Unveiling Hadronic Mass Generation Through Light Meson Structure with ePIC

Love Preet

for the ePIC collaboration

University of Regina, Canada

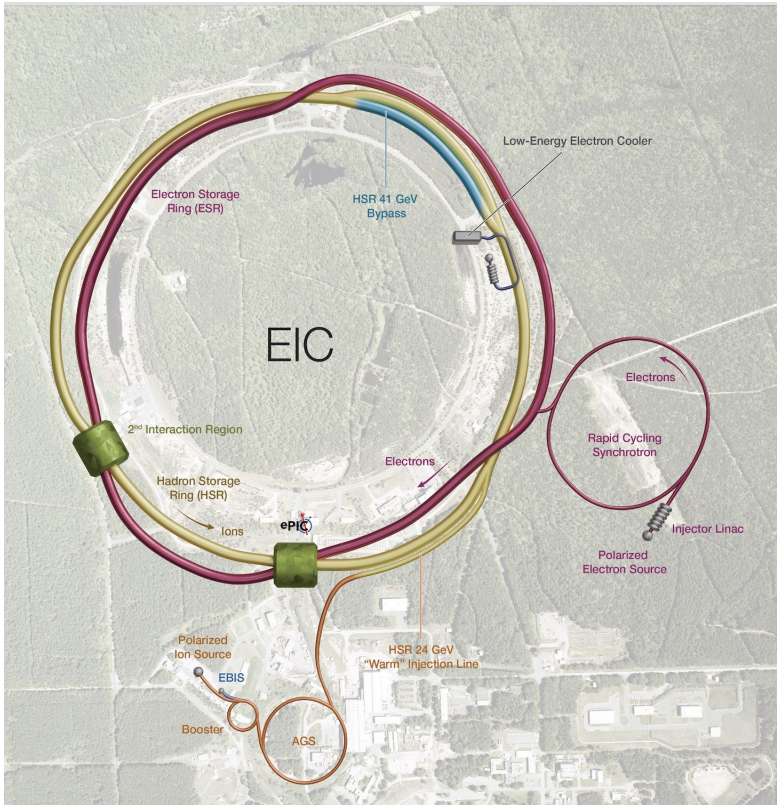
Feb 16, 2025

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.

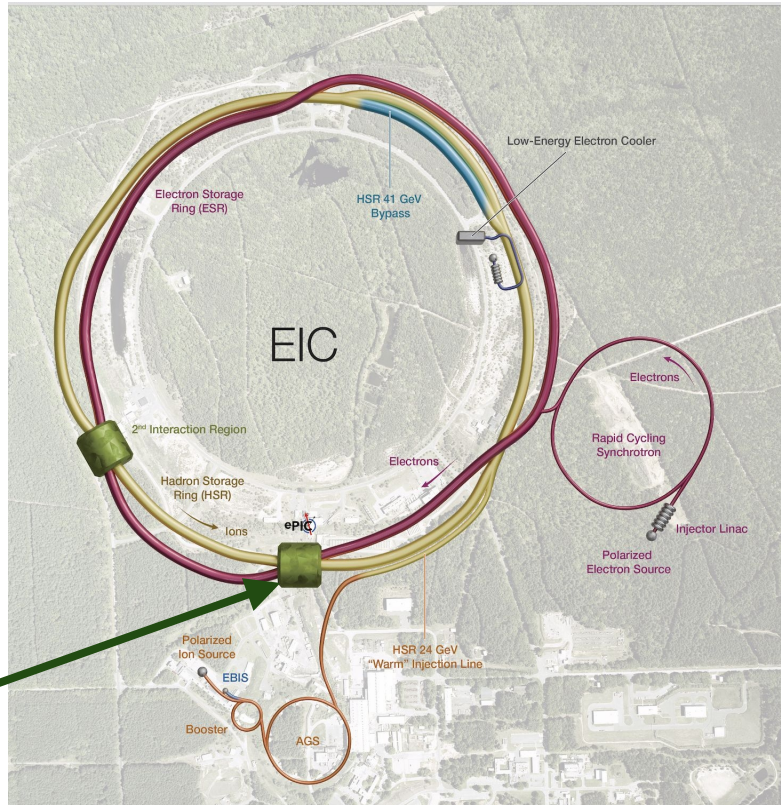


https://agenda.infn.it/event/43344/overview

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.

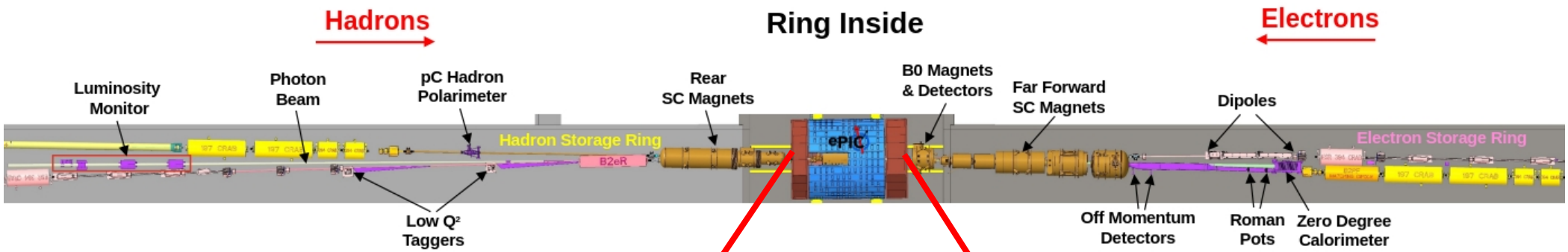
Detector will go there !



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

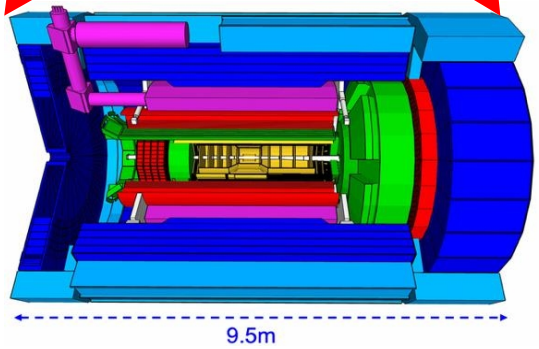
The ePIC Detector

Electron-Proton and -Ion Collider (ePIC) detector



Ring Outside

Far-Backward detectors



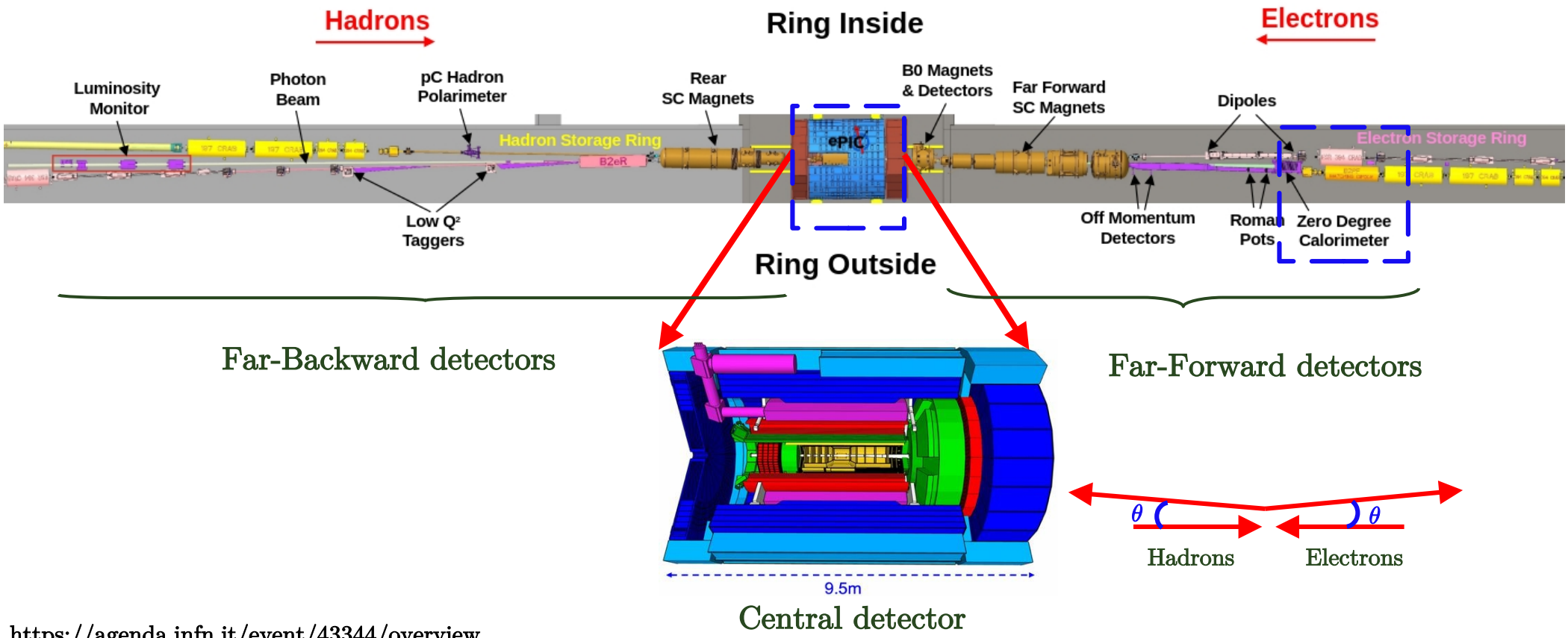
Central detector

Far-Forward detectors

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

The ePIC Detector

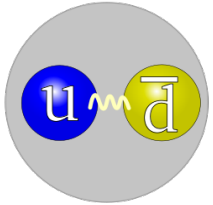
Electron-Proton and -Ion Collider (ePIC) detector



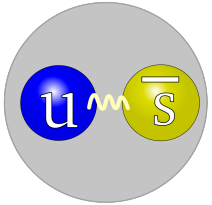
https://agenda.infn.it/event/43344/overview

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.

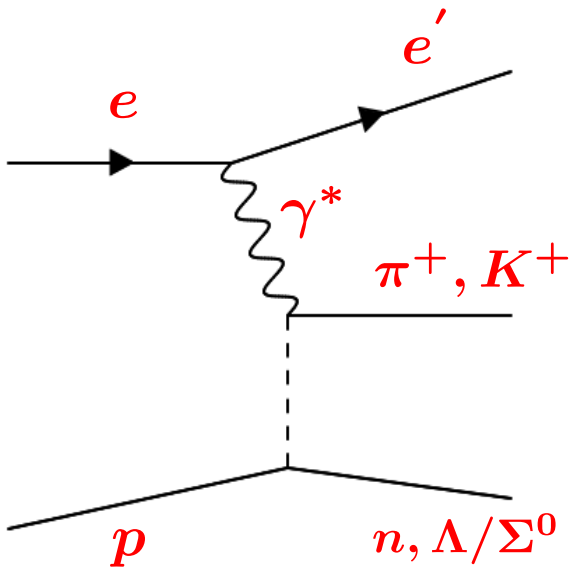
http://lichen.phys.uregina.ca/

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 !

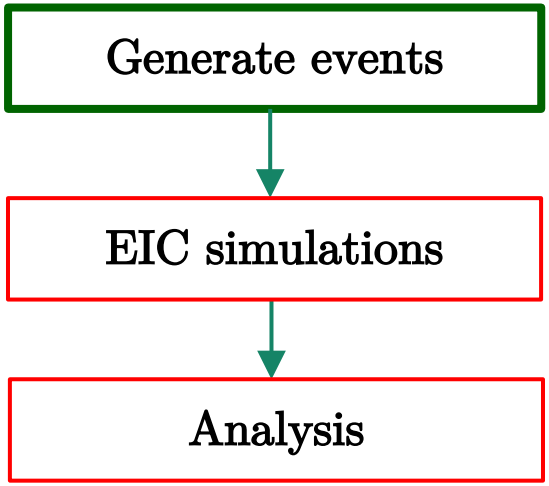


https://arxiv.org/abs/2403.06000

*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

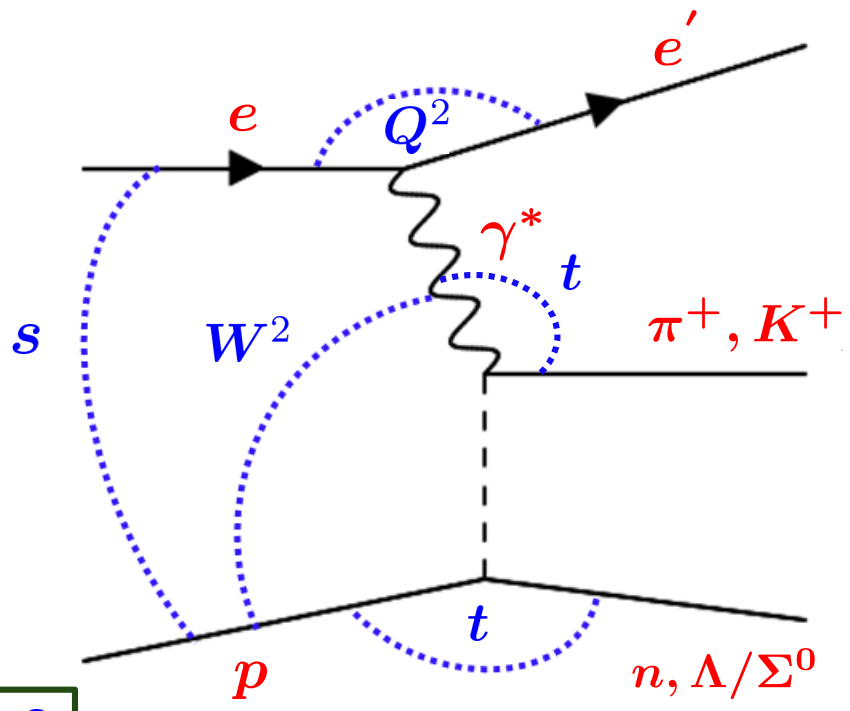
$$Q^2 = -q^2 = (e - e^{'})^2$$

  - 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.

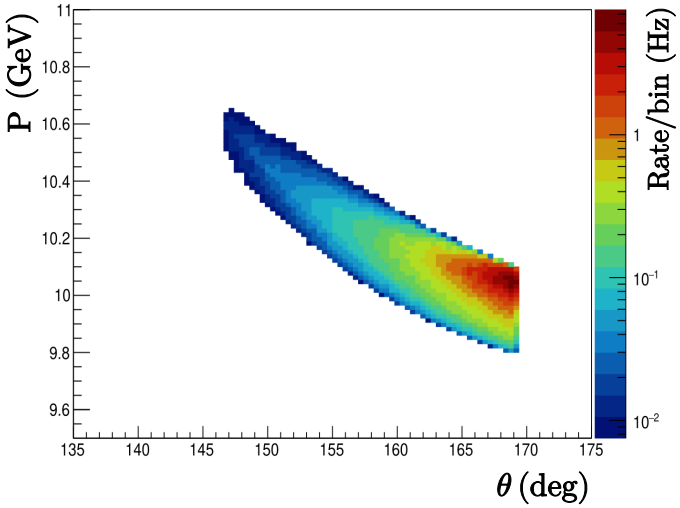
https://github.com/JeffersonLab/DEMPgen

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

DEMP Kinematics – Truth Distributions

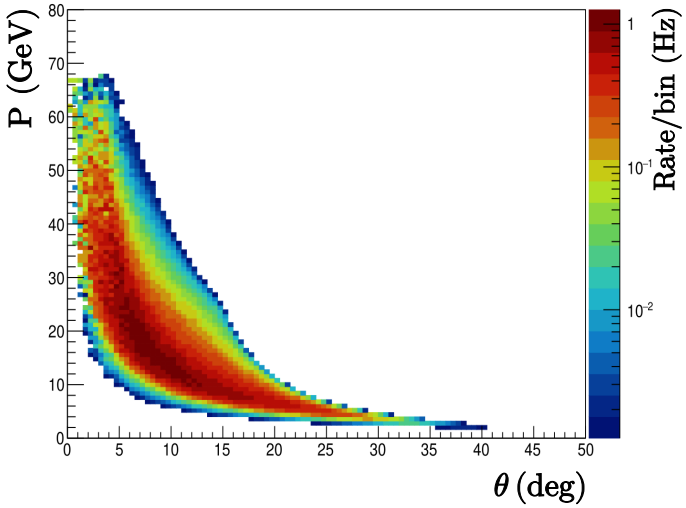
- Generated events for 10(e) on 100(p) GeV collisions using DEMPgen.
- e' and π^+ hit the central detector, neutron in ZDC.
- Note that the Z scale is a rate in Hz.

e' truth θ vs P



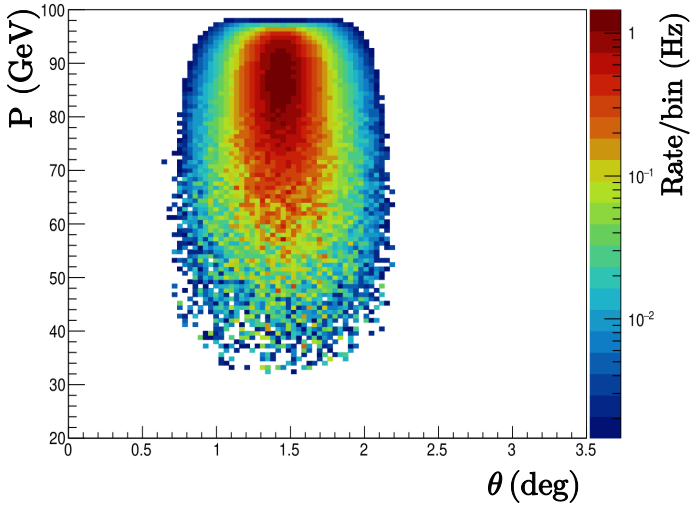
P ~ 9.95 - 10.15 GeV

π^+ truth θ vs P



~ 5 - 50 GeV

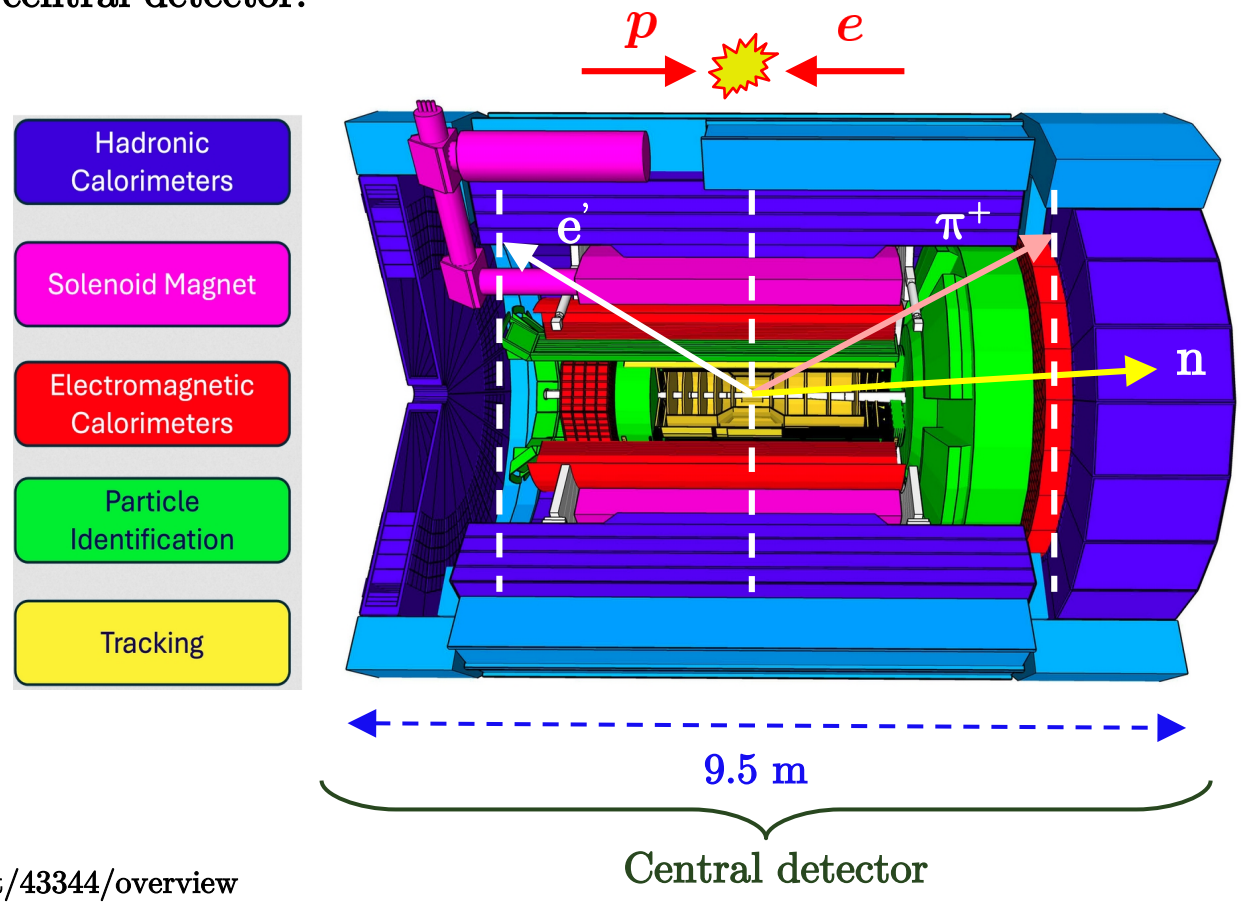
n truth θ vs P



~ 60 - 96 GeV

DEMP Kinematics – Visualizing with ePIC

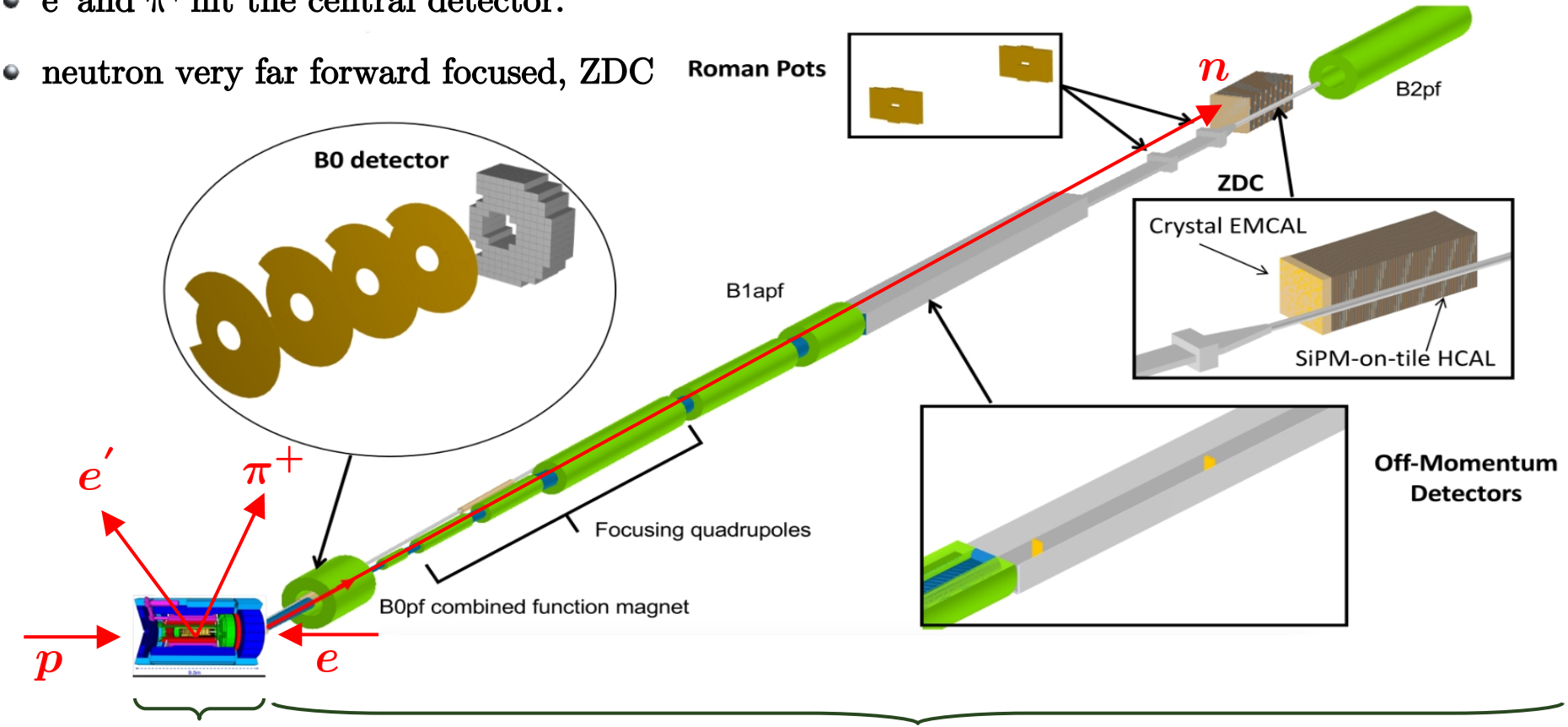
- e' and π^+ hit the central detector.



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

DEMP Kinematics – Visualizing with ePIC

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

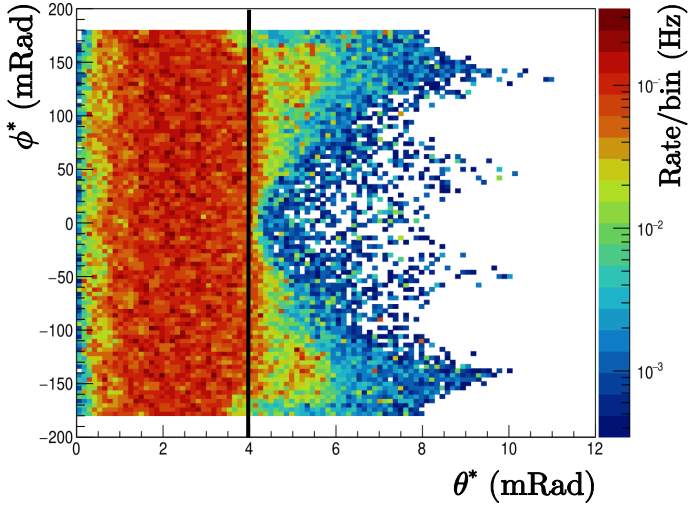


https://agenda.infn.it/event/43344/overview

ZDC Neutron Reconstruction

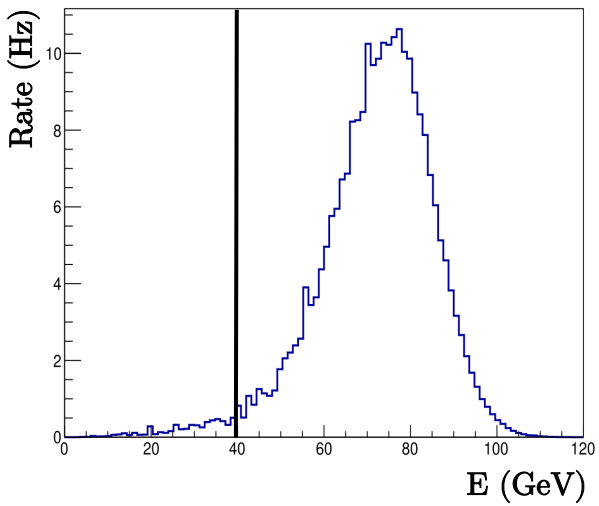
- Processed same 10(e) on 100(p) events through ePIC simulations.
- Select a region with uniform acceptance ($\theta^* < 4$ mRad) and $E_{ZDC} > 40$ for analysis.
- Events fall on face of ZDC.
- Hexagonal pattern seen, consequence of ZDC reconstruction algorithm.

n θ^* vs ϕ^* distribution



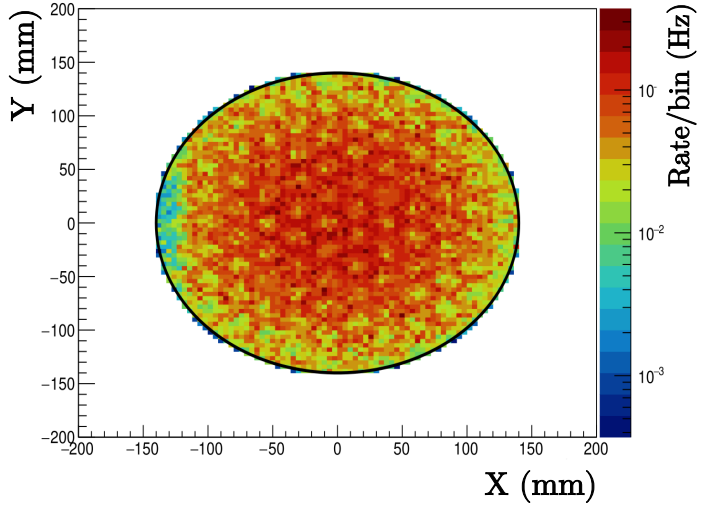
$\theta^* < 4$ mRad

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

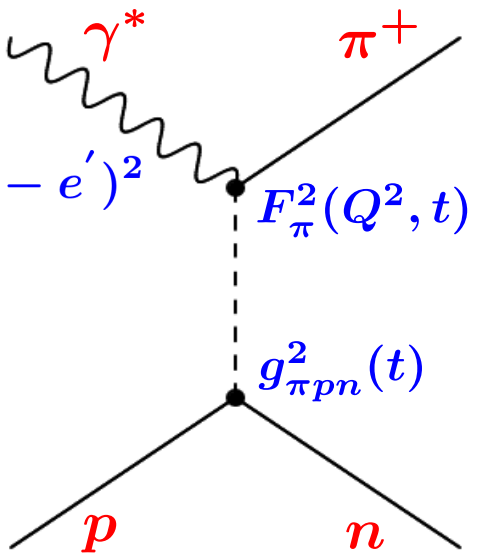
- Measure e'π^+n triple coincidence events.

- 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.

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

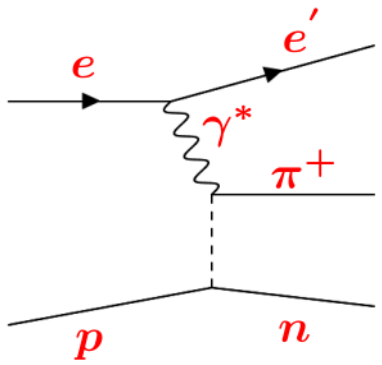


-t Reconstruction

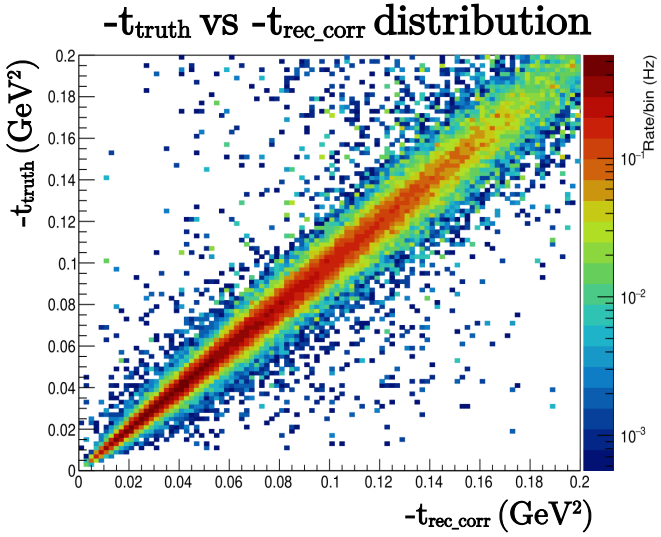
- Can calculate -t via proton – baryon (corrected) vertex :

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

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



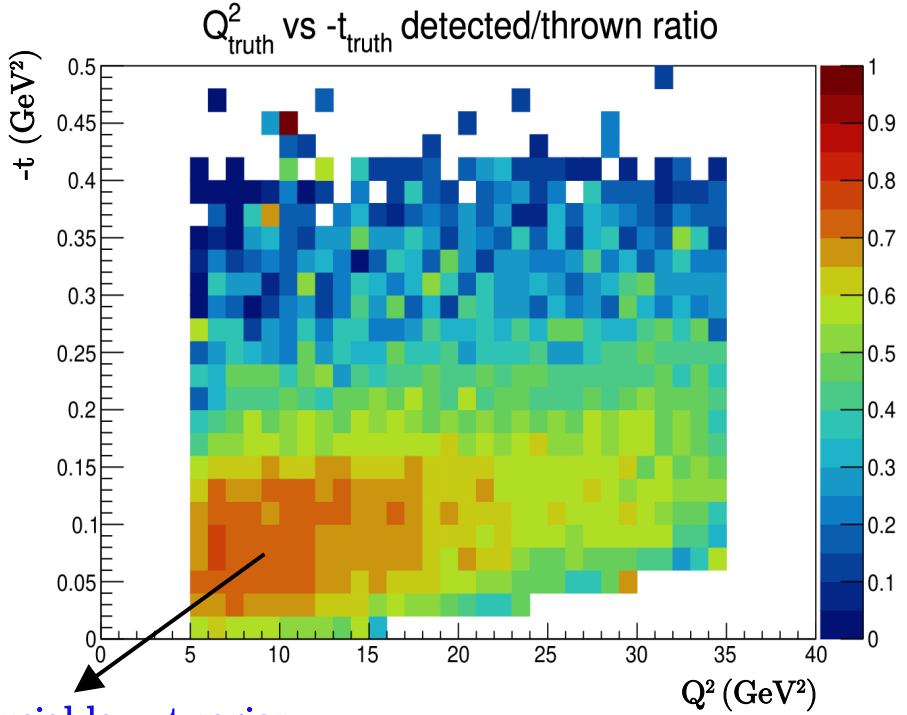
- Corrected the neutron 4 vector using the following information :
  - ZDC hit angles (θ, ϕ),
  - P_{Miss} from e' and π^+, $p_{miss} = |\vec{p_e} + \vec{p_p} - \vec{p_{e'}} - \vec{p_{\pi^+}}|$
  - and the mass of the remaining particle.



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.



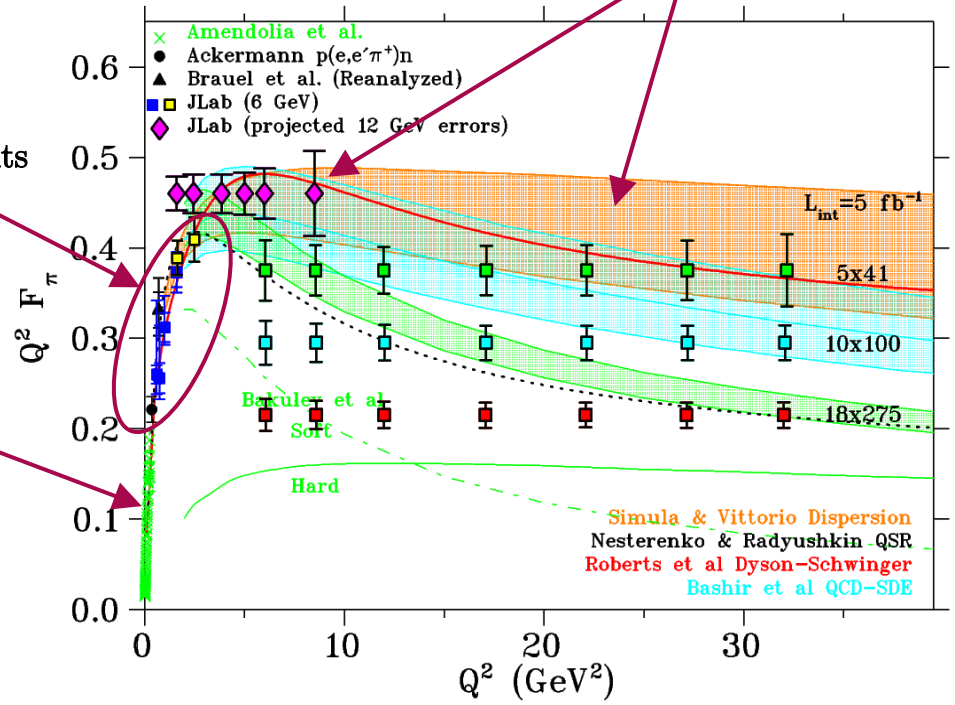
Detection efficiency best in crucial low -t region.

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

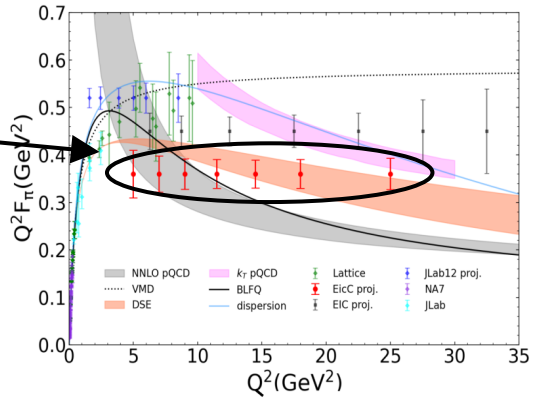
πe elastic scattering data



- 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 +

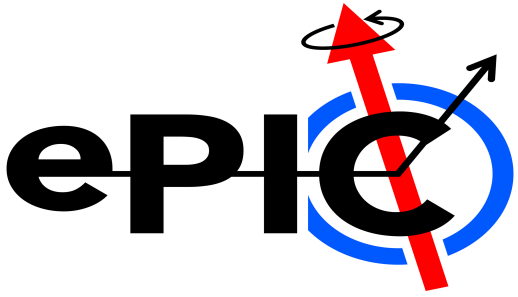


Thanks for listening, any questions?

G. M. Huber, S. J. D. Kay, and L. Preet

University of Regina

NSERC CRSNG



UNIVERSITY of York

Science and Technology Facilities Council

EIC-Canada

This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), FRN: SAPPJ-2023-00041

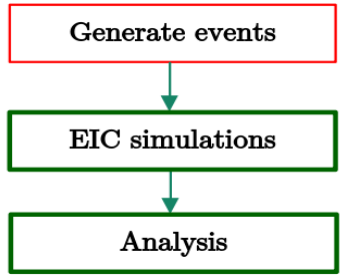
& UK Research and Innovation: Science and Technology Facilities council (UKRI:STFC) grant ST/W004852/1

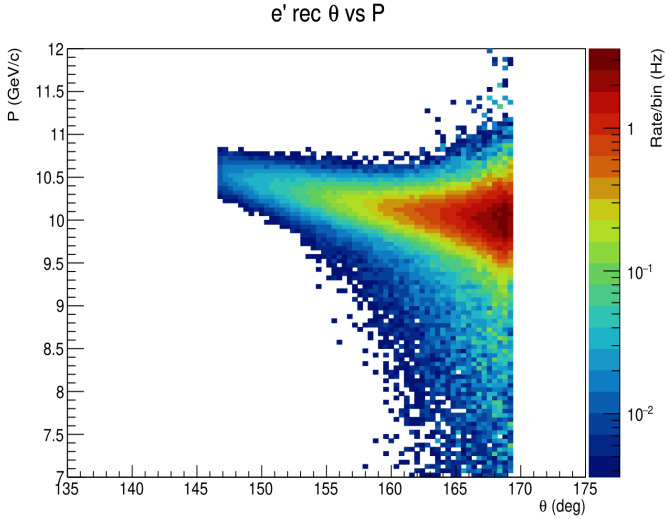
Email : navisaharan3@gmail.com

BACKUP SLIDES

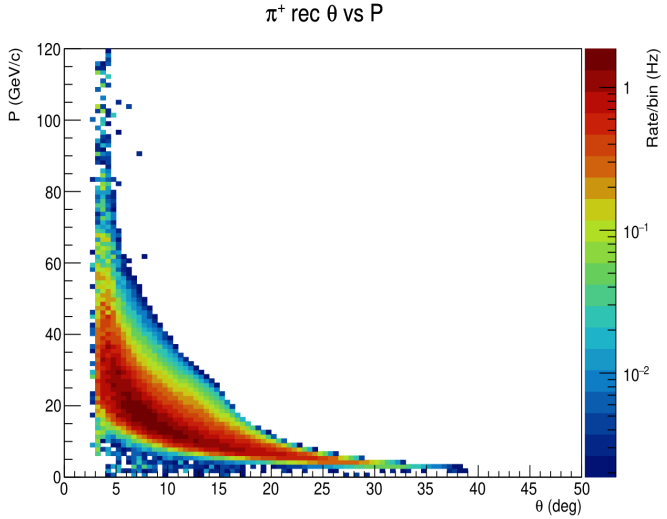
DEMP Kinematics – Reconstructed Distributions

- Processed same 10(e) on 100(p) events through ePIC simulations.
- e' and π^+ hit the central detector, neutron in ZDC.
- Note that the Z scale is a rate in Hz.

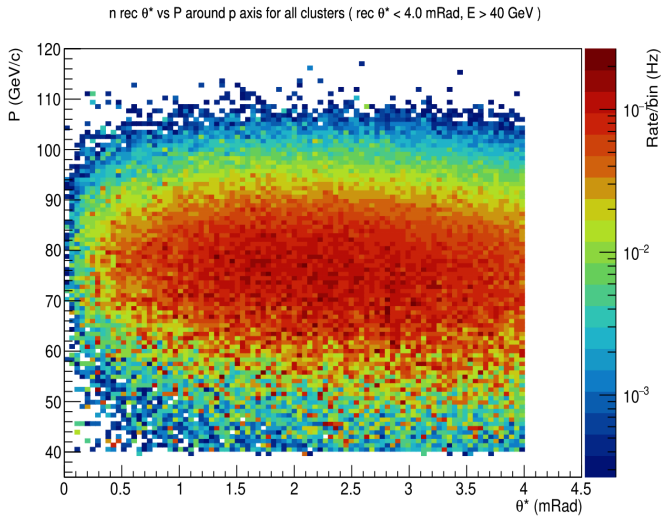




P ~ 9.5 - 10.5 GeV



~ 5 - 50 GeV



~ 54 - 92 GeV

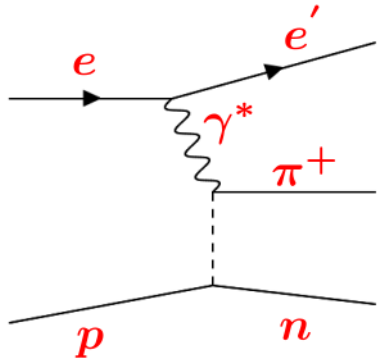
θ^* is rotated by 25 mRad around proton axis

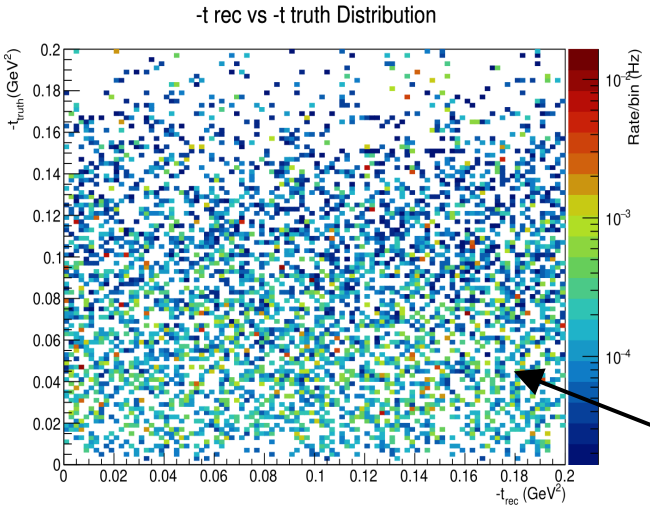
-t Reconstruction (Method – 1)

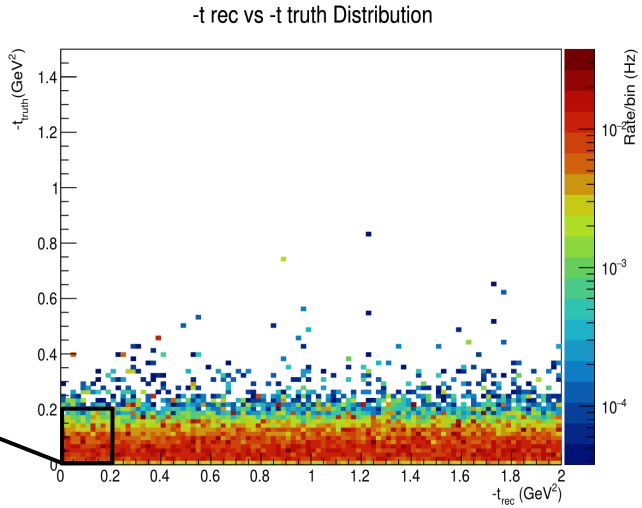
- Can calculate -t via lepton – meson vertex :

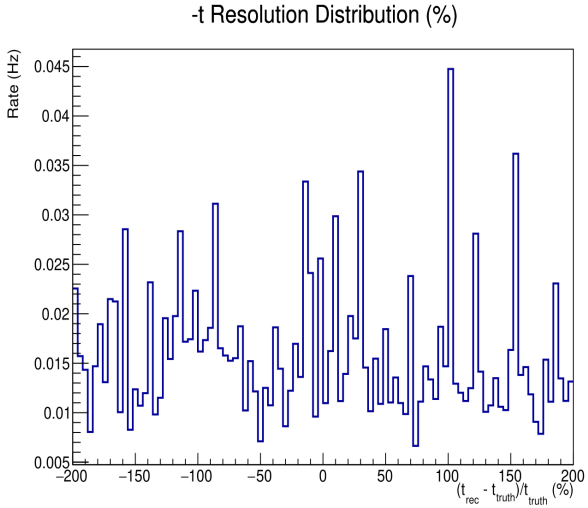
$$-t_{truth} = -(\gamma^* - \pi^+)^2 \qquad -t_{rec} = -(\gamma^* - \pi^+)^2$$

- Insufficient resolution !









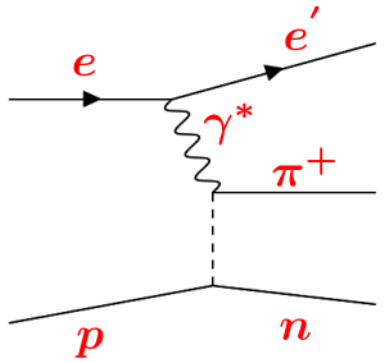
https://www.sciencedirect.com/science/article/abs/pii/S0168900223002280

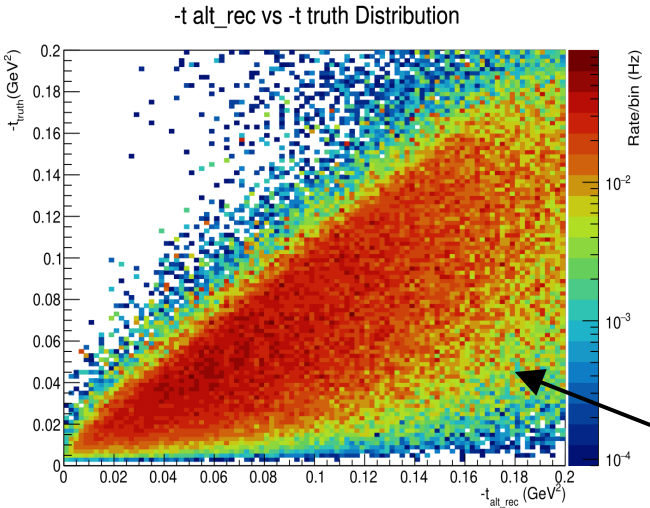
-t Reconstruction (Method – 2)

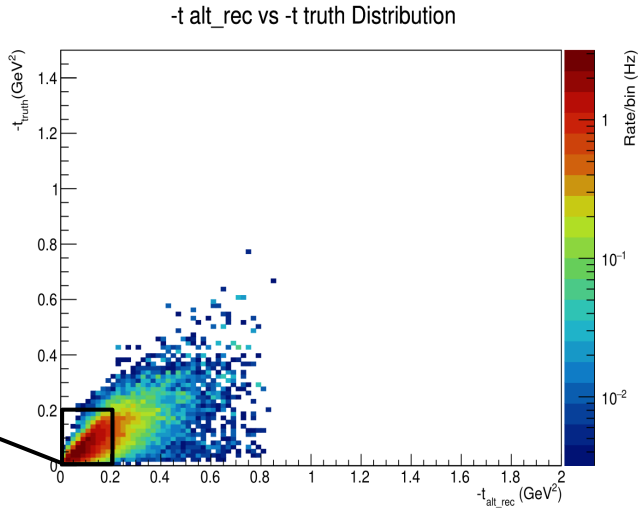
- Can calculate -t via proton – baryon vertex :

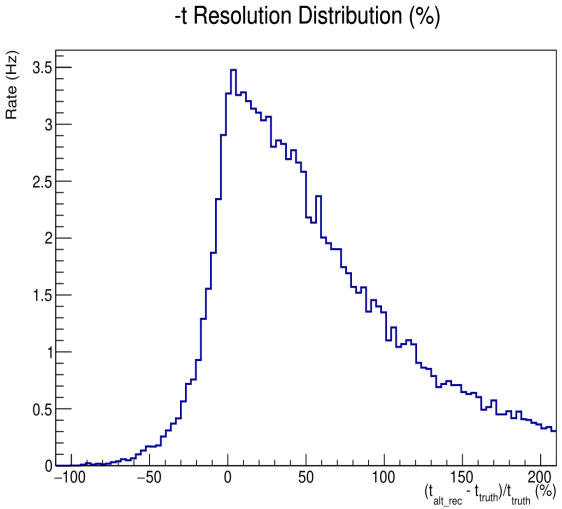
$$-t_{truth} = -(\gamma^* - \pi^+)^2 \qquad -t_{alt\_rec} = -(p - n)^2$$

- Not great, not terrible !







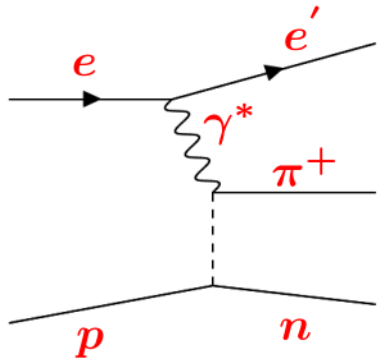


https://www.sciencedirect.com/science/article/abs/pii/S0168900223002280

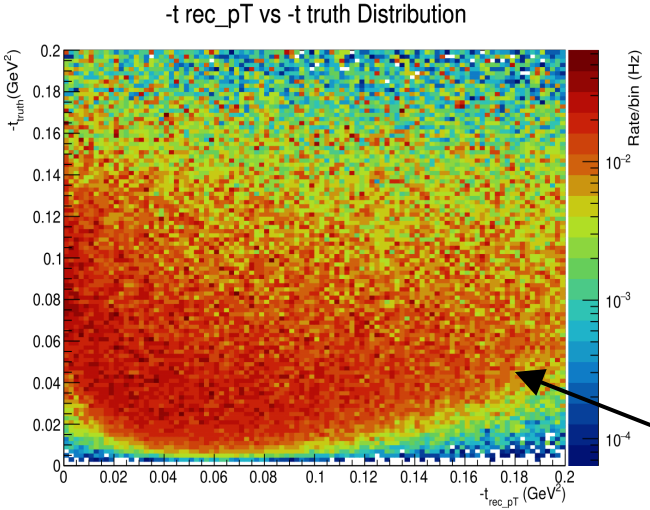
-t Reconstruction (Method – 3)

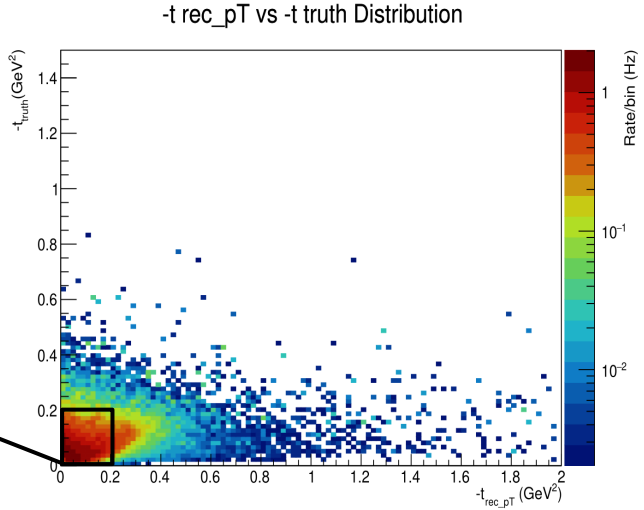
- Can calculate -t via p_T of e' and $^+$:

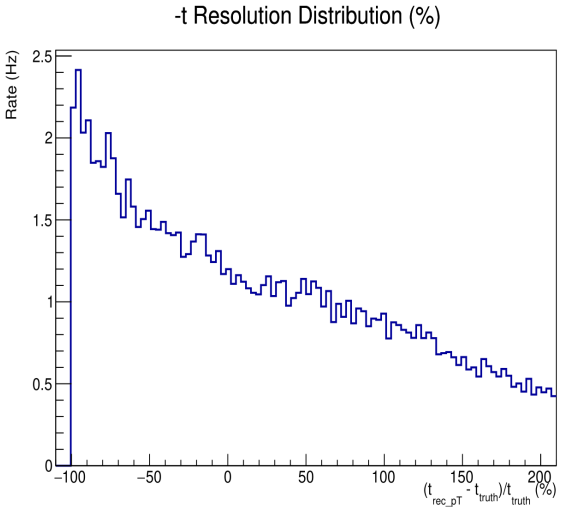
$$-t_{truth} = -(\gamma^* - \pi^+)^2 \qquad -t_{rec\_pT} \approx -(p_{T,\pi^+} + p_{T,e'})^2$$



- Even worse !
- Valid for small -t and Q^2 !







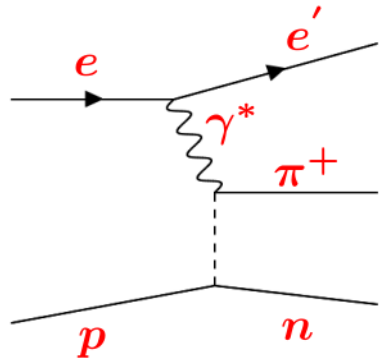
https://arxiv.org/pdf/2005.14706.pdf

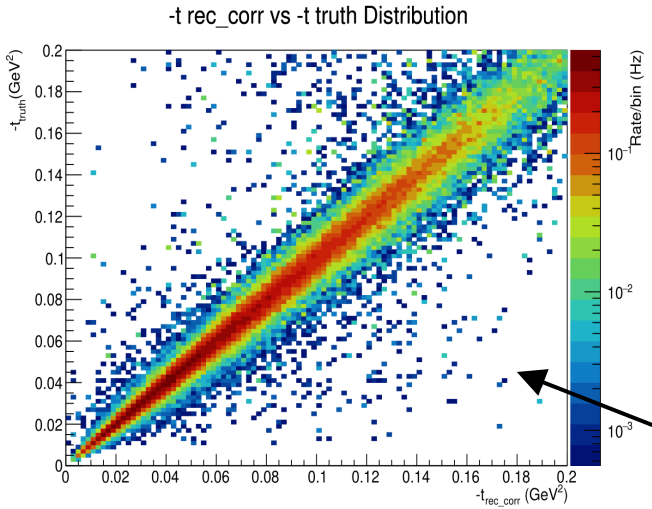
-t Reconstruction (Method – 4)

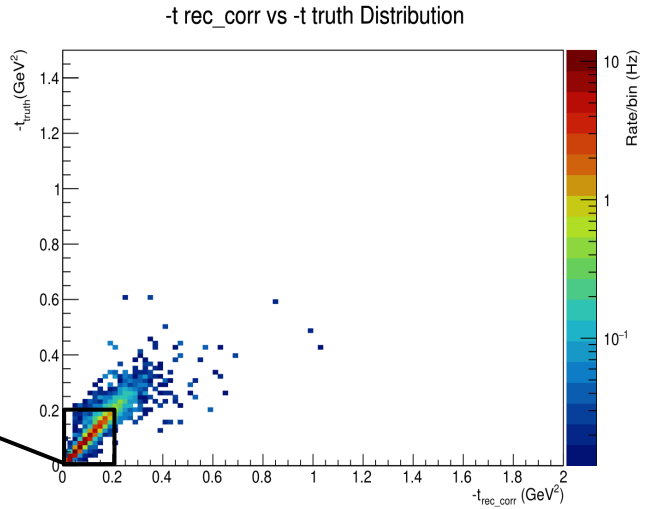
- Can calculate -t via proton – baryon (corrected) vertex :

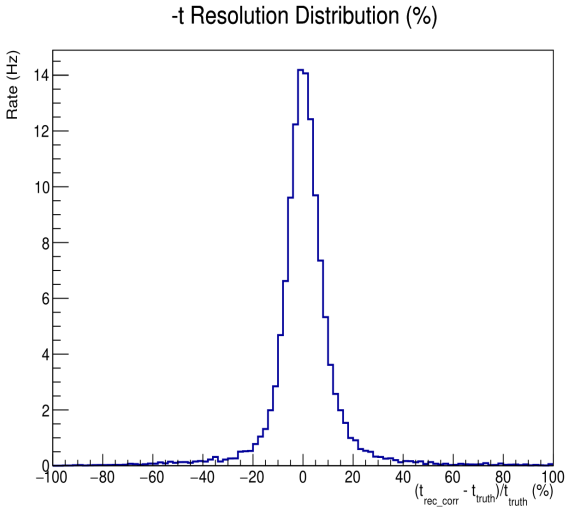
$$-t_{truth} = -(\gamma^* - \pi^+)^2 \qquad -t_{rec\_corr} = -(p - n_{corr})^2$$

- 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.





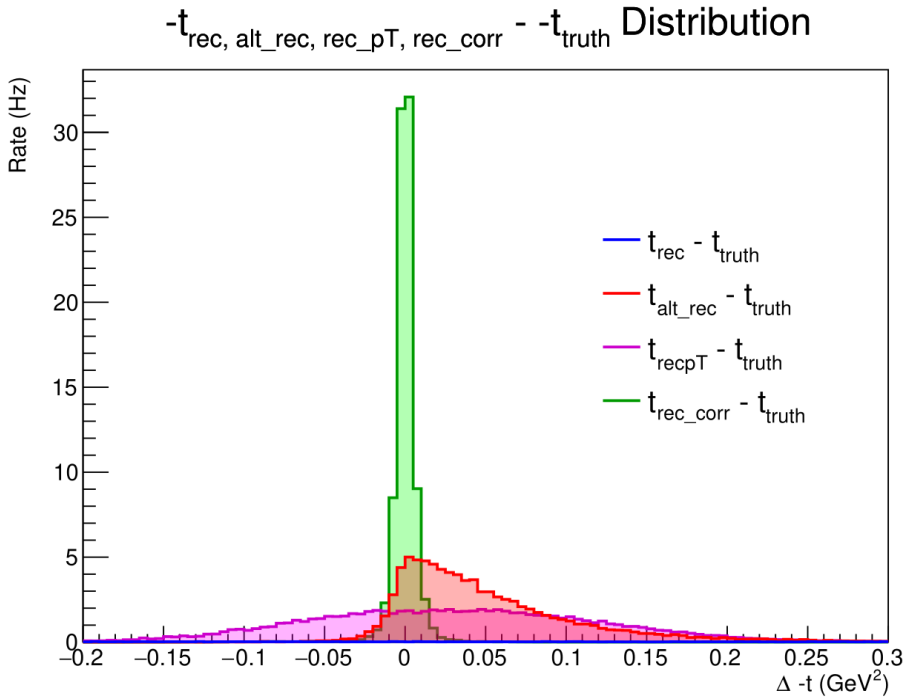




https://www.sciencedirect.com/science/article/abs/pii/S0168900223002280

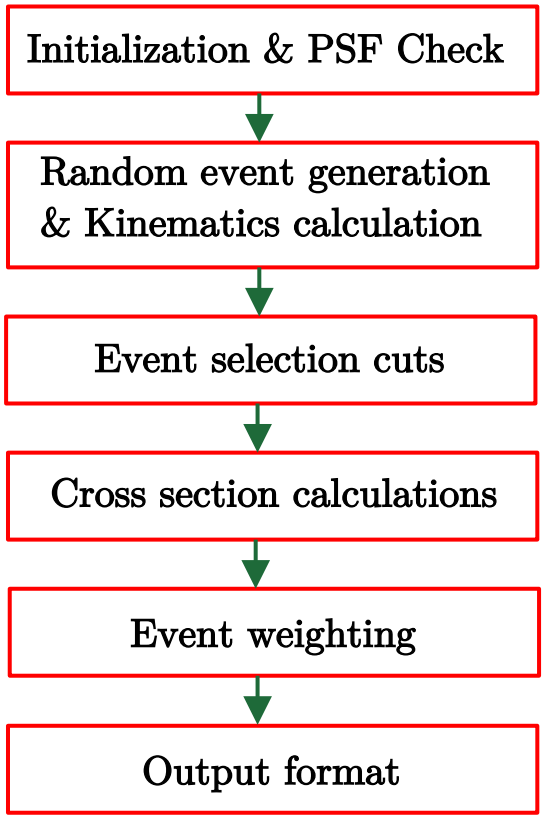
Comparison of -t Reconstruction Methods

- Corrected neutron track method clearly gives best -t resolution.
- ~ ±0.01 in -t for this method.



Monte Carlo Event Generator - DEMPgen

- How does the generator work?



Described based on the latest release, DEMPgen – v1.2.2

Event weight in DEMPgen

- Event weight is calculated for the generated events using the following equation

$$\text{Weight} = \frac{\sigma \times PSF \times CF \times \mathcal{L}}{N_{Gen}}$$

Where,

σ is the 5-fold cross section in the collider frame.

PSF is the phase space factor.

CF is a conversion factor to convert μb to cm^2.

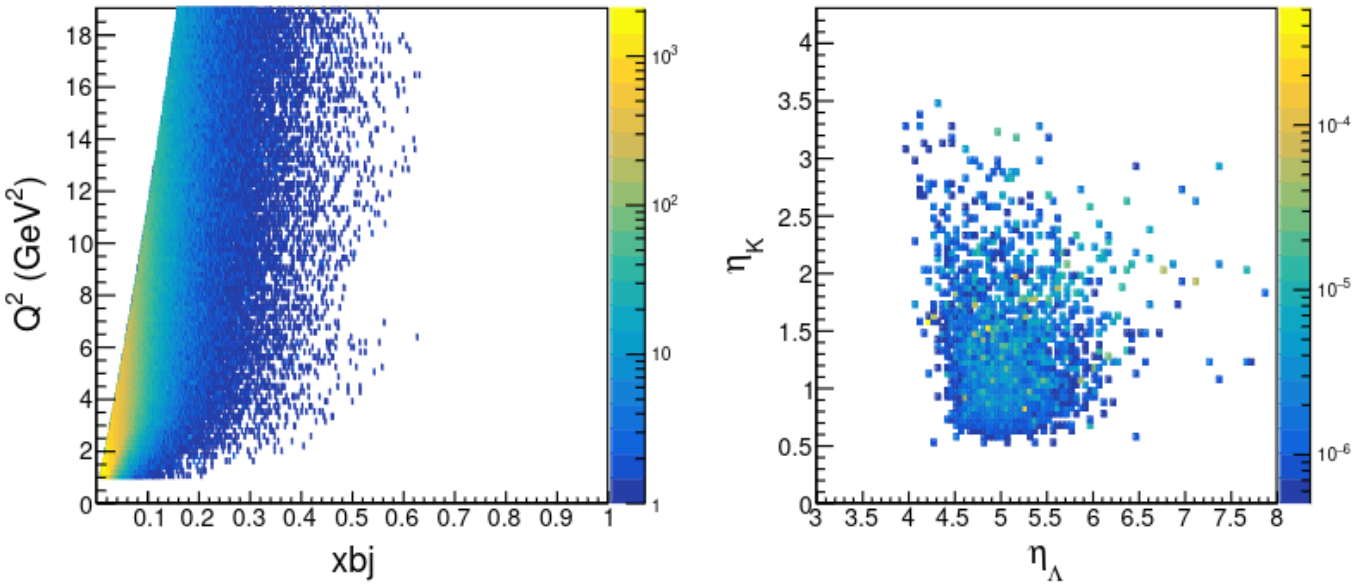
$\mathcal{L}$ is the luminosity and

N_{Gen} is the number of events that the DEMPgen tried to produce.

$$PSF = (E_{e'Max} - E_{e'Min}) d\Omega_{e'}(\theta, \phi)\, d\Omega_K(\theta, \phi)$$

DEMPgen in the Scientific Community

- Zhoudunming Tu utilized DEMPgen v1.0.0 to generate kinematic distribution plots for exclusive Λ hyperon polarization studies.
  - Calculate the runtime of the experiment to achieve desired event yield.

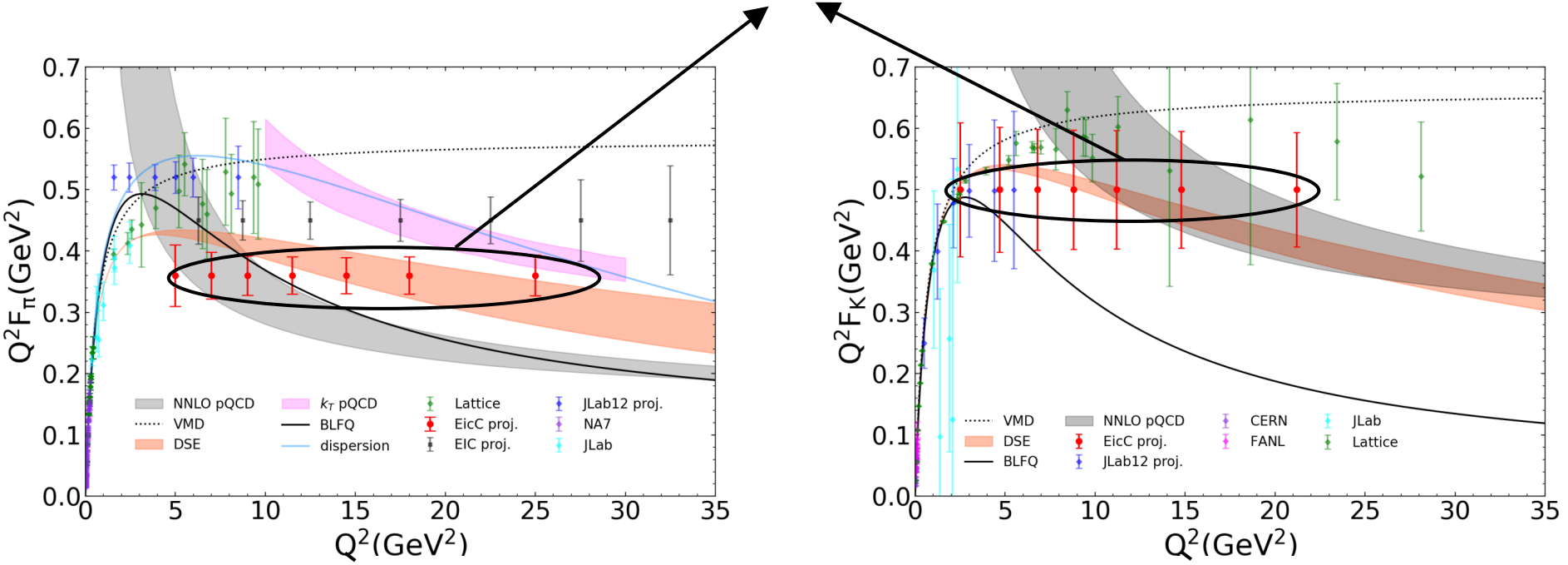


https://journals.aps.org/prc/abstract/10.1103/PhysRevC.109.055205

DEMPgen in the Scientific Community

- Weizhi Xiong conducted simulation studies using DEMPgen to measure the feasibility of DEMP reactions at the Electron-ion collider in China (EicC).

EicC F_π & F_K Projections at 3.5(e) on 20(p) GeV collisions.



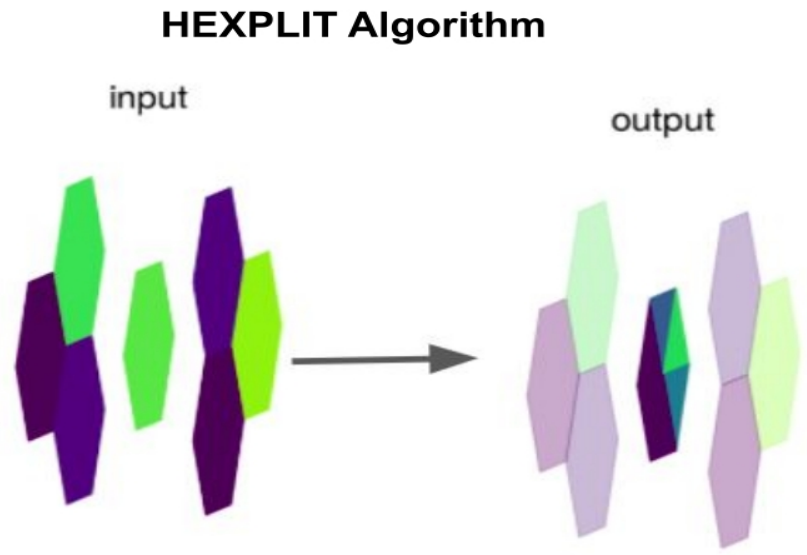
https://indico.pnp.ustc.edu.cn/event/2444/contributions/14518/attachments/5291/8168/EicC_Meson_strcuture_8th_CDR.pdf

DEMPgen Modularity

- Structured modularly, enabling the addition of new exclusive reactions over time.
- To add a new reaction:
  - Find the appropriate theoretical model for the given reaction.
  - Parametrize the cross-section components over wide kinematic ranges.
  - Input the parametrized values into the .txt file, similar to the K^+ module.
  - Set up the masses for the ejectile, & recoil in the main DEMPgen routine.
- Contact us at *Garth.Huber@uregina.ca*, *stephen.kay@york.ac.uk*, & *Love.Preet@uregina.ca* if you encounter any issues.

ZDC Neutron Reconstruction

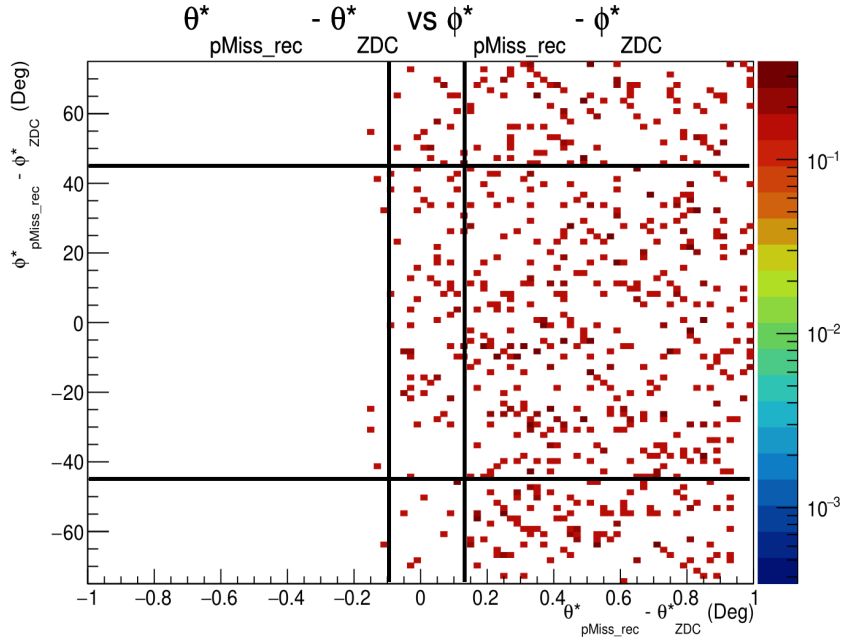
- Detector cells arranged in a hexagonal cell.
  - Provide better spatial resolution and uniform coverage.



S. Paul, M. Arratia arXiv:2308.06939

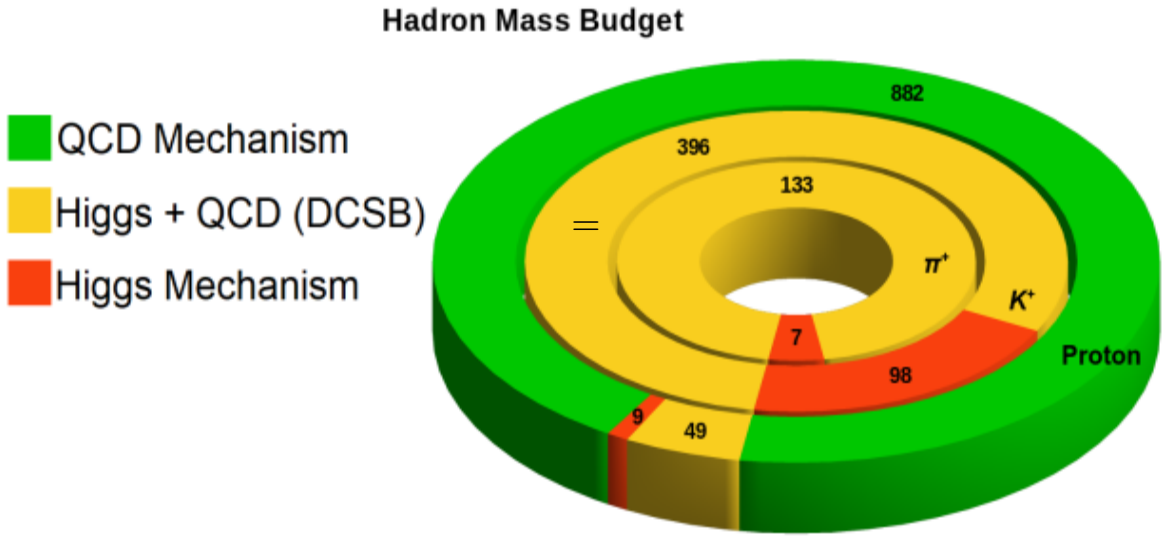
Background Events

- Main source of background is SIDIS, $p(e,e' \pi^+)X$, events.
- Compare SIDIS events for same beam energy.
- Very few fall in comparable $\Delta\theta$ and $\Delta\phi$ range.



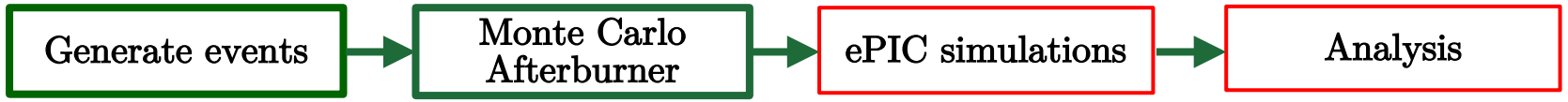
Hadronic Mass Budget

- Only the portion in red is directly from the Higgs current !

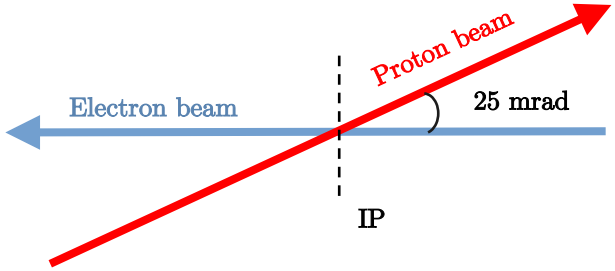


Simulation studies using ePIC simulations

- Incoming beams collide at a crossing angle of 25 mrad.



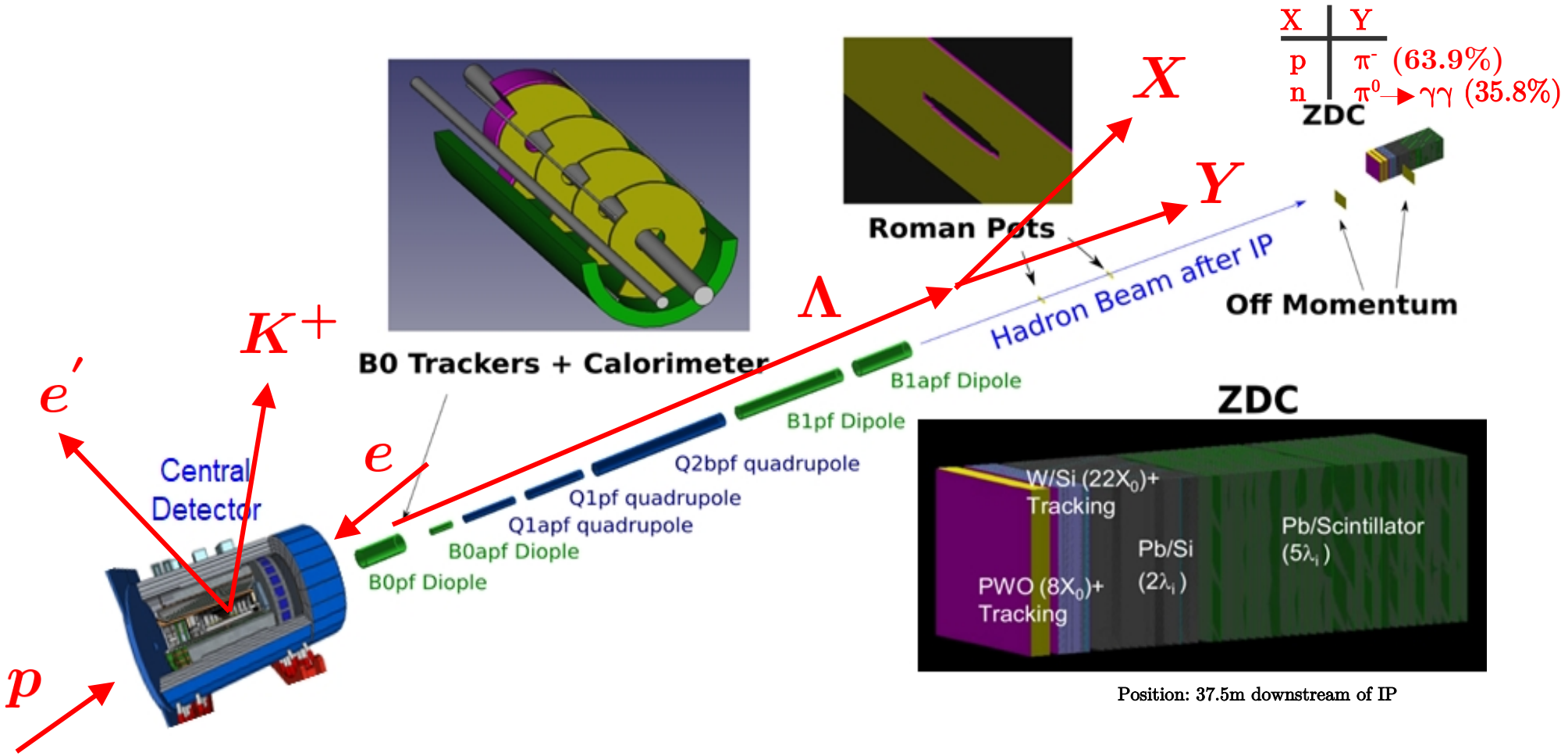
  - Monte Carlo afterburner includes crossing angle, beam energy spread, angular beam divergence, bunch length, etc.



- DEMPgen has the capability to generate events directly with the correct crossing angles.
  - Turned it off to maintain compatibility with EIC simulations framework.

https://github.com/eic/afterburner

K^+ DEMP reactions at the EIC



Position: 37.5m downstream of IP

K^+ DEMP reactions at the EIC