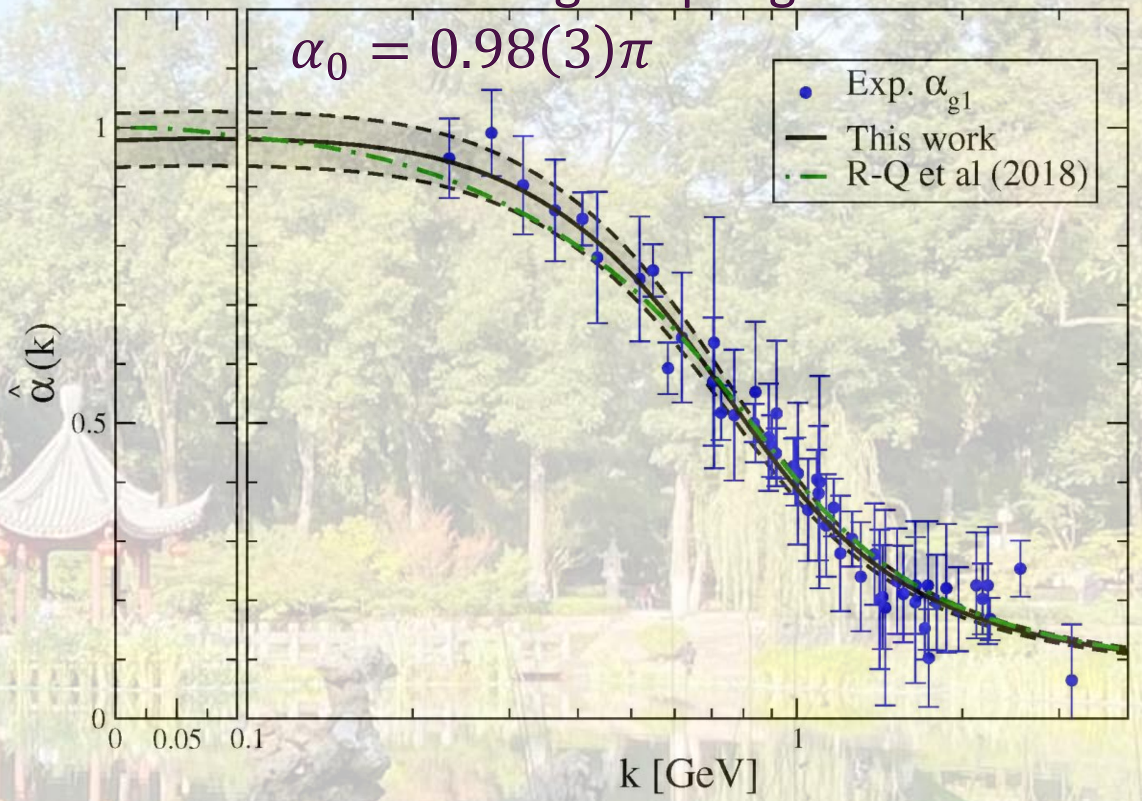
i. pointwise (almost) identical to the process-dependent (PD) effective charge,$\alpha_{g_1}$, defined via the Bjorken sum rule;

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

$\alpha_0 = 0.98(3)\pi$

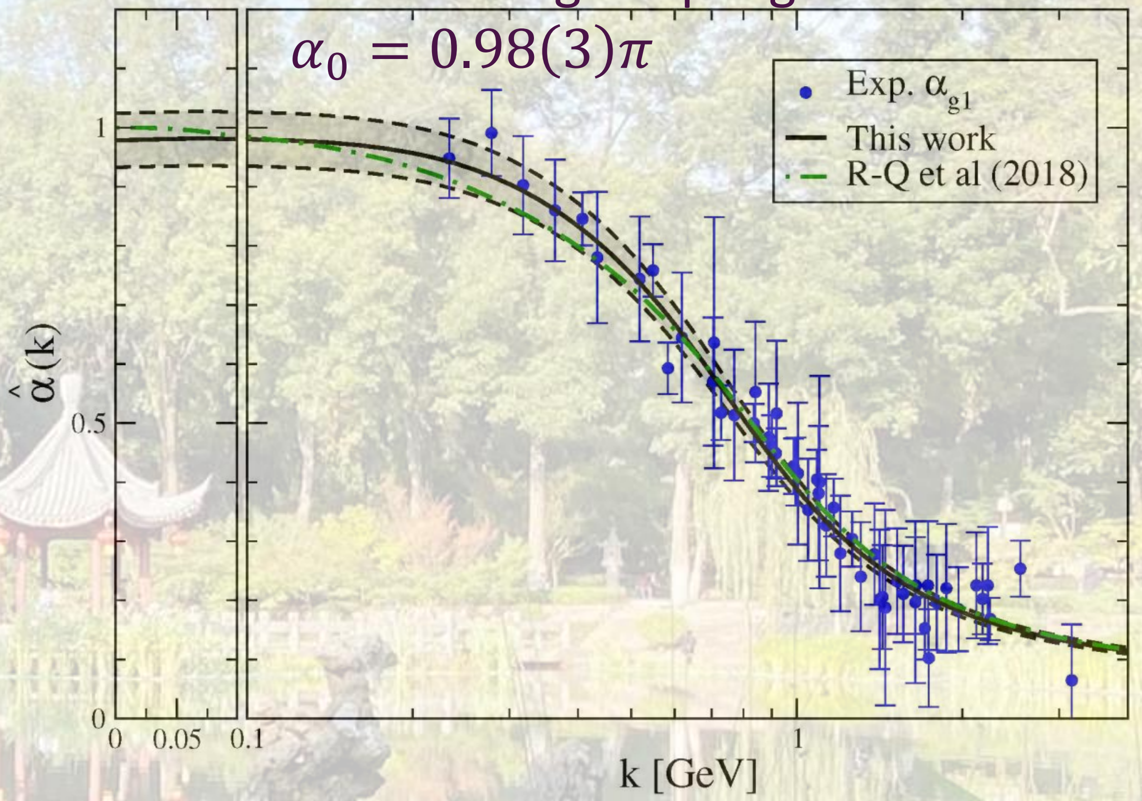


# RGI PI Effective Charge

- 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

$\alpha_0 = 0.98(3)\pi$




- 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.

# 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

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

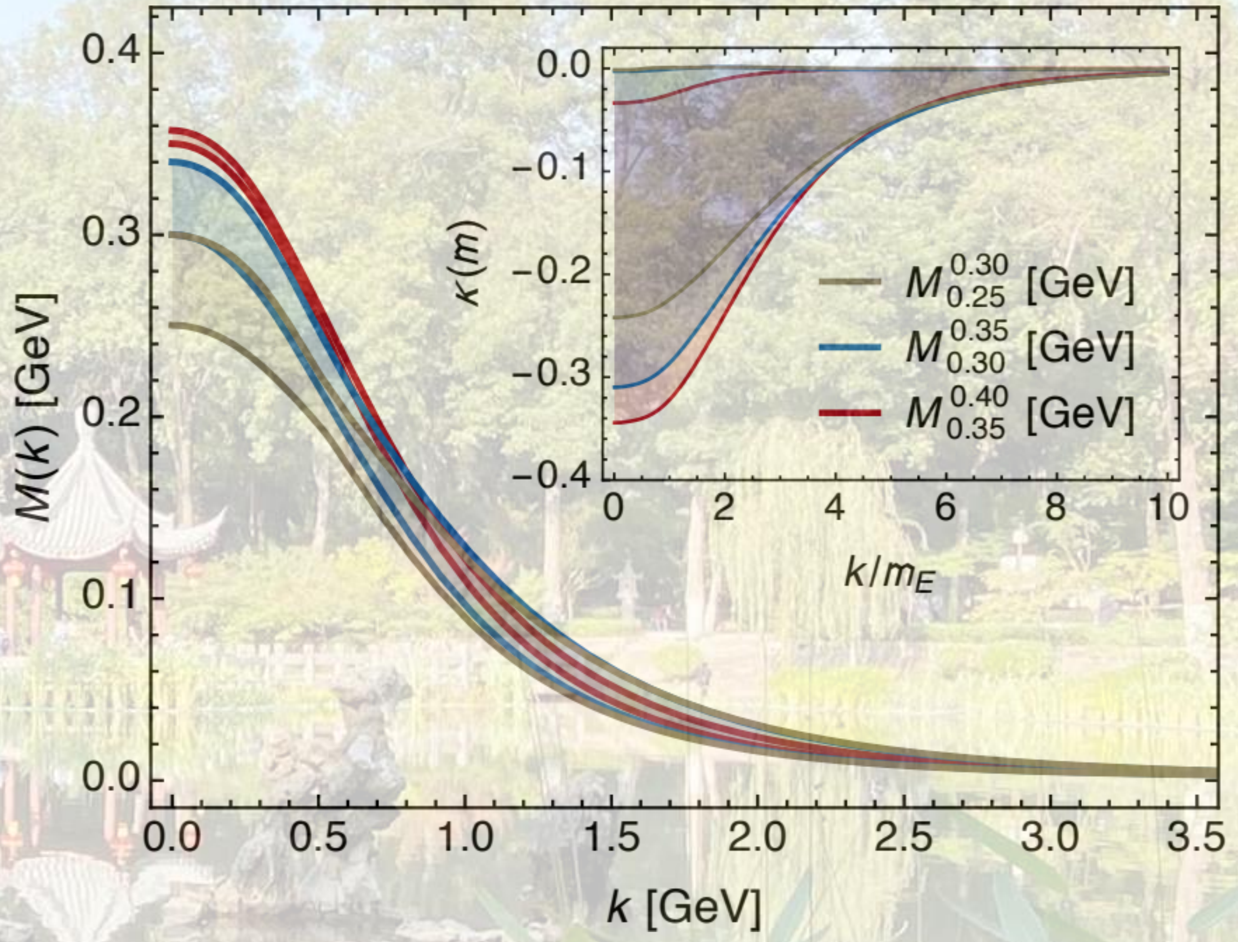
$$\Sigma(p) = Z_2 \int_{dq}^{\Lambda} 4\pi\hat{\alpha}(k^2)\mathcal{D}_{\mu\nu}(k)\gamma_\mu S(q)\hat{\Gamma}^a_\nu(q,p)\,,$$

- 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

$\alpha_0 = 0.98\,\pi$

- ➢ 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

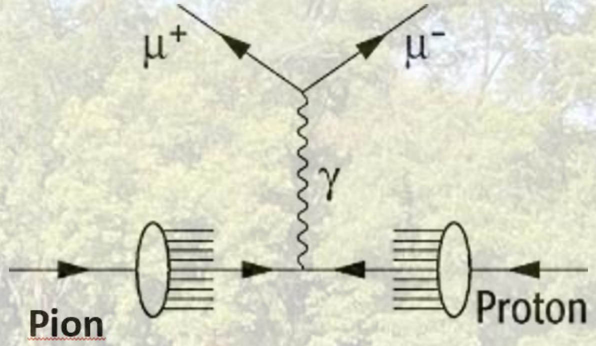
# Empirical Consequences of EHM

- 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 $\pi$ 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:

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

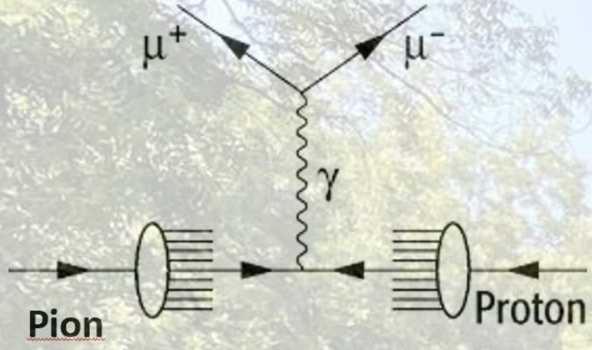



- Consider a theory in which quarks scatter via a vector-boson exchange interaction whose $k^2 >> m_G^2$ behaviour is $(1/k^2)^\beta$
- Then at a resolving scale $\zeta_H$ … $u_\pi(x;\zeta_H) \sim (1-x)^{2\beta}$

  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

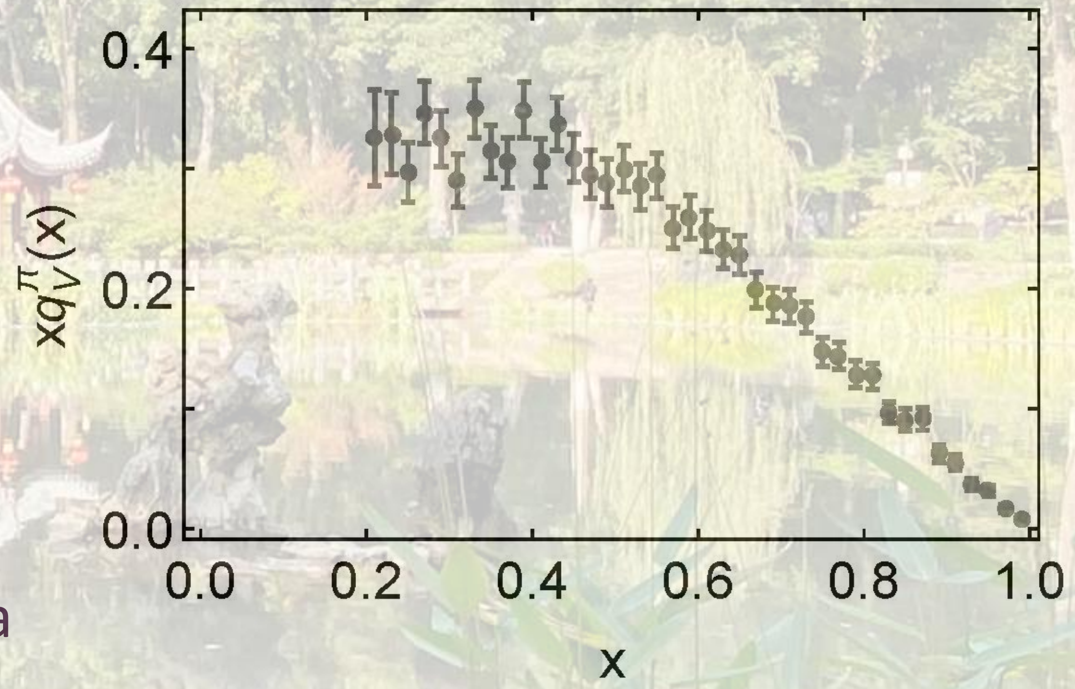
- Owing to absence of pion targets, the pion's valence-quark distribution functions have hitherto been measured via the Drell-Yan process:

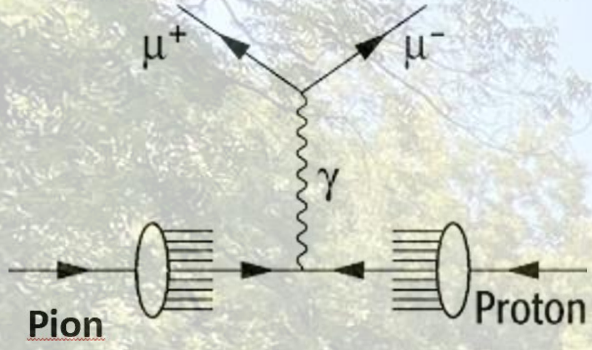
  $\pi\, p \to \mu^+\, \mu^-\, X$

- 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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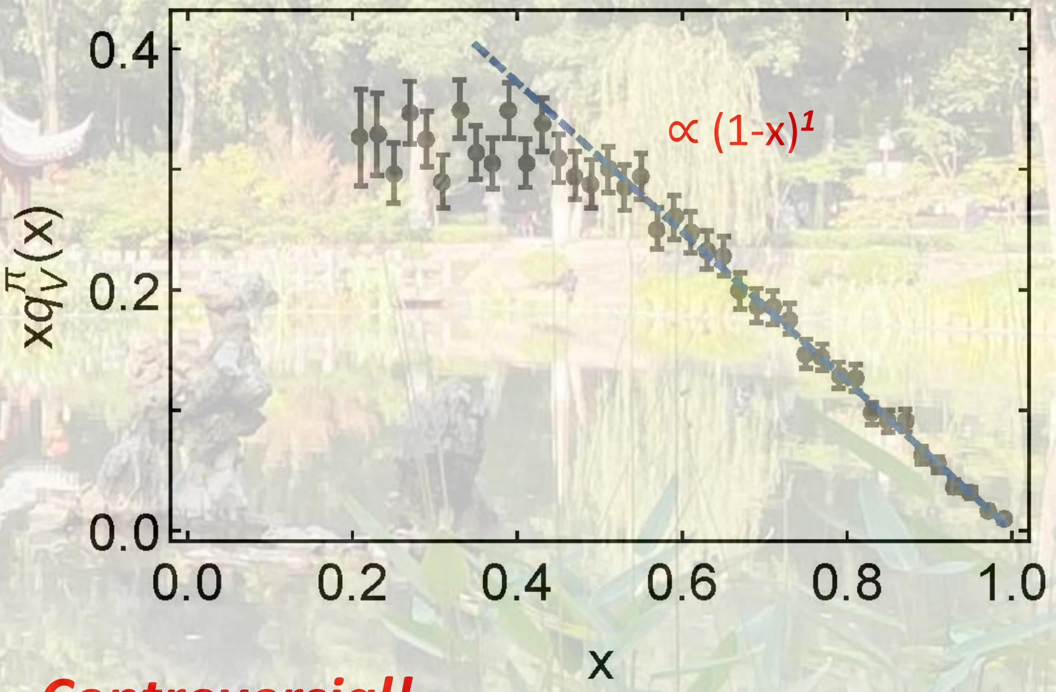
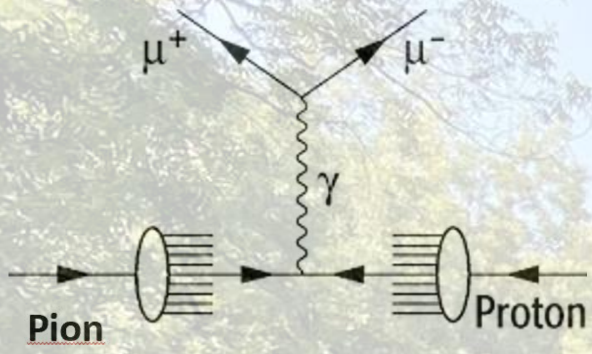
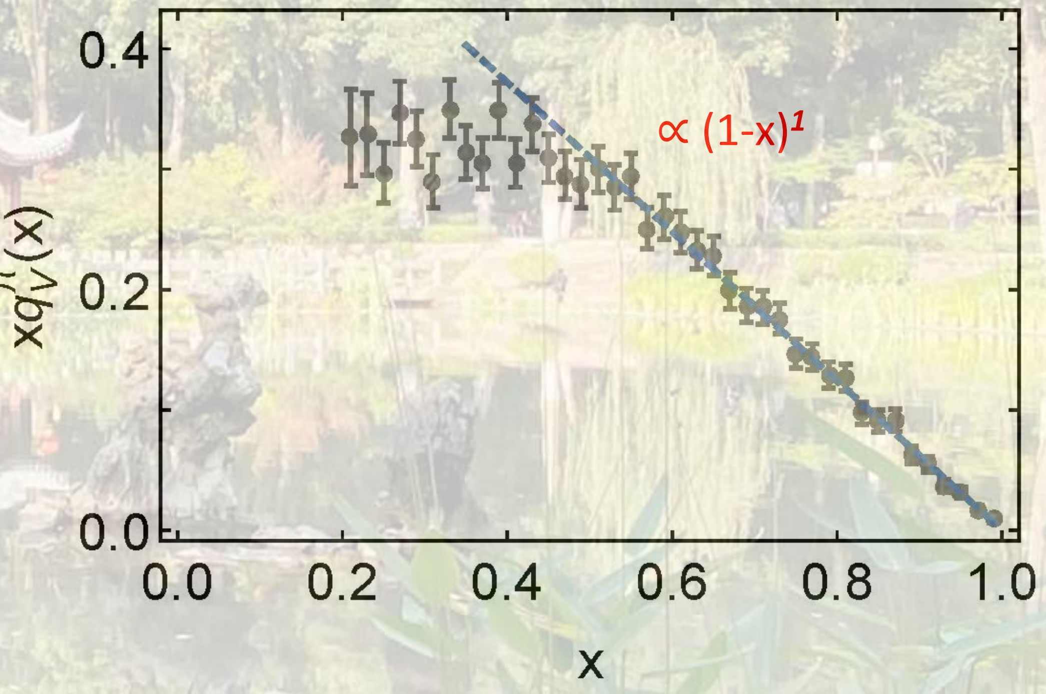



***Factor of 2 discrepancy with QCD!*** ***Controversial!***




# Empirical status of the Pion's valence-quark distributions

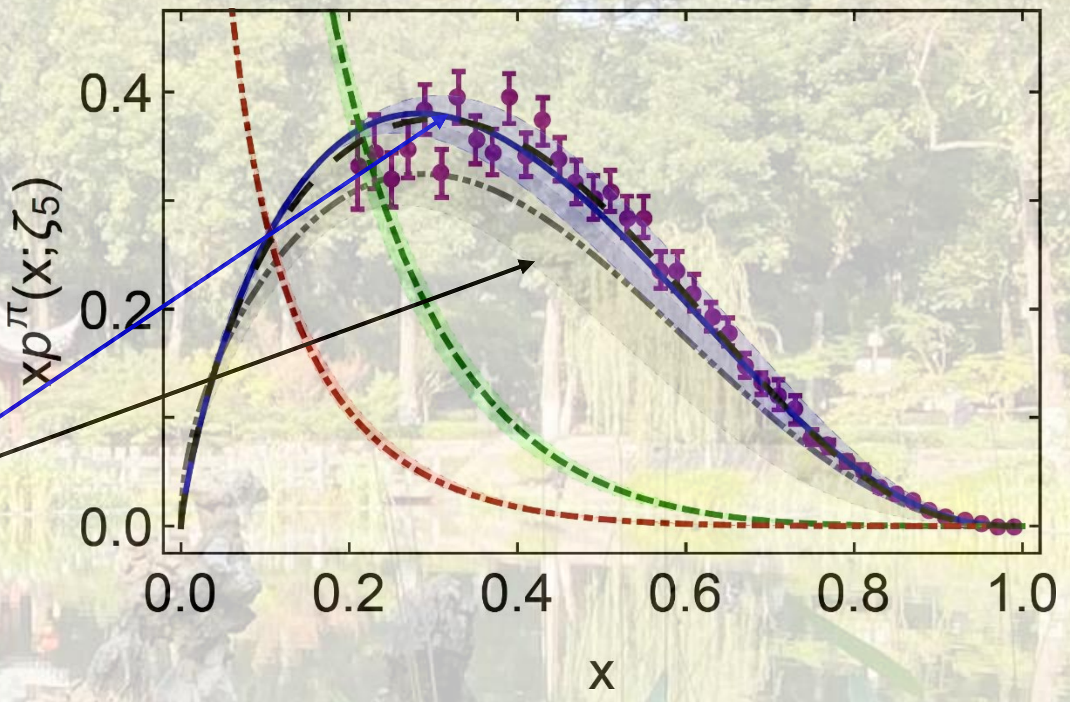
- Conway *et al*. [Phys. Rev. D **39**, 92 (1989)]
  - Leading-order analysis of Drell-Yan data
- Ensuing years, great deal of fog
- Perceptions ebbed and flowed
  - Is this data a fundamental challenge to Standard Model?



# $\pi$ 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*

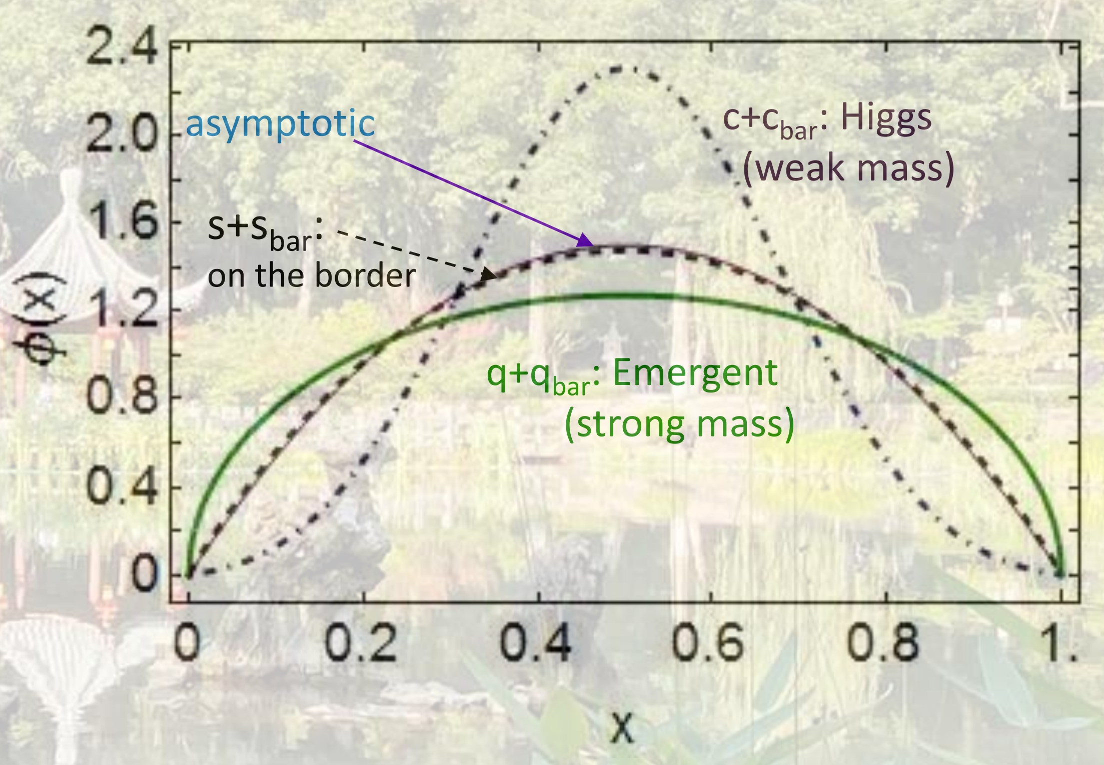
$\beta^{contm}(\zeta_5) = 2.66(12)$
$\beta^{lattice}(\zeta_5) = 2.45(58)$



*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

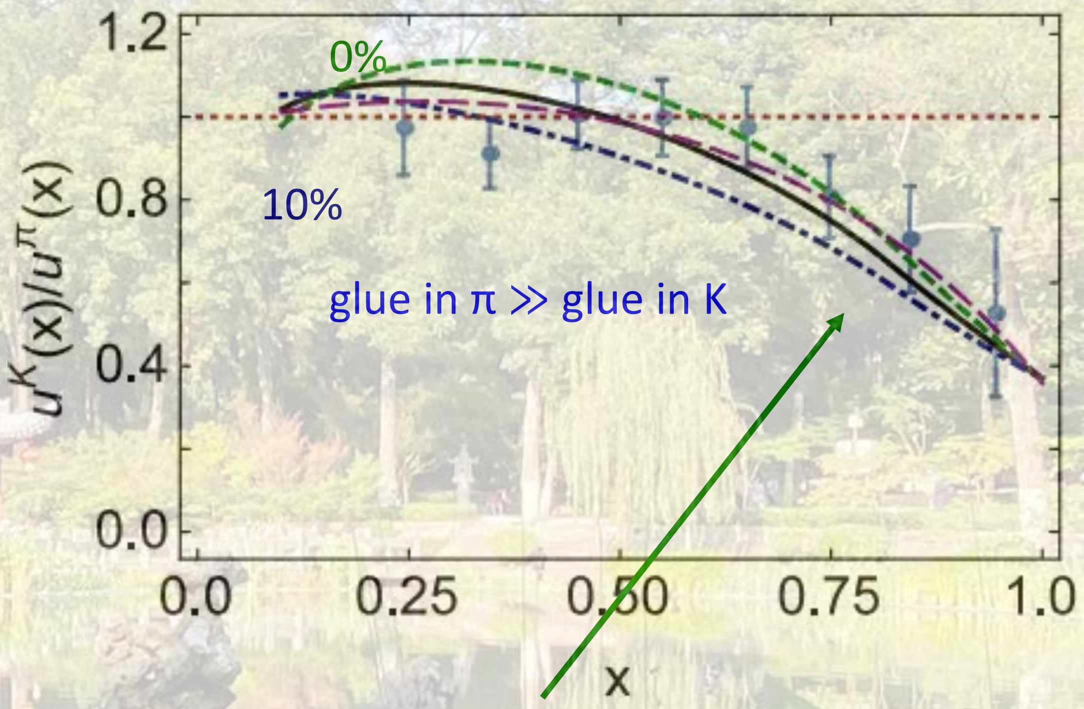
- When does Higgs mechanism begin to influence mass generation?
- limit $m_{quark} \to \infty$
  $\varphi(x) \to \delta(x-½)$
- limit $m_{quark} \to 0$
  $\varphi(x) \sim (8/\pi)\,[x(1-x)]^{½}$
- Transition boundary lies just above $m_{strange}$
- *Hence … Comparisons between distributions of truly light 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 $u^{\pi}(x;\zeta)$ & $u^{K}(x;\zeta)$ 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

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

*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

# $\pi$ & $K$ PDFs

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

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

  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 $u^K(x;\zeta)/\,u^\pi(x;\zeta)$
  – 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*

INSIGHT

# $\pi$ & $K$ 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*

# Future

- Challenge: Explain 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
- Theory Institute at CERN … join theorists from high-energy nuclear & particle physics in dialogue with the experimentalists … address the Emergence of Hadron Mass
- Workshop is meant to start a collaborative effort between the experimentalists proposing these new measurement campaigns, the phenomenologists doing global data analyses, and the hadron-structure theorists.
- 5-days workshop 30$^{th}$ March – 3$^{rd}$ April … about 30 participants
  - Present their work.
  - Panel discussions shall be organized at each day.
  - Informal proceedings shall be compiled after the workshop.