The Opportunities of Pion and Kaon Structure Measurements at EicC

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Impacts of Measuring the Pion and Kaon Structures

- **To understand QCD:** the pQCD prediction of pion form factor at high Q^2 (> 10 GeV^2) is different from the monopole form (to be tested in experiment). [G. Lepage, S. Brodsky, Phys. Rev. D 22, 2157 (1980); Lei CHANG et al, Phys. Rev. Lett. 111, 141802 (2013); Fei GAO et al, Phys. Rev. D 96, 034024 (2017)…]

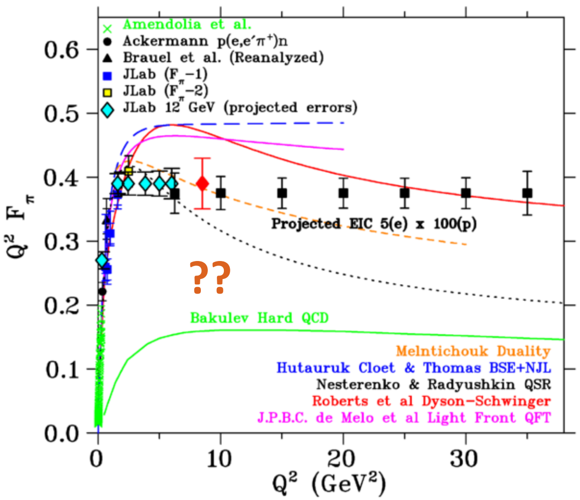
- **To understand EHM and DCSB:** How does the lightest hadron (π) get its mass is a fundamental question. The precision data of pion form factor and structure function could test PDAs, EHM and DCSB, which are the mechanisms for the hadron to get its mass from the strong interaction. [C. Roberts, S. Schmidt, arXiv:2006.08782; J. Gasser, H. Leutwyler, Phys. Rep. 87, 77 (1982); P. Maris, C. Roberts, Phys. Rev. C 56, 3369 (1997); P. Maris, C. Roberts, P. Tandy, Phys. Lett. B 420, 267 (1998)…]

- **To understand Higgs Modulation in hadron structure:** in pure QCD, the pion and kaon structure are identical. The current quark mass modulates the hadron structure (to be tested in experiment). [C. Shi et al., Phys. Rev. D 92, 014035 (2015); Z.-F. Cui, M. Ding, F. Gao, et al., arXiv:2006.14075…]

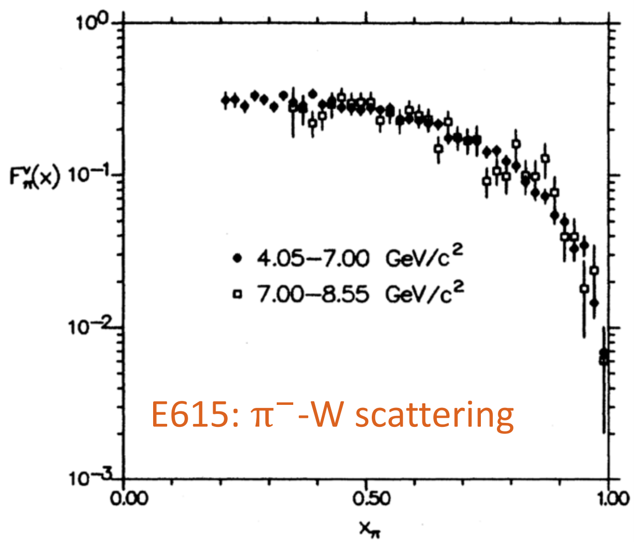
Impacts of Measuring the Pion and Kaon Structures

- There are much less experimental data on the pion and kaon structures so far, compared to the nucleon structure data. [some interesting experiments are listed here. Pion electroproduction: Jlab F_π; Pion-Nucleus Drell-Yan: CERN NA3/10, Fermilab E615 data; Leading neutron tagged DIS: ZEUS@HERA, H1@HERA; Pion-Nucleus photon/JPsi production: CERN NA24, WA11/70, Fermilab E706]

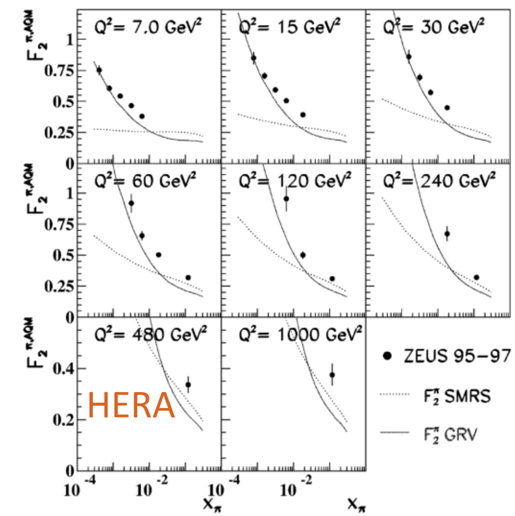
Pion electroproduction



Drell-Yan process



Tagged DIS



- More precision data of pion in a wide Q^2 range are useful to confirm the end-point behavior at large x, to test the QCD evolution in the meson sector, and to test the saturated strong coupling in the nonperturbative region (near the hadronic scale) by the evolution.

Sullivan Process and Structure of Virtual Pion

One-pion exchange of the t channel is dominant at small |t|, and it could be exploited to study the internal structure of the virtual pion. At $|t|<0.6$ GeV^2, it is guaranteed to extract the structure of the real pion from a proper extrapolation of the structure of the virtual one. [J. Sullivan, Phys. Rev. D 5, 1732 (1972); H. Holtmann et al., Phys. Lett. B 338, 363 (1994); S.-X. Qin, C. Chen, C. Mezrag, C. Roberts, Phys. Rev. C 97, 015203 (2017)]

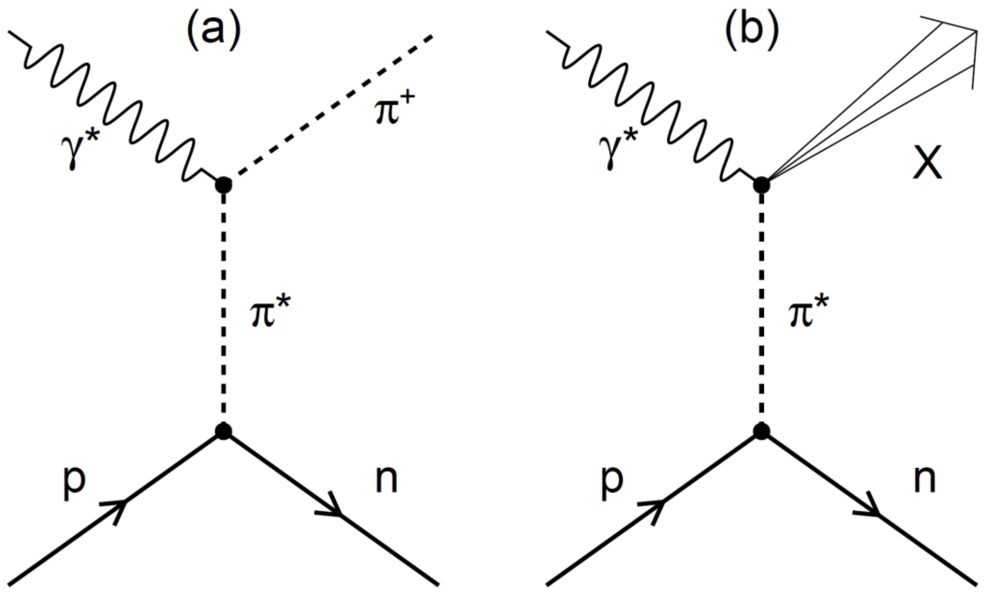
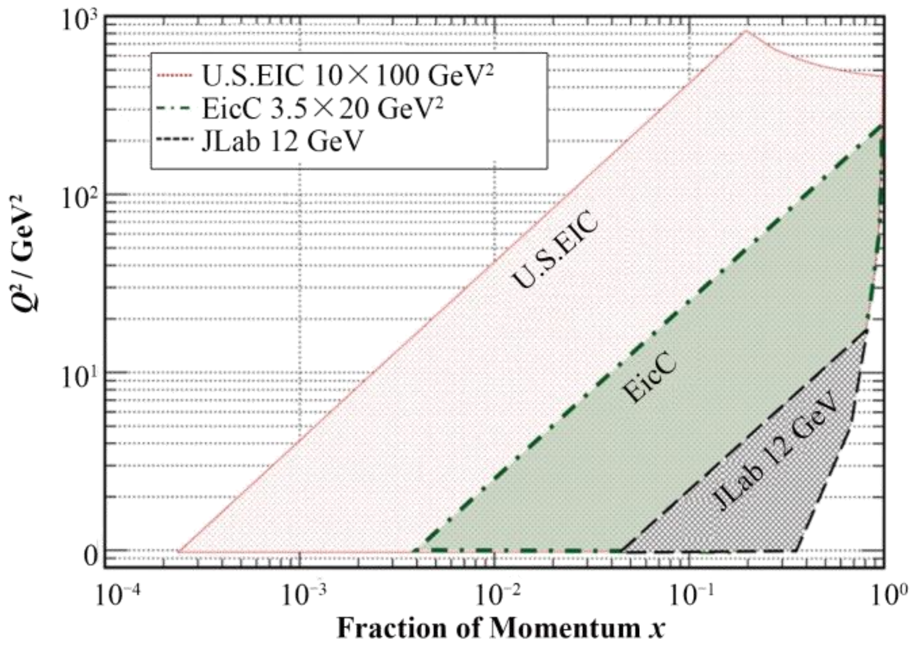


Diagram (a) is for the pion form factor measurement; Diagram (b) is for the pion structure function measurement.

A high intensity electron beam could provide such a clean virtual photon probe.

Electron-ion collider in China (EicC)

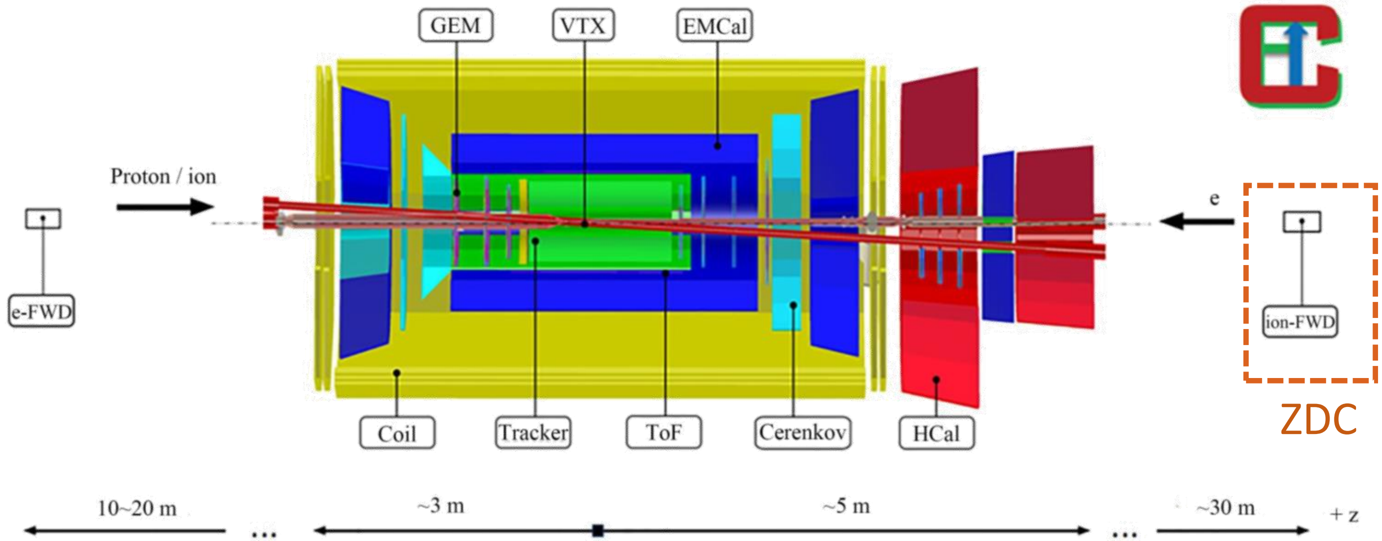
- EicC is the widely discussed electron-ion collider in China, which is proposed to be built for the upgrading the new high intensity heavy ion accelerator facility (HiAF) in Huizhou, Guangdong Province, China.
- Its suggested collision energy covers the gap between the on-going JLab-12 GeV facility and the EIC in US.



The main goals are to study the hadron physics and the QCD dynamics in the high luminosity frontier.

Chinese Language White Paper of EicC: http://www.j.sinap.ac.cn/hjs/CN/Y2020/V43/I2/20001

Electron-ion collider in China (EicC)



Y.-T. **Liang**

从探测器概念设计出发，由探测器模拟反馈逐步提出 EicC 各个子探测器的细节要求。如对散射电子的探测要求建议在不同赝快度空间采用不同能量分辨的量能器，如在电子前冲方向靠近束流管的端盖部分采用能量分辨高的晶体量能器，其它部分采用能量分辨稍低的抽样型量能器。对强子的探测鉴别也需在不同 η 范围考虑不同探测技术，如在离子束流前冲一侧（$1<\eta<4$），末态强子前冲动量较大（可高达约 15 GeV·c^{-1}），而其它部分（$-3<\eta<1$）末态强子动量较低（<6 GeV·c^{-1}）。在不同动量范围内有效区分 π/K/p 粒子，对粒子鉴别技术等选取显然也会不同。

Detector conceptual design:
Central system contains the barrel and end-cap detectors around the beamlines, which covers the pseudorapidity of $|\eta| < 3$.
Forward detectors and ZDCs are also suggested, which could PID/measure the charged particles of $|\eta| < 5$.

Simulation of the Exclusive Meson production in e-p collision

To write an event generator and to estimate the statistic, we adapt a simple model for the differential cross-section:

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, s)\frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}cos(\phi_\pi)\frac{d\sigma_{LT}}{dt} + \epsilon cos(2\phi_\pi)\frac{d\sigma_{TT}}{dt}\right]$$

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

$$\epsilon^{-1} = 1 + 2\left(1+\frac{\nu^2}{Q^2}\right)\left(4\frac{\nu^2}{Q^2}\frac{1-y}{y^2} - 1\right)$$

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

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

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

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

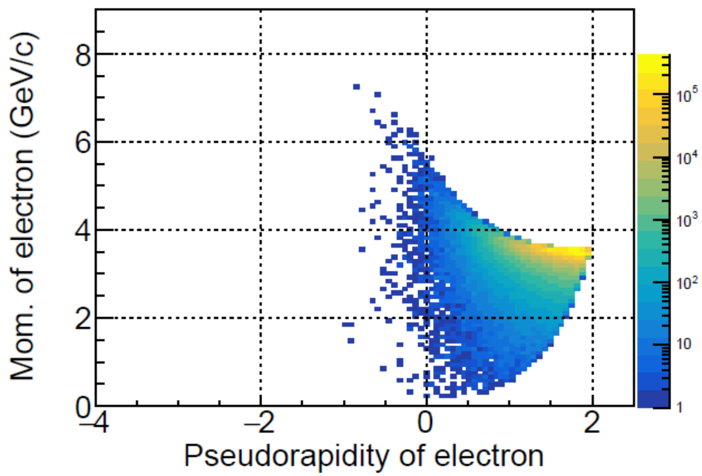
More sophisticated models:
[M. Vanderhaeghen, M. Guidal, J.-M. Laget, Phys. Rev. C 57, 1454 (1998); T.K. Choi, K.J. Kong, B.G. Yu, arXiv:1508.00969; R. Perry, A. Kizilersu, A. Thomas, Phys. Lett. B 807, 135581 (2020)…]

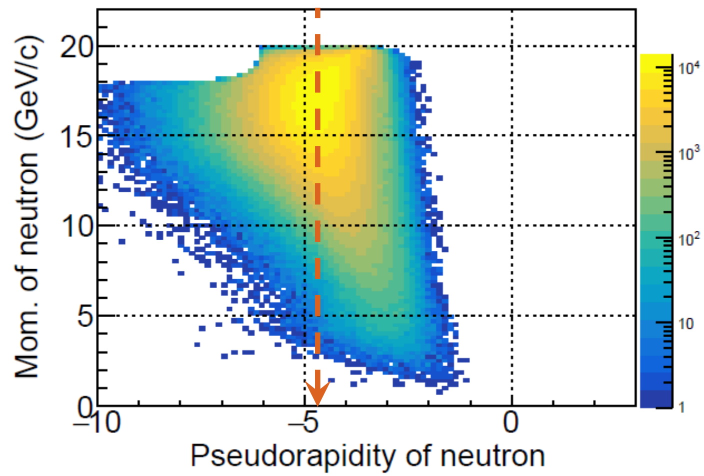
Pion pole contribution

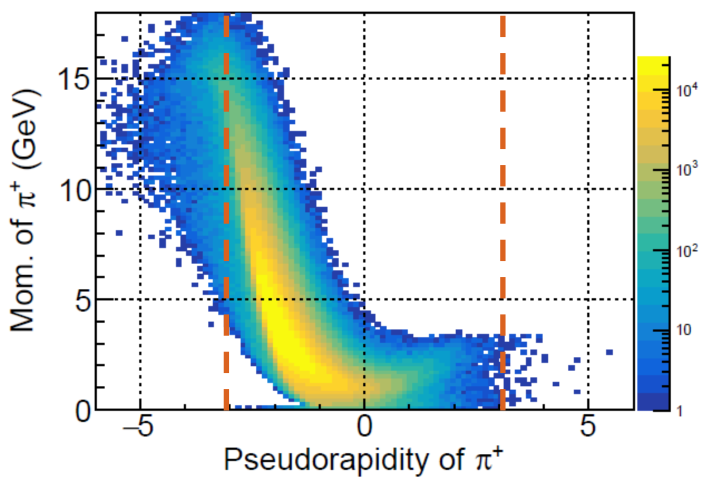
Born term formula

The Kinematics of the Final-State Particles

A MC simulation of the exclusive channel $\mathbf{ep \to en\pi^+}$ at EicC





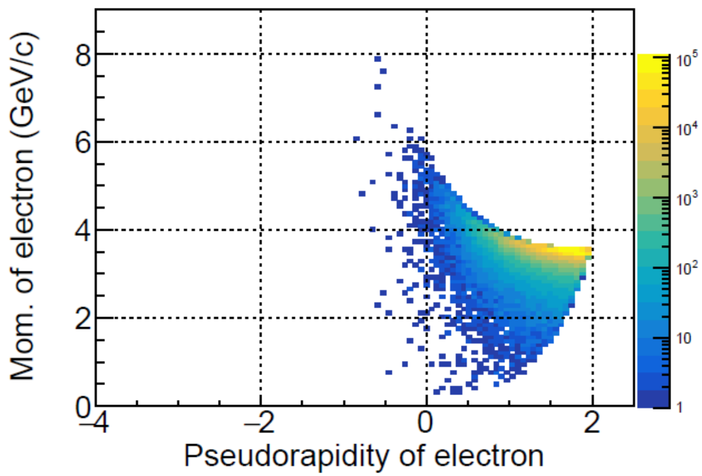


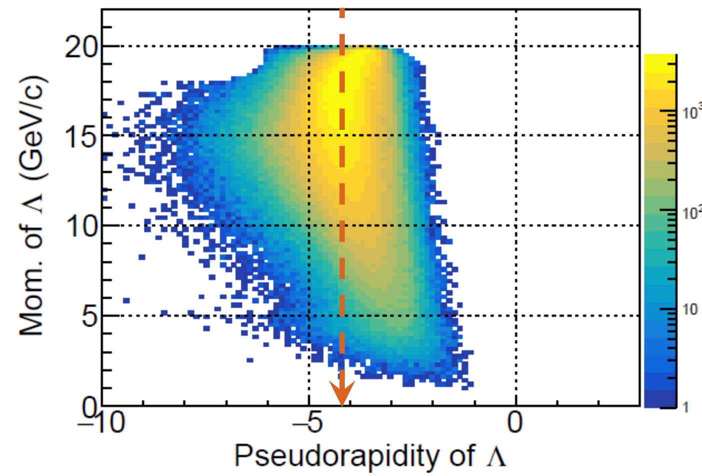
The majority of final electron and π^+ go to the central detectors $|\eta| < 3$.

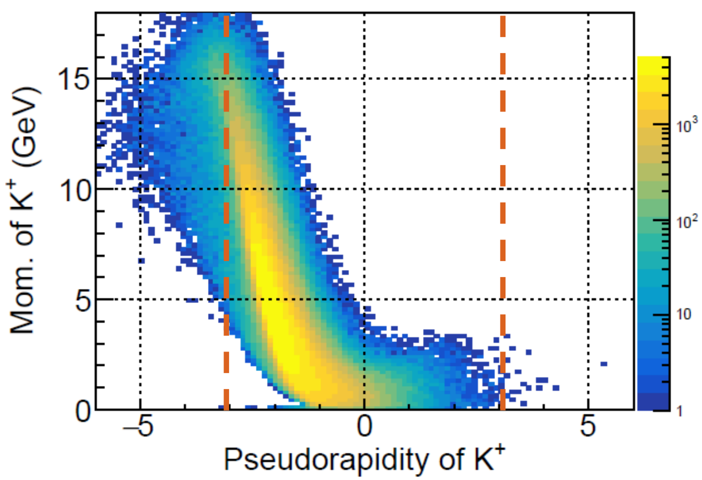
The final neutron goes to the extreme forward region and should be collected with ZDC.

The Kinematics of the Final-State Particles

A MC simulation of the exclusive channel $\mathbf{ep \rightarrow e\Lambda K^{+}}$ at EicC





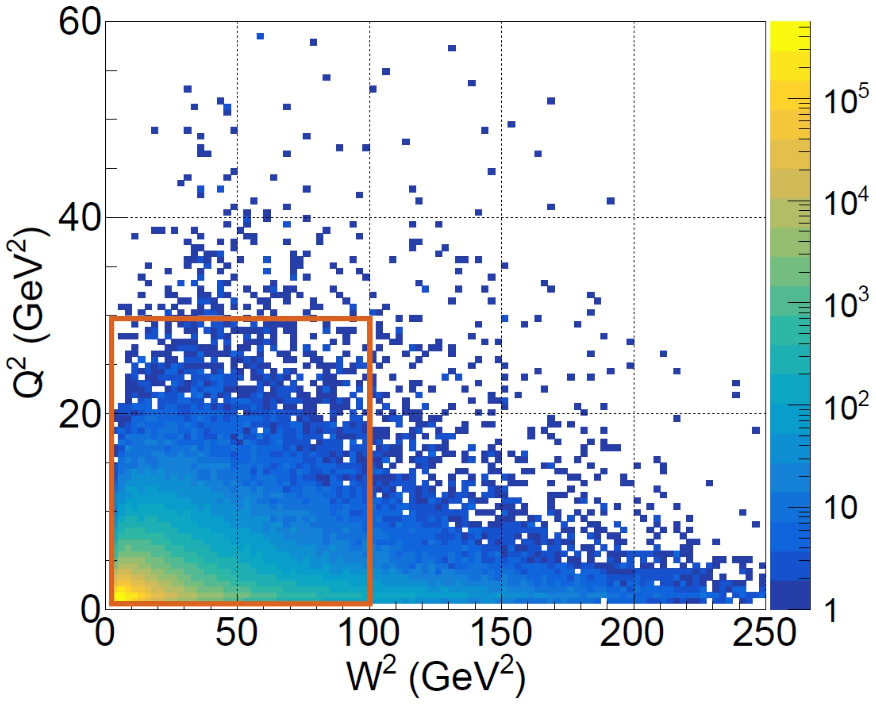


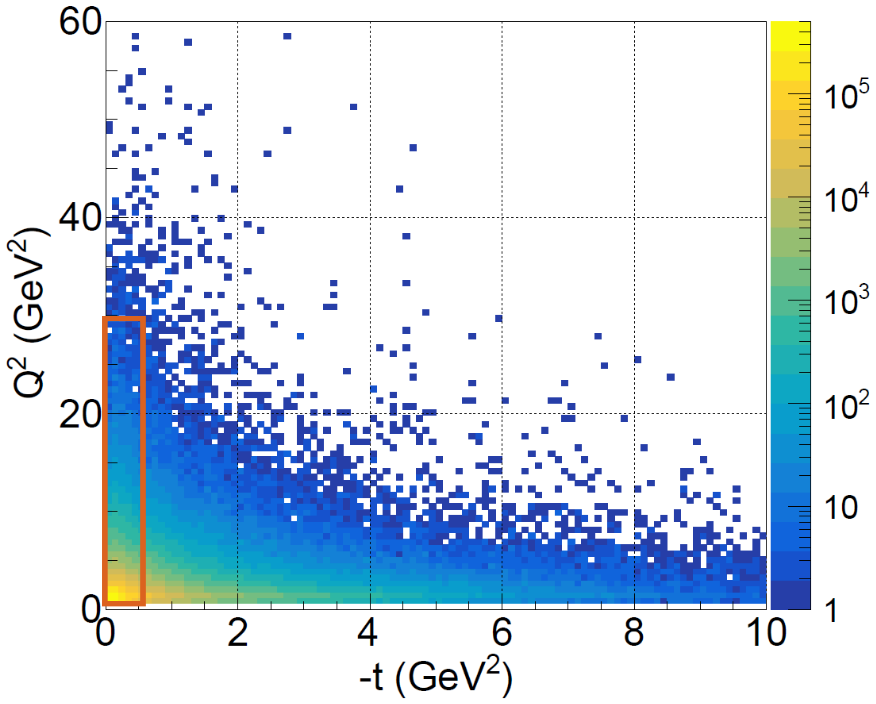
The majority of final electron and K^{+} go to the central detectors $|\eta| < 3$.

Λ (p, π^{-}) goes to the forward region. We will discard the charged particles of $|\eta| > 5$, since they are hard to be separated from the beam.

Distributions of the Invariant Variables for the channel $ep \rightarrow en\pi^+$

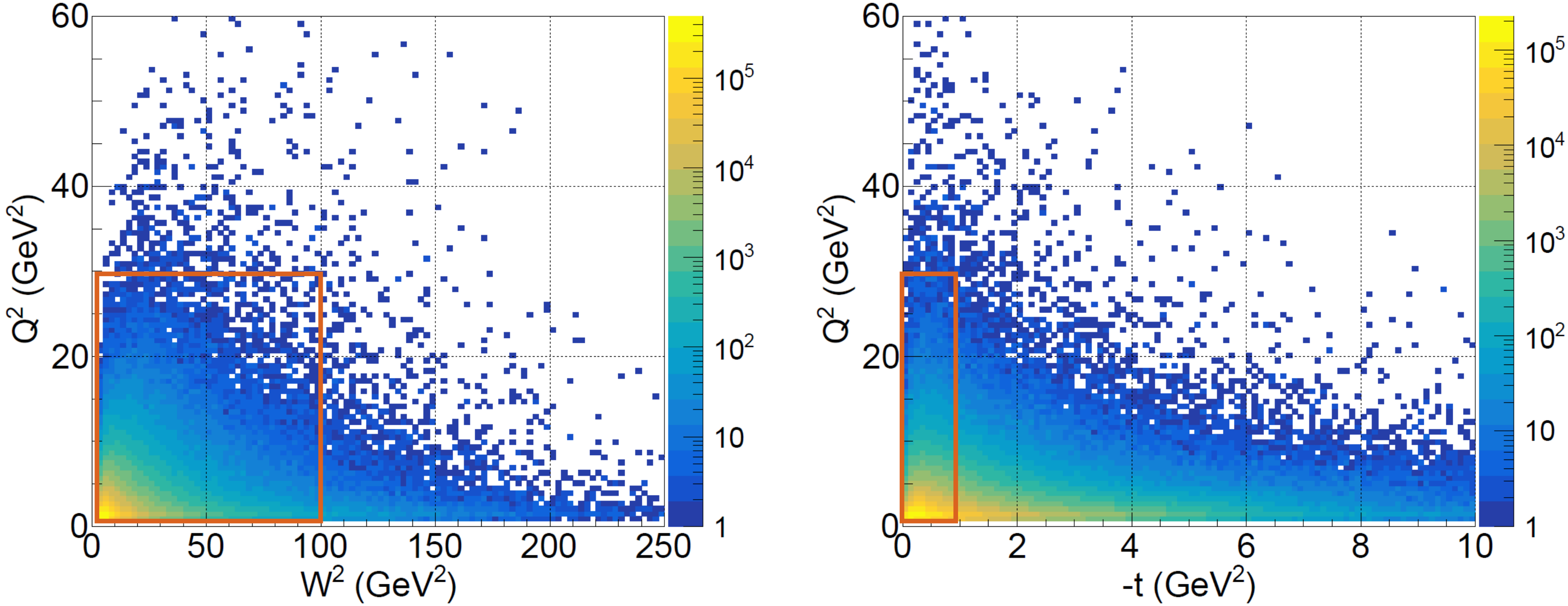
The distributions of 4 million MC events are shown below.
The rectangles show the region where are used to extract the pion form factor.





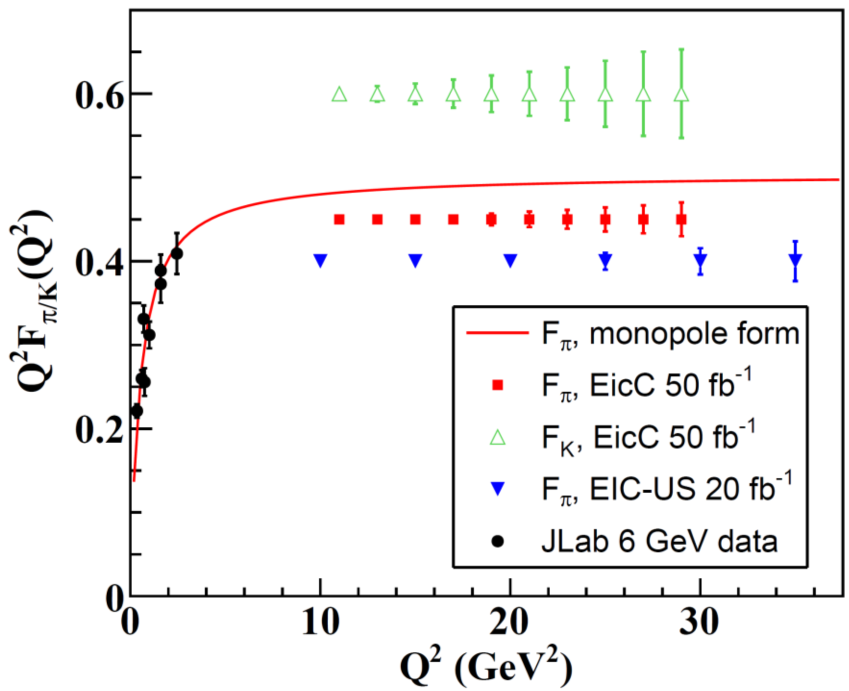
Distributions of the Invariant Variables for the channel $ep \to e\Lambda K^+$

The distributions of 3.6 million MC events are shown below.
The rectangles show the region where are used to extract the kaon form factor.



Statistical Error Projections for Pion and Kaon Form Factors

Assuming an integrated luminosity of 50 fb^{-1} at EicC, the estimated statistical errors of the pion and kaon form factors are shown below. For forward neutrons, we assume a 100% acceptance. For forward Λ, we will collect the charged decays (p, π^-), and the branching ratio is 64%. For the acceptance of forward p and π^-, we require $|\eta| < 5$. These shown errors can be regarded as the ideal case for the future experimental running.



Simulation of the Leading Neutron Tagged DIS

- To measure the pion structure, we can use the pion cloud around the high energy proton. In coincidence with the electron-π^+ DIS process, we observe at the same time a leading neutron (spectator), which carries a large fraction of the longitudinal momentum of incoming nucleon and has an almost unaltered transverse momentum.

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

$$F_2^{\mathrm{LN}(4)}(Q^2, x_B, x_L, t) = F_2^{\pi}(x_\pi, Q^2) f_{\pi \text{ in p}}(x_L, t)$$

$$f_{\pi \text{ in p}}(x_L, t) = \frac{1}{2\pi}\frac{g_{\pi\mathrm{NN}}^2}{4\pi}(1 - x_L)\frac{-t}{(m_\pi^2 - t)^2} exp\left(-R_{\pi\mathrm{N}}^2 \frac{m_\pi^2 - t}{1 - x_L}\right)$$

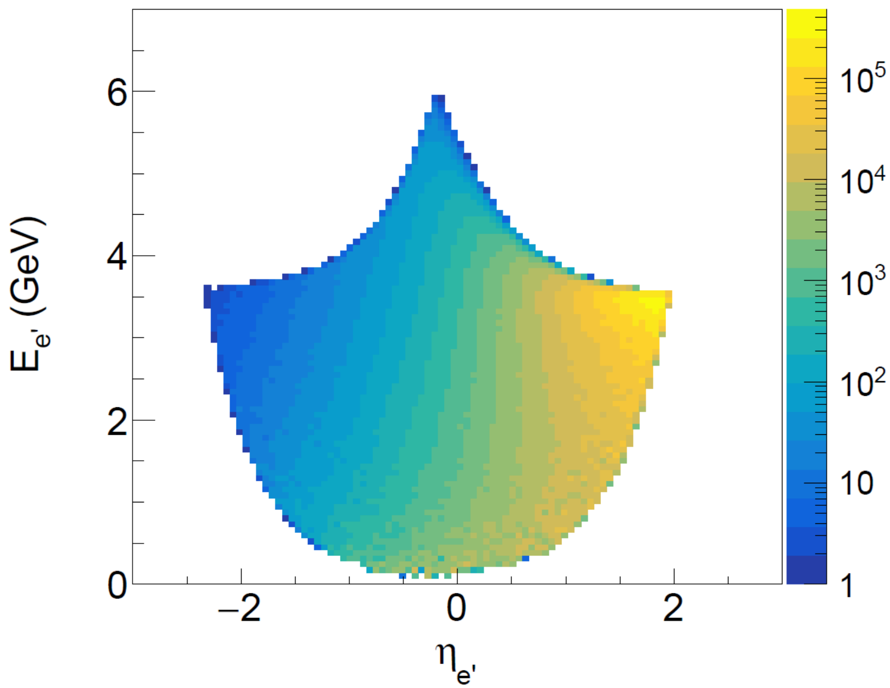
[H. Holtmann et al., Phys. Lett. B 338, 363 (1994); S. Chekanov et al. (ZEUS Collaboration), Nucl. Phys. B 637, 3 (2002); F. Aaron et al. (H1 Collaboration), Euro. Phys. J. C 68, 381 (2010)]

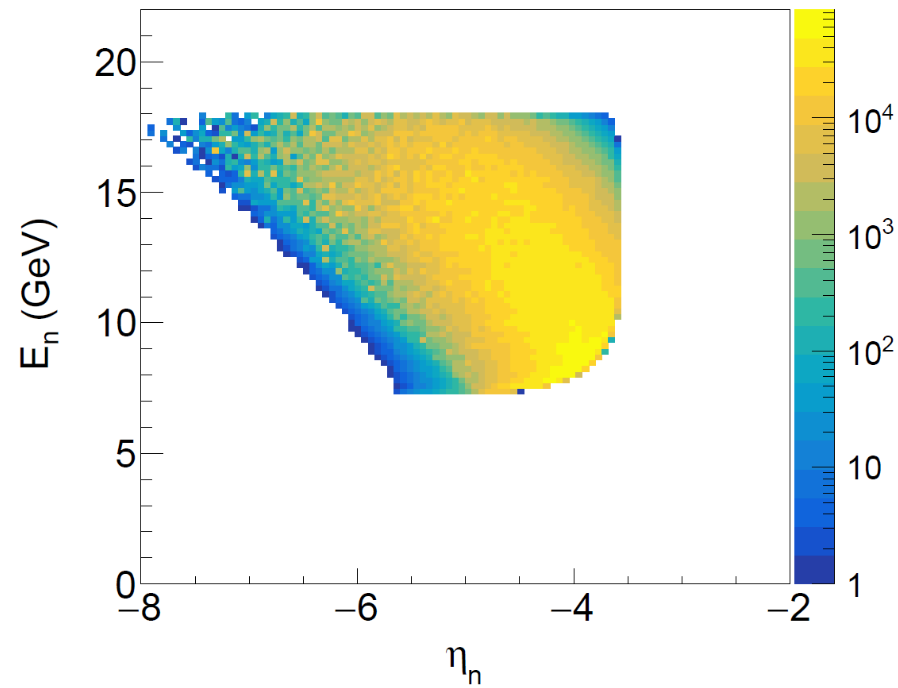
We write an event generator based on the model above, to investigate the experimental setup and the statistics at EicC

The Kinematics of the Scattered Electron and the Final Leading Neutron

In the event generation, we have used the following cuts:
(1) $1 < Q^2 < 50\ \text{GeV}^2$; (2) $W^2 > 3.5\ \text{GeV}^2$;
(3) $0.01 < -t < 1\ \text{GeV}^2$; (4) $0.6 < x_L < 0.8$.

$$W^2 = (P_e + P_p - P_{e'})^2$$
$$x_L = \frac{P_n \cdot q}{P_p \cdot q}$$





Distributions of the Invariant Variables for the channel ep → e'nX

In the event generation, we have used the following cuts:
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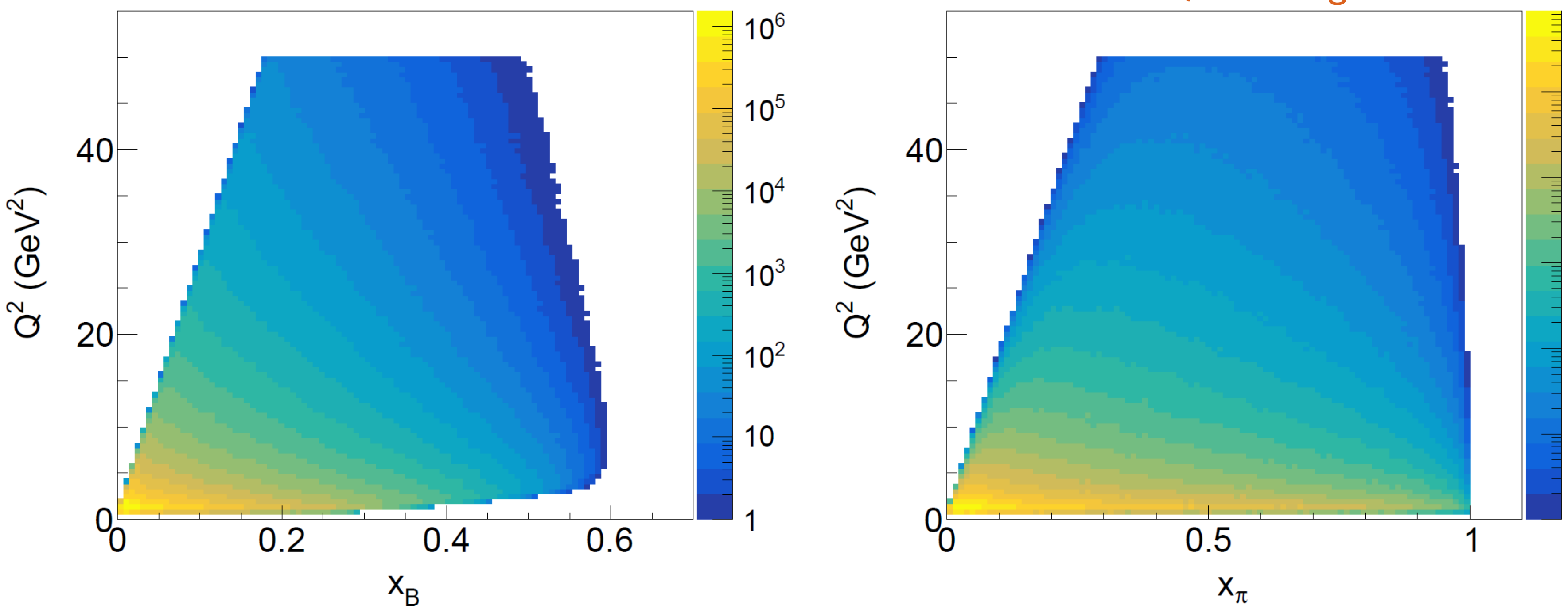
(3) $0.01 < -t < 1\ \mathrm{GeV}^2$; (4) $0.6 < x_L < 0.8$.

$$x_\pi = \frac{Q^2}{2P_\pi \cdot q} = \frac{x_B}{1 - x_L}$$

A broader Q^2 coverage is seen.



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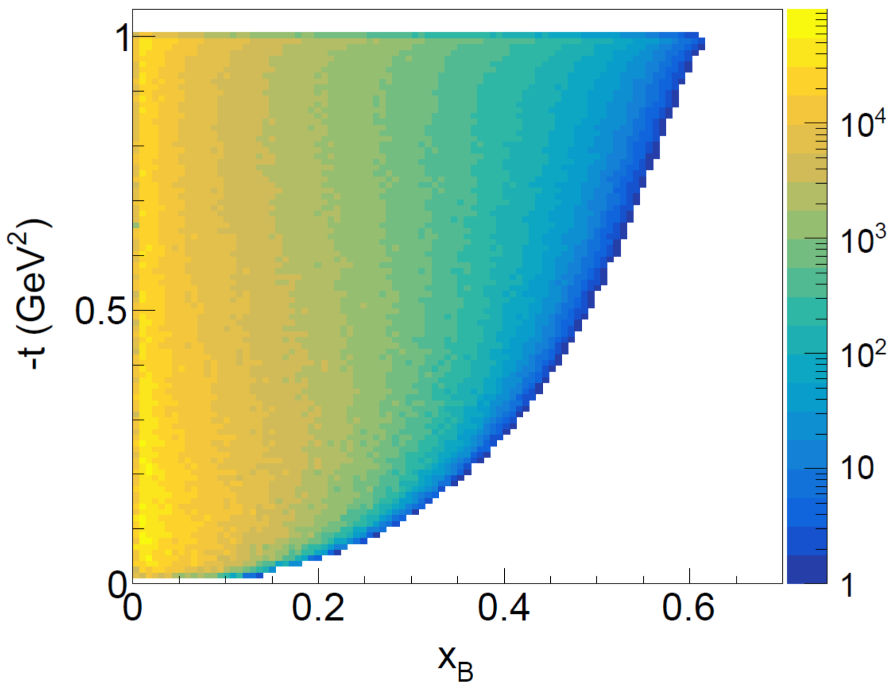
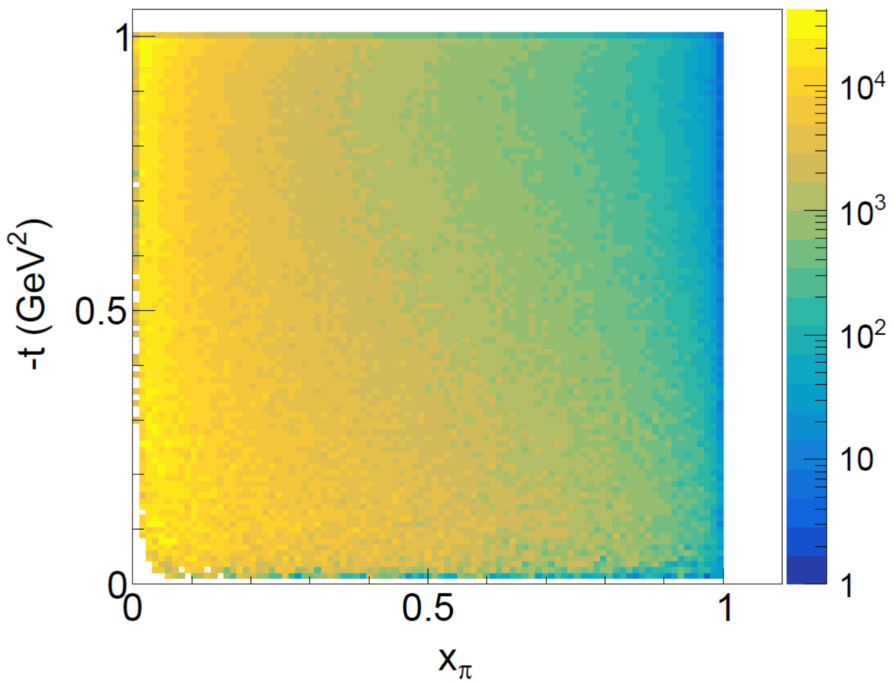
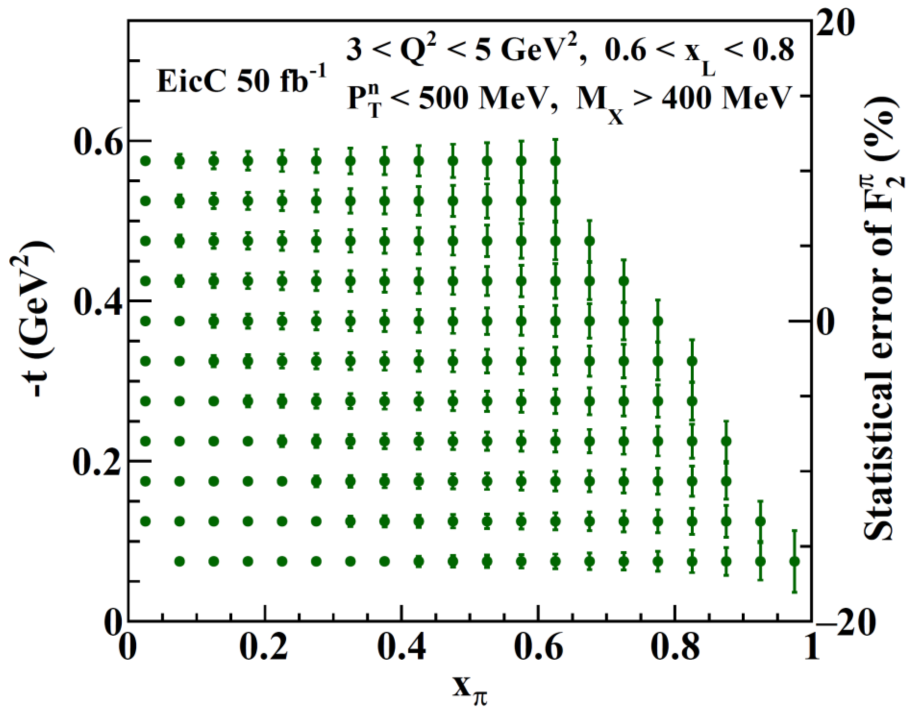




Statistical Error Projections for Pion Structure Function at EicC

Assuming an integrated luminosity of 50 fb^{-1} at EicC, the estimated statistical errors of the pion structure functions are shown below. At Q^2 = 4 GeV^2, the suggested experiment provides the pion structure functions from sea quark region (0.01) to the large x region (0.95) with good precisions.

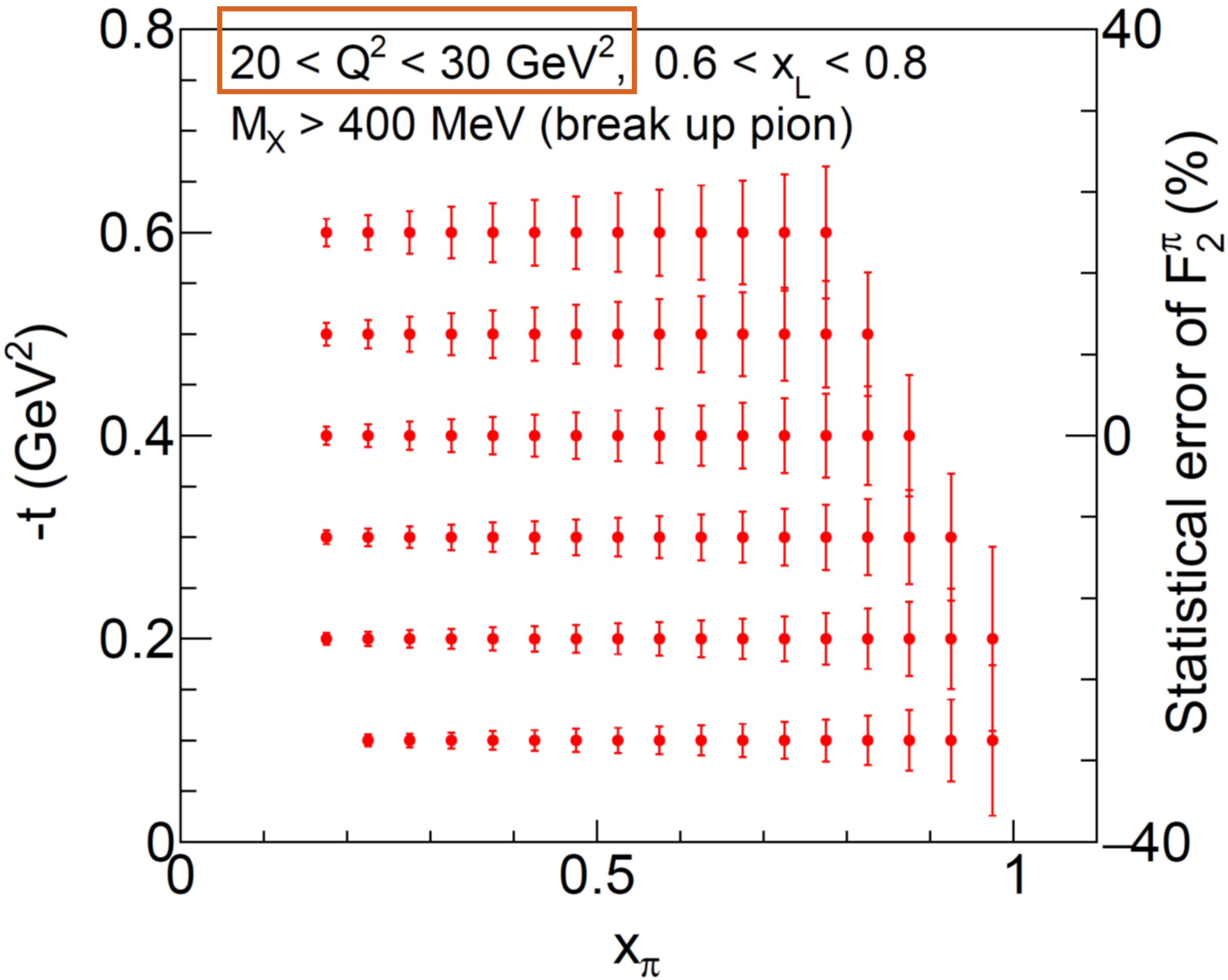


A few data points with quite large errors are excluded, to have a better presentation of the result.

$$M_X^2 = (P_e + P_p - P_{e'} - P_n)^2$$

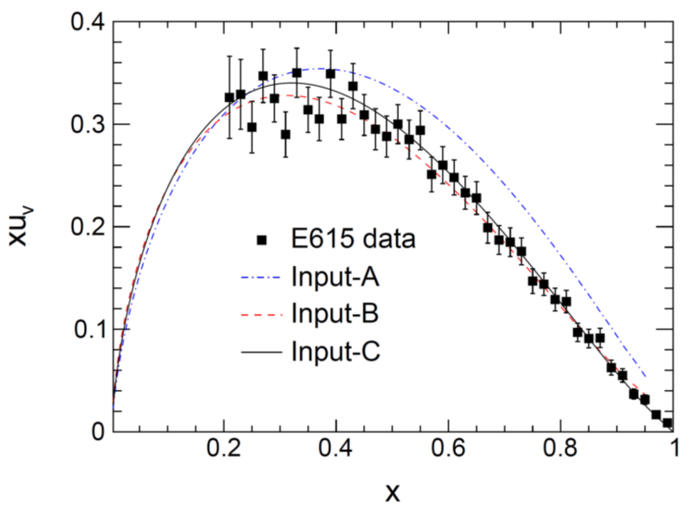
The requirement $M_X > 0.4$ GeV is to break up the pion and to access the extremely large x_π region.

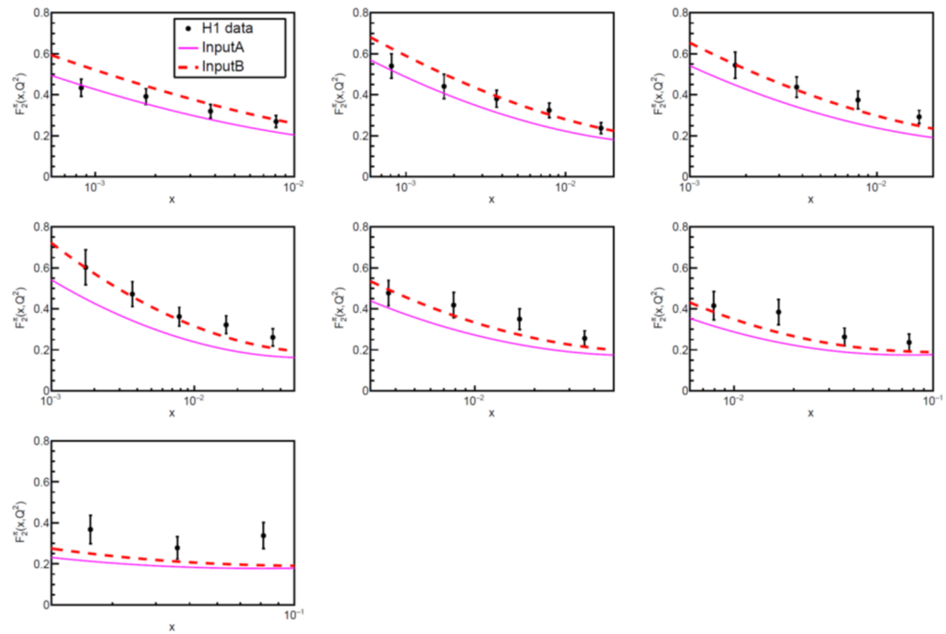
Statistical Error Projections for Pion Structure Function at EicC



piIMParton: a PDF SET of pion

- ***piIMParton*** provides the dynamical parton distribution functions of pion from the parton-parton recombination corrected QCD evolution equations, with a phenomenological nonperturbative input deduced from the maximum information entropy. [C. Han et al., Phys. Lett. B 800, 135066 (2020)]





- **piIMParton PDFs could be used for the simulation purpose.**

https://github.com/lukeronger/piIMParton

Summary

- The precision data on pion and kaon structures in a wide kinematical domain of x_π vs. Q^2 are highly needed.

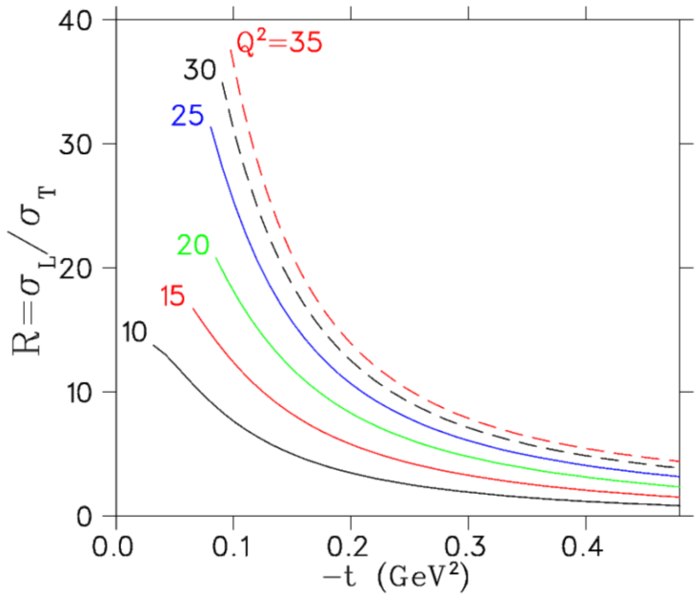
- EicC provides a good opportunity to explore the pion and kaon structures. We will focus the Q^2 range [10, 20] GeV^2 for form factor measurement, and the Q^2 range [1, 40] GeV^2 for the structure function measurement.

- Comments/questions (rwang@impcas.ac.cn, xchen@impcas.ac.cn)

Thank you!

Backup: without and with L-T separation

In the hard scattering regime, QCD scalling predicts $\sigma_L \propto 1/Q^6$ and $\sigma_T \propto 1/Q^8$.



- T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203.
- Predictions are for ε>0.995 Q^2, W kinematics shown earlier.

At small t & high Q^2, $\sigma_L \gg \sigma_T$.
No need for L-T separation!!
Transverse part is just a small correction.

L-T separation method:

Measuring $(\frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt})$ at two energies

Q^2, GeV²	W, GeV	$\sqrt{s}$, GeV	ε
10	10	12	**0.449**
10	10	16	**0.862**
10	10	20	**0.951**
15	10	12	**0.388**
15	10	16	**0.846**
15	10	20	**0.946**
20	10	12	**0.324**
20	10	16	**0.829**
20	10	20	**0.940**