Probing Emergent Hadronic Mass with Deep Exclusive Meson Production

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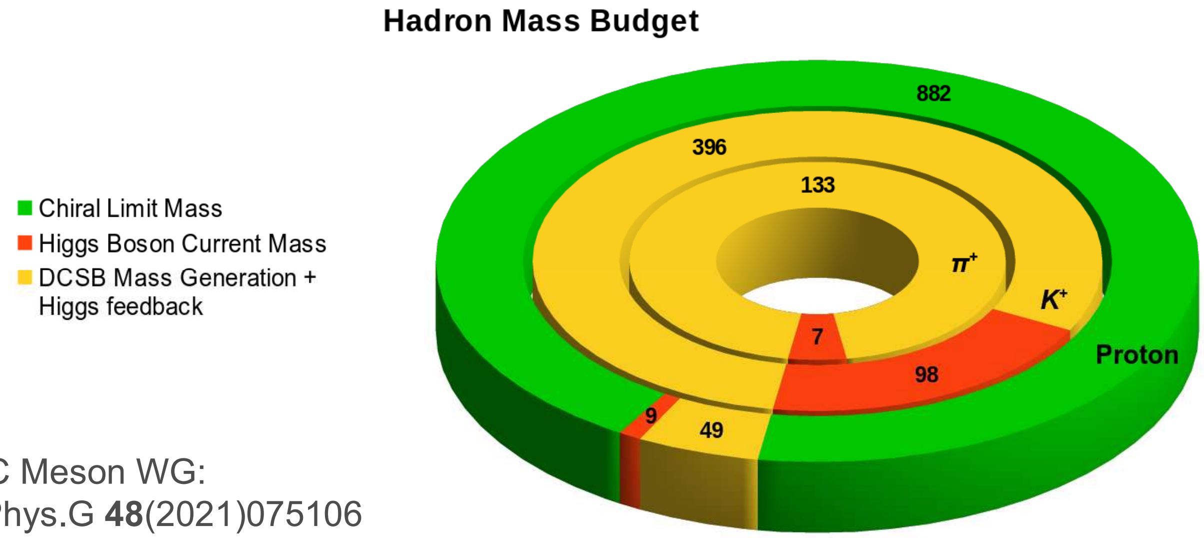
Emergent Hadronic Mass

- **Within the Standard Model:**
  - proton is described by QCD → 3 valence quarks
  - pion also described by QCD → 1 valence quark and 1 valence antiquark
  - ρ meson also described by QCD → 1 valence quark and 1 valence antiquark
    - Here, $m_\rho(770) \approx ⅔\, m_p(938)$ **OK**
  - Expect $m_\pi \approx ⅔\, m_{p,}$ but instead, $m_\pi(140) \approx 1/7\, m_p(938)$, ***X***
- Why ~1 GeV proton mass, but ~1/7 GeV pion mass?
  - How is this achieved?
  - Does nature fine tune?
  - Is there something peculiar about the pion (and by logical extension, the kaon)?
- **Are the answers in QCD?**

Contrasts in Hadron Mass Budgets

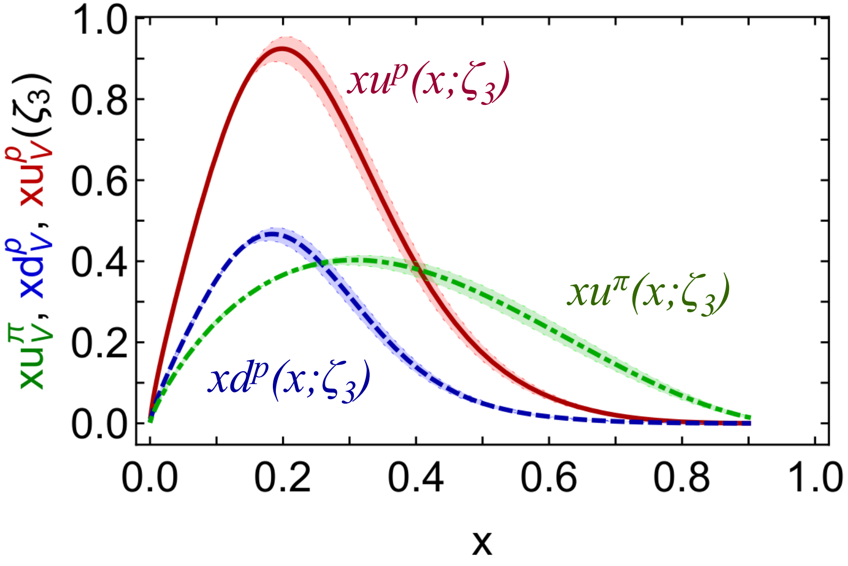


EIC Meson WG:
J.Phys.G **48**(2021)075106

Stark Differences between proton, K^+, π^+ mass budgets

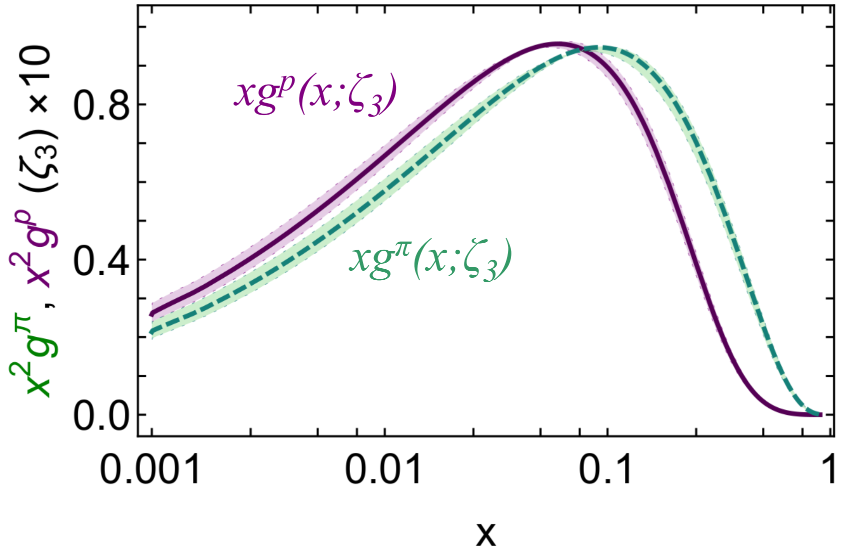
- Due to Emergent Hadronic Mass (EHM), Proton mass large in absence of quark couplings to Higgs boson (chiral limit).
- Conversely, and yet still due to EHM and DCSB, *K* and π are massless in chiral limit (i.e. they are Goldstone bosons of QCD).
- The mass budgets of these crucially important particles demand interpretation.
- Equations of QCD stress that any explanation of the proton's mass is incomplete, unless it simultaneously explains the light masses of QCD's Goldstone bosons, the π and *K*.

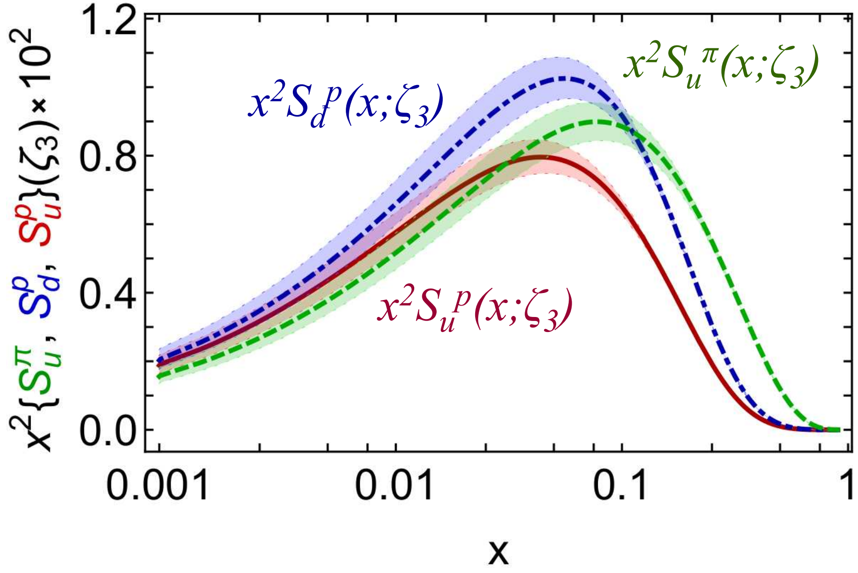
π and Proton 3D Structure are Different!



Computed valence PDFs for the proton and pion, evolved to $\zeta_3=m_{J/\psi}=3.097$ GeV

These differences translate into sea quark and gluon distribution functions in protons and pions





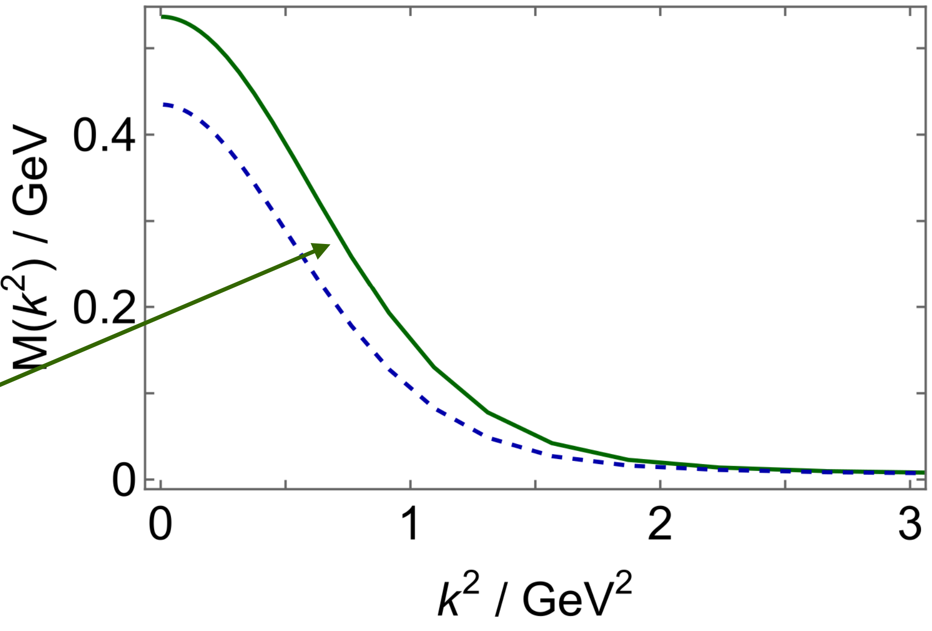
Figures from:
"Proton and pion distribution functions in counterpoint", Y. Lu et al, PLB **830**(2022)137130

In the valence–quark, strong QCD region, such differences can only be probed by a high energy facility at luminosity frontier

Synergy: Emergent Mass and π^+ Form Factor

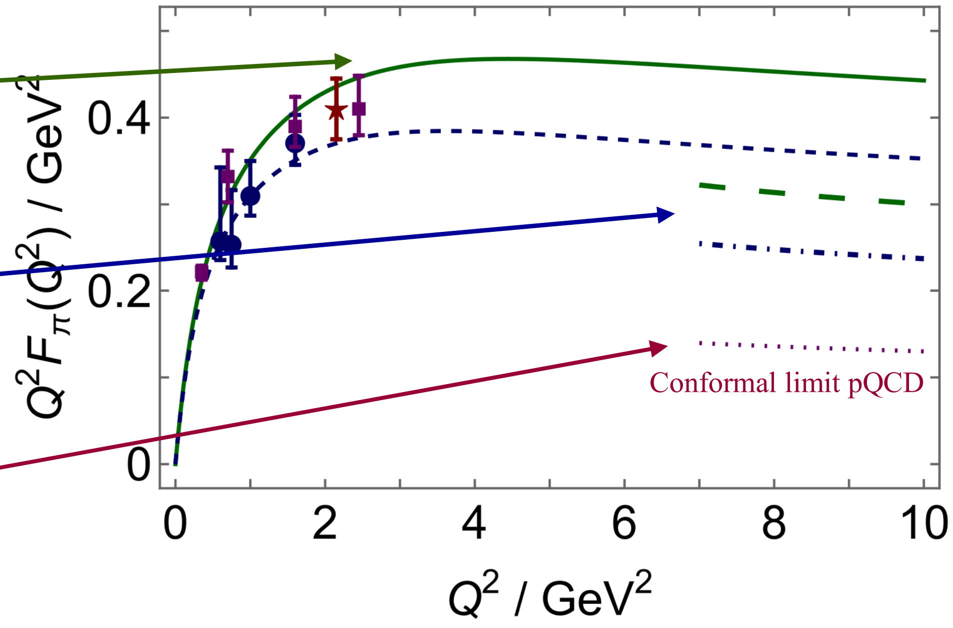
At empirically accessible energy scales, π^+ form factor is sensitive to emergent mass scale in QCD

- **Two dressed–quark mass functions distinguished by amount of DCSB**
    - DCSB emergent mass generation is 20% stronger in system characterized by solid green curve, which is more realistic case



- **$F_\pi(Q^2)$ obtained with these mass functions**
    - r_π=0.66 fm with solid green curve
    - r_π=0.73 fm with solid dashed blue curve
- **$F_\pi(Q^2)$ predictions from QCD hard scattering formula, obtained with related, computed pion PDAs**
- **QCD hard scattering formula, using conformal limit of pion's twist–2 PDA**

$$\phi_\pi^{cl}(x) = 6x(1-x)$$



Chen, et al., PRD **98**(2018)091505(R); Aguilar et al, EPJA **55**(2019)190

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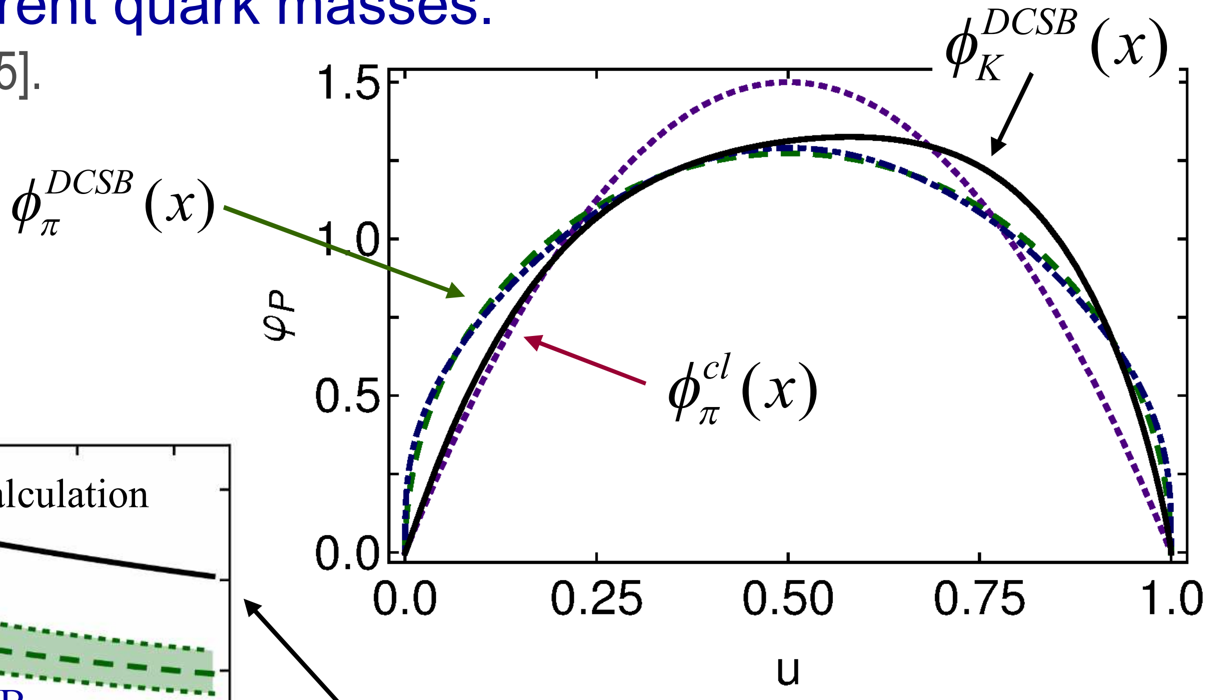
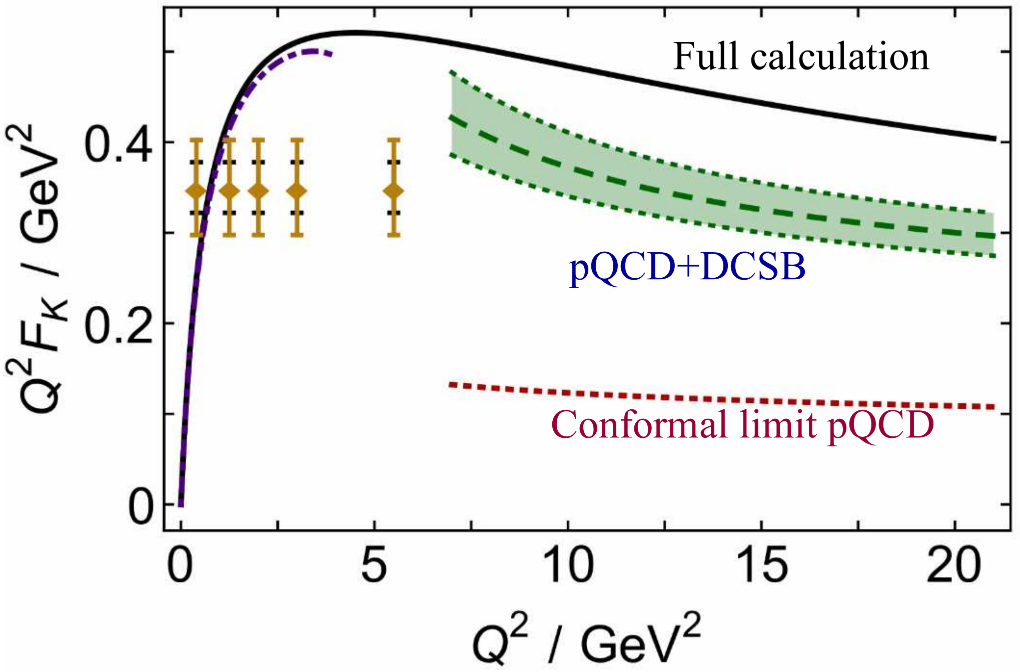
K⁺ properties also strongly influenced by EHM

- ***K*⁺ PDA also is broad, concave and asymmetric.**
- While the heavier s quark carries more bound state momentum than the u quark, the shift is markedly less than one might naively expect based on the difference of u, s current quark masses.

[C. Shi, et al., PRD **92** (2015) 014035].





- **F_K DCSB model prediction for JLab kinematics**

[F. Guo, et al., arXiv: 1703.04875].

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Measurement of F_π via Electroproduction

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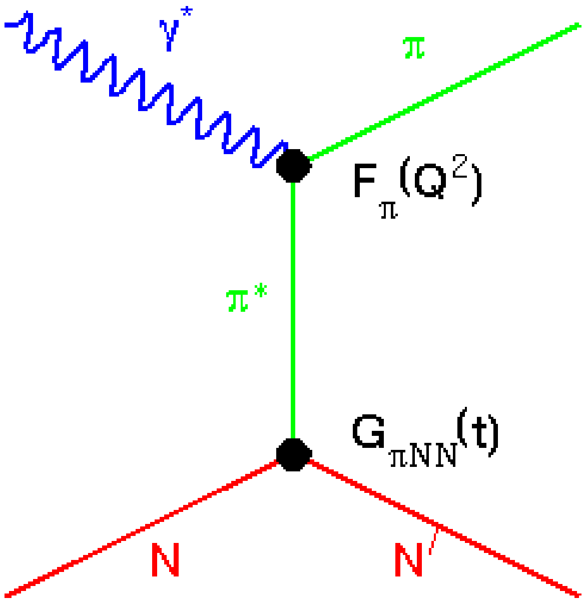
Above $Q^2>0.3$ GeV^2, F_π is measured indirectly using the “pion cloud” of the proton via pion electroproduction $p(e,e'\pi^+)n$

$$\left|p\right\rangle = \left|p\right\rangle_0 + \left|n\pi^+\right\rangle + \ldots$$

- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In Born term model, F_π^2 appears as

$$\boxed{\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)}\, g_{\pi NN}^2(t)\, F_\pi^2(Q^2,t)}$$



Drawbacks of this technique:

1. Isolating σ_L experimentally challenging.
2. The F_π values are in principle dependent upon the model used, but this dependence is expected to be reduced at sufficiently small $-t$.

DEMP Experimental Issues

- Deep Exclusive Meson Production (DEMP) cross section is small, can exclusive $p(e,e'\pi^{+})n$ and $p(e,e'K^{+})\Lambda$ channels be cleanly identified?
    - High momentum, forward angle (5.5^{o}) meson detection is required, with good Particle ID to separate π^{+}, K^{+}, p
    - Good momentum resolution required to reconstruct crucial kinematics, such as M_{miss}, Q^2, W, t
- Need to measure the longitudinal cross section $d\sigma_L/dt$ needed for form factor extraction

Hall C of Jefferson Lab has been optimized for specifically such studies

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Projected JLab–12 F_π Data

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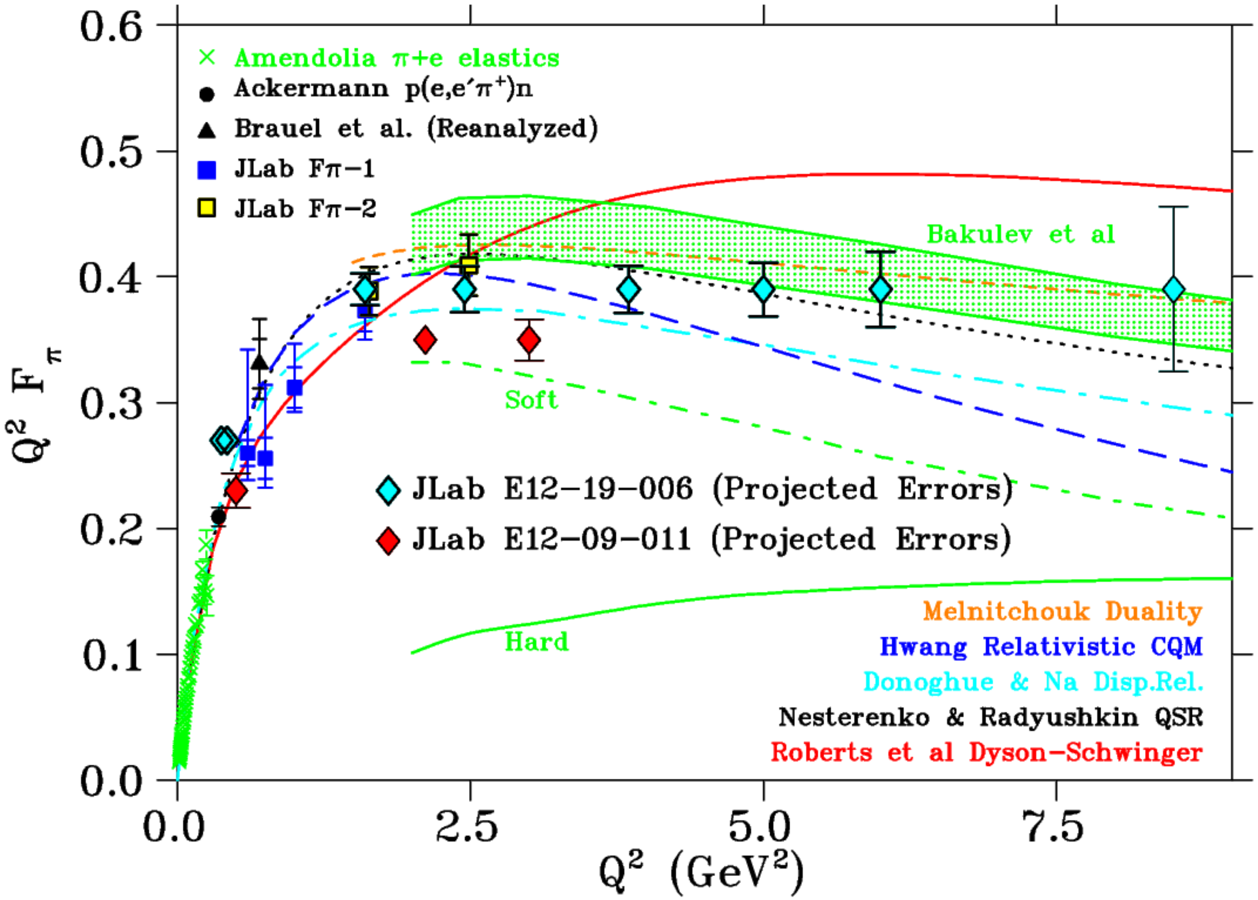
SHMS+HMS will allow measurement of F_π to Q^2=6.0 to high precision, and to 8.5 with lower precision

No other facility worldwide can perform this measurement



y–positions of projected points are arbitrary.

Error bars are calculated from obtained statistics and projected systematic uncertainties.

The ~10% measurement of F_π at Q^2=8.5 GeV^2 is at higher $-t_{min}$=0.45 GeV^2

Data taking completed September 2022
(E12–19–006: G. Huber, D. Gaskell and T. Horn, spokespersons)

Projected JLab–12 K^+ Form Factor

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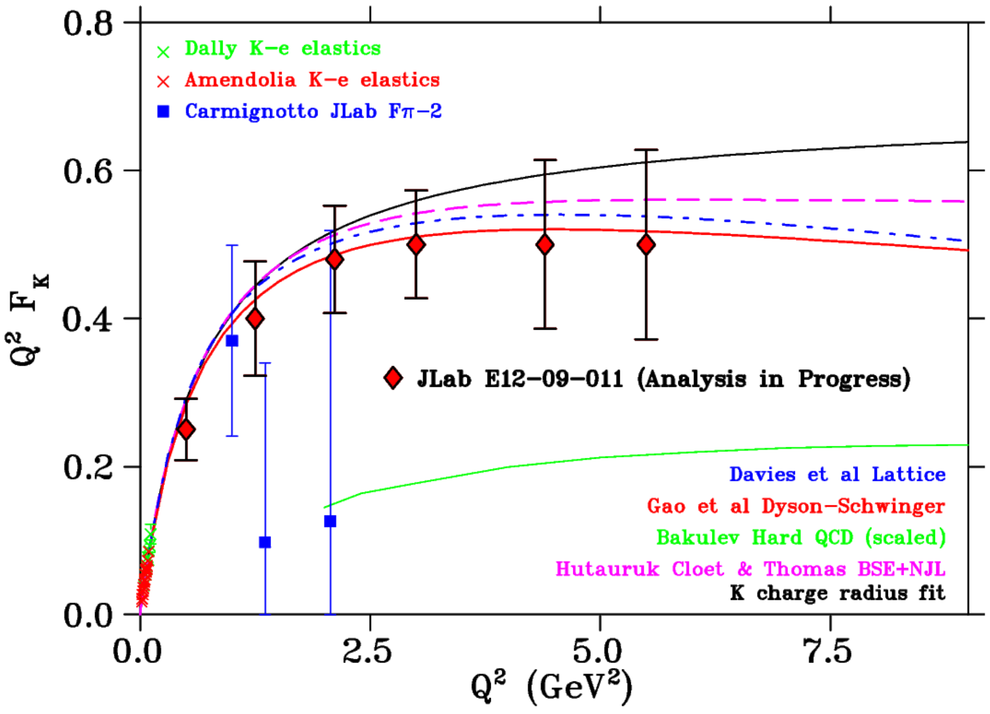
- First measurement of F_K well above the resonance region.
- Measure form factor to Q^2=3 GeV^2 with good overlap with elastic scattering data.
    - Limited by $-t$<0.2 GeV^2 requirement to minimize non–pole contributions.
- Data will provide an important second $q\bar{q}$ system for theoretical models, this time involving a strange quark.

p(*e,e'K*$^+$)Λ W>2.5 GeV

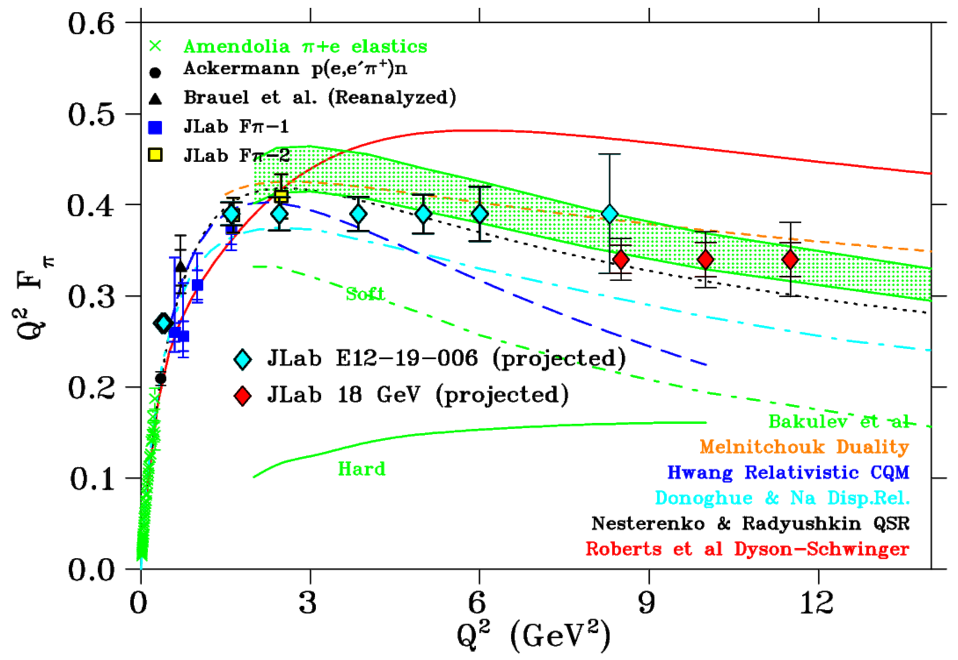


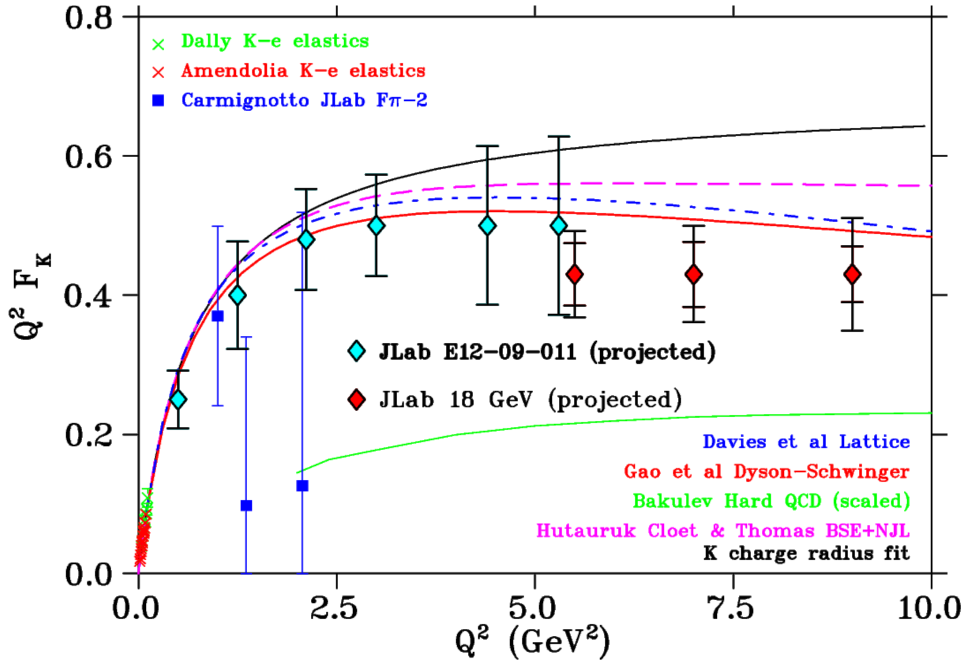
Extraction of F_K from Q^2>4 GeV^2 data is more uncertain, due to higher $-t_{min}$

Partially completed in 2019 as an early SHMS commissioning experiment: LT–separation
(E12–09–011: T. Horn, G. Huber and P. Markowitz, spokespersons)

Projected JLab–18 with HMS+SHMS

- Y-axis values of projected data are arbitrary
- The errors are projected, based on Δε from beam energies on earlier slides, and T/L ratio calculated with Vrancx Ryckebusch model
- Inner error bar is projected statistical and systematic error
- Outer error bar also includes a model uncertainty in the form factor extraction, added in quadrature
- F_π errors based on Fπ–2 and E12–19–006 experience
- F_K errors more uncertain, as E12–09–011 analysis not yet completed





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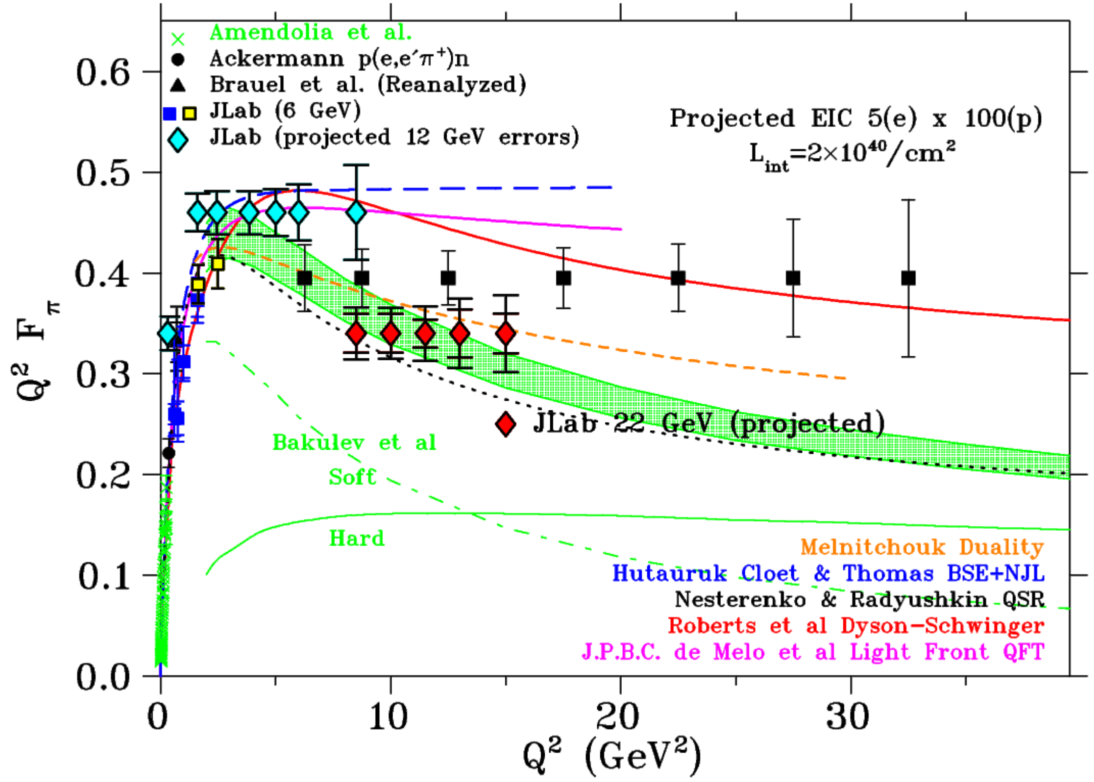
Importance of JLab–22 F_π in EIC Era



- Quality L/T–separations impossible at EIC (can't access ε<0.95)
- JLab will remain ONLY source of quality L–T separated data!
- **Phase 2: 22 GeV beam with upgraded VHMS**
    - Extends region of high quality F_π values to Q^2=13 GeV^2
    - Somewhat larger errors to Q^2=15 GeV^2
- Provides MUCH improved overlap of F_π data set between JLab and EIC!

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Synergy between Experiment and Theory

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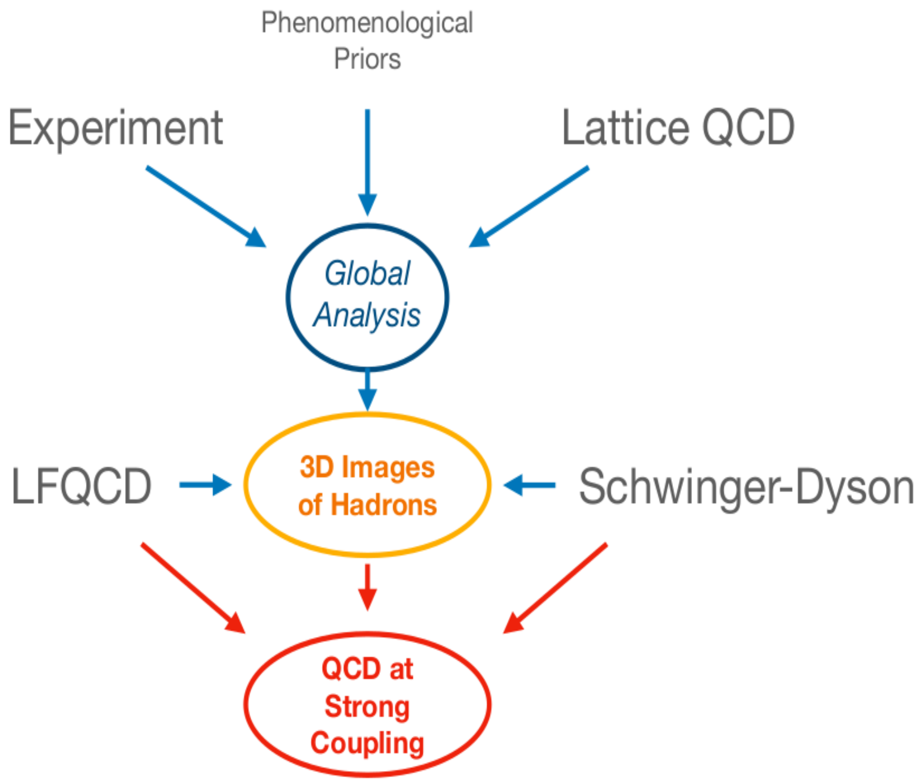


Phenomenological Priors

Experiment

Lattice QCD

Global Analysis

LFQCD

3D Images of Hadrons

Schwinger-Dyson

QCD at Strong Coupling

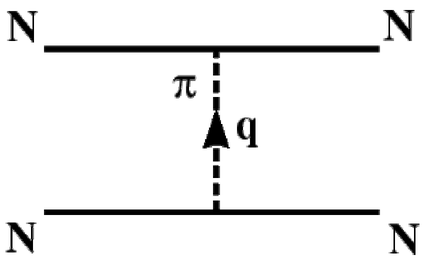
EIC Meson Working Group:
J.Phys.G **48**(2021)075106

- **In comparison to the nucleon, experimental probes of π, K have been relatively sparse**
- **Substantial ambiguities remain regarding their partonic, quark–gluon structure, hobbling our understanding of Strong QCD**
- **One may expect future knowledge of π, K structure to be derived from an interplay between several methods:**
  - Experimental data
  - QCD phenomenology
  - Lattice QCD
  - QCD global analyses of current and future experimental data

JLab and Electron–Ion Collider (EIC) will be dominant sources of needed data and will drive global efforts

The Pion has Particular Importance

- The pion is responsible for the long–range part of the nuclear force, acting as the basis for meson exchange forces, and playing a critical role as an elementary field in nuclear structure Hamiltonians.



- As the lightest meson, it must be a valence $q\bar{q}$ bound state, but understanding its structure through QCD has been exceptionally challenging.
  - e.g. Constitutent Quark Models that describe a nucleon with m_N=940 MeV as a qqq bound state, are able to describe the ρ-meson under similar assumptions, yielding a constituent quark mass of about

$$m_Q \approx \frac{m_N}{3} \approx \frac{m_\rho}{2} \approx 350\text{ MeV}$$

- The pion mass m_π≈140 MeV seems “too light”.
- **We exist because nature has supplied two light quarks and these quarks combine to form the pion, which is unnaturally light and hence very easily produced.**

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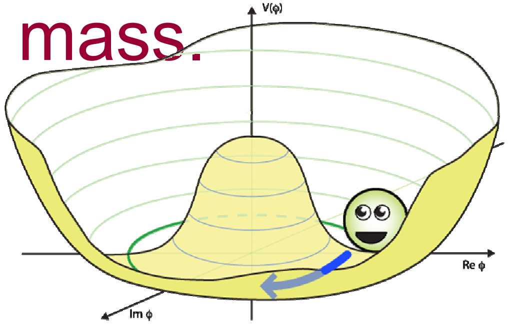
The Pion as a Goldstone Boson

- A remarkable feature of QCD is Dynamical Chiral Symmetry Breaking (DCSB) because it cannot be derived directly from the Lagrangian and is related to nontrivial nature of QCD vacuum.
  - Explicit symmetry breaking, which is put in “by hand” through finite quark masses, is quite different.
- DCSB is now understood to be one of the most important emergent phenomena in the Standard Model, responsible for generation of the vast majority of baryonic mass.



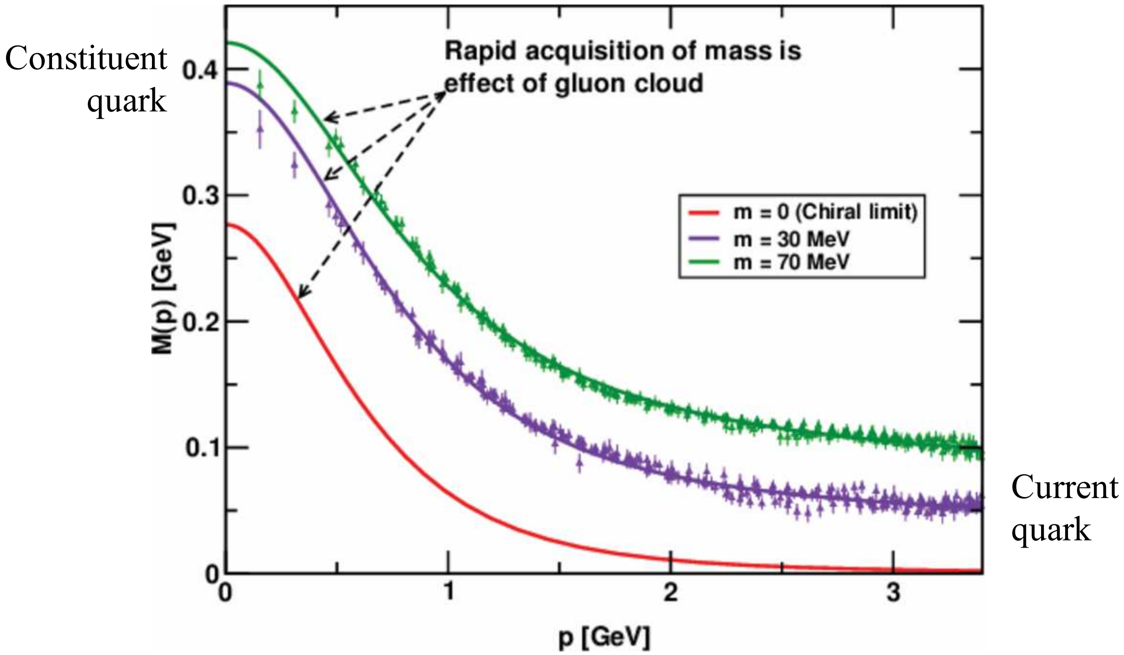
- **Two important consequences of DCSB:**
  1. Valence quarks acquire a dynamical or constituent quark mass through their interactions with the QCD vacuum.
  2. The pion is the spin-0 boson that arises when Chiral Symmetry is broken, similar to how Higgs boson arises from Electroweak Symmetry Breaking.

Recent Theoretical Advances

Amazing progress in the last few years.

- **We now have a much better understanding how Dynamical Chiral Symmetry Breaking (DCSB) generates hadron mass.**
- Quenched lattice–QCD data on the dressed–quark wave function were analyzed in a Bethe–Salpeter Equation framework by Bhagwat, et al.
- For the first time, the evolution of the current–quark of pQCD into constituent quark was observed as its momentum becomes smaller.

- The constituent–quark mass arises from a cloud of low–momentum gluons attaching themselves to the current quark.
- **This is DCSB:** an essentially non-perturbative effect that generates a quark *mass from nothing*: namely, it occurs even in the chiral (m=0) limit.



M.S. Bhagwat, et al., PRC **68** (2003) 015203.
L. Chang, et al., Chin.J.Phys. **49** (2011) 955.

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Implications for Pion Structure

Craig Roberts (2016): ***"No understanding of confinement within the Standard Model is practically relevant unless it also explains the connection between confinement and DCSB, and therefore the existence and role of pions."***

- For the pQCD derivation on slide #13, the normalization for F_π has been based on the conformal limit of the pion's twist–2 PDA.

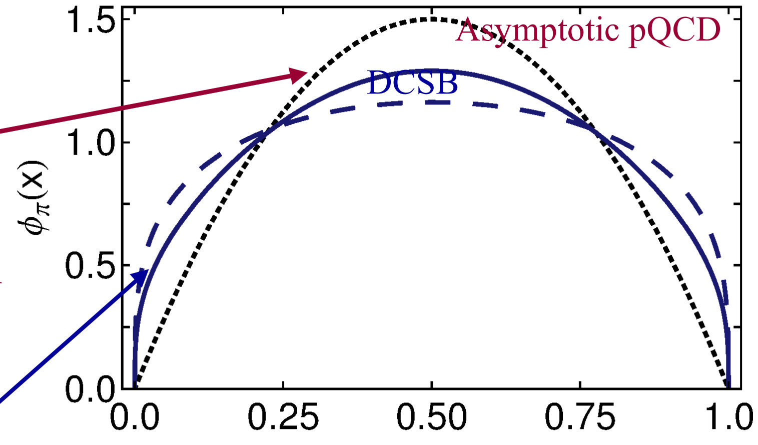
$$\phi_\pi^{cl}(x) = 6x(1-x)$$

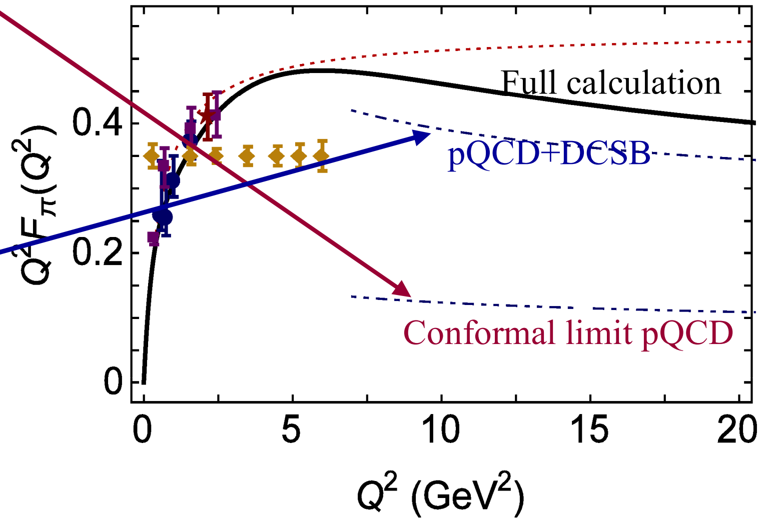
- This leads to "too small" F_π values in comparison with present & projected JLab data.

- Recent works incorporating DCSB effects indicate that at experimentally accessible energy scales the actual pion PDA is broader, concave function, close to

$$\phi_\pi(x) = (8/\pi)\sqrt{x(1-x)}$$

- Simply inputting this $\varphi_\pi(x)$ into the pQCD expression for F_π brings the calculation much closer to the data.
- **Underestimates full computation by ~15% for $Q^2 \geq 8$ GeV^2. Addresses issue raised in 1977.**





L. Chang, et al., PRL **110** (2013) 132001; **111** (2013) 141802.

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