Meson Form Factors with ePIC

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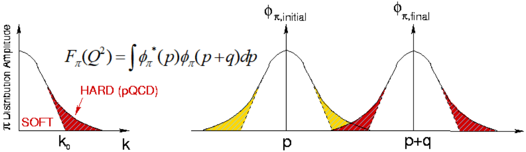
ePIC Collaboration
Meeting
11/01/23

- Charged pion ($\pi^{\pm}$) and kaon ($K^{\pm}$) form factors (F_π, F_K) are key QCD observables
  - Describe momentum space distributions of partons within hadrons



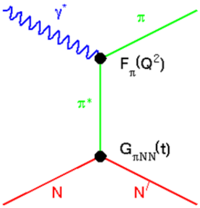
- Meson wave function can be split into ϕ_π^{soft} ($k < k_0$) and ϕ_π^{hard}, the hard tail
  - Can treat ϕ_π^{hard} in pQCD, cannot with ϕ_π^{soft}
  - Form factor is the overlap between the two tails (right figure)
- **F_π and F_K of special interest in hadron structure studies**
  - π - Lightest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

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

Measurement of F_π at High 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 σ_L
- In the Born term model, F_π^2 appears as -

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



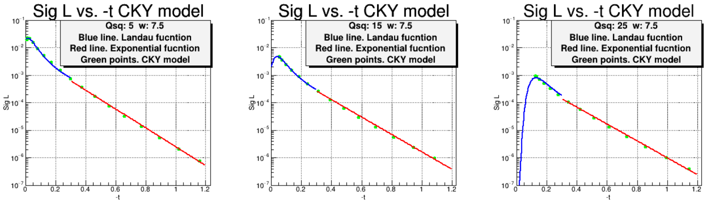
- We do not use the Born term model
- Drawbacks of this technique -
  - Isolating σ_L experimentally challenging
  - Theoretical uncertainty in F_π extraction
    - Model dependent (smaller dependency at low -t)
- Measure **D**eep **E**xclusive **M**eson **P**roduction (**DEMP**)

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
- 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
- Event generator being modified to generate kaon events

DEMP Event Generator - Pions

- 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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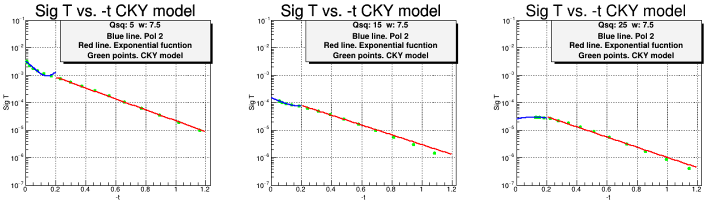
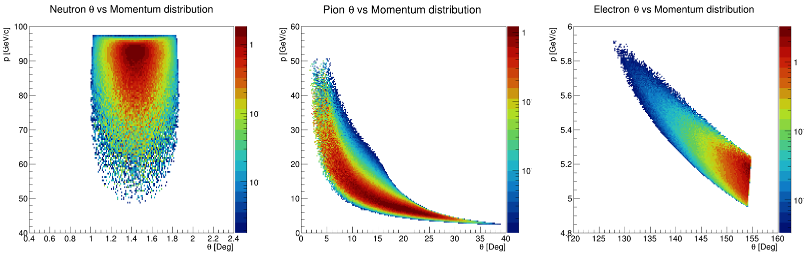


DEMP Kinematics for $-t < 0.5\ GeV^2$

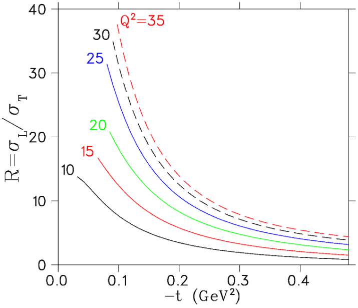
- $5(e^-)$ on $100(p)$ GeV collisions, 25 $mrad$ crossing angle
- Events weighted by cross section
- No smearing
- Old YR plots, just to demonstrate event kinematics



- Neutrons within 0.2° of outgoing proton beam, offset is due to the crossing angle ($25\ mrad \approx 1.4^\circ$)

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 $d\sigma_{UNS}/dt$
- Examine π^+/π^- ratios as a test of the model



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

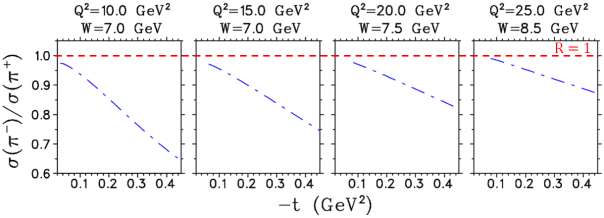
T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

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

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

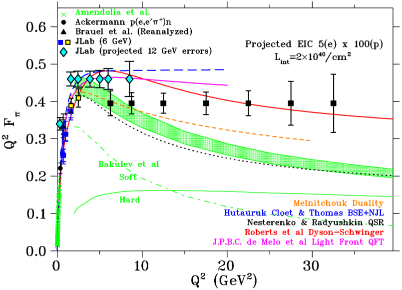
- R will be diluted if σ_T *not* small *or* if there are significant non-pole contributions to σ_L
- Compare R to model expectations



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

EIC F_π Data

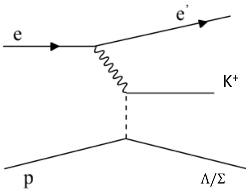
- ECCE appeared to be capable of measuring F_π to $Q^2 \sim 32.5\ GeV^2$
- **Error bars represent real projected error bars**
  - 2.5% point-to-point
  - 12% scale
  - $\delta R = R$, $R = \sigma_L/\sigma_T$
  - $R = 0.013 - 014$ at lowest $-t$ from VR model
- Uncertainties dominated by R at low Q^2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



- Results look promising, need to test π^- too
- No reason to expect ePIC should be too different

F_K at the EIC - Challenges and Possibilities

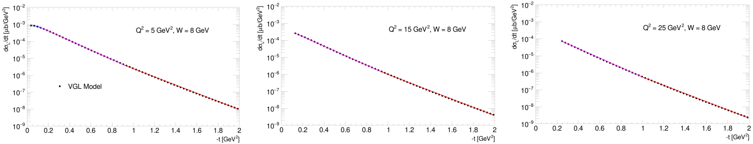
- F_K at the EIC via DEMP will be extremely challenging
- Would need to measure two reactions
  - $p(e, e'K^+\Lambda)$
  - $p(e, e'K^+\Sigma)$
  - Need both for pole dominance tests



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

- 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**

- URegina MSc student Love Preet working on adding Kaon DEMP event generator module to DEMPGen
    - Starting with $p(e, e'K^+\Lambda)$
- Parametrise a Regge-based model in a similar way to the pion
- For $p(e, e'K^+\Lambda)$ module, use the Vanderhagen, Guidal, Laget (VGL) model
- Parametrise σ_L, σ_T for $1 < Q^2 < 35$, $2 < W < 10$, $-t < 2.0$
    - Parametrise with a polynomial, exponential and exponential



VGL Model - M. Guidal, J.-M. Laget, M. Vanderhaeghen, PRC 61 (3000) 025204

F_K at the EIC - Generator Updates

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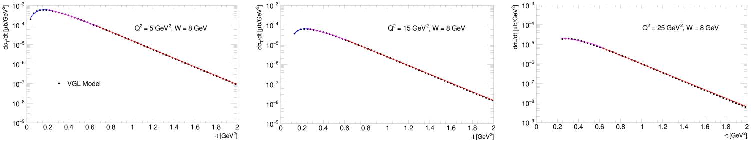
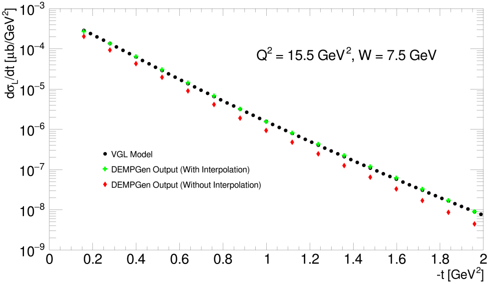


VGL Model - M. Guidal, J.-M. Laget, M. Vanderhaeghen, PRC 61 (3000) 025204

DEMPGen Improvements

- In addition to adding the $p(e, e'K^+\Lambda)$ module, improvements to the generator implemented
- New method to interpolate parametrisation
- Interpolation matches generator output very closely
  - Even at points far from the initial parametrisation
- Will incorporate improvements in pion model too in the near future



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?
- Worked closely with the ECCE proto-collaboration
  - Carried out F_π feasibility studies
  - Existing DEMP event generator utilised
  - Will continue to develop simulations with ePIC
- Kaon form factor feasibility studies are a priority
  - Kaon event generator and simulations in progress
    - Λ^0 particle gun studies are enough to begin with
  - F_π study refinements and revalidation with ePIC also planned
  - Closer look at different beam energy combinations
  - Also need to examine π^- for model validation tests

Thanks for listening, any questions?

Meson Structure Working Group - Stephen JD Kay, Garth M Huber, Zafar Ahmed, Love Preet, 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

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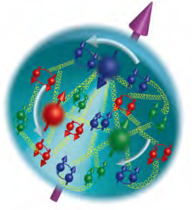
The University of Regina is situated on the territories of the nehiyawak, Anihsināpēk, Dakota, Lakota, and Nakoda, and the homeland of the Métis/Michif Nation. The University of Regina is on Treaty 4 lands with a presence in Treaty 6.

Backup Zone

Understanding Dynamic Matter

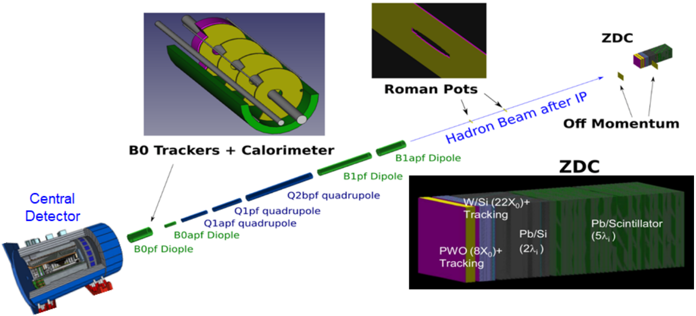
- Interactions and structure are not isolated ideas in nuclear matter
  - Observed properties of nucleons and nuclei (mass, spin) emerge from this complex interplay
  - Properties of hadrons are emergent phenomena



- 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

EIC Detector Overview



- Feed generator output into detector simulations
- Far forward detectors critical for form factor studies

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

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 $Q^2 \to \infty$, 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 -

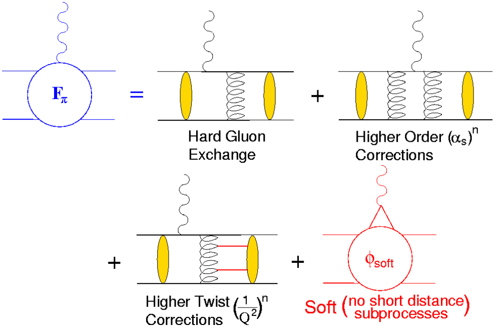
$$Q^2 F_\pi \xrightarrow[Q^2\to\infty]{} 16\pi\alpha_s(Q^2)f_\pi^2$$

- This is a **rigorous** prediction of pQCD
- Q^2 **reach of 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

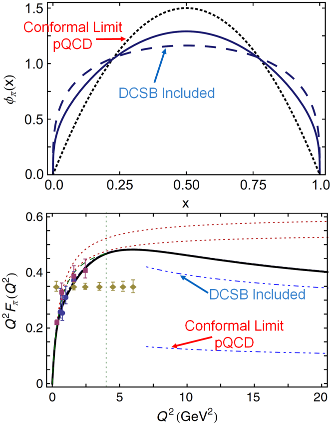
- At experimentally accessible Q^2, both the hard and soft components contribute



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

Connecting Pion Structure and Mass Generation

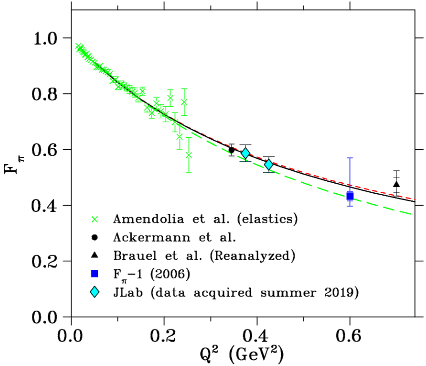
- ϕ_π as shown before has a broad, concave shape
- Previous pQCD derivation (conformal limit) did not include DCSB effects
- Incorporating DCSB changes $\phi_\pi(x)$ and brings F_π calculation much closer to the data
  - "Squashes down" PDA
- Pion structure and hadron mass generation are interlinked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

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)**

Simulation Results - Neutron Reconstruction

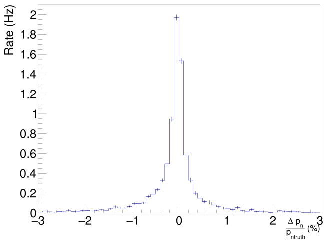
- High energy ZDC hit requirement used as a veto
  - ZDC neutron ERes is relatively poor though

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

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

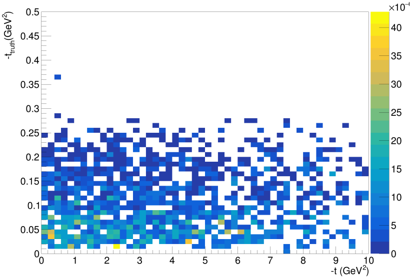
$$p_{miss} = |\vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}|$$

- 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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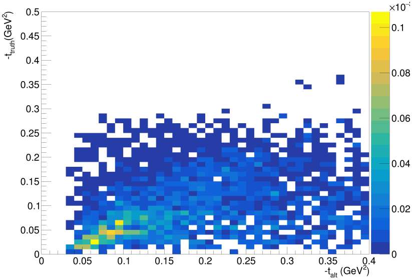
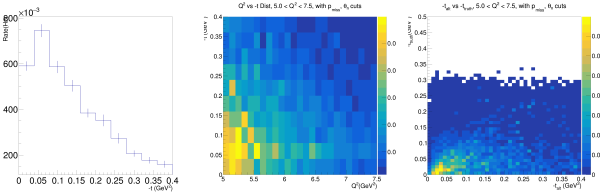


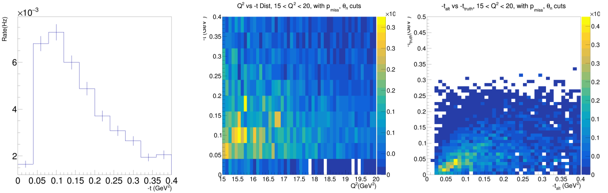
- x-axis $-t$ scale an order of magnitude smaller now!

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

Simulation Results - Q^2 $15 - 20$ GeV^2



- Predicted $e'\pi^+n$ triple coincidence rate, binned in Q^2 and $-t$
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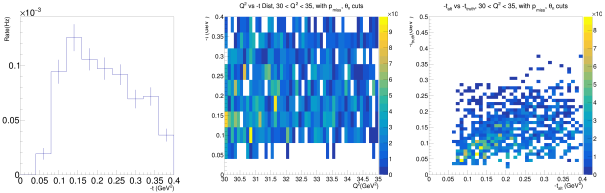
Simulation Results - Q^2 $30 - 35$ GeV^2



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Isolating σ_L from σ_T in an e-p Collider

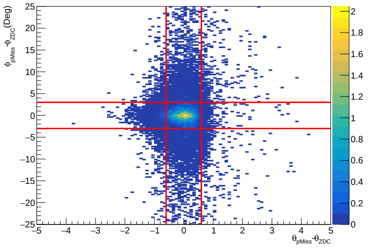
- For a collider -

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

  - 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**

$\Delta\theta$ and $\Delta\phi$ Cuts

- Make use of high angular resolution of ZDC
- Compare hit θ/ϕ positions of neutron on ZDC to calculated θ/ϕ from p_{miss}
- If no other particles produced, quantities should be correlated
  - True for DEMP events
- Energetic neutrons from inclusive background processes will be less correlated
  - Additional lower energy particles produced



- $\theta_{pMiss} - \theta_{ZDC}$ and $\phi_{pMiss} - \phi_{ZDC}$ cut upon, in addition to other cuts
- $|\theta_{pMiss} - \theta_{ZDC}| < 0.6^\circ$, $|\phi_{pMiss} - \phi_{ZDC}| < 3.0^\circ$

F_K at the EIC - Generator Updates

- Working on adding Kaon DEMP events to DEMPGen
    - Starting with $p(e, e'K^+\Lambda)$
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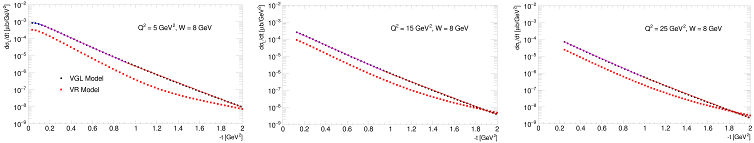

VGL Model Paper - `https://doi.org/10.1016/S0375-9474(97)00612-X`

F_K at the EIC - Generator Updates

- Working on adding Kaon DEMP events to DEMPGen
  - Starting with $p(e, e'K^+\Lambda)$
- Parametrise a Regge-based model in a similar way to the pion
- For $p(e, e'K^+\Lambda)$ module, use the Vanderhagen, Guidal, Laget (VGL) model
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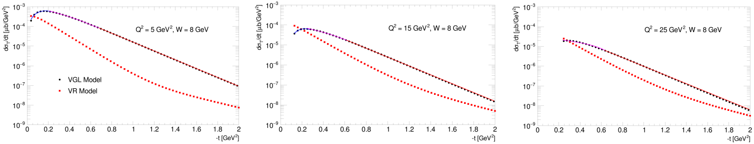

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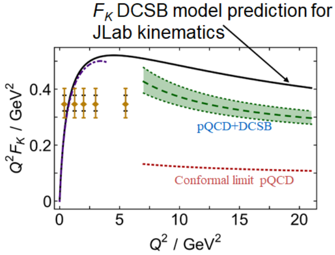
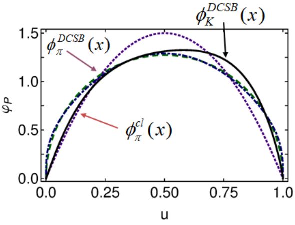
What About the Kaon?

- K^+ PDA (ϕ_K) is also broad and concave, but asymmetric
- Heavier s quark carries more bound state momentum than the u quark

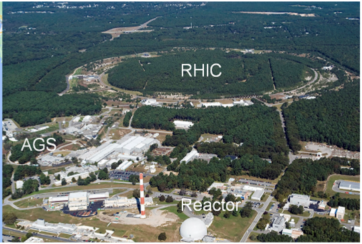




C. Shi, et al., PRD 92 (2015) 014035, F. Guo, et al., PRD 96(2017) 034024 (Full calculation)

The Electron-Ion Collider

- Major announcement in January 2020
  - Brookhaven National Lab (**BNL**) was chosen as the site of the future Electron-Ion Collider (**EIC**)
  - BNL is situated on Long Island, New York
  - Existing site of the Relativistic Heavy Ion Collider (**RHIC**) and the Alternating Gradient Synchrotron (**AGS**)



Upgrading RHIC - eRHIC

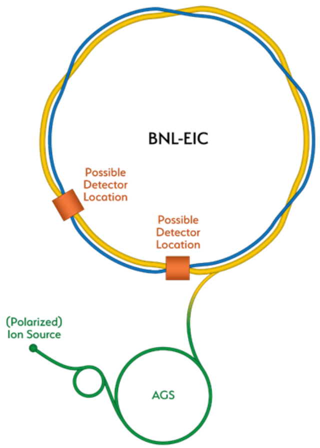


Image - Brookhaven National Lab

- Use existing RHIC
  - Up to 275 *GeV* polarised proton beams
  - Existing tunnel, detector halls, hadron injector complex (AGS)
- New 18 *GeV* electron linac
  - New high intensity electron storage ring in existing tunnel
- Achieve high $\mathcal{L}$, high E e-p/A collisions with full acceptance detectors
- High $\mathcal{L}$ achieved by state of the art beam cooling techniques

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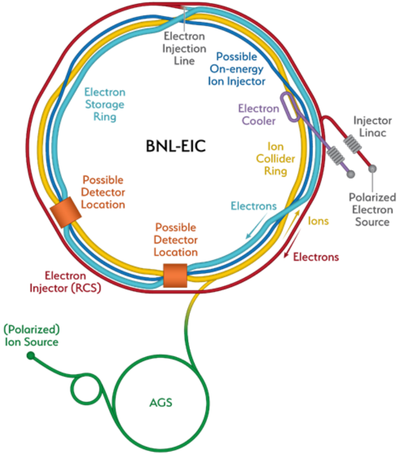

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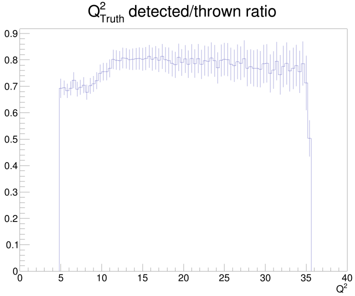
Simulation Results - Detection Efficiency

- 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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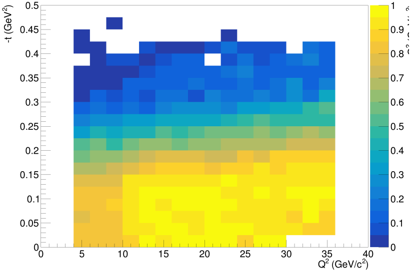
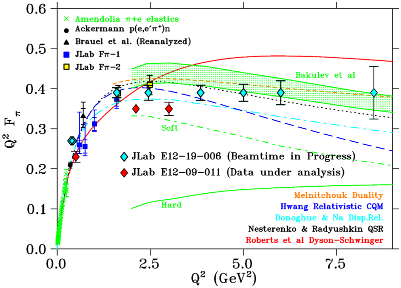


Current and Projected JLab F_π Data

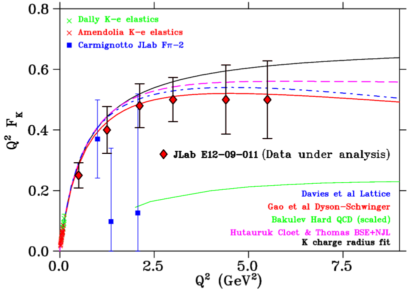
- JLab 12 *GeV* program includes measurements of F_π to higher Q^2
- JLab Hall C is the only facility worldwide that can perform this measurement
- Projected error bars show on plot, y positioning of points arbitrary
- Models all disagree!
  - Contributions from sea quarks and gluons highly uncertain at high Q^2



- **A world leading, high impact measurement**

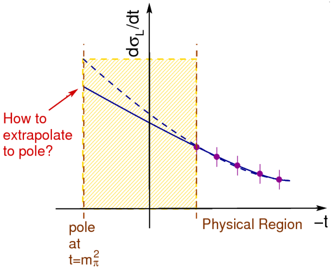
Current and Projected JLab F_K Data

- Data has all been acquired and analysis is in progress
- Projected errors bars, y positioning of points arbitrary
- **No existing data above $Q^2 \sim 2.25\ GeV^2$**
- Error bars on sparse existing data are very large
- Kaon structure even more poorly known than the pion



Chew-Low Method to determine F_π

- $p(e, e'\pi^+)n$ data obtained away from $t = m_\pi^2$ pole
- "Chew Low" extrapolation method - must know analytical dependence of $d\sigma_L/dt$ in unphysical region
- Extrapolation method last used in 1972 by Devenish and Lyth
- Very large systematic uncertainties
- Failed to produce a reliable result
- Different polynomial fits equally likely in physical region
  - Form factor values divergent when extrapolated
- **We do not use the Chew-Low method**



Extracting F_π at JLab

- 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
- Ideally, want a better understanding of the model dependence of the result
- 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**

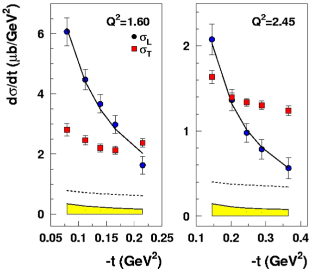
VGL - Vanderhaeghen-Guidal-Laget Model - Vanderhaeghen, Guidal, Laget, PRC 57(1998) 1454

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

VGL model incorporates π^+ production mechanism and spectator neutron effects

- 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

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

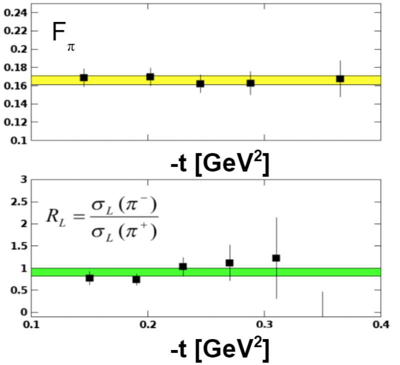


Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature. Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.
$\Lambda_\pi^2 = 0.513, 0.491\ GeV^2$, $\Lambda_\rho^2 = 1.7\ GeV^2$
T. Horn, et al., PRL 97(2006) 192001

- Test #1 - Measure F_π at fixed Q^2/W, but vary $-t$
  - F_π values should not depend on -t
- Test #2 - π^+ t-channel diagram is purely isovector
- Use a deuterium target to measure $\sigma_L\,[n(e,e'\pi^-)p]$
- Examine the ratio -

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

- Will test at $Q^2 = 1.6, 3.85, 6.0\ GeV^2$



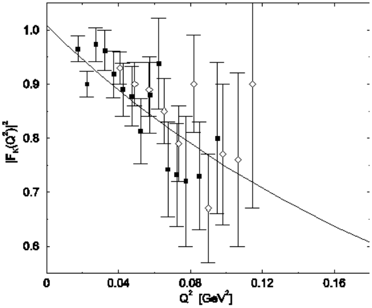
T. Horn, C.D. Roberts, J. Phys. G43 (2016) no.7, 073001
G. Huber et al, PRL112 (2014)182501
R. J. Perry et al., arXiV:1811.09356 (2019)

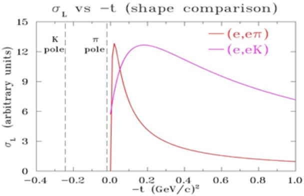
F_K Measurement at JLab

- 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

- Again, 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