



清华大学
Tsinghua University

PWO-Based ECAL

R&D For HIAF-Spectrometer

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➤ Strange Resonances

✓ Λ^* , Σ^* , Ξ^* , Ω^* ,

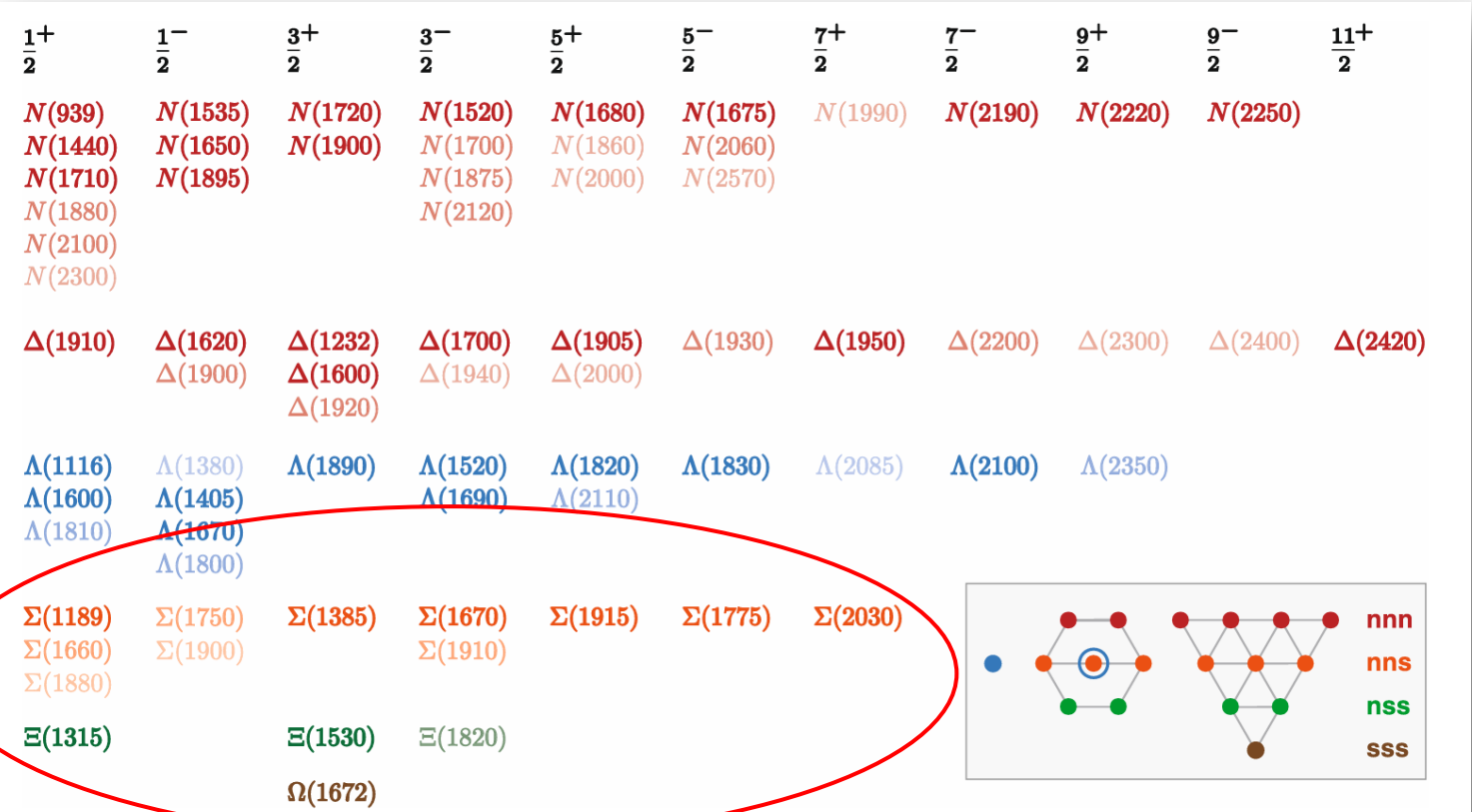
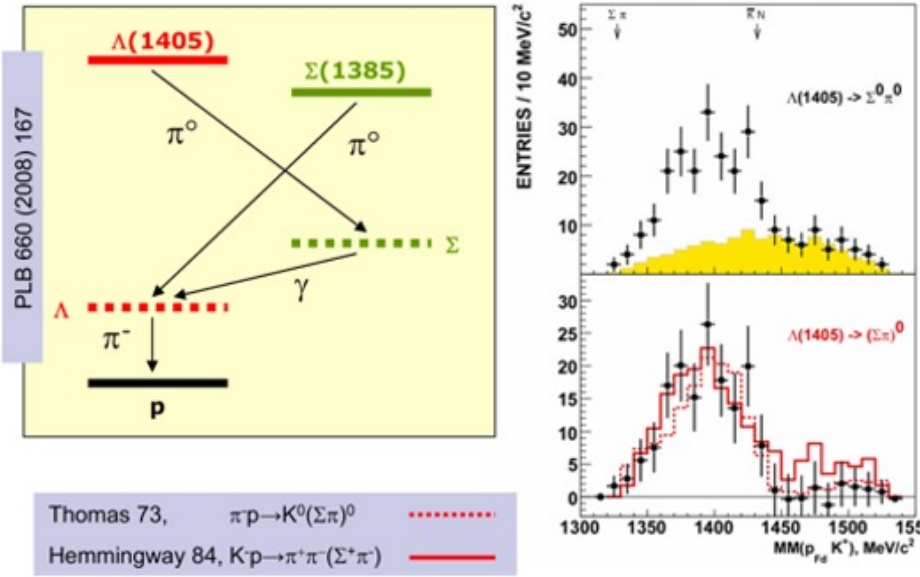
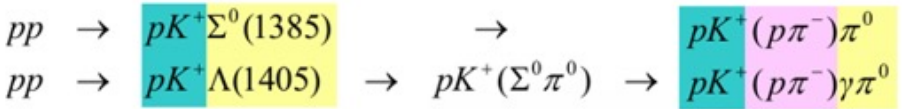


Fig. 1 Light and strange baryon spectrum from the PDG [1] up to $J^P = 11/2^+$. The columns correspond to different J^P and the colors to isospin and hypercharge. The different font weights represent four-, three- and two-star resonances

■ Reaction ($p_{\text{beam}}=3.65 \text{ GeV/c}$):

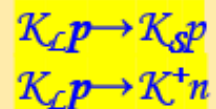


➤ Kaon-Proton Collisions:

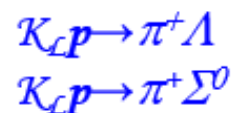
- ✓ JLab Hall-D KLONG-Experiment@GlueX: K_L Proton Scattering
- ✓ Expect to run in 2028 (Tsinghua: Bingsong Zou, Zhihong Ye)

Target $\rightarrow$ *Proton*

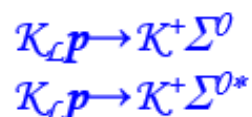
Elastic & Charge-Exchange



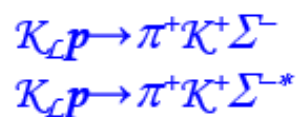
Two-body with $S = -1$



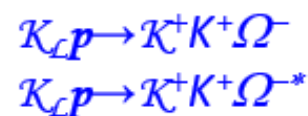
Two-body with $S = -2$



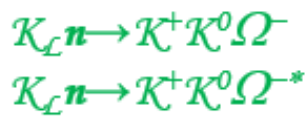
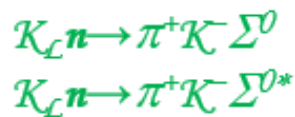
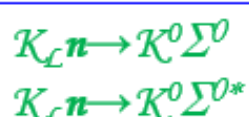
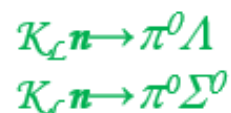
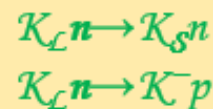
Three-body with $S = -2$



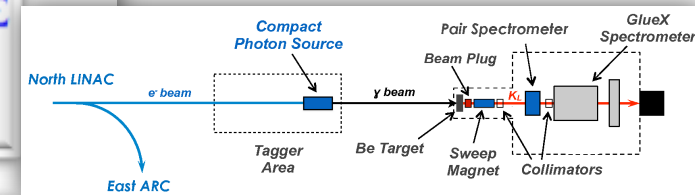
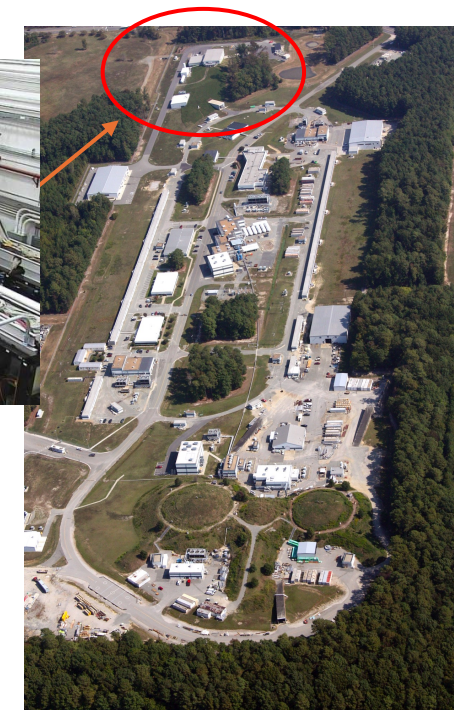
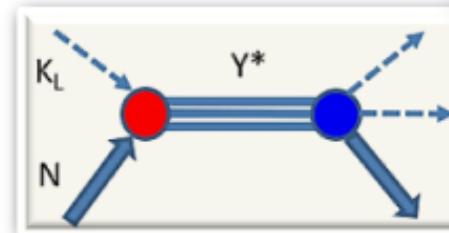
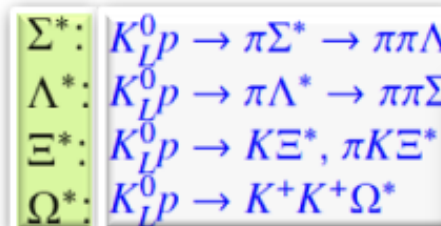
Three-body with $S = -3$



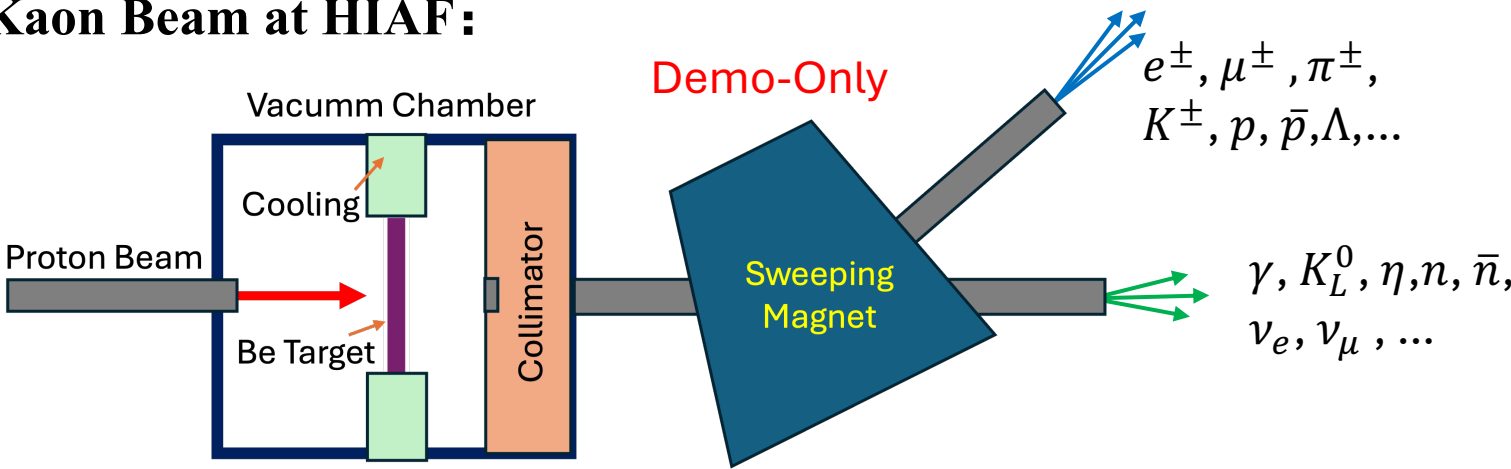
Neutron [first measurements]



• To search for "missing" hyperons, we need measurements of production reactions:



➤ **Kaon Beam at HIAF:**

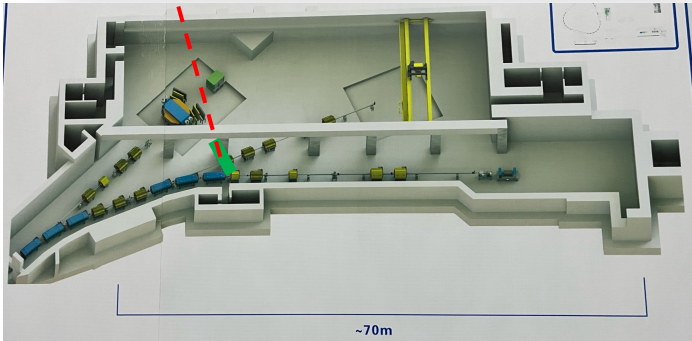
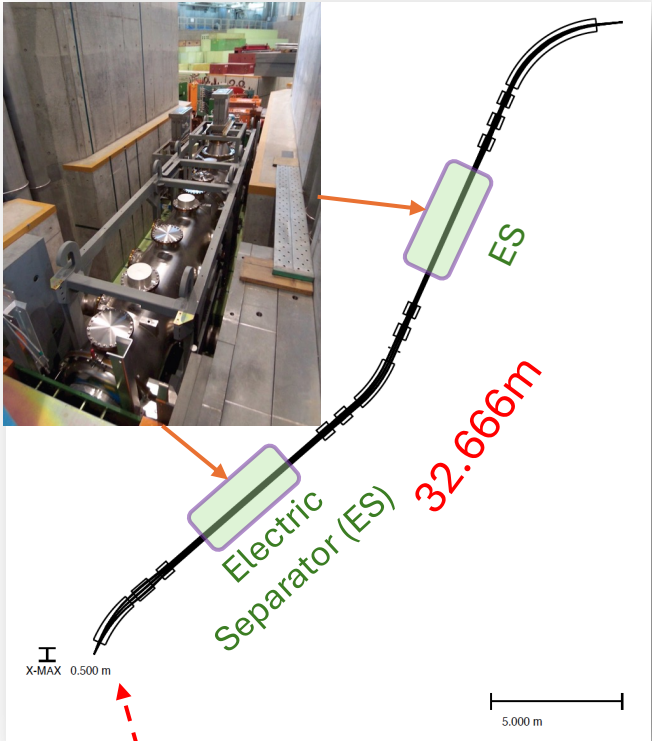


- ❑ 9.3GeV Proton-Beam, $L = 1.8 \times 10^{12}$ p/sec, Production Target: Be/Pt@6cm,
- ❑ Secondary Particles: $P = 2.23 \pm 2\%$, Angles = $xz \pm 50\text{mrad}$, $yz \pm 15\text{mrad}$

$L \text{ (s}^{-1}\text{)}$	π^+	π^-	K^+	K^-	μ^+	μ^-
6cm Be	4.5×10^7	2.7×10^7	1.8×10^5	0.6×10^5	4.8×10^6	9×10^7
6cm Pt	1.3×10^8	8.1×10^7	3.6×10^6	1.2×10^6	1.4×10^7	2.7×10^8

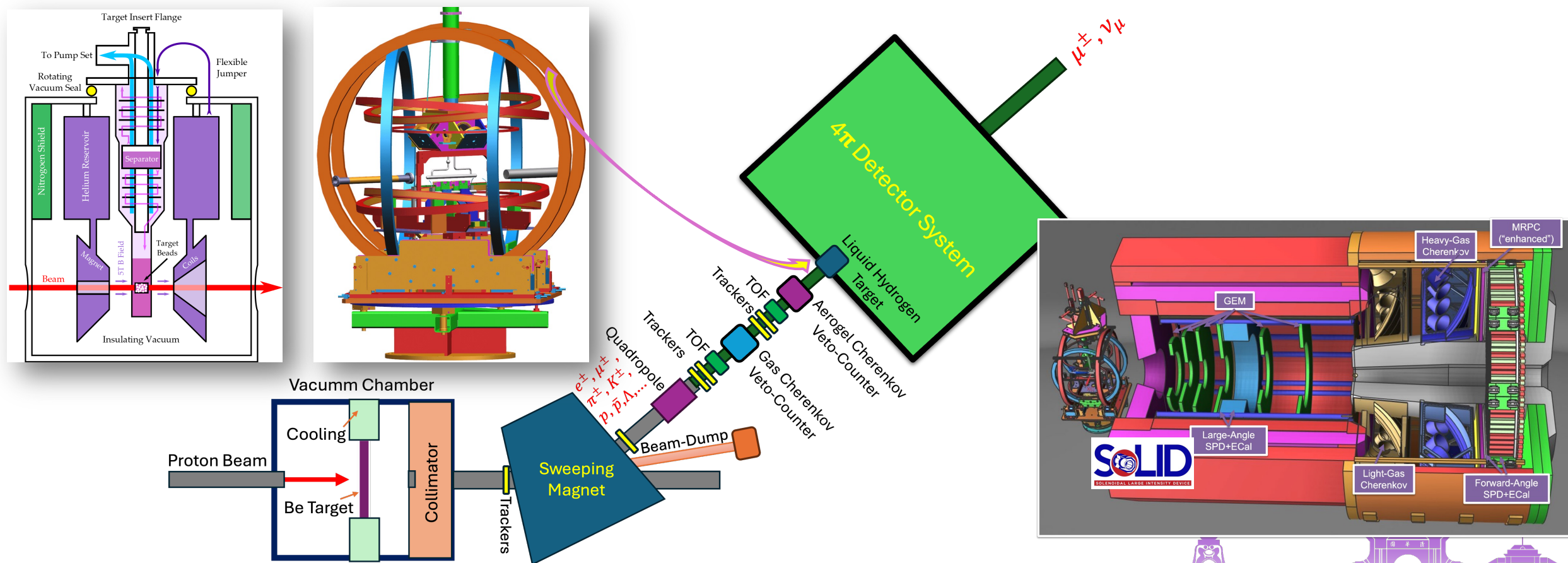
- ❑ Compared with J-PARC: 30GeV-Proton, $L = 5.6 \times 10^{13}$ p/sec,

- ✓ K1.8: $P_K = 1.8 \text{ GeV/c}$, $L = 1.3 \times 10^6 \text{ s}^{-1}$ (1.5msr-%, 6cm Pt)
- ✓ K1.8BR: $P_K = 0.8 \sim 1.2 \text{ GeV/c}$, expected $L \leq 5.5 \times 10^6 \text{ s}^{-1}$ (K/Pi~7.0)

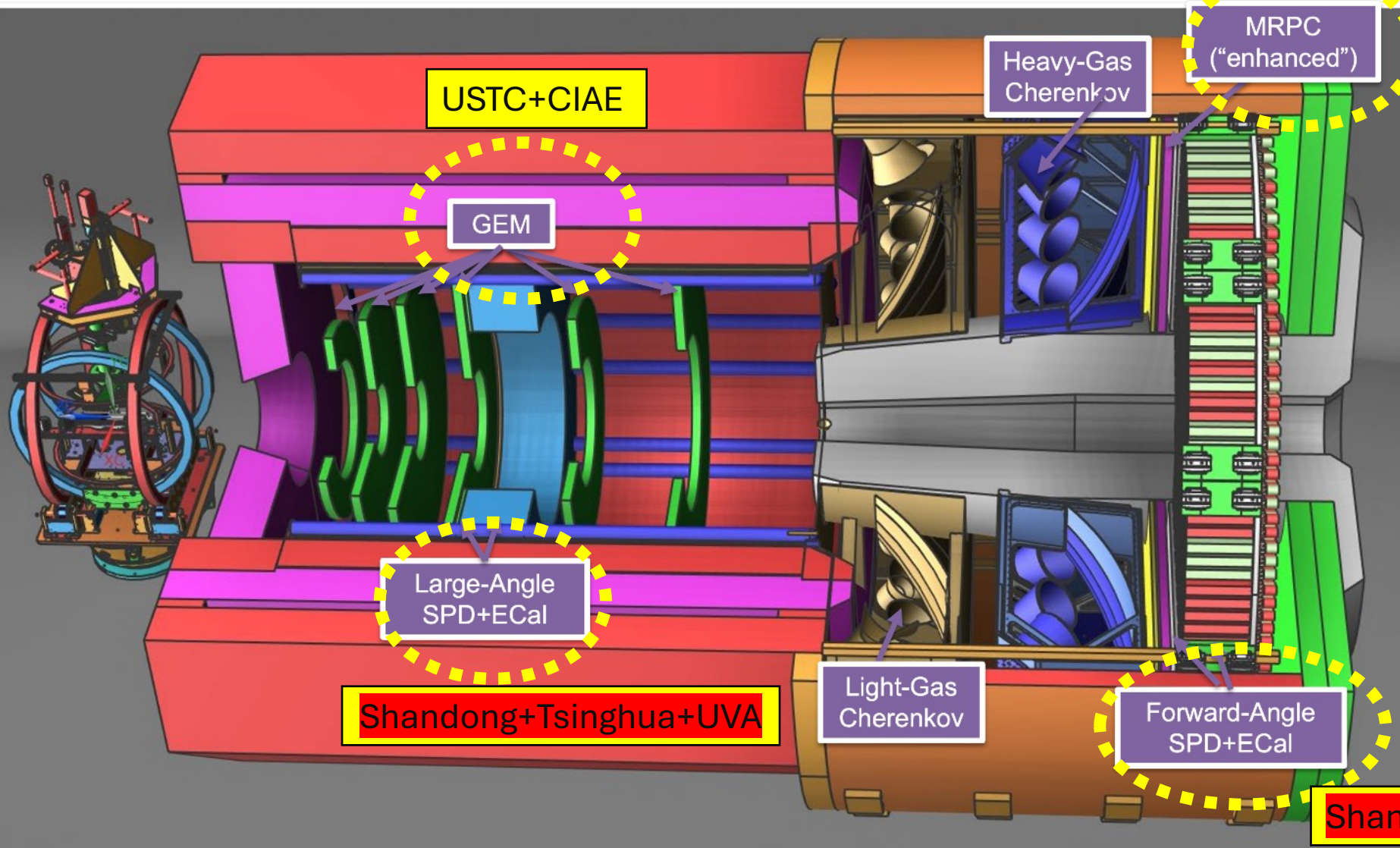


➤ Our Dream Experimental Setup:

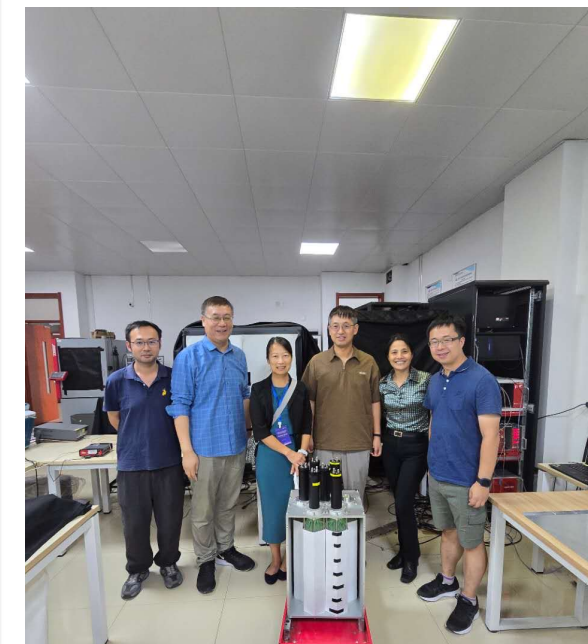
- ❑ Full Acceptance (4π) Spectrometers
- ❑ Longitudinally- & Transversely Polarized Proton(NH₃)and Neutron Targets (He³)
- ❑ Possibly Polarimetry to measure final proton polarization.



■ SoLID at Jefferson Lab



Tsinghua+USTC

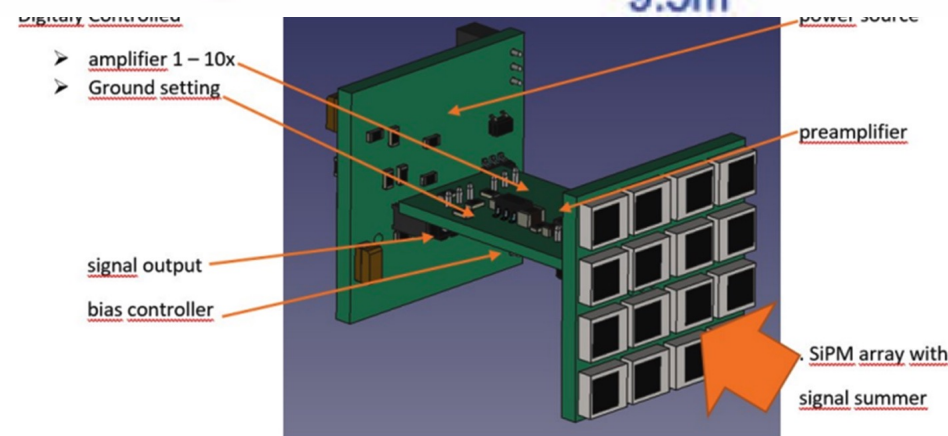
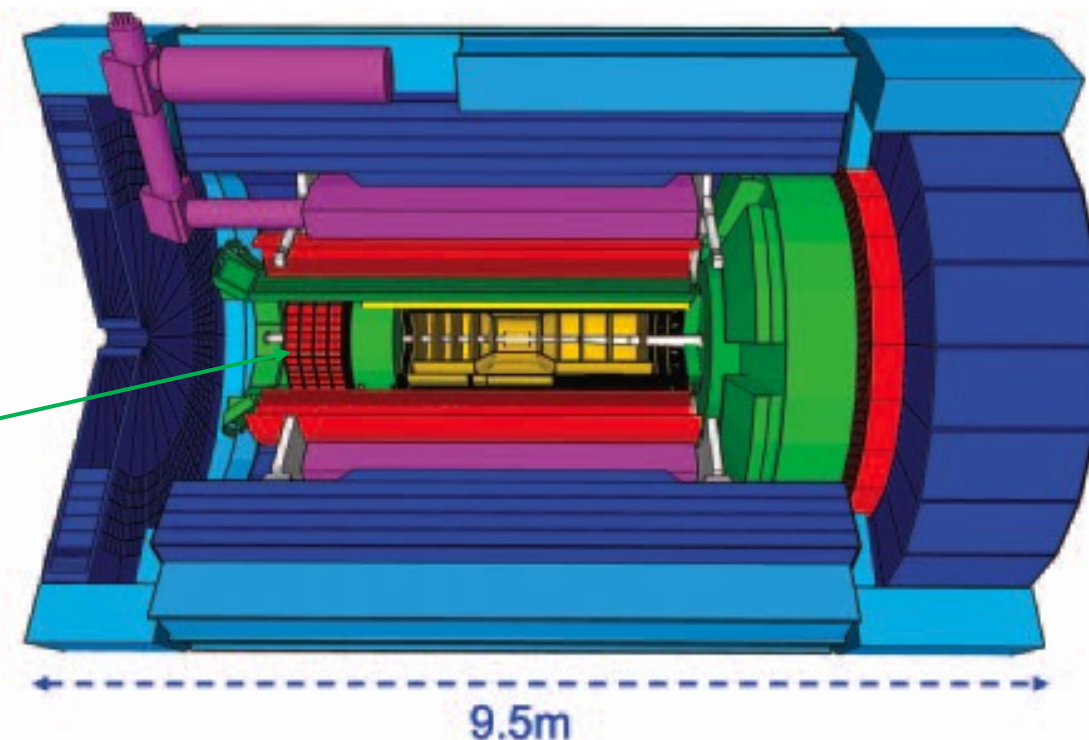
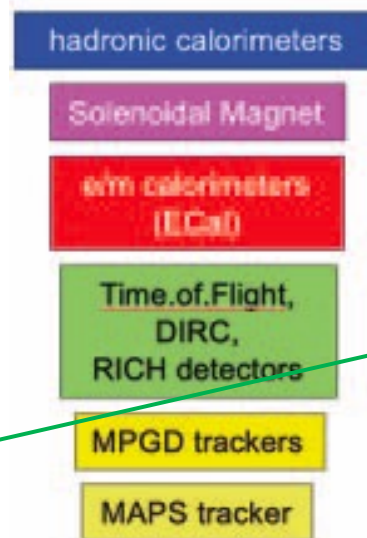
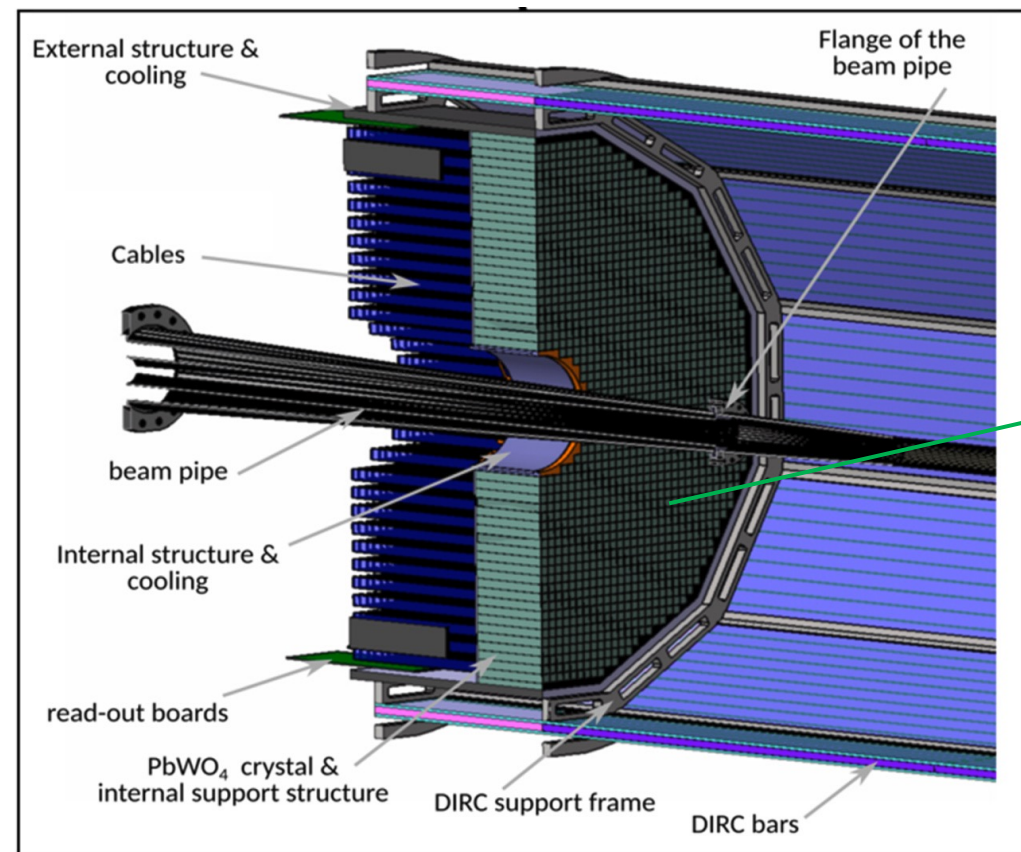


ECAL Team@SoLID:
SDU: Cunfeng-Feng, Dong Liu,
Weizhi Xiong
THU: Yi Wang, Zhihong Ye
UVA: Xiaochao Zheng

Shandong+Tsinghua+UVA



■ US-EIC EEMCAL

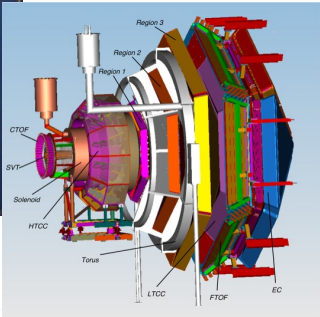
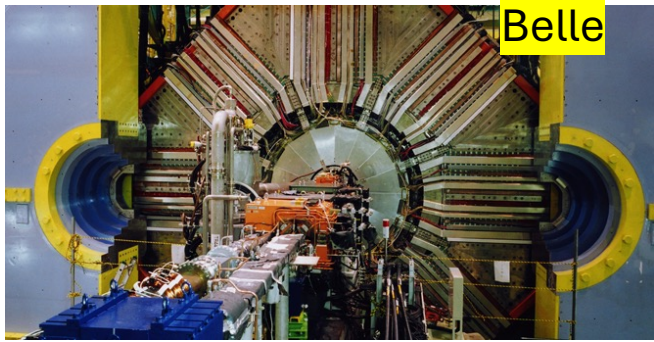
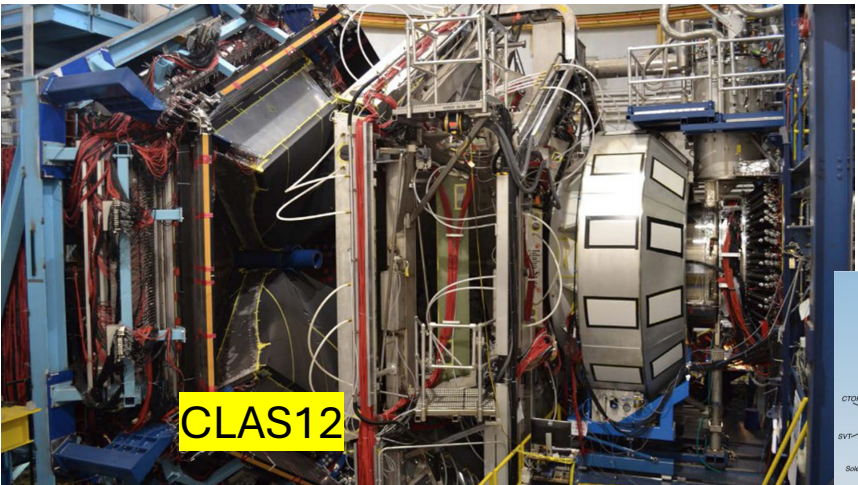
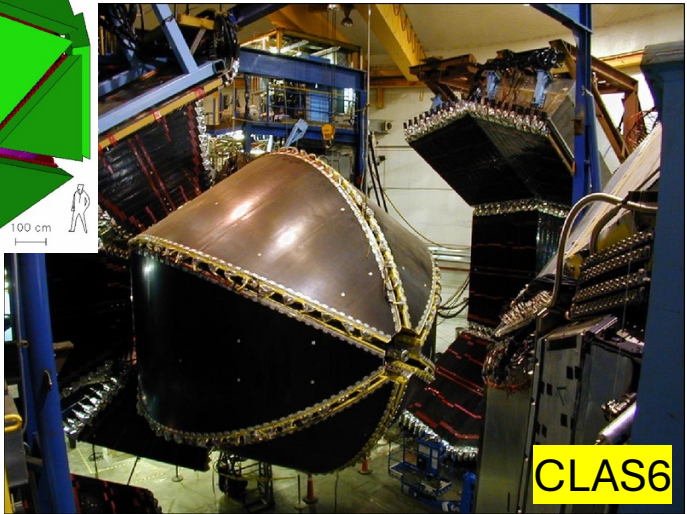
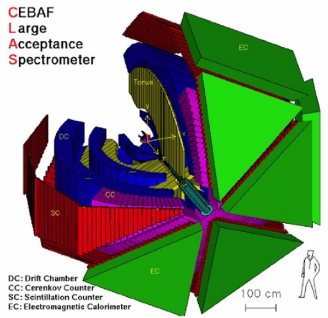
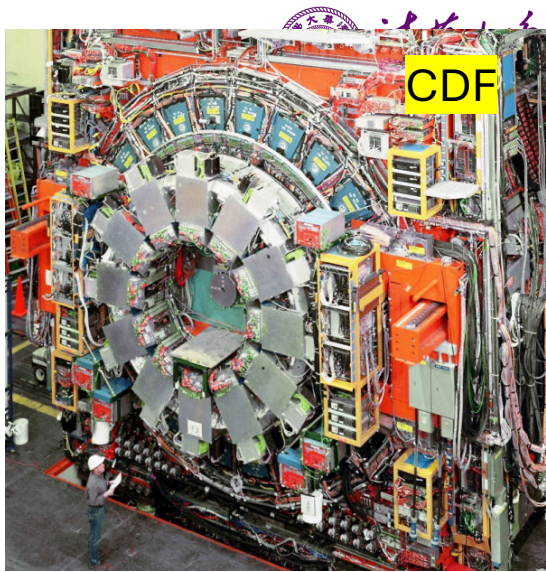
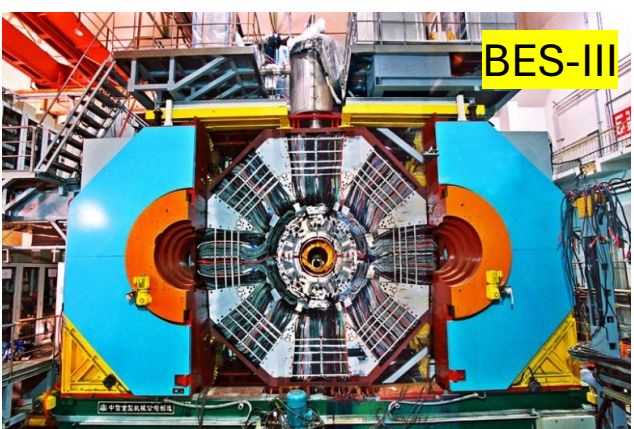
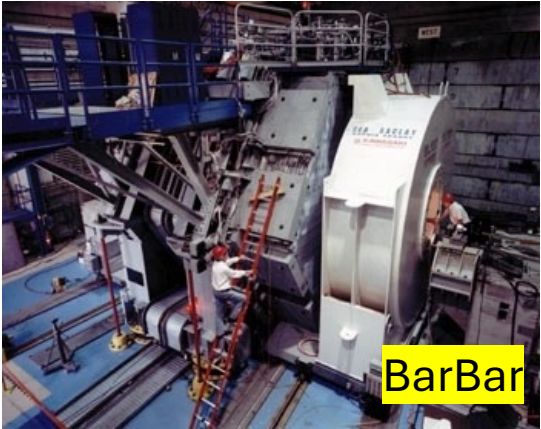
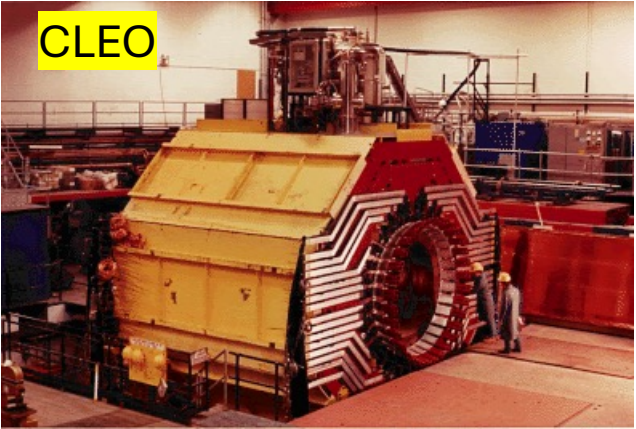


❑ Cannot use PMT in 1.8T, use SiPM or MCP



Full Acceptance Spectrometer

■ Other Major Light-Hadron Spectrometer (past and now)

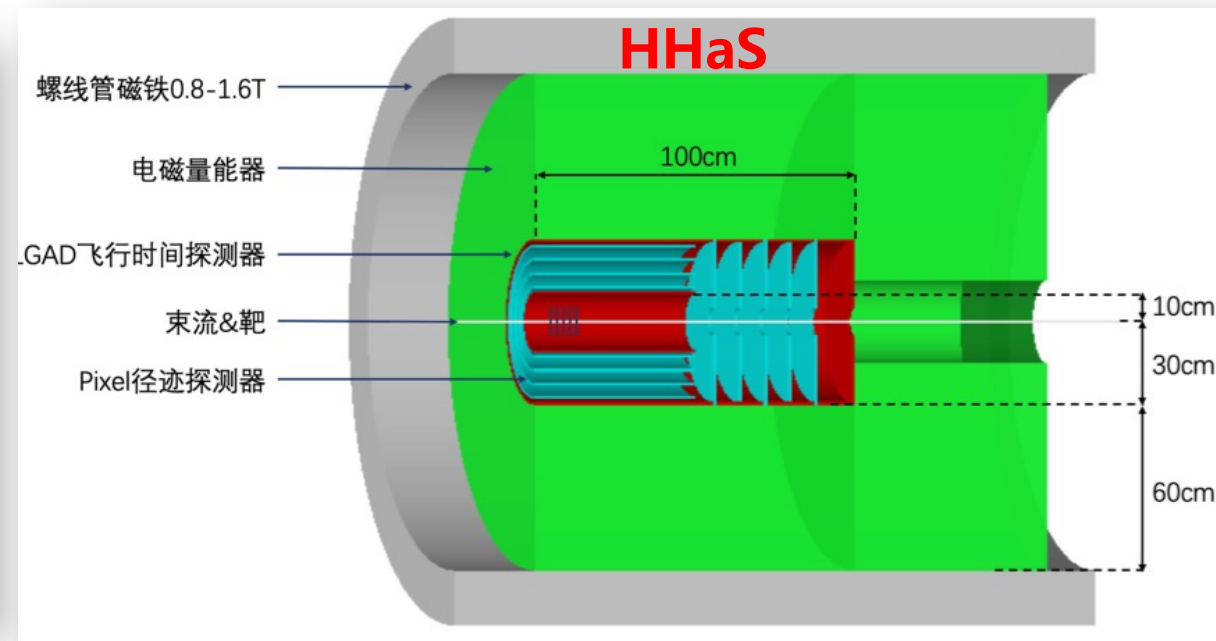
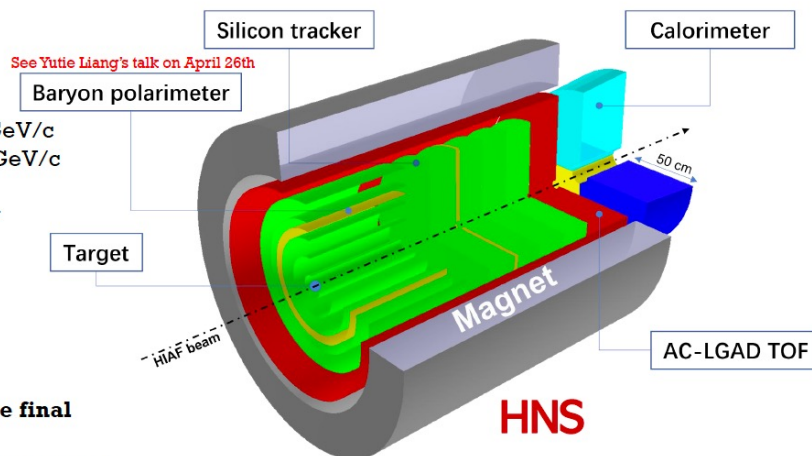


■ Two Designs at IMP for HIAF

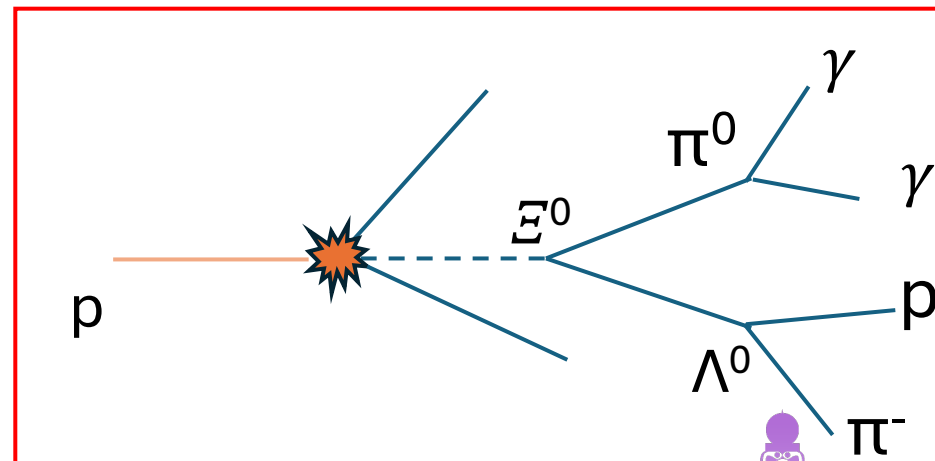
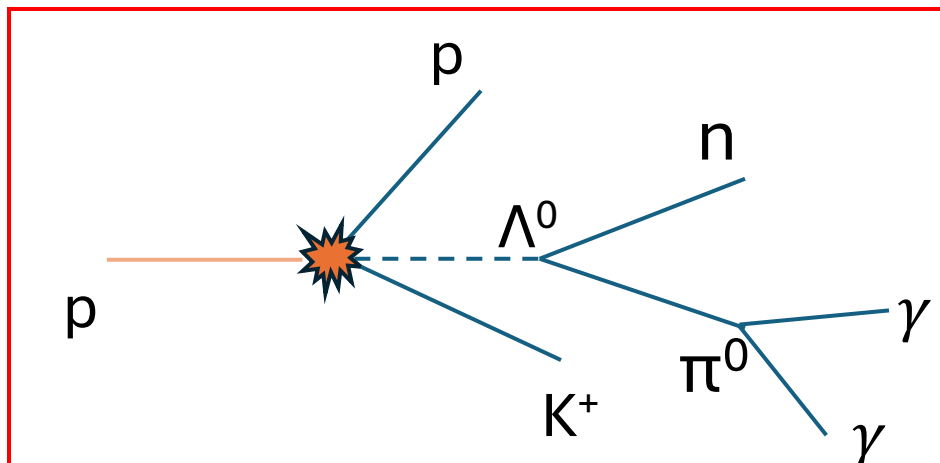
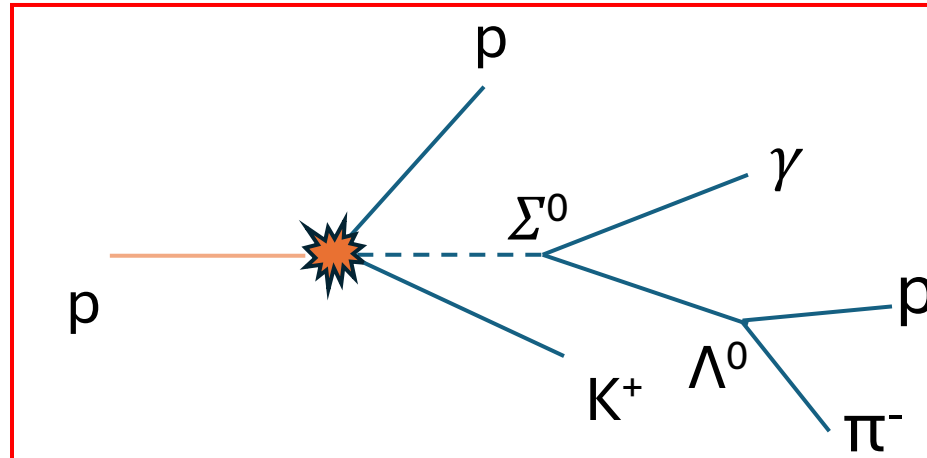
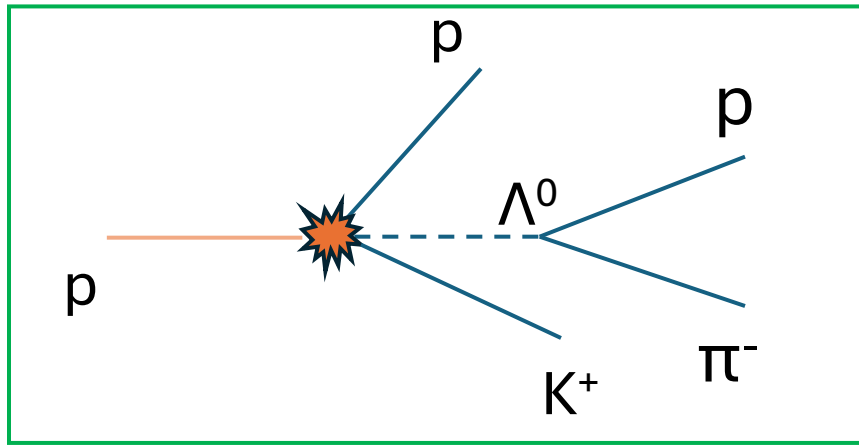
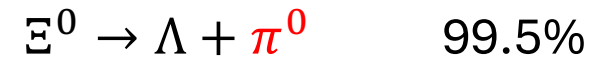
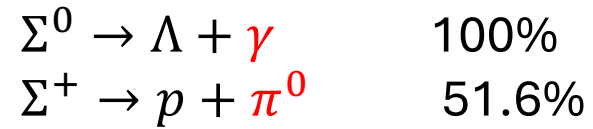
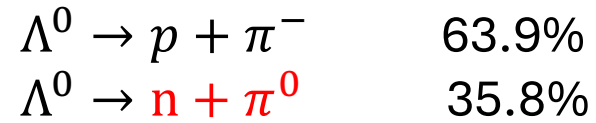
- ❑ Both designs look very identical, but different focuses in physics; Hope to unite ASAP
- ❑ Start with the proton-proton collision channels: $p + p \rightarrow p + K + \Lambda/\Sigma$
- ❑ Complementary to our physics (light strange-hadrons) under study
- ❑ Polarized-Targets to be developed by Shandong Univ (Xiaqing Li)
- ❑ Tsinghua will contribute to the high-precision ECAL

Hyperon-Nucleon Spectrometer

- **Momentum resolution:**
 - $\sim 2\%$ @ 1 GeV when $\eta < 2.5$
- **PID:**
 - K, π separation ($\sim 3\sigma$) up to 2 GeV/c
 - K, p separation ($\sim 3\sigma$) up to 5 GeV/c
- **Vertex resolution:**
 - Excellent vertex resolution for background suppression
 - Material budget ($< 10\%$)
- **Acceptance:**
 - 5 to 100 degree
- **High event rate**
 - 100MHz
- **Baryon Polarimeter** → determine final state proton's polarization
- **Provide detector R&D platform in forward region**

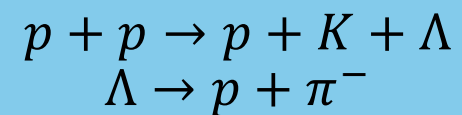


➤ Hadron Detection and Reconstruction



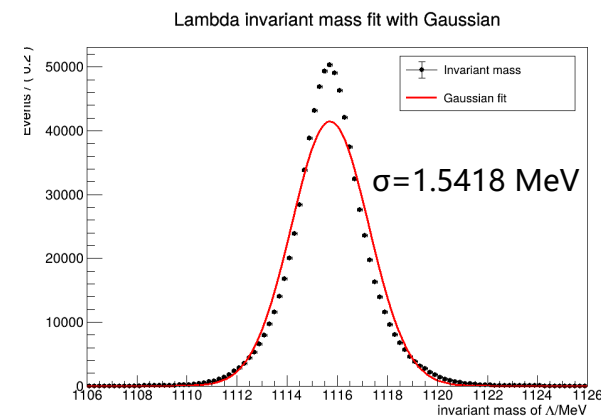
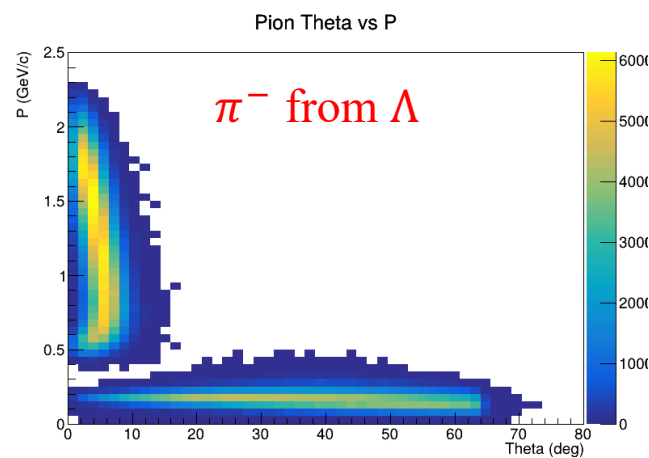
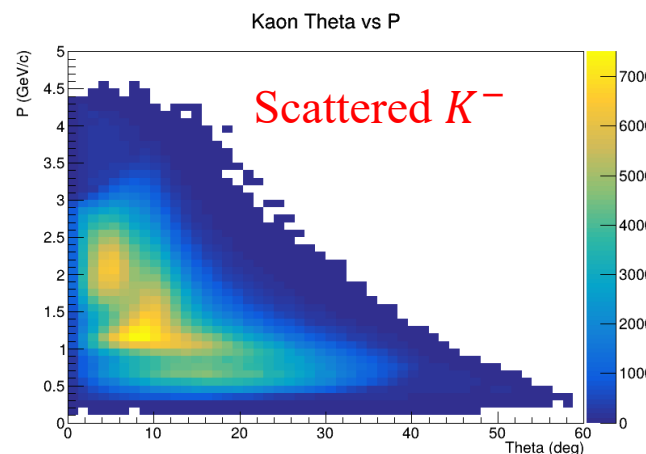
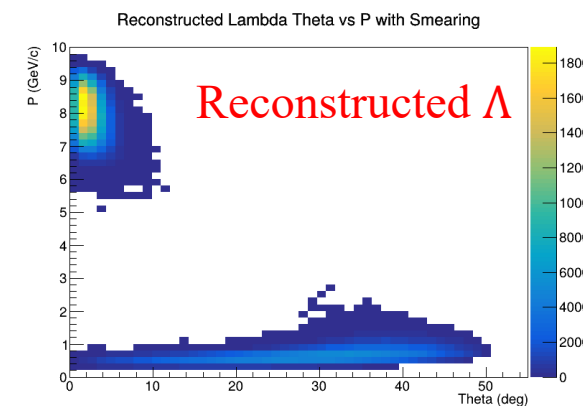
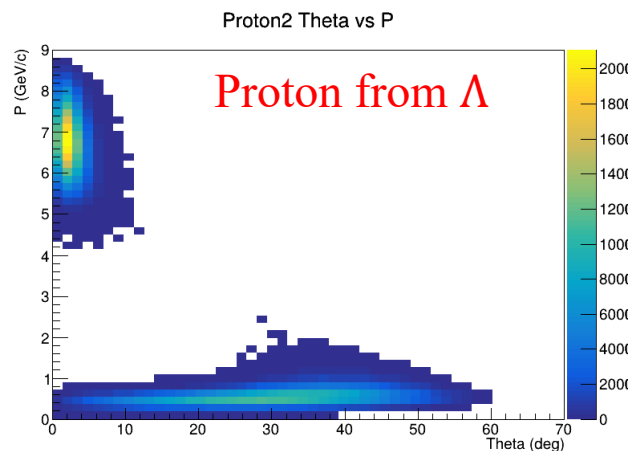
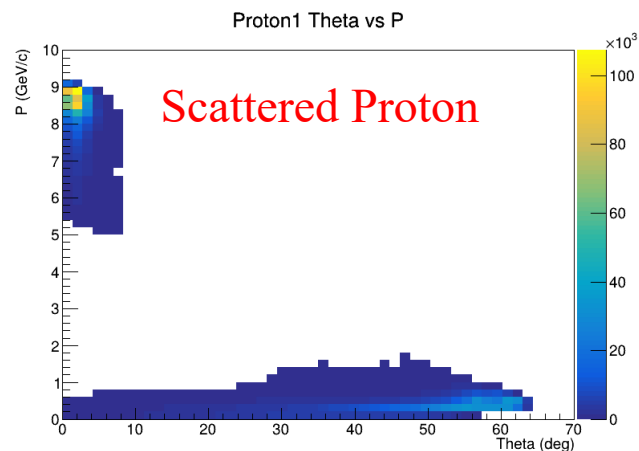
➤ Hadron Detection and Reconstruction

- ❑ Physics Calculation done by Bochao Liu@XJTU
- ❑ Monte-Calo simulation using JAM2 by Tsinghua



Assumed Resolution:

- $\delta p/p=3\%$
- $\delta\theta=5\text{mrad}$
- $\delta\phi=10\text{mrad}$



Hadron Spectroscopy

➤ Hadron Detection and Reconstruction

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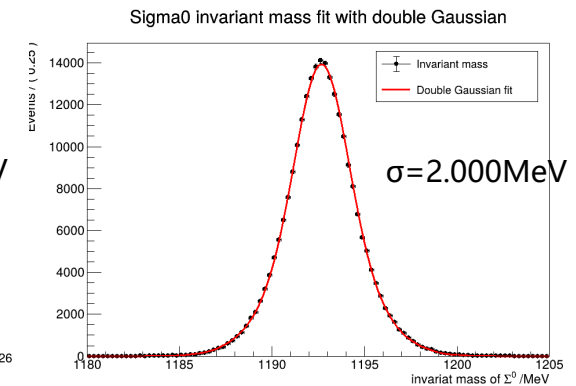
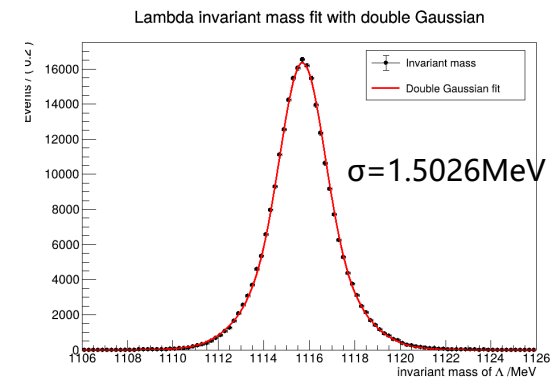
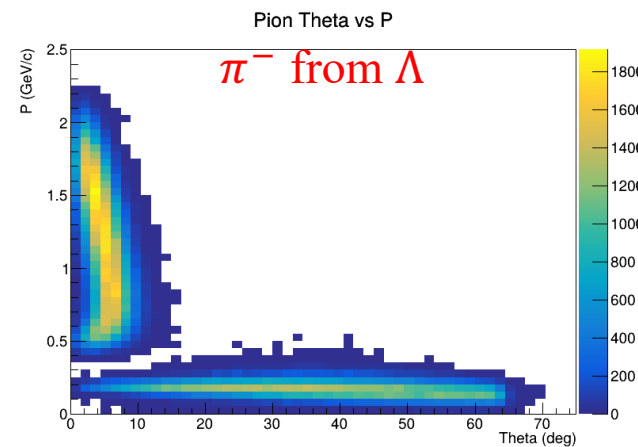
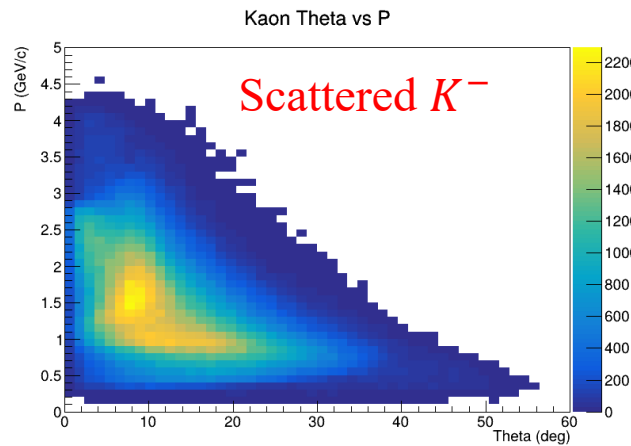
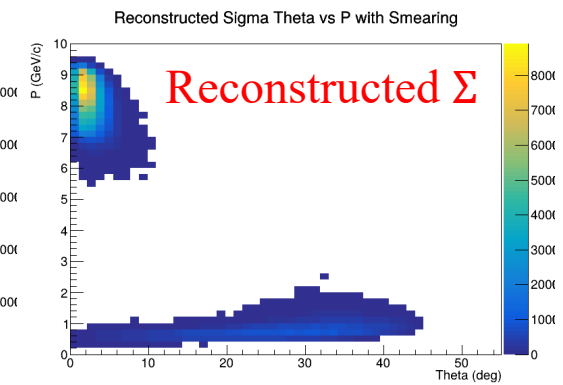
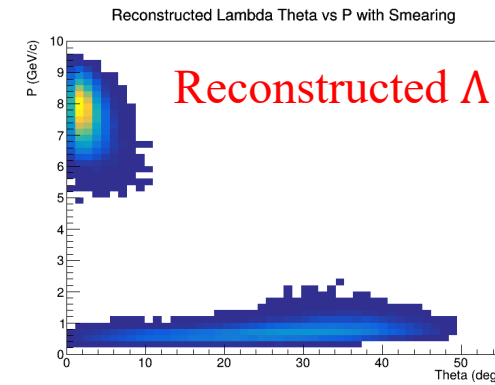
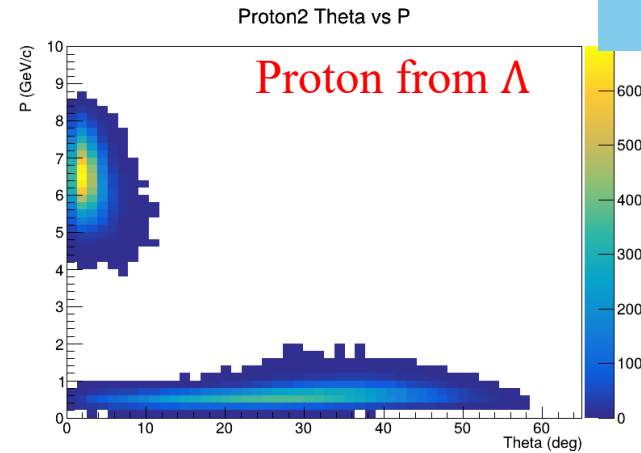
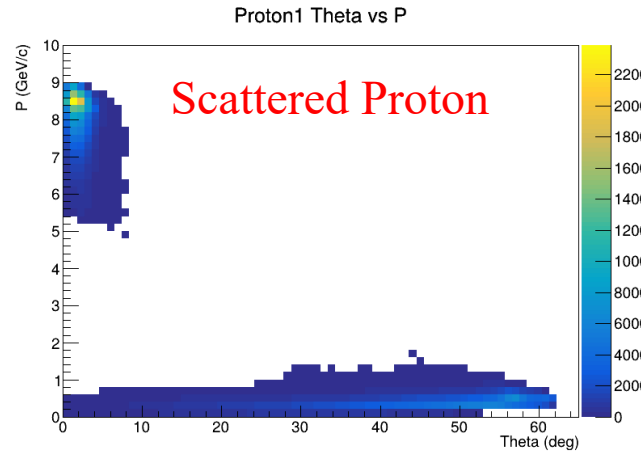
$$p + p \rightarrow p + K + \Sigma$$

$$\Sigma \rightarrow \Lambda + \gamma,$$

$$\Lambda \rightarrow p + \pi^-$$

Assumed Resolution:

- $\delta p/p = 3\%$
- $\delta\theta = 5\text{mrad}$
- $\delta\phi = 10\text{mrad}$
- $\delta E_\gamma = 3\%/\sqrt{\text{GeV}}$



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$$p + p \rightarrow p + K + \Sigma$$

$$\Sigma \rightarrow \Lambda + \gamma,$$

$$\Lambda \rightarrow n + \pi^0$$

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

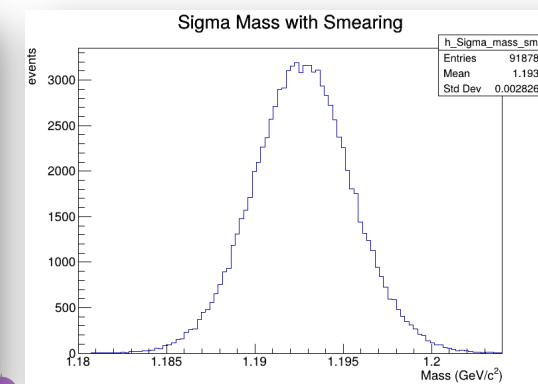
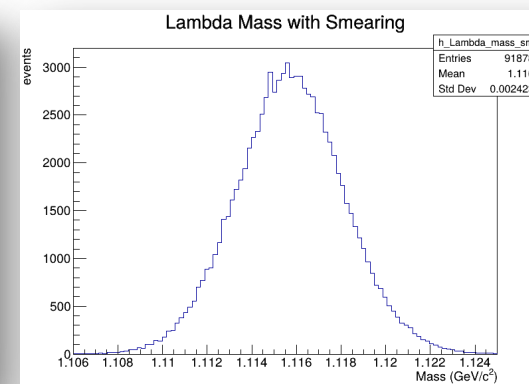
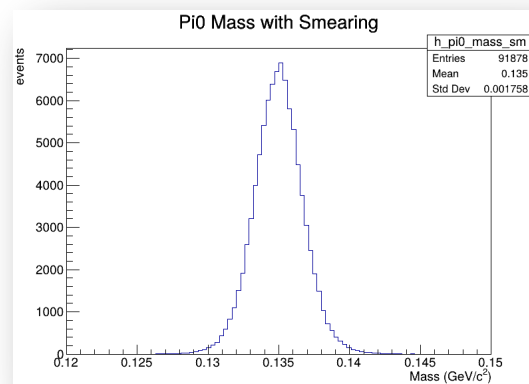
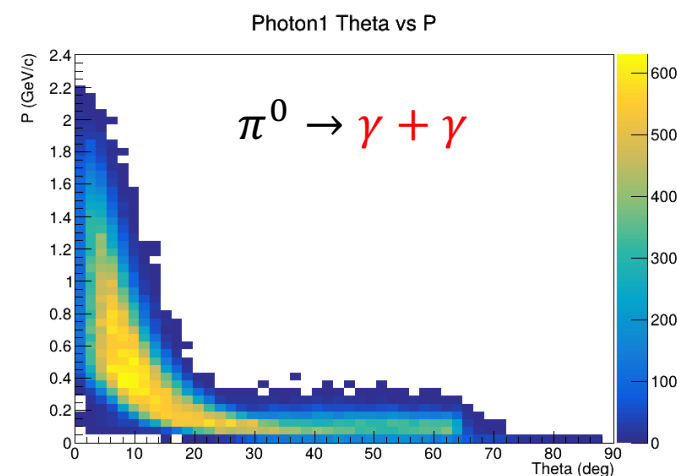
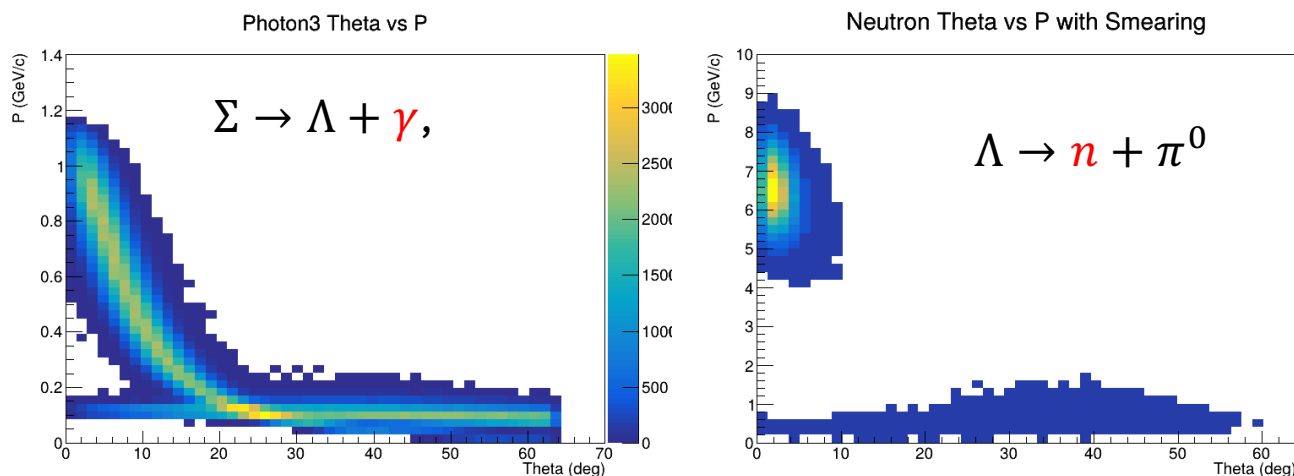
Assumed Resolution:

- $\delta p/p = 3\%$
- $\delta\theta = 5\text{mrad}$
- $\delta\phi = 10\text{mrad}$
- $\delta E_\gamma = 3\%/\sqrt{\text{GeV}}$

❑ Photons in the final state:

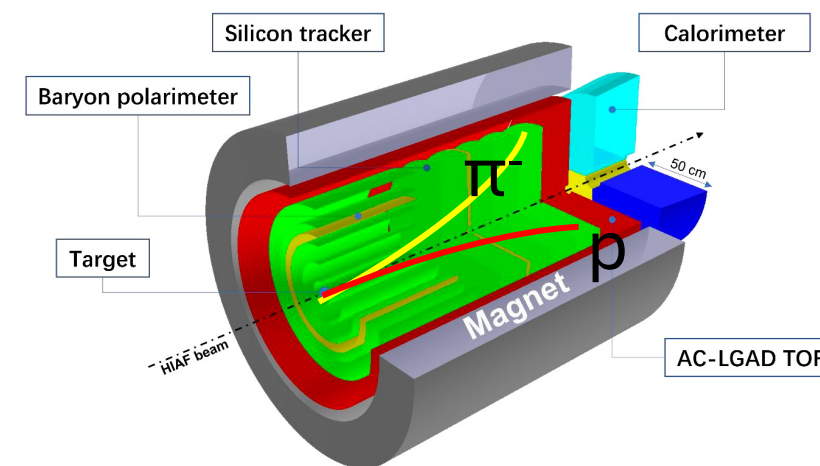
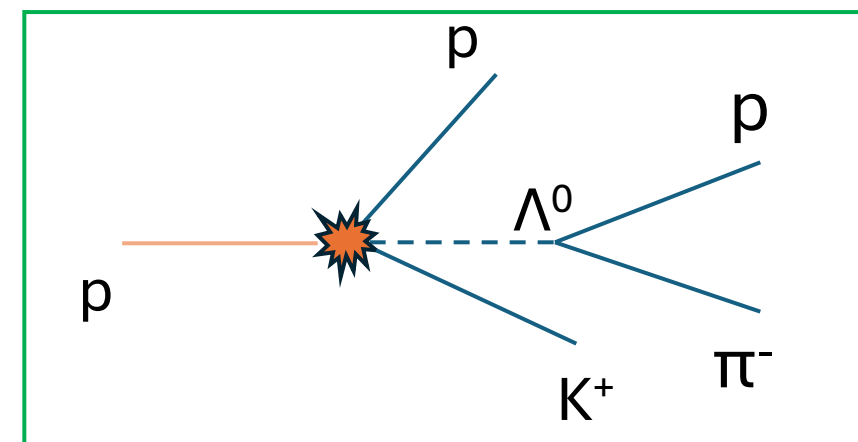
✓ $E \leq 2.2\text{GeV}$

✓ $\theta \leq 65^\circ$, mainly $\leq 30^\circ$



➤ Hadron Detection and Reconstruction

- ❑ Assume a 1m spectrometer to detect all final state particles:
 - ✓ Tracking in strong B-field determines reaction vertexes, decay-vertexes and momentum of charged particles
 - ✓ TOF determines reaction-time, velocities & PID
 - ✓ ECAL measures photons
 - ✓ Neutrons require missing-mass reconstruction

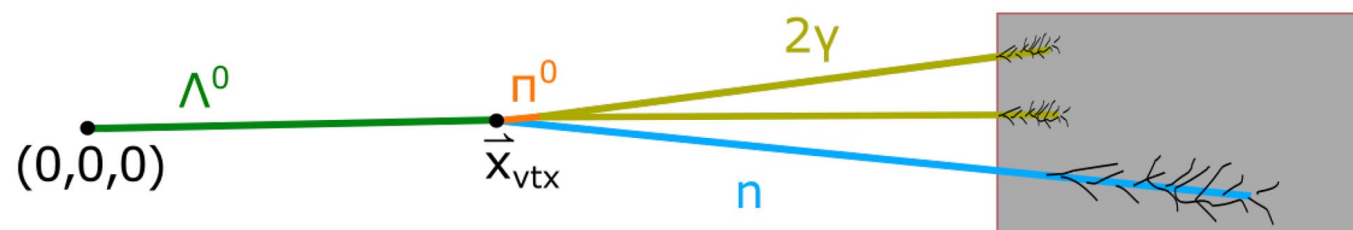


➤ Hadron Detection and Reconstruction

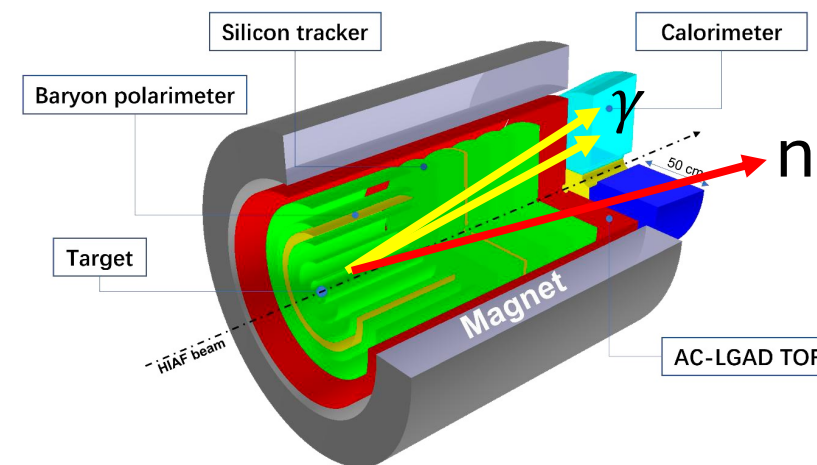
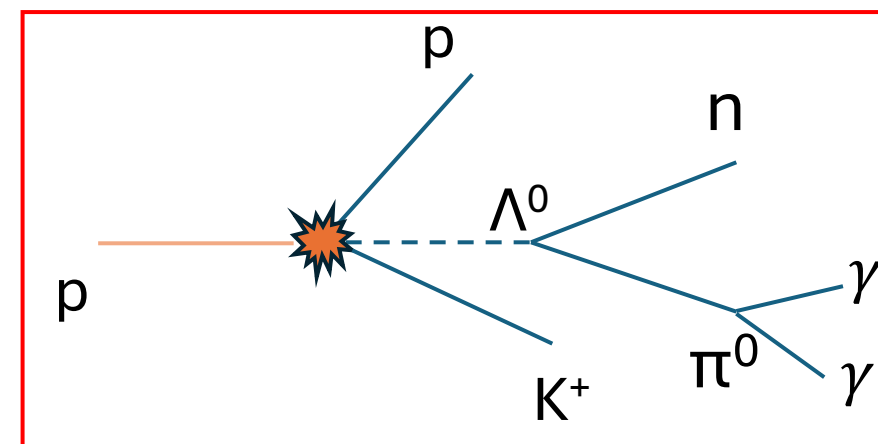
❑ Assume a 1m spectrometer to detect all final state particles:

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❑ Challenges: all neutral particles in reaction&decay



US-EIC, PHYSICAL REVIEW D 111, 092013 (2025)



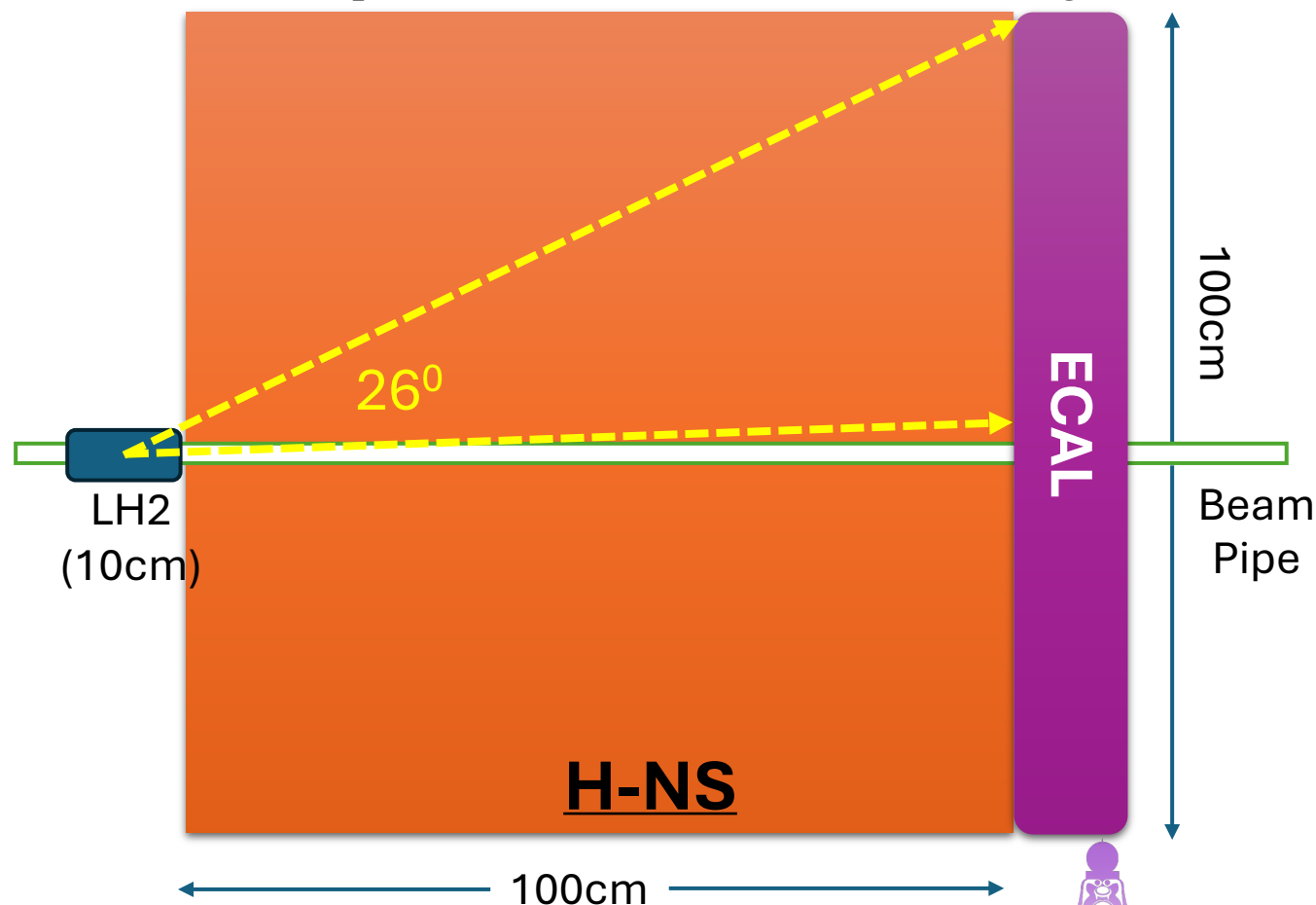
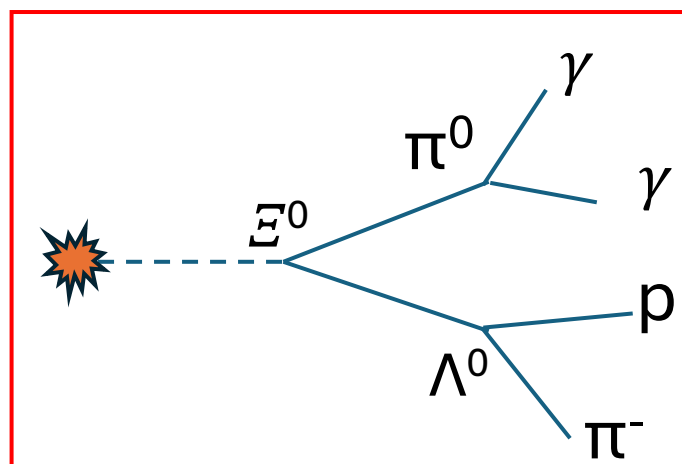
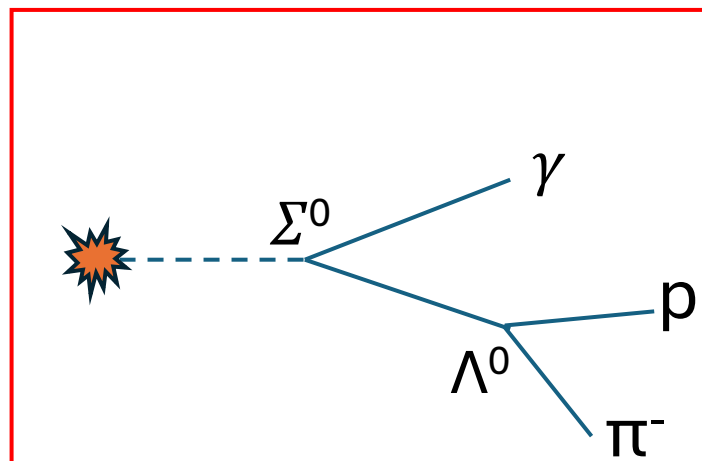
➤ Hadron Detection and Reconstruction

□ For HNS & HaaS

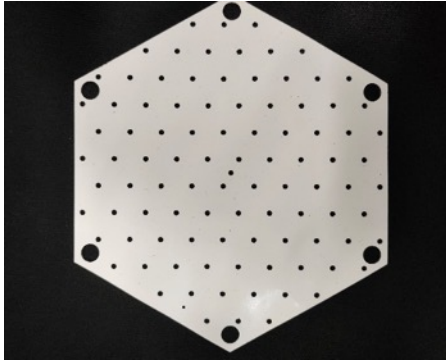
✓ Photon angle coverage: $2^\circ \sim 26^\circ$

(7% @ 26°)

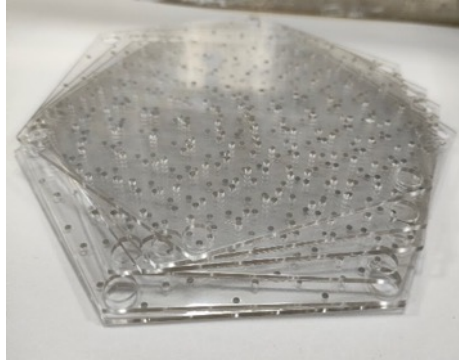
✓ If ECAL position resolution is 25mm, then angular resolution $\sim 3 \text{ mrad}$



➤ Shashlyk ECal Material Overview (by Shandong) :



lead sheet with reflective coating

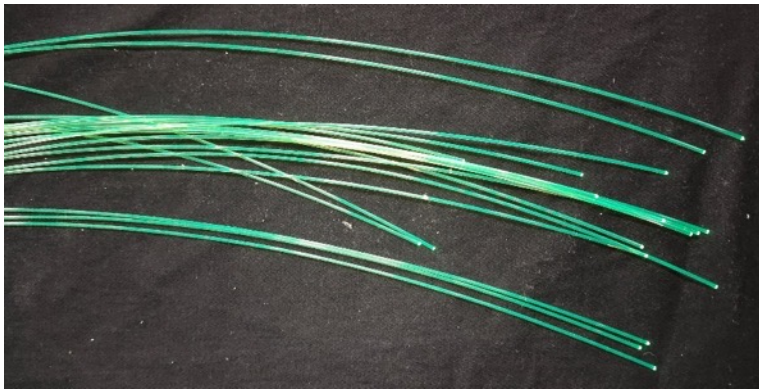


plastic scintillator



High reflectivity, effectively improve the brightness

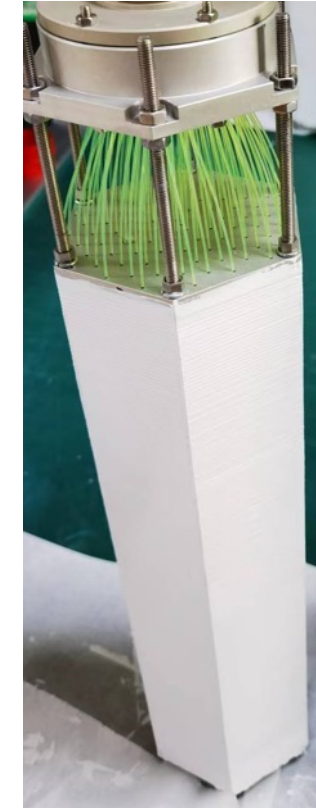
ESR with air coupling



Wavelength-Shifting Fiber

Part	Type/Material
scintillator	KEDI enhanced
WLS fiber	Y11 multi-cladding
outside surface	TiO ₂
fiber end reflector	ESR film
lead	paint TiO ₂ *

*instead of reflective layer between lead



optical reflective glue



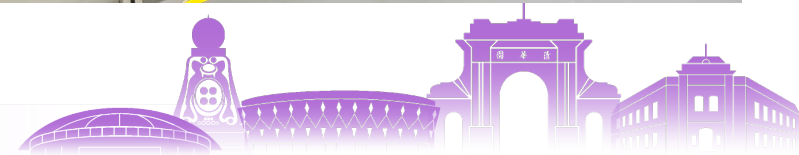
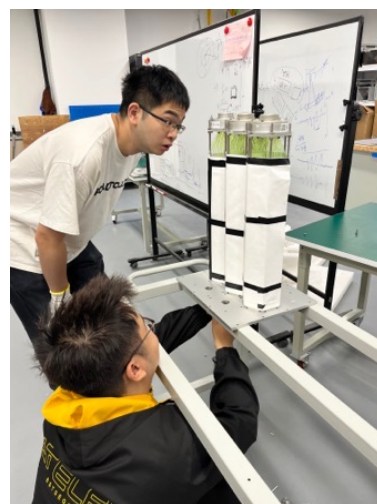
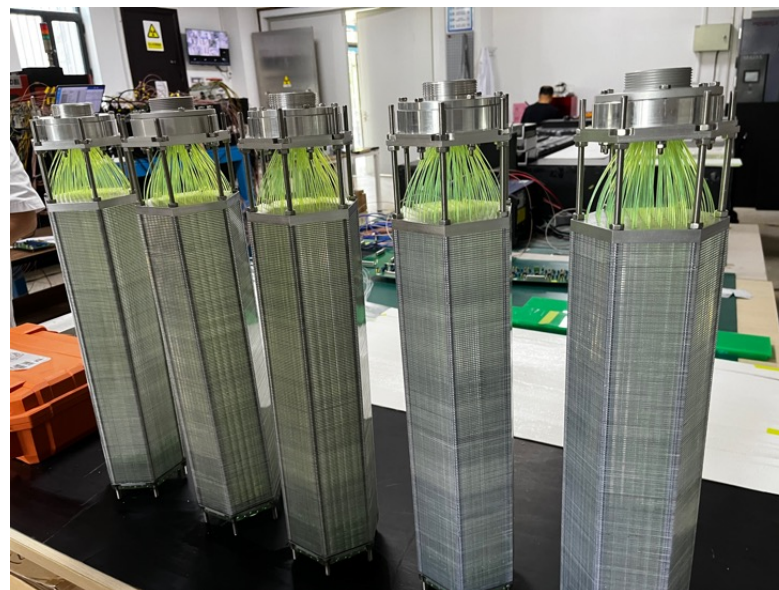
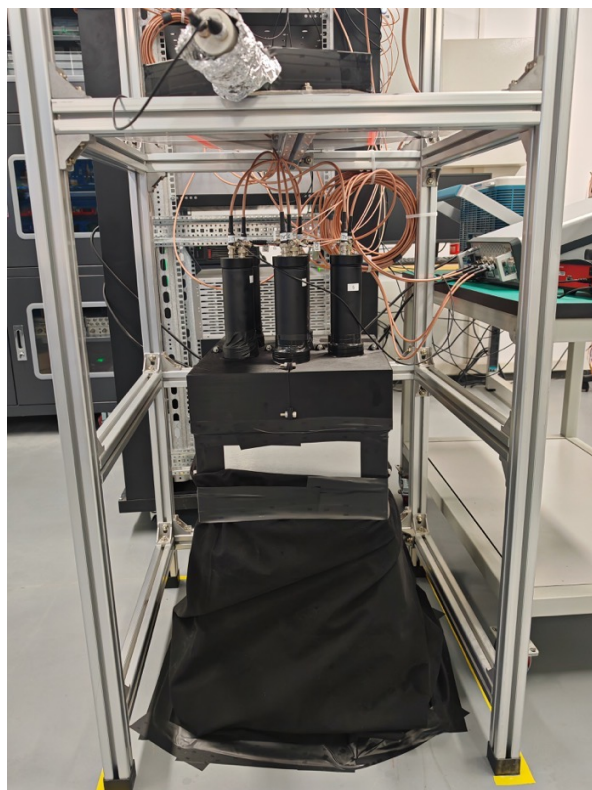
Tyvek



➤ Shashlyk ECal Testing (by Tsinghua&UVA):

❑ Beam test result :

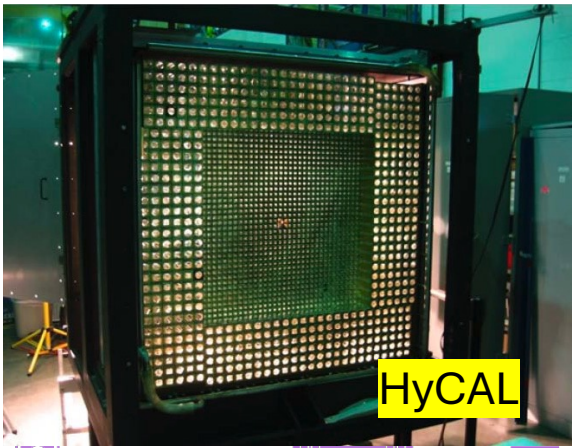
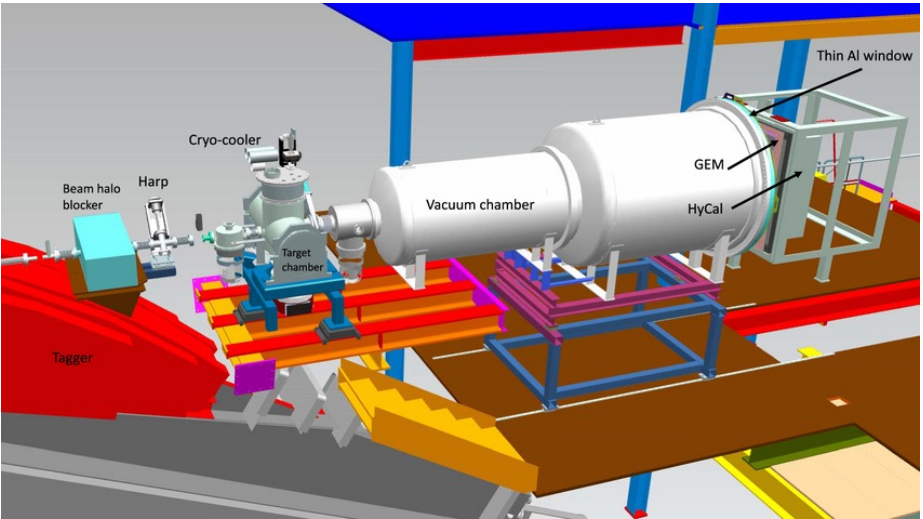
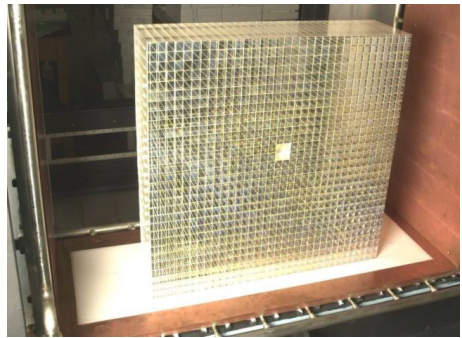
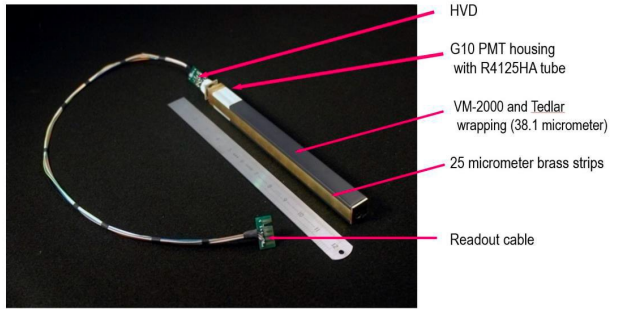
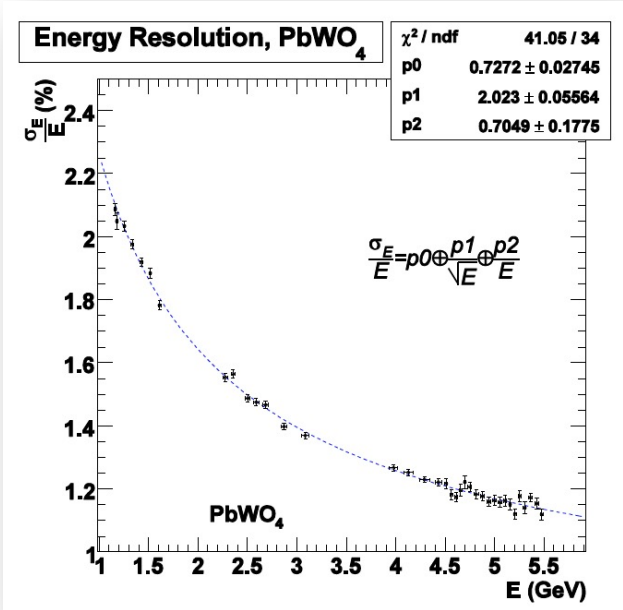
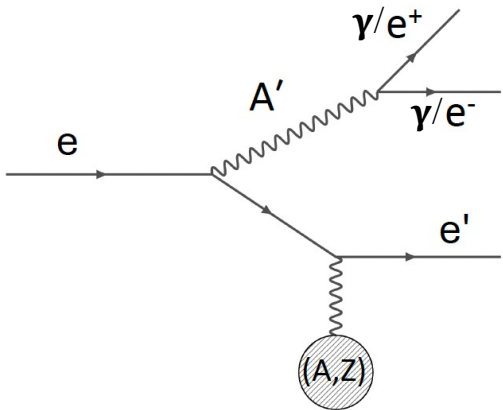
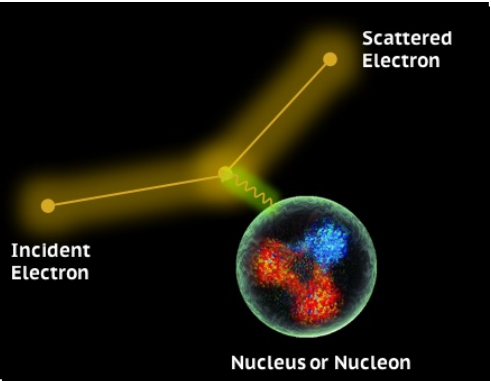
- $\delta E/E \sim 5\%/\sqrt{E}$
- Position $\sim 10\text{mm}$



PbWO₄ ECAL

■ HYCAL for PRAD-II/X17@Hall-B, JLab

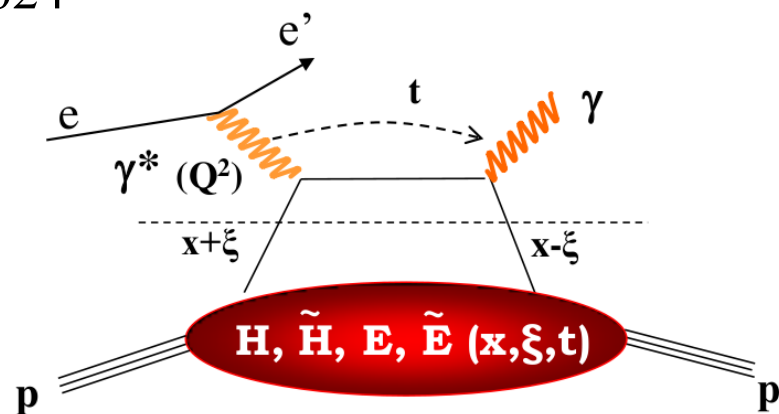
- ❑ First experiment completed in 2017
- ❑ Second experiment to run in 2026
- ❑ ECAL resolution: ~2%



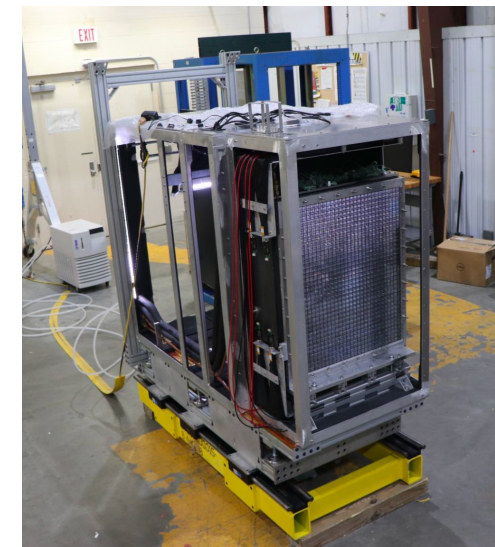
➤ NPS@Hall-C, JLab

❑ Experiment completed in 2024

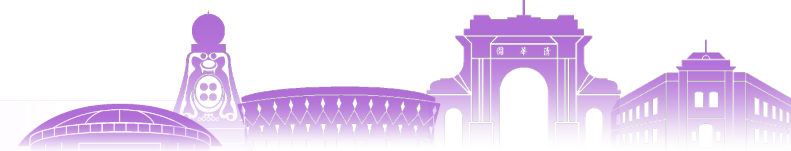
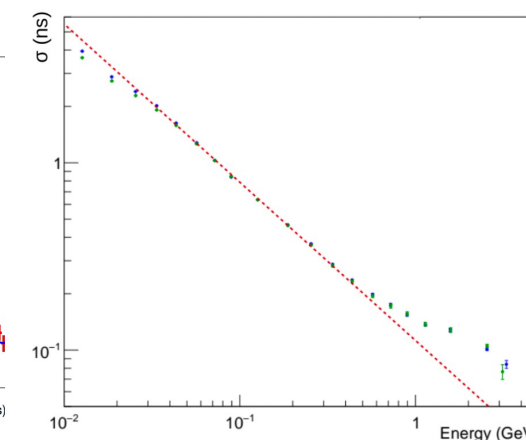
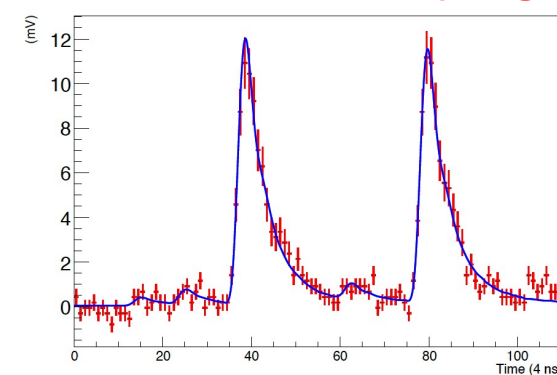
- ✓ $\delta E/E \sim 1.3\%/\sqrt{E}$
- ✓ Position $\sim 2.5\text{mm}$
- ✓ Timing: 300ps



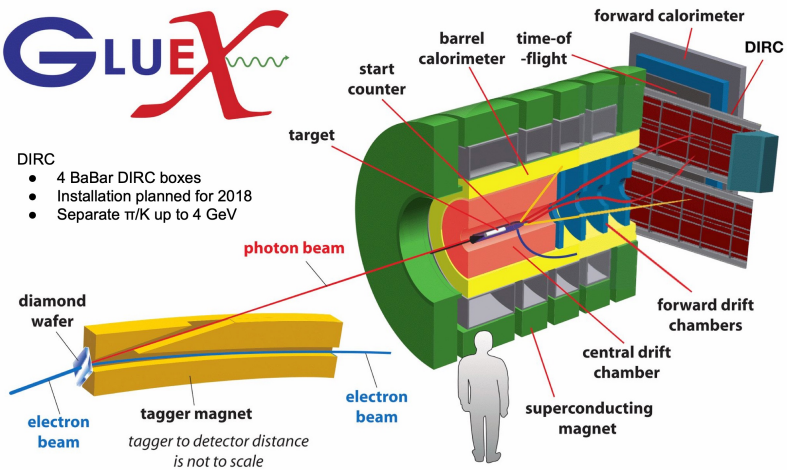
F250 flash-ADC@JLab



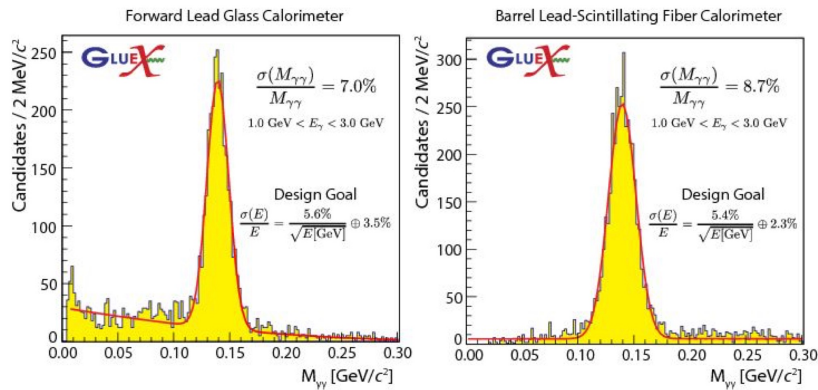
Wave-Form Sampling



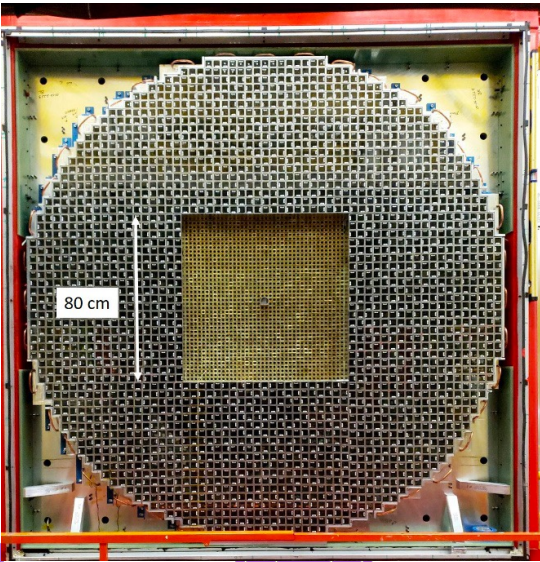
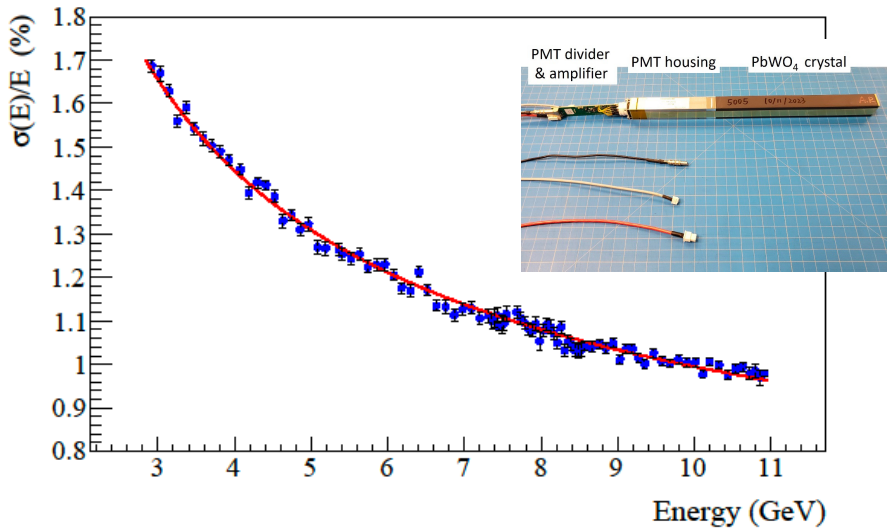
■ GlueX@Hall-D, JLab



□ GlueX-ECAL give 7~9%, but with big detector (>5m)

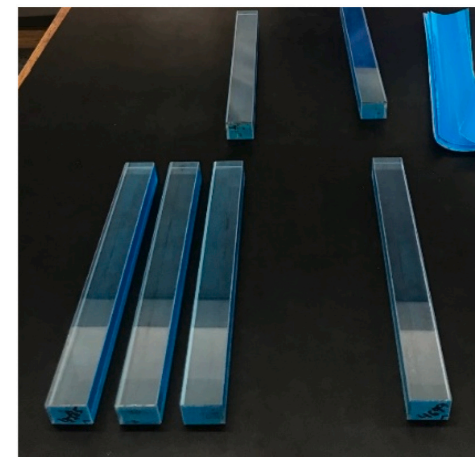


□ Hybrid-ECAL for eta-Factory (<2%)



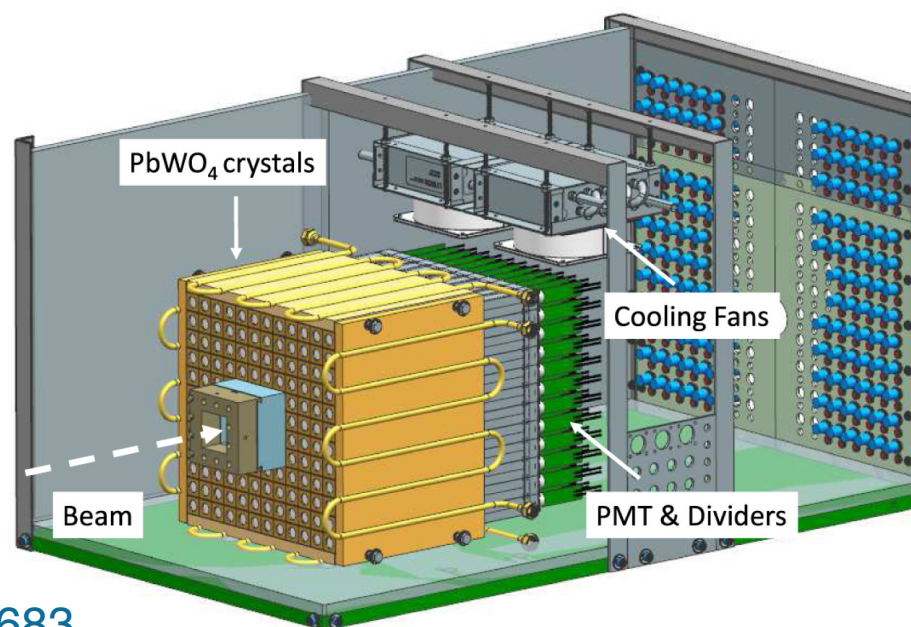
➤ Adopt Hall-C NPS ECAL

- ❑ Total Area: 35 x 35 Array (70cmx70cm)
- ❑ 1225 Crystal + PMT (or SiPM)
- ❑ PbWO₄ Module: 20.5mm x 20.5mm x 200mm
- ❑ Triggerless Waveform Sampling DAQ
- ❑ Supporting Frame & Cooling System
- ❑ High-Voltage
- ❑ Others:
 - ✓ LED Monitoring System
 - ✓ Enviromental Monitor System



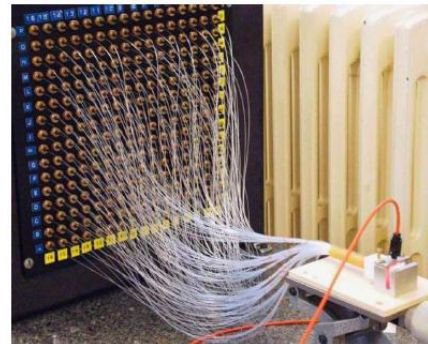
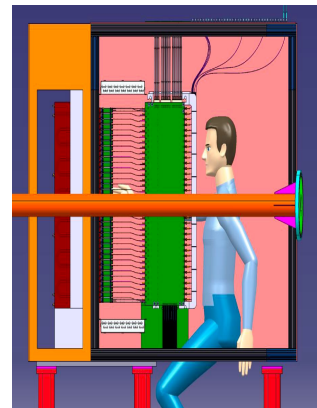
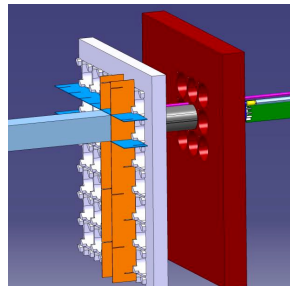
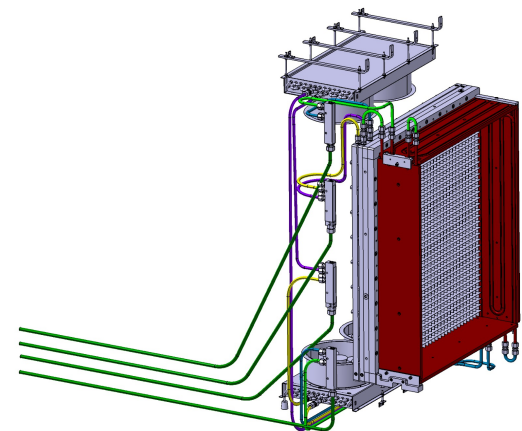
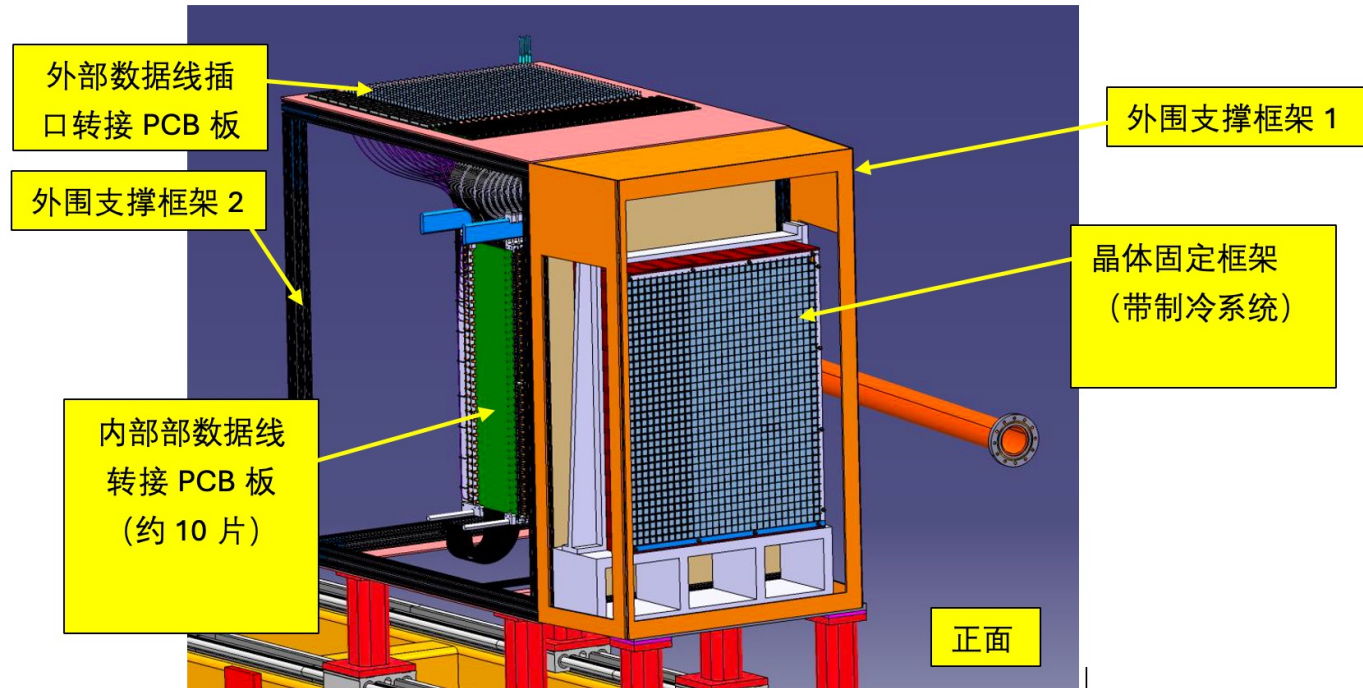
Density (g/cm ³)	8.28
Hardness (Moh)	4
Refractive index	2.17
Melting point (°C)	1123
Crystal structure	Tetragonal symmetric
Hygroscopic	No
Wavelength max emission (nm)	420
Decay constant (ns)	5 - 15
Photon yield (ph/MeV)	15 - 25
Molière radius (cm)	2.0

Radiation Length = 0.89 cm



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➤ Adopt Hall-C NPS ECAL



➤ Planning:

❑ Physics Simulation+ Geant4

- ✓ pp collision to create Λ^0 , Σ^0 , Ξ^0
- ✓ Geant4 to study distribution of photons, reconstruction of hadrons with realistic detector resolution
- ✓ Put requirements for performance of the Hadron Spectrometer

❑ 3x3 Small Prototype (THU+SDU)

✓ Crystal & PMT&SiPM Testing

15 PWO Crystals provided by CCNU (Daicui Zhou)

✓ Light Guide+PMT+PreAMP Design&Assembly

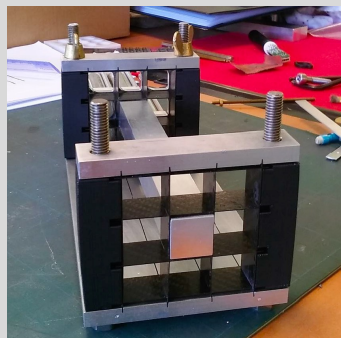
✓ Cosmic Ray Testing

✓ LED-System Design

✓ Supporting Frame Design

✓ Cooling System Design

✓ Beam Test



❑ 35x35 Full-Size ECAL Prototype

✓ Procurement of 1300 PbWO4 Crystals, Q&A

✓ Procurement of PMT, Testing

✓ Full size Supporting Frame

✓ Full size LED System

✓ Slow Control

✓ DAQ

✓ Cosmic-Ray and Beam Tests

✓ Use in real experiment (like CEE)



- THU team is mainly interested in spectroscopy of light hadron with strangeness
- Aim for secondary kaon beam, polarized targets and a full-acceptance spectrometer
- Developing a PWO-based ECAL for light-hadron decaying into photons
- Tsinghua Univ. & Shandong Univ work together to develop PbWO₄-ECAL prototypes
 - Simulation to pin down requirements for physics measurements
 - Development of a 3x3 small ECAL prototype is ongoing
 - Aim for a 35x35 full-size ECAL



THANKS!



清华大学
Tsinghua University