Unveiling Hadronic Mass Generation Through Light Meson Structure with ePIC

Love Preet

for the ePIC collaboration

University of Regina, Canada

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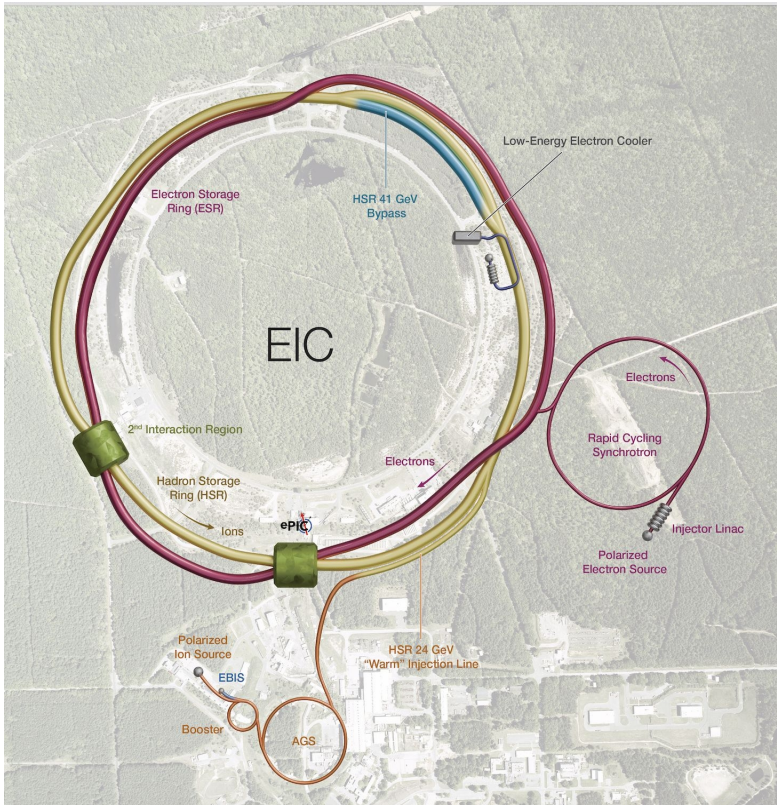
WNPPC 2025

University of Regina

What is the Electron–Ion Colider (EIC)?

- World's first polarised electron–ion collider
  - Different ion species (p, d, Pb, ^{3}He, Au...)
  - High Luminosity ($10^{33} - 10^{34}$ cm^{-2} s^{-1})
  - Both beams polarised (~ 70 %)
  - Variable beam energies (e^- 5–18 GeV, ion 41–275 GeV)
  - Need to precisely image quarks, gluons and their interactions !
- To be constructed at Brookhaven National Lab (BNL) in the U.S.



https://agenda.infn.it/event/43344/overview

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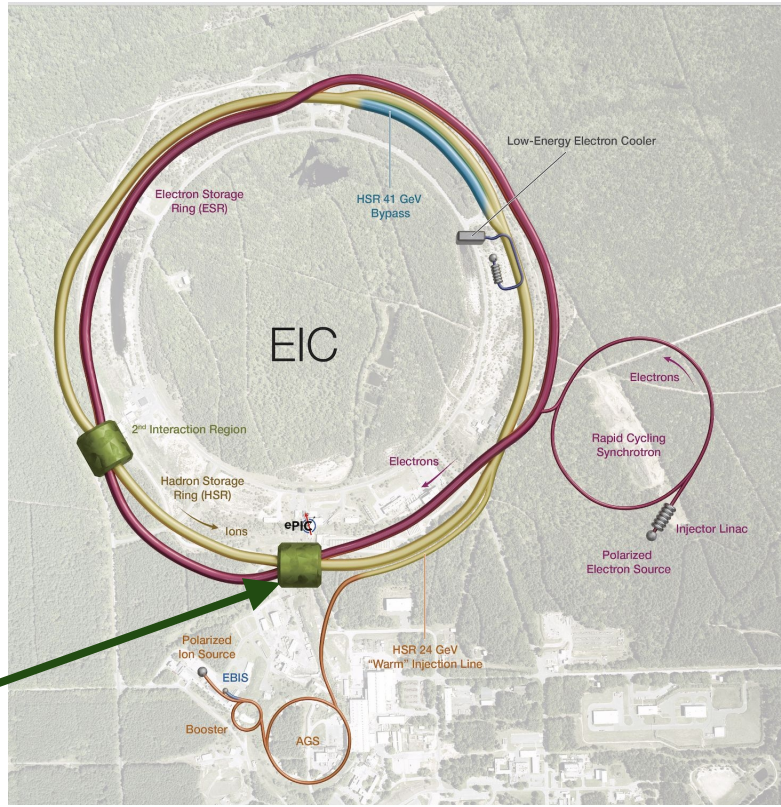
Detector will go there !



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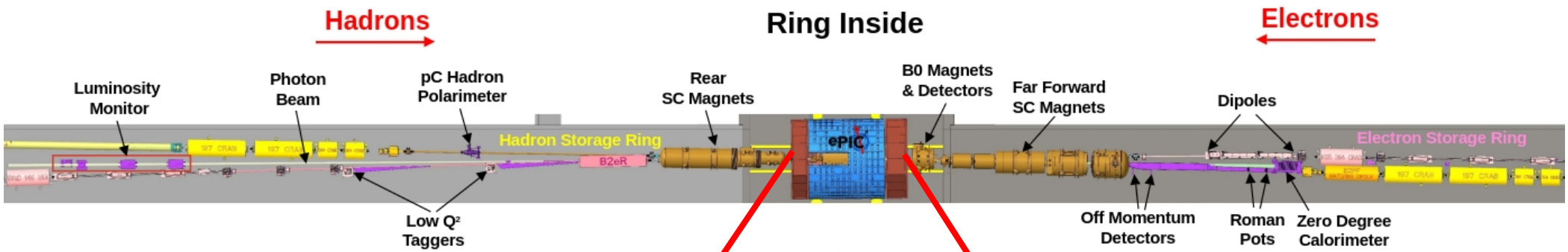
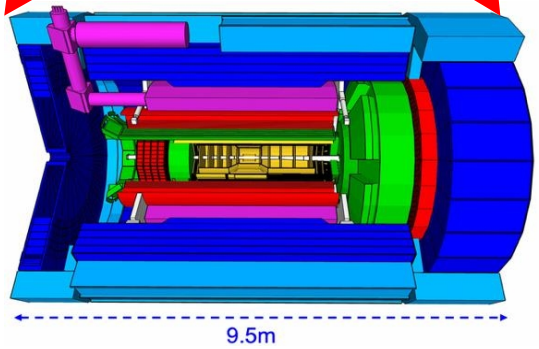
The ePIC Detector

Electron-Proton and -Ion Collider (ePIC) detector



Ring Outside

Far-Backward detectors



Central detector

Far-Forward detectors

https://agenda.infn.it/event/43344/overview

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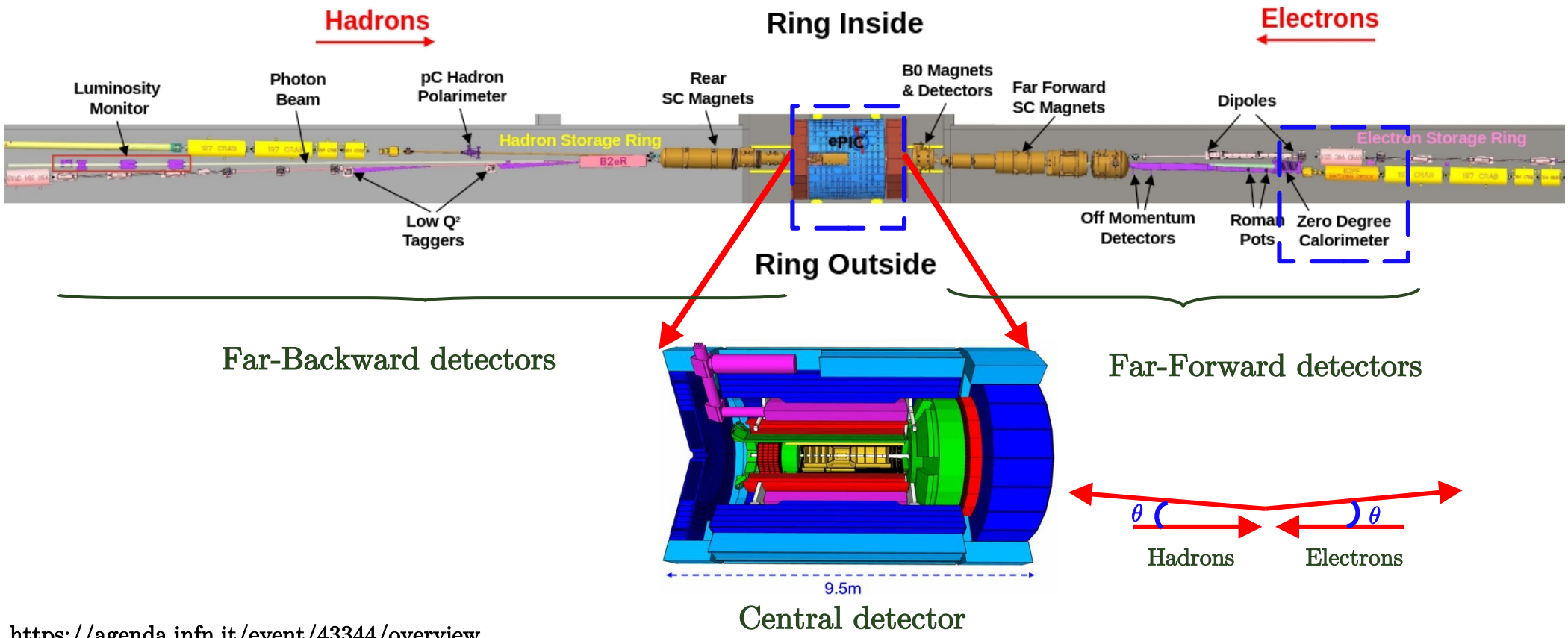

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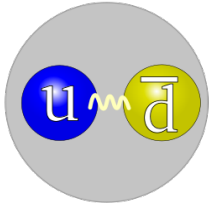
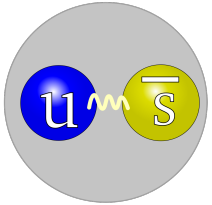
Meson Form Factors

- Higgs mechanism is directly responsible for ~1 % of the visible mass in the Universe.
  - Where does the rest of the mass come from?
  - One of the key questions will be addressed by the EIC.
- Emergence of hadronic mass generation can be studied through the internal structure of the lightest mesons, the pion and the kaon.



Pion (π^+)



Kaon (K^+)

  - Can examine this internal structure by looking at quantities like the form factor.
  - Form factor describes the spatial distribution of partons within a hadron.
- One of the ways to measure the form factor is through Deep Exclusive Meson Production (DEMP) reactions.

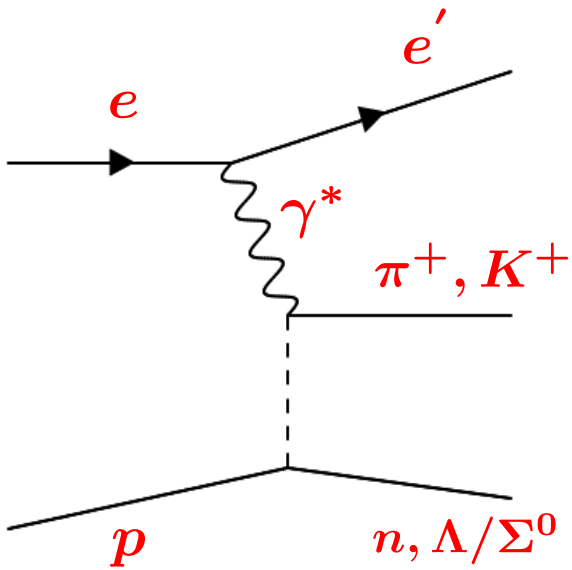
http://lichen.phys.uregina.ca/

DEMP at the EIC

- For π^+, K^+ electroproduction reactions:

$$e + p \rightarrow e' + \pi^+ + n$$
$$\rightarrow e' + K^+ + \Lambda/\Sigma^0$$

- At Jlab Hall C*, we detect e', π^+ (K^+), and reconstruct n (Λ/Σ^0).
- At EIC (triple coincidence experiment), we need to track all the three final state particles.
  - Missing momentum resolution is insufficient to uniquely reconstruct recoil.
- To assess feasibility, need an event generator !

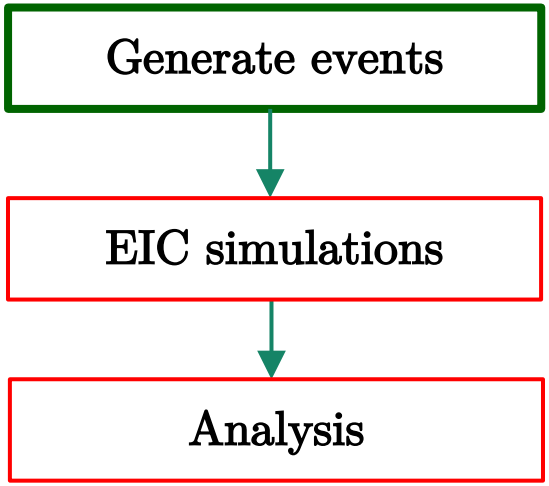


https://arxiv.org/abs/2403.06000

*Follow my colleagues' discussions in the same session.

Feasibility Studies at the EIC

- Focus on feasibility studies of DEMP reactions through ePIC simulations at EIC.
- The first step will be to generate an event sample.



Kinematic Variables

- Basic kinematic invariants can be written as

$$e + p \rightarrow e^{'} + \pi^{+} + n$$
$$\rightarrow e^{'} + K^{+} + \Lambda/\Sigma^{0}$$

  - ep squared CM energy

$$s = (e + p)^2$$

  - γ^{*}p squared CM energy

$$W^2 = (\gamma^{*} + p)^2$$

  - Photon virtuality

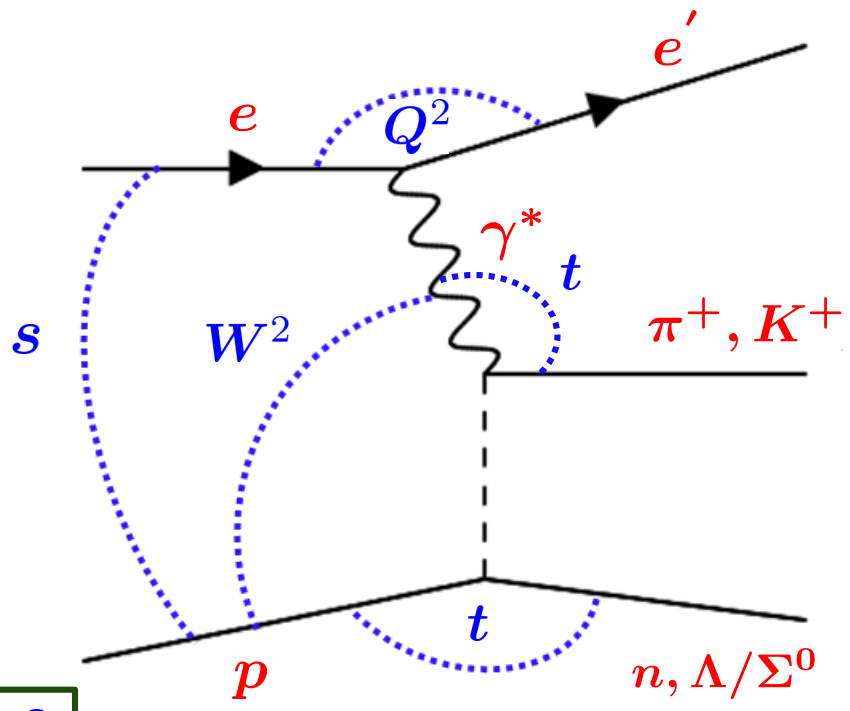
$$Q^2 = -q^2 = (e - e^{'})^2$$

  - Squared 4-momentum transfer to the nucleon

$$t = (p - Recoil)^2 = (\gamma^{*} - Ejectile)^2$$

Ejectile : π^{+}, K^{+}

Recoil : n, Λ, Σ^{0}



Monte Carlo Event Generator - DEMPgen

- Developed the first Monte Carlo event generator, DEMPgen, to simulate DEMP events.
- Focuses on two key modules:
  - Colliding beam kinematics mode for the Electron-Ion Collider.
  - Fixed target kinematics mode for the SoLID experiment.
- For the EIC, it currently incorporates three reactions:
  - $p(e,e' \pi^+ n)$ → π^+ electroproduction
  - $p(e,e' K^+ \Lambda)$
  - $p(e,e' K^+ \Sigma^0)$

  } K^+ electroproduction
- Consider the head-on collision between the electrons & protons at different beam energies, including, 5(e) × 41(p), 5(e) × 100(p), 10(e) × 100(p), and 18(e) × 275(p).
- It is a weighted event generator.

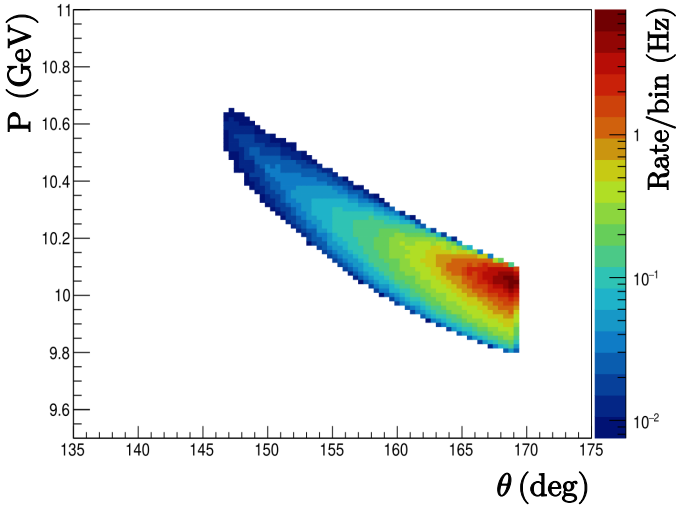
https://github.com/JeffersonLab/DEMPgen

https://doi.org/10.1016/j.cpc.2024.109444

DEMP Kinematics – Truth Distributions

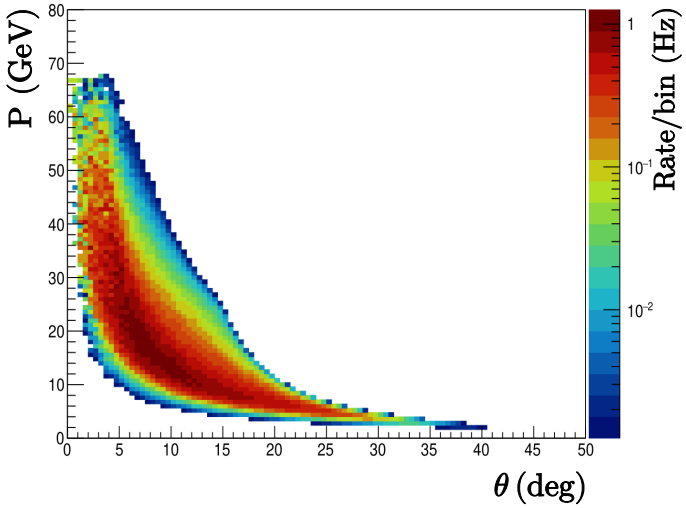
- Generated events for 10(e) on 100(p) GeV collisions using DEMPgen.
- e' and π^+ hit the central detector, neutron in ZDC.
- Note that the Z scale is a rate in Hz.

e' truth θ vs P



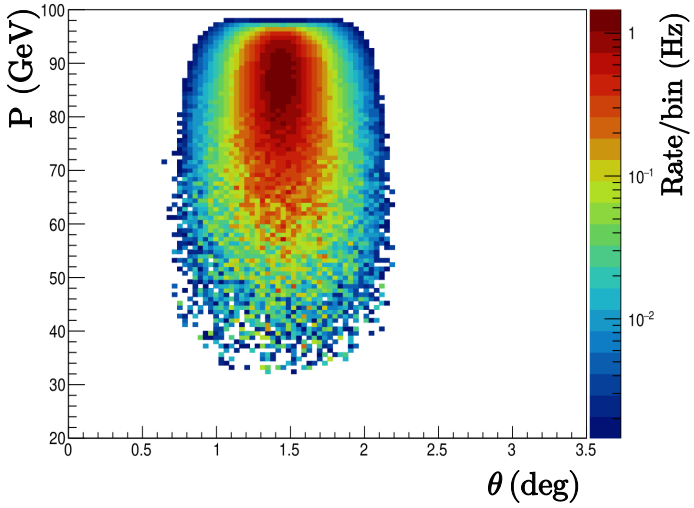
P ~ 9.95 - 10.15 GeV

π^+ truth θ vs P



~ 5 - 50 GeV

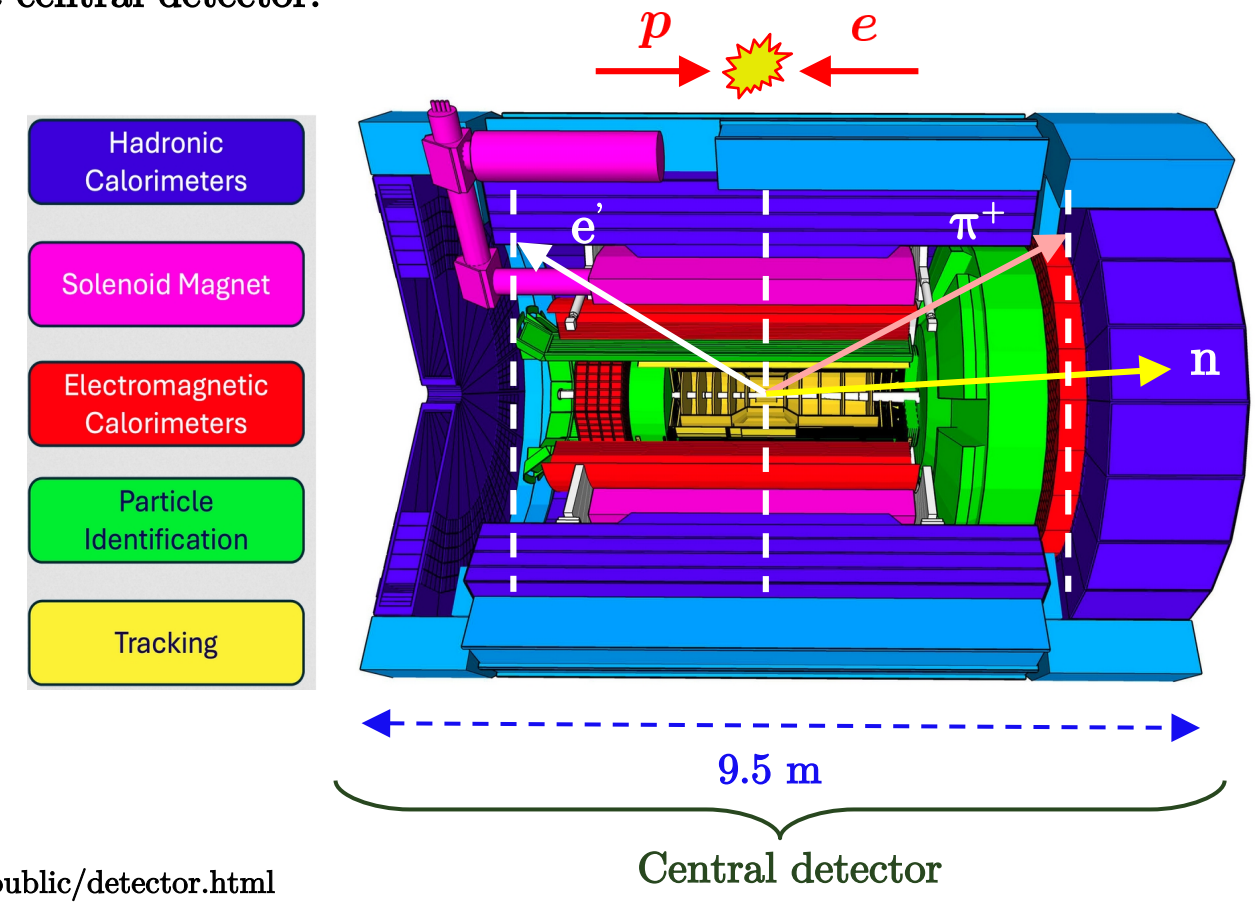
n truth θ vs P



~ 60 - 96 GeV

DEMP Kinematics – Visualizing with ePIC

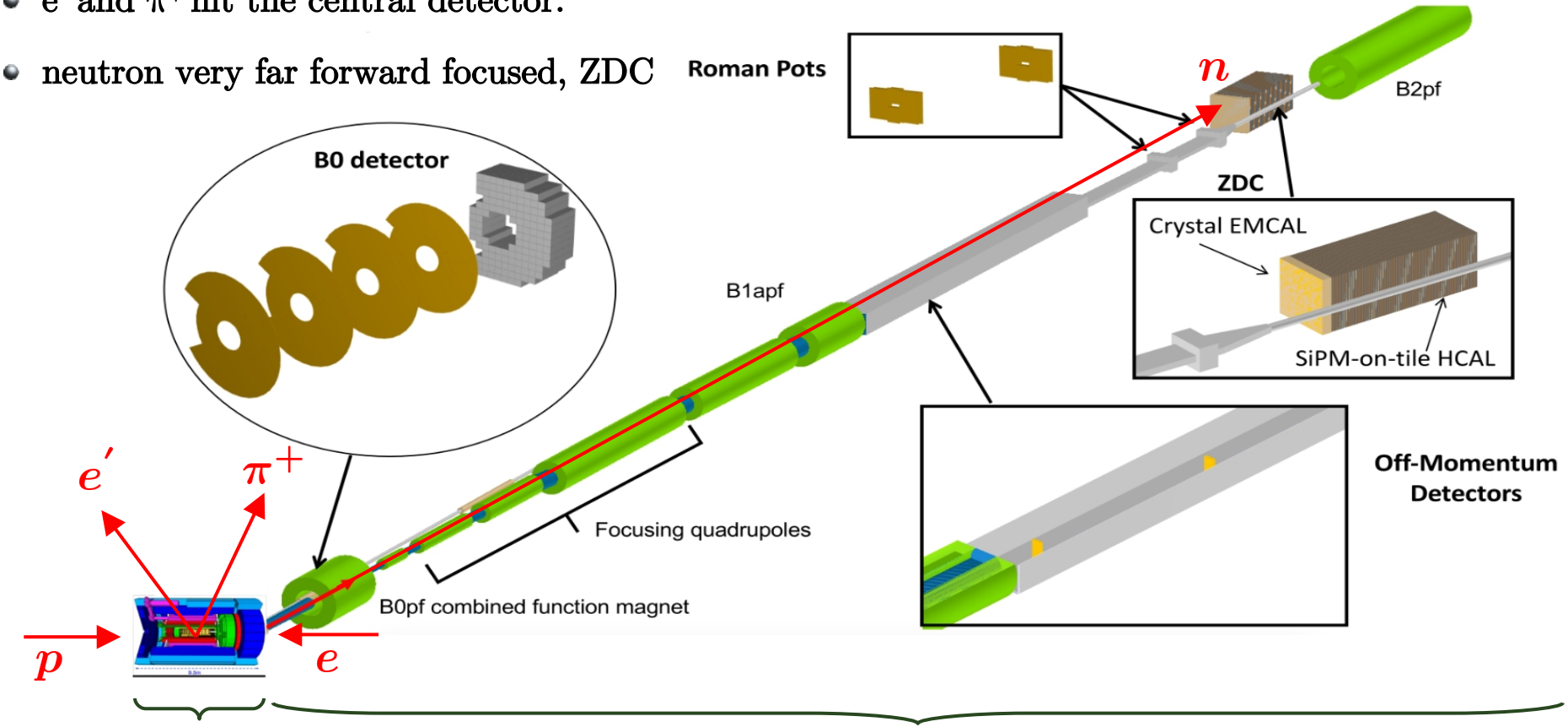
- e' and π^+ hit the central detector.



https://www.epic-eic.org/public/detector.html

DEMP Kinematics – Visualizing with ePIC

- e' and π^+ hit the central detector.
- neutron very far forward focused, ZDC



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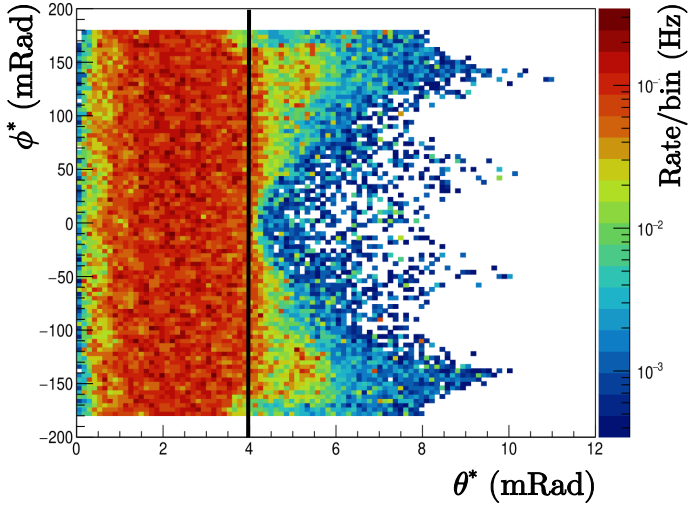
ZDC Neutron Reconstruction

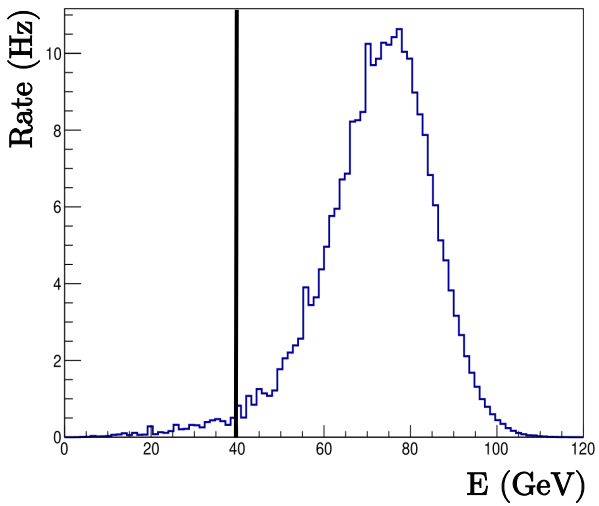
- Processed same 10(e) on 100(p) events through ePIC simulations.
- Select a region with uniform acceptance ($\theta^* < 4$ mRad) and $E_{ZDC} > 40$ for analysis.
- Events fall on face of ZDC.
- Hexagonal pattern seen, consequence of ZDC reconstruction algorithm.

n θ^* vs ϕ^* distribution



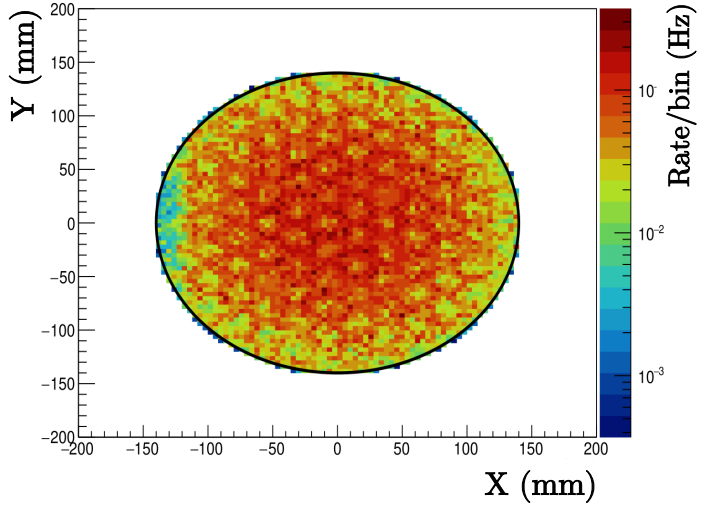
$\theta^* < 4$ mRad

n Energy ($\theta^* < 4$ mRad)



$E_{ZDC} > 40$ GeV

n X vs Y position



θ^*, ϕ^* are rotated by 25 mRad around proton axis

Accessing Form Factor from DEMP at the EIC

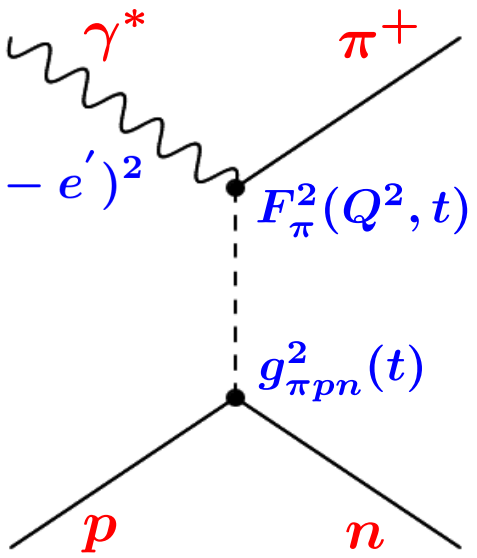
- Measure e'π^+n triple coincidence events.

- In the Born model, F_π^2 appear as

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

- Q^2 , -t reconstruction resolution is crucial for extracting F_π^2 from the measured cross section.

$$e + p \rightarrow e' + \pi^+ + n$$

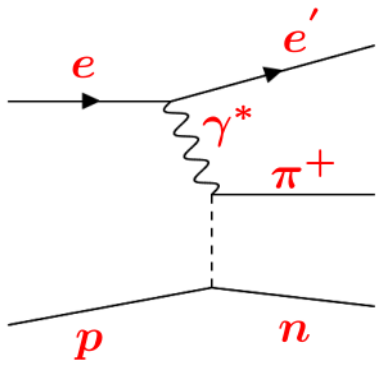


-t Reconstruction

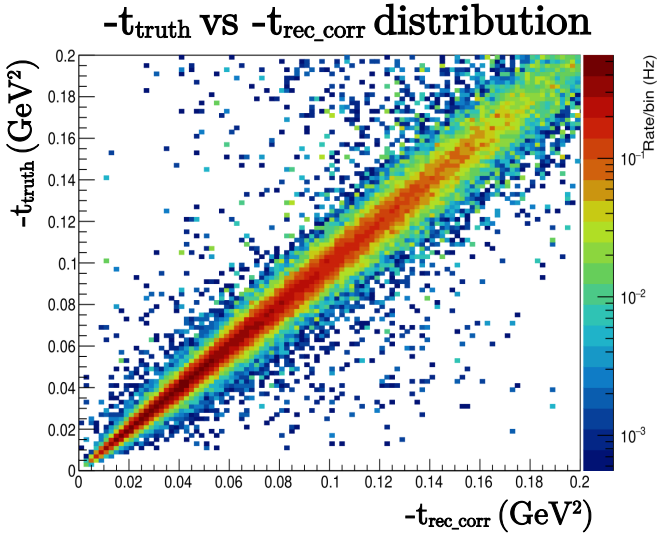
- Can calculate -t via proton – baryon (corrected) vertex :

$$-t_{truth} = -(\gamma^* - \pi^+)^2$$

$$-t_{rec\_corr} = -(p - n_{corr})^2$$



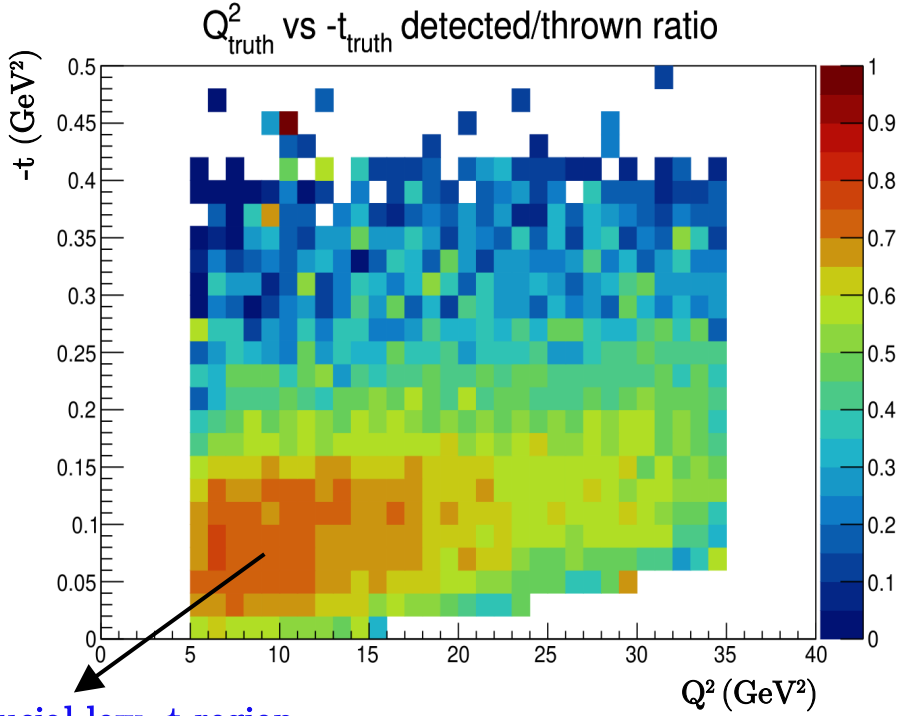
- Corrected the neutron 4 vector using the following information :
  - ZDC hit angles (θ, ϕ),
  - P_{Miss} from e' and π^+, $p_{miss} = |\vec{p_e} + \vec{p_p} - \vec{p_{e'}} - \vec{p_{\pi^+}}|$
  - and the mass of the remaining particle.



https://www.sciencedirect.com/science/article/abs/pii/S0168900223002280

DEMP Detection Efficiency

- Triple coincidence $(e'\pi^+ n)$ detection efficiency.
- Cuts on Q^2, $\Delta\theta$, $\Delta\phi$, W, E_{ZDC}, and -t to cleanly identify exclusive events.



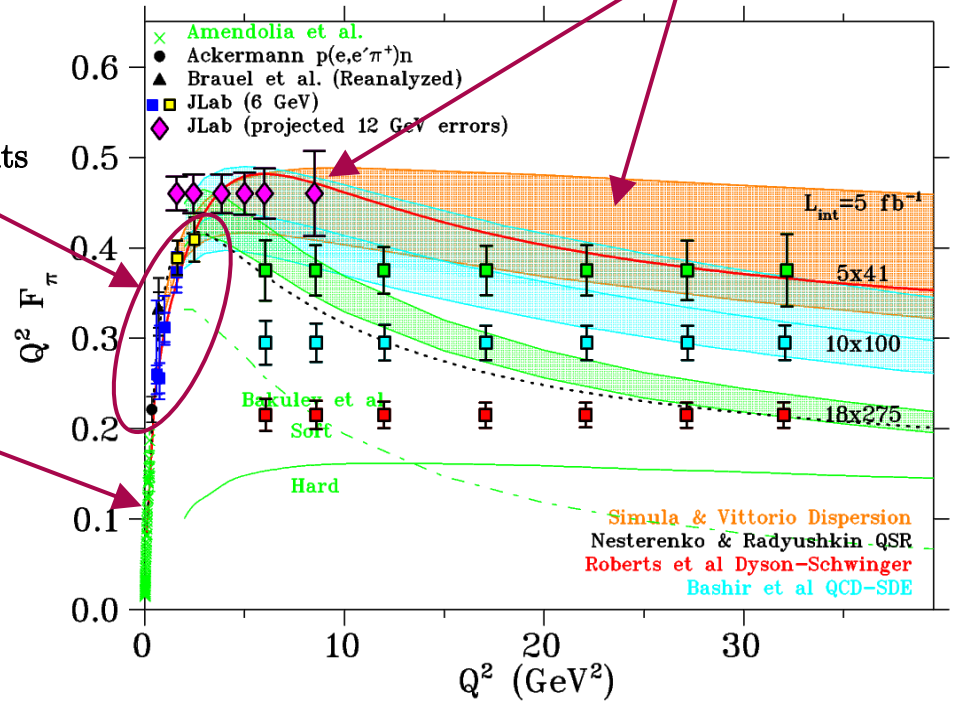
Detection efficiency best in crucial low -t region.

ePIC DEMP F_π Projections

- F at 5(e) X 41(p), 10(e) X 100(p), and 18(e) X 275(p).
- Plan to extend our studies to higher Q^2 ! Jlab - 12 GeV and EIC projections

DESY and Jlab - 6 GeV results

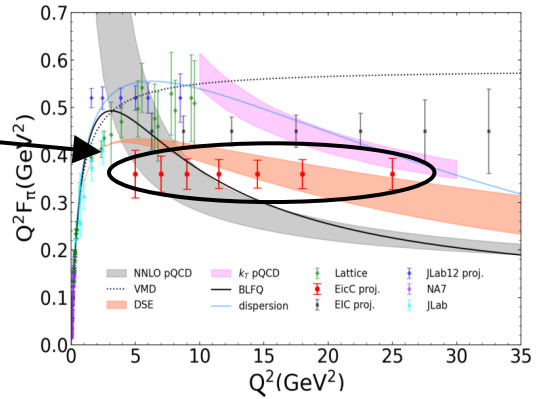
πe elastic scattering data



- Error bars represent real projected error bars :
  - 2.5 % point-to-point syst. unc.
  - 12 % scale syst. unc.
  - $R = \sigma_L/\sigma_T = 0.013 - 0.14$ at the lowest -t from VR model.
  - δR, syst. unc. in R for model subtraction to isolate σ_L.
  - Statistical uncertainty included.

Summary

- Mesons form factors can provide valuable insights into hadronic mass generation mechanisms.
  - EIC can potentially push deep into unexplored territory.
  - Enabling F_π measurements up to $Q^2 \sim 35$ GeV^2, or even higher !
- ePIC simulation results look very promising.
  - Signs that we can push F_π studies even higher in Q^2.
  - Need to investigate kaons next.
- Extend the parametrization ranges in the pion module to access higher Q^2 regimes.
- Weizhi Xiong conducted simulation studies using DEMPgen at the Electron-ion collider in China (EicC).
- The EIC is an exciting opportunity for our generation of physicists - Expected program: 2030 +



Thanks for listening, any questions?

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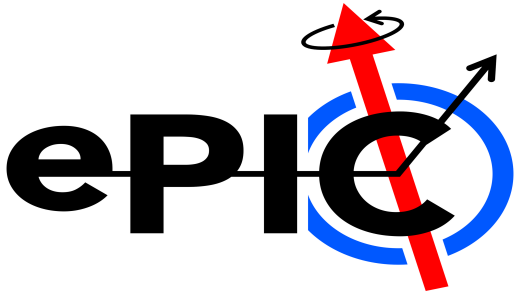

UNIVERSITY of York

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