



2022 한국고에너지물리학회 가을학술대회
The Korean Society of High Energy Physics (KSHEP)
Pusan National University, Busan, Korea, 17-19 November 2022

Status and prospects of the nuclear matter study in Korea: Activities in **CENuM**

Byungsik Hong

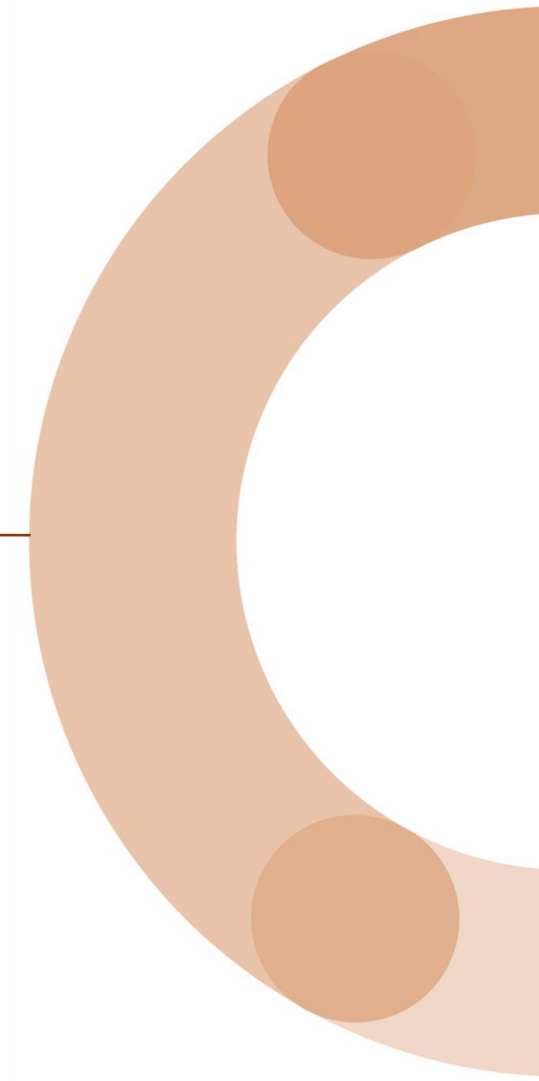
Center for Extreme Nuclear Matters (CENuM), Korea University

Outline

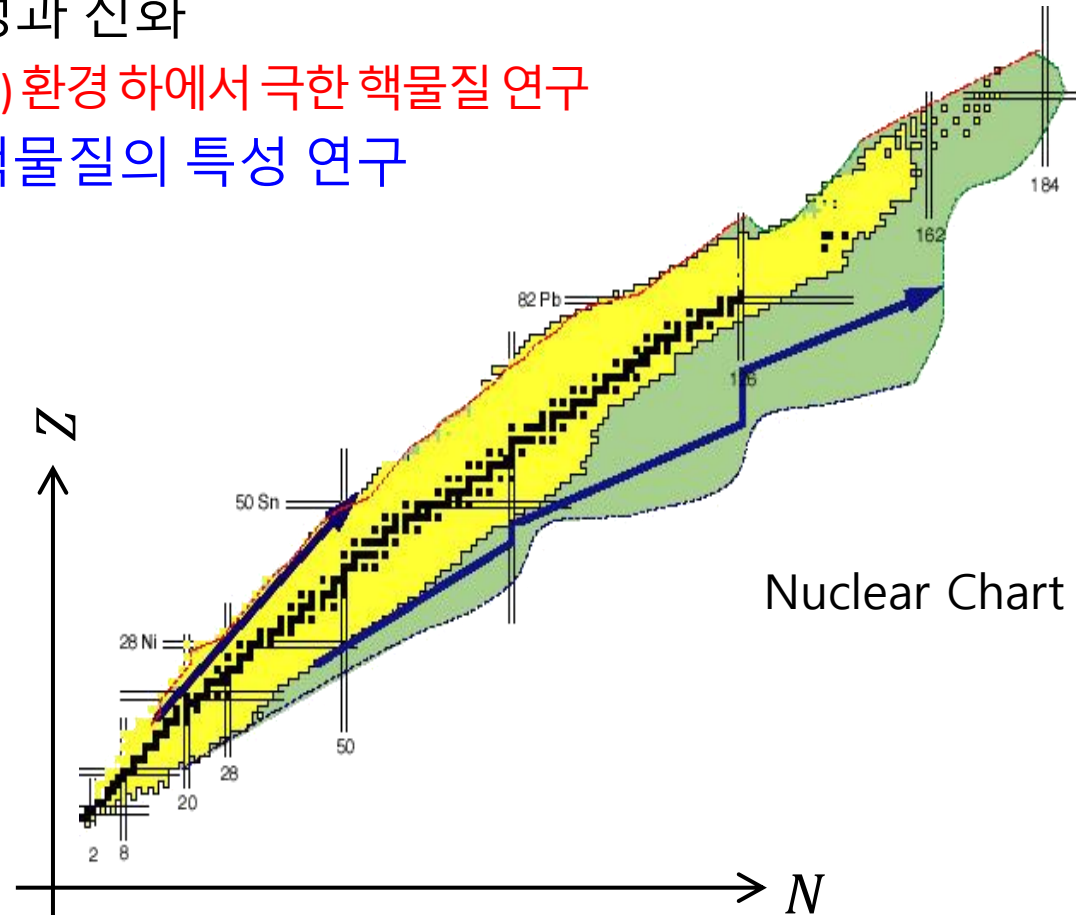
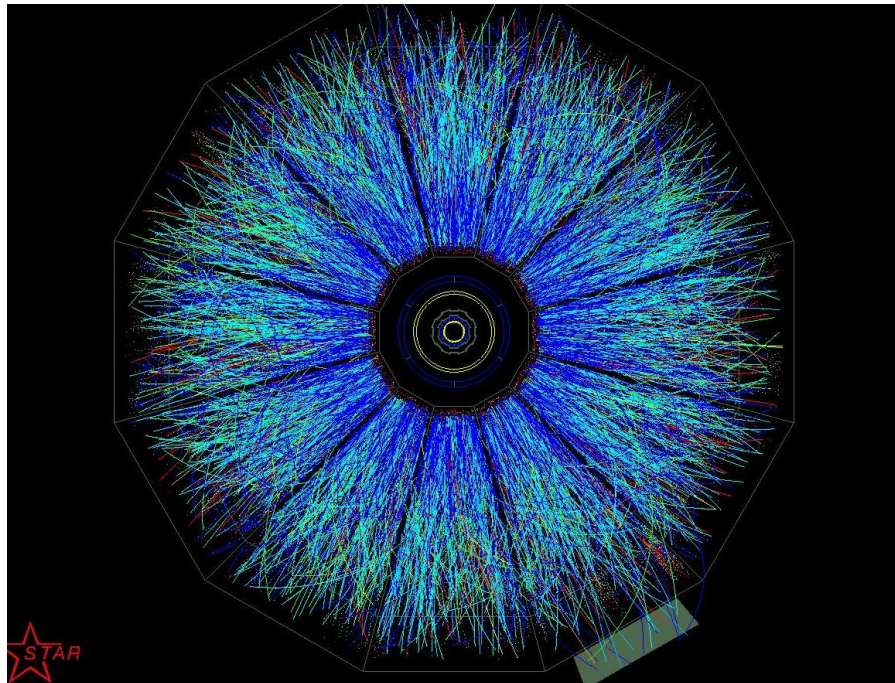
- 1. Introduction to CENuM**
- 2. Research topics in CENuM**
- 3. Preparation for LAMPS @ RAON**
- 4. Summary**

Part 1.

Introduction to CENuM



- **강한상호작용(핵력)에 의해 결합된 물질의 구조 및 특이한 동역학 연구**
 - 저에너지 핵물리: 약 만개에 이르는 핵의 기원과 구조
 - 빅뱅 핵합성, 초신성 폭발, 중성자별의 충돌: 중력파 등
 - 고에너지 핵물리: 초기 우주물질의 생성과 진화
 - 초고온($\sim 10^{13}$ K), 초고밀도($> 10^{12}$ kg/cm³) 환경 하에서 극한 핵물질 연구
 - 비섭동 양자색소역학(QCD)을 이용한 핵물질의 특성 연구

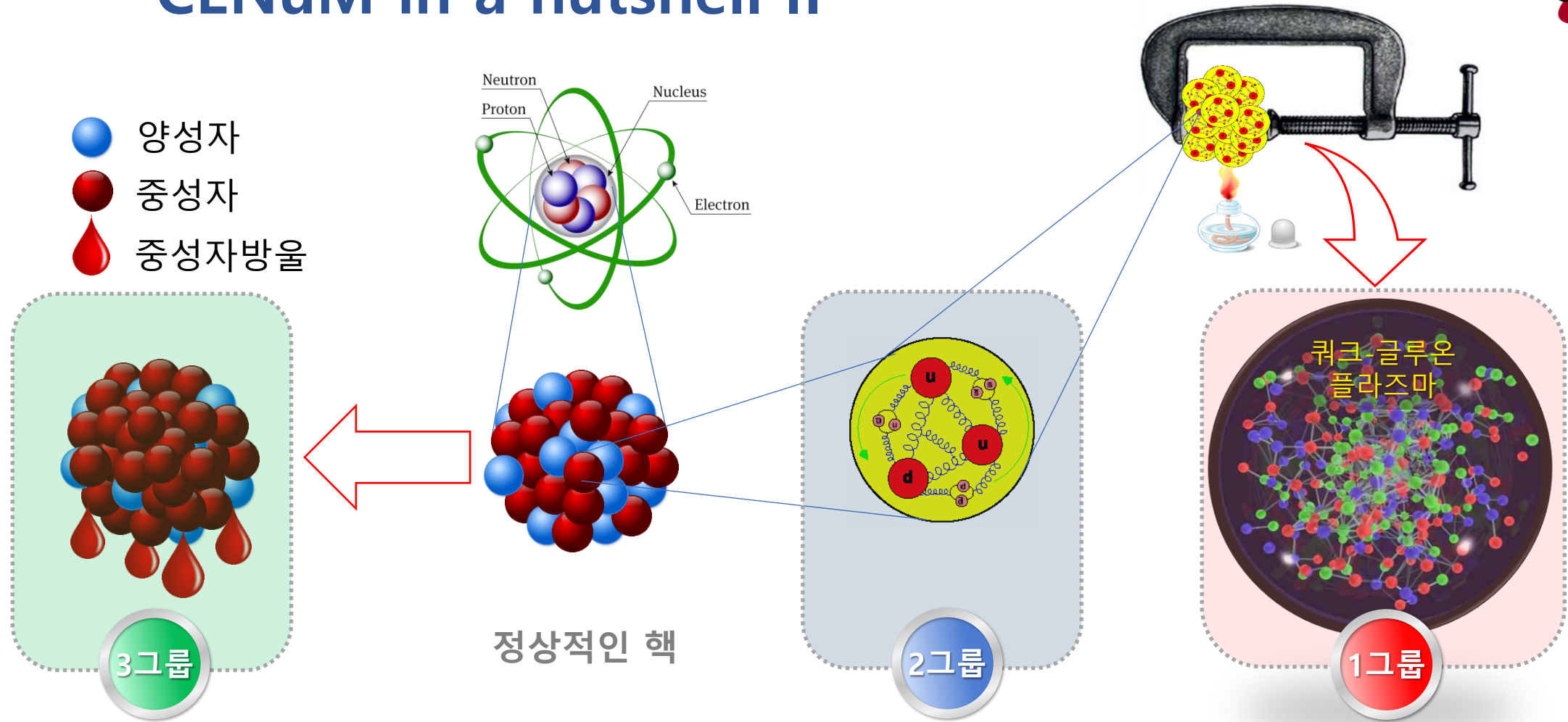


● Center for **Extreme Nuclear Matters**

- 극한 핵물질 연구센터
- 한국연구재단 지원 선도연구센터 (SRC)
- 2018년 설립

● 구성

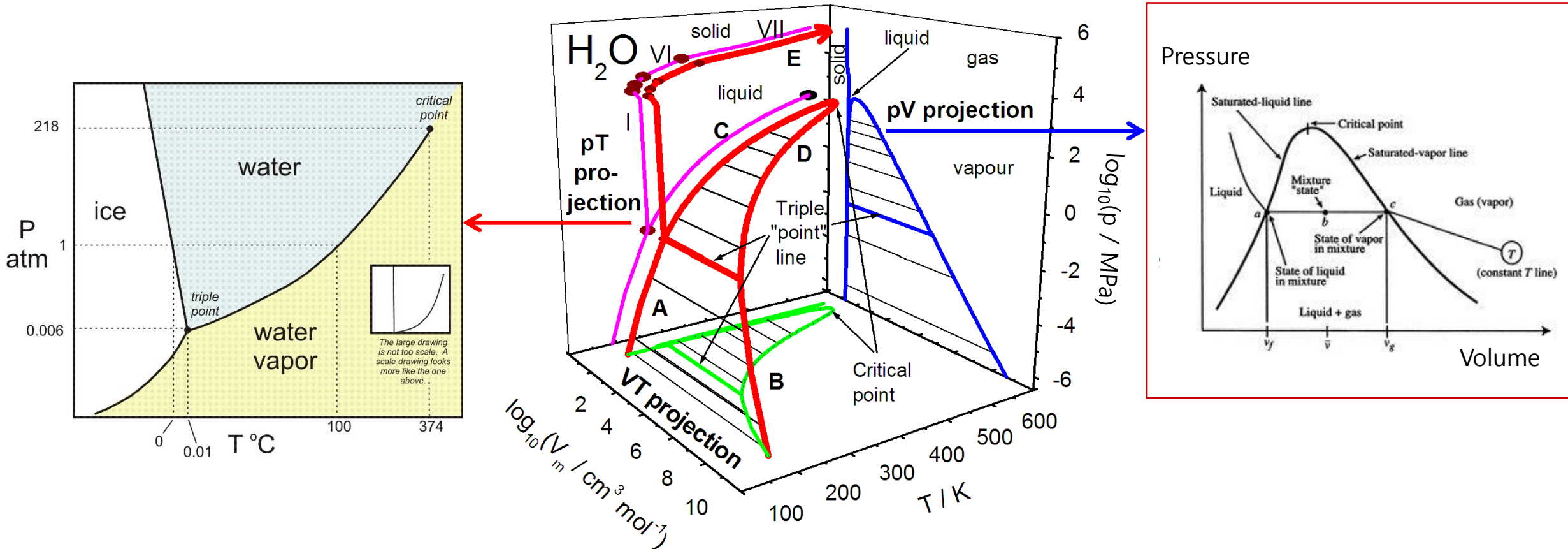
- 제1그룹 (극한 QCD 물질 그룹)
 - 초기 우주물질인 쿼크-글루온 플라즈마(QGP)의 형성과 진화 이해
 - 고온(10^{16} K 또는 1 TeV), 고 파톤밀도 물질의 비섭동 양자색소역학 현상 이해
 - 권민정 (인하대), 조성태 (강원대), 김용선 (세종대)
- 제2그룹 (강입자물질 그룹)
 - 핵자의 궁극적인 3차원적 구조 연구
 - 핵자 가둠현상과 비섭동 양자색소역학에서 대칭성의 부분적 회복과정 이해
 - 김현철 (인하대), 안정근 (고려대), 남승일 (부경대)
- 제3그룹 (희귀 핵물질 그룹)
 - 저에너지 핵반응과 핵 구조, 중성자 과잉 압축 핵물질의 특성 연구
 - RAON 실험 준비
 - 홍병식 (고려대), 김경식 (항공대), 현창호 (대구대)



- 최종 목표: 강입자-핵-핵물질의 구조와 특성을 온도와 밀도의 함수로 일관되게 설명할 수 있는 **비섭동 양자색소역학 유효이론**을 개발하고 이를 검증하기 위한 실험결과를 얻는다.

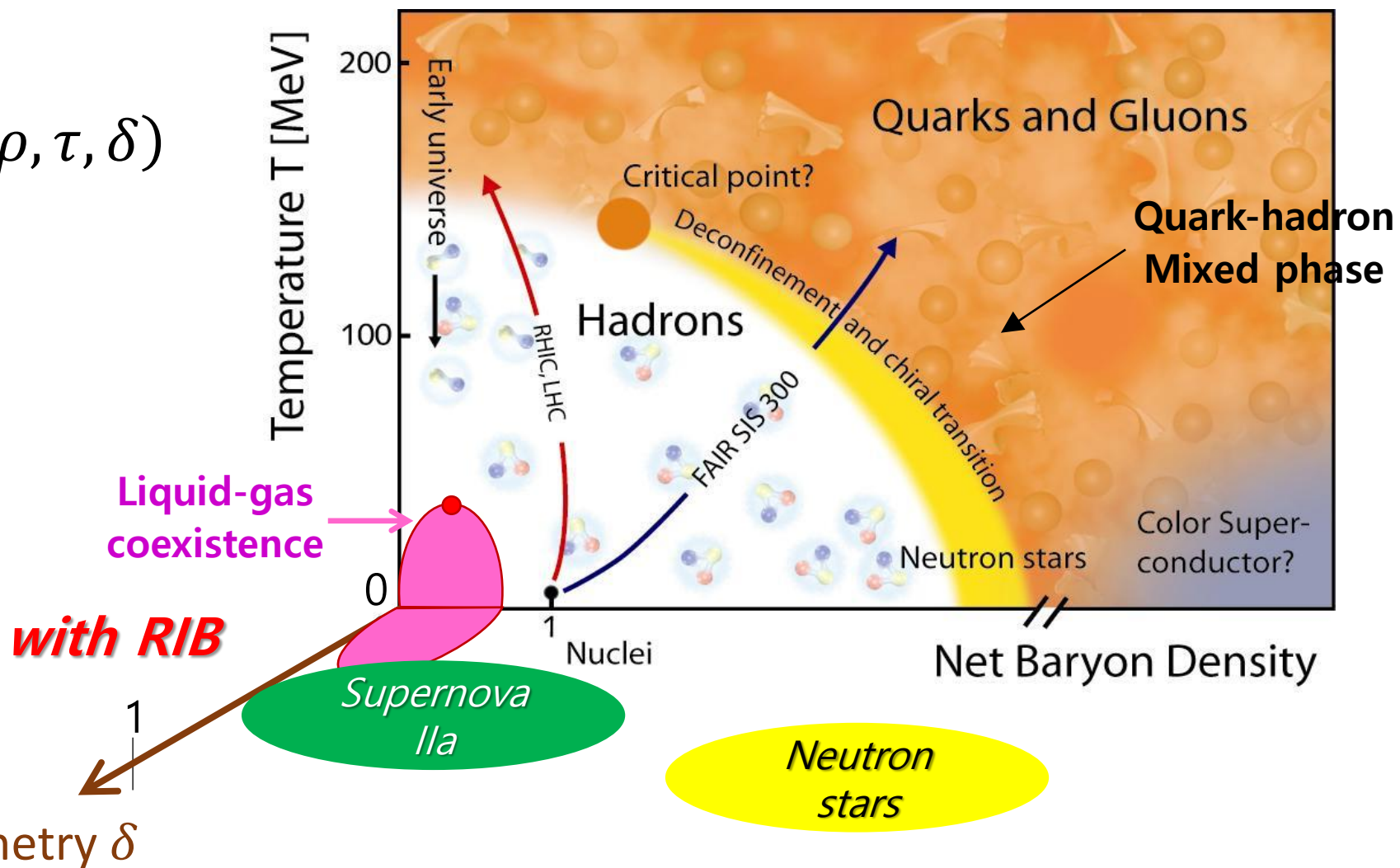
- States or Phases: Solid (ice), Liquid (water), Gas (vapor)

Phase diagram of H₂O



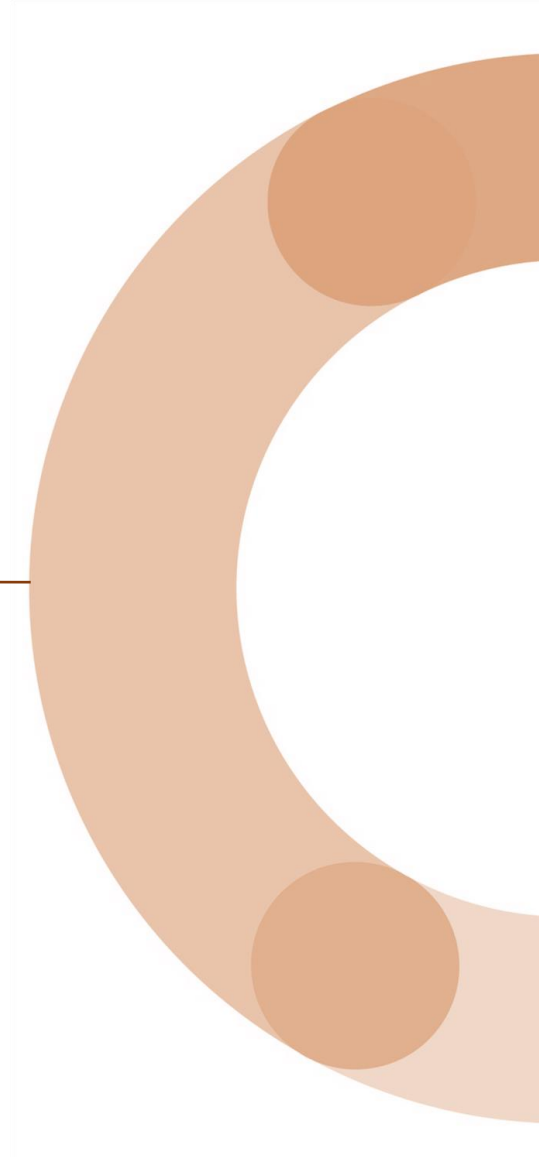
Variables:

$$(p, \tau, V) \rightarrow (\rho, \tau, \delta)$$

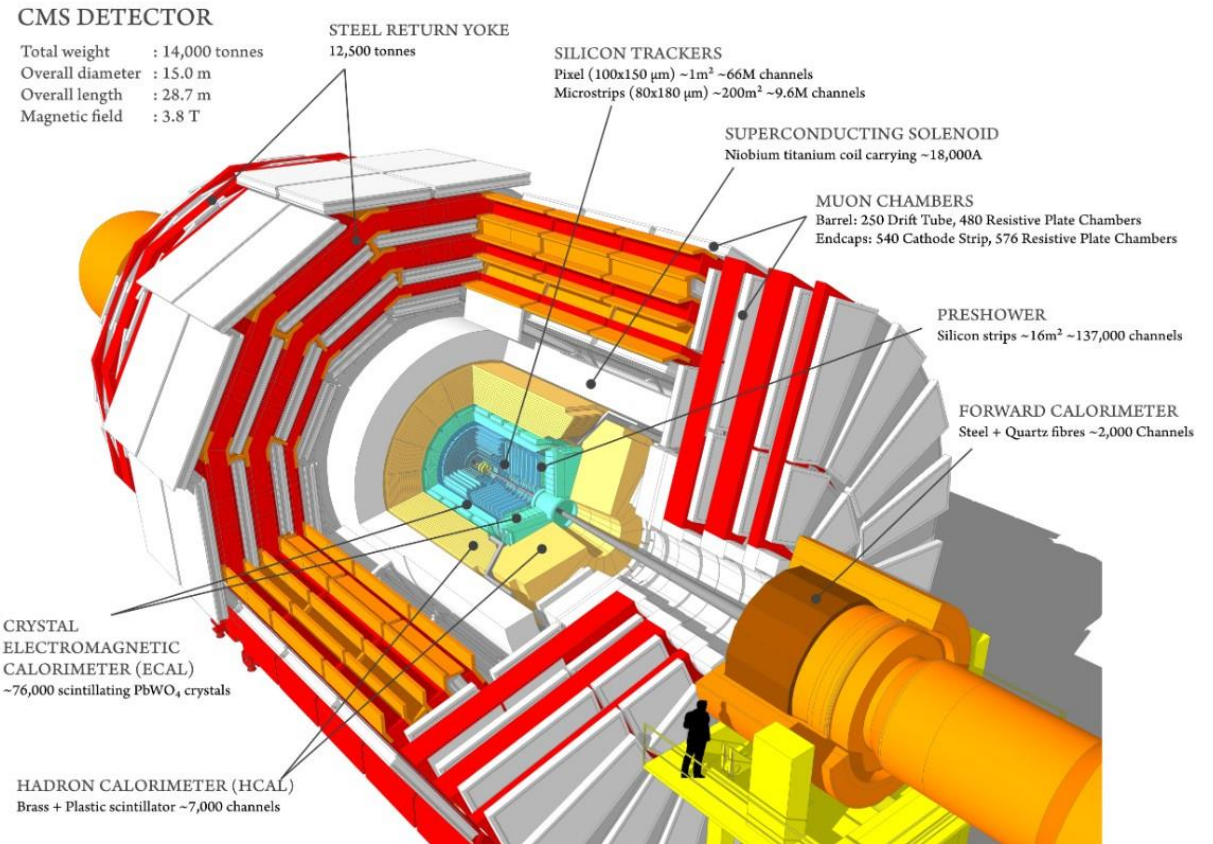
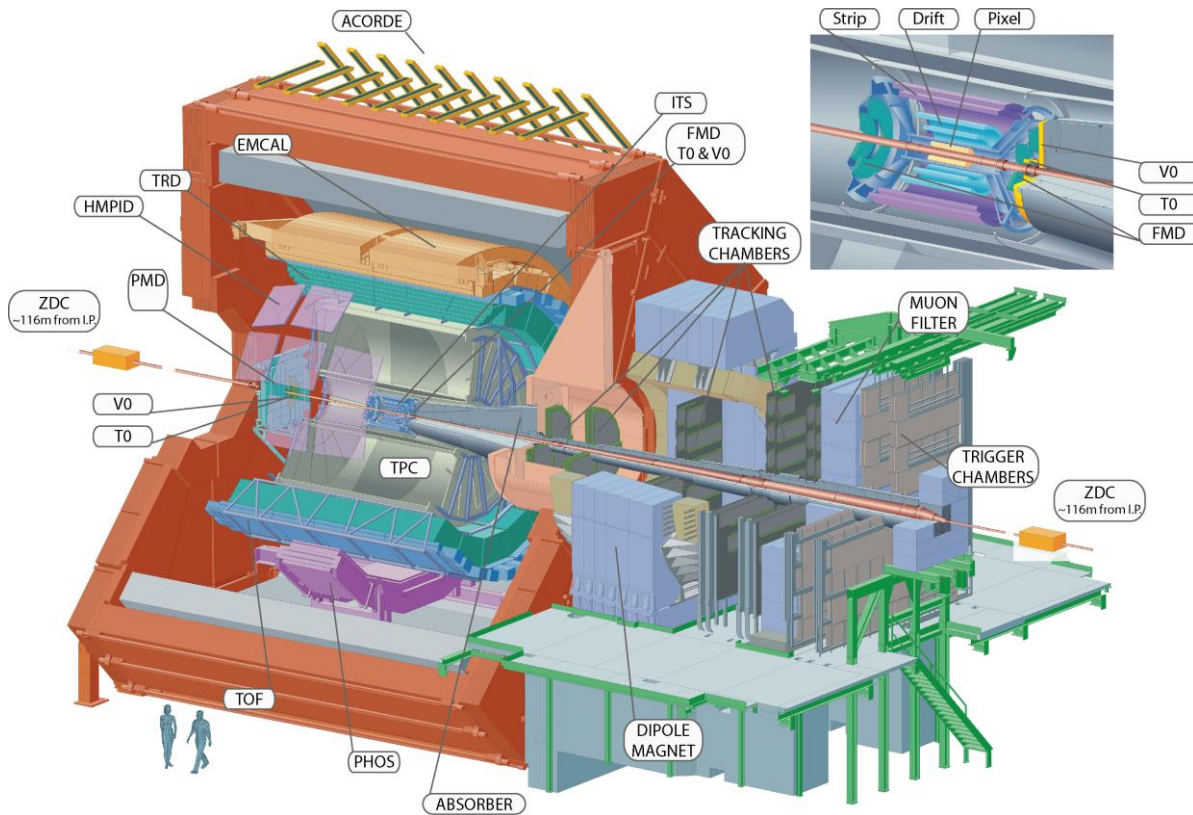


Part 2.

Research topics in CENuM



- LHC의 ALICE와 CMS 중이온 충돌을 이용한 quark-gluon plasma (QGP) 연구
 - 주로 무거운 쿼크를 포함한 강입자와 쿼코니움 분석
 - 무거운 쿼크를 포함한 강입자 생성을 설명하는 이론 개발

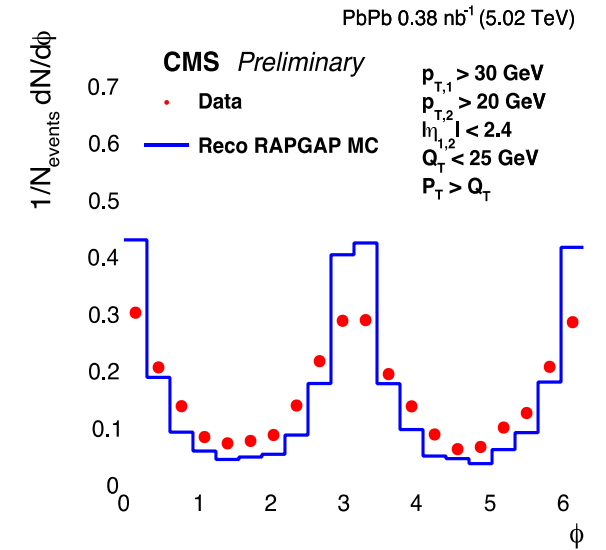
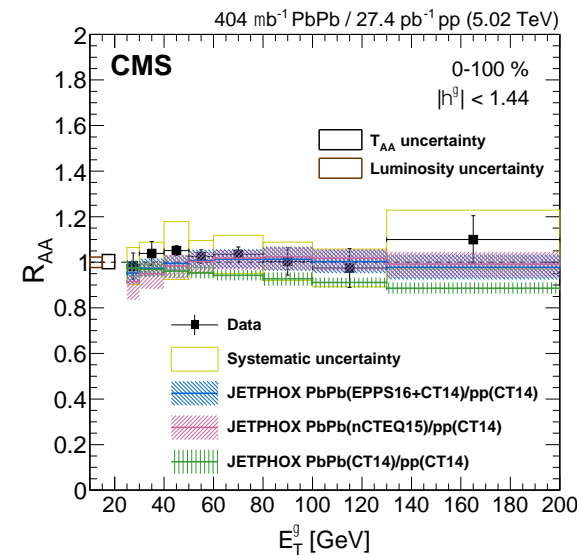
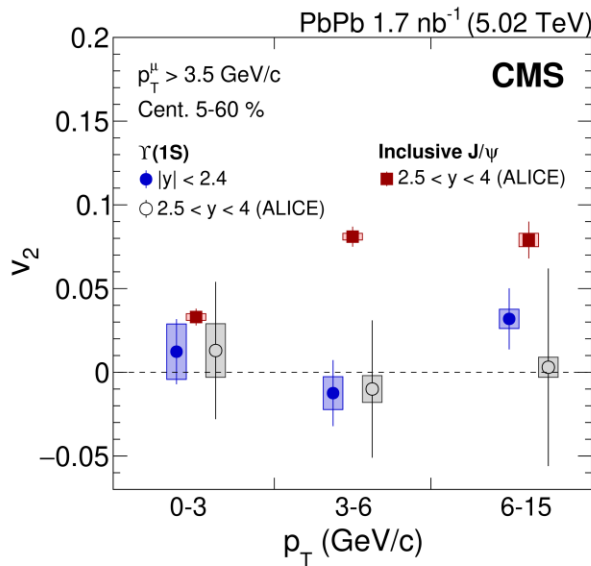
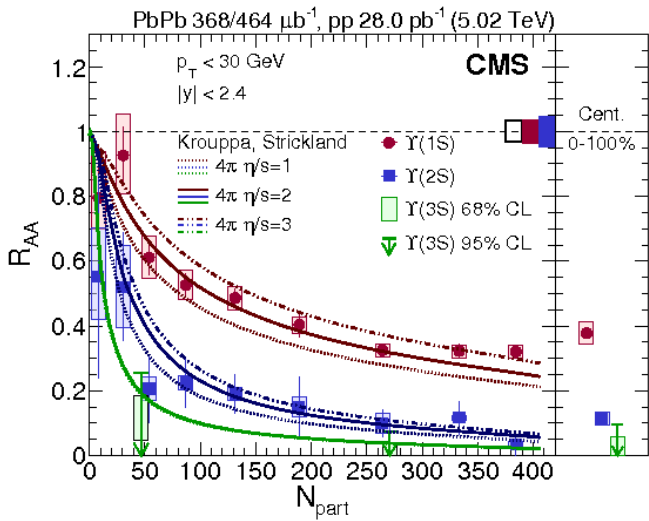


- (CMS) Pb+Pb $\Upsilon(nS)$
- 주저자: 박재범
- PLB790, 270 (2019)

- (CMS) Pb+Pb $\Upsilon(nS)$ 의 유체흐름
- 주저자: 김용선
- PLB819, 136385 (2021)

- (CMS) Pb+Pb 광자
- 주저자: 고연주
- JHEP07, 116 (2020)

- (CMS) Pb+Pb UPC 제트쌍
- 주저자: 김용선
- HIN-18-011
(Submitted to PRL)



쿼크니움의 결합에너지 크기에 따른 순차적인 억제현상 측정

핵물질의 팽창과정에서 무거운 쿼크를 포함한 강입자는 상호작용을 거의 하지 않음을 증명

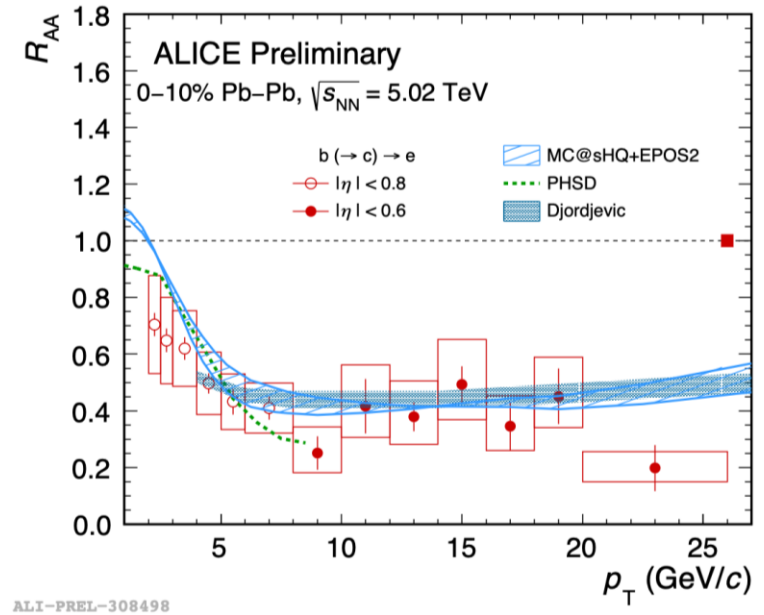
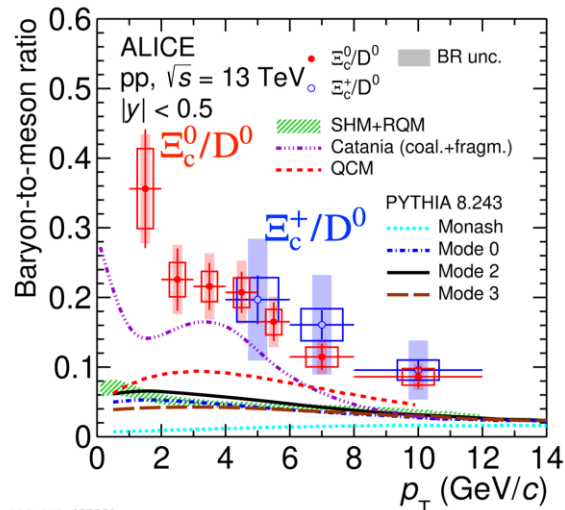
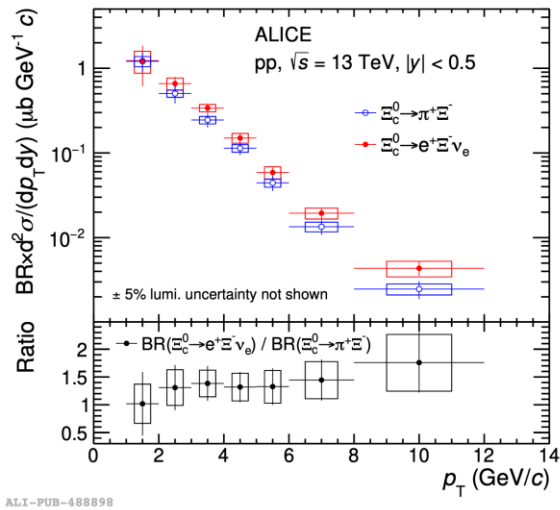
Glauber 모델의 핵 두께 축척 가정의 정당성 증명

양성자 및 핵 내부에 존재하는 글루온의 편광성을 발견

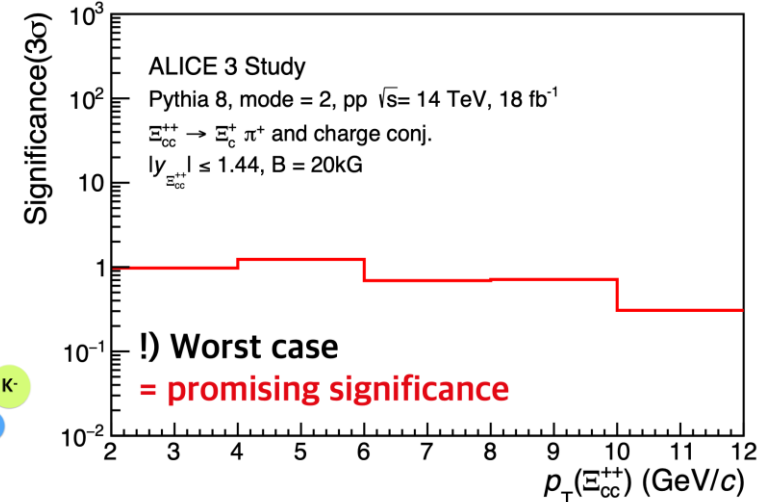
제 1그룹 연구내용

→ (ALICE) Pb+Pb에서 B 핵변환인자
 → 주저자 박종한 (논문 작성 중)

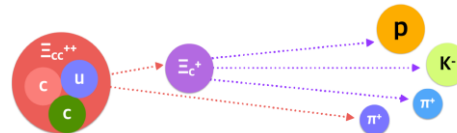
↓ (ALICE) p+p에서 $\Xi_c^{0,+}$ 바리온 분석
 ↓ 주저자: 서진주
 ↓ PRL127, 272001(2021)



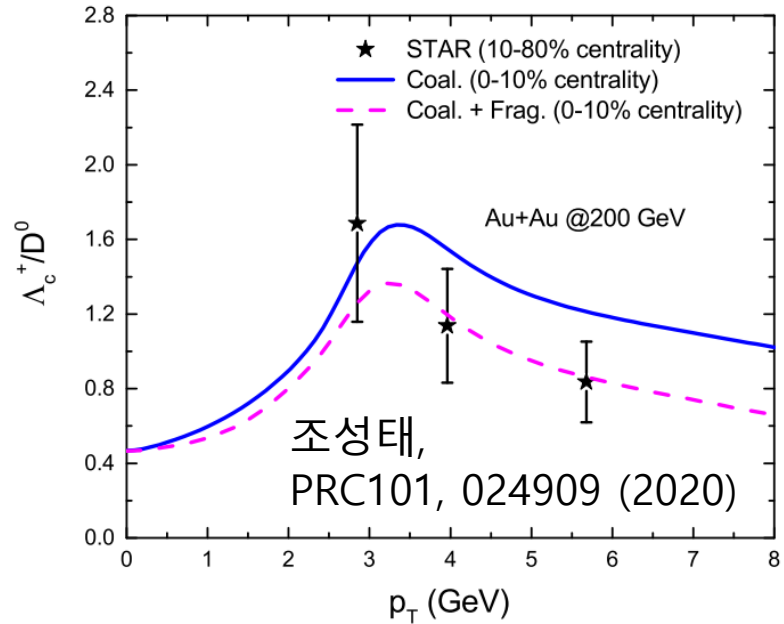
ALI-PREL-308498



→ (ALICE) ALICE3 검출기를 이용해 p+p에 의한 Ξ_{cc}^{++} 입자 측정 가능성 연구
 → ALICE3 Letter Of Intent (LOI)

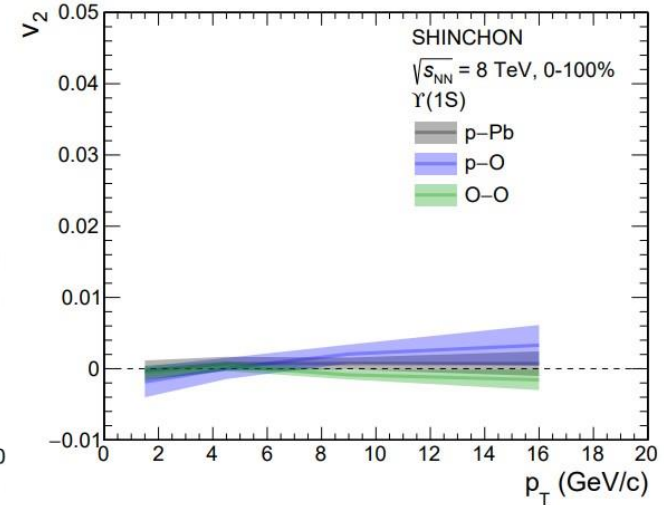
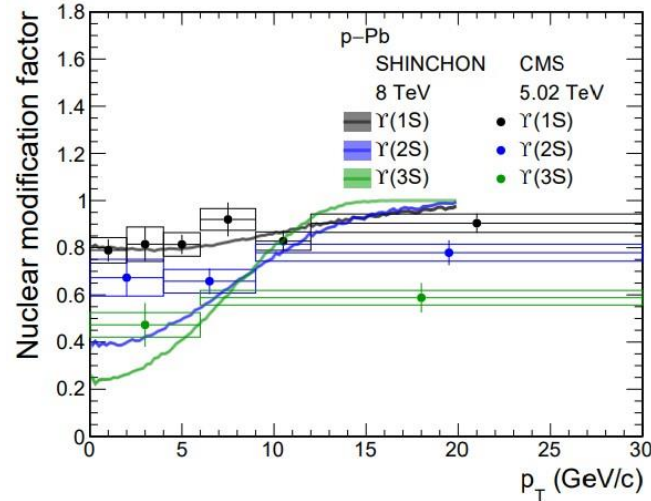
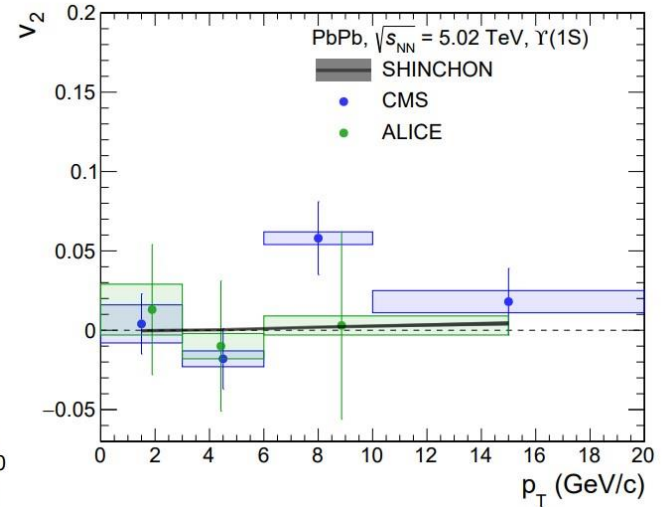
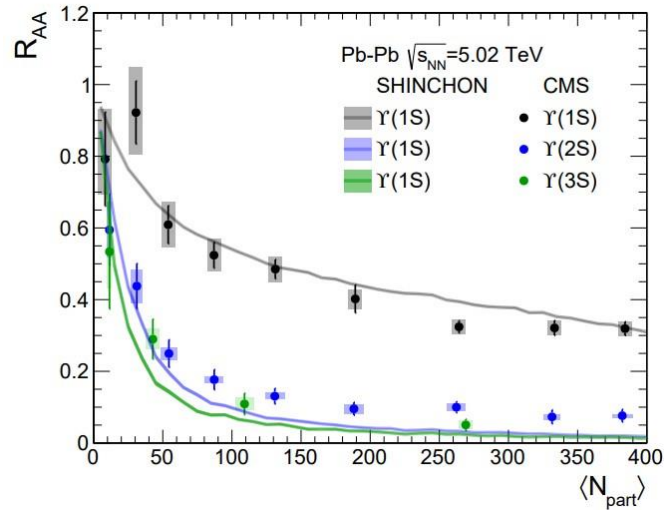


↓ QCD 매질효과 이론: 쿼크융합모형 (quark coalescence model)



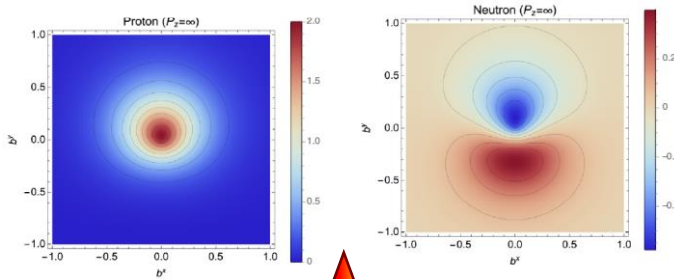
→ SHINCHON 중이온충돌 시뮬레이션 도구

- Monte-Carlo Glauber와 IP-Glasma 모델 등을 이용해 QGP 초기조건 구현
- 에너지 밀도 및 유체흐름 조건 반영
- CENuM+HIM 공동연구자
- arXiv:2209.12303



바리온의 구조

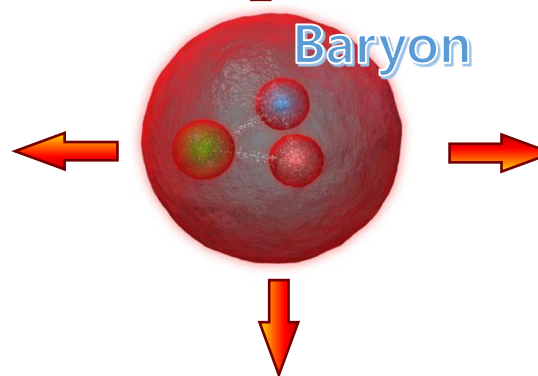
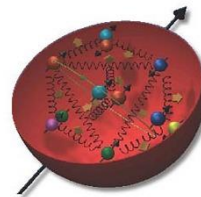
바리온의 횡축면 전하분포 (JLAB)



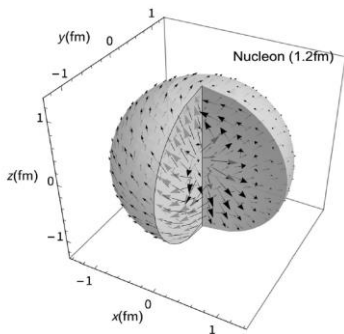
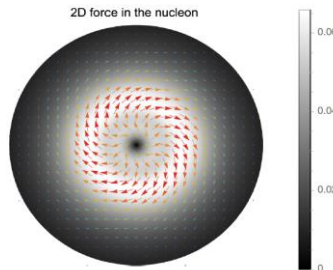
바리온의 질량
(EIC의 첫 번째 미션)



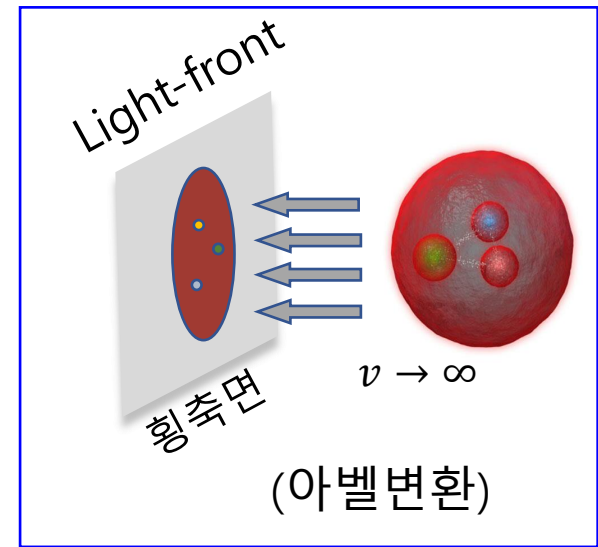
바리온의 스핀
(EIC의 두 번째 미션)



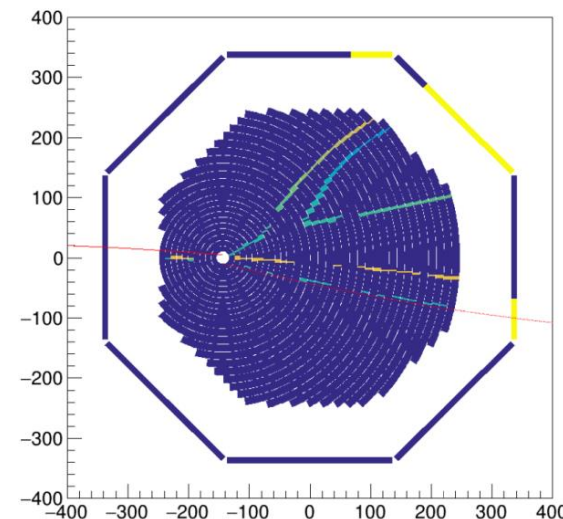
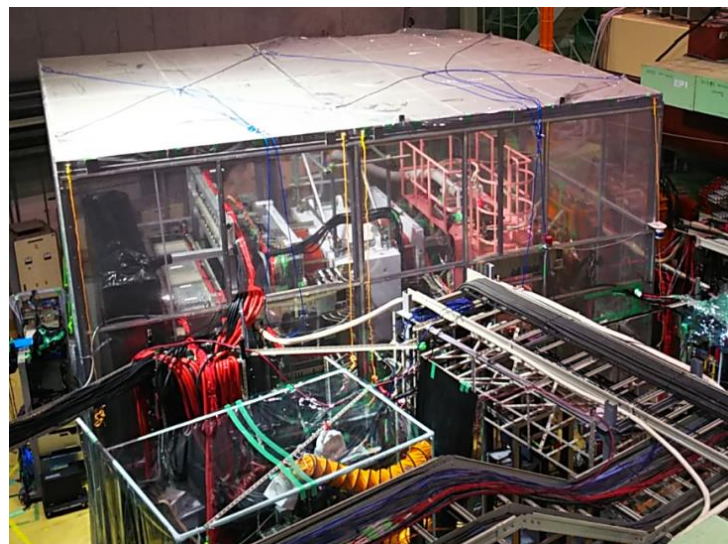
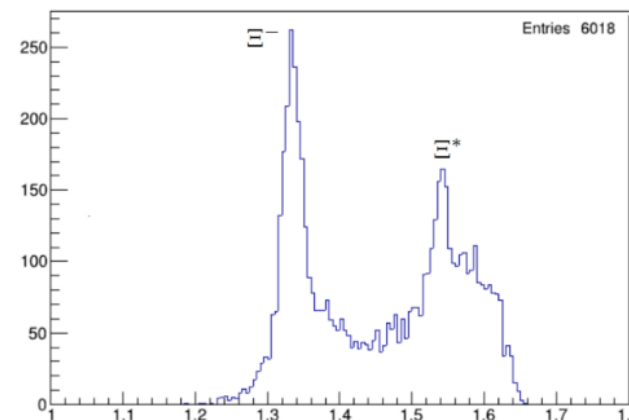
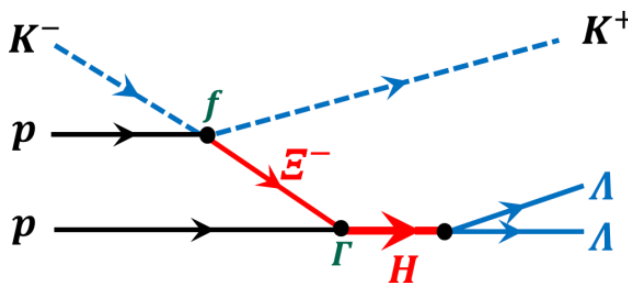
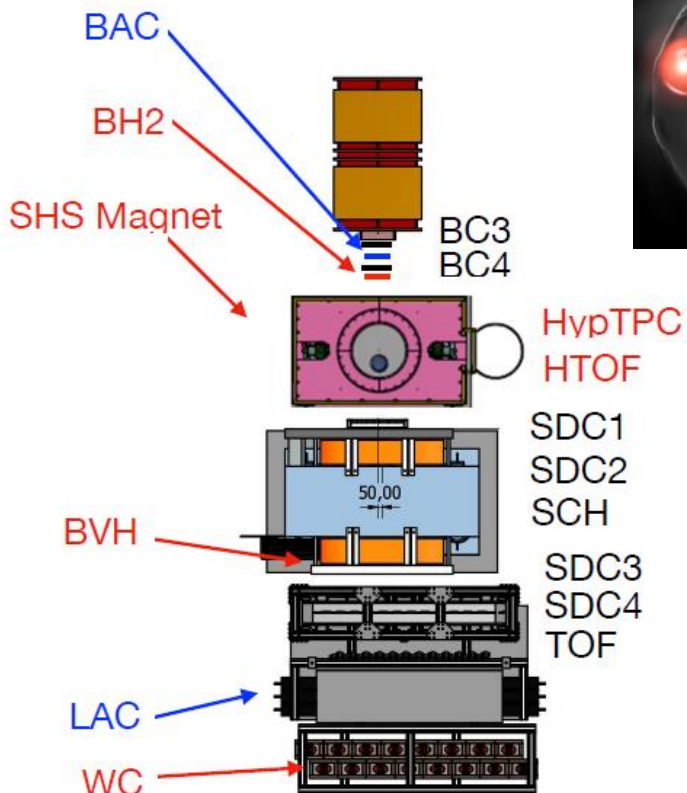
바리온의 안정성
(JLAB & EIC)



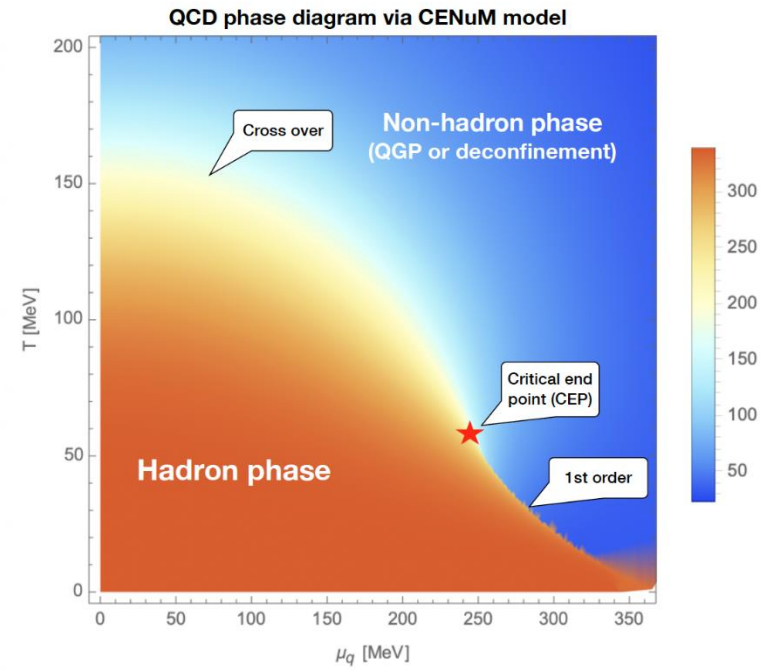
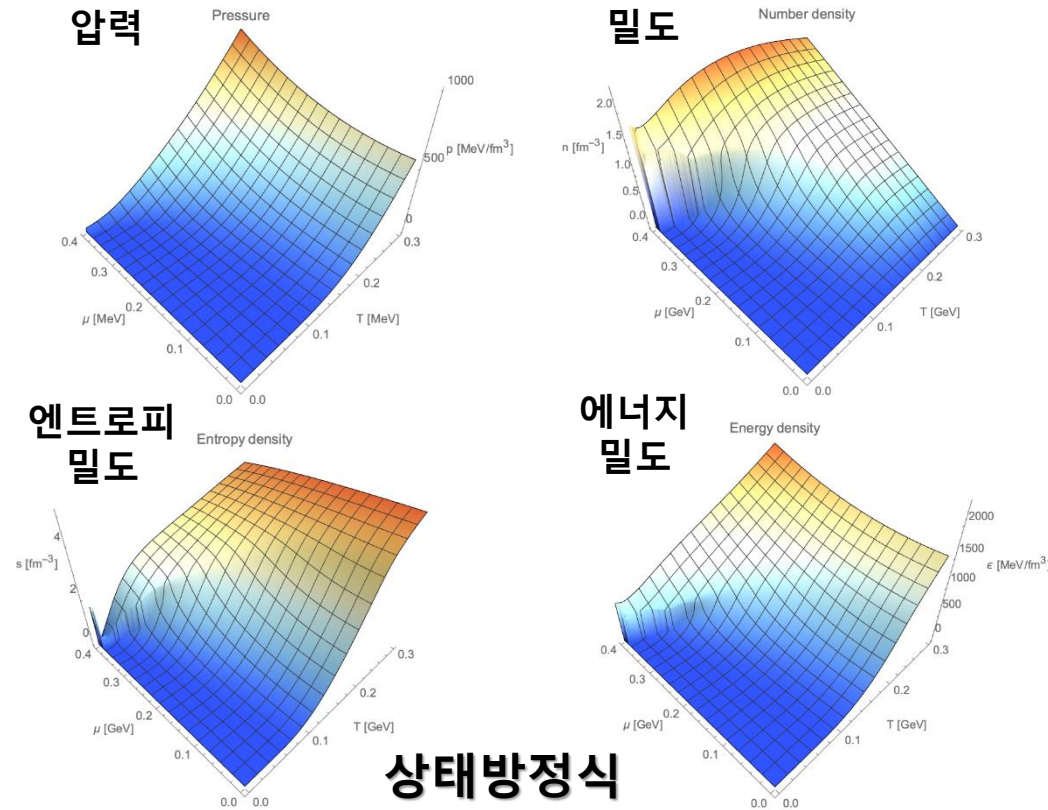
- 중입자의 2차원 횡축 전하구조
- SU(3) 바리온의 전자기 전이 형태인자
- SU(3) 바리온의 축벡터 전이 형태인자
- 양성자의 중력 형태인자와 안정성
- 무거운 맛깔 입자(Σ_c)의 경우로 확장



- 특이 강입자 탐색
 - J-PARC E42 H -이중 바리온 (여섯 쿼크 입자) 탐색 실험 (Spokesperson: 안정근)
 - HypTPC, 초전도전자석, 체렌코프 등 제작
 - 2021년 데이터 취득 후 현재 데이터 분석 중

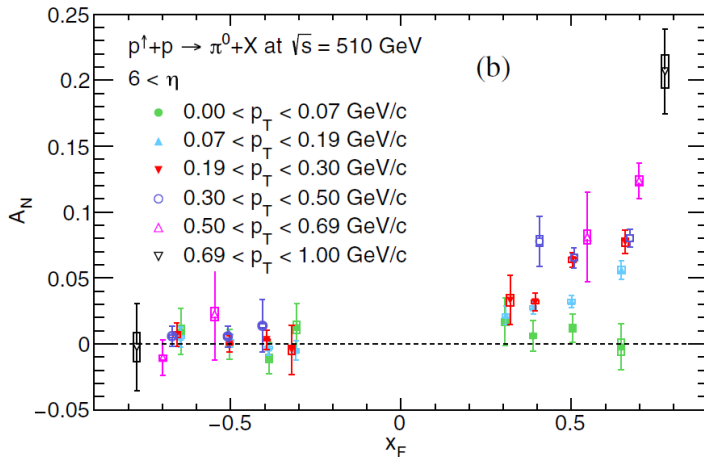
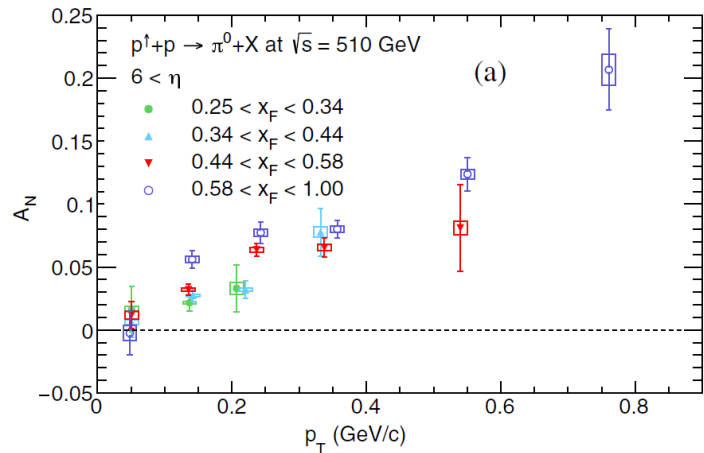


- 유한온도-유한밀도 QCD와 강입자 생성
 - QCD 매질을 이해하기 위한 유효모형 개발
 - 인스탄톤 진공과 폴리아코프 고리를 이용해 손지기 대칭성의 자발적 붕괴와 회복, 쿼크 가둠을 유효적으로 기술
 - 극한 쿼크 매질의 상태방정식을 유도하고 상전이 구조 분석



QCD 2차원 위상구조도

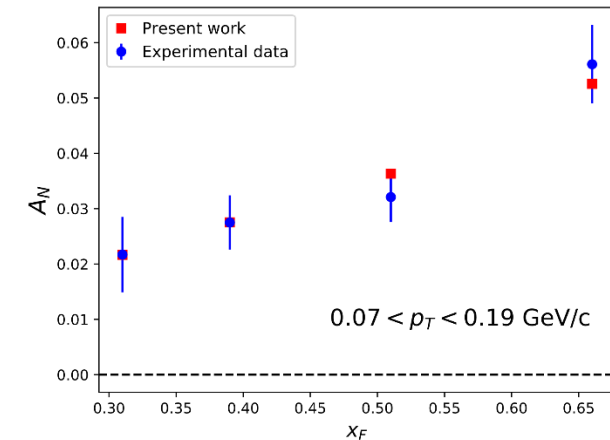
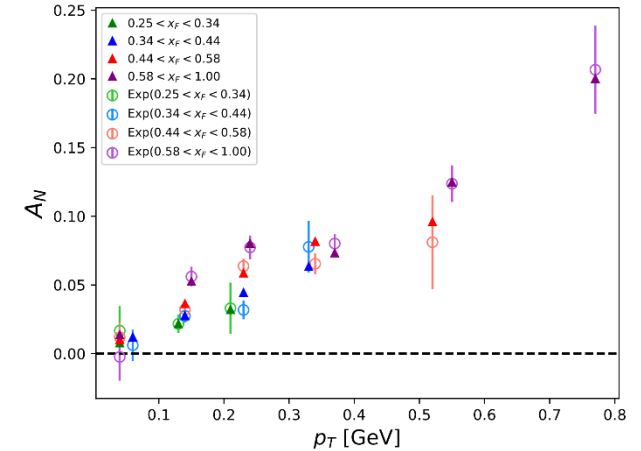
- $p^\uparrow + p \rightarrow \pi^0 + X$ (RHICf 실험 @ BNL)
 - ↓ (1그룹) 전방 π^0 의 단일스핀비대칭도 측정: 주저자 (김민호), PRL124, 252501 (2020)
 - ↘ (2그룹) 삼중 레제온 스핀 비대칭 이론으로 실험결과 설명: PRD106, 054001 (2022)



(실험)
김민호, 흥병식

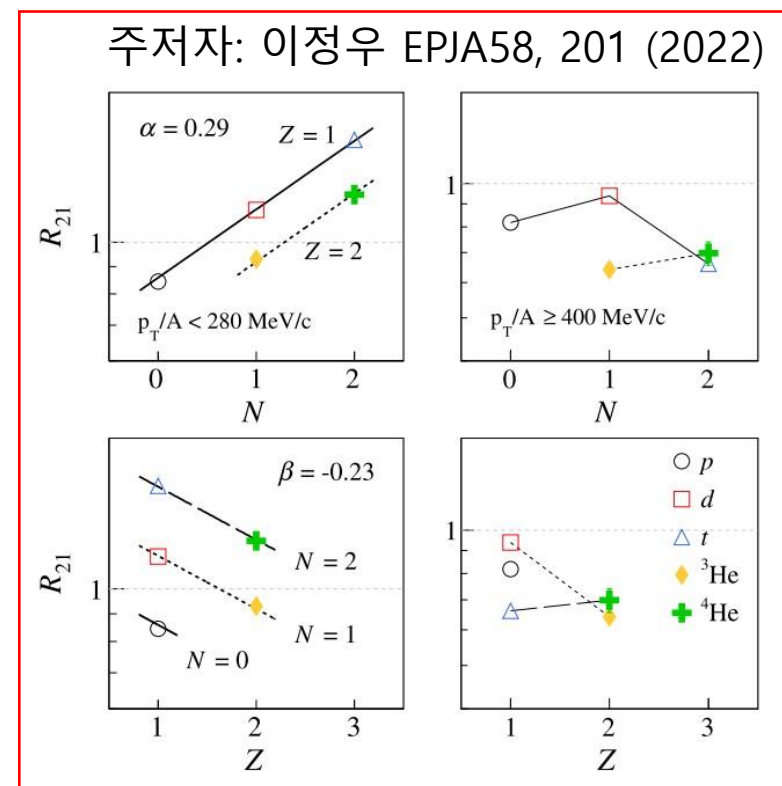
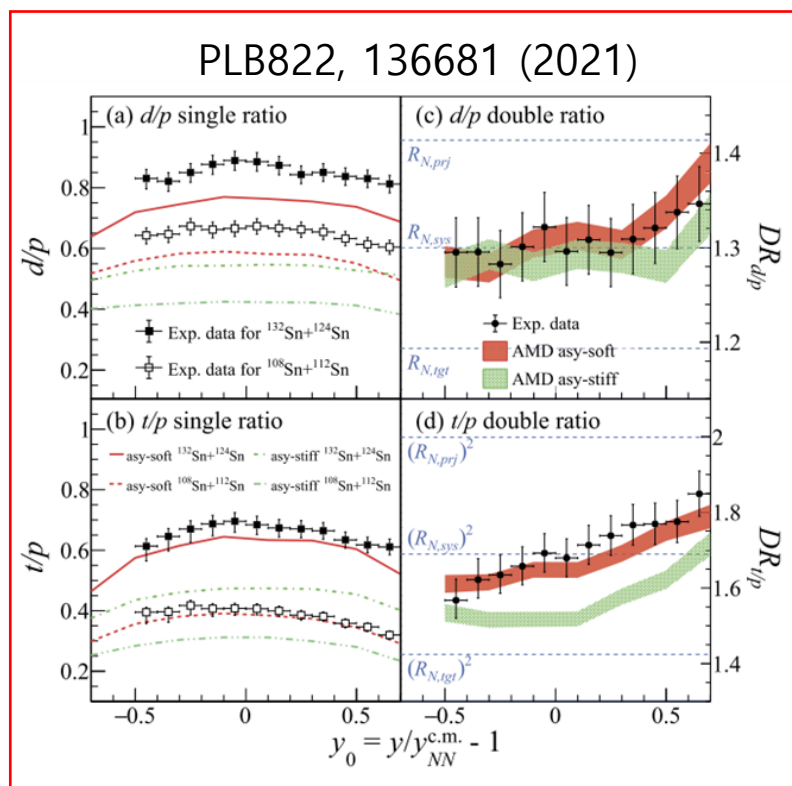
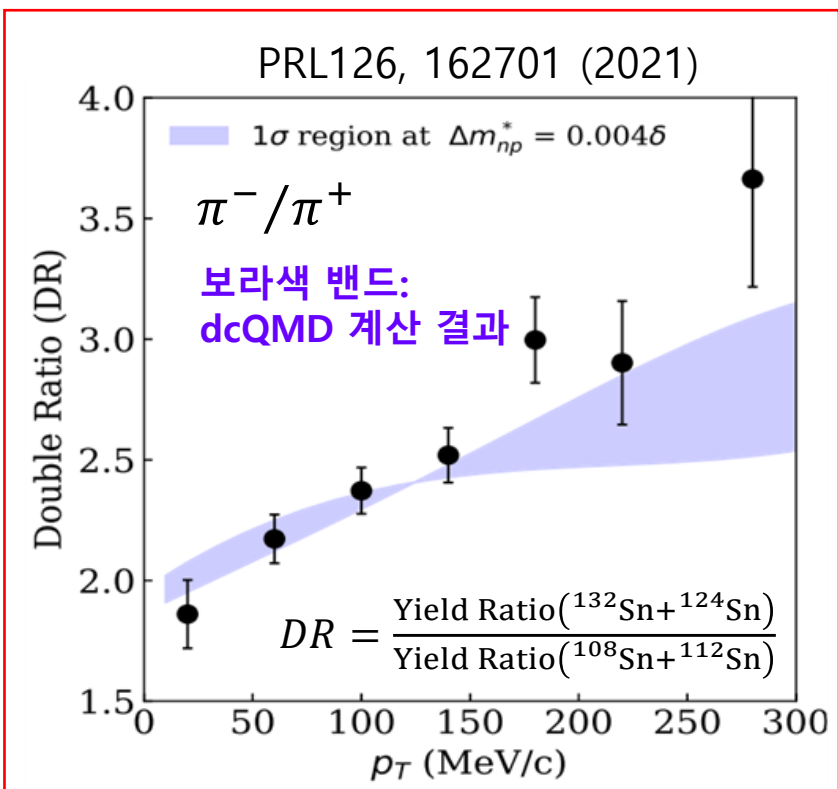
1그룹과 2그룹의
공동연구

(이론)
김희진, S. Clymton,
김현철

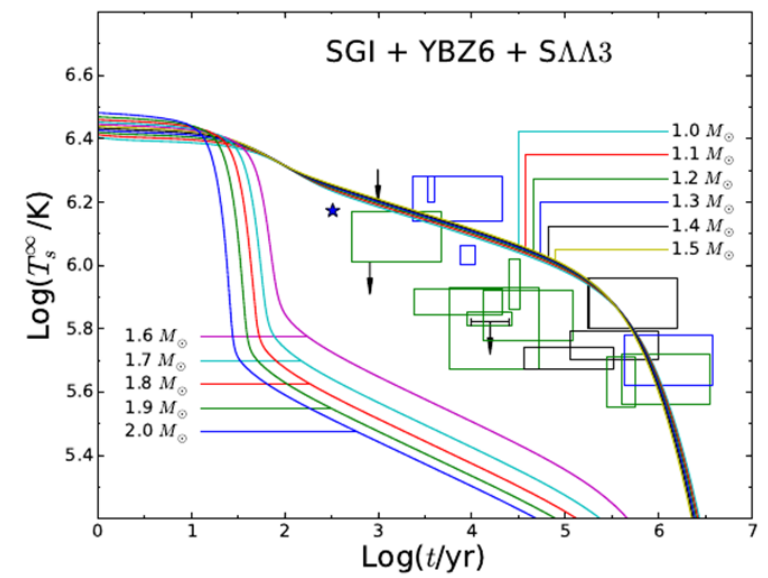
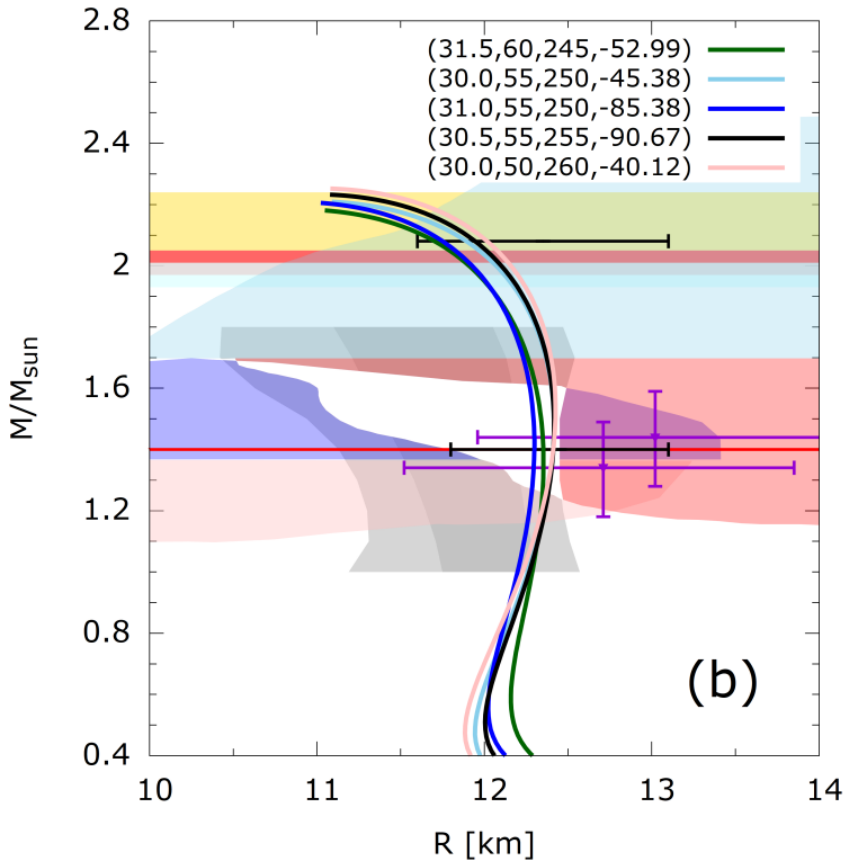
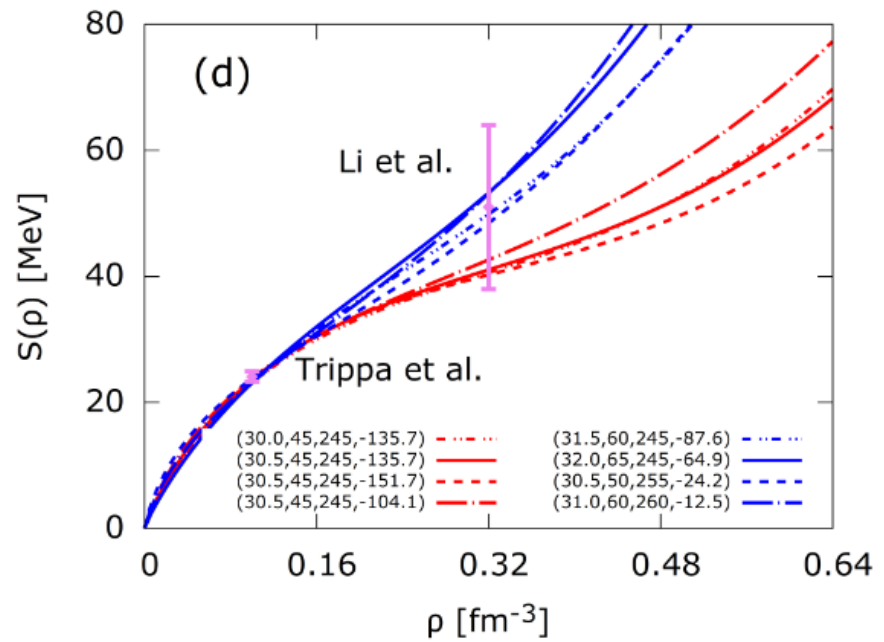


- 핵물질 상태방정식
 - SπRIT 실험 @ RIKEN
 - 270 A MeV $^{108,112,124,132}\text{Sn} + ^{112,124}\text{Sn}$
 - TPC 궤도추적 소프트웨어 (SπRITROOT) 작성
 - π^\pm , $Z=1$ 동위원소, Isoscaling 분석 완료 및 논문 출판

- 핵물질 상태방정식
 - FAZIA 실험 @ GANIL
 - 32, 52 A MeV에서 $^{58,64}\text{Ni} + ^{58,64}\text{Ni}$
 - 데이터 분석 진행 중



- 독자적인 **KIDS 에너지밀도범함수(EDF)** 모델 개발
 - 저에너지 유효장 이론을 이용하여 핵물질의 에너지밀도를 섭동 전개
 - 핵물질과 원자핵을 하나의 모형으로 정확하게 기술하는 방법 제시
 - KIDS EDF 모델을 이용하여 핵대칭에너지의 밀도의존성 연구 (arXiv:2110.09802)
 - 결과: 핵대칭에너지의 범위, 중성자별의 질량-반지름 관계, 중성자별의 냉각곡선

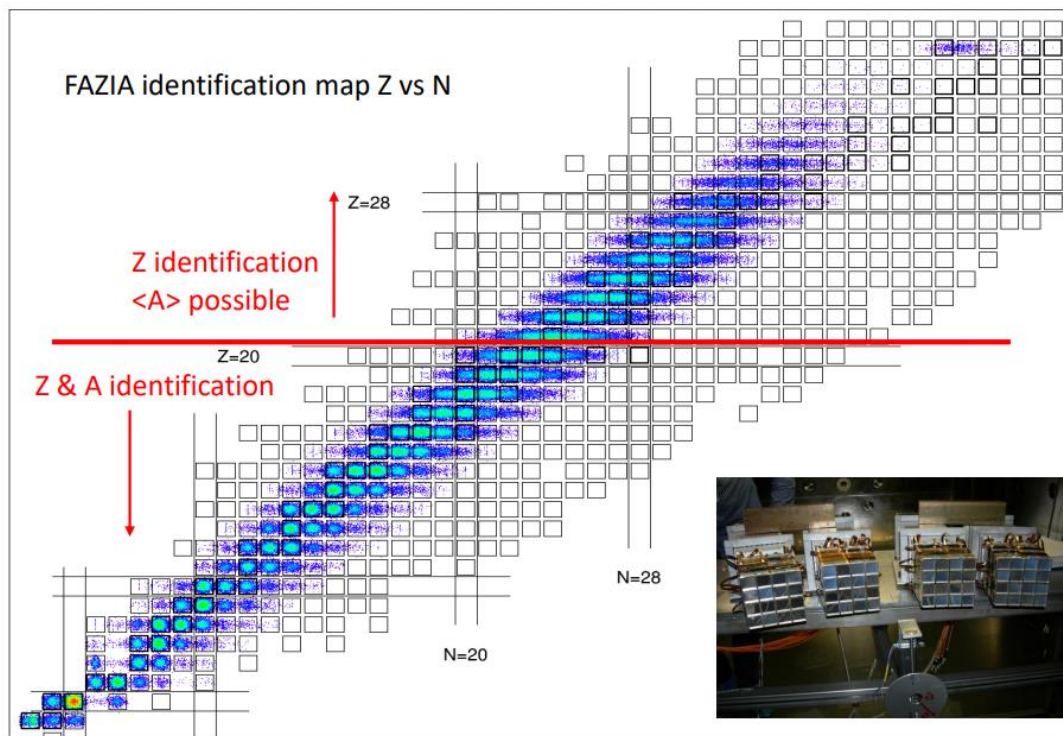


- FAZIA: A charged-particle detector for heavy-ion collisions at intermediate beam energies
- One FAZIA block consists of 16 Si₁+Si₂+CsI telescopes with a cross-sectional area of 2 X 2 cm².
- Development of new Si detectors in Korea



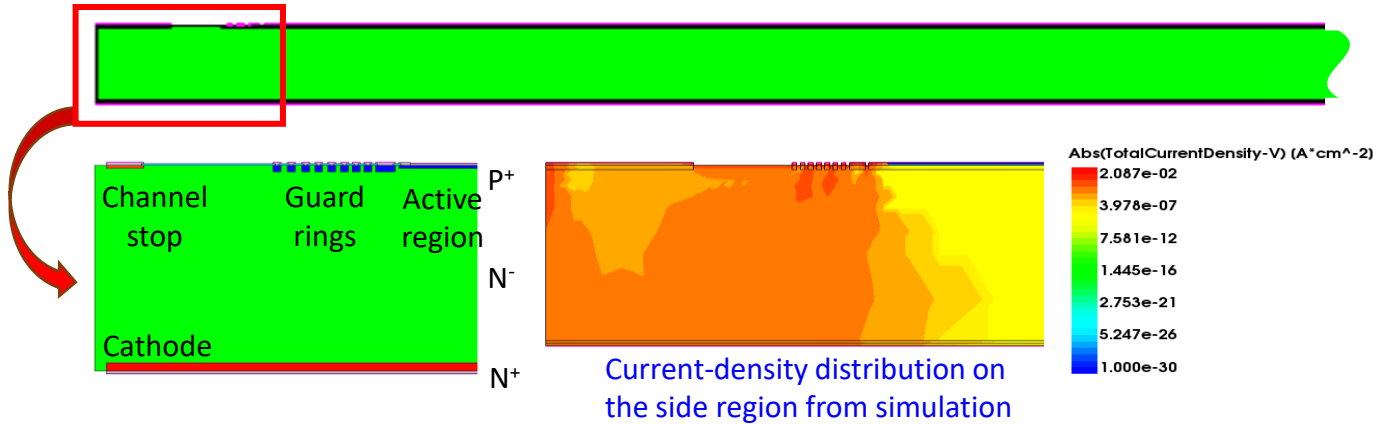
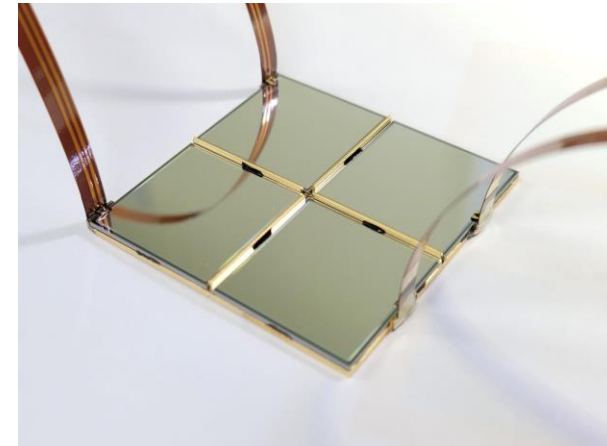
PID from ⁸⁰Kr+⁴⁰⁻⁴⁸Ca at 35 AMeV in the IsoFAZIA experiment @ LNS, Catania in 2015

New 750 μm thick Si detector modules (Processed in CiS, Germany)

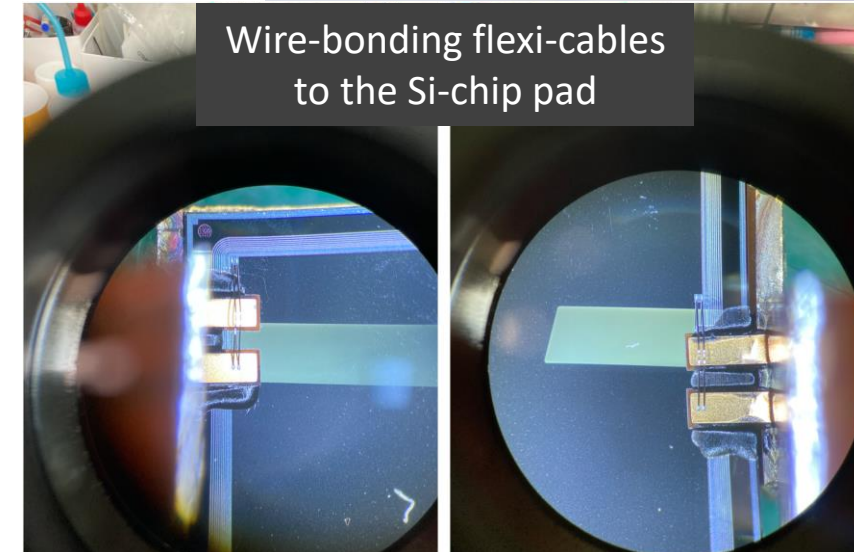


- Design and construction of the new thick Si detectors
 - The detailed structure, dimensions, and doping profiles are finalized by intense simulations.
 - Low total current, $\mathcal{O}(10 \text{ nA})$, is expected in the working-voltage range.
 - Si wafers will be processed at ETRI & NNFC in Korea.
- Development of the new FEE card
 - Original schematics were provided by the FAZIA Collaboration.
 - But several changes were applied for more effective functioning.
- The next step is to design and produce the $150 \mu\text{m}$ thick detectors.

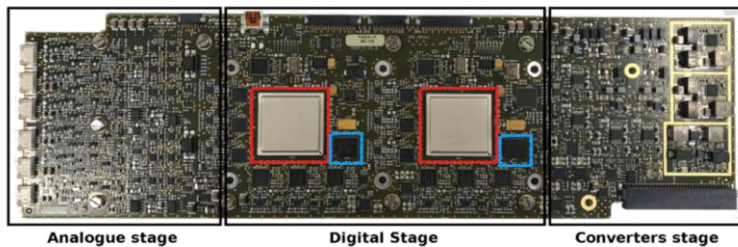
Assembly of quartetto



Wire-bonding flexi-cables to the Si-chip pad



FAZIA / FEE(Front-End Electronics) Old Card



New FEE card made in Korea



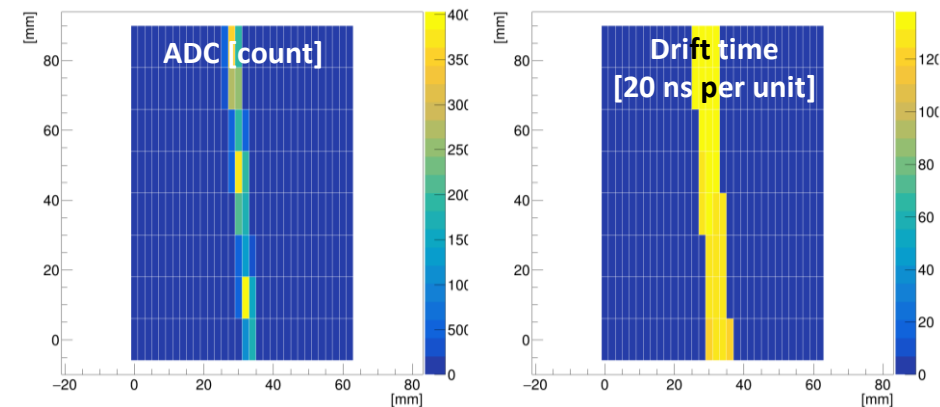
- Superconducting magnet
 - $B_{max} = 1.5$ T
 - Diameter & length of the detector space = 60 cm each
 - Conductive cooling
 - Construction done in 2019



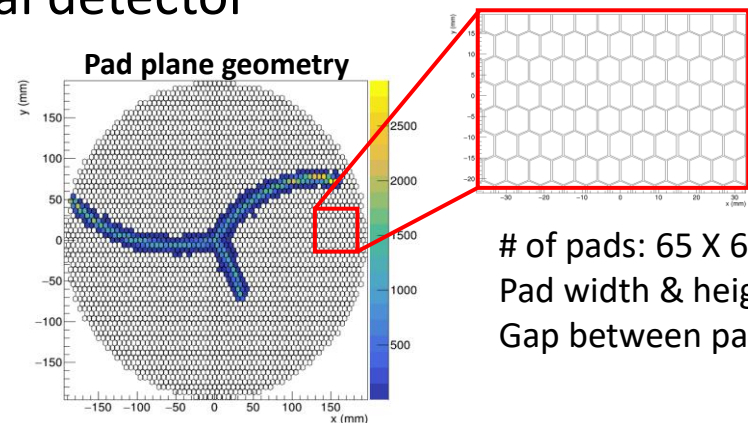
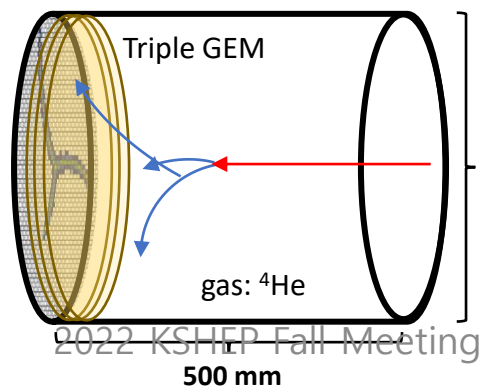
- AT-TPC: Construction of prototype
 - # of pads: $64 \times 16 = 1024$
 - Pad size: 1.9×11.9 mm² (gap between pads: 0.1 mm)
 - Performance test is on going using cosmic muons & alpha source.
 - Beam test using (α, p) reaction at CRIB is forseen in 2023.



Event display for cosmic muon events

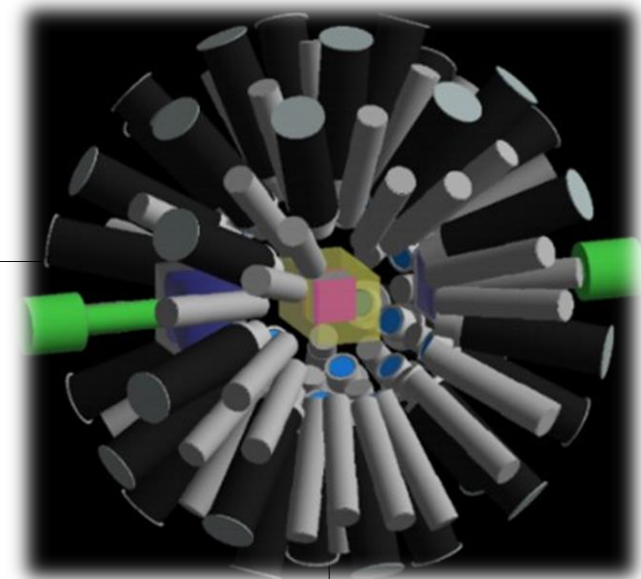
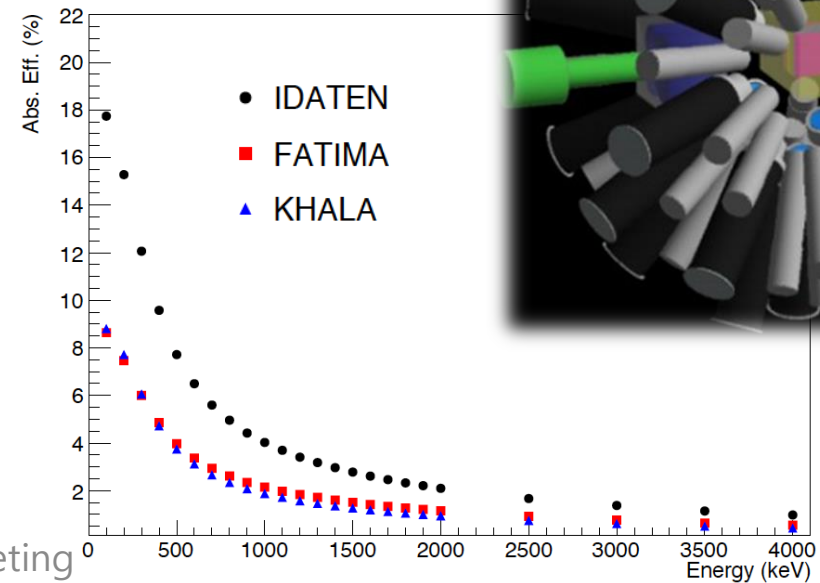
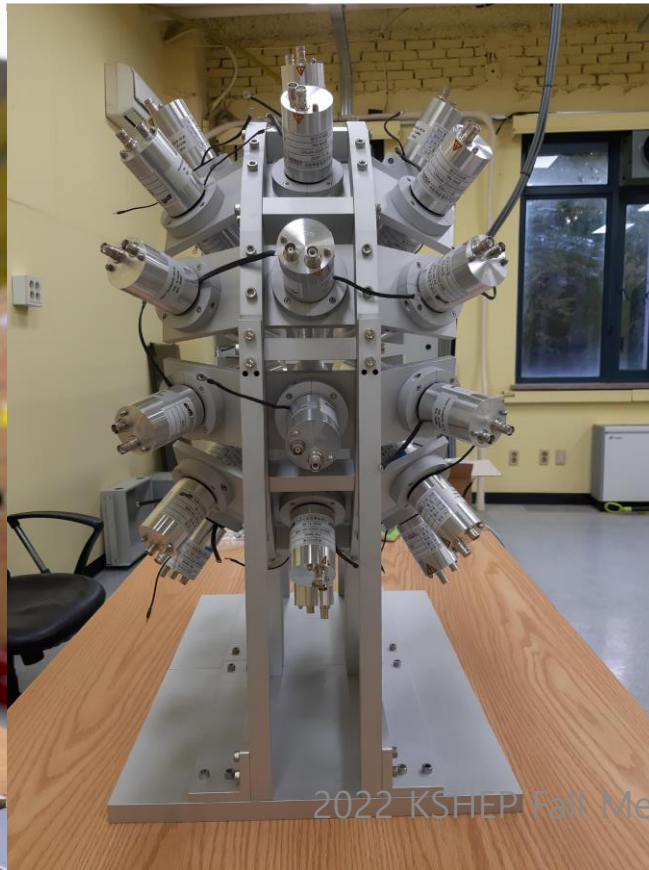


- AT-TPC: Design of real detector



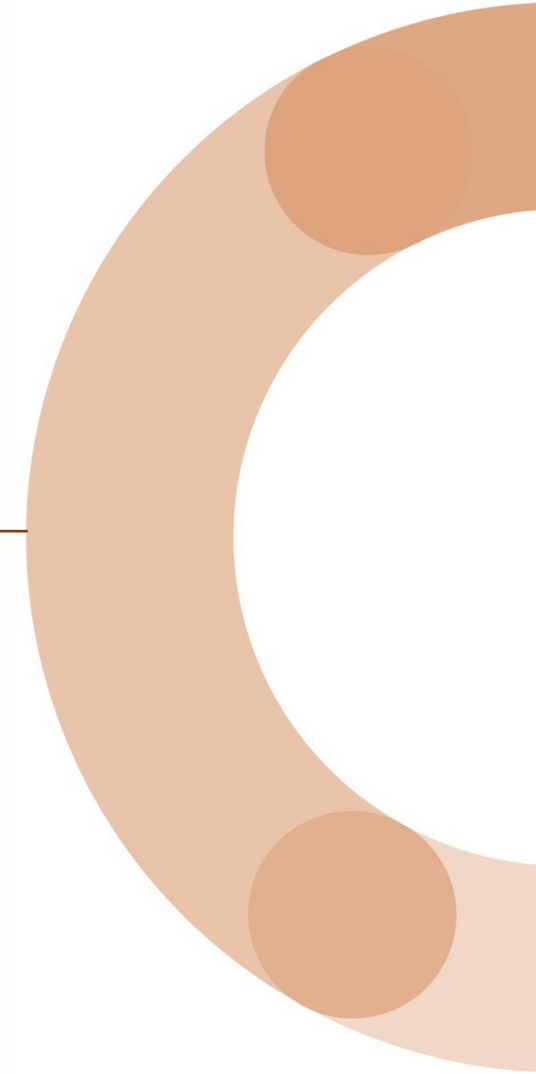
of pads: $65 \times 65 = 3,300$
 Pad width & height: 6 mm each
 Gap between pads: 0.5 mm

- KHALA: Korea High-resolution Array of LaBr₃(Ce)
- Total 36 [LaBr₃(Ce)+PMT] modules
- $R_t < 150$ ps (fast timing measurement), $R_E < 3.5\%$
- Formed IDATEN Collaboration = KHALA at CENuM + FATIMA in Europe.
 - IDATEN will perform extensive campaign experiments at RIBF in 2023.



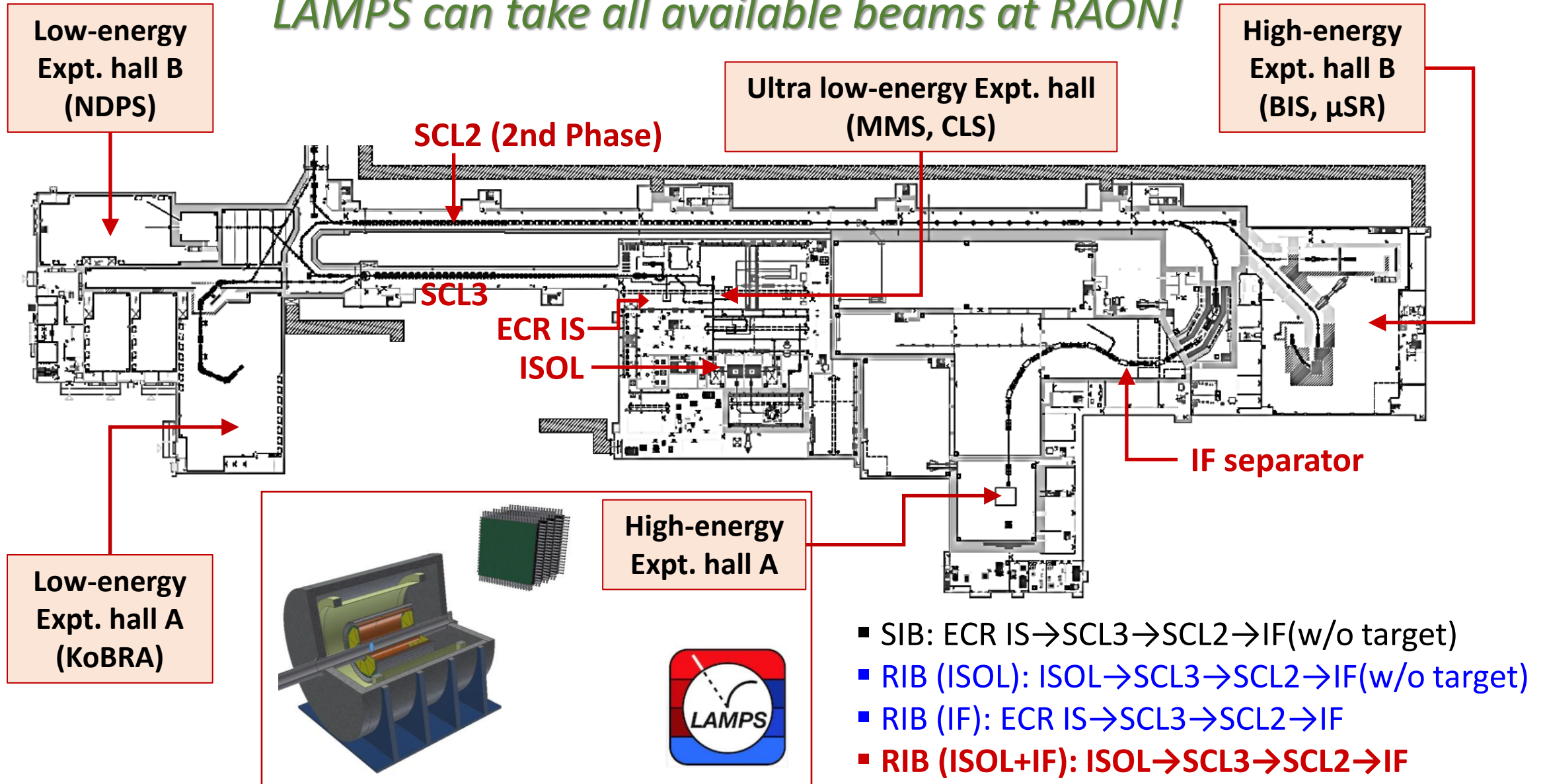
Part 3.

Preparation for LAMPS @ RAON



Uniqueness of LAMPS

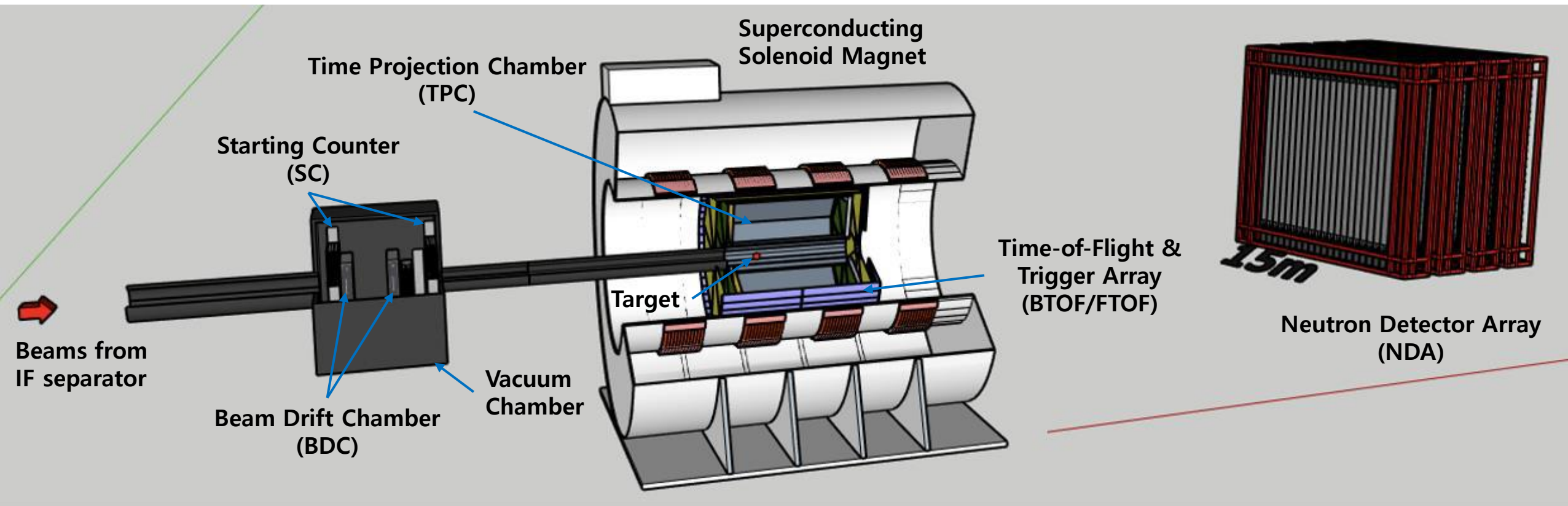
LAMPS can take all available beams at RAON!



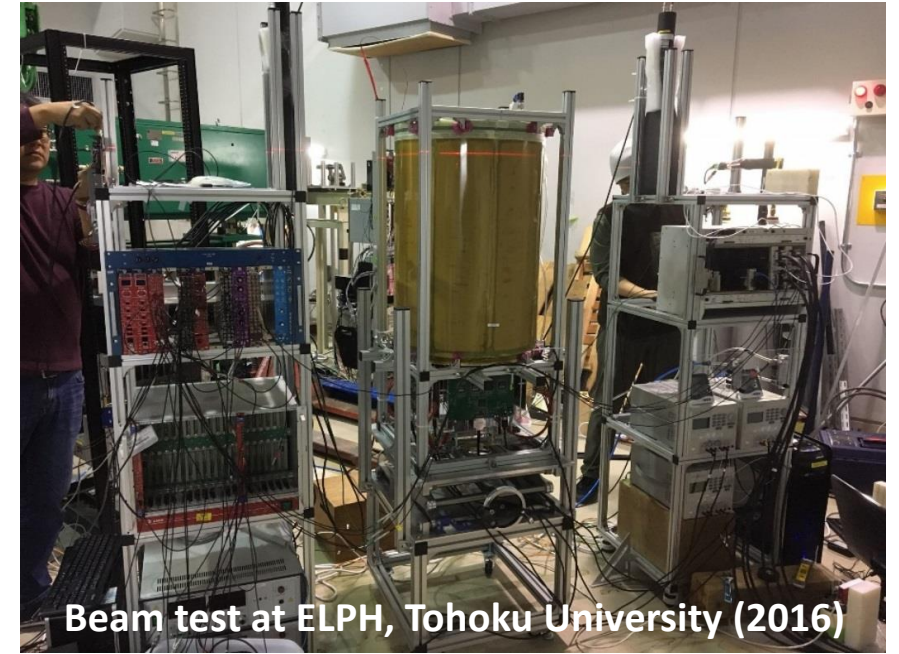
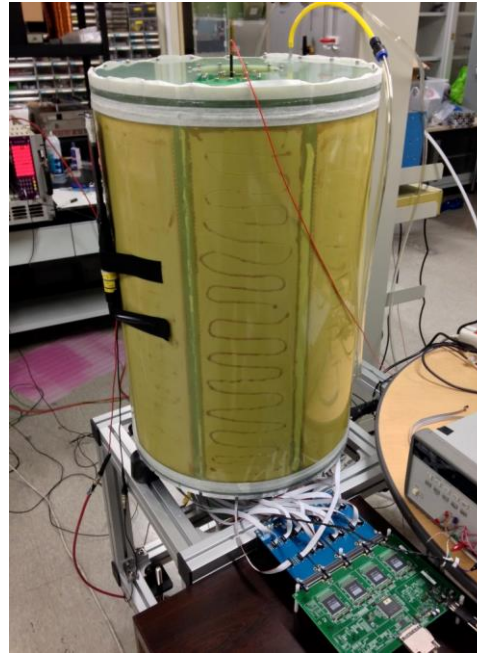
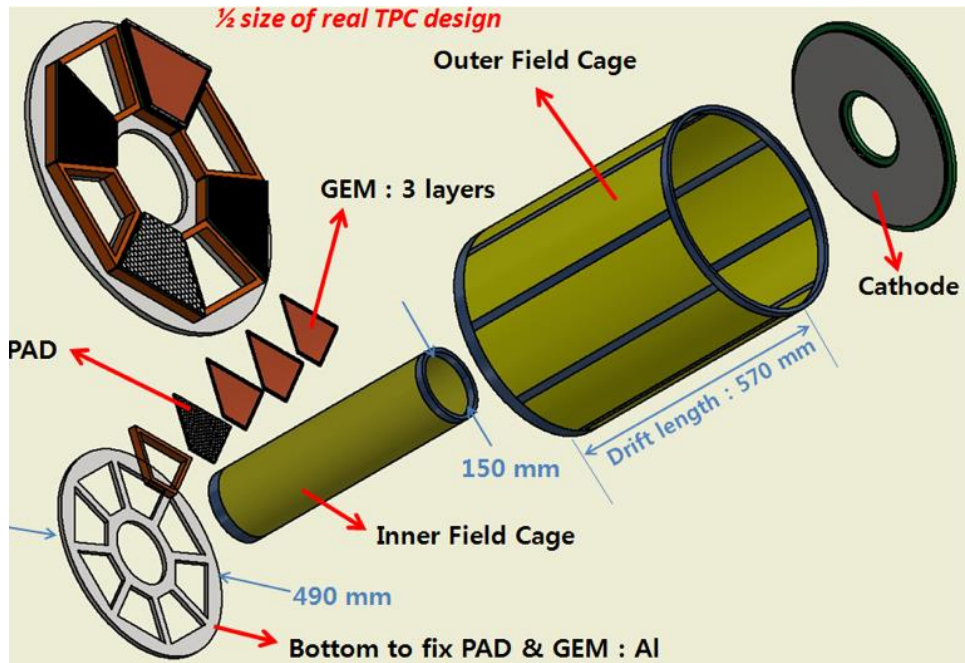
Overview of LAMPS

- **Large Acceptance Multi-Purpose Spectrometer**

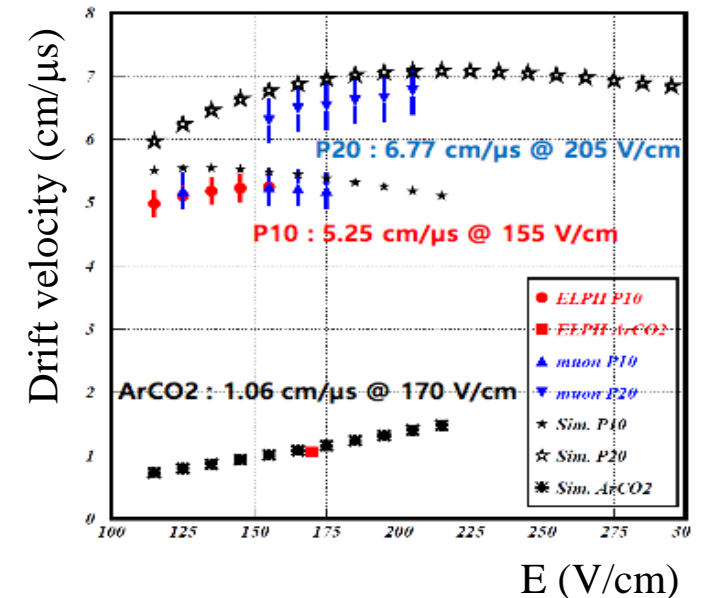
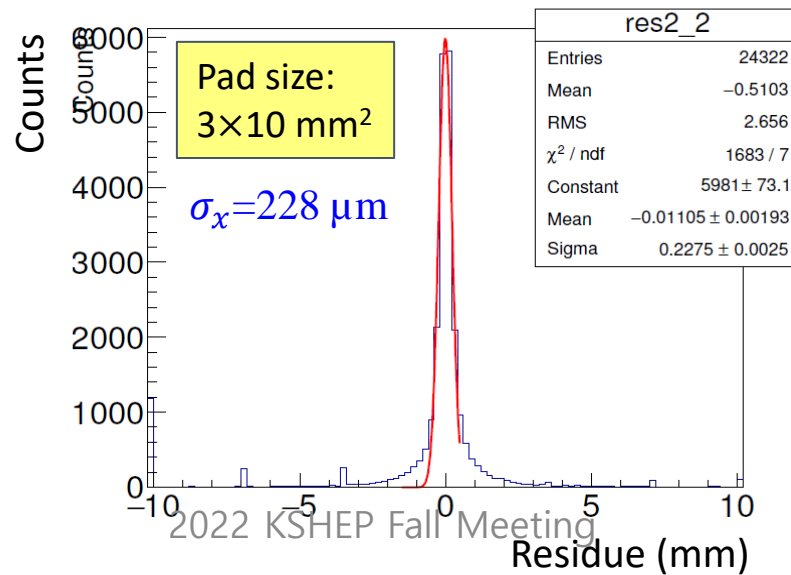
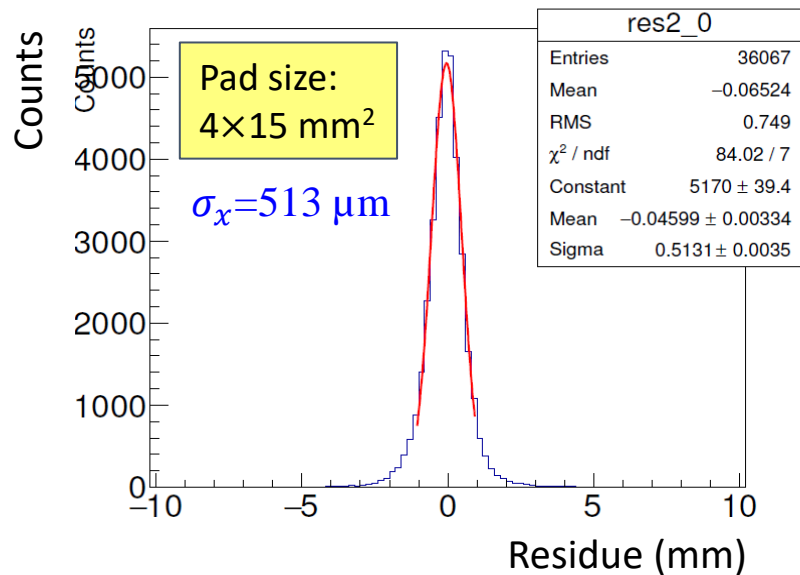
- Beam energies up to 250 MeV/u for ^{132}Sn with an intensity as large as 10^8 pps
- Comprehensive detector system to investigate the nuclear equation of state (EoS) and symmetry energy
- All detector components and magnet were already developed, manufactured, and assembled.
- Integration and commissioning of the whole LAMPS system is being planned at the end of 2022.

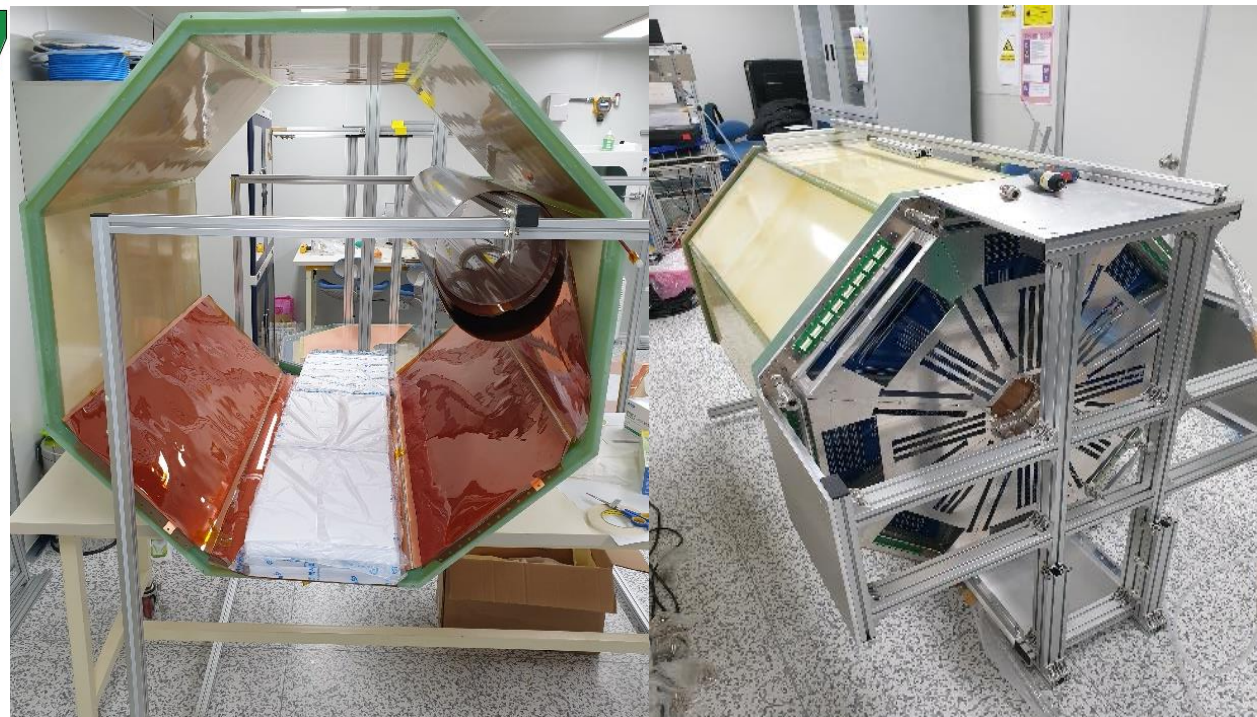
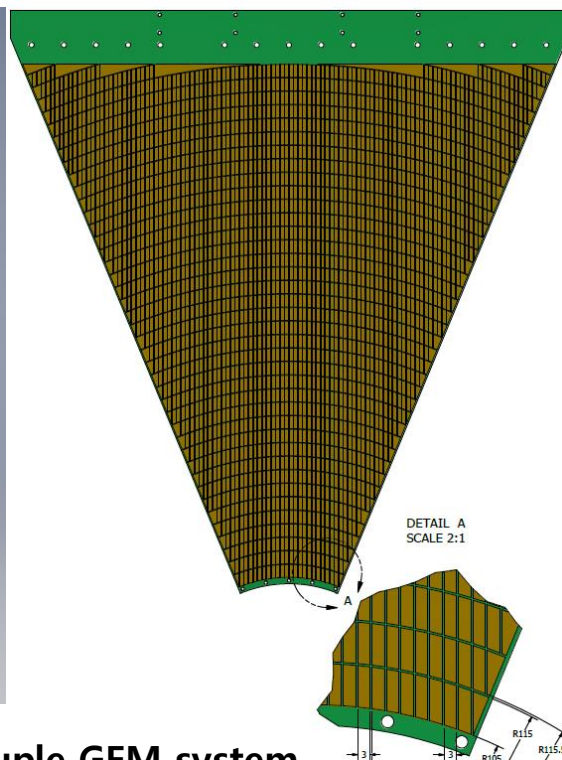
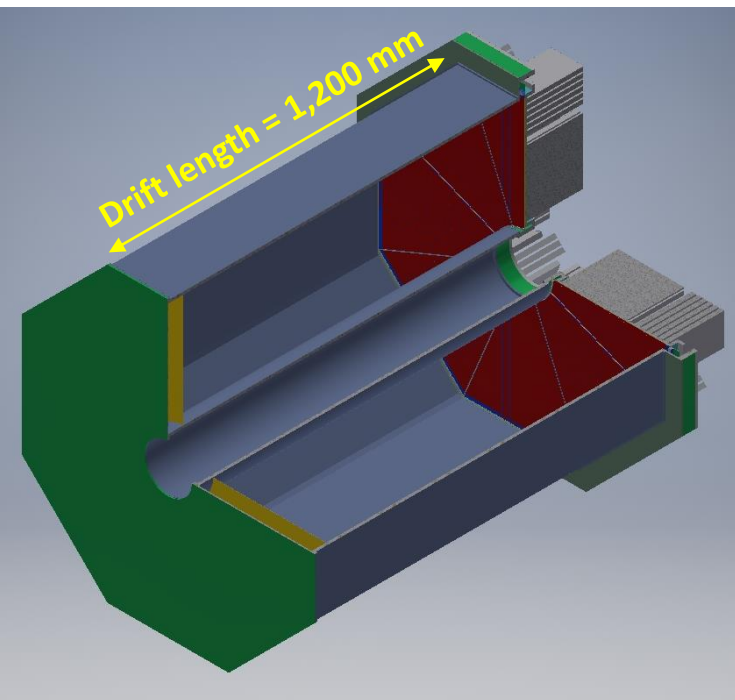


TPC: Performance test with prototype



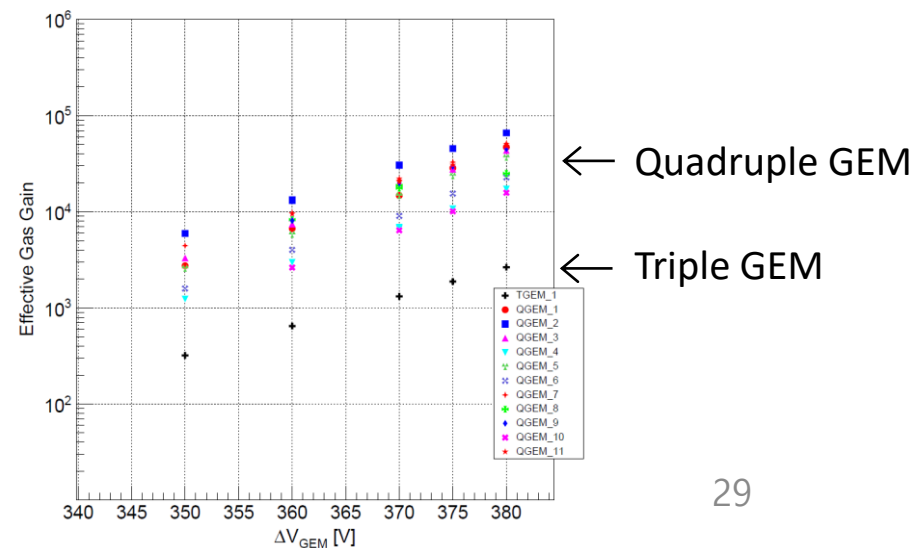
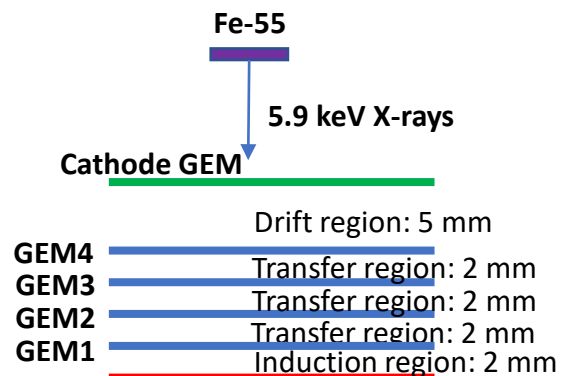
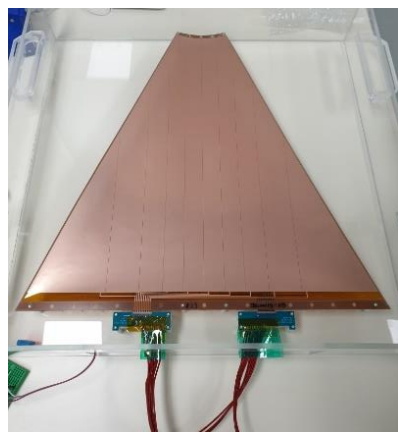
Beam test at ELPH, Tohoku University (2016)





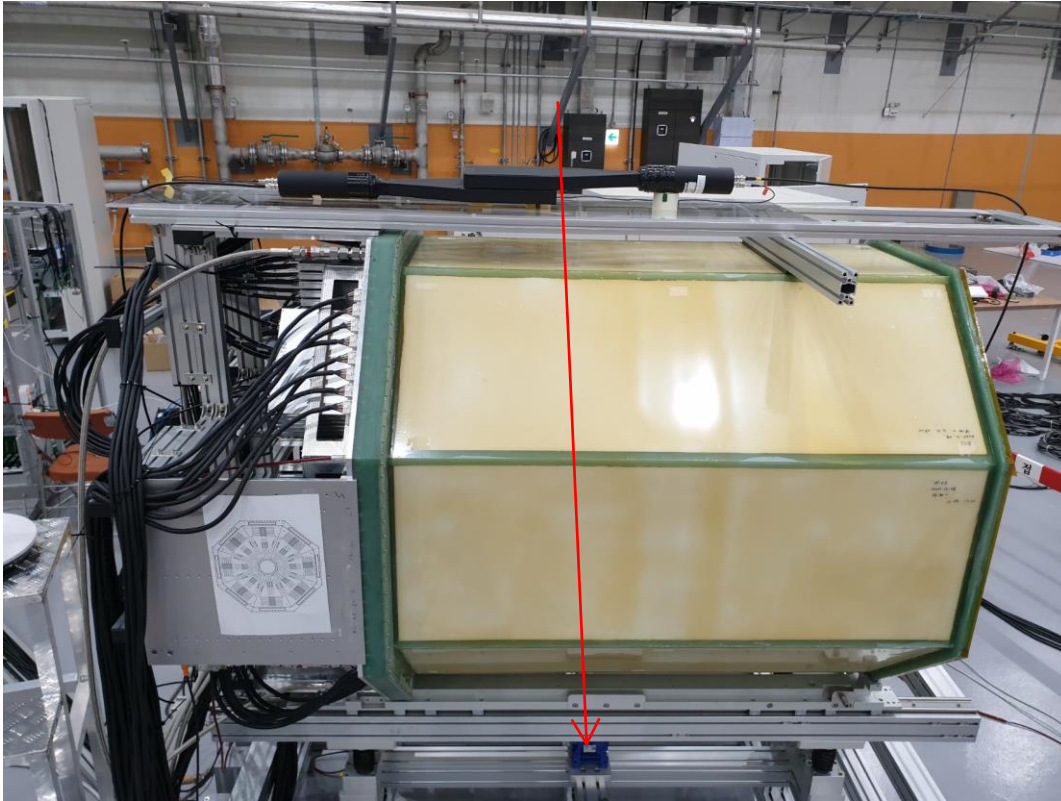
- Pad Dim.: $3 \times 10 \text{ mm}^2$
- Ch. #: 2,618/sector
× 8 sectors = 21,584
- FEE (GET electronics):
11 AsAD/sector
× 8 sectors
= 88 AsAD

Quadruple GEM system

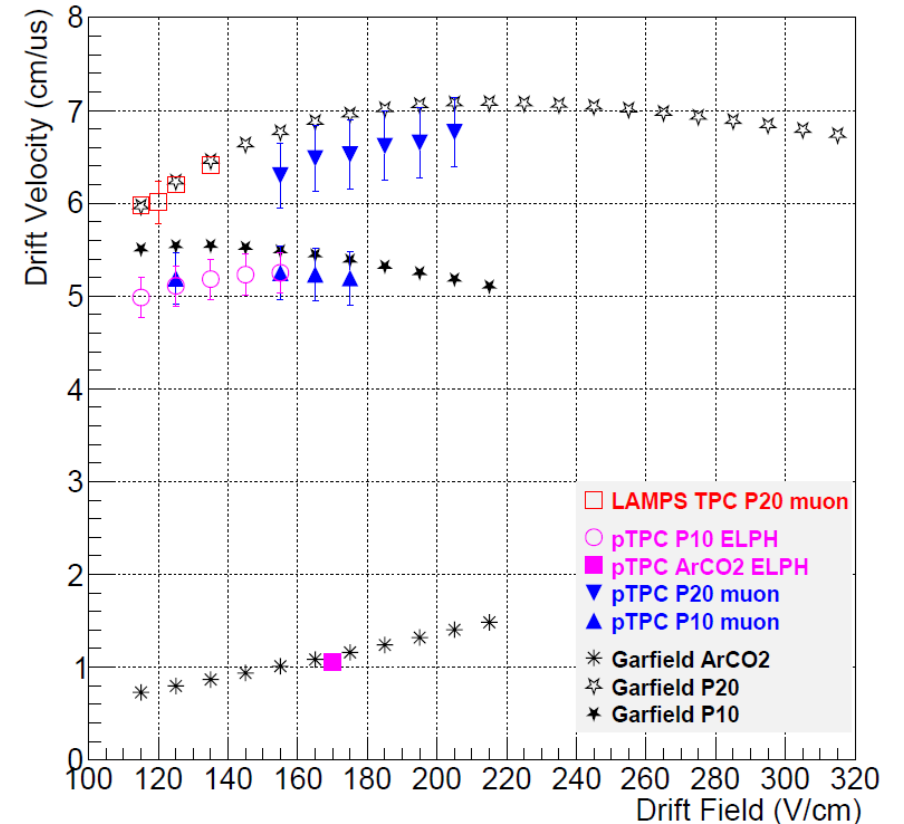


- Cosmic muon trigger

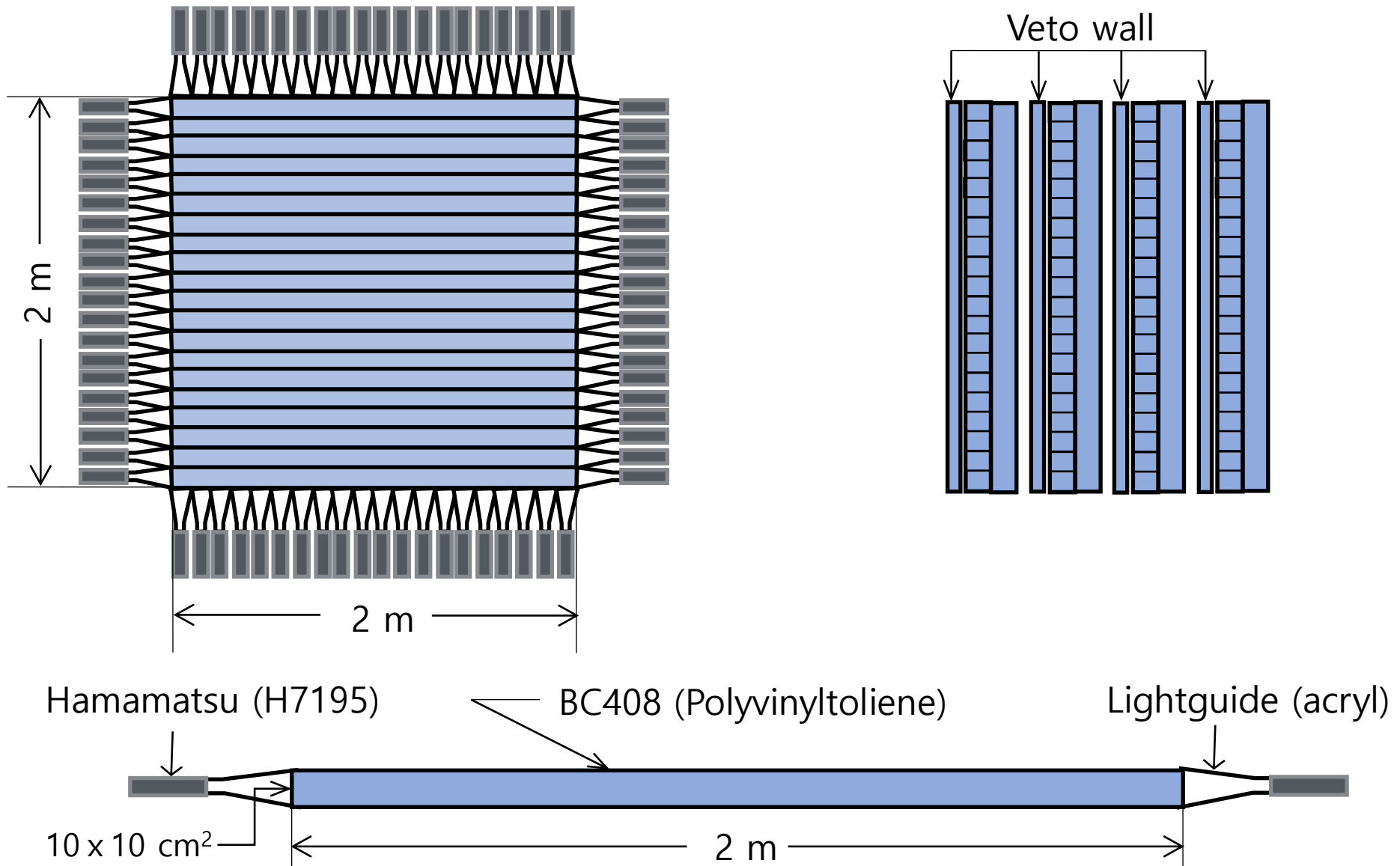
- Coincidence of two scintillators (scintillator size: 20 x 20 cm² each)
- Trigger position : 30, 60 and 90 cm
- Measured drift field points: 115, 125 and 135 V/cm



Drift velocity data (preliminary)

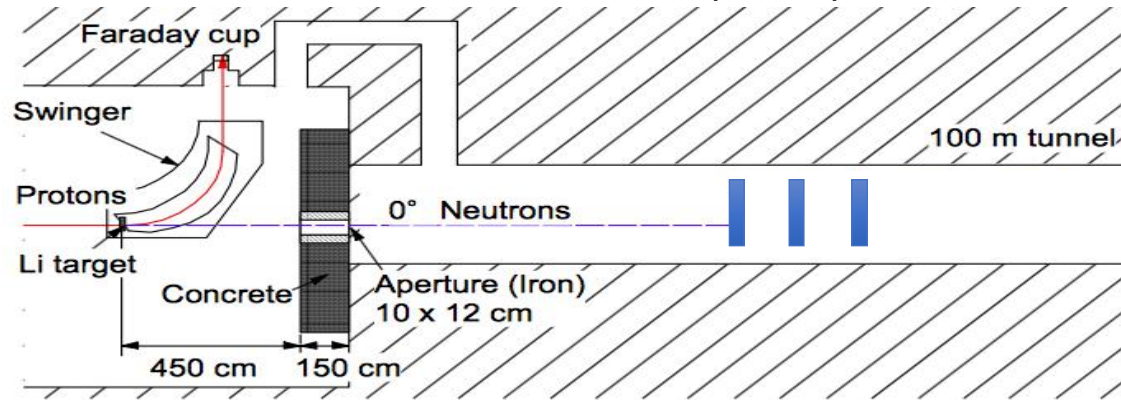


Neutron Detector Array (NDA): Structure



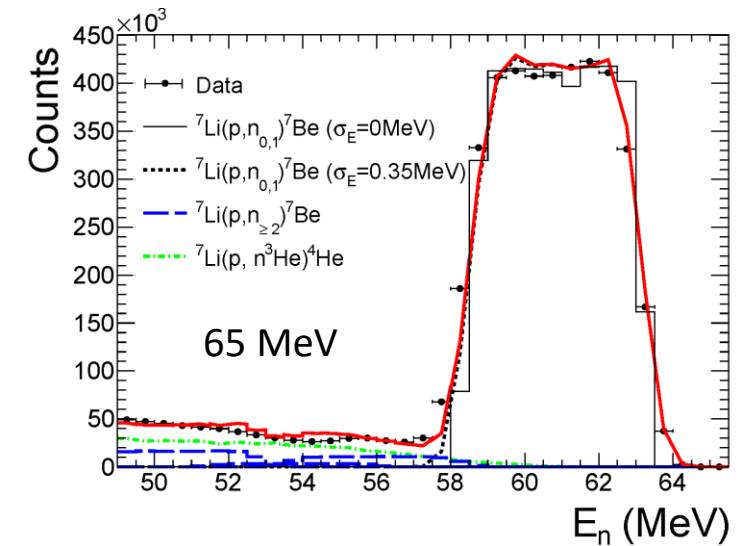
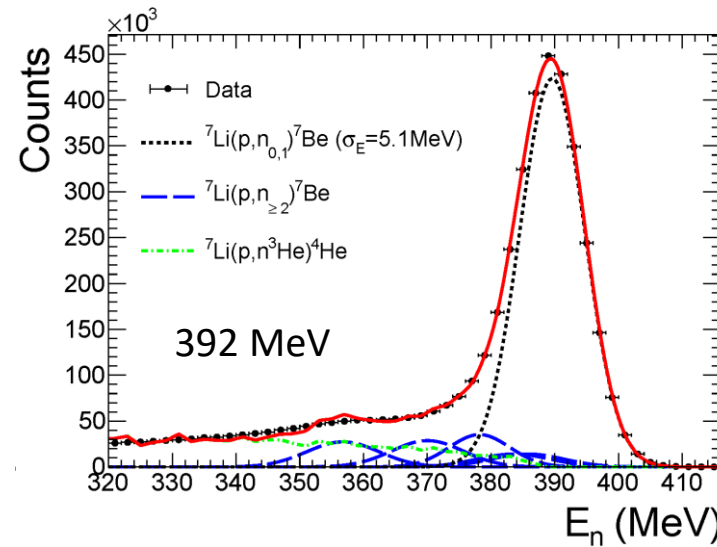
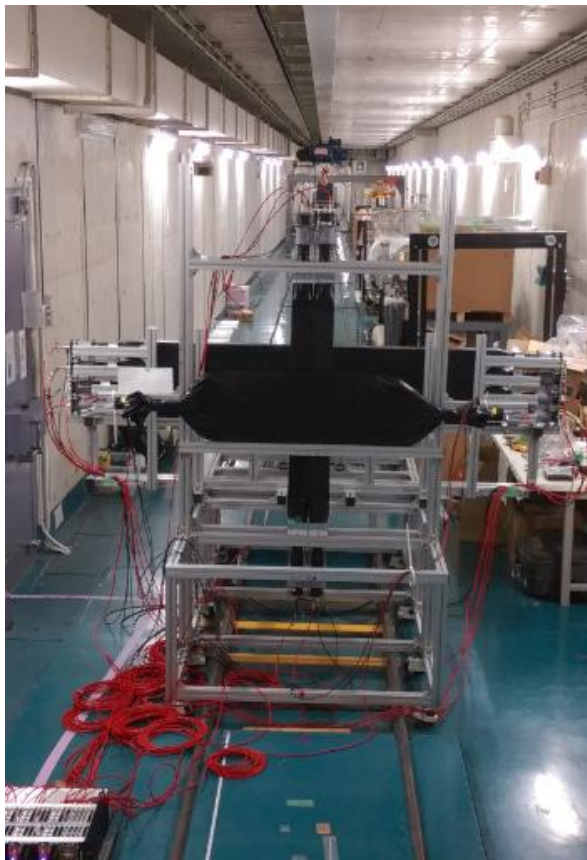
NDA: Performance test with prototype

Beam test at RCNP (2016)

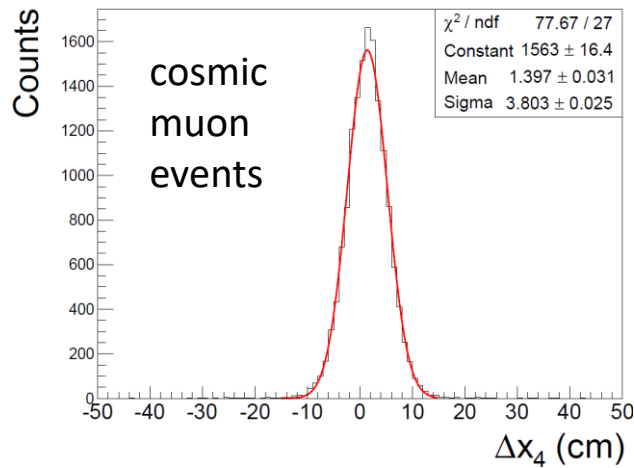


- Beam specifications

- Production reaction: $p + {}^7\text{Li} \rightarrow n + {}^7\text{Be}$
- Neutron beam flux: $1 \times 10^{10} \text{ n/sr}/\mu\text{C}$
- Neutron energy: 65 and 392 MeV
- Background neutrons above 3 MeV is $< 1\%$ [NIMA 629, 43 (2011)]



- Significant energy-loss effect in the Li target at 65 MeV
- Low-energy background dominated by the 3-body decays ${}^7\text{Li}(p, n {}^3\text{He}) {}^4\text{He}$
- Energy resolution (FWHM): 3.1% @ 392 MeV, 1.3% @ 65 MeV



← Position difference between the projected hit position and the detected hit position for cosmic muons: $\Delta x_4 \equiv x_{D4,proj} - x_{D4,hit}$

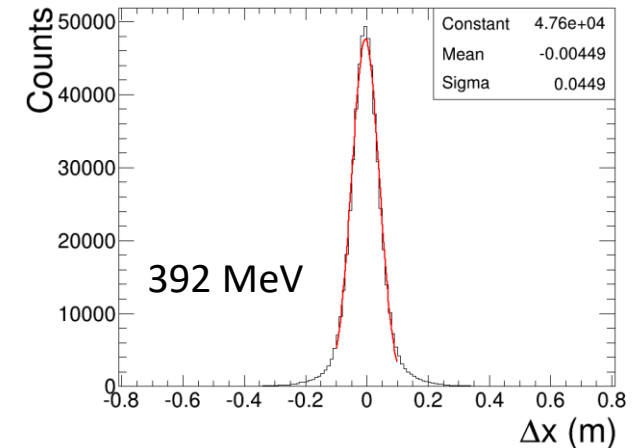
← Relative position resolution for cosmic muons for one bar:

$$\sigma_x = \frac{\sigma(\Delta x_4)}{1.87} = 2.0 \text{ cm}: R_x(\mu) = 4.8 \text{ cm (FWHM)}$$

→ Hit position difference between neighboring scintillators for neutrons with simultaneous hits: $\Delta x_{S1} \equiv x_{D1} - x_{D2}$ for 10 MeV threshold and $\delta t < 3 \text{ ns}$

→ Relative position resolution for neutrons for one bar:

$$\sigma_n = \frac{\sigma(\Delta x_{S1})}{\sqrt{2}} = 4.5 \text{ cm}: R_x(n) = 7.5 \text{ cm (FWHM)}$$



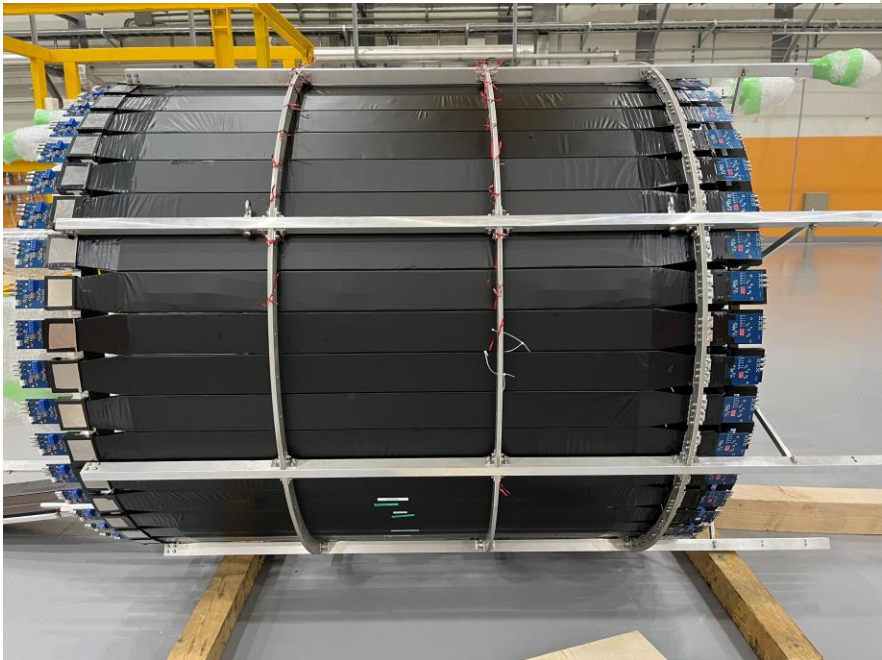
Comparison of performances by cosmic rays for similar configuration of neutron detectors [NIMA 927, 280 (2019)]

	LAMPS (this work)	MoNA [13]	NEBULAR [14]	LAND [15]
Dimensions (cm ³)	10 × 10 × 200	10 × 10 × 200	12 × 12 × 180	10 × 10 × 200
Time resolution (ps)	309	423	376	588
Position resolution (cm)	4.8	5.2	6.1	7.1

- Installation of all modules in the frame was completed at the Sejong campus of Korea University in Dec. 2018 to test the performance.
- The whole system was disassembled and transported to the RAON site in Sindong in March and assembled again with the three additional veto walls in September in 2022.
- The fully assembled system will take the cosmic muon data at the RAON site very soon.

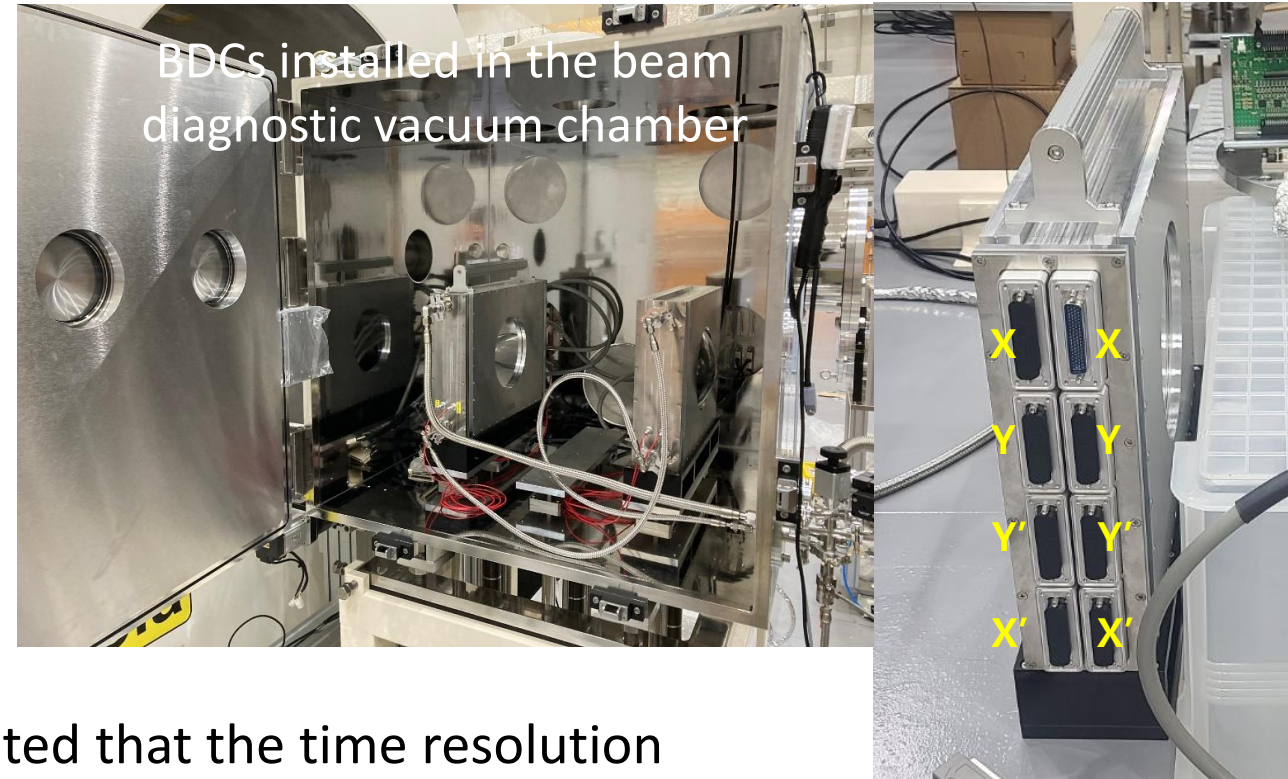
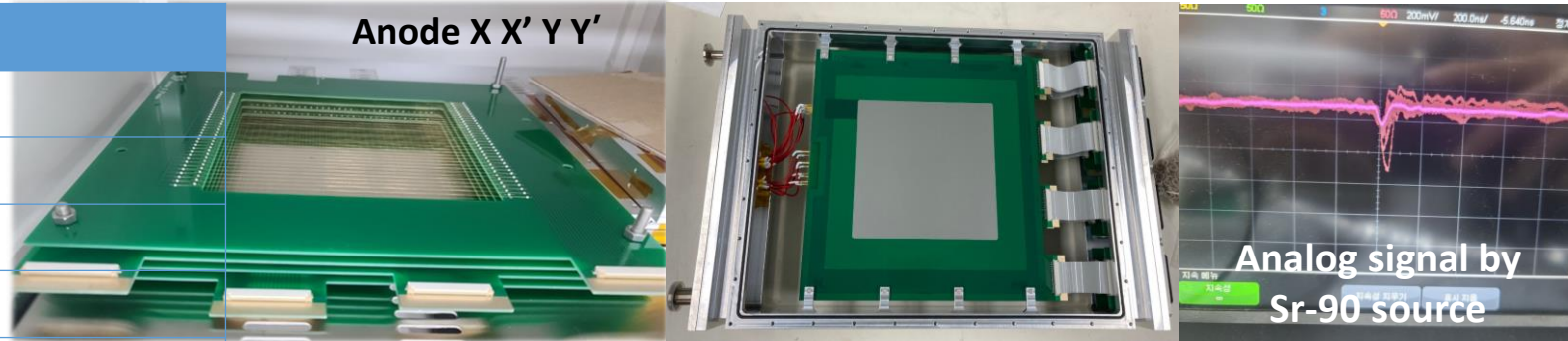


- Number of scintillators & dimensions:
 - BTOF: (48) 1500 X 90 X 10 mm³ each
 - FTOF: (48) 500 X (90, 24) X 5 mm³ each
- MPPC readout from both ends
- Installation completed in 2022
- The performance test with cosmic muons is in progress.



Beam Drift Chamber (BDC)

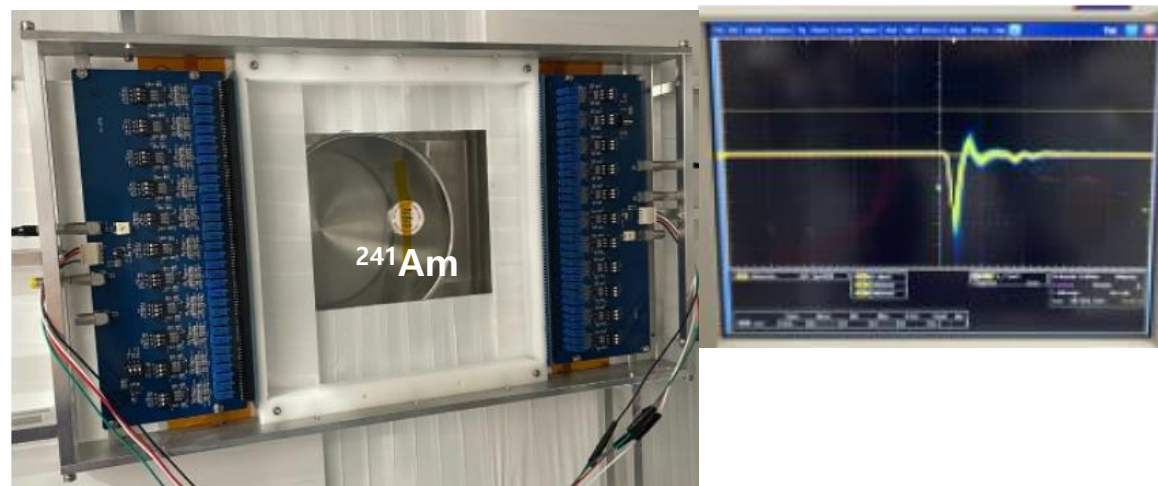
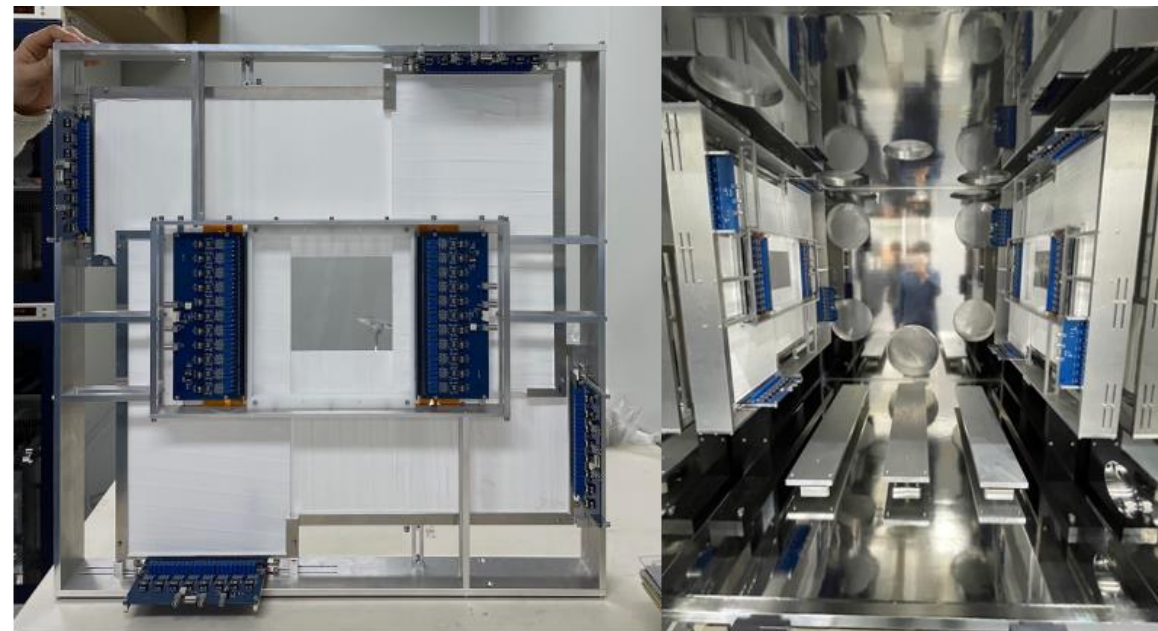
Parameter	Value
Anode wire	ϕ 20 μm Au-W
Potential wire	ϕ 80 μm Cu-Be or Au-W
Cathode	2 μm -thick Al-mylar, 9 layers
Cell size	5 mm (max. drift length 2.5 mm)
Active area	170 x 170 mm ²
Anode configuration	XX'YY'XX'YY', 8 layers
Number of channel	256 (32 wires/plane, 8 planes)
Operation gas	i-C ₄ H ₁₀ below 1 atm P10 (Ar 90% + CH ₄ 10%) at 1 atm
High voltage	2 channels for cathode & potential wires
Readout	ASD(RP-2125)+TDC(V1190A)+QDC(V792)
Body dimension	490(L) x 360(H) x 100(W) mm ³
Beam window (variable)	12 μm Al-mylar (up to 20 kPa) 50 μm Al-mylar (up to 50 kPa)



- HV & vacuum tests completed
- Preliminary results with source demonstrated that the time resolution was about 80 ps in σ (Goal: 100 ps).

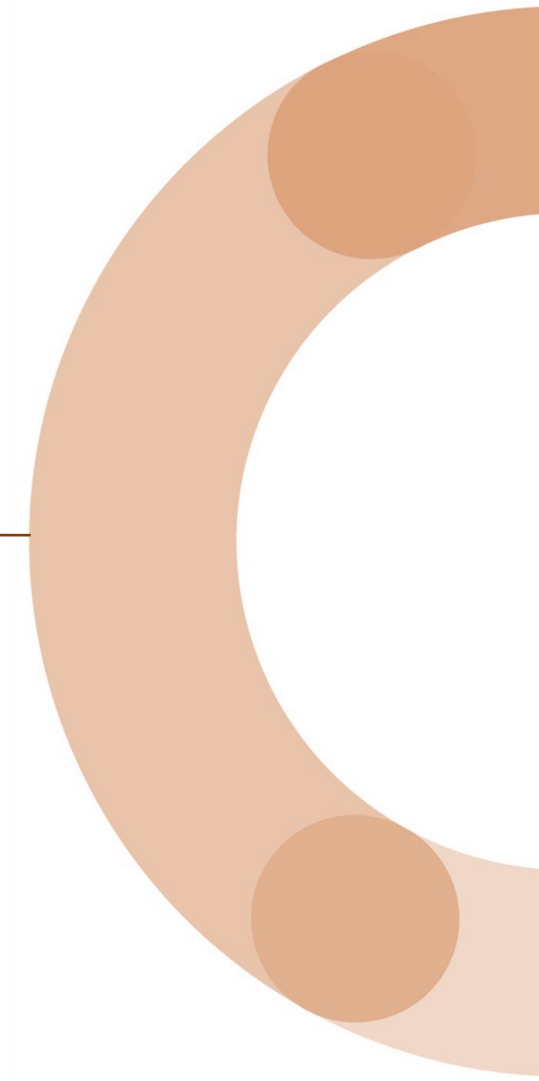
Starting Counter (SC)

- Primary function
 - Providing an accurate reference time ($\sigma_t \lesssim 100$ ps) for entire experiment when actual beams arrive.
- Structure & dimensions
 - Two sets of (1 SC + 4 Veto counters)
 - SC: 210 X 210 X 0.2 mm³ (Active area: 200 X 200 mm²)
 - Veto: 410 X 210 X 5 mm³ (Adjustable area)
- Material
 - SC & Veto: EJ-230 polytoluene-based scintillator
 - Lights collected by MPPC on a sensor board
 - 2 sensor boards on a SC scintillator & 1 board for Veto
 - 33 MPPCs on a sensor board for SC & 24 MPPCs for Veto
- Electronics
 - Conventional CAEN TDC, QDC for the time and charge information
- Installation & α source (²⁴¹Am) test
 - Full system installed in the vacuum chamber
 - $\sigma_t \sim 130$ ps \rightarrow Using two SC's, ~ 92 ps is achievable.



Part 4.

Summary



- Center for Extreme Nuclear Matters (CENuM)
 - SRC research center dedicated to study the nuclear-matter from the low-energy RIB collisions to the high-energy heavy-ion collisions at LHC.
 - Main research topics
 - Exploring the nuclear phase diagram
 - Understanding the non-perturbative (high-density and/or low-energy) QCD
 - Physics is closely connected to the evolution of the Universe and the various astrophysical objects like neutron stars.

- Potential Collaboration with high-energy physics and the astrophysics groups
 - Detector development
 - Theoretical development
 - Physics idea and analysis

- *We are looking forward to fruitful Collaboration within KSHEP in the future!*