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ICEN 2026

Collective flow & symmetry potential in Xe+Sn at 100 MeV/u

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Contents

Part 1.

Motivation:
Nuclear equation of state, symmetry energy, and effective nucleon mass

Motivation: Equation of State

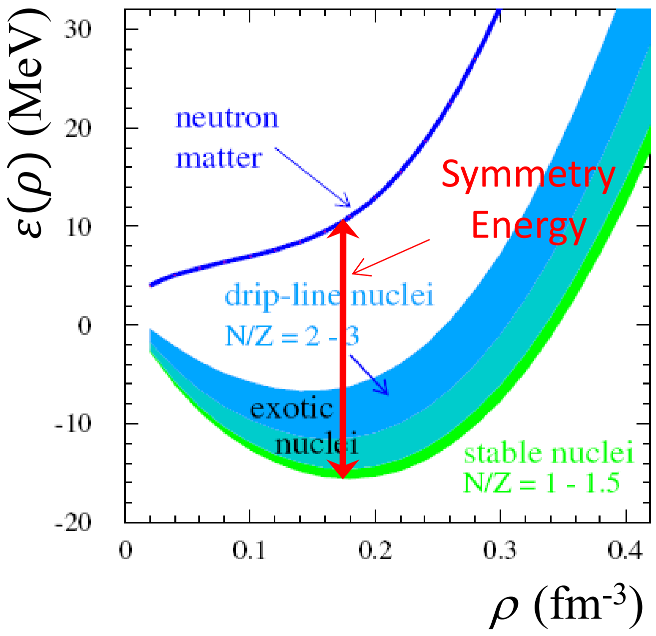
- Equation of state (EoS) & symmetry energy E_{sym} of nuclear matter $[\delta = (N-Z)/(N+Z)]$:

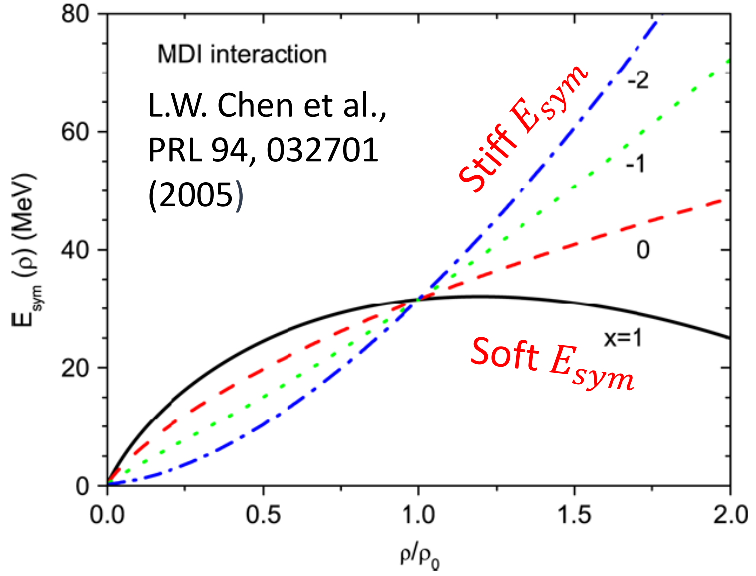
$$E/A = \varepsilon(\rho,\delta) = \varepsilon(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4) + \cdots$$

$$E_{sym}(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

$$L = \frac{3}{\rho_0}P_{sym} = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial\rho}\bigg|_{\rho=\rho_0},\ K_{sym} = 9{\rho_0}^2\frac{\partial^2 E_{sym}(\rho)}{\partial\rho^2}\bigg|_{\rho=\rho_0}$$

- Theoretical approach
  - Estimate of $\varepsilon(\rho,\delta)$ by using some density functionals or variational calculations
- Experimental approach
  - Constrain EoS & E_{sym} with the controlled laboratory experiments at specific densities, which is largely determined by the beam energy and less effectively by the system size





Motivation: Symmetry Energy

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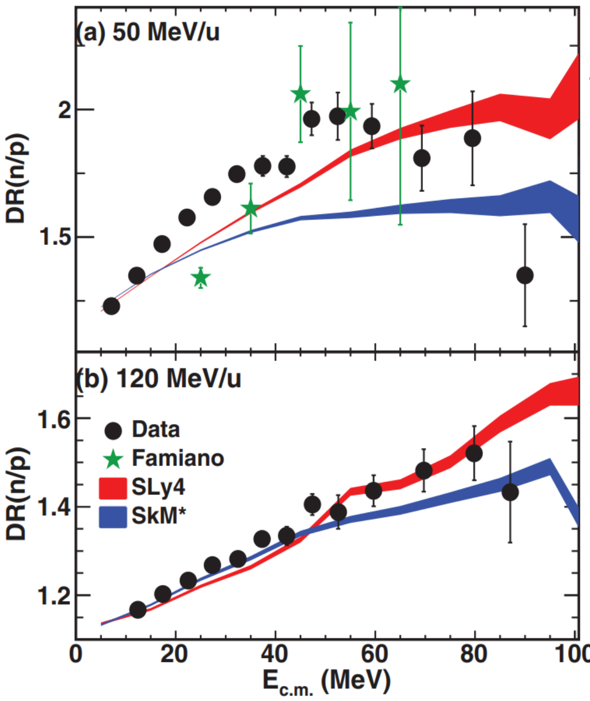
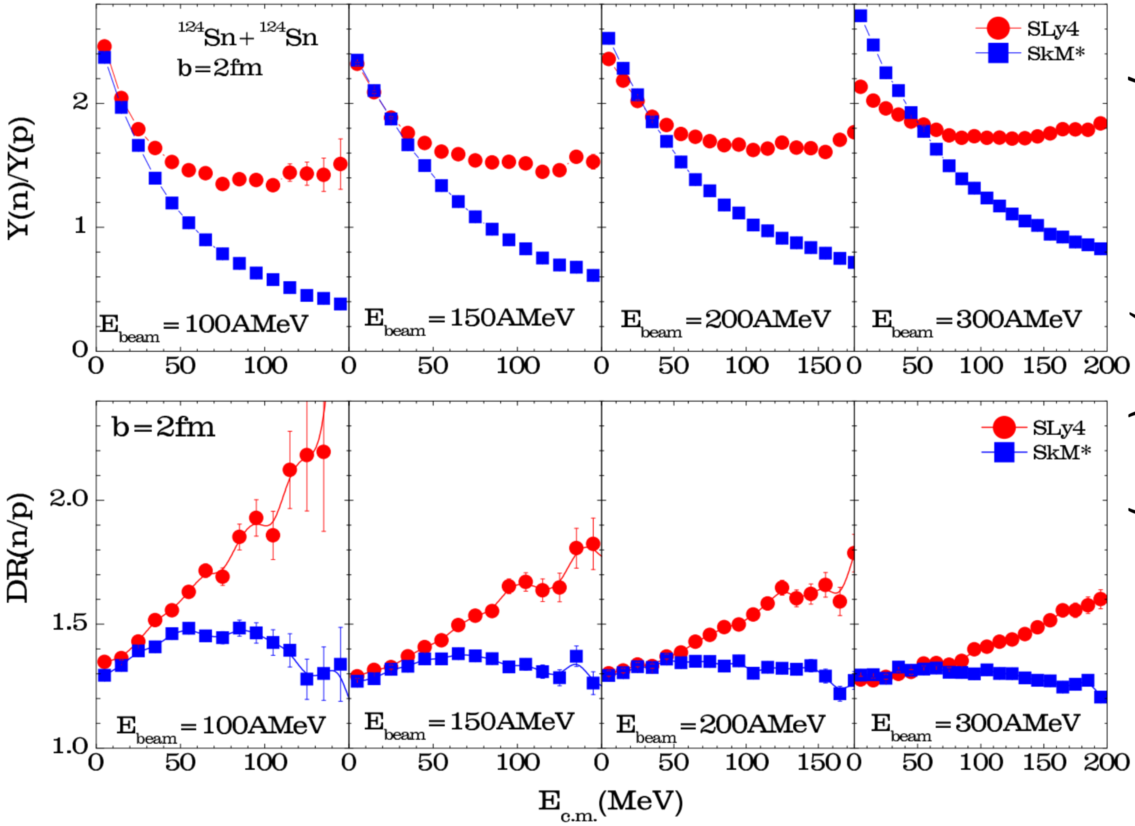
INDRA FAZIA

- One of major uncertainties for $E_{sym}(\rho)$
  - Momentum dependent symmetry potential: Effective masses of neutrons and protons (*see next page*)
- Model comparison
  - ImQMD (Y. Zhang & J. Yang, et al.)
  - Two parameter sets SLy4 & SkM*
    - Previously used for particle ratios

Parameter set	ρ_0	E_0	K_0	S_0	L	K_{sym}	m^*/m	m_n^*/m	m_p^*/m	
SLy4	0.16	-15.97	230	32	46	-120	0.69	0.68	0.71	$m_n^* < m_p^*$
SkM*	0.16	-15.77	217	30	46	-156	0.79	0.82	0.76	$m_n^* > m_p^*$



D.D.S. Coupland et al., Phys. Rev. C 94, 011601(R) (2016)



Y. Zhang et al., Phys. Lett. B 732, 186 (2014)

Motivation: Effective mass

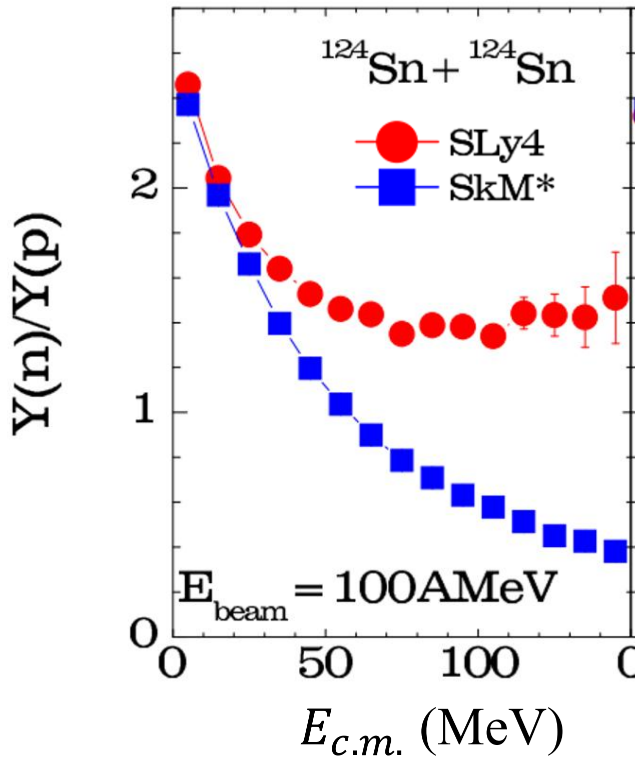
Y. Zhang et al., Phys. Lett. B 732, 186 (2014)
Z. Chajecki's presentation in NuSYM25

- Symmetry potential

$$U_{sym}(\rho(\vec{r}),\vec{p},\delta) = \left(\frac{1}{2m^*}-\frac{1}{2m}\right)p^2 + U_{sym}(\rho(\vec{r}),0,\delta)$$

- Effective mass describes how the potential energy depends on momentum: $m^* = \frac{m}{1+\frac{m}{p}\left(\frac{\partial U_{sym}}{\partial p}\right)}$

- In asymmetric matter, the potentials that neutrons and protons feel are expected to be different: (effective mass splitting) $\Delta m^*_{np} = \frac{m^*_n - m^*_p}{m_N}$



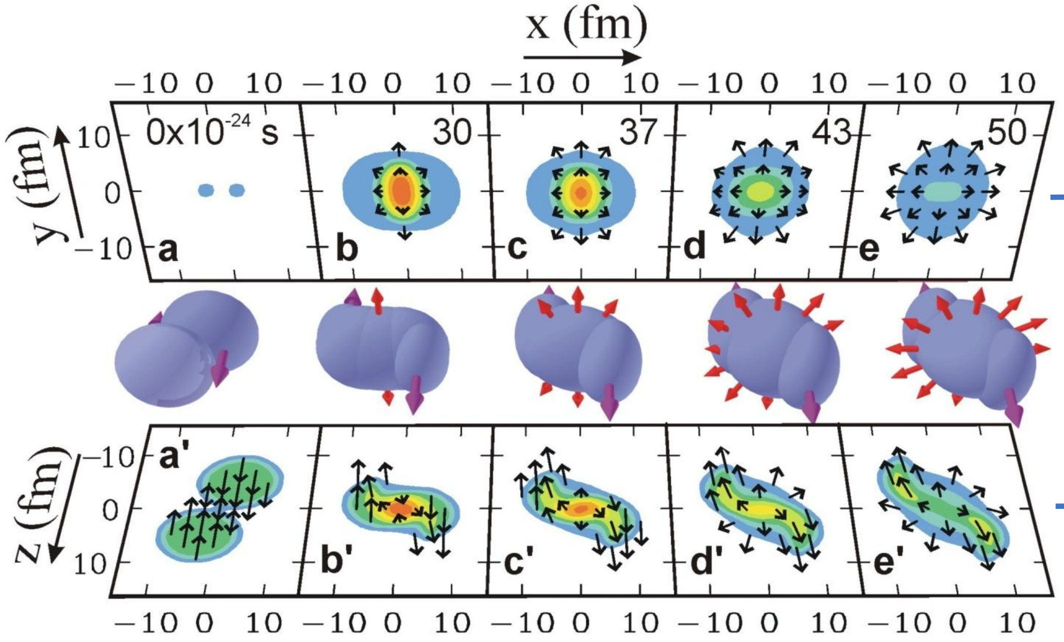
$(m^*_n < m^*_p)$ more neutrons accelerated to high energies

$(m^*_p < m^*_n)$ more protons accelerated to high energies

- The purpose of this work
  - We want to use the collective flow observables instead of the n/p yield ratios.
  - Learn whether the directed and elliptic flow observables are sensitive to possible splitting of the effective masses of protons and neutrons. (Check consistency with the YR and DR results.)
  - Learn whether the collective flow results for different particle species are consistent.
  - Understand if the effects of secondary decays (by GEMINI++) are important.

Motivation: Collective flow

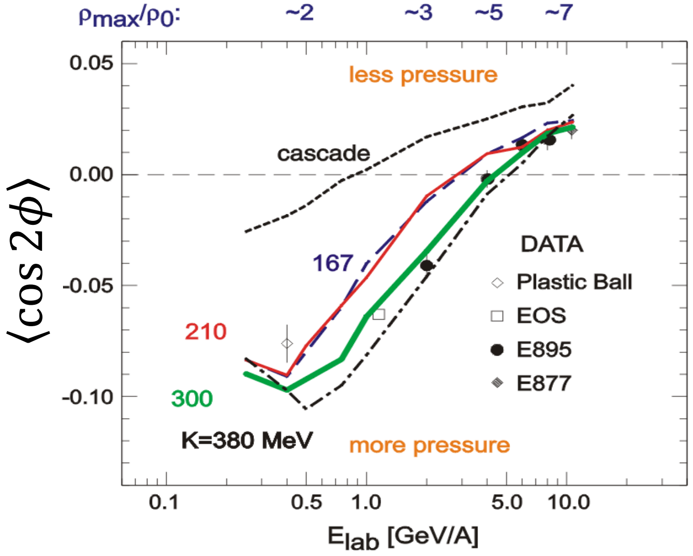
Figure adopted from Danielewicz et al., Science 298,1592 (2002)



elliptic flow or squeeze out

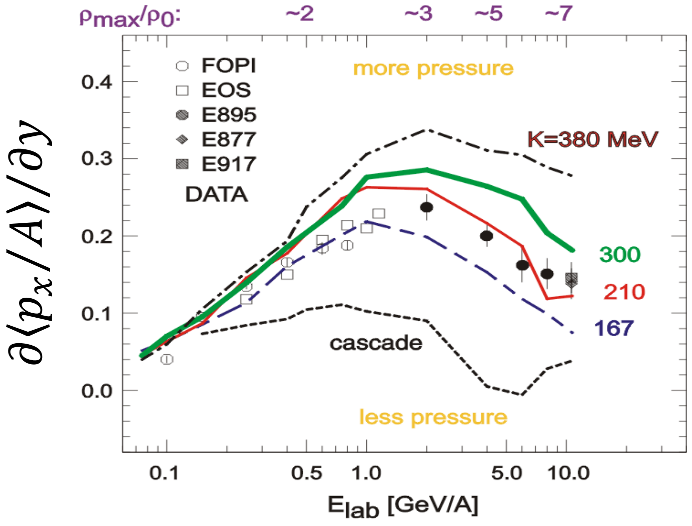
directed flow

Approximate symmetric matter



in plane

out of plane



$$\frac{dN}{d(\phi-\psi_r)} = \frac{N_0}{2\pi}\left[1 + 2\sum_{n\geq 1} v_n \cos\big(n(\phi-\psi_r)\big)\right]$$

$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle, \qquad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$

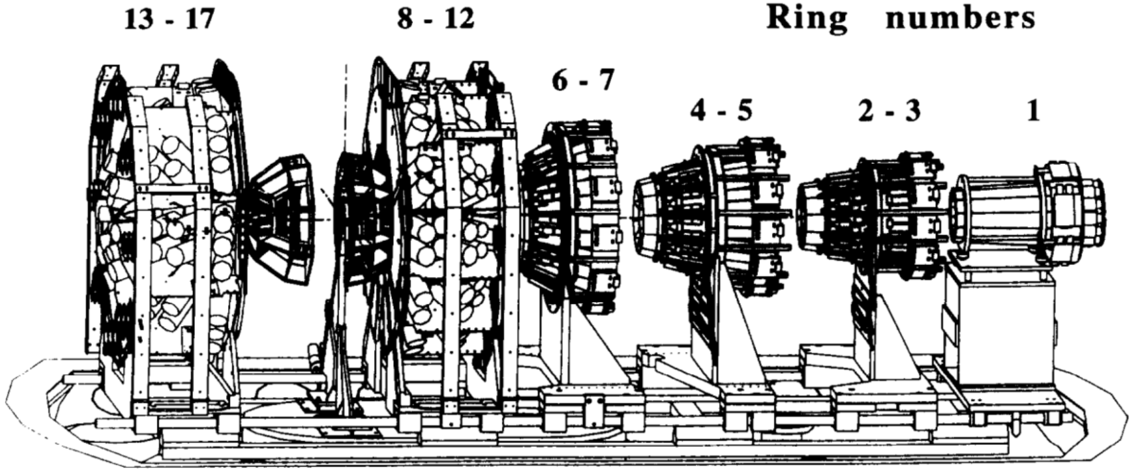
Part 2.

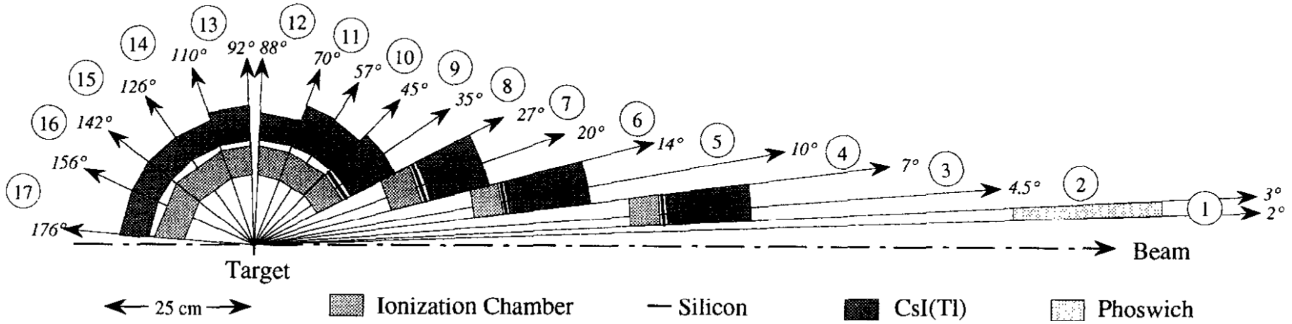
Analysis results for collective flow in Xe+Sn @ 100 MeV/u & model comparison

Seonho Nam (thesis), B. Hong (Korea Univ.)
A. Chbihi (GANIL)
Y. Zhang, J. Yang (CIAE)

INDRA experiment

J. Pouthas et al., NIMA 357, 418 (1995)
Operational since 1993

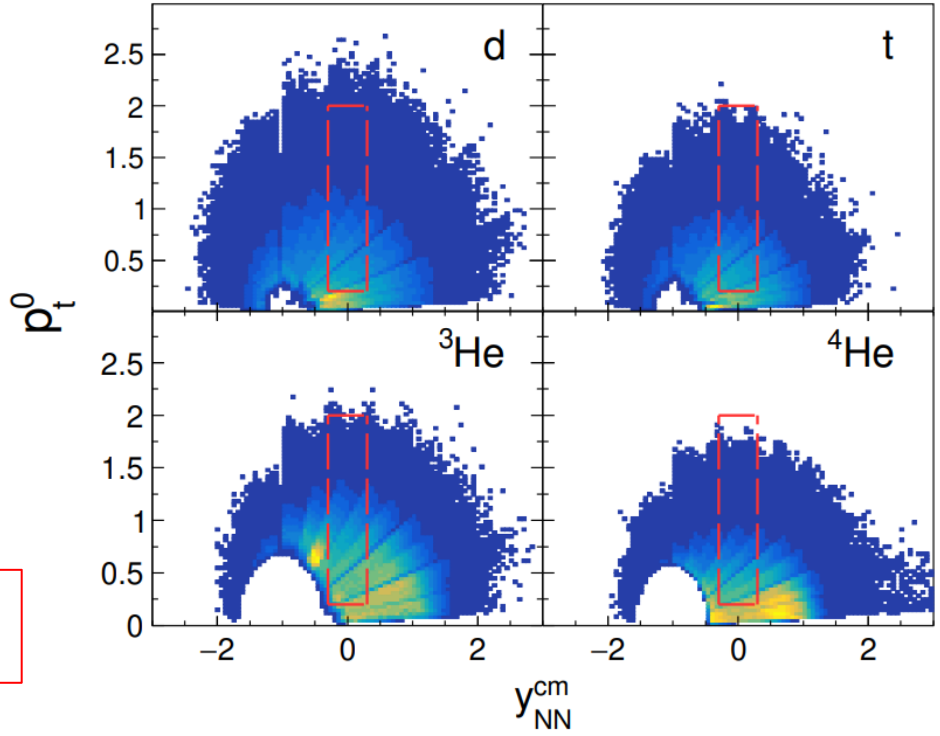




$$p_t^0 = \frac{p_t/A}{p_{beam}/[0.5(A_P+A_T)]}, \quad y_{NN}^{cm} = \frac{y_{cm}}{y_{beam}}$$

- Data
  - 4^{th} INDRA campaign at GSI (1998)
  - $^{129}Xe + ^{124}Sn$ @ 100 MeV/u
  - Centrality: $b/b_{geom} \cong 0.32$ estimated by the transverse energy distribution of LCPs

↓ Acceptance plots for Z = 1 & 2 particles



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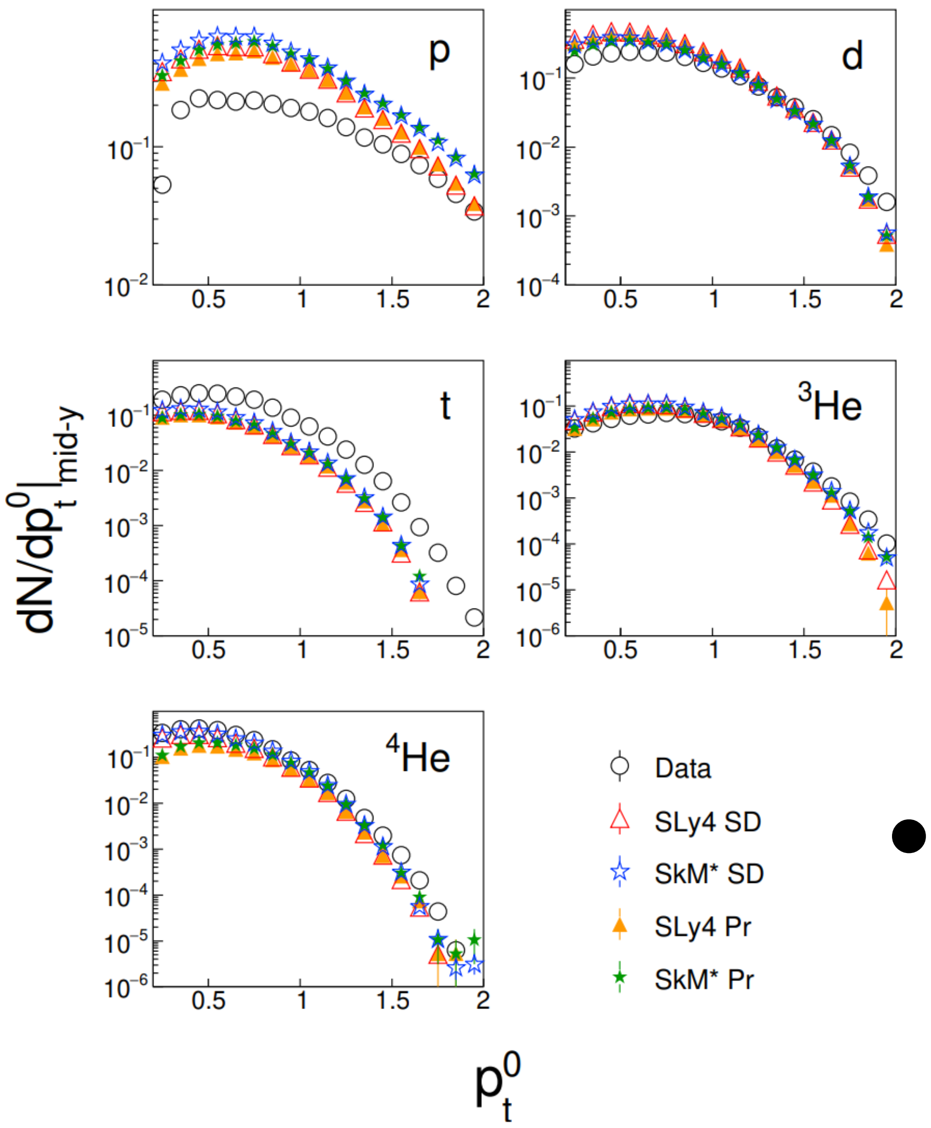
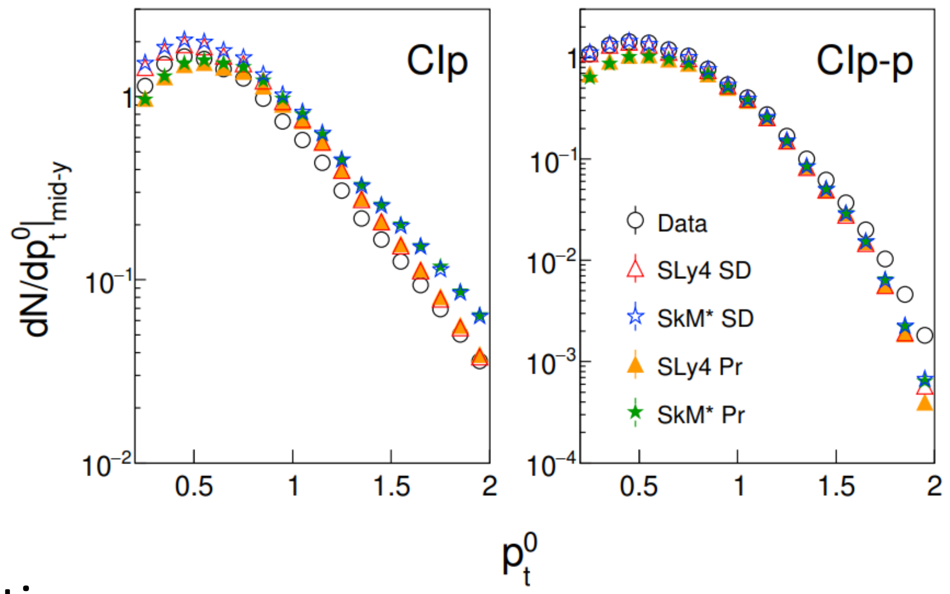
Transverse momentum spectra



- Coalescence-Invariant proton spectrum (Clp)

$$\frac{dN_{CIp}}{dp_t^0} = \sum_{A<5} Z \frac{dN(Z,A)}{dp_t^0}$$

- Clp-p: free proton component is subtracted from Clp

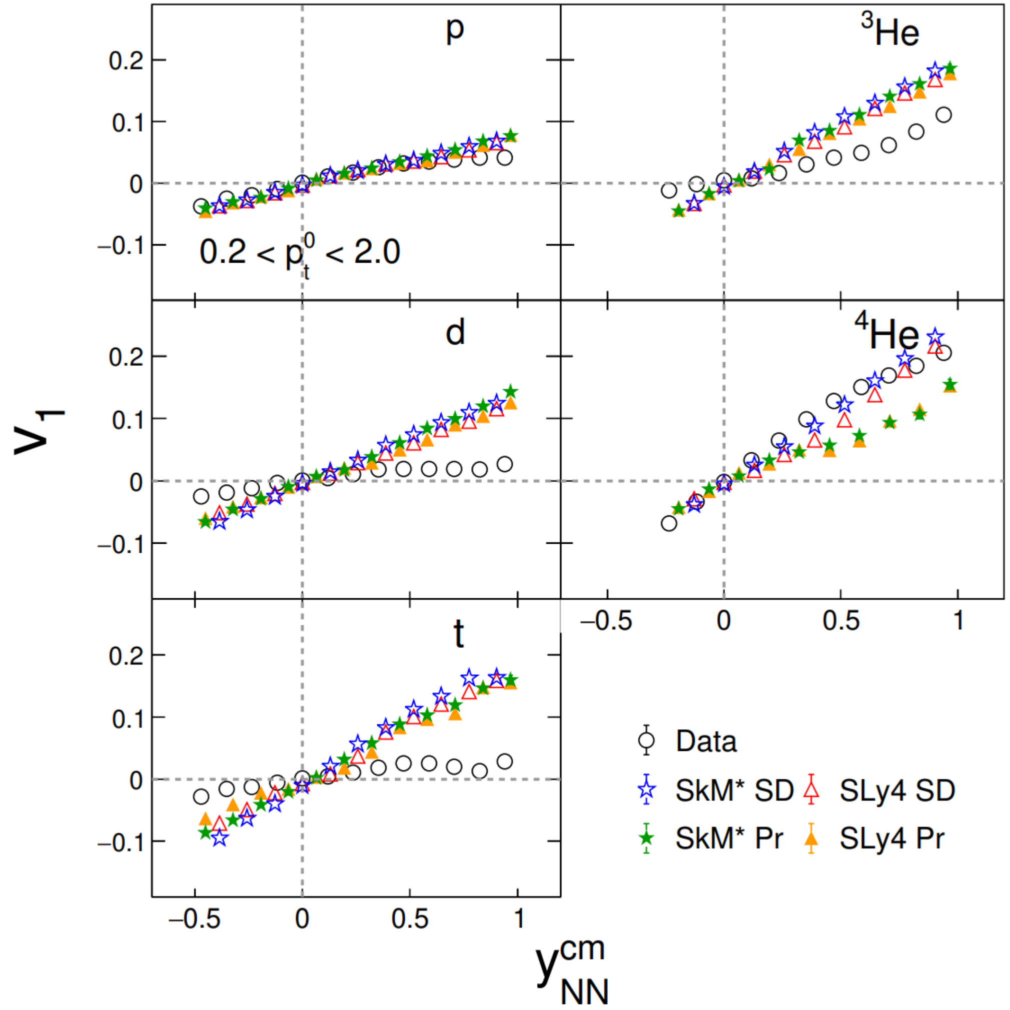


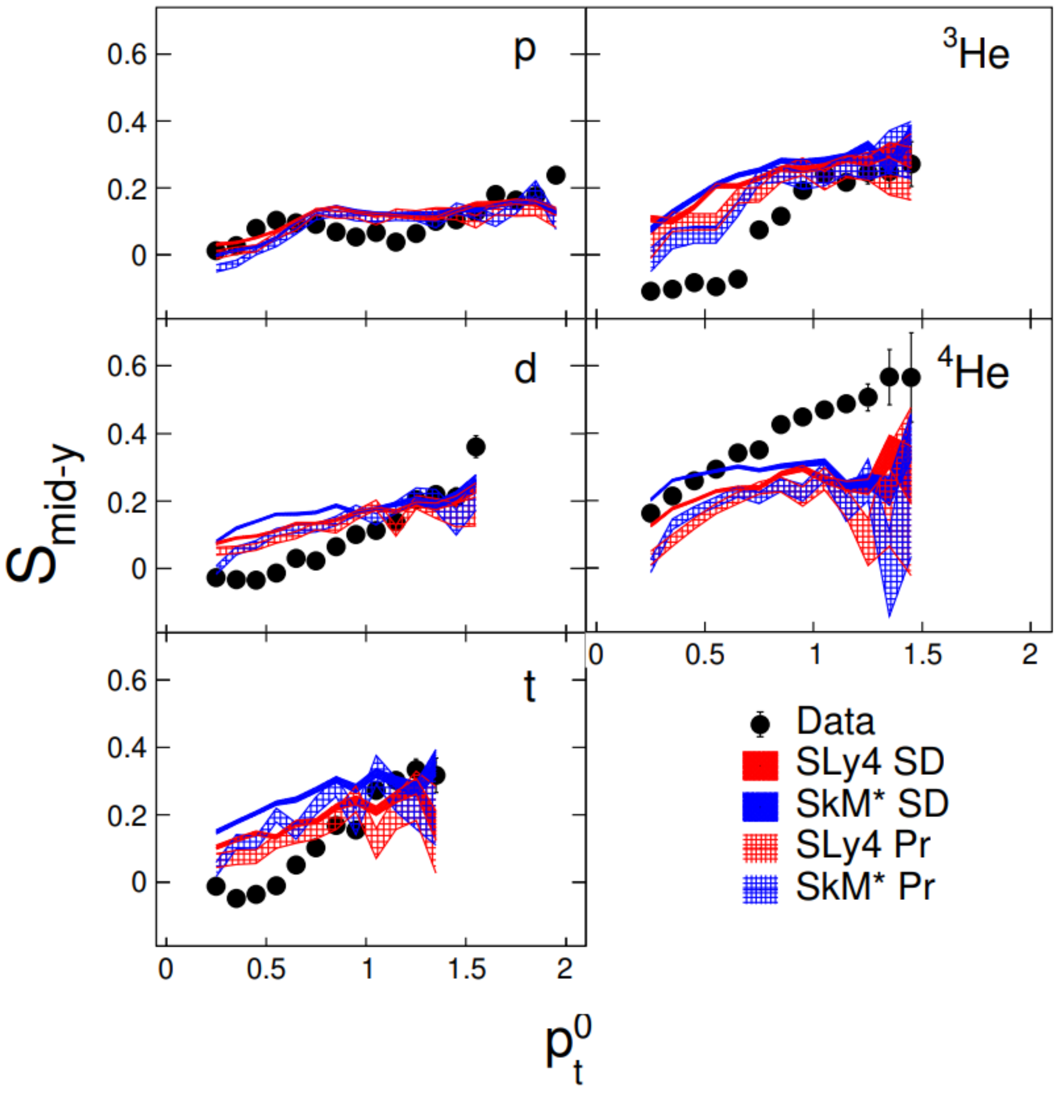
- **Pr**: Primary
- **SD**: Secondary decays included

- Observations
  - *Secondary decay effect is significant at low p_t^0 only for p & ^{4}He.*
  - *ImQMD⨁GEMINI++ produce too many protons and too few tritons.*
  - *Clp-p: good agreement between the data and model calculations.*

Directed flow v_1

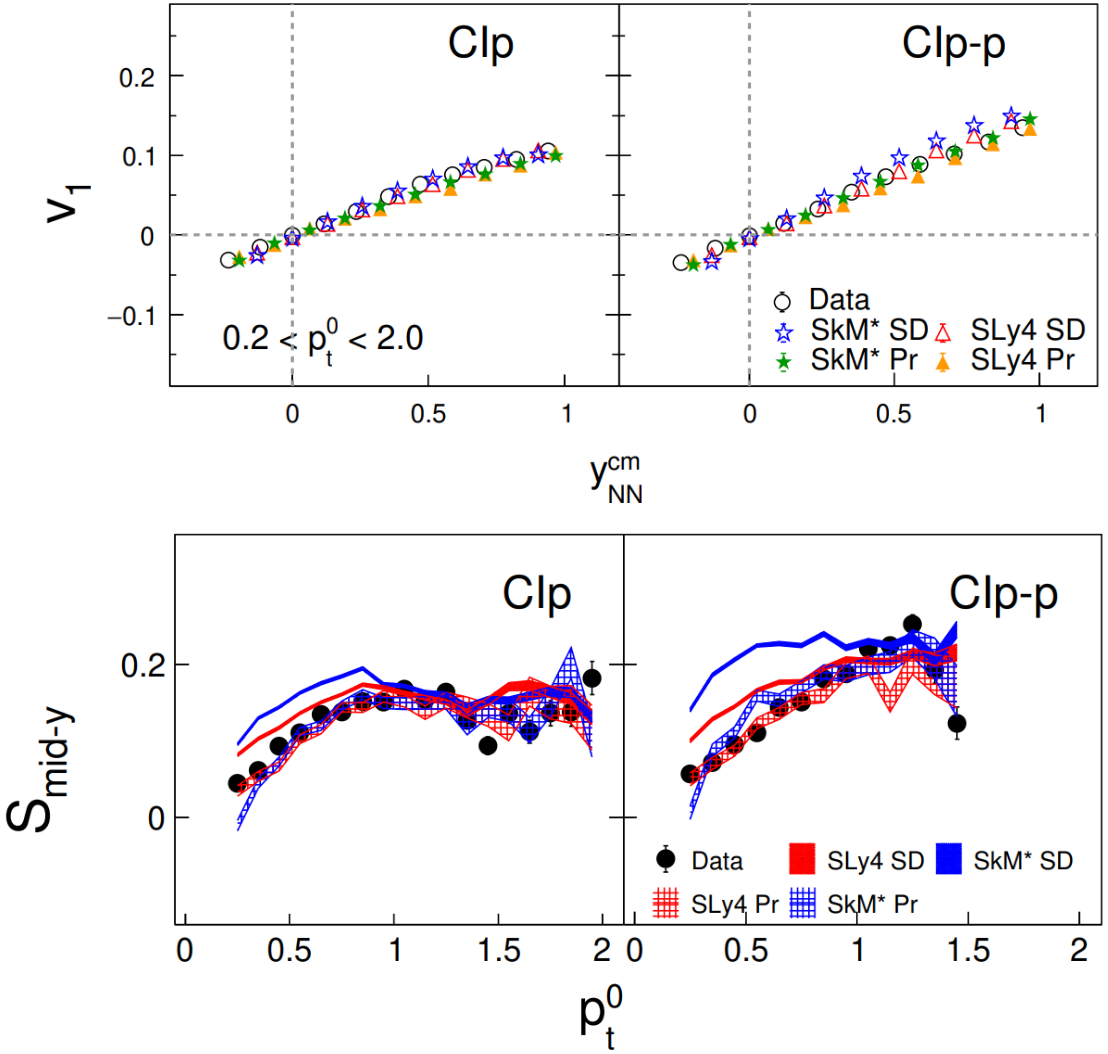
$$S_{mid-y} = \left.\frac{dv_1}{dy_{NN}^{cm}}\right|_{|y_{NN}^{cm}|<0.3}$$



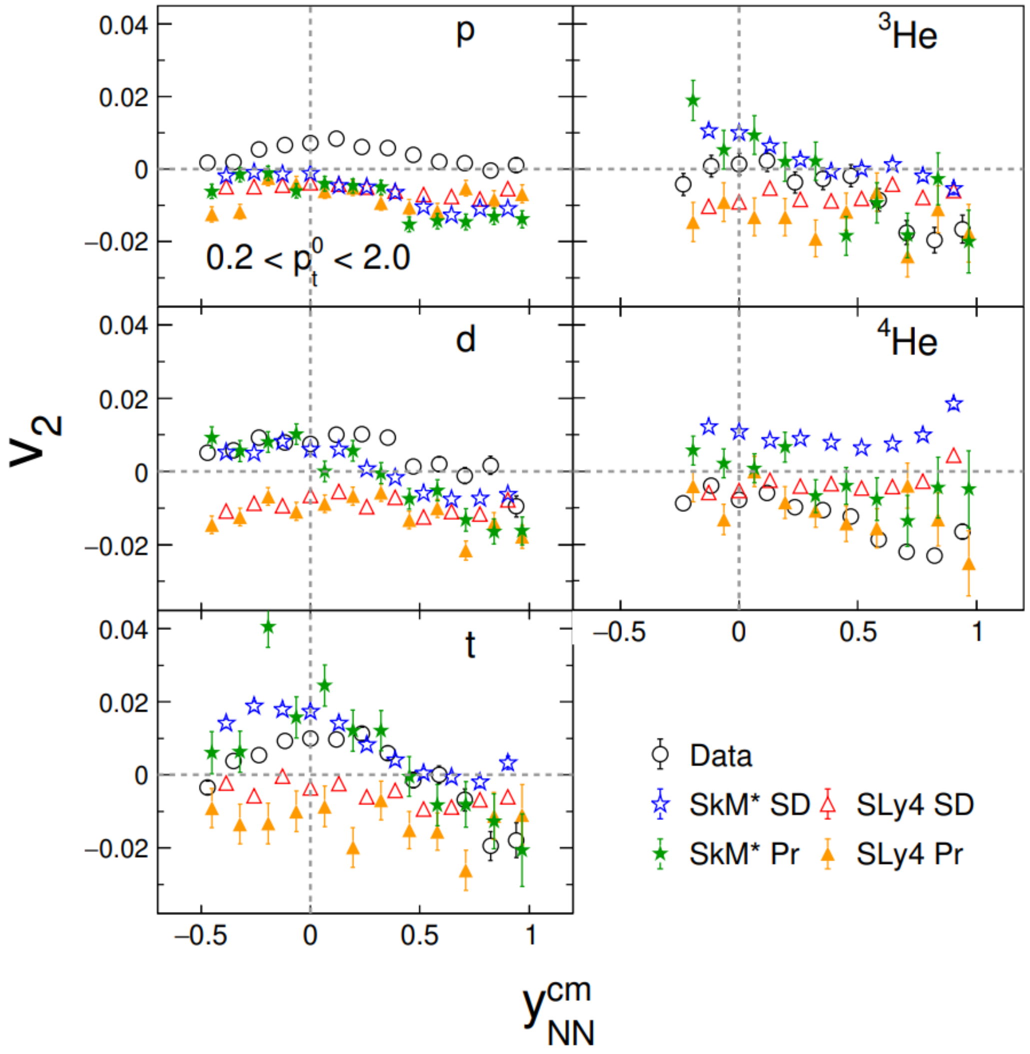


Directed flow v_1

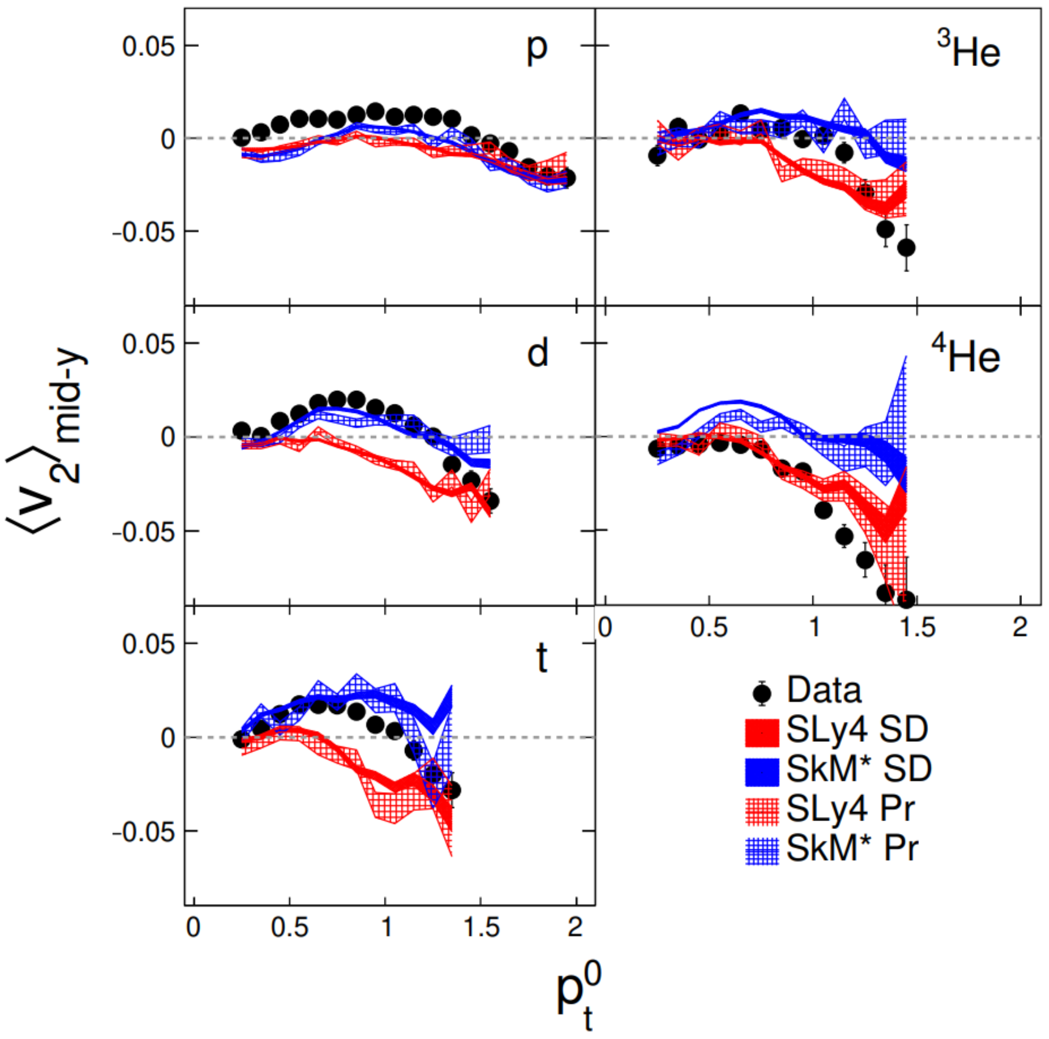
- Observations for v_1
  - *Rapidity dependence of v_1 for individual species is not reproduced by the model except for protons.*
  - *ImQMD⨁GEMINI++: Secondary decay increases the v_1 values, especially, at the low-p_t^0 region.*
  - *Clp-p/Clp*
    - *Good agreement between the data and model calculations for the rapidity dependence ↗*
    - *The p_t^0 dependence shows that the secondary decay process worsens the agreement. →*
- After all, the directed flow data for different particle species cannot be consistently described by ImQMD!



Elliptic flow v_2



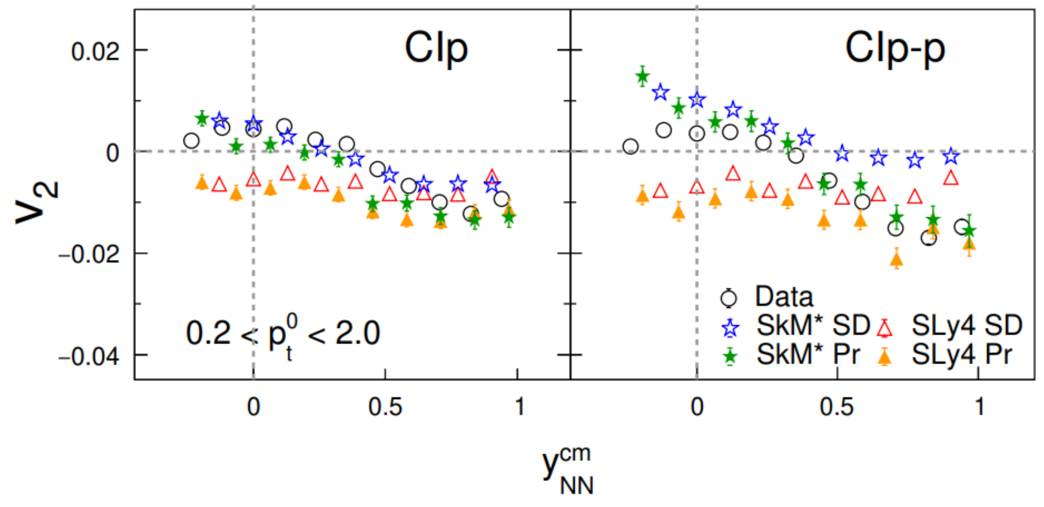
$\langle v_2 \rangle_{mid-y}$ = Mean of v_2 in $|y_{NN}^{cm}| < 0.3$

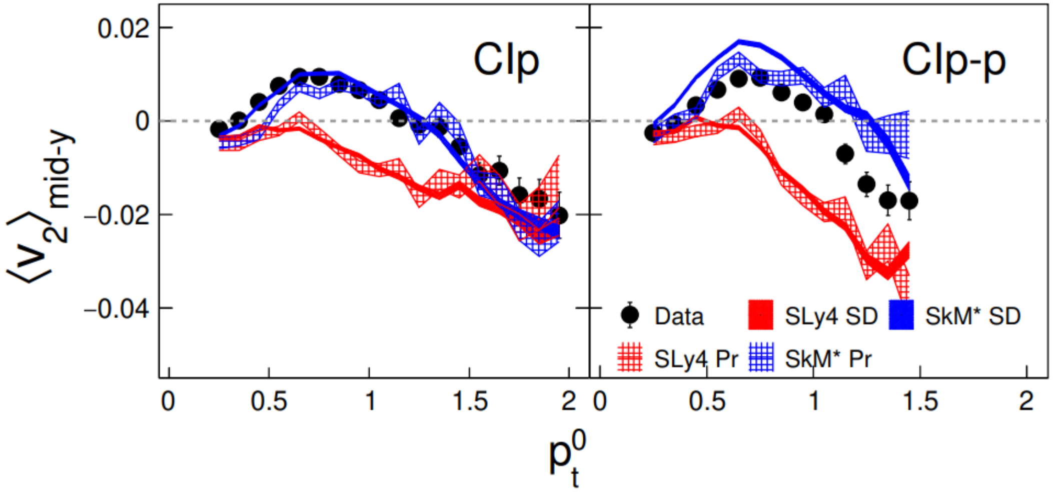


Elliptic flow v_2

- Observations for v_2
  - *Except protons & ^{4}He, the rapidity and p_t^0 dependences of v_2 consistently prefer the SkM*.*
    - *There are several sources for protons, which makes the interpretation complicated.*
    - *The production mechanism for ^{4}He might be different from that for other LCPs.*
    - *Clp-p even prefers primary rather than the decayed SkM* option in forward rapidities.*
  - *Overall, the secondary decay (by GEMINI++) does not play a significant role in v_2.*

- **Conclusion**
  - Effect of afterburner on v_2 is relatively small.
    - → v_2 is developed before the decay processes happen (in relatively early time).
    - → Therefore, v_2 may preserve more information on the underlying mean-field dynamics.
  - Clear sensitivity to the effective mass effect for v_2: LCP consistently supports SkM* with $m_n^* > m_p^*$.





Submitted to PRC

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Part 3.

Upgrade of FAZIA detector

B. Hong
J. Park
S. Nam

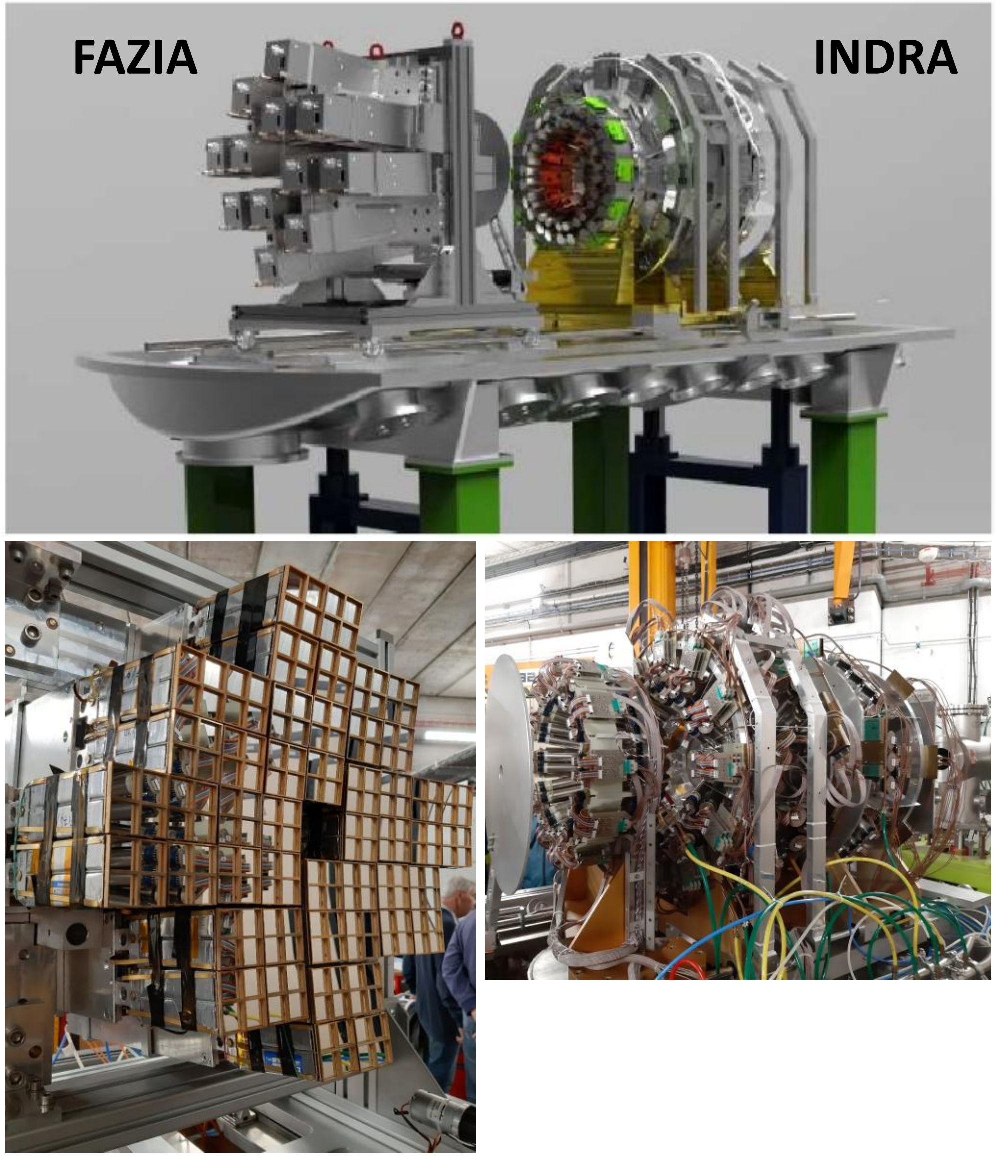
M. Kweon G. Kim
W. Jeong S. Yang
S.H. Lee

Florence

G. Casini
S. Valdré

N. Le Neindre

INDRA-FAZIA experiment



- FAZIA detector
  - Charged –particle detection system for nuclear experiments at intermediate beam energies (Presently at GANIL)
- Collaboration status
  - 5 countries (France, Italy, Korea, Poland, Spain)
  - ~30 collaborators including students

❖ Short history of the Korean participation

- Korean group (part of LAMPS Collaboration) was designing the Si-CsI telescope for the low-energy nuclear collision experiments at RAON.
- IAC of RAON reviewed the status of our detector development and recommended to cooperate with FAZIA in Europe, because FAZIA had been the most advanced Si-CsI detector system for nuclear physics.
- We started the discussion with some FAZIA members about the possibility joining the Collaboration in various meetings.
- Finally, we attended the FAZIA Workshop at GANIL in September 2019 and presented the official application.
- CENuM, representing the whole Korean group, signed on the MoU in 2020.
- A new MoU was signed for the period of 2023-2027.

FAZIA detector

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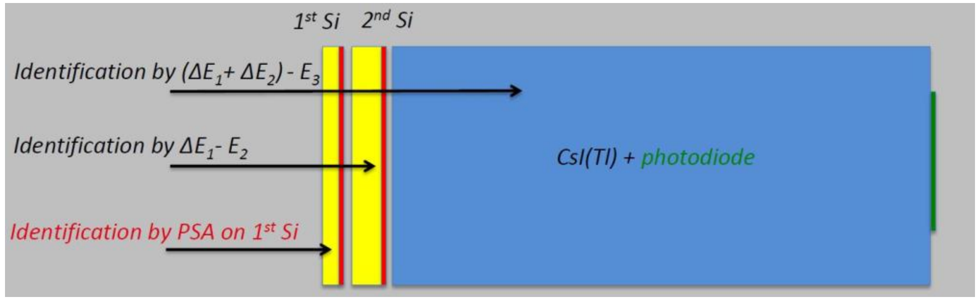
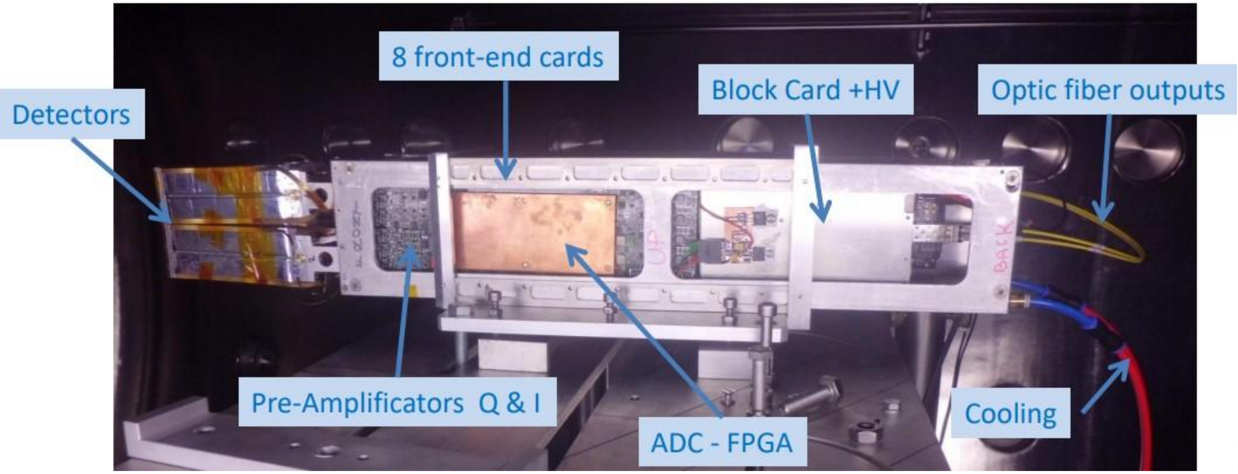
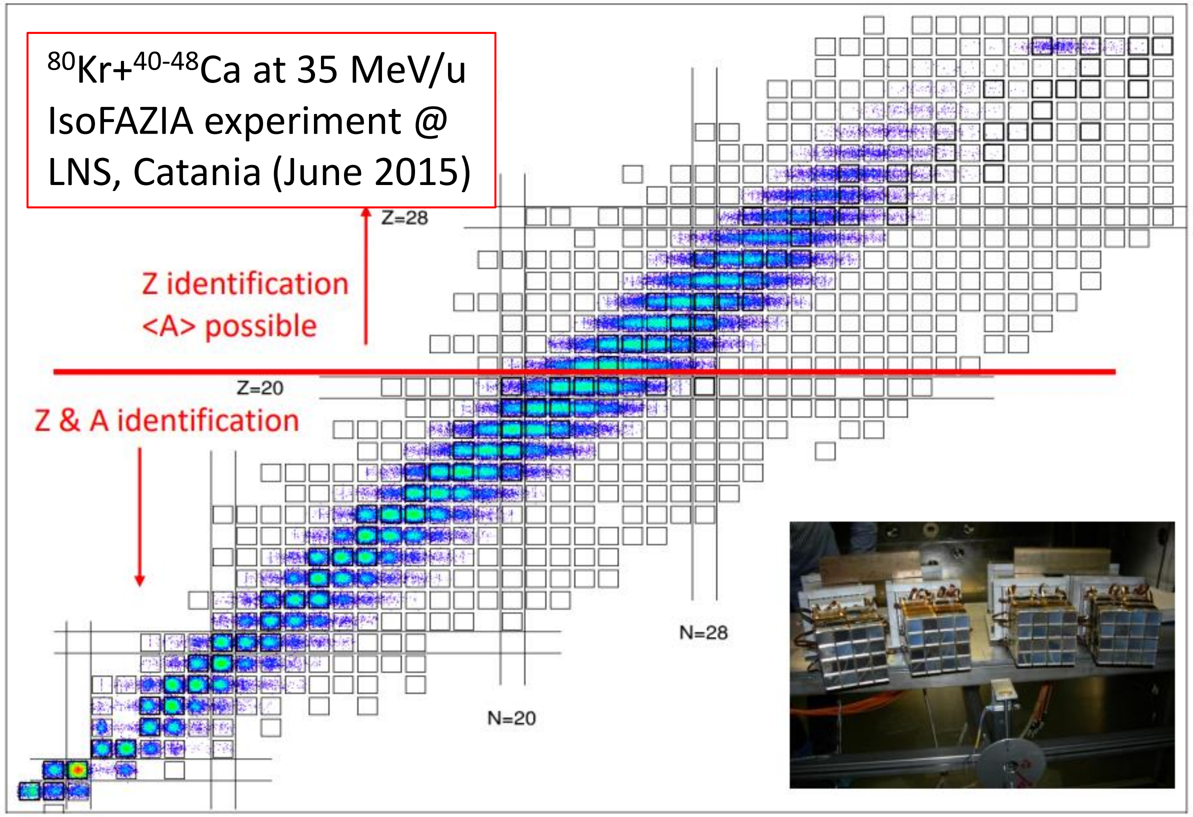
∗ nTD: Neutron Transmutation Doped

- One FAZIA block consists of 16 Si_1+Si_2+CsI telescopes (Area of each telescope: 2×2 cm^2)
  - Present configuration: Si_1(nTD) 300 μm thick, Si_2(nTD) 500 μm thick, CsI 10 cm thick (PD readout)
  - PID by the traditional ΔE vs. E method and the refined Pulse-Shape Analysis (PSA) technique
  - Current detector optimized for charged particles in heavy-ion collisions from 15 to 100 MeV/u







Performance of FAZIA detector

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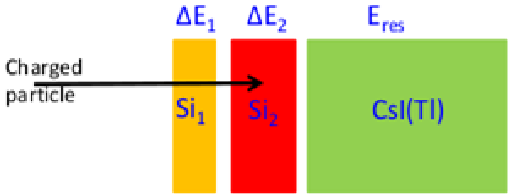
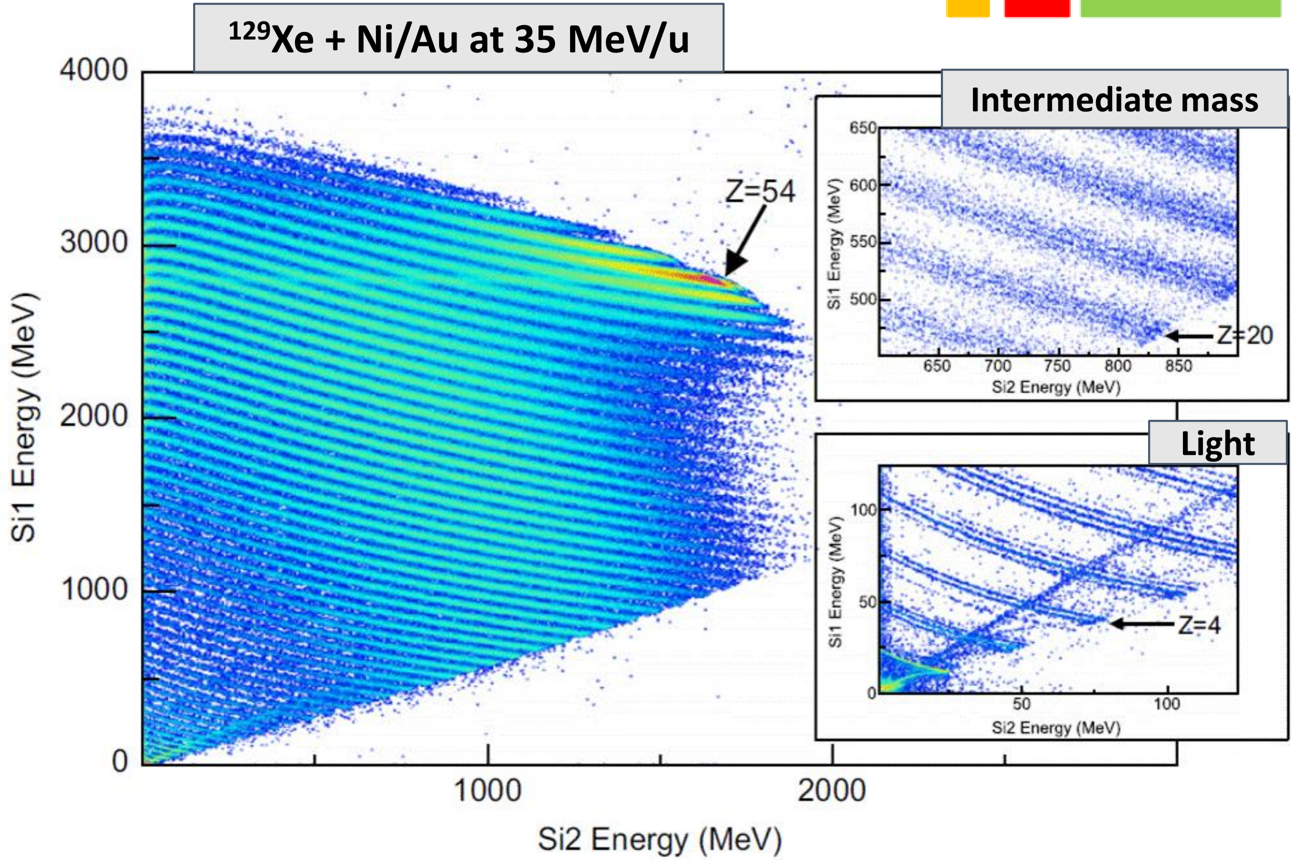
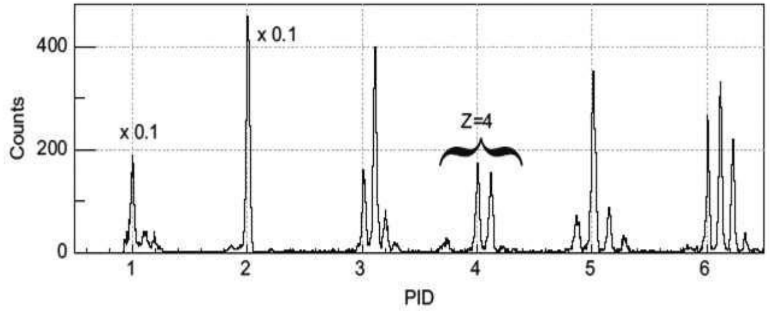
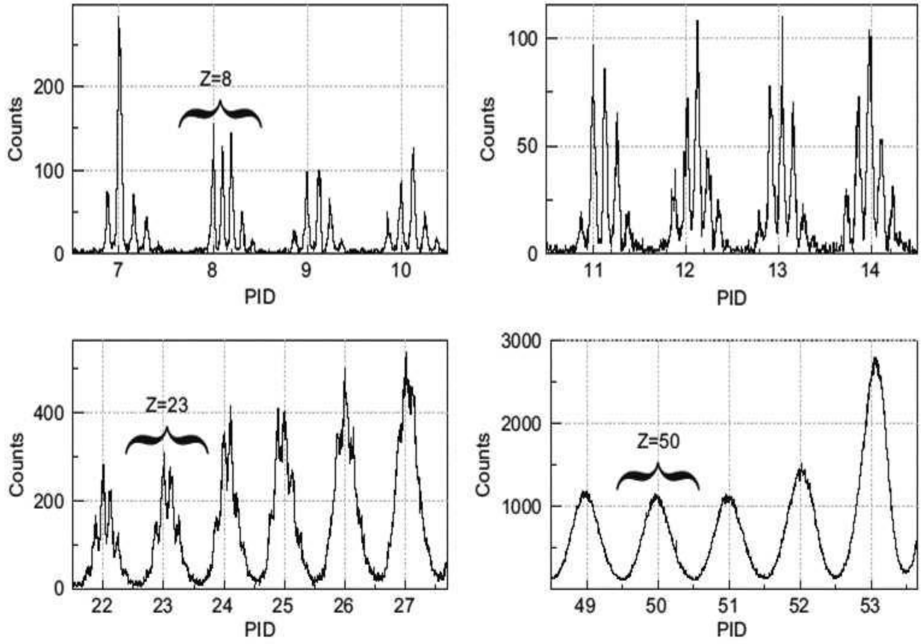
G. Pasquali et al., EPJA 50, 47 (2014)









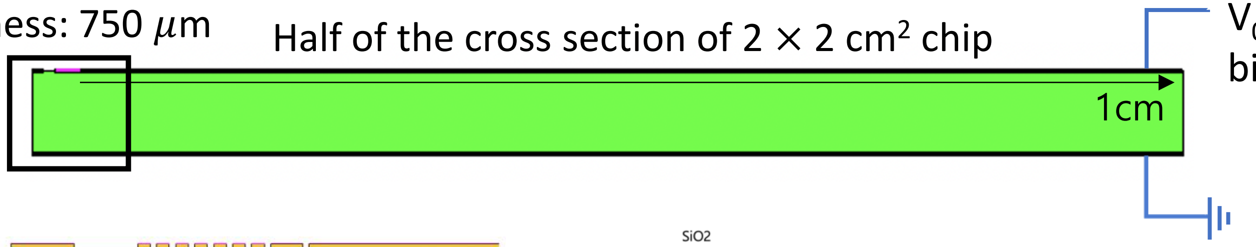
- Mass discrimination up to $Z \sim 23$ and charge identification up to $Z \sim 54$

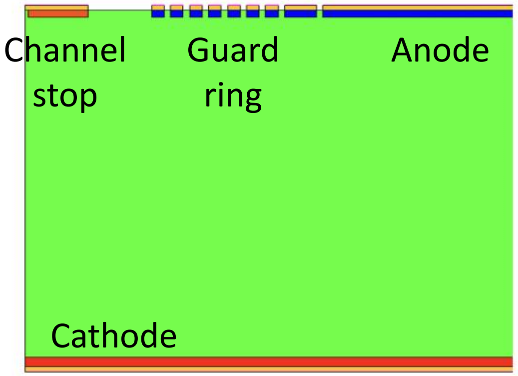
Design of PIN sensor using Synopsys TCAD*

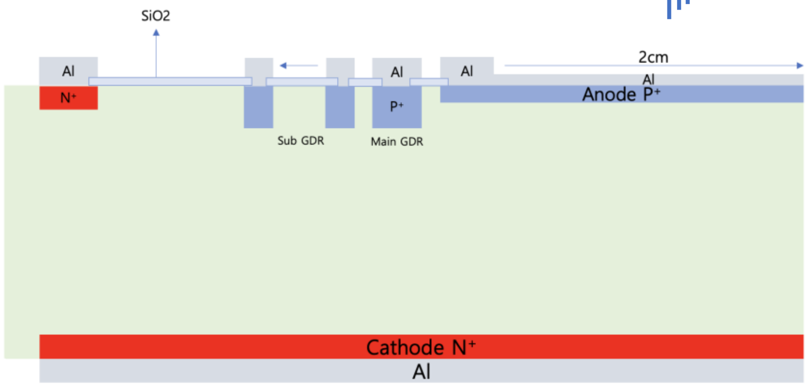
* TCAD: Technology Computer Aided Design

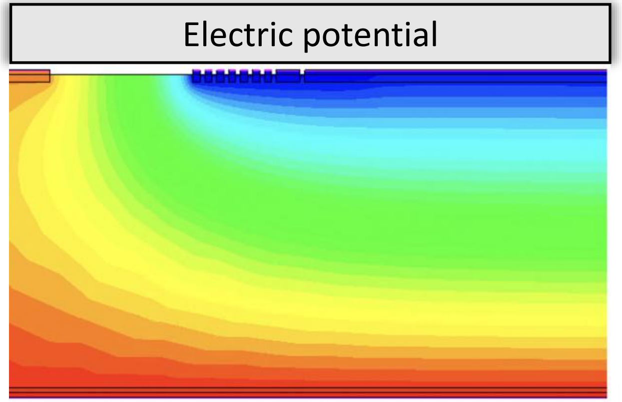
- **Necessity of upgrade for FAZIA detector**
  - Extension of the beam energy coverage
  - Preparation of experiments at the various Labs. other than GANIL, e.g., RAON, FRIB, etc.
  - Enlargement of the acceptance for the original FAZIA detector system currently at GANIL

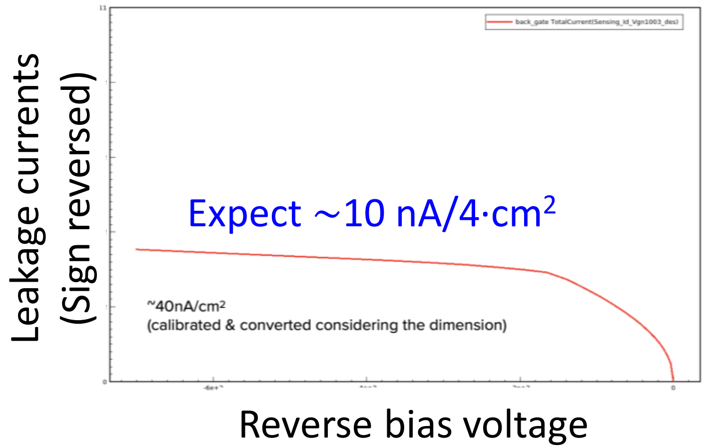
Input parameters				
Temp.	300 K		Doping density	
V_0	0 ~ -700 V		(blue)	P^+ Boron 1×10^{19} cm^{-3}
Carrier lifetime	e^-	1×10^{-4} s^{-1}	(green)	N^- Phosphorus
	hole	3×10^{-4} s^{-1}	(red)	N^+ Phosphorus











Development of Si sensors

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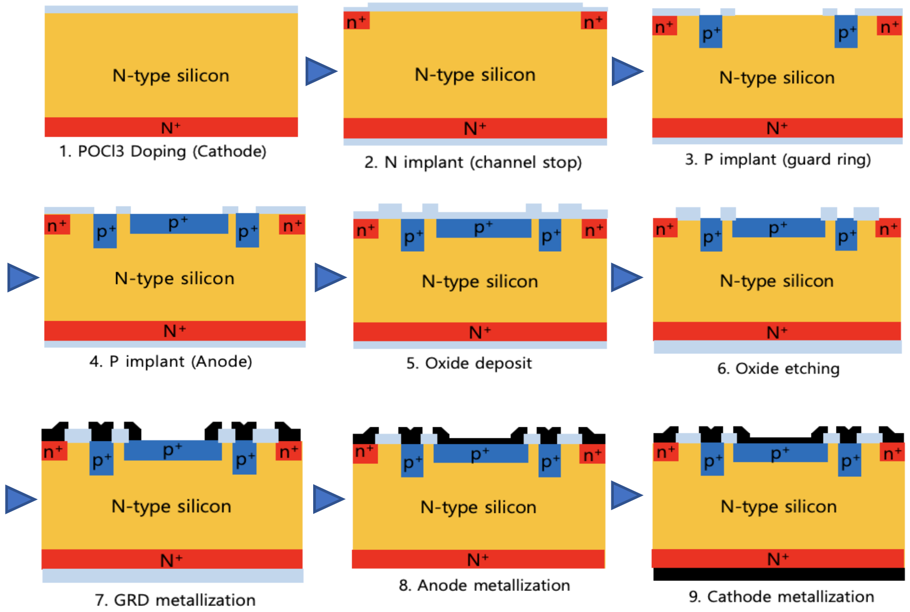
Part of flow for the Si wafer process



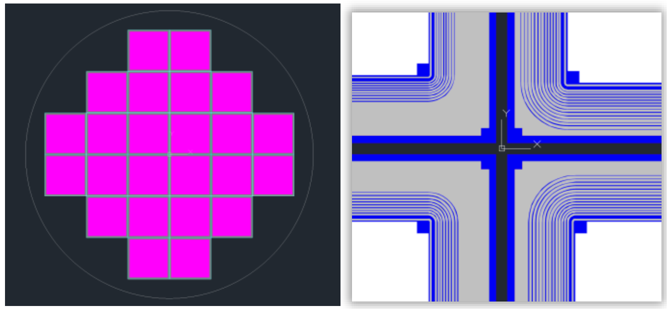
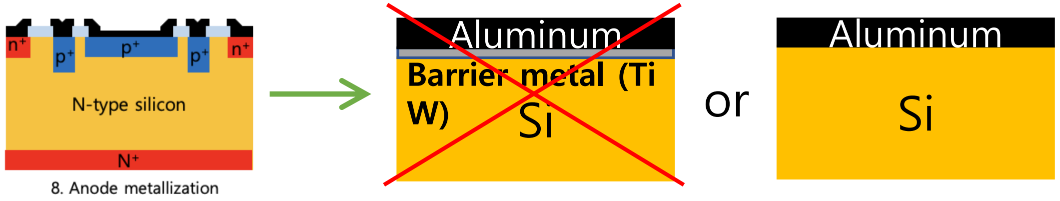
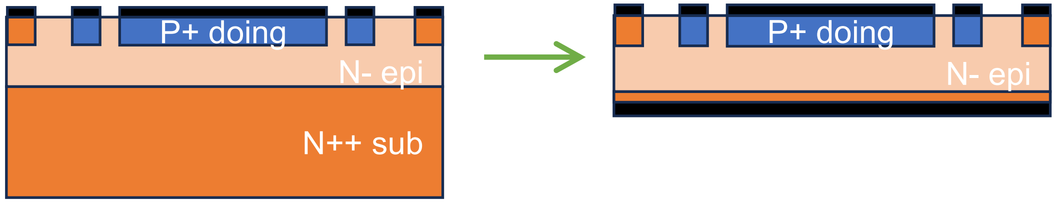


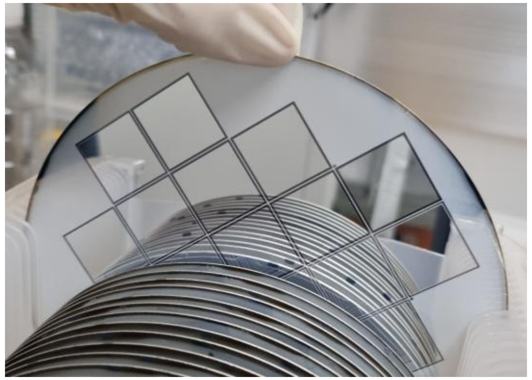
Photo mask (by MicroImage): Tested various guard ring patterns & different sensor designs

Barrier metal effect for thick (750/675 μm) sensors



Thinning of epitaxial wafer for thin (115 μm) sensors

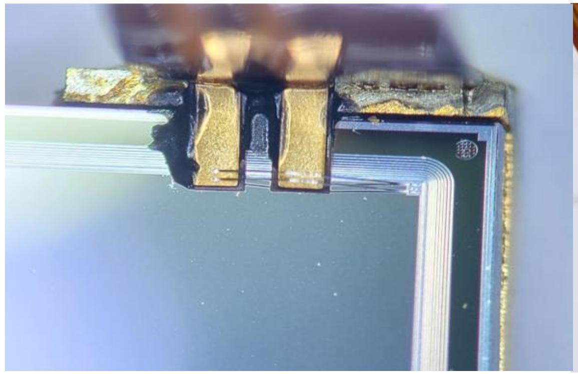


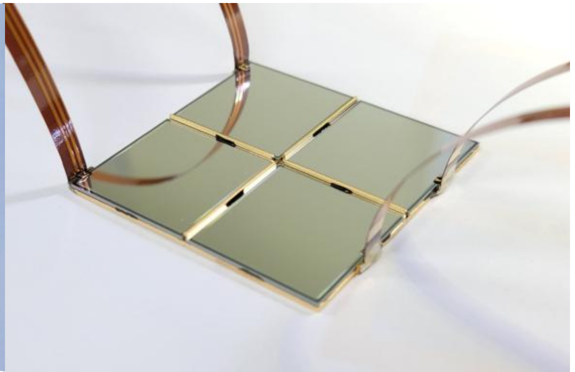


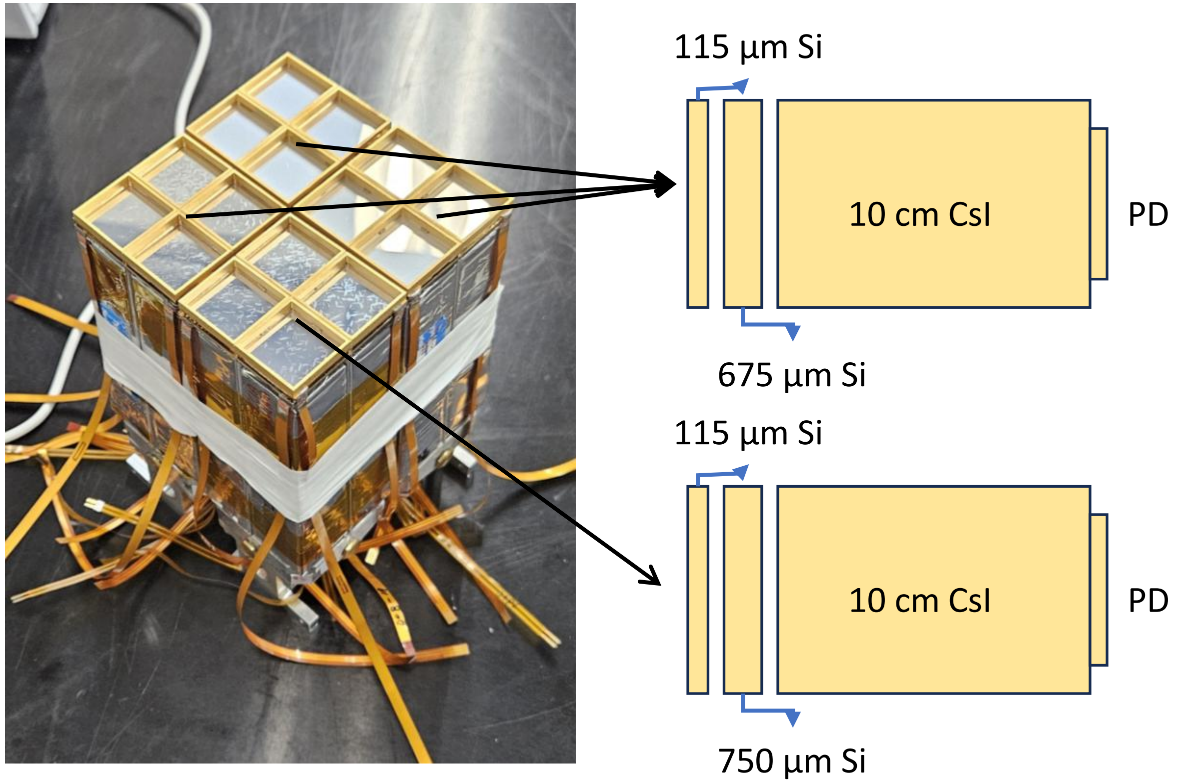
Wafer processing (by ETRI)

Thinning (by TRinno Tech) & dicing (by MEMSPACK)

Assembly







- Chip assembly for a quartetto
  - Four chips are mounted in one quartetto frame.
  - Backside of the sensor connected to ground
  - Wire-bonding connection to apply the reverse-bias voltage to the sensors
  - Assembly was carried out in collaboration with MEMSPACK, a local company in Korea.

- Quartetto assembly
  - Four quartettos are assembled into one block detector.
  - Si sensors
    - Energy resolution ~0.6% in junction side
  - CsI(Tl)
    - Supplied by INFN-Florence
    - Energy resolution: ~10% measured by stand-alone setup using the ^{241}Am source

New front-end electronics cards

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- New FEE cards development in collaboration with NOTICE, a local company in Korea
  - We started with the original schematics, provided by FAZIA, for FEE design.
  - Out-of-dated digital parts are replaced, e.g., Vertex-5 → KINTEX-7 for FPGA.
  - Development of the new VHDL firmware for new FPGA chips
  - Two prototype FEE cards were tested for their performance at GANIL and INFN-Firenze.
  - They were also tested with beams at CNAO (The National Center for Oncological Hadrontherapy in Pavia), Italy in 2024, which validated for further production.
  - Total 55 FEE cards, which must be enough for four blocks, were manufactured in 2025.

Prototype FEE card

- **Analog part**: To amplify analog signals from the detector
- **Digital part**: Signal processing (analog to digital conversion)
- **Conversion part**: Power distribution Application of bias voltage

Proton beam test at RAON

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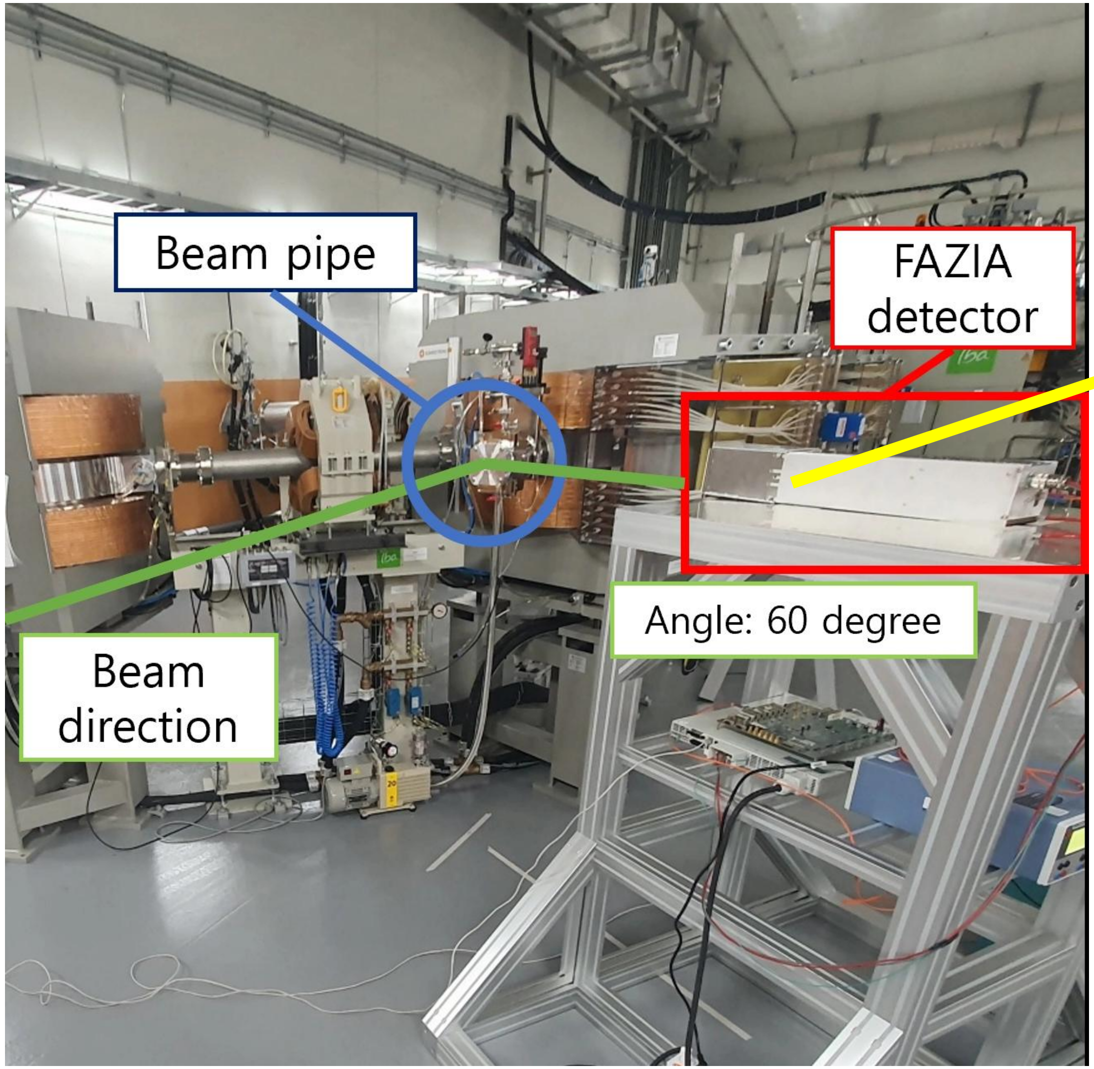
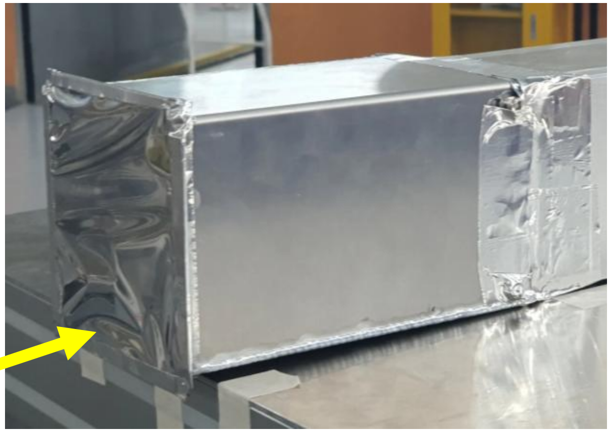
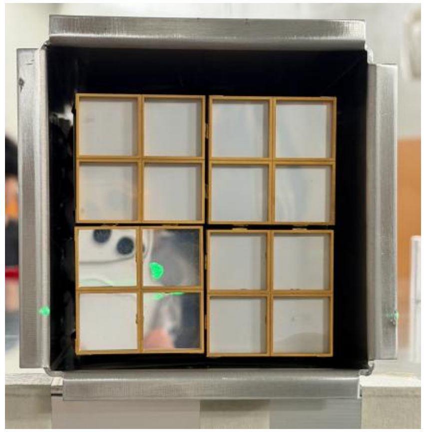


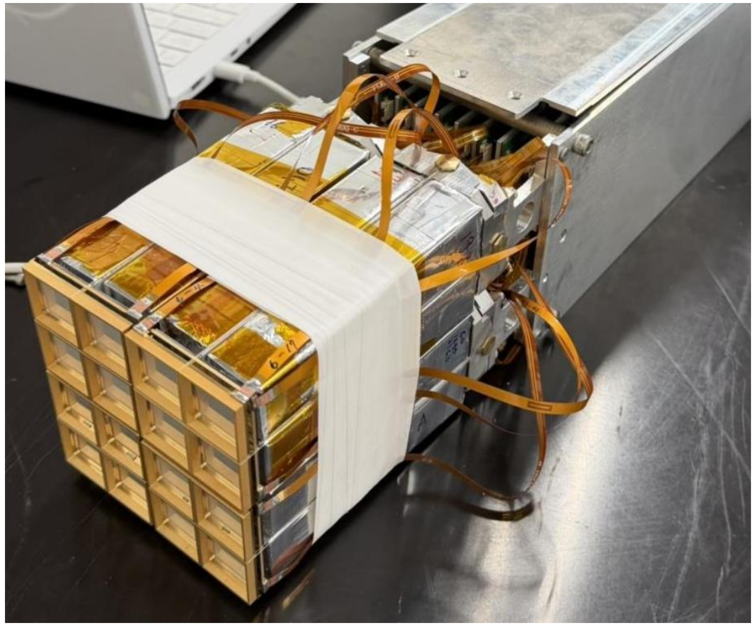


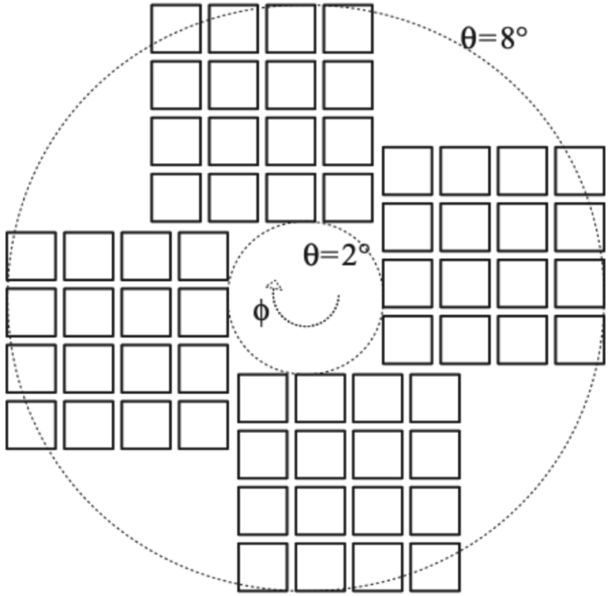


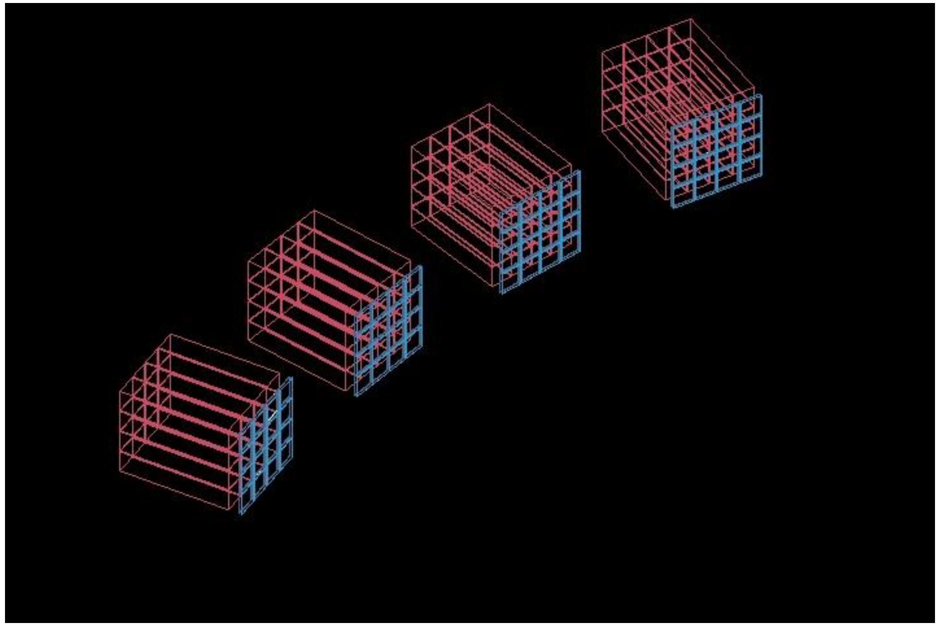
- The first FAZIA block built in Korea with new electronics was tested using the protons at RAON.
  - Beamtime: 10-11 February 2026
  - Beam energy: 40~70 MeV (10 MeV step)
  - Beam current: 30 nA
    - The minimum beam current for stable operation of cyclotron was ~10^{14} pps, but we asked to decreased the intensity as low as possible not to risk the detector.
    - Event rate: ~250 events/s
- Analysis is in progress.

Plan

- Construction of total 4 blocks by the end of this year
- Another test with protons beams at RAON is scheduled in 21-22 Sep. 2026.
- Next step is to test the FAZIA blocks produced in Korea using the ion beams.
- Finally, we would like to have some physics runs in the Labs. such as RAON, GANIL, FRIB, etc.







Summary

- Analysis of Xe + Sn @ 100 MeV/u
  - Effect of afterburner on collective flow is relatively small over entire phase space
    - → Elliptic flow is developed in early stage of collision.
    - → It preserves more direct information on the underlying mean-field dynamics.
  - v_2 shows clear sensitivity to the effective mass effect
    - → LCP consistently supports SkM* in ImQMD with $m_n^* > m_p^*$.

- Upgrade of FAZIA detector
  - Upgrade program is being mostly progressed in Korea with great help from INFN and GANIL.
  - Si PIN sensors with thickness of 675/750 μm and 115 μm have been developed.
  - Dedicated electronics have been designed and produced.
  - The beam test of the first block manufactured in Korea was performed at RAON.
  - We plan to have total of four blocks in Korea by the end of 2026.