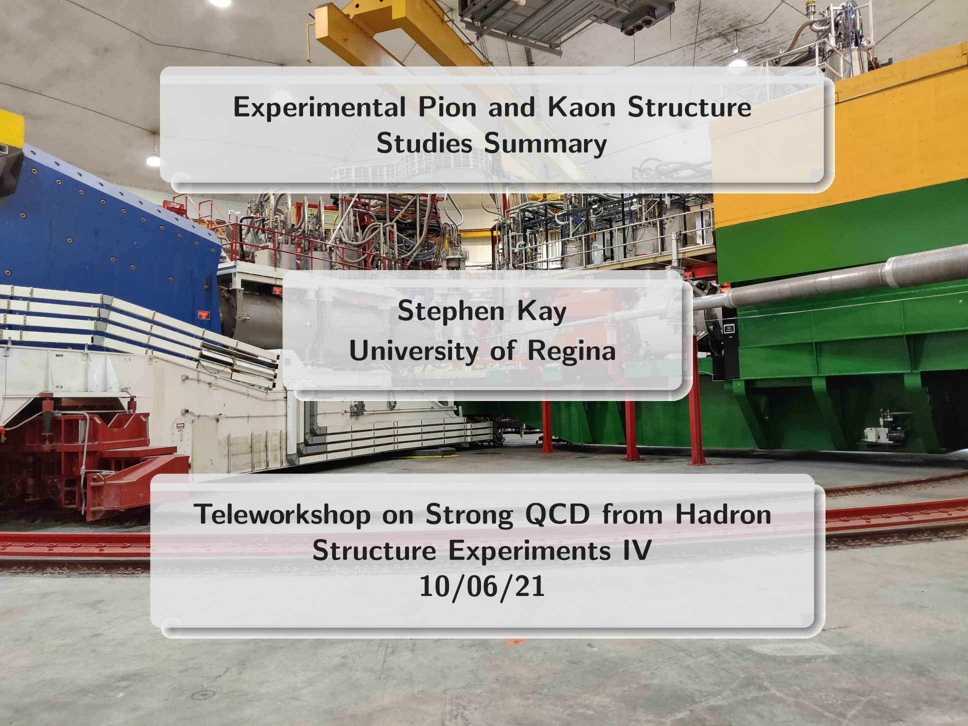
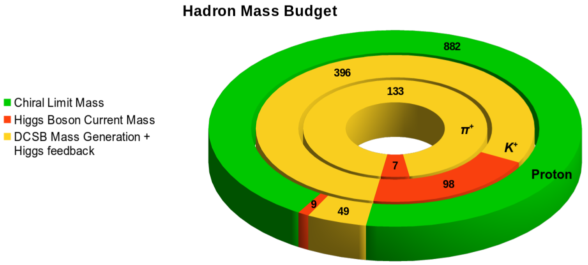


Experimental Pion and Kaon Structure Studies Summary

Stephen Kay
University of Regina

Teleworkshop on Strong QCD from Hadron Structure Experiments IV
10/06/21

Emergent Dynamics in QCD



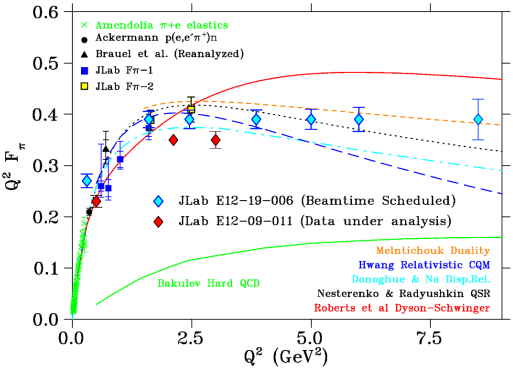
- Only the portion in red is from the Higgs current!
- Need to account for more than just protons!
- Properties of hadrons are emergent phenomena
- Experimental insight crucial to complete understanding of how hadrons and nuclei emerge from quarks and gluons

Meson Form Factors - Upcoming JLab Program

- E12-09-011 (Spokespeople: T. Horn, G Huber, P. Markowitz)
  - Ran in 2018-2019, analysis in progress
  - LT separated kaon cross section
  - Will attempt to extract F_K
- E12-19-006 (Spokespeople: D. Gaskell, T. Horn, G. Huber)
  - Low Q^2 part ran in June/July 2019
  - **Large experimental run this year (and in 2022)**
  - LT separated pion cross section
  - F_π to high Q^2 (8.5 GeV^2)
  - Pion reaction mechanism studies

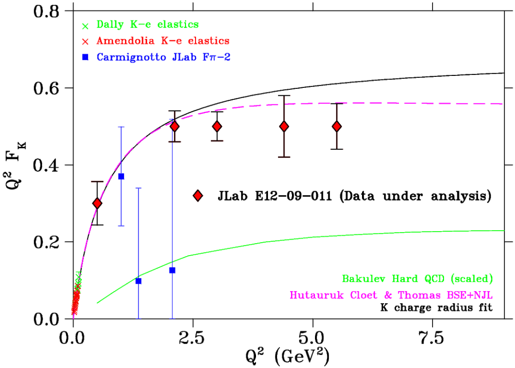
Current and Projected JLab F_π Data

- Points with projected errors shown below
- Low Q^2 data already acquired
- High Q^2 data this year and in 2022
- y positioning of points arbitrary

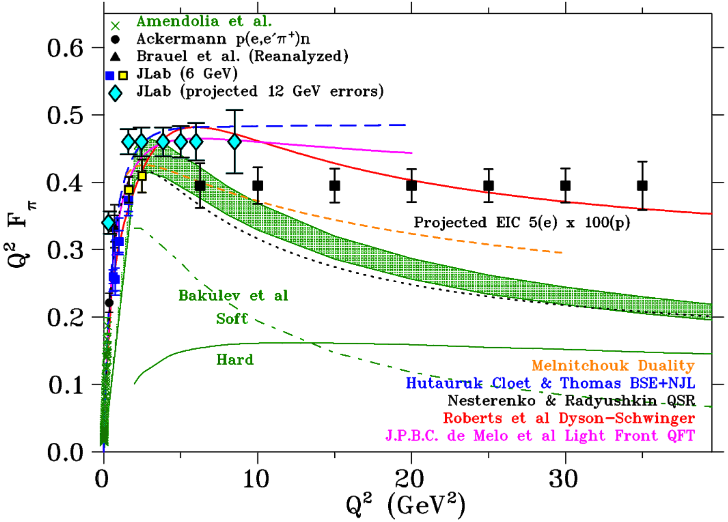


Current and Projected JLab F_K Data

- Points with projected errors shown below
- Data has all been acquired and analysis is in progress
- *y* positioning of points arbitrary



EIC Kinematic Reach for F_π



Extracting F_π at JLab

- **We do not use a Born Term model**
- Only reliable approach for extracting F_π from σ_L is to use a model that incorporates the π^+ production mechanism and the spectator nucleon
- JLab F_π experiments so far use the VGL Regge model
  - Reliably describes σ_L across a wide kinematic domaon
- Want a better understanding of the model dependence
- There has been considerable recent interest
  - T.K. Choi, K.J. Kong, B.G. Yu, arXiv 1508.00969
  - T. Vrancx, J. Ryckebusch, PRC 89(2014)025203
  - M.M. Kaskulov, U. Mosel, PRC 81(2010)045202
  - S.V. Goloskokov, P.Kroll, EPJC 65(2010)137
- **We aim to publish our experimentally measured cross section data so that updated values of F_π can be extracted as the models improve**

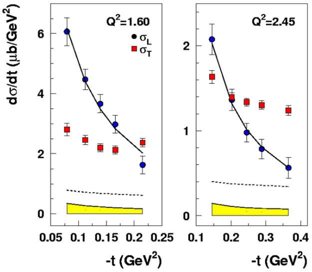
VGL - Vanderhaeghen-Guidal-Laget Model - Vanderhaeghen, Guidal, Laget, PRC 57(1998) 1454

$F_\pi(Q^2)$ from JLab Data

VGL model incorporates π^+ production mechanism and spectator neutron effects, also, includes more than just the t-channel!

- Feynman propagator - $\frac{1}{t-m_\pi^2}$ replaced by π and ρ Regge propagators
- Represents the exchange of a series of particles, compared to a single particle
- Free parameters - $\Lambda_\pi, \Lambda_\rho$ - Trajectory cutoff parameters
- At small $-t$, σ_L only sensitive to F_π

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



Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature. Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.
$\Lambda_\pi^2 = 0.513, 0.491\ GeV^2$, $\Lambda_\rho^2 = 1.7\ GeV^2$
T. Horn, et al., PRL 97(2006) 192001

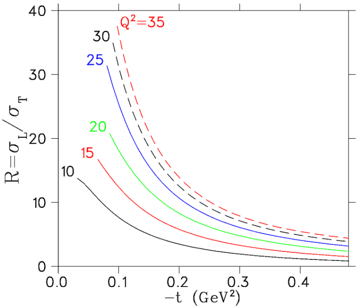
Form Factors at the EIC

- JLab measurements push the Q^2 reach of data considerably
- Still can't answer some key questions regarding the emergence of hadronic mass however
- Can we get quantitative guidance on the emergent pion mass mechanism?
  $\rightarrow$ Need F_π data for $Q^2 = 10 - 40\ GeV^2$
- What is the size and range of interference between emergent mass and the Higgs-mass mechanism?
  $\rightarrow$ Need F_K data for $Q^2 = 10 - 20\ GeV^2$
- Beyond what is possible at JLab in the 12 GeV era
  - Need a different machine $\rightarrow$ **The Electron-Ion Collider (EIC)**

But... we need models for other purposes too!

σ_L Isolation with a Model at the EIC

- QCD scaling predicts $\sigma_L \propto Q^{-6}$ and $\sigma_T \propto Q^{-8}$
- At the high Q^2 and W accessible at the EIC, phenomenological models predict $\sigma_L \gg \sigma_T$ at small $-t$
- Can attempt to extract σ_L by using a model to isolate dominant $d\sigma_L/dt$ from measured $d\sigma_{UNS}/dt$
- Critical to confirm the validity of the model used!



Predictions are assuming $\epsilon > 0.9995$ with the kinematic ranges seen earlier

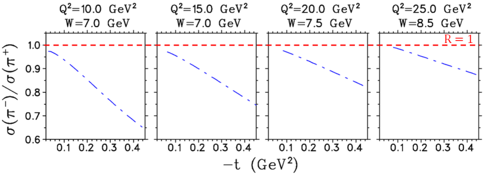
T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

Model Validation via π^-/π^+ ratios

- Measure exclusive ${}^2H(e,e'\pi^+n)n$ and ${}^2H(e,e'\pi^-p)p$ in same kinematics as $p(e,e'\pi^+n)$
- π t-channel diagram is purely isovector $\rightarrow$ G-Parity conserved

$$R = \frac{\sigma\left[n(e,e'\pi^-p)\right]}{\sigma\left[p(e,e'\pi^+n)\right]} = \frac{|A_V - A_S|^2}{|A_V - A_S|^2}$$

- R will be diluted if σ_T *not* small *or* if there are significant non-pole contributions to σ_L
- Compare R to model expectations



- Also need good database of Λ/Σ^0 cross sections for K^+

T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

Our Wishlist

- Need more models of the $p(e, e'\pi^+ n)$ and $p(e, e'K^+\Lambda)$ reactions
  - Essential that values of F_π and F_K are adjustable in the model
  - Can use FF as free parameter in the data fit
  - VGL result was fit to the σ_L data by varying the cutoff parameter
- The more models we have available, the better!
- Model for extraction of σ_L from unseparated cross section will be critical for any future EIC data

S.J.D. Kay, D. Gaskell, T. Horn, G.M. Huber, P. Markowitz, V. Berdnikov, J. Roche, P. Stepanov, C. Yero, N. Heinrich, M. Junaid, V. Kumar , J. Murphy, R. Trotta, A. Usman

This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), FRN: SAPIN-2021-00026, and the National Science Foundation (NSF), PHY1714133 and PHY2012430

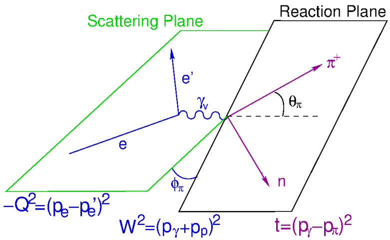
- The physical cross section for the electroproduction process is given by -

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

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

- $\epsilon \rightarrow$ Virtual photon polarisation

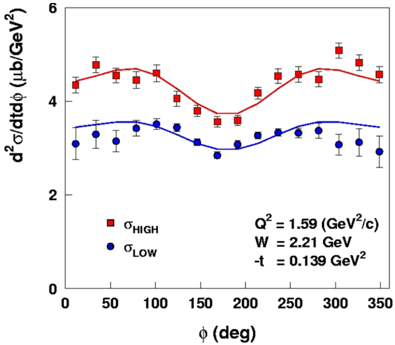
- L-T separation required to isolate σ_L from σ_T
- Need data at lowest $-t$ possible, σ_L has maximum pole contribution here



Measuring $\frac{d\sigma_L}{dt}$ at JLab

- Rosenbluth separation required to isolate σ_L
  - Fix W, Q^2 and $-t$, measure cross section at two beam energies
  - Carry out simultaneous fit at two different ϵ values to determine interference terms

- Careful control of point-to-point systematics crucial, $1/\Delta\epsilon$ error amplification in σ_L
- Spectrometer acceptance, kinematics and efficiencies must all be carefully studied and understood



T. Horn, et al., PRL 97(2006) 192001