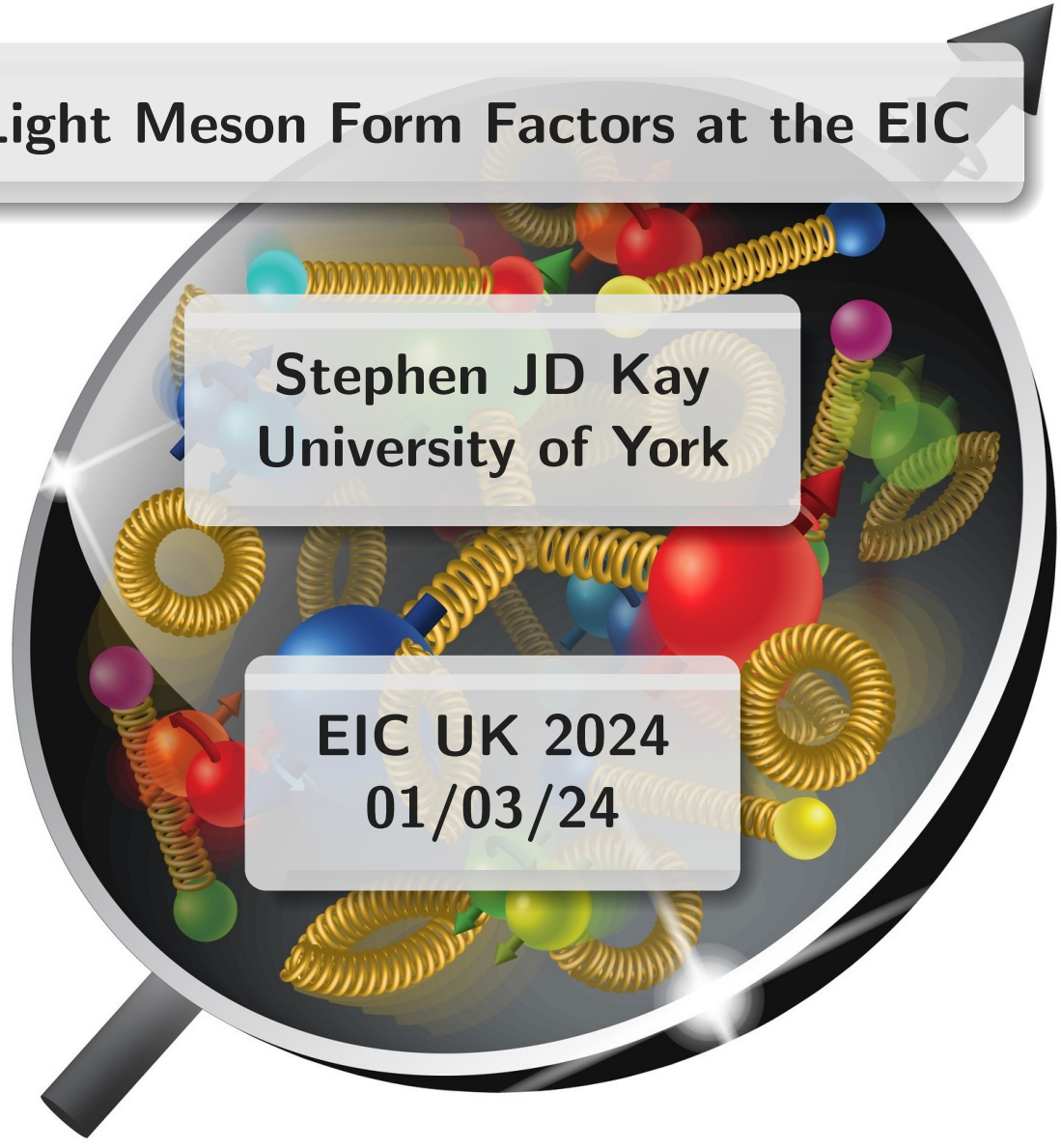
Light Meson Form Factors at the EIC



Stephen JD Kay
University of York

EIC UK 2024
01/03/24

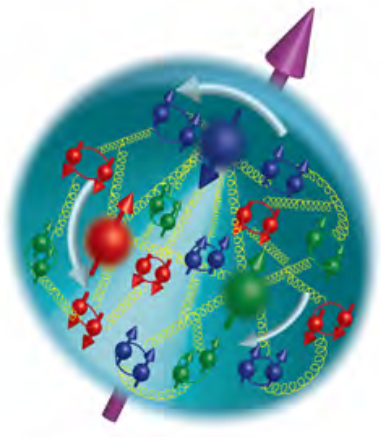
Outline

- Meson Form Factors - Context
- Measuring Form Factors
- Pion Form Factors at the EIC
  - Progress so far
  - Improvements with ePIC
- Kaon Form Factors at the EIC

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

Understanding Dynamic Matter

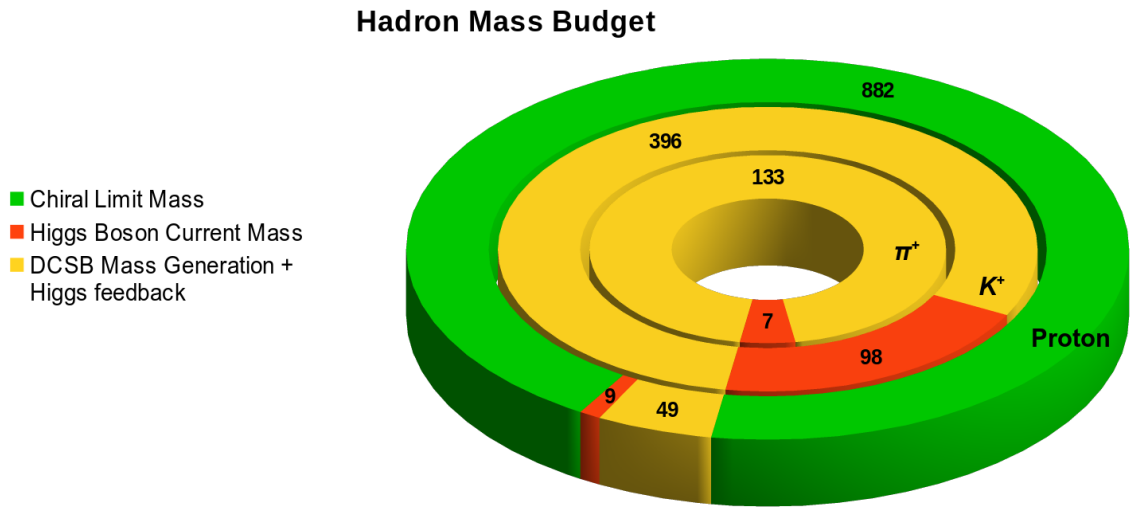
- Interactions and structure are not isolated ideas in nuclear matter
  - Observed properties of nucleons and nuclei (mass, spin) emerge from this complex interplay
  - Properties of hadrons are emergent phenomena



- 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?
  - How does QCD generate $\sim 99\%$ of the mass of hadrons?
- **A major puzzle of the standard model to try and resolve!**

Image - A. Deshpande, Stony Brook University

Hadron Mass Budgets

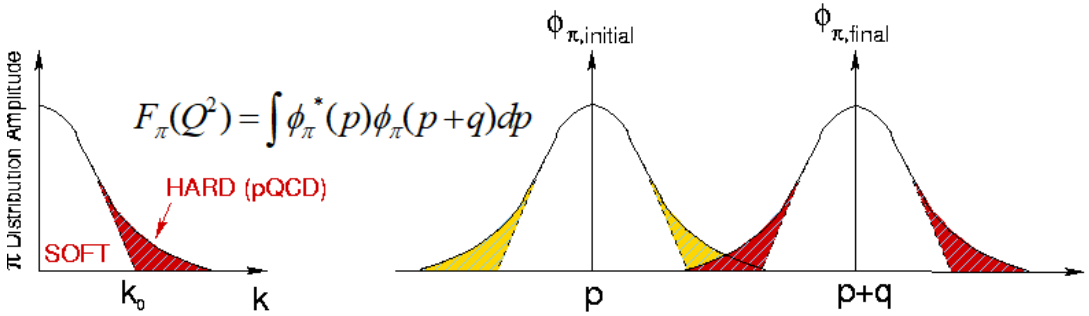


- Multiple mechanisms at play to give hadrons their mass
- Only the portion in red is directly from the Higgs current
- **The simple $q\bar{q}$ valence structure of mesons makes them an excellent testing ground**
- What can we examine to look at their structure?

J Arrington et al 2021 J. Phys. G: Nucl. Part. Phys. 48 075106 - http://dx.doi.org/10.1088/1361-6471/abf5c3

Meson Form Factors

- 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

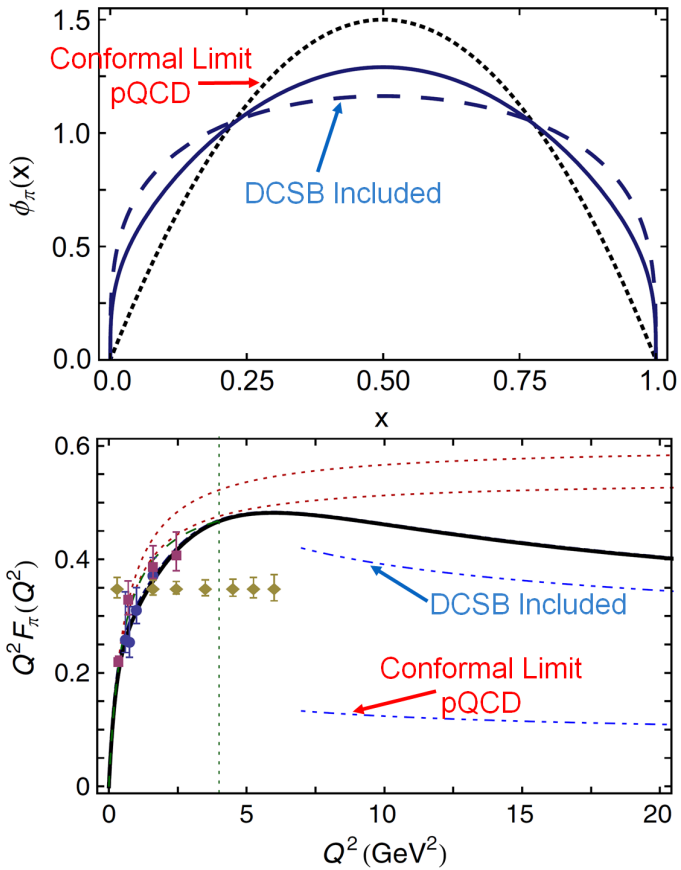


- Meson wave function can be split into ϕ_π^{soft} $(k < k_0)$ and ϕ_π^{hard}, the hard tail
  - Can treat ϕ_π^{hard} in pQCD, cannot with ϕ_π^{soft}
  - Form factor is the overlap between the two tails (right figure)
- **F_π and F_K of special interest in hadron structure studies**
  - π - Lightest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

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

Connecting Pion Structure and Mass Generation

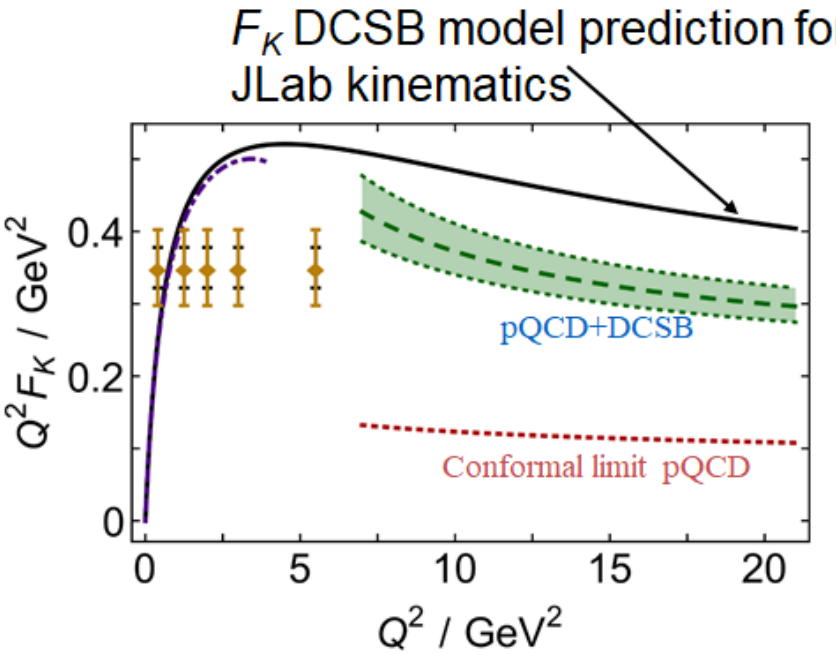
- Calculating the pion PDA, ϕ_π, without incorporating DCSB produces a broad, concave shape
- Incorporating DCSB changes $\phi_\pi(x)$ and brings F_π calculation much closer to the data
  - "Squashes down" PDA
- Pion structure and hadron mass generation are interlinked

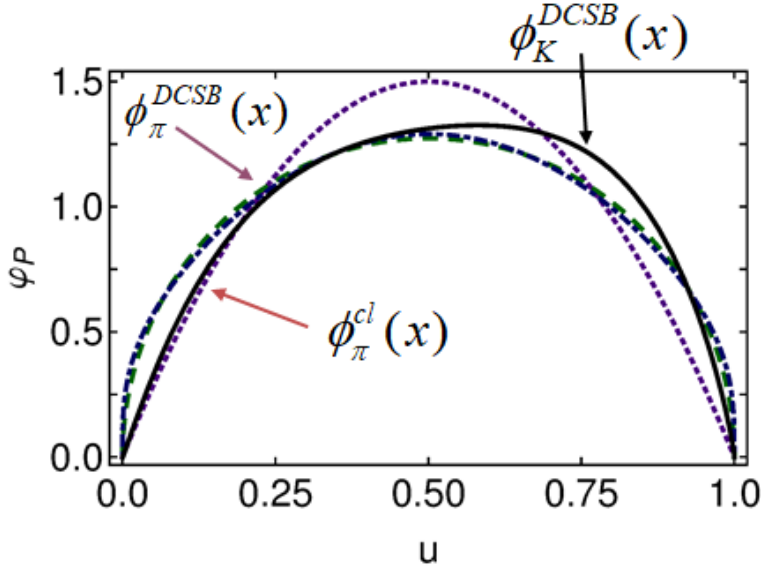


L. Chang, et al., PRL110(2013) 132001, PRL111(2013), 141802

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



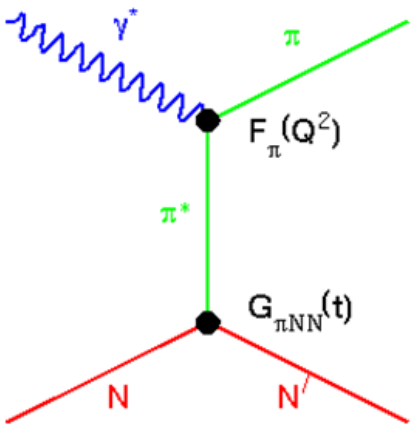


C. Shi, et al., PRD 92 (2015) 014035, F. Guo, et al., PRD 96(2017) 034024 (Full calculation)

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**)

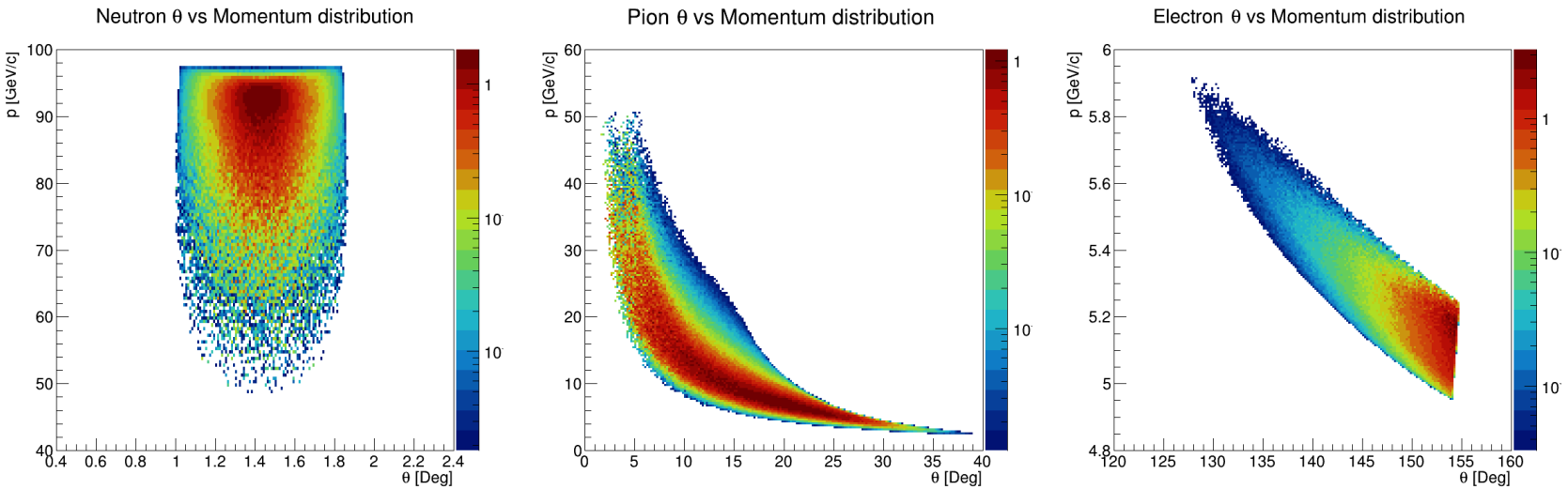
DEMP Studies at the EIC

- 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 $d\sigma_{uns}/dt$
- Feasibility of pion form factor measurements demonstrated with ECCE simulations
  - Feed in events generated from DEMP event generator - DEMPgen
  - Need to refine simulations with mature ePIC design
- Event generator recently modified to generate kaon events
  - Next extension of studies

A. Bylinkin. et. al., NIMA 1052 (2023) 168238 https://doi.org/10.1016/j.nima.2023.168238, DEMPgen https://github.com/JeffersonLab/DEMPgen/releases/tag/v1.1.0

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

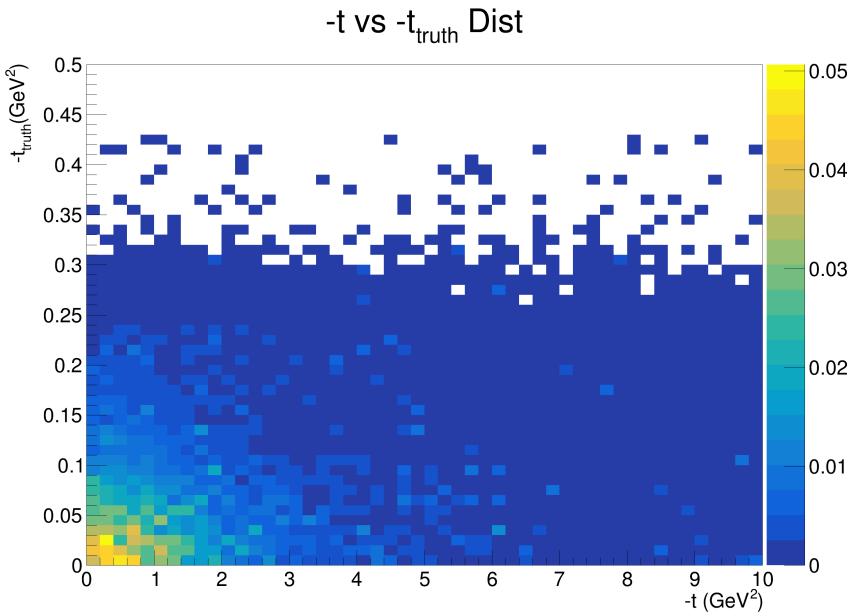
- $5(e^-)$ on $100(p)$ *GeV* collisions, 25 *mrad* crossing angle
- Events weighted by cross section
- No smearing
- Old YR plots, just to demonstrate event kinematics



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

Simulation Results - t Reconstruction

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



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

More details in NIMA 1052 (2023), 168238 https://doi.org/10.1016/j.nima.2023.168238

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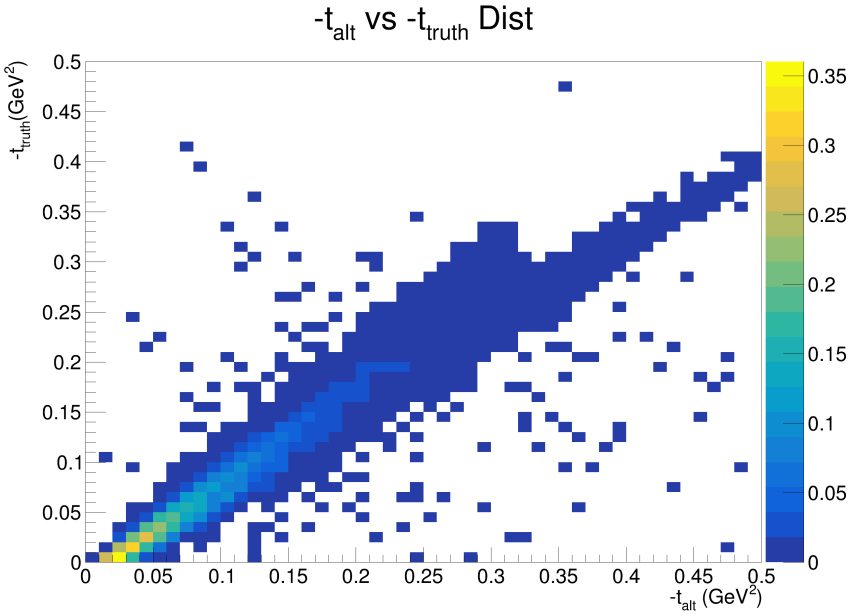
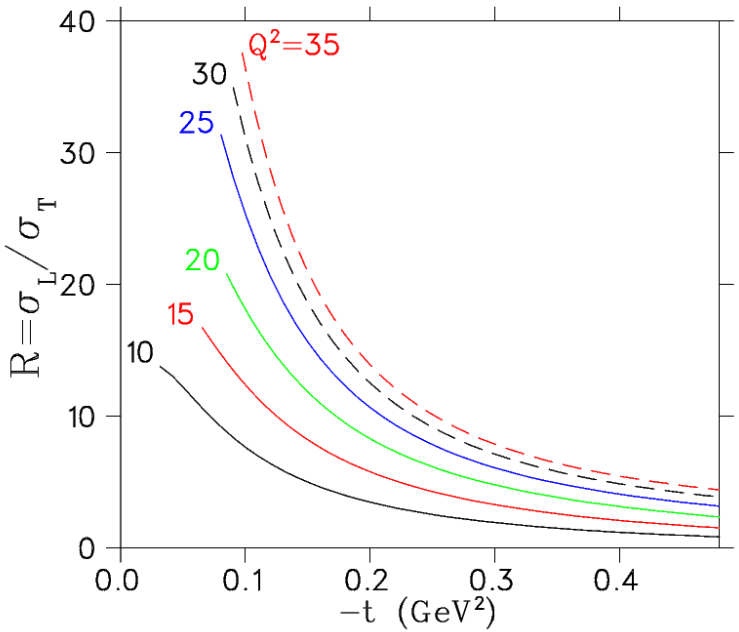


- Plot from ECCE analysis
- x-axis $-t$ scale an order of magnitude smaller now!

More details in NIMA 1052 (2023), 168238 https://doi.org/10.1016/j.nima.2023.168238

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

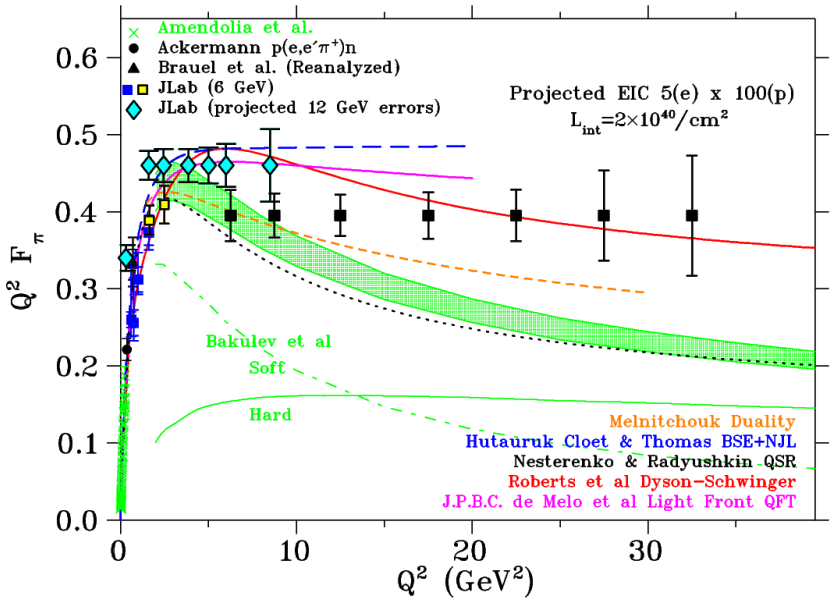


Predictions are assuming $\epsilon > 0.9995$ with the kinematic ranges seen earlier

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

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



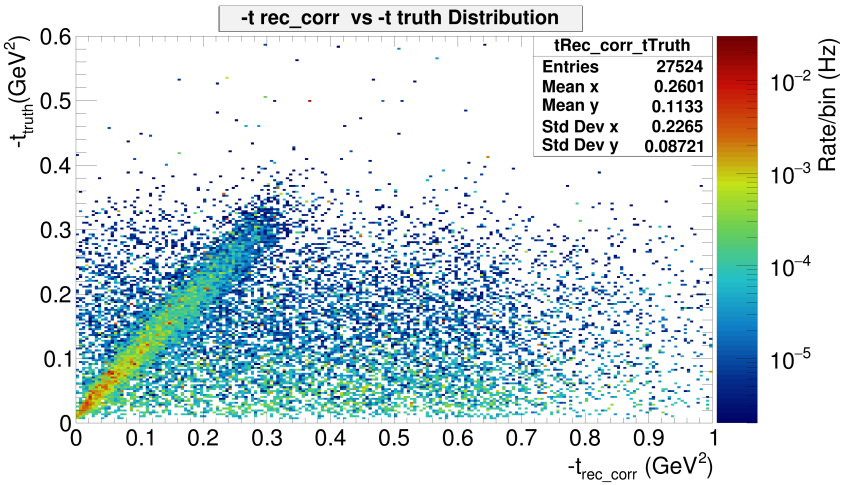
- Results look promising, need to test π^- too
- Improvements with ePIC look promising

ePIC F_π Simulations

- Need to process full F_π analysis again with ePIC
- Major roadblocks for analysis cleared
  - Event weight accessible
  - ZDC HCal now implemented
    - B. Schmookler and group at UCRiverside working on ZDC HCal design/construction - `https://arratialab.ucr.edu/eic`
- Samples from DEMPgen in simulation chain
- DEMP is a key benchmarking channel for FF detectors
  - Well defined, but progressively more complicated reconstruction
    - $ep \to e'\pi^+ n$
    - $ep \to e'K^+\Lambda^0(\Lambda^0 \to n\pi^0$ OR $\Lambda^0 \to \pi^- p)$
    - $ep \to e'K^+\Sigma^0(\Sigma^0 \to \gamma\Lambda^0)$
  - Systematically understand FF detector performance and reconstruction

ePIC F_π Simulations - t Resolution

- Preliminary ePIC studies under way
- -t resolution looks improved
  - Beampipe exit window in simulation
- Next step is to study DEMP kaon events



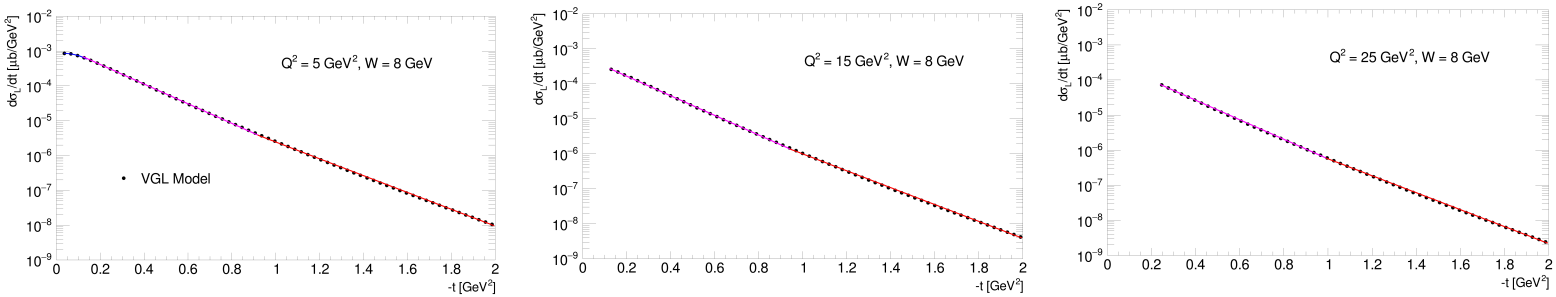
- Same -t determination method as ECCE

- Kaon channels implemented in DEMPgen recently

Plot from L.Preet, University of Regina

F_K at the EIC - Generator Updates

- URegina MSc student Love Preet added new Kaon DEMP event generator module to DEMPgen
  - Starting with $p(e, e'K^+\Lambda)$
- Parametrise a Regge-based model
- 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

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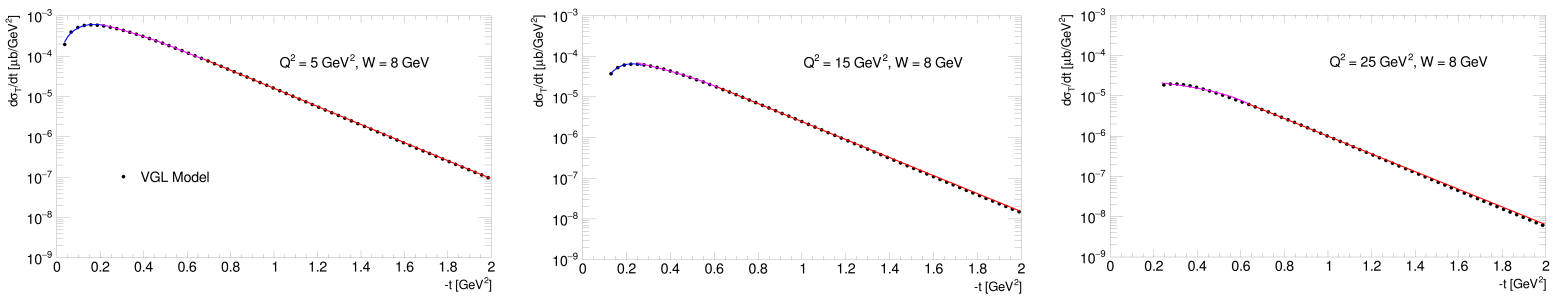


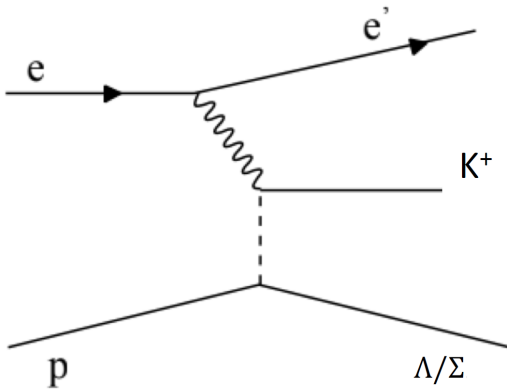
VGL Model - M. Guidal, J.-M. Laget, M. Vanderhaeghen, PRC 61 (3000) 025204

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

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

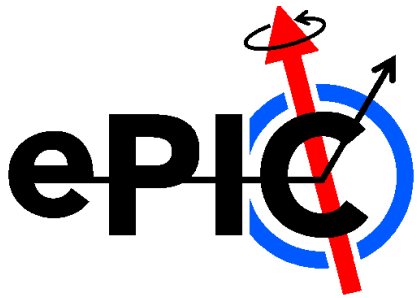


  - Consider just the Λ channel for now
    - Λ plays a similar role to neutron in π studies
    - Very forward focused, **but**, Λ will decay
      - $\Lambda \rightarrow n\pi^0$ - ~ 36 %
      - $\Lambda \rightarrow p\pi^-$ - ~ 64 %
    - Neutral channel potentially best option
      - **Very challenging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

Summary

- Meson form factors can provide valuable insights into hadron mass generation mechanisms
  - EIC can potentially push deep into unexplored territory
  - F_π up to $Q^2 \sim 30\ GeV^2$
- ePIC simulations in progress
  - Promising signs of -t resolution improvements
  - Acceptance issues under investigation
- F_K studies next
  - Challenging final states
- DEMP reactions key benchmarking channel for FF detectors
- Analysis will feature in TDR and associated papers

Thanks for listening, any questions?



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Science and Technology Facilities Council

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