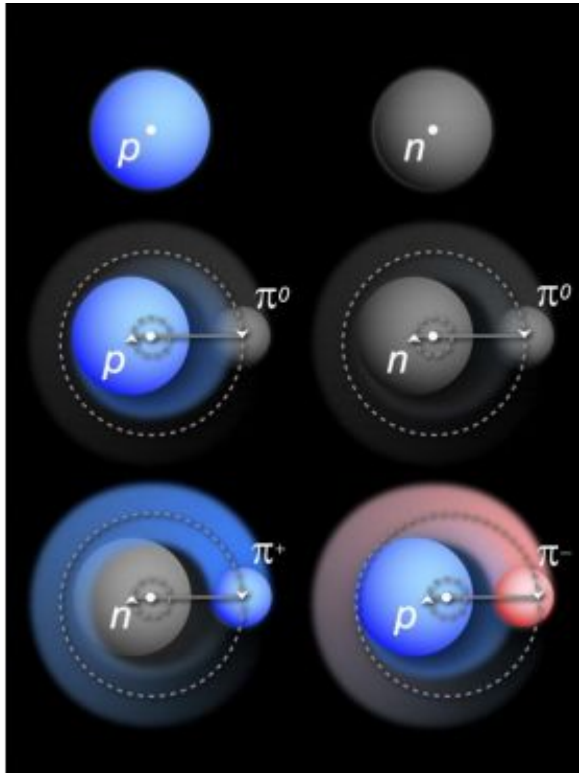


Meson Structure Program at EicC

Weizhi Xiong

Shandong University

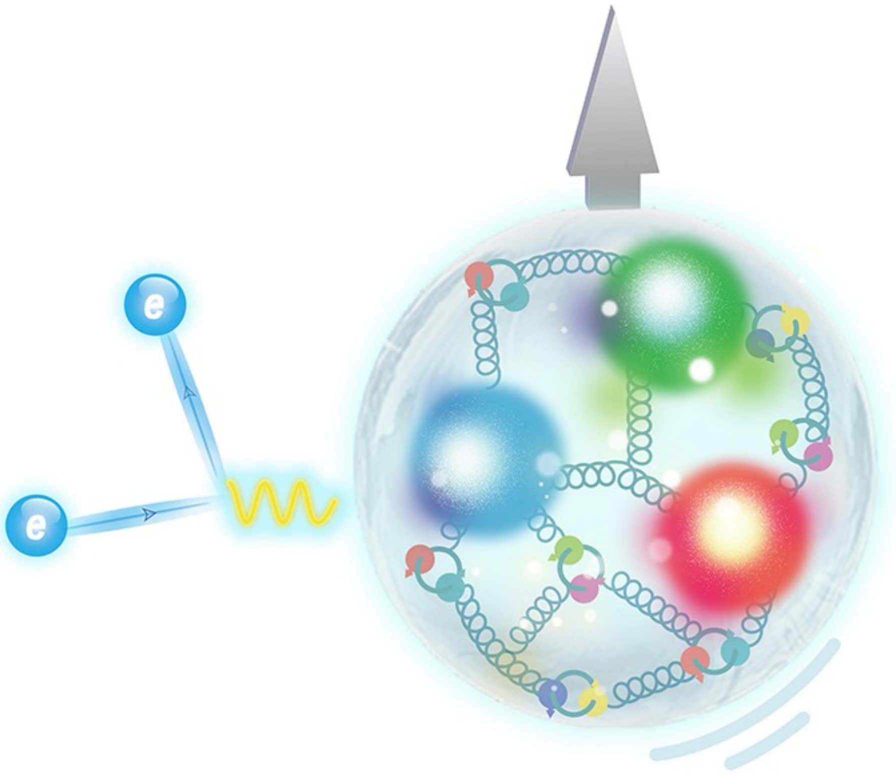
On Behalf of the EicC Exclusive Physics Working Group

EicC 8th CDR Meeting

Aug. 17th – 20th 2024

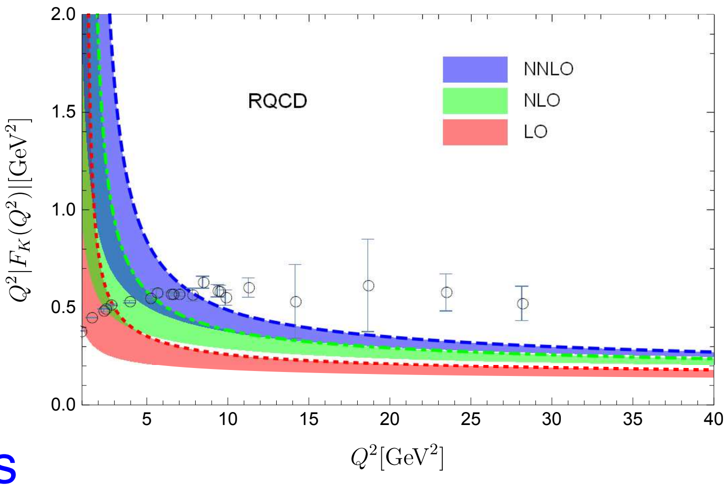
Outline

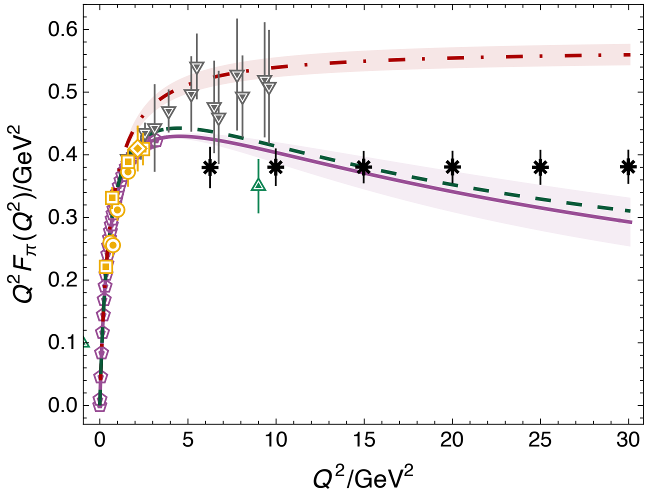
- Introduction
- Meson structure program at EicC
- Strength and complementarity of EicC
- Summary



Physics Motivation

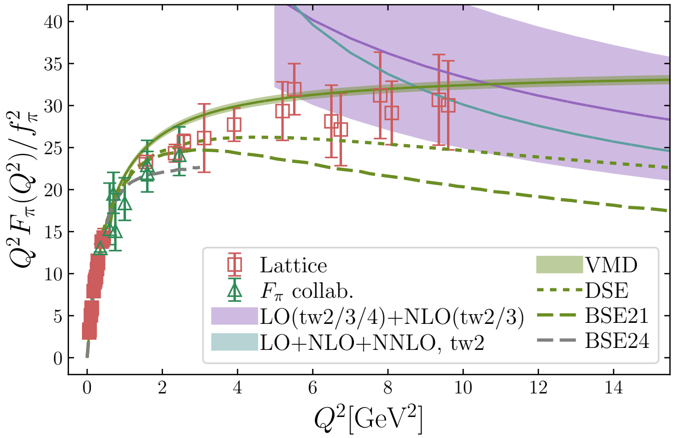
- π/K form factors and structure functions are of special interests in hadron structure physics
  - ➢ pion: lightest QCD quark system
  - ➢ kaon: replaces one light quark with a heavier strange quark
  - ➢ Both are Nambu-Goldstone bosons

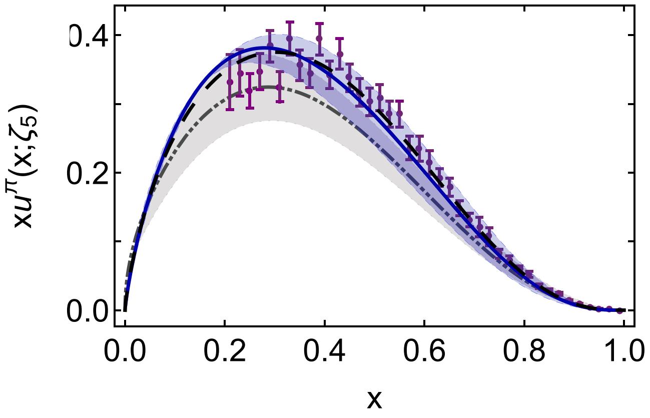




- A simpler problem in QFT than that associated with the nucleon

- Important test ground for many theoritical preditions: Lattice QCD, Dyson-Schiwinger method and many more



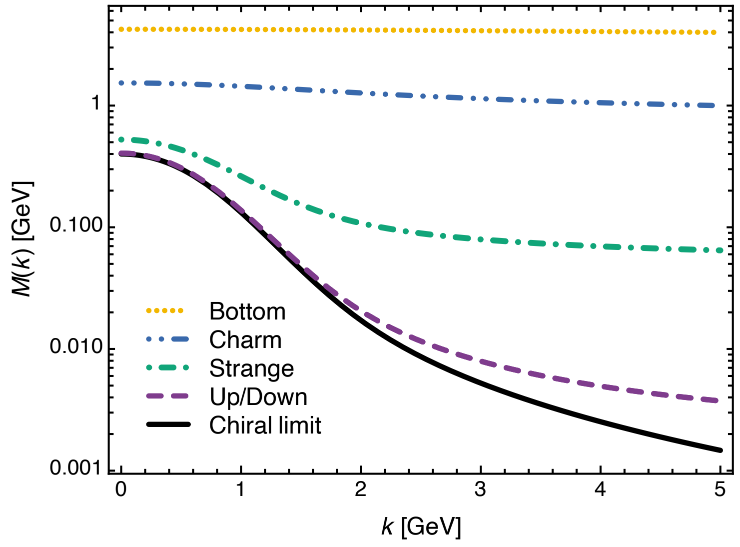


L. Chen, W. Chen, F. Feng, Y. Jia arXiv:2407.21120
Z. Q. Yao, D. Binosi and C. D. Roberts, PLB 855, 138823 (2024)
H. T. Ding et al. arXiv:2404.04412
Z.-F. Cui et al., Eur. Phys. J. C 80, 1064 (2020)

Physics Motivation

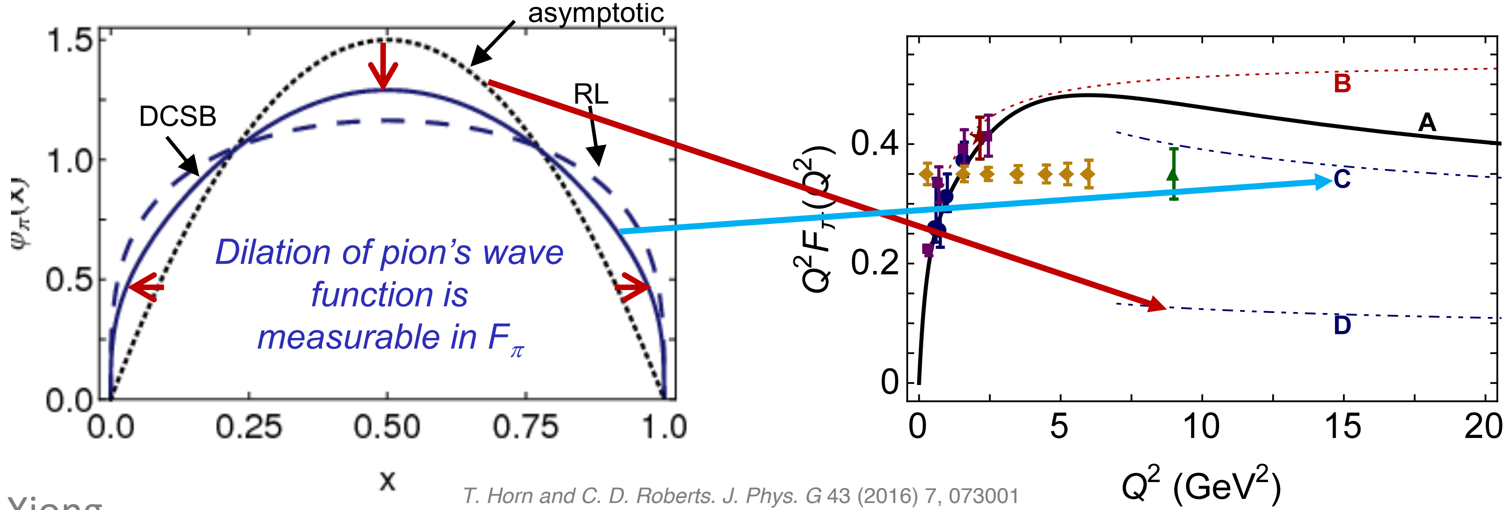
- Important in checking the Emergent Hadron Mass (EHM) mechanism and the interplay between EHM and Higgs Boson mechanism
- Gain unique insight on EHM through meson form factor (FF) and structure functions (SF)

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



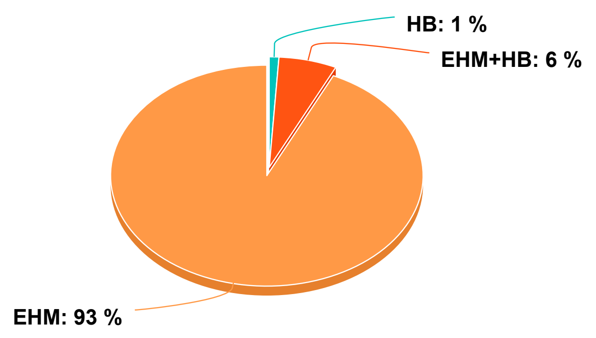
Parton distribution amplitude (PDA)

Pion electromagnetic form factor

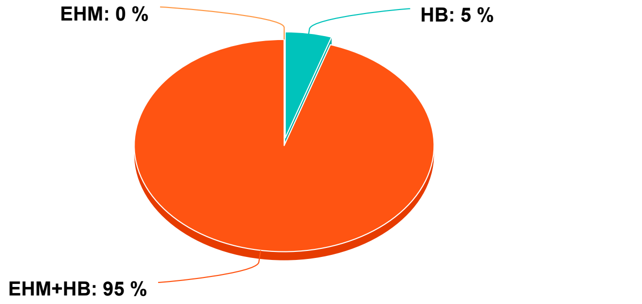


T. Horn and C. D. Roberts. J. Phys. G 43 (2016) 7, 073001
L. Chang et al. *Phys. Rev. Lett.* 111 (2013) 14, 141802

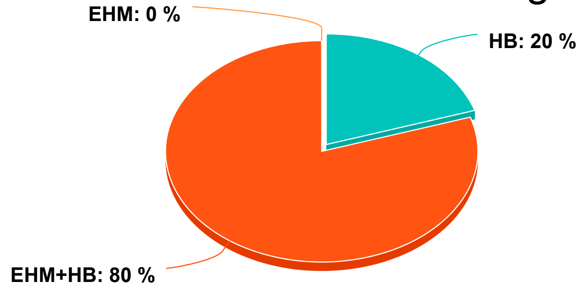
Proton mass budget



Pion mass budget



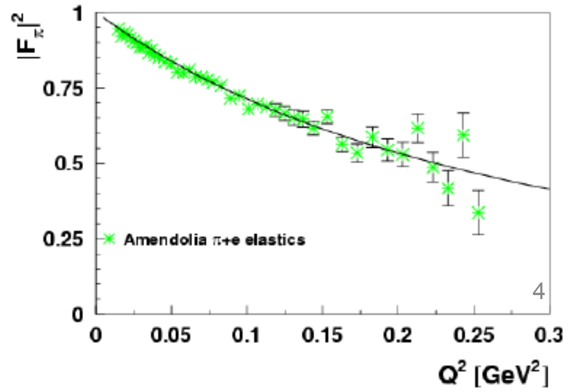
Kaon mass budget



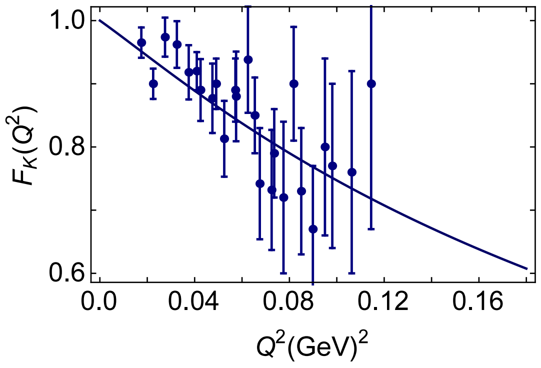
Accessing Meson Structure – Elastic Scat. and Drell-Yan

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_π = 0.657 ± 0.012 fm
  - r_K = 0.560 ± 0.031 fm



Amendolia et al, NPB277,168 (1986)



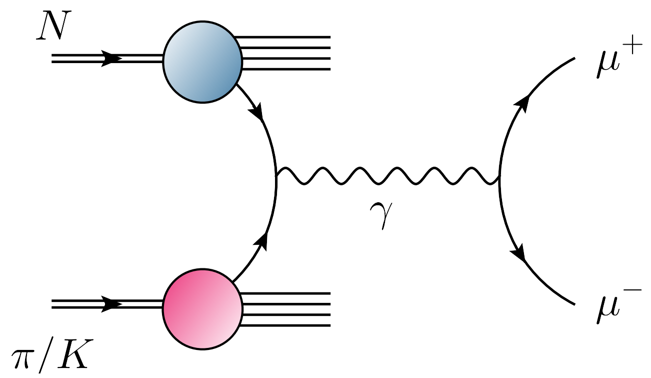
T. Horn and C. D. Roberts. J. Phys. G 43 (2016) 7, 073001

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

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

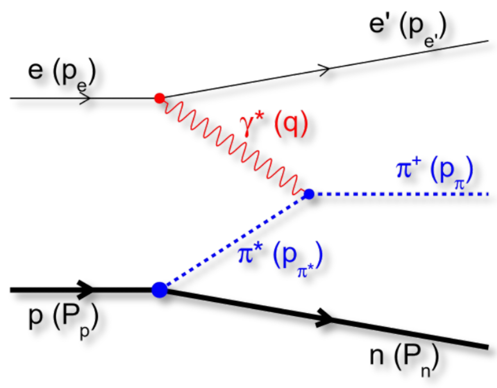


C. D. Roberts, D. G. Richards, T. Horn and L. Chang, PPNP 120, 103883 (2021)

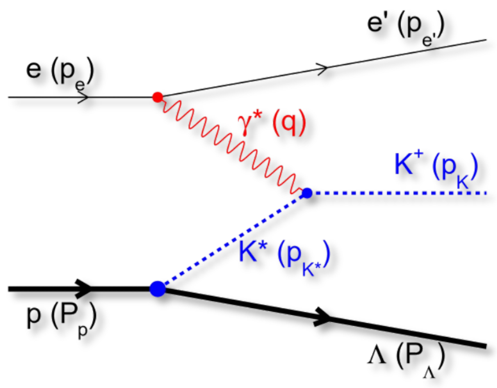
Accessing Meson Structure - Sullivan Process

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

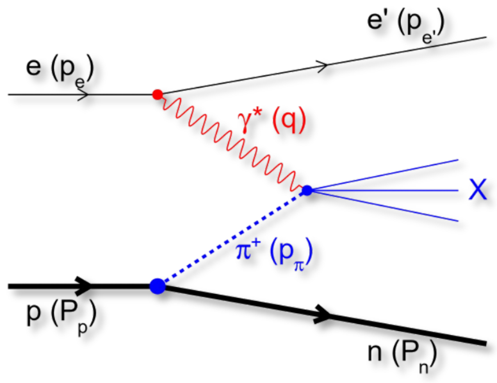
Pion Form Factor (FF)



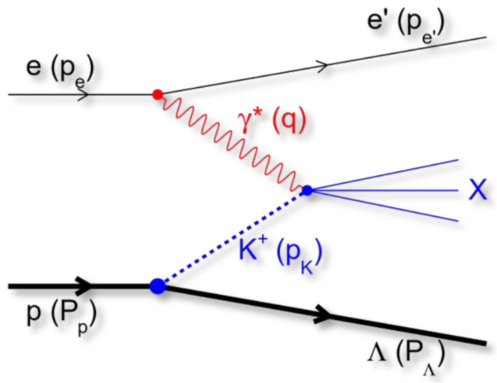
Kaon Form Factor (FF)



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

Meson From Factor from Sullivan Process

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

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

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

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

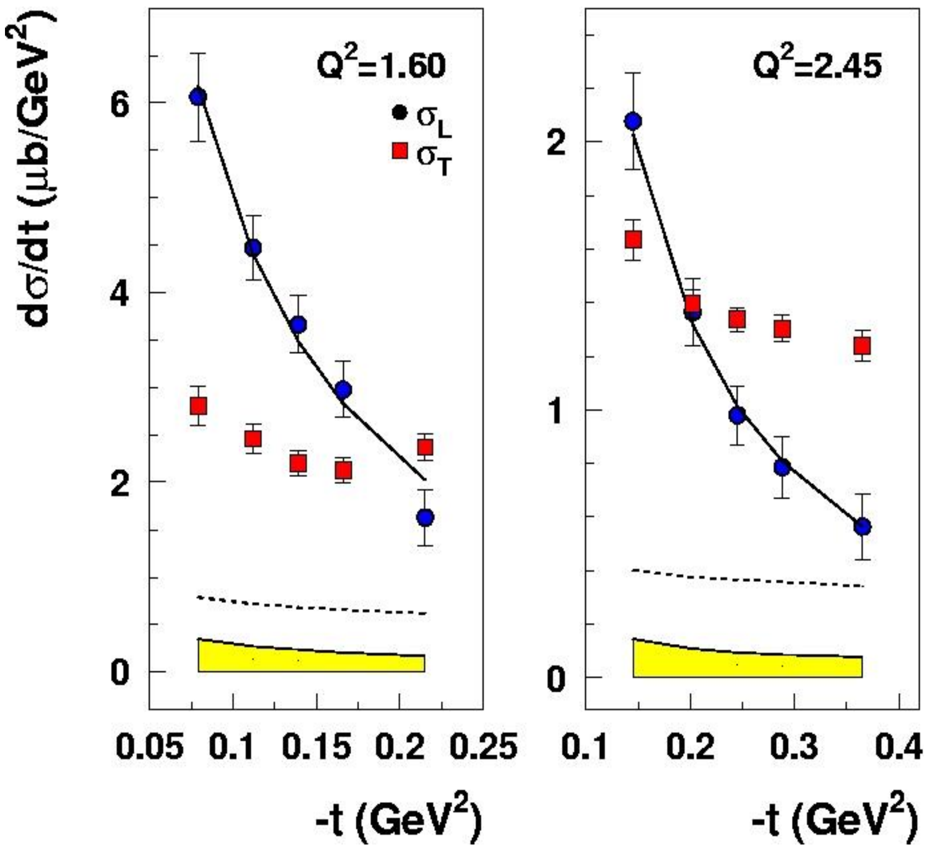
$$\left.\begin{aligned}\sigma_1 &= \sigma_T + \epsilon_1\sigma_L\\ \sigma_2 &= \sigma_T + \epsilon_2\sigma_L\end{aligned}\right\} \quad \frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{(\epsilon_1-\epsilon_2)}\frac{1}{\sigma_L}\sqrt{\Delta\sigma_1^2 + \Delta\sigma_2^2}.$$

- *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

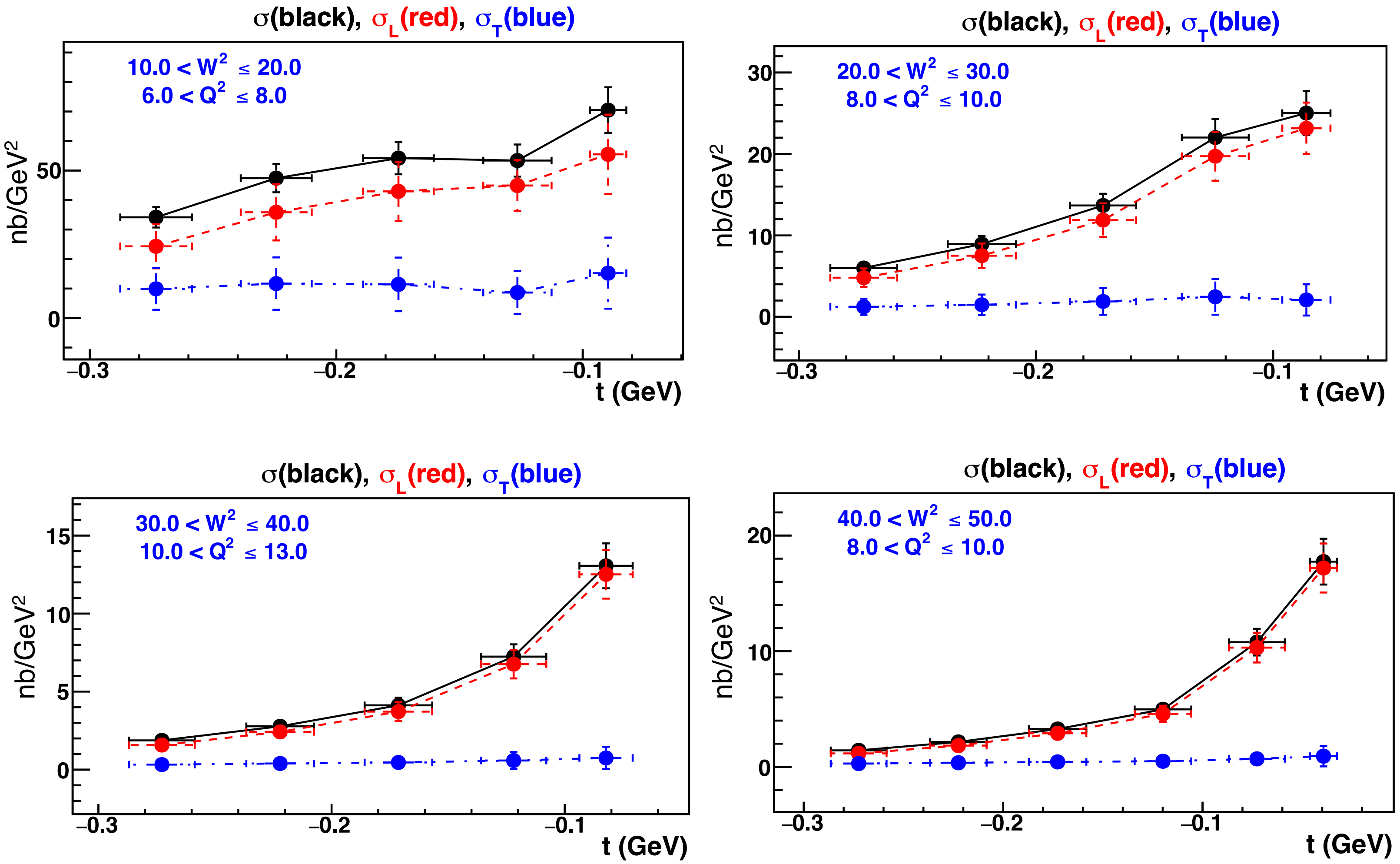
[Horn et al., PRL **97**, (2006) 192001]



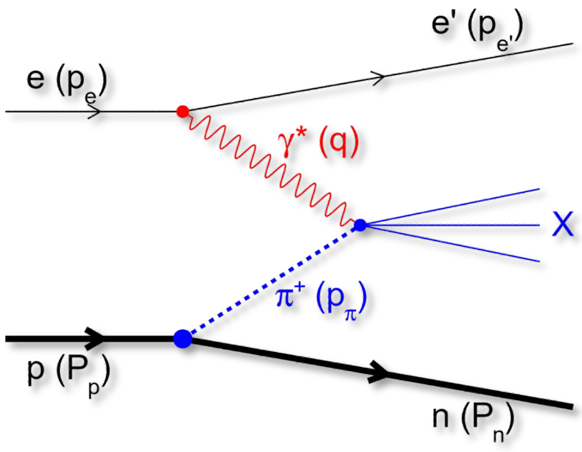
Meson From Factor from Sullivan Process

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

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



Meson Structure Function from Sullivan Process



leading neutron of large rapidity

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

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

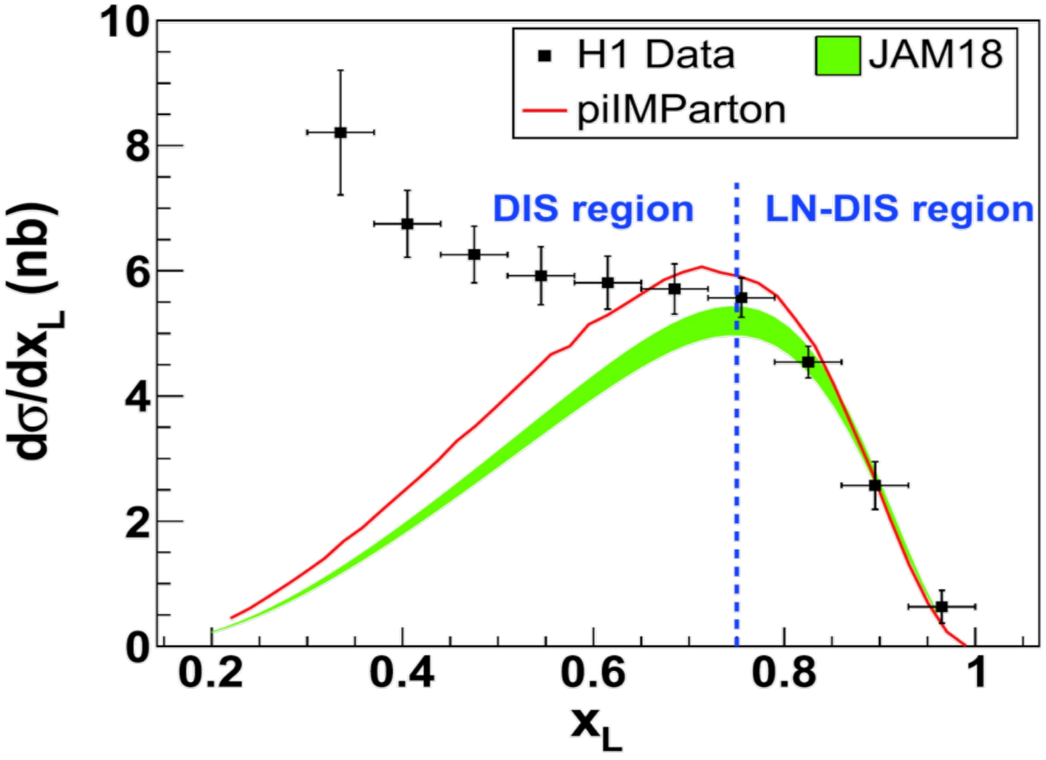
$$\frac{{\rm d}^4\sigma(ep \to enX)}{{\rm d}x_{\rm B}{\rm d}Q^2{\rm d}x_{\rm L}{\rm d}t} = \frac{4\pi\alpha^2}{x_{\rm B}Q^4}\left(1 - y + \frac{y^2}{2}\right)F_2^{\rm LN(4)}(Q^2, x_{\rm B}, x_{\rm L}, t)$$

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

pion SF **pion flux**

Very large uncertainty, could be ~25%

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

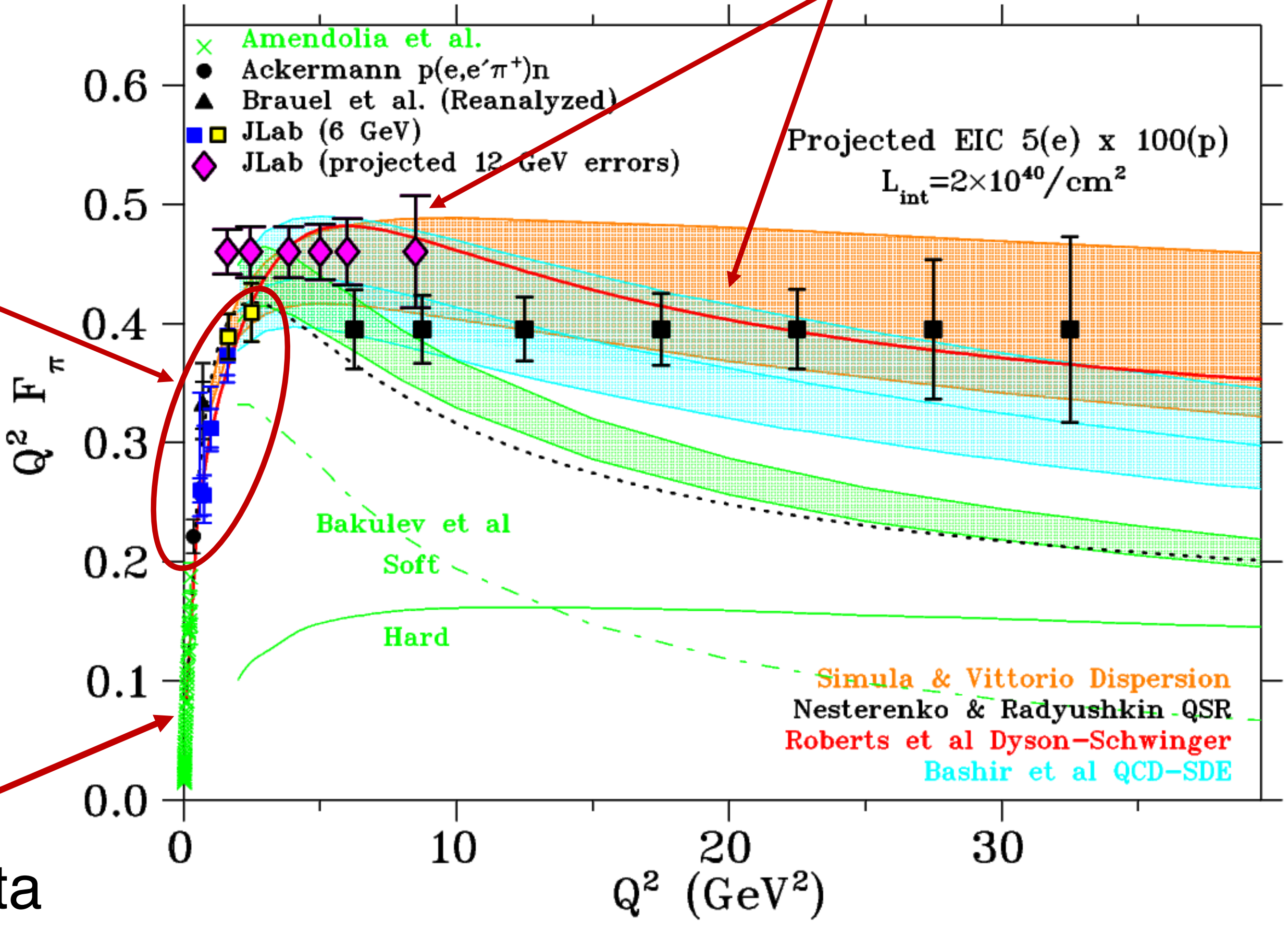


One has to measure the final baryon in this case

Existing World Data on Meson Structure (Pion)

JLab-12GeV and EIC projections

DESY and Jlab-6GeV results

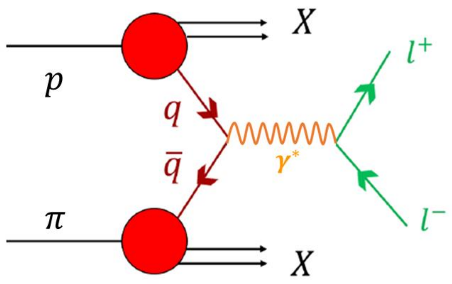


πe elastic scattering data

Existing World Data on Meson Structure (Pion)

Pion − induced Drell − Yan

$\pi^- p \rightarrow \mu^+ \mu^- X$

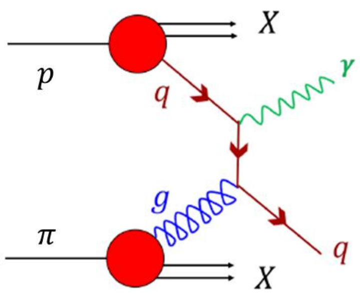


sensitive to valence

NA10, E615, COMPASS (new)

Pion − induced prompt − gamma

$\pi^- p \rightarrow \gamma X$

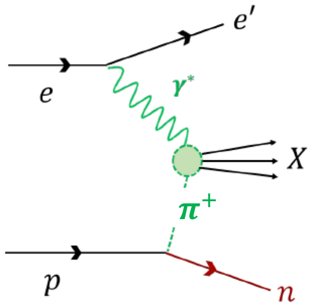


sensitive to gluon

WA70

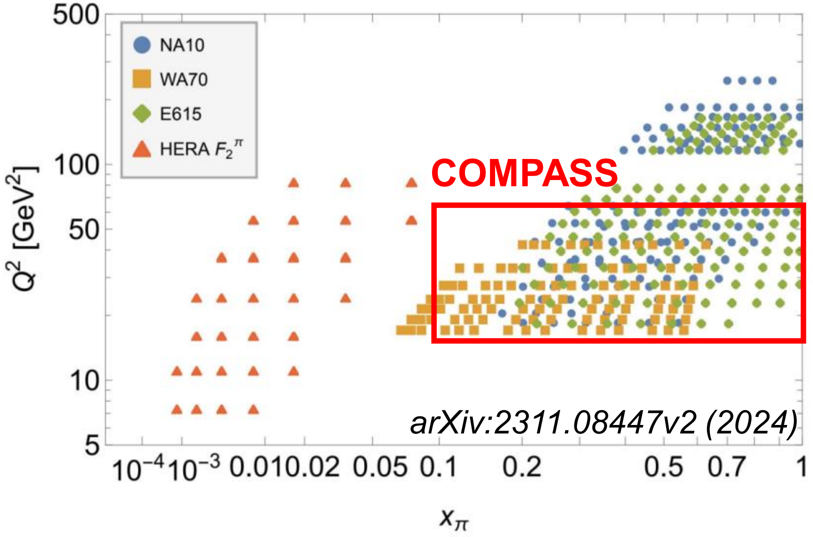
Sullivan process (leading-neutron DIS)

$p \rightarrow \pi^+ n$



sensitive to quark and gluon

HERA



- Data for global fit of pion PDF is very limited. Each of them has their own difficalties.
- **Pion-induced Drell-Yan : A normalization issue occurs between E615 and NA10 data, by up to 20%. COMPASS data is a new data in 30 years and will be an independence check.**
- Pion-induced prompt-gamma : Data has large systematics due to the background γ signals from the secondary π^0 decay.
- The interest of using Sullivan process to study pion structure is increasing. The equivalence of pion cloud and pion beam data remains a subject to be studied.

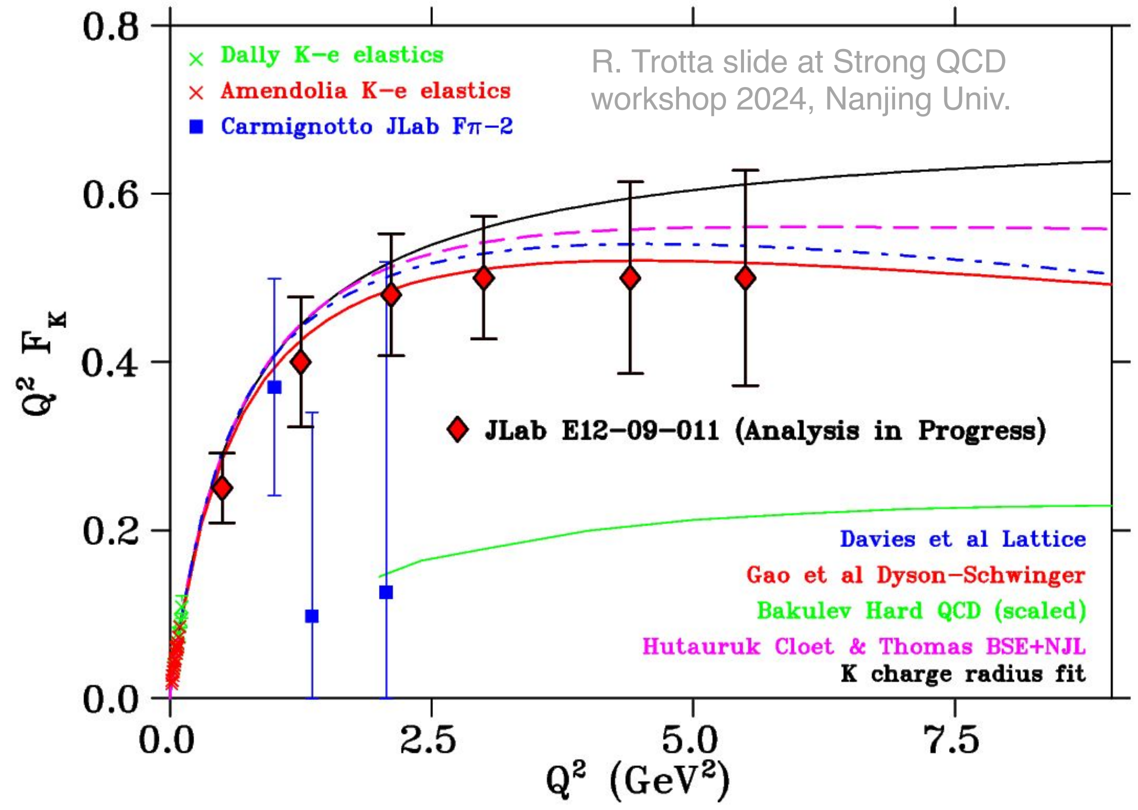
Slide Courtesy of **Chia-Yu Hsieh** from Hadron 12th Workshop on Hadron Physics and Opportunities Worldwide, Dalian

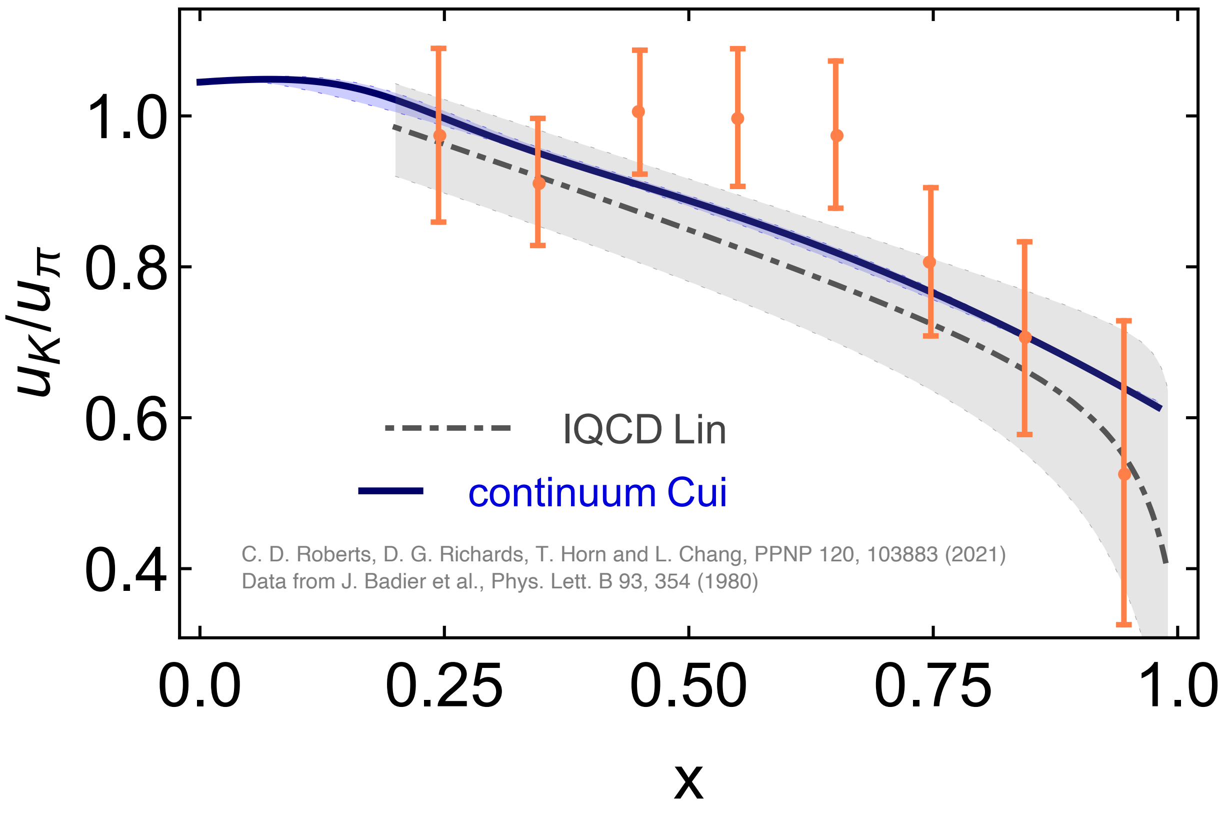
Existing World Data on Meson Structure (Kaon)

Very Few Data for Kaon!

- Forseable data only up to $Q^2 \sim 6$ GeV^2, analysis in progress

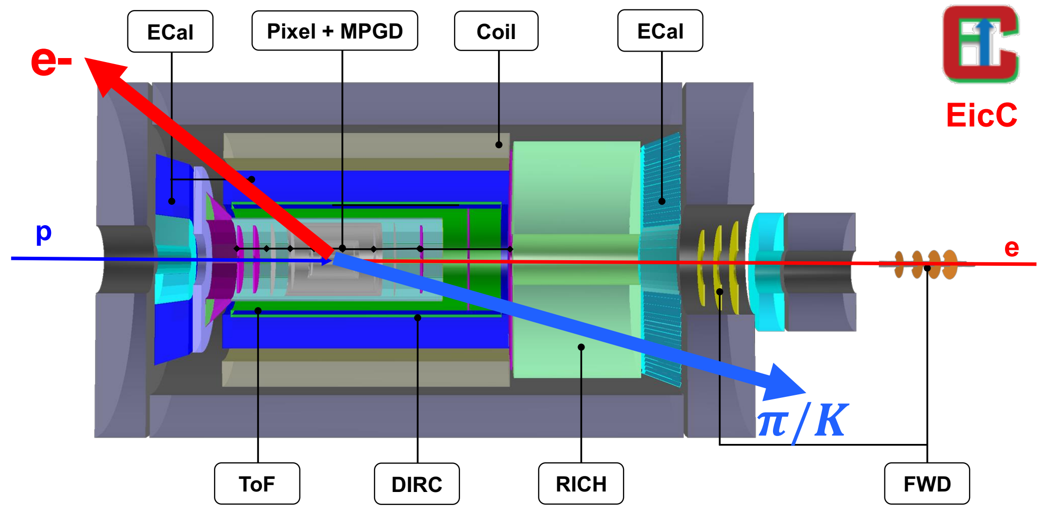
- For kaon PDF: Only 8 data points measured 40 years ago at CERN
- No structure function data yet with Sullivan process



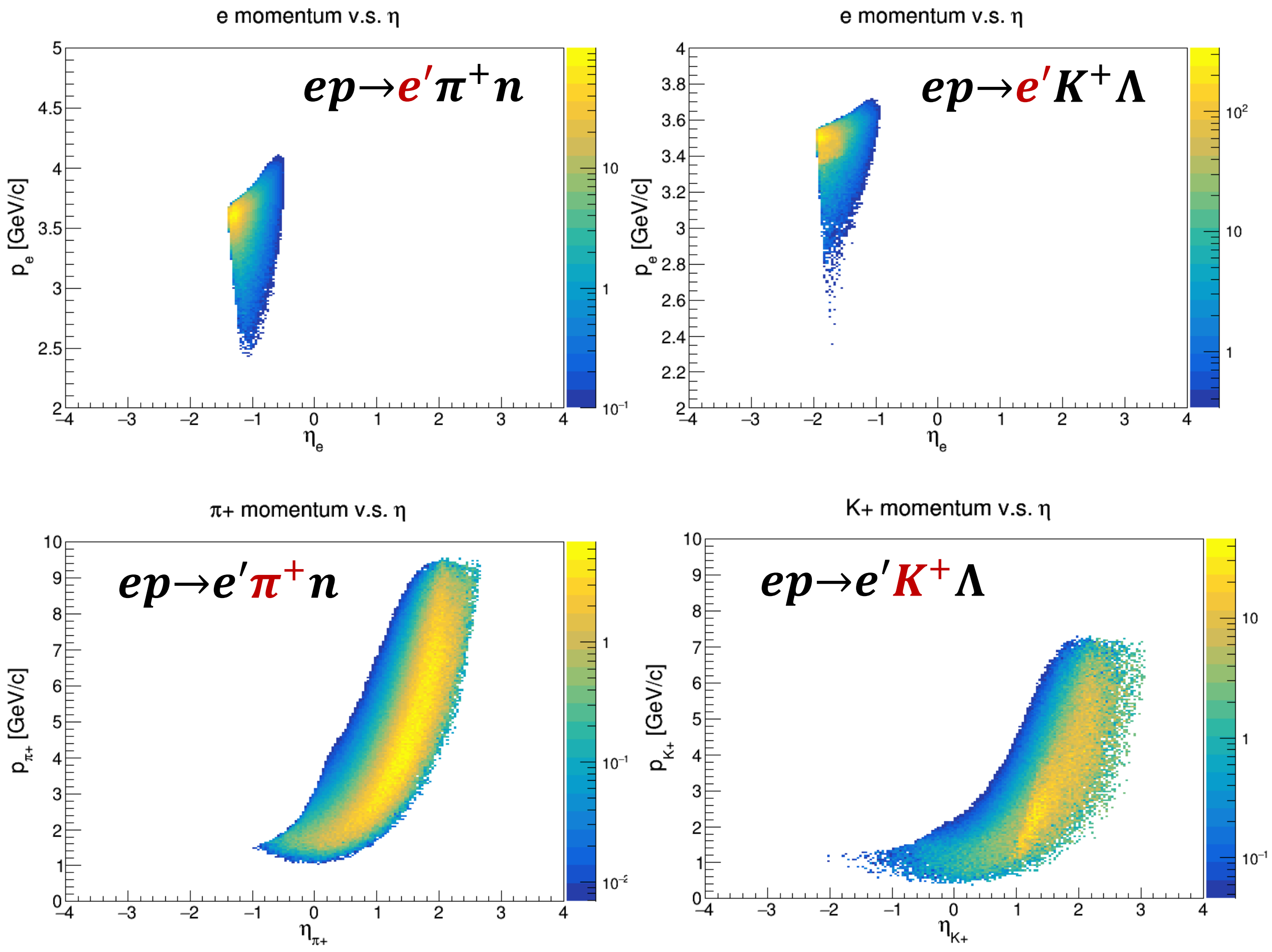


Meson Structure Measurement with EicC

- 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



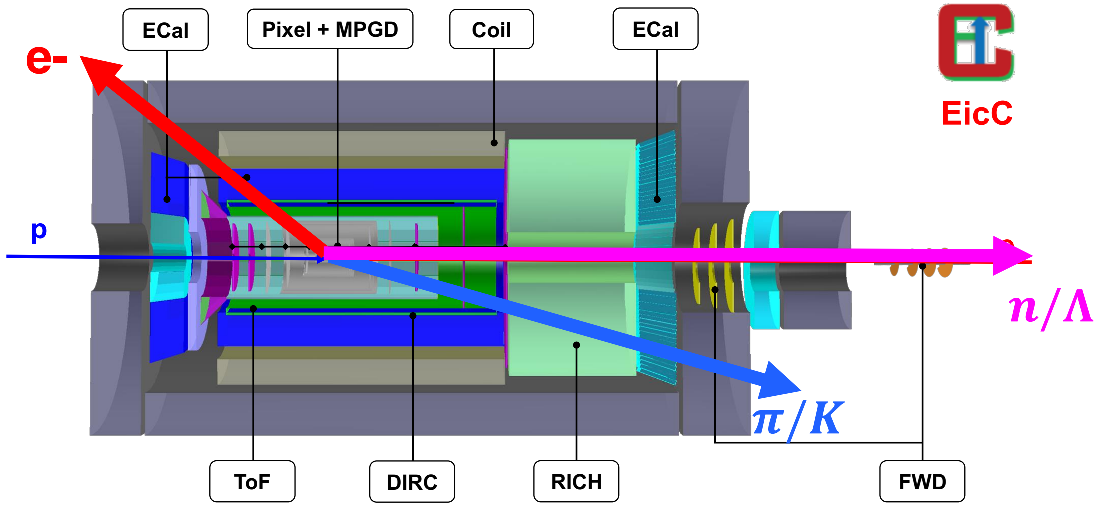
3.5 GeV (e) x 20 GeV (p)



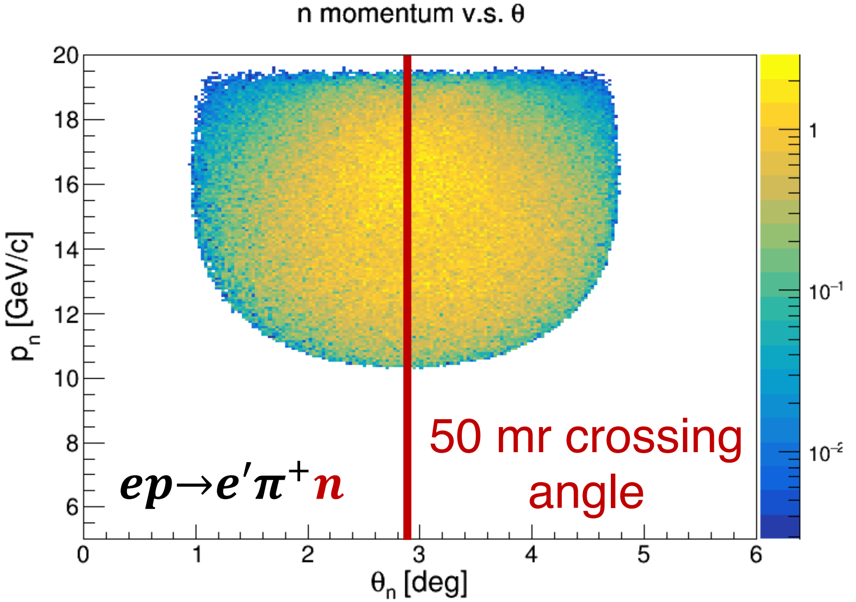
Meson Structure Measurement with EicC

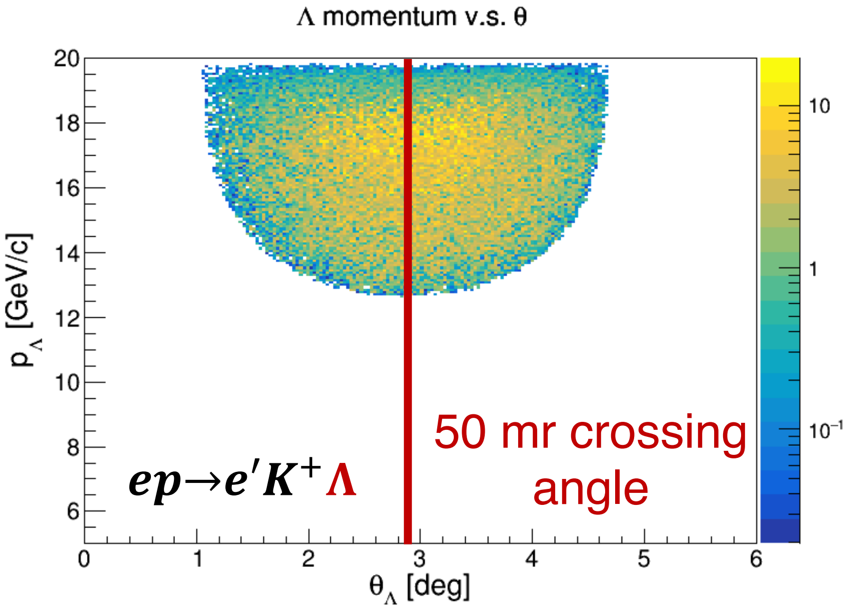
- "Spectator" neutron and Λ move very close to the initial p-beam, very difficult to detect, need far-forward detectors

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



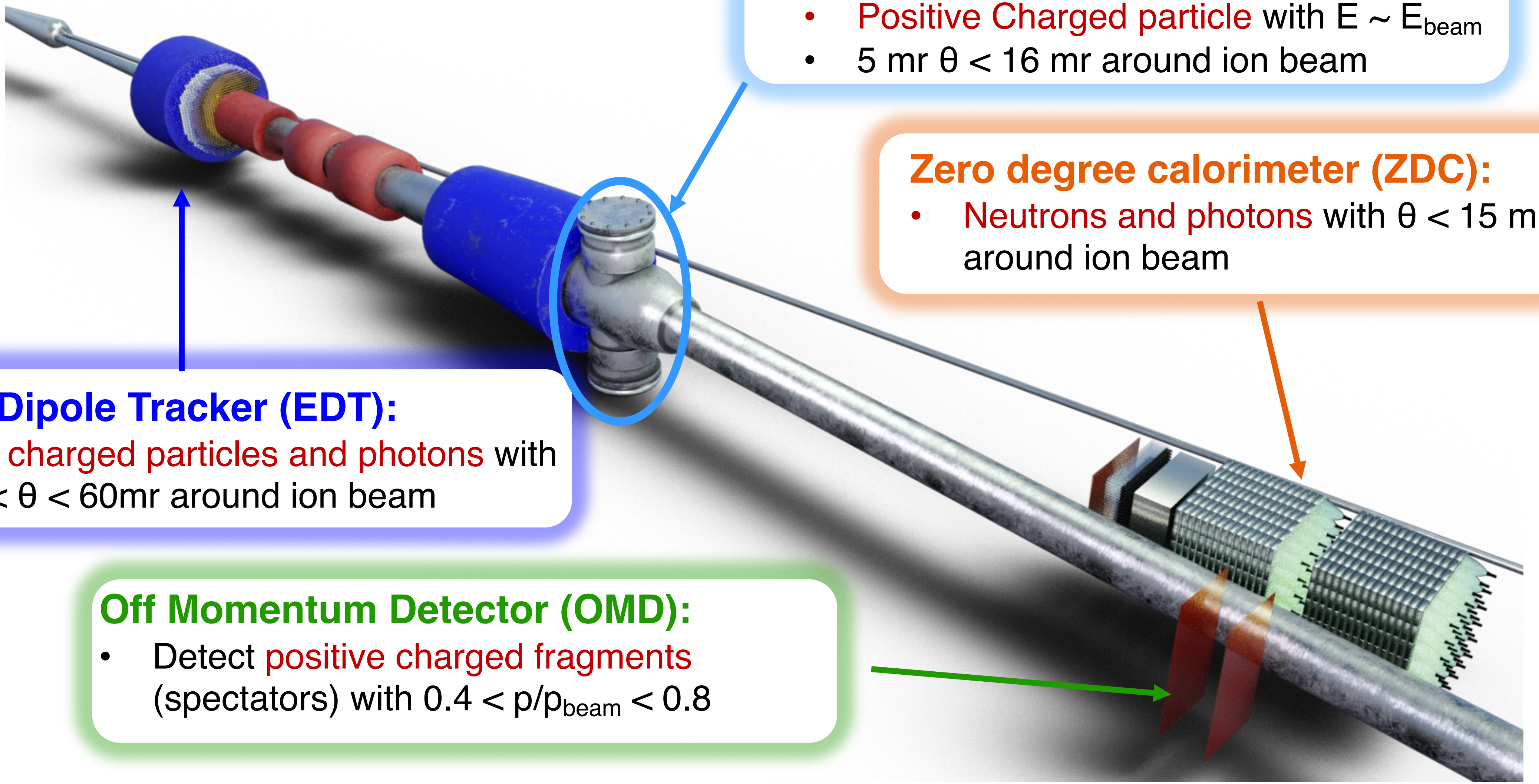
EicC





3.5 GeV (e) x 20 GeV (p)

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 $\theta < 15$ 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 $0.4 < p/p_{beam} < 0.8$

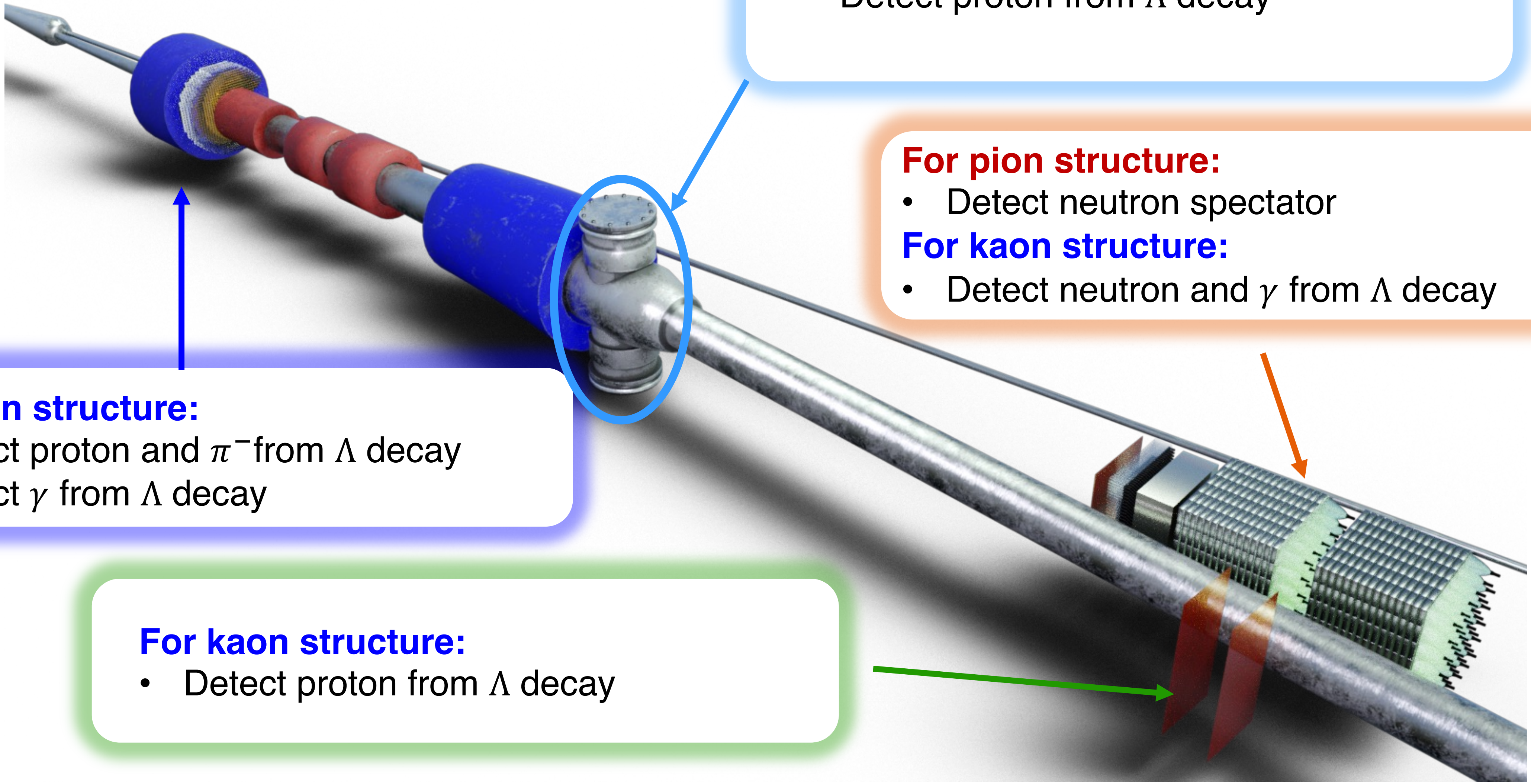
Current Design for EicC Far-Forward (FF) Region

1. neutral channel: $\Lambda \to n\pi^0$, with BR 36%
2. charged channel: $\Lambda \to p\pi^-$, with BR 64%

For kaon structure:
- Detect proton from Λ decay

For pion structure:
- Detect neutron spectator

For kaon structure:
- Detect neutron and γ from Λ decay



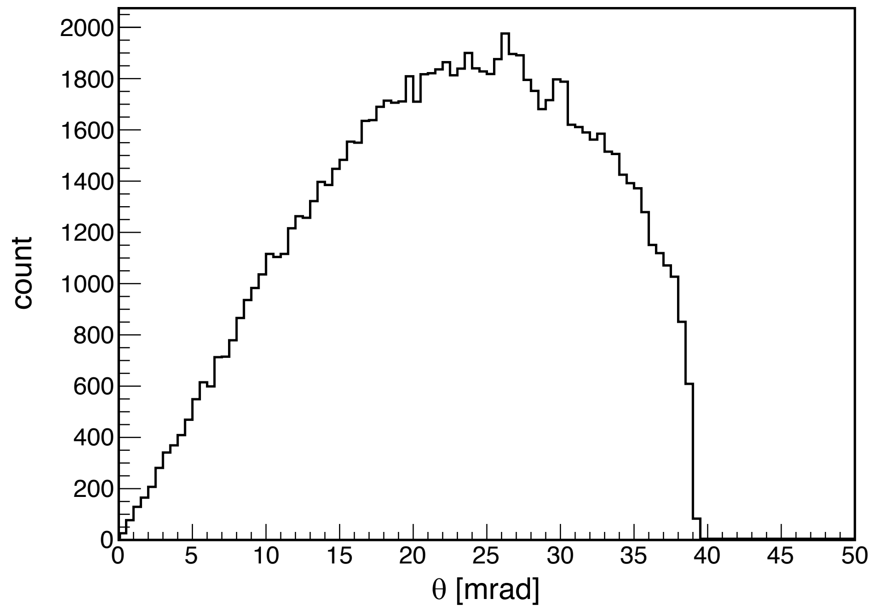
For kaon structure:
- Detect proton and $\pi^-$from Λ decay
- Detect γ from Λ decay

For kaon structure:
- Detect proton from Λ decay

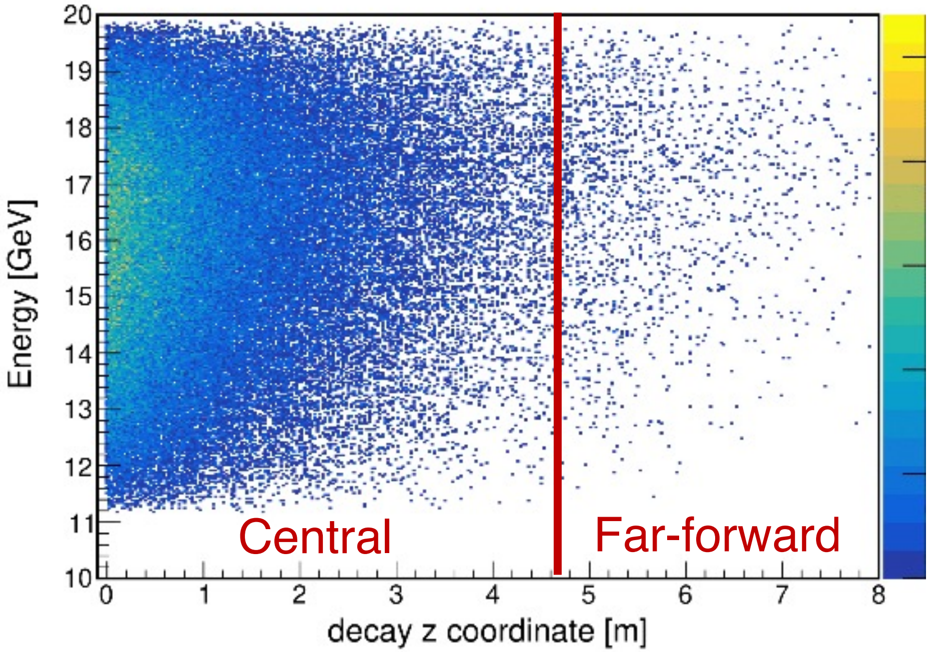
Forward Λ Detection

- Crucial for kaon form factor and structure-function study using Sullivan process: $ep \to e\Lambda K^+/X$
- 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

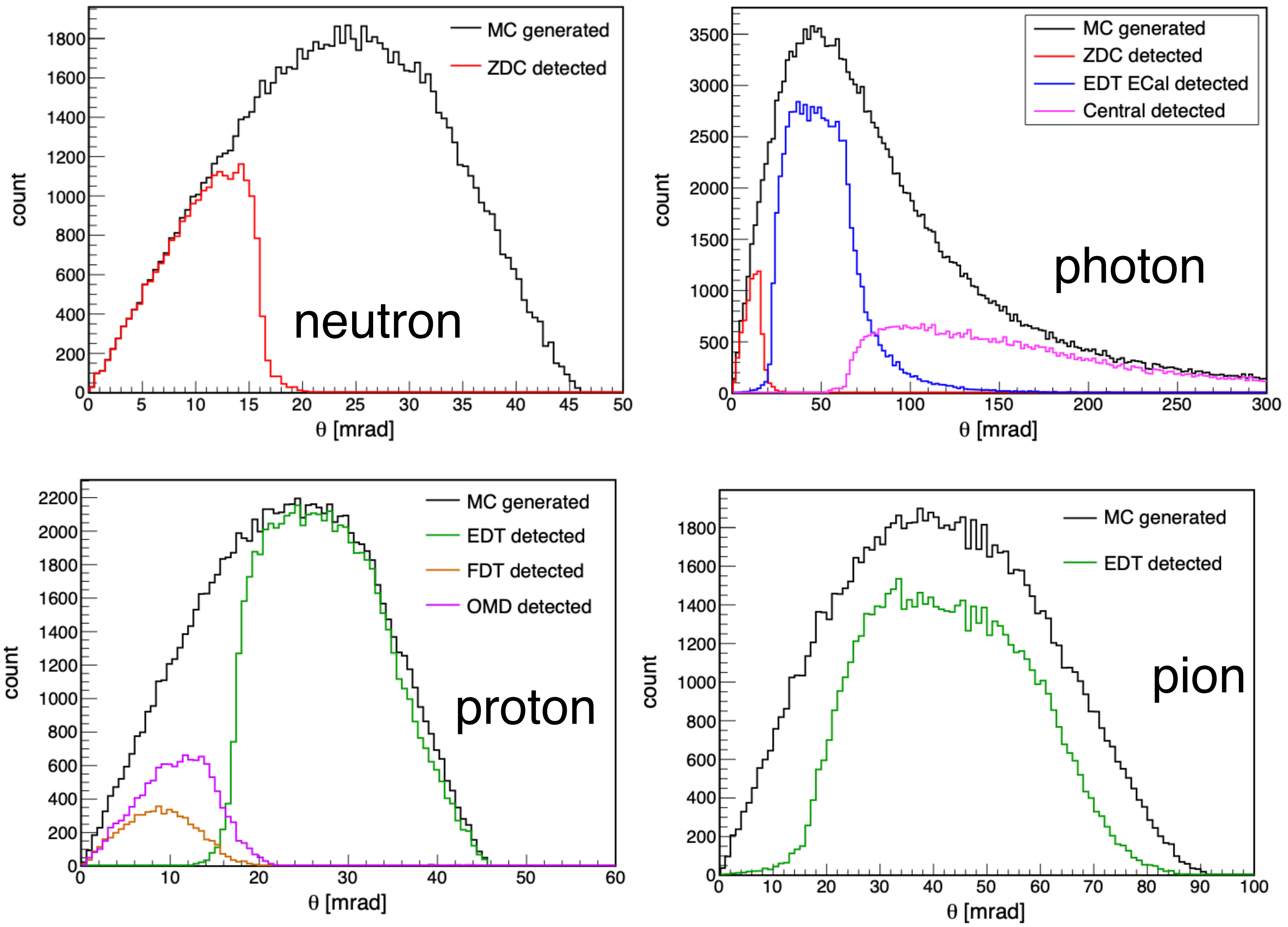


Forward Λ Detection

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

- Require all FF detectors work collectively

➢ overall efficiency: ~ 40%

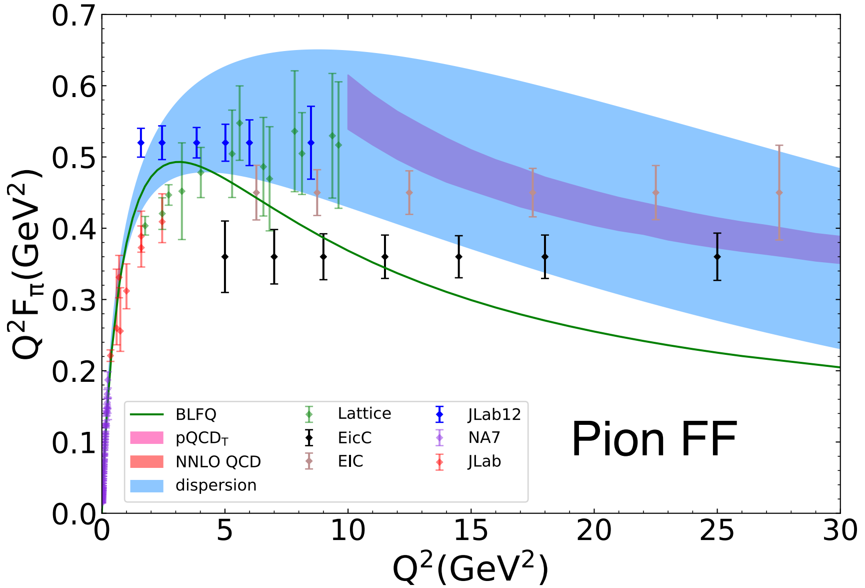


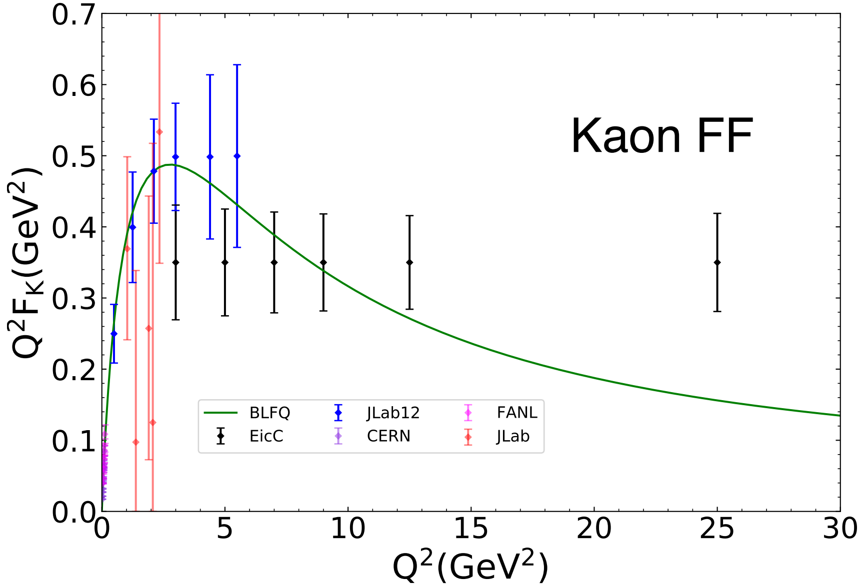
Pion FF Projections

- 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
- For kaon measurement, additional 5% uncertainty from Σ^0 background

- Impact on pion:
  - ➢ Provide valueable cross-check for JLab and EIC results

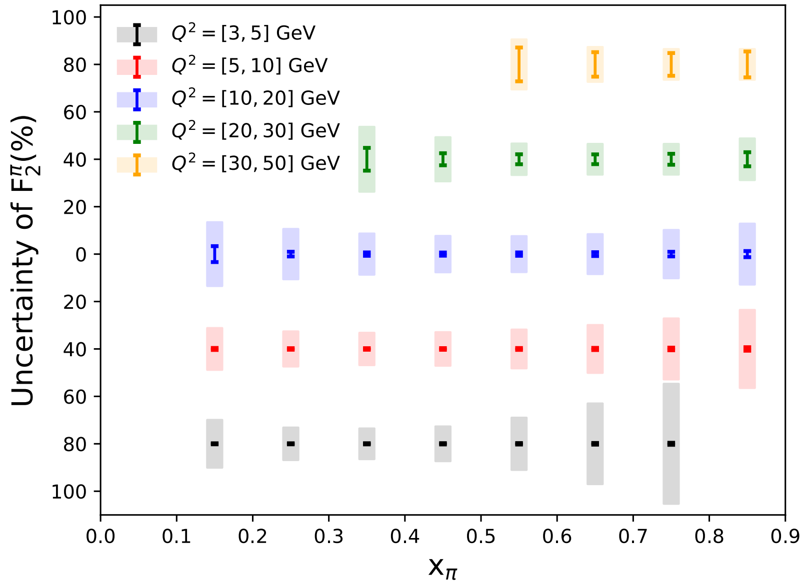
- Impact on kaon:
  - ➢ Extend Q^2 coverage from ~GeV^2 to ~25 GeV^2

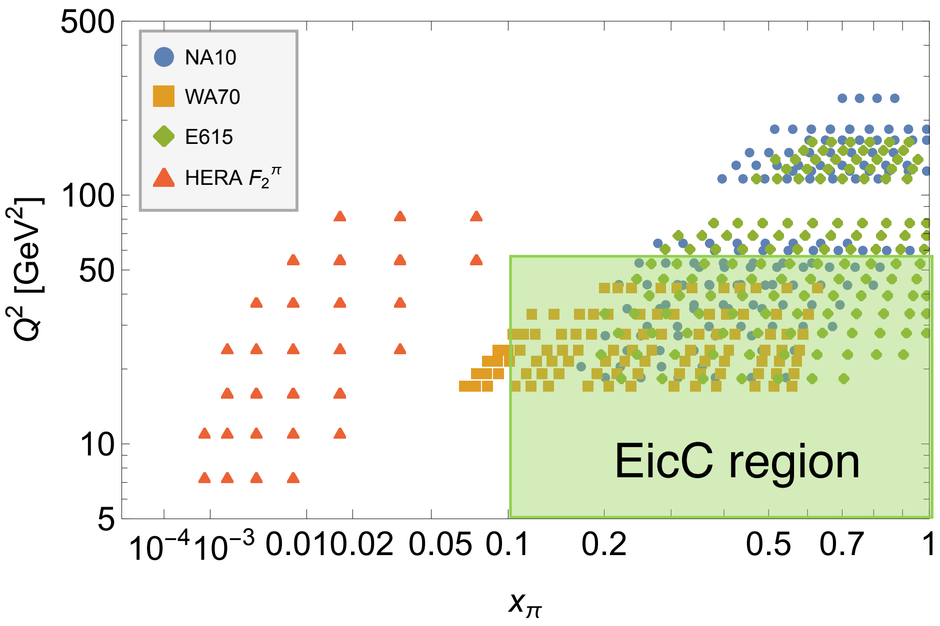


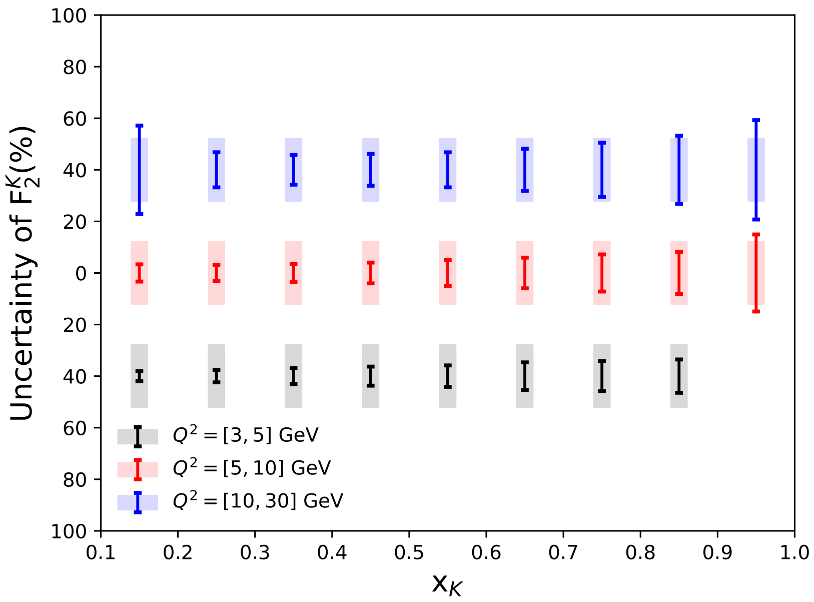


Pion Structure Function Projection

- energy setting: 3.5 GeV e x 20 GeV p
- Integrated luminosity: 50 fb^{-1}
- Include full detector acceptance
- include syst. from detector resolution
- Acceptance uncertainty 5% for pion and 10% for kaon SF







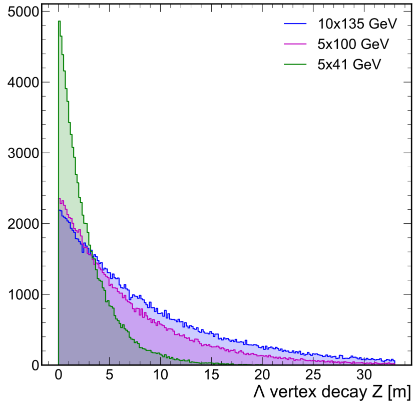
Strength And Complementarity of EicC

Forward Λ detection for Kaon Structure

1. Better overall Λ detection efficiency

- At US-EIC, energy is too high so that many Λ decays after their far-forward detectors

- At EicC, most of Λ decays before FF detectors



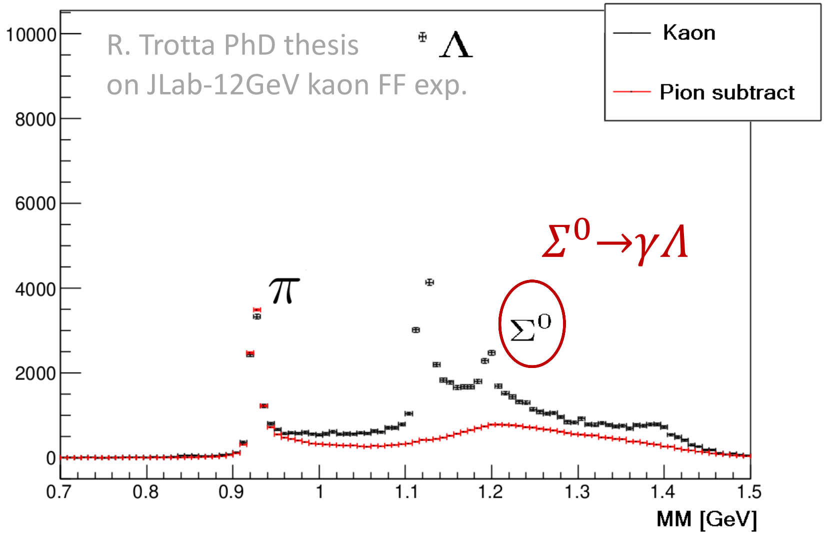
From EIC yellow report

Table 8.18: $e + p \to e' + X + \Lambda$: Percentage of decayed Λ's in different detection ranges.

E_{beams}	$Z_{vtx} < 5$ m	5 m $< Z_{vtx} < 30$ m	$Z_textvtx > 30$ m
5 GeV on 41 GeV	83.0%	16.6%	0.4%
10 GeV on 100 GeV	52.1%	46.7%	1.2%
10 GeV on 130 GeV	41.8%	54.2%	4%
18 GeV on 275 GeV	23.3%	56.2%	20.5 %

2. Better efficiency for charged decay $\Lambda \to p\pi^-$

- Λ decays 64% of the time into $p\pi^-$
  - ➢ better stat.
- Charged particle resolution typically better than neutral particles
  - ➢ better resolution
  - ➢ better background rejection



3. Benefit of collider mode for SF measurement

- JLab energy only marginal for kaon SF measurement
- For fixed target mode, need to measure very soft Λ using recoil detector, difficult due to high background rate

Strength And Complementarity of EicC

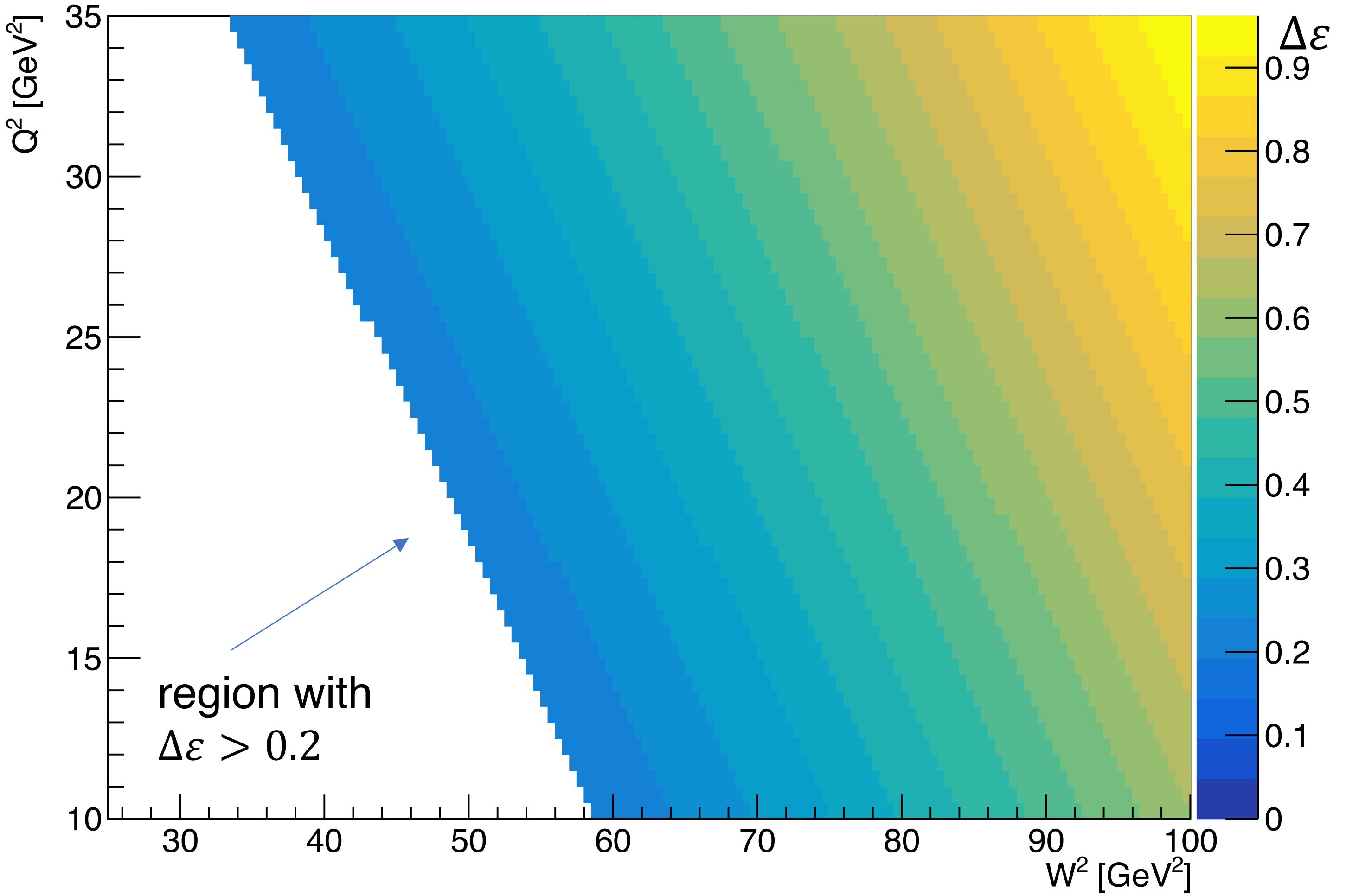
Potential of L-T separation

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

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{(\epsilon_1-\epsilon_2)}\frac{1}{\sigma_L}\sqrt{\Delta\sigma_1^2+\Delta\sigma_2^2}.$$

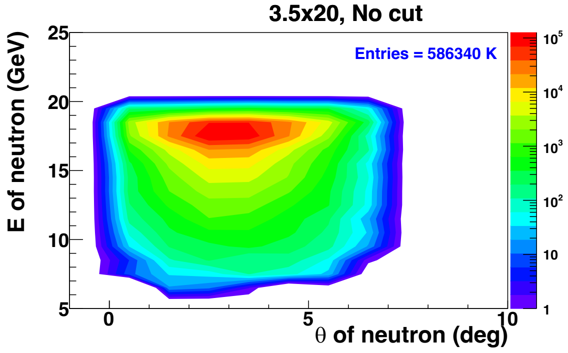
- L-T separation typically require $\Delta\varepsilon > 0.2$, not a problem at JLab
- At high $\sqrt{s}$, ε is very close to 1
- Need $\sqrt{s} \sim$ 10GeV to reach $\varepsilon < 0.8$, not possible at EIC
- Reachable at EicC, projection study ongoing

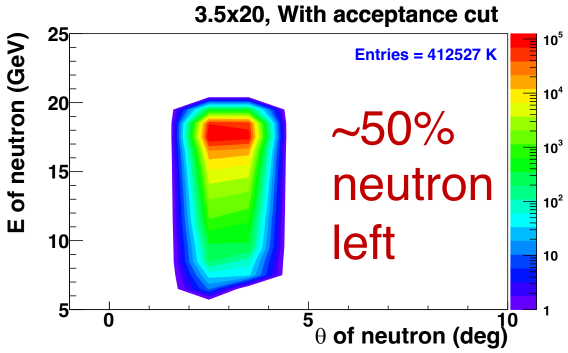
ε diffrence between 5x26 GeV runs and 2.8x12 GeV runs

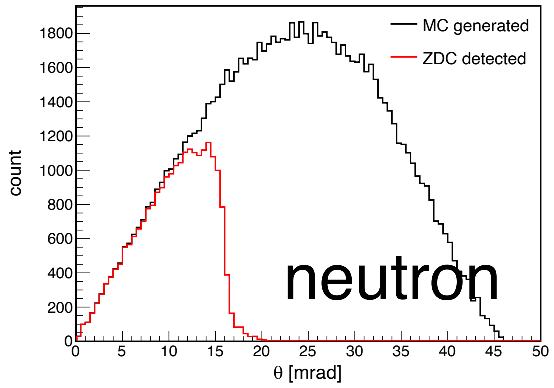


Plot by Zihan Yu（俞子涵） from SDU

Additional Improvement to Think About

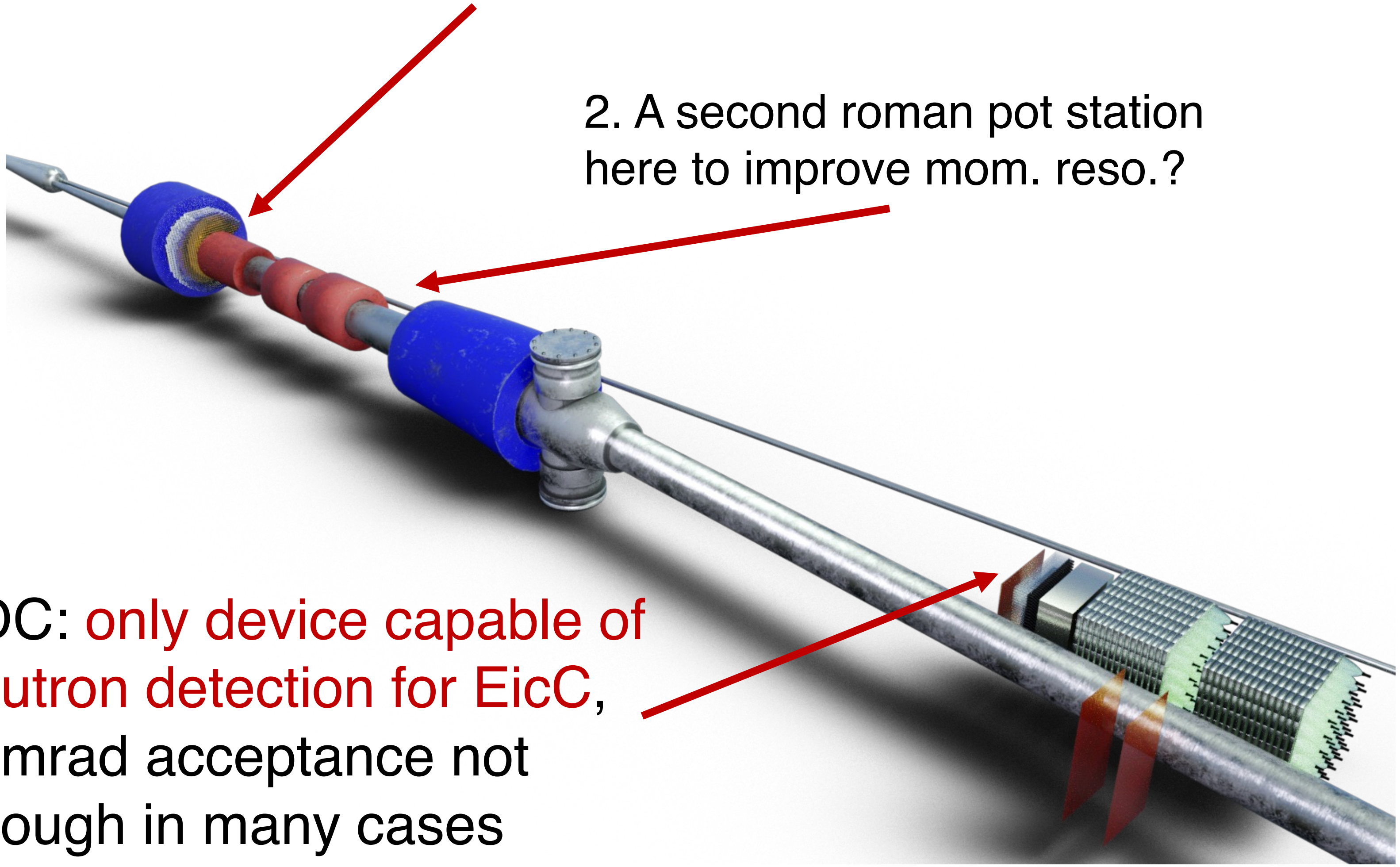






1. Additional compact HCal after the EDT?

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

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
  - Might be the best place to measure kaon structure using Sullivan process
    - Very few space-like Kaon structure data!

- Full simulation for EicC central and far-forward detectors
- Projection studies done for meson FF and SF, would like to also extract meson PDFs but… not enough time
- Sullivan process can also used to meson Meson GPD

- Special thanks to Prof. Huber, Prof. Horn and Prof. Roberts for many helpful discussions