Meson Structure Program at EicC

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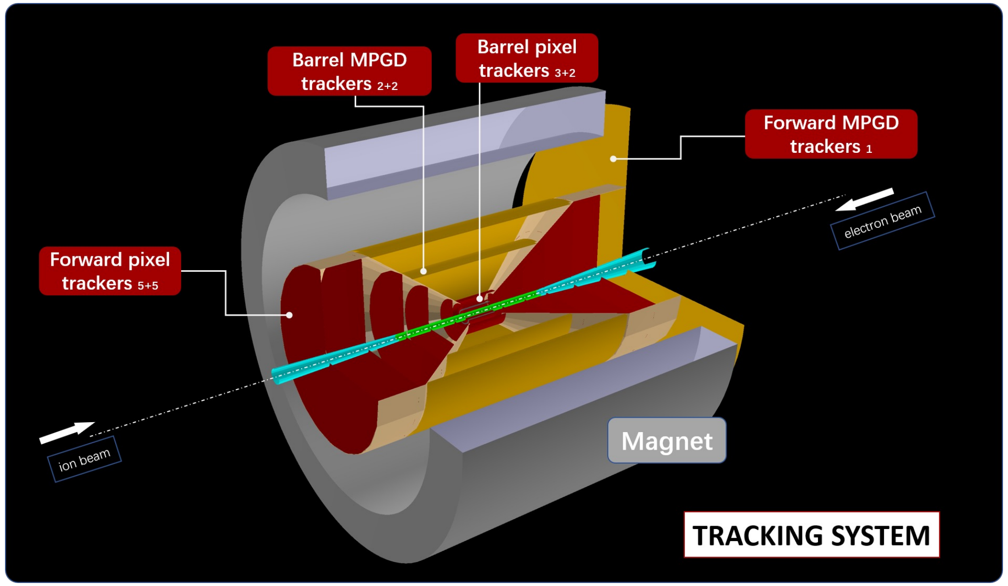
On Behalf of the EicC Exclusive Physics Working Group

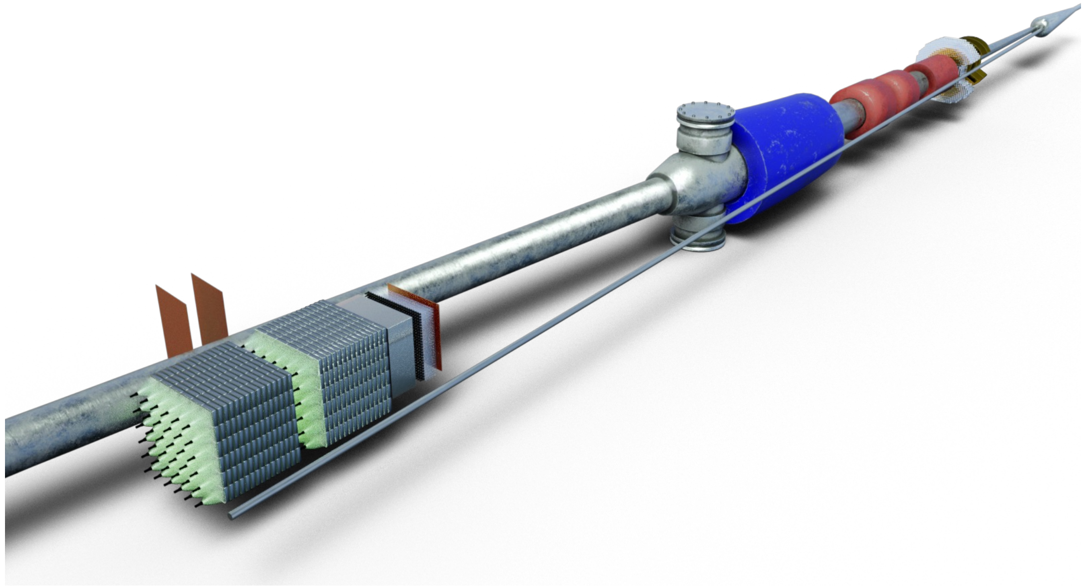
Strong QCD from Hadron Structure Experiments - VI

May 14th – 17th 2024

Outline

- Physics motivation
- EicC and its capacity in meson structure measurements
- Current projections and future tasks
- Summary

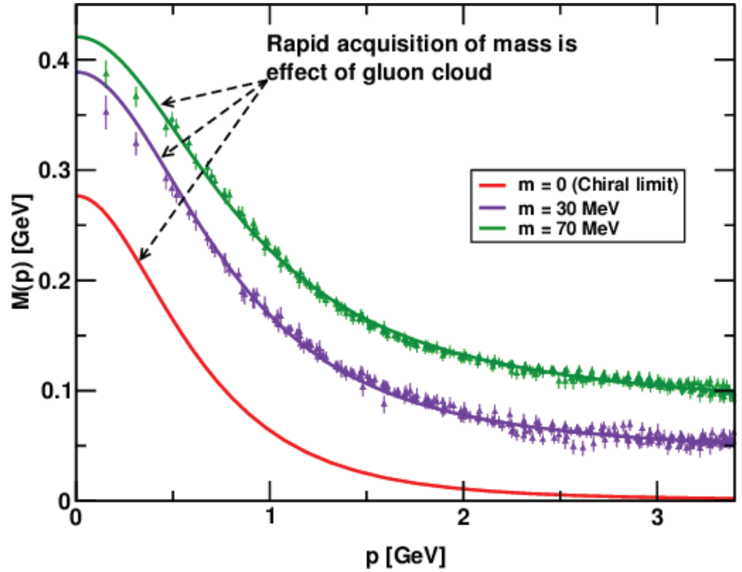


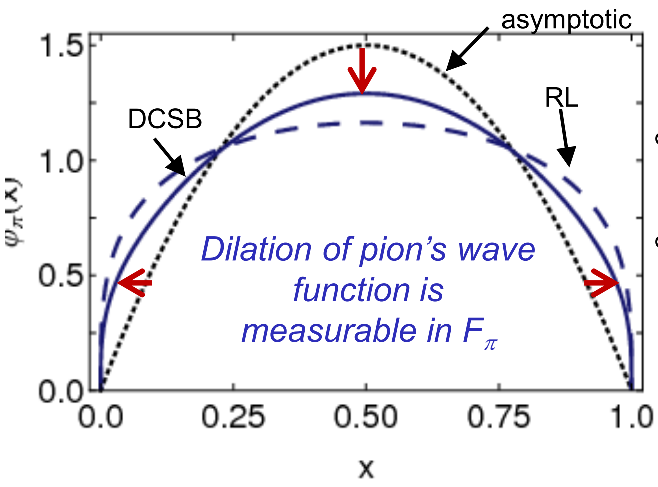


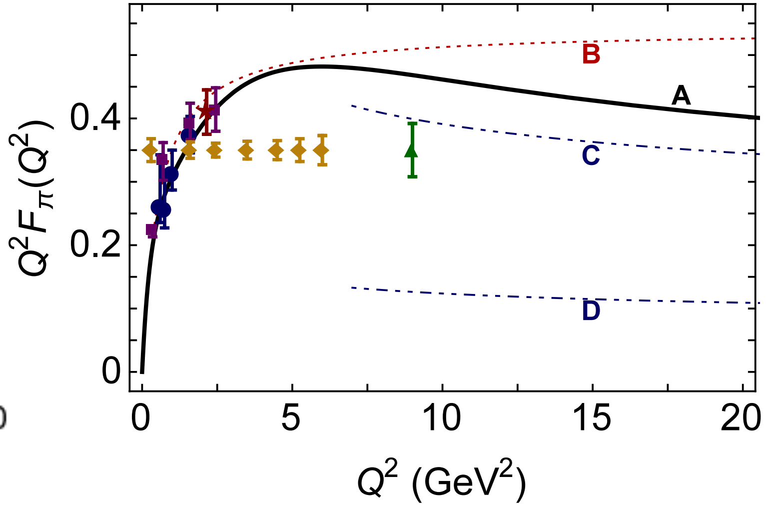
Physics Motivation

- π/K form factors and structure functions are of special interests in hadron structure physics
  - ➢ pion: lightest QCD quark system
  - ➢ kaon: replaces one light quark with a heavier strange quark

- Important in checking the Emergent Hadron Mass (EHM) mechanism and the interplay between EHM and Higgs Boson mechanism
  - ➢ Talk by Prof. Roberts tomorrow morning (May 15)







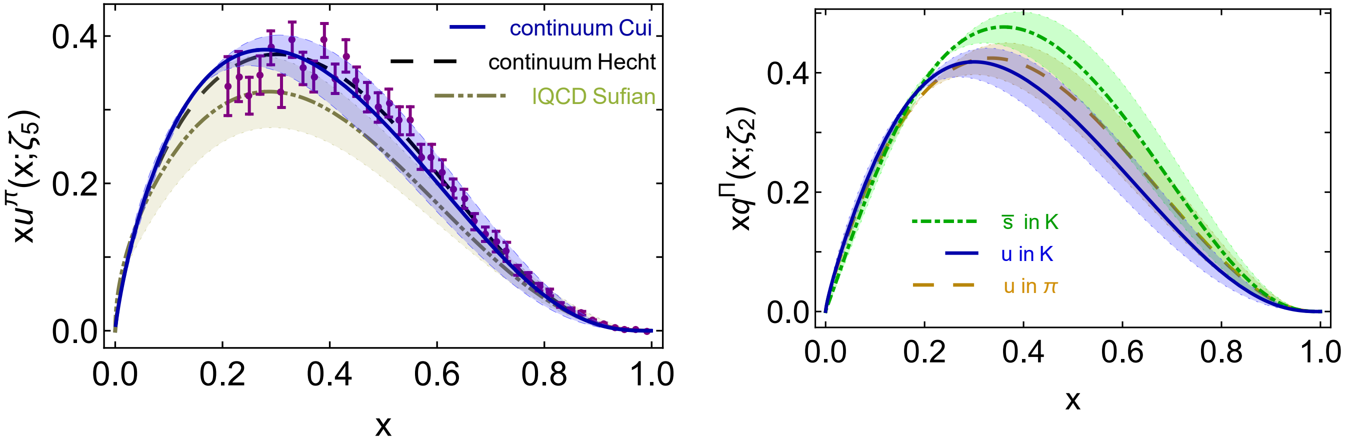
C. D. Roberts, D. G. Richards, T. Horn and L. Chang, PPNP 120, 103883 (2021)
T. Horn and C. D. Roberts. J. Phys. G 43 (2016) 7, 073001
L. Chang et al. *Phys. Rev. Lett.* 111 (2013) 14, 141802

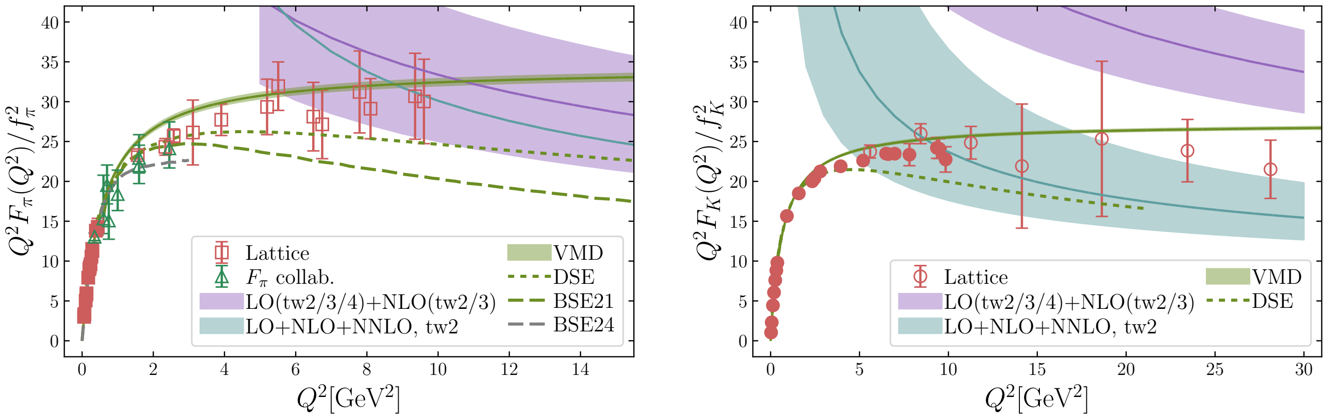
Physics Motivation

- A simpler problem in QFT than that associated with the nucleon
- Important test ground for many theoritical preditions: Lattice QCD, Dyson-Schiwinger method and many more:

M. Ding et al, Phys. Rev. D 101 (2020) 054014;
Z.-F. Cui et al, Eur. Phys. J. A 57 (2021) 5;
Z.-F. Cui et al, Eur. Phys. J. C 80 (2020) 1064;
T. Nguyen et al, Phys. Rev. C 83 (2011) 062201;
Chen Chen et al, Phys.Rev.D 93 (2016) 074021;
Chao Shi et al, Phys.Rev.D 98 (2018) 5, 054029
Lei Chang et al, Phys. Rev. Lett. 111 (2013) 141802;
Fei Gao et al, Phys. Rev. D 96 (2017) 034024
X. Gao et al, Phys. Rev. Lett. 128 (2022) 142003;
H.-W. Lin et al, Phys. Rev. D 103 (2021) 014516;
Z. Fan, H.-W. Lin, Phys. Lett. B 823 (2021) 136778;
Salas-Chavira et al, Phys. Rev. D 106 (2022) 094510
…

C. D. Roberts, D. G. Richards, T. Horn and L. Chang, PPNP 120, 103883 (2021)



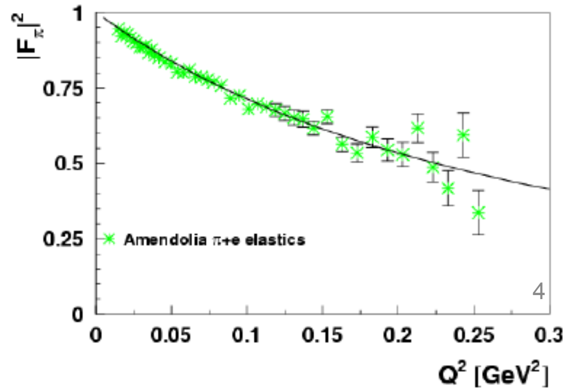


H. T. Ding et al. arXiv:2404.04412

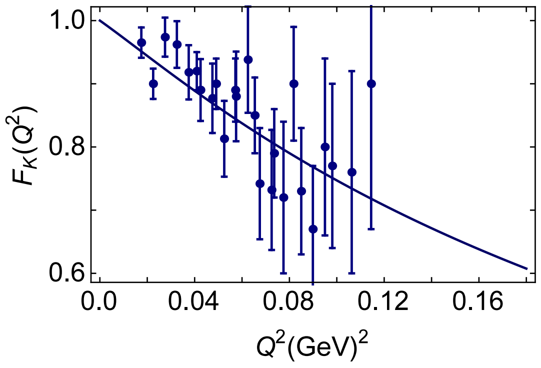
Accessing Meson Structure

Meson Form Factor

- Elastic scattering of high energy meson beam from atomic electron target
  - Model independent way to measure form factor
  - Limited at low Q^2, need TeV meson to reach Q^2 = ~1GeV^2
  - $r_\pi = 0.657 \pm 0.012$ fm
  - $r_K = 0.560 \pm 0.031$ fm



Amendolia et al, NPB277,168 (1986)



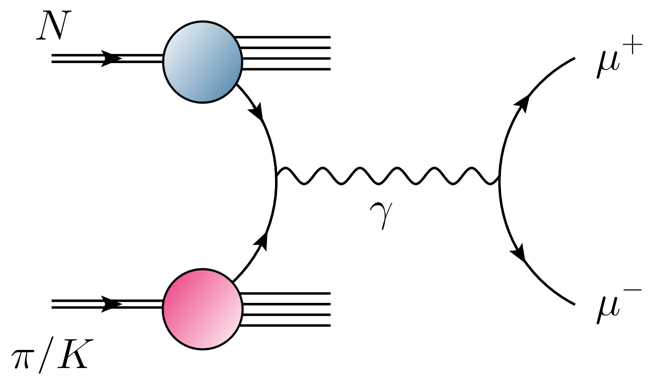
T. Horn and C. D. Roberts. J. Phys. G 43 (2016) 7, 073001

Meson Structure Function

- Drell-Yan process: quark-antiquark annihilation between pion's and proton's, virtual photon decays into lepton pair

- Information about the quark-gluon momentum fractions

$$\frac{d^2\sigma}{dx_\pi dx_N} = \frac{4\pi\alpha_{em}^2}{9M_\gamma^2}\sum_q e_q^2[q_\pi(x_\pi)\bar{q}_N(x_N) + \bar{q}_\pi(x_\pi)q_N(x_N)]$$

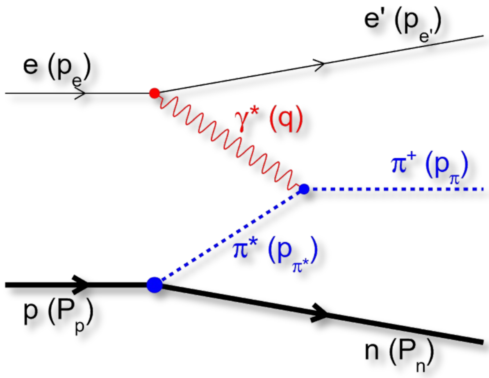


C. D. Roberts, D. G. Richards, T. Horn and L. Chang, PPNP 120, 103883 (2021)

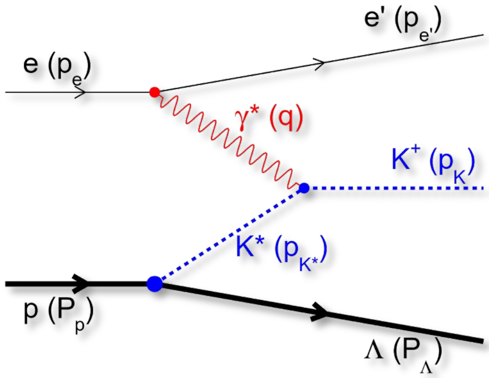
Accessing Meson Structure - Sullivan Process

Sullivan processes at small t (<0.6/0.9 GeV^2) is sensitive to pion and kaon structures.

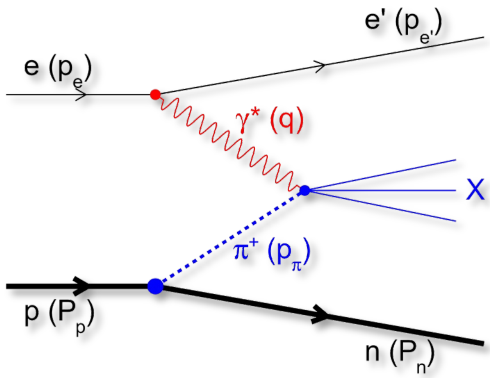
Pion Form Factor (FF)



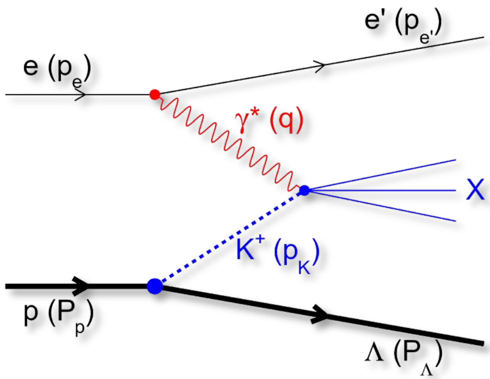
Kaon Form Factor (FF)



Pion Structure Function (SF)



Kaon Structure Function (SF)



Exclusive processes for meson form factor measurements.

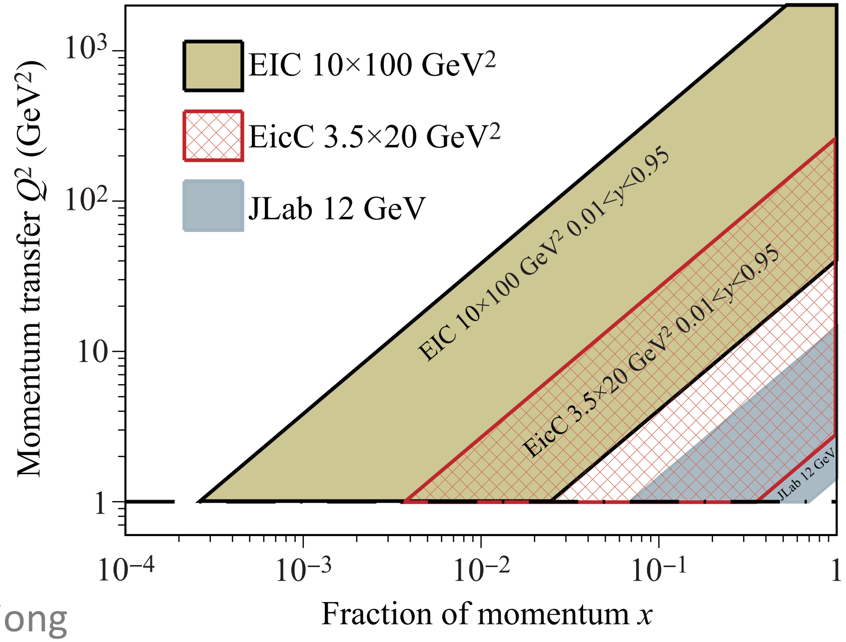
Leading baryon semi-inclusive deep inelastic scattering processes for meson structure measurements

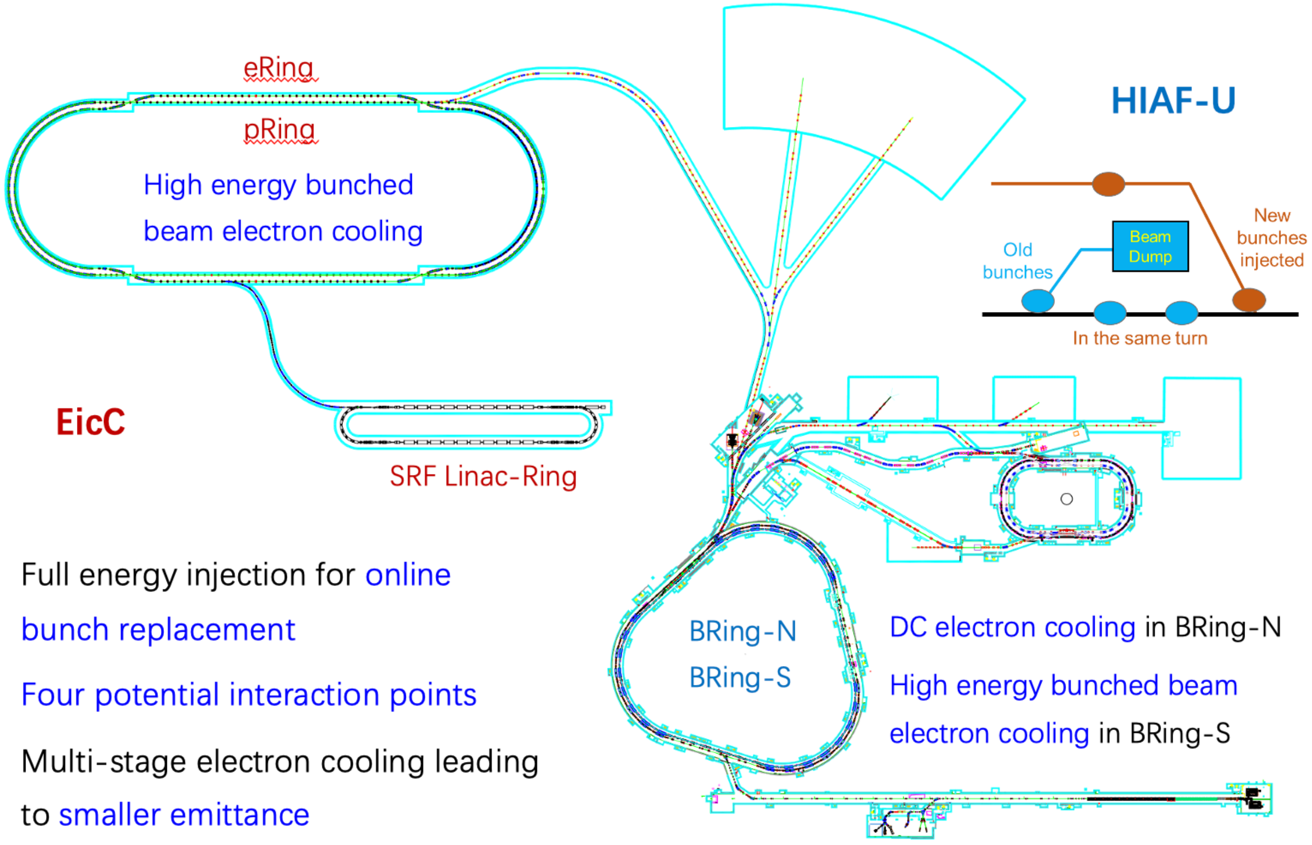
Essential processes to access meson structures at JLab, EIC and EicC

Electron-Ion Collider in China (EicC)

- Nominal beam energy setting and luminosity
  - ➢ 3.5 GeV electron x 20 GeV proton, with luminosity 4.25 x 10^{33} s^{-1} cm^{-2}
  - ➢ Center of mass energy: 16.7 GeV
- 50 mrad crossing angle
- Polarized e and ion beams

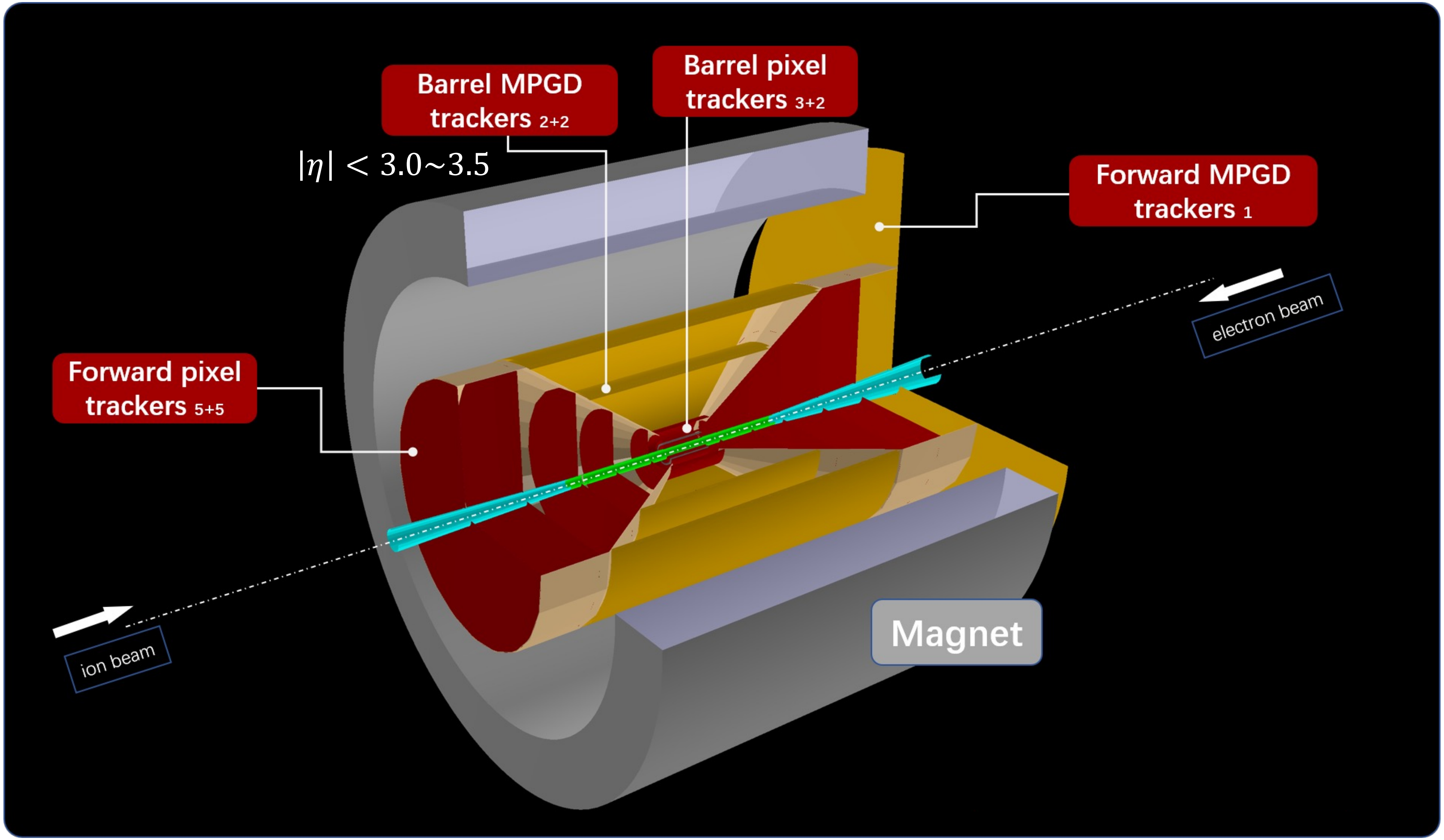
EicC white paper



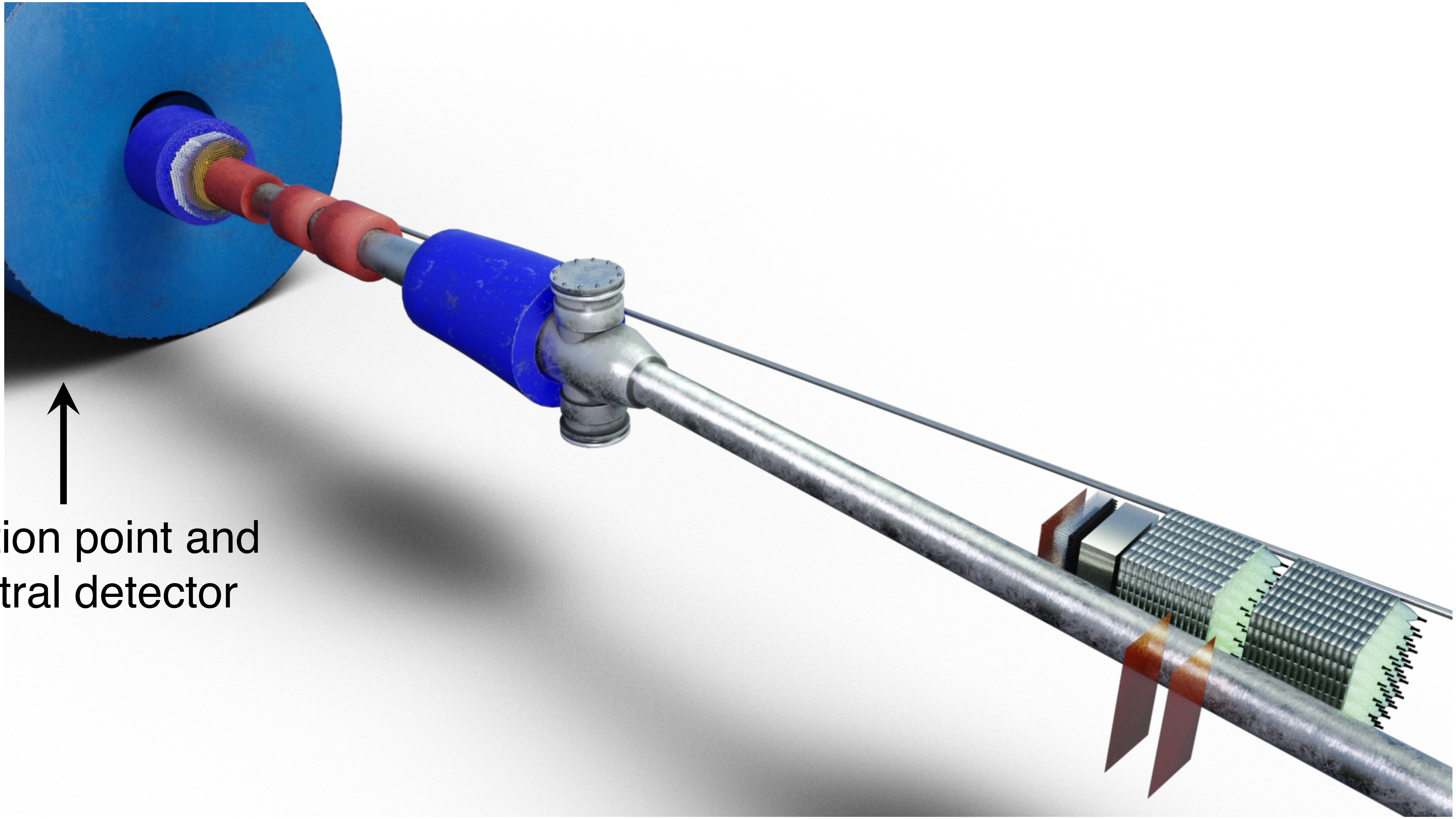


- ✓ Full energy injection for online bunch replacement
- ✓ Four potential interaction points
- ✓ Multi-stage electron cooling leading to smaller emittance

EicC Central Detector

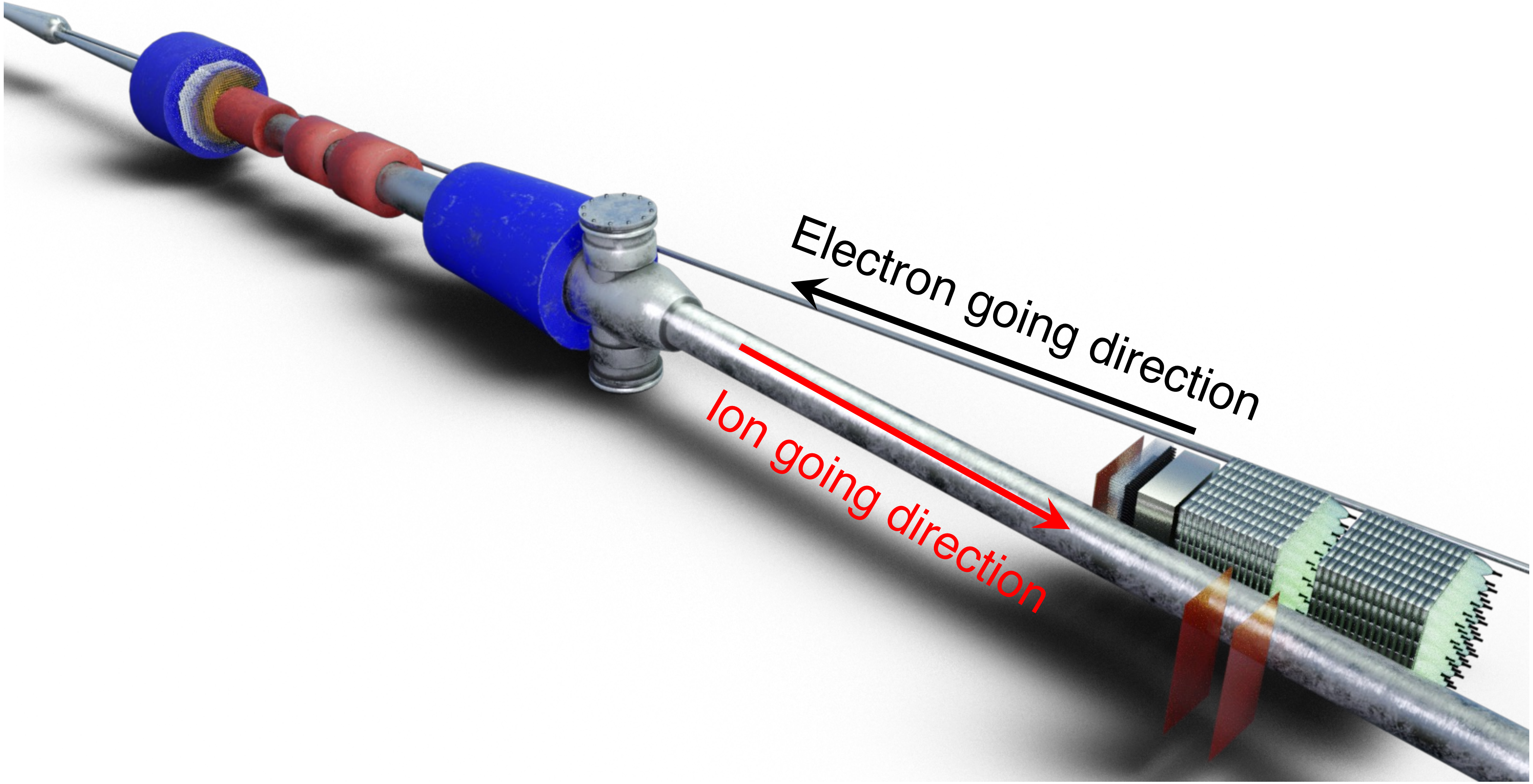


Current Design for EicC Far-Forward (FF) Region



Interaction point and
the central detector

Current Design for EicC Far-Forward (FF) Region



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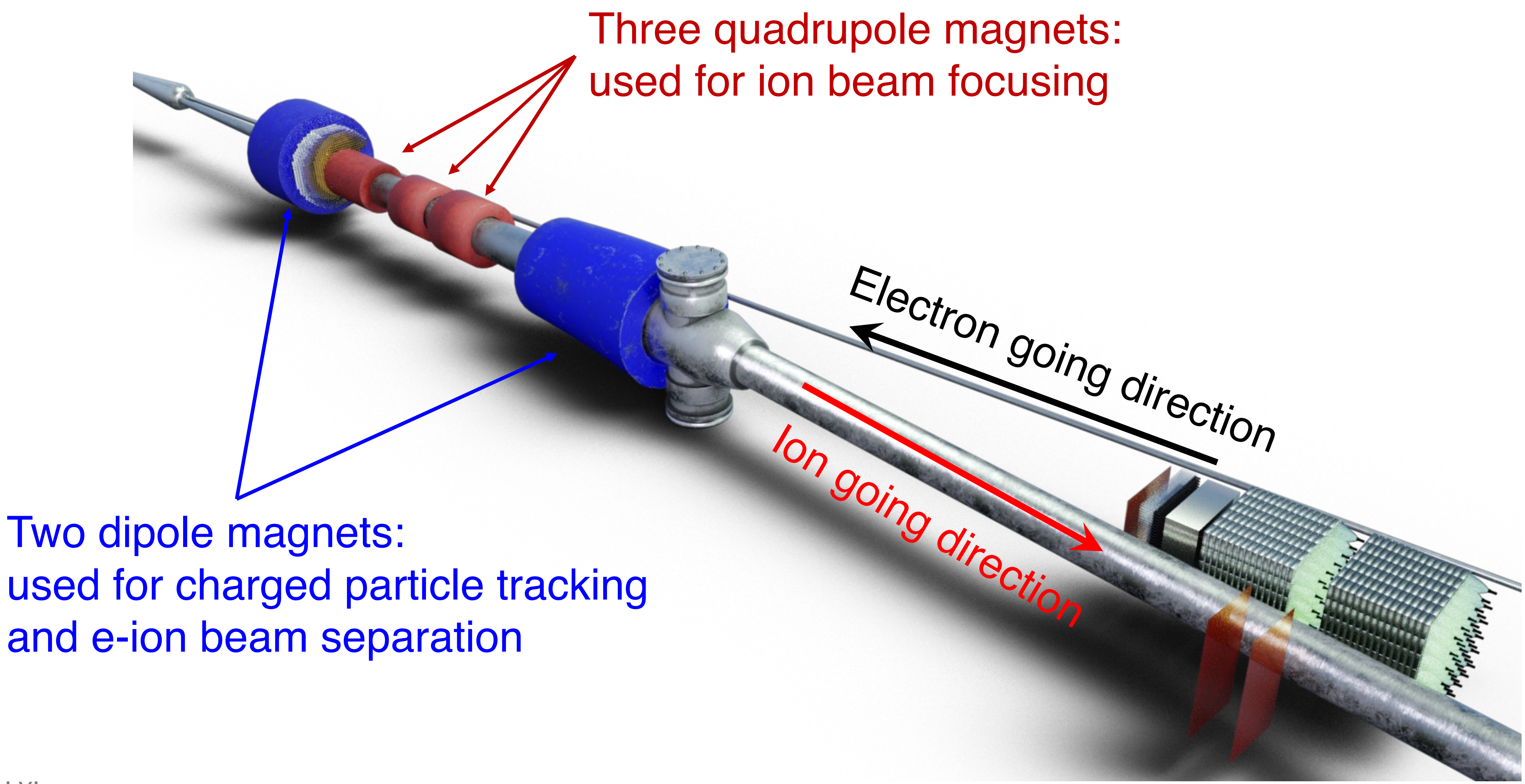
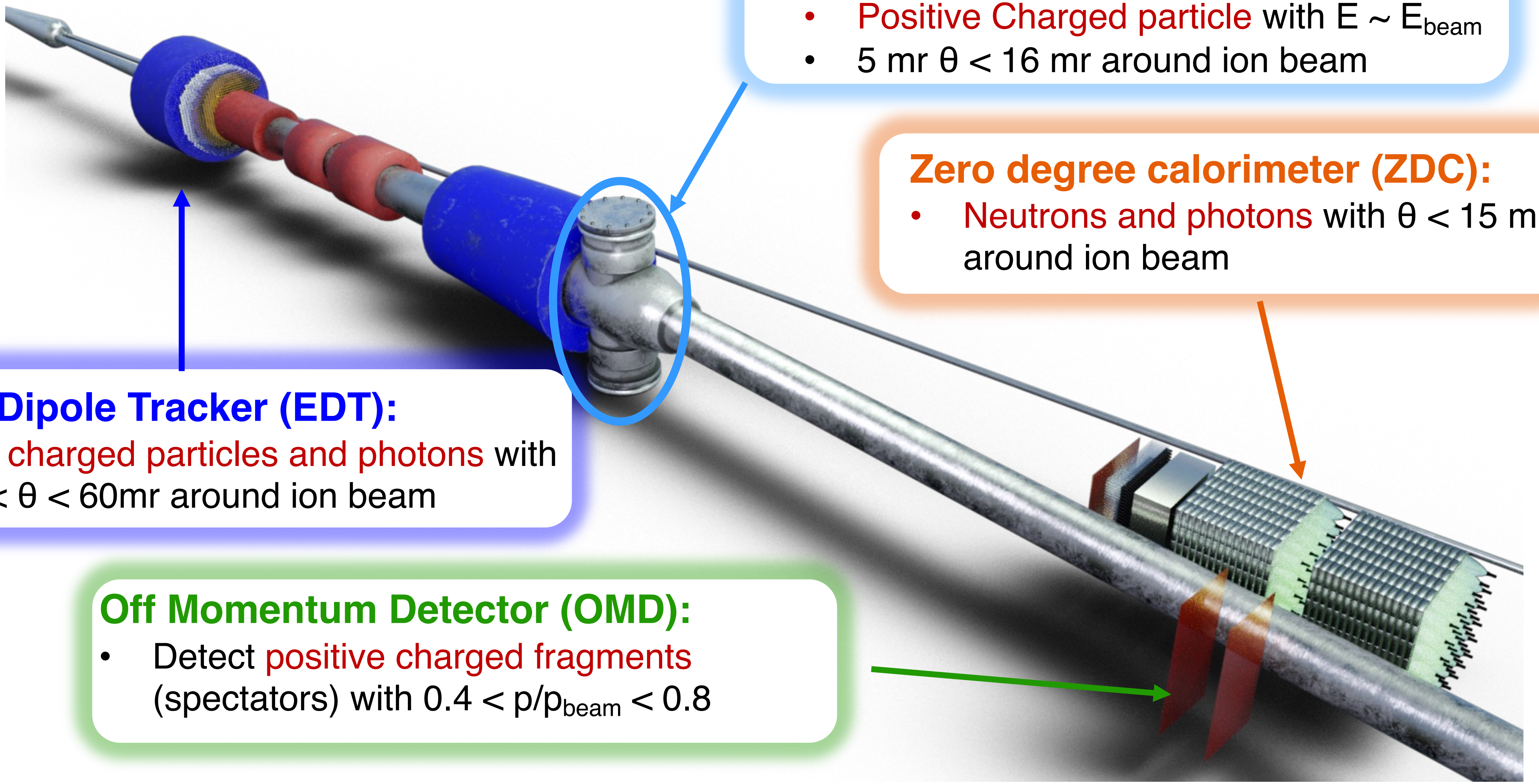


Current Design for EicC Far-Forward (FF) Region



Roman Pot Station:
- Located inside the ion beam pipe
- Positive Charged particle with $E \sim E_{beam}$
- 5 mr θ < 16 mr around ion beam

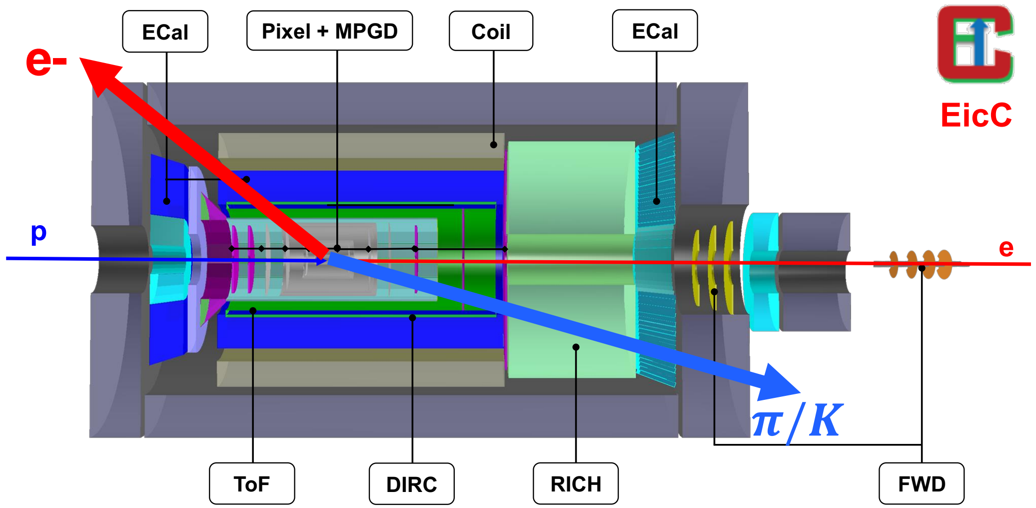
Zero degree calorimeter (ZDC):
- Neutrons and photons with θ < 15 mr around ion beam

Endcap Dipole Tracker (EDT):
- Detect charged particles and photons with 15mr < θ < 60mr around ion beam

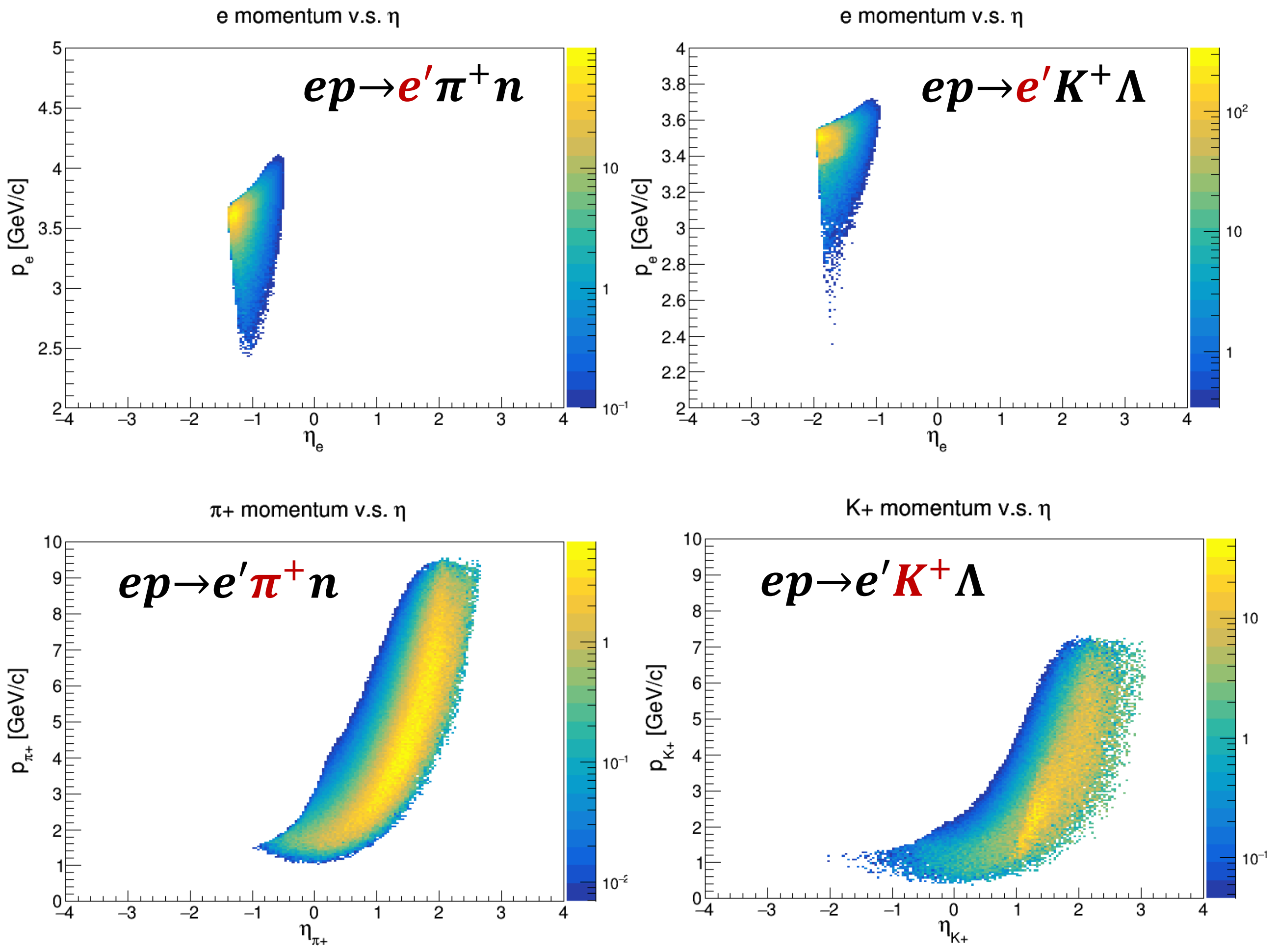
Off Momentum Detector (OMD):
- Detect positive charged fragments (spectators) with $0.4 < p/p_{beam} < 0.8$

Meson Structure Measurement with EicC

- Scattered electron and meson very well covered by central detector
- Acceptance and resolution studied extensively for central detector, fast simulation exist
  - Eff. > 95% for both particles



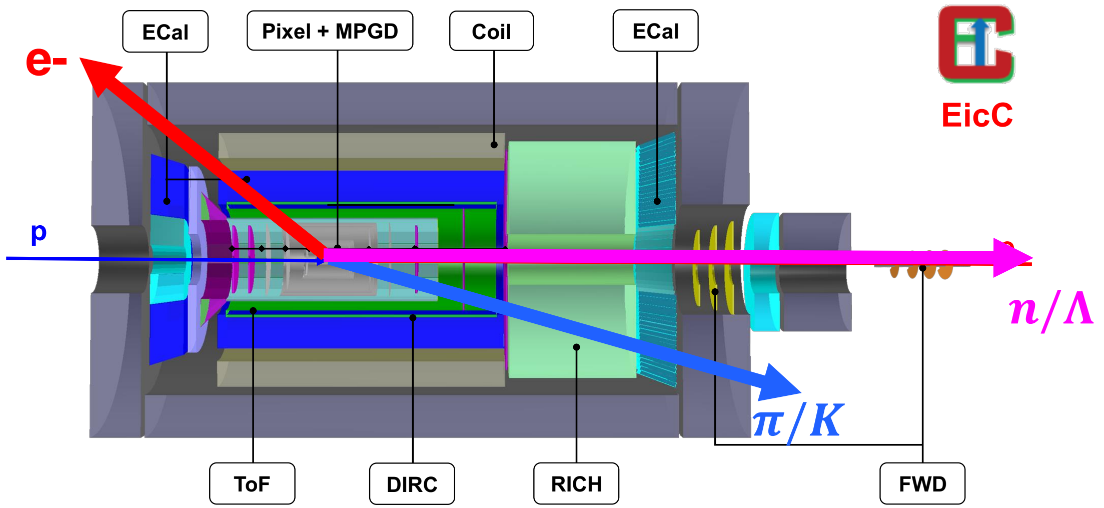
3.5 GeV (e) x 20 GeV (p)

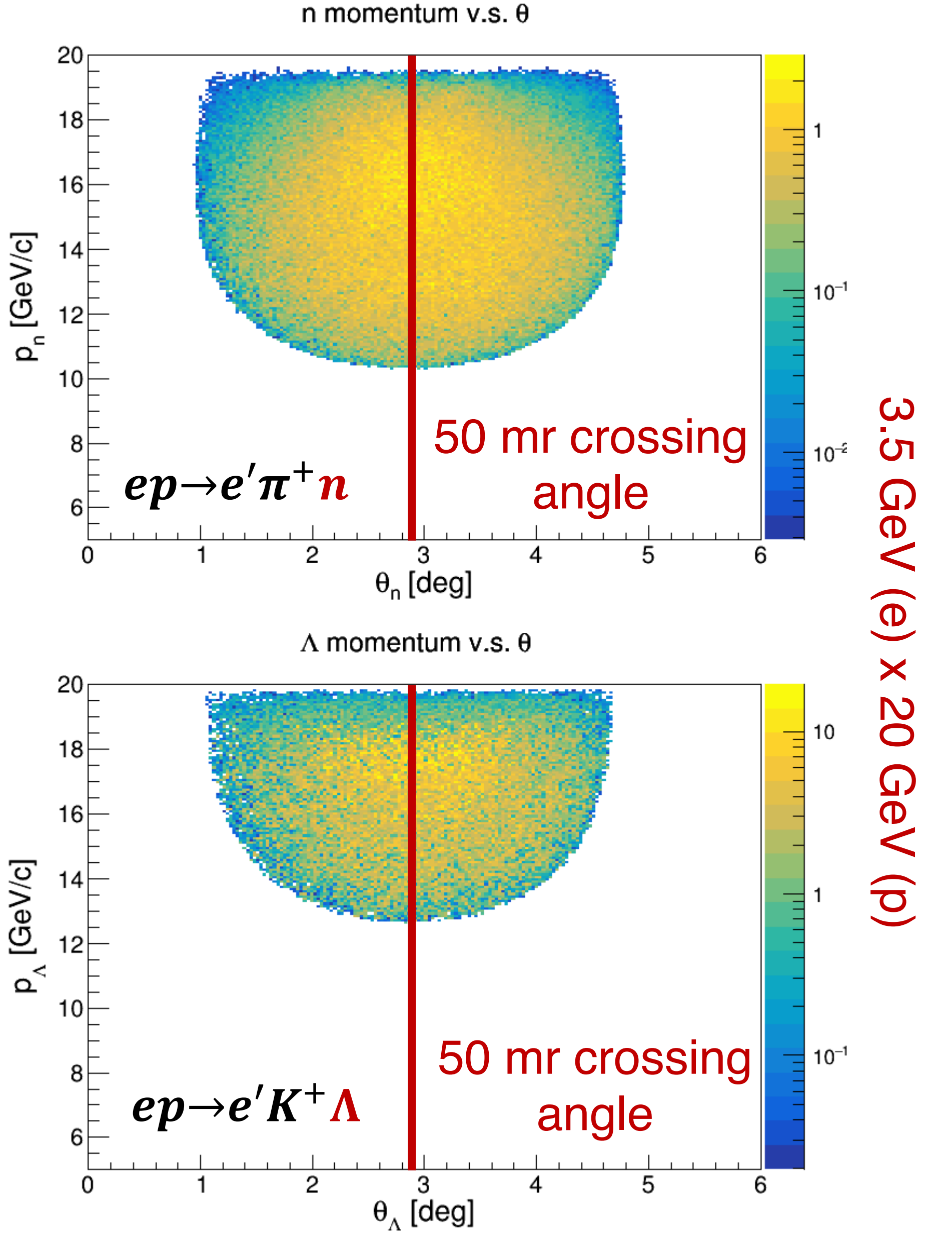


Meson Structure Measurement with EicC

- "Spectator" neutron and $\boldsymbol{\Lambda}$ move very close to the initial p-beam, very difficult to detect, need far-forward detectors

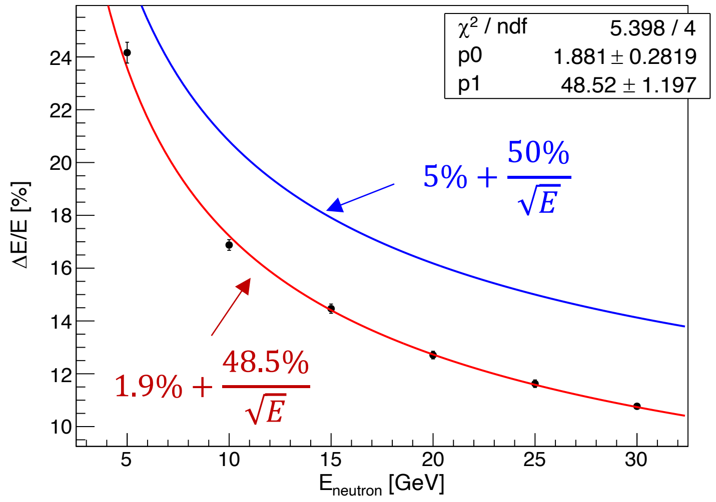
- Pion FF and SF require ZDC for neutron detection
- Kaon FF and SF need all detectors in far-forward region for $\boldsymbol{\Lambda}$:
  - ➢ $\Lambda \to \pi^0 n$ with 36% chance (neutral decay)
  - ➢ $\Lambda \to \pi^- p$ with 64% chance (charged decay)

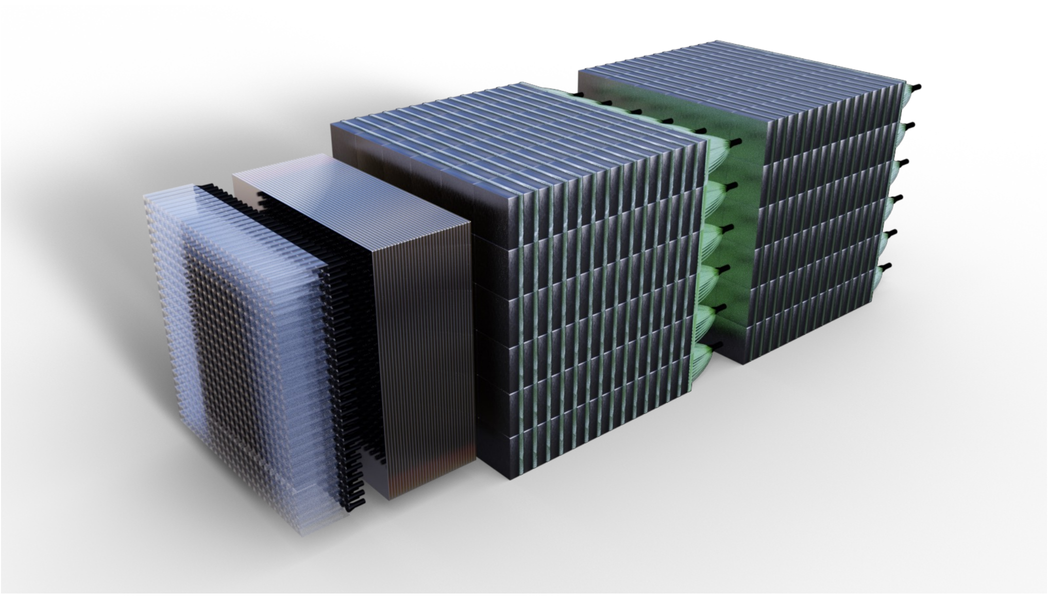




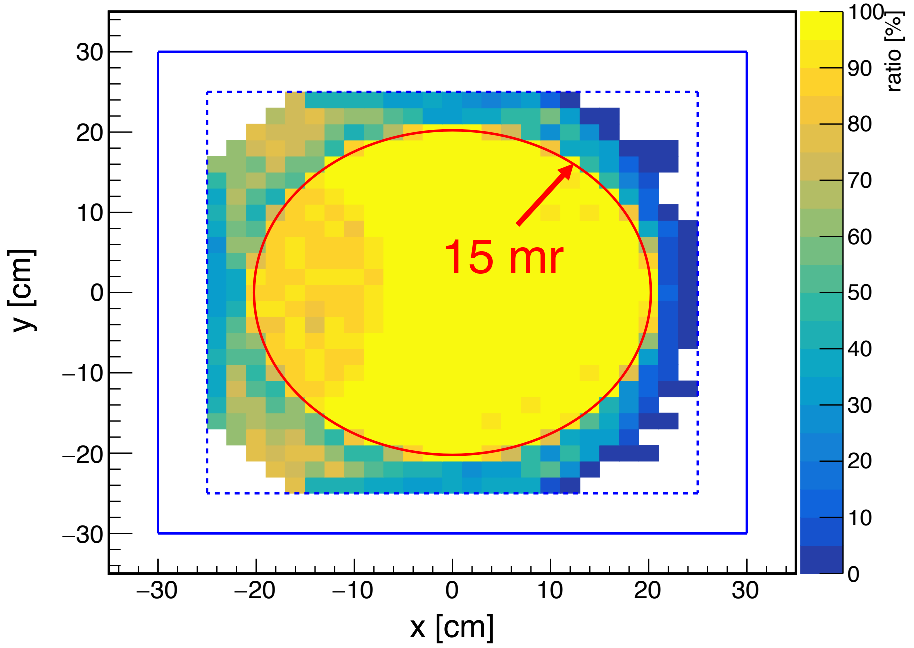
Neutron Detection for Pion FF and SF

- Main detector for neutron is ZDC:
  - 15 mrad acceptance around the ion beam
  - Nearly 100% accept rate for neutrons of interest
  - Energy resolution : 1.9% + 48.5%/sqrt(E [GeV])
  - Position resolution : 2.4 mr /sqrt(E [GeV])





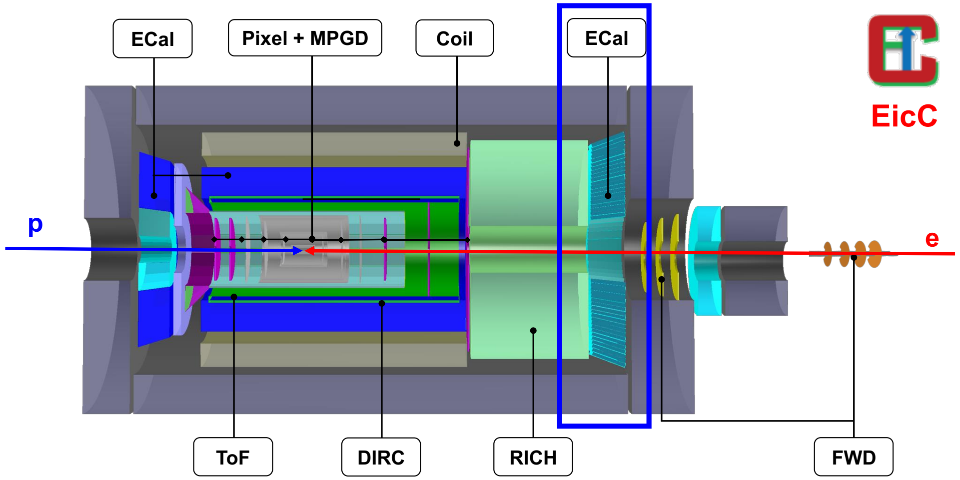
Accept/Throw Ratio for 15 GeV neutron

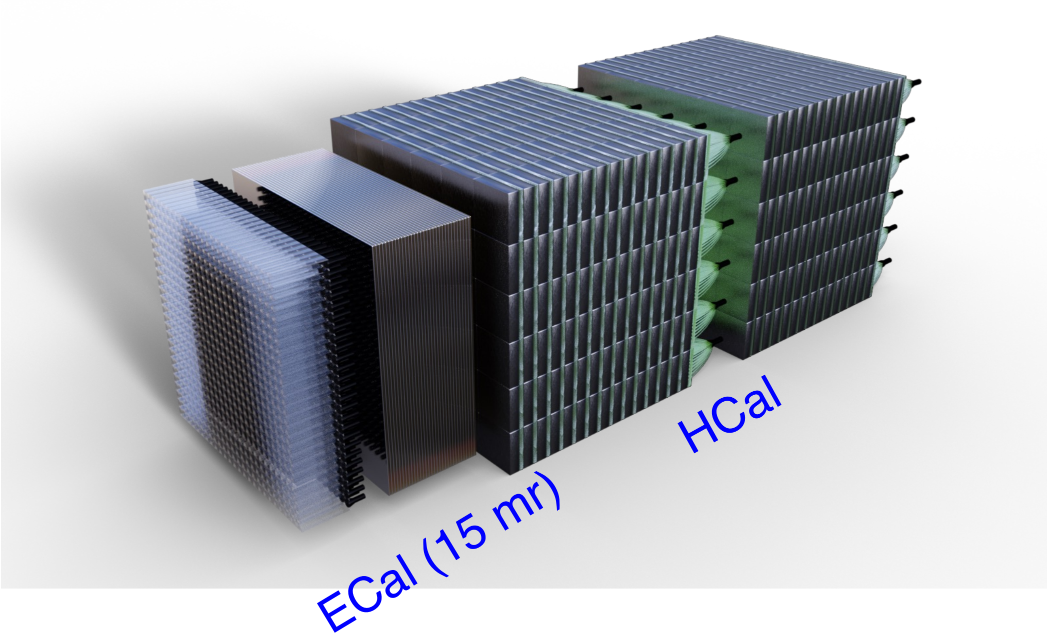


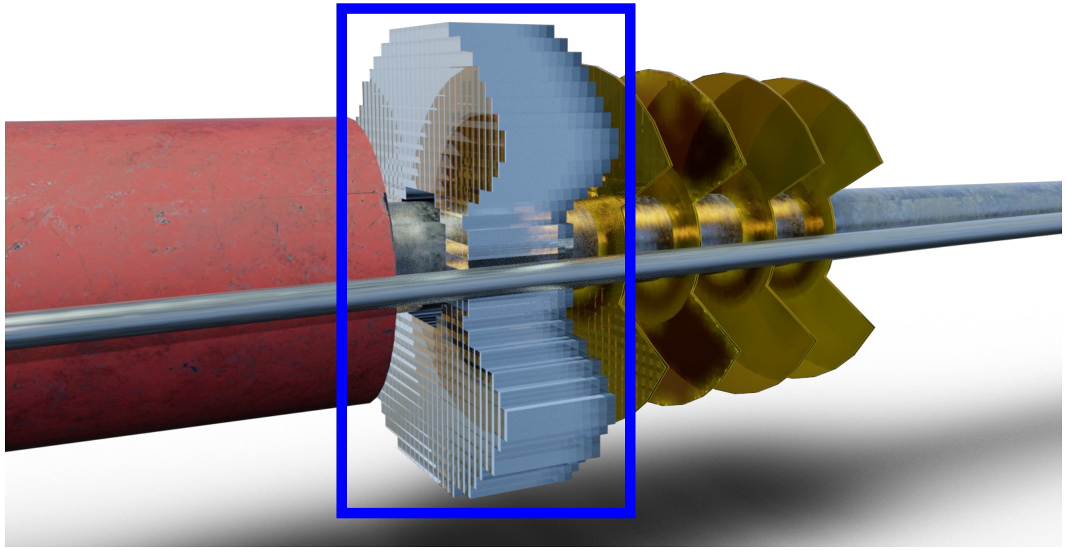
Λ Detection for Kion FF and SF (Neutral Channel)

- $\Lambda \to \pi^0 n$ with 36% branching ratio
- Neutrons only detected by ZDC (15 mr acceptance)
- Photons can be detected by ZDC, EDT-ECal and EMCal on central detector ion endcap

$\eta < 3$





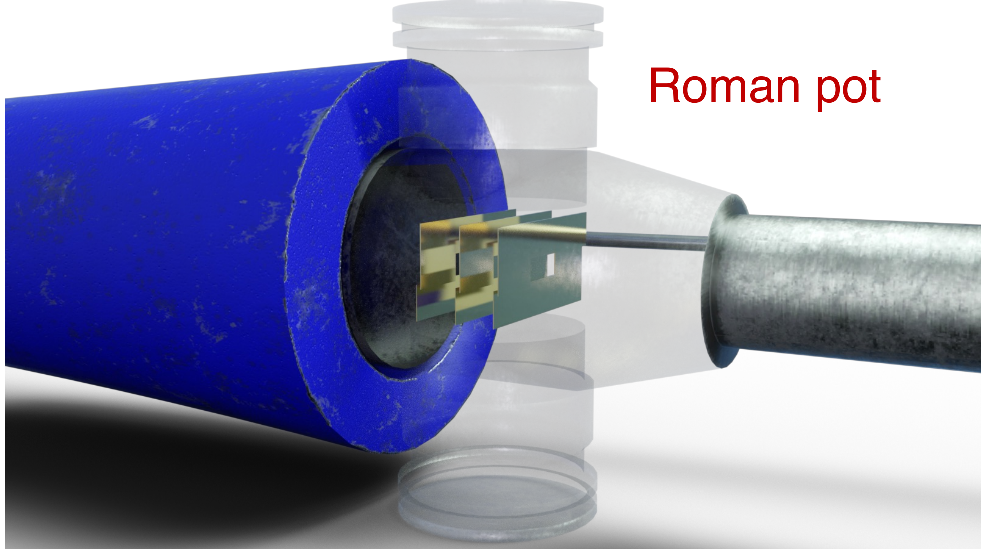


EDT-ECal (20-60 mr)

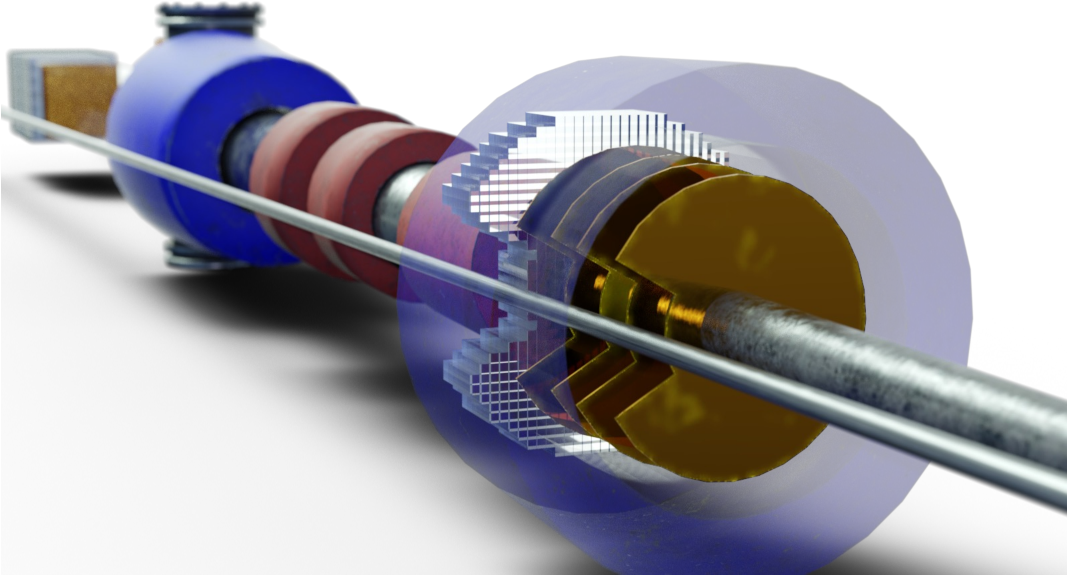
Λ Detection for Kion FF and SF (Charged Channel)

- $\boldsymbol{\Lambda \rightarrow \pi^- p}$ with 64% branching ratio
- π^- can only be detected by EDT (16 – 60 mr)
- Proton will be detected by EDT, Roman pots (~5-16mrad) as well as OMD

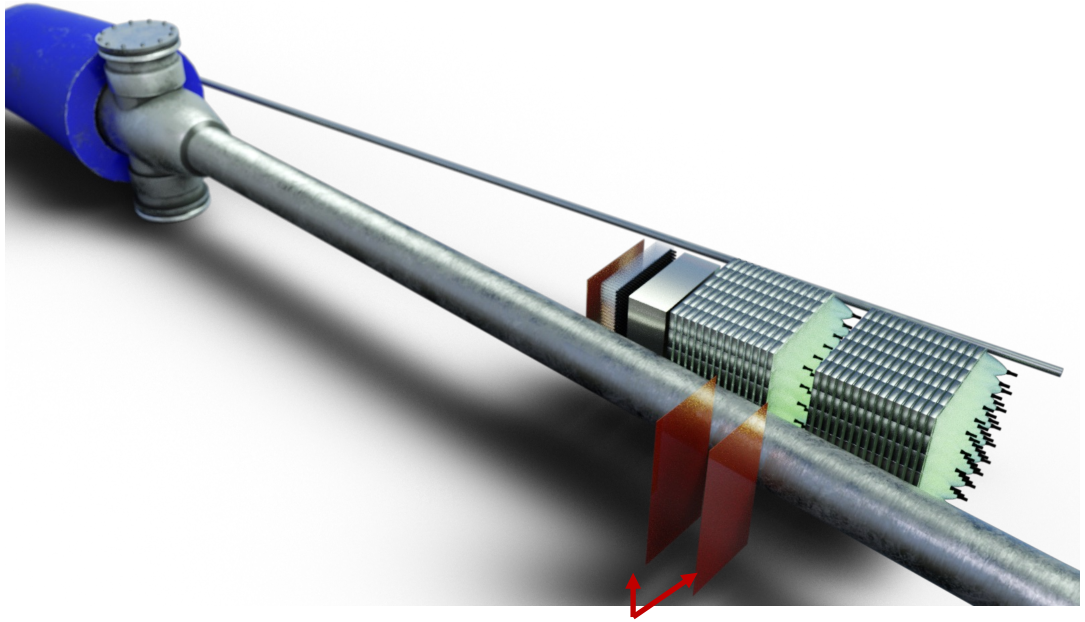
- EDT resolution: ~0.6% for p, 0.2mr for θ
- RP resolution: ~6.0% for p, 1.2mr for θ



Roman pot



EDT trackers

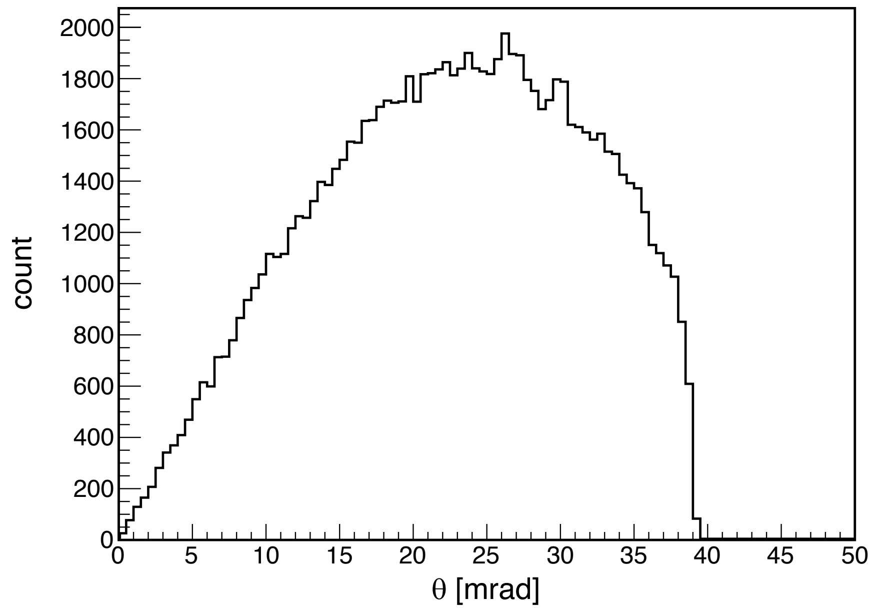


Off-momentum detectors

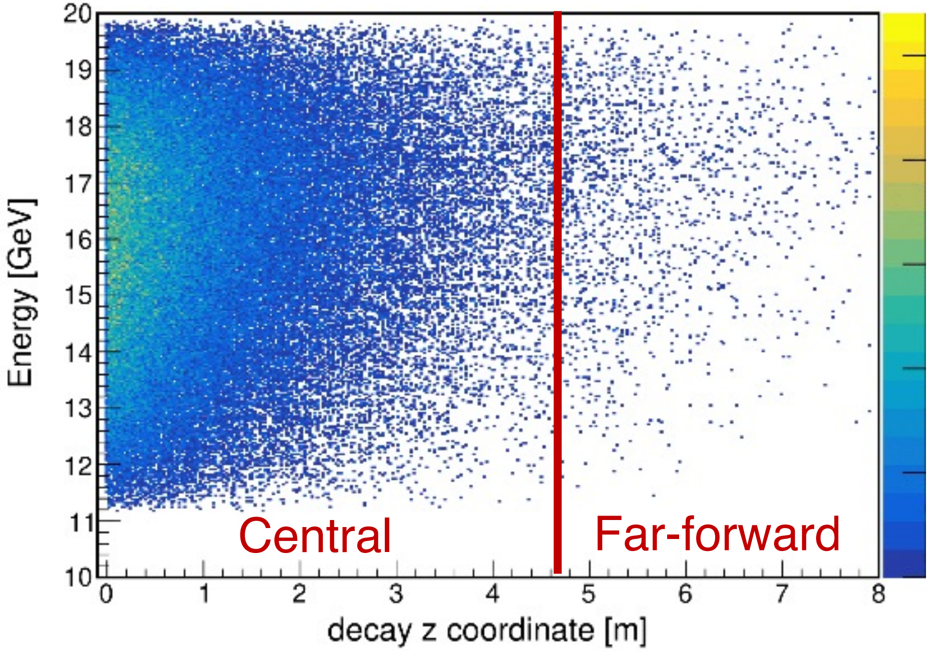
Forward Λ Detection

- Crucial for kaon form factor and structure-function study using Sullivan process: $ep \rightarrow e\Lambda K^+/X$
- Λs go mostly forward, as well as their decay products
- Potentially very good complementary to EIC kaon structure measurement
  - Most Λs decay before reaching far-forward region
  - Probably much better acceptance for charged decay channel

3.5 GeV e X 20 GeV p



Using R. Wang's generator

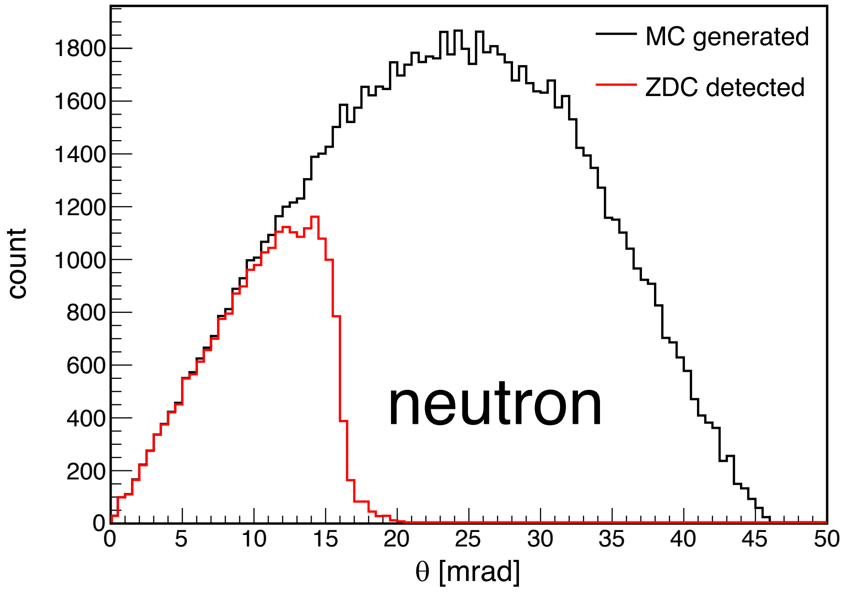


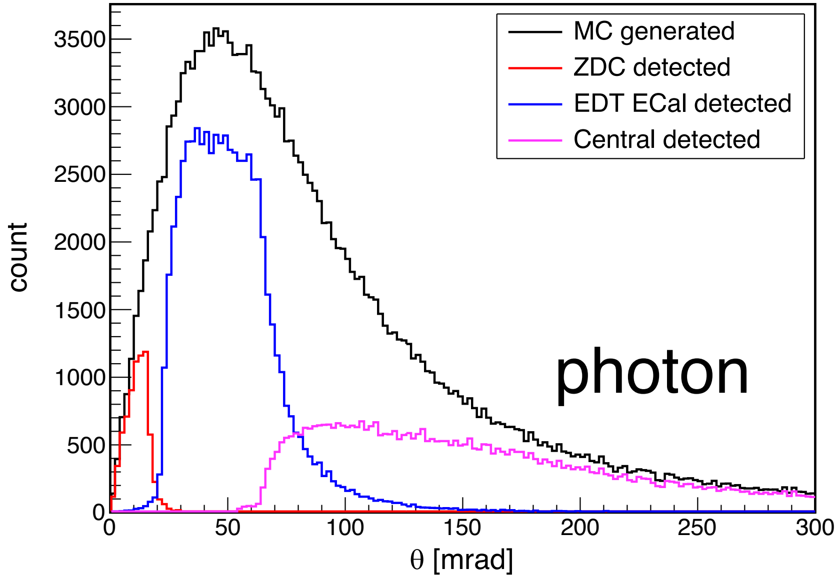
Forward Λ Detection

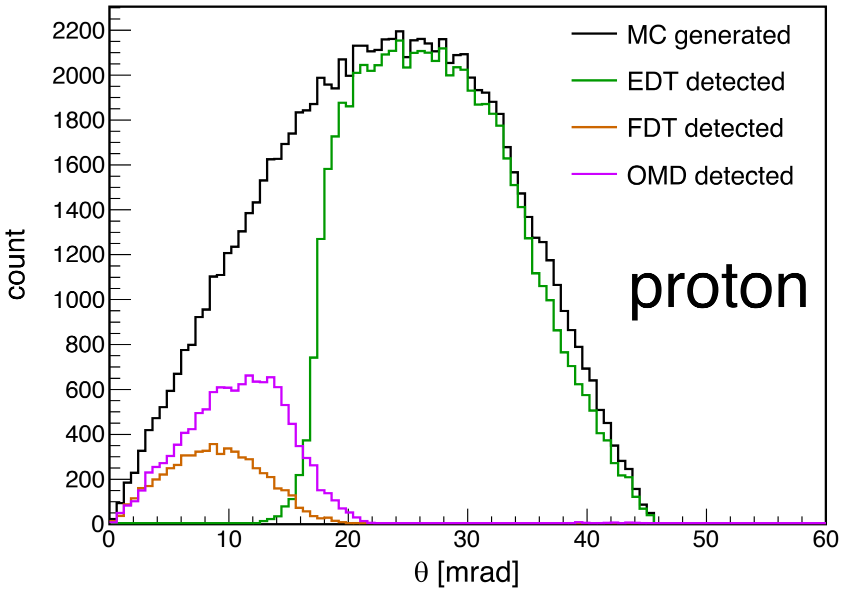
- Λs go mostly forward, as well as their decay products
  1. neutral channel: $\Lambda \to n\pi^0$, with BR 36%
  2. charged channel: $\Lambda \to p\pi^-$, with BR 64%

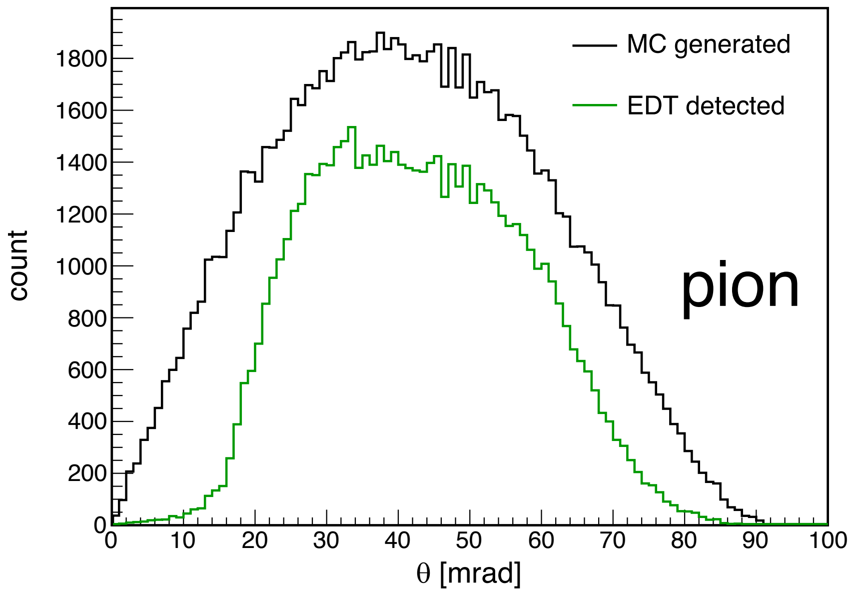
- Require all FF detectors work collectively

➢ overall efficiency: ~ 40%









Meson From Factor Extraction

- Generally, one can apply L-T separation (like JLab) and isolate σ_L, where the meson factors live

$$\sigma_L \propto F_\pi^2$$

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \epsilon \frac{d\sigma_\mathrm{L}}{dt} + \frac{d\sigma_\mathrm{T}}{dt} + \sqrt{2\epsilon(\epsilon+1)}\,\frac{d\sigma_\mathrm{LT}}{dt}\cos\phi + \epsilon\,\frac{d\sigma_\mathrm{TT}}{dt}\cos 2\phi.$$

- Measure two CS at same Q^2 and W, and solve for σ_L and σ_T

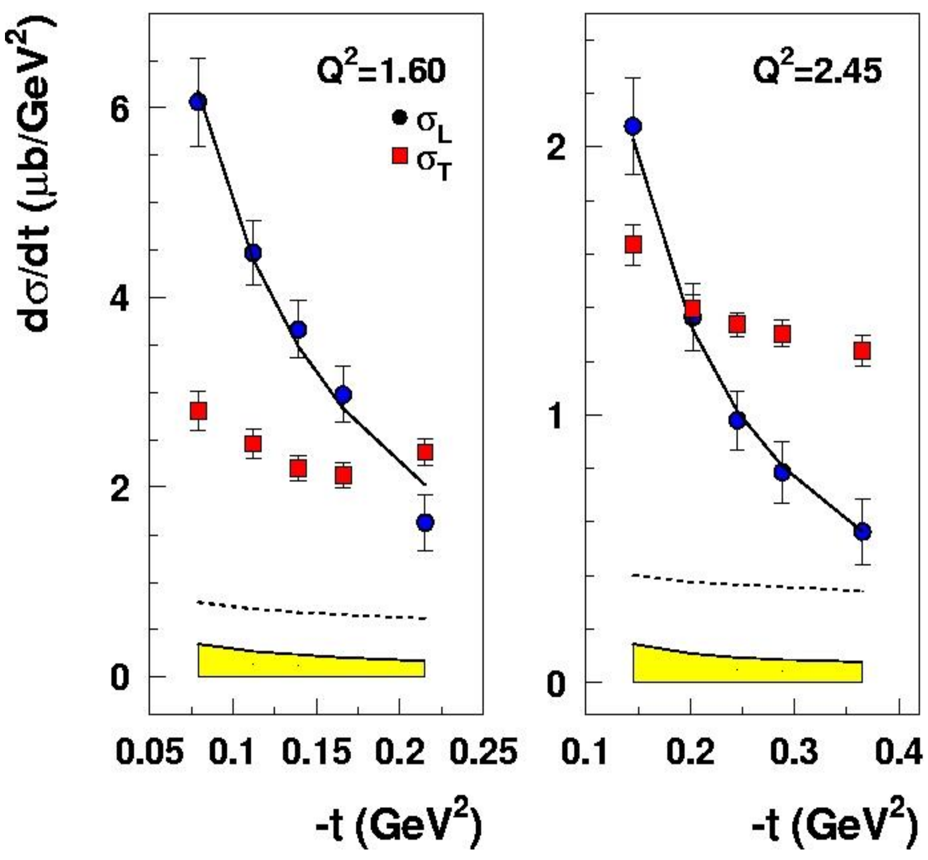
$$\left.\begin{aligned}\sigma_1 &= \sigma_T + \epsilon_1\sigma_L \\ \sigma_2 &= \sigma_T + \epsilon_2\sigma_L\end{aligned}\right\} \qquad \frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{(\epsilon_1-\epsilon_2)}\frac{1}{\sigma_L}\sqrt{\Delta\sigma_1^2 + \Delta\sigma_2^2}.$$

- *Δε* amplifies uncertainty, ideally need *Δε* > 0.2 (need small center-of-mass energy), difficult for EIC

- Alternatively, one may also use models to isolate σ_L (with additional uncertainties)

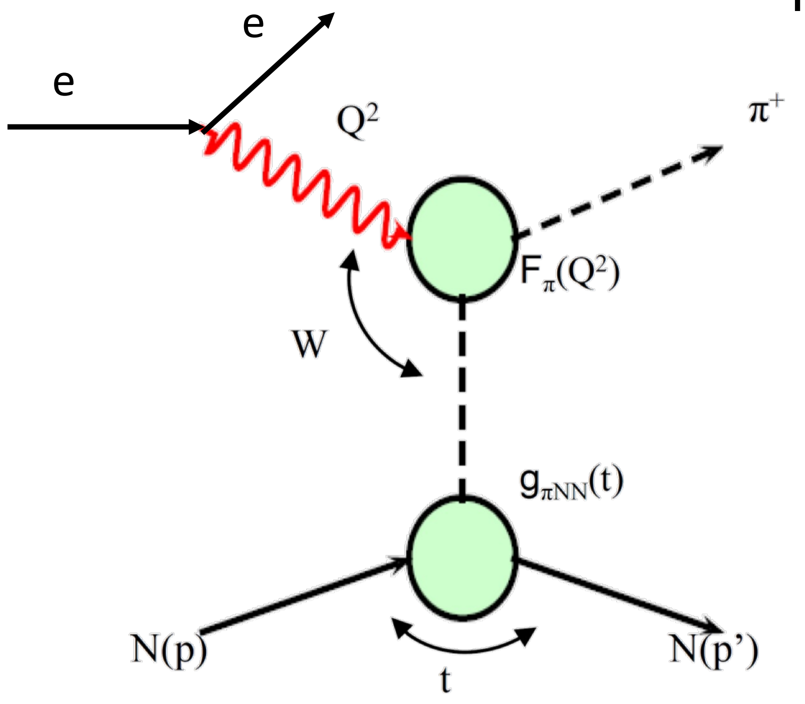
- L-T separation possible at EicC, but definitely not the entire kinematic region

*[Horn et al., PRL **97**, (2006) 192001]*



Event Generator for Pion FF

To write an event generator and to estimate the statistics, we adapt the π-pole model for the differential cross-section:



Pion form factor measurement

$$\frac{d^3\sigma}{dQ^2 dx_B dt} = \Gamma(Q^2, x_B, s)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right]$$

$$\Gamma(Q^2, x_B, s) = \frac{\alpha y^2(1-x_B)}{2\pi x_B(1-\epsilon)Q^2}$$

$$\epsilon = \frac{1 - y - \frac{Q^2}{4E^2}}{1 - y + \frac{y^2}{2} + \frac{Q^2}{4E^4}}$$

$$N\frac{d\sigma_L}{dt} = 4\hbar c(eg_{\pi NN}(t))^2 \boxed{\frac{-t}{(t-m_\pi^2)^2} Q^2 F_\pi^2(Q^2)}$$

Pion pole and pion form factor

$$N = 32\pi(W^2 - m_p^2)\sqrt{(W^2 - m_p^2)^2 + Q^4 + 2Q^2(W^2 + m_p^2)}$$

$$g_{\pi NN}(t) = g_{\pi NN}(m_\pi^2)\left(\frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - t}\right)$$

$$F_\pi(Q^2) = \frac{1}{1 + Q^2/\Lambda_\pi^2}$$

Previous pion FF projection study done by Rong Wong from IMP

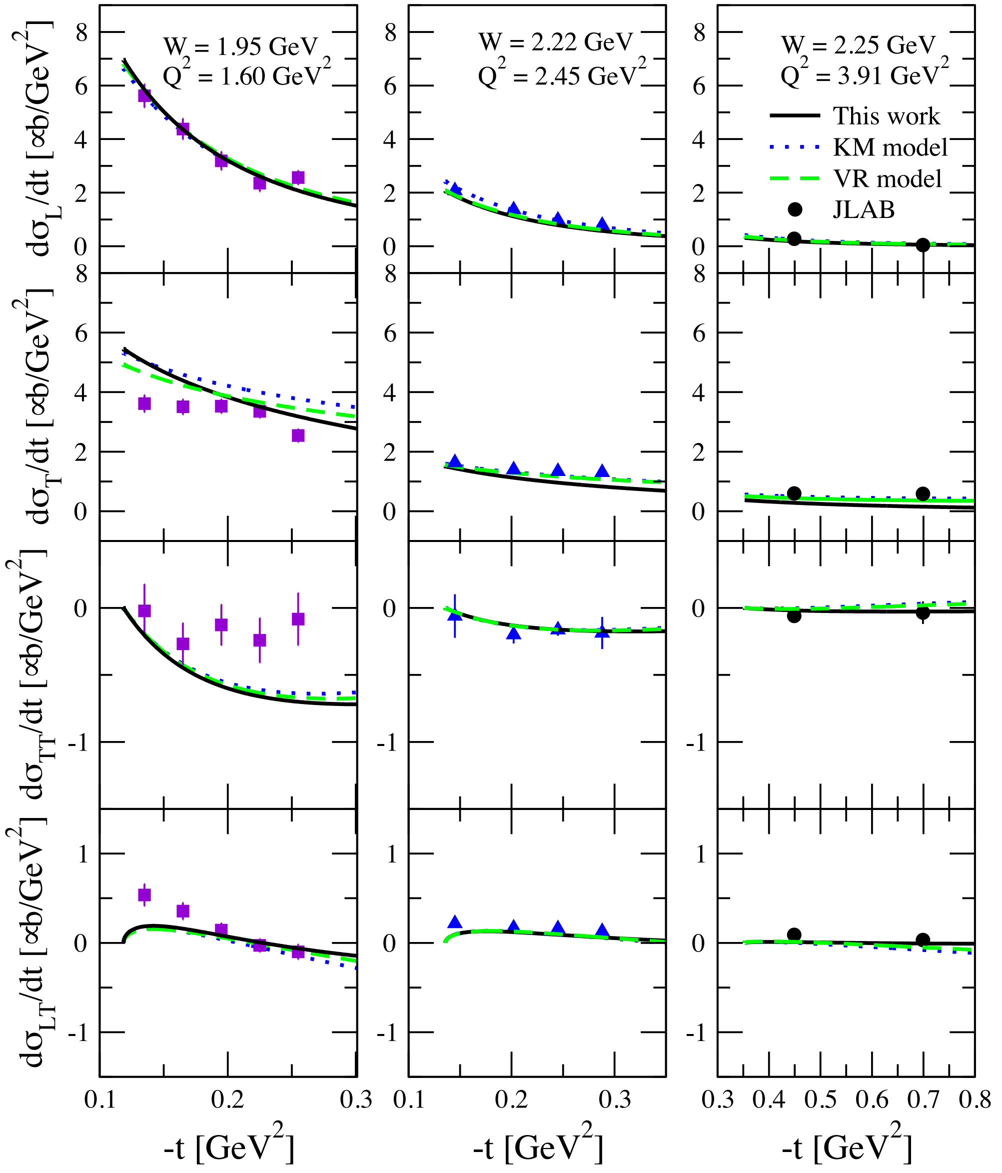
Event Generator for Pion FF

- Use DEMPgen for EIC (arXiv2403.06000)
  1. Regge-based p(e,e’π+)n model of T.K. Choi, K.J. Kong, B.G. Yu (CKY)
     (*J. Korean Phys. Soc.* 67 (2015) 7, 1089-1094)

- Encounter some issues with the generator at lower energies

- Developmental group (Prof. G. Huber, L. Preet, S. Kay and W. Li) been very helpful and provided fixes very quickly

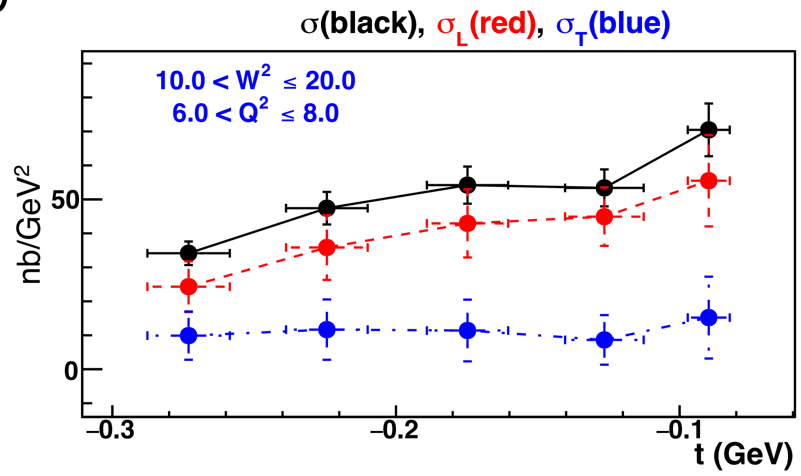
(*J. Korean Phys. Soc.* 67 (2015) 7, 1089-1094)

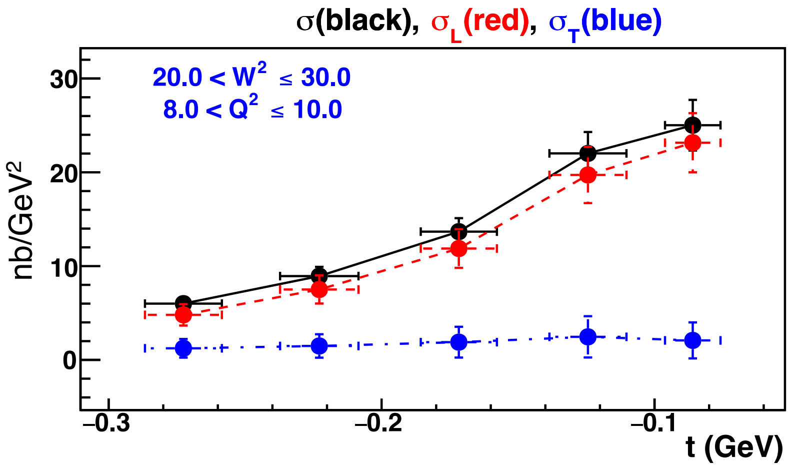


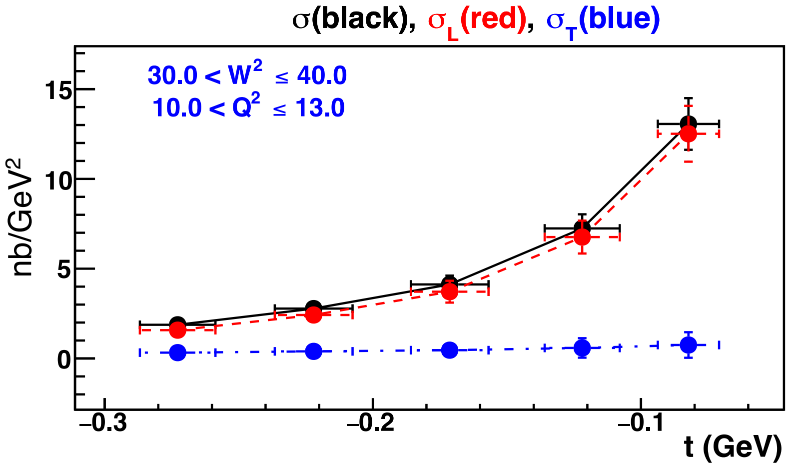
Pion FF Projections

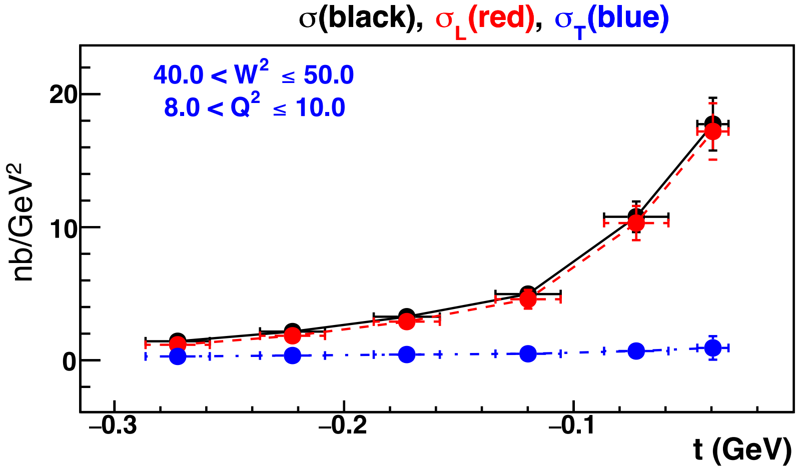
- In hard scattering regime, QCD scaling predicts $\sigma_L \propto Q^{-6}$, $\sigma_T \propto Q^{-8}$
- CKY model also predict $\sigma_L \gg \sigma_T$ at high enough Q^2 and W^2
- At the moment, assume conservatively 100% uncertainty in $R = \sigma_T / \sigma_L$ from model subtraction
- In reality, uncertainty of R maybe better controlled by board kinematic coverage and π^-/π^+ measurement from eD

$$R = \frac{\sigma[n(e, e'\pi^- p)]}{\sigma[p(e, e'\pi^+ n)]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$





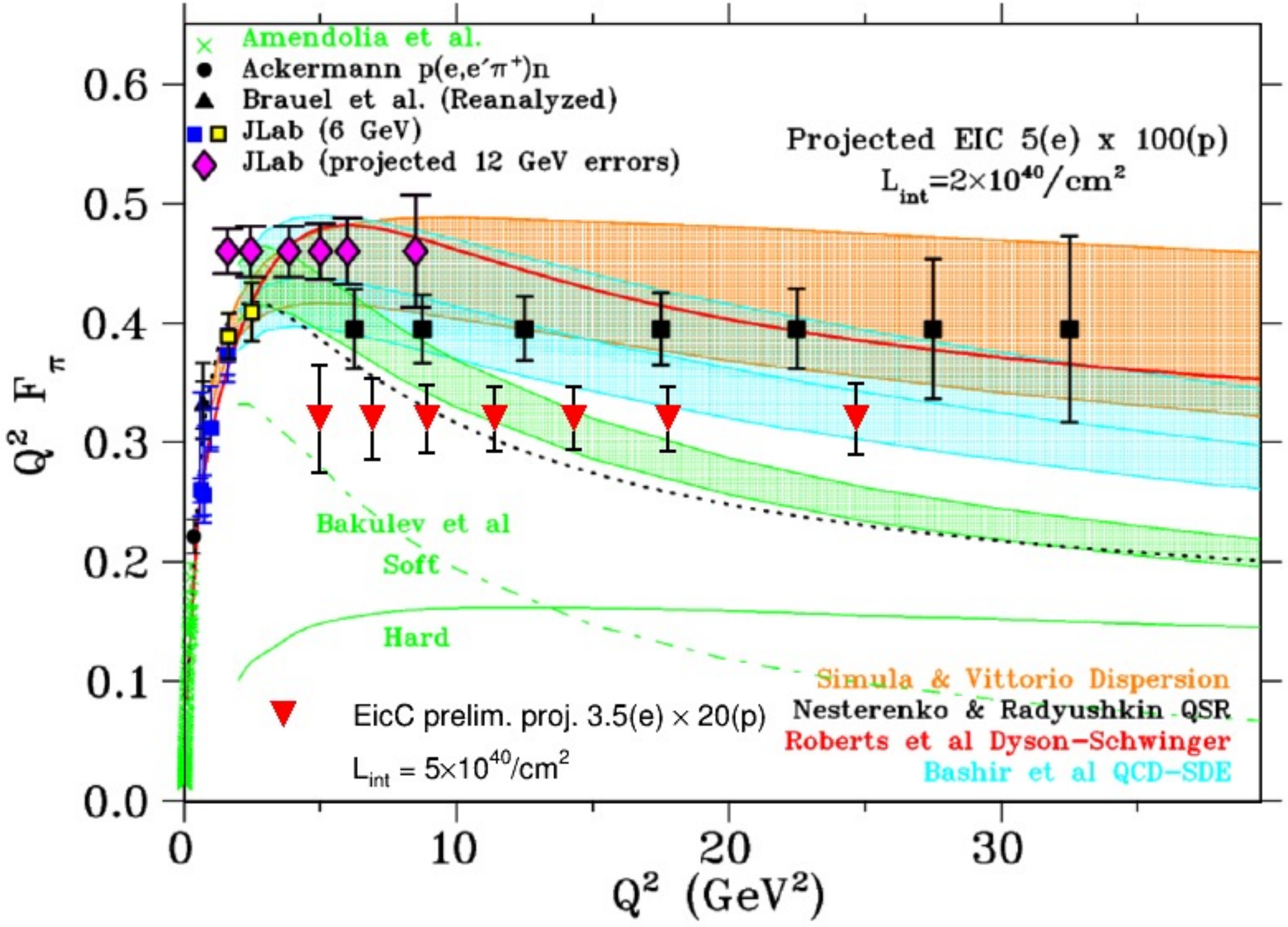




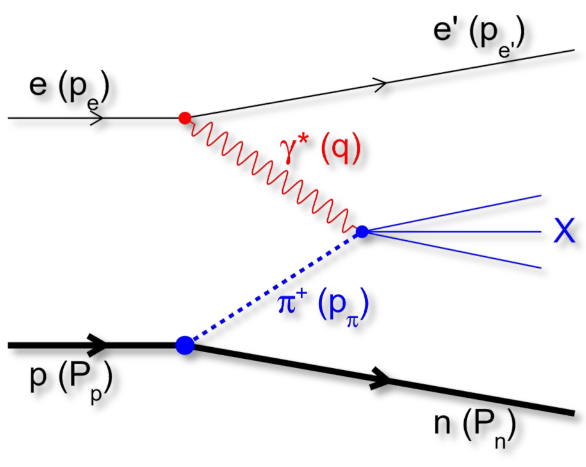
Pion FF Projections

- energy setting: 3.5 GeV e x 20 GeV p
- Integrated luminosity: 50 fb^{-1}
- Include full detector acceptance
- 100% uncertainty in $R = \sigma_T / \sigma_L$ from model subtraction
- 2.5% point-to-point syst. uncertainty
  12% scaling syst. uncertainty
- Projection for kaon FF on-going, have DEMPgen and CKY model to kaon

arXiv2403.06000



Event Generator for Pion SF



leading neutron of large rapidity

$$Q^2 \equiv -q^2, \quad x_B \equiv \frac{Q^2}{2P_p \cdot q}, \quad y \equiv \frac{P_p \cdot q}{P_p \cdot P_e}$$

$$x_L \equiv \frac{P_n \cdot q}{P_p \cdot q}, \; t \equiv (P_p - P_n)^2 = p_{\pi^*}^2 \quad x_\pi \equiv \frac{Q^2}{2p_\pi \cdot q} = \frac{x_B}{1-x_L}$$

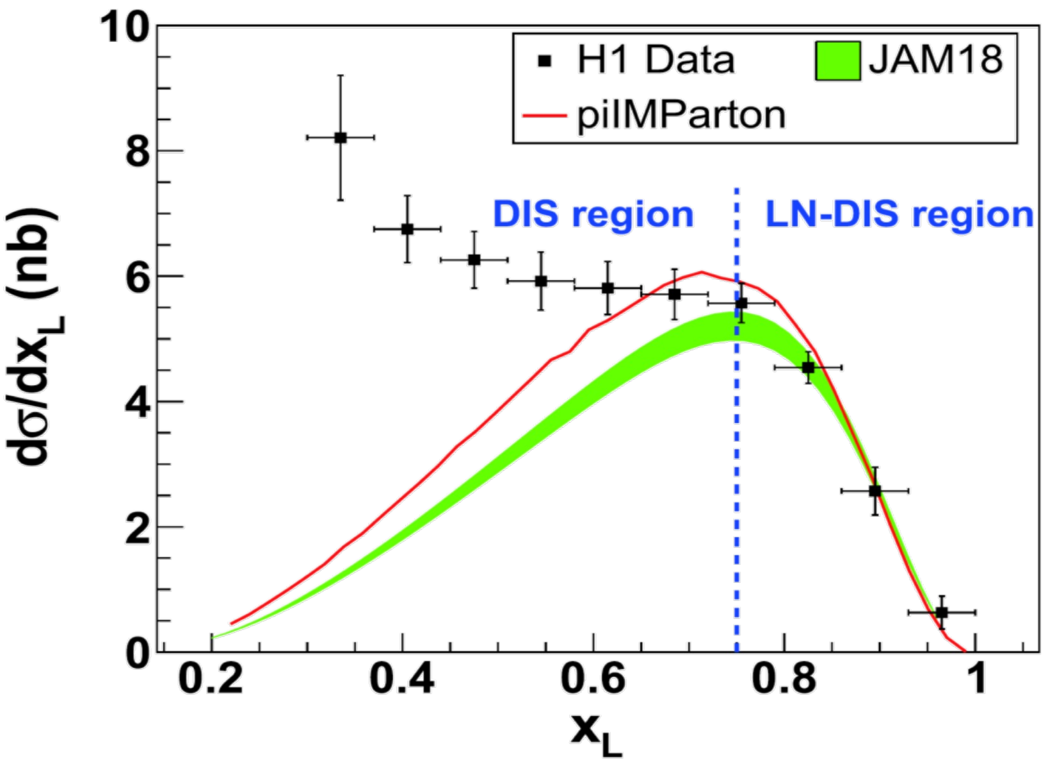
$$\frac{d^4\sigma(ep \to enX)}{dx_B dQ^2 dx_L dt} = \frac{4\pi\alpha^2}{x_B Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LN(4)}(Q^2, x_B, x_L, t)$$

$$= \frac{4\pi\alpha^2}{x_B Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{\pi}\left(\frac{x_B}{1-x_L}, Q^2\right) f_{\pi^+/p}(x_L, t)$$

pion flux

pion SF

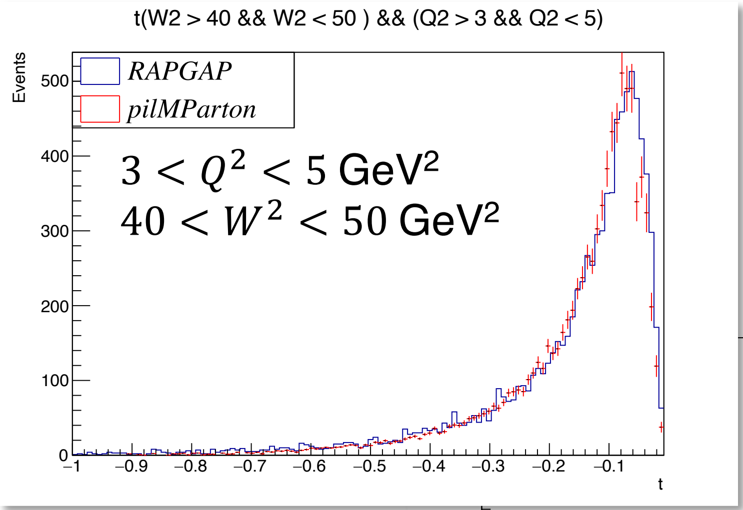
G. Xie et al., Chin. Phys. C 45, 053002 (2021)

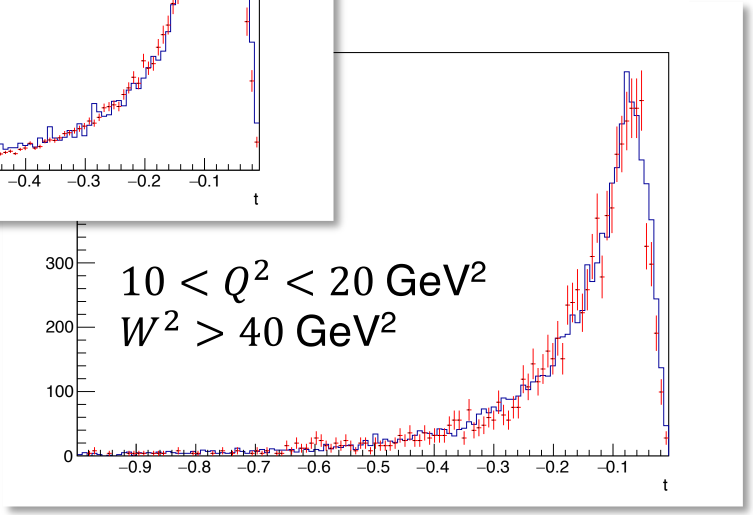


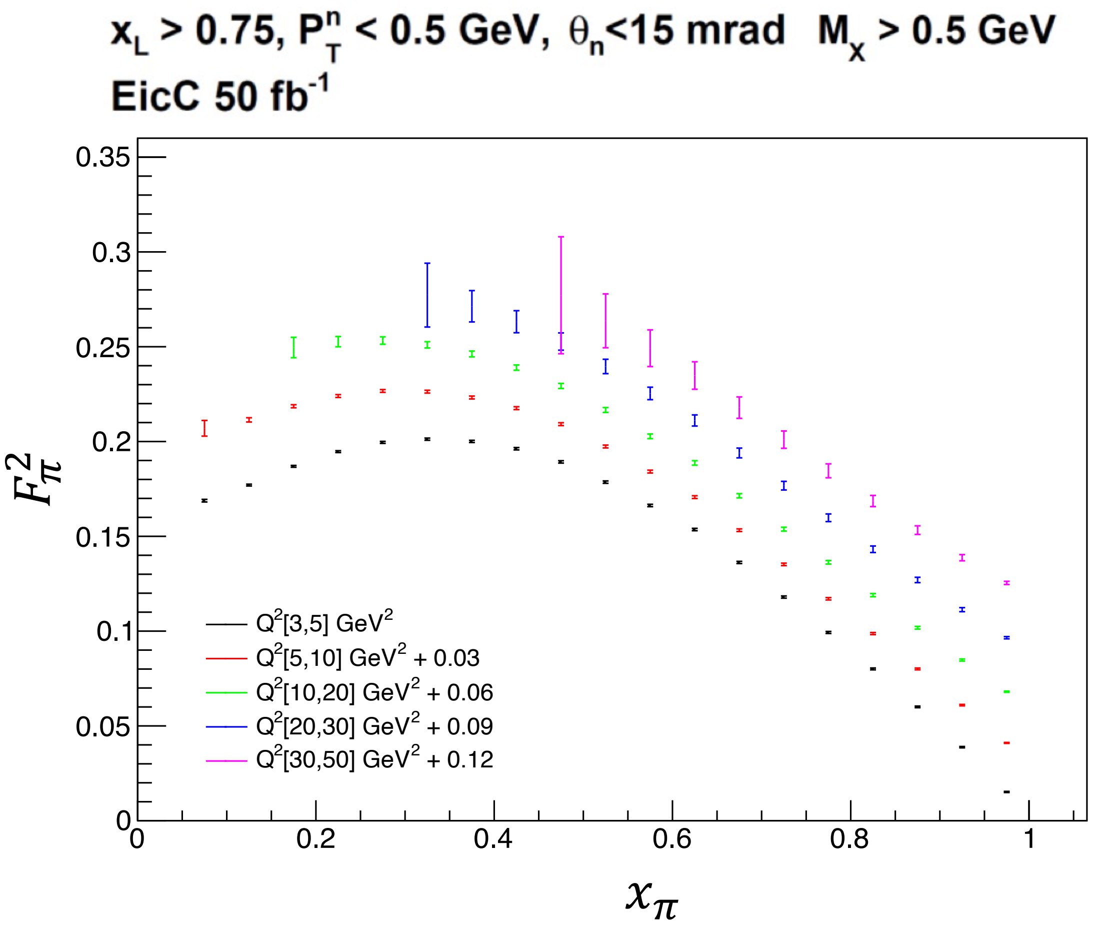
Pion SF generator developed by Rong Wong from IMP, based on the piIMParton model

Pion Structure Function Projection

- Comparisons with RAPGAP generator (provided by Jixie Zhang), reasonable agreement over a board range





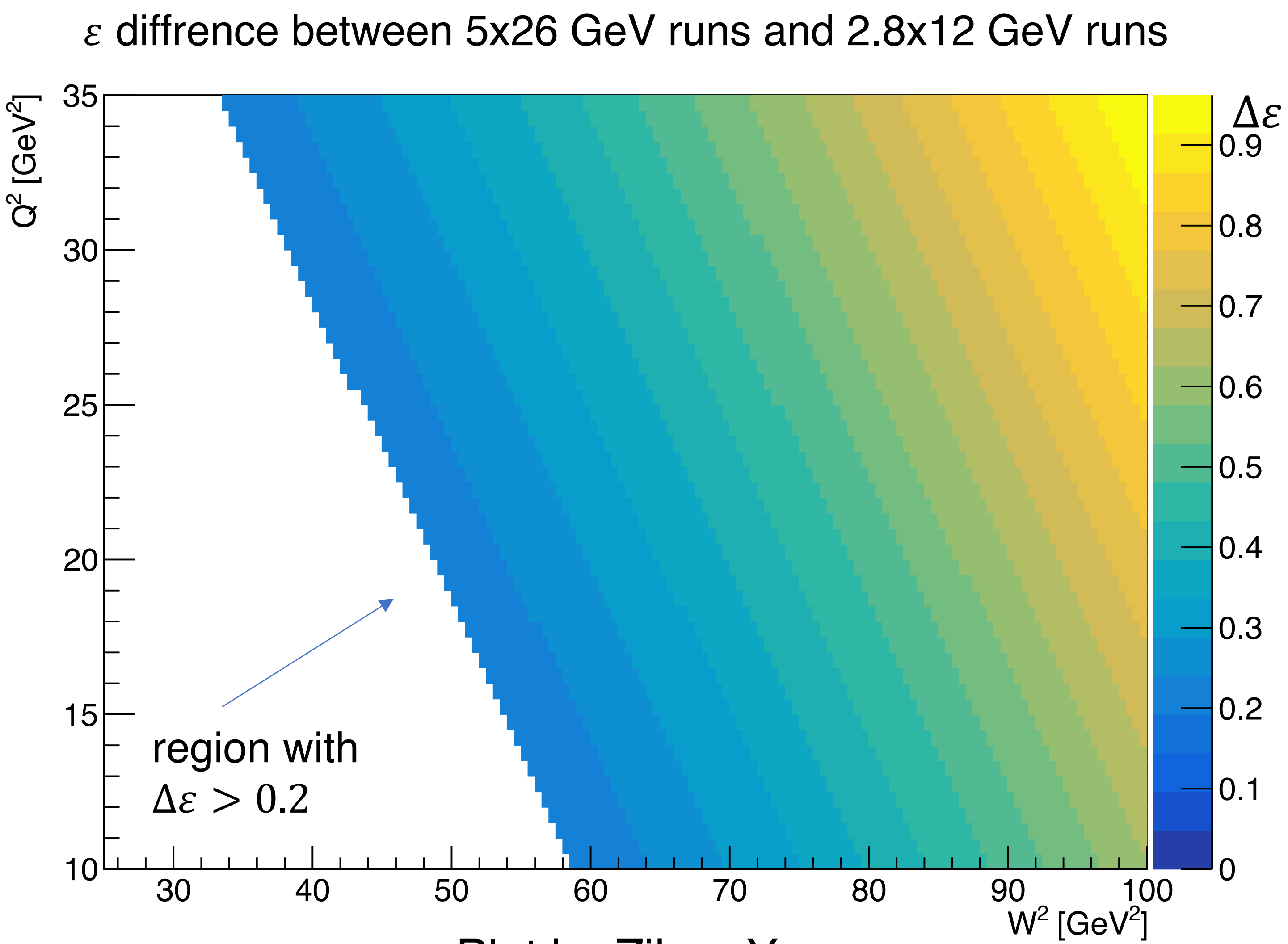


Stat. uncertainty only
detailed systematic studies ongoing
Study by Ting Lin

Possibility of L-T Separation with EicC

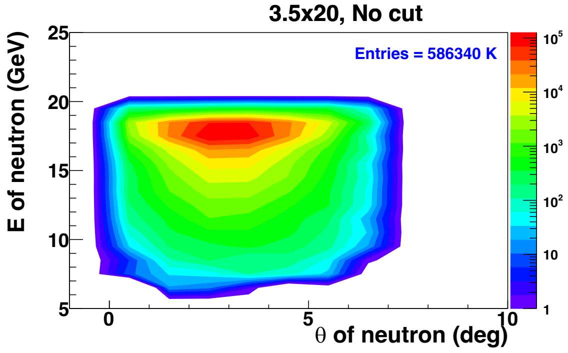
- Have large area with $\Delta\varepsilon$ close or larger than 0.2
- $\Delta\varepsilon$ increase at higher Q^2 and higher W
- Typical event rates drop at higher Q^2 and higher W

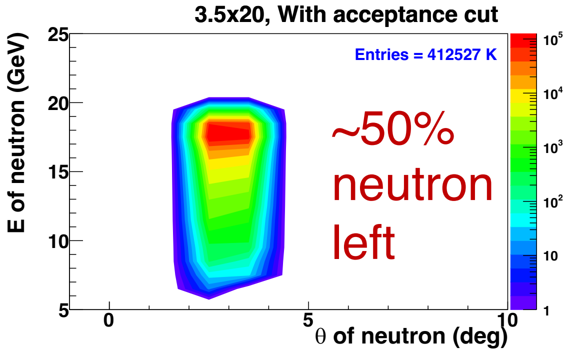
Need accurate event rate estimation to draw a definite conclusion, work in progress

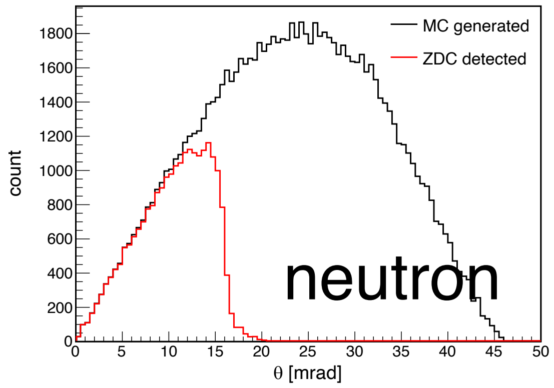


Plot by Zihan Yu

Additional Improvement to Think About

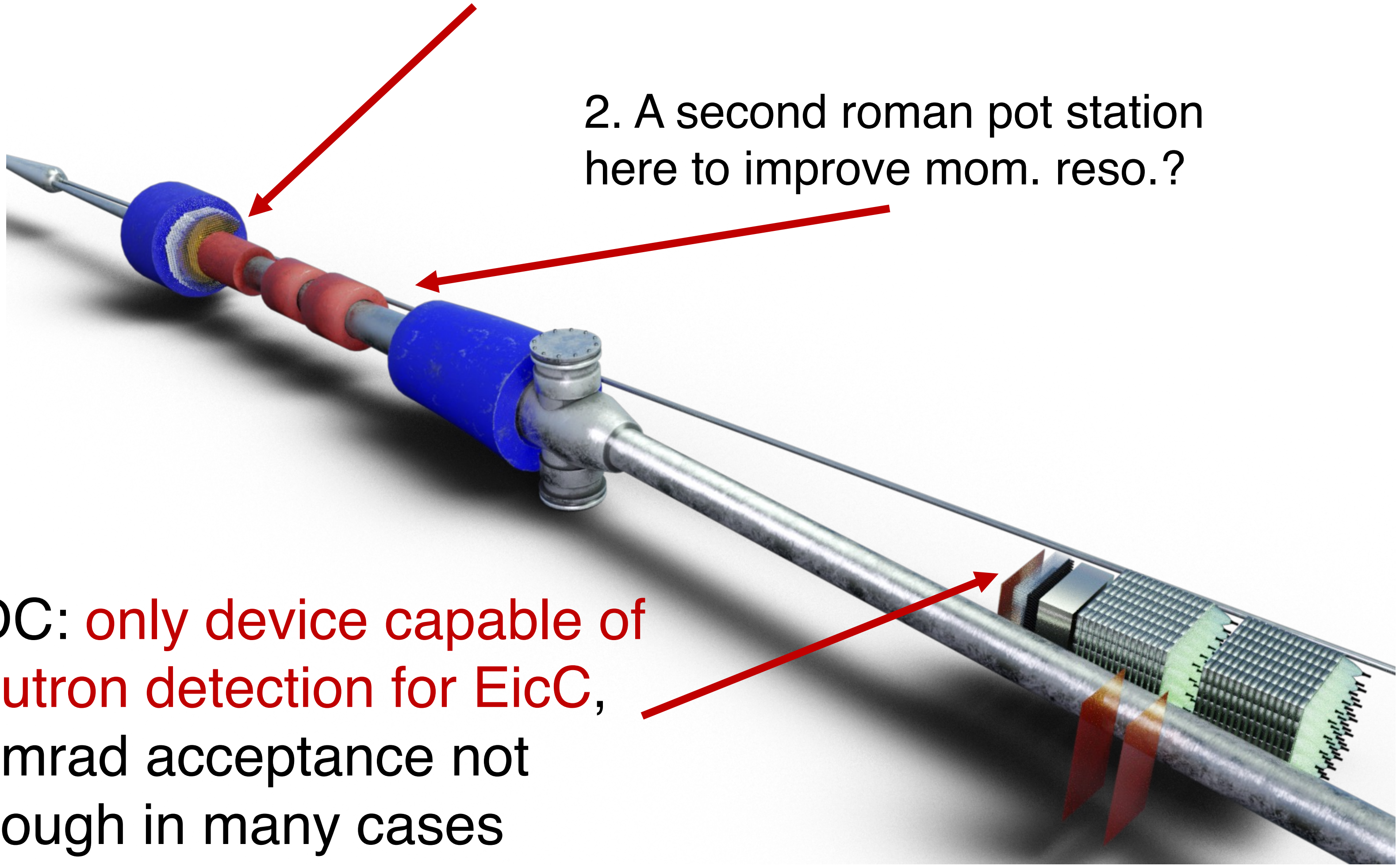






1. Additional compact HCal after the EDT?

2. A second roman pot station here to improve mom. reso.?

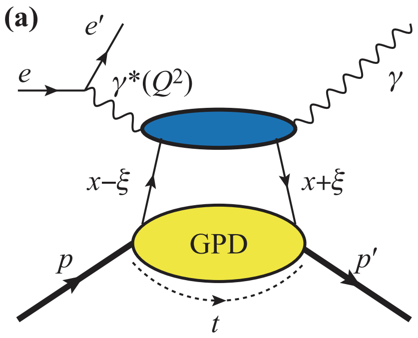


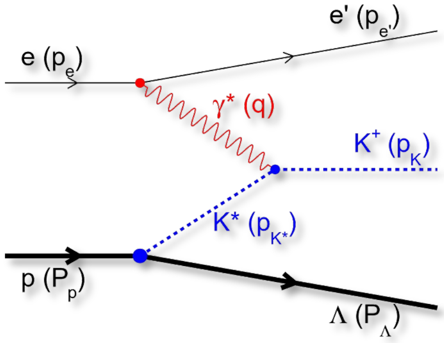
ZDC: only device capable of neutron detection for EicC, 15mrad acceptance not enough in many cases

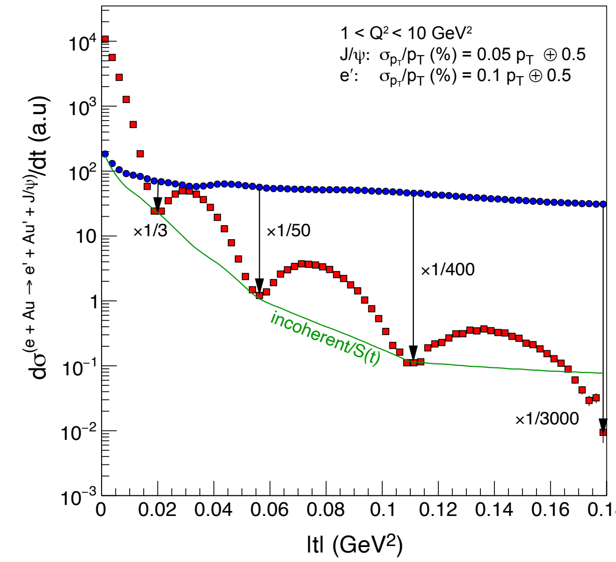
Working iteratively with the accelerator folks on these improvements

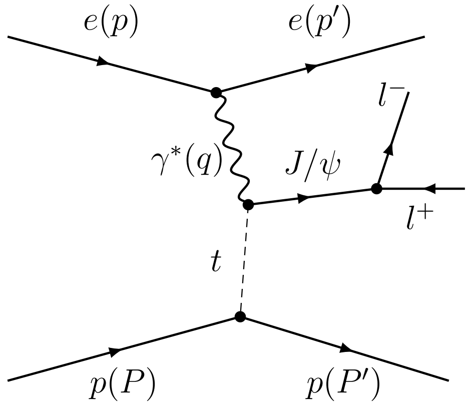
Many Other Interesting Exclusive Physics

- Deeply virtual Compton scattering (DVCS)
- Exotic states: X 3872, Zc 3900…
- Meson form factor, structure functions, GPD…
- Diffractive measurements
- Spectator tagging for tagged DIS, SIDIS, SRC…
- J/ψ production near threshold
- …









Summary

- Meson structure: ideal test ground for many physics production, essential for checking EHM
- EicC offers a unique and complemetary meson structure program to JLab and EIC
  - CM energy ~16.7 GeV, in between JLab and EIC
- Full simulation for EicC central and far-forward detectors
- Preliminary pion FF projection obtained with the EicC, working actively on pion SF and kaon structure measurements
  - Aiming to have projections for all by end of July
  - Aiming for publication by end of the year
- Special thanks to Prof. Huber, Prof. Horn and Prof. Roberts for many helpful discussions