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

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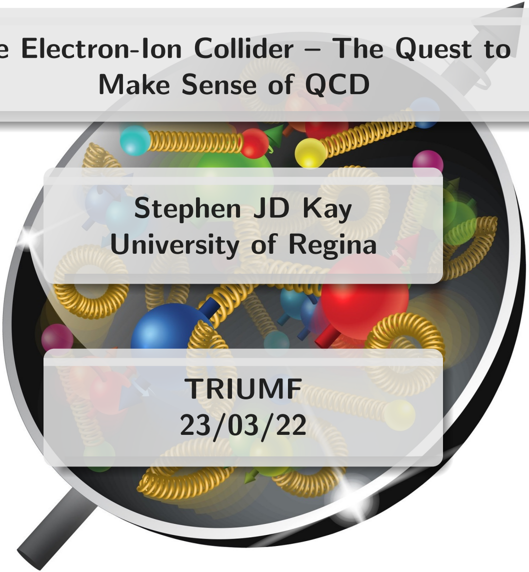
TRIUMF
23/03/22



Outline

- QCD - What don't we understand?
- The EIC - Features and Capabilities
- Canadian Contributions at the EIC
- Outlook and Future Plans

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Part I - Quantum Chromodynamics

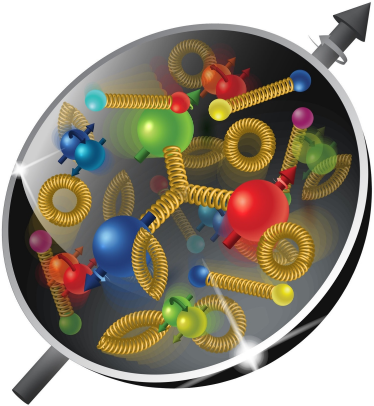


Image - Brookhaven National Lab, https://www.flickr.com/photos/brookhavenlab/

Making Sense of the Universe - Building Blocks

- 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

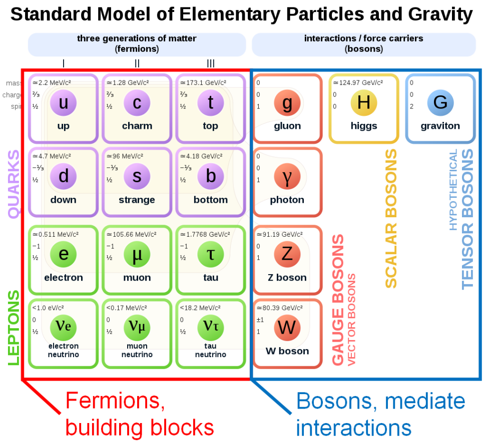
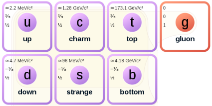
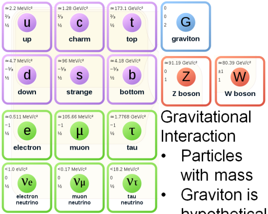


Image - Modified Wikimedia Commons



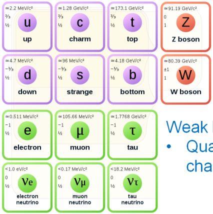
Strong Interaction

- 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



Weak Interaction

- Quark flavour changing

EM Interaction

- Electrically charged objects

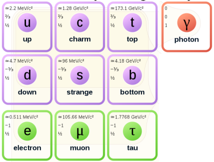
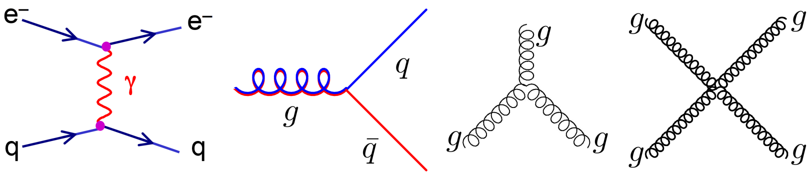


Image - Modified Wikimedia Commons

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



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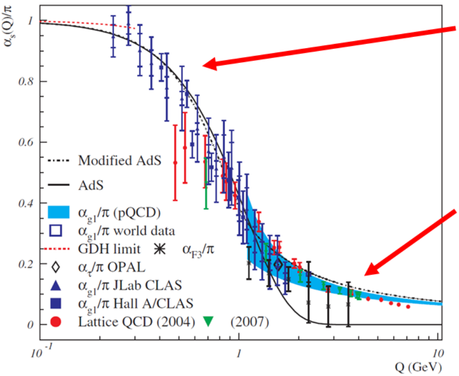
The Dual Nature of QCD



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!

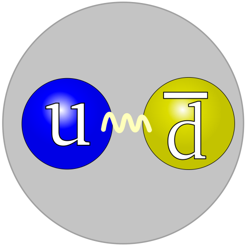
Short Distance (High Energy) Interaction :

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

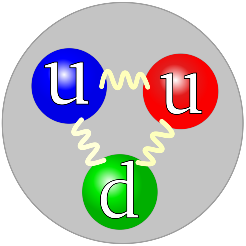
Image - Modified from S.J. Brodsky et. al. PRD 81:096010, 2010

Building Hadrons - Gluing Quarks Together

- **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
  - Mesons - $q\bar{q}$
  - Baryons - qqq



Meson

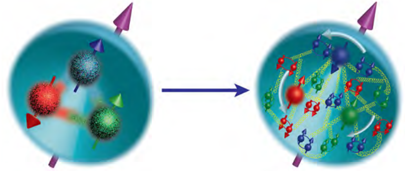


Baryon

The Proton - Mass from nothing?

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

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

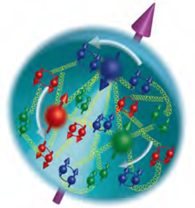


- Where does the mass come from?
- Massless gluons and nearly massless quarks, through their interactions, generate most of the mass
- $\sim$ 99% of the mass of hadrons $\rightarrow$ most of the visible mass in the universe!
- We cannot adequately explain these processes
- **QCD is not "solved"**

Image - A. Deshpande, Stony Brook University

Understanding Dynamic Matter

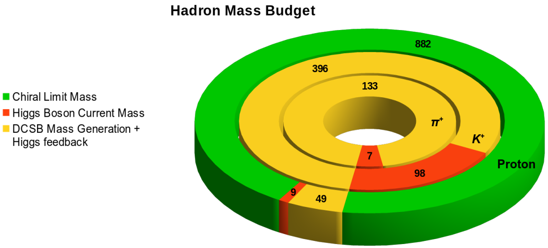
- Interactions and structure are not isolated ideas in nuclear matter
  - Observed properties of nucleons and nuclei (mass, spin) emerge from this complex interplay
  - Properties of hadrons are emergent phenomena



- 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

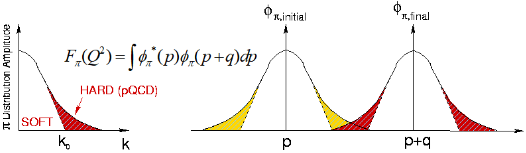


- Multiple mechanisms at play
- DCSB not experimentally demonstrated
- What can we examine to understand hadron structure?
- **The simple $q\bar{q}$ valence structure of mesons makes them an excellent testing ground**

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

Studying Meson Structure - Meson Form Factors

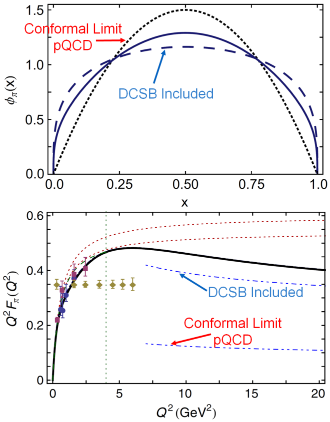
- Charged pion ($\pi^{\pm}$) and Kaon ($K^{\pm}$) form factors (F_{π}, F_{K}) are key QCD observables
  - Describe the spatial distribution of partons within a hadron



- Meson wave function can be split into 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 and simple QCD quark system
  - K - Another simple system, contains strange quark

Connecting Pion Structure and Mass Generation

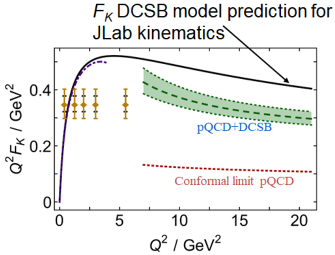
- Calculating the pion PDA, ϕ_π, without incorporating DCSB produces a broad, concave shape
- Incorporating DCSB changes $\phi_\pi(x)$ and brings F_π calculation much closer to the data
  - "Squashes down" PDA
- Pion structure and hadron mass generation are interlinked

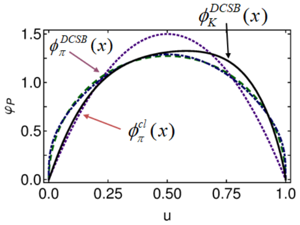


L. Chang, et al., PRL110(2013) 132001, PRL111(2013), 141802

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



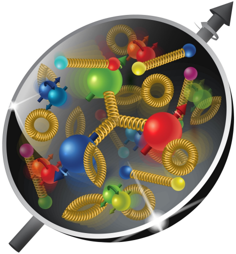


- Form factors are not the only quantity we can examine
- **Lots of other problems to resolve!**

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

Why an Electron-Ion Collider?

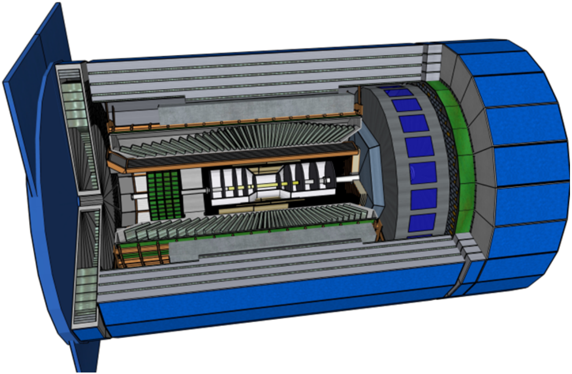
- Three important open questions -
  - **How does the mass of the nucleon arise?**
  - *How does the spin of the nucleon arise?*
  - *What are the emergent properties of dense systems of gluons?*



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

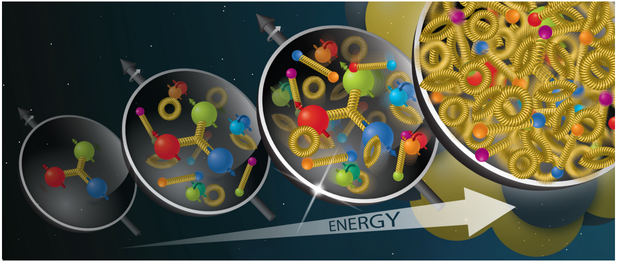
Image - Brookhaven National Lab, https://www.flickr.com/photos/brookhavenlab/

Part II - The Electron-Ion Collider



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



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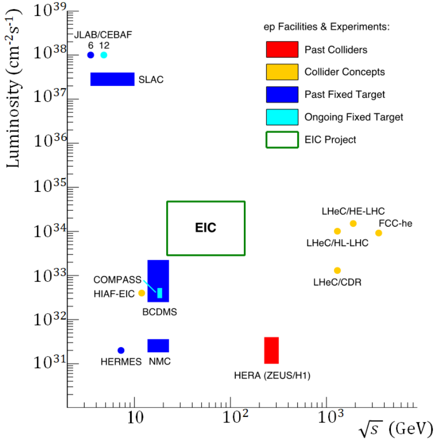
The EIC - A Unique Facility



- 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

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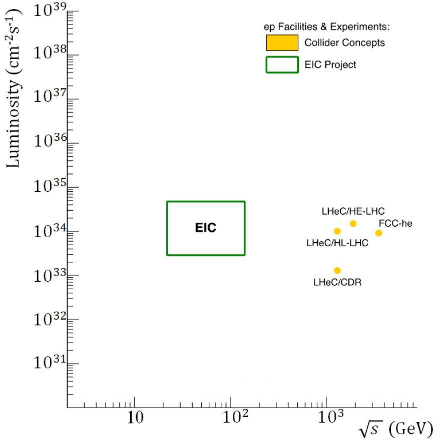

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  - Wide range in $\sqrt{s}$

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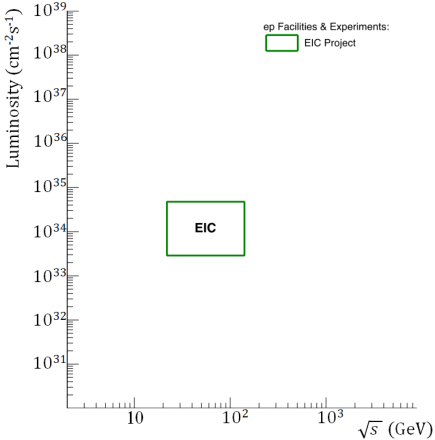
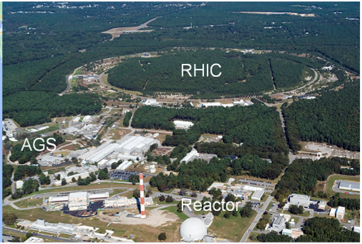


- A lot of Deep Inelastic Scattering (DIS) facilities
- However, if we need:
  - High luminosity
  - Wide range in $\sqrt{s}$
  - Polarised lepton **and** ion beams (p, d, ^{3}He)
  - Nuclear beams
- Only the EIC ticks all the boxes
- EIC is unique

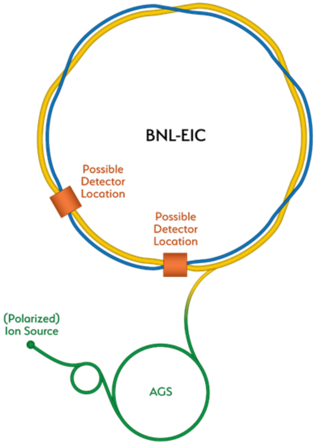
Image - A. Desphpande, modified, https://sites.nationalacademies.org/cs/groups/bpasite/documents/webpage/bpa_178993.pdf

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)



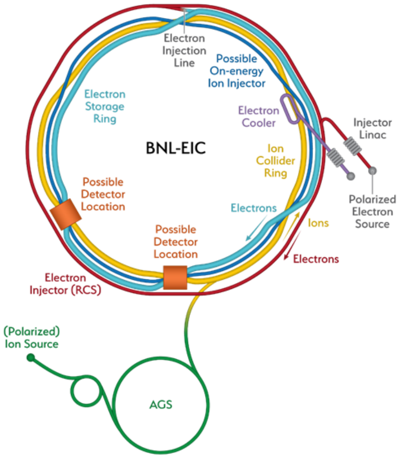
eRHIC - Putting Another Ring on It



- 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
- 25 mrad crossing angle
  - LHC $\approx$ 150 μrad

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

eRHIC - Putting Another Ring on It



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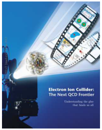
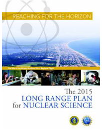
  - LHC ≈ 150 μrad

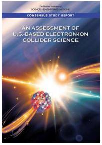
Image - Brookhaven National Lab, `https://www.flickr.com/photos/brookhavenlab/`

A Long Road

- Many years of planning and reviews to get to where we are







- EIC White Papers (2012, 2014, 2016)
  - Development of EIC science case
    - 2012 - arXiV 1212.1701
    - 2016 - Eur.Phys.J.A 52 (2016) 268
- Nuclear Science Advisory Committee (2015)
  - "We recomend a high-energy high-luminosity polarised EIC as the highest priority for new facility construction"
- National Academy of Science Review (2018)
  - Very strong endorsement for the EIC
  - "questions to be addressed are profound... science case is compelling"

Apologies if the slide title reminded you that Star Trek:Enterprise exists.

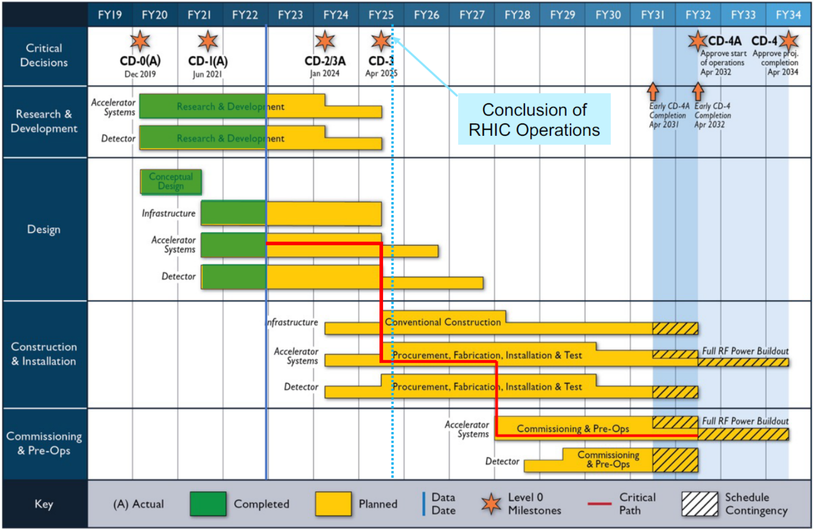
US Department of Energy - Project Overview

- The US Department of Energy (US-DOE) follows a rigorous project management procedure for large projects
  - EIC is a US$1.7-2.8 billion project
- Key checkpoints known as **critical decisions (CDs)**

- Several key milestones passed
  - CD-0 - Mission need - Dec 2019
  - Site selection - Jan 2020
  - CD-1 - Approve alternative selection and cost range - June 2021
- Expect first beam in early 2030's

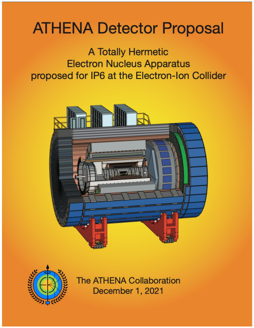
- CD-4 - Project completion - expected by mid 2030's
  - Physics program expected to run into 2050's!
- Project includes <u>one detector</u> with scope to build another later

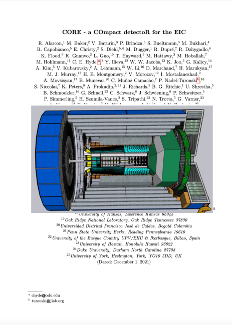
EIC Timeline

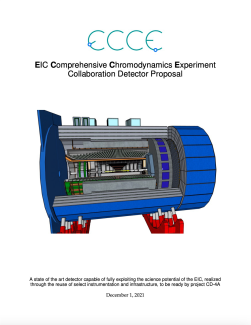


Deciding on a Detector

- Three detector proposals went through a lengthy review process in 2021-2022



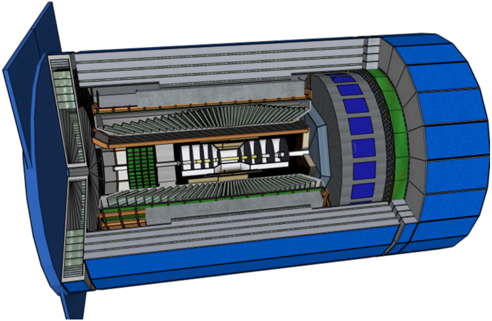




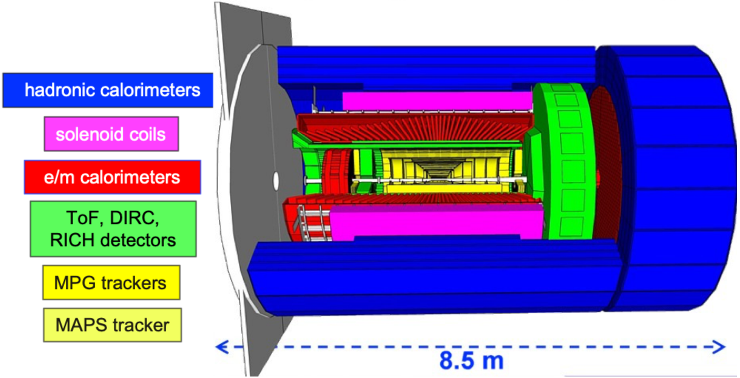
- Detector advisory panel recommended ECCE as the "reference design" in April 2022
- Enthusiastically supported the idea of a second detector

Detector 1 - The ePIC Collaboration

- New detector 1 collaboration, **ePIC**
  - 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

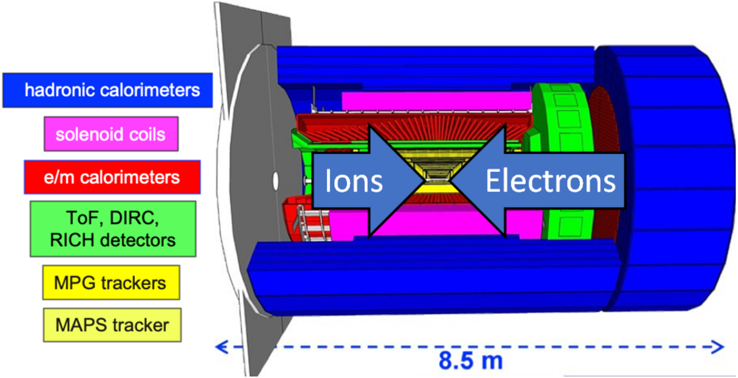


ePIC Detector Overview - Central Barrel



- Main part of the detector is the central barrel region
  - Very asymmetric detector due to e/A collisions

ePIC Detector Overview - Central Barrel



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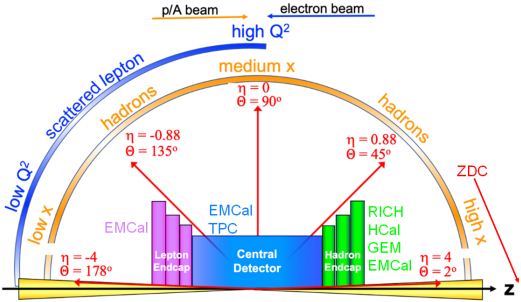
  - Very asymmetric detector due to e/A collisions

ePIC Detector Overview - Central Barrel (Conceptual)

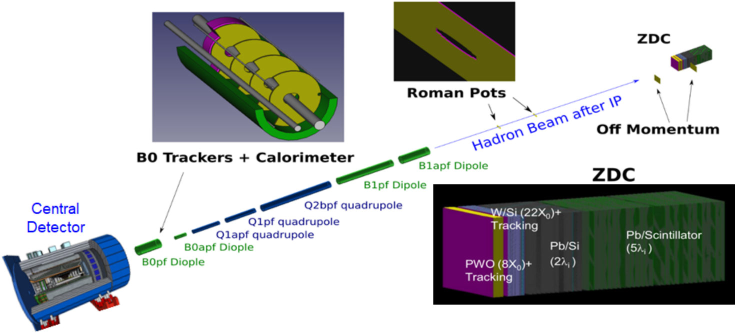


- Conceptual diagram useful to visualise where particles go
- For those that aren't particle/high energy physicists (myself included!), η is the pseudorapidity -

$$\eta = -ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

ePIC Detector Overview - Far Forward too!

- More than just the central barrel though!
- Lessons learned from HERA
  - Detector and accelerator integration **crucial**



- Far forward and far backward detectors vital for some studies
- Remember, there's a lot of questions to answer!

EIC Users Group - A Global Endeavour

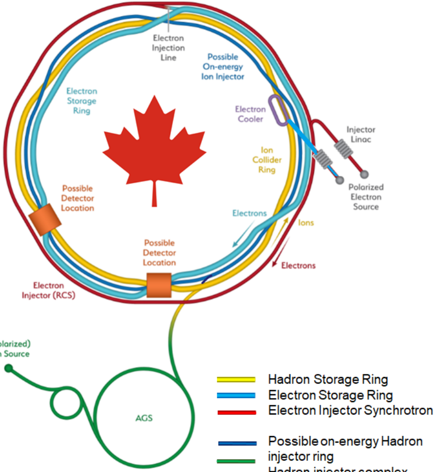
- 1384 members from 270 institutions spread across 36 countries (as of March 2023)
- 32 members from 8 Canadian institutions

EIC UG - https://phonebook.sdcc.bnl.gov/eic/client/ - Note that there are no collaborators in Atlantis (that I know of), the map just thinks that's where Hawaii is for some reason.

EIC-Canada - Contributions Closer to Home

- Canadian subatomic physicists involved in the planning and development of the EIC for many years
- EIC participation is fully endorsed in the Canadian Subatomic Physics Long Range Plan (SAP-LRP)
- EIC-Canada collaboration formed to co-ordinate participation
- Investigators and researchers from three institutions currently
  - University of Manitoba
  - Mount Allison University
  - University of Regina
- Opportunities for PhD, 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!

Part III - Canadian Contributions to the EIC



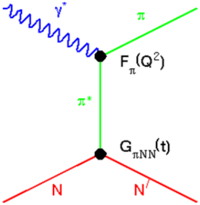
So, what can we measure?

- 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

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 -

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



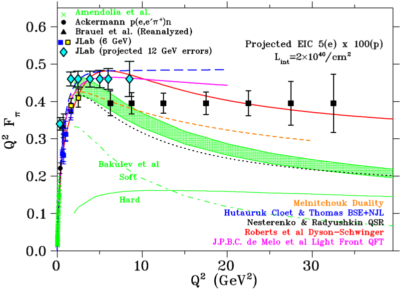
- We do not use the Born term model
- Drawbacks of this technique -
  - Isolating σ_L experimentally challenging
  - Theoretical uncertainty in F_π extraction
    - Model dependent (smaller dependency at low -t)
- Measure **D**eep **E**xclusive **M**eson **P**roduction (**DEMP**)

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 our DEMP event generator DEMPGen
  - Multiple beam energy combinations to consider
    - Maggie Kerr at MtA put in a lot of work investigating this
- Event generator being modified to generate kaon events

EIC F_π Data - Reaching for Some Answers

- ECCE appeared 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 Q^2 range
- Data here can address mass generation questions
  - One of the key science questions for the EIC!



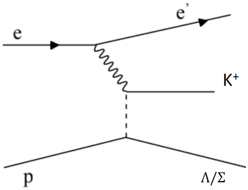
- More details in upcoming ECCE analysis note
- Will re-evaluate with ePIC

- Want to study the kaon as well as the pion

F_K at the EIC - Challenges and Possibilities

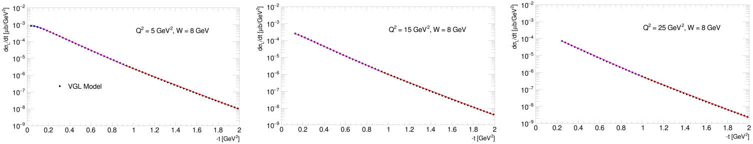
- F_K at the EIC via DEMP will be extremely challenging
- Would need to measure two reactions
  - $p(e, e'K^+\Lambda)$
  - $p(e, e'K^+\Sigma)$
  - Need both for pole dominance tests

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



- 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 (2000) 025204

F_K at the EIC - Generator Updates

- URegina MSc student Love Preet working on adding Kaon DEMP event generator module to DEMPGen
  - Starting with $p(e, e'K^+\Lambda)$
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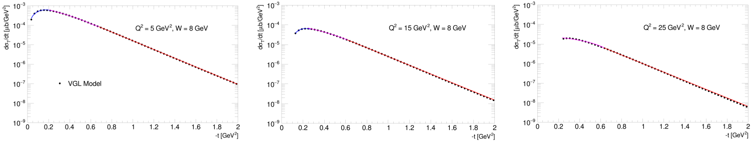


VGL Model - M. Guidal, J.-M. Laget, M. Vanderhaeghen, PRC 61 (2000) 025204

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?
- F_π work already featured in the EIC yellow report
- Worked closely with the ECCE proto-collaboration
  - Carrying out feasibility studies
  - Existing DEMP event generator utilised
  - **Activities were a priority for the ECCE Diffractive and Tagging group**
  - Will continue to develop simulations with ePIC
  - Kaon event generator and simulations in progress
- Results to be published in an upcoming NIM paper
  - arXiv:2208.14575v1
  - Expect to see this in print soon!

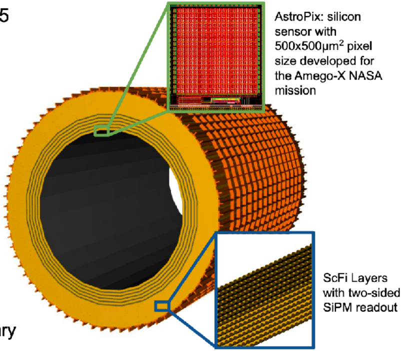
R. Abdul Khalek et al. EIC Yellow Report. 2021. arXiv:2103.05419, Sections 7.2.1 and 8.5.1

Introducing the ePIC Imaging Barrel ECal

Addressing the unique challenges for the barrel region in ePIC

Hybrid concept: 6 layers of Astropix interleaved with the first 5 Pb/ScFi layers, followed by a large volume with the rest of the Pb/ScFi layers

- ✓ Deep calorimeter (21 X_0) but still very compact at ~ 40 cm
- ✓ Excellent energy resolution ($5.2\% / \sqrt{E} \oplus 1.0\%$)
- ✓ Unrivaled low-energy electron-pion separation by combining the energy measurement with shower imaging
- ✓ Unrivaled position resolution due to the silicon layers
- ✓ Deep enough to serve as inner HCal
- ✓ Very good low-energy performance
- ✓ Wealth of information enables new measurements, ideally suited for particle-flow
- ✓ Makes the tracking MPGD layer behind the DIRC unnecessary



Checks all the boxes!

Slides courtesy of Z.Papandreou, University of Regina

URegina - ePIC Barrel ECal Partners

A large, international collaboration with extensive expertise in calorimetry, silicon sensors, and large detector systems

The Imaging Calorimeter for ePIC

EIC-Korea Consortium

EIC-Canada Consortium

European Institutions

US Institutions

Slides courtesy of Z.Papandreou, University of Regina

URegina - ePIC Barrel ECal Technology

Pb/ScFi layer technology

Our Pb/ScFi layers follow the GlueX Design

Energy resolution at GlueX: $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$ [1)]

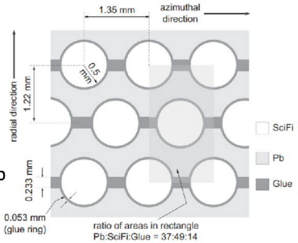
- GlueX has 15.5 X_0, and could not constrain the constant term (due to low energies)

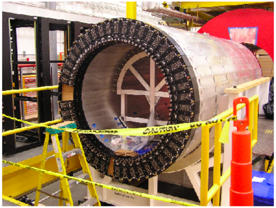
Position resolution in z: 1.1cm/√E [2)]

- 2-side SiPM readout, Δt measurement

Mature technology used in Barrel ECals (GlueX, KLOE)

- Detailed studies on **calorimetry performance**, including the light collection uniformity in fibers, light collection efficiencies, etc.
- **Module construction** (lead handling, swaging, Pb/ScFi layers assembly, module machining) fully developed for GlueX
  Z. Papandreou, https://halldweb.jlab.org/DocDB/0031/003164/
  - Equipment (swager machine, presses) still available for EIC!
- Assembly and installation of self-supporting barrel based on GlueX experience





1) Nucl. Instrum. Meth. A, vol. 896, pp. 24–42, 2018
2) Nucl. Instrum. Meth. A, vol. 596, pp. 327–337, 2008

Slides courtesy of Z.Papandreou, University of Regina

URegina - ePIC Barrel ECal Test Setup

Supported by EICGENR&D 2022 #25

Mini BCAL test setup in Hall D

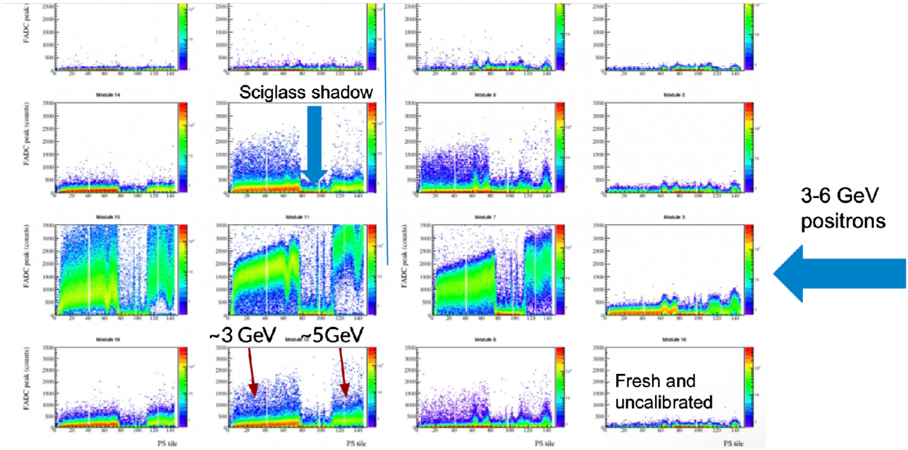
- Detector being cabled by Regina students, behind the GlueX Pair Spectrometer on upstream platform
- Can view 3-6 GeV positrons
- 70-cm-long prototype, $16X_0$
- 74-75 V bias on SiPMs
- No cooling of SiPMs (21 C ambient)
- 40 SiPMs per side
- 16 FADC readouts per side

University of Regina

Argonne NATIONAL LABORATORY

Slides courtesy of Z.Papandreou, University of Regina

Mini BCAL test going well



Slides courtesy of Z.Papandreou, University of Regina

UManiToba Research Efforts

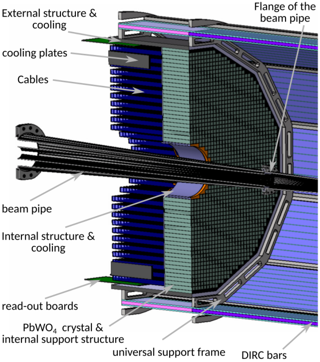
- Wide range of ongoing hardware, software and simulation projects at the University of Manitoba
- Leading role in setting up the ePIC analysis framework
  - Full simulation and analysis framework
- Partnered with URegina on the barrel ECal
- Utilising polarimetry expertise to simulate and design compton polarimeter for ePIC
  - Used to measure e^- beam polarisation
- Simulations and projections for precision electroweak studies at the EIC

University of Manitoba

UManitoba - Electron EndCap Calorimeter

- UManitoba is also working on the Electron EndCap Calorimeter (EEMC)

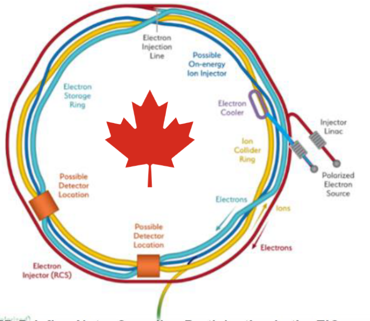
- Short-term objectives (2023-2025)
  - Explore potential for $PbWO_4$ pulse shape discrimination (PSD) for e^- PID
- Longer-term objectives
  - Proceed with full $PbWO_4$ PSD implementation
  - Develop robust calorimeter clustering algorithms
  - EEMC construction and commissioning



TRIUMF - EIC Accelerator Contributions

Towards a Canadian Contribution to EIC

- TRIUMF and EIC Canada are collaborating on pursuing funding to support a Canadian contribution to the EIC
- A briefing document has been prepared for Innovation, Science and Economic Development Canada to initiate discussions
- Motivation: The funding would supply critical infrastructure to EIC, supporting both the EIC and the CINP community while augmenting TRIUMF's core competence in cutting edge accelerator technology



ISED Briefing Note: Canadian Participation in the EIC

Nigel Smith, Oliver Kester, Bob Laxdal (TRIUMF)
Wouter Deconinck (U.Manitoba), Garth Huber (U.Regina), representing EIC-Canada
February 13, 2023

The Electron-Ion Collider

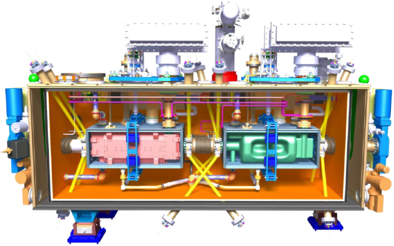
The Electron-Ion Collider (EIC) is a new US$2.5B particle collider facility to be built at Brookhaven National Laboratory (BNL), on Long Island, New York, by the US Department of Energy (US-DOE) by the end of the current decade. The EIC is the only new collider worldwide to be built in the foreseeable future and it is the next discovery machine. The facility will answer fundamental questions about the origin of mass and spin of protons and neutrons, and about the strongly interacting emergent dynamics inside subatomic particles, enabling a multidimensional tomography of subatomic particles.

Slides courtesy of B. Laxdal, TRIUMF

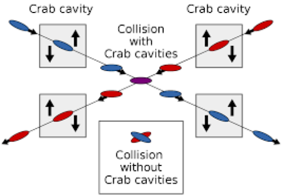
TRIUMF - EIC Accelerator Contributions

Towards a Canadian Contribution to EIC

- The contribution would be similar in concept to in-kind contributions TRIUMF has made to CERN
- Most recently TRIUMF is commissioned to produce 5 crab cavity cryomodules for the Hi-Luminosity upgrade at CERN
- Crab cavities interact with the beam upstream and down stream of the interaction point to provide better overlap of the colliding bunches



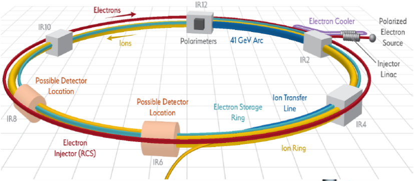
CERN Hi-Lumi Crab Cavity Cryomodule

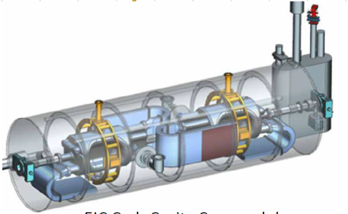


Slides courtesy of B. Laxdal, TRIUMF

Towards a Canadian Contribution to EIC

- The EIC will require crab cavity systems in both the hadron ring and the electron ring
- Both 197MHz and 394MHz crab cavities have been specified
- TRIUMF is interested in
  - Deliverables within the 394MHz crab cavity package including cavities and cryomodule
  - Design work on pulsed kicker systems for rapid beam transfer (collaboration with CLS envisaged)
- Initial collaboration meetings are happening this spring at JLab and BNL





EIC Crab Cavity Cryomodule

Slides courtesy of B. Laxdal, TRIUMF

Part IV - Closing Remarks

Next Steps - Where now?

- Critical phase, detector design needs to be established
- Recent US Inflation Reduction Act (IRA) funding of $\sim$ \$140m is a game changer
  - Progress **not constrained by funding**
  - Significantly reduces risk to the schedule
- The project is now very much full steam ahead
- Expect to secure CD2/3a in early 2024
  - CD2 - Performance baseline approval, establishes total project cost, schedule, performance, annual funding profile
  - CD3a - Long lead Procurement approval, key factor in mitigating risk, determining overall project schedule and cost
- CD3 before RHIC operations conclude in 2025
- Excellent progress defining the EIC project detector, ePIC, and establishing the collaboration responsible for the experiment

Summary

- *"An EIC can uniquely address three profound questions about nucleons... the science it will achieve is unique and world leading"*
- US IRA funding for the EIC a significant shot in the arm
- The EIC is an exciting opportunity for our generation of physicists - Expected program: 2030-2060
- Canada is well positioned to contribute to this program
  - EIC is listed as a flagship project for Canadian science in the SAP-LRP!
- Substantial CFI application for calorimetry expected in 2024
- 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?

University of Regina

NSERC CRSNG

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.

With thanks to all of my colleagues in the ePIC, Meson Structure Working Group and EIC-Canada Collaborations.

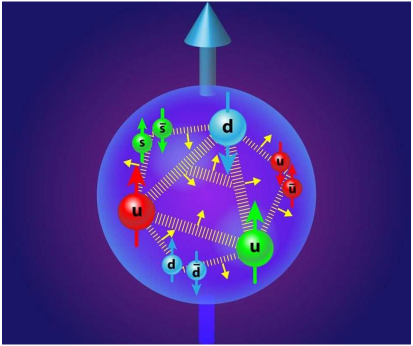
Research featured in this talk was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), FRN: SAPIN-2021-00026 and FRN: SAPPJ-2021-00026.

Backup Zone

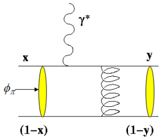
Combining Quarks

- Quarks (and their color charge) are confined inside strongly–interacting particles called **hadrons**
- **Hadrons** are **colour neutral** objects formed of quarks
  - Cannot isolate objects with colour charge
  - Empirical observation known as **confinement**

- Often talk about two different types of quarks -
  - Valence Quarks - Required for correct hadron quantum numbers
  - Sea Quarks - Virtual $q\bar{q}$ pairs, allowed by the uncertainty principle



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 -

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

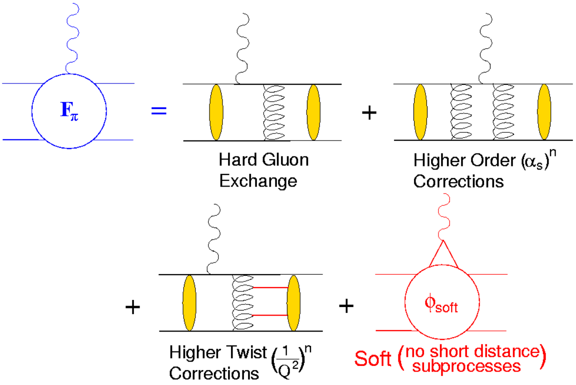
  - This is a **rigorous** prediction of pQCD
  - Q^2 **reach of existing data doesn't extend into transition region**
    - Need unique, cutting edge experiments to push into this region

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

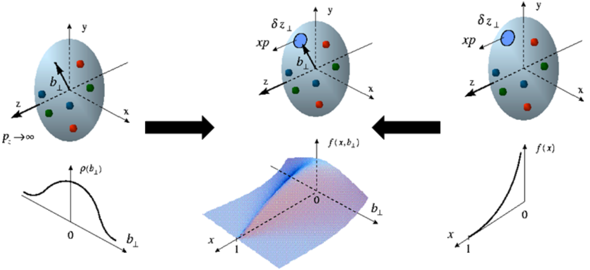
The Pion in pQCD

- At very large Q^2, F_π can be calculated using pQCD via -

$$F_\pi(Q^2) = \frac{4_F\alpha_s(Q^2)}{Q^2}\left|\sum_{n=0}^{\infty} a_n \left(\log\left(\frac{Q^2}{\Lambda^2}\right)\right)^{-\gamma_n}\right|^2 \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q}\right)\right]$$



Visualising Hadrons with Generalised Parton Distirbutions



Form factors - Transverse charge and current densities

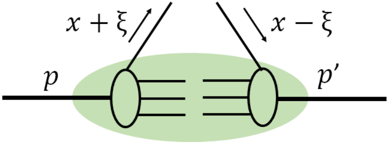
Generalised Parton Distributions - Correlated quark momentum and helicity distributions in transverse space

Parton Distribution Functions - Quark longitudinal helicity and momentum distributions

Images - G.M. Huber, University of Regina

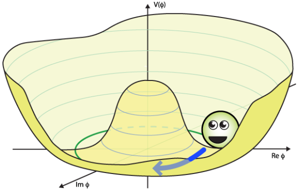
PDFs and GPDs

- Can represent hadron structure using **P**arton **D**istribution **F**unctions (PDFs) or **G**eneralised **P**arton **D**istributions (GPDs)
- GPDs - universal quantities which reflect the structure of the nucleon independently of the probing reaction
  - GPDs - Interference between partons with longitudinal momentum fractions $x + \xi$ and $x - \xi$, interrelating longitudinal momentum and transverse spatial structure within a fast moving hadron

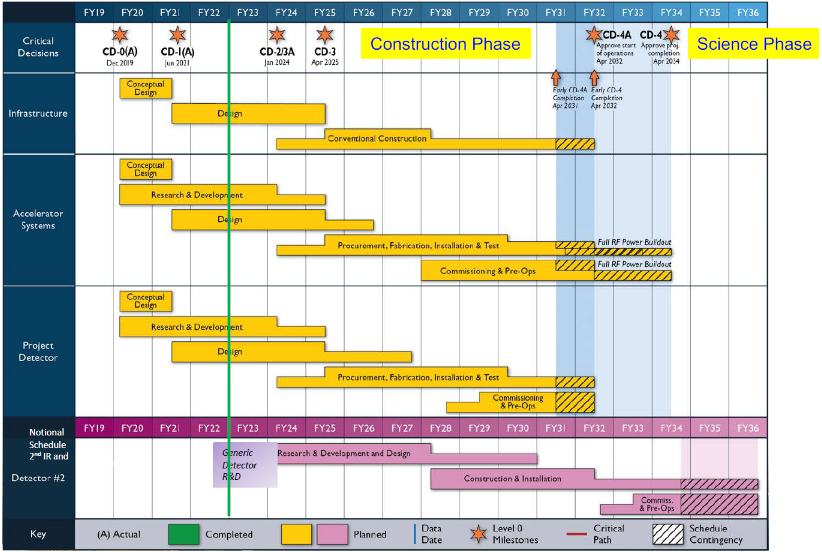


The Pion as a Goldstone Boson

- DCSB cannot be derived directly from the QCD Lagrangian
  - It is related to the nontrivial nature of the QCD vacuum
  - Explicit symmetry breaking, which is put in "by hand" through finite quark masses, is quite different
- DCSB is one of the most important emergent phenomena in the standard model
- **Two important consequences of DCSB:**
- 1. Valence quarks acquire a dynamical or constituent quark mass through their interactions with the QCD vacuum.
- 2. The pion is the spin-0 boson that arises when Chiral Symmetry is broken (Similar to Higgs from Electroweak Symmetry Breaking)

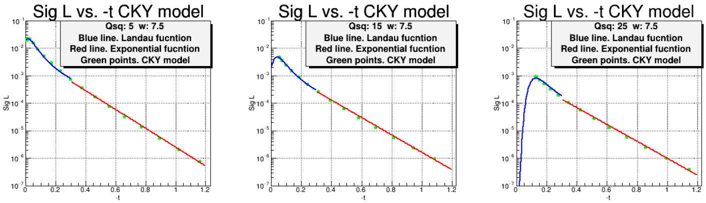


Detector 2 Timeline



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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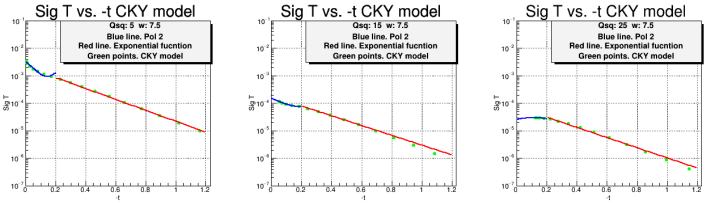
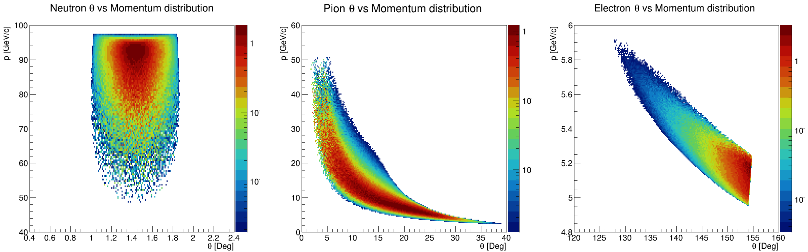


EIC DEMP Acceptance for $-t < 0.5\ GeV^2$

- $5(e^-)$ on $100(p)$ *GeV* collisions, 25 *mrad* crossing angle
- Events weighted by cross section
- No smearing



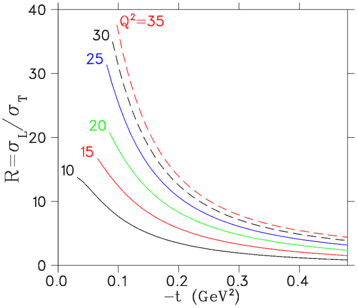
- Neutrons within 0.2° of outgoing proton beam, offset is due to the crossing angle ($25\ mrad \approx 1.4^\circ$)

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

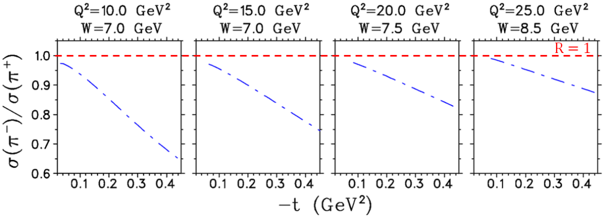
T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

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



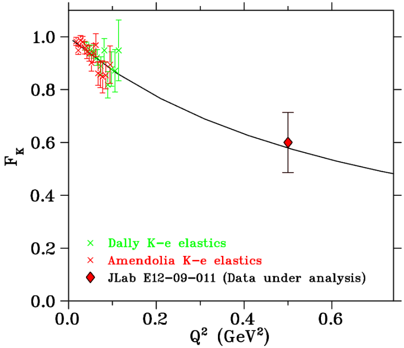
T.Vrancx, J. Ryckebusch, PRC 89(2014)025203

F_K Validation

- Need to 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



Simulation Results - Neutron Reconstruction

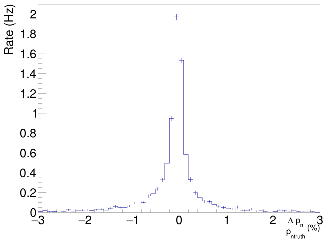
- High energy ZDC hit requirement used as a veto
  - ZDC neutron ERes is relatively poor though

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

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

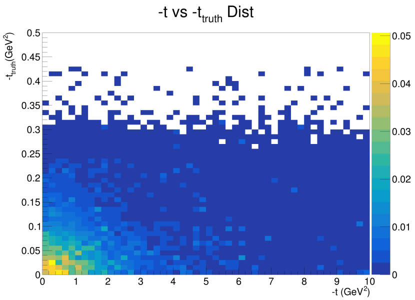
$$p_{miss} = |\vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}|$$

- 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!

- 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
  - $-t_{alt} = -(p_p - p_n)^2$
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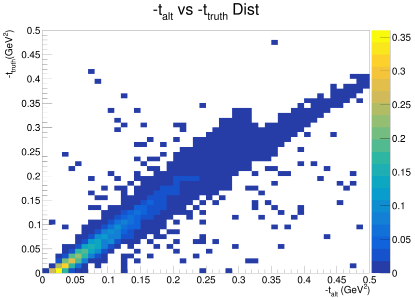
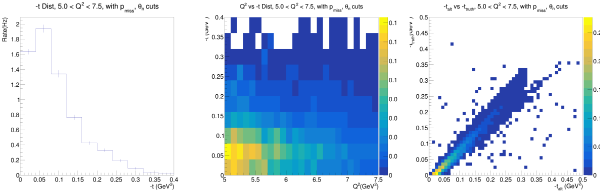


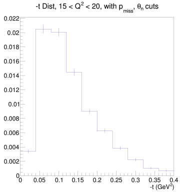
- x-axis $-t$ scale an order of magnitude smaller now!

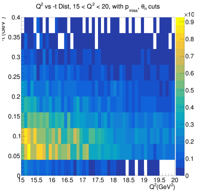
Simulation Results - Q^2 $5 - 7.5$ GeV^2

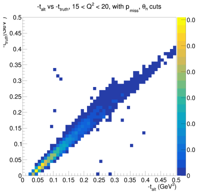


- Predicted $e'\pi^+n$ triple coincidence rate, binned in Q^2 and $-t$
  - 5 (e', GeV) on 100 (p, GeV) events
  - $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$ assumed
  - $-t$ bins are 0.04 GeV^2 wide
  - Cut on θ_n $(\theta_n = 1.45 \pm 0.5^\circ)$ and $\vec{p}_{miss} = \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}$ (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

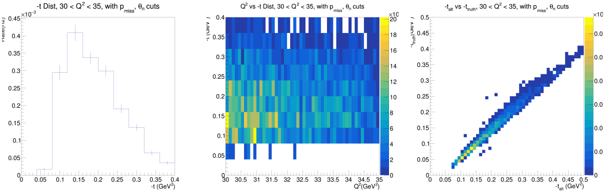






- Predicted $e'\pi^+n$ triple coincidence rate, binned in Q^2 and $-t$
  - 5 (e', GeV) on 100 (p, GeV) events
  - $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$ assumed
  - $-t$ bins are 0.04 GeV^2 wide
  - Cut on θ_n ($\theta_n = 1.45 \pm 0.5^\circ$) and $\vec{p}_{miss} = \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}$ (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 $30 - 35$ 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
  - 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

Isolating σ_L from σ_T in an e-p Collider

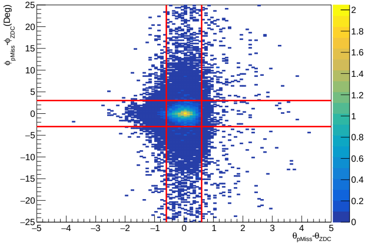
- For a collider -

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

    - 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

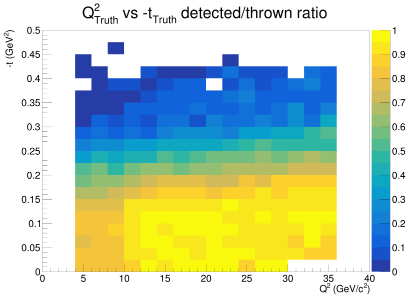
- Make use of high angular resolution of ZDC
- Compare hit θ/ϕ positions of neutron on ZDC to calculated θ/ϕ from p_{miss}
- If no other particles produced, quantities should be correlated
  - True for DEMP events
- Energetic neutrons from inclusive background processes will be less correlated
  - Additional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



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

EIC Simulation Results for ECCE

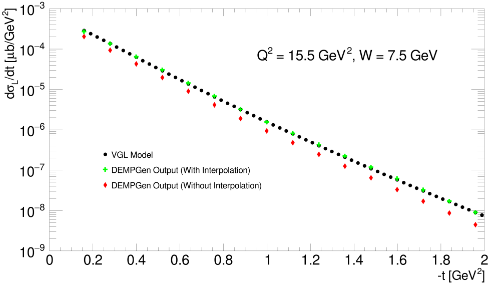
- My recent work has focused on EIC simulations
- Work showed importance of a large, high quality **Z**ero **D**egree **C**alorimeter
- **Examined detection efficiency for DEMP events**
- $\text{Efficiency} = \frac{\text{Accepted}}{\text{Thrown}}$
- **Simulation results utilised for form factor projections**



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

DEMPGen Improvements

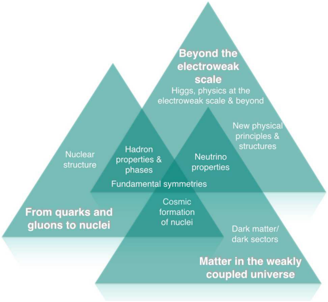
- In addition to adding the $p(e, e'K^{+}\Lambda)$ module, improvements to the generator implemented
- New method to interpolate parametrisation
- Interpolation matches generator output very closely
  - Even at points far from the initial parametrisation
- Will incorporate improvements in pion model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



Canadian Subatomic Physics Long Range Plan

Excerpts from the 2022-2036 Plan

- Hadron properties and phases
  - How do quarks and gluons give rise to the properties of nucleons and other hadrons, and to the hadronic phases of matter in extreme conditions?
- Nuclear Structure
  - How does nuclear structure emerge from nuclear forces and ultimately from quarks and gluons?
- Cosmic Formation of Nuclei
  - How do the properties of nuclei explain the formation of the elements in the universe?



SubatomicPhysics.ca

EIC is listed as a flagship project for Canadian science!