Studying meson structure at the EIC through the Sullivan process

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Perceiving EHM through AMBER@CERN - VII
10/05/22

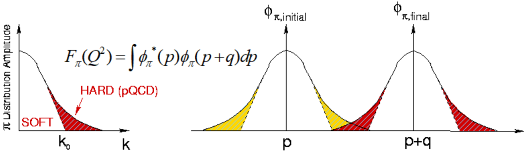
Outline

- Meson Form Factors
- Form Factors at the EIC through DEMP
- Kaon Form Factors at the EIC - Outlook
- Structure Functions at the EIC

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

Meson Form Factors

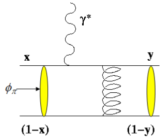
- Charged pion ($\pi^{\pm}$) and Kaon ($K^{\pm}$) form factors (F_{π}, F_K) are key QCD observables
  - Describe the spatial distribution of partons within a hadron



- 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

Rigorous Predictions for the Pion from pQCD

- At very large four-momentum transfer squared, Q^2, F_π can be calculated using pQCD



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

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

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

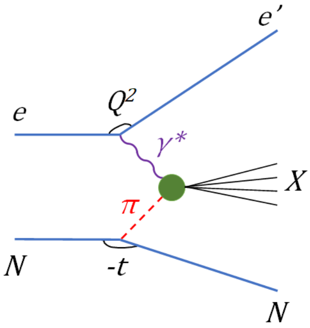
$$Q^2 F_\pi \xrightarrow[Q^2 \to \infty]{} 16\pi\alpha_s(Q^2) f_\pi^2$$

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

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

The Sullivan Process

- At low $-t$, meson electroproduction cross section displays behaviour characteristic of pole dominance
- Can use the Sullivan process to study meson structure
  - Scattering from nucleon-meson fluctuations
- Can study form factors
  - X is a real π or K
- Can study structure functions too
  - Tagged DIS

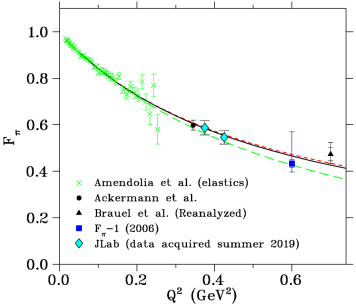


- Low Q^2 data vital, establish that form factor extraction using this method is measuring the **physical pion form factor**

F_π Validation - Electroproduction Cross Check

- Low Q^2 data is an important test
  - Does electroproduction really measure the on-shell form factor?

- Test with $p(e, e'\pi^+)n$ measurements at same kinematics as $e\pi^+$ elastics
- New data points at $Q^2 = 0.375$ and 0.425 $GeVc^{-2}$, DESY (Ackermann) point at 0.35 $GeVc^{-2}$
- -t closer to pole than DESY data, 0.008 GeV^2 vs 0.013 GeV^2



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

- In addition to new low Q^2 data, JLab measurements will extend to $Q^2 = 8.5$ GeV^2

Form Factors at the EIC

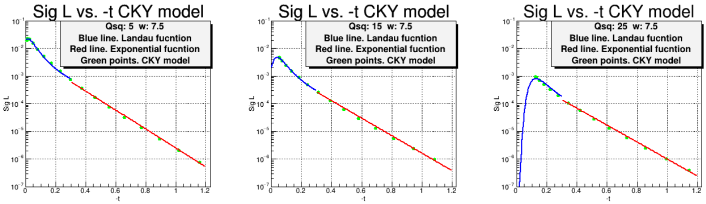
- Upcoming JLab measurements push the Q^2 reach of pion (F_π) and kaon (F_K) form factor data considerably
- Still can't answer some key questions regarding the emergence of hadronic mass however
- Can we get quantitative guidance on the emergent pion mass mechanism?
  $\rightarrow$ Need F_π data for $Q^2 = 10 - 40\ GeVc^{-2}$
- 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 have the potential to 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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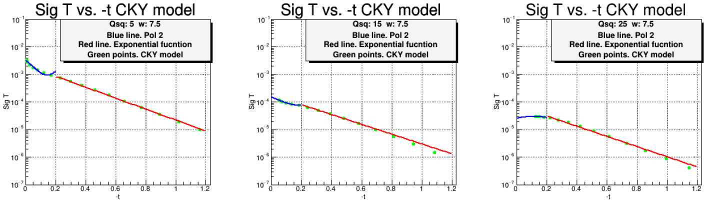
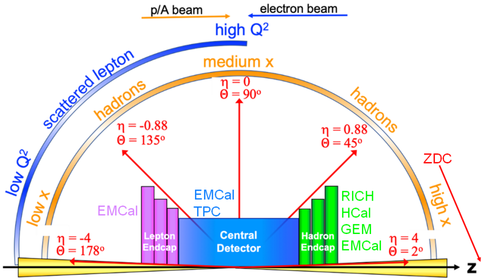


EIC Detector Overview



- Feed generator output into detector simulations
- Various detector concepts
- All share common elements
- 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

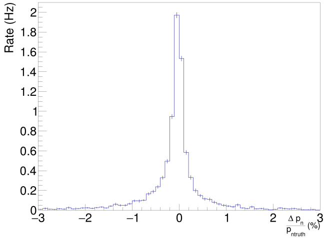
- High energy ZDC hit requirement used as a veto
  - ZDC neutron ERes is relatively poor though

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

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

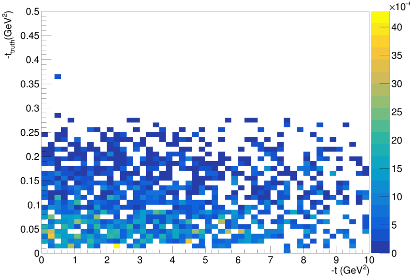
$$p_{miss} = |p_e + p_p - p_{e'} - p_{\pi^+}|$$

- 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 $-t$ scale here runs to 10 GeV^2!

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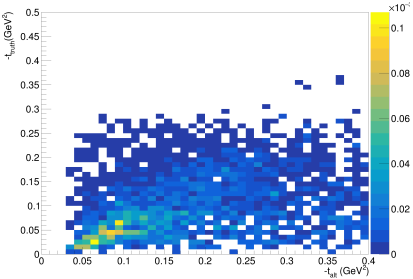
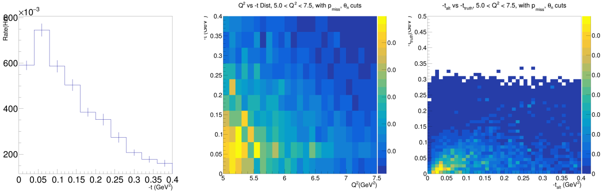
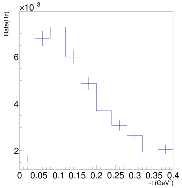


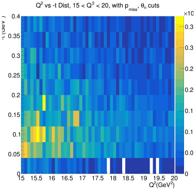
Simulation Results

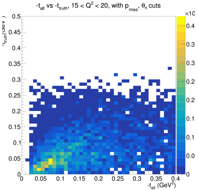


- Predicted $e'\pi^+n$ triple coincidence rate, binned in Q^2 and $-t$
  - 5 (e', GeV) on 100 (p, GeV) events
  - $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$ assumed
  - $-t$ bins are 0.04 GeV^2 wide
  - Cut on θ_n ($\theta_n = 1.45 \pm 0.5°$) and $\vec{p}_{miss} = \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}$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

Simulation Results







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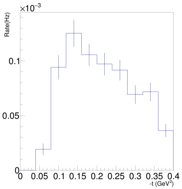

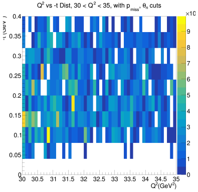

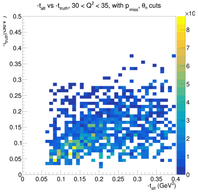

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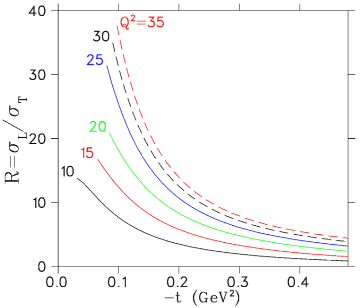
σ_L Isolation With a Model at the EIC

- 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

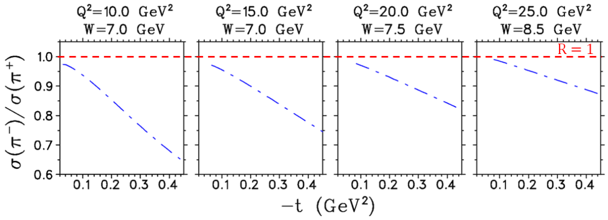
T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

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

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

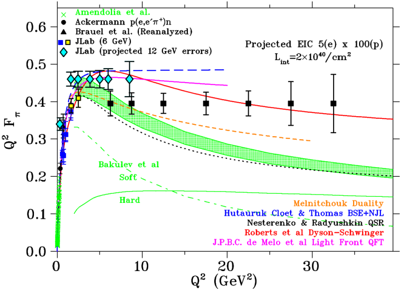
- R will be diluted if σ_T *not* small *or* if there are significant non-pole contributions to σ_L
- Compare R to model expectations



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

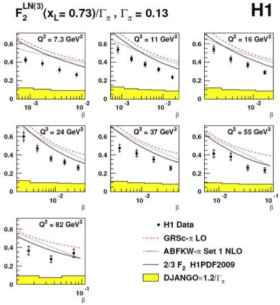
- Kaon form factor measurements at the EIC via DEMP measurements will be extremely challenging
- Would need to measure two reaction channels
  - $p(e, e'K^+\Lambda)$
  - $p(e, e'K^+\Sigma)$
  - Need both for pole dominance tests
- Exclusive reactions, need to detect all products
- Consider just the Λ channel for now
  - Λ plays a similar role to neutron in pion studies
  - Very forward focused, **but**, Λ will decay
  - Two decay channels
    - $\Lambda \rightarrow n\pi^0$ - ~ 36 %
    - $\Lambda \rightarrow p\pi^-$ - ~ 64 %
  - Neutral channel potentially best option
    - **Very challenging 3 particle final state**
- But... we should still see what we can do!

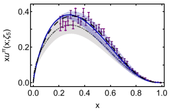
F_K at the EIC - Challenges and Possibilities

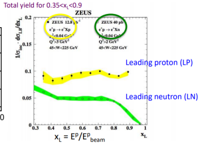
- Need to update DEMPGen with a kaon module
- Regina MSc student is working on parametrising the Vrancx Ryckebusch model
  - `http://rprmodel.ugent.be/calc/`
- Use similar approach to pion model in generator
  - Need Λ and Σ modules
- In parallel, will begin studies of Λ reconstruction in ZDC
  - Can 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 our focus over the summer
- Colleagues elsewhere have been looking at other aspects of meson structure too
  - $\rightarrow$ Pion and Kaon structure functions

Structure Functions at the EIC - Brief Overview

- Knowledge of the pion structure function is limited
  - HERA TDIS data - low x through the Sullivan process (top)
  - Pionic-Drell-Yan from nucleons in nuclei at large x (bottom)
- One π exchange is the dominant mechanism
  - Can extract π SF
  - In practice, use in-depth model and kinematic studies, include rescattering, absorption...



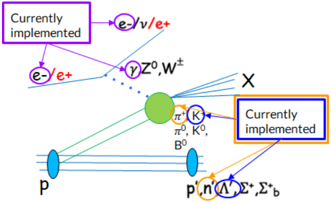




Figures, DESY 08-176 JHEP06 (2009) 74 Eur. Phy. J. C (2020) DOI:10.1140/epjc/s10052-020-08578-4
Slides and images courtesy of R. Trotta, CUA, trotta@cua.edu

Structure Functions at the EIC - Brief Overview

- Use fast Monte Carlo that includes Sullivan process for simulations
  - PDFs, form factor, fragmentation function projections

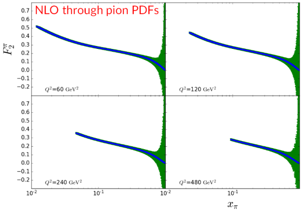


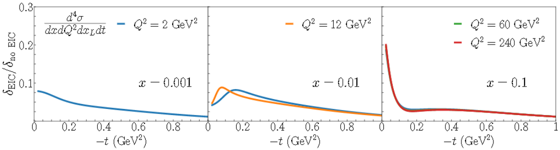
- π SF: Measure DIS cross section with tagged n at small $-t$
- K SF: Measure DIS cross section with tagged Λ/Σ at small $-t$
- Various beam energy combinations
  - 5 on 41, 5 on 100, 10 on 100, 10 on 135, 18 on 275
- Only e-P currently implemented, want to incorporate e-D too

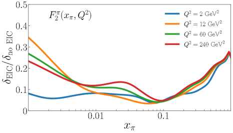
Slides and images courtesy of R. Trotta, CUA, trotta@cua.edu

Structure Functions at the EIC - Brief Overview

- Reasonable uncertainties in mid to large x
  - Increase rapidly as $x \to 1$
- **Despite this, coverage in mid to high x unprecedented**
- Access to a significant range of Q^2 and x for small $-t$
  - Allows for improved insights into the gluonic content of π







J Arrington, et al., J. Phys. G (2021) arXiv:2102.11788.
Slides and images courtesy of R. Trotta, CUA, trotta@cua.edu

Meson Structure at the EIC - Outlook

- EIC can push the Q^2 reach of F_π measurements
  - Can we measure F_K too?
- F_π work already featured in the EIC yellow report
- Worked closely with the ECCE proto-collaboration
  - Carried out feasibility studies
  - Kaon event generator and simulations in progress
  - **Activities were a priority for the ECCE Diffractive and Tagging group**
  - Continuing to develop simulations for Detector 1
- Pion structure function opportunity looks excellent
  - Unprecedented coverage in mid to high x
- Results from simulation have been written up in an ECCE analysis note and for an upcoming 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?

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

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