Introduction of China Hyper-Nuclear Spectrometer (CHNS)

A future experiment at HIAF

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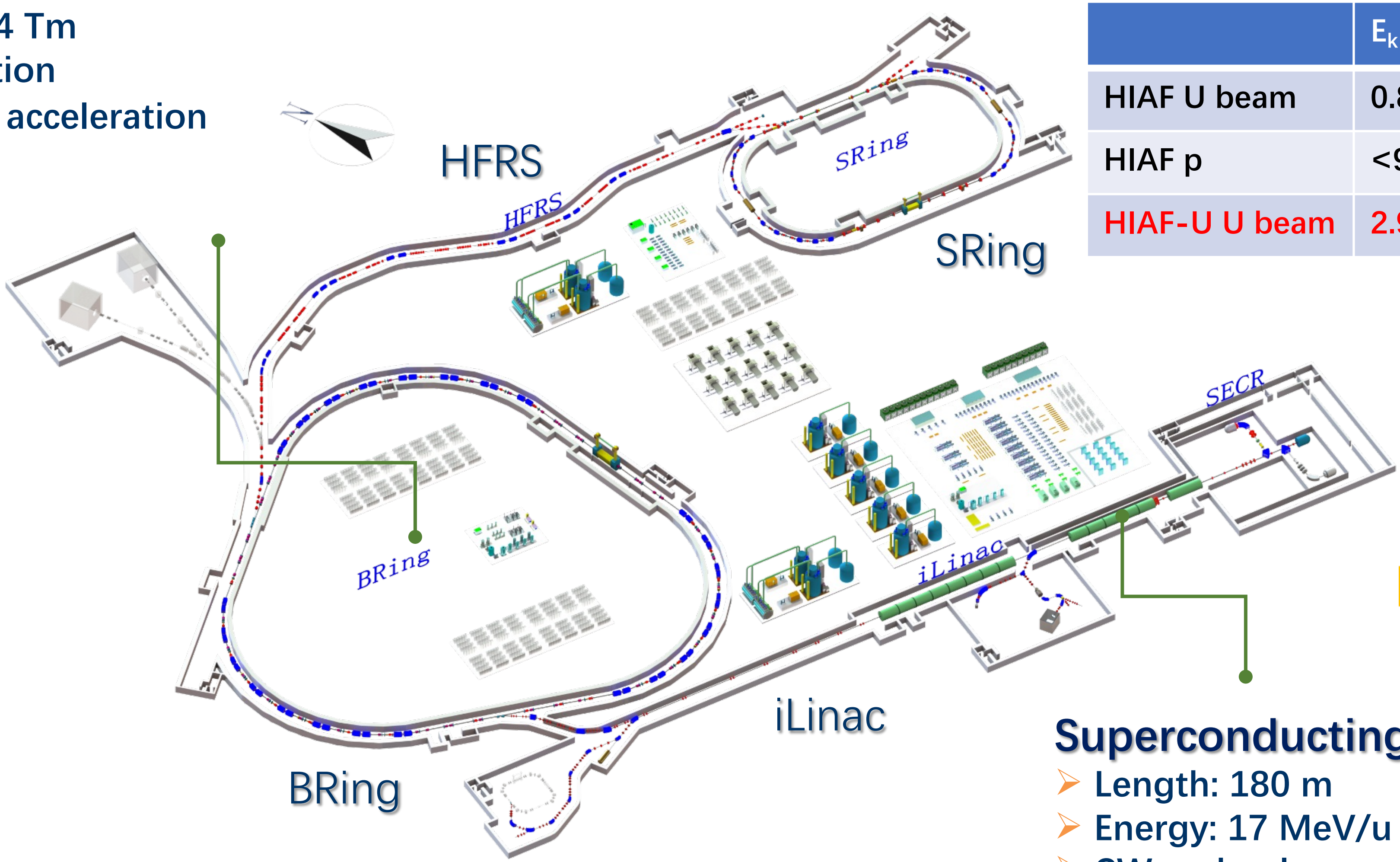
第二届惠州大科学装置高精度物理研讨会 – Aug. 24-26 @ Guangzhou

High Intensity heavy-ion Accelerator Facility (HIAF)

Booster Ring:
- Circumference: 569 m
- Rigidity: 34 Tm
- Accumulation
- Cooling & acceleration

HIAF total investment: 2.5 billion RMB **(Funded)**



	E_k (GeV/u)	$\sqrt{s_{NN}}$ (GeV)
HIAF U beam	0.8-2.45	2.24-2.85
HIAF p	<9.3	<4.58
HIAF-U U beam	2.95-9.1	3.01-4.54

Ion species	Energy (GeV/u)	Intensity (ppp)
p	9.3	5.0×10^{13}
$^{12}C^{6+}$	4.2	6.0×10^{12}
$^{78}Kr^{19+}$	1.7	2.5×10^{12}
$^{209}Bi^{31+}$	0.85	3.0×10^{11}
$^{238}U^{35+}$	0.835	2.0×10^{11}

Superconducting Ion Linac:
- Length: 180 m
- Energy: 17 MeV/u (U^{34+})
- CW and pulse modes

Mao's talk on 24th Aug.

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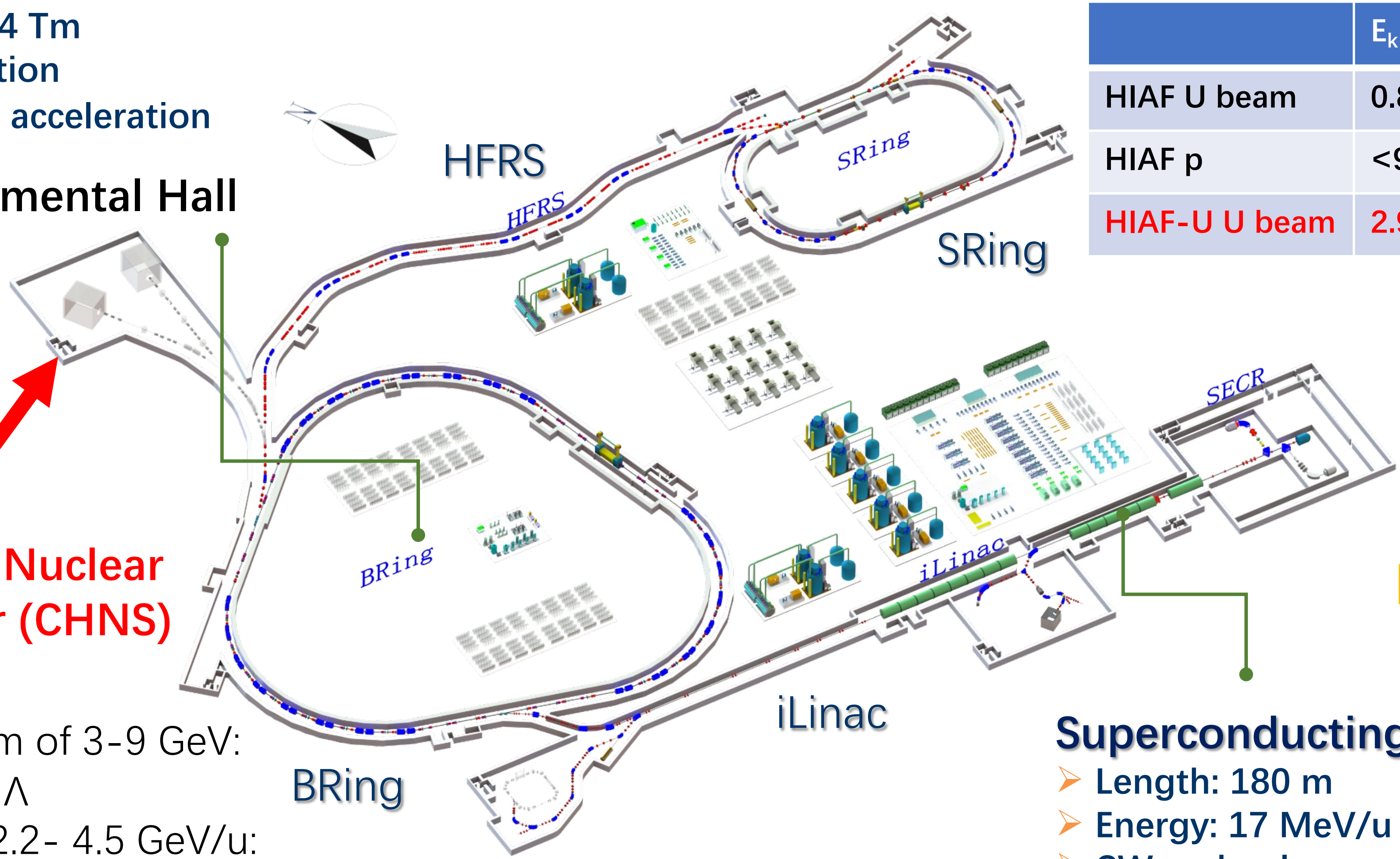
Experimental Hall



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China Hyper-Nuclear Spectrometer (CHNS)

- Proton beam of 3-9 GeV:
  pp → p K+ Λ
- U beam at 2.2- 4.5 GeV/u:
  U+U → $^{3}_{\Lambda}H$ + ···

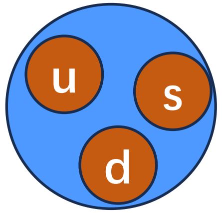
Superconducting Ion Linac:
- Length: 180 m
- Energy: 17 MeV/u (U^{34+})
- CW and pulse modes

Mao's talk on 24th Aug.

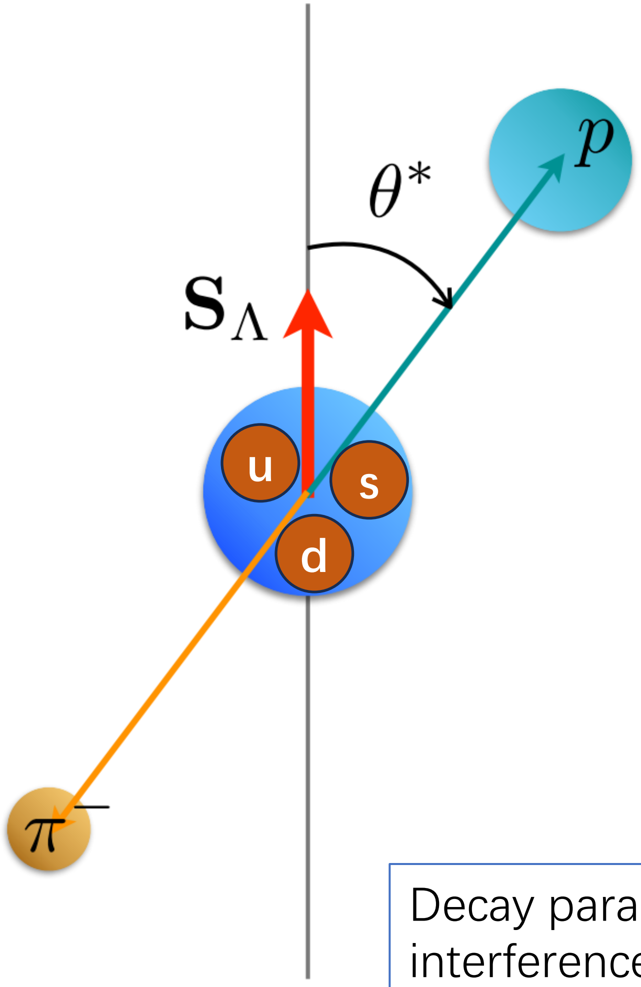
Λ Hyperon

- Mass of strange quarks being close to the QCD cut-off scale
- Unique position to explore the transition zone where quarks and gluon become comfined into hadron

$$\frac{m_s}{\Lambda_{QCD}} = 0.475$$



Λ Hyperon



- Mass of strange quarks being close to the QCD cut-off scale
- Unique position to explore the transition zone where quarks and gluon become comfined into hadron

$$\frac{m_s}{\Lambda_{QCD}} = 0.475$$

- Their **spin is traceable** through their self-analysis decay

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

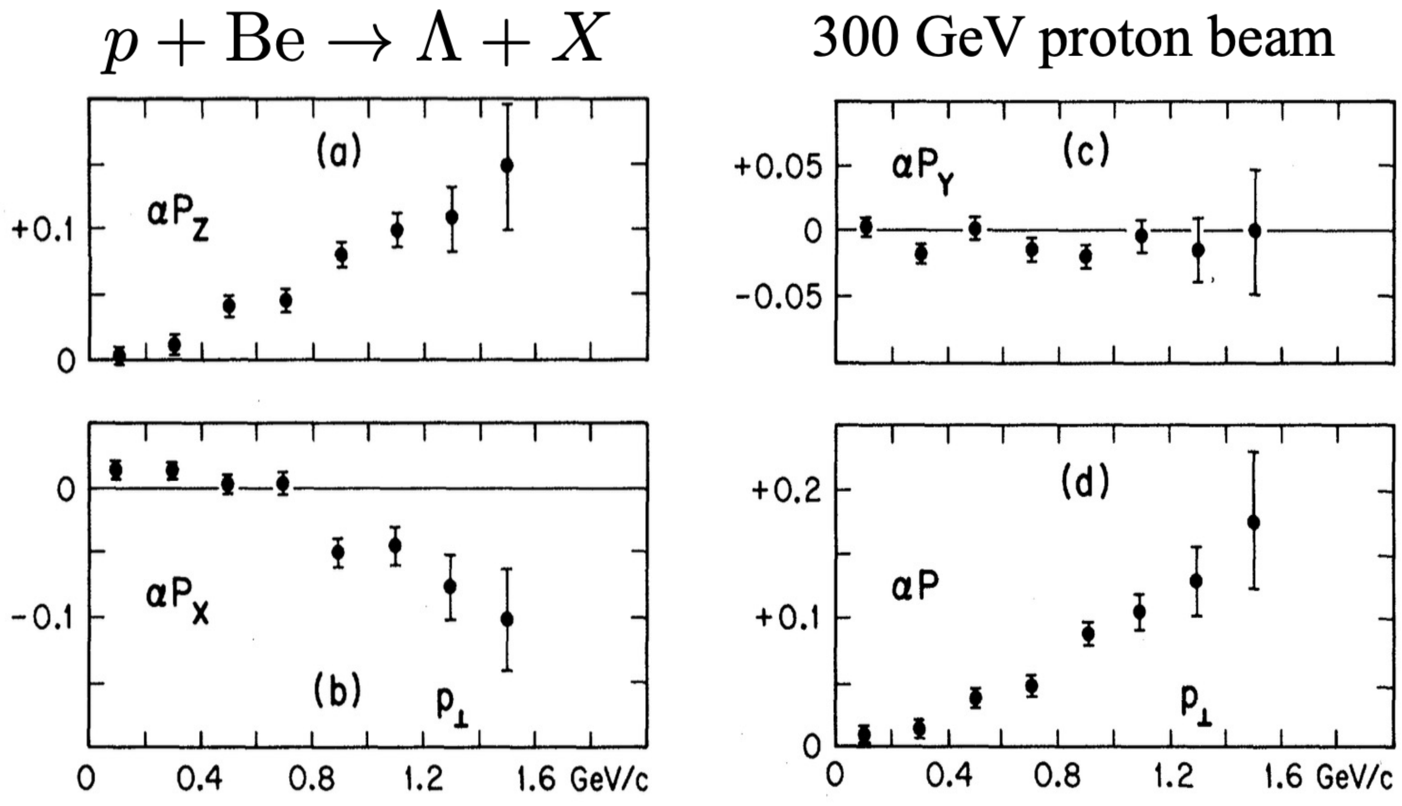
parity violating weak decay

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} \propto \mathcal{A}\left(1 + \alpha_\Lambda P_\Lambda \cos\theta^*\right)$$

Decay parameter that indicates the interference between the parity violation and conserving decay amplitudes

Polarization of Λ

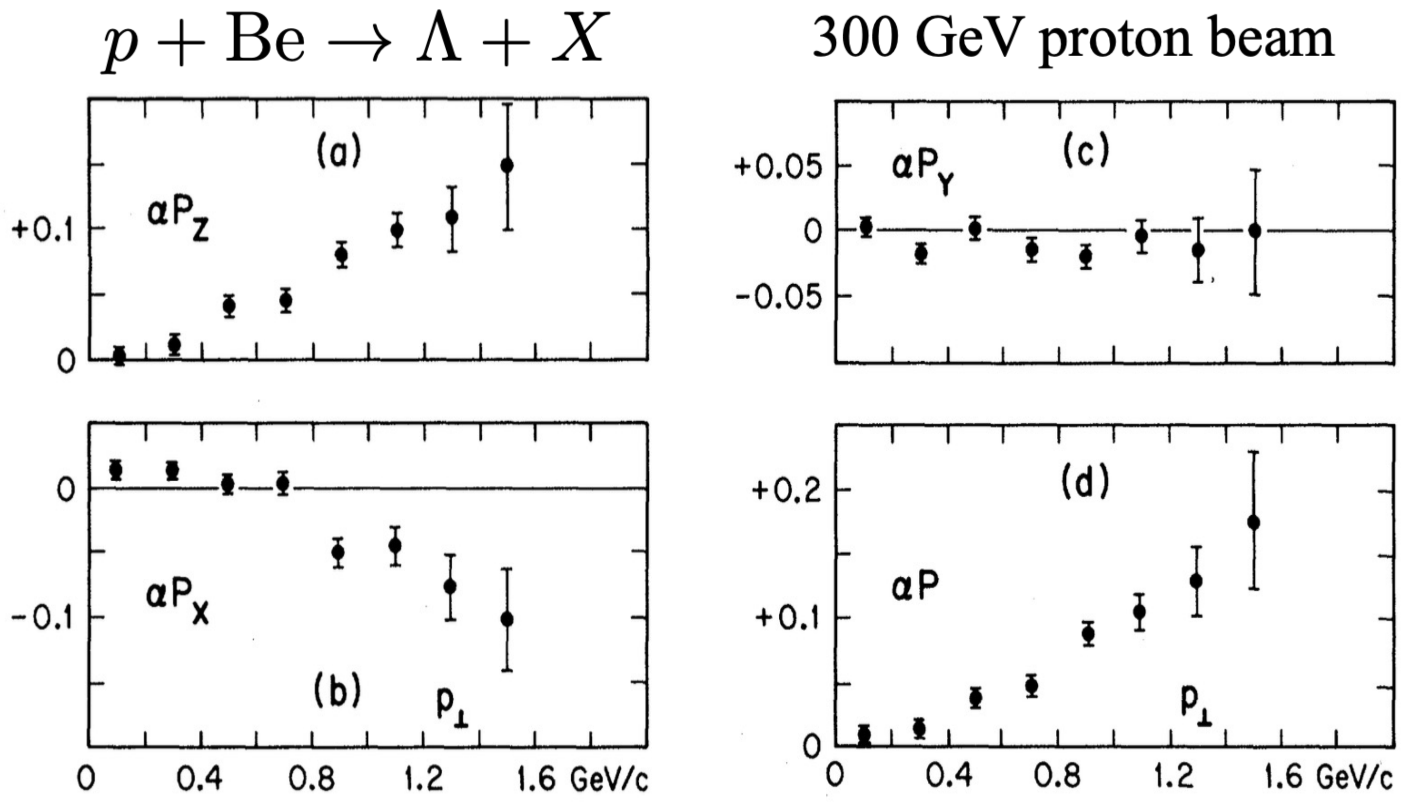
Observation of spontaneous Λ polarization in pp/pA



G. Bunce *et al.*, Phys. Rev. Lett. 36 (1976) 1113.

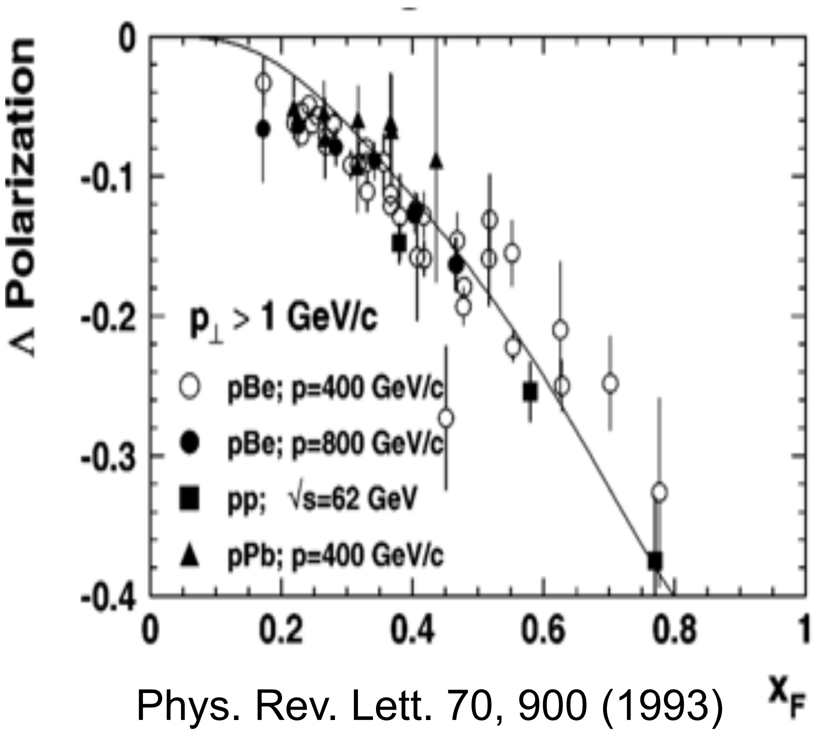
- First measurement of spontaneous Λ polarization in $p + Be \to \Lambda$+X with 300 GeV proton beam
- Lowest order QCD predicts negligible polarization for Λ with large Pt

Observation of spontaneous Λ polarization in pp/pA



G. Bunce *et al.*, Phys. Rev. Lett. 36 (1976) 1113.

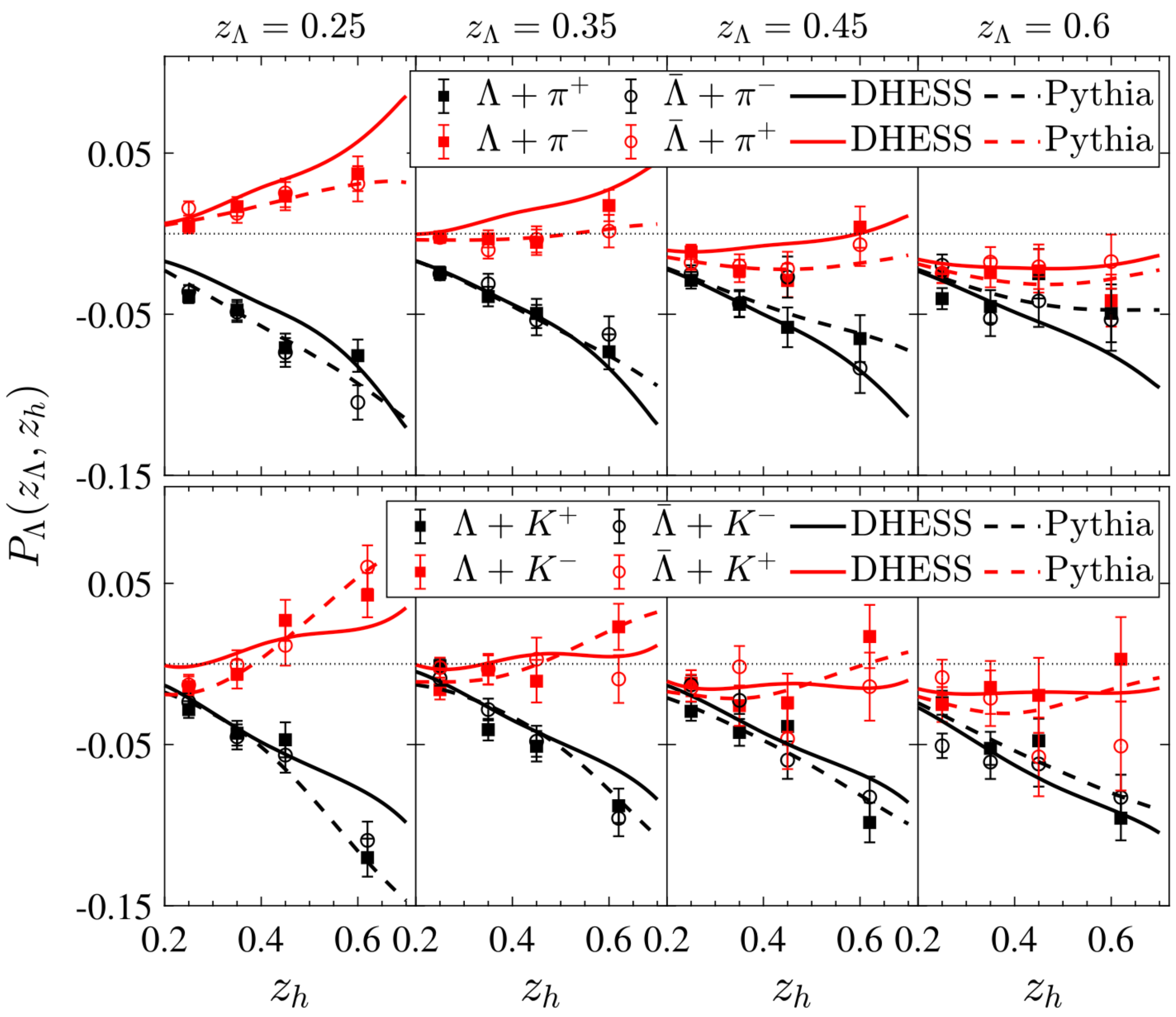
Polarization is independent to energy and target mass



Phys. Rev. Lett. 70, 900 (1993)
Phys. Rev. Lett. 67. 1193 (1991)
…

- First measurement of spontaneous Λ polarization in $p + Be \to \Lambda$+X with 300 GeV proton beam
- Lowest order QCD predicts negligible polarization for Λ with large Pt
- Follow that, spontaneous Λ polarization was studied in many pp and pA interaction

Λ polarization in $e^+e^- \to \Lambda h X$



- First observation of the spontaneous polarization of Λ hyperons in e^+e^- annihilation
- Clear environment to study the polarization due to fragmentation of the partons, free of initial state effect
- Extract the polarized fragmentation function

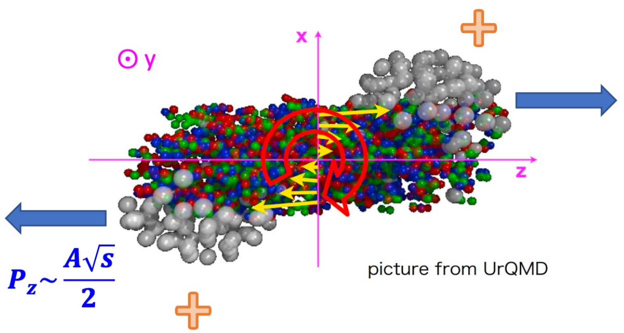
$$D_{1Tq}^{\perp\Lambda}$$

Y. Guan *et al.* (Belle Collaboration), Phys. Rev. Lett. 122, 042001 (2019).

U. D'Alesio *et al.*, Phys. Rev. D 102, 054001 (2020);
D. Callos *et al.*, Phys. Rev. D 102, 096007 (2020);
K.b. Chen *et al.*, Phys. Lett. B 816, 136217 (2021).

Λ polarization in heavy-ion collision

STAR Collabotation, Phys. Rev. C 104, L061901(2021)

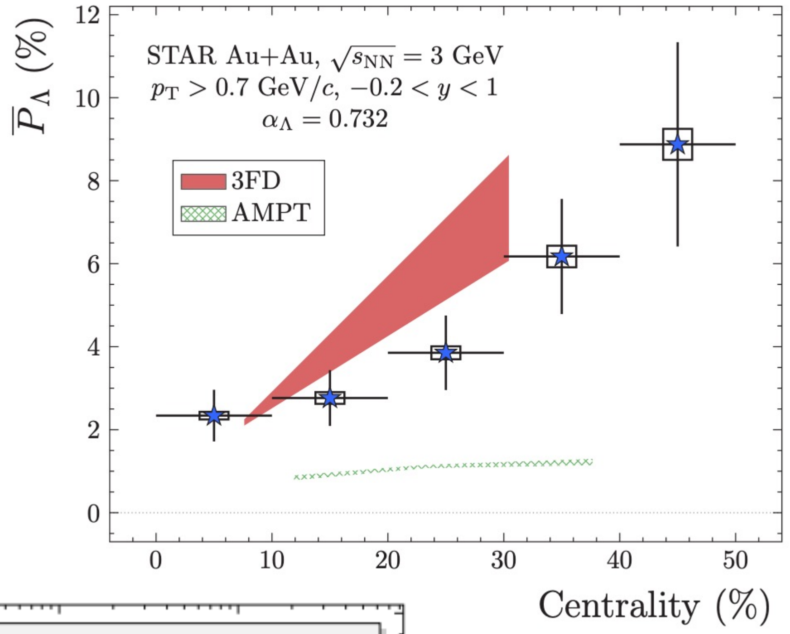


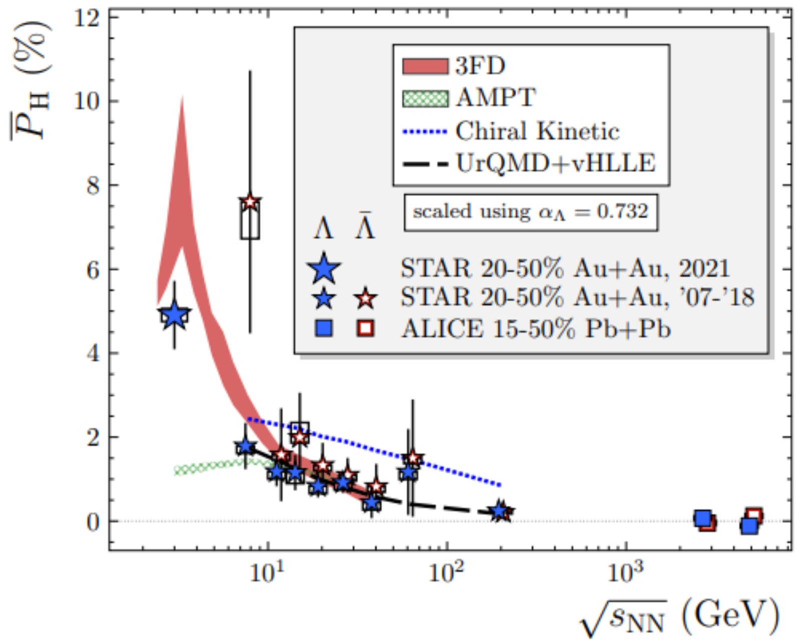
$$J_0 \sim \frac{Ab\sqrt{s}}{2} \sim 10^6 \hbar$$

Global angular momentum

$$eB \sim \gamma \alpha_{\mathrm{EM}} \frac{Z}{b^2} \sim 10^{18}\ \mathrm{G}$$

Strong magnetic field



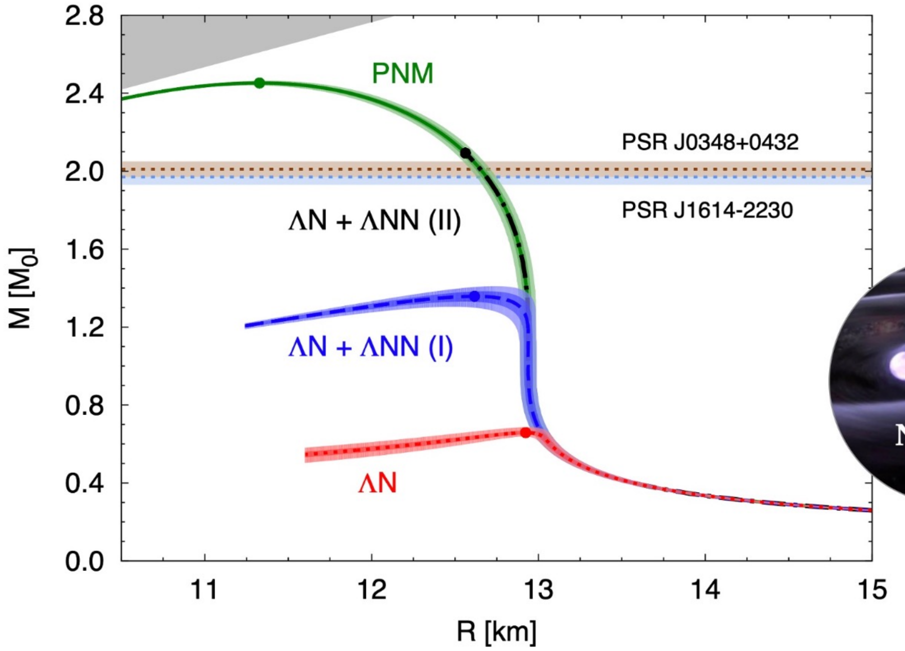


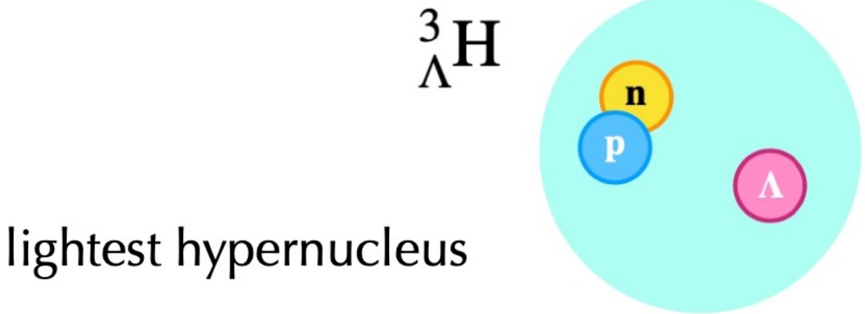
- Λ polarization in heavy-ion collision has been studied intensively in heavy ion collision.
- This effect can be attributed to the vorticity of the QGP, strong magnetic fields, and quantum anomalies.
  - Clear centrality dependent
  - Expect vanished at $\sqrt{s_{NN}} \sim 2m_N$

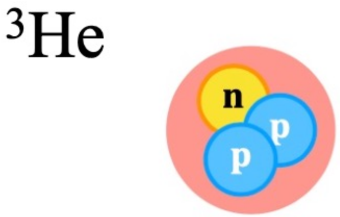
Nucleus, hyperon and hyper-nuclei

➢ Hyper-nuclei

- Y-N interaction is not well constrained due to short lifetime of the hyperons.
- Hyper-nuclei provide a “laboratory” to study YN interaction.
- Strangeness in high-density nuclear matter. EoS of neutron stars.



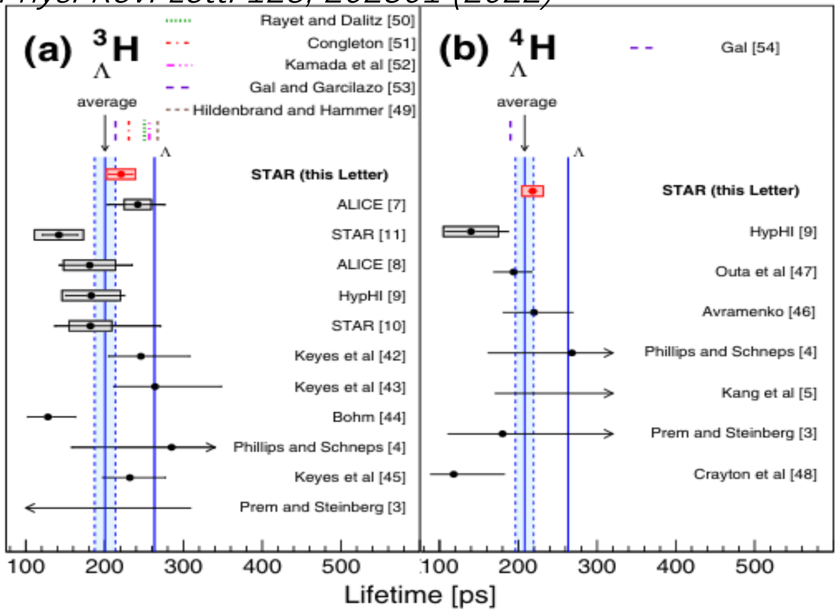


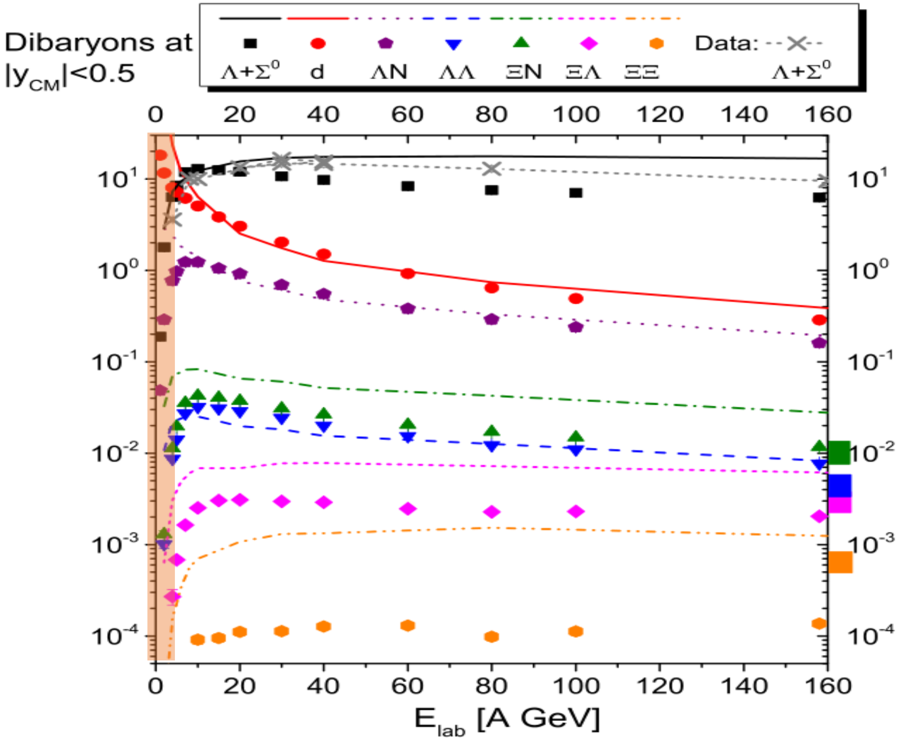


Observables for hyper-nuclei at heavy-ion collisions

- Massive heavy-ion reactions provide an abundant source of strangeness
- Hyper nuclei **lifetime, yield** and **flow**
- Search for **multiple strangeness hyper nuclei** and **dibaryon**
- **Hyper nuclei polarization**

STAR Collabotation, Phys. Rev. Lett. 128, 202301 (2022) $\sqrt{s_{NN}}$= 3GeV Au+Au





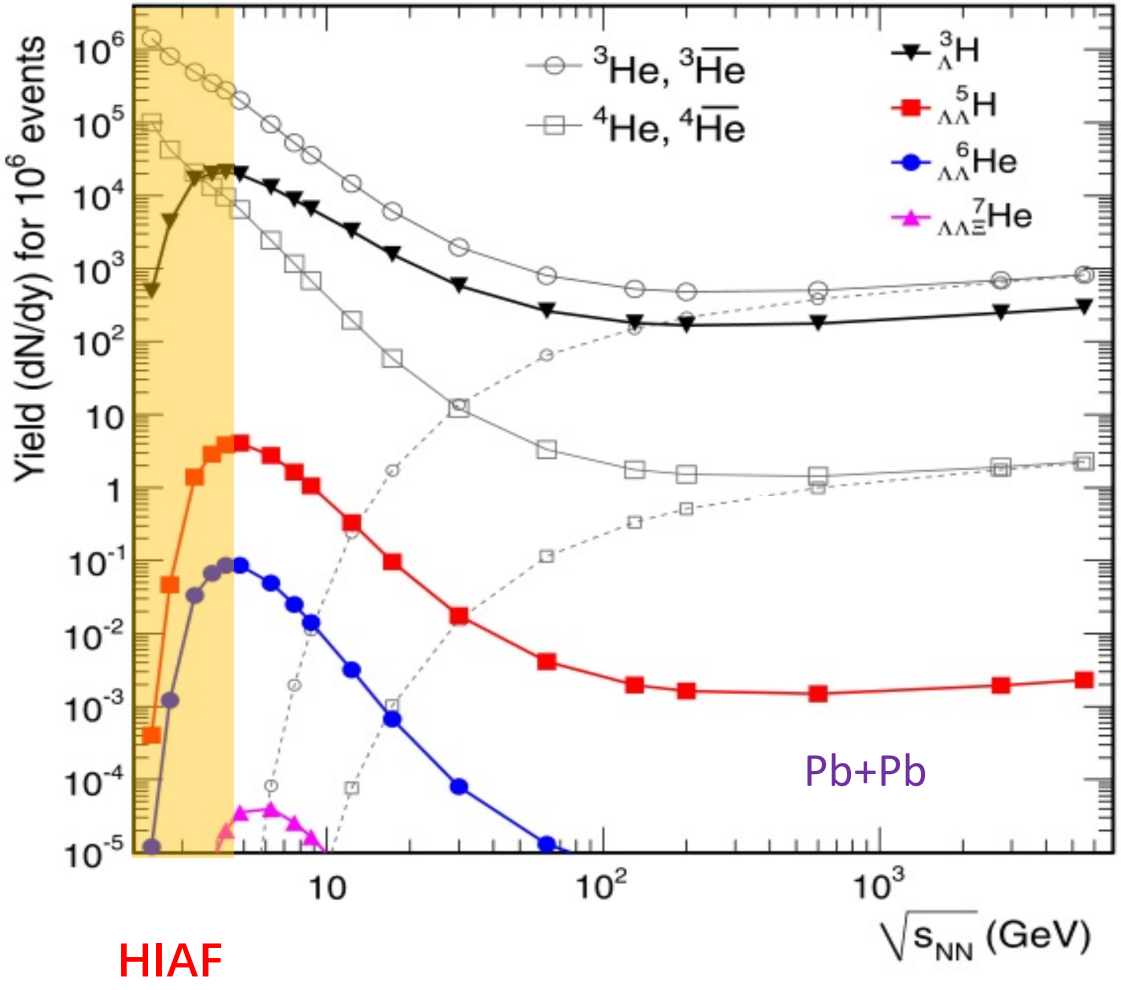
Slides from Xionghong

U+U at HIAF $\sqrt{s_{NN}}$= 2.2-4.5GeV

Phys. Lett. B 714, 85 (2012)

Physics at CHNS

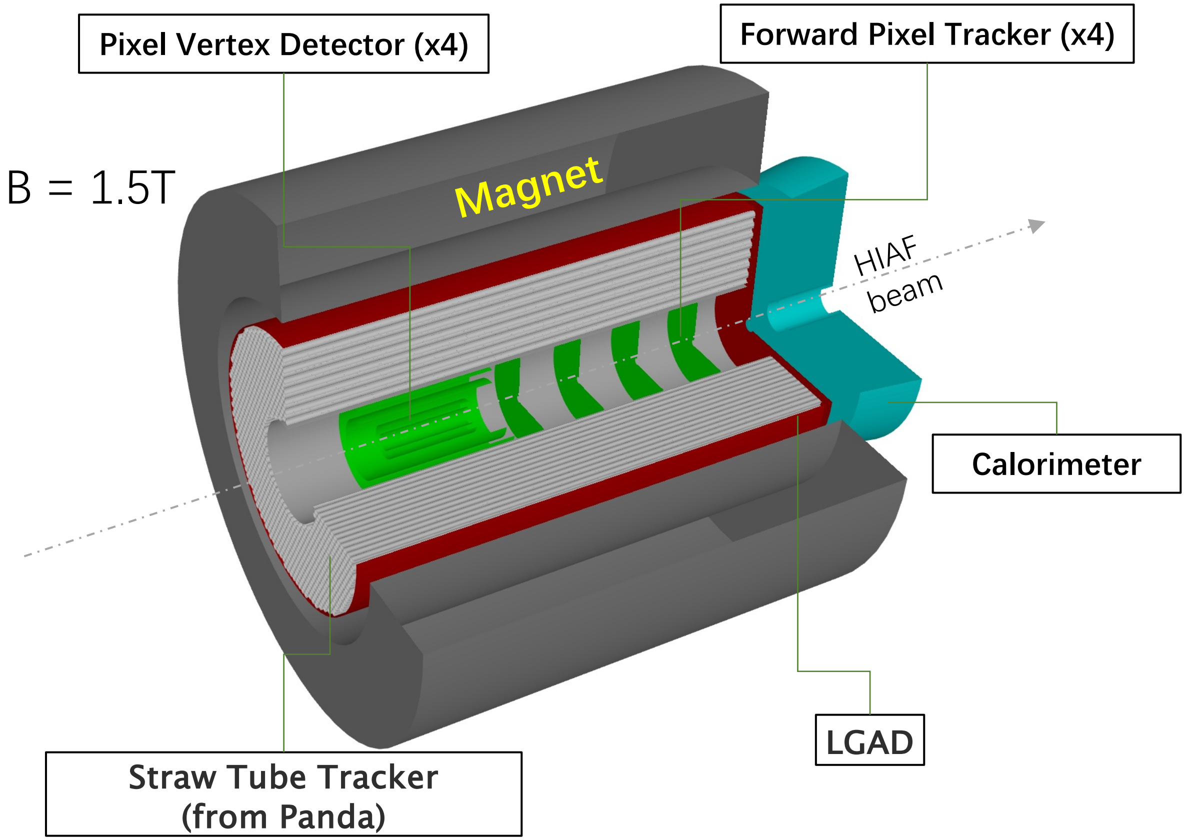
- **Hyperon polarization in p-p and p-A**
  - Offers a cleaner and more controlled environment compared to heavy-ion
  - Larger cross section compared to e^+e^-
  - Pt and y dependent
  - Disentangle the initital state effect and the role of fragmentation
- **Hyper-Nuclei physics**
  - High yield rate
  - Hyper nuclei lifetime, yield and flow
  - Search for multiple strangeness hyper nuclei
- **Other topics**
  - QCD phase structure, dibaryon, etc.



Phys. Lett. B 697, 203 (2011)

Conceptual Design 1 and requirements

Silicon + Straw Tube

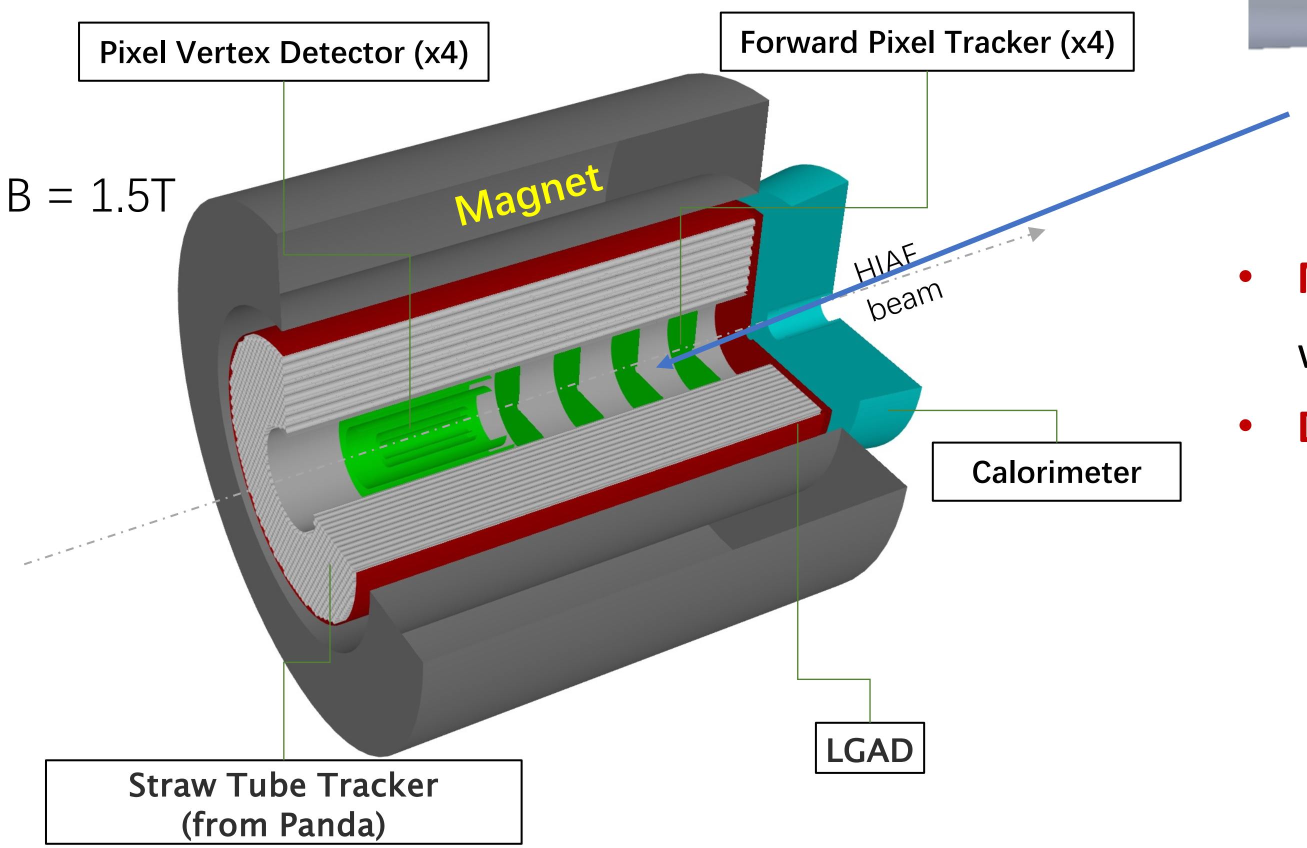


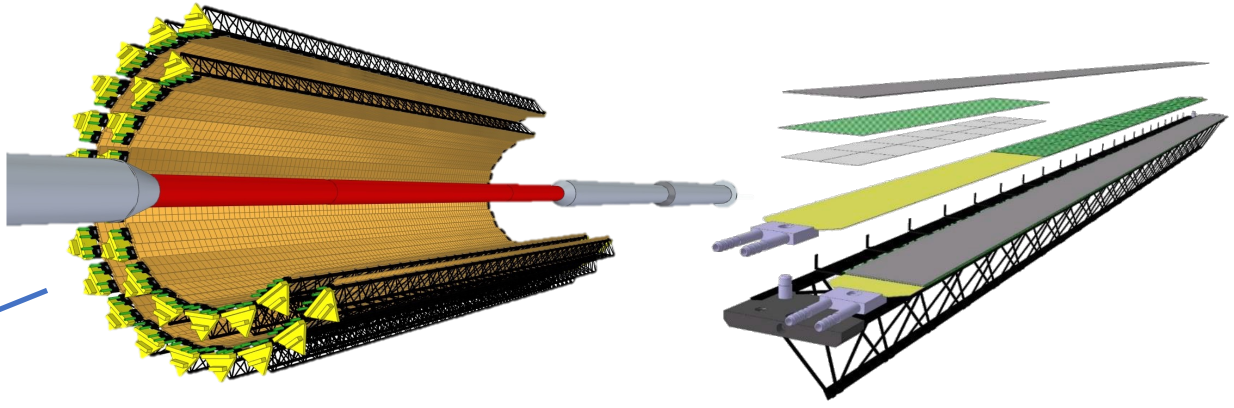
Perfromance Requirements:

- **Momentum resolution:**
  - ~1%@1GeV when η<2.5
  - Good spacial resolution, σ~10 μm
- **PID:**
  - K, π, proton separation (~3σ) a Pt up to 1 GeV/c in barrel region. And up to 1.8 GeV/c in forward region
  - Additional d, t, He^3, He^4 for hyper nuclei physics
  - dE/dx and TOF
- **Vertex resolution:**
  - Excellent vertex resolution for background suppression
  - Low material budget (<5%)
- **Acceptance:**
  - 10 to 100 degree
- **High event rate**
  - >MHz for heavy ion collision

Conceptual Design 1

Silicon + Straw Tube

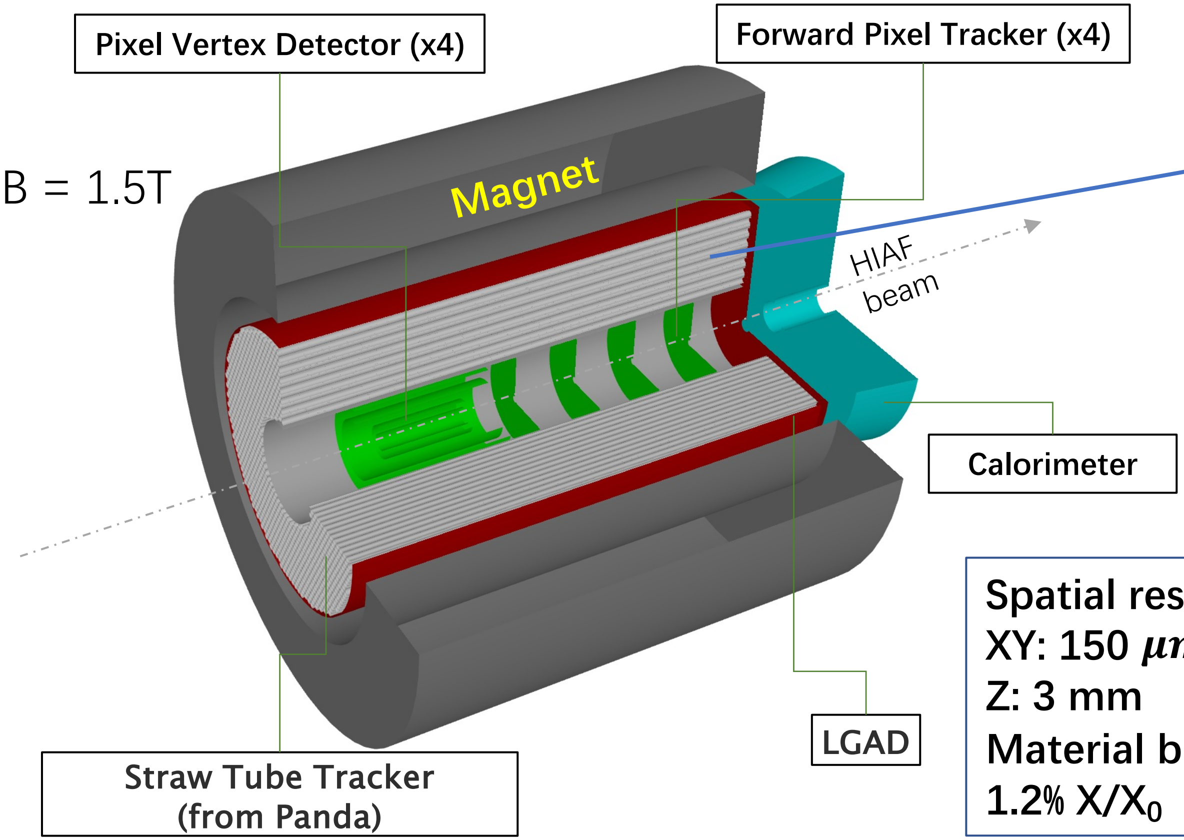


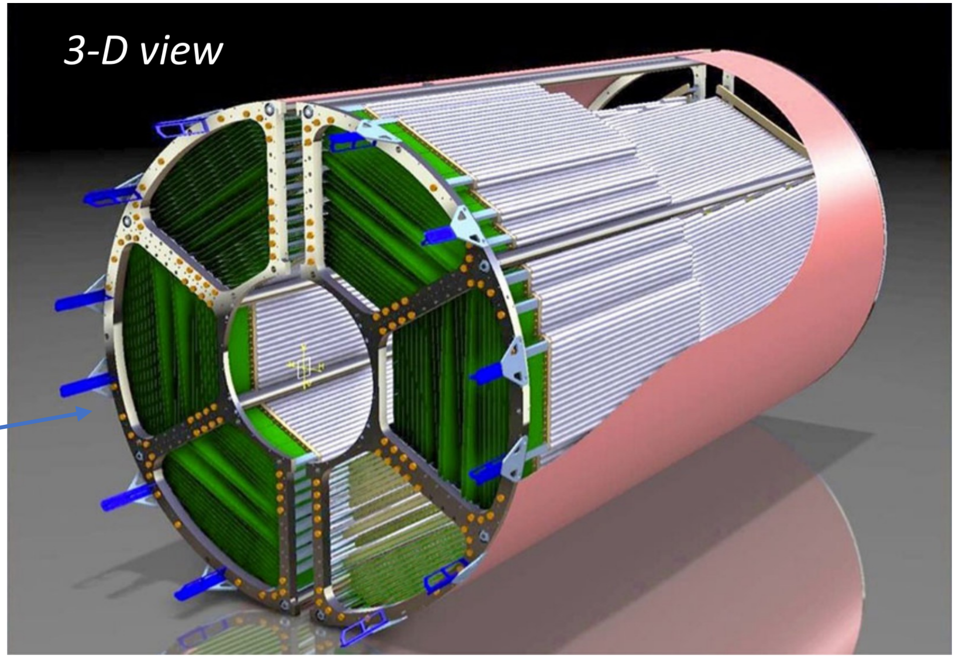


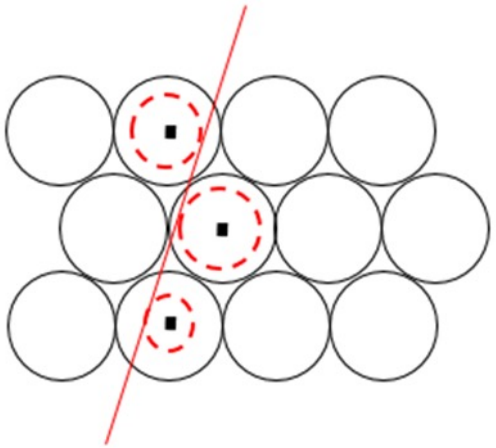
- **MIC6 MAPS pixel chip:** development and manufacture with the **domestic process**
- **Detector assembly and integration:**
  - Vertex detector: Stave module design (spatial resolution: **~ 5 μm with pixel size 30 μm,** total material **< 0.35%X/X_0 per layer**)
  - Forward tracker: Ladder module aligned to disc super-module (spatial resolution: ~ **5 μm with pixel size 30 μm, total material < 0.45%X/X_0 per layer**)

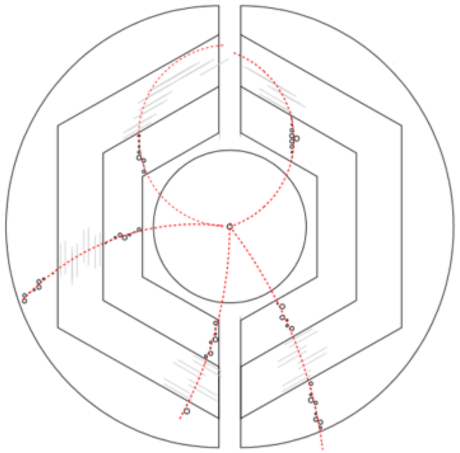
Conceptual Design 1

Silicon + Straw Tube





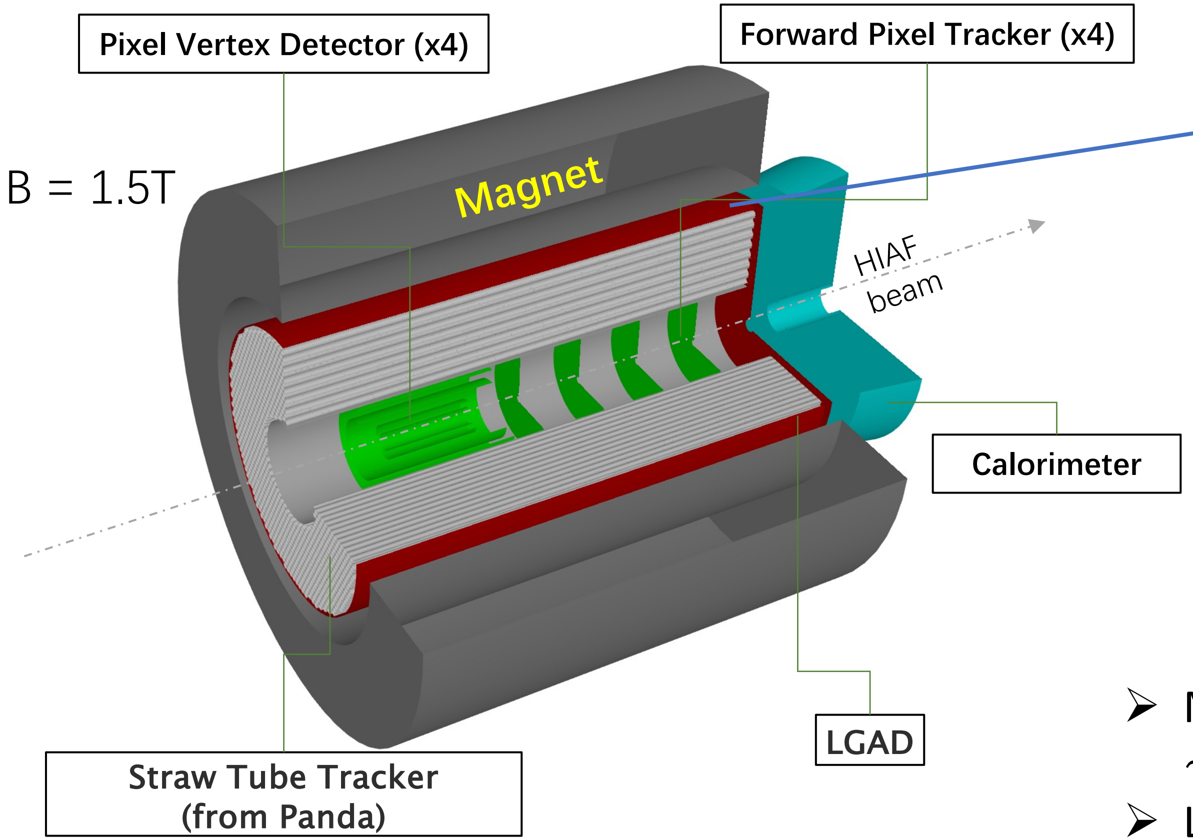


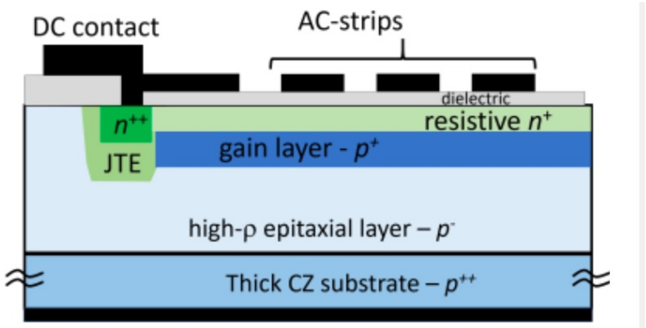


Spatial resolution:
XY: 150 μm
Z: 3 mm
Material budget:
1.2% X/X_0

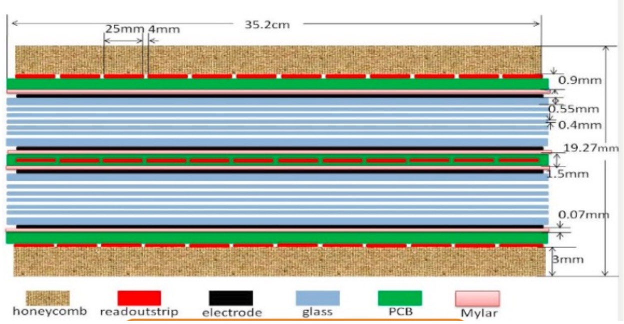
Conceptual Design 1

Silicon + Straw Tube





Low-Gain Avalanche Detector (LGAD)

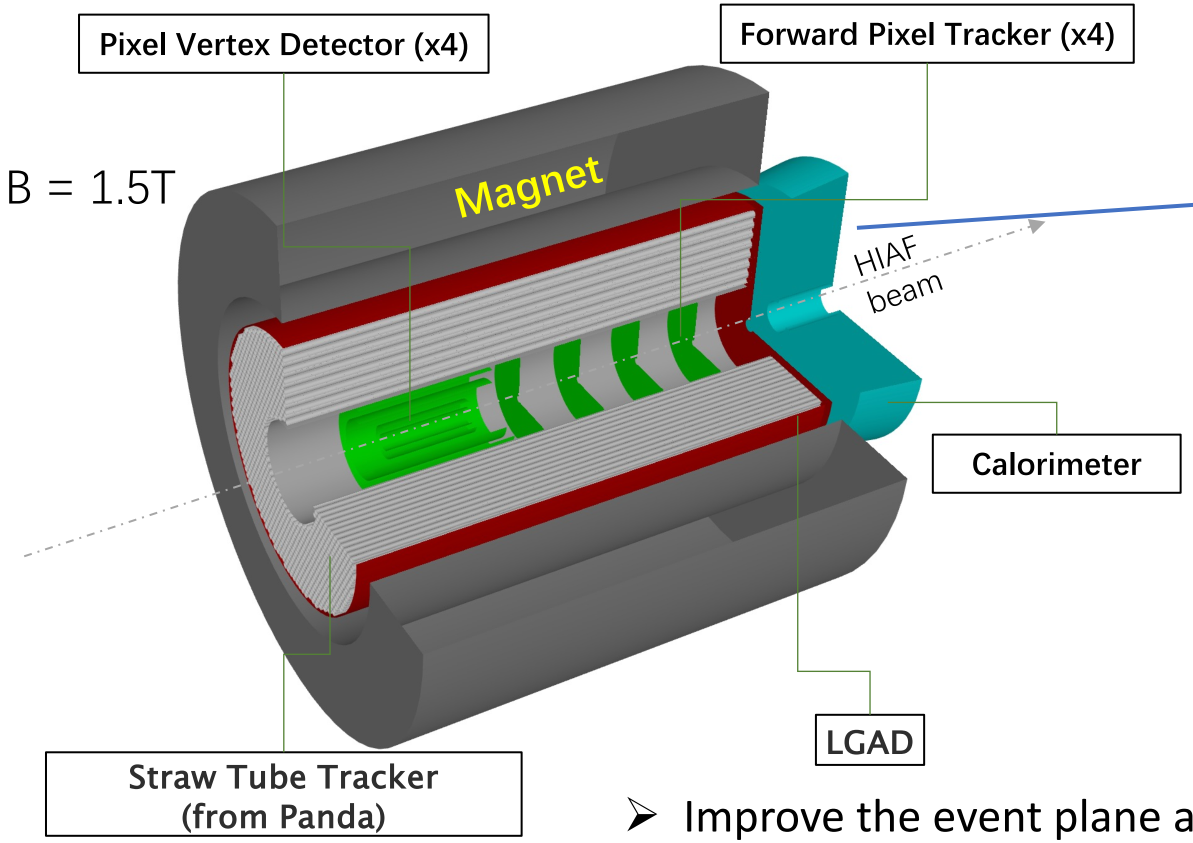


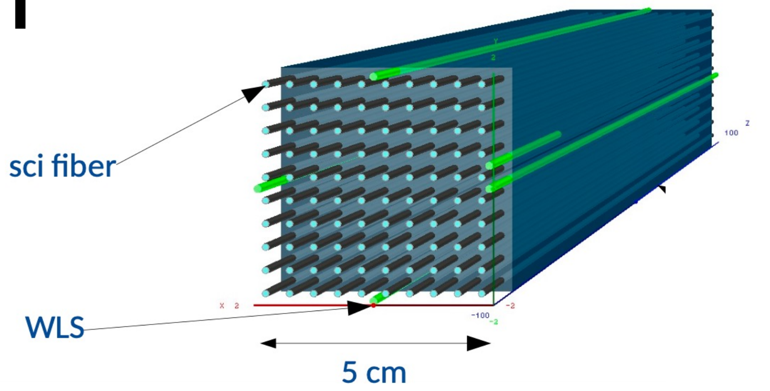
Multistage Resistive Plate Chamber Detector(MRPC)

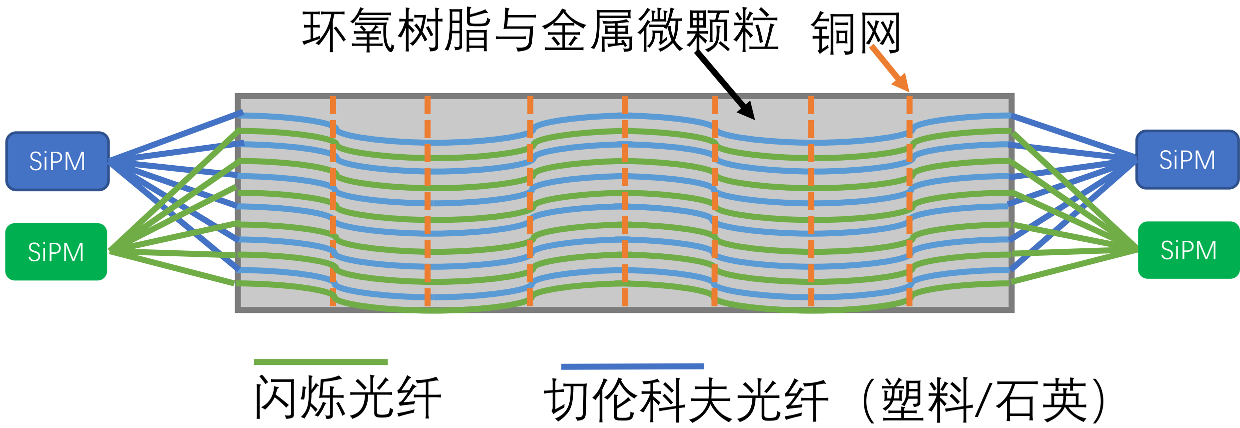
- MRPC and LGAD for low momentum particle identification, ~ 30 ps @0.1-2.0 GeV/c.
- LGAD can provide position measurement as well, σ~30 μm

Conceptual Design 1

Silicon + Straw Tube





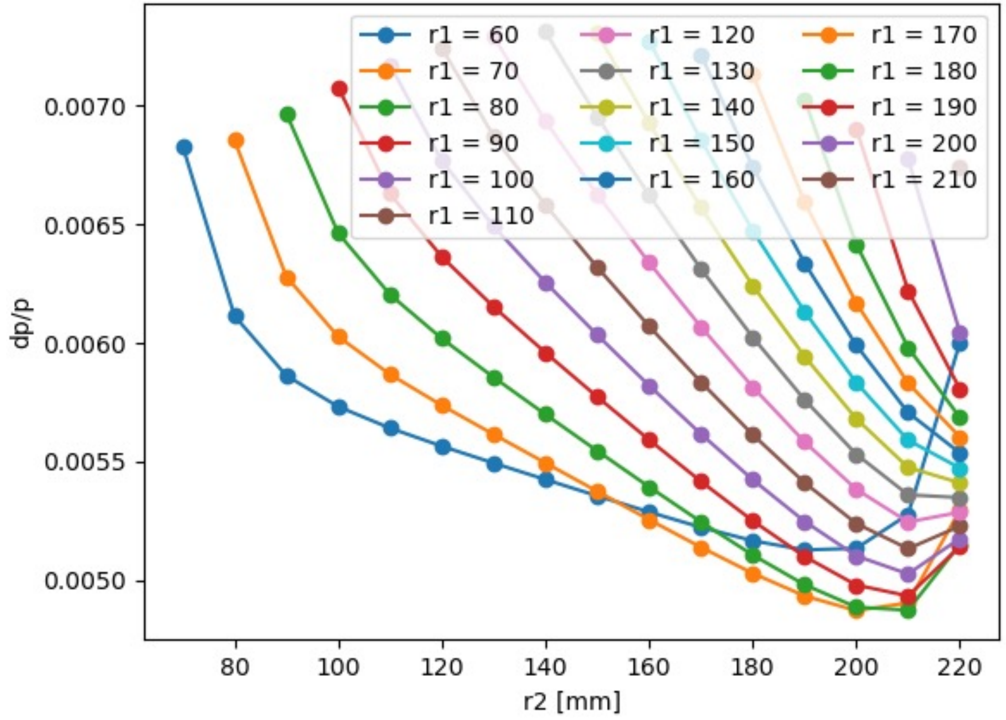


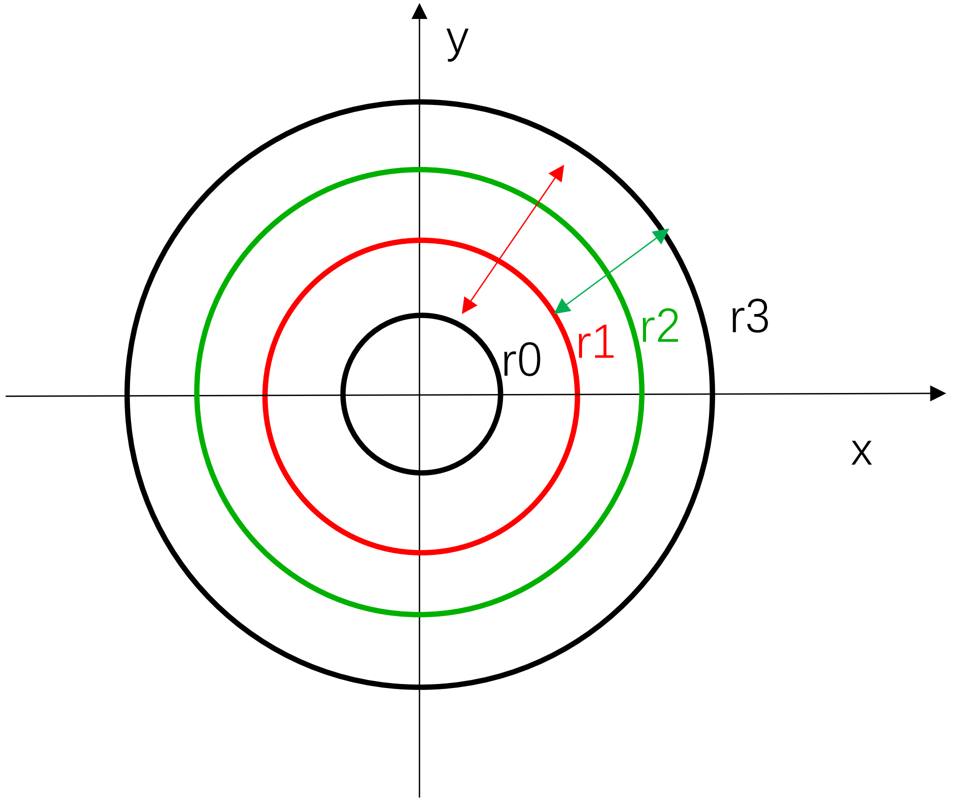
- Cherenkov light & scintillation light dual read out Calorimeter
- EM shower: $\sim 5\%/\sqrt{E[\mathrm{GeV}]}$
- Hadronic shower: $\sim 60\%/\sqrt{E[\mathrm{GeV}]}$

➢ Improve the event plane and centrality measurement
➢ Improve the PID capability
➢ Neutral track reconstruction, Σ polarization, etc.

Optimization for vertex detector

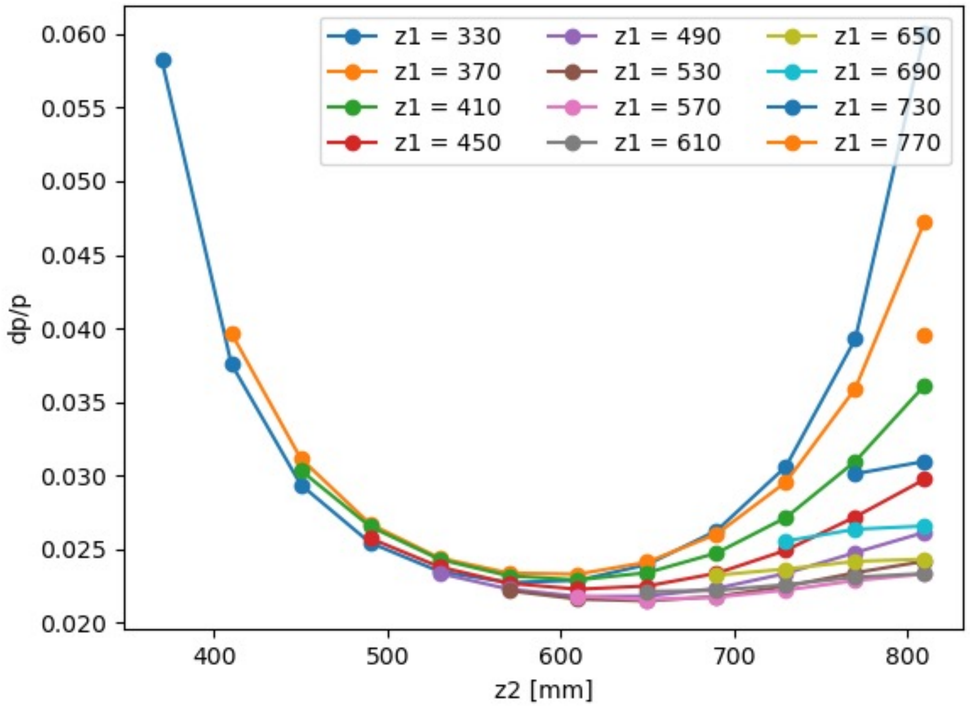
- For barrel region
  - Fix r0 and r3, adjust r1 from r0 to r3
  - At each r1, adjust r2 from r1 to r3

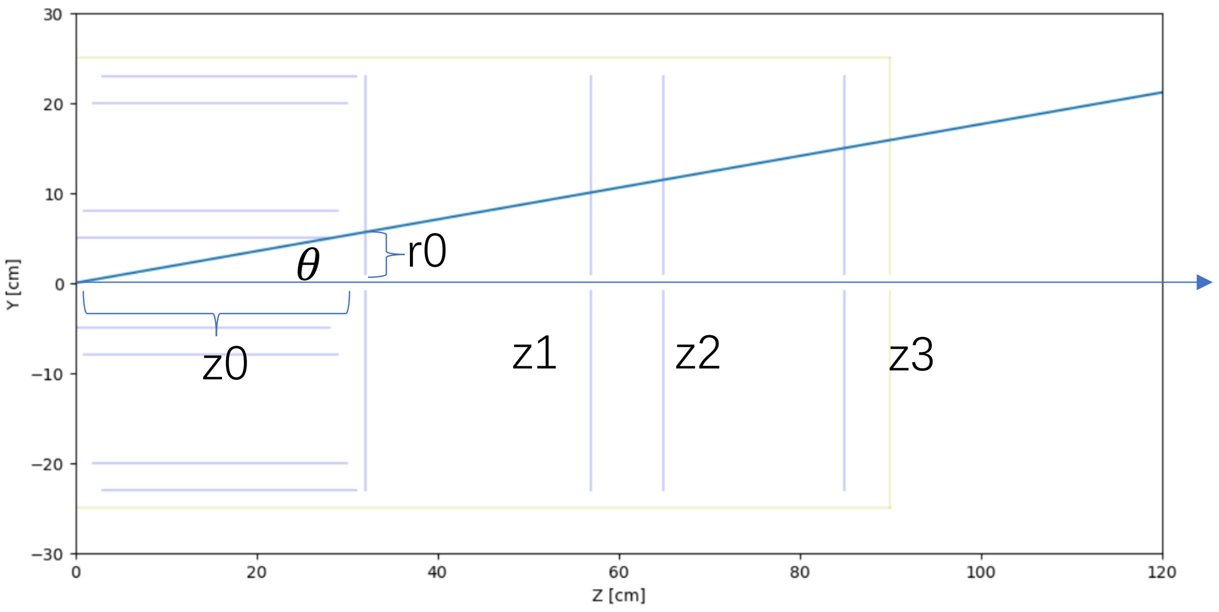




Optimization for vertex detector

- For the forward region
  - Fix z0 and z3
  - Adjust z1 in [z0, z3], while z2 in [z1,z3



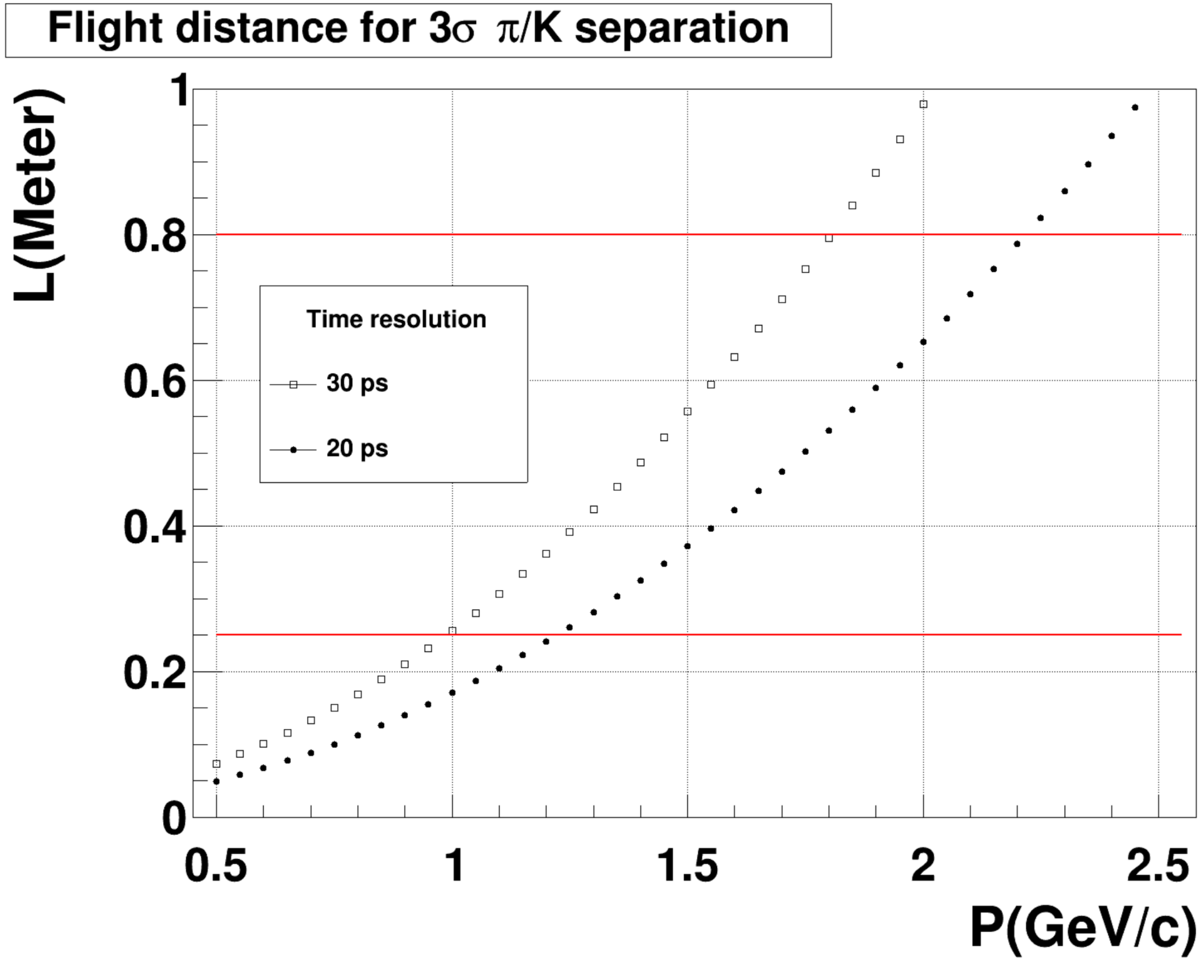


Detector configuration – LGAD

Assume a time resolution of 30 ps

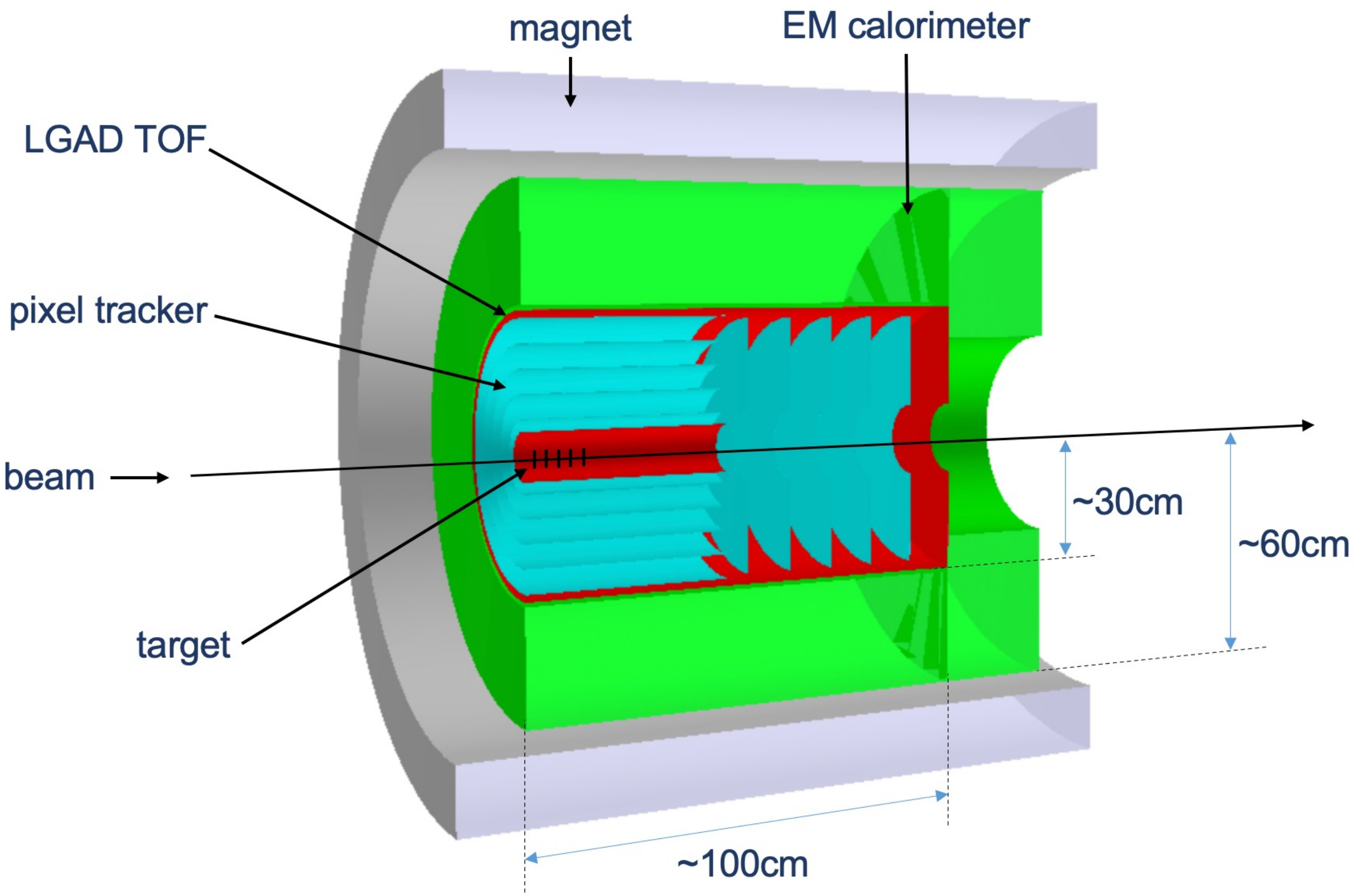
LGAD barrel, can cover a Pt up to 1 GeV/c.

LGAD endcap, is better to be placed at > 0.8 meter, to cover momentum up to 1.8 GeV/c.



Conceptual Detector Design 2

<u>All silicon tracker + Ecal design ➔ η physics</u>



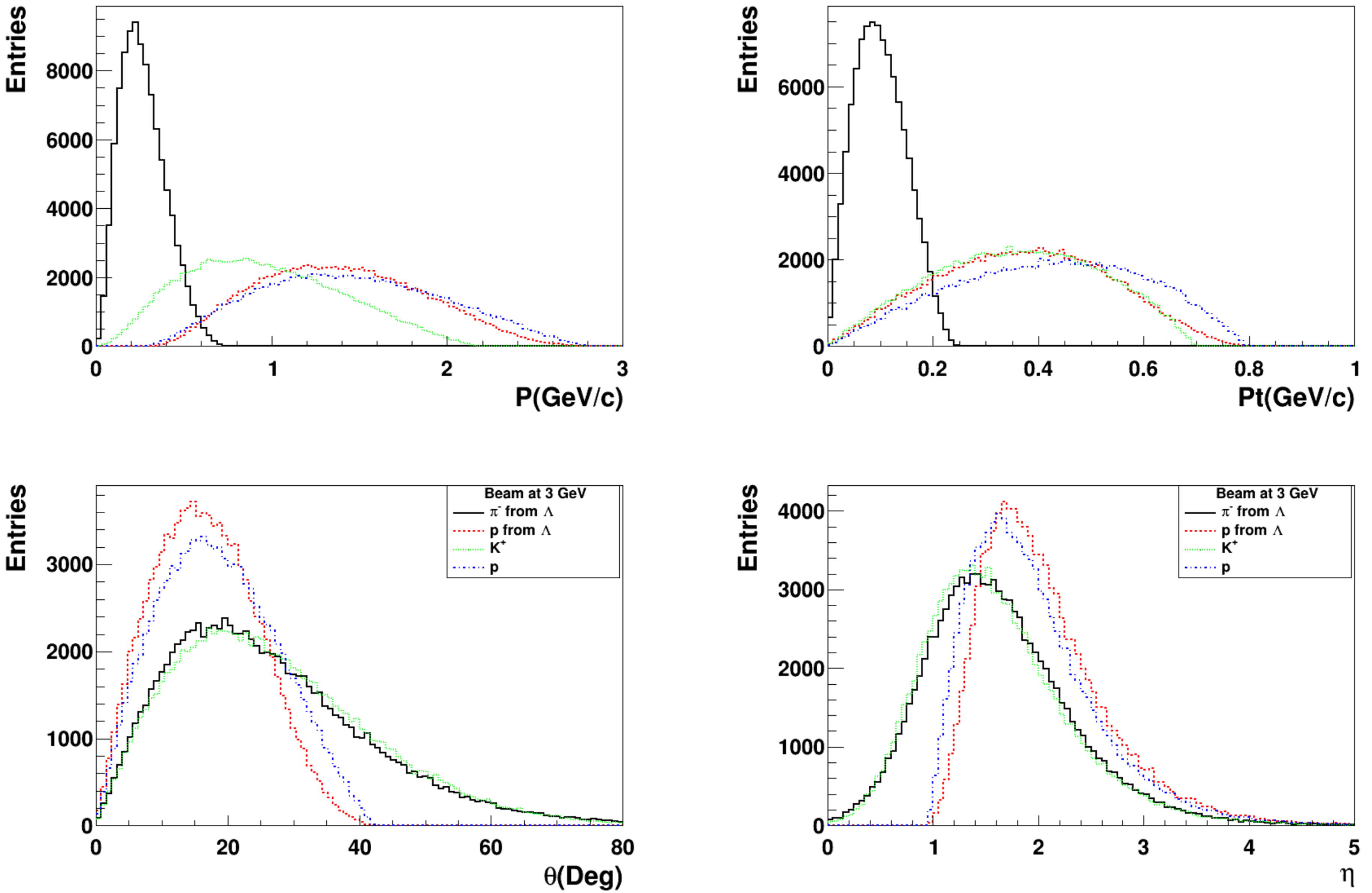
B = 0.8 T

Properties:

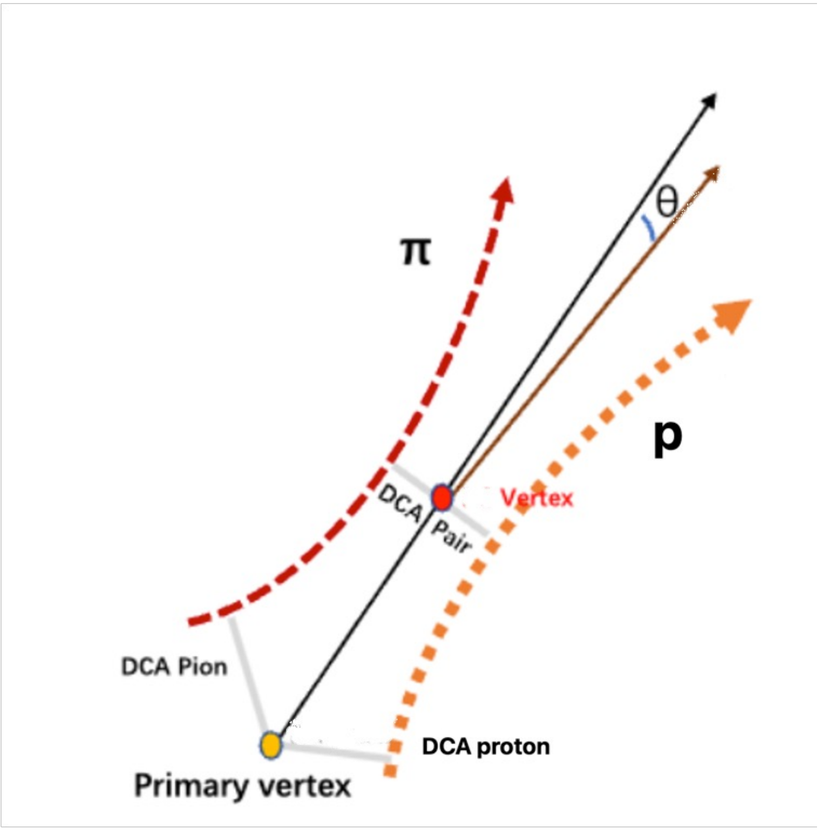
- High event rate:
  - >MHz for heavy ion collision
- Compact design:
  - Radius of Tracker+TOF is less than 30 cm
- Good performance:
  - Spatial resolution: ~30 μm
  - Time resolution: ~30 ps
  - Energy resolution: 2~5% @1GeV
- Large acceptance:
  - 10 to 100 degree, cover most of Pt up to y_{cms}=1

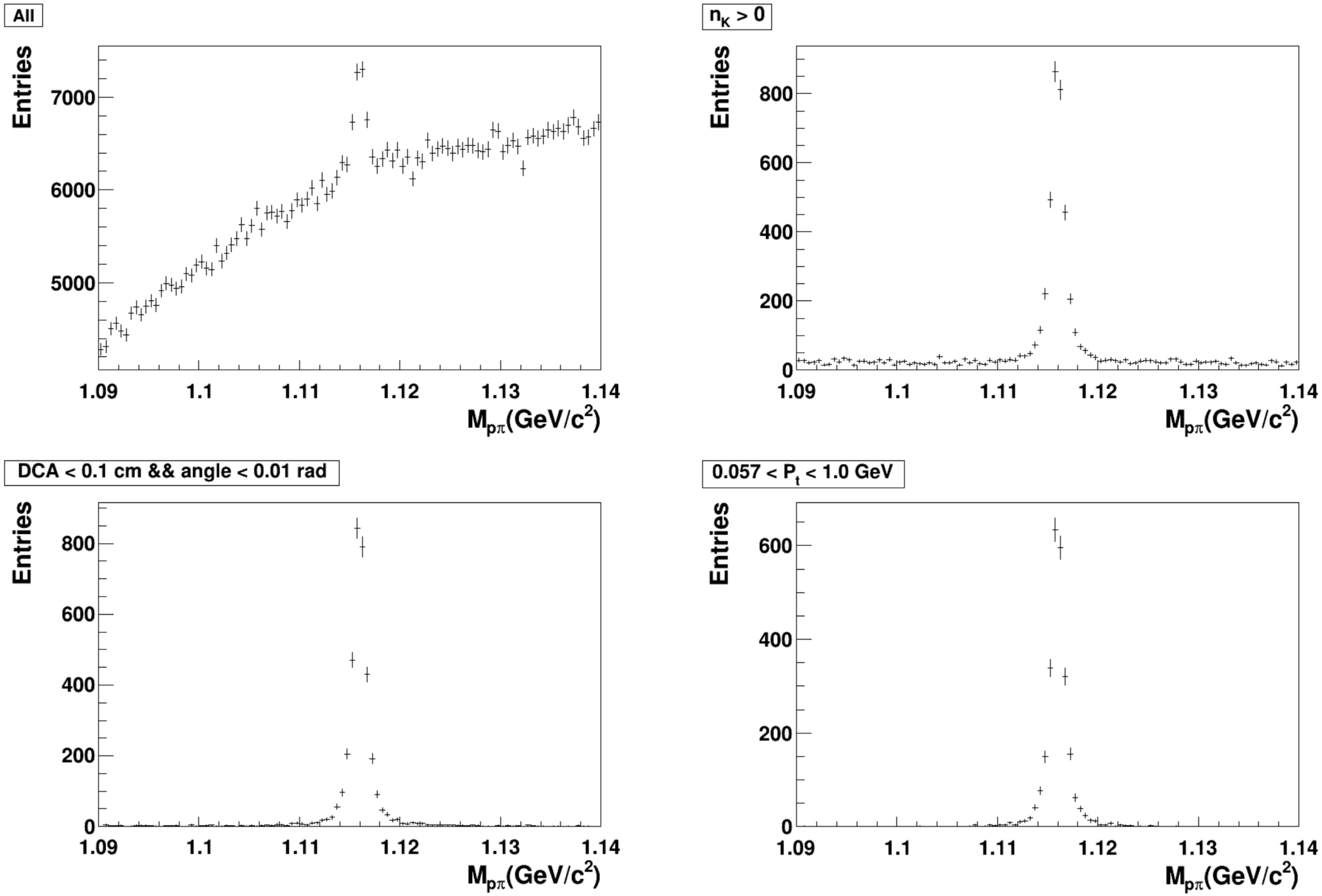
Details can be found in Hao's talk on 24th Aug.

Simulation of pp → p K^+ Λ with PLUTO



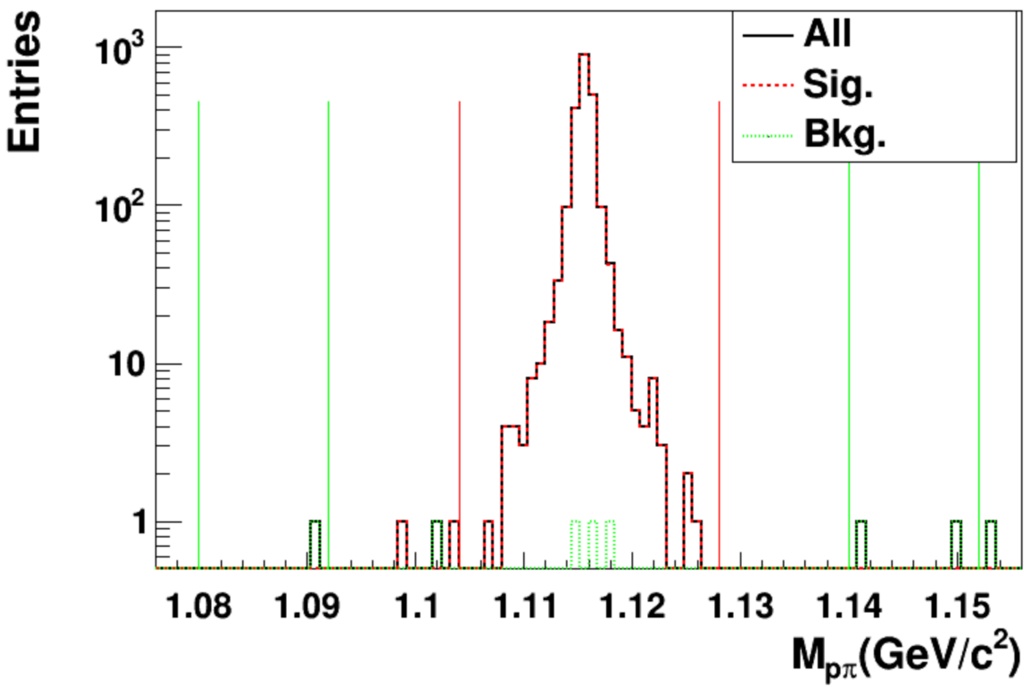
Reconstruction of Λ signal

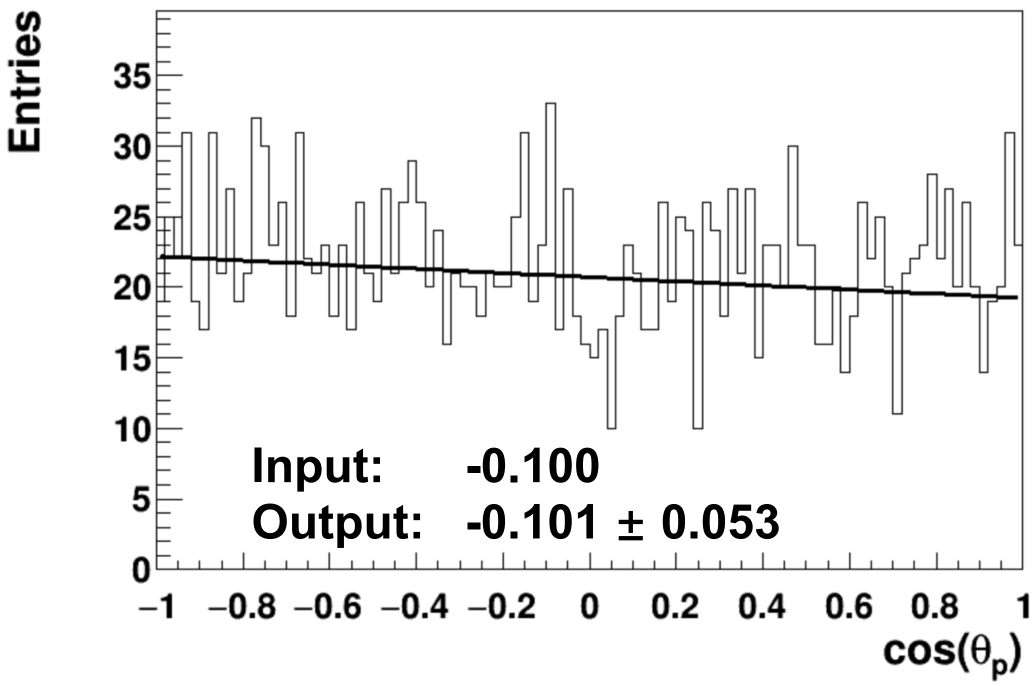




Based on detector configuration 1

Extraction of Λ polarization



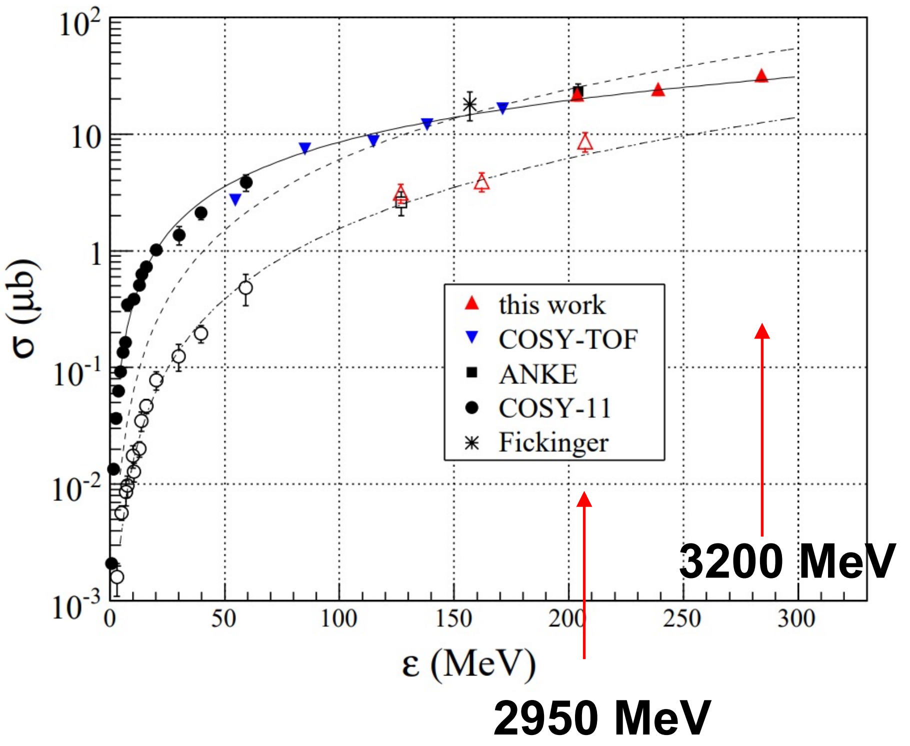


Based on detector configuration 1

Evaluation of pp → p K⁺ Λ yield at HIAF

Table 1. Total cross sections for the reactions $pp \to pK^+\Lambda$ and $pp \to pK^+\Sigma^0$. The first uncertainty refers to statistical and the second to systematical ones.

ε (MeV)	acc (%)	counts	σ_{tot} (μb)
$pp \to pK^+\Lambda$			
204	1.95	7228	$21.8 \pm 0.3 \pm 2.7$
239	1.72	89684	$24.4 \pm 0.1 \pm 3.0$
284	1.63	3322	$32.0 \pm 0.9 \pm 3.9$
$pp \to pK^+\Sigma^0$			
127	1.28	676	$3.1 \pm 0.2 \pm 0.6$
162	1.51	12644	$3.9 \pm 0.1 \pm 0.7$
207	1.45	800	$8.6 \pm 0.5 \pm 1.6$



HIAF will provide $1*10^{12}$ ppp
Assume event rate: 100MHz
Events in one month: $3600*24*30*10^8*0.3 = 10^{13}$
Expected number of Λ: $>10^5$

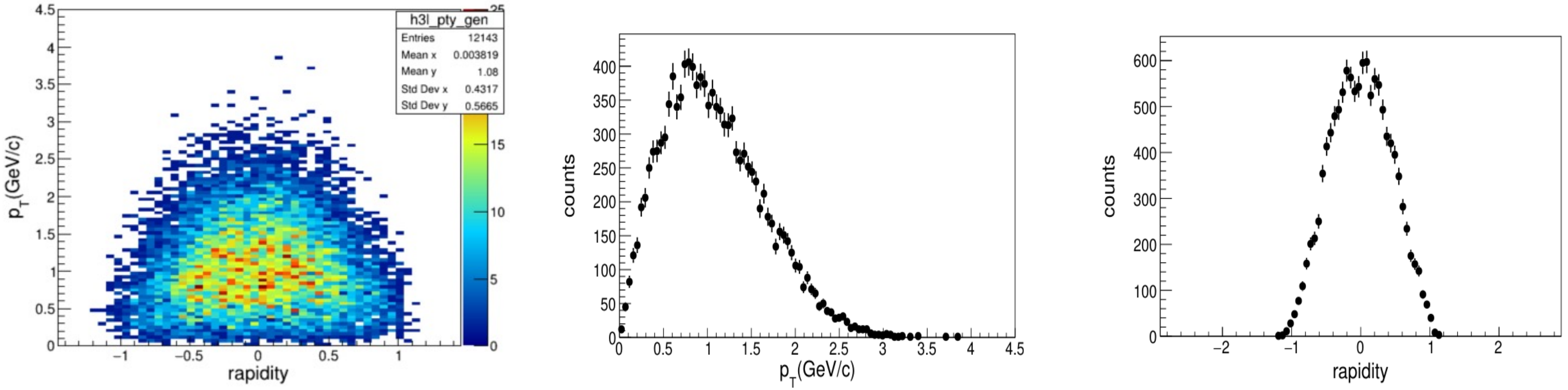
The experiments were carried out with the time-of-flight detector *COSY-TOF* located at an external beam line of the COoler SYnchrotron COSY (Forschungszentrum Jülich). The COSY machine provides proton beams of very high quality (spill length ≈ 5 min; several 10^6 protons/s; low emittance of $< 5\,\pi$ mm mrad; relative momentum uncertainty $\Delta p/p < 10^{-3}$).

${}^{3}_{\Lambda}\mathrm{H}$ production via JAM+coalescence

- JAM: event-generator and hadronic transport model for high baryon heavy-ion collisions

arXiv:2208.0129

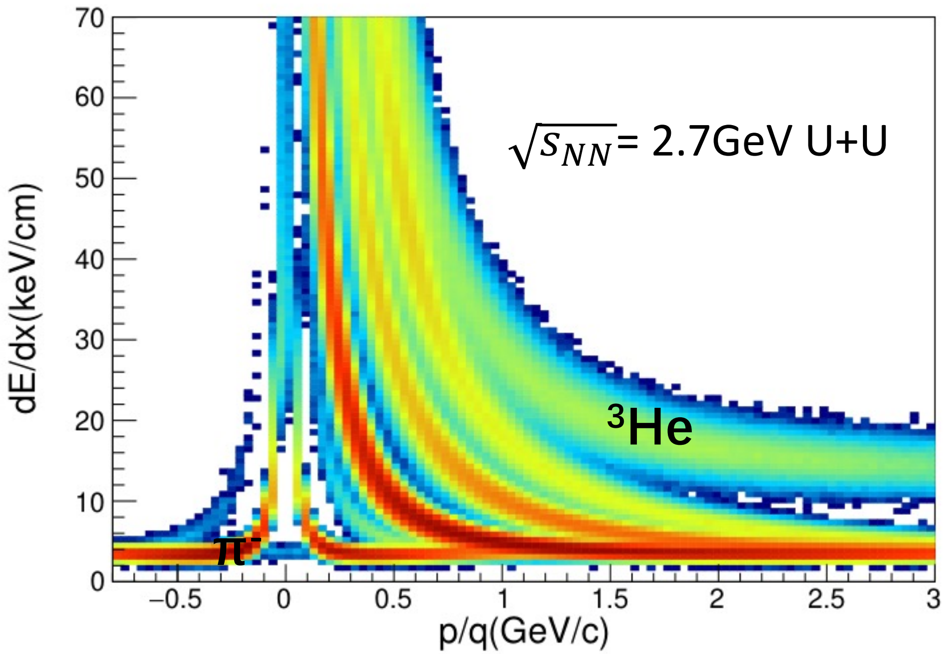
- Collision system: E_{beam}=2 GeV U+U, $\sqrt{s_{NN}}$= 2.7GeV, y_{cm}=0.9, 2×10^{6} events
- Light nuclei and ${}^{3}_{\Lambda}\mathrm{H}$ are formed by the coalescence nucleons(hyperon) when they are close in coordinate and momentum space
- ${}^{3}_{\Lambda}\mathrm{H}$ production rate per event: 0.006

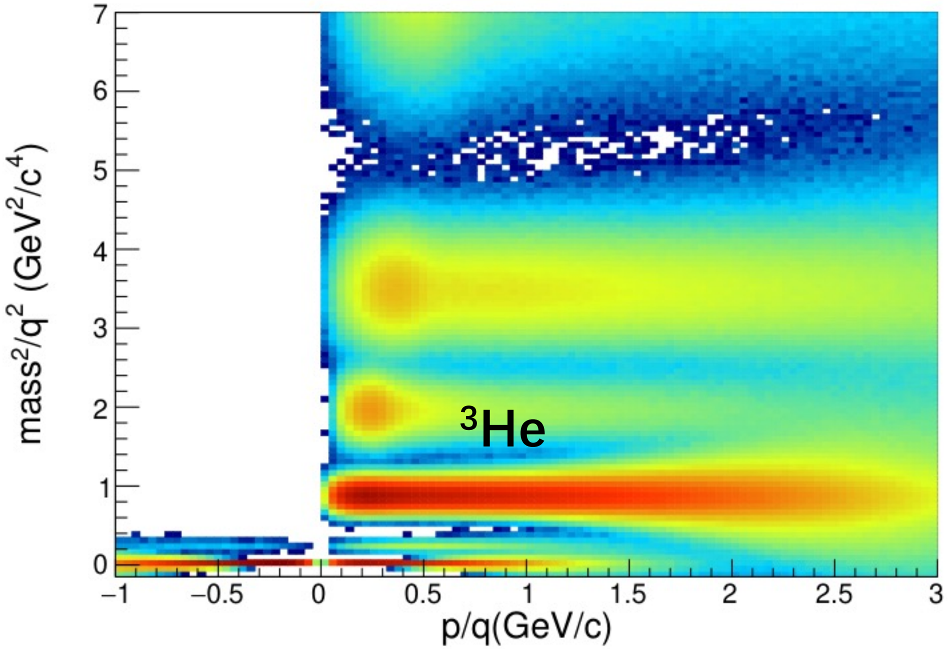


Slides from Xionghong

Particle identification and topological cuts

Decay channel: ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^{-} + {}^{3}\mathrm{He}$ (assuming branch fraction =100%)



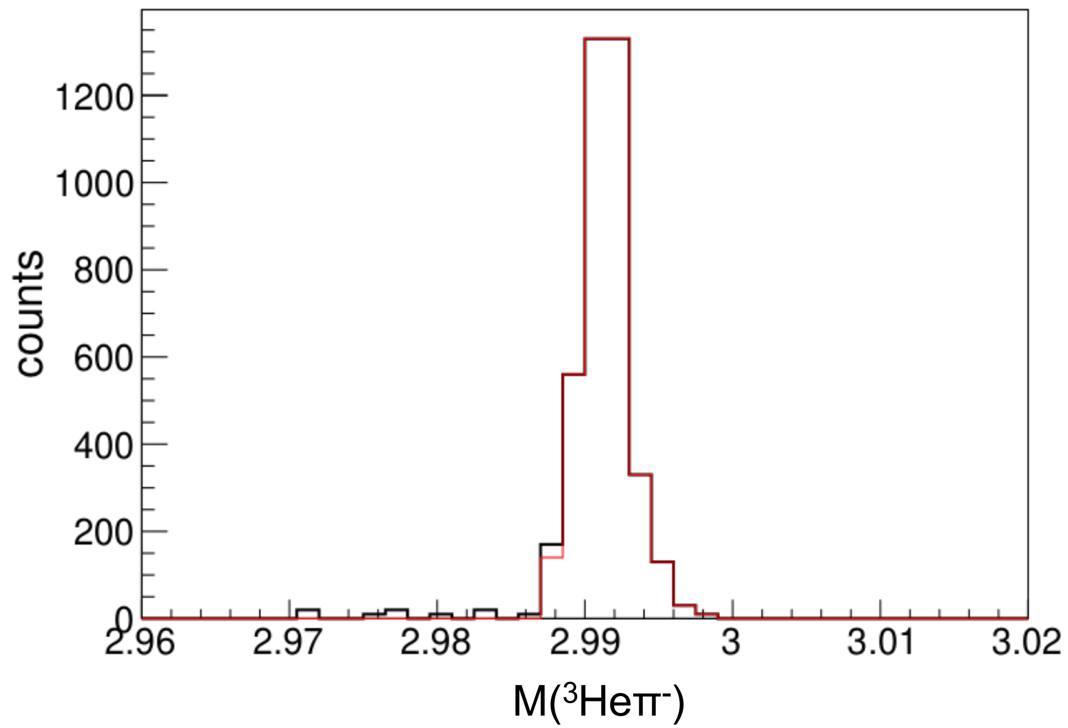


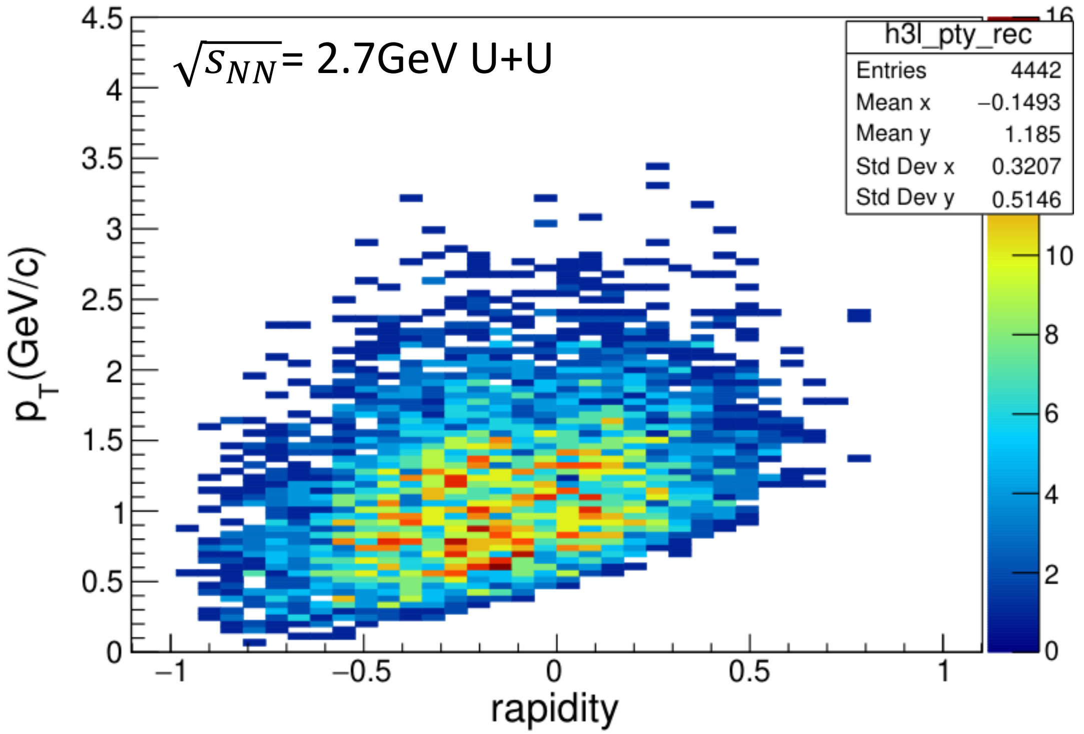
- π^{-} are selected based on the dE/dx; ^{3}He are selected using both dE/dx and TOF
- Topological cuts for reconstructing ${}^{3}_{\Lambda}\mathrm{H}$: vertex of daughter particles

Slides from Xionghong

Based on detector configuration 2

Reconstructed $^{3}_{\Lambda}\mathrm{H}$ candidates





- After the PID and topological cuts, the signal purity is ~93%
- The detector acceptance: 51.5%
- The average efficiency for PID and topological cuts: 70.7%

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Based on detector configuration 2

Light hyper-nuclei production at HIAF

Assuming data of $\sqrt{s_{NN}}$= 2.7 GeV U+U collisions will be collected for one month: >5×10^{11} events

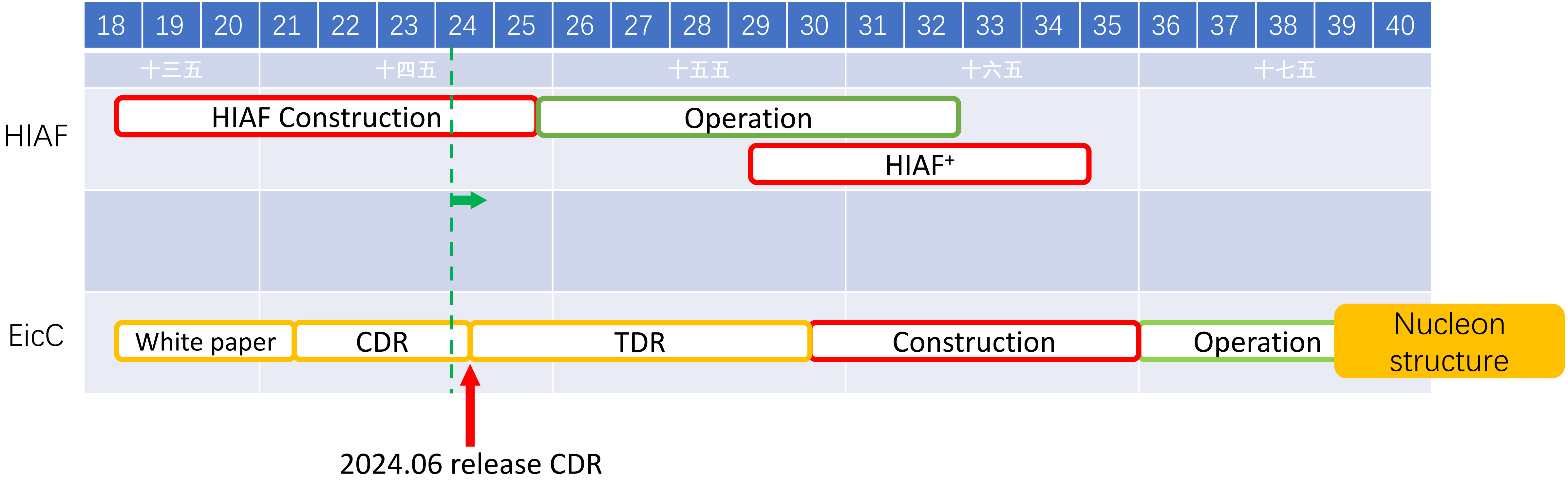
Phys. Lett. B 714, 85 (2012); Phys. Lett. B 697, 203 (2011)

	yield per event	Total yield	Possible candidates
${}^{3}_{\Lambda}\mathrm{H}$	6×10^{-3}	3×10^{9}	~10^{8}(30% π^{-} + ^{3}He)
${}^{4}_{\Lambda}\mathrm{H}$	6×10^{-4}	3×10^{8}	~10^{7}(70% π^{-} + ^{4}He)
${}^{5}_{\Lambda}He$	2×10^{-5}	1×10^{7}	π^{-} + ^{4}He +p
${}^{4}_{\Lambda\Lambda}\mathrm{H}$	10^{-5}	5×10^{6}	π^{-} + ${}^{4}_{\Lambda}He$
${}^{5}_{\Lambda\Lambda}\mathrm{H}$	10^{-7}	5×10^{4}	π^{-} + ${}^{5}_{\Lambda}He$

- Precision measurements for life time, yield, flow
- Possible observations for double hyperon nuclei and polarization

Slides from Xionghong

Timelines



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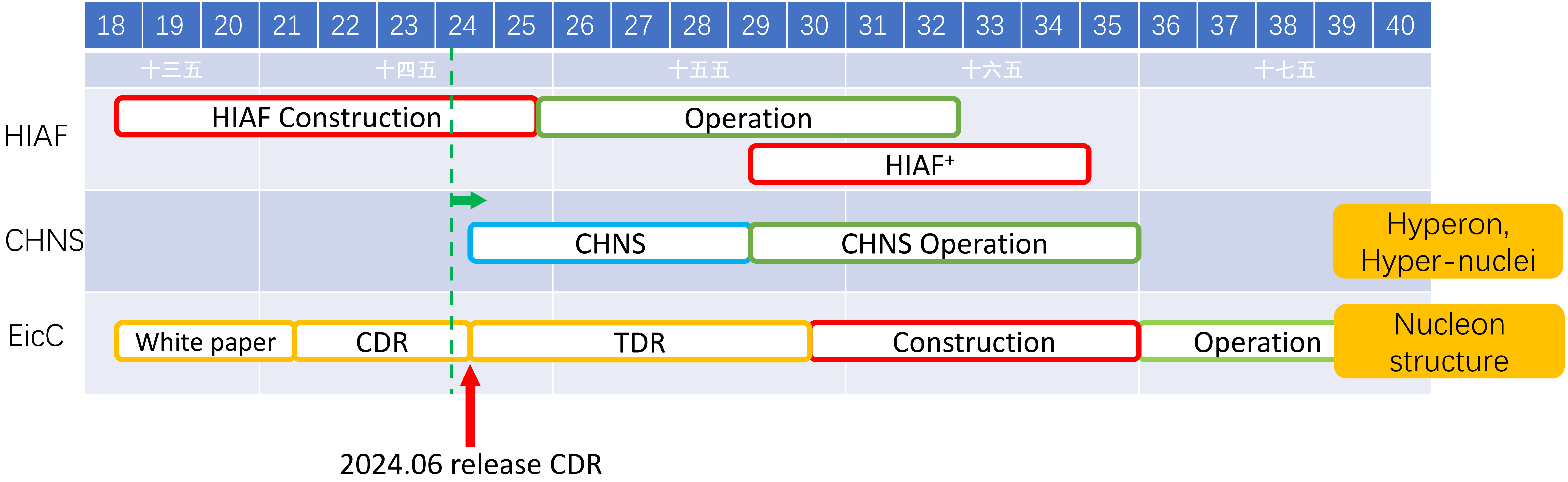
十三五
十四五
十五五
十六五
十七五
HIAF
HIAF Construction
Operation
HIAF+
EicC
White paper
CDR
TDR
Construction
Operation
Nucleon structure
2024.06 release CDR

Timelines



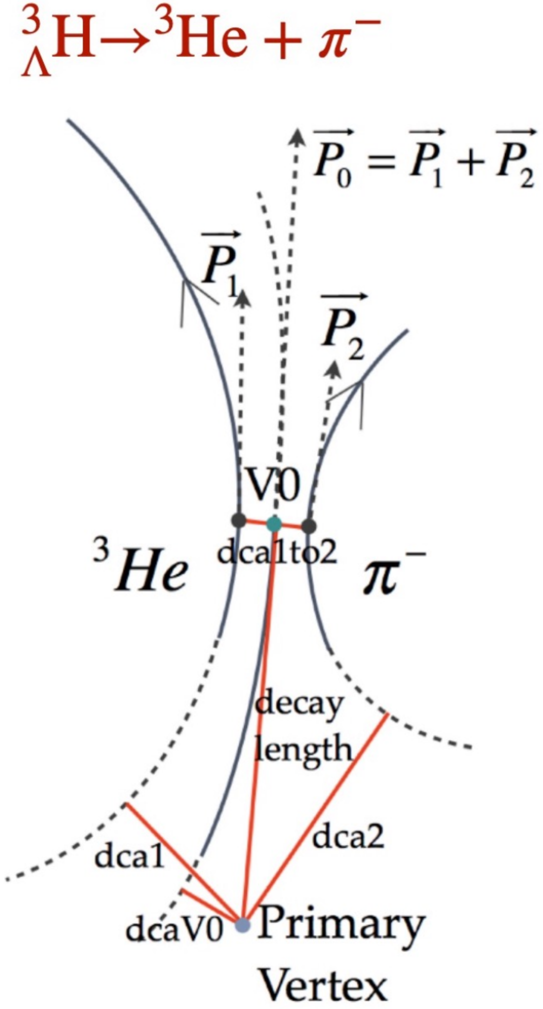
- Synchronization of CHNS and EicC TDR.
- Physics at HIAF before EicC operation.

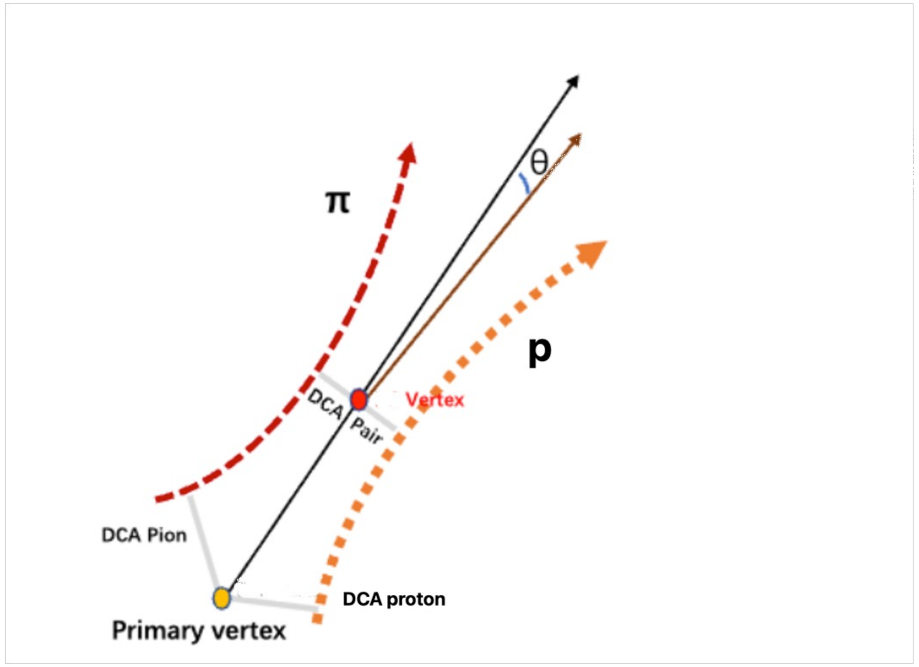
Summary

- **High Intensity heavy-ion Accelerator Facility (HIAF) at Huizhou provides good beam condition for Nuclear/Particle physics experiment**
- **China Hyper-Nuclear Spectrometer (CHNS) is proposed to study**
  - **Polarization of hyperon, Hyper-nuclei production**
- **Detector design, and physics projection is ongoing**
- **Possible extend to η physics with the ECal.**

Thank you!

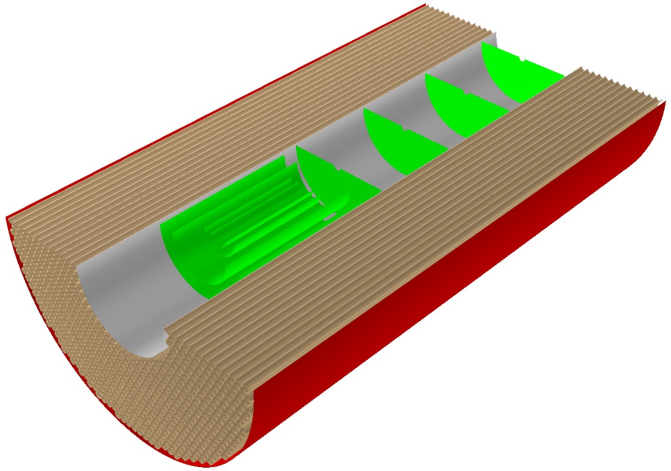
Reconstructed ${}^{3}_{\Lambda}\mathbf{H}$ candidates





Slides from Xionghong

Detector performance



- **Magnetic field of 1.5 Tesla**

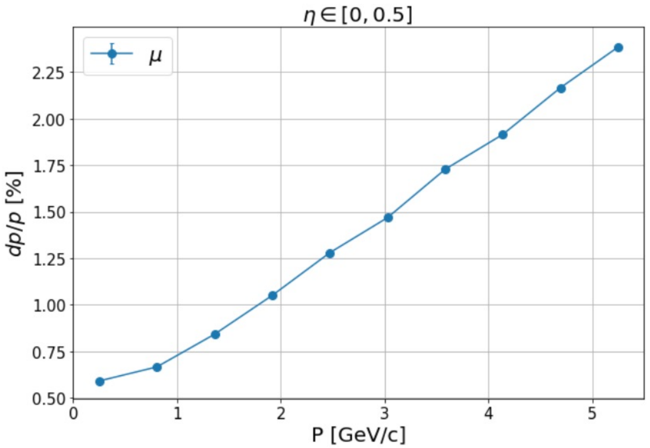
Barrel:

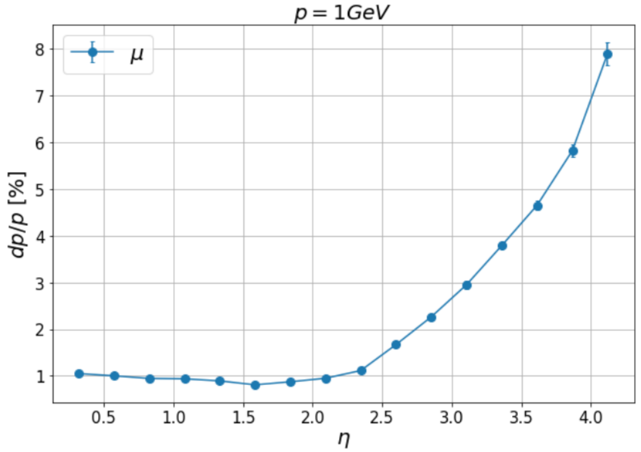
R(cm)	Length(cm)	Pitch Size(μm)	Material Bedget (X/X0 %)	Tech
5.0	28	20	0.05	ITS3
8.0	28	20	0.05	ITS3
20.0	28	20	0.05	ITS3
23.0	28	20	0.05	ITS3
25.0	90	55	1.00	LGAD

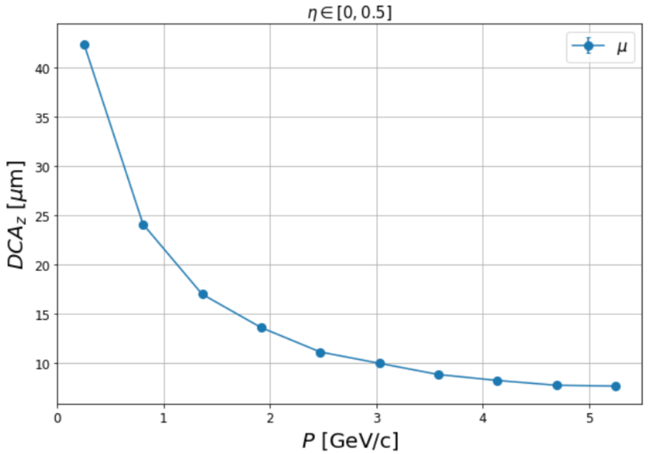
Disk:

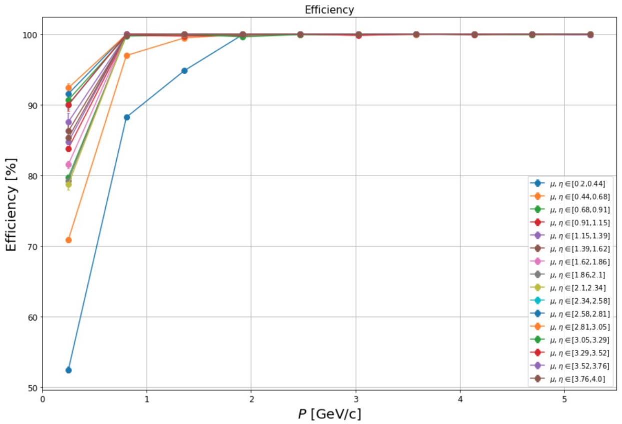
In R(cm)	Out R(cm)	Z(cm)	Pitch Size(μm)	Material Bedget (X/X0 %)	Tech
1.0	23	32	20	0.05	ITS3
1.0	23	57	20	0.05	ITS3
1.0	23	65	20	0.05	ITS3
1.0	23	85	20	0.05	ITS3
1.0	25	90	55	1.00	LGAD

Detector performance (silicon only)







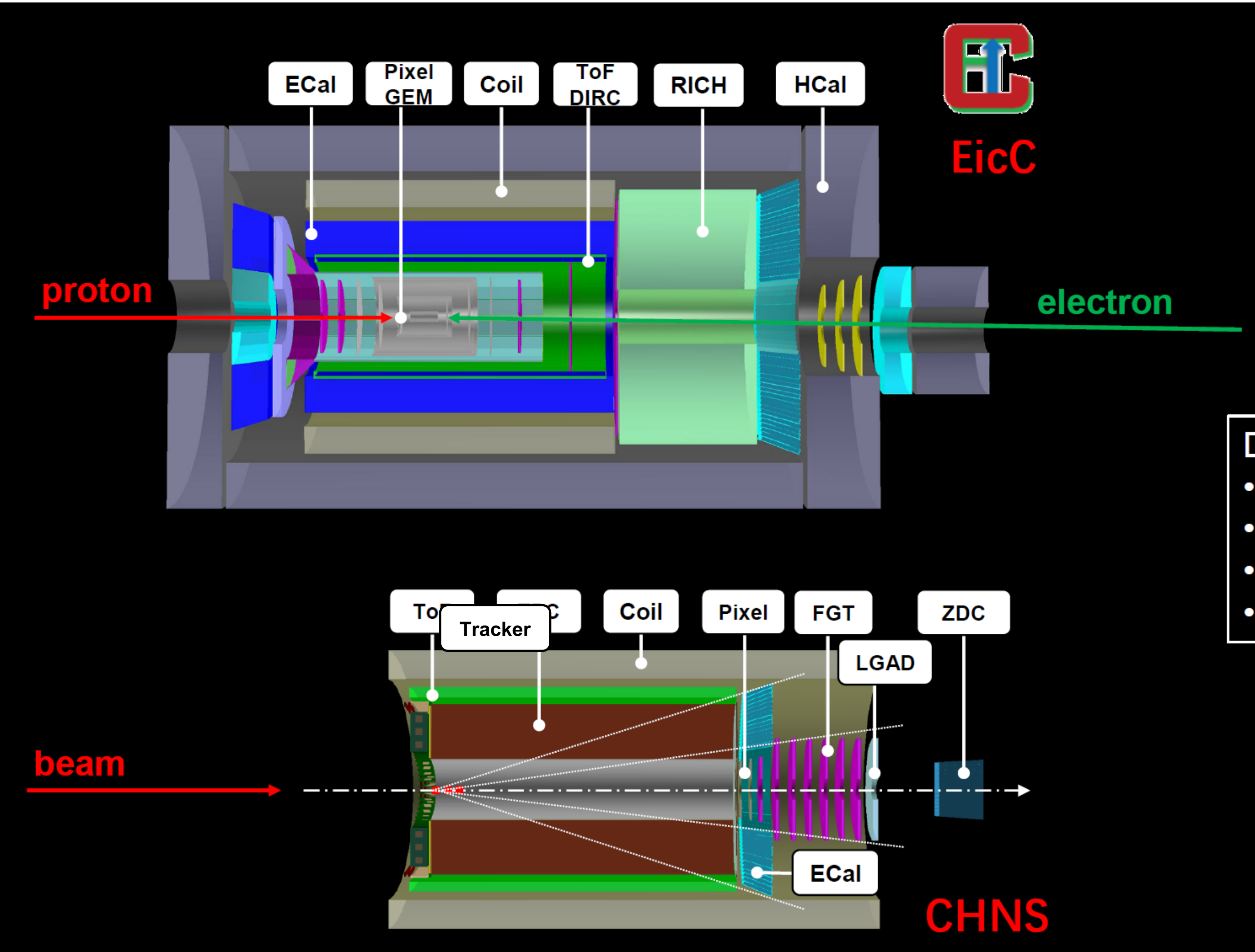


Detector design ST

Element	Material	$X[mm]$	X_0 $[cm]$	X/X_0
Film Tube	Mylar, 27 μm	0.085	28.7	3.0×10^{-4}
Coating	Al, 2×0.03 μm	2×10^{-4}	8.9	2.2×10^{-6}
Gas	Ar/CO_2(10 %)	7.85	6131	1.3×10^{-4}
Wire	W/Re, 20 μm	3×10^{-5}	0.35	8.6×10^{-6}
			$\sum_{straw}$	4.4×10^{-4}

$$\frac{\sigma E}{E} \sim 6\%$$

CHNS vs EicC



Detectors in Common
- Solenoid
- ToF
- ECal
- Pixel + GEM