Meson Structure at EicC

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Outline

- Motivations for meson structure measurement
- Previous experiments & EicC opportunity
- Simulations and discussions
- Forward neutron detector
- Summary

Motivations

- **How to understand the masses of the proton and π meson (K meson) is fundamental and profound question in QCD.**

At extremely low scale, proton is made of 3 valence quarks and pion is made of 1 valence quark and 1 valence anti-quark.

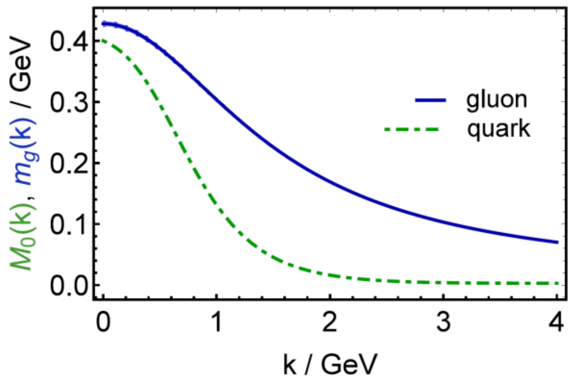
?

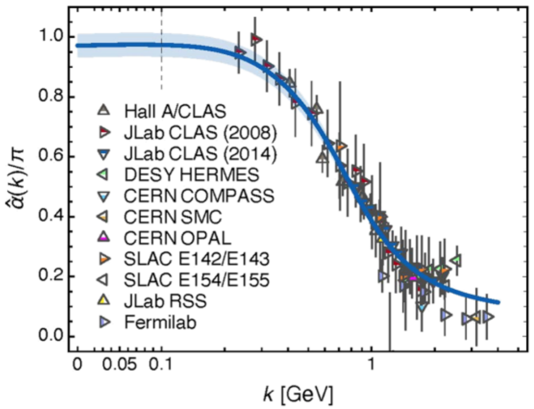
$$m_p \gg m_\pi$$

- **Gluon self-interactions!**

In the deep infrared region, the gluon acquire a big effective mass. The light quark becomes massive by dressing up with gluons.

Chiral limit mass function:





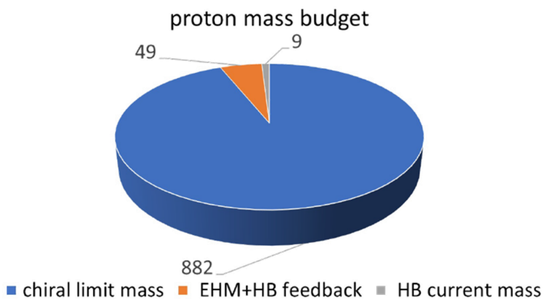
Infrared-safety strong running coupling & scale-invariant in extremely low scale region & parameter-free prediction & frame independent

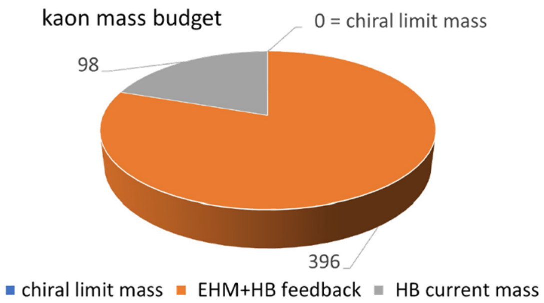
Motivations

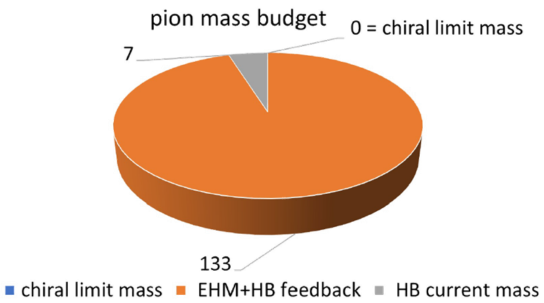
- **Two mechanisms for the hadron mass: HB and EHM**

HB: Higgs Boson mechanism
EHM: Emergent Hadron Mass mechanism

- **Three parts of hadron mass: HB mass, HB+EHM mass, chiral-limit mass**







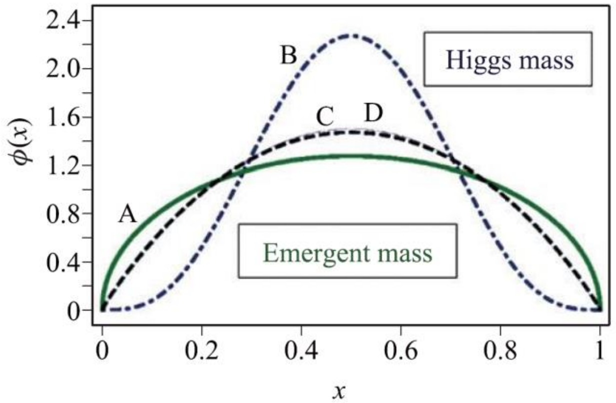
For the proton, the chiral-limit mass is dominant.

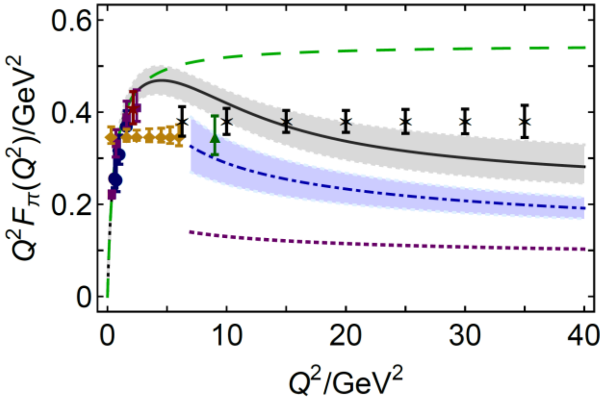
For the pion, the chiral-limit mass is zero due to the Nambu-Goldstone nature. The pion mass is mainly from the constructive interference between HB and EHM.

For the kaon, the HB mass is negligible.

Motivations

- With EHM mechanism, the DSE calculation gives quite different form factors and structure functions of π and k from the predictions of HB mass only.





Monopole FF

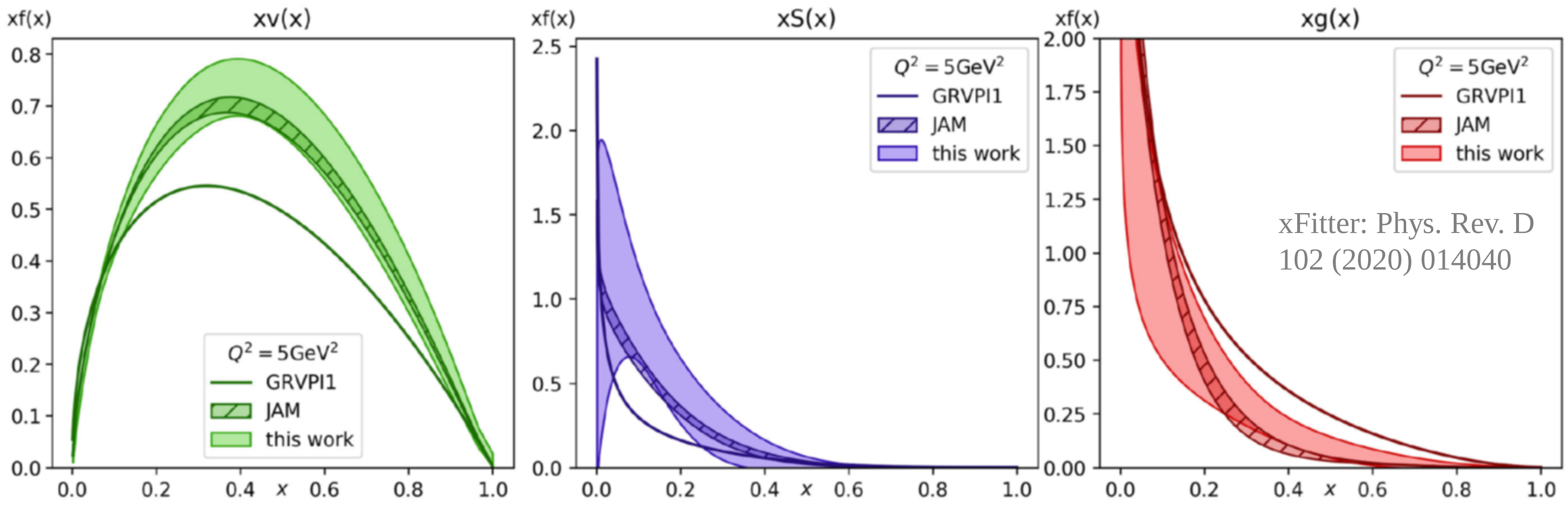
EHM+HB FF

Asymptotic FF

Measuring the form factors of π and k mesons at high Q^2 is one way see EHM!

Motivations

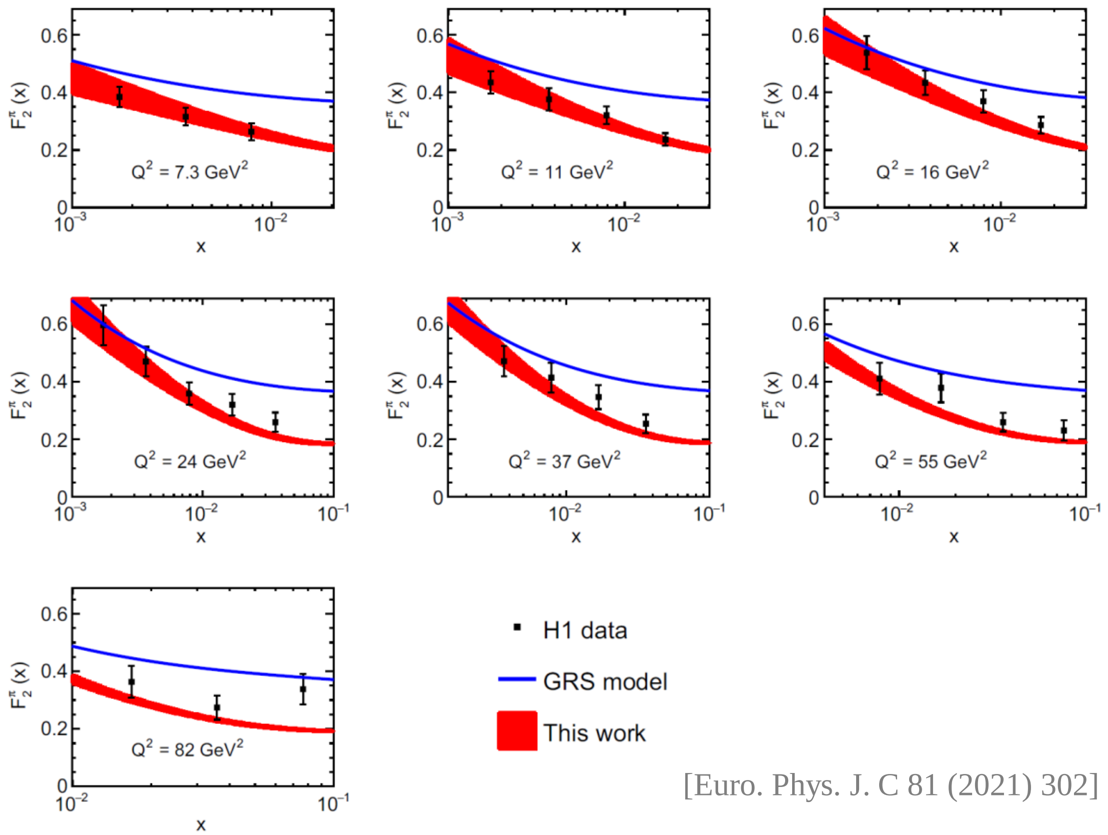
- The π & K mesons are so simple in the quark model. **However, we know not much about the pion structure and very little about the kaon structure.**
- There are some global analyses of the pion-induced Drell-Yan data and the neutron-tagged DIS data at HERA. The extracted pion PDFs are shown below. JAM used both the pion-induced Drell-Yan data and the neutron-tagged DIS data. xFitter used only the Drell-Yan data.



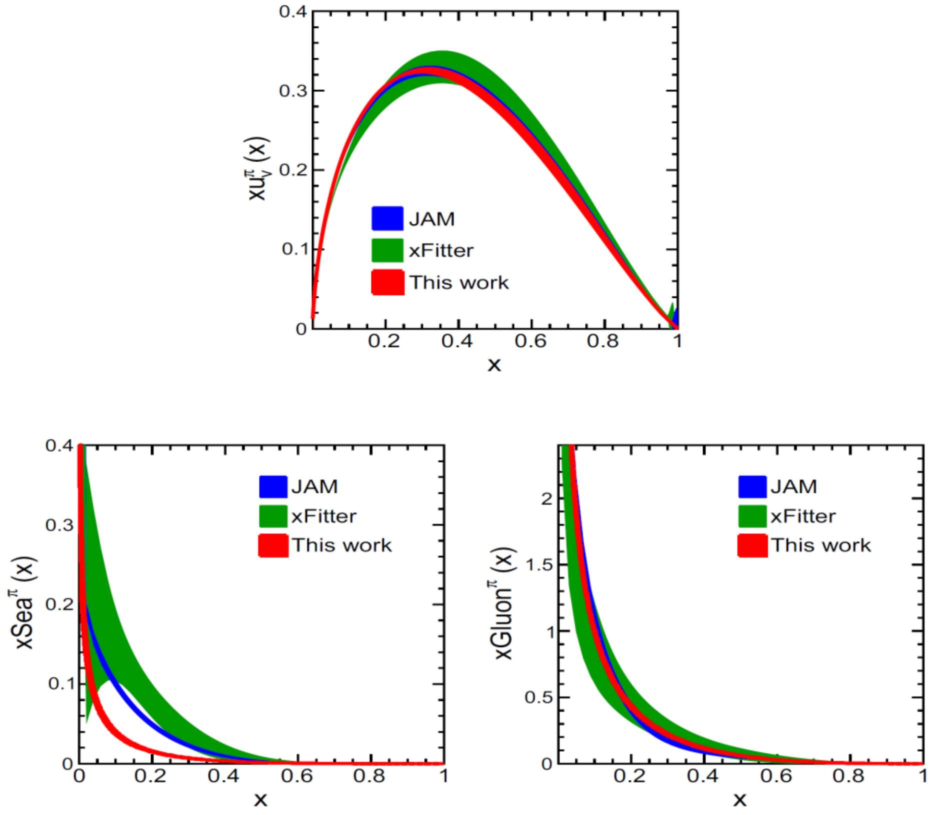
Neutron-tagged DIS data is crucial to reduce the uncertainties of sea quark and gluon distributions of the pion!

Motivations

We have performed an analysis to the current available data under the assumption that all sea quarks and gluons come from gluon radiations. **The purely dynamically produced sea quarks agree well with the H1 leading neutron-tagged DIS data. (Infrared-safety strong coupling is used)**



[Euro. Phys. J. C 81 (2021) 302]

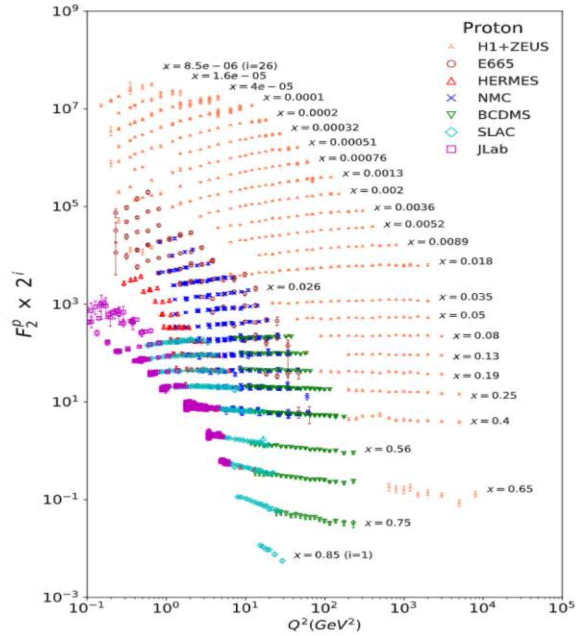


Motivations

- The asymptotic freedom and perturbative QCD calculations are successfully tested in experiments. Now it is a new age to test QCD at long distance. We need to understand QCD in all the kinematical regions.

Measuring the pion and kaon structure functions provides a way to test the fruitful calculations from the nonperturbative approaches (lQCD and the continuum DSE)!

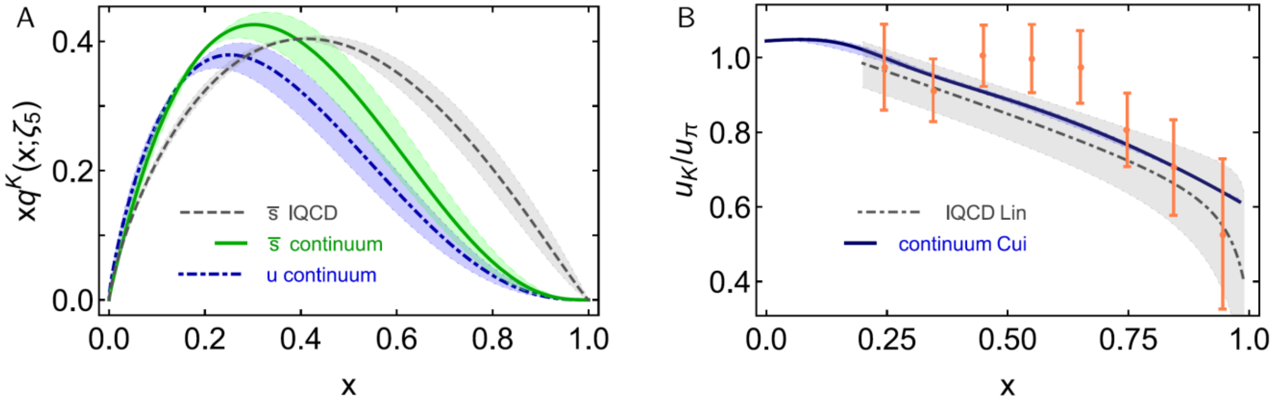
The Q^2-dependence is well described by AP equation of pQCD



non-pQCD predictions to be tested.

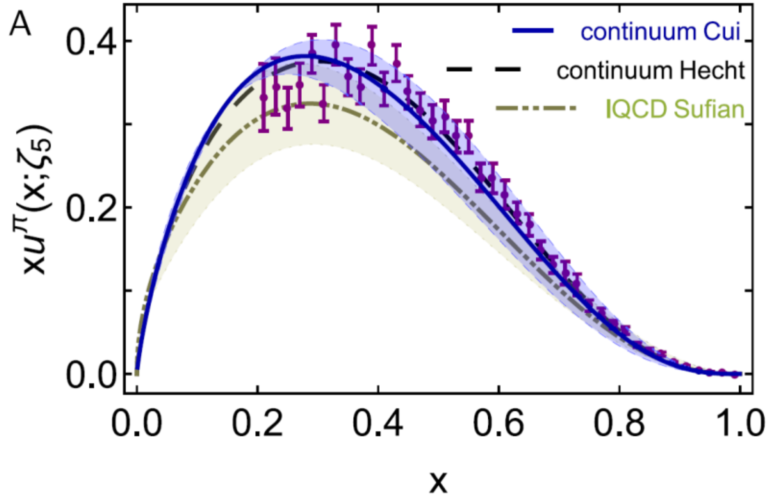
$$q^{\Pi}(x;\zeta_H) \overset{x\simeq 1}{=} c(\zeta_H)(1-x)^{\beta_\Pi(\zeta_H)}, \quad \beta_\Pi(\zeta_H) = 2$$

[Progress in Particle and Nuclear Physics 120 (2021) 103883]



Motivations

- The QCD analysis of Drell-Yan data with next-to-leading soft-gluon re-summation gives the large-x behavior consistent with the DSE calculations. We need more data to better understand this large-x behavior. Neutron-tagged DIS data at large-x are needed to have the similar analysis.



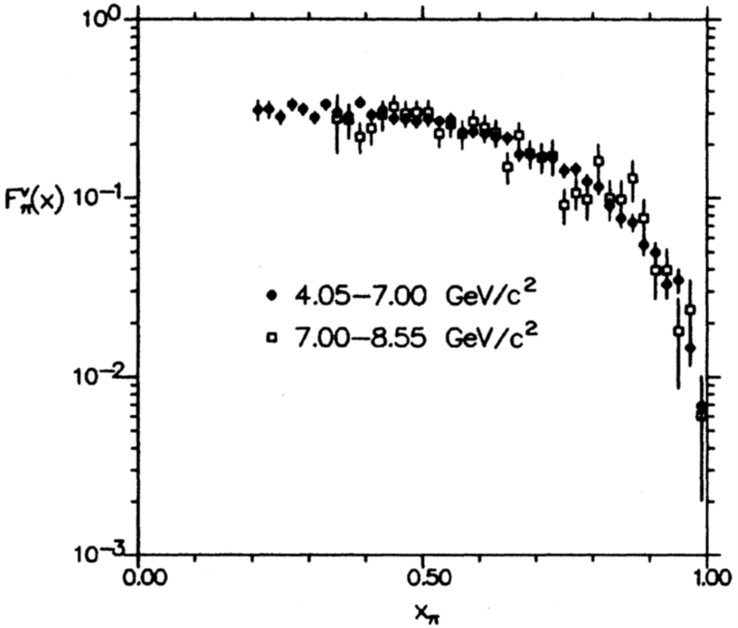
$$q^{\pi}_{\mathrm{E615}}(x;\zeta_4 = 4\ \mathrm{GeV}) \overset{x\simeq 1}{\propto} (1-x)^{2.4}$$

With soft-gluon re-summation

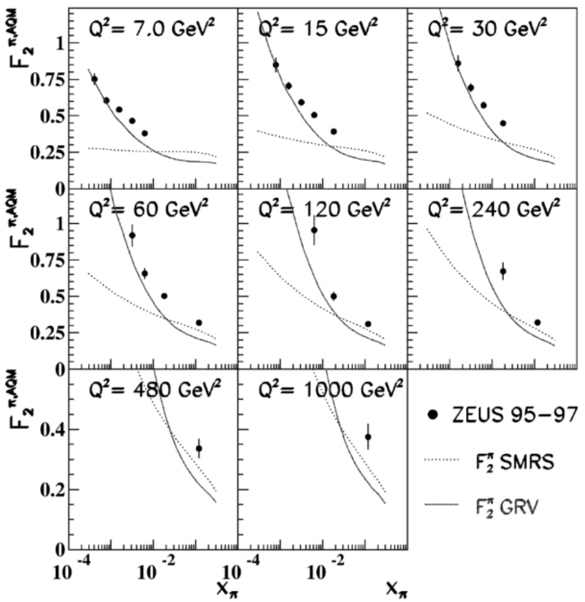
Previous experiments

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 Fπ; 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]

Part of pion data

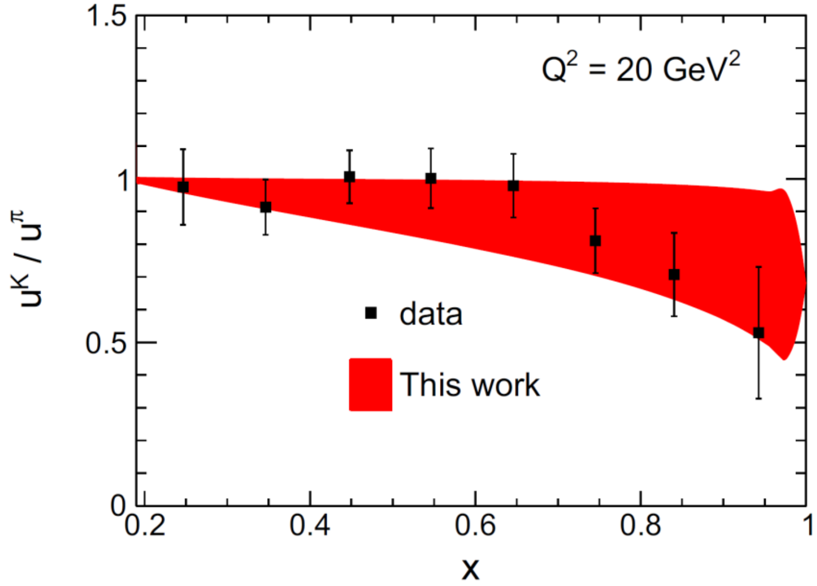


Drell-Yan data



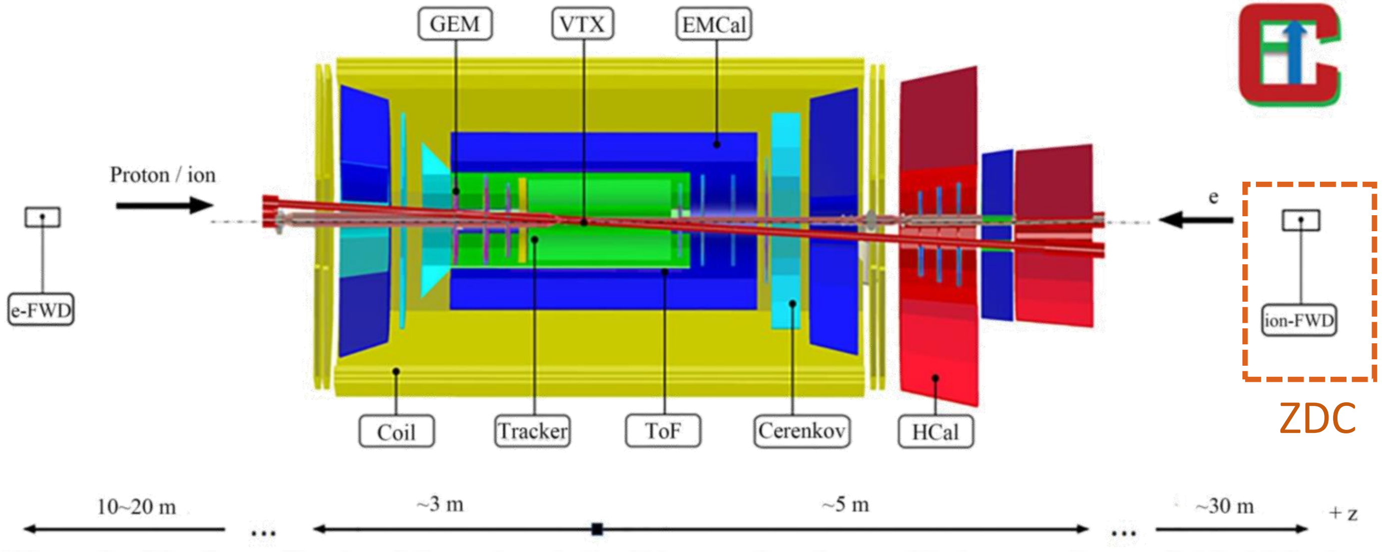
Tagged DIS data at HERA

We know little on kaon structure experimentally!



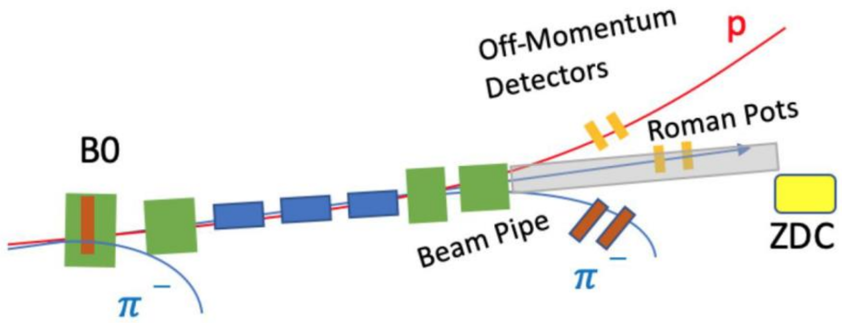
EicC opportunity

EicC conceptual design



Y.-T. **Liang**

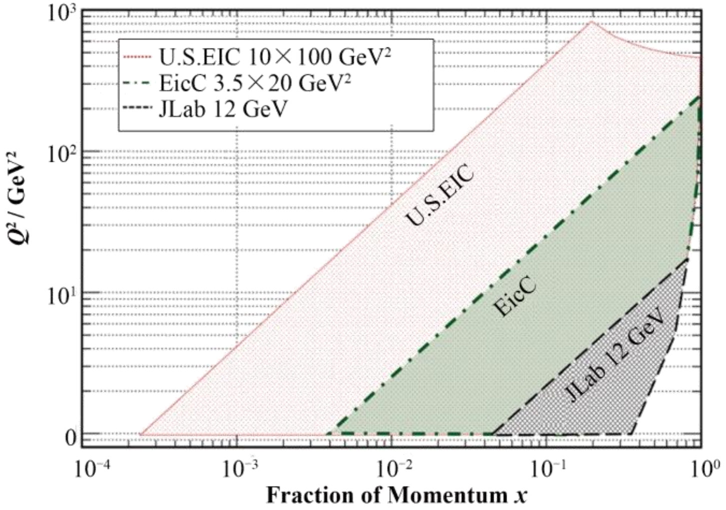
EIC far-forward detector complex



- $\Lambda \to n + \pi^0$: additional high-res/granularity EMCal+tracking before ZDC – seems doable
- $\Lambda \to p + \pi^-$: additional trackers in opposite direction on path to ZDC – more challenging

EicC opportunity

The EicC kinematical coverage bridges well the JLab-12GeV domain and EIC-US domain!



[J. Phys. G: Nucl. Part. Phys. 48 (2021) 075106]

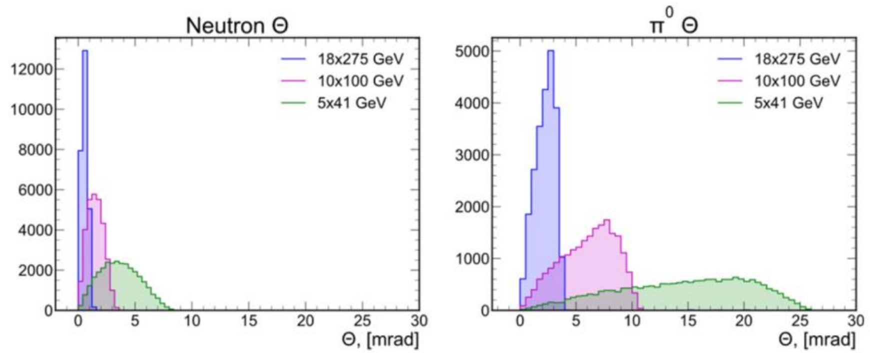


Figure 20. Angular distributions for detected decay products of $\Lambda \to n + \pi^0$: (a) neutrons; and (b) π^0. Beam energy settings: 18×275, 10×100, and 5×41.

Angle distributions of forward particles at EIC-US

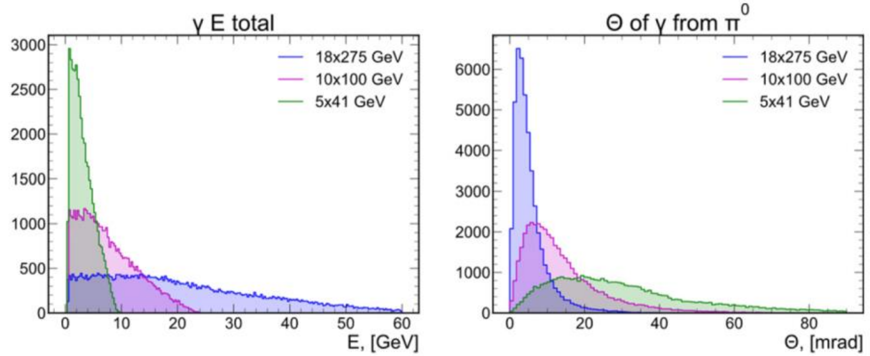
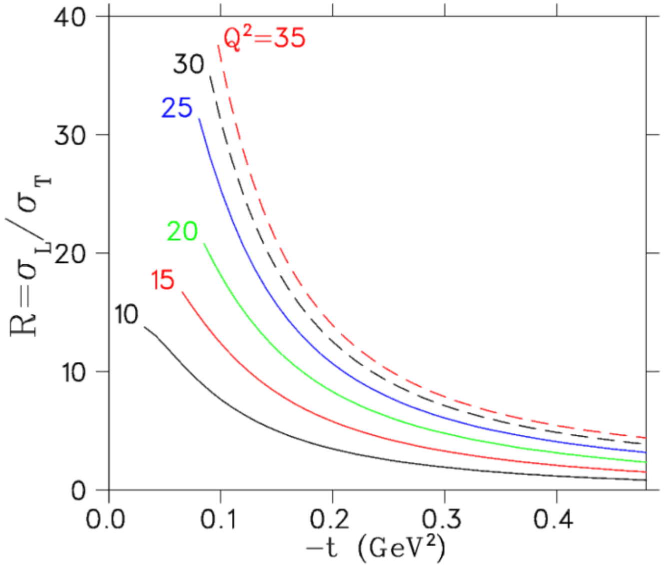


Figure 21. Energy and angular Θ distributions for the detected $\gamma\gamma$ used to reconstruct the π^0 from a Λ decay channel.

Not-very-high c.m. energy is good for forward particle measurements. (large angle spread at EicC!)

EicC opportunity

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.

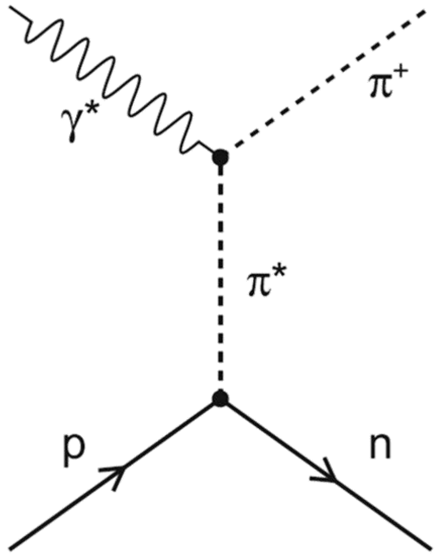
At small t & high Q^2, $\sigma_L \gg \sigma_T$.
No need for L-T separation?
Transverse part is just a small correction.

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**

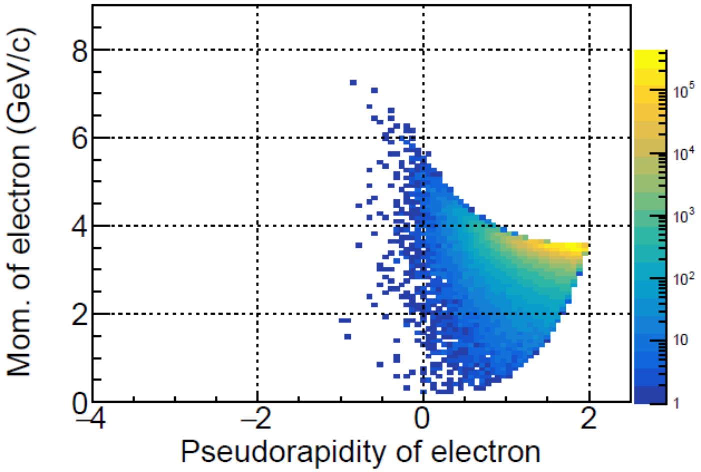
L-T separation is possible at the future EicC!

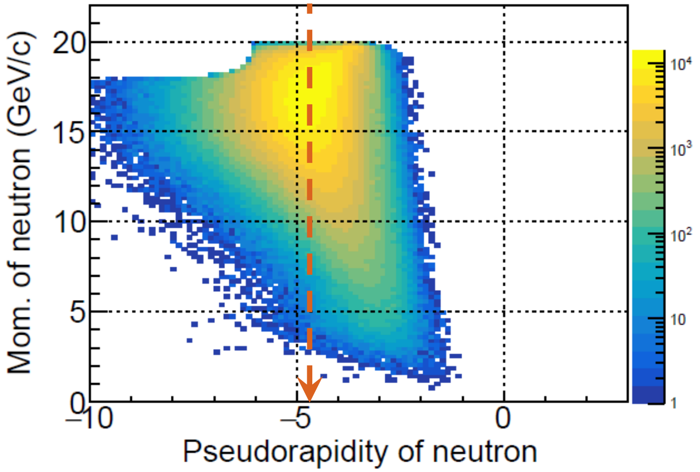
Simulations for EicC

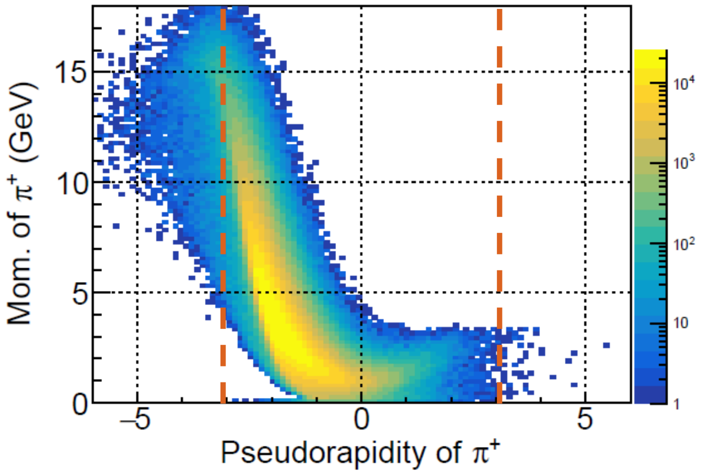


Sullivan process: the elastic scattering between electron probe and the virtual pion.

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





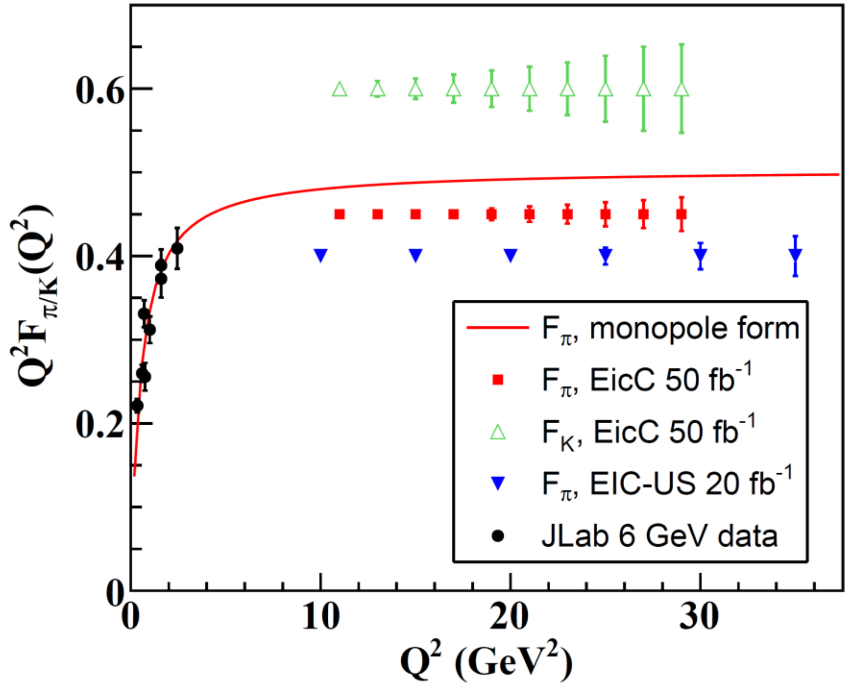


The majority of final electron and π^+ go to the central detectors $|\eta| < 3$.

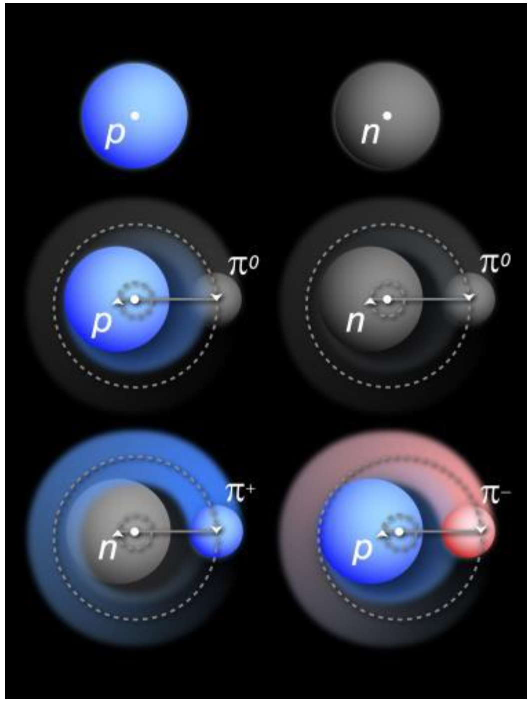
The final neutron goes to the extreme forward region and should be collected with ZDC.

Simulations for EicC

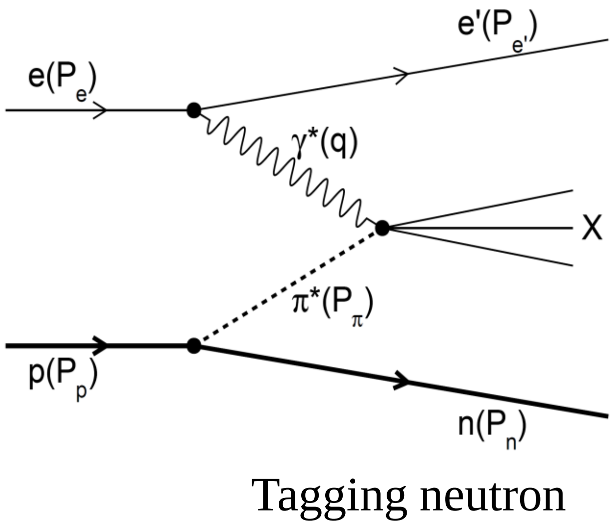
Assuming an integrated luminosity of 50 fb^{-1} at EicC, the estimated statistical errors of the pion and kaon form factors are shown below. For forward neutrons, we assume a 100% acceptance. For forward Λ, we will collect the charged decays (p, π^-), and the branching ratio is 64%. For the acceptance of forward p and π^-, we require $|\eta| < 5$. These shown errors can be regarded as the ideal case for the future experimental running. (The background processes and the performances of the end-cap and forward detectors are not considered so far.)

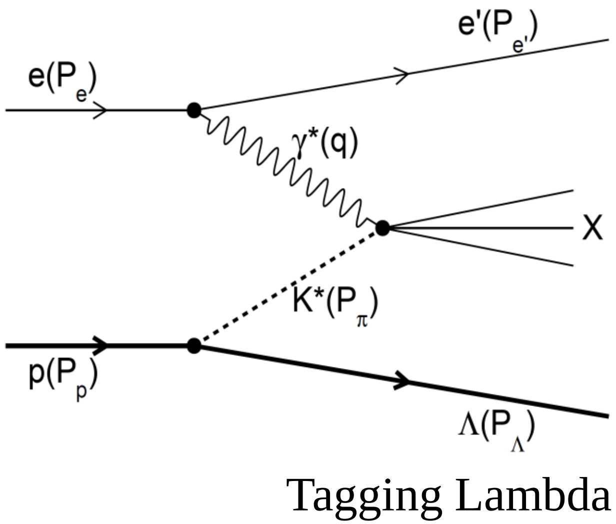


The pion and kaon structure functions can be accessed by electron scattering from the 'meson cloud' outside the proton through the Sullivan process, by tagging the neutrons and Λ's.



[J. Arrington, arXiv:1208.4047]





Leading neutron DIS

Leading Λ baryon DIS

Simulations for EicC

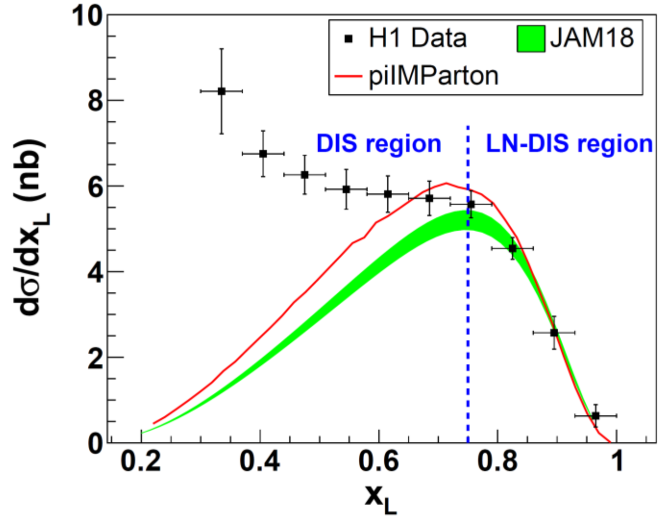
We have constructed the leading-neutron and leading-Lambda DIS event generators (TaggedN_DIS.cpp & TaggedLambda_DIS.cpp) based on the pion/kaon pole flux, pion PDF from JAM analysis, and kaon PDF from IMParton analysis.

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

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

$$f_{\pi^+/p}(x_L,t) = \frac{1}{2\pi}\frac{g^2_{pn\pi}}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2-t)^2}\exp\left(R^2_{n\pi}\frac{t-m_\pi^2}{1-x_L}\right)$$

Using p-Lambda-K coupling and the kaon mass for the kaon flux around the proton

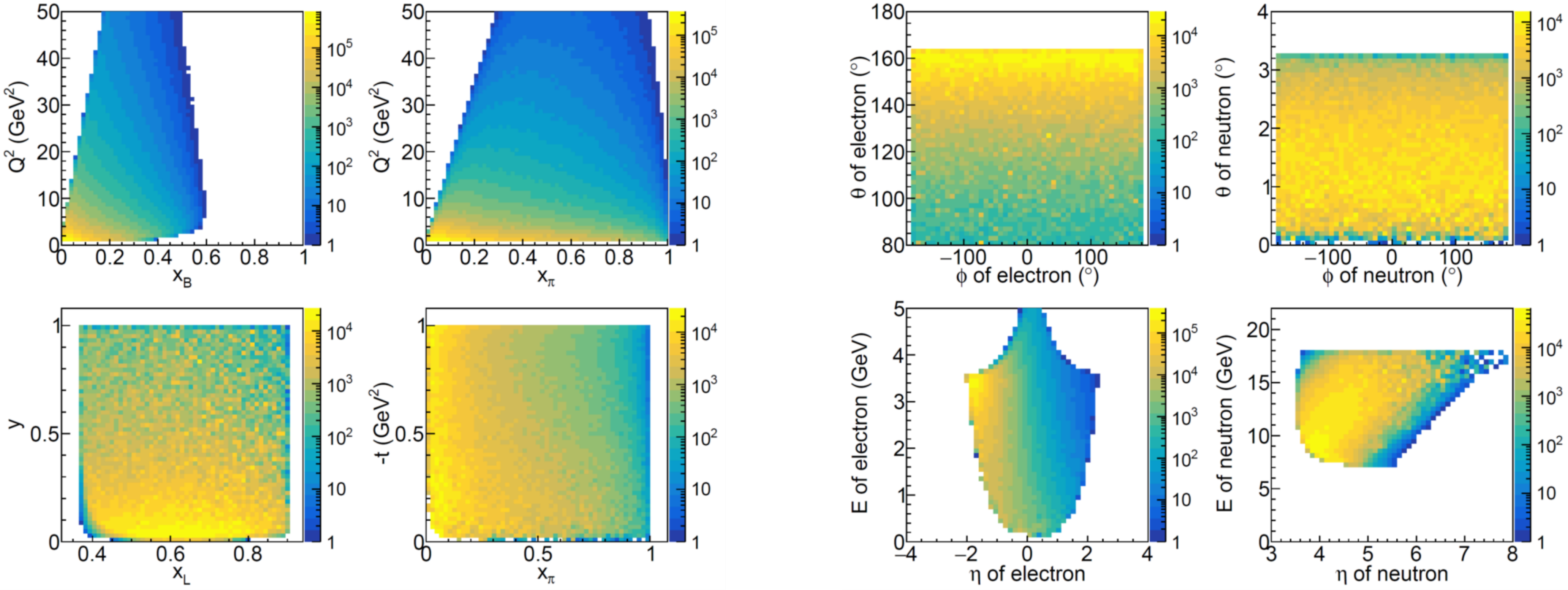


[Chinese Physics C 45 (2021) 053002]

The model for the simulation is checked with previous HERA data.

Simulations for EicC

$ep \to enX$



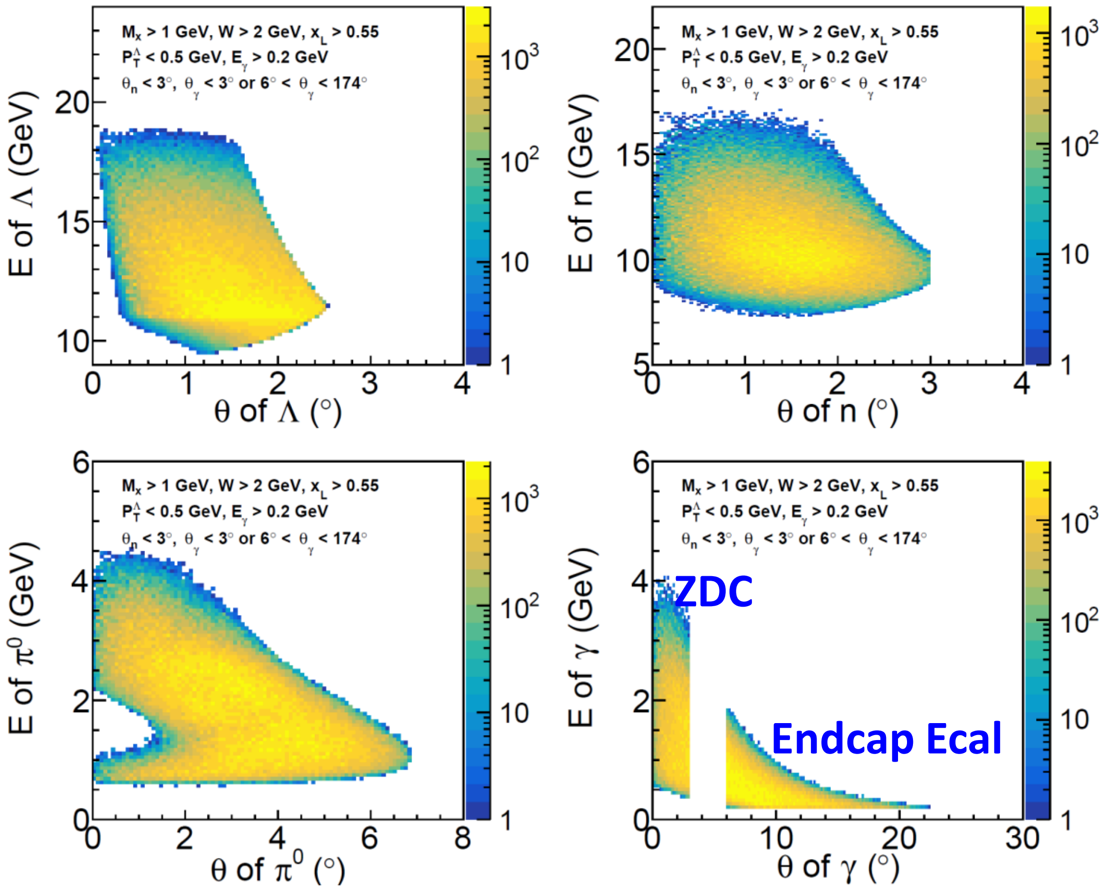
[Chinese Physics C 45 (2021) 053002]

Invariant kinematic distributions of the neutron-tagged DIS events at EicC energy.

The scattered electrons are collected with the central detectors. ZDC should cover the angle from 0 to 3 Deg.

Simulations for EicC

$ep \to e\Lambda X$



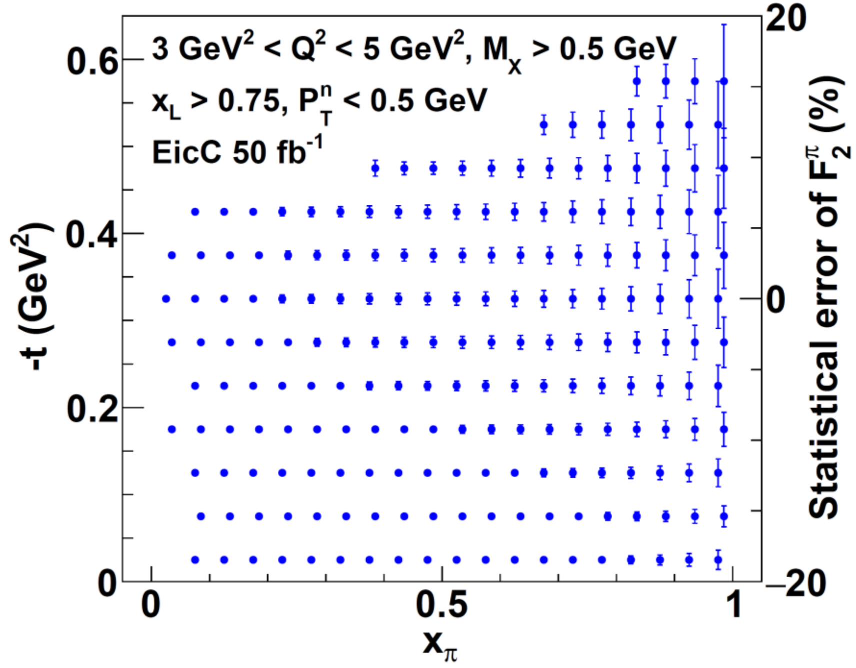
arXiv:2109.08483

To measure the kaon structure, we tag the neutron and two gammas from Lambda decay, with the far-forward detector ZDC of EicC and the central ECal.

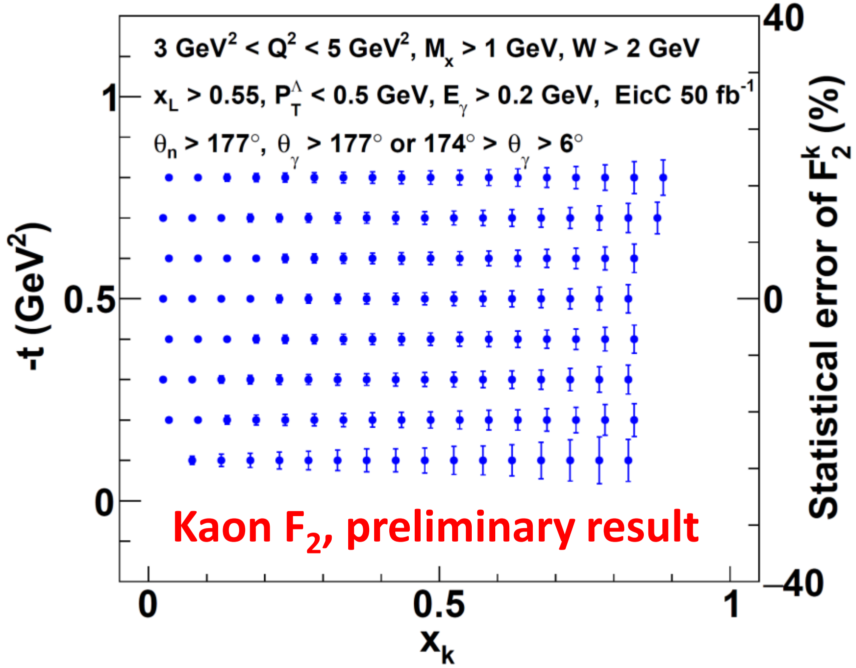
We assume ZDC covers the angle from 0 to 3 Deg. The gammas are supposed to be detected with ZDC and Endcap Ecal.

Simulations for EicC

[Chinese Physics C 45 (2021) 053002]



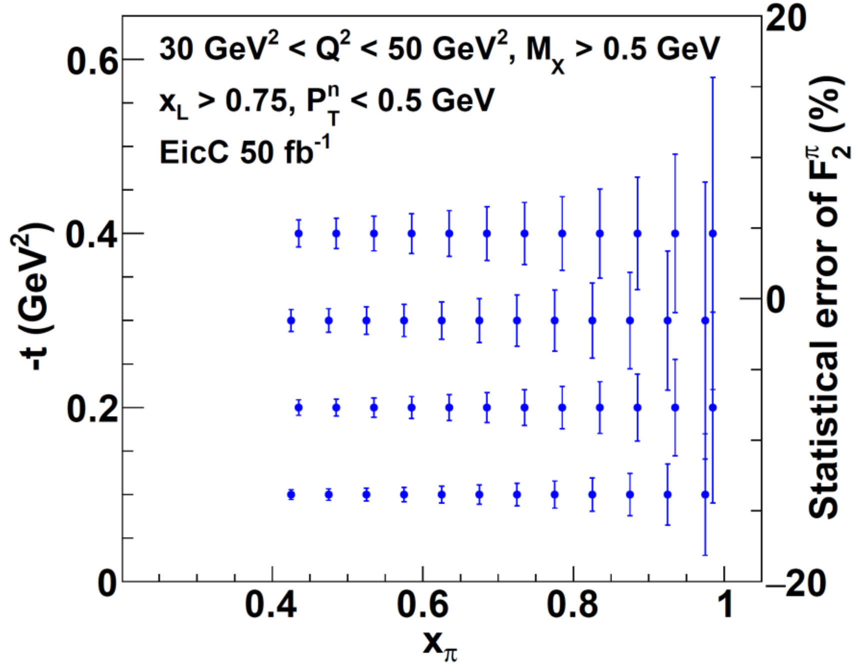
[arXiv:2109.08483]



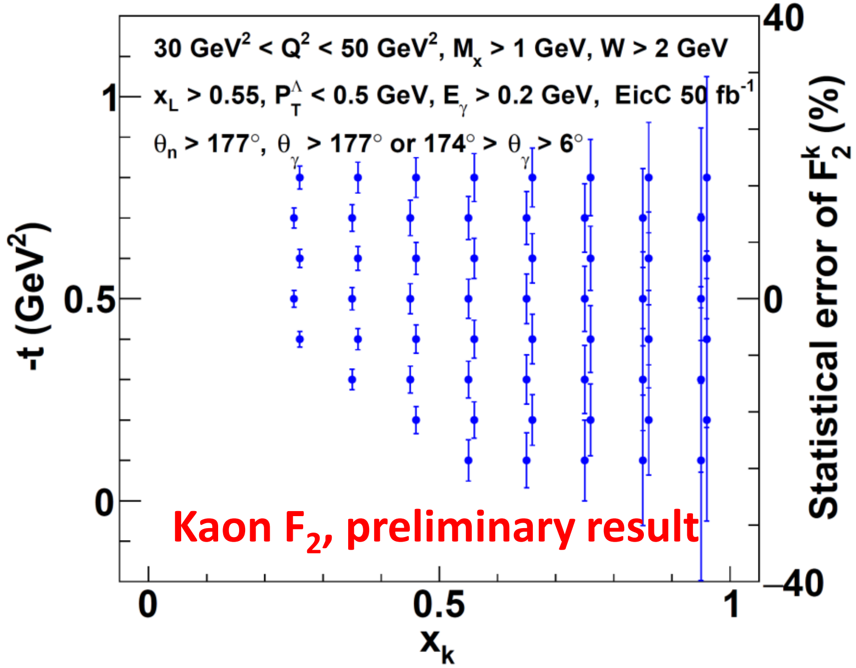
For Lambda-tagged events, we use the wider bins. Under the 50 fb^{-1} luminosity, the uncertainties on the kaon structure are small, which will play an important role in the synergy to JLab12GeV, Amber, EIC measurements and the future global QCD analysis.

Simulations for EicC

[Chinese Physics C 45 (2021) 053002]



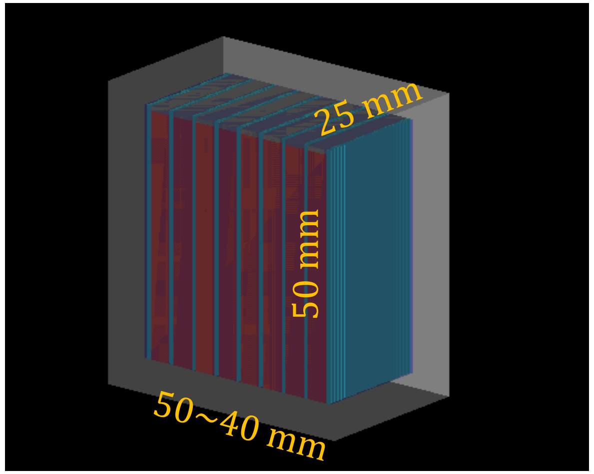
[arXiv:2109.08483]

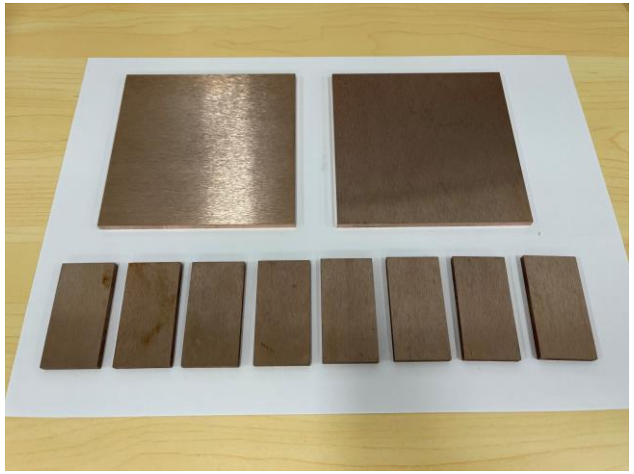


EicC also will provide the meson structure function data at high Q^2, though with relatively larger uncertainties. This is vital for the extraction of the gluon distribution via scaling violation.

Forward neutron detector

- Zero-degree calorimeter, R&D



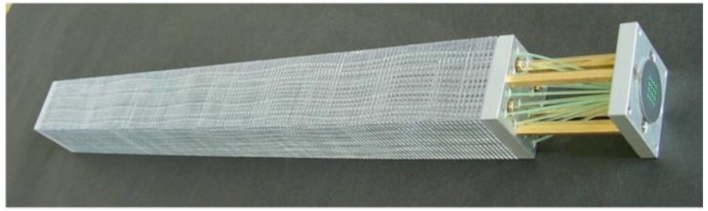


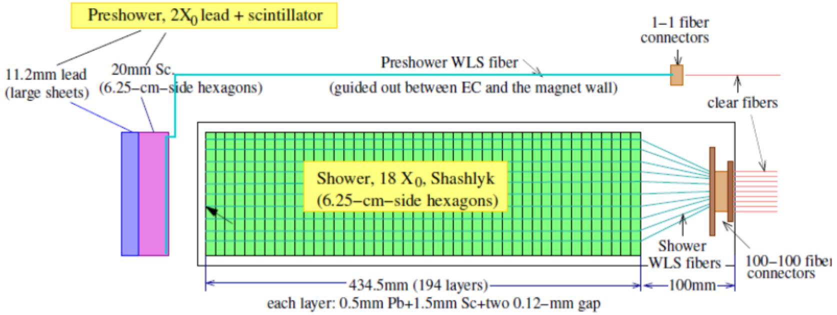
Tungsten-copper alloy
+ scintillator / silica fibre

from Hengne LI

$$\frac{\delta E}{E} \sim \frac{(35\%)}{\sqrt{E/\mathrm{GeV}}}$$

- Optimized Shashlik calorimeter



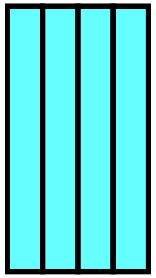


from Ye TIAN

Forward neutron detector

- An alternative solution: time of flight detector

As the energy of the forward neutron at EicC is not that high compared to that at EIC-US, we would possibly measure the time of flight, to reconstruct the momentum of the neutron. We could improve the energy resolution of the neutron. (smaller neutron efficiency but probably higher energy resolution)



Several layers of plastic scintillators to measure the time of flight of the neutron

The forward neutron is around 10 GeV,

$$\gamma \sim 10, \beta \sim 1$$

Assume flight distance ~ 100 m, then tof = 333 ns.

Assume δtof = 200 ps, then $d\beta \sim 0.06\%$.

$$\frac{\delta E}{E} = \frac{\delta\gamma}{\gamma} = \gamma^2 \delta\beta \sim 6\%$$

$$\left(\gamma = \frac{1}{\sqrt{1-\beta^2}} \rightarrow \frac{d\gamma}{\gamma} = \gamma^2 d\beta \right)$$

Summary

- Measuring the pion & kaon form factors and structure functions are the important ways to reveal EHM and Higgs modulation of the dynamical chiral symmetry breaking.
- EicC data at low energy would allow the L-T separation of the exclusive pion/kaon electroproduction, which could be used to test the assumption that the longitudinal cross section is dominant.
- The Q^2 for the form factor measurement could reach 30 GeV^2 (statistical uncertainty less than 6% for F^{π}).
- For the structure function measurement, EicC would provide a broad kinematical range. (Q^2 up to 50 GeV^2, $0.01 < x_{\pi} < 0.95$, $0.05 < x_K < 0.85$)
- At $Q^2 \sim 4$ GeV^2, the pion&kaon structure function measurements at EicC would achieve high statistical precision. (For $x_{\pi} < 0.9$ the statistical uncertainty is less than 2%; For $x_K < 0.8$ the statistical uncertainty is less than 5%.)
- The high-performance of the forward detector system is important and should be investigated for the next step.

Thank You !

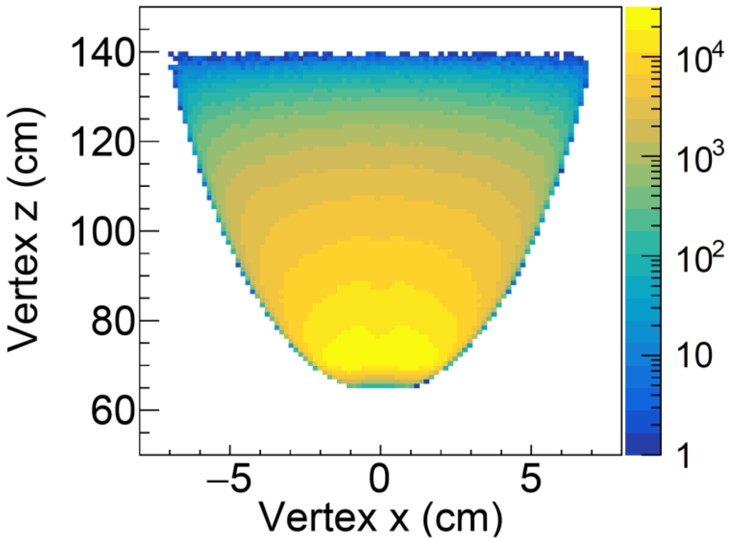
Thank You !

Backup: possibility of Λ-Σ separation in kaon structure experiment

Leading Λ tagged DIS is one kind of SIDIS, but in the forward region.

It is impossible to distinguish the Λ and Σ by the invariant mass.

- $\Lambda \rightarrow n\pi^0, \Sigma \rightarrow \Lambda\gamma$, we probably could count the number of photons and the transverse momentum conservation
- The decay vertex of leading Λ is quite different from that of Σ



Decay vertex of Λ

Backup: details of L-T separation at EicC

$\sqrt{s}$, GeV	L /cm²/s	Q^2, GeV²	W, GeV	y	t, GeV²	ε
12	1×10^{33}	10	10	0.762	0.1	**0.449**
16	2×10^{33}	10	10	0.428	0.1	**0.862**
20	2×10^{33}	10	10	0.273	0.1	**0.951**
12	1×10^{33}	15	10	0.797	0.1	**0.388**
16	2×10^{33}	15	10	0.447	0.1	**0.846**
20	2×10^{33}	15	10	0.286	0.1	**0.946**
12	1×10^{33}	20	10	0.298	0.1	**0.324**
16	2×10^{33}	20	10	0.467	0.1	**0.829**
20	2×10^{33}	20	10	0.832	0.1	**0.940**

To do the L-T separation, EicC is suggested to run at c.m. energy from 12 GeV to 20 GeV, which is hard to be realized at EIC-US of much higher energy.