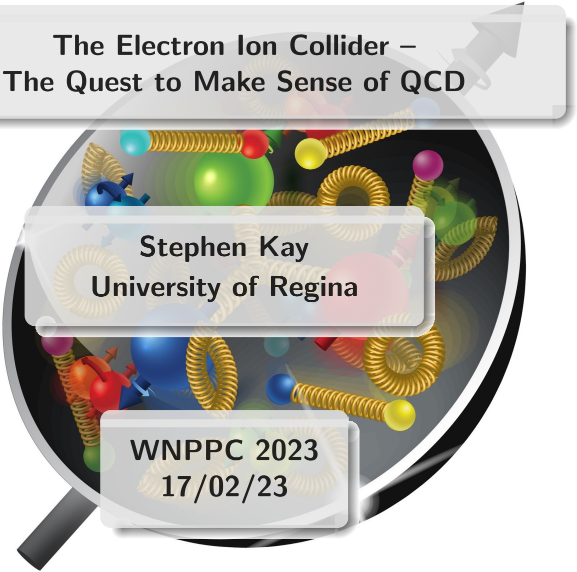
The Electron Ion Collider –
The Quest to Make Sense of QCD



Stephen Kay
University of Regina

WNPPC 2023
17/02/23

Outline

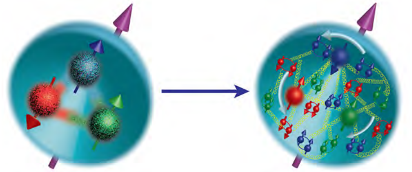
- Why an EIC?
- The EIC - A unique facility
- Current Status
- Light Meson Structure at the EIC

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

The Proton - More than meets the eye

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

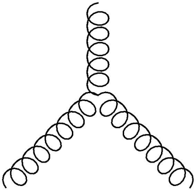
$$m_p \approx 938\ MeV/c^2,$$
$$m_u \approx 3\ MeV/c^2, m_d \approx 6\ MeV/c^2,$$
$$(2 \times 3) + 6 = 938?$$



- 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!
- We cannot adequately explain these processes
- **QCD is not "solved"**

Why an Electron-Ion Collider?

- Three important open questions -
  - **How does the mass of the nucleon arise?**
  - *How does the spin of the nucleon arise?*
  - *What are the emergent properties of dense systems of gluons?*
- Interactions and structure are not isolated ideas in nuclear matter
  - Quarks bound by gluons, gluons self interact
  - Observed properties of nucleons and nuclei (mass, spin) emerge from this complex interplay



- Need a specific facility designed to address these questions and understand hadrons.
  - The Electron-Ion Collider (EIC)

Features of the EIC - A Versatile Machine

- Answering our open questions requires a versatile machine
- The Electron-Ion Collider (EIC) is the right tool
  - High Luminosity ($10^{33} - 10^{34}$ $cm^{-2}s^{-1}$)
  - Both beams polarised
  - Different species (d, Pb, ^{3}He, Au...)
  - Variable beam energies (e^{-} $5 - 18$ GeV, Ion $41 - 275$ GeV)
  - Need to precisely image quarks, gluons and their interactions

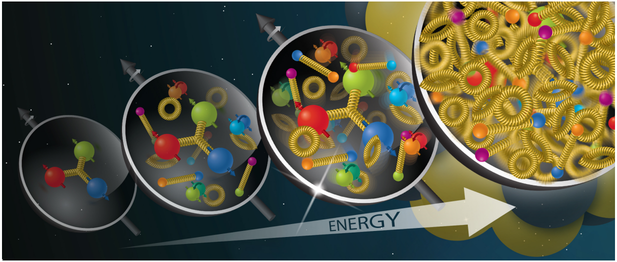
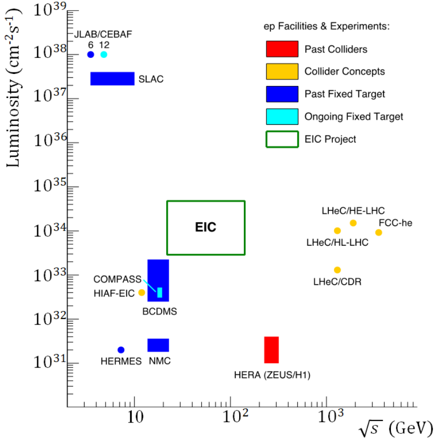


Image - Brookhaven National Lab, https://www.flickr.com/photos/brookhavenlab/

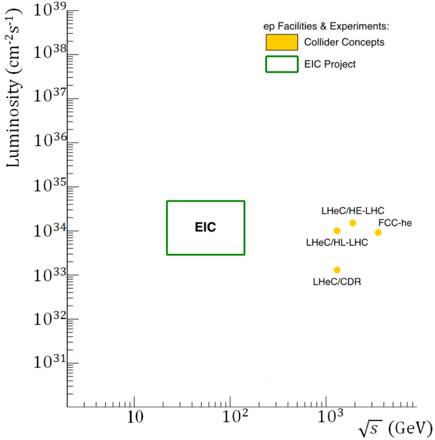
The EIC - A Unique Facility



- A lot of Deep Inelastic Scattering (DIS) facilities
- However, if we need:

Image - A. Desphpande, modified,
https://sites.nationalacademies.org/cs/groups/bpasite/documents/webpage/bpa_178993.pdf

The EIC - A Unique Facility



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- However, if we need:
  - High luminosity
  - Wide range in $\sqrt{s}$

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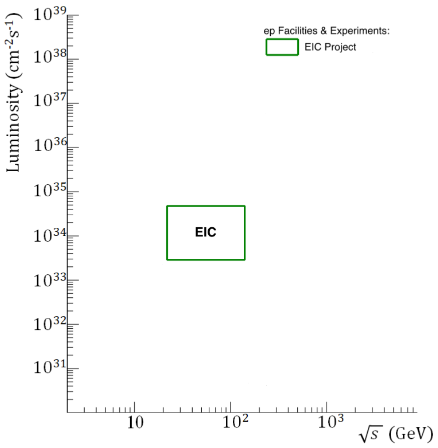
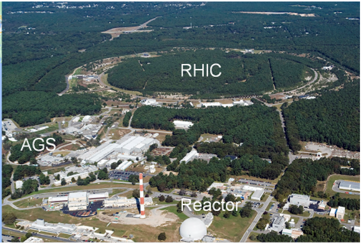


- A lot of Deep Inelastic Scattering (DIS) facilities
- However, if we need:
  - High luminosity
  - Wide range in $\sqrt{s}$
  - Polarised lepton **and** ion beams (p, d, ^{3}He)
  - Nuclear beams
- Only the EIC ticks all the boxes
- EIC is unique

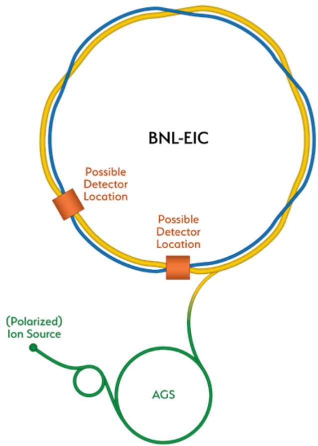
Image - A. Desphpande, modified,
https://sites.nationalacademies.org/cs/groups/bpasite/documents/webpage/bpa_178993.pdf

EIC Site Selection

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

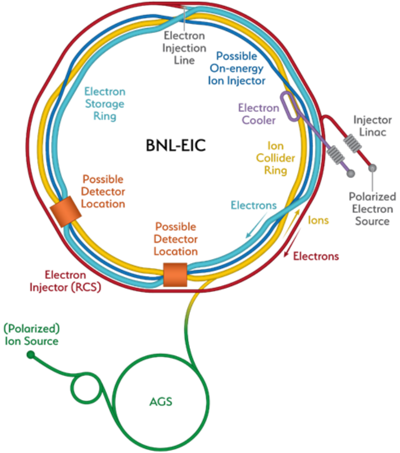


eRHIC



- 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
- High $\mathcal{L}$ achieved by state of the art beam cooling techniques

eRHIC



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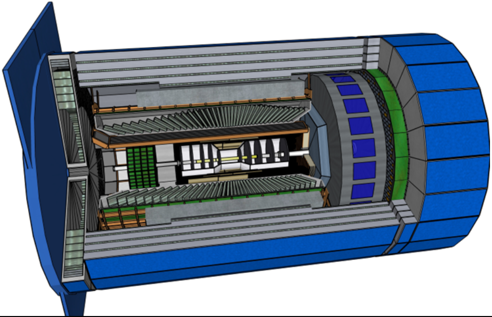
Detector 1 - The ePIC Collaboration

- Major detector proposal process finished last year
- New detector 1 collaboration, **ePIC**, electron-Proton/Ion Collider experiment
- Responsible for constructing a detector which will deliver upon the core science goals of the EIC
- Large scale simulation effort now in full swing
    - Develop final detector design

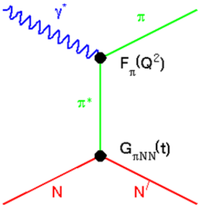


So, what can we measure?

- To answer our initial questions, need to measure internal structure of hadrons
  - How does this structure evolves with a changing energy scale?
- Seek to understand a wide range of QCD objects
- Light mesons, like the charged pion ($u\bar{d}/\bar{u}d$) and kaon ($u\bar{s}/\bar{u}s$) are an ideal testing ground
- Can measure **D**eep **E**xclusive **M**eson **P**roduction (**DEMP**) reactions at the EIC to study light meson structure
- To examine this structure, we can measure quantities such as the electromagnetic form factors of the charged pion and kaon, F_π and F_K
  - Form factors describe momentum space distributions of partons within hadrons
- Light meson structure is a focus at the University of Regina

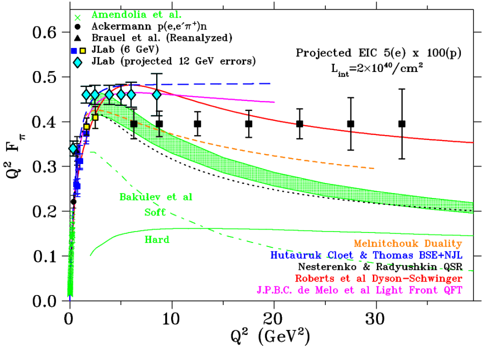
DEMP Studies at the EIC

- Measurements of the $p(e, e'\pi^+ n)$ reaction at the EIC can potentially extend the Q^2 reach of F_π
  - $Q^2 \rightarrow$ Four-momentum transfer squared
  - Want to see how F_π evolves with Q^2
- A challenging measurement however
  - Need good identification of $p(e, e'\pi^+ n)$ triple coincidences



- 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
  - More on this event generator in the next talk by L. Preet!

Pion Form Factors at the EIC



- Simulated DEMP reactions at the EIC
- Potential to extend measurements of F_π to very high Q^2
- Note - y positioning of points arbitrary
- Higher Q^2 data on F_π vital for our understanding of hadronic physics
- Want to study the kaon as well as the pion
  - More on this in the next talk by L. Preet!

Summary

- *"An EIC can uniquely address three profound questions about nucleons... the science it will achieve is unique and world leading"*
- US Inflation reduction act (IRA) recently injected significant ($\sim$ US\$100's millions per year) funding for the EIC project
- The EIC is an exciting opportunity for <u>our</u> generation of physicists - Expected program: 2030-2060
- Canada is well positioned to contribute to this program
- The project is building momentum, opportunities to contribute only going to grow from here!
- **First physics collisions expected within a decade!**

Quoted text from the US National Academy of Sciences 2018 report - https://nap.nationalacademies.org/catalog/25171/an-assessment-of-us-based-electron-ion-collider-science

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

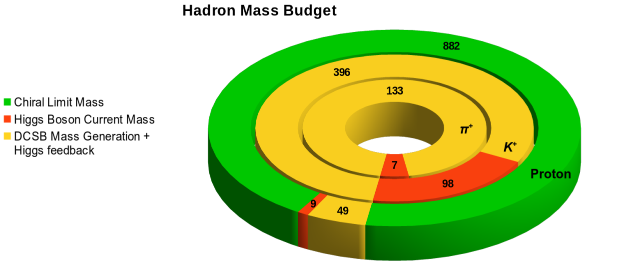
EIC-Canada

This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), FRN: SAPPJ-2021-00026

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

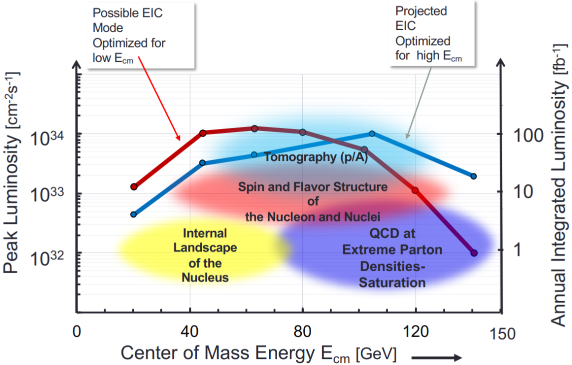
Emergent Dynamics in QCD



- Only the portion in red is from the Higgs current!
- Need to account for more than just protons!
- Properties of hadrons are emergent phenomena
- How do hadrons and nuclei emerge from quarks and gluons?
    - Need experimental insight from facilities like the EIC

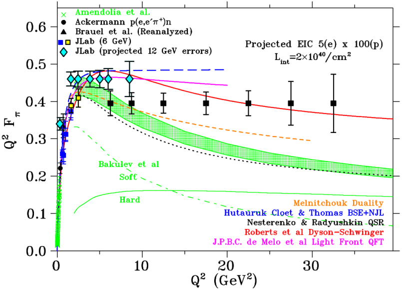
The Benefits of Being Unique

- Broad and unique capabilities, wide range of topics examinable
- Orders of magnitude higher luminosity than previous machines
- This is unexplored terrain
- Capabilities demand frontier ideas and technologies



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

EIC Users Group

- 1380 members from 269 institutions spread across 36 countries (as of Feb 2023)
- 32 members from 8 Canadian institutions

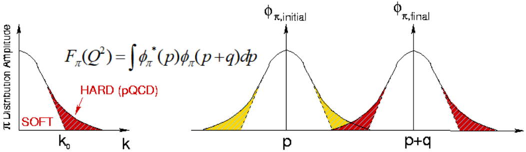
EIC UG - https://phonebook.sdcc.bnl.gov/eic/client/

EIC Canada

- Canadian subatomic physicists involved in the planning and development of the EIC for many years
- EIC Canada collaboration formed to co-ordinate participation
- Investigators and researchers from three institutions currently
  - University of Manitoba
  - Mount Allison University
  - University of Regina
- Current opportunities for MSc and undergraduate projects
- More and more opportunities expected as the project develops!
- `https://eic-canada.org/` for more information
- More Canadian members of the user group or the EIC Canada collaboration always welcome!

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 $\phi_{\pi}^{\mathrm{soft}}$ $(k < k_0)$ and $\phi_{\pi}^{\mathrm{hard}}$, the hard tail
  - Can treat $\phi_{\pi}^{\mathrm{hard}}$ in pQCD, cannot with $\phi_{\pi}^{\mathrm{soft}}$
  - 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

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 -

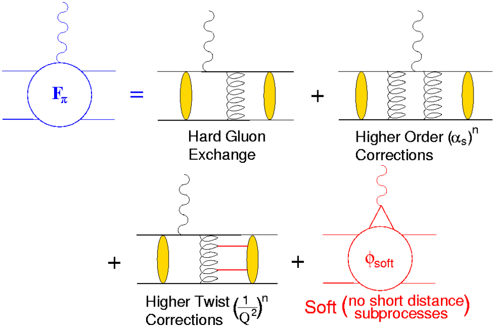
$$Q^2 F_\pi \xrightarrow[Q^2\to\infty]{} 16\pi\alpha_s(Q^2)f_\pi^2$$

- 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

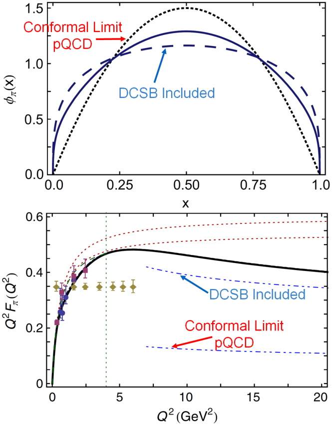
- At experimentally accessible Q^2, both the hard and soft components contribute



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

Connecting Pion Structure and Mass Generation

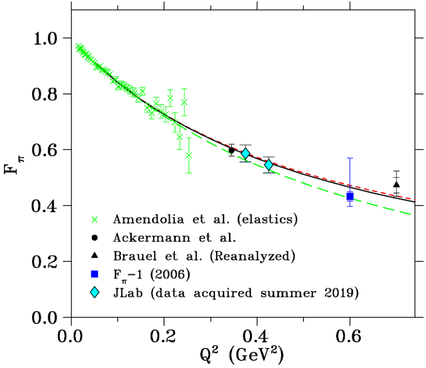
- ϕ_π as shown before has a broad, concave shape
- Previous pQCD derivation (conformal limit) did not include DCSB effects
- Incorporating DCSB changes $\phi_\pi(x)$ and brings F_π calculation much closer to the data
    - "Squashes down" PDA
- Pion structure and hadron mass generation are interlinked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

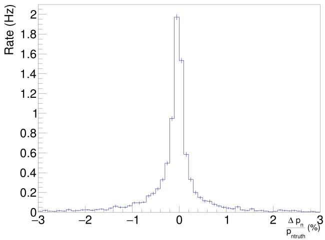
- High energy ZDC hit requirement used as a veto
  - ZDC neutron ERes is relatively poor though

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

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

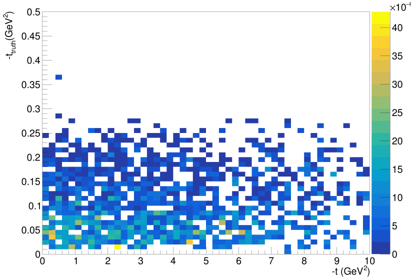
$$p_{miss} = |\vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}|$$

- 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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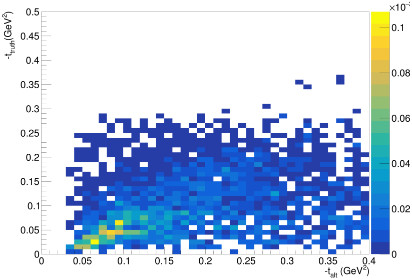
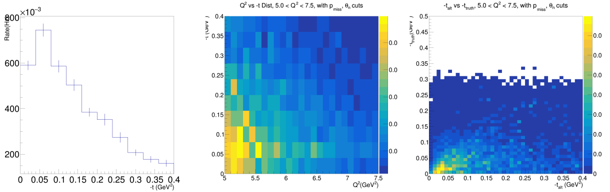


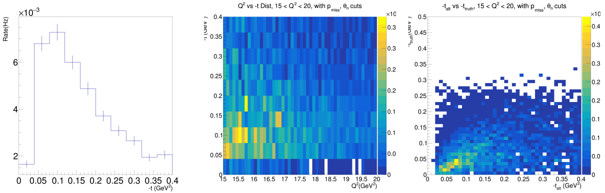
- x-axis $-t$ scale an order of magnitude smaller now!

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 $-t$
  - 5 (e', GeV) on 100 (p, GeV) events
  - $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$ assumed
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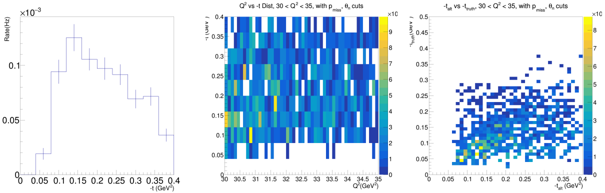
    - New cut on difference between p_{miss} and detected ZDC angles implemented too, $|\Delta\theta| < 0.6^\circ$, $|\Delta\phi| < 3.0^\circ$
- $-t_{min}$ migrates with Q^2 as expected

Simulation Results - Q^2 $30 - 35$ 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
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Isolating σ_L from σ_T in an e-p Collider

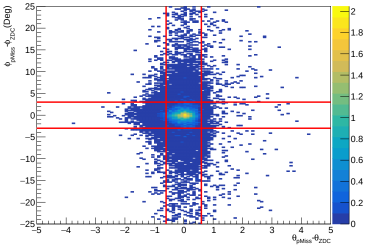
- For a collider -

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

  - 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

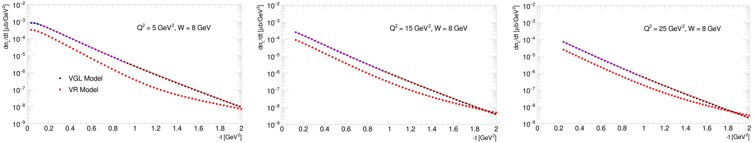
- Make use of high angular resolution of ZDC
- Compare hit θ/ϕ positions of neutron on ZDC to calculated θ/ϕ from p_{miss}
- If no other particles produced, quantities should be correlated
  - True for DEMP events
- Energetic neutrons from inclusive background processes will be less correlated
  - Additional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

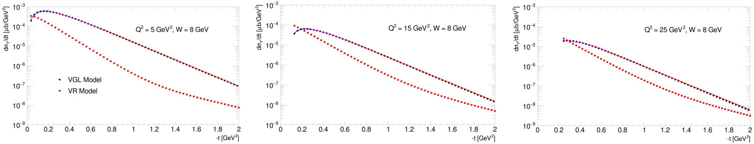
- Working on adding Kaon DEMP events to DEMPGen
  - Starting with $p(e, e'K^+\Lambda)$
- Parametrise a Regge-based model in a similar way to the pion
- For $p(e, e'K^+\Lambda)$ module, use the Vanderhagen, Guidal, Laget (VGL) model
- Parametrise σ_L, σ_T for $2 < Q^2 < 35$, $2 < W < 10$, $-t < 2.0$
-



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

F_K at the EIC - Generator Updates

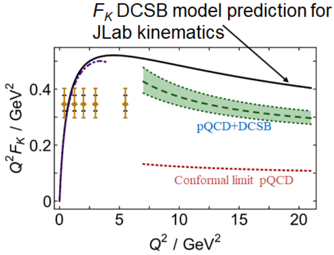
- Working on adding Kaon DEMP events to DEMPGen
  - Starting with $p(e, e'K^+\Lambda)$
- Parametrise a Regge-based model in a similar way to the pion
- For $p(e, e'K^+\Lambda)$ module, use the Vanderhagen, Guidal, Laget (VGL) model
- Parametrise σ_L, σ_T for $2 < Q^2 < 35$, $2 < W < 10$, $-t < 2.0$
-

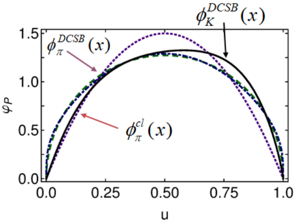


VGL Model Paper - `https://doi.org/10.1016/S0375-9474(97)00612-X`

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



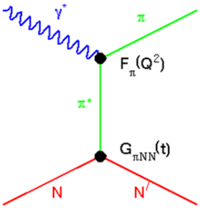


C. Shi, et al., PRD 92 (2015) 014035, F. Guo, et al., PRD 96(2017) 034024 (Full calculation)

Measurement of F_π at High Q^2

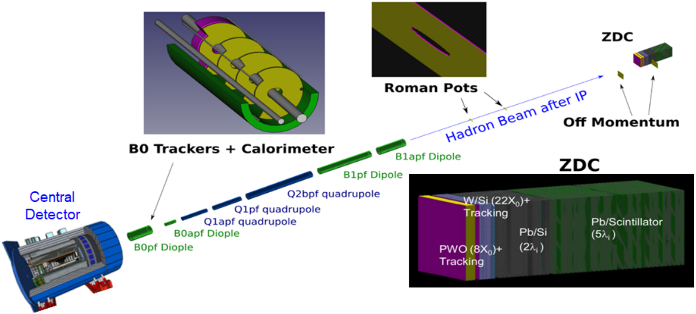
- To access F_π at high Q^2, must measure F_π indirectly
  - Use the "pion cloud" of the proton via $p(e, e'\pi^+)n$
- At small $-t$, the pion pole process dominates σ_L
- In the Born term model, F_π^2 appears as -

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



- 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**)

EIC Detector Overview



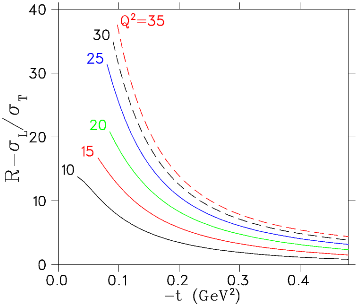
- Feed generator output into detector simulations
- Far forward detectors critical for form factor studies

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

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