NANJING UNIVERSITY

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

Vector Meson Production and Vector Meson Dominance

Emergence of Hadron Mass

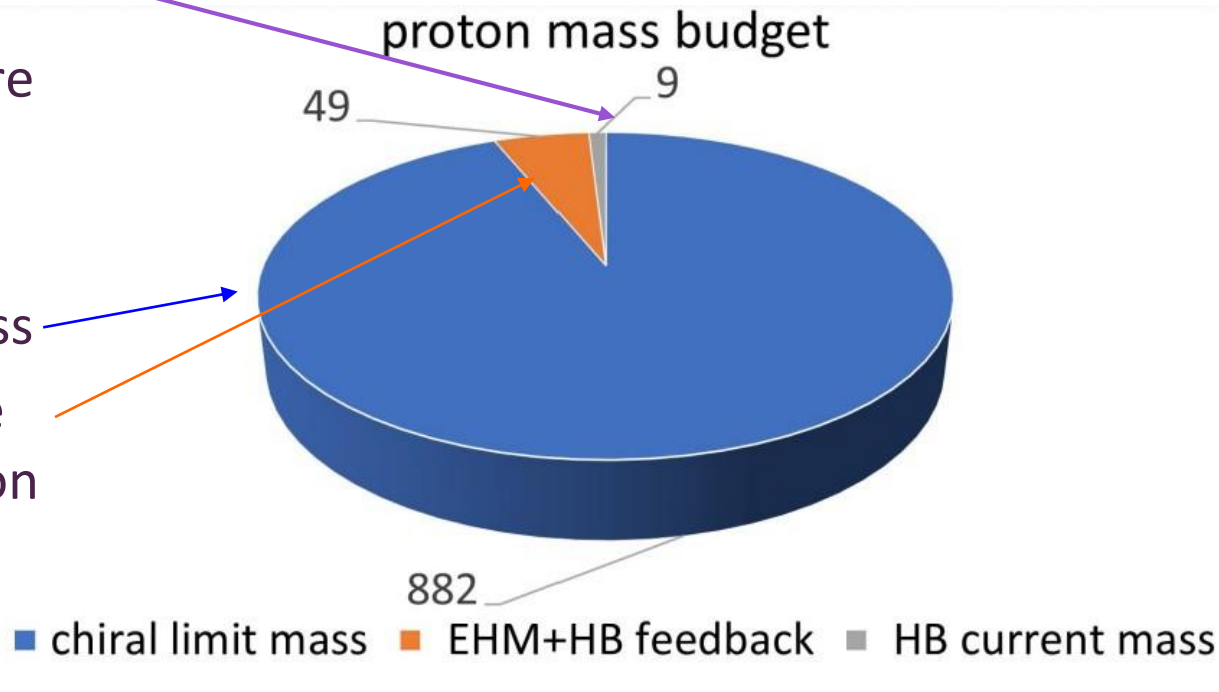
- Proton mass budget

  Only 9 MeV/939 MeV is directly from Higgs

- Plainly, there is another phenomenon in Nature that is extremely effective in producing mass:

  Emergent Hadron Mass (EHM)

  - ✓ Alone, it produces 94% of the proton's mass
  - ✓ Remaining 5% is generated by constructive interference between EHM and Higgs-boson



- ✓ What is EHM?
- ✓ Can it be explained by mere mechanisms, like a Swiss watch?
- ✓ If so, what are they?

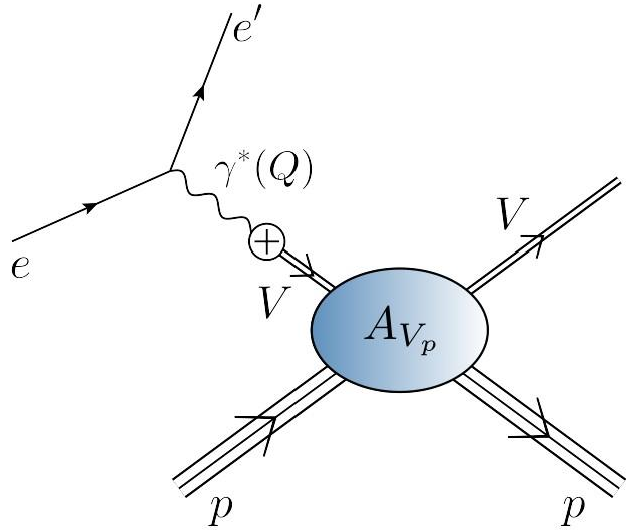
Phenomenon of Emergent Mass

- Empirical status:
  - proton is stable compound object formed from three valence light-quarks
  - proton electric and magnetic charge radii: $r_E \approx 0.84$ fm, $r_M \approx 0.82$ fm
    - *Fresh extraction of the proton charge radius from electron scattering*, Z.-F. Cui, D. Binosi, C. D. Roberts, S. M. Schmidt, NJU-INP 033/21, arXiv: 2102.01180 [hep-ph], Phys. Rev. Lett. **127** (2021) 092001
    - *Pauli radius of the proton,* Zhu-Fang Cui (崔著钫), Daniele Binosi, Craig D. Roberts and Sebastian M. Schmidt, NJU-INP 050/21, e-print: 2109.08768 [hep-ph]
  - evidently, proton never decays (if it did, wouldn't be many of us here)
- Mass of proton $m_p = 939$ MeV.
- Mass of valence quarks in proton = 9 MeV
  - ***Missing mass = 930 MeV = 99%***
- Higgs mechanism of mass generation responsible for only 1% of proton mass
- ***Where should science look to find the remaining 99% of visible mass in the Universe?***
- ***Is the answer contained within the SM?***
- ***How will science know when the answer is found? What are the "smoking gun" signals?***

Femtoscopy of the Origin of the Nucleon Mass, G. Krein & T.C. Peixoto,
Few Body Syst. **61** (2020) 4, 49 • e-Print: 2011.11615 [hep-ph]

$V + p \to V + p$

- Interaction of heavy vector-meson, J/ψ or Υ, with proton offers prospects for access to
  - a QCD van der Waals interaction, generated by multiple gluon exchange
    - may relate to, *inter alia*, the observation of hidden-charm pentaquark states
  - and Proton Mass via QCD trace anomaly
    - connection with emergent hadron mass (EHM)



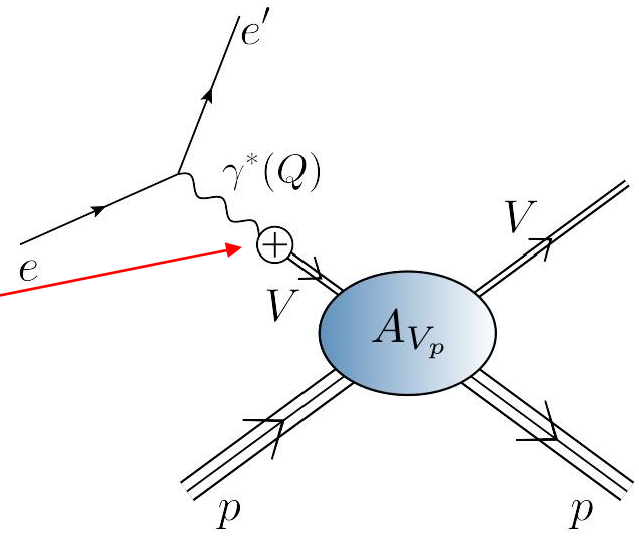
- Don't have vector-meson beams, so experiments at modern e-accelerators attempt to access such interactions via electromagnetic production reactions e + p → e' + V + p
- Same is proposed at future electron ion colliders
- Why?
  - Typically assumed that single-pole vector meson dominance (VMD) can reliably be used to draw direct link between e + p → e' + V + p & V + p → + V + p

$e + p \to e' + V + p$ & $V + p \to V + p$

- Interaction supposed to take place in a sequence of steps:
  a. $e \to e' + \gamma^{(*)}(Q)$
  b. $\gamma^{(*)}(Q) \to V$
  c. $V + p \to V + p$
- Step (b) expresses VMD hypothesis
- Assumes that:
  i. photon, at best = real, but generally spacelike ($Q^2 \geq 0$), transmutes into an on-shell vector-meson, with timelike momentum $Q^2 = -m_V^2$
  ii. $Q^2 \geq 0$ strength and character of the transition in (b) is unchanged from that measured in the real process of vector-meson decay,

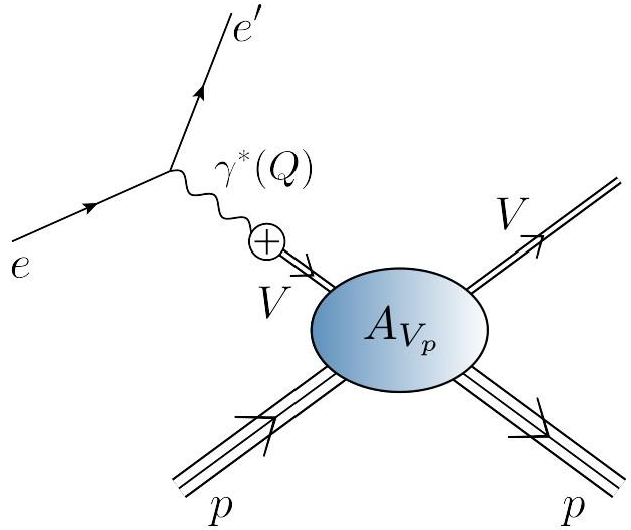
$$V \to \gamma^* \, (Q^2 = -m_V^2) \to e^+ + e^- \, ,$$

i.e., γV coupling is fixed at on-shell value, acquiring NO momentum dependence, irrespective of the size of m_V^2, which defines the arm on required extrapolation



$e + p \to e' + V + p$ & $V + p \to V + p$

- Standard use of VMD
- Step b. γ(∗)(Q) → V



$$\left.\frac{d\sigma_{\gamma N\to\Upsilon N}}{dt}\right|_{t=0} = \frac{3\Gamma(\Upsilon\to e^+e^-)}{\alpha m_\Upsilon}\left(\frac{k_{\Upsilon N}}{k_{\gamma N}}\right)^2 \left.\frac{d\sigma_{\Upsilon N\to\Upsilon N}}{dt}\right|_{t=0}$$

$V + p \to V + p$

$Q^2 = 0$ photoproduction cross-section

Translation via a constant computed at $Q^2 = -m_V^2$

More on the VMD *Ansatz*

- VMD Ansatz introduced before the development of QCD [Sakurai:1960ju]
- Used in analysing energetic electromagnetic interactions of light hadrons,
  viz. states with masses similar to proton
- Still used today and for a much wider range of systems
- Why?
  - Alternative = develop sophisticated, nonperturbative reaction theory that can explain quark+antiquark scattering from hadron targets into vector-meson final-states.
- Not Done
- Notwithstanding this, lack of alternative does not validate VMD expedient
- Fidelity should be reconsidered with QCD constraints in mind.

Vector-meson production and vector meson dominance, Yin-Zhen Xu (徐胤禛), Si-Yang Chen (陈斯阳), Zhao-Qian Yao (姚照千), Daniele Binosi, Zhu-Fang Cui (崔著钫) and Craig D. Roberts, NJU-INP 044/21, arXiv:2107.03488 [hep-ph], Eur. Phys. J. C (2021) *in press*

Trace Anomaly via Heavy-meson photo-production?

- Is there a relation between the electromagnetic vector-meson production reaction

  $e + p \to e' + V + p$ and the purely hadronic process $V + p \to V + p$?

- Answer depends on the fidelity of single-pole VMD assumption
- If this VMD assumption is false …

  Then all existing cross-section estimates and conclusions based on VMD must be reviewed

- For JLab, EIC, EicC this means … will need to rethink access to and understanding of
  - hidden-charm pentaquark production
  - origin of the proton mass via trace anomaly
- How to check validity of VMD?

Photon Vacuum Polarisation

- Physical process $V \to e^+ e^-$ described by leptonic decay constant, f_V:

$$f_V m_V \epsilon_\mu^\lambda(Q) = \mathrm{tr}_{\mathrm{CD}} Z_2 \int_{dk}^{\Lambda} \gamma_\mu \chi_V^\lambda(k,Q)$$

  $\epsilon_\mu{}^\lambda$ is the polarisation vector

  and $\chi_V{}^\lambda$ is the meson's Bethe-Salpeter wave function

  simply related to $\Gamma_V{}^\lambda$, meson's Bethe-Salpeter amplitude

- In terms of this decay constant, the (real) decay width is

$$\Gamma_{V\to e^+e^-} = \frac{8\pi\alpha_{\mathrm{em}}^2}{3}\frac{f_V^2}{m_V}\bar{e}_V^2 \qquad 2(\bar{e}_{\rho^0}^2, \bar{e}_\omega^2, \bar{e}_\phi^2, \bar{e}_{J/\psi}^2, \bar{e}_\Upsilon^2) = (1, \tfrac{1}{9}, \tfrac{2}{9}, \tfrac{8}{9}, \tfrac{2}{9})$$

- The decay is typically connected with a dimensionless constant: $g_V = \dfrac{m_V}{f_V}$

- Related to this, the "current-field identity", definitive of VMD: $\gamma_\gamma V = e\dfrac{m_V^2}{g_V}$

VMD assumes this to be immutable: same on-shell and off-shell, no matter how far off-shell.

Photon Vacuum Polarisation

- Describes ALL QCD corrections to photon propagation
- Ward-Green-Takahashi identity

$$Q_\mu \Pi'_{\mu\nu}(Q) = 0 = \Pi'_{\mu\nu}(Q) Q_\nu$$

$$\Pi_{\mu\nu}(Q) = T_{\mu\nu}(Q)\, Q^2\, \Pi(Q^2)\,,$$

$$\Pi(Q^2) = \Pi'(Q^2) - \Pi'(Q^2 = 0)$$

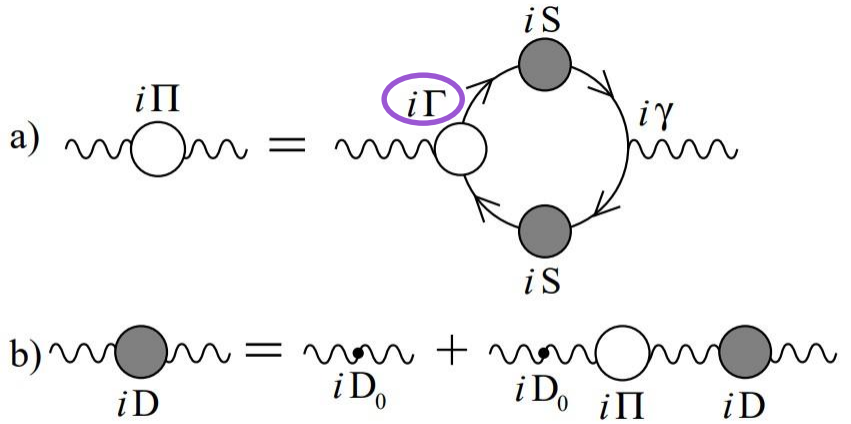


Fig. 2.1. The Dyson-Schwinger equation for the photon propagator.

- Follows that $\Pi(Q^2) = 0$, i.e., the photon begins massless and remains massless in interacting theory (No Schwinger mechanism for the QED photon)
  - this is a constraint from Nature
- $\Pi(Q^2)$ connected to vector-mesons through the dressed photon-quark vertex
- In neighbourhood of a vector-meson pole, ignoring any hadronic width:

$$\frac{1}{Z_2}[\Gamma^\gamma_\nu(k,Q)]_{tu} \overset{Q^2+m_V^2\simeq 0}{=} \text{regular terms}$$
$$+ \int_{dl}^{\Lambda} 2 \frac{[\Gamma^\lambda_V(k;Q)]_{ut}[\Gamma^\lambda_V(l;Q)]_{rs}}{Q^2+m_V^2}[S(l_-)\gamma_\nu S(l_+)]_{sr}\,,$$

Photon Vacuum Polarisation

- Consequently, statement of simple fact:

$$Q^2\,\Pi(Q^2) \overset{Q^2+m_V^2\simeq 0}{=} \bar{e}_V^2\,\frac{2f_V^2 m_V^2}{Q^2+m_V^2}$$

V-meson e+ e- decay constant

- Thus, on $Q^2 + m_V^2 \simeq 0$ the timelike photon is indistinguishable from the vector-meson.
- This is merely the statement that e+ e− collisions with a tuned centre-of-mass energy can be used to produce vector-mesons.
- However: VMD assumption asserts that the photon is also indistinguishable from the vector-meson on $Q^2 \simeq 0$: $Q^2\Pi(Q^2) = \frac{2\bar{e}_V^2 f_V^2}{m_V^2}$
  - Very different statement
- Plainly false because photon is massless & associated Ward-Green-Takahashi identity demands:

$$Q^2\Pi(Q^2)\big|_{Q^2\simeq 0} \equiv 0 \quad \neq \frac{2\bar{e}_V^2 f_V^2}{m_V^2}$$

Current Field Identity

$$\gamma_{\gamma V} = e \frac{m_V^2}{g_V}$$

- Used in all analyses that attempt to link

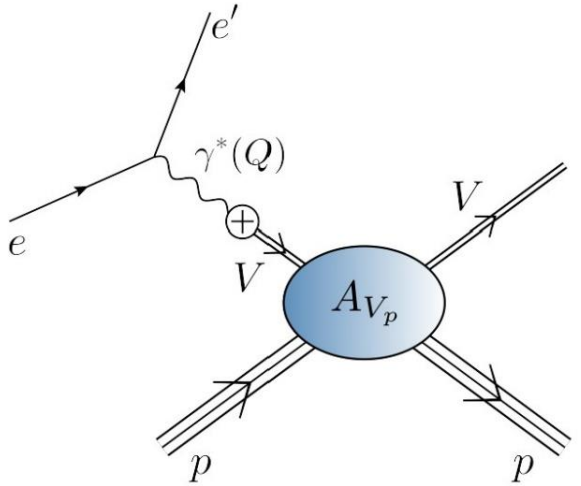
  $e + p \to e' + V + p$ with the purely hadronic process $V + p \to V + p$
- Necessarily generates a massive photon

  In fact, a tachyonic photon
- Hence, cannot alone be used to develop or support a VMD phenomenology
- This contradiction recovers the objection to current-field identity first raised in 1963
- Remedy for this flaw was proposed in 1967:
  - Construct a local Lagrangian for pointlike photons & vector-mesons & nucleons
  - Tune couplings to ensure cancellation of the tachyonic photon mass
- BUT QCD interactions do not generate pointlike hadrons
- SO, this solution is untenable.
- Is there a QCD alternative?

Photon Quark Vertex

$$\frac{1}{Z_2}[\Gamma^\gamma_\nu(k,Q)]_{tu} \stackrel{Q^2+m_V^2\simeq 0}{=} \text{regular terms} + \int_{dl}^{\Lambda} 2\frac{[\Gamma^\lambda_V(k;Q)]_{ut}[\Gamma^\lambda_V(l;Q)]_{rs}}{Q^2+m_V^2}[S(l_-)\gamma_\nu S(l_+)]_{sr},$$

- Another place to look for justification of VMD assumption suggested by this identity
- Dressed photon-quark vertex describes how photon (timelike, real, or spacelike) couples to q + $\bar{q}$ pair
- This is general character of the interaction expressed here →
  - (a′) e → e′ + γ∗(Q)
  - (b′) γ∗(Q) → q + $\bar{q}$
  - (c′) q + $\bar{q}$ + p → V + p
- In general, $\Gamma^\gamma_\nu(k;Q)$ is momentum dependent
- So, question to be addressed is:
  - Are there any conditions under which $\Gamma^\gamma_\nu(k;Q)|_{Q^2\simeq 0}$ has link to an on-shell vector-meson that may be approximated by $\gamma_{\gamma V} = e\frac{m_V^2}{g_V}$ or something similar?



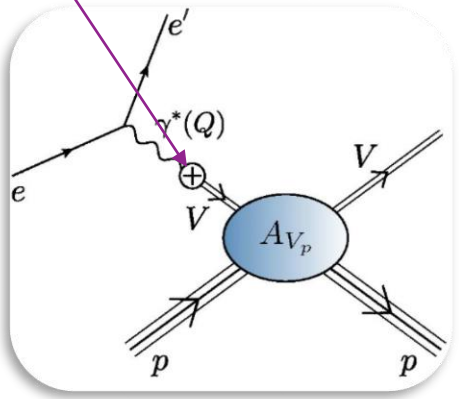
To answer this, one must compute $\Gamma^\gamma_\nu(k;Q)$

Photon-quark vertex - SCI

- If q + $\bar{q}$ interaction is momentum-INDEPENDENT (SCI) then $\Gamma^\gamma_\nu(k;Q) = \Gamma^\gamma_\nu(Q)$ does not depend on k.

Only term in vector meson bound-state amplitude

$$\epsilon^\lambda \cdot \Gamma^\gamma(Q) \overset{Q^2+m_V^2\simeq 0}{=} \epsilon^\lambda \cdot \gamma \frac{2 f_V m_V E_V}{Q^2+m_V^2}$$



- Similarly, vector meson Bethe-Salpeter amplitude does not depend on k.
- VMD valid if

$$R_V(Q^2)\big|_{Q^2=0} = \frac{1}{P_T(Q^2)} \frac{2 f_V m_V E_V}{Q^2+m_V^2}\bigg|_{Q^2=0} = \frac{2 f_V E_V}{m_V}$$

- Translates into validity of VMD iff $R_V(Q^2) \equiv 1$
- Results:

V	ρ	ϕ	J/ψ	Υ
$R_V(0)$	0.42	0.37	0.15	0.12

Photon-quark vertex

- If q + $\bar{q}$ interaction is momentum-INDEPENDENT (SCI) then $\Gamma^\gamma_\nu(k;Q)$ does not depend on k.
- Translates into validity of VMD iff $R_V(Q^2) \equiv 1$
- Results:

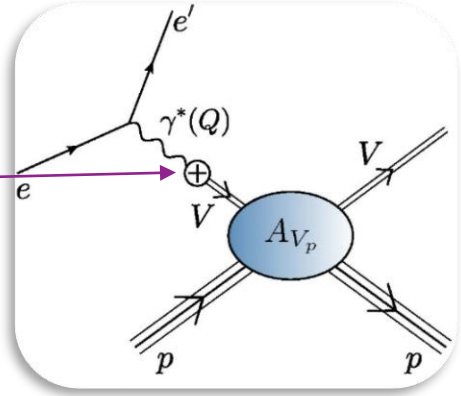
V	ρ	ϕ	J/ψ	Υ
$R_V(0)$	0.42	0.37	0.15	0.12

Phenomenology: introduce a Q^2-dependent "off-shell" factor to model this suppression

$$\gamma_{\gamma V} \to F_{\gamma V}(Q^2)\gamma_{\gamma V}$$

- e + p → e' + V + p & V + p → V + p
- Discussion
  - Vector-mesons composed of the lighter quarks, use of VMD assumption leads one to overestimate connection in cross-sections by a factor of six
  - Overestimate exceeds a factor of fifty for vector-mesons composed of heavy quarks
- Since the SCI produces photons and vector-mesons that both possess a pointlike character, these poor outcomes are likely the best achievable, so far as the fidelity of the VMD assumption is concerned in connection with vector-meson photoproduction.
- Results are worse for electroproduction

Photon-quark vertex - realistic interaction



- Photon-quark vertex
- This statement is always true: $\epsilon^\lambda \cdot \Gamma^\gamma(k;Q) \overset{Q^2+m_V^2\simeq 0}{=} \frac{2 f_V m_V}{Q^2+m_V^2}\Gamma_V^\lambda(k;Q)$

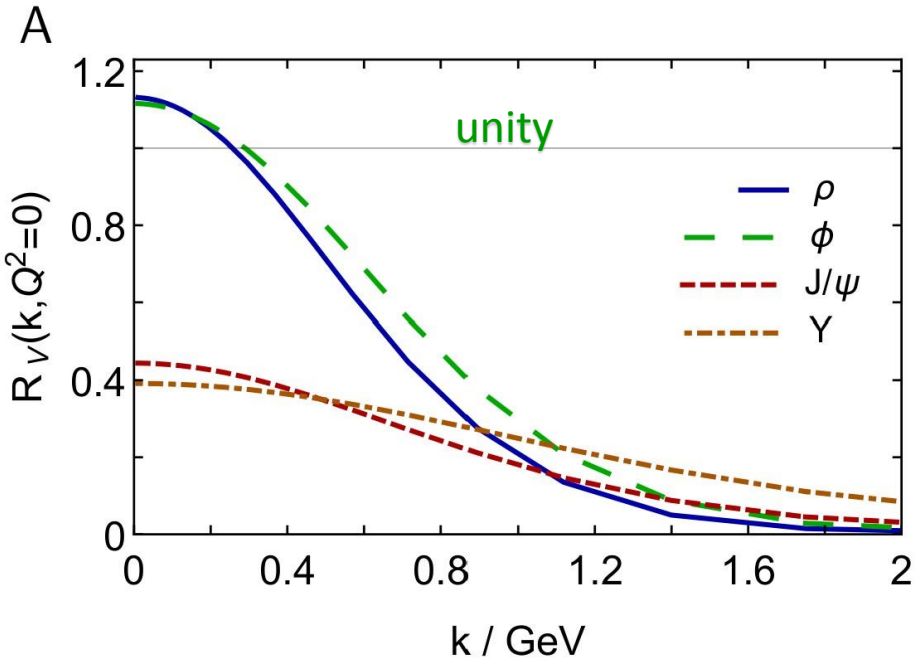
  Vertex and Bethe-Salpeter amplitude depend on two new variables involving relative momentum: k^2 and $k\cdot Q$
- VMD validity would require

  this ratio to be unity:

  Leading term in vector meson bound-state amplitude

$$R_V(k^2;Q^2=0) := \frac{2f_V}{m_V}\frac{F_1^0(k^2;-m_V^2)}{G_1^0(k^2;Q^2=0)}$$

Leading term in photon-quark vertex



- Might be workable for light mesons

  but plainly false for heavy mesons
- Are there any conditions under which $\Gamma_\nu^\gamma(k;Q)|_{Q^2\simeq 0}$

  has link to on-shell vector-meson that may be approximated by VMD current-field identity?
- No.

Craig Roberts. cdroberts@nju.edu.cn "Vector meson production and vector meson dominance"

Fidelity of VMD with realistic q + $\bar{q}$ interactions

$$R_V(k^2; Q^2 = 0) := \frac{2 f_V}{m_V} \frac{F_1^0(k^2; -m_V^2)}{G_1^0(k^2; Q^2 = 0)}$$

- Mathematics
  - On-shell photon is a massless pointlike object
  - On-shell vector-meson is a massive composite object
  - So, ratio $R_V(k^2; Q^2 = 0)$ reveals there is no overlap between these two states at $Q^2 = 0$
- QCD
  - Vector-meson compositeness requires $F_1^0(k^2; -m_V^2)$ vanishes as $\frac{1}{k^2}$ with increasing k^2, up to logarithmic corrections
  - For the pointlike photon $G_1^0(k^2; Q^2 = 0) \to 1$ with increasing k^2, again up to logarithmic corrections.

Fidelity of VMD with realistic q + $\bar{q}$ interactions

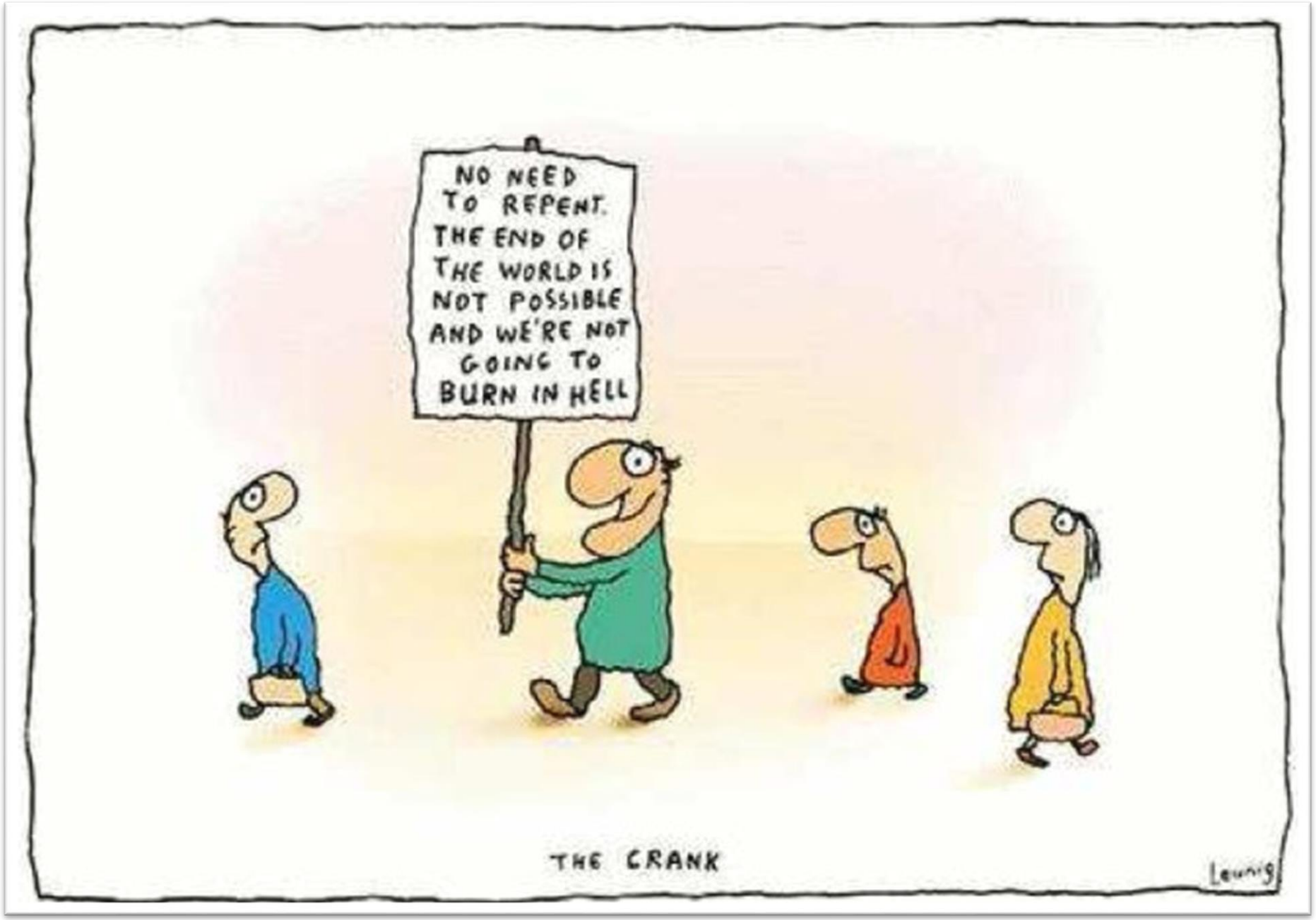
- $Q^2 = 0$ photon-quark vertex has only three nontrivial momentum-dependent components,
- On-shell vector-meson has eight distinct, momentum-dependent terms.

  ⇒ Numerous other comparison figures can be drawn
- Only three $Q^2 = 0$ ratios can be unity.
  - J/ψ and Υ … not one of them is unity
  - Other five are identically zero.
- Abundantly clear that momentum-dependence in any quark+antiquark loop describing scattering in process e + p → e' + V + p is very different from that in process V + p → V + p
- Consequently, the form-factor expedient is inadequate in the realistic case.

$$\gamma_{\gamma V} \to F_{\gamma V}(Q^2)\gamma_{\gamma V}$$

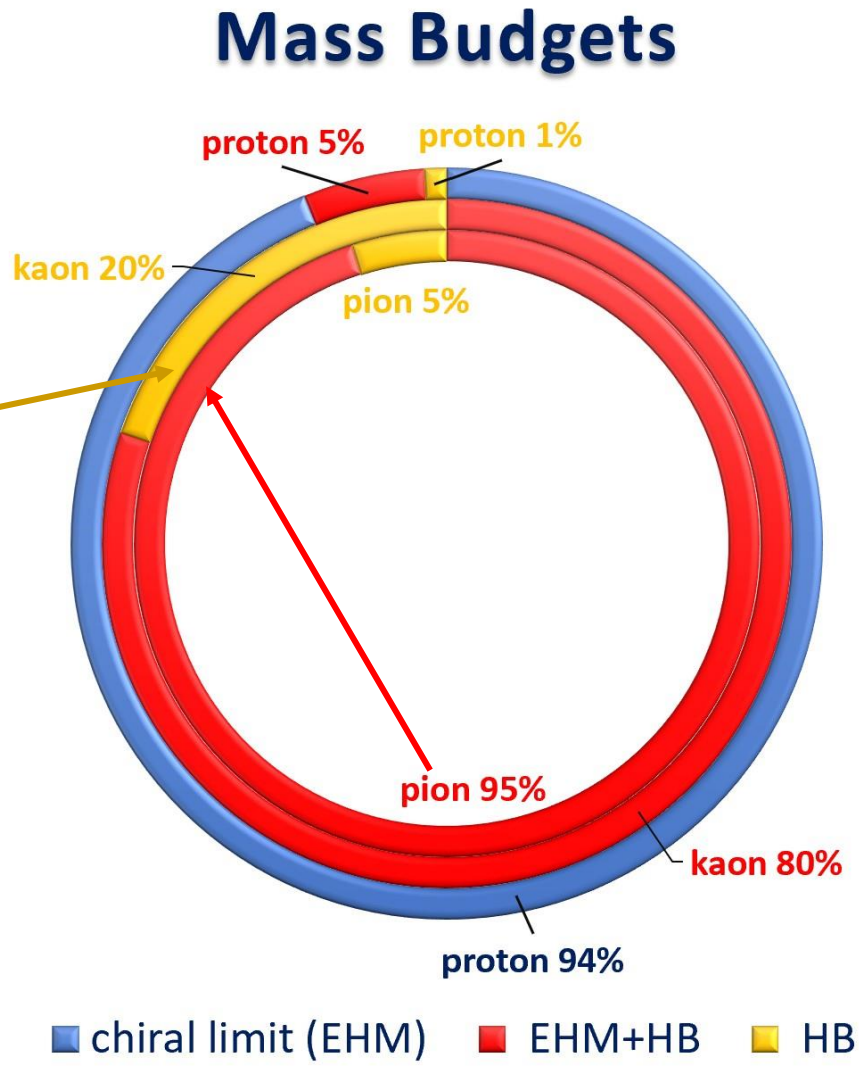
VMD for Heavy Vector Mesons?

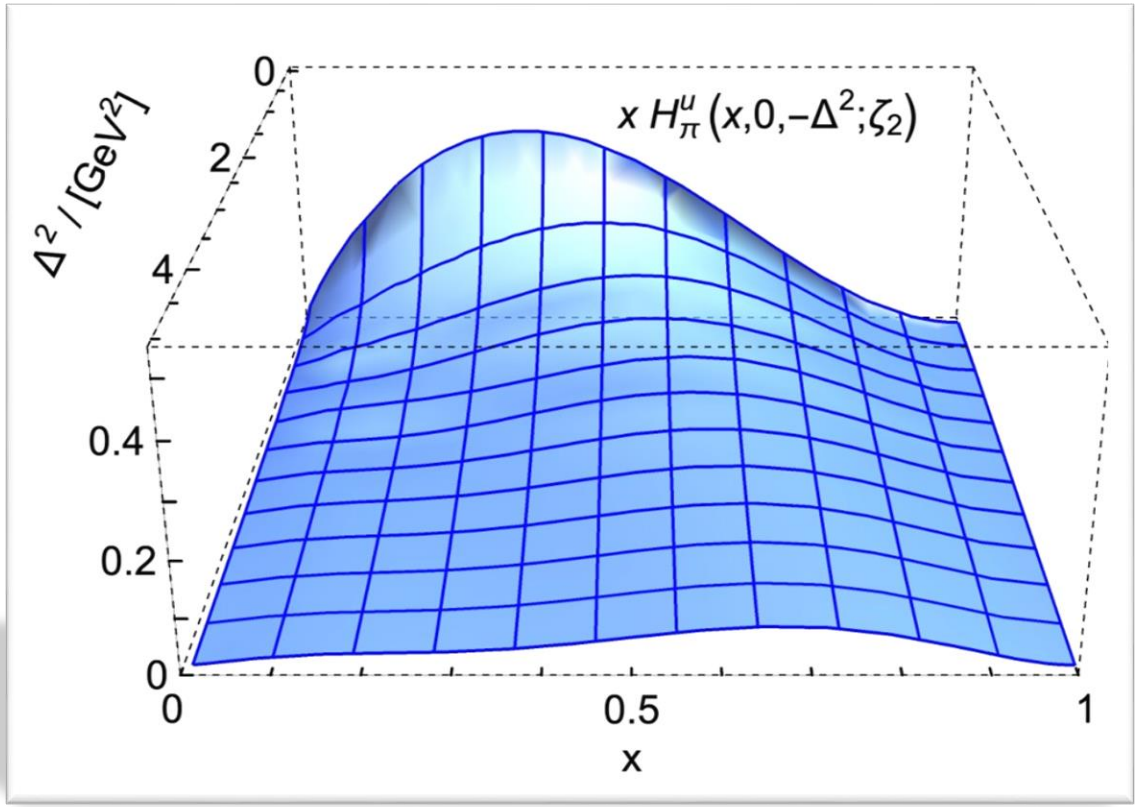
- Many other tests, all failed by VMD assumption for heavy vector-mesons:
- Simply: for heavy-mesons the momentum-dependence of the $Q^2=0$ photon-quark vertex is entirely different from that of vector-meson bound-state amplitude
- So, VMD assumption is false for heavy vector-mesons.
- No model-independent way to estimate and/or correct for the degree by which VMD distorts any interpretation $e + p \to e' + V + p$ in terms of $V + p \to V + p$
- Only $V + p \to V + p$ for which a QCD multipole expansion can be used to draw connections with the proton's glue distribution
- No existing attempt to connect $e + p \to e' + V + p$ & $V + p \to V + p$ via VMD is reliable.
  - See also Du, Guo, *et al*., Deciphering the mechanism of near-threshold J/ψ photoproduction, Eur. Phys. J. C 80 (11) (2020) 1053 … even if VMD were valid, then coupled-channels effects are likely to break the connection
- This undermines any interpretation of $e + p \to e' + V + p$ reactions as a route to either
  - hidden-charm pentaquark production
  - or as a means of uncovering the origin of the proton mass.


NO NEED TO REPENT. THE END OF THE WORLD IS NOT POSSIBLE AND WE'RE NOT GOING TO BURN IN HELL
THE CRANK
Lewis

Emergence of Hadron Mass - Contrasts

- Compare proton and pion mass budgets
- Pion is a Nambu-Goldstone boson
  - So, massless in chiral-limit
  - No blue annulus
  - EHM+HB is 95% of the total
- Kaon is somewhere in between
  - HB = 20%
  - EHM+HB = 80%
- Critically, without Higgs mechanism of mass generation, π and K would be indistinguishable from each other
- Always distinguishable from proton.
- Yet, all states are supposed to be in QCD!
- What is, wherefrom, whereto mass?





Generalised Parton Distribution Functions

Measures of Pseudoscalar Meson Structure

Measures of pion and kaon structure from generalised parton distributions, Jin-Li Zhang, Khépani Raya, J. M. Morgado, *et al*, NJU-INP 032/21, arXiv: 2101.12286 [hep-ph], Phys. Lett. B **815** (2021) 136158

Revealing pion and kaon structure via generalised parton distributions, Khépani Raya, Zhu-Fang Cui (崔著钫), Lei Chang (常雷), José-Manuel Morgado, Craig D. Roberts and José Rodriguez-Quintero, NJU-INP 051/21, e-Print: 2109.11686 [hep-ph]

- What do do in absence of any model-independent link
  between $e + p \to e' + V + p$ & $V + p \to V + p$?
- Increasingly many robust connections
  being drawn between EHM and the properties of pions and kaons
- Revealed in both phenomenological sketches and theoretical predictions
- Crucially, the links can be verified empirically
- Motivates new analyses of
  π- and K-meson
  generalized parton distributions (GPDs)

Revealing pion and kaon structure via generalised parton distributions, Khépani Raya, Zhu-Fang Cui (崔著钫), Lei Chang (常雷), José-Manuel Morgado, Craig D. Roberts and José Rodriguez-Quintero, NJU-INP 051/21, e-Print: 2109.11686 [hep-ph]

Mass-squared distributions - Nambu-Goldstone bosons

- Meson Mass-squared form factor, expressed via meson GPDs

$$\theta_2^{\mathsf{P}}(\Delta^2) = \int_{-1}^{1} dx\, x \times \left[H^u_{\mathsf{P}}(x,0,-\Delta^2;\zeta_{\mathcal{H}}) + H^{\bar{h}}_{\mathsf{P}}(x,0,-\Delta^2;\zeta_{\mathcal{H}})\right]$$

ζ_H = Hadron scale

- Stress-energy tensor, $T_{\mu\nu}$: $\langle \mathsf{P}(P_{\mathsf{P}})|T_{\mu\mu}|\mathsf{P}(P_{\mathsf{P}})\rangle = m_{\mathsf{P}}^2\, \theta_2^{\mathsf{P}}(\Delta^2=0) = m_{\mathsf{P}}^2$ $\quad \theta_2^P(\Delta^2=0) = 1$

  Mass-squared sum rule

- At ζ_H, all hadron properties carried by dressed-valence degrees-of-freedom

$$m_P^2\theta_2^P(0) = m_P^2[\theta_2^{P_u}(0;\zeta_H) + \theta_2^{P_{\bar{h}}}(0;\zeta_H)] = m_P^2[\langle x\rangle_{\zeta_H}^{P_u} + \langle x\rangle_{\zeta_H}^{P_{\bar{h}}}]$$

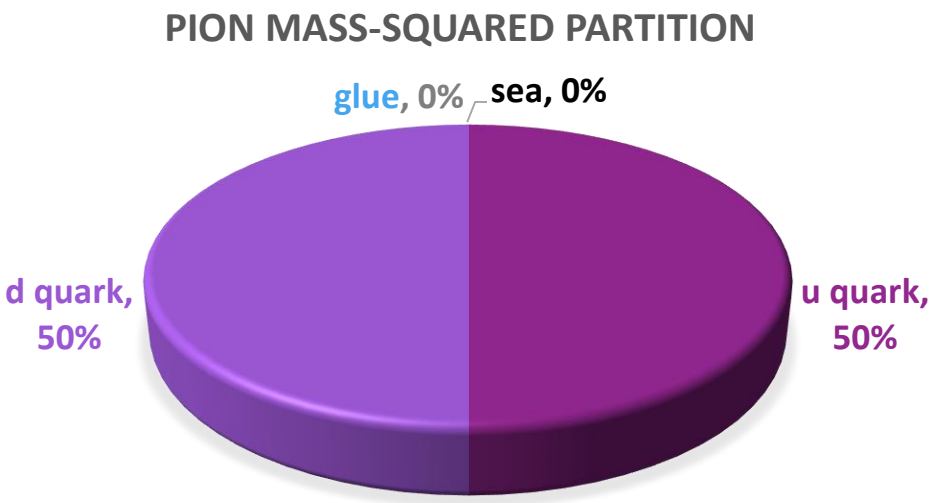
  Mass-squared fraction is given by the light-front momentum fraction associated with the parton class

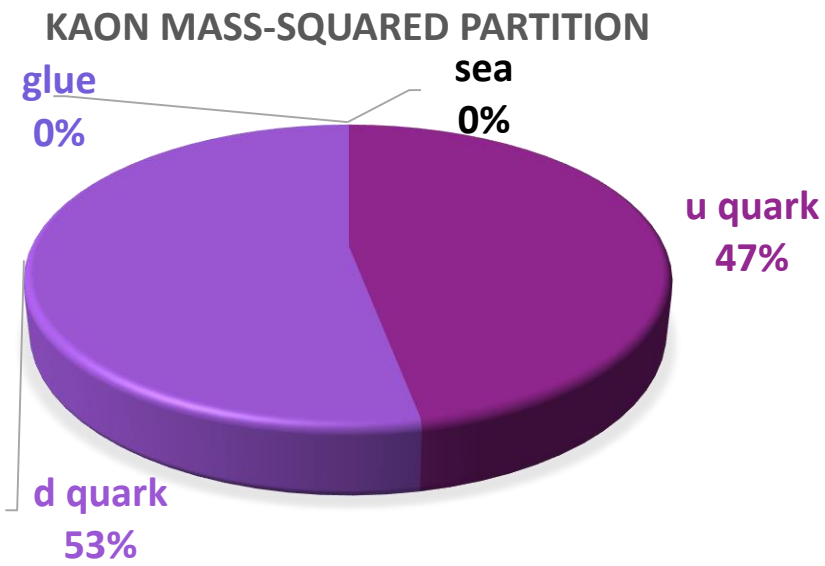
- At ζ_H:
  - π: valence u-quark 50% & valence $\bar{d}$ quark = 50%
  - K: valence u-quark 47% & valence $\bar{d}$ quark = 53%

Revealing pion and kaon structure via generalised parton distributions, Khépani Raya, Zhu-Fang Cui (崔著钫), Lei Chang (常雷), José-Manuel Morgado, Craig D. Roberts and José Rodriguez-Quintero, NJU-INP 051/21, e-Print: 2109.11686 [hep-ph]

Mass-squared distributions - Nambu-Goldstone bosons

- Hadron scale: $\zeta = \zeta_H$





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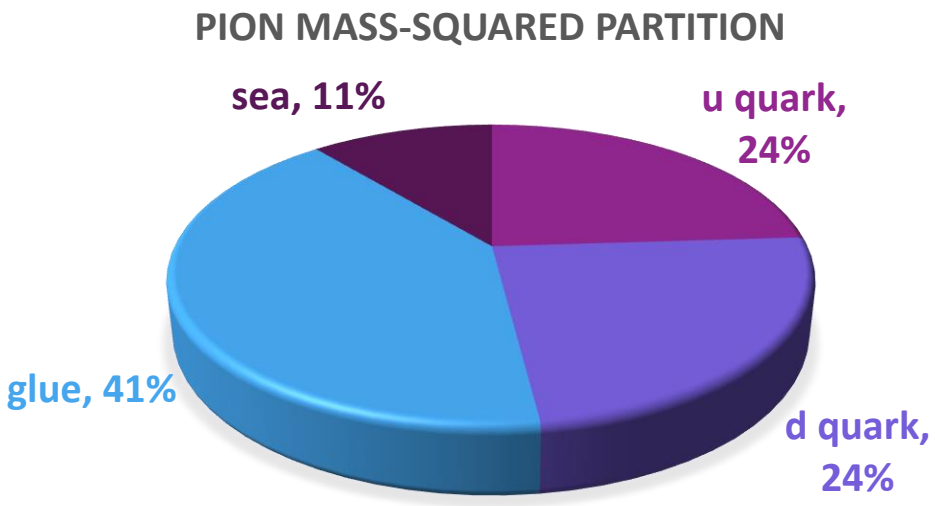
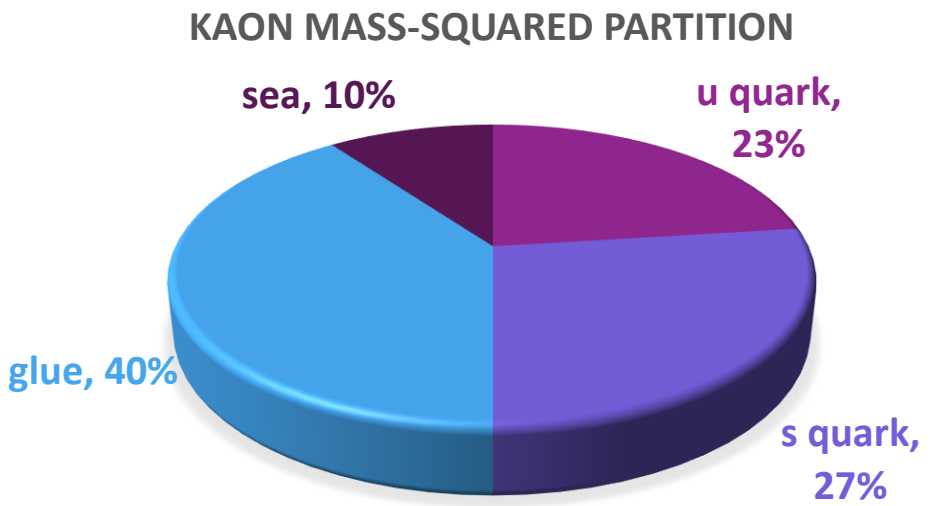
Mass-squared distributions - Nambu-Goldstone bosons

- All-orders evolution to $\zeta = \zeta_2 := 2$ GeV

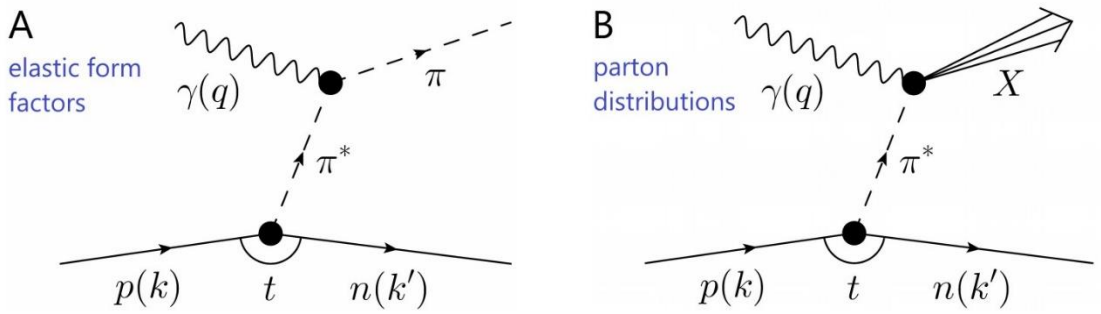




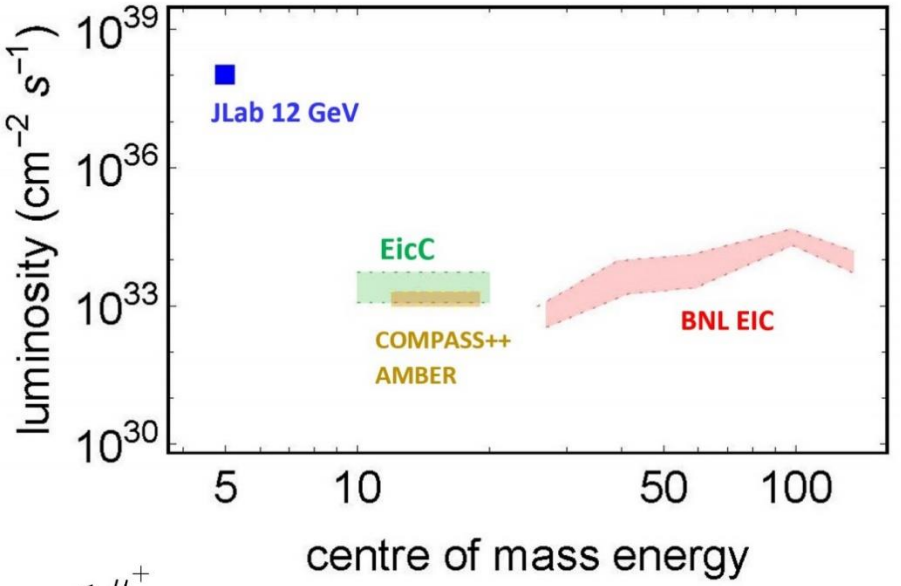
Get off the ground!

- *The Message*
  - The ground state proton is not enough
  - Ground state of the hydrogen atom did not give us QED
  - Studies of the proton alone cannot reveal all the wonders of QCD,
    if QCD is truly the theory of strong interactions in the Standard Model
  - Modern and planned high-luminosity facilities
    provide unprecedented opportunities
    to move beyond the 100-year focus
    on the structure of just one (or two = neutron) hadron(s)
  - *How much richer will be our store of knowledge*
    once insights into the full array of Nature's hadrons is in our hands!

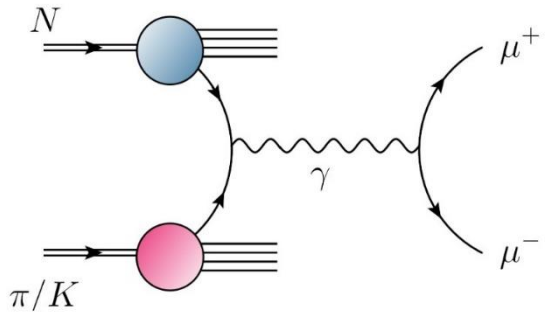
Era of Meson Targets



- JLab & EIC & EicC
  - High luminosity electron (+ ion) beams
  - Access to meson targets via the Sullivan Process,
    i.e., a baryon's "meson cloud"



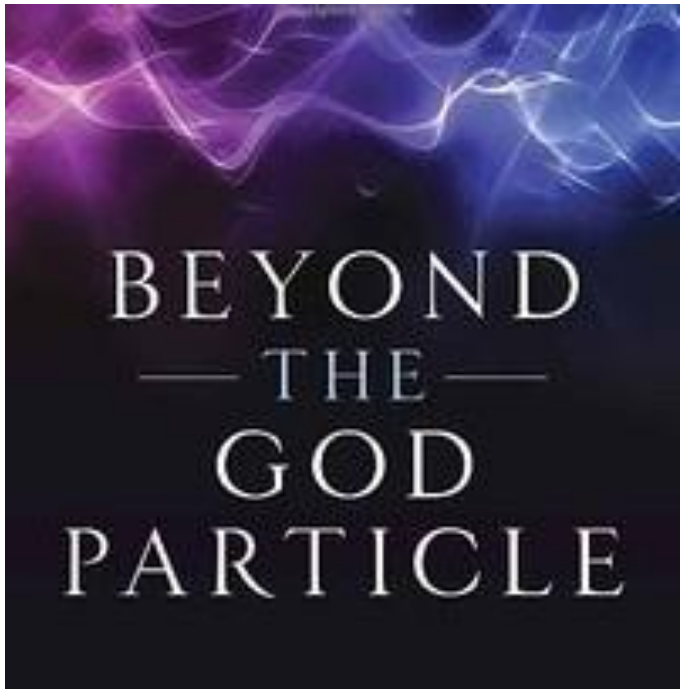
- AMBER @ CERN SPS
  - High-intensity beams of pions
    ($\gtrsim 10^7$ pions/sec in Phase-1 = approved)
    and kaons (5×10^6 kaons/sec Phase-2 = proposal being prepared)
  - Drell-Yan, J/ψ production, prompt photon production
    … from proton and nuclear targets



Meson Structure Worldwide Plans and Goals

- ✓ Letter of Intent: A New QCD facility at the M2 beam line of the CERN SPS. This document covers all ideas for future experiments as of January 2019.
- ✓ Proposal for Phase-1: COMPASS++/AMBER: Proposal for Measurements at the M2 beam line of the CERN SPS Phase-1: 2022-2024. This document covers the three phase-1 experiments (start in 2022).
- ✓ *Pion and Kaon Structure at the Electron-Ion Collider*, Arlene C. Aguilar *et al.*, NJU-INP 001/19, arXiv:1907.08218 [nucl-ex], Eur. Phys. J. A 55 (2019) 190/1-15
- ✓ *Strong QCD from Hadron Structure Experiments*, S. J. Brodsky *et al.*, arXiv:2006.06802 [hep-ph], Int. J. Mod. Phys. E 29 (2020) 08, 2030006/1-122
- ✓ *Selected Science Opportunities for the EicC,* Xurong Chen, Feng-Kun Guo, Craig D. Roberts and Rong Wang, NJU-INP 022/20, arXiv:2008.00102 [hep-ph], Few Body Syst. 61 (2020) 4, 43/1-37. Invited contribution to the Special Issue: "New Trends in Hadron Physics: a Few-Body Perspective"
- ✓ *Insights into the Emergence of Mass from Studies of Pion and Kaon Structure*, Craig D. Roberts, David G. Richards, Tanja Horn and Lei Chang, NJU-INP 034/21, arXiv: 2102.01765 [hep-ph], Prog. Part. Nucl. Phys. 120 (2021) 103883/1-65
- ✓ *Electron-Ion Collider in China,* D. P. Anderle *et al.*, NJU-INP 035/21, arXiv:2102.09222 [nucl-ex], Front. Phys. (Beijing) 16 (2021) 6, 64701
- ✓ *Revealing the structure of light pseudoscalar mesons at the Electron-Ion Collider,* John Arrington *et al.*, NJU-INP 036/21, arXiv: 2102.11788 [nucl-ex], J. Phys. G 48 (2021) 7, 075106

Epilogue



- Nature has two sources of mass
  - Higgs mass-generating mechanism = understood
  - Phenomenon of Emergent Hadron Mass = much to learn
- EHM (possibly/probably?) lies within the Standard Model,

  i.e., in strong QCD
- Basic predictions:
  - Gluons acquire mass ⇒ running coupling saturates on infrared domain, restoring approximate conformal behaviour
  - Enigmatically, the unusually light Nambu-Goldstone bosons provide the clearest windows onto the Emergence of Mass in Nature
- With modern and on-the-horizon facilities having the capacity to deliver practical pion and kaon “targets”, science can *finally* move beyond the proton and study an entirely different form of hadron matter = the mesons without which observable Universe could not exist

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Thankyou
非禮勿言
非禮勿聽