Study on neutron-neutron correlation in Borromean nucleus ^{11}Li via the quasi-free (*p,pn*) reaction

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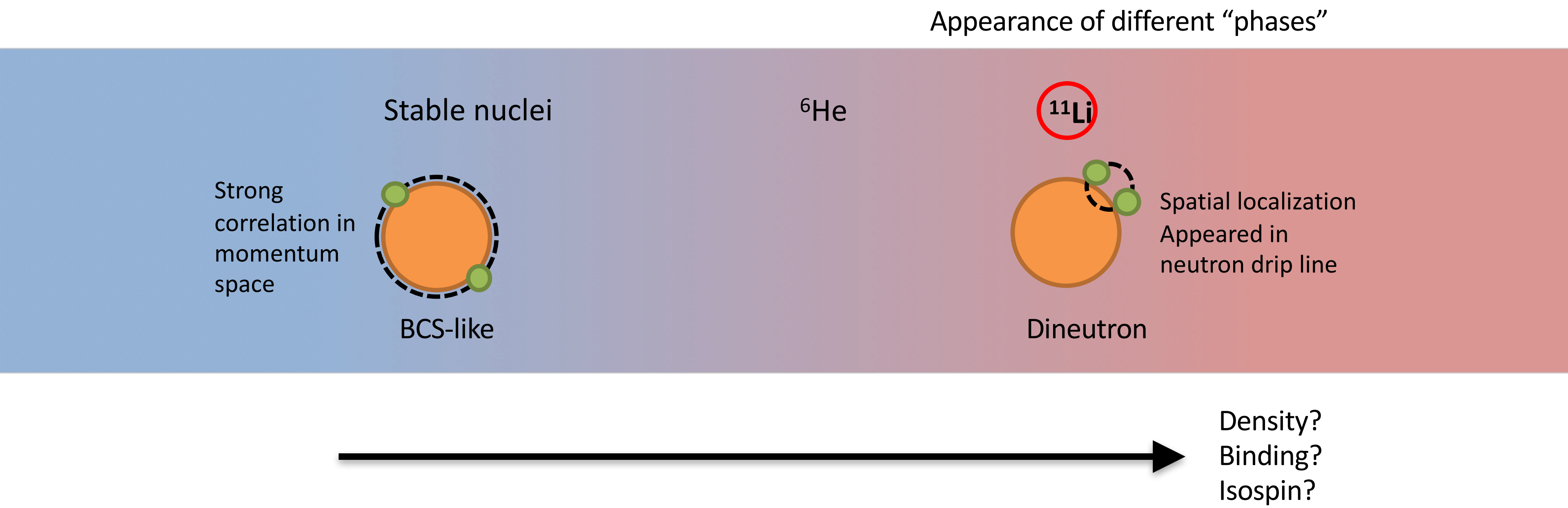
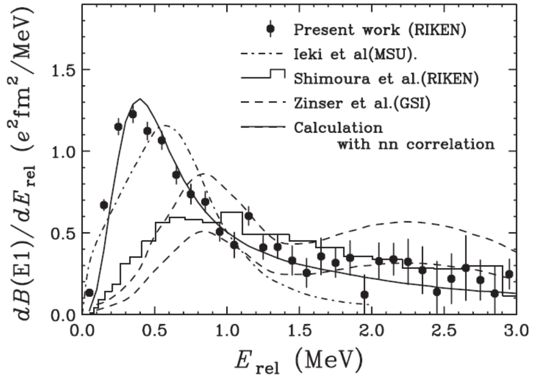
Neutron-neutron correlation



What is the control parameter?
How the correlation evolves?

Studies on ^{11}Li

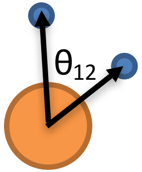
- 1967: Prediction of dineutron
  - G. F. Bertsch, R. Broglia, and C. Riedel, Nucl. Phys. A **91**
- 1992: Momentum distribution
  - I. Tanihata *et al.*, Phys. Rev. B **287**
- 1993: Importance of n-n correlation
  - M. V. Zhukov *et al.*, Phys. Rep. **231**
- 1993: Coulomb dissociation
  - K. Ieki *et al.*, Phys. Rev. Lett. **70**
- 1999: Neutron removal (C target)
  - H. Simon *et al.*, Phys. Rev. Lett. **83**
- 2004: ^{6}He charge radius
  - L.-B. Wang *et al.*, Phys. Rev. Lett. **93**
- 2006: Charge radii of $^{6-11}$Li
  - R. Sánchez *et al.*, Phys. Rev. Lett. **96**
- 2007: ^{8}He charge radius
  - P. Müller *et al.*, Phys. Rev. Lett. **99**
- 2006: Coulomb breakup
  - T. Nakamura *et al.*, Phys. Rev. Lett. **96**
- 2008: Precise mass
  - M. Smith *et al.*, Phys. Rev. Lett. **101**
- 2010: Importance of final state interaction (FSI)
  - Y. Kikuchi *et al.*, Phys. Rev. C **81**
- 2013: Proton-induced knockout
  - Yu. Aksyutina *et al.*, Phys. Rev. B **718**
- 2013: Core excitation
  - Y. Kikuchi *et al.*, Phys. Rev. C **87**



*E*1 cluster sum rule (based on 3-body model)

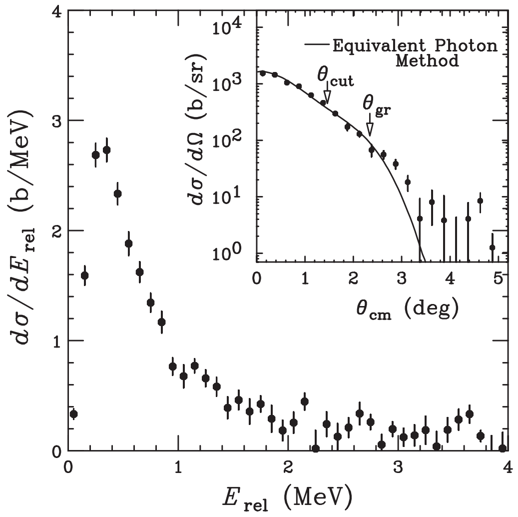
$$B(E1) = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \langle r_1^2 + r_2^2 + 2\boldsymbol{r_1}\cdot\boldsymbol{r_2}\rangle = \frac{3}{\pi}\left(\frac{Ze}{A}\right)^2 \langle r_{c,2n}^2\rangle,$$

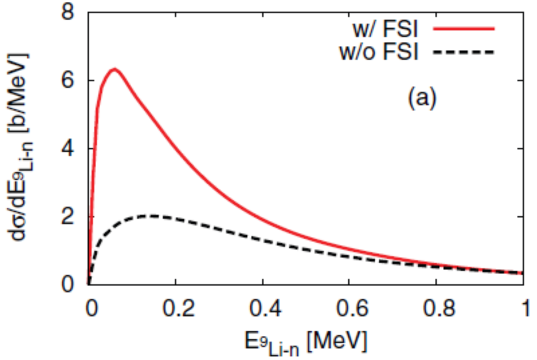
$$\rightarrow \langle\theta_{12}\rangle = 48^{+14}_{-18}\ \text{degrees}$$



c.f. No correlation → θ_{12} = 90 deg.

Role of final state interaction (FSI)





- 2006: Coulomb breakup
  - T. Nakamura *et al.*, Phys. Rev. Lett. **96**
- 2008: Precise mass
  - M. Smith *et al.*, Phys. Rev. Lett. **101**
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Spectrum is largely distorted by the FSI.

→ Integrated strength conserves, but it escapes to higher E_{rel}.

→ Uncertainty in $B(E1)$ determination.

^{9}Li core excitation ^{11}Li

- 1967: Prediction of dineutron
  - G. F. Bertsch, R. Broglia, and C. Riedel, Nucl. Phys. A **91**
- 1992: Momentum distribution
  - I. Tanihata *et al.*, Phys. Rev. B **287**
- 1993: Importance of n-n correlation
  - M. V. Zhukov *et al.*, Phys. Rep. **231**
- 1993: Coulomb dissociation
  - K. Ieki *et al.*, Phys. Rev. Lett. **70**
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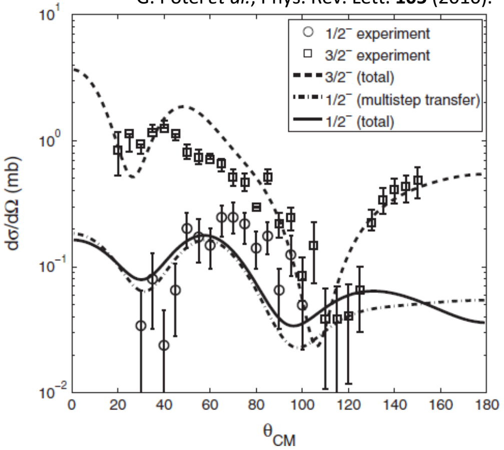
  - Yu. Aksyutina *et al.*, Phys. Rev. B **718**
- 2013: Core excitation
  - Y. Kikuchi *et al.*, Phys. Rev. C **87**

G. Potel *et al.*, Phys. Rev. Lett. **105** (2010).



^{9}Li core in ^{11}Li ground state is not inert.

- c.f. α core in ^{6}He.

→ *E*1 sum rule value is reduced by ~15%.

$$\langle \theta_{12} \rangle = 48^{+14}_{-18} \text{ degrees}$$

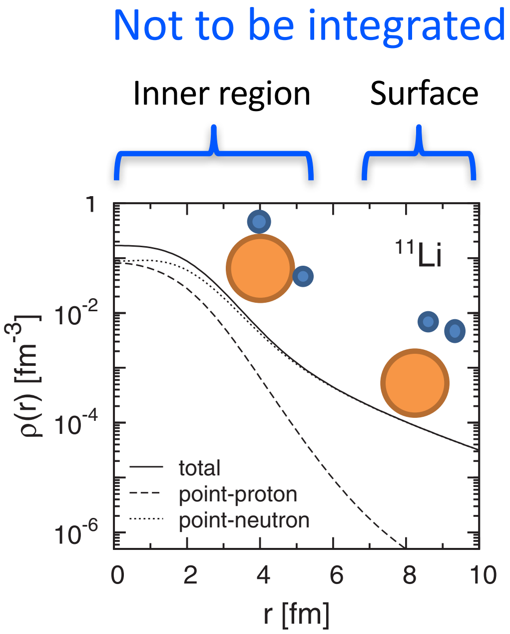
→ ~ 65±11 degrees

→ Large model dependence

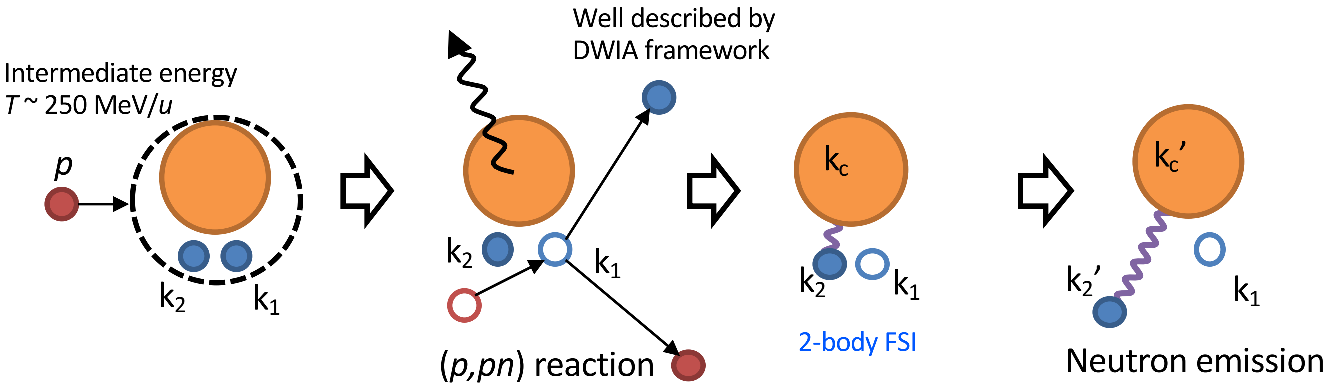
Goal

- Model-independent extraction of the momentum (spatial) distribution.

- Behavior of dineutron as a function of radius.
  - Is it emerging only near the surface or also in the inner region?



Quasi-free (*p,pn*) on Borromean nuclei

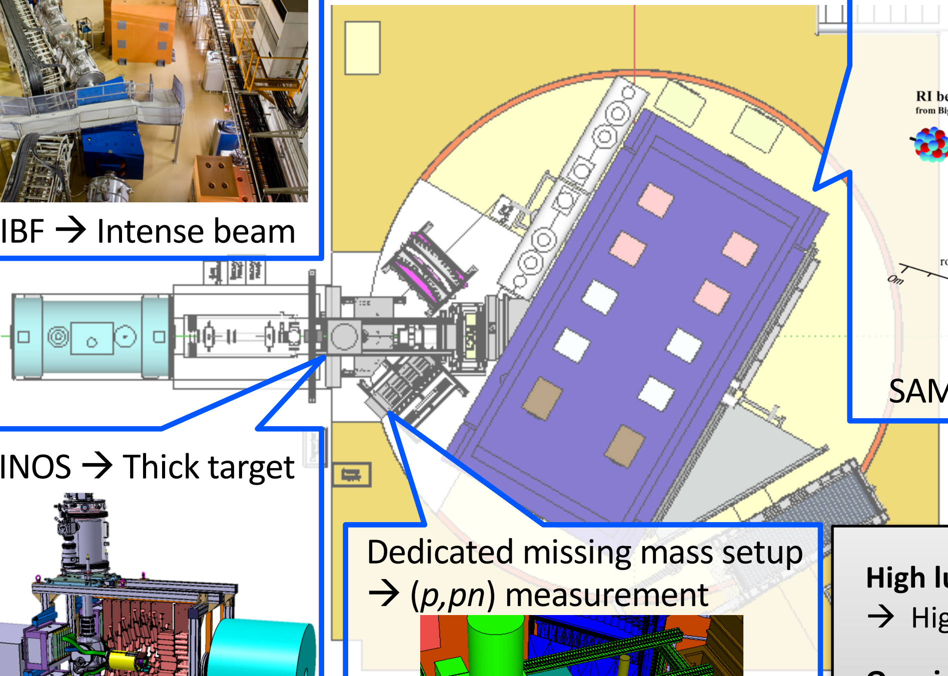


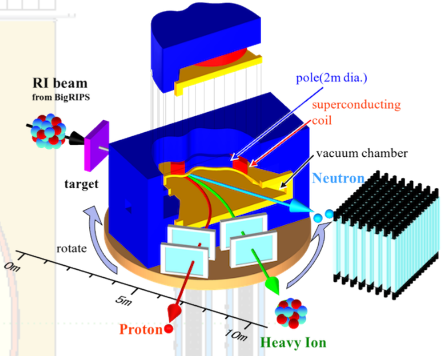
- Momentum is directly measured. → spatial configuration (Fourier tr.)
- Effect of FSI is minimized.
  - 3-body FSI … energies and momenta can be exchanged among subsystems.
  - ➔ ✔ 2-body FSI … fully described by Lippmann-Schwinger equation.
    → Reliable reconstruction of ground state correlation.
- Transparent probe.
  - c.f. Neutron removal reaction induced by nuclear target = surface probe
    - H. Simon *et al.*, Phys. Rev. Lett. **83**, 496 (1999).
- Pioneering experiment at GSI.
  - Yu. Aksyutina *et al.*, Phys. Rev. B **666**, 430 (2008).

Experimental setup

Cocktail beam:
^{11}Li (180 kpps)
^{14}Be (25 kcps)
^{17}B (18 kcps)
^{19}B (0.1 kcps)

RIBF → Intense beam

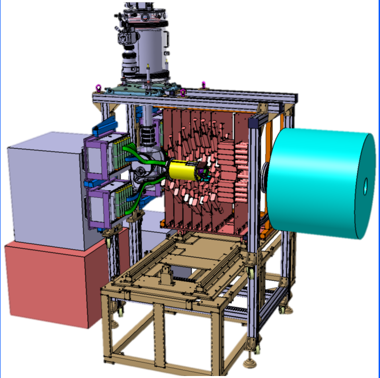




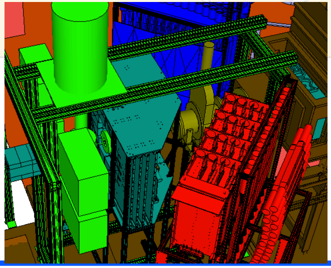
SAMURAI → Large acceptance

15-cm-thick
Liquid H_2
= 1 g/cm^2

MINOS → Thick target



Dedicated missing mass setup
→ (*p,pn*) measurement



High luminosity
→ Higher multipole extraction

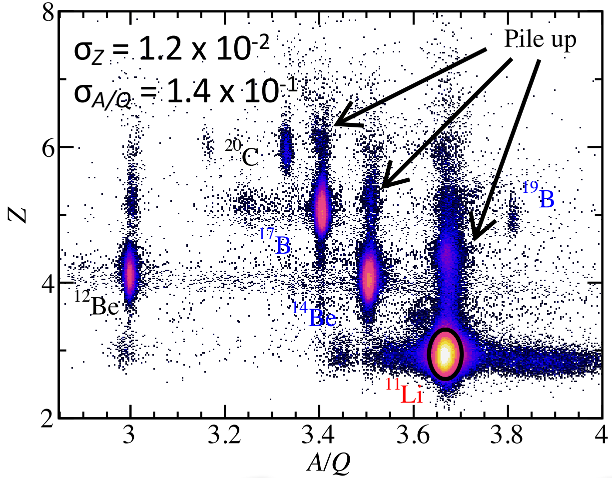
Quasi-free (*p,pn*) reaction
→ Minimization of FSI

Kinematical complete measurement
→ Tagging of core excitation

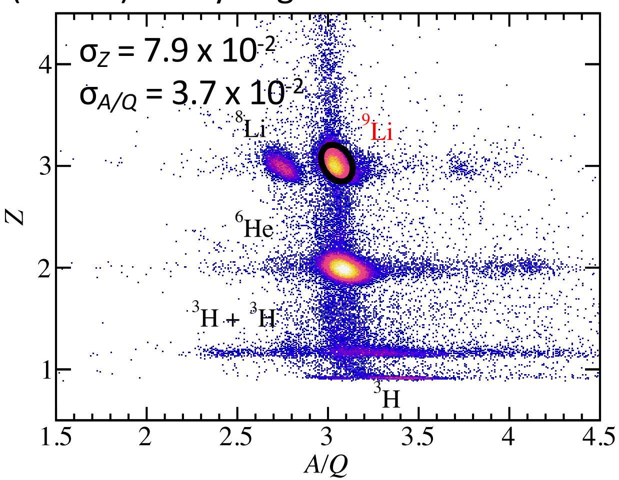
PRELIMINARY RESULTS

^{11}Li(p,pn)^{9}Li + n channel

Beam PID



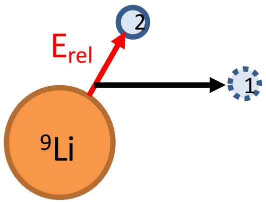
(Part of) Heavy fragment PID for ^{11}Li beam



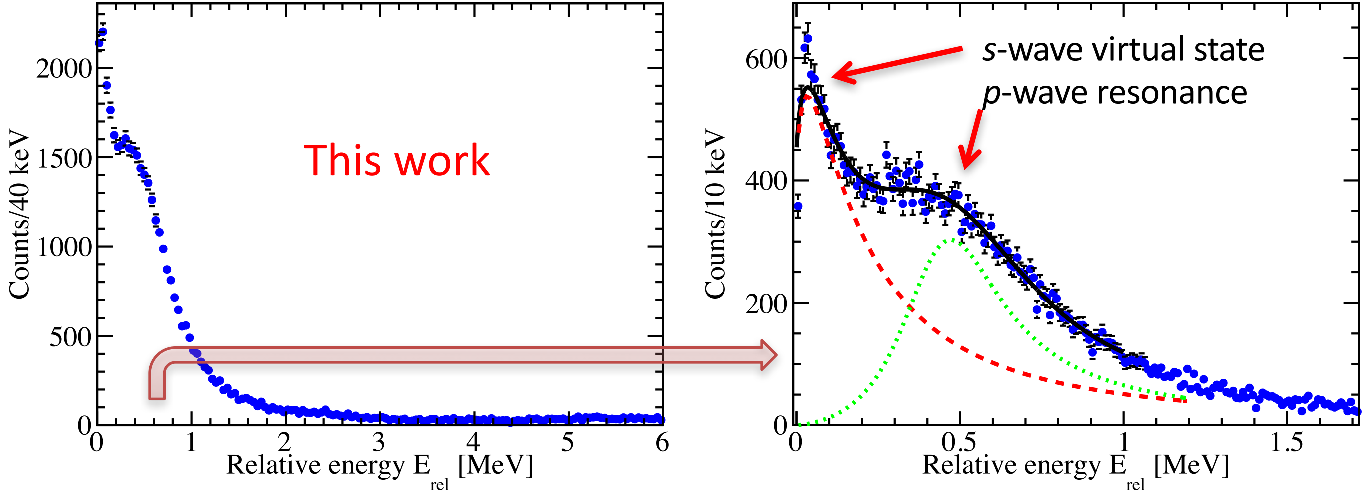
Borromean cocktail beam: ^{11}Li, ^{14}Be, ^{17}B, ^{19}B

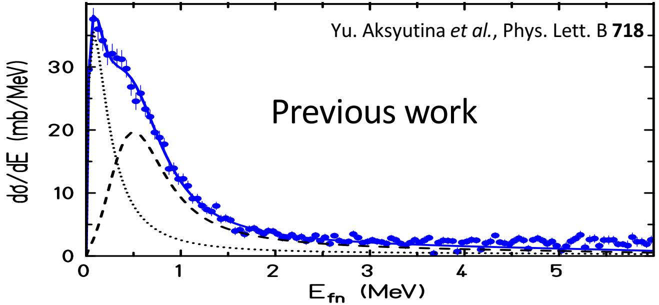
→ (p,pn) → ^{10}Li* →

- ^{9}Li + n → This channel was analyzed and presented in this talk
- (^{9}Li + n + γ)
- ^{8}Li + n + n
- ^{8}Li + n + n + γ
- ^{7}Li + n + n + n
- ^{7}Li + n + n + n + γ
- ^{6}He + p + n + n + n
- …



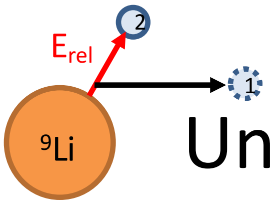
^{10}Li invariant mass spectrum: Better resolution and statistics



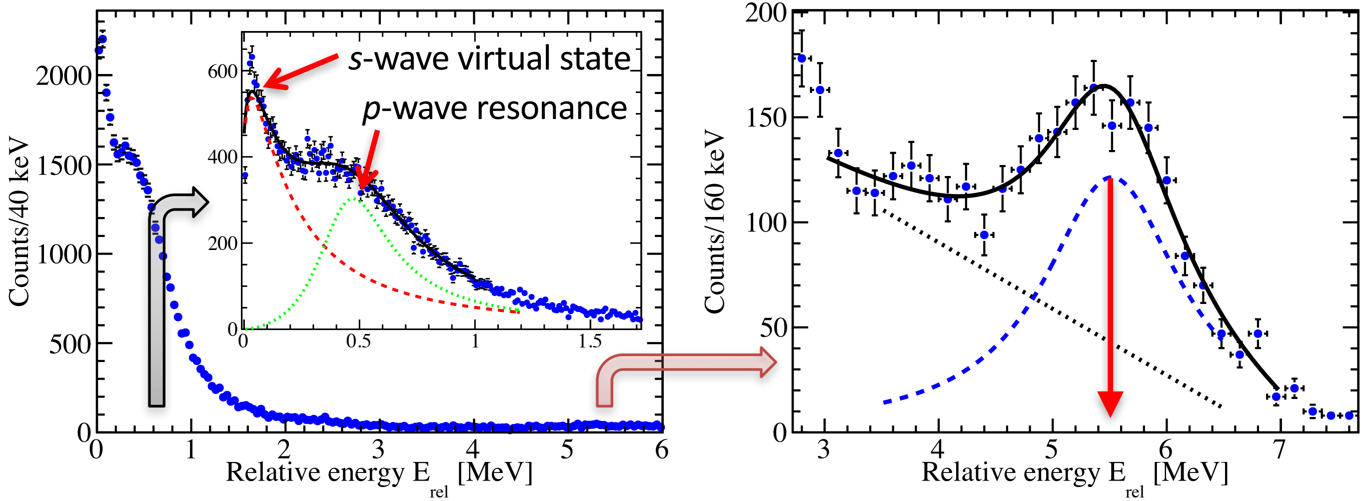


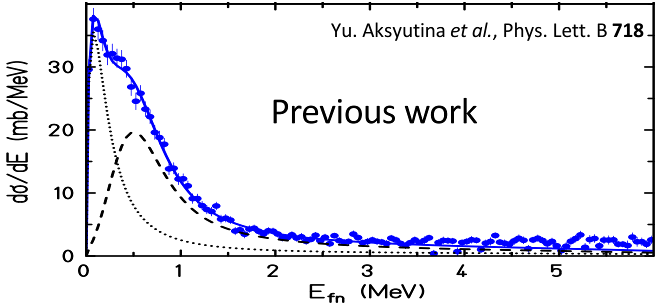
	s-wave virtual state		p-wave resonance	
a	$-17.0(1.3)$ fm	E_r	$0.514(6)$ MeV	This work
ϵ	(fixed at 0.352 MeV)-	Γ	$0.38(19)$ MeV	
a	$-22.4(8)$ fm	E_r	$0.566(14)$ MeV	[1]
ϵ	$0.352(22)$ MeV	Γ	$0.548(30)$ MeV	
a	-30^{+12}_{-31} fm	E_r	$0.510(44)$ MeV	[2]
ϵ	0.3 MeV	Γ	$0.54(16)$ MeV	
a	$-24 \leq a \leq -13$ fm	E_r	≈ 0.4 MeV	[3]
ϵ	-	Γ	≈ 0.2 MeV	

[1] Yu. Aksyutina et al., Phys. Lett. B **666**, 430 (2008).
[2] H. Simon et al., Nucl. Phys. A **791**, 267 (2007).
[3] H. B. Jeppesen et al., Nucl. Phys. A **745** 155 (2004).



^{10}Li invariant mass spectrum: Unexpectedly narrow resonance is found





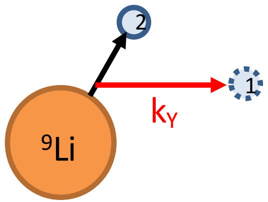
New resonance:

- E_r = 5.52±0.04 MeV
- Γ = 0.72±0.10 MeV
- *d*-wave resonance

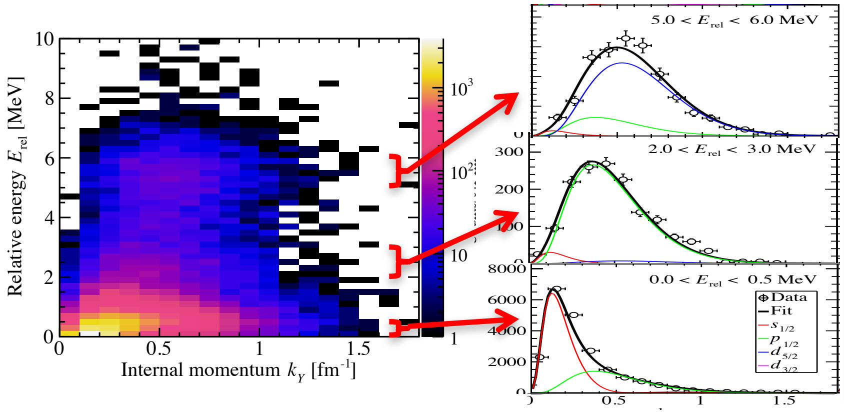
  → Multipole decomposition analysis (next page)

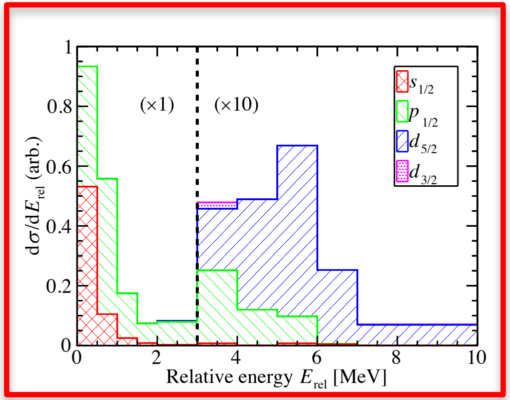
E_r and Γ cannot be reproduced simultaneously.

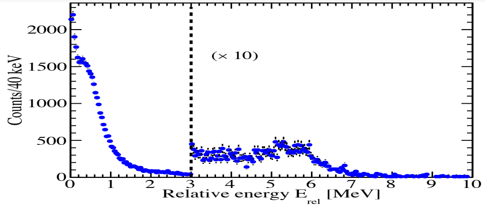
→ Test case for ^9Li-*n* interaction.



Angular momentum determination





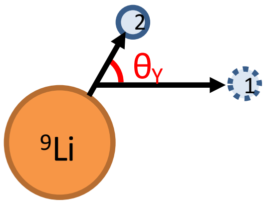


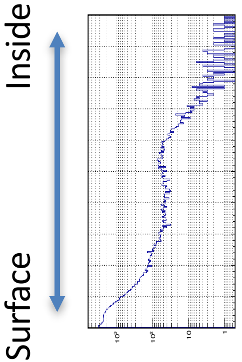
		$(s_{1/2})^2$	$(p_{3/2})^2$	$(p_{1/2})^2$	$(d_{5/2})^2$	$(d_{3/2})^2$
	This work	35 ± 4	$0^{(*1)}$	59 ± 1	6 ± 4	
Exp.	[1] Neutron removal	45 ± 10	3–5	55 ± 10		
	[2] Neutron removal	45 ± 10	3–5	45 ± 10	10 ± 8	
	[3] (*p*,*pn*)				11 ± 2	
Theor.	[4] C. C. 3-body model	44.0	2.5	46.9	3.1	1.7
	[5] Reaction x-sec.	33 ± 6				
	[6] TOSM	46.9	2.5	42.7	4.1	1.9

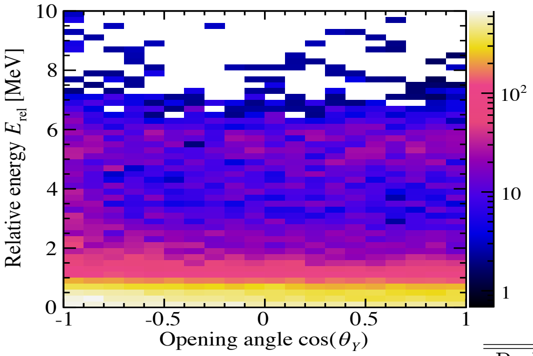
- Components with $\ell>2$ are not taken account.
- Systematic uncertainty coming from the DWIA calculation is not included.

[1] H. Simon et al., Phys. Rev. Lett. **83**, 496 (1999).
[2] H. Simon et al., Nucl. Phys. A **791**, 267 (2007).
[3] Yu. Aksyutina et al., Phys. Lett. B **718**, 1309 (2013).
[4] Y. Kikuchi et al., Phys. Rev. C **87**, 034606 (2013).
[5] H. T. Fortune et al., Phys. Rev. C **91**, 017303 (2015).
[6] K. Ikeda et al., *Clusters in Nuclei: Volume 1* (2010).

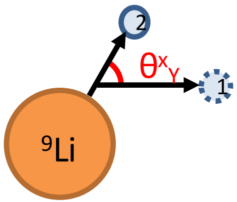
Opening angle: Behavior of dineutron



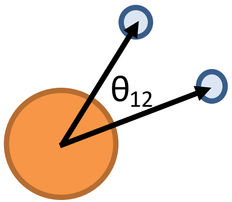




Jacobian "Y"-coordinate

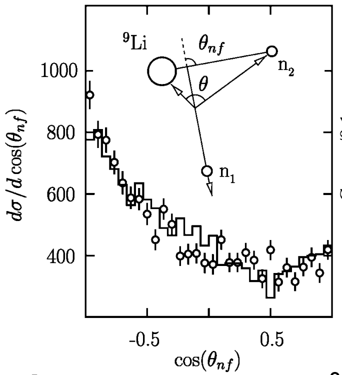


"V"-coordinate

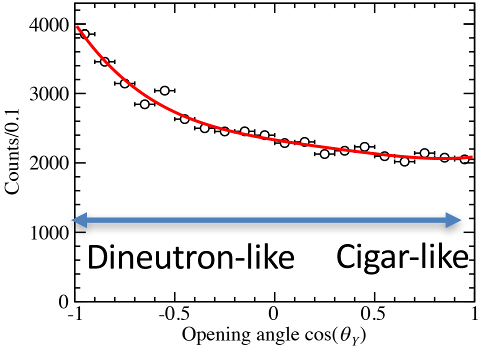


Probe	$\langle\theta^x_Y\rangle$ [deg.]	θ_{12} [deg.]	Reference
Coulomb breakup		48^{+14}_{-18}	[1]
+ Core excitation		65 ± 11	
		$65.2^{+11.4}_{-13.0}$	[2]
Compilation	72.2	61.7	[3]
Neutron removal	76.6(2.1)		[4]
This work	85 ± 10		

[1] T. Nakamura et al., Phys. Rev. Lett. **96**, 252502 (2006).
[2] K. Hagino and H. Sagawa, Few-Body Syst. **57**, 185 (2016).
[3] N. B. Shulgina et al., Nucl. Phys. **825**, 175 (2009).
[4] H. Simon et al., Phys. Rev. Lett. **83**, 496 (1999).

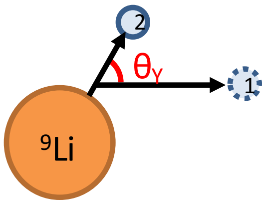


Ref. [4] → $\langle\theta^x_Y\rangle = 76.6 \pm 2.1^\circ$

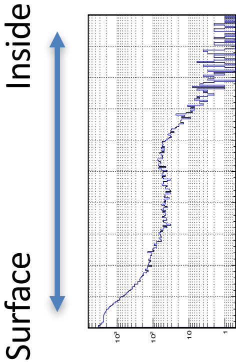


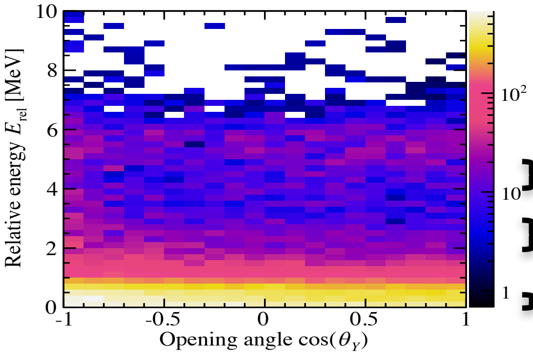
→ $\langle\theta^x_Y\rangle = 85 \pm 10^\circ$

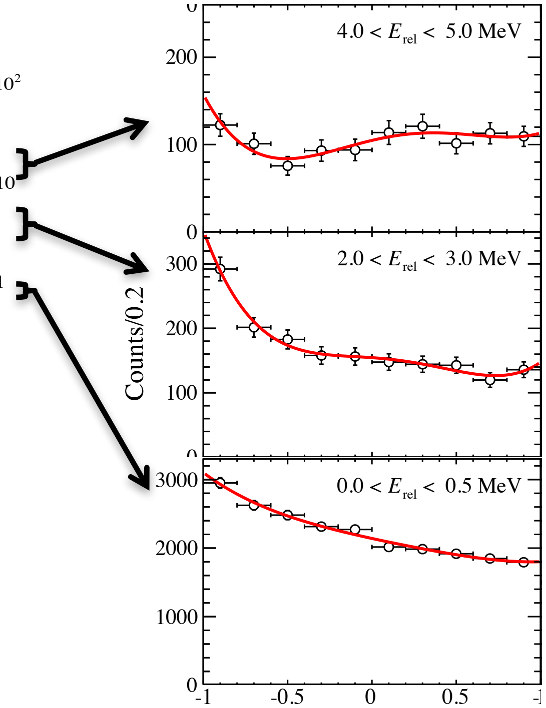
- Dineutron correlation is observed.
- Weaker dineutron is indicated.



Opening angle: Behavior of dineutron

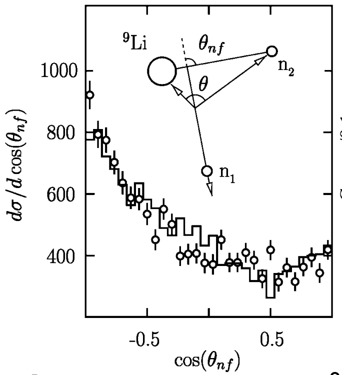


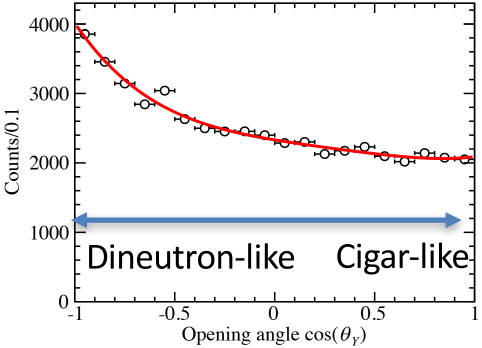




Weaker correlation inside

Dineutron at surface





Ref. [4] → $\langle \theta^x_Y \rangle = 76.6 \pm 2.1^\circ$

→ $\langle \theta^x_Y \rangle = 85 \pm 10^\circ$

- Dineutron is developed at the surface.

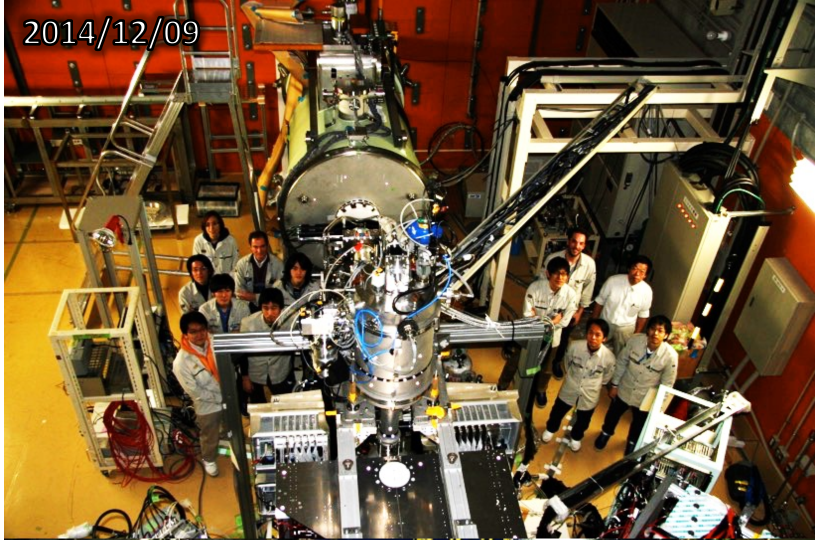
Collaborators

Experimentalists:

<u>Y.Kubota</u>, M.Dozono, Y.Kiyokawa, M.Kobayashi, S.Ota (CNS); H.Baba, T.Isobe, T.Motobayashi, H.Otsu, V.Panin, M.Sako, M.Sasano, H.Sato, Y.Shimizu, L.Stuhl, T.Uesaka, K.Yoneda, J.Zenihiro (RNC); **A.Corsi**, G.Authelet, D.Calvet, A.Delbart, J.-M.Gheller, A.Gillibert, V.Lapoux, A.Obertelli, E.C.Pollacco, J.-Y.Roussé, C.Santamaria (Saclay); C.Caesar, S.Paschalis (TU Darmstadt); J.Feng, Z.H.Yang (Peking Univ.); F.Flavigny (Orsay); J.Gibelin, F.M.Marqués, N.A.Orr (Caen); K.Hasegawa, T.Kobayashi, T.Sumikama (Tohoku); Y.Kanaya, S.Kawakami, Y.Maeda (Miyazaki); D.Kim (Ehwa Womans Univ.); N.Kobayashi, S.Koyama, T.Miyazaki (Tokyo); Y.Kondo, T.Nakamura, T.Ozaki, A.Saito, M.Shikata, Y.Togano, J.Tsubota (TITECH); Z.Korkulu (ATOMKI); N.Nakatsuka (Kyoto); Y.Nishio, A.Ohkura, S.Sakaguchi, Y.Shindo, M.Tabata, J.Yasuda (Kyushu); S.Reichert (TU Munich)

Theorists:

Y.Kikuchi (RNC); K.Ogata (RCNP)

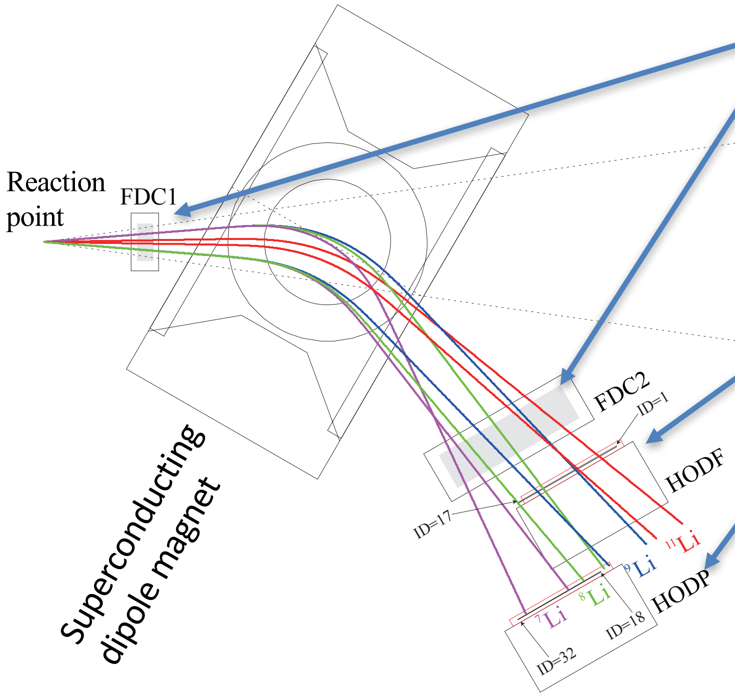


Summary

- Quasi-free (*p,pn*) measurement on Borromean nuclei ^{11}Li, ^{14}Be, ^{17,19}B for the study of neutron-neutron correlation.
  - ✔ High luminosity → Higher multipole decomposition.
  - ✔ Quasi-free (*p,pn*) → Minimum FSI.
  - ✔ Kinematical complete measurement → Core excitation.

- ^{11}Li(*p,pn*)^{10}Li*→^{9}Li+*n* channel was analyzed.
  - New *d*-wave resonance in ^{10}Li at E_r = 5.52 MeV, Γ = 0.72 MeV.
  - Neutron wave function *s*:*p*:*d* = 35:59:6.
  - Integrated opening angle $\langle\theta^{x}_{Y}\rangle$ = 85±10°
    - → Indication of "weaker" dineuton correlation.
  - Dineutron correlation develops at the surface.

Heavy fragment (SAMURAI)



Two sets of MWDCs (FDC1, FDC2)
→ Incident/outgoing angles, positions

Plastic scintillator hodoscope (HODF, HODP)
→ TOF, ΔE

→Rigidity reconstruction

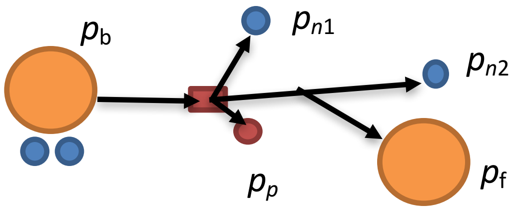
Incident angle/position
+ field strength
+ rigidity (free param.)
→ outgoing position (calc.)

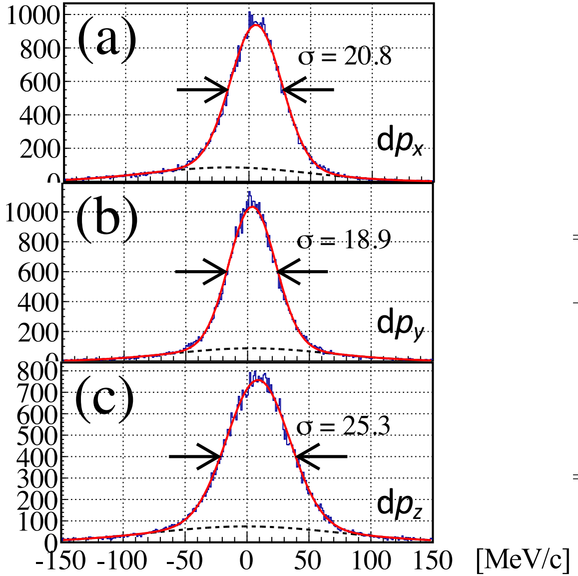
Overall check of detector responses

Momentum conservation:

$p_{\mathrm{b}} + 0 = p_p + p_{n1} + p_{n2} + p_{\mathrm{f}}$

$\rightarrow dp := p_p + p_{n1} + p_{n2} + p_{\mathrm{f}} - p_{\mathrm{b}} = 0$





Width = Straggling + Resolution

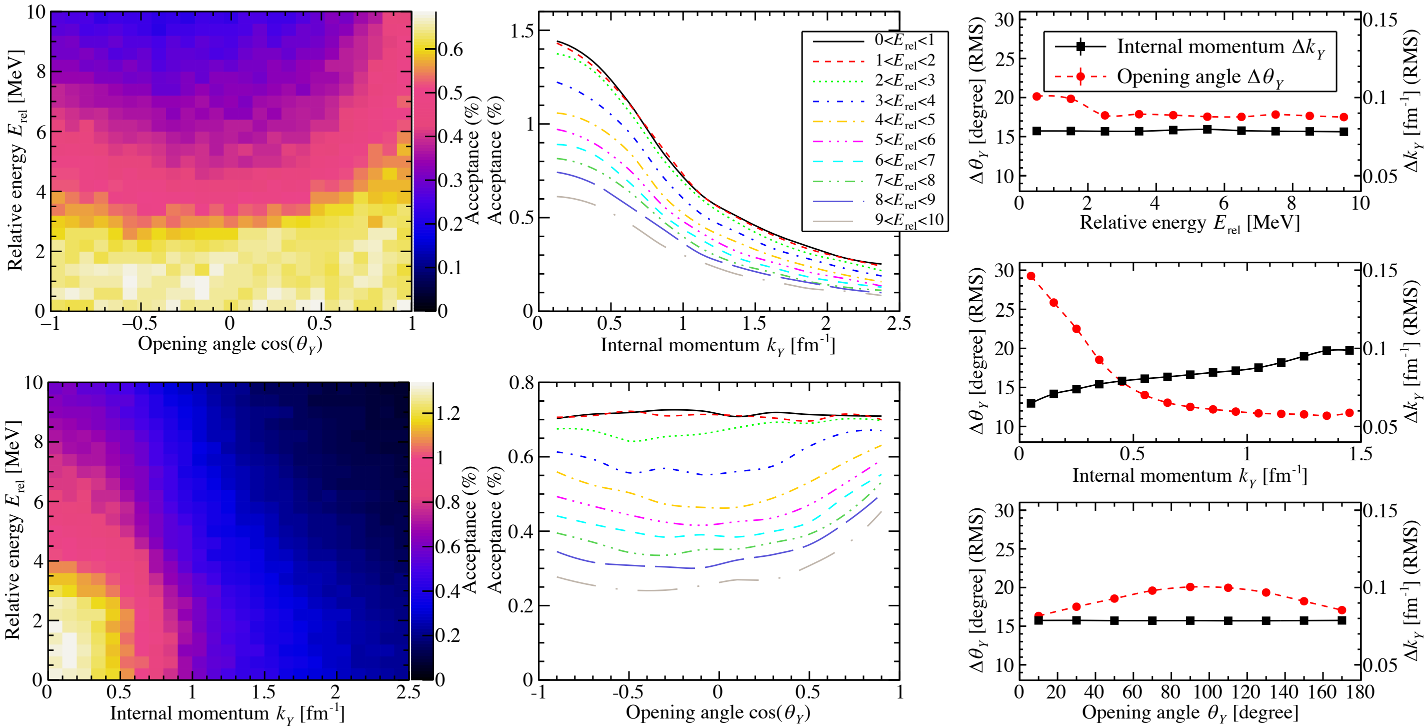
Direction	Experiment	Straggling (Simulation)	Resolution (Simulation)	Simulation total
x	48.9	31.0	43.7	53.1
y	44.4	31.5	29.0	43.4
z	59.4	19.9	59.0	61.7

Designed: ~ 50

Unit is MeV/c, in FWHM.

All the detectors worked well and were reasonably calibrated.

Monte-Carlo simulation for acceptance/resolution evaluation



→ No singularity. No problem for “correlation study”.