Pion and Kaon Form Factors at the EIC

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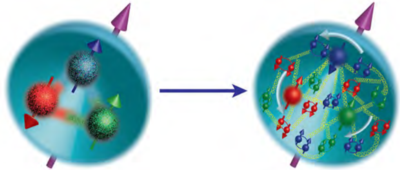
ECCE Diffractive and Tagging
10/06/21

Emergent Dynamics in QCD

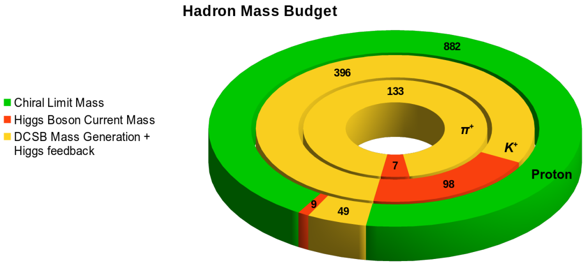
- Consider the proton, a baryon with *uud* valence quarks

$$m_p \approx 938\ MeV/c^2,$$
$$m_u \approx 3\ MeV/c^2, m_d \approx 6\ MeV/c^2,$$
$$(2 \times 3) + 6 = 938?$$



- Where does the mass come from?
- Massless gluons and nearly massless quarks, through their interactions, generate most of the mass
- $\sim 99\%$ of the mass of hadrons $\rightarrow$ most of the visible mass in the universe!

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

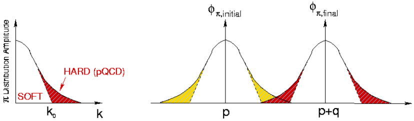
Meson Form Factors

- 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

Charged Meson Form Factors

- Simple $q\bar{q}$ valence structure of mesons makes them an excellent testing ground
- Pion form factor , F_π, is the overlap integral -

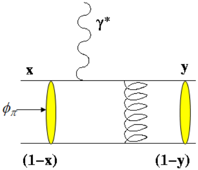
$$F_\pi(Q^2) = \int \phi_\pi^*(p)\phi_\pi(p+q)dp$$



- 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}
- Study of Q^2 dependence of form factor focuses on finding description of hard and soft contributions

- 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 of 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 asymptotic 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

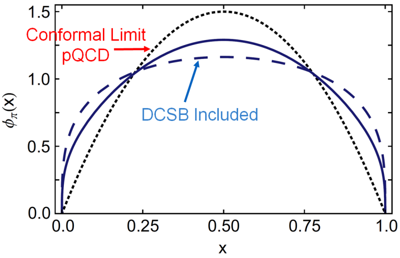
Implications for Pion Structure (1 of 2)

- 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 -

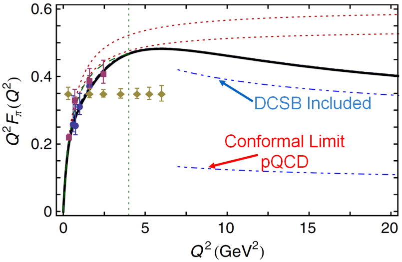
$$\phi_\pi(x) = \frac{8}{\pi}\sqrt{x(1-x)}$$



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

Implications for Pion Structure (2 of 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 $Q^2 \geqslant 8\ GeV^2$

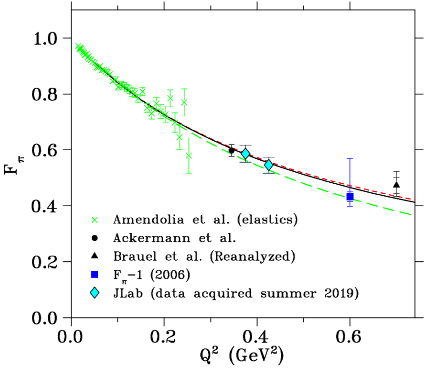


L. Chang, et al., PRL111(2013) 141802

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

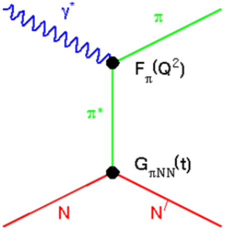
Measurement of F_π at Higher Q^2

- To access higher 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



Form Factors at the EIC

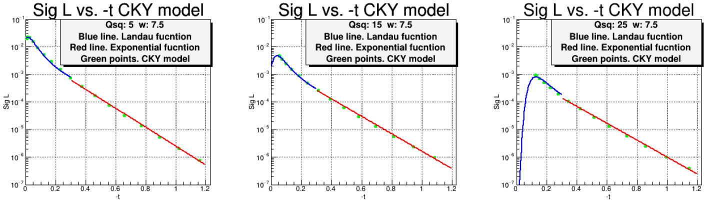
- JLab measurements push the Q^2 reach of data considerably
- Still can't answer some key questions regarding the emergence of hadronic mass however
- Can we get quantitative guidance on the emergent pion mass mechanism?
  $\rightarrow$ Need F_π data for $Q^2 = 10 - 40\ GeV^2$
- What is the size and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

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
- 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

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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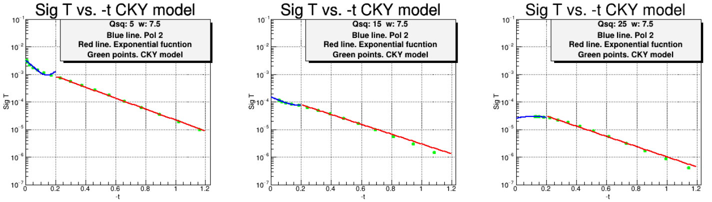


Isolating σ_L from σ_T in an e-p Collider

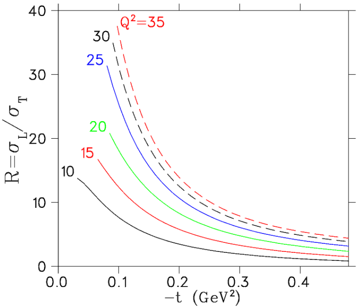
- For a collider -

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

  - 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

- 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

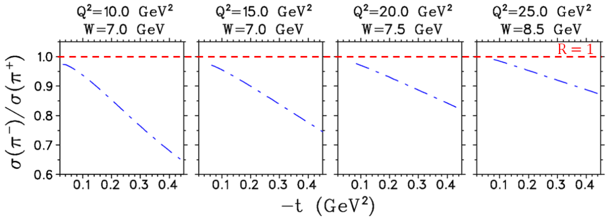
T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

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

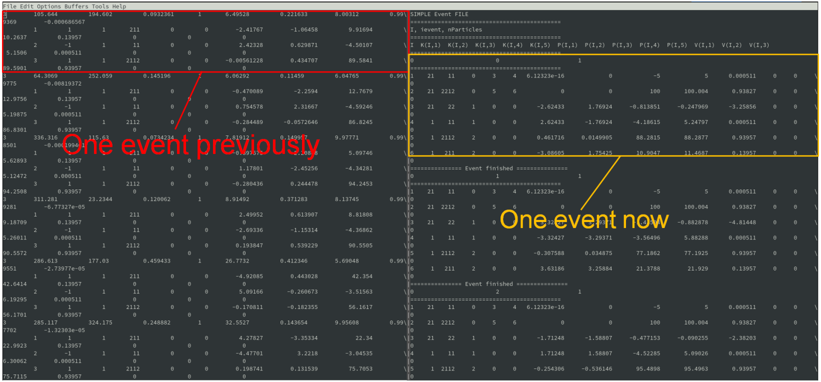


T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

Generator Updates

- Latest version at - `https://github.com/sjdkay/DEMPgen/tree/bill`
- Some quality of life updates
  - Beam energies not hard coded
  - Random number generation improved
  - Can now handle larger number of events thrown per run
- Modified calculation of event weight in output
  - Needed to switch to a "unit" weight
  - Cross checking integrated yield with old determination
- Format of LUND output changed to be read in by EIC smear
- **Currently, EIC Smear and Fun4All cannot deal with the weight, it is not retained**
  - **We require the weight to be retained to get absolute rates**
  - We need absolute rates to get realistic FF projections with error bars

Generator Updates - New Output Format



Generated Files Status

- With change to output, files read in fine by EIC smear
- Focusing on lower beam energy combinations
- Files processed through EIC smear and on the JLab iFarm
  - `/lustre19/expphy/volatile/eic/sjdkay/EIC_Smear/`

Beam Energy	#Thrown /File	#Events /File	Total #Events	Comments
5on100	10^9	17000	1.7×10^6	
5on41	10^9	178500	1.785×10^7	$Q^2 < 5$ cut
5on41	10^9	200000	2×10^7	$Q^2 < 4$ cut
5on41	10^9	220000	2.21×10^7	$Q^2 < 3$ cut

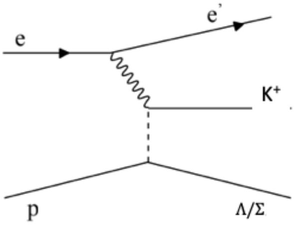
Event Rejection

- Various cuts to remove vents outside of model validity in DEMPGen, e.g. Q^2 too low
- End up with small fraction of thrown events in resulting file
  - Fraction of retained events varies with beam energy combination

```
lark> more data/LundFiles/eic_DEMPGen_5on100_1000000000_50.txt
Total events tried                                              1000000000
Total events recorded                                                16766
Max weight value                                                 2.396e+07
Number of events with w more than 10.6                           535523240
Number of events with wsq negative                               380560723
Number of events with qsq less than 5                             51239604
Number of events with -t more than threshold                      30596434
Number of events with unit weight outside of 0 to 1                     45
Number of events with unit weight greater than random number           474
Number of events with w less than threshold                              0
Number of events with mom not conserve                                   0
Number of events with Sigma negative                                  5784
Number of lund events                                                16766
Seed used for the Random Number Generator                          6194580
```

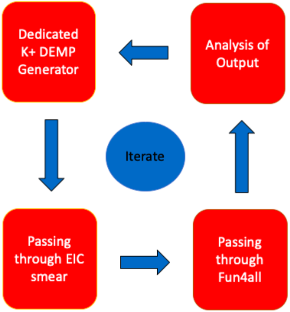
Exclusive K^+ at EIC

- K^+ has two exclusive electroproduction channels
  - $p(e, e'K^+\Lambda)$ and $p(e, e'K^+\Sigma^0)$
- σ_L is dominant in t-channel process
- If the pole process dominates, ratio of the Λ/Σ^0 should behave like the ratio $g_{KN\Lambda}/g_{KN\Sigma^0}$
- Limited kinematics range $(Q^2, W, -t)$
- Charged final states $(\Lambda \to \pi^- + p)$ are difficult.



K^+ Studies Plan

- K^+ DEMP Generator
  - Modifying the existing π^+ DEMP generator
  - Need to include both Λ and Σ^0 channels
  - Modification of K^+ kinematics $(Q^2, W, -t)$
  - Work being led by UoR PhD student Ali Usman
- Four step iterative process
- Need to accurately detect γ in far-forward detectors
  - Only distinction between Λ and Σ^0, Σ^0 decays to $\Lambda\gamma$



K^+ Studies Goals

- June Goals
  - Generate $K^+\Lambda$ Events
  - 5 on 41 energy
  - Perform phase space studies
- July/August Goals
  - Λ/Σ^0 ratios
  - Compare both IRs and different beam energy combinations
  - Detector optimisations (resolution and positioning)

Next Steps

- Need to develop analysis plugin for our studies
- Process large numbers of events through the simulation
- Simulate $K\Lambda$ and $K\Sigma^0$ events
  - PhD student Ali Usman is working on adding in a module to the event generator
- Will focus on generating events at 5on41 for $K\Lambda$ studies
- Once $K\Lambda$ module is working, need a $K\Sigma$ module too
- **Need event weighting to be retained by Fun4All**

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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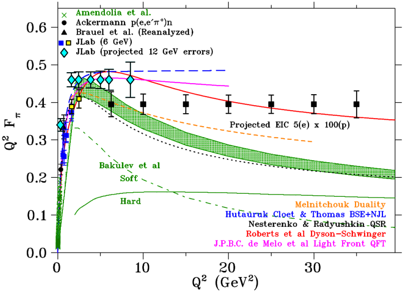
EIC Kinematic Reach for F_π

Assumptions

- $5(e^-)$ on $100(p)$
- $\int \mathcal{L} = 20\ fb^{-1} yr^{-1}$
- Clean identification of $p(e, e'\pi^+ n)$
- Syst.Unc: 2.5% pt-pt, 12% scale
- $R = \sigma_L/\sigma_T = 0.013 - 0.14$ at lowest $-t$ from VR model
- $\delta R = R$ Syst.Unc in model subtraction to isolate σ_L
- π pole dominance at small $-t$ confirmed in $^2H\ \pi^+/\pi^-$ ratios



- Results look promising, but need further studies and further energy combinations

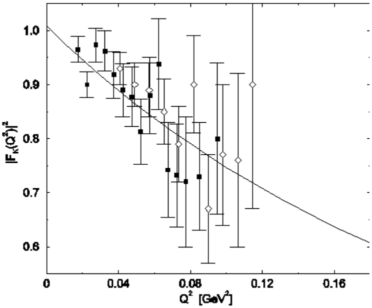
J Arrington et al 2021 J. Phys. G: Nucl. Part. Phys. 48 075106

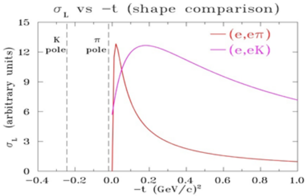
F_K Measurement at JLab

- 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