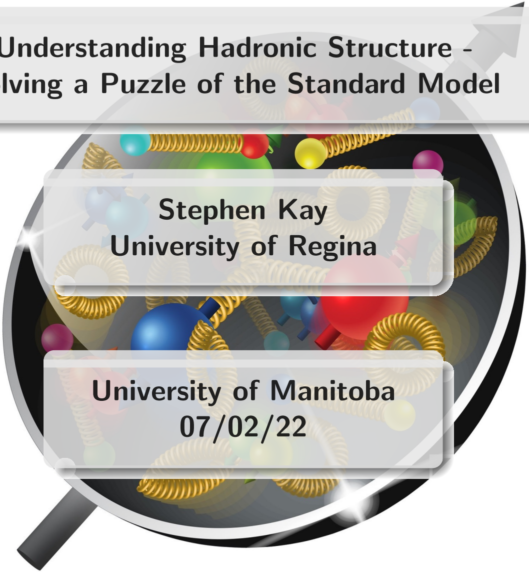
Understanding Hadronic Structure - Solving a Puzzle of the Standard Model



Stephen Kay
University of Regina

University of Manitoba
07/02/22

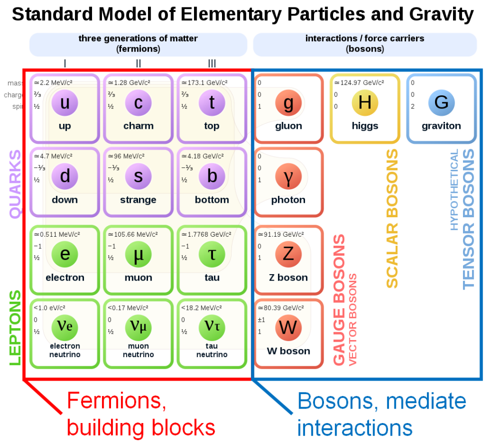
Outline

- Hadron Physics and QCD
- Understanding Hadron Structure
  - Form Factors
- Current Facilities - Jefferson Lab
  - The Kaon and Pion LT experiments
- Future Facilities and Experiments
  - Future Jefferson Experiments and Lab Facilities
  - The Electron-Ion Collider
- Outlook

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

Making Sense of the Universe

- Standard Model is the toolkit we use to describe objects in our universe
  - **And their interactions**
- Fermions, building blocks of observable objects in the universe
- Bosons, force carriers, mediate interactions between objects



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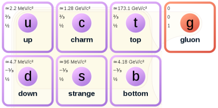
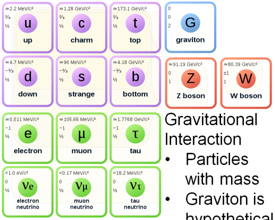
Making Sense of the Universe

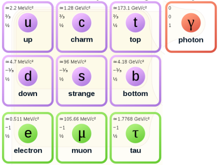


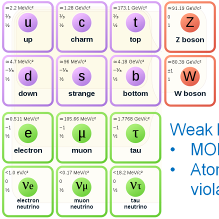
Strong Interaction
- Colour charged objects
- Majority of visible mass in the universe due to particles in this section and their interactions
- The topic of this talk



Gravitational Interaction
- Particles with mass
- Graviton is hypothetical

EM Interaction
- Electrically charged objects



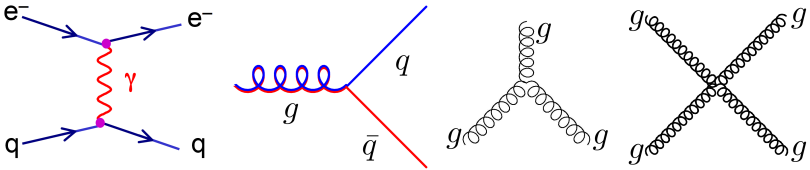


Weak Interaction
- MOELLER
- Atomic parity violation

Image - Modified Wikimedia Commons

Quantum Chromodynamics

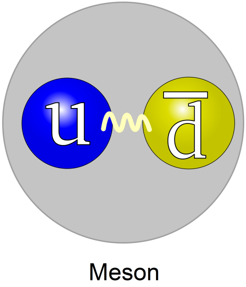
- Our theory of the strong interaction is known as **Q**uantum **C**hromo**D**ynamics (**QCD**)
- Interactions occur between objects that are "colour" charged, such as quarks, via the exchange of **gluons**, g
- Analogous to **photons**, γ, in EM interactions
- Small, but crucial, difference, gluons are colour charged
    - Gluons can self interact

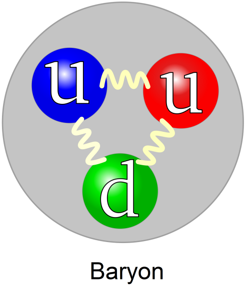


Images - Modified Wikimedia Commons

Building Hadrons

- Hadrons are **colour neutral** objects formed of quarks
  - Cannot isolate objects with colour charge
  - Empirical observation known as **confinement**
- Considering only the valence quarks, two easy ways to make a colour neutral object





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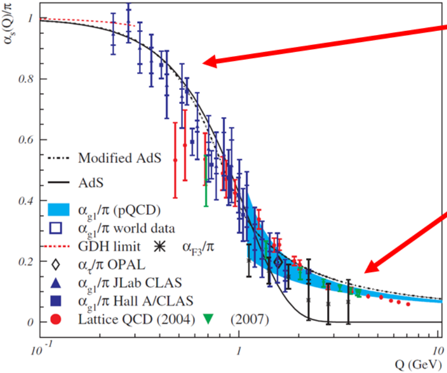
The Dual Nature of QCD



Long Distance (Low Energy) Interaction :

- Quarks strongly bound within hadrons
- Colour confinement
- Quantitative QCD description of hadron properties remains a puzzle
- Unfortunately, this is the regime under which we live!

Short Distance (High Energy) Interaction :

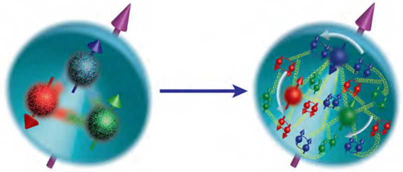
- Short range interaction is weak
- Quarks inside hadrons behave as though they are nearly unbound
- Can understand behaviour using **perturbative QCD (pQCD)**
- Asymptotic Freedom

Image - Modified from S.J. Brodsky et. al. PRD 81:096010, 2010

The Proton - More than meets the eye

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

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

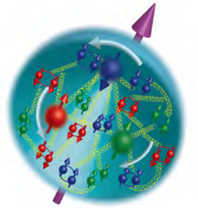


- **Where does the mass come from?**
- Massless gluons and nearly massless quarks, through their interactions, generate most of the mass
- $\sim$ 99% of the mass of hadrons $\rightarrow$ most of the visible mass in the universe!
- Can we understand the transition between our two pictures?

Image - A. Deshpande, Stony Brook University

Understanding Dynamic Matter

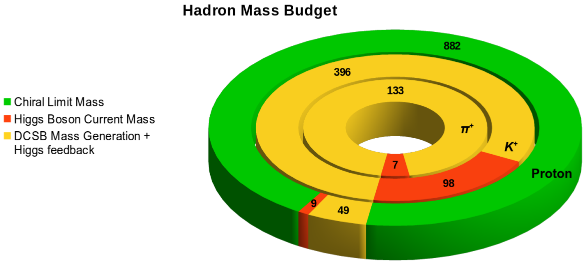
- Interactions and structure are not isolated ideas in nuclear matter
  - Observed properties of nucleons and nuclei (mass, spin) emerge from this complex interplay
  - Properties of hadrons are emergent phenomena



- Mechanism known as **D**ynamical **C**hiral **S**ymmetry **B**reaking (**DCSB**) plays a part in generating hadronic mass
- How do our two distinct regions of QCD behaviour connect?
- Need to account for more than just protons!
- **A major puzzle of the standard model to try and resolve!**

Image - A. Deshpande, Stony Brook University

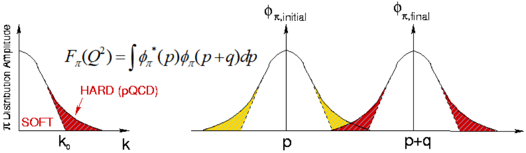
More Than Just Protons



- Multiple mechanisms at play
- DCSB not experimentally demonstrated
- What quantities can we examine to understand hadron structure?
- **The simple $q\bar{q}$ valence structure of mesons makes them an excellent testing ground**

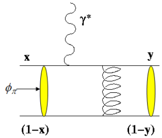
Meson Form Factors

- Charged pion ($\pi^{\pm}$) and Kaon ($K^{\pm}$) form factors (F_{π}, F_K) are key QCD observables
  - Describe the spatial distribution of partons within a hadron



- 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 and simple QCD quark system
  - K - Another simple system, contains strange quark

Rigorous Predictions for the Pion from pQCD



- At very large four-momentum transfer squared, Q^2, F_π can be calculated using pQCD
  - 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 -

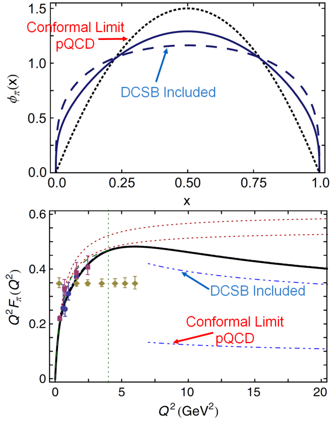
$$Q^2 F_\pi \xrightarrow[Q^2\to\infty]{} 16\pi\alpha_s(Q^2) f_\pi^2$$

  - This is a **rigorous** prediction of pQCD
  - Q^2 **reach of existing data doesn't extend into transition region**
    - Need unique, cutting edge experiments to push into this region

Eqns - G.P. Lepage, S.J. Brodsky, PLB 87, p359, 1979

Connecting Pion Structure and Mass Generation

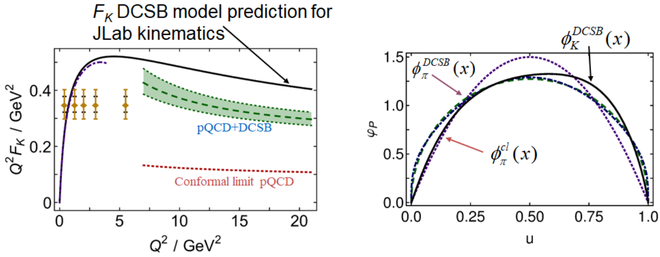
- ϕ_π as shown before has a broad, concave shape
- Previous pQCD derivation (conformal limit) did not include DCSB effects
- Incorporating DCSB changes $\phi_\pi(x)$ and brings F_π calculation much closer to the data
  - “Squashes down” PDA
- Pion structure and hadron mass generation are interlinked



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



- Form factors are not the only quantity we can examine
- **How can we measure F_π or F_K at high Q^2 anyway?**

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

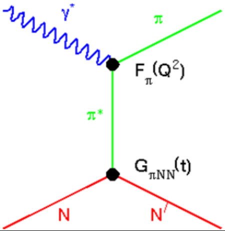
Examining Meson Form Factors at Current Facilities

How can we access F_π at high Q^2 experimentally?

- At high Q^2, must measure F_π indirectly
  - Scatter e^- off the "pion cloud" of the proton
  - Exchange a virtual photon γ^*, produce a real pion - $p(e, e'\pi^+)n$
- In a simple theoretical picture, can link F_π to a part of the cross-section, σ_L, for this reaction

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

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



Isolating σ_L

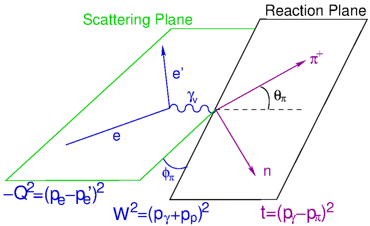
- The physical cross section for the electroproduction process is given by -

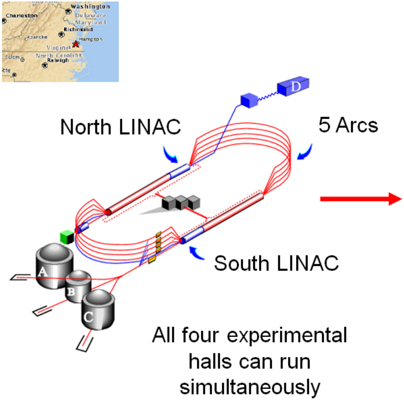
$$2\pi \frac{d^2\sigma}{dtd\phi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi,$$

$$\epsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2} \tan^2 \frac{\theta_{e'}}{2}\right)^{-1}$$

- $\epsilon \rightarrow$ Virtual photon polarisation

- L-T separation required to isolate σ_L from σ_T
- Where can we do a measurement like this?
  - Thomas Jefferson National Accelerator Facility, Jefferson Lab

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Charleston
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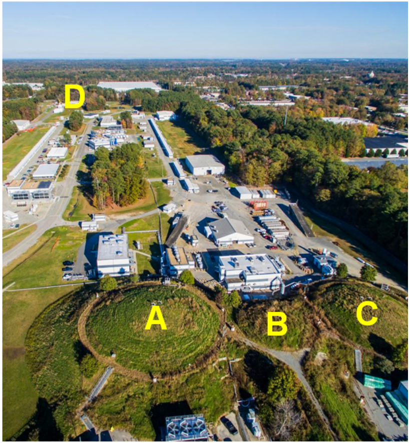
C
All four experimental halls can run simultaneously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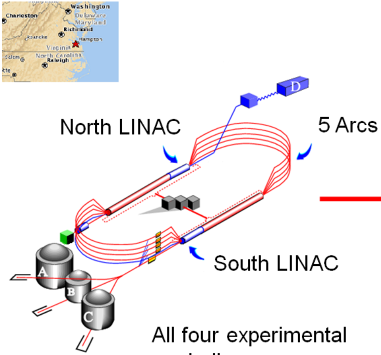

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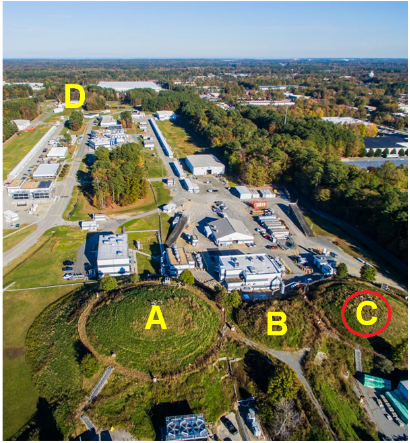
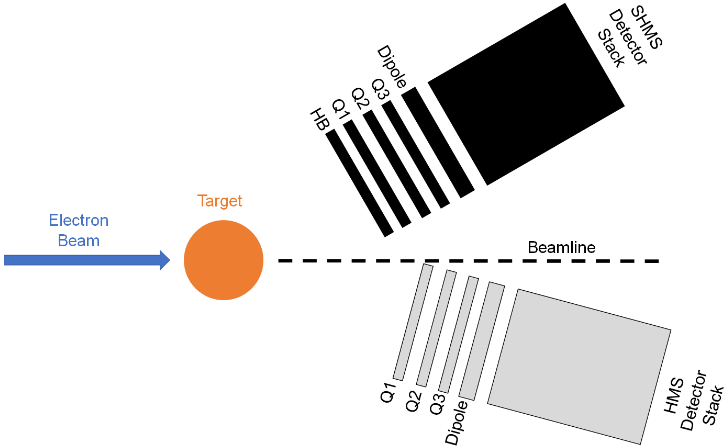


Meson Form Factors - JLab Program

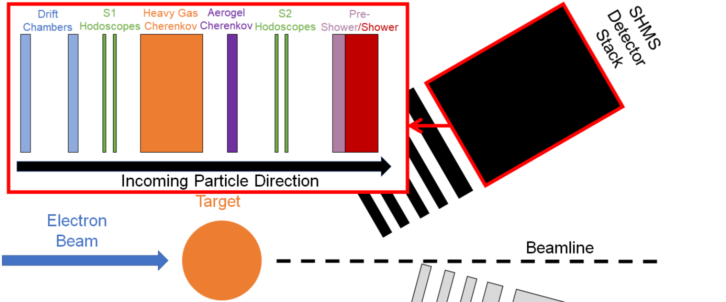
- Two major form factor experiments in JLab Hall C
- Measure pion and kaon electroproduction reactions to extract form factors
- High impact experiments, previous F_π experiment papers cited hundreds of times
- E12-09-011 (Spokespeople: T. Horn, G Huber, P. Markowitz)
  - Ran in 2018-2019, analysis in progress
  - LT separated kaon cross section, will attempt to extract F_K
- E12-19-006 (Spokespeople: D. Gaskell, T. Horn, G. Huber)
  - Low Q^2 part ran in June/July 2019
  - **Large experimental run in 2021 and ongoing in 2022**
  - LT separated pion cross section, F_π to high Q^2 (8.5 GeV^2)

Hall C in the 12 GeV era

Hall C in the 12 GeV era

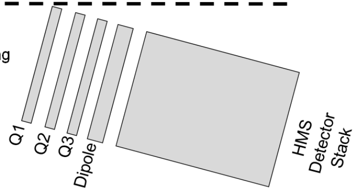


Hall C in the 12 GeV era

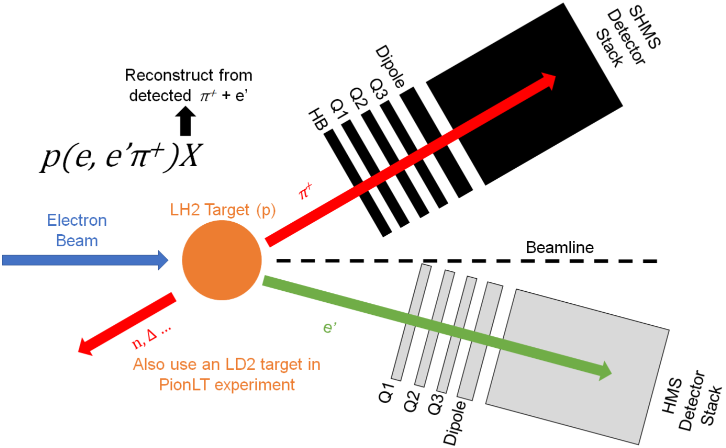


- Drift chambers and hodoscopes for tracking
- Threshold Cherenkovs for Particle ID
- Shower calorimetry
- Can also insert a Noble Gas Cherenkov before the drift chambers too

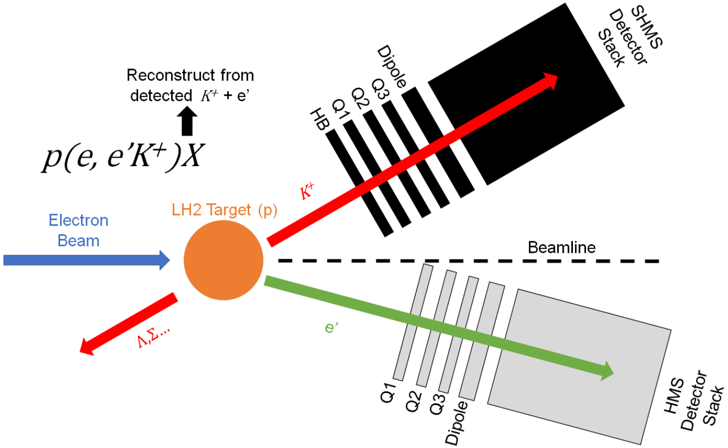
HMS detector stack is similar



Hall C in the 12 GeV era - Pion/KaonLT Experiment



Hall C in the 12 GeV era - Pion/KaonLT Experiment



Measuring $\frac{d\sigma_L}{dt}$ at JLab

- Rosenbluth separation required to isolate σ_L
  - Fix W, Q^2 and $-t$, measure cross section at two beam energies
  - Carry out simultaneous fit at two different ϵ values to determine interference terms

- Careful control of point-to-point systematics crucial, $1/\Delta\epsilon$ error amplification in σ_L
- Spectrometer acceptance, kinematics and efficiencies must all be carefully studied and understood

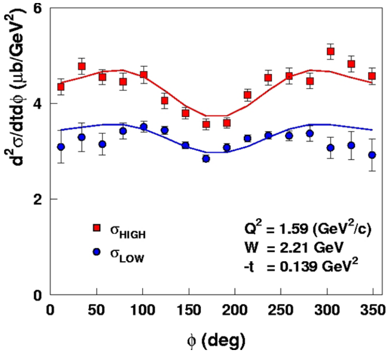
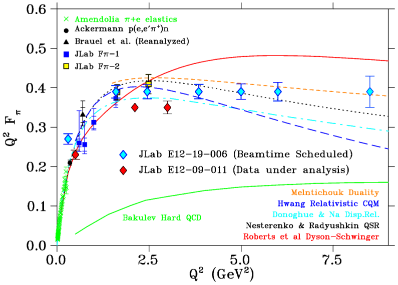


Figure - T. Horn, et al., PRL 97(2006) 192001

Current and Projected JLab F_π Data

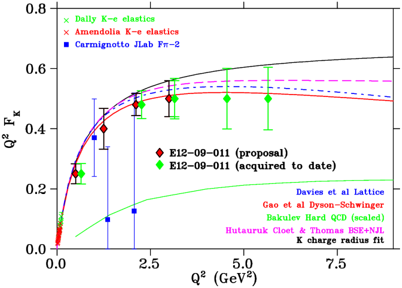
- JLab 12 *GeV* program includes measurements of F_π to higher Q^2
- JLab Hall C is the only facility worldwide that can perform this measurement
- Projected error bars show on plot, *y* positioning of points arbitrary
- Models all disagree!
  - Contributions from sea quarks and gluons highly uncertain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



- **New experiments and facilities on the horizon**
    - New opportunities

Hadron Structure at Future Facilities

The **So**lendoial **L**arge **I**ntensity **D**evice (**SoLID**)

- **SoLID** is an upcoming high acceptance detector at JLab
  - To be installed after MOELLER in Hall A
  - Expected to be operational before the end of this decade
- Two different detector configurations
  - **S**emi-**I**nclusive **D**eep **I**nelastic **S**cattering (**SIDIS**)
  - **P**arity **V**iolating **D**eep **I**nelastic **S**cattering (**PVDIS**)
- **D**eep **E**xclusive **M**eson **P**roduction (DEMP) reactions allow us to probe a different aspect of hadron structure with SoLID
  - Can examine **G**eneralised **P**arton **D**istributions (**GPDs**)

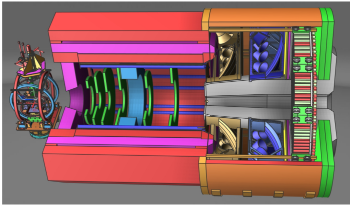
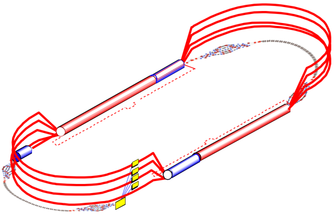


Image - SoLID Collaboration

Taking JLab Into the Future - JLab20

- Could upgrade energy of JLab accelerator again
- Replace some arcs with a Fixed Field Alternating Gradient (**FFA**) arcs, new injector
- Could push energy to the $20 - 24$ *GeV* range
- Fixed target experiments still useful, facility has unique capabilities
  - What can we do with existing equipment?
  - New equipment?
- But, what about entirely new facilities?



Proposed replacement of two arcs with FFA arcs, new injector not shown.

- If this goes ahead, will be beyond 2030.

Image - Alex Bogacz, 20-24 GeV FFA CEBAF Energy Upgrade

- 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**)

Putting (Another) Ring on it - eRHIC

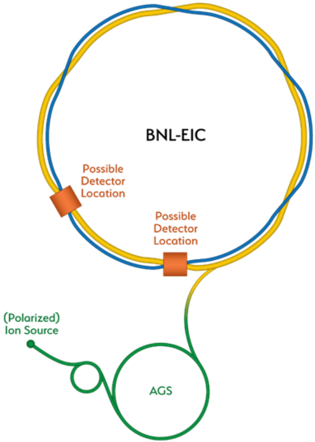


Image - Brookhaven National Lab

- 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

Putting (Another) Ring on it - eRHIC

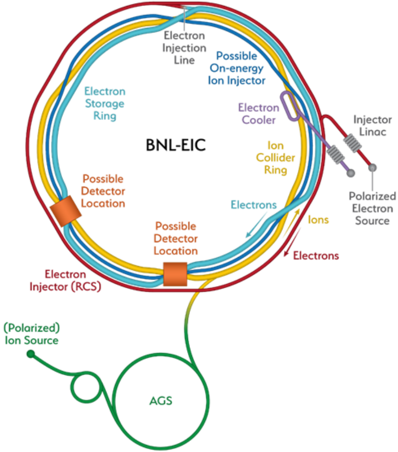


Image - Brookhaven National Lab

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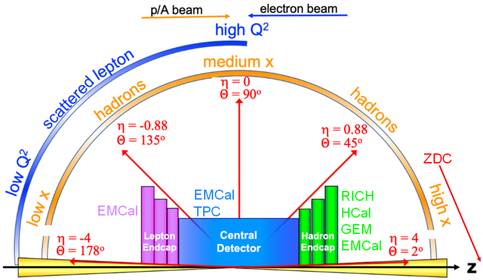
Form Factors at the EIC

- JLab measurements push the Q^2 reach of data considerably
- Still cannot 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 EIC software framework to assess the feasibility of the study with updated design parameters
  - Feed in events generated from UoR DEMP event generator
  - Multiple detector concepts to evaluate
- Event generator being modified to generate kaon events

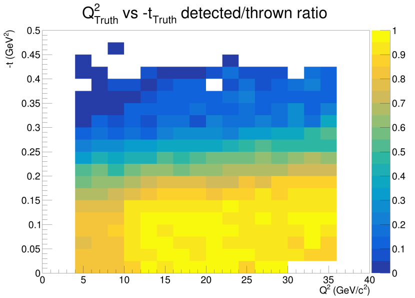
EIC Detector Overview



- 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/

EIC Simulation Results for ECCE

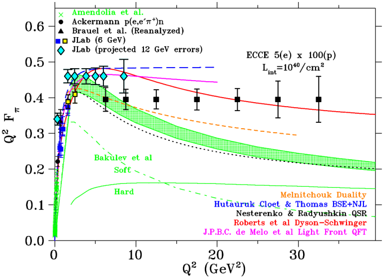
- My recent work has focused on EIC simulations
- Work showed importance of a large, high quality **Z**ero **D**egree **C**alorimeter
- **Examined detection efficiency for DEMP events**
- $\text{Efficiency} = \frac{\text{Accepted}}{\text{Thrown}}$
- **Simulation results utilised for form factor projections**



- Detection efficiency highest for low $-t$
- Nearly independent of Q^2
- Dictated by size of ZDC

EIC F_π Data - Reaching for Some Answers

- ECCE appears to be capable of measuring F_π to $Q^2 \sim 32.5\ GeV^2$
- **Error bars represent real projected error bars**
- Overlap with JLab data at the low end of the Q^2 range
- Data pushes into region where we can distinguish between models
- Data here can address mass generation questions
    - One of the key science questions for the EIC!



- Results look promising, need to test other detector concepts
- More details in upcoming ECCE analysis note

Form Factors at the EIC - Outlook

- EIC has the potential to push the Q^2 reach of F_π measurements
  - Can we measure F_K too?
- F_π work already featured in the EIC yellow report
- Now working closely with detector proto-collaborations
  - Carrying out feasibility studies
  - UoR DEMP event generator utilised
  - Kaon event generator update 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!
- Could also examine the GPD $\tilde{E}$ at the EIC

R. Abdul Khalek et al. EIC Yellow Report. 2021. arXiv:2103.05419, Sections 7.2.1 and 8.5.1

Closing Remarks - Future Plans

Short Term Plans - JLab Hall C and EIC Prep

- Numerous projects and opportunities in the 1-3 year term
- **Hall C form factor experiments are ongoing**
- A lot of data to analyse
  - Can extract more than just form factors from the data
  - Beam helicity asymmetries, u-channel analysis, η and η' cross sections...
- **Planning and preparation for the EIC already ongoing**
- Detector collaboration formation expected soon
  - EIC-Canada can play an important role
  - Revisit pion form factors with updated simulations
- New studies and projects
  - Kaon form factors at the EIC
  - $\tilde{E}$ at the EIC
  - Detector design?

Intermediate Term Plans - Hall A, Hall C and the EIC

- In the 3-10 year term, many new opportunities to explore
- Many exciting experiments in Hall A within this time period
  - MOELLER
  - SoLID
- **Preparation and planning for future SoLID experiments**
  - $\tilde{E}$ GPD studies
  - Involvement in the PVDIS program?
- **EIC project ramping up significantly in this time period**
  - Experiment planning, simulations, projections
  - Detector construction?
- **Opportunities in Hall C too**
  - If results from Kaon LT are promising, build on this
  - Considerable theoretical interest in the Kaon form factor
  - Even with the EIC, Hall C will be our <u>only</u> source of L/T separated cross section data

Long Term Plans - The EIC

- Dominating the horizon into the next decade is the EIC
- The US National Academy of Sciences summarises the potential of the EIC better than I can!
- *An EIC can uniquely address three profound questions about nucleons...*
    - **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?*
- *"... the science it will achieve is unique and world leading"*
- The EIC is an exciting opportunity for the next generation of physicists - Expected program: 2030-2060
- Canada is well positioned to contribute to this program

Thanks for listening, any questions?

The University of Regina is situated on the territories of the nēhiyawak, 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.

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