New Perspectives on the Charged Pion Form Factor

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The Pion has Particular Importance

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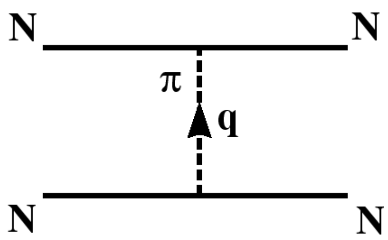
- The pion is responsible for the long-range part of the nuclear force, acting as the basis for meson exchange forces, and playing a critical role as an elementary field in nuclear structure Hamiltonians.



- 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

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

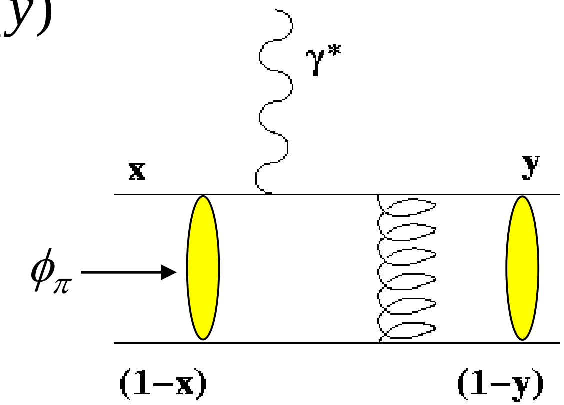
- The pion mass m_π≈140 MeV seems “too light”.

- **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.**

The Pion in perturbative QCD

At very large Q^2, pion form factor (F_π) can be calculated using pQCD

$$F_\pi(Q^2) = \frac{4}{3}\pi\alpha_s \int_0^1 dxdy \frac{2}{3}\frac{1}{xyQ^2}\phi(x)\phi(y)$$



at asymptotically high Q^2, the pion distribution amplitude becomes

$$\phi_\pi(x) \underset{Q^2\to\infty}{\longrightarrow} \frac{3f_\pi}{\sqrt{n_c}} x(1-x)$$

and F_π takes the very simple form

$$Q^2F_\pi(Q^2) \underset{Q^2\to\infty}{\longrightarrow} 16\pi\alpha_s(Q^2)f_\pi^2$$

f_π=93 MeV is the $\pi^+\to\mu^+\nu$ decay constant.

G.P. Lepage, S.J. Brodsky, Phys.Lett. **87B**(1979)359.

This only relies on asymptotic freedom in QCD, *i.e.* $(\partial\alpha_S/\partial\mu)<0$ as $\mu\to\infty$.

Q^2F_π should behave like $\alpha_s(Q^2)$ even for moderately large Q^2.
→ Can study the renormalization of α_S quark-gluon coupling, and QCD's transition between asymptotic freedom and confinement.

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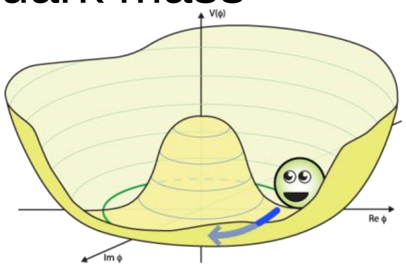
The Pion as a Goldstone Boson

- **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 >98% 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.



- **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.”***

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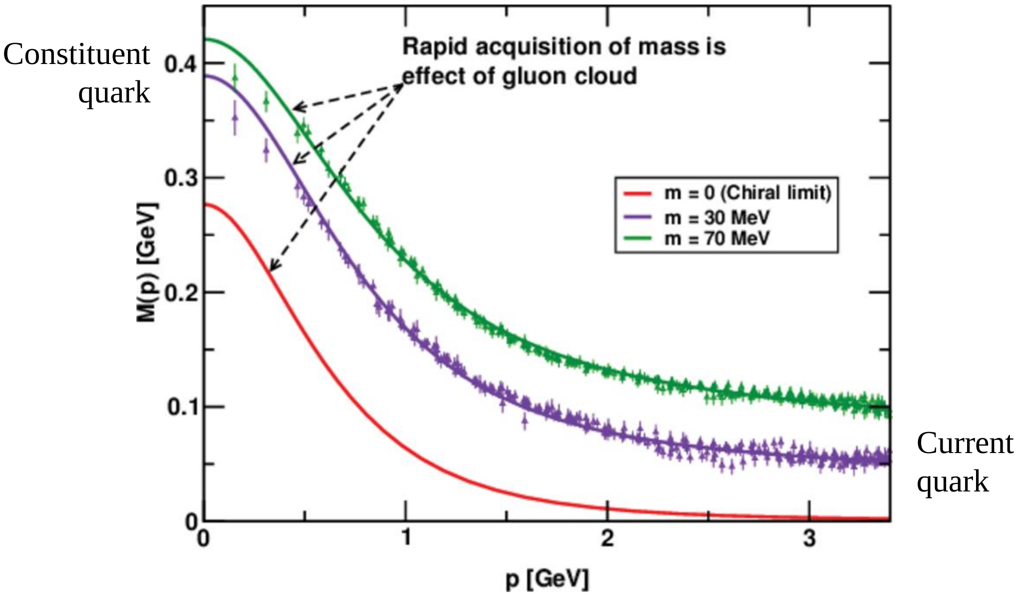
Recent Theoretical Advances

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

- There has been an ongoing argument for the last ~30 years on the proper normalization of α_S far from the Z^0 pole.

  (e.g. Brodsky et al., PRD **67** (2003) 055008; Isgur, Llewellyn-Smith PRL **52** (1984) 1080; etc.)

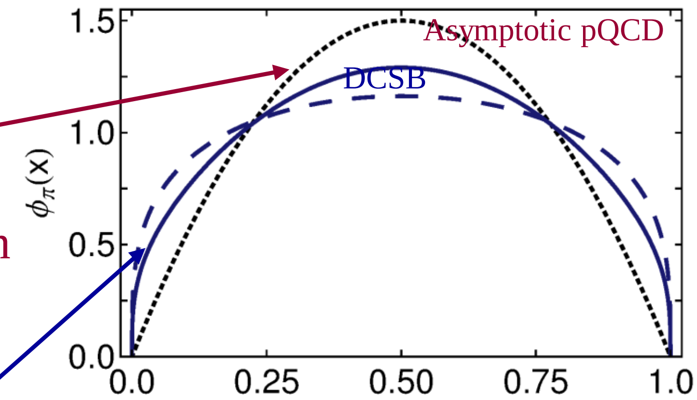
- **Recent theoretical advances finally shed light on this controversy.**
  - For the pQCD derivation on slide #3, the normalization for F_π has been based on the conformal limit of the pion's twist-2 PDA.

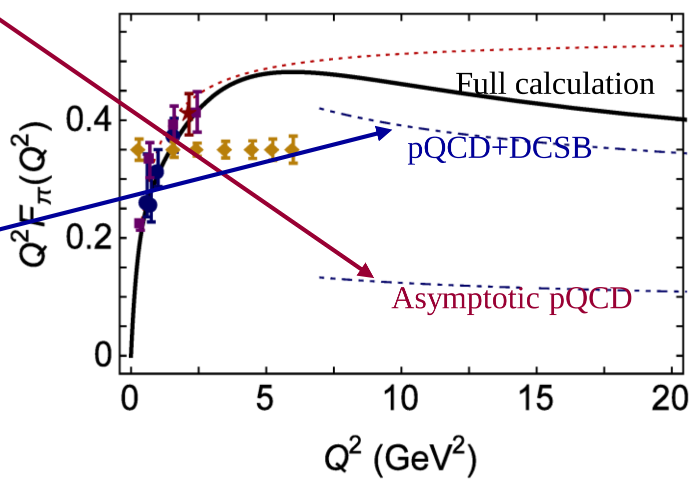
$$\phi_\pi^{cl}(x) = 6x(1-x)$$

  - This leads to "too small" F_π values in comparison with present & projected JLab data.
  - Recent works incorporating DCSB effects indicate that at intermediate energy scales the actual pion PDA is a 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 (slide #3) brings the calculation much closer to the data.
  - **Underestimates full computation by ~15% for $Q^2 \geq 8$ GeV^2. Experimentally testable at JLab.**





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

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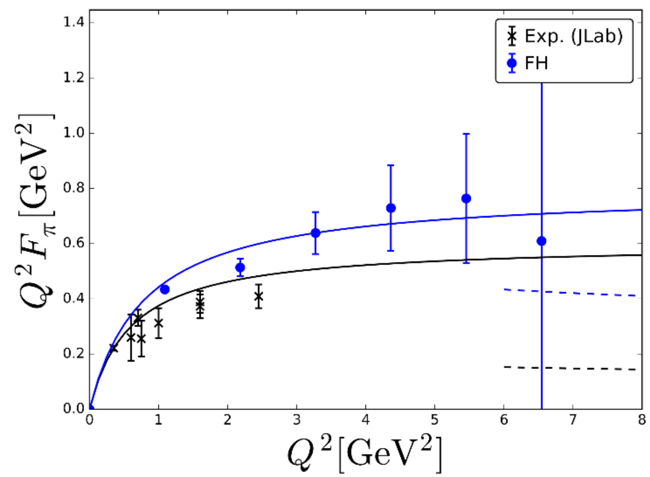
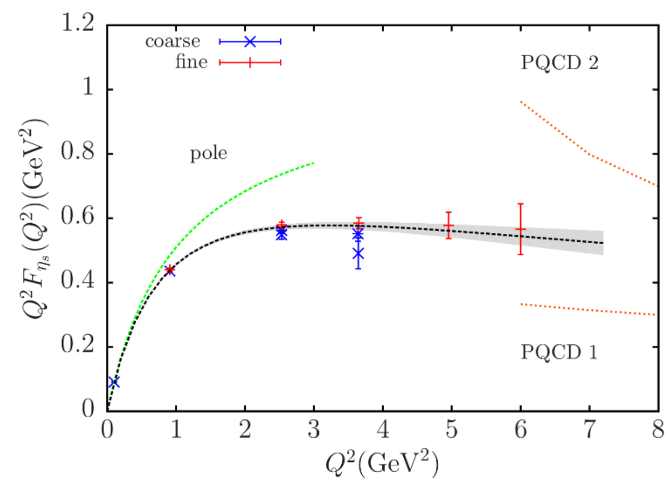
New Lattice QCD at Higher Q^2

- **Lattice QCD calculations traditionally have difficulty predicting hadron structure at high-momentum transfer.**
- **Form factors drop rapidly with Q^2, so one is attempting to extract a much weaker signal from data-sets with finite statistics.**
- **QCDSF/UKQCD/CSSM Collab. address with new technique relating matrix elements to energy shifts.**
- Simulate single set of u,d,s gauge configurations corresponding to $m_\pi \approx 470$ MeV.
- **Confident future LQCD will provide insight into transition of perturbative to non-perturbative QCD.**
- **HPQCD Collab. study pseudoscalar η_s meson made of valence s quarks accurately tuned on full QCD ensembles of gluon field configurations.**
- Qualitatively similar to pion since $m_s < \Lambda_{QCD}$, but numerically much faster.
- F_π result flat for $2 < Q^2 < 6$ GeV^2, far above asymptotic QCD value (similar to slide #6).
- **Confident future LQCD calcs will provide rigorous comparison with high Q^2 experiment.**



Chambers et al., arXiv: 1702.01513



Koponen et al., arXiv: 1701.04250

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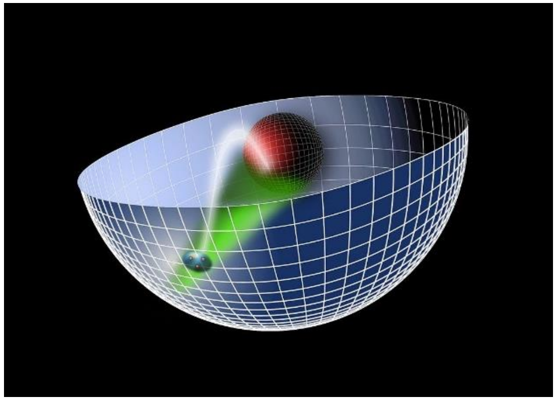
AdS/QCD

- **A remarkable breakthrough in the last decade is the discovery by Brodsky and de Teramond of a higher dimensional gravity dual to semi-classical light-front QCD.**



- The goal of holographic QCD models is to find a weakly coupled theory in 5D anti-de Sitter (ADS) space-time for which the dual strongly coupled theory is as close to QCD as possible.
- Allows analytic calculations of hadronic properties to be performed in the non-perturbative regime.
- In these models, confinement is simulated by imposing boundary conditions on the extra 5^{th} dimension *z*.

- Complications arise when one introduces spontaneous and explicit Chiral Symmetry Breaking effects.
- Until now, it has been not possible to treat the pion on a consistent basis with other hadrons, due to the fact that it is "too light", as discussed on slide #2.

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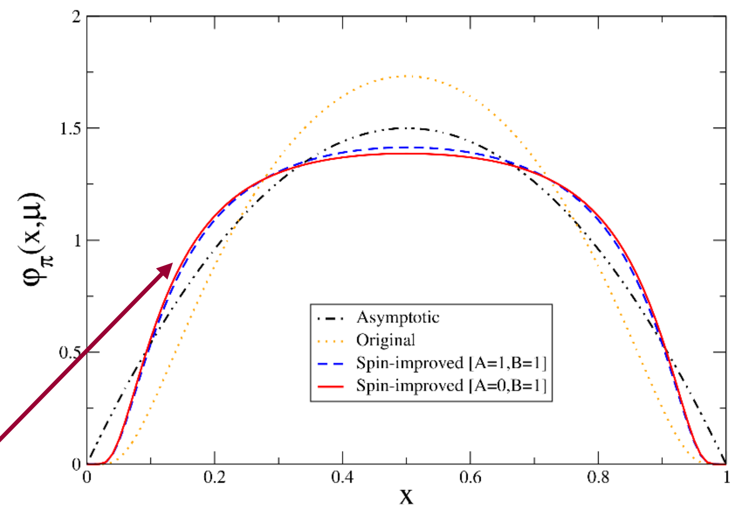
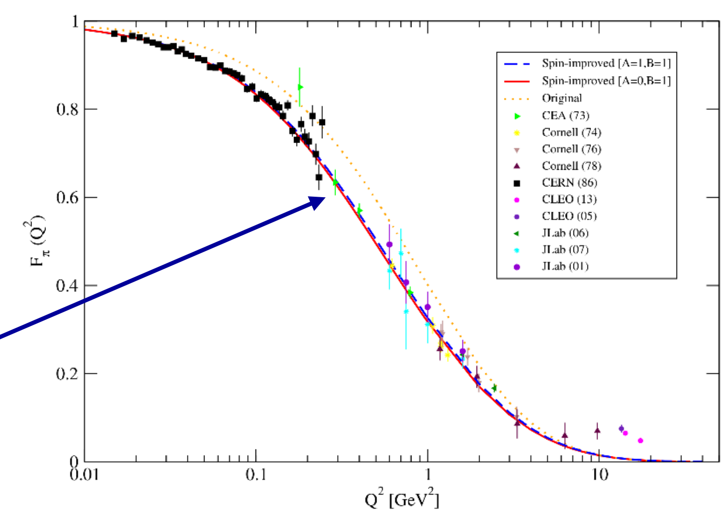
New AdS/QCD Calculation

- Ahmady, Chistie and Sandapen consider the pion light-front wave-function, incorporating both the physics of confinement and Chiral Symmetry Breaking, in the AdS/QCD framework.
- Take into account quark dynamical spin effects in the holographic pion wavefunction (i.e. momentum-dependent helicities).
- Now able to treat the pion with same parameters as for other hadrons.
- Obtain a broad, flat pion PDA very similar to Twist-2,3 calcs on slide #6.
- Good agreement with expt. for $f_\pi, \sqrt{\langle r_\pi^2 \rangle}$ and F_π at low Q^2.
- Additional work needed for Q^2>2 GeV^2.
- Supports the idea of the emergence of a universal, fundamental AdS/QCD scale.





Adhmady, Chistie, Sandapen, PRD **95** (2017) 074008.

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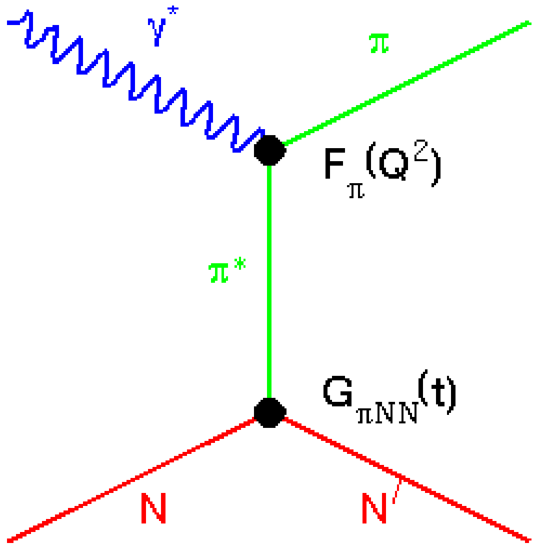
Measurement of F_π via Electroproduction

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

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

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

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



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 $-t$.

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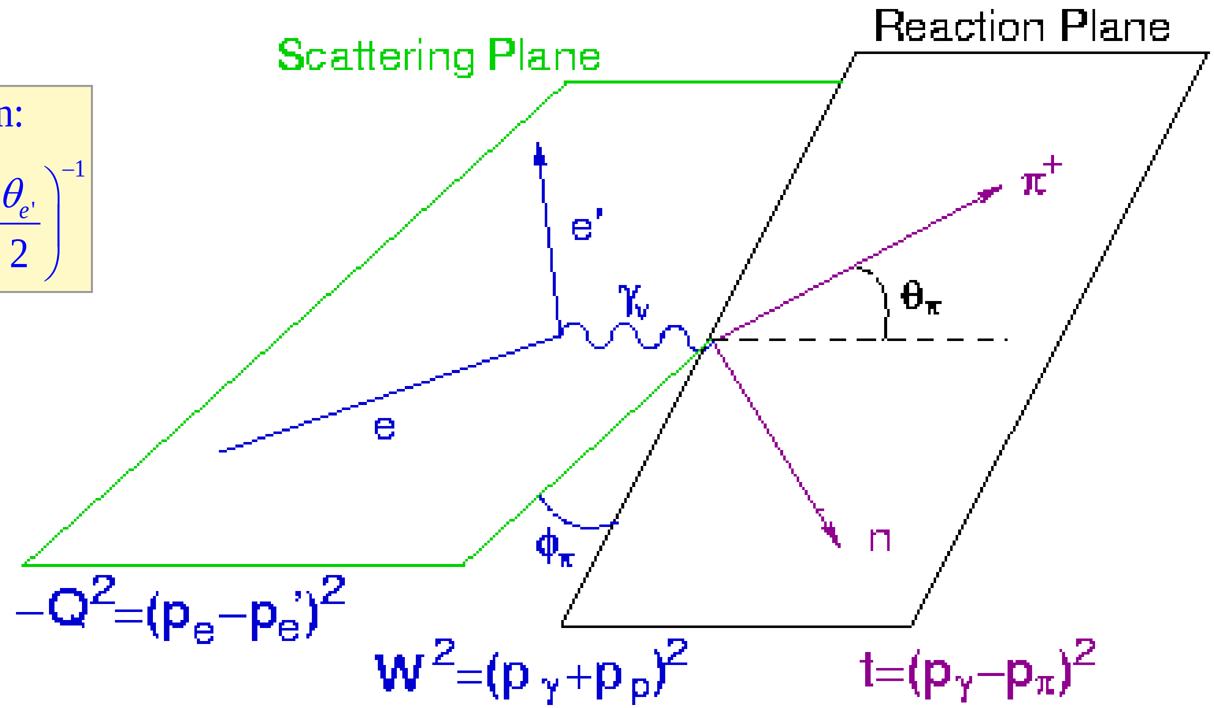
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Virtual-photon polarization:

$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$



- **L-T separation required to separate σ_L from σ_T.**
- **Need to take data at smallest available $-t$, so σ_L has maximum contribution from the π^+ pole.**

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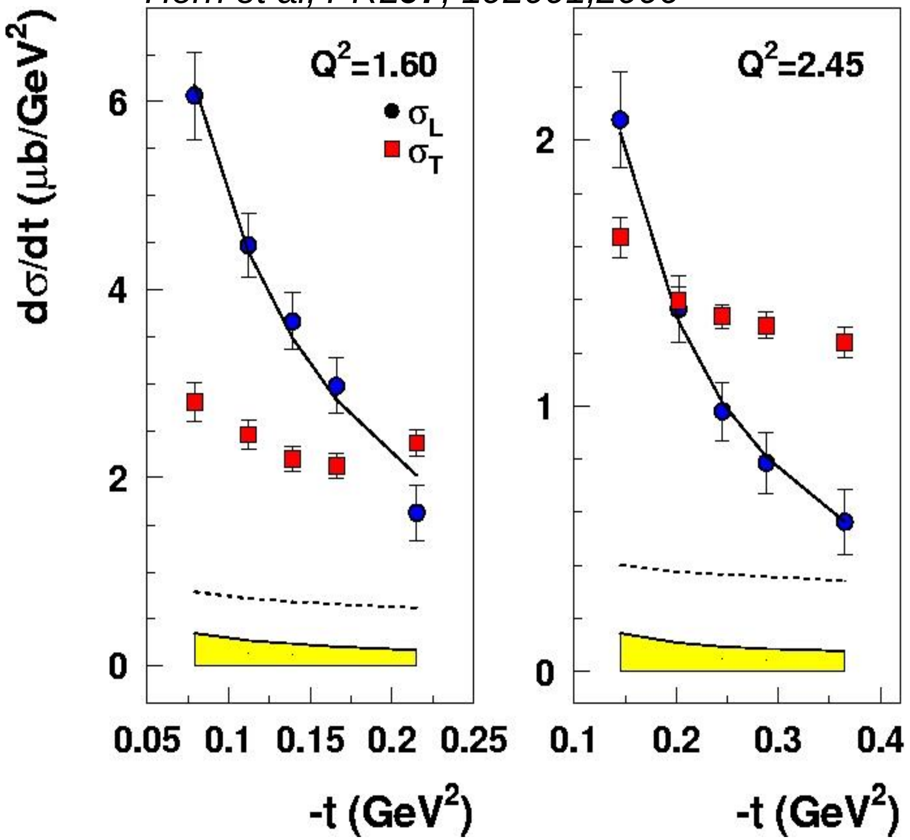
F_π Extraction from JLab data

- **Model is required to extract F_π from σ_L**
- **JLab F_π experiments used the VGL Regge model**
  [Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)]
  - Propagator replaced by π and ρ Regge trajectories
  - Most parameters fixed by photoproduction data
  - 2 free parameters: Λ_π, Λ_ρ
  - At small $-t$, σ_L only sensitive to Λ_π

$$F_\pi(Q^2) = \frac{1}{1+Q^2/\Lambda_\pi^2}$$

*Horn et al, PRL**97**, 192001,2006*



Model of: T.K. Choi, K.J. Kong, B.G. Yu [arXiv: 1508.00969]
may allow a second way to extract F_π from σ_L data.

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Newly Upgraded JLab Hall C

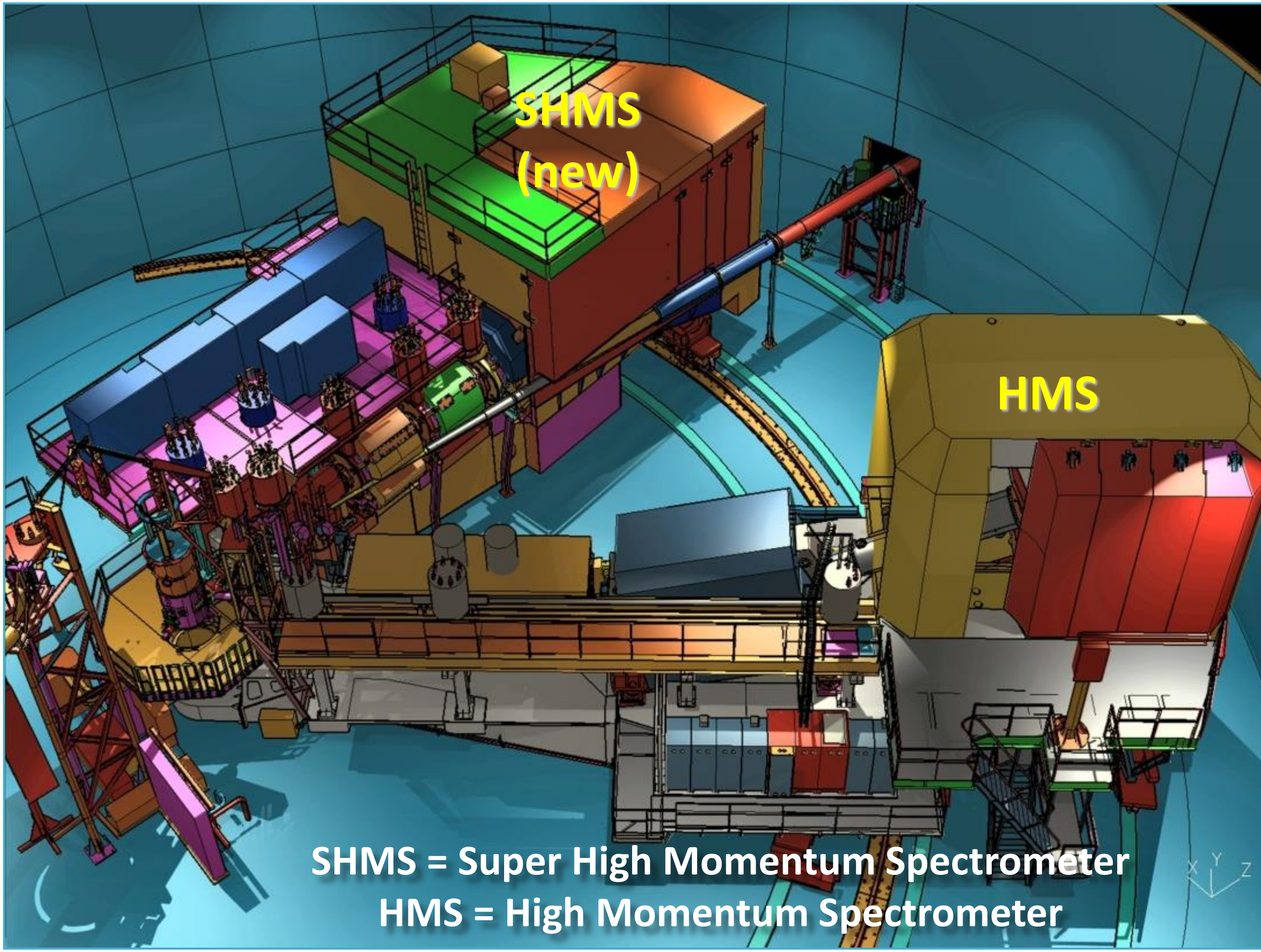
SHMS:
- 11 GeV/c Spectrometer
- Partner of existing 7 GeV/c **HMS**

MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter
- All derived from existing HMS/SOS detector designs

Well-Shielded Detector Enclosure

Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS



JLab Current and Projected Data

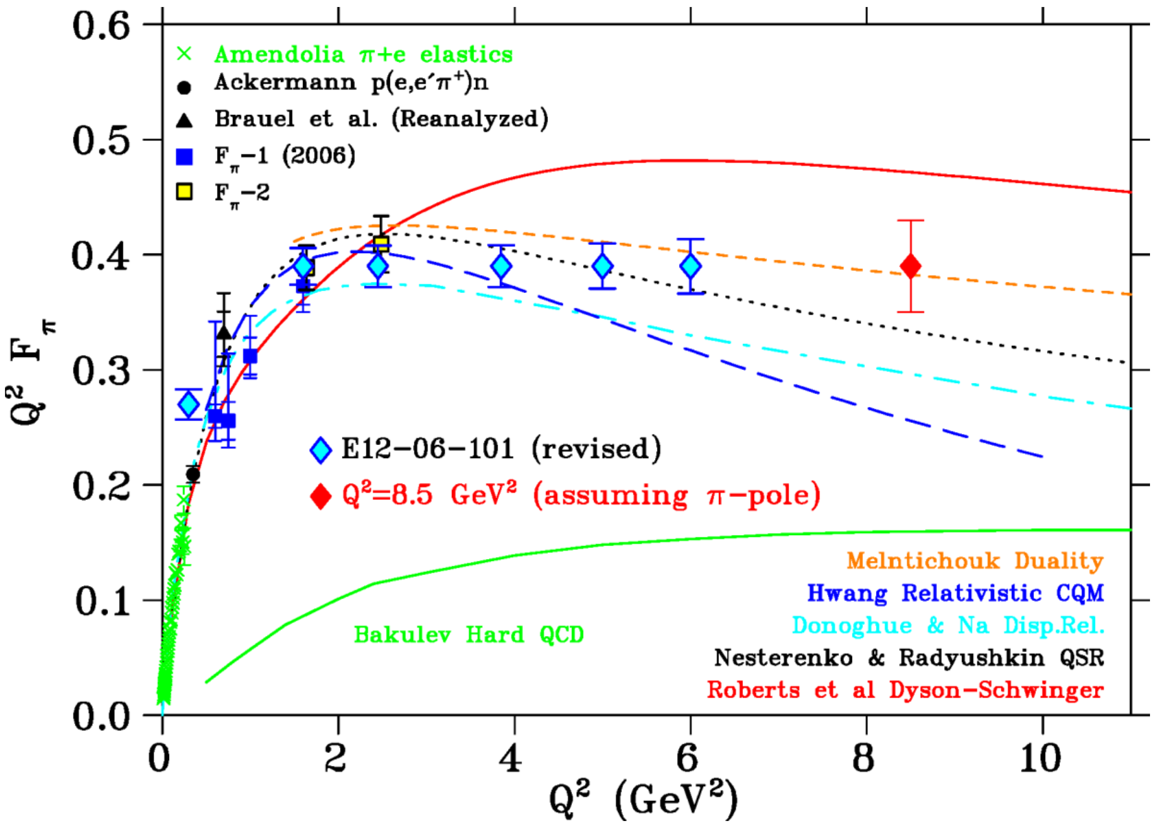
Upgraded JLab will allow measurement of F_π to much higher Q^2.

No other facility worldwide can perform this measurement.

New overlap points at Q^2=1.6,2.45 will be closer to pole to constrain $-t_{min}$ dependence.

New low Q^2 point will provide best comparison of the electroproduction extraction of F_π vs. elastic $\pi+e$ data.

E12-06-101 Spokespersons:
G.M. Huber, D. Gaskell



The ~10% measurement of F_π at Q^2=8.5 GeV^2 is at higher $-t_{min}$=0.45 GeV^2. Requires additional measurements (not yet approved) to verify π-pole dominance in σ_L.

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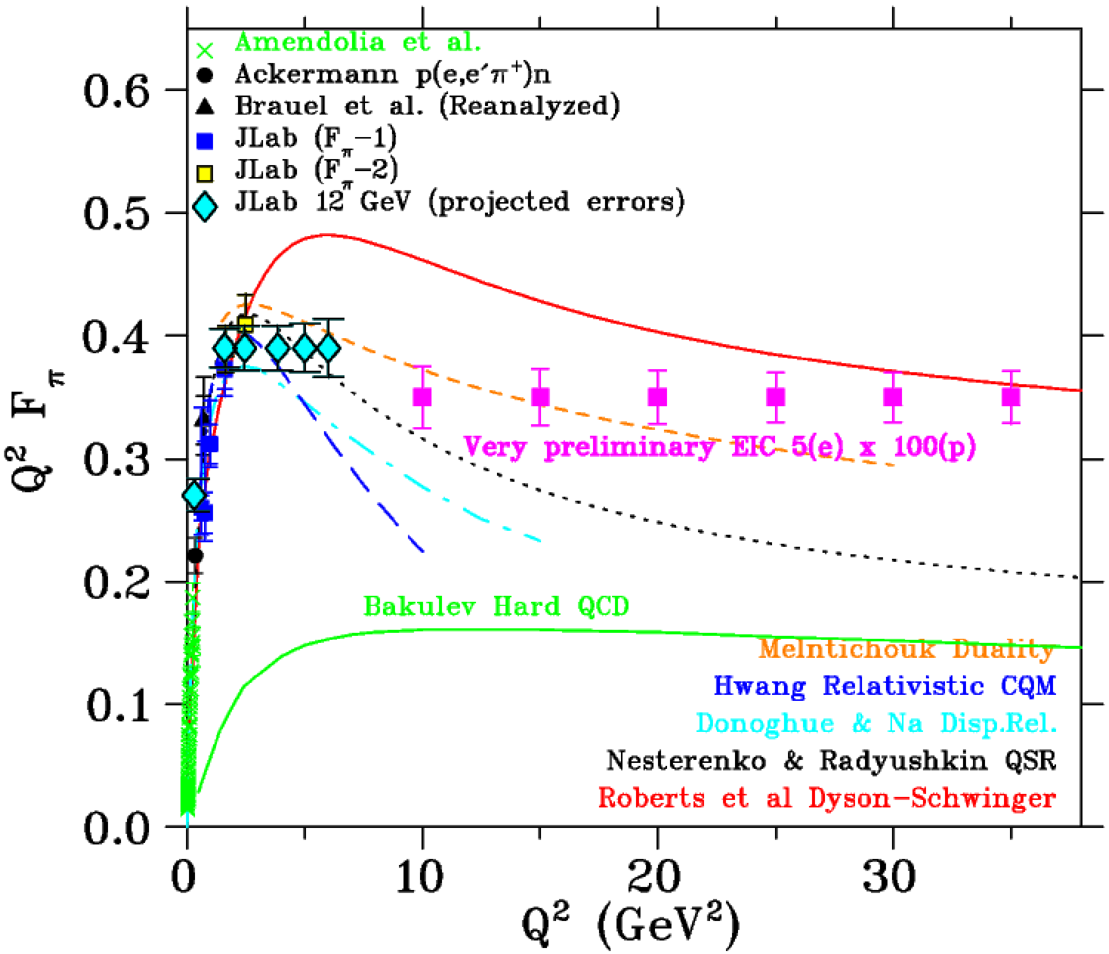
Electron-Ion Collider (Very Tentative)



Assumptions:

- $5(e^-) \times 100(p)$.
- Integrated L=20 fb^{-1}/yr.
- Identification of exclusive $p(e,e'\pi^+n)$ events.
- 10% exp. syst. unc.
- $R=\sigma_L/\sigma_T$ from VR model, and π pole dominance at small $-t$ confirmed in ^2H π^-/π^+ ratios.
- 100% syst. unc. in model subtraction to isolate σ_L.

Much more study needed to confirm assumptions.

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Summary

- **As I have illustrated, we are about to enter a revolutionary new period in our understanding of the charged pion form factor.**
- **Theoretical advances on many fronts:**
  - Links between Dynamical Chiral Symmetry Breaking (DCSB), quark confinement, and the generation of hadron mass are becoming clearer.
  - Lattice QCD proof-of-principle first F_π predictions for Q^2>3 GeV^2.
  - AdS/QCD allowing analytic calculations in the non-perturbative regime.
- **New experimental capabilities:**
  - Upgraded JLab Hall C will allow for the first time (since pioneering measurements at Cornel in 1970's) be able to acquire high quality data needed to test these theoretical developments with authority.
  - Longer term, an EIC may allow access to the hard QCD regime.
- **In coming years, we expect to shed substantive light on the properties and role of pions. Stay tuned!**

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