Meson Structure at the EIC

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Workshop on Hadron Structure at High-Energy, High-Luminosity Facilities
26/10/21

Outline

- Meson Form Factors
- Measuring Form Factors
  - Pion Form Factor
  - Kaon Form Factor
- What can we achieve at the EIC?

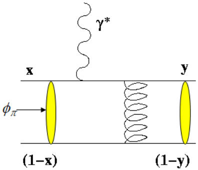
Cover Image - Brookhaven National Lab, `https://www.flickr.com/photos/brookhavenlab/`

Meson Form Factors

- Pion and Kaon form factors (F_π, F_K) are key QCD observables
  - Describe the spatial distribution of partons within a hadron
- F_π and F_K of special interest in hadron structure studies
  - π - Lightest QCD quark system, crucial in understanding dynamic mass generation
  - K - Next simplest system, contains strangeness
- Clearest case for studying transition from perturbative to non-perturbative regime
- Existing data are good, but need to push Q^2 reach further

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

$$F_\pi(Q^2) = \frac{4_F \alpha_s(Q^2)}{Q^2} \left| \sum_{n=0}^{\infty} a_n \left(\log\left(\frac{Q^2}{\Lambda^2}\right)\right)^{-\gamma_n} \right|^2 \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q}\right)\right]$$



The Pion in pQCD 2/2

- At asymptotically high Q^2 ($Q^2 \to \infty$), the pion distribution amplitude becomes -

$$\phi_\pi(x) \to \frac{3f_\pi}{\sqrt{n_c}} x(1-x)$$

  - With $f_\pi = 93\ MeV$, the $\pi^+ \to \mu^+\nu$ decay constant
- F_π takes the form -

$$Q^2 F_\pi \to 16\pi\alpha_s(Q^2) f_\pi^2$$

- This only relies on asymptotitc freedom in QCD, i.e. $(\partial\alpha_s/\partial\mu) < 0$ as $\mu \to \infty$
- $Q^2 F_\pi$ should behave as $\alpha_s(Q^2)$, even for moderately large Q^2
- Pion form factor seems to be the best tool for experimental study of the nature of the quark-gluon coupling constant renormalisation

Eqns - G.P. Lepage, S.J. Brodsky, PLB 87, p359, 1979 | Closing Statement - A.V. Efremov, A.V. Radyushkin PLB 94, p245, 1980

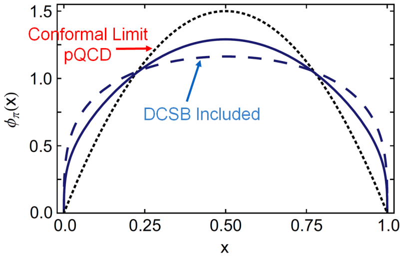
Implications for Pion Structure 1/2

- Previous pQCD derivation used normalisation of F_π based on the conformal limit of the pion's twist 2-PDA -

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

- Gives F_π that are "too small"
- Incorporating the DCSB effects yields Pion PDA -

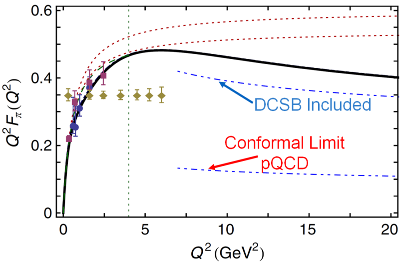
$$\phi_\pi(x) = \frac{8}{\pi}\sqrt{x(1-x)}$$



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

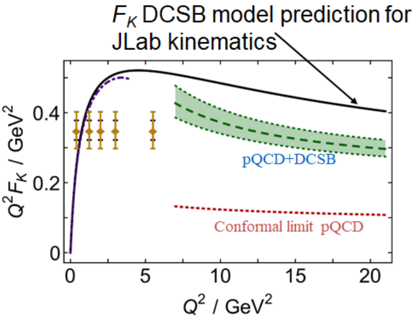
Implications for Pion Structure 2/2

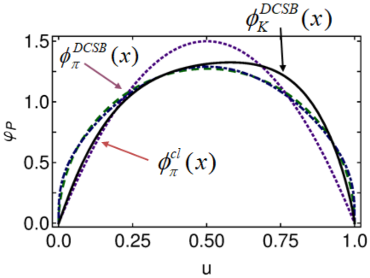
- Using this $\phi_\pi(x)$ in the pQCD expression brings the F_π calculation much closer to the data
- Underestimates the full computation by $\sim 15\%$ for $Q^2 \geqslant 8\ GeV^2$



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

- K^+ PDA is also broad, concave and asymmetric
- Heavier s quark carries more bound state momentum than the u quark, shift is less then one might expect based on the difference in current quark masses.

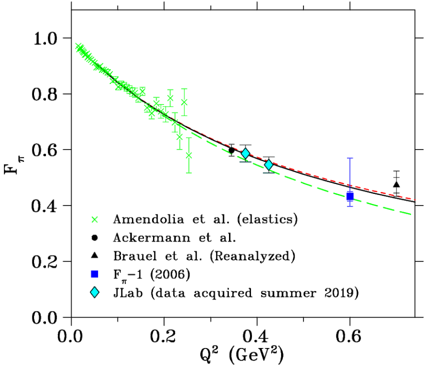




C. Shi, et al., PRD 92 (2015) 014035, F. Guo, et al., PRD 96(2017) 034024 (Full calculation)

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 used 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 (!)

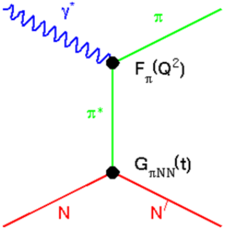


Amendolia, et al., NPB 277(1986) p168, P. Brauel, et al., ZPhysC (1979), p101, H. Ackermann, et al., NPB137 (1978), p294

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

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

- Drawbacks of this technique -
  - Isolating σ_L experimentally challenging
  - Theoretical uncertainty in F_π extraction
    $\rightarrow$ Model dependent
    (smaller dependency at low -t)

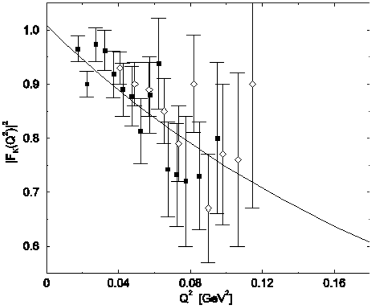


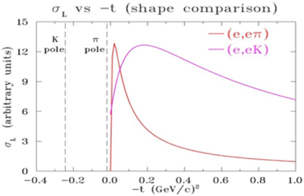
Measurement of F_K

- Similar to F_π, elastic K^+ scattering from e^- used to determine F_K at low Q^2
- Can "kaon cloud" of the proton be used in the same way as the pion to extract F_k from electroproduction?
- Kaon pole further from kinematically allowed region

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_K^2)} g_K^2(T) F_K^2(Q^2,t)$$

- Issues are being explored and tested in JLab E12-09-011





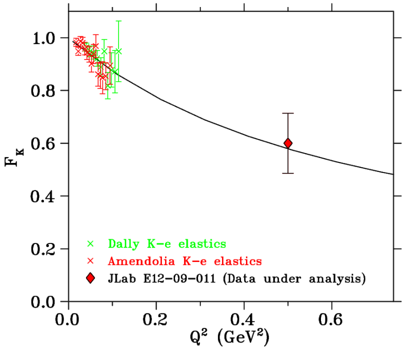
Amendolia, et al., PLB178(1986)435

F_K Validation

- Low Q^2 data is an important test
- Due to experimental setup, can simultaneously study Λ^0 and Σ^0 channels
- Can conduct a pole dominance test through the ratio -

$$\frac{\sigma_L\left[p(e,e'K^+)\Sigma^0\right]}{\sigma_L\left[p(e,e'K^+)\Lambda^0\right]}$$

- Should be similar to ratio of $g^2_{pK\Lambda}/g^2_{pK\Sigma}$ if t-channel exchange dominates



Form Factors at the EIC

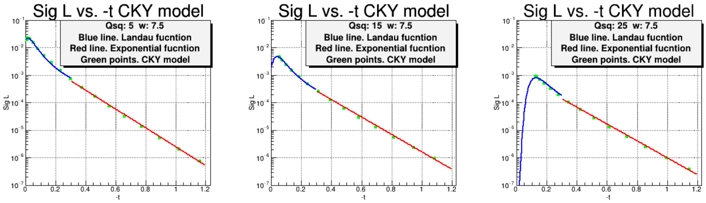
- JLab measurements push the Q^2 reach of data considerably
- Still can't answer some key questions regarding the emergence of hadronic mass however
- Can we get quantitative guidance on the emergent pion mass mechanism?
  $\rightarrow$ Need F_π data for $Q^2 = 10 - 40\ GeVc^{-2}$
- What is the size 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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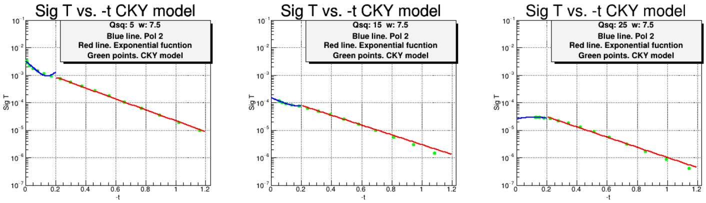
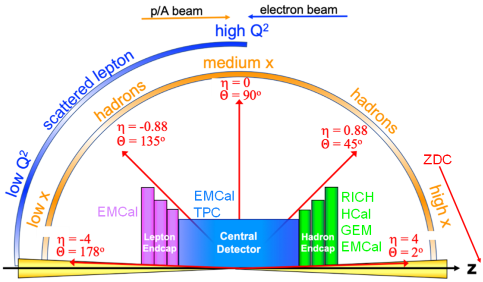
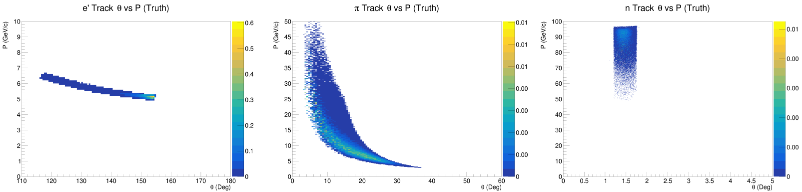


EIC Detector Overview



- 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/`

$p(e, e'\pi^{+}n)$ - Particle Distributions



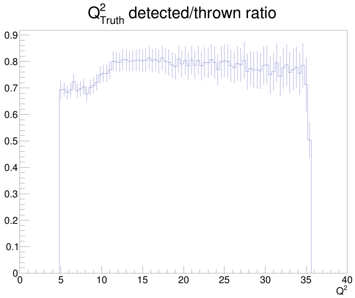
- Truth level particle distributions for $p(e, e'\pi^{+}n)$ events
- Neutrons take most of the momentum, forward focused
- Electrons and pions spread over wider range of angles

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 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 - Detection Efficiency

- Can examine truth quantities too, quick check of detection efficiency
- $\text{Efficiency} = \frac{\text{Accepted}}{\text{Thrown}}$
- Detection efficiency fairly high, $\sim 80\%$
- Nearly independent of Q^2
- Detection efficiency highest for low $-t$
  - Falls off rapidly with increasing $-t$
  - Dictated by size of ZDC



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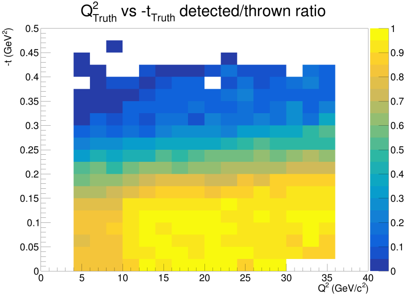
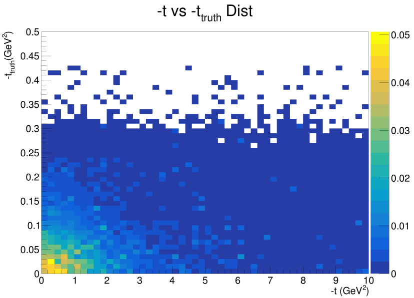


Simulation Results - t Reconstruction

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



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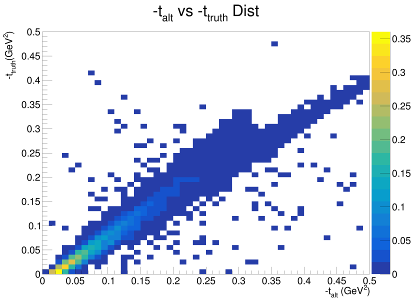

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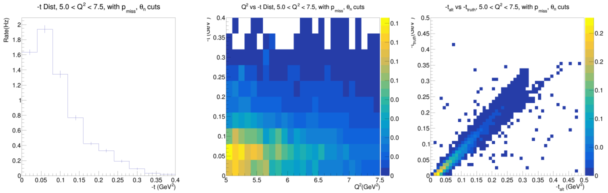
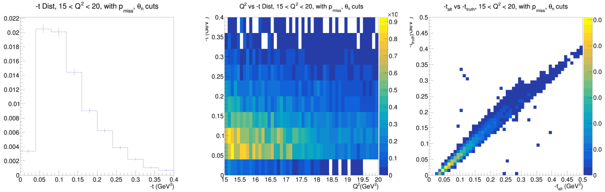


- Predicted $e'\pi^{+}n$ triple coincidence rate, binned in Q^2 and $-t$
  - 5 (e', GeV) on 100 (p, GeV) events
  - $\mathcal{L} = 10^{34}cm^{-2}s^{-1}$ assumed
  - $-t$ bins are 0.04 GeV^2 wide
  - Cut on θ_n $(\theta_n = 1.45 \pm 0.5^{\circ})$ and $\vec{p}_{miss} = \vec{p}_e + \vec{p}_p - \vec{p}_{e'}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

Simulation Results



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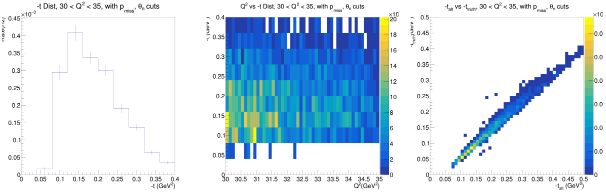

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Isolating σ_L from σ_T in an e-p Collider

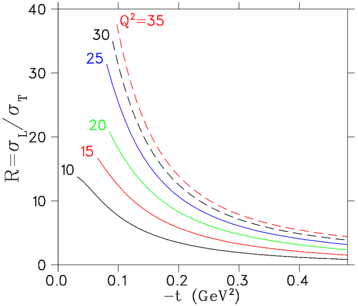
- For a collider -

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

  - 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

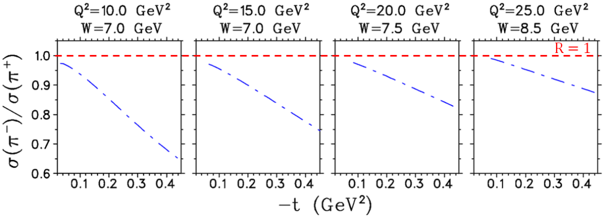
T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

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

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

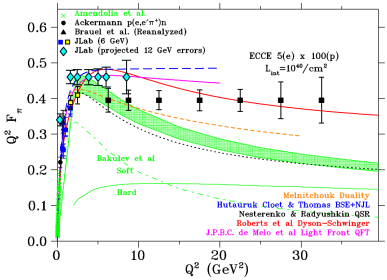
- R will be diluted if σ_T *not* small *or* if there are significant non-pole contributions to σ_L
- Compare R to model expectations



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

EIC Kinematic Reach for F_π

- 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 other detector concepts
- More details in upcoming ECCE analysis note

Summary and Outlook

- EIC has the potential to push the Q^2 reach of F_π measurements
- Work already featured in the EIC yellow report
- Now working closely with detector proto-collaborations
  - Carrying out feasibility studies
  - Existing DEMP event generator utilised
  - Kaon event generator and simulations in progress
  - **Activities are a priority for the ECCE Diffractive and Tagging group**
- Results from simulation have been written up in an ECCE analysis note
  - 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, Daniele Binosi, Huey-Wen Lin, Timothy Hobbs, Arun Tadepalli, Rachel Montgomery, Paul Reimer, David Richards, Rik Yoshida, Craig Roberts, Thia Keppel, John Arrington, Lei Chang, Ian L. Pegg, Jorge Segovia, Carlos Ayerbe Gayoso, Wenliang Li, Yulia Furletova, Dmitry Romanov, Markus Diefenthaler, Richard Trotta, Tanja Horn, Rolf Ent, Tobias Frederico

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