Dissecting Hadrons in Continuum QCD Approach

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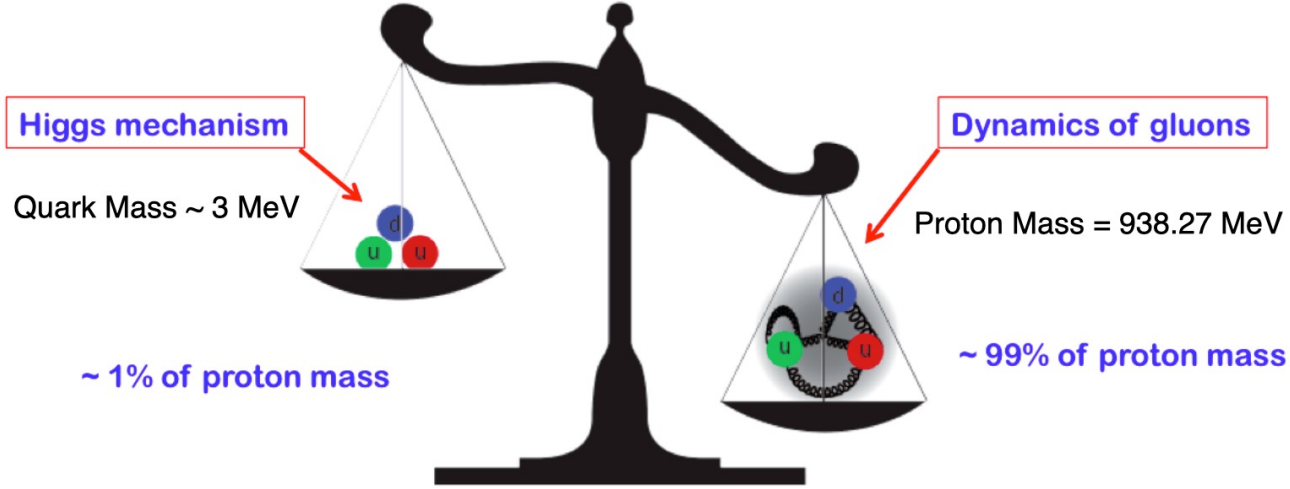
QCD: Facts and Challenges

QCD is characterized by two **emergent** phenomena: **confinement** and dynamical generation of mass (**DGM**).

$$\mathcal{L}_{\rm QCD} = \sum_{j=u,d,s,\ldots} \bar{q}_j[\gamma_\mu D_\mu + m_j]q_j + \tfrac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu},$$
$$D_\mu = \partial_\mu + ig\tfrac{1}{2}\lambda^a A^a_\mu\,,$$
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu + \partial_\nu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu,$$

- Quarks and gluons do not reach detectors.
- Formation of color-singlet bound states: "**Hadrons**" mesons, baryons, tetraquarks, molecules

- Emergence of hadron masses (EHM) from QCD **dynamics**

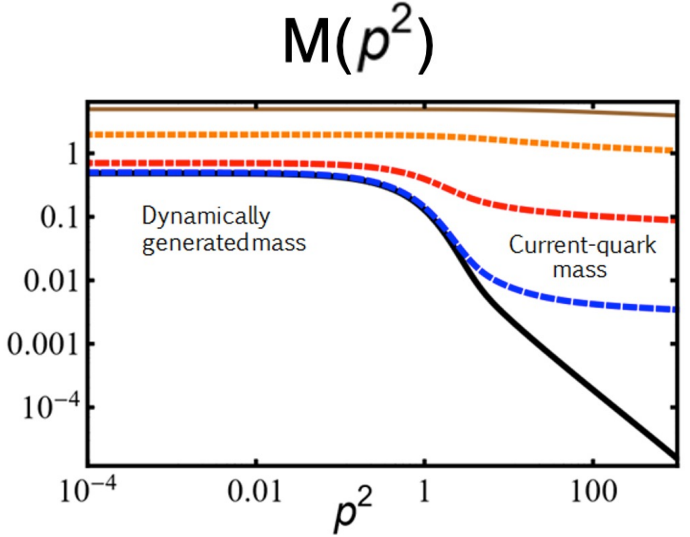


QCD: Current Understanding and Challenges

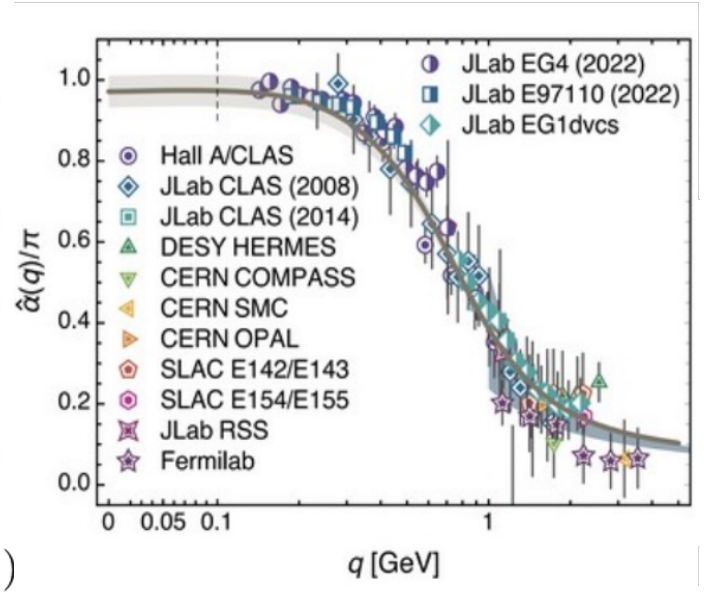
Origins of **confinement** and **dynamical mass generation** can be traced back to the Green functions of **quarks** and **gluons**.

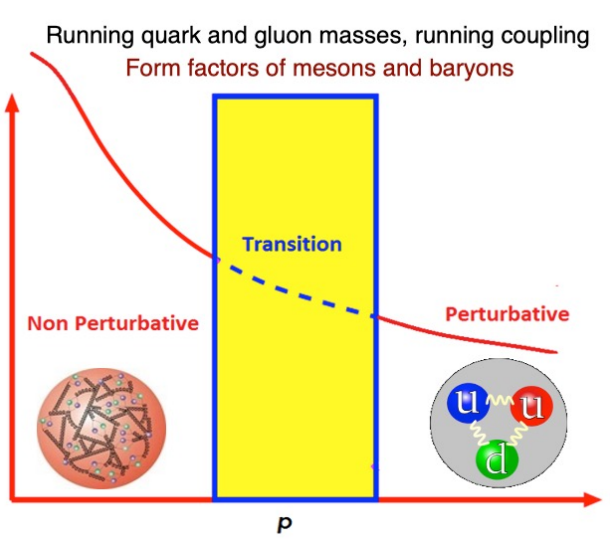
These emergent phenomena of **QCD**, non-existent in perturbation theory are naturally linked to the infrared enhancement of the **strong running coupling**.

The effects of of the pattern of **dynamical mass generation** are traceable in the **Q^2 evolution** of the **meson** and **baryon form factors** explored and planned in the **JLab** and the **EIC**.



$$S_f^{-1}(p) = Z_f^{-1}(p^2)(i\gamma \cdot p + \mathbf{M_f(p^2)})$$





QCD – Schwinger-Dyson Equations

Gauge Technique – Non Perturbative Solutios

- A. Salam, R. Delbourgo, Phys. Rev. 135 (1964) 6, B1398-B1427.

DCSB - Non-perturbative QED

- P.I. Fomin, V.A. Miransky, Phys. Lett. B64 (1976) 166-168.

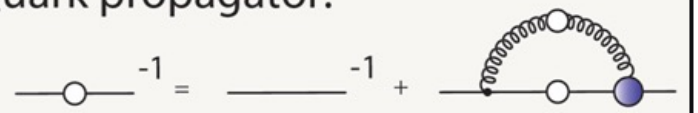
DCSB – Non-abelian Gauge Theories

- V. Miransky, V. Gusynin, Y. Sitenko, Phys. Lett. B100 (1981) 157-162

DCSB – MT Model - Vector Mesons

- P. Maris, P. Tandy, Phys. Rev. C60 (1999)

Quark propagator:



$$S(p^2,\mu^2) = \frac{Z(p^2,\mu^2)}{i\,\gamma\cdot p + M(p^2)}$$

PHYSICAL REVIEW VOLUME 135, NUMBER 6B 21 SEPTEMBER 1964

Renormalizable Electrodynamics of Scalar and Vector Mesons. II

ABDUS SALAM*
Imperial College, London, England

ROBERT DELBOURGO†
Imperial College, London, England

The "gauge technique" for solving field theories introduced in an earlier paper is applied to scalar and vector electrodynamics.

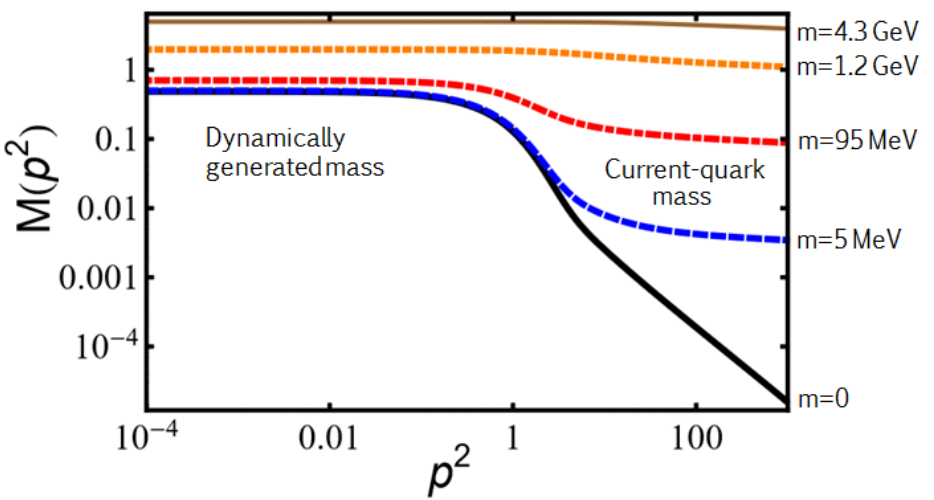
A. Dyson-Schwinger Set;

For a typical 3-field (e.g., electron-photon) interaction the well-known Dyson equations

$$S^{-1}=Z_2S_0^{-1}+Z_1e^2\int\Gamma S\Gamma_0 D \qquad \text{(I.1)}$$

$$D^{-1}=Z_3D_0^{-1}+Z_1e^2\int\Gamma S\Gamma_0 S \qquad \text{(I.2)}$$

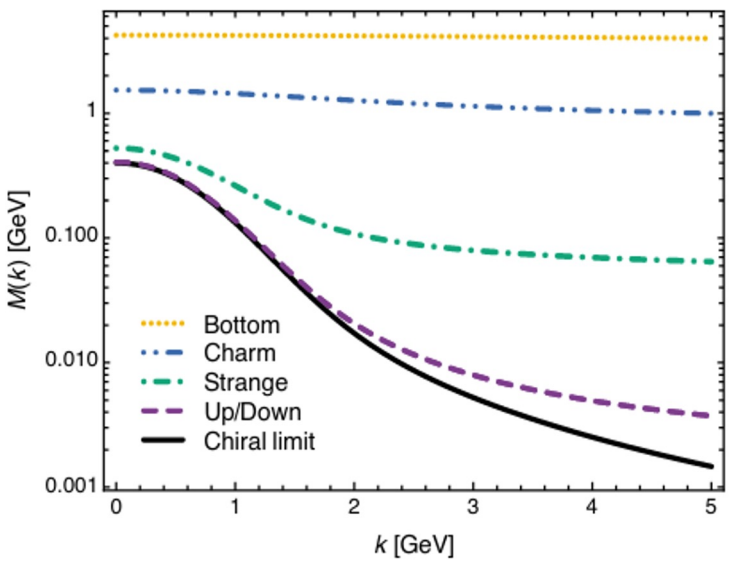
SDE: electron propagator

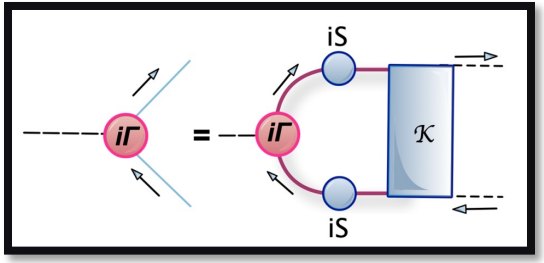


π: Bound State and Goldstone Boson

The pattern of **dynamical chiral symmetry breaking** and the **Bethe-Salpeter amplitude** to be computed by solving the **Bethe-Salpeter equation**.

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





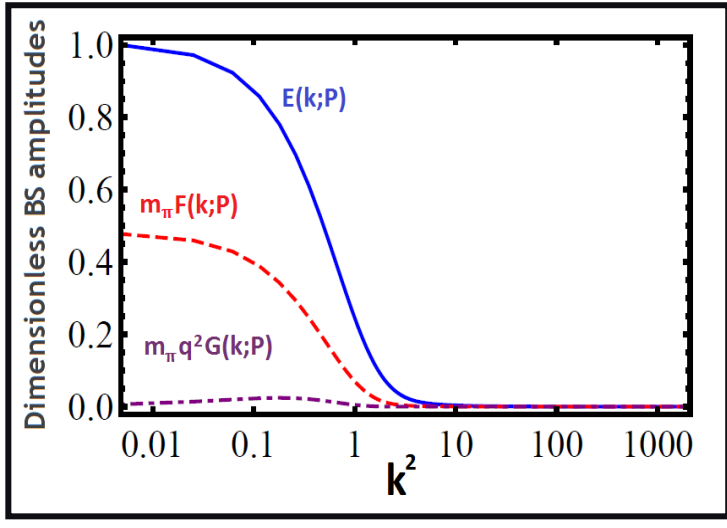
$$S(p) = \frac{1}{i\gamma\cdot p\, A(p^2) + B(p^2)}$$

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

$$F_R(k;0) + 2 f_\pi F_\pi(k;0) = A(k^2)$$

$$G_R(k;0) + 2 f_\pi G_\pi(k;0) = 2A'(k^2)$$

$$H_R(k;0) + 2 f_\pi H_\pi(k;0) = 0$$



π: Probing Quarks with Photons

In studying the **elastic form factors**, it is the **photon** which probes the **dressed quarks** inside the **bound states**, highlighting the importance of the **quark-photon vertex**.

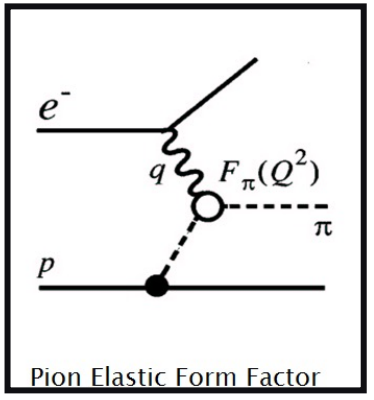
Gauge covariance (WTI,TTI, LKFT), kinematic singularities, perturbation theory, multiplicative renormalizability

$$\Gamma^L_\mu(p,k,q) = \sum_{i=1}^{4} \lambda_i \, L^i_\mu(p,k)$$

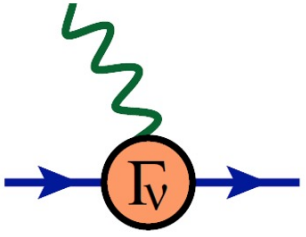
$$\begin{aligned}
L^1_\mu &= \gamma_\mu \\
L^2_\mu(p,k) &= (\not{p} + \not{k})(p+k)_\mu \\
L^3_\mu(p,k) &= -(p+k)_\mu \\
L^4_\mu(p,k) &= -\sigma_{\mu\nu}\,(p+k)^\nu
\end{aligned}$$

$$\Gamma^T_\mu(p,k,q) = \sum_{i=1}^{8} \tau_i(p^2,k^2,q^2) T^i_\mu(p,k)$$

$$\begin{aligned}
T^1_\mu &= p_\mu (k\cdot q) - k_\mu (p\cdot q)\,, \\
T^2_\mu &= [p_\mu (k\cdot q) - k_\mu (p\cdot q)]\,(\not{p} + \not{k})\,, \\
T^3_\mu &= q^2 \gamma_\mu - q_\mu \not{q}\,, \\
T^4_\mu &= q^2\,[\gamma^\mu\,(\not{k} + \not{p}) - (k+p)^\mu] \\
&\quad +2(k-p)^\mu \sigma_{\nu\lambda}\, p^\nu k^\lambda\,, \\
T^5_\mu &= -\sigma_{\mu\nu}\, q^\nu\,, \\
T^6_\mu &= \gamma_\mu (p^2 - k^2) + (p+k)_\mu \not{q}\,, \\
T^7_\mu &= \tfrac{1}{2}(p^2 - k^2)\,[\gamma_\mu(\not{p} + \not{k}) - (p+k)_\mu] \\
&\quad -(p+k)_\mu \sigma_{\nu\lambda}\, p^\nu k^\lambda\,, \\
T^8_\mu &= \gamma_\mu \sigma_{\nu\lambda}\, p^\nu k^\lambda - p_\mu \not{k} + k_\mu \not{p}\,.
\end{aligned}$$



Pion Elastic Form Factor

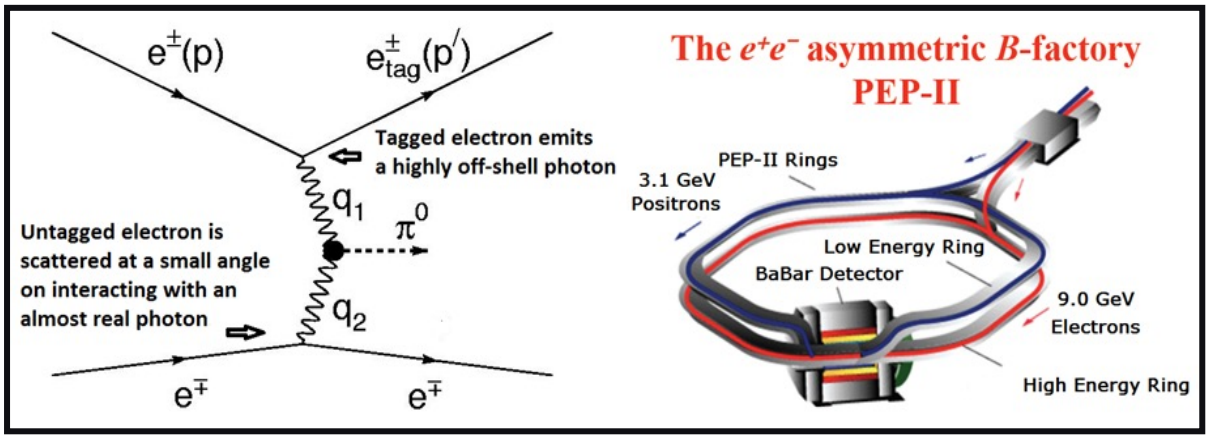


AB, R. Bermudez, L. Chang, C.D. Roberts
Phys. Rev. C85, 045205 (2012)

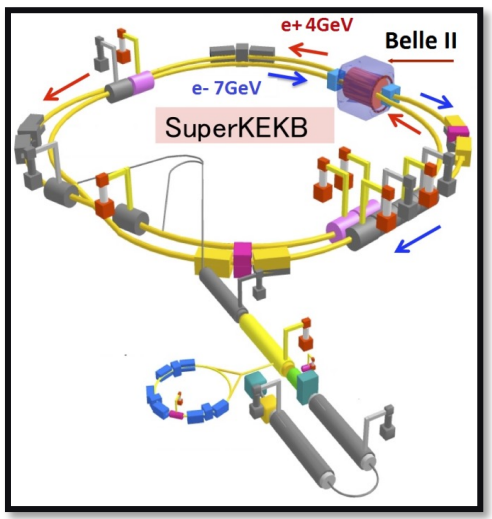
L. Albino, AB, L. Gutiérrez, B. El Bennich, E. Rojas
Phys. Rev. D100 054028 (2019)
V. Banda, AB, Phys. Rev. D 107 (2023) 7, 073008

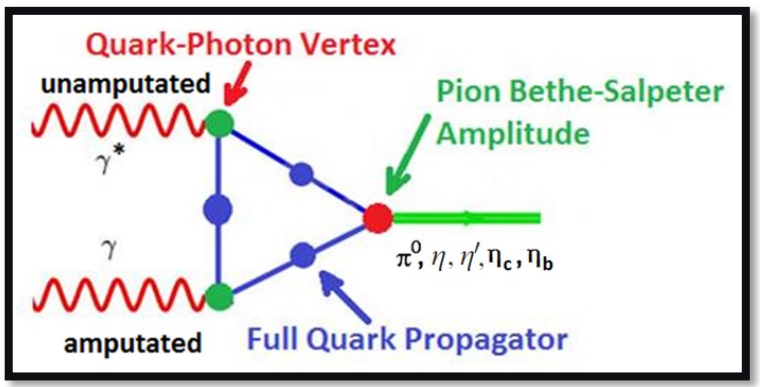
J. Roberto Lessa, F. Serna, B. El-Bennich, AB,
O. Oliveira, Phys. Rev. D 107 (2023) 7, 074017

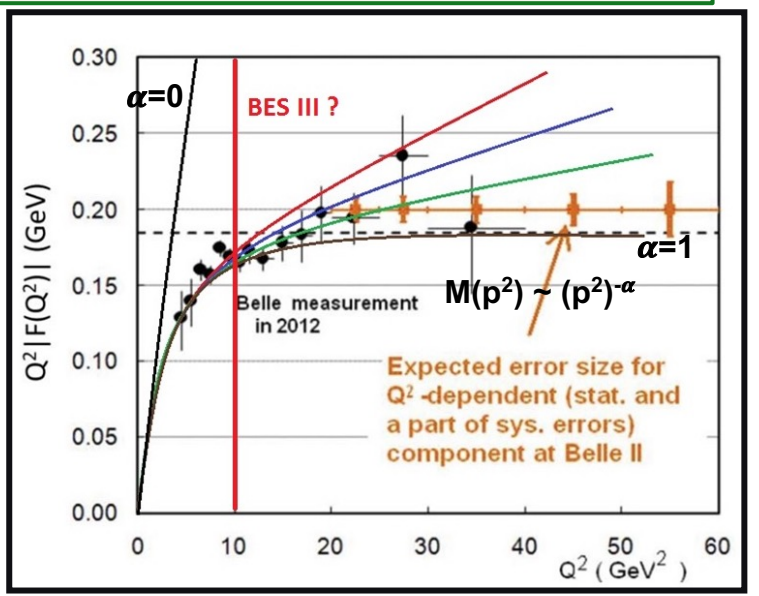
$\pi^0 \rightarrow \gamma^*\gamma$ Transition Form Factor



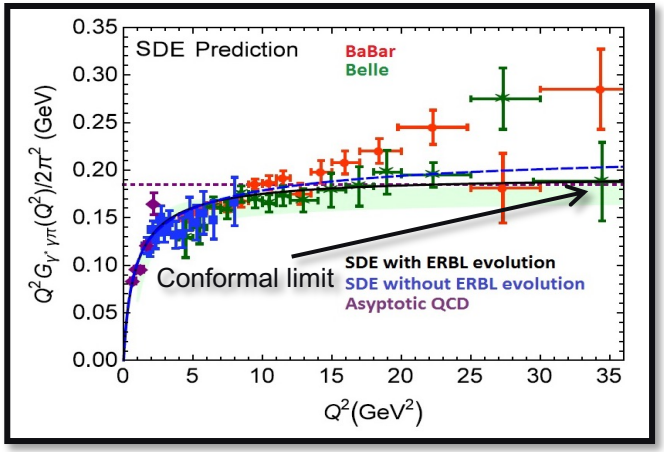
The pattern of **dynamical chiral symmetry breaking** dictates the **Q^2 evolution** of the **transition form factor**. Experiment and **asymptotic QCD** for largest Q^2 provide verifications.

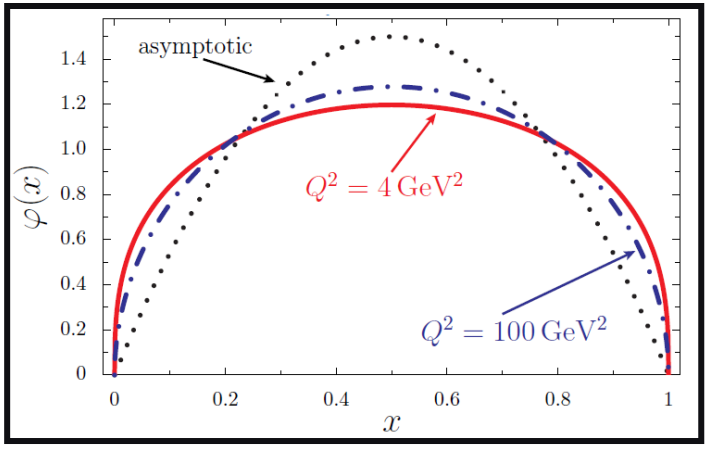


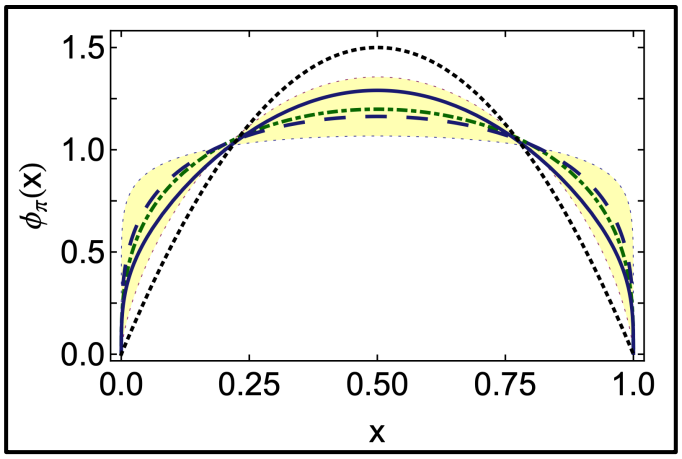




$\pi^0 \longrightarrow \gamma^*\gamma$ Transition Form Factor







Satisfies abelian anomaly and agrees with the prediction of **asymptotic QCD**.

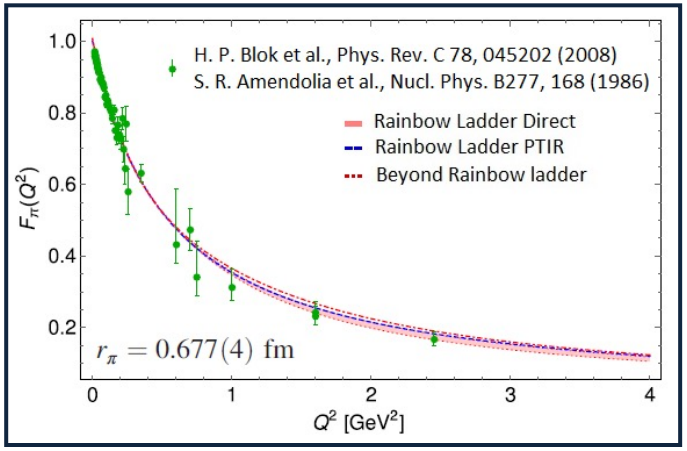
Agrees well with experiment from low to intermediate range of momenta and favors Belle results.

The **distribution amplitude (PDA)** is broad and concave at the **hadronic** scale.

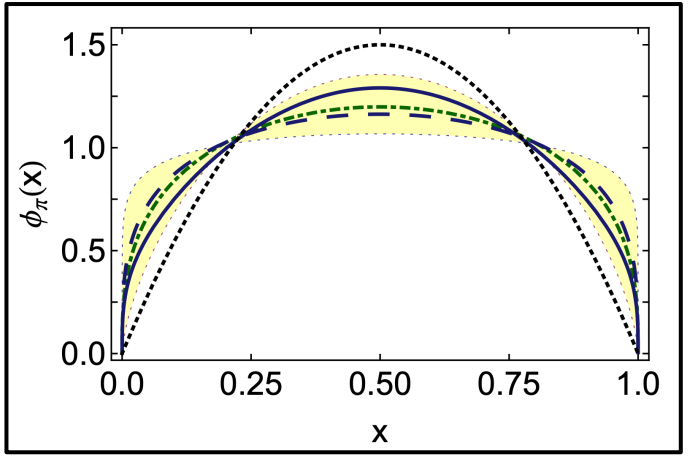
Within an error band stemming from the construction of the **PDA** from the **lattice moments**, it is in good agreement.

K. Raya, et. al. Phys. Rev. D 93 (2016) 7, 074017, L. Chang, et. al., Phys. Rev. Lett. 110 (2013) 13, 132001,
I.C. Cloet, et. al. Phys. Rev. Lett. 111 (2013) 092001, RQCD collaboration, JHEP 08 (2019) 065, JHEP 11 (2020) 037

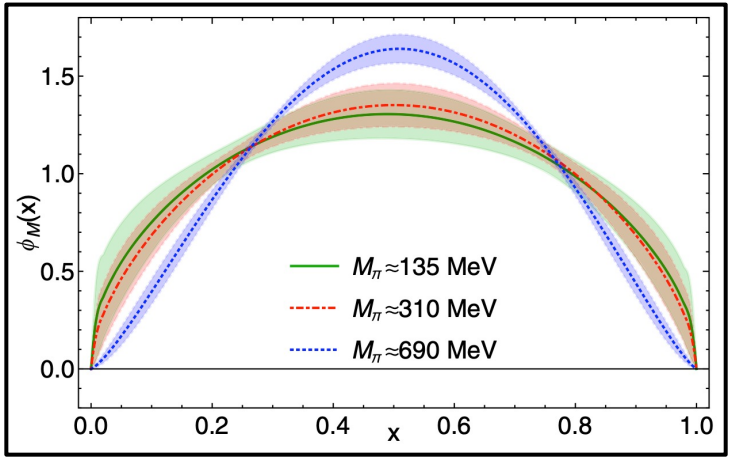
π Electromagnetic Form Factor



A. Miramontes et. al., Phys. Rev. D 105 (2022) 7, 074013



I.C. Cloet, et. al. Phys. Rev. Lett. 111 (2013) 092001



R. Zhang, et. al., Phys. Rev. D 102 (2020) 9, 094519

The **electromagnetic form factor** of π is central to the Jlab and planned EIC research.

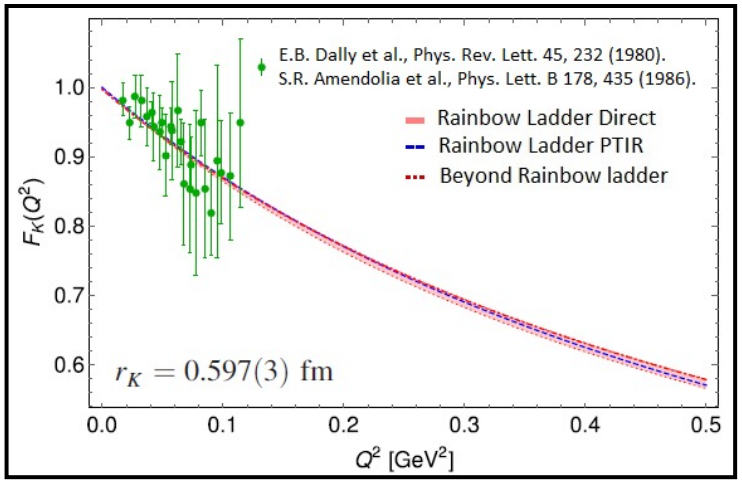
Jefferson Lab: Lattice Hadron Physics Collaboration, Frederic D.R. Bonnet, et. al. Phys. Rev. D 72 (2005) 054506

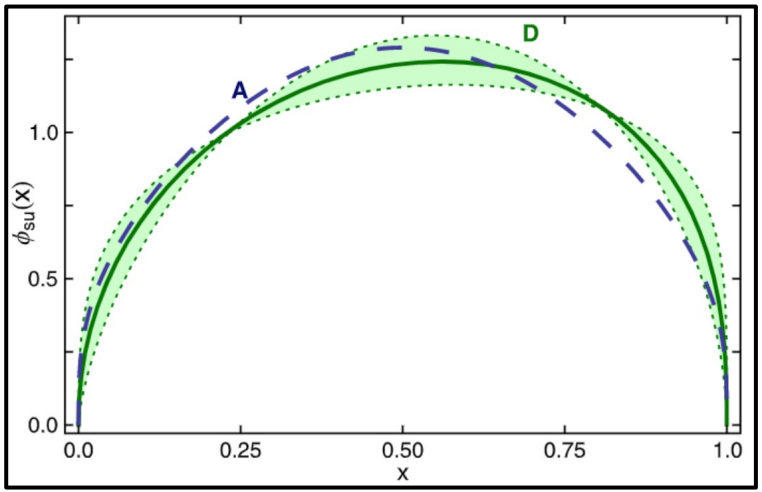
Our computation is consistent with the **valence quark distribution amplitude (PDA)** which is broad and concave at the **hadronic** scale.

The results agree with earlier computation of the **electromagnetic form factors** of π.

L. Chang, I.C. Cloet, C.D. Roberts, S.M. Schmidt, P. Tandy, Phys. Rev. Lett. 111 (2013) 14, 141802

K Electromagnetic Form Factor





A. Miramontes et. al., Phys. Rev. D 105 (2022) 7, 074013

J. Segovia et. Al. , Phys. Lett. B 731 (2014) 13-18

The **electromagnetic form factors** of π and **K** can be measured till $Q^2 \sim 8$ GeV^2 (10-40 GeV^2) and 5 GeV^2 (10-20 GeV^2) respectively in the **12 GeV** upgrade of **JLab (EIC)**.

A. Aguilar, Eur. Phys. J. A55 (2019) 10, 190

The results obtained from the **Schwinger-Dyson equations** appear robust under the calculational scheme employed and ingredients used as in the computation of the **transition form factors** and the **distribution amplitudes** of mesons.

π and K Form Factors: Probing the Standard Model

A muon with spin s has a **magnetic moment**: $\mu = g \frac{e}{2m} s$

The factor **g** is called the gyro-magnetic factor. The **Dirac equation** for a charged elementary fermion with spin 1/2 implies **g = 2**.

The **anomalous magnetic moment** is the deviation from g = 2, parameterized by $a_\mu = (g-2)/2$.

It appears due to radiative corrections. **Renormalization** of **QED** was established in 1943 and 1947-1948 by Tomonaga, Schwinger and Feynman.

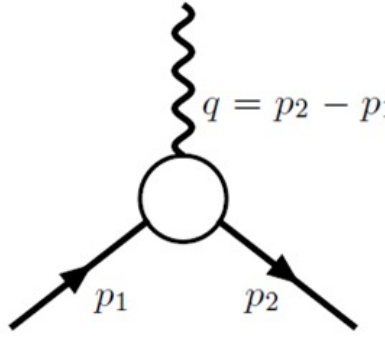
The leading contribution to a_μ, calculated by Schwinger in 1949, is: $a_\mu = \frac{\alpha}{2\pi}$

The **amplitude** of a muon scattering off an external electromagnetic field A is: ($q=p_2-p_1$):

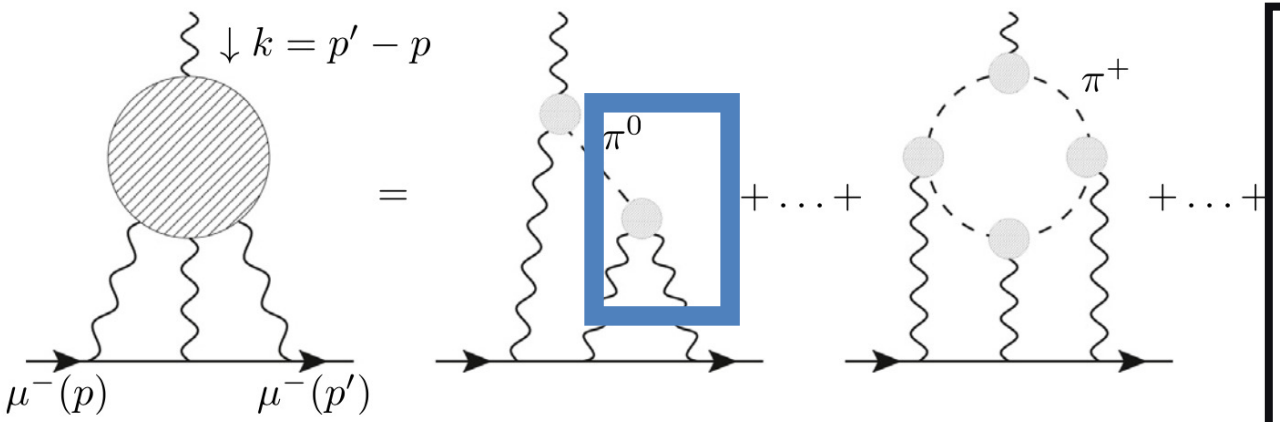
$$\mathcal{M} = -ie\langle \mu_{p2}|J^\mu(0)|\mu_{p1}\rangle A_\mu(q)$$

$$\langle \mu_{p2}|J^\mu(0)|\mu_{p1}\rangle = \bar{u}_{p2}\Gamma^\mu(p_2,p_1)u_{p1}$$

$$\Gamma^\mu(p_2,p_1) = \left[F_D(q^2)\gamma^\mu + F_P(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m}\right]$$

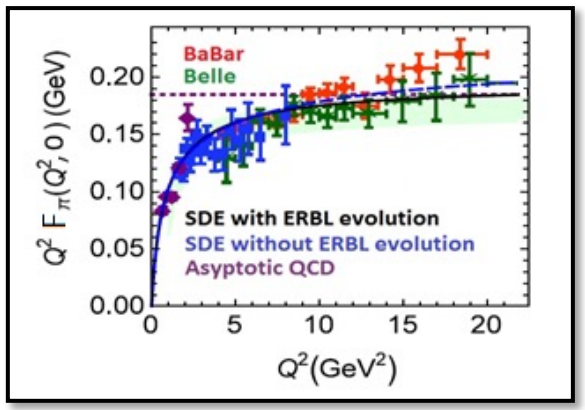


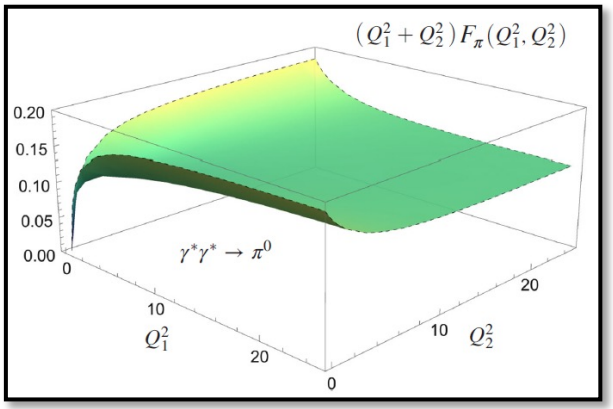
Neutral Pseudoscalar Pole Contributions



$$a_\mu^{\pi^0\text{-pole}} = (61.4 \pm 2.1) \times 10^{-11}$$
$$a_\mu^{\eta\text{-pole}} = (14.7 \pm 1.9) \times 10^{-11}$$
$$a_\mu^{\eta'\text{-pole}} = (13.6 \pm 0.8) \times 10^{-11}$$
$$a_\mu^{\eta_c\text{-pole}} = (0.9 \pm 0.1) \times 10^{-11}$$
$$a_\mu^{\eta_b\text{-pole}} = (0.0026 \pm 0.0001) \times 10^{-11}$$
$$a_\mu^{\text{PS-pole}} = (90.6 \pm 4.9) \times 10^{-11}$$

The transition form factor $\pi^0 \to \gamma^*\gamma$ extended to $\pi^0 \to \gamma^*\gamma^*$.





Dispersive methods:

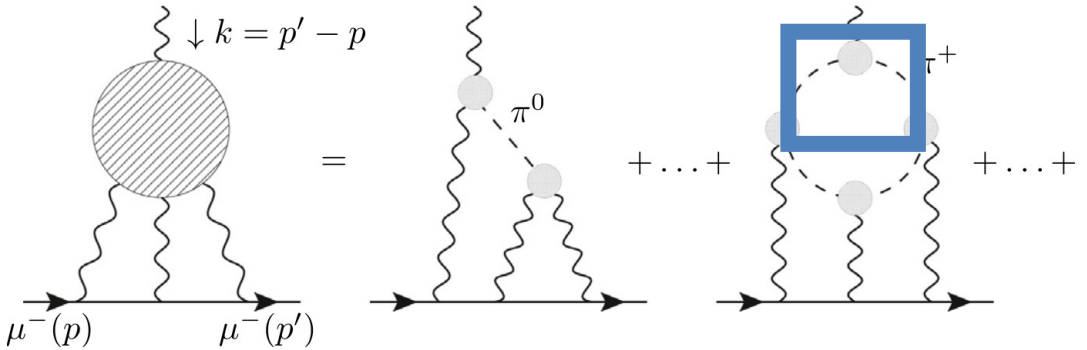
$$a_\mu^{\pi^0\text{-pole}} = 63.6(2.7) \times 10^{-11}$$
$$a_\mu^{\eta\text{-pole}} = 16.3(1.4) \times 10^{-11}$$
$$a_\mu^{\eta'\text{-pole}} = 14.5(1.9) \times 10^{-11}$$

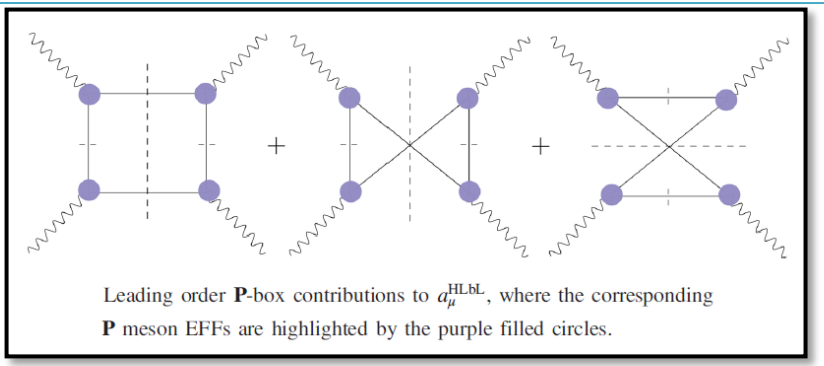
Lattice:

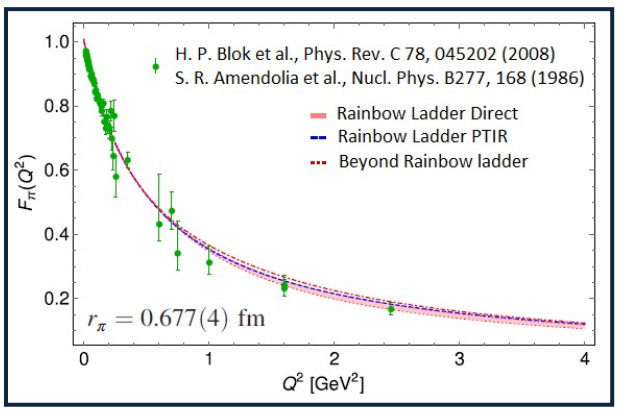
$$a_\mu^{\pi^0\text{-pole}} = 59.7(3.6) \times 10^{-11}$$

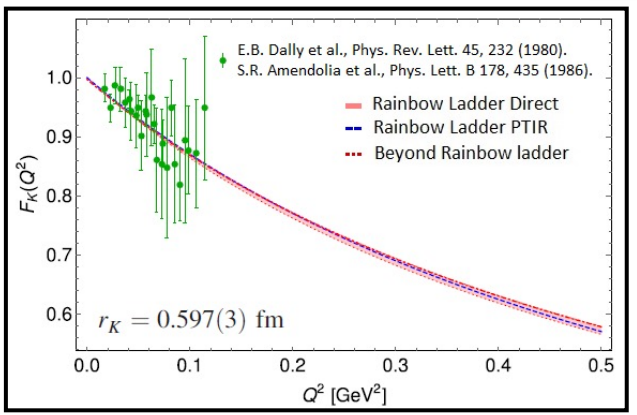
K. Raya, AB, P. Roig,
Phys. Rev. D 101 (2020) 7, 074021

π and K Form Factors : Probing the Standard Model




Leading order **P**-box contributions to $a_\mu^{\rm HLbL}$, where the corresponding **P** meson EFFs are highlighted by the purple filled circles.





A. Miramontes, AB, K. Raya, P. Roig, Phys. Rev. D 105 (2022) 7, 074013

Radial excitations of **π** and **K**:

A. Miramontes, et. al. in preparation (Preliminary)

$$a_\mu^{\pi_1-\text{box}} = (-3.2 \pm 0.6) \times 10^{-13}$$

$$a_\mu^{K_1-\text{box}} = -6.8 \times 10^{-14}$$

$$a_\mu^{K^+\text{-box,DSE}} = -0.48(2) \times 10^{-11}$$

Eichmann, et. al. Phys.Rev.D 101 (2020) 5, 054015

$$a_\mu^{\pi^\pm-\text{box}} = -(15.6 \pm 0.2) \times 10^{-11}$$

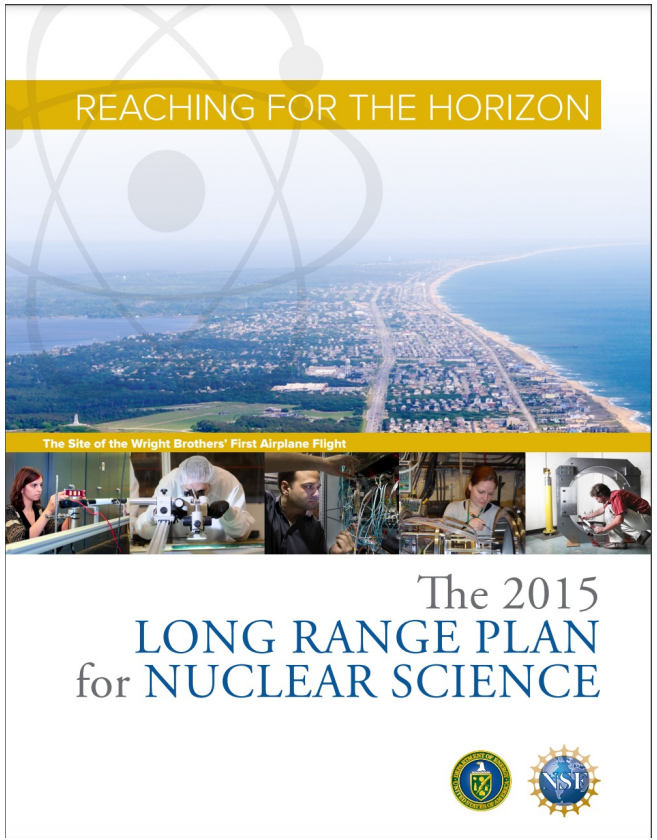
$$a_\mu^{K^\pm-\text{box}} = -(0.48 \pm 0.02) \times 10^{-11}$$

Dispersive methods:

$$a_\mu^{\pi\text{-box}} = -15.9(2) \times 10^{-11}$$

$$a_\mu^{K^+\text{-box,VMD}} = -0.50 \times 10^{-11}$$

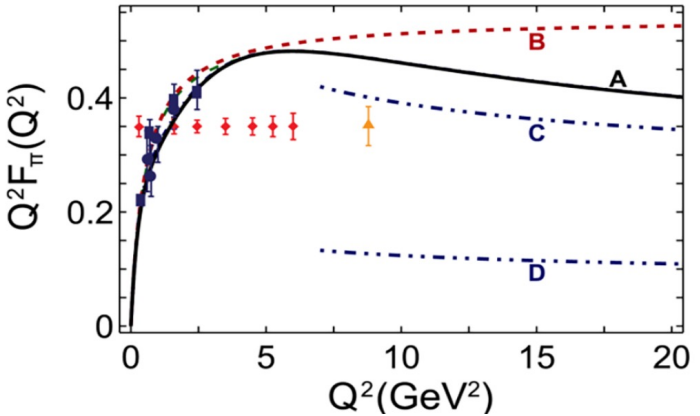
π Form Factor at Large Q^2

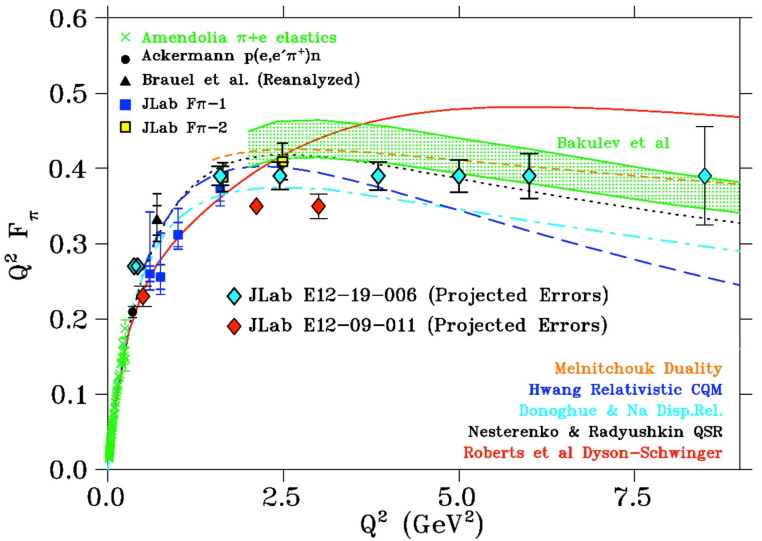


The study of the **pion form factor** is one of the **flagship goals** of the **JLab 12-GeV upgrade**… regime in which the phenomenology of **QCD** begins a **transition** from **large-** to **short-distance** scale behavior.

The **pion form factor** can potentially be measured till **Q^2 ~ 6-8** in the **12 GeV** upgrade of the **JLab**.

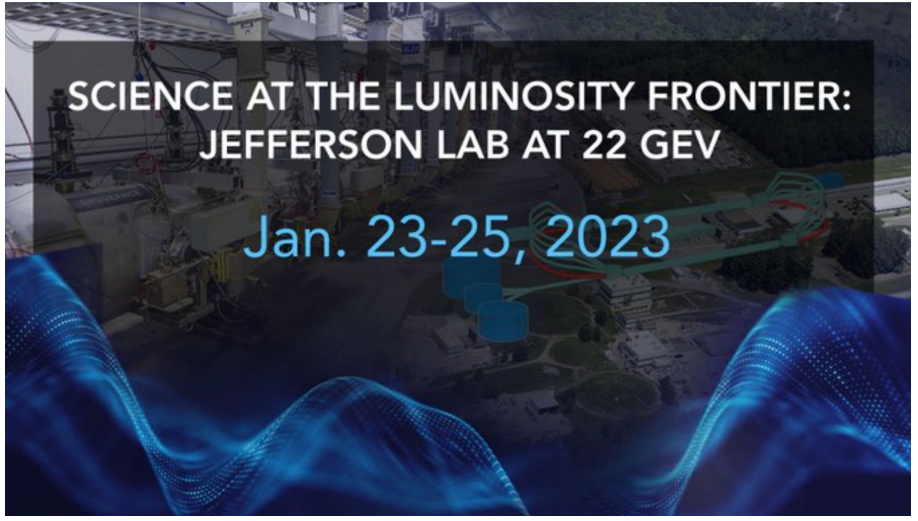
Courtesy Garth Huber

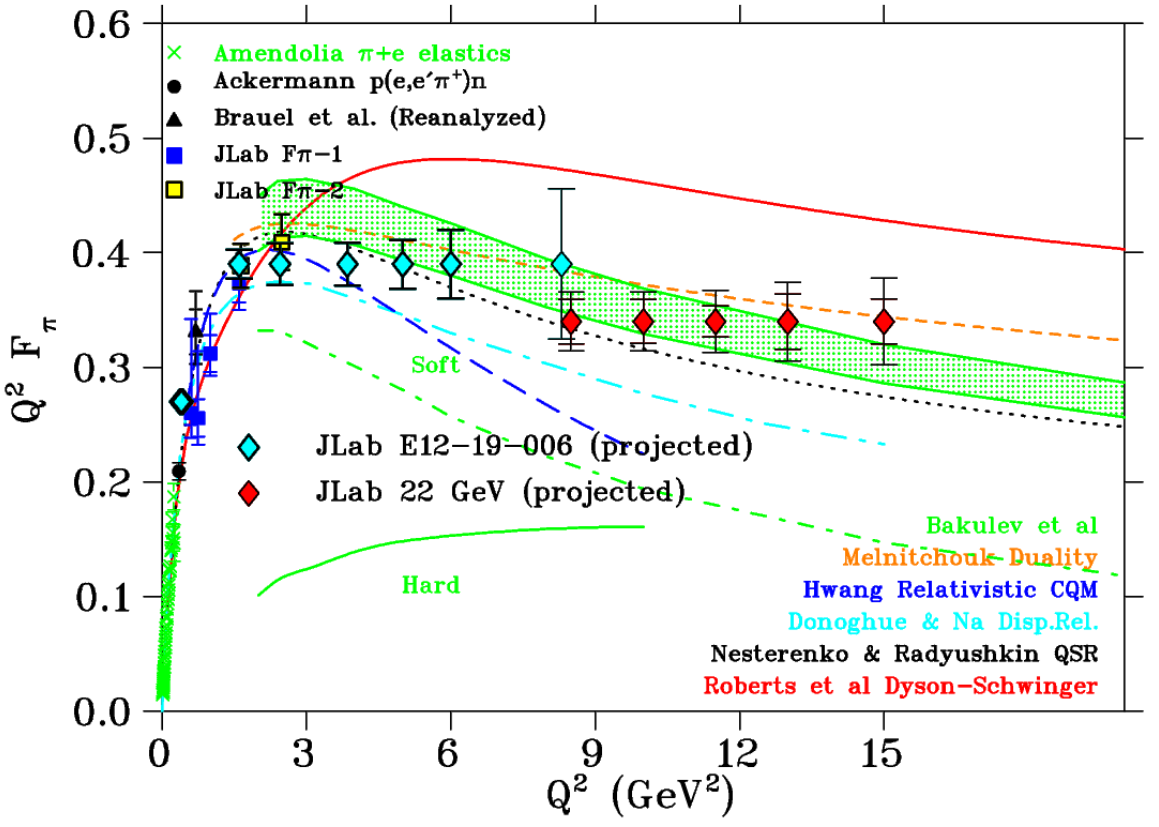




π Form Factor at Large Q^2

With a potential and desirable next **22-GeV** upgrade of the **JLab**, the **pion electromagnetic form factor** could be measured till **Q^2 ~ 15 GeV^2**.



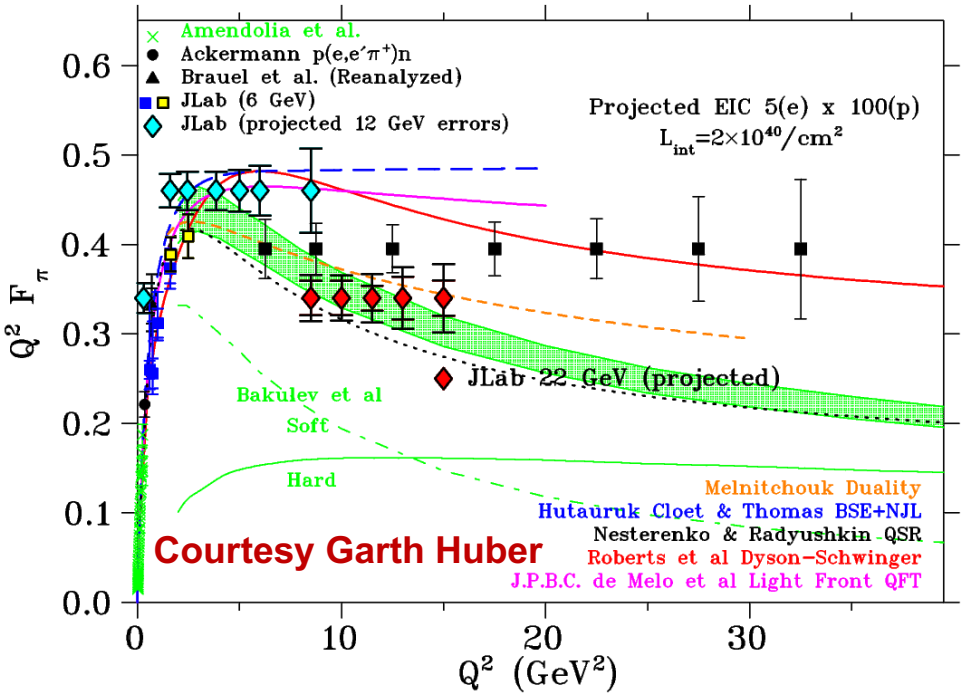


Courtesy Garth Huber

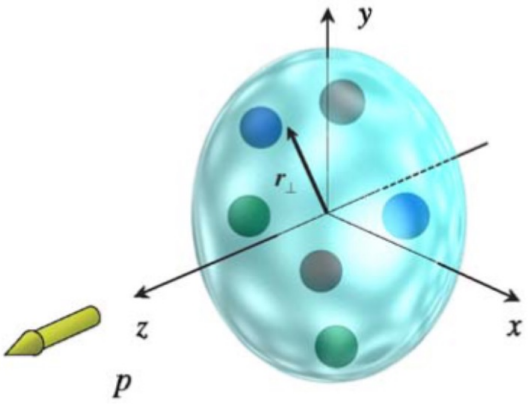
π and K Form Factor at Large Q^2

Science Question: Can we get quantitative guidance on the **emergent pion mass** mechanism?
Key measurement: **Pion form factor** data for **Q^2: 10-40 GeV^2**.

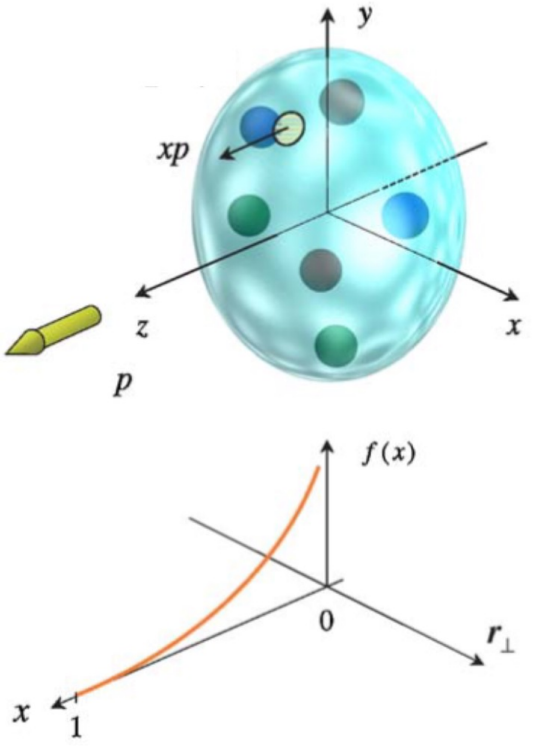
Science Question: How much interference is between emergent and Higgs mass mechanism?
Key measurement: **Kaon form factor** data for **Q^2: 10-20 GeV^2**.



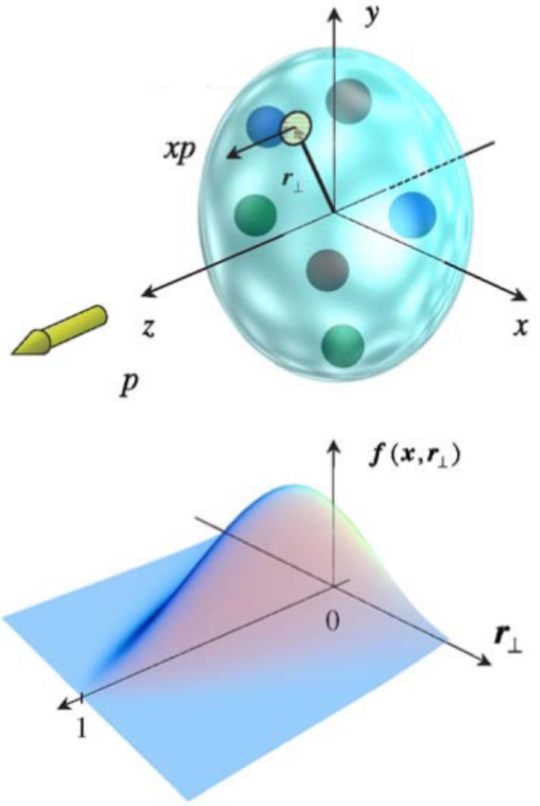
π and K: Towards a 3-Dimensional Picture



Fourier transform of the elastic form factor

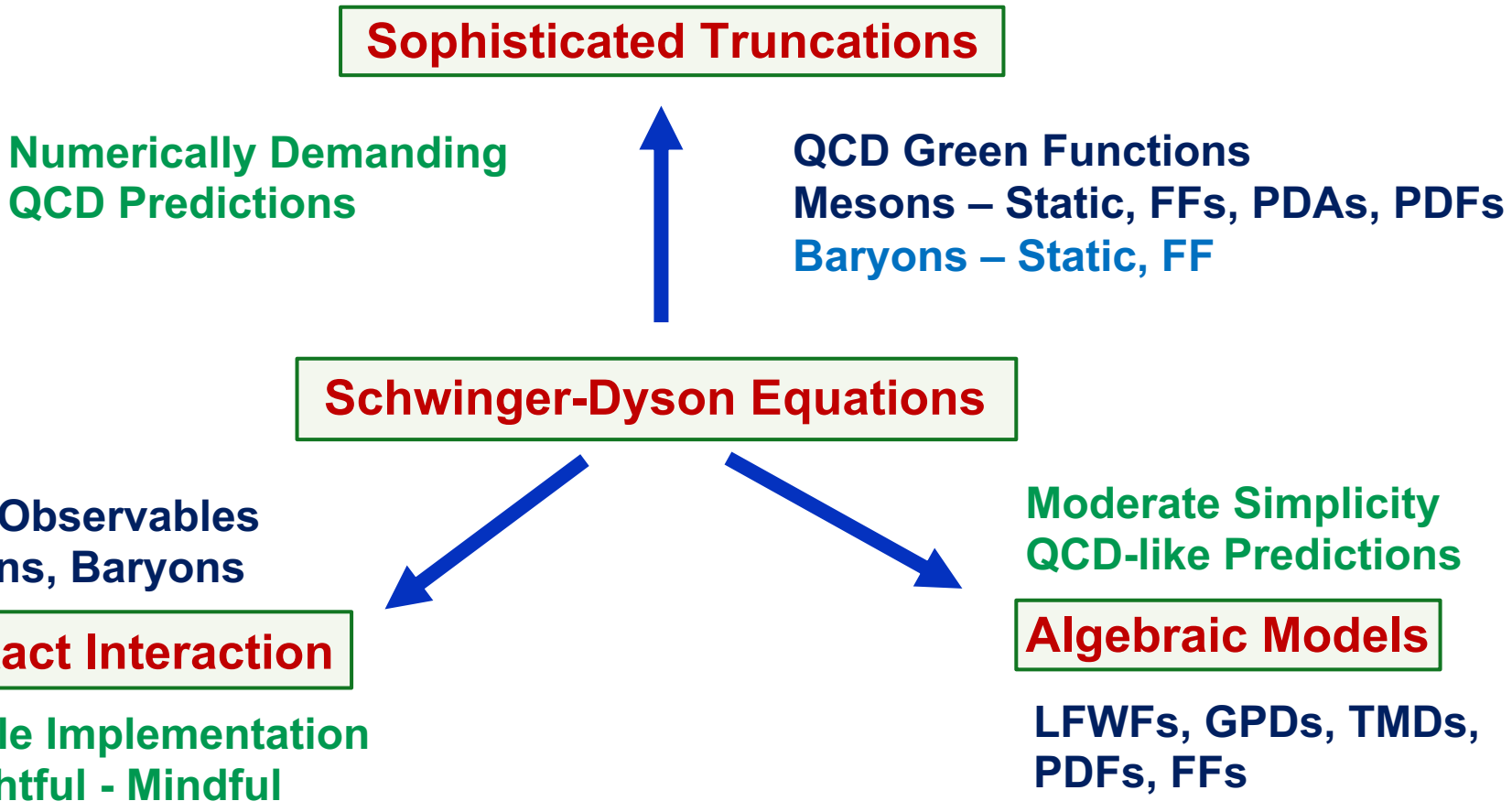


Parton Distribution



Skew-less Generalized Parton Distribution

Towards Algebraic Models



The Algebraic Model (AM)

- It retains the **constant term** from original models, setting it to M_q.
- There is a **term linear** in **w** with the coefficient $(M_h^2 - M_q^2)$. For same **flavored quarks**, it ceases to contribute by construction.
- There is a **quadratic term w^2** with coefficient m_M^2. The condition

$$|M_{\bar{h}} - M_q| \leq m_{\mathrm{M}} \leq M_{\bar{h}} + M_q$$

- It guarantees the **positivity** of

$$\Lambda^2(w)$$

The quark propagator:

$$S_{q(\bar{h})}(k) = [-i\gamma \cdot k + M_{q(\bar{h})}]\Delta(k^2, M^2_{q(\bar{h})})$$

$$\Delta(s,t) = (s+t)^{-1}$$

Bethe-Salpeter Amplitude:

$$n_{\mathrm{M}}\Gamma_{\mathrm{M}}(k,P) = i\gamma_5 \int_{-1}^{1} dw\, \rho_{\mathrm{M}}(w)[\hat{\Delta}(k_w^2, \Lambda_w^2)]^{\nu}$$

$$\hat{\Delta}(s,t) = t\Delta(s,t), \quad k_w = k + (w/2)P$$

$M_{q(\bar{h})}$ is constituent quark mass for a given flavor

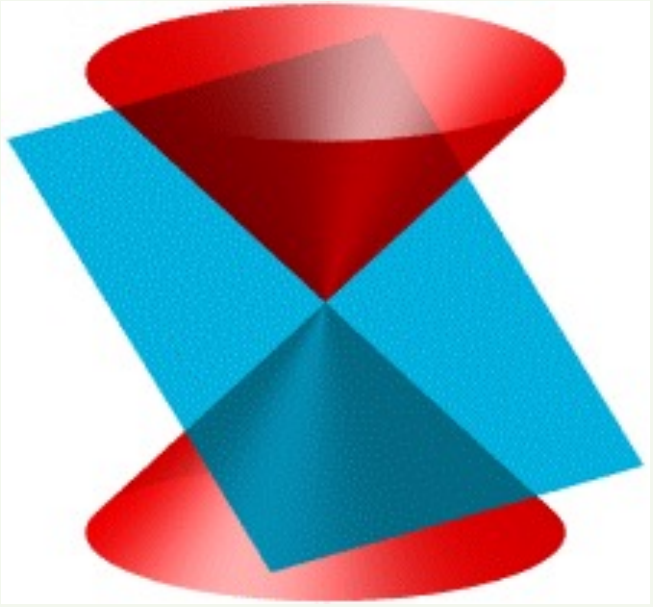
n_{M} is a normalization constant

$\rho_{\mathrm{M}}(w)$ is a spectral density

$$\Lambda^2(w) = M_q^2 - \frac{1}{4}(1-w^2)m_{\mathrm{M}}^2 + \frac{1}{2}(1-w)(M_{\bar{h}}^2 - M_q^2)$$

The Light Front Wavefunction

For a quark in pseudo-scalar meson **M**, the **leading twist** (2-particle) **light front wave function**, ψ_M , can be obtained via the light front projection of the meson's **BSWF**.



Bethe-Salpeter Wavefunction:

$$\chi_{\mathrm{M}}(k,P) = S_q(k+P/2)\Gamma_{\mathrm{M}}(k,P)S_{\bar{h}}(k-P/2)$$

Light Front Wavefunction:

$$\psi^q_{\mathrm{M}}(x,k^2_\perp) = \mathrm{tr}\int_{dk_\parallel} \delta(n\cdot k - x n\cdot P)\gamma_5 \gamma\cdot n \chi_{\mathrm{M}}(k-P/2,P)$$

$$n \text{ lightlike}, n^2=0 \text{ and } n\cdot P = -m_{\mathrm{M}}$$

BSA:

$$f_{\mathrm{M}}\phi^q_{\mathrm{M}}(x) = \frac{1}{16\pi^3}\int d^2k_\perp \psi^q_{\mathrm{M}}(x,k^2_\perp)$$

The Algebraic Model:

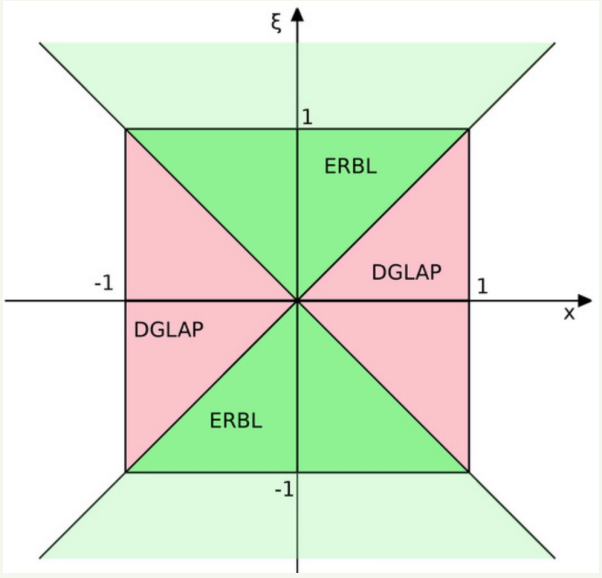
$$\psi^q_{\mathrm{M}}(x,k^2_\perp) = 16\pi^2 f_{\mathrm{M}} \frac{\nu \Lambda^{2\nu}_{1-2x}}{(k^2_\perp + \Lambda^2_{1-2x})^{\nu+1}}\phi^q_{\mathrm{M}}(x)$$

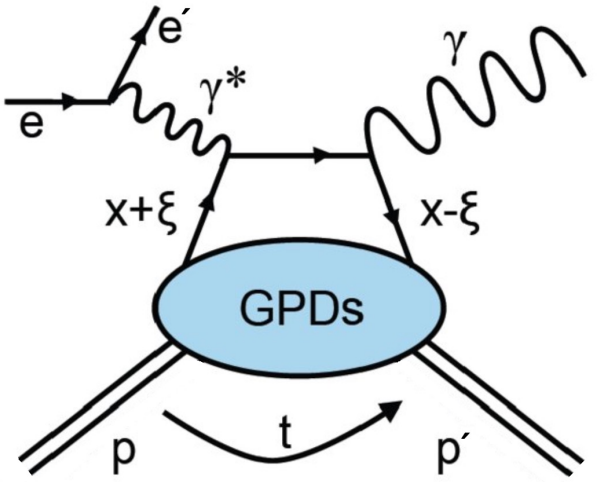
The GPDs from the overlap representation

Valence quark **GPD** from the overlap representation of the **LFWF**.

Both x and ξ have support on [−1,1].

The overlap representation is only valid in the **DGLAP** region, **|x|>ξ**.





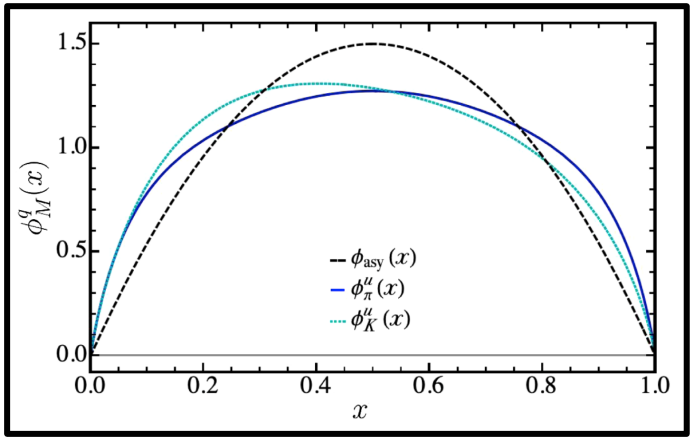
$$P = (p + p')/2$$
$$-t = \Delta^2 = (p - p')^2$$
$$x = \frac{n \cdot k}{n \cdot P}$$
$$\xi = -\frac{n \cdot \Delta}{2n \cdot P}$$

$$H^q_{\rm M}(x,\xi,t) = \int \frac{d^2k_\perp}{16\pi^3} \psi^{q*}_{\rm M}(x^-, (\mathbf{k}^-_\perp)^2) \psi^q_{\rm M}(x^+, (\mathbf{k}^+_\perp)^2)$$

$$x^\pm = \frac{x \pm \xi}{1 \pm \xi} \qquad \mathbf{k}^\pm_\perp = k_\perp \mp \frac{\Delta_\perp}{2} \frac{1-x}{1 \pm \xi}$$

$$\Delta^2_\perp = \Delta^2(1-\xi^2) - 4\xi^2 m^2_{\rm M}$$

From the PDAs to the LFWFs



π and K PDAs

Z.-F. Cui, et. al.,
Eur. Phys. J. C 80, 1064 (2020).

$$(\bar{x} = 1 - x)$$

$$\phi_\pi^u(x) = 20.226\, x\bar{x} \left[1 - 2.509\sqrt{x\bar{x}} + 2.025 x\bar{x}\right]$$

$$\phi_K^u(x) = 18.04\, x\bar{x} \left[1 + 5x^{0.032}\bar{x}^{0.024} - 5.97 x^{0.064}\bar{x}^{0.048}\right]$$

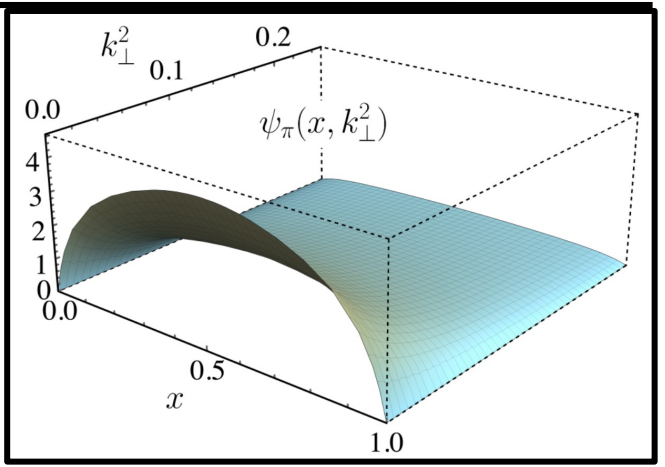
Drawing upon accumulated information on the **PDAs** of π and **K**, we parameterize them as corrections to the asymptotic PDA form on the hadronic scale.

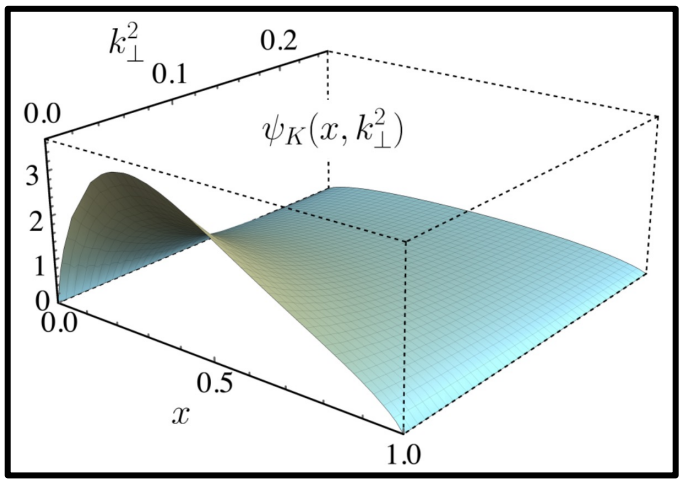
LFWF $\psi_{\rm M}^q(x, k_\perp^2)$

↓

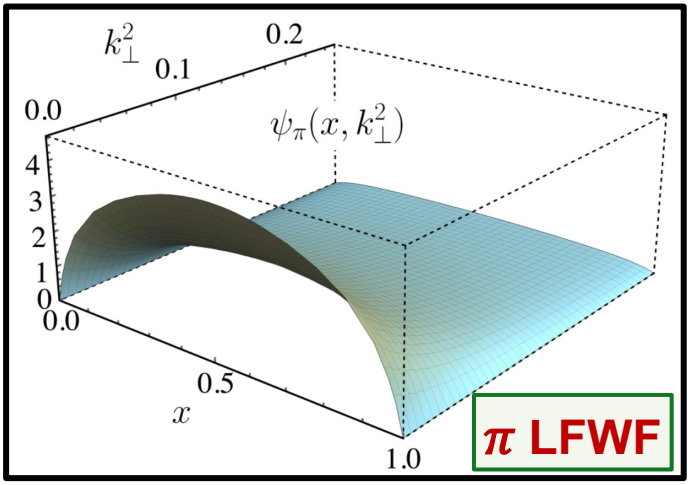
PDA

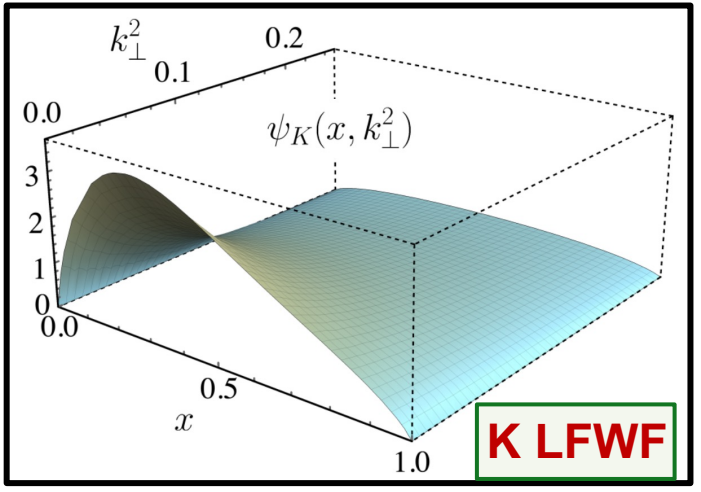
$$\frac{16\pi^2 f_{\rm M}\, \nu \Lambda_{1-2x}^{2\nu}}{(k_\perp^2 + \Lambda_{1-2x}^2)^{\nu+1}} \phi_{\rm M}^q(x)$$





From the LFWFs to the GPDs



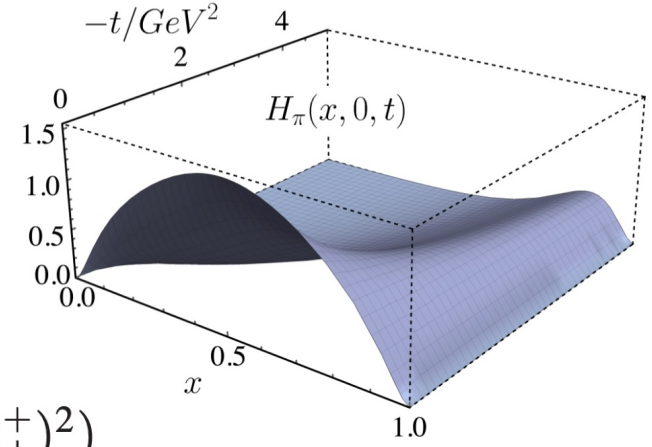


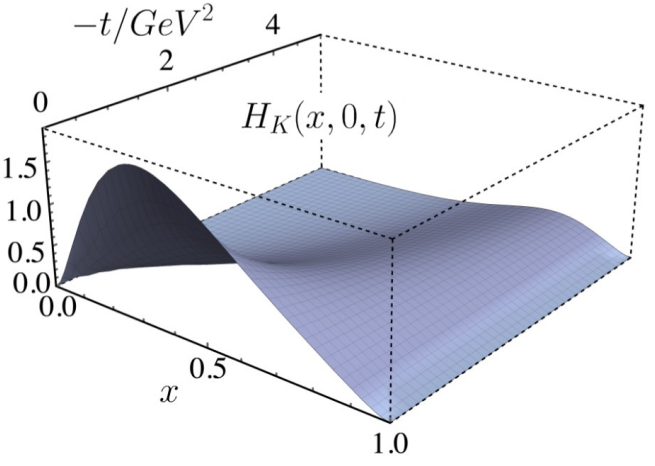
$$H^q_{\mathrm{M}}(x,\xi,t)$$

$$\int \frac{d^2k_\perp}{16\pi^3}\psi^{q*}_{\mathrm{M}}(x^-,(\mathbf{k}^-_\perp)^2)\psi^{q}_{\mathrm{M}}(x^+,(\mathbf{k}^+_\perp)^2)$$

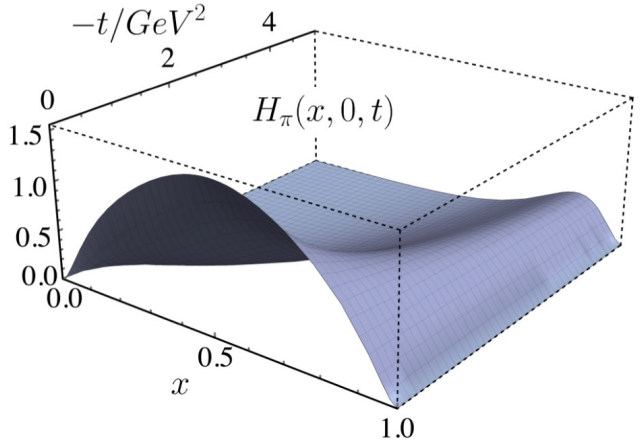
Overlap Representation of the GPDS

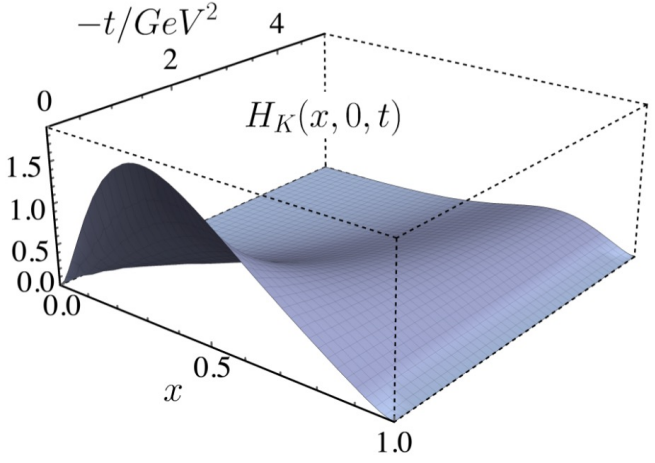
L. Albino, M. Higuera, K. Raya, AB
Phys. Rev. D 106 (2022) 3, 034003





From the GPDs to the PDFs

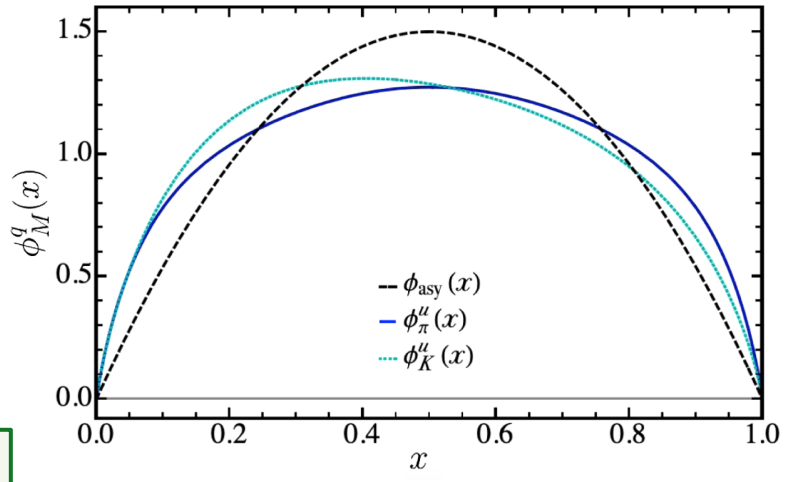


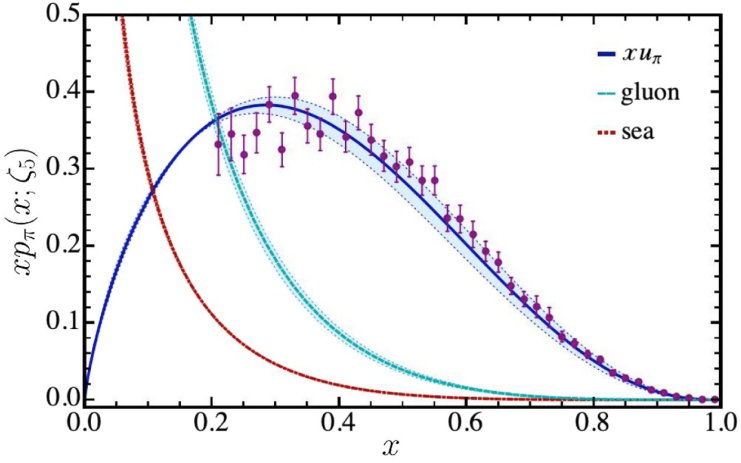


$$q_{\rm M}(x) \equiv H^q_{\rm M}(x,0,0)$$

DGLAP Evolution Equations

L. Albino, M. Higuera, K. Raya, AB
Phys. Rev. D 106 (2022) 3, 034003

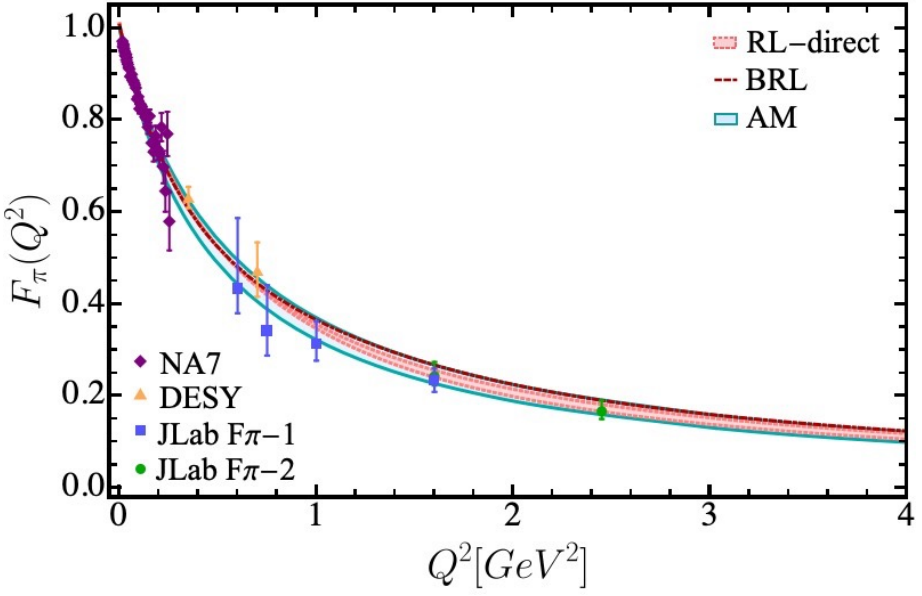


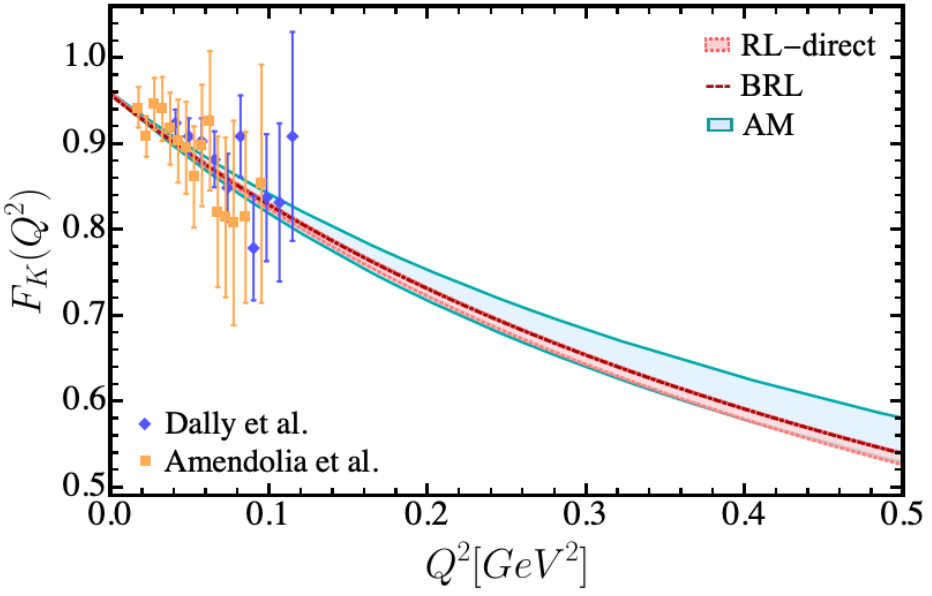


Completing the Cycle – Back to Form Factors

The **electromagnetic form factors** using our **algebraic model** can be obtained either through the knowledge of the **GPDs** or the direct evaluation of the **triangle diagram**.

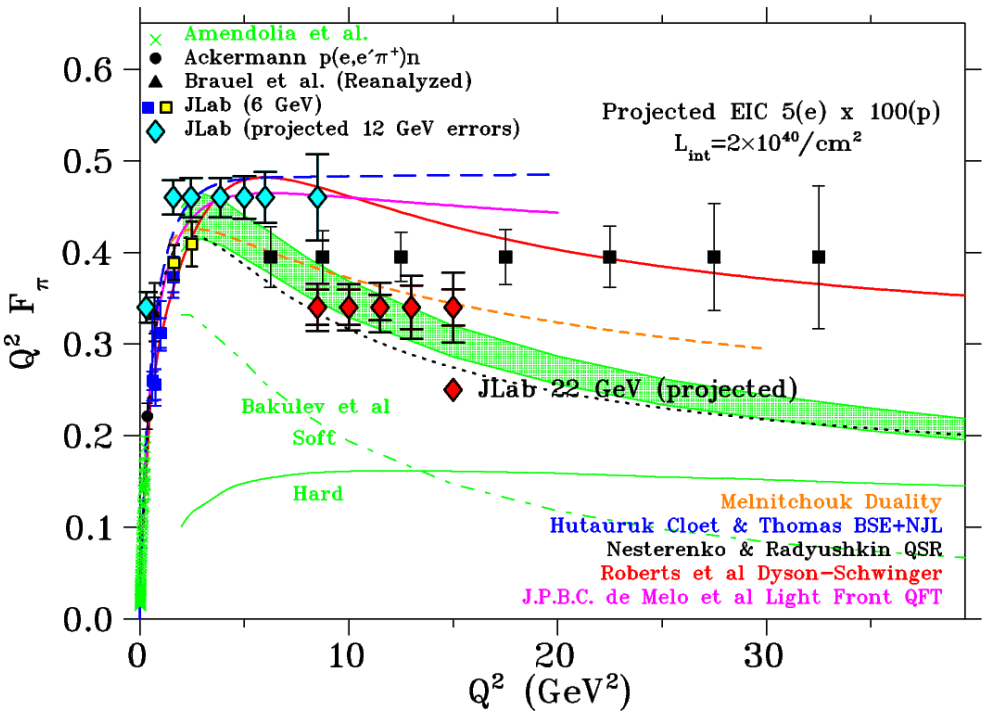
Such an exercise provides stringent constraints on the efficacy of the **algebraic model** we have constructed by direct comparison with the refined calculation of these **form factors.**

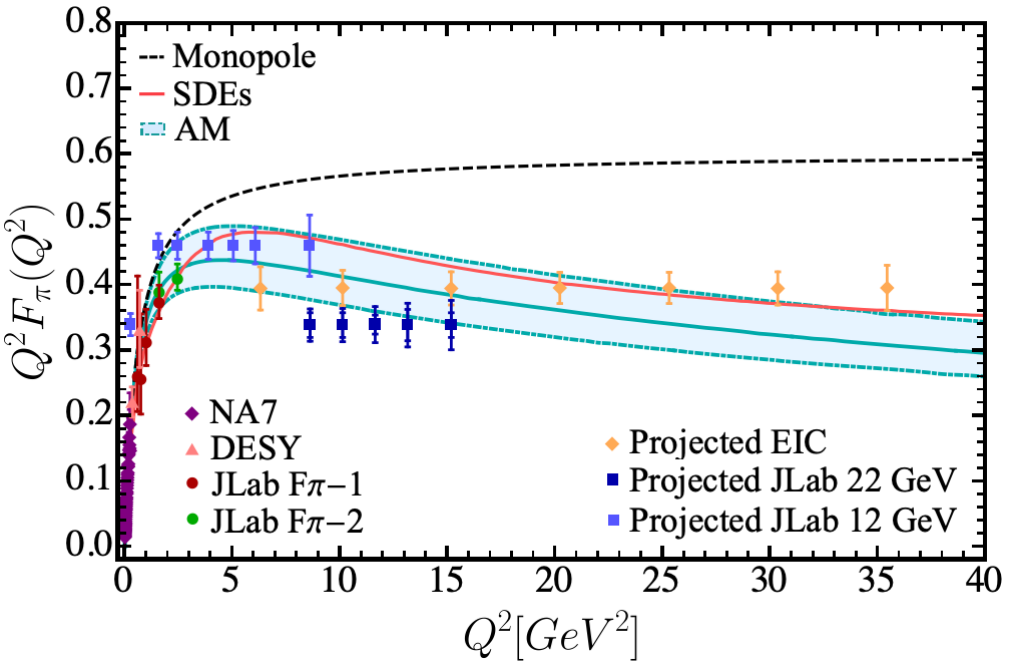




Completing the Cycle – Back to Form Factors

We can extend this analysis of the **Algebraic Model** to compute the **pion electromagnetic form factors** to larger **Q^2** range: **0-40 GeV^2** which would likely cover the photon virtualities accessible to the **JLab12**, **JLab22** and **EIC programs**:

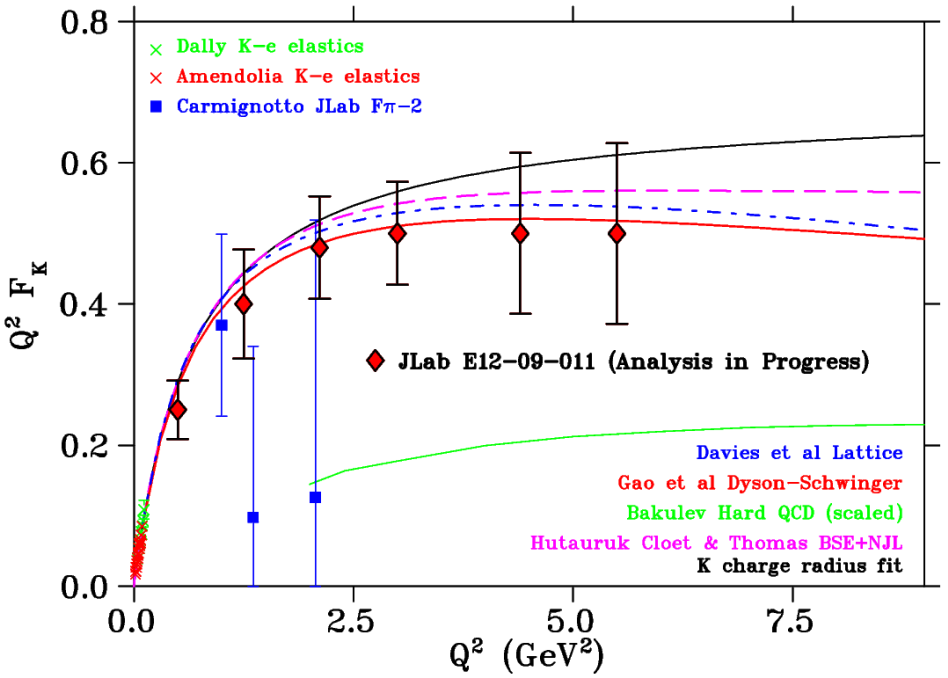




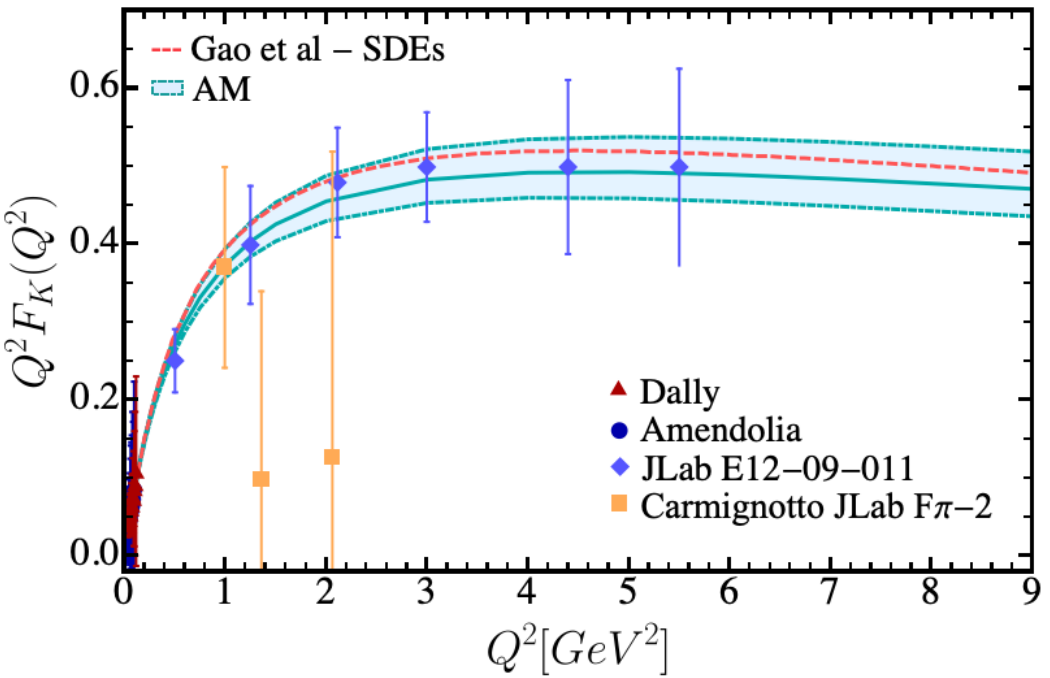
Completing the Cycle – Back to Form Factors

There is an analysis underway of the **kaon electromagnetic form factor** till **5.5 GeV²** of the data obtained in **JLab E12-09-011** experiment.

Courtesy Garth Huber



Algebraic Model results



Summary and Outlook

- The interplay of **QCD akin** truncations of **Schwinger-Dyson equations** and **algebraic model** based upon these studies shed important light on the **internal structure** of **pion** and **kaon.**
- **QCD akin** refined computation of **pion** and **kaon electromagnetic form factors** at low and intermediate virtualities of the probing photon in electroproduction processes:

A. Miramontes AB, K. Raya, P. Roig, Phys. Rev. D 105 (2022) 7, 074013
L. Chang, I.C. Cloët, C.D. Roberts, S.M. Schmidt, P.C. Tandy, Phys. Rev. Lett. 111 (2013) 14, 141802

- Results for the **pion electromagnetic form factor** at large photon virtualities accessible to the potential **22GeV upgrade** of the **JLab** and **EIC** are also available:

L. Chang, I.C. Cloët, C.D. Roberts, S.M. Schmidt, P.C. Tandy, Phys. Rev. Lett. 111 (2013) 14, 141802
J. Arrington, et al. (Feb 23, 2021, J.Phys. G 48 (2021) 7, 075106

- More recently, **pion** and **kaon form factors** have been computed in the the **time-like region**

A.S. Miramontes, H. Sanchis Alepuz, R. Alkofer, Phys. Rev. D 103 (2021) 11, 116006
A.S. Miramontes, AB, Phys. Rev. D 107 (2023) 1, 014016

Summary and Outlook

- Carefully constructed **Algebraic Models** can enable computation of the **GPDs**, **PDFs** and **EFF** with relative ease which is reminiscent of a **contact interaction** while mimicking the reliability of **QCD akin** refined truncations of **Schwinger-Dyson equations**.

L. Albino, M. Higuera, K. Raya, AB Phys. Rev. D 106 (2022) 3, 034003

- Despite these encouraging results and synergy with experimental endeavors at **JLab** and **EIC**, further improvements and extensions in the **continuum QCD approach** are desirable.

- Deeper research into the theoretical foundations of the truncations involved at the level of the **Green functions** of the fundamental degrees of freedom, i.e., **quarks**, **gluons**, as well as **quark-gluon** and **gluon-gluon** interactions continues vigorously.

- **Schwinger-Dyson equations** have also been of substantial success in the studies of **baryons** such as the **transition form factors** of **nucleon** to its **excited states** which is a hallmark of **CLAS**, **CLAS12** and **CLAS22** programs at **JLab** and hold the promise to offer a reliable tool for the future **JLab** and **EIC era** research into the heart of **hadronic matter**.

N → N*(1520) Transition Form Factors

Thank you for your attention