Pion and Kaon Form Factor Measurements at the EIC

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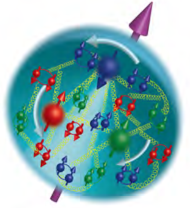
CAP Congress 2022
07/06/22

Outline

- Meson form factors
- Form factors at the EIC through DEMP
- Kaon form factors at the EIC - Outlook

Cover Image - Brookhaven National Lab, https://www.flickr.com/photos/brookhavenlab/

Understanding Dynamic Matter

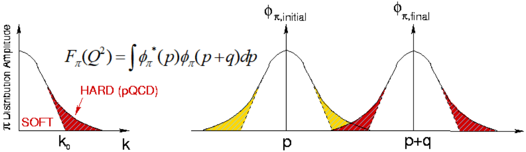


- Interactions and structure are not isolated ideas in nuclear matter
  - Observed properties of nucleons and nuclei (mass, spin) emerge from this complex interplay
  - Properties of hadrons are emergent phenomena
- Mechanism known as **D**ynamical **C**hiral **S**ymmetry **B**reaking (**DCSB**) plays a part in generating hadronic mass
- QCD behaves very differently at short and long distances (high and low energy)
  - How do our two distinct regions of QCD behaviour connect?
- **A major puzzle of the standard model to try and resolve!**
- How can we examine hadronic structure?

Image - A. Deshpande, Stony Brook University

Meson Form Factors

- Charged pion ($\pi^{\pm}$) and Kaon ($K^{\pm}$) form factors (F_{π}, F_{K}) are key QCD observables
  - Describe the spatial distribution of partons within a hadron



- Meson wave function can be split into ϕ_{π}^{soft} $(k < k_0)$ and ϕ_{π}^{hard}, the hard tail
  - Can treat ϕ_{π}^{hard} in pQCD, cannot with ϕ_{π}^{soft}
  - Form factor is the overlap between the two tails (right figure)
- F_{π} **and** F_{K} **of special interest in hadron structure studies**
  - π - Lightest and simple QCD quark system
  - K - Another simple system, contains strange quark

The Pion in pQCD

- At very large Q^2, F_π can be calculated using pQCD

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

- As $Q^2 \rightarrow \infty$, the pion distribution amplitude, ϕ_π becomes -

$$\phi_\pi(x) \rightarrow \frac{3f_\pi}{\sqrt{n_c}}x(1-x)$$ $f_\pi = 93\ MeV$, $\pi^+ \rightarrow \mu^+\nu$ decay constant

- F_π can be calculated with pQCD in this limit to be -

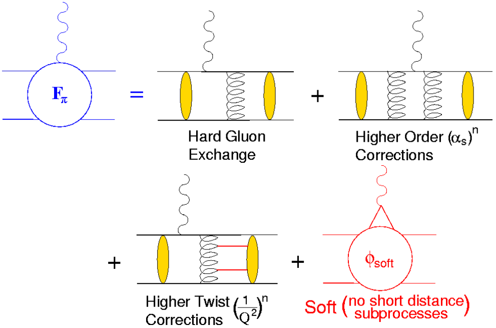
$$Q^2 F_\pi \xrightarrow[Q^2\rightarrow\infty]{} 16\pi\alpha_s(Q^2)f_\pi^2$$

- This is a **rigorous** prediction of pQCD
- Q^2 **reach of existing data doesn't extend into this region**
  - Need unique, cutting edge experiments to push into this region

Eqns - G.P. Lepage, S.J. Brodsky, PLB 87, p359, 1979

The Pion in pQCD

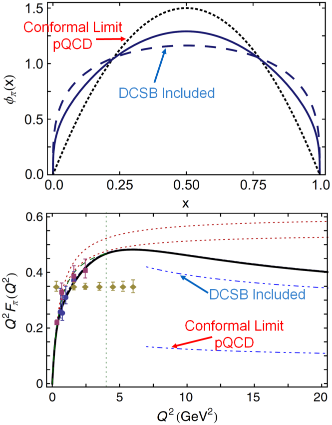
- At experimentally accessible Q^2, both the hard and soft components contribute



- Interplay of hard and soft contributions poorly understood
- Experiments can study the transition from soft to hard regime

Connecting Pion Structure and Mass Generation

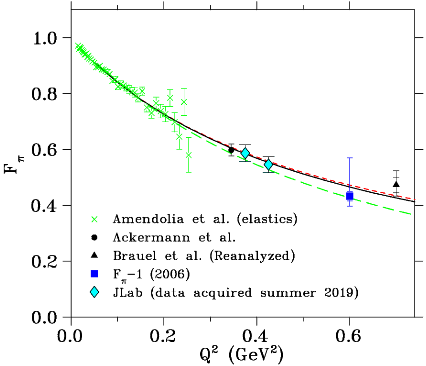
- ϕ_π as shown before has a broad, concave shape
- Previous pQCD derivation (conformal limit) did not include DCSB effects
- Incorporating DCSB changes $\phi_\pi(x)$ and brings F_π calculation much closer to the data
  - "Squashes down" PDA
- Pion structure and hadron mass generation are interlinked
- How can we measure F_π or F_K?



L. Chang, et al., PRL110(2013) 132001, PRL111(2013), 141802

Measurement of F_π - Low Q^2

- At low Q^2, F_π can be measured model independently
  - High energy elastic π^- scattering from atomic electrons in H
- CERN SPS - 300 GeV pions to measure F_π up to $Q^2 = 0.25\ GeV^2$
- Used data to extract pion charge radius - $r_\pi = 0.657 \pm 0.012\ fm$
- Maximum accessible Q^2 approximately proportional to pion beam energy
  - $Q^2 = 1\ GeV^2$ requires 1 TeV pion beam (!)

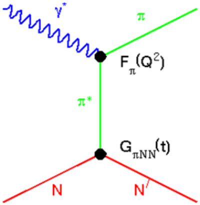


Amendolia, et al., NPB 277(1986) p168, P. Brauel, et al., ZPhysC (1979), p101, H. Ackermann, et al., NPB137 (1978), p294

Measurement of F_π at Higher Q^2

- To access F_π at high Q^2, must measure F_π indirectly
  - Use the "pion cloud" of the proton via $p(e,e'\pi^+)n$
- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In the Born term model, F_π^2 appears as -

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



- We do not use the Born term model
- Drawbacks of this technique -
  - Isolating σ_L experimentally challenging
  - Theoretical uncertainty in F_π extraction
    - Model dependent
      (smaller dependency at low -t)

Form Factors at the EIC

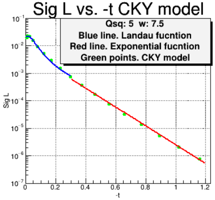
- Upcoming JLab measurements push the Q^2 reach of pion (F_π) and kaon (F_K) form factor data considerably
- Still can't answer some key questions regarding the emergence of hadronic mass however
- Can we get quantitative guidance on the emergent pion mass mechanism?
  $\rightarrow$ Need F_π data for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

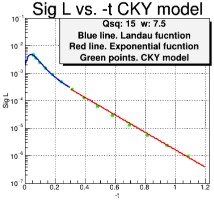
DEMP Studies at the EIC

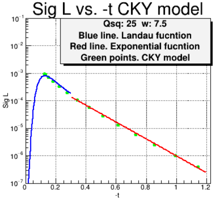
- Measurements of the $p(e, e'\pi^+ n)$ reaction at the EIC can potentially extend the Q^2 reach of F_π measurements even further
- A challenging measurement however
  - Need good identification of $p(e, e'\pi^+ n)$ triple coincidences
  - Conventional L-T separation not possible $\rightarrow$ would need lower than feasible proton energies to access low ϵ
  - Need to use a model to isolate $d\sigma_L/dt$ from $d\sigma_{uns}/dt$
- Utilise new EIC software framework to assess the feasibility of the study with updated design parameters
  - Feed in events generated from a DEMP event generator
  - Multiple detector concepts to evaluate
- Event generator being modified to generate kaon events

DEMP Event Generator

- Want to examine exclusive reactions
  - $p(e, e'\pi^+ n)$ exclusive reaction is reaction of interest
    $\rightarrow p(e, e'\pi^+)X$ SIDIS events are background
- Generator uses Regge-based $p(e, e'\pi^+)n$ model from
  T.K. Choi, K.J. Kong and B.G. Yu (CKY) - arXiv 1508.00969
  - MC event generator created by parametrising CKY σ_L, σ_T for
    $5 < Q^2 < 35$, $2 < W < 10$, $0 < -t < 1.2$







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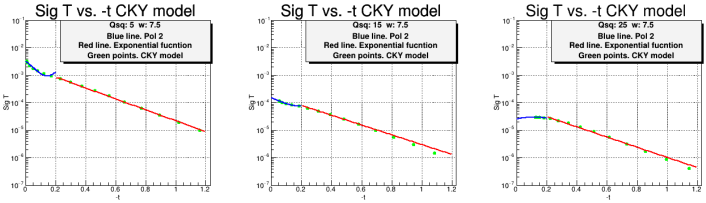
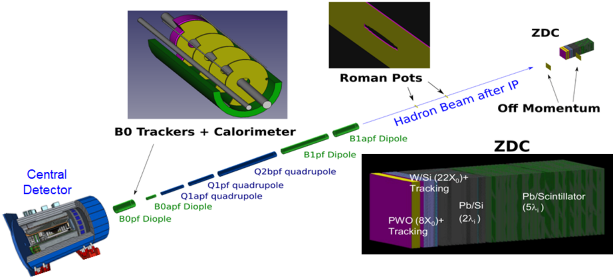


EIC Detector Overview



- Feed generator output into detector simulations
- Far forward detectors critical for form factor studies
- Current simulation effort has been focused on the EIC Comprehensive Chromodynamics Experiment (ECCE)
  - `https://www.ecce-eic.org/`

Selecting Good Simulated Events

- Pass through a full Geant4 simulation (ECCE)
  - More realistic estimates of detector acceptance/performance than earlier studies
- Identify $e'\pi^+n$ triple coincidences in the simulation output
- For a good triple coincidence event, require -
  - **Exactly** two tracks
    - One positively charged track going in the $+z$ direction (π^+)
    - One negatively charged track going in the $-z$ direction (e')
  - At least one hit in the zero degree calorimeter (ZDC)
    - For 5 (e', GeV) on 100 (p, GeV) events, require that the hit has an energy deposit over 40 GeV
- Both conditions must be satisfied
- Determine kinematic quantities for remaining events

Simulation Results - Neutron Reconstruction

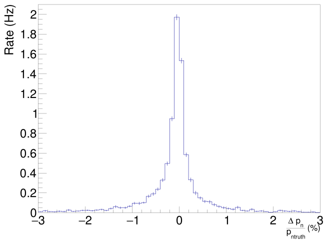
- High energy ZDC hit requirement used as a veto
  - ZDC neutron ERes is relatively poor though

$$\frac{35\%}{\sqrt{E}} \oplus 2\%$$

- However, position resolution is excellent, $\sim 1.5\ mm$
- Combine ZDC position info with missing momentum track to reconstruct the neutron track

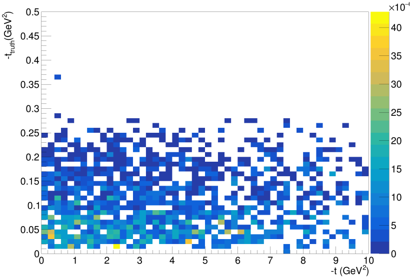
$$p_{miss} = |\vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}|$$

- Use ZDC angles, θ_{ZDC} and ϕ_{ZDC} rather than the missing momentum angles, θ_{pMiss} and ϕ_{pMiss}
- Adjust E_{Miss} to reproduce m_n
- After adjustments, reconstructed neutron track matches "truth" momentum closely



Simulation Results - t Reconstruction

- Reconstruction of $-t$ from detected e' and π^+ tracks proved highly unreliable
  - $-t = -(p_e - p_{e'} - p_\pi)^2$
- Calculation of $-t$ from reconstructed neutron track matched "truth" value closely
  - $-t_{alt} = -(p_p - p_n)^2$
- Only possible due to the excellent position accuracy provided by a good ZDC



- Note that the x-axis $-t$ scale here runs to 10 GeV^2!

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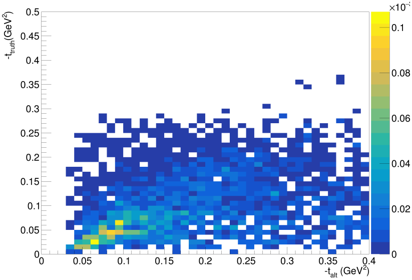
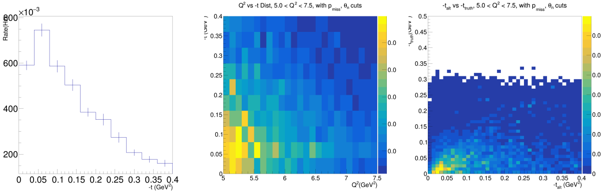
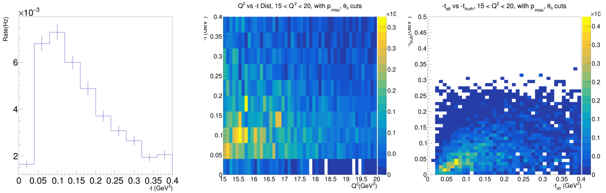


- x-axis $-t$ scale an order of magnitude smaller now!

Simulation Results - Q^2 $5 - 7.5$ GeV^2



- Predicted $e'\pi^+n$ triple coincidence rate, binned in Q^2 and $-t$
  - 5 (e', GeV) on 100 (p, GeV) events
  - $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$ assumed
  - $-t$ bins are 0.04 GeV^2 wide
  - Cut on θ_n $(\theta_n = 1.45 \pm 0.5^\circ)$ and $\vec{p}_{miss} = \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}$ (varies by Q^2 bin) to simulate removal of SIDIS background
    - New cut on difference between p_{miss} and detected ZDC angles implemented too, $|\Delta\theta| < 0.6^\circ$, $|\Delta\phi| < 3.0^\circ$
- $-t_{min}$ migrates with Q^2 as expected



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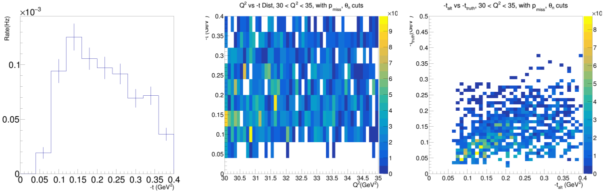

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Isolating σ_L from σ_T in an e-p Collider

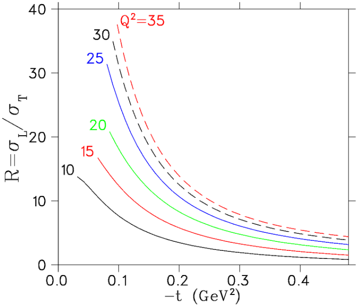
- For a collider -

$$\epsilon = \frac{2(1-y)}{1+(1-y)^2} \quad \text{with} \quad y = \frac{Q^2}{x(s_{tot} - M_N^2)}$$

  - y is the fractional energy loss
- Systematic uncertainties in σ_L magnified by $1/\Delta\epsilon$
  - Ideally, $\Delta\epsilon > 0.2$
- To access $\epsilon < 0.8$ with a collider, need $y > 0.5$
  - Only accessible at small s_{tot}
  - Requires low proton energies ($\sim 10\ GeV$), luminosity too low
- **Conventional L-T separation not practical, need another way to determine σ_L**

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

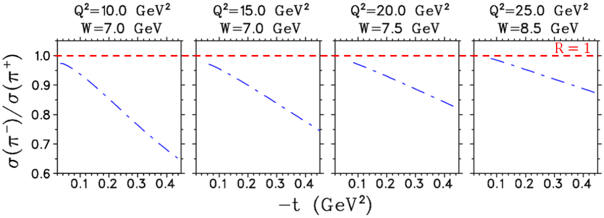
T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

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

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

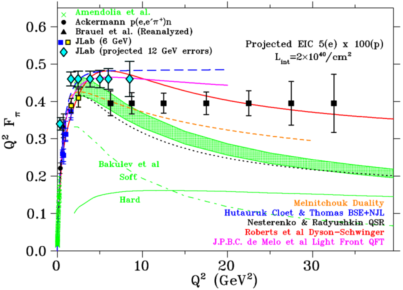
- R will be diluted if σ_T *not* small *or* if there are significant non-pole contributions to σ_L
- Compare R to model expectations



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

EIC F_π Data

- ECCE appears to be capable of measuring F_π to $Q^2 \sim 32.5\ GeV^2$
- **Error bars represent real projected error bars**
  - 2.5% point-to-point
  - 12% scale
  - $\delta R = R$, $R = \sigma_L/\sigma_T$
  - $R = 0.013 - 014$ at lowest $-t$ from VR model
- Uncertainties dominated by R at low Q^2
- Statistical uncertainties dominate at high Q^2

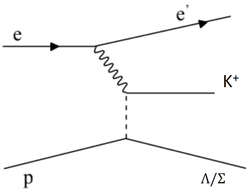


- Results look promising, need to test π^- too
- More details in upcoming ECCE NIM paper

F_K at the EIC - Challenges and Possibilities

- F_K at the EIC via DEMP will be extremely challenging

- Would need to measure two reactions
  - $p(e, e'K^+\Lambda)$
  - $p(e, e'K^+\Sigma)$
  - Need both for pole dominance tests



$$R = \frac{\sigma_L\left[p(e, e'K^+\Sigma^0)\right]}{\sigma_L\left[p(e, e'K^+\Lambda^0)\right]} \rightarrow R \approx \frac{g^2_{pK\Sigma}}{g^2_{pK\Lambda}}$$

- Consider just the Λ channel for now
  - Λ plays a similar role to neutron in π studies
  - Very forward focused, **but**, Λ will decay
    - $\Lambda \rightarrow n\pi^0$ - ~ 36 %
    - $\Lambda \rightarrow p\pi^-$ - ~ 64 %
  - Neutral channel potentially best option
    - **Very challenging 3 particle final state**

F_K at the EIC - Challenges and Possibilities

- Need to update DEMPGen with a kaon module
- Regina MSc student (Love Preet) is working on this module
  - Parametrisation based upon previous data and Vrancx/Ryckebusch Regge model guidance
  - `http://rprmodel.ugent.be/calc/`
- Use similar approach to pion model in generator
  - Need Λ and Σ modules
- In parallel, will begin studies of Λ reconstruction in ZDC
  - Can use particle gun
  - May need to use likelihood analysis for Λ reconstruction
  - Should also examine charged decay channel
- Kaon model updates and simulations will be focus over the summer

Form Factors at the EIC - Outlook

- EIC has the potential to push the Q^2 reach of F_π measurements into the 30 GeV^2 range
  - Can we measure F_K too?
- F_π work already featured in the EIC yellow report
- Worked closely with the ECCE proto-collaboration
  - Carrying out feasibility studies
  - Existing DEMP event generator utilised
  - Kaon event generator and simulations in progress
  - **Activities were a priority for the ECCE Diffractive and Tagging group**
  - Will continue to develop simulations with Detector 1 collaboration
- Results from simulation have been written up in an ECCE analysis note and NIM paper
  - Expect to see this soon!

R. Abdul Khalek et al. EIC Yellow Report. 2021. arXiv:2103.05419, Sections 7.2.1 and 8.5.1

Thanks for listening, any questions?

Meson Structure Working Group - S.J.D. Kay, G.M. Huber, Z. Ahmed, Ali Usman, John Arrington, Carlos Ayerbe Gayoso, Daniele Binosi, Lei Chang, Markus Diefenthaler, Rolf Ent, Tobias Frederico, Yulia Furletova, Timothy Hobbs, Tanja Horn, Thia Keppel, Wenliang Li, Huey-Wen Lin, Rachel Montgomery, Ian L. Pegg, Paul Reimer, David Richards, Craig Roberts, Dmitry Romanov, Jorge Segovia, Arun Tadepalli, Richard Trotta, Rik Yoshida

EIC-Canada

This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), FRN: SAPPJ-2021-00026

The University of Regina is situated on the territories of the nehiyawak, Anihsināpēk, Dakota, Lakota, and Nakoda, and the homeland of the Métis/Michif Nation. The University of Regina is on Treaty 4 lands with a presence in Treaty 6.