Measurement of pion structure with Sullivan process and ZDC ECAL development

Initial Stages 2025 @ Taipei, Taiwan

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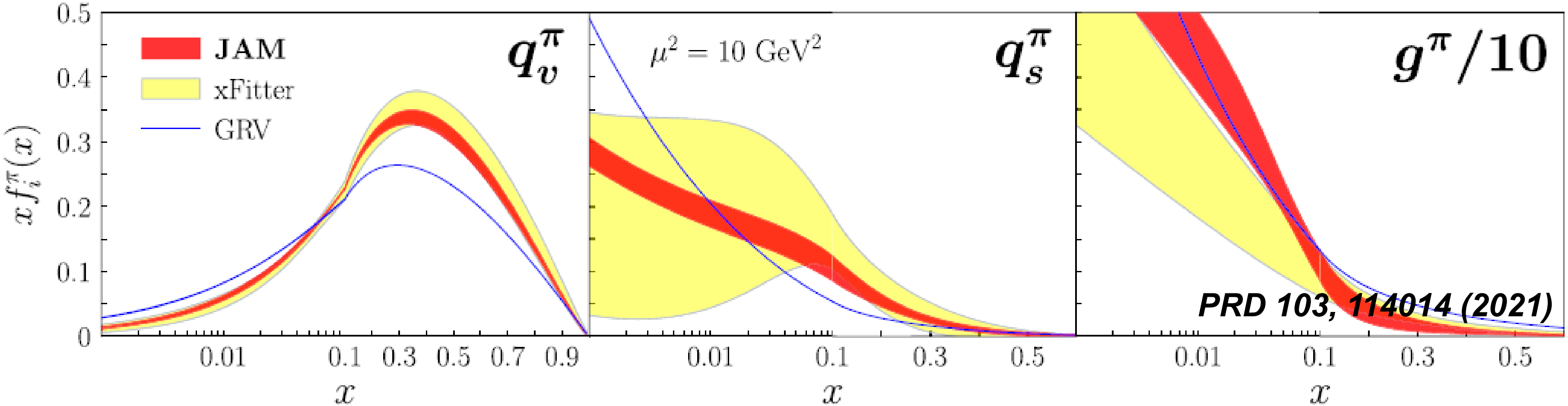
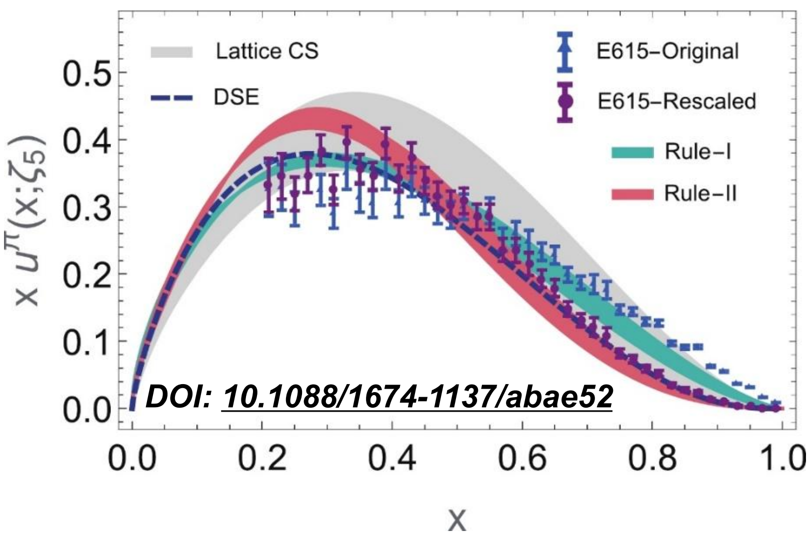
on behalf of the ePIC collaboration

Global Fit of Pion PDF

Pion PDF from Global Fit



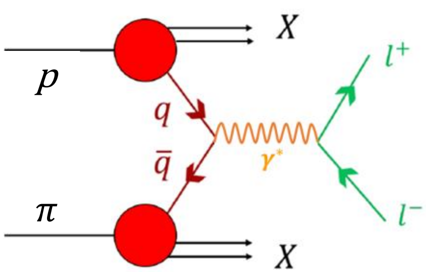
Pion valence @ 5.2GeV



- The **pion is the lightest hadron with the simplest structure**, but its **PDFs remain poorly known** rare pion beams.
- Theorist is especially interested in **large-x region of the pion valence PDF (x>0.8) ~ (1-x)$^\beta$** since it provides a **test of QCD at the transition between perturbative (calculable) and non-perturbative (non-calculable) dynamics**.

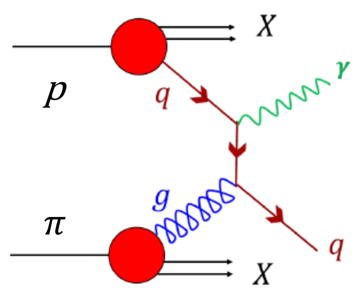
Global Fit of Pion PDF

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



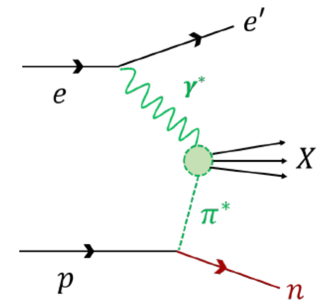
sensitive to valence
moderate-x to large-x
Low statistics and large uncertainty

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



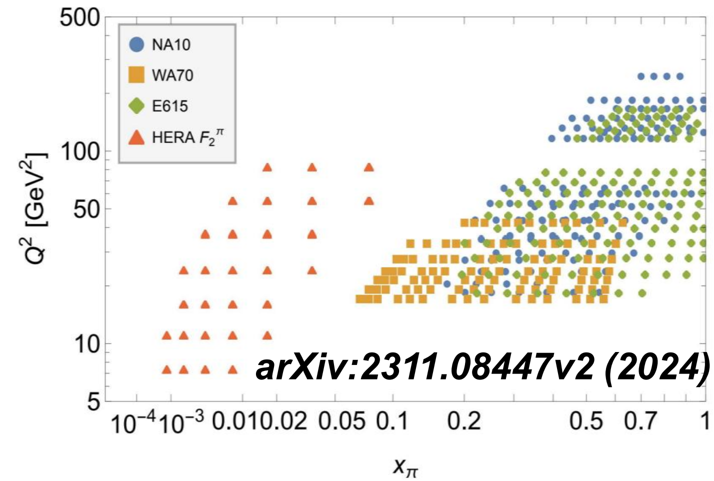
sensitive to gluon
in moderate-x
Low statistics and large uncertainty

$Sullivan\ process$
$e + \pi^+(virtual) \rightarrow nX$

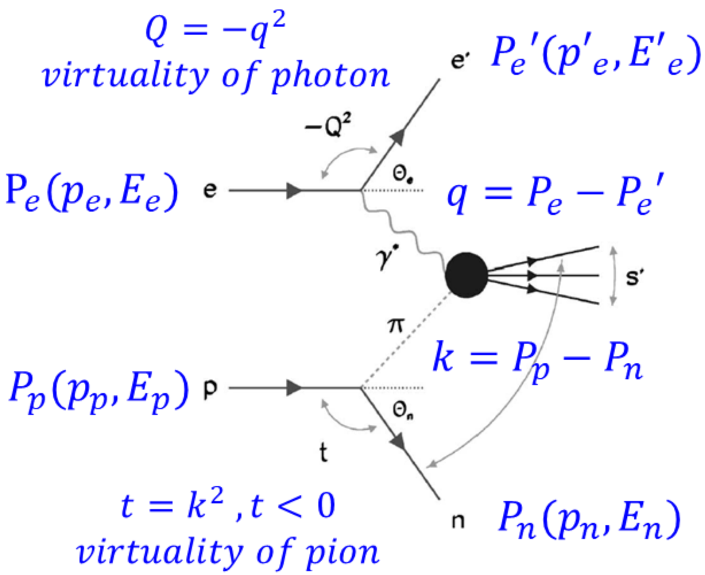


sensitive to all valence, gluon , and sea
current data is sensitive to low-x valence
Could contribute high statistics

Pion PDFs		Drell-Yan NA10	Drell-Yan E615	Prompt-gamma WA70	*Sullivan* HERA
1992	SMRS	O	O	O	
1992	GRV	O	O	O	
Old fits mainly dominated by pion induced DY. New fits include data from Sullivan process					
2018	JAM	O	O		O
2020	xFitter	O	O	O	



Sullivan Process for Pion Structure Study



J.D. Sullivan, *"One-pion exchange and deep-inelastic electron–nucleon scattering"*, Phys. Rev. D 5, 1732 (1972).

- **Pion kinematics**

① $t = k^2 = (1 - x_L)m_p^2 - p_T^2/x_L - [(1 - x_L)/x_L]m_n^2$, **pion virtuality, t<0**

② $x_\pi = \frac{Q^2}{(2k \cdot q)} \approx \frac{x}{(1-x_L)}$, **momentum fraction of parton in pion**

- **Neutron observables**

① $x_L \approx E_n / E_n$: **Neutron longitudinal momentum**

② $p_T \approx x_L E_p \theta_n$: **Neutron transverse momentum**

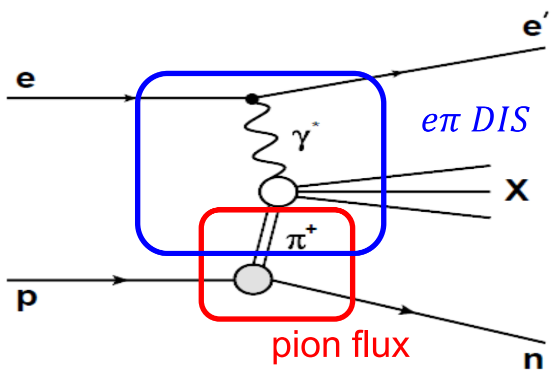
The essential measured quantities are x_L and p_T of very forward angle neutron ➔ zero-degree calorimeter.

The nucleon is not a rigid 3-quark system; **it is dressed by a cloud of mesons.** Therefore, the proton's wavefunction is expanded not just as a bare $|uud\rangle$ state, but as **a superposition that includes pion–baryon and kaon-hyperon components.** The **pion and kaon structures can be explored through the Sullivan process** from DIS data.

$$|p\rangle = Z^{1/2}|uud\rangle + a\,|n\pi^+\rangle + b\,|p\pi^0\rangle + c\,|\Delta^{++}\pi^-\rangle + d\,|\Lambda K^+\rangle + e\,|\Sigma^0 K^+\rangle + f\,|\Sigma^+ K^0\rangle + \cdots$$

probe proton | probe pion | probe kaon

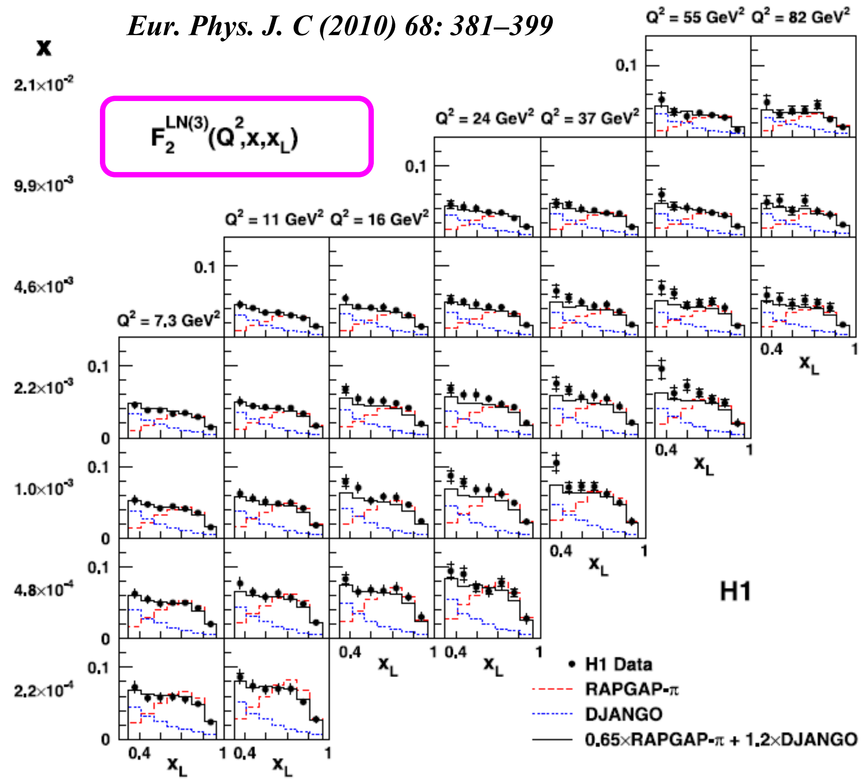
Sullivan Process for Pion Structure Study



$$\frac{d^3\sigma(ep\to e'nX)}{dx\,dQ^2\,dx_L} = f_{\pi/p}(x_L,t)\cdot\sigma(e\pi\to e'X)$$

$$= \frac{4\pi\alpha^2}{xQ^4}\left(1-y+\frac{y^2}{2}\right)F_2^{LN(3)}(Q^2,x,x_L)$$

Leading neutron form factor is affected by pion flux model



- The cross section of the **pion-cloud Sullivan process = "pion flux × pion structure function".**
- There are two ambiguous in pion PDF extraction.

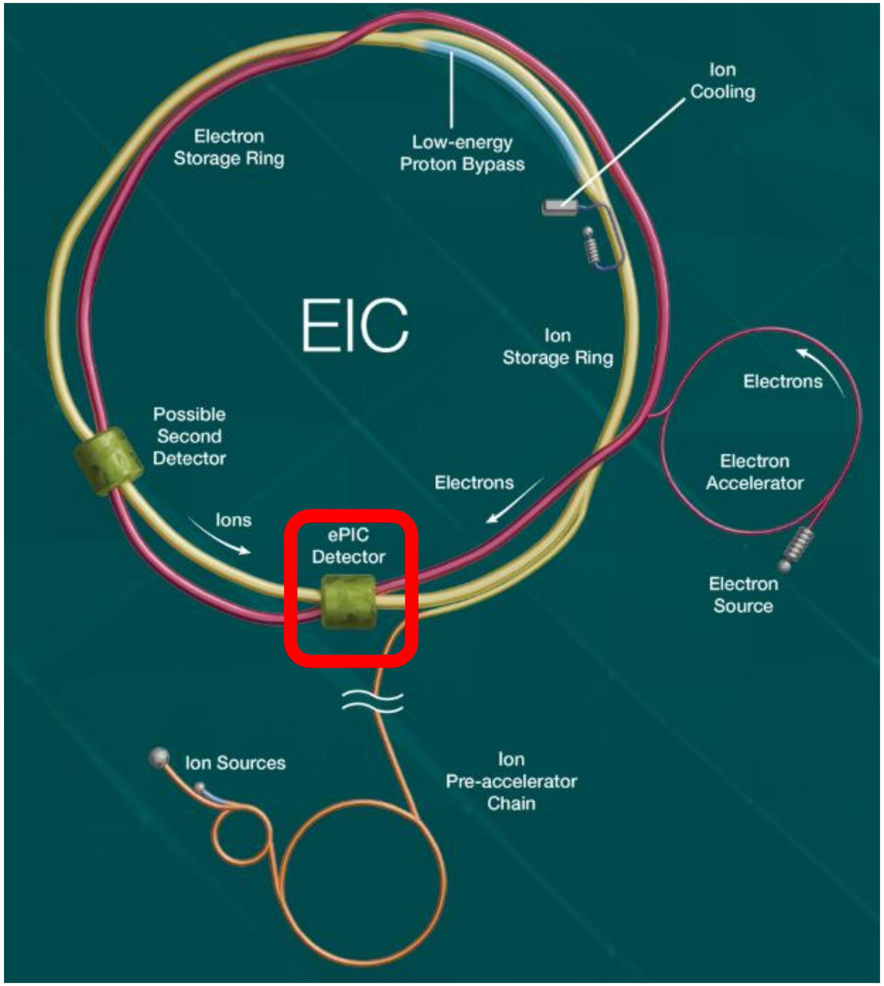
(1) Pion flux parametrization currently still gives large uncertainty.

(2) Virtual (off-shell) pion and real (on-shell) pion :

- Sullivan process probes a virtual pion, $t < 0$, pion cloud.
- A real pion beam corresponds to $t > 0$.

To approximate the real pion, experiments extrapolate from negative to close to zero ($t \sim m_\pi^2 \to 0$).

ePIC Experiment @ BNL



Electron-Ion Collider (EIC)
@ Brookhaven National Laboratory (BNL)

- **Collaboration**

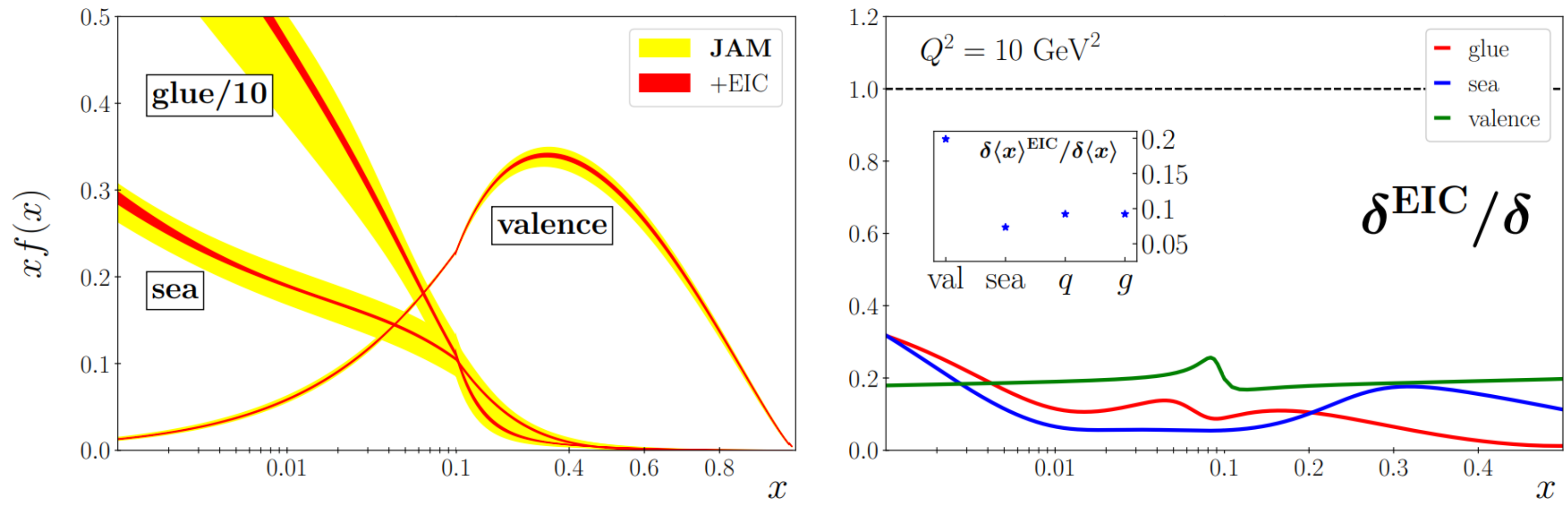
~500 scientists, 171 institutions, 26 countries

- **Physics Goals**
- **3D structure of protons and nuclei.**
- **proton spin puzzle (polarized beam)**
- **nuclear interaction in nuclei**

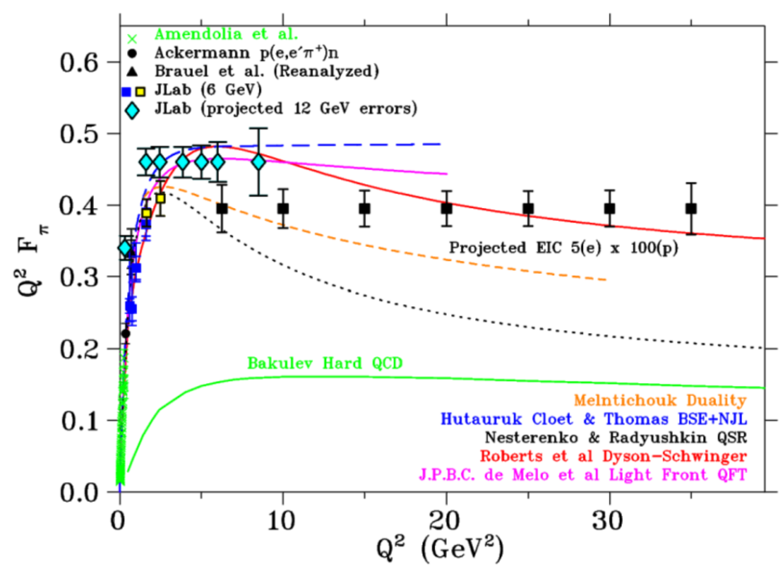
- **Beam**
- **Electrons:** 5 – 18 GeV,
  Luminosity ~ $10^{33-34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (polarized)
- **Protons:** up to 275 GeV,
  Luminosity ~ $10^{33-34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (polarized)
- **Heavy ions (e.g. Au, Pb):** up to 100 GeV

- **Timeline**
- **2022 : starting detector R&D**
- Late 2020s : detector commission
- **Early 2030s : 1st physics run**

Projection of Pion PDF in EIC/ePIC



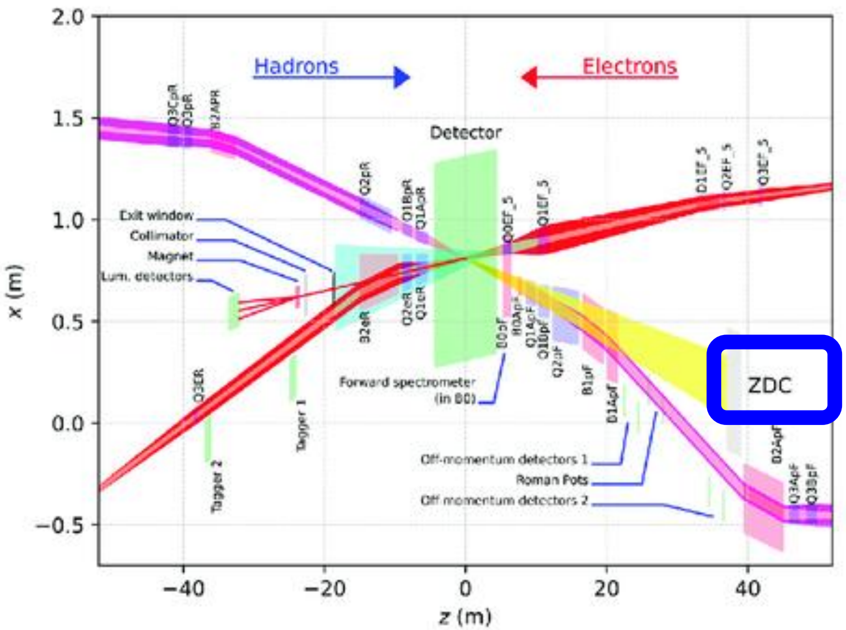
J. Phys. G: Nucl. Part. Phys. **48 075106**

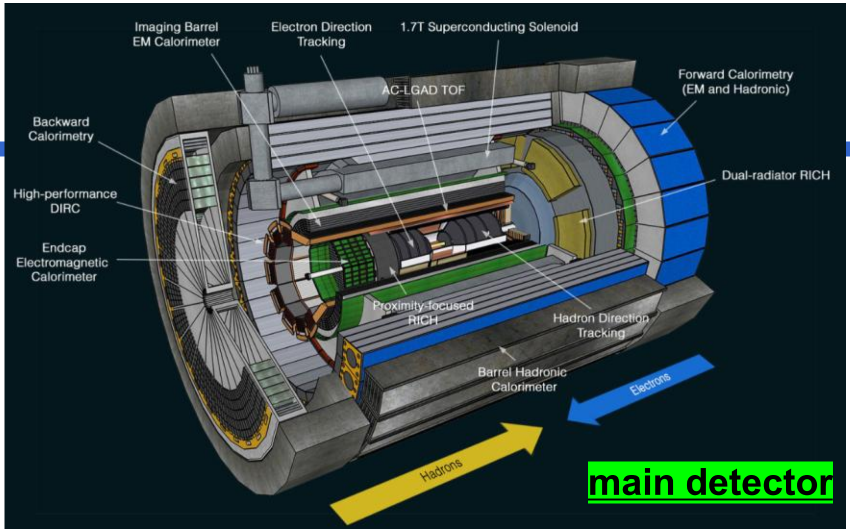


- **EIC impact on pion PDFs :** With the input of EIC data, the uncertainty of pion valence reduces around 80% uncertainty. For pion gluon/sea, the uncertainty reduces 90%.
- **Pion Form factor :** ePIC will cover larger kinematics compare to the currently available data set.

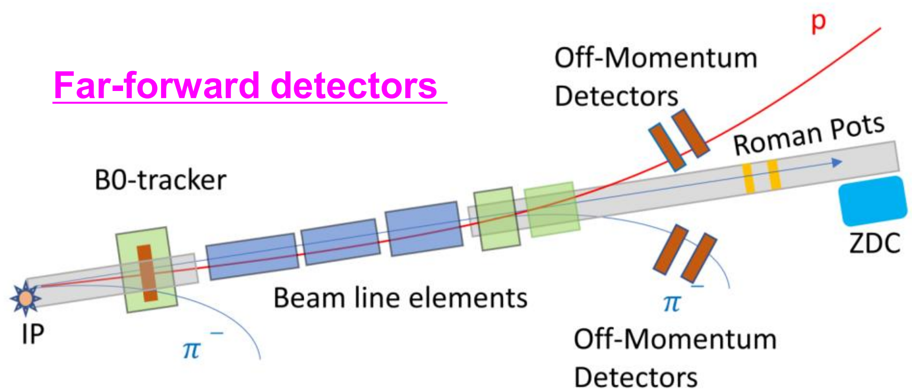
ePIC Detectors

Far-backward detector | **Main detector ePIC** | **Far-forward detector**



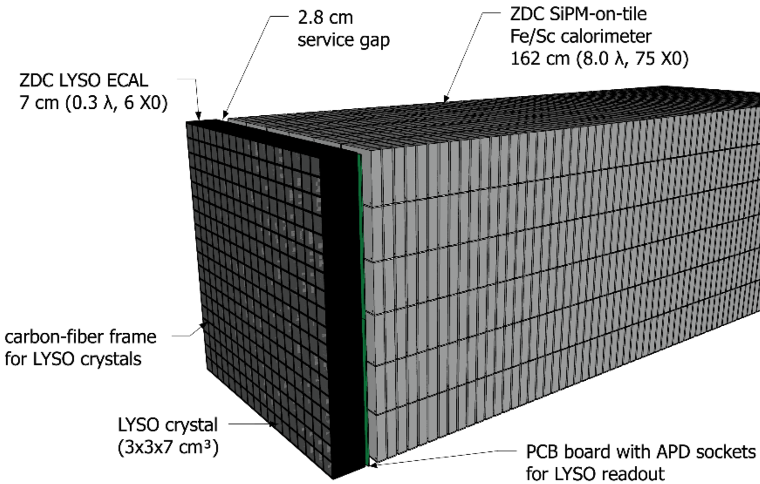


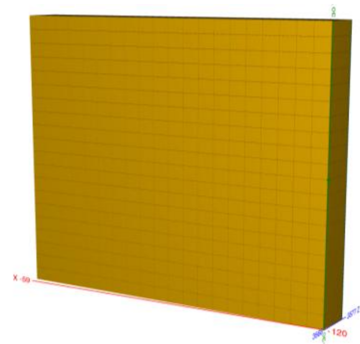
Far-forward detectors



- **EIC Detector System**
  - **main detectors :** Tracks electrons and hadrons, PID, vertexing.
  - **Far-forward:** Detects protons, neutrons, fragments.
  - **Far-backward:** Detects low-angle scattered electrons
- **Far-forward detectors** :
  - **B0 acker** – Detects small-angle charged particles for exclusive reactions.
  - **Off-Momentum Detectors** – Tag decay products and spectator fragments.
  - **Roman Pots** – Measure forward protons to study exclusive processes.
  - **ZDC – Capture forward neutrons/photons for pion/kaon and nuclear studies.**

Zero Degree Calorimeter (ZDC) Current Design





ECAL
LYSO + SiPM
detect gamma
60cm*60cm
20*20 cells
3cm*3cm*7cm / cell
7cm ~ **6X0** in Z

- Pion-exchange Sullivan process for pion structure

$$e + p \rightarrow e' + X + n$$

- Kaon-exchange Sullivan process for kaon structure

$$e + p \rightarrow e' + X + \Lambda \qquad \boldsymbol{\Lambda} \rightarrow \boldsymbol{n} + \boldsymbol{\pi^0} \rightarrow \boldsymbol{n + 2\gamma}$$

- Spectator-neutron tagging for nuclear physics

$$e + d \rightarrow e' + X + n$$

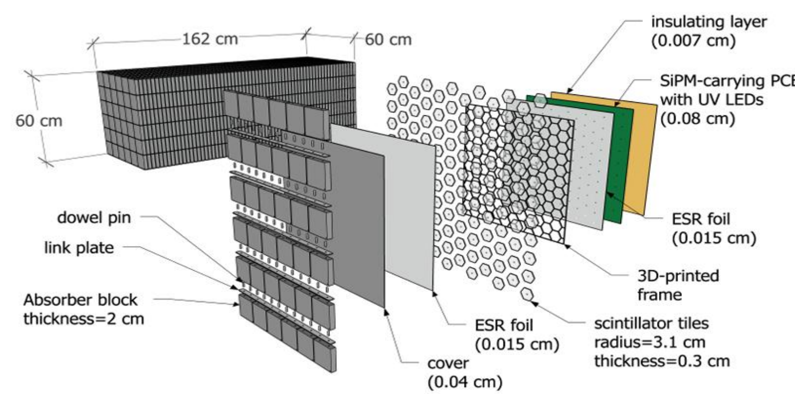
$$e + A \rightarrow e' + X + (A-1) + n$$

- Background, secondary photons showers

$$\pi^0 \rightarrow \gamma\gamma$$

ZDC aims to measure gamma up to 40 GeV and neutron up to 300 GeV. Therefore, it is composed by ECAL and HCAL.

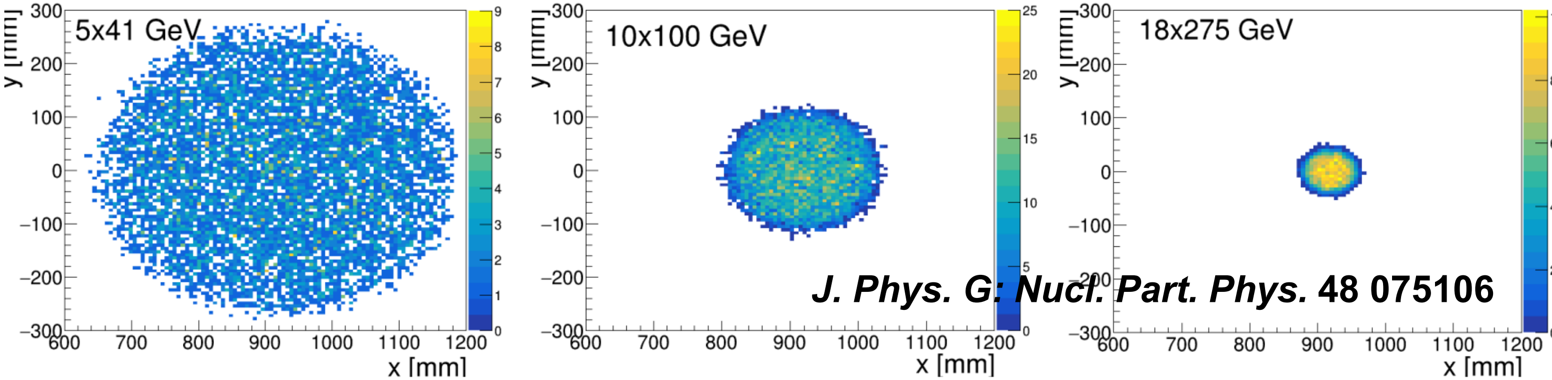
HCAL
sampling calorimeter
detect neutron



64 layers, 8 slice/layer
1 layer = steel + scintillator tile + SiPM
65cm in X, 60cm in Y, 163cm in Z

Zero Degree Calorimeter (ZDC) MC Simulation

Simulation : Acceptance of neutrons in ZDC



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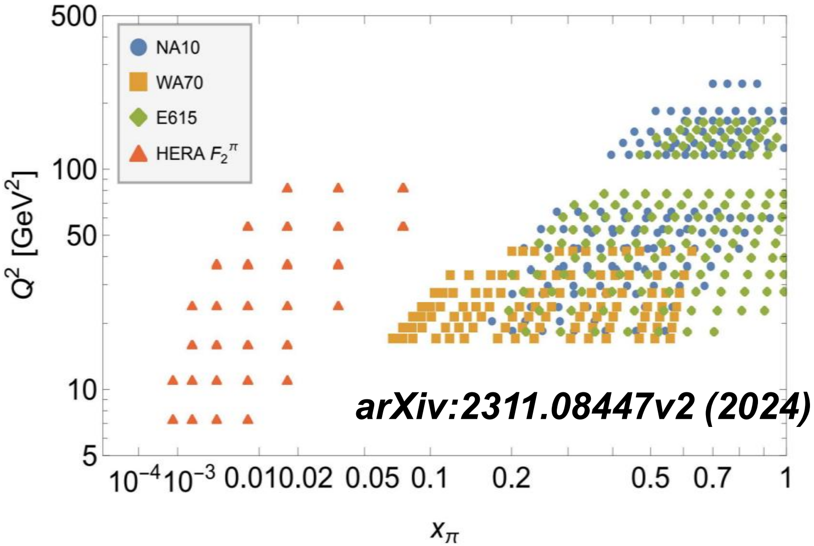
sensitive to high-x ← **sensitive to low-x**

Kinematic coverage of current data



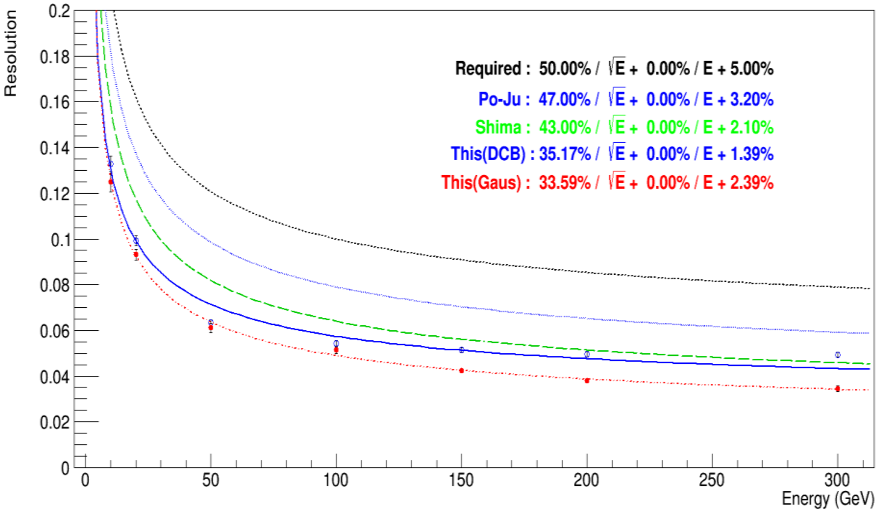
arXiv:2311.08447v2 (2024)

- In pion structure studies, ePIC used the highest beam energy, 18 × 275 GeV, to maximize kinematic coverage. To better reach the high-x_π region, lower energies (10 × 135 GeV and 5 × 41 GeV) were also chosen, **providing access to large x_π over a broader Q^2 range.**

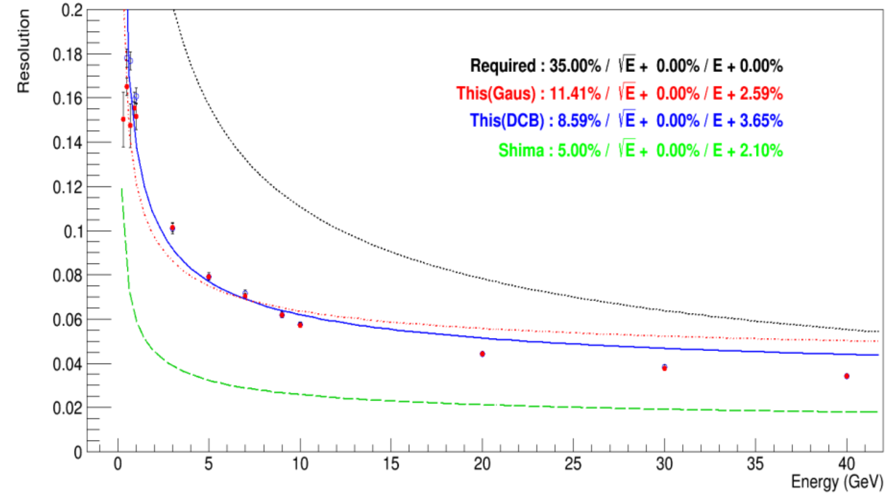
- **60cm* 60cm coverage of ZDC is required to perform 5x41 GeV ep DIS.**

Zero Degree Calorimeter (ZDC) MC Simulation

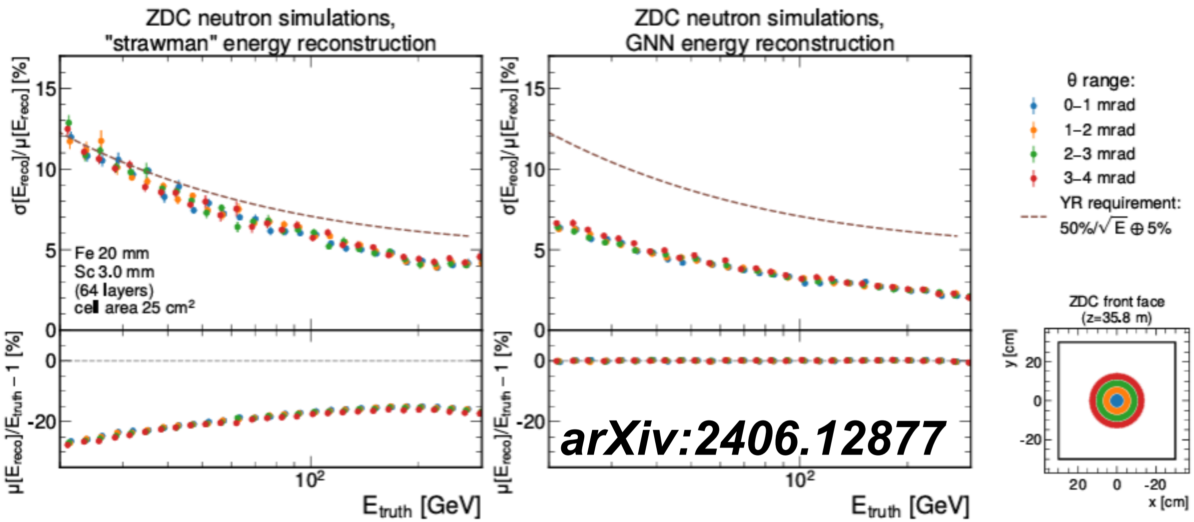
Energy resolution : 10-300GeV neutron



Energy resolution : 10-40GeV gamma



Energy resolution after applying GNN regression



- Current ZDC design satisfied the physics requirement.
- GNN energy regression improve the energy reconstruction.

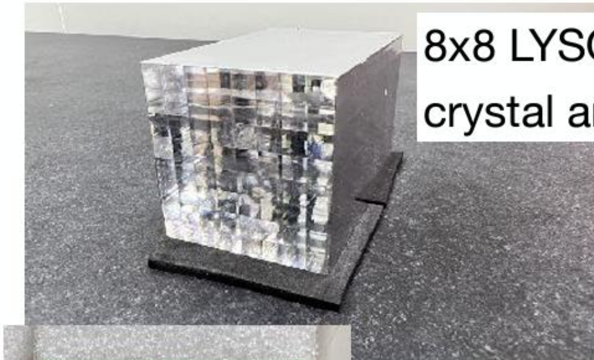
Zero Degree Calorimeter (ZDC) Requirements

Physics process	Final State particles	HCAL		ECAL	
		Energy resolution	Angular resolution	Energy resolution	Spatial resolution
Spectator tagged e+d breakup	Neutrons	$\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$	$\frac{\sigma_\theta}{\theta} \leq \frac{2\ mrad}{\sqrt{E}}$	N/A	N/A
Incoherent vetoing of e+A events	Neutrons photons	$\frac{\sigma_E}{E} \leq \frac{100\%}{\sqrt{E}}$	N/A	**100 MeV photon sensitivity**	N/A
u-channel backward DVCS	Photons	N/A	N/A	$\frac{\sigma_E}{E} \leq \frac{20\%}{\sqrt{E}} \oplus 3\%$	< 1–2 cm
Pion/Kaon structure functions	Neutrons photons	$\boldsymbol{\frac{\sigma_E}{E} \leq \frac{35-50\%}{\sqrt{E}} \oplus 3-5\%}$	$\boldsymbol{\frac{\sigma_\theta}{\theta} \leq \frac{2\ mrad}{\sqrt{E}}}$	$\boldsymbol{\frac{\sigma_E}{E} \leq \frac{2-5\%}{\sqrt{E}} \oplus 1-3\%}$	**< 1–2 cm**

- **In the requirement of ZDC, the study of pion and kaon structure give the most demanded requirement,**
  - **35-50% energy resolution and 2 mrad angular resolution for HCAL (neutron).**
  - **2-5% energy resolution and 1-2 cm position resolution for ECAL (gamma).**

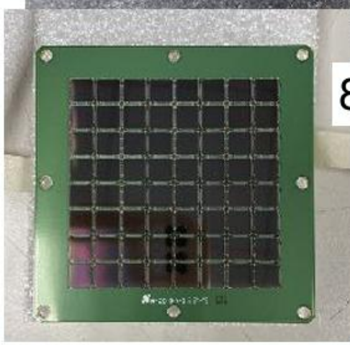
- Collaboration : groups from **Japan (RIKEN, Kobe, Shinshu, Tsukuba)**, **Taiwan (NCU, NTU Academia Sinica)**, **Korea (Sejong)**, and **USA (Kansas, PNNL, UC Riverside)**.

1st Prototype ZDC ECAL

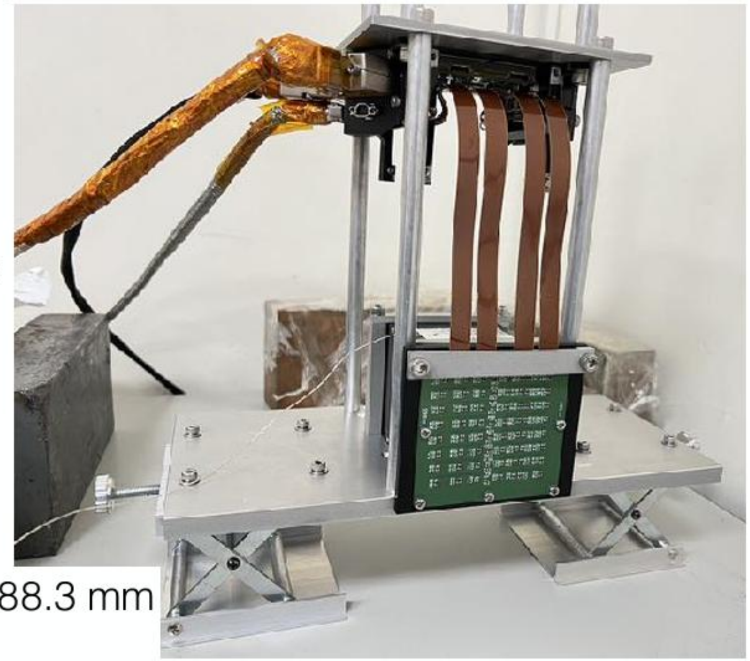


8x8 LYSO crystal array

LYSO calorimeter prototype



8x8 SiPM array

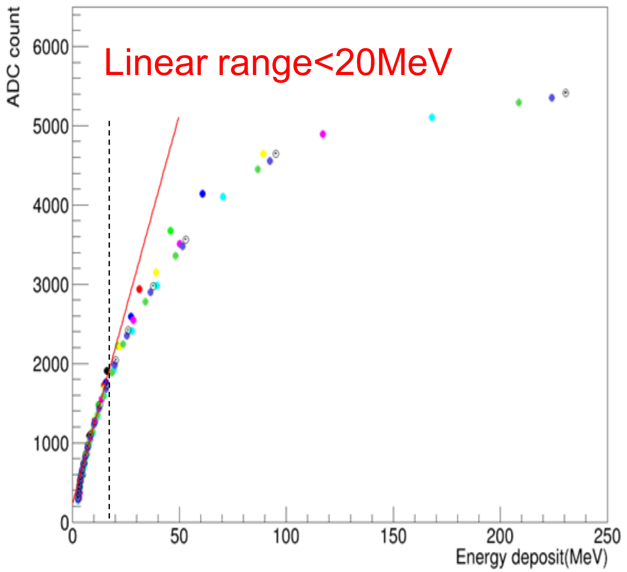


One crystal: 7.12 mm x 7.12 mm x 88.3 mm
8x8 array: 56.96 mm x 56.96 mm

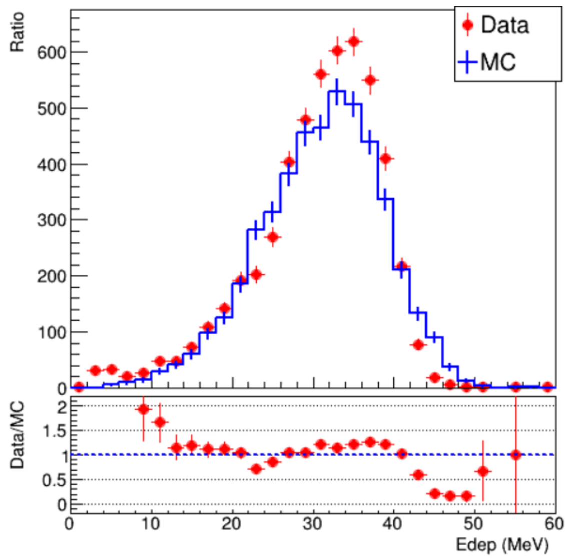
		crystal				sensor		
	Detector	**name**	**Size**	**Length**	**Array**	**Type**	**Sensor per crystal**	**DAQ**
1st prototype 2023-2024	**LYSO + SiPM**	LYSO	1cm*1cm	8.8cm (8X0)	8x8	SiPM Onsemi MICROFC-60035	1	CITIROC

1st Prototype ZDC ECAL

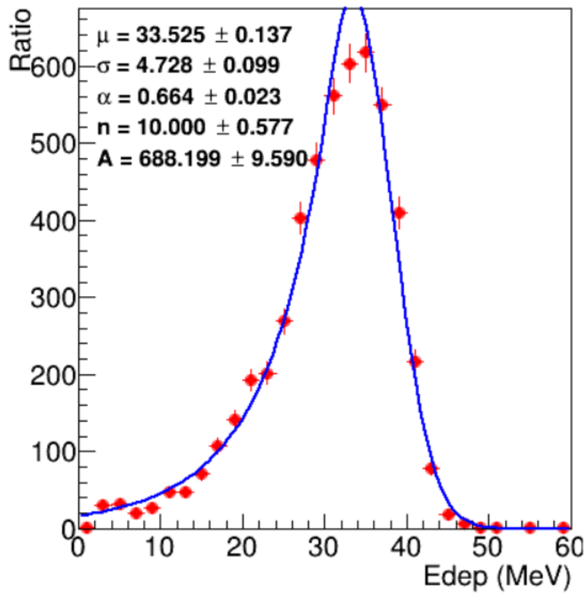
Beam energy VS ADC
SiPM saturation effect



47MeV positron beam
Data/MC

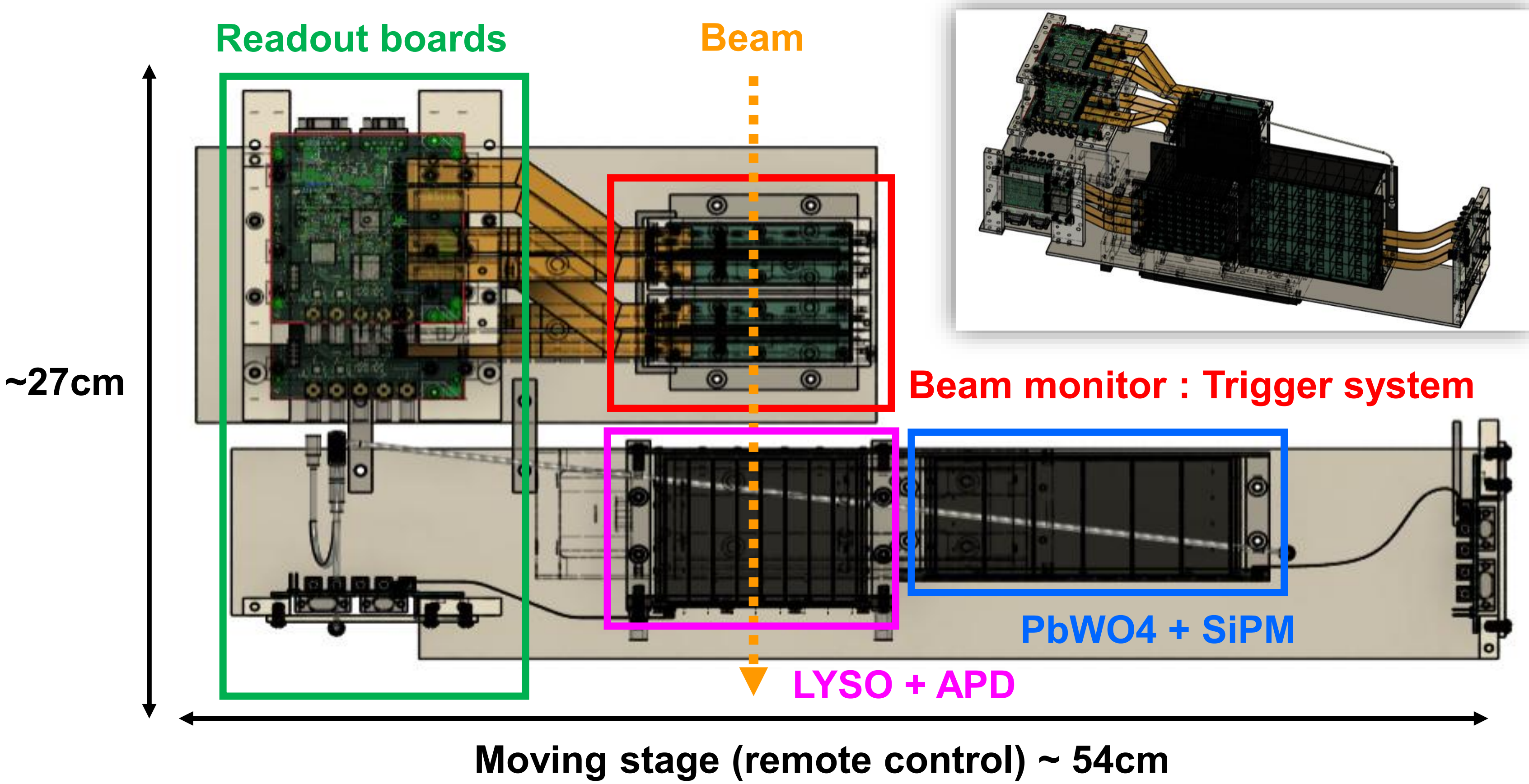


47MeV positron beam
Energy resolution



- Test beam @ Feb. 2024, with 50MeV – 800 MeV positron beam, in Japan
- **Most of the data fall within the saturated range**, except for the 47 MeV data, which is approximately 60% within the linear range. The energy resolution without energy regression is **14% for the 47 MeV beam. After accounting for the beam momentum resolution, the energy resolution improves to approximately 11%.**
- **Goal of the next generation is to reduce gain of the system.**

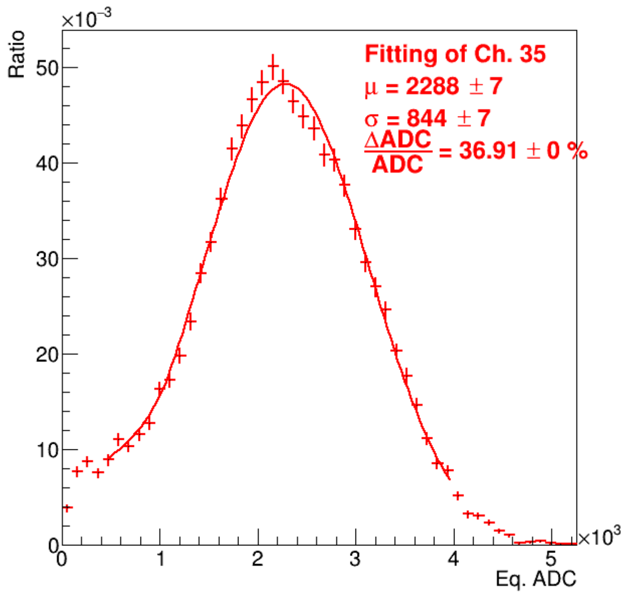
2nd ZDC ECAL Prototype



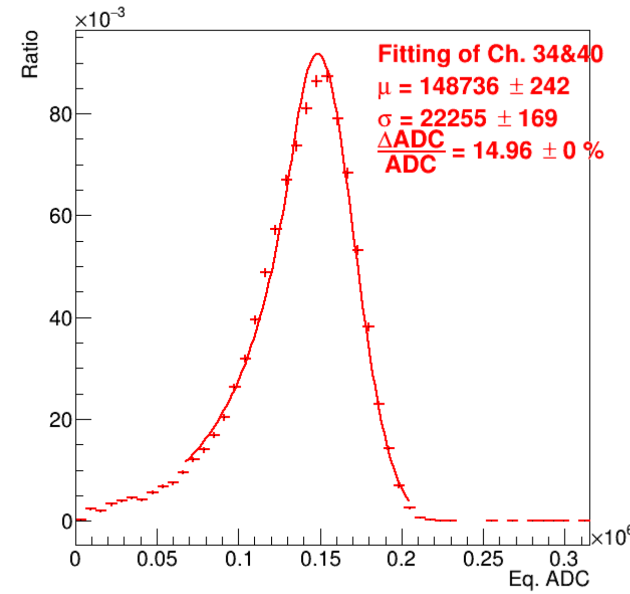
	Detector	Crystal				Sensor		DAQ
		name	Size of one cell	Length	Array	Type	sensor/crystal	
2nd prototype 2024-2025	LYSO + APD	LYSO	1cm*1cm	**6.6cm (6X0)**	8x8	**APD C30739ECERH**	1	CITIROC
	PbWO4 + SiPM	**PbWO4**	2cm*2cm	**5.3cm (6X0)**	6x6	SiPM Onsemi MICROFC-60035	2	CITIROC

2nd ZDC ECAL Prototype

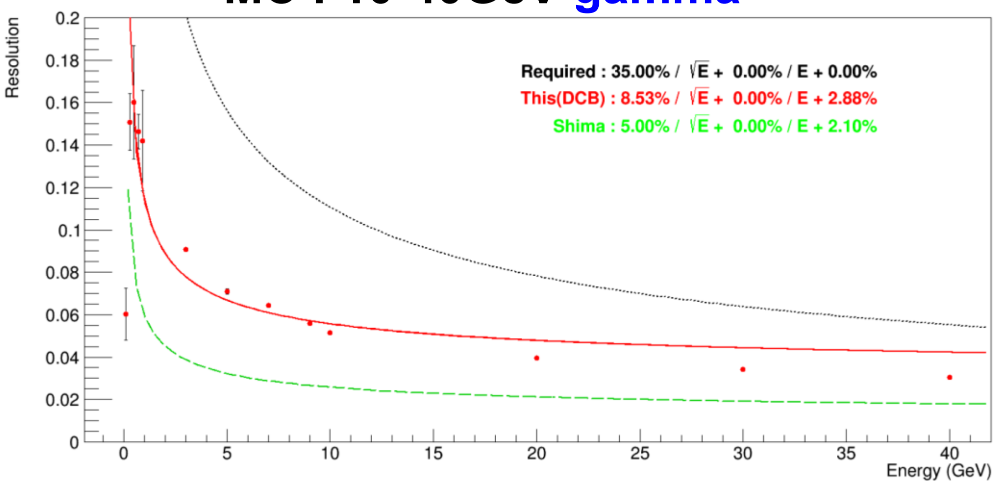
LYSO + APD @ 706 MeV positron beam



PbWO4 + SiPM @ 706 MeV positron beam



MC : 10-40GeV gamma



- Test beam @ Feb. 2024, with **50MeV – 800 MeV positron beam**, in Japan.
- Preliminary results gave energy resolution without energy regression.

LYSO + APD ~40% (> 15% requirement)

PbWO4+SiPM ~ 15% (~ 15% requirement)

ZDC ECal Prototypes

	Detector	Crystal				Sensor		DAQ
		name	Size of one cell	Length	Array	Type	sensor/crystal	
1st prototype 2023-2024	**LYSO + SiPM**	LYSO	1cm*1cm	6.6cm (6X0)	8x8	SiPM Onsemi MICROFC-60035	1	CITIROC
2nd prototype 2024-2025	**LYSO + APD**	LYSO	1cm*1cm	6.6cm (6X0)	8x8	**APD C30739ECERH**	1	CITIROC
	PbWO4 + SiPM	**PbWO4**	2cm*2cm	5.3cm (6X0)	6x6	SiPM Onsemi MICROFC-60035	2	CITIROC
3rd prototype 2025-2026	**LYSO + filter +SiPM**	LYSO	1cm*1cm	6.6cm (6X0)	8x8	**SiPM Hamamatsu S14160-3015PS**	4	**H2GCROC**
	PbWO4 + SiPM	PbWO4	2cm*2cm	5.3cm (6X0)	6x6	**SiPM Hamamatsu S14160-3015PS**	16	**H2GCROC**

- **1st prototype @ 2023-2024**
  - LYSO + SIPM : saturated already with 20MeV electron beam
  - We move to lower gain system on the 2nd prototype.
- **2nd prototype, 2 systems @ 2024-2025**
  - LYSO + APD : ~ 40% energy resolution @ 706 MeV (>15% requirement)
  - **PbWO4 + SiPM : ~ 15% energy resolution @ 706 MeV (~15% requirement)**
- **3rd prototype, 2 systems @ 2025-2026 (under developing)**
  - **Change SiPM model to Hamamatsu (EIC collaboration prefers)**
  - **Change DAQ to H2GCROC (EIC collaboration prefers)**
  - **Same crystals will be used. For LYSO, add filter to reduce the light yield.**

Summary and To Do

- **The pion is the lightest hadron and has the simplest structure, but its structure is still not well known.** This is pion beams are rare.

- For many years, studies relied mainly on pion-induced Drell–Yan data, which had poor statistics. As a result, pion PDFs stayed very uncertain for about 30 years. Around 2020, the JAM group began using Sullivan process data (pion cloud), which revived interest in studying the pion PDF. The **Sullivan process can give high statistic data to study pion structure. Two things are important for the extraction of pion PDF :**

  (1) Use a good pion flux model → reduce uncertainty in pion PDF.

  (2) Measure forward neutrons very accurately → Zero-Degree Calorimeter (ZDC).

- **The future EIC will measure meson structure (pion and kaon), with the ZDC as a key detector.** We have developed two ZDC prototypes, and a third is now under construction. **'$PbWO_4$ + SiPM' system(2nd prototype), already meets the physics requirement with ~15% energy resolution using ~1 GeV positron beam. For the third prototype, we will upgrade the sensor and readout to approach the final design, with a test beam planned in Japan next year.**