Background study for an Axion-like Particle Search at the DAMSA Experiment

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On behalf of the DAMSA collaboration

2021.08.11

Workshop Darkness on the table (Busan)

Contents

Search for Axion-like Particles at DAMSA

With the 2012 discovery of the Higgs boson at CERN and its increasingly Standard Model-like properties, **the primary interests of the field of particle physics** are the study of the **remaining 95% of the matter and energy** in the universe, using accelerators.

unseen aboriginal particles (UAPs)

DAMSA experiment is proposed, as a part of ARI^{3}AA project, **to search ALPs in the low-energy and high-intensity proton beams facility** at RAON (2028~) in Korea.

ARI^{3}AA: A Research Innovation and Infrastructure Initiative for the discovery of unseen Aboriginal particles at Accelerators project

The Thinker by François Auguste René Rodin (1879–1889)

DAMSA: **Dump produced Aboriginal Matter Searches at an Accelerator**

- Fixed target experiment based on intensive proton beam accelerator
- To search for Axion-like Particle (ALP) in sub-GeV energy regime

담사 (damsa, 潭思) → thinking deeply (깊이 생각하는 것)
→ deep thought (깊은 생각)

DAMSA collaboration

- 4 theorists and 6 experimentalists from 9 universities

Theorists

Jong-Chul Park
(Chungnam Nat'l Univ.)

Seodong Shin
(Chonbuk Nat'l Univ.)

Doojin Kim
(Texas A&M)

Kyoungchul Kong
(U. of Kansas)

Experimentalists

Youngjoon Kwon
(Yonsei University)

Inkyu Park
(Univ. of Seoul)

Min Sang Ryu
(Kyungpook Nat'l Univ.)

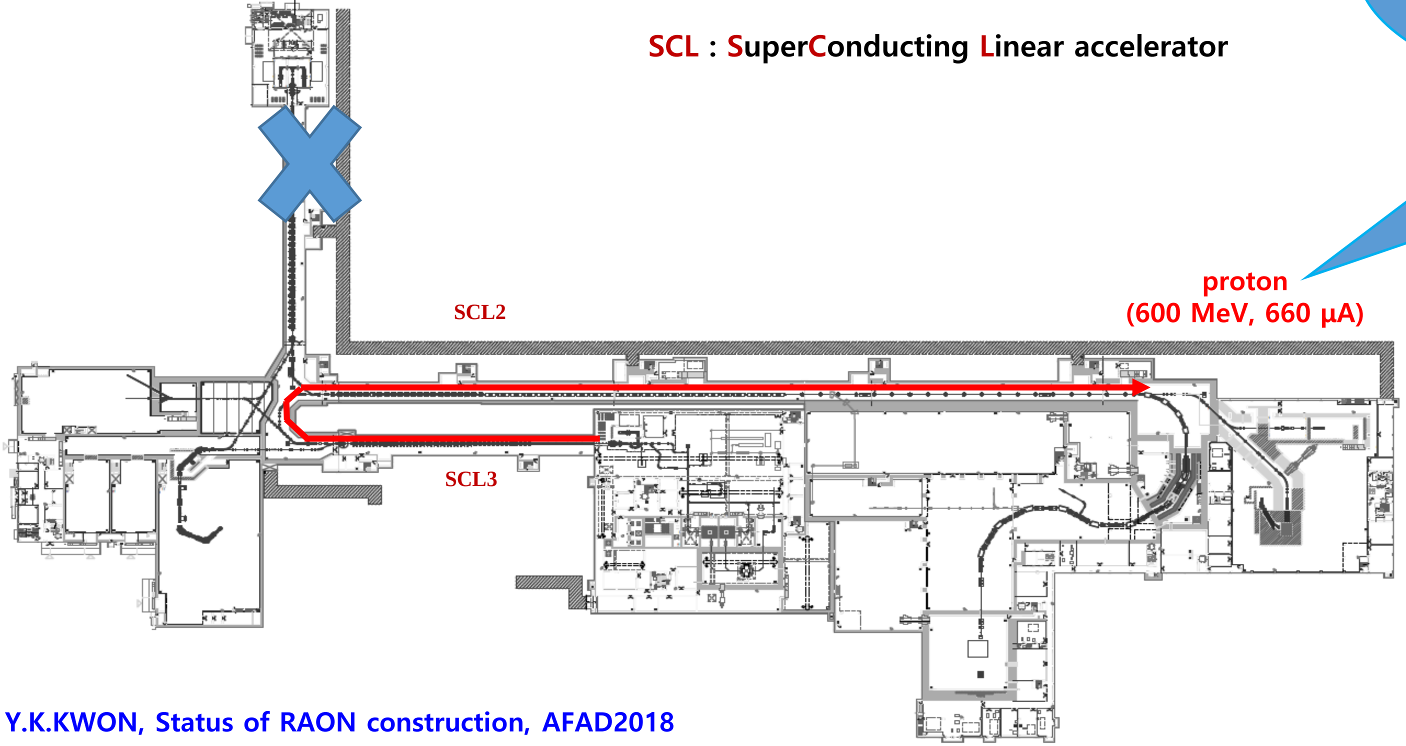
Un-Ki Yang
(Seoul Nat'l University)

Wooyoung Jang and **Jaehoon Yu**
(U. of Texas at Arlington)

Beam dump experiment at RAON

RAON (Rare isotope Accelerator complex for ON-line experiments)

SCL : SuperConducting Linear accelerator



RAON will provide an excellent opportunity to search for the ALPs with 600 MeV proton beams (660 uA).

Y.K.KWON, Status of RAON construction, AFAD2018

The RAON is the rare isotope accelerator and experimental facilities for the nuclear science with the **proton and RI beams.**

It consists of two main accelerators, called SCL2 and SCL3, and several experimental facilities. The SCL3 and SCL2 will be constructed in 2021 and 2028, respectively.

The expected number of protons on the target (POT) per year is ~1.5×10^{23}.

Min Sang RYU's talks at APS and KPS in 2021
Study of Neutron Induced Electro-magnetic Backgrounds to an Axion-like Particle Search at the DAMSA Experiment

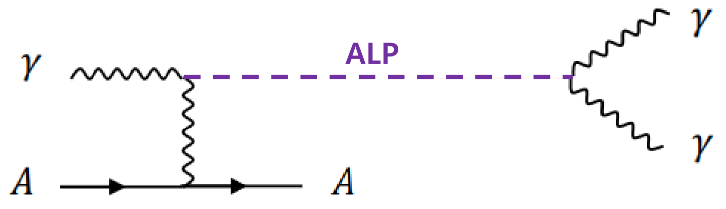
Doojin KIM's talks at APS and KPS in 2021
- X20.00006 in 2021 APS April Meeting
  Searching for Axion-like Particles at Rare Nuclear Isotope Accelerator Facilities
- F1.04 in 2021 KPS Spring Meeting
  Search for Axion-like Particles at the DAMSA experiment

Raon User Workshop in 21-23 July 2021
https://indico.ibs.re.kr/event/434/
Jaehoon Yu's talk: A proposal for DAMSA Experiment
Doojin Kim's talk: DAMSA: An Axion-like Particle Search at the RAON Facility

WooYoung Jang's talk at DPF21 of APS in July 2021
A neutron-induced background mitigation study for Axion-like Particle search at RAON Facilities

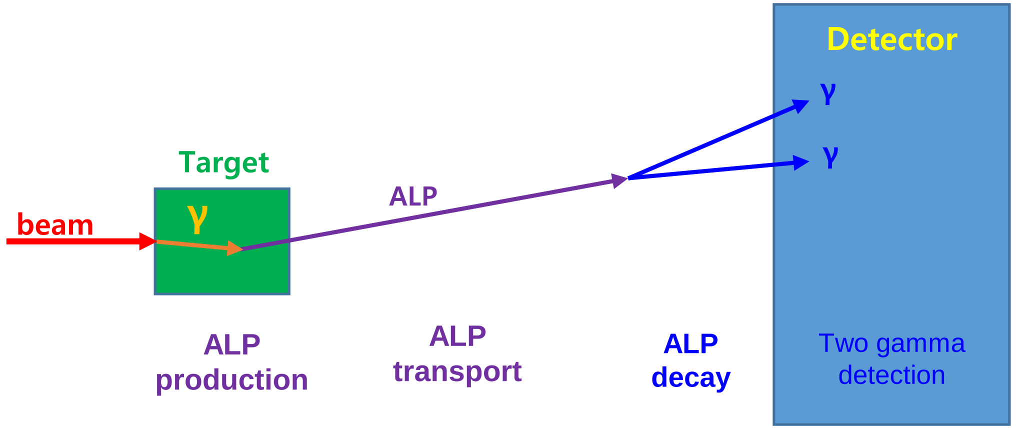
ALP production by Primakoff process

Production and detection of ALPs



Primakoff process

ALP decay



Primakoff process

$$\gamma\,(p_1) + A\,(p_2) \;\rightarrow\; a(k_1) + \; N(k_2)$$

Production cross-section of ALPs

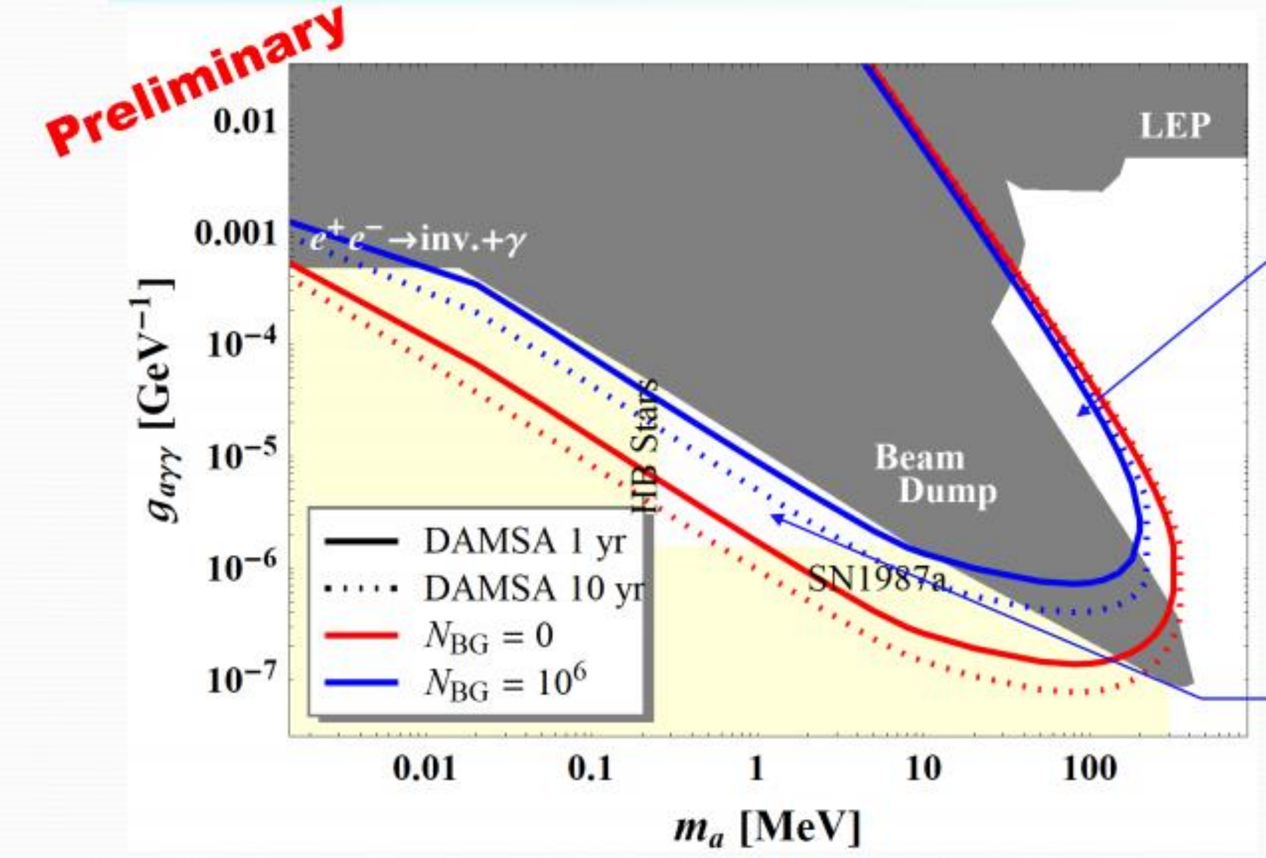
$$\frac{d\sigma_P^p}{d\cos\theta} = \frac{1}{4} g_{a\gamma\gamma}^2 \alpha Z^2 F^2(t) \frac{|\vec{p}_a|^4 \sin^2\theta}{t^2}$$

$$t = (p_1 - k_1)^2 = m_a^2 + E_\gamma (E_a - |\vec{p}_a| \cos\theta)$$

Z: atomic number,
α: fine structure constant
$F(t)$: form factor
$|\vec{p}_a|$: magnitude of the outgoing three-momentum of the ALP at the angle θ relative to the incident photon momentum
E_γ: incident photon energy

Expected ALP sensitivity at DAMSA by Primakoff process

Doojin Kim's talk at Raon User Workshop in 21-23 July 2021, **DAMSA: An Axion-like Particle Search at the RAON Facility**



DAMSA can probe the ALP parameter region that has never been explored.

Short-lived ALPs (high mass)

DAMSA will cover part of the so-called "cosmological triangle" where only (standard) cosmology would constrain.

Long-lived ALPs (low mass)

According to above sensitivity, backgrounds treatment is much crucial for low mass ALPs detection.

GEANT4 simulation study

Goals of GEANT4 simulation study for DAMSA experiment

1) **Target material and structure** with iron (Fe) and tungsten (W) due to the Z dependency of σ_{ALP} (~ Z^2)

2) **Particle production rate in the target (Fe & W)** against the primary protons

3) **Detector geometry and angular coverage**

4) **Transportation rate of particle to the detector with E_{kin} (> 5 MeV)** against the primary protons
neutrino NC & CCQE interaction ➔ produce π^0 ➔ decay 2γ
neutron spallation: can be the worst background for the ALP search at the DAMSA experiment.

5) **Neutron-induced background mitigation study in the W target (latest study)**
- **neutron moderator (polyurethane)**
- **ALP Decay chamber (vacuum vessel)**

WooYoung Jang's talk at DPF21 of APS
A neutron-induced background mitigation study for Axion-like Particle search at RAON Facilities

NC: neutral current
CCQE: charged current quasi-elastic scattering

Setup of GEANT4 simulation

Physics List

Particles	Process name	Physics List
EM particles	Electromagnetic	G4EmStandardPhysics_option3
hadrons	Elastic	G4HadronElasticPhysics
	Inelastic	G4HadronPhysicsQGSP_BIC_AllHP
Isotopes (stable & unstable)	Decay	G4DecayPhysics
	Radioactive decay	G4RadioactiveDecayPhysics
Ions	inelastic	G4IonBinaryCascadePhysics

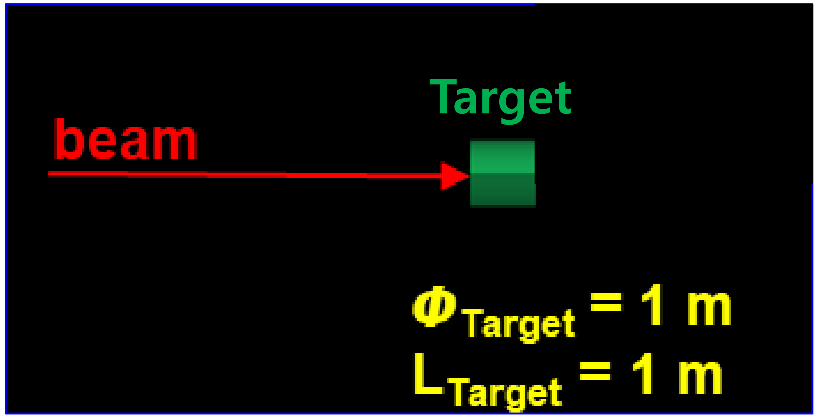
Quark-gluon string pre-compound (QGSP) model for collision of high-energy hadrons
Binary cascade (BIC) model for inelastic process of hadrons
High precision (HP) data for low-energy neutron and light ions

Energy threshold

Material	Z	A	Density (g/cm^3)	Energy threshold (keV) with 1 mm range cut			
				gamma	e-	e+	p, n, & d
Vacuum				0.99	0.99	0.99	100
Iron	26	56	7.874	20.6	1295.9	1211.7	100
Tungsten	74	184	19.35	106.6	2309.8	2130.8	100

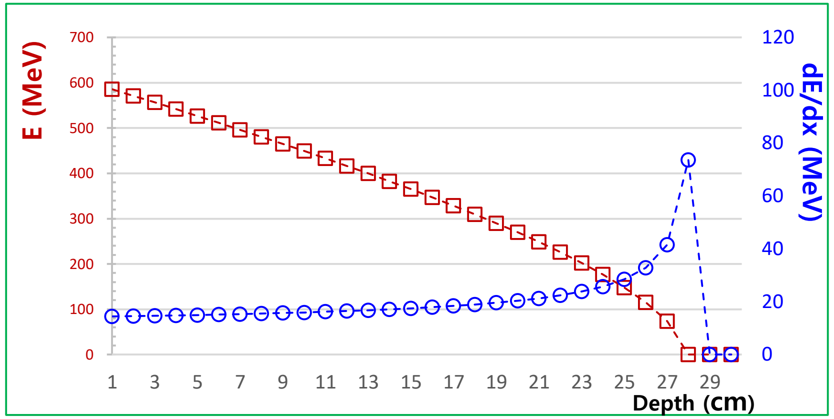
Interaction depth of 600 MeV protons in target

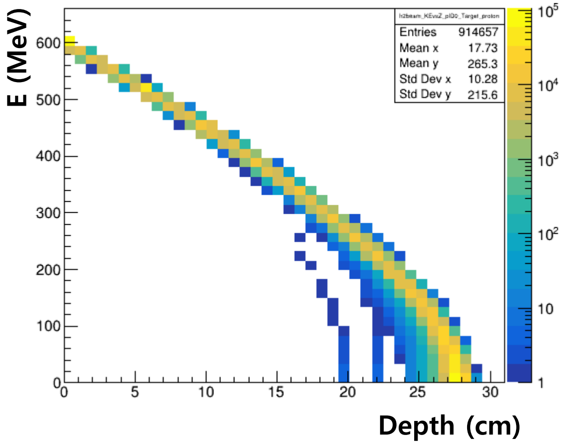
Beams on the target



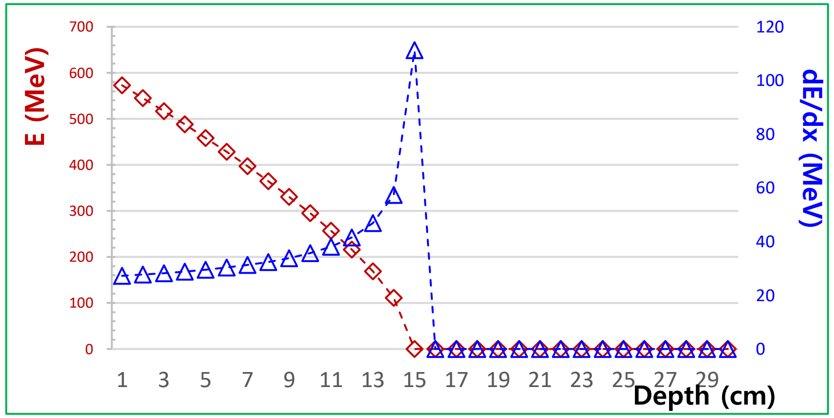
LISE++ | GEANT4

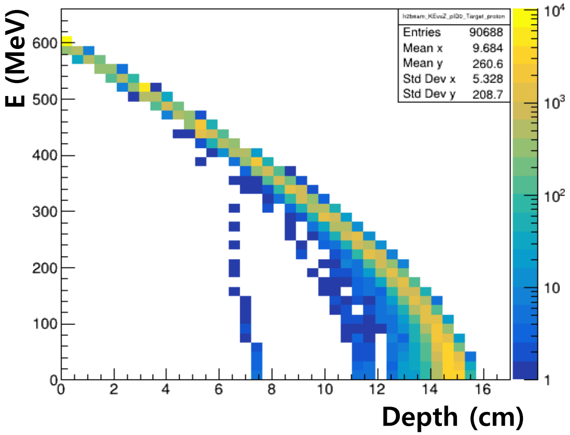
Iron (Fe)





Tungsten (W)





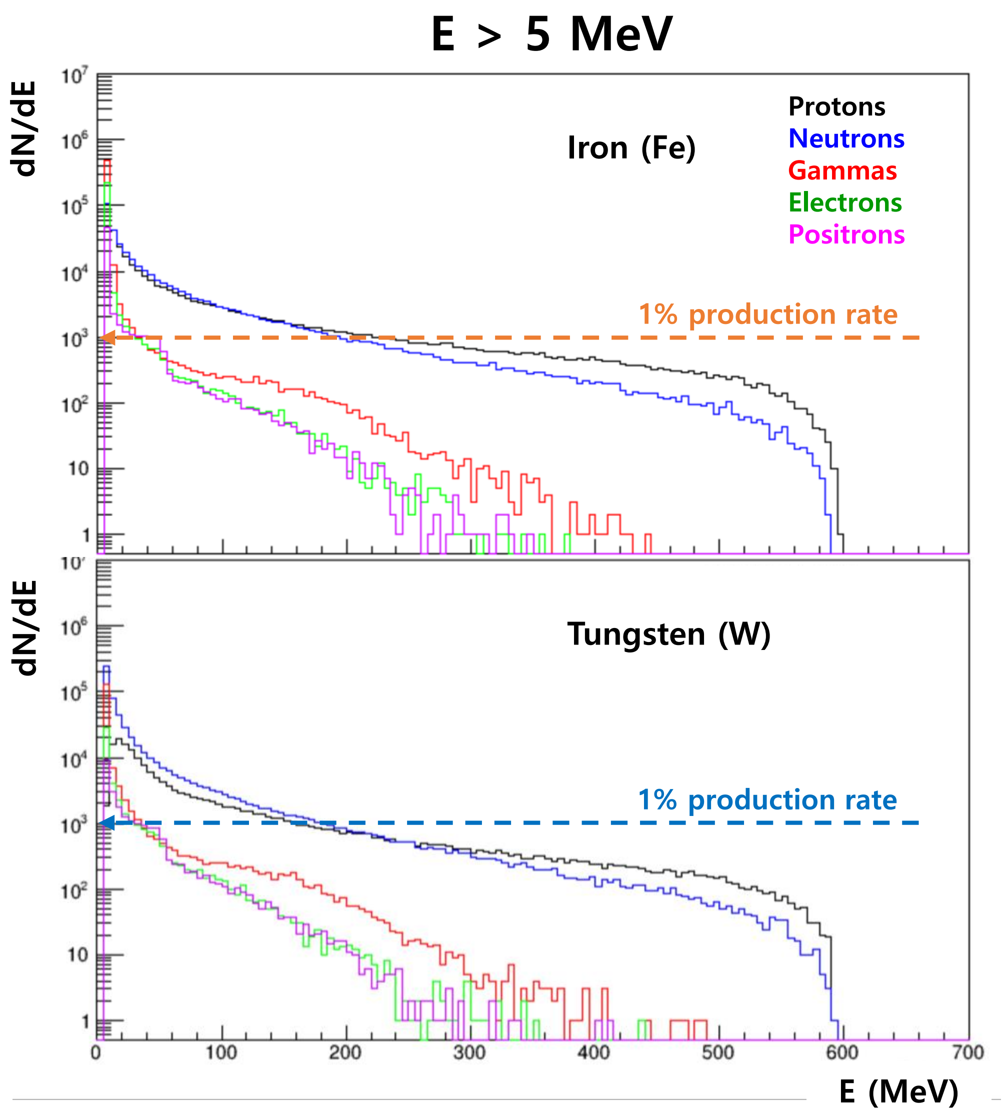
The length of full energy deposition ($L_{FullEdep}$) is decreased with the density of target materials.

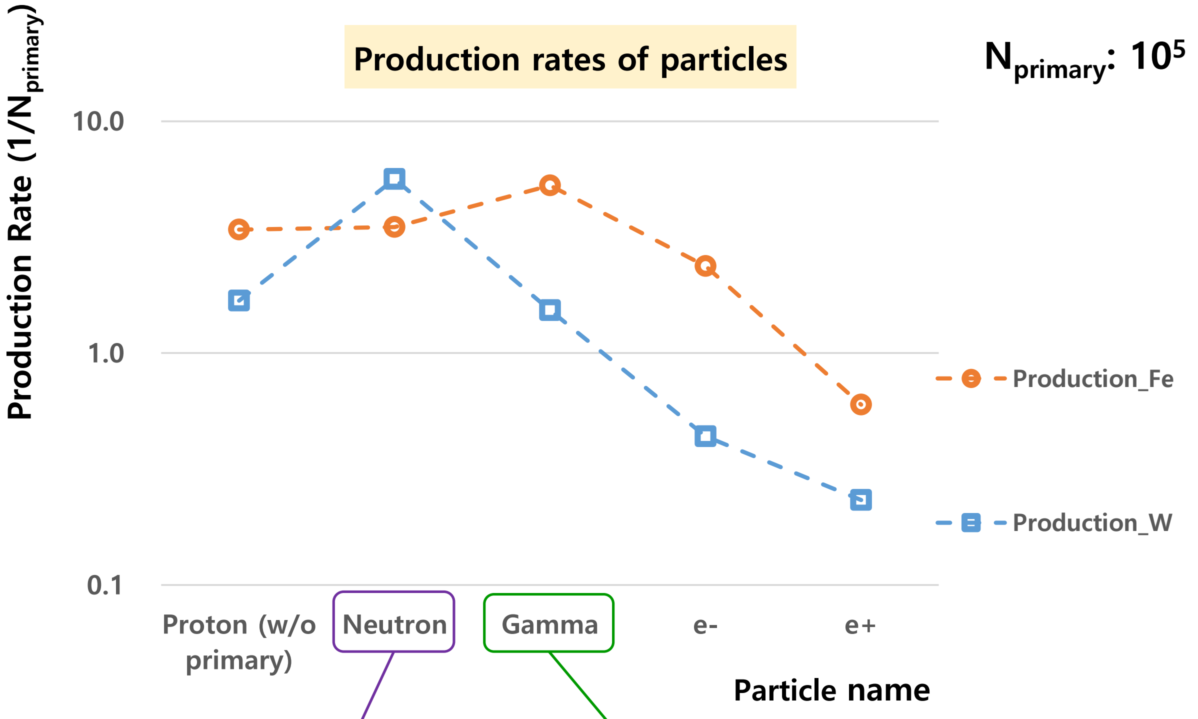
The ratio of the length of full energy deposition to nuclear interaction length (λ_{INT}) is similar value and dependency is not big.

The 600 MeV protons are stopped ~1.6λ_{INT}.

Material	Z	A	Density (g/cm^3)	Length of Full Energy deposition $L_{FullEdep}$ (cm)	Nuclear interaction length λ_{INT} (cm)	ratio ($L_{FullEdep}$ / λ_{INT})
Iron (Fe)	26	56	7.874	~28	16.77	~1.67
Tungsten (W)	74	184	19.35	~15	9.946	~1.56

Particle production rate in the targets



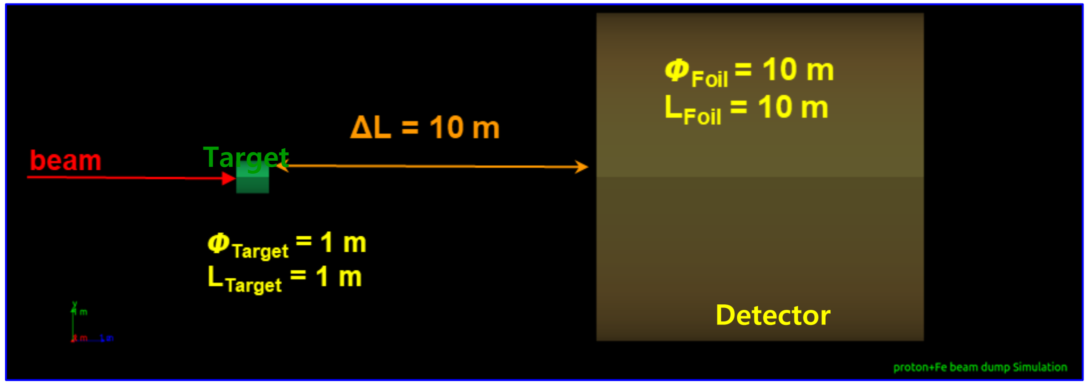


More **neutrons** in the tungsten target:
Production rate ~5.6 **in W**
~3.5 **in Fe**

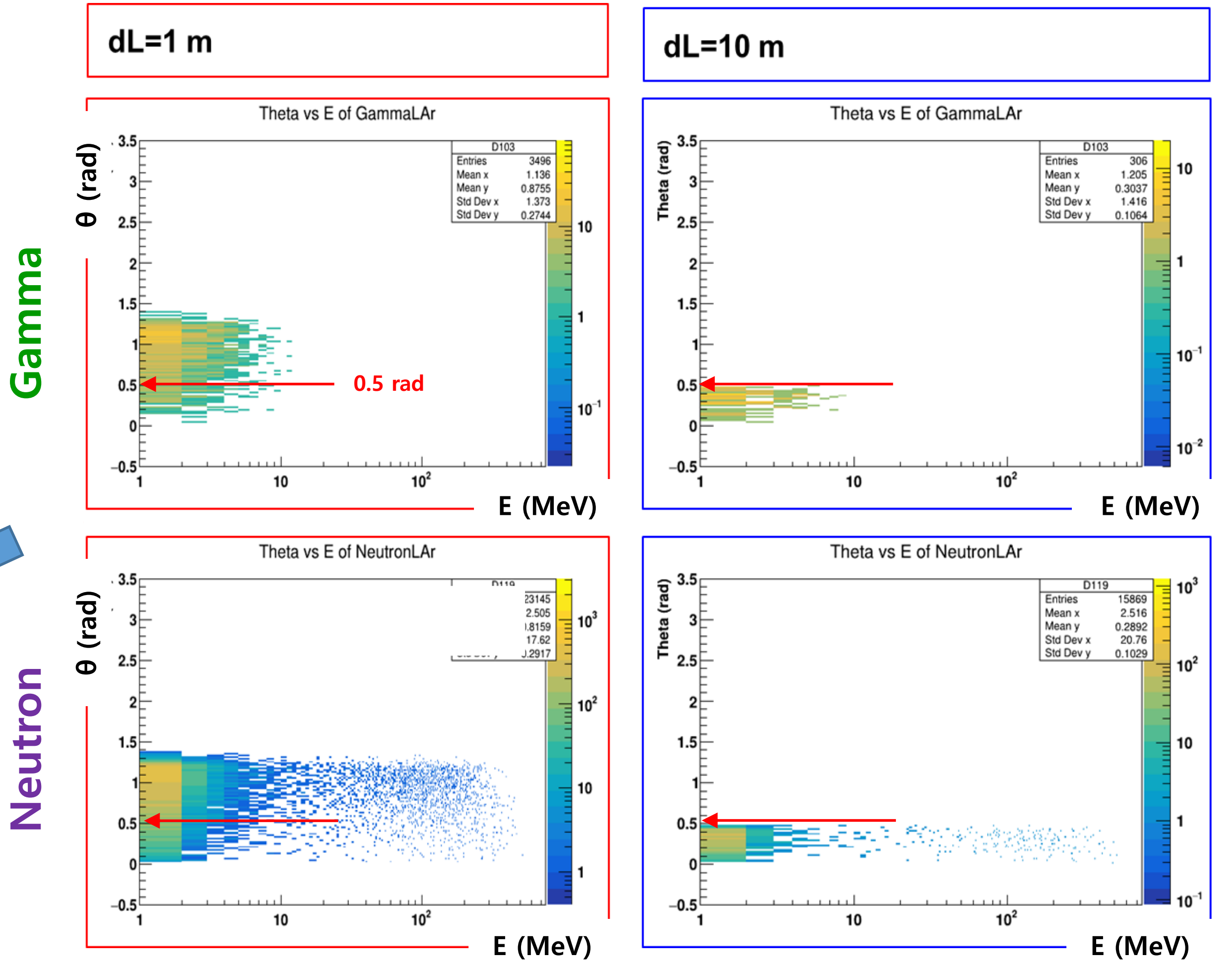
More **gammas** in the iron target:
Production rate ~5.3 **in Fe**
~1.5 **in W**

Detection acceptance at 1 & 10 m far from the target

600 MeV protons (10^5) on Iron (G4_Fe)



Correlation between polar angle and kinetic energy of neutrons and gammas



If we install the detector as close to the end of the target as possible, we can make a similar angular coverage as 10 m.

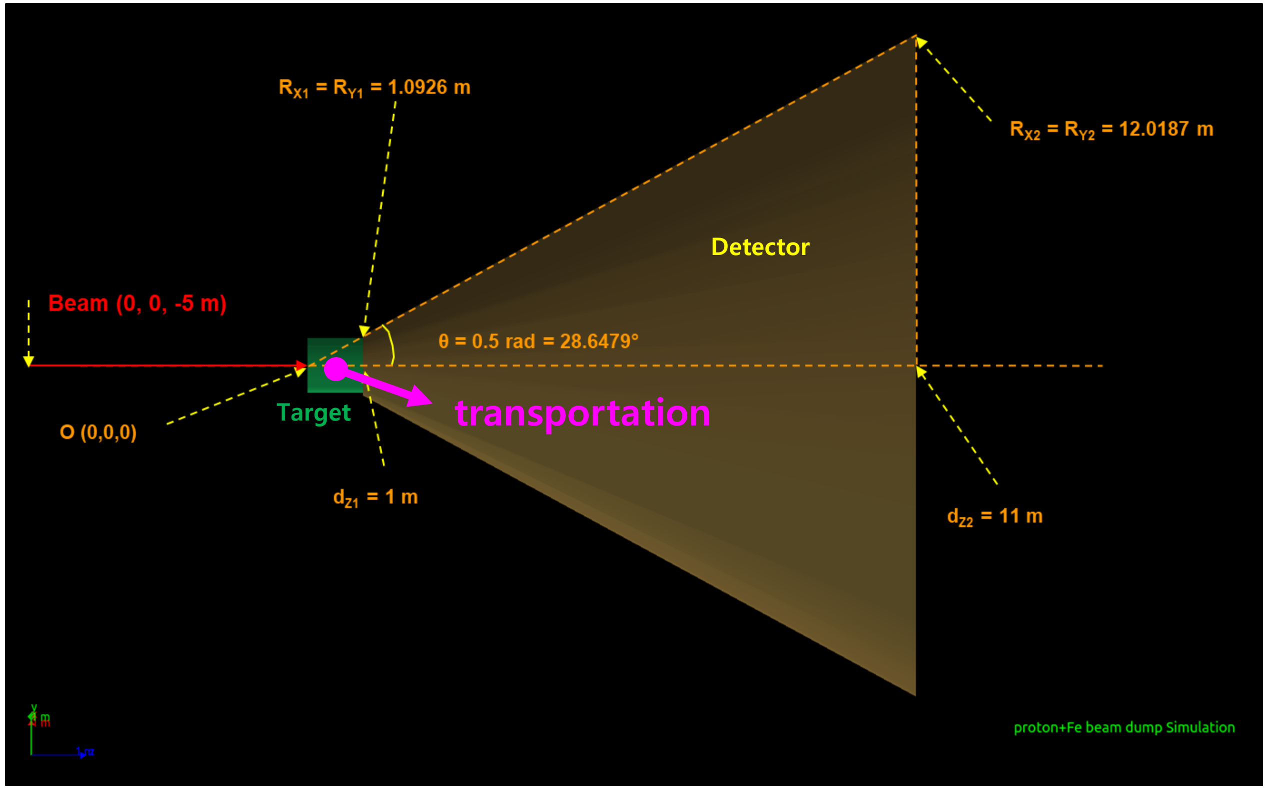
The new detector structure with the polar angle acceptance (θ < 0.5 rad) at the distance ΔL=0 m, can detect more signals from early ALP decay.

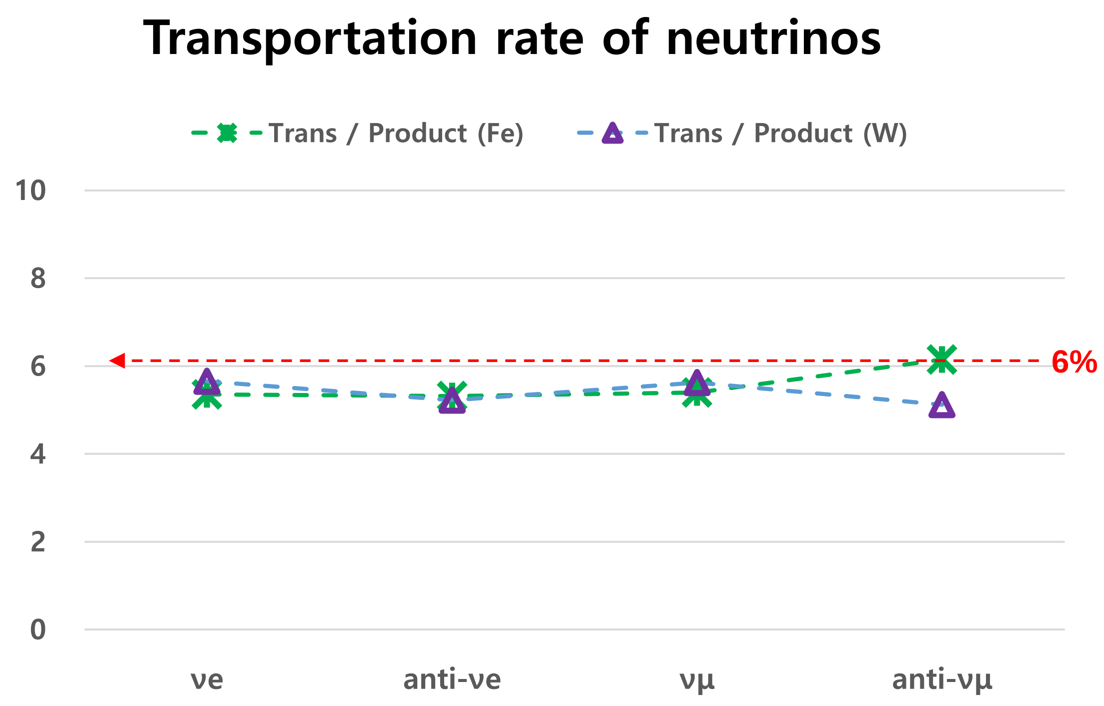
It means we have wider ALP mass range.

Transportation rate of neutrinos within angular coverage

New geometrical acceptance suggested to cover more ALP detection
- **Closest distance between dump and detector** ➔ $\Delta L = 0$ m
- **Polar angle acceptance (θ < 0.5 rad)**
  ➔ Trapezoidal shape of detector

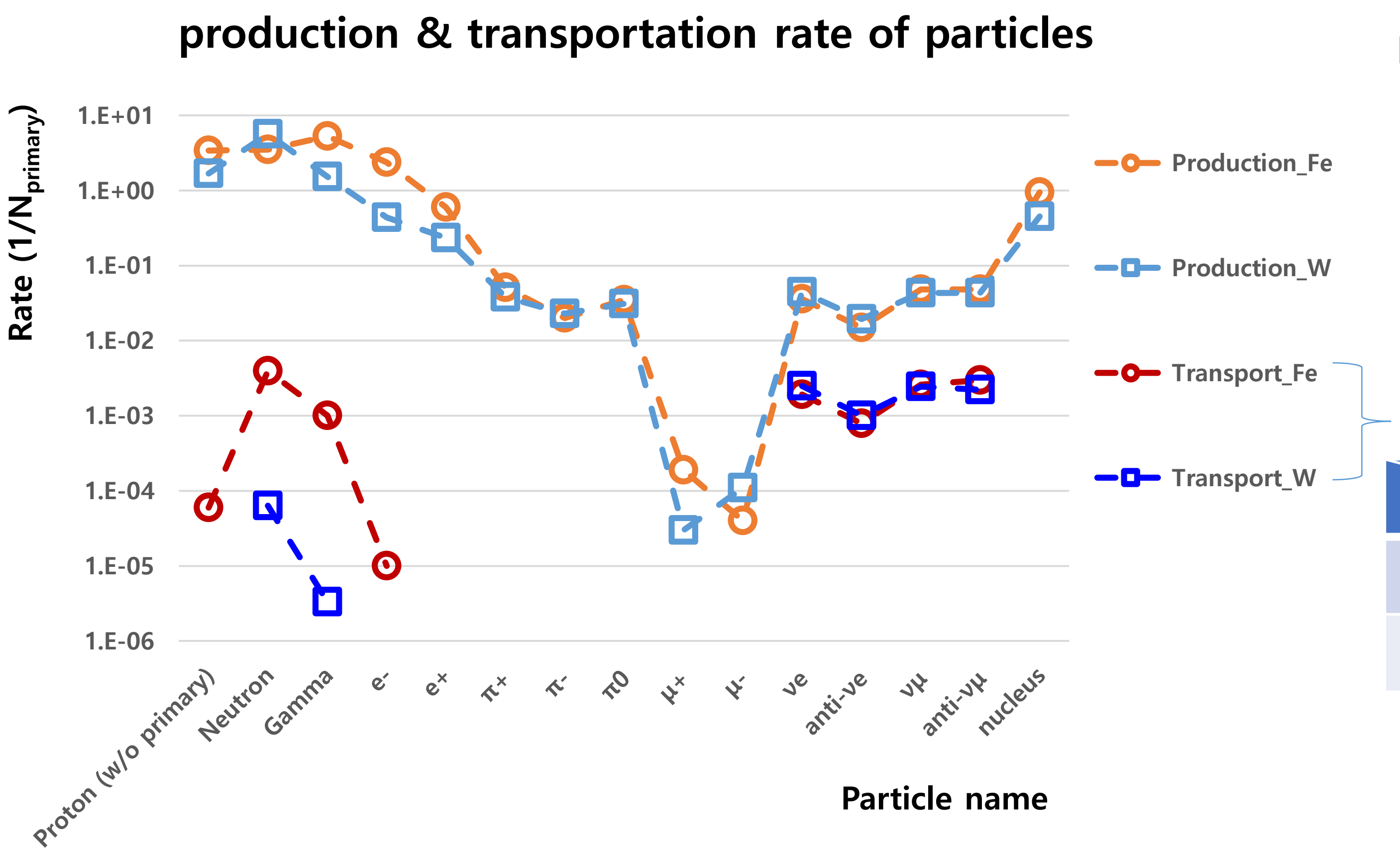
Even if the production yield of neutrinos are low, we assume if all particles are homogeneously produced and transported, transported particle yields to detector can be similar to ~6.13%.





- **Geometrical acceptance to full solid angle at r=1.09**
  ➔ **Area of sphere at r=1.09) = $4\pi r^2$ = ~15.0 mm²**
  ➔ **solid angle ($\Omega = S/r^2$ = ~0.919 mm² / 1.09² mm² = 0.770)**
  ➔ **0.919/15.0 = 0.0613x100% = 6.13%**

Transportation rate of particles from target to detector



Primary protons (N_p) = 10^5

E>5 MeV

Transportation rate of particles per $N_{primary}$

particle / target	proton (w/o primary)	Neutron	gamma	e-	e+
iron	6×10^{-5}	4×10^{-3}	1×10^{-3}	1×10^{-5}	$< 10^{-5}$
Tungsten (N_p=10^6)	$< 10^{-6}$	6.3×10^{-5}	3.3×10^{-6}	$< 10^{-6}$	$< 10^{-6}$

More **neutrons** are produced in the W target.
But the transportation rate of **neutrons** is two orders of magnitude less than the Fe target.

Transportation rate of gamma in the W target is three orders of magnitude less than the Fe target.

GEANT4 simulation for background study

5) Neutron-induced background mitigation study with W target (latest study)
- neutron moderator (polyurethane)
- ALP Decay chamber (vacuum vessel)

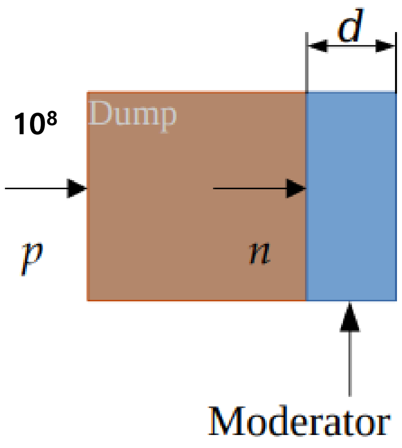
WooYoung Jang's talk at DPF21 of APS
A neutron-induced background mitigation study for Axion-like Particle search at RAON Facilities

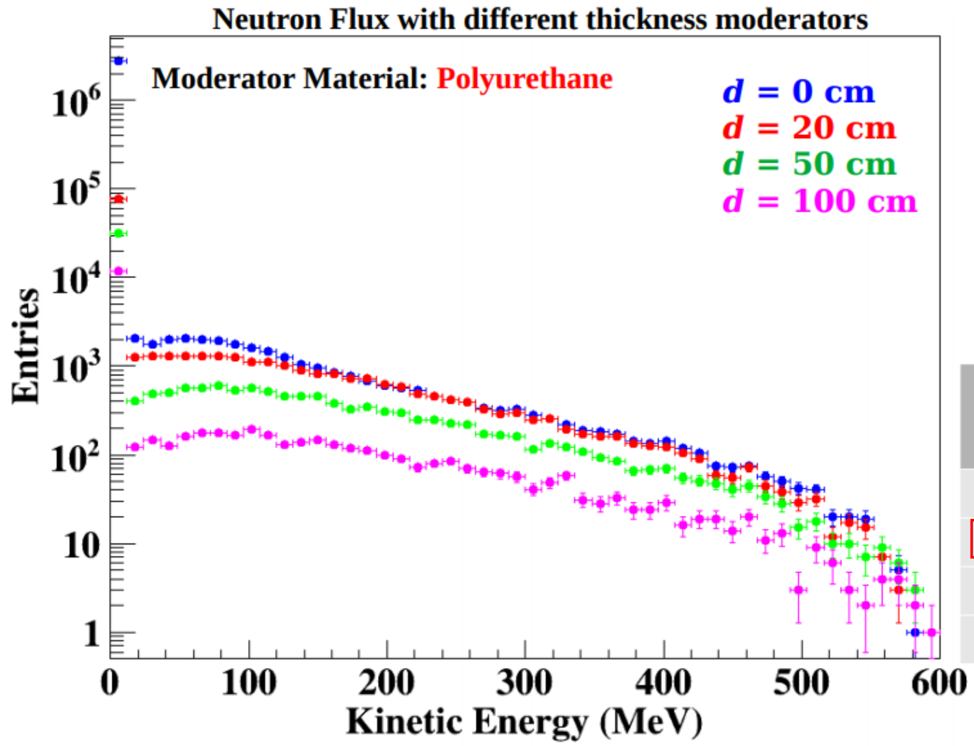
Rejection power of neutron moderator

WooYoung Jang's talk at DPF21 of APS, A neutron-induced background mitigation study for Axion-like Particle search at RAON Facilities

Neutron moderator (Polyurethane, 20-100 cm)

Number of primary protons: 10^8





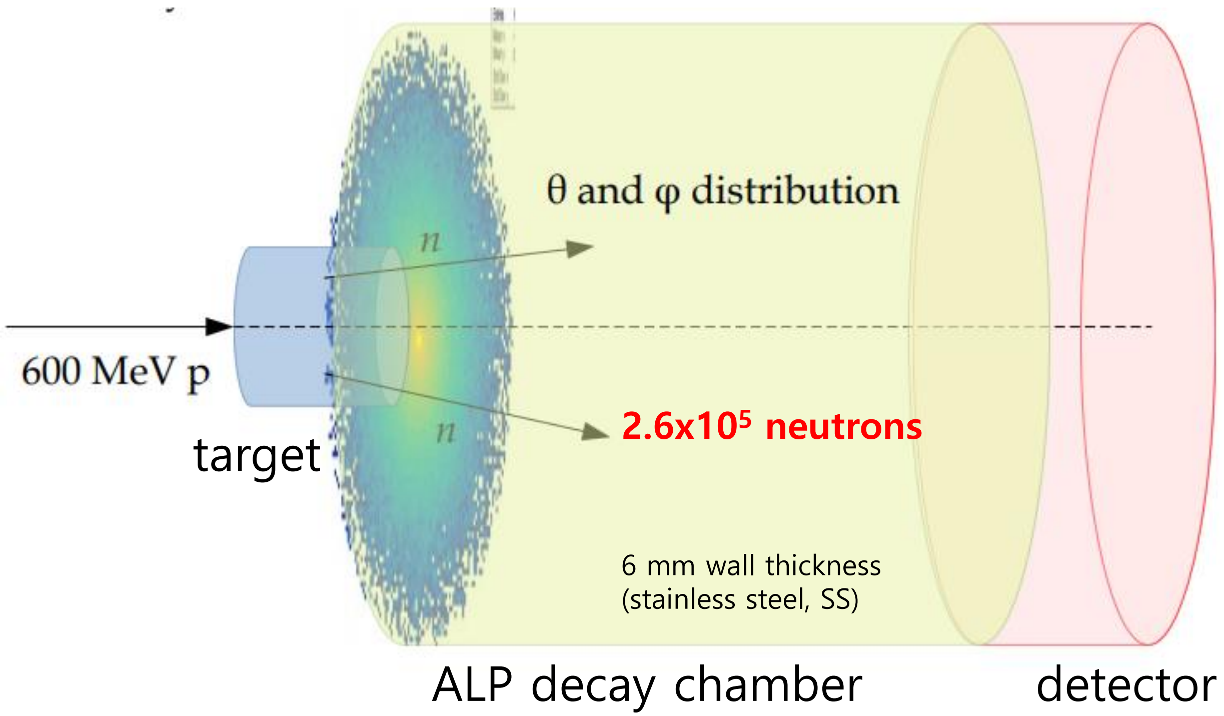
Thickness (d, cm)	Neutron Survival Rate
10	13.1 %
20	3.5 %
50	1.5 %
100	0.5 %

Rejection power with 20 cm is dominant at KE < 100 MeV.

ALP decay chamber

WooYoung Jang's talk at DPF21 of APS, A neutron-induced background mitigation study for Axion-like Particle search at RAON Facilities

ALP Decay chamber (vacuum vessel) with 6 mm SS



Primary protons 10^8 injected to target

ALP Decay chamber
vacuum vessel with 6 mm SS wall thickness

2.6×10^5 neutrons enter decay chamber
- **transportation rate = ~2.6×10^{-3}**

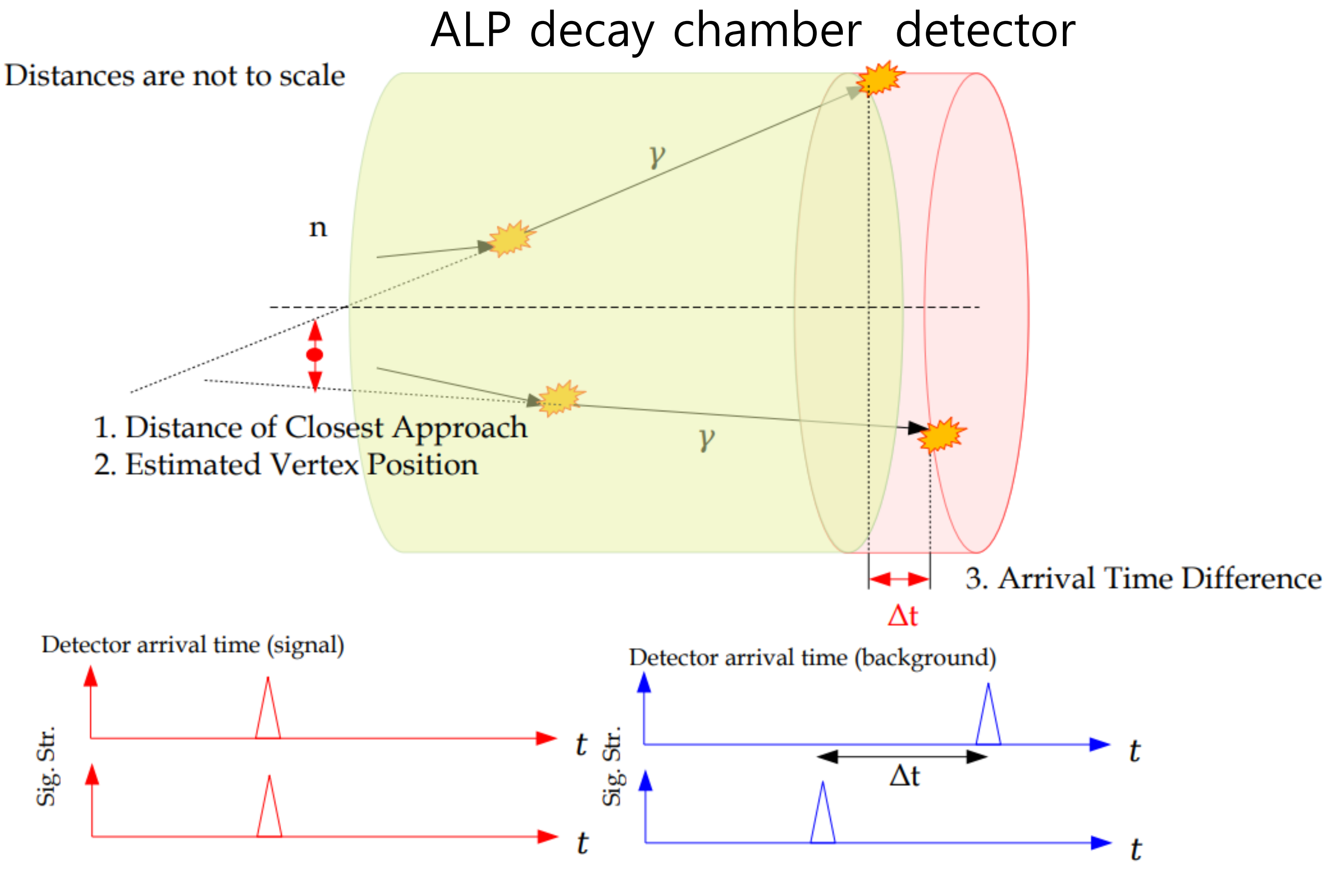
➔ 1.6×10^6 photons produced from neutrons

➔ **3.2×10^3 photons with KE > 5 MeV**

Finally, **5.1×10^5 photon pair** combination possible

How to mitigate the effect of neutron-induced photons?

WooYoung Jang's talk at DPF21 of APS, A neutron-induced background mitigation study for Axion-like Particle search at RAON Facilities

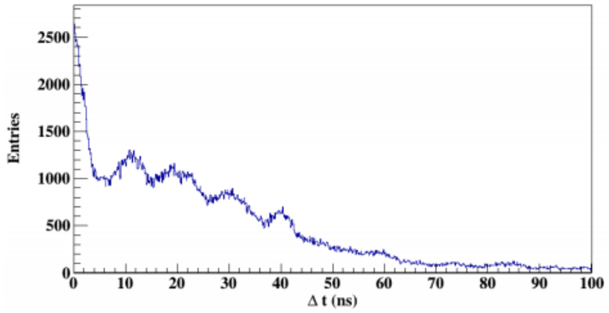


1) Distance cut of closest approach (DCA) of photon pairs
➔ 2.9% photon pair is survived with DCA cut (< 1 cm)

2) Back-tracing (vertex position) of two photon tracks
➔ 3.7% photon pair is survived with back-tracing cut

Arrival time difference of photon pair

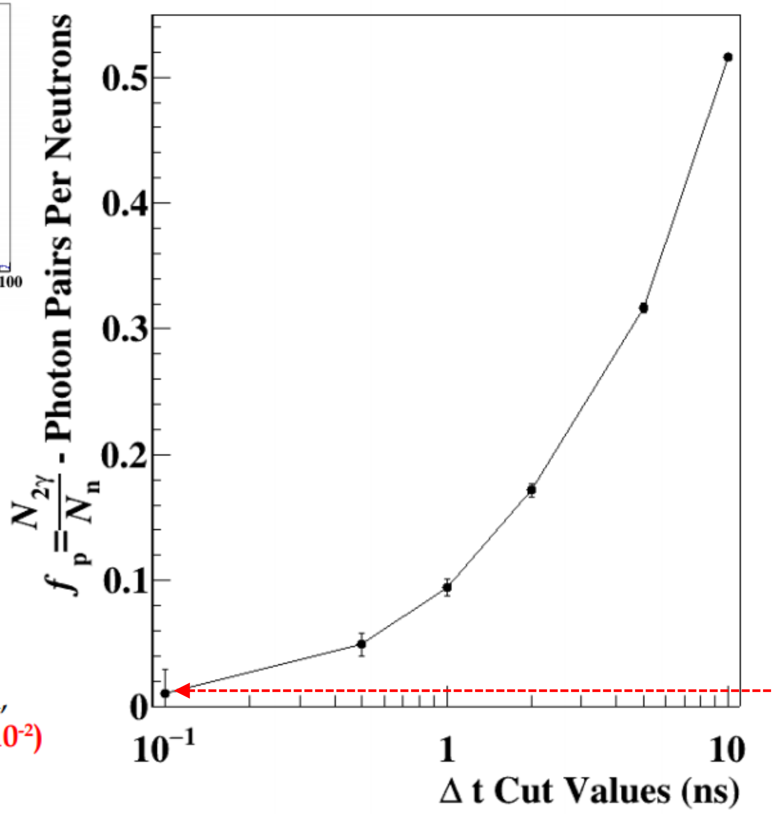
WooYoung Jang's talk at DPF21 of APS, A neutron-induced background mitigation study for Axion-like Particle search at RAON Facilities



$N_{2\gamma}/N_n$ after cut

Δt cut (ns)	$N_{2\gamma}/N_n$
<10	0.516
<5	0.317
<2	0.172
<1	0.095
<0.5	0.049
<0.1	0.010

If we assume a 100 ps timing resolution, the timing difference cut provides ~O(10^-2) level background reduction.



The neutron-induced photon pair can come later than two photons from ALP decay.

3) Arrival time difference cut with σ_{DET} = 100 ps
➔ 1% of photon pair is survived with timing difference cut

Summary

- The **DAMSA is proposed**, as a part of ARI^3AA project, **to search ALPs in the low-energy and high-intensity proton beams** (600 MeV, 660 μA) facility at RAON in Korea.
- Expected ALP production mechanism: Primakoff process
  ➔ ALP decays into two gammas

- **Background study at DAMSA using GEANT4**
- **Geometrical acceptance**
  ➔ closest distance between dump and detector
  ➔ $\theta < 0.5$ radian in the polar angle (~ 6.1% of full solid angle)

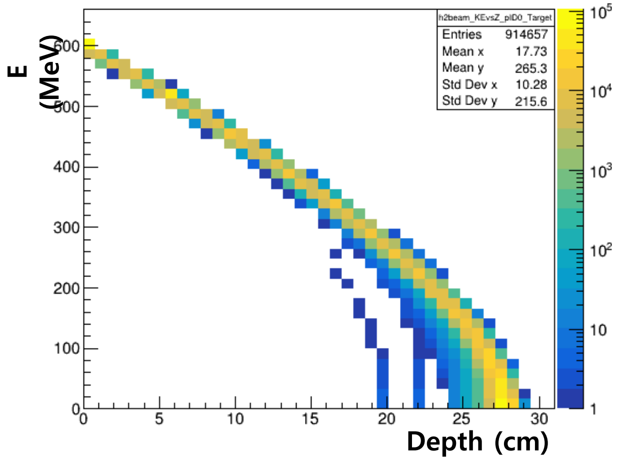
- **Transportation rate of particles at different target materials**
  ➔ transportation rate of neutrons in tungsten target over 10^{-2} lower than that in the iron target
  ➔ In the tungsten target, no transported gamma observed within the given statistics
  Need further study with higher statistics to finalize the dump material and detector geometry

- **Reduction factor of two photon pair by neutron-induced background mitigation study (Wooyoung Jang Dr)**
  - with moderator (20 cm polyurethane) and decay chamber (6 mm SS vacuum vessel)
  ➔ $\varepsilon_{mod.}$ = 3.5% with 20 cm polyurethane
  ➔ ε_{DCA} = 2.9% with DCA cut (< 1 cm)
  ➔ $\varepsilon_{BackTracing}$ = 3.7% with back-tracing cut
  ➔ $\varepsilon_{\Delta t}$ = 1% with detection time resolution (100 ps)

Thank you for your attention!

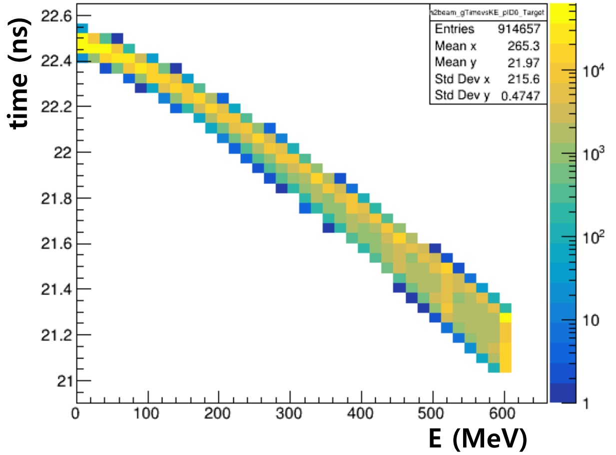
BACKUP

Distribution of primary protons with iron dump

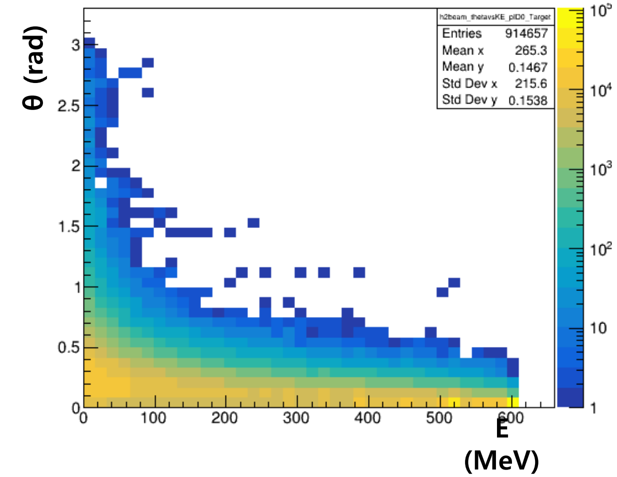


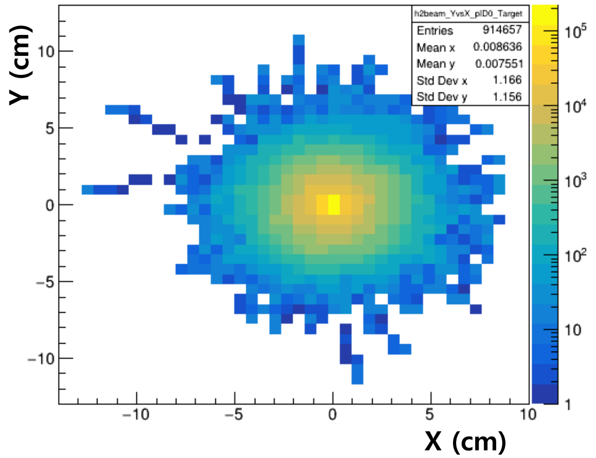
<<< Beam >>>
Particle name: protons
Energy: 600 MeV
\# of primary: 10^5

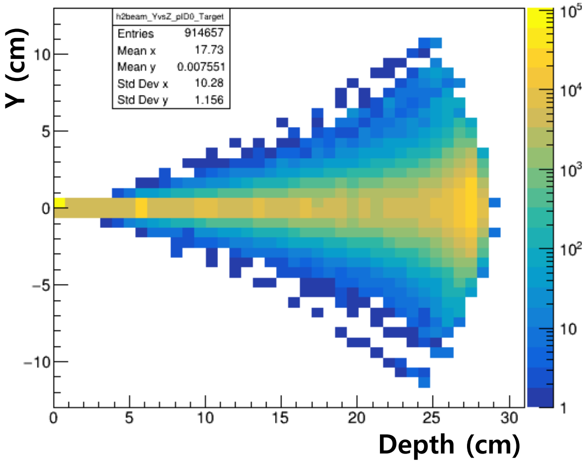
<<< dump >>>
Material: G4_Fe
Volume size: 1 m dia.
1 m long

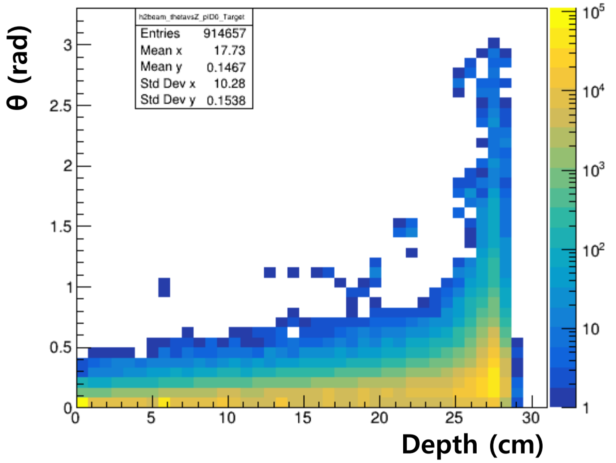


QGSP_BIC_HP
Quark-gluon string pre-compound (QGSP) model for collision of high-energy hadrons
Binary cascade (BIC) model for inelastic process of hadrons
High precision (HP) data for low-energy neutron and light ions

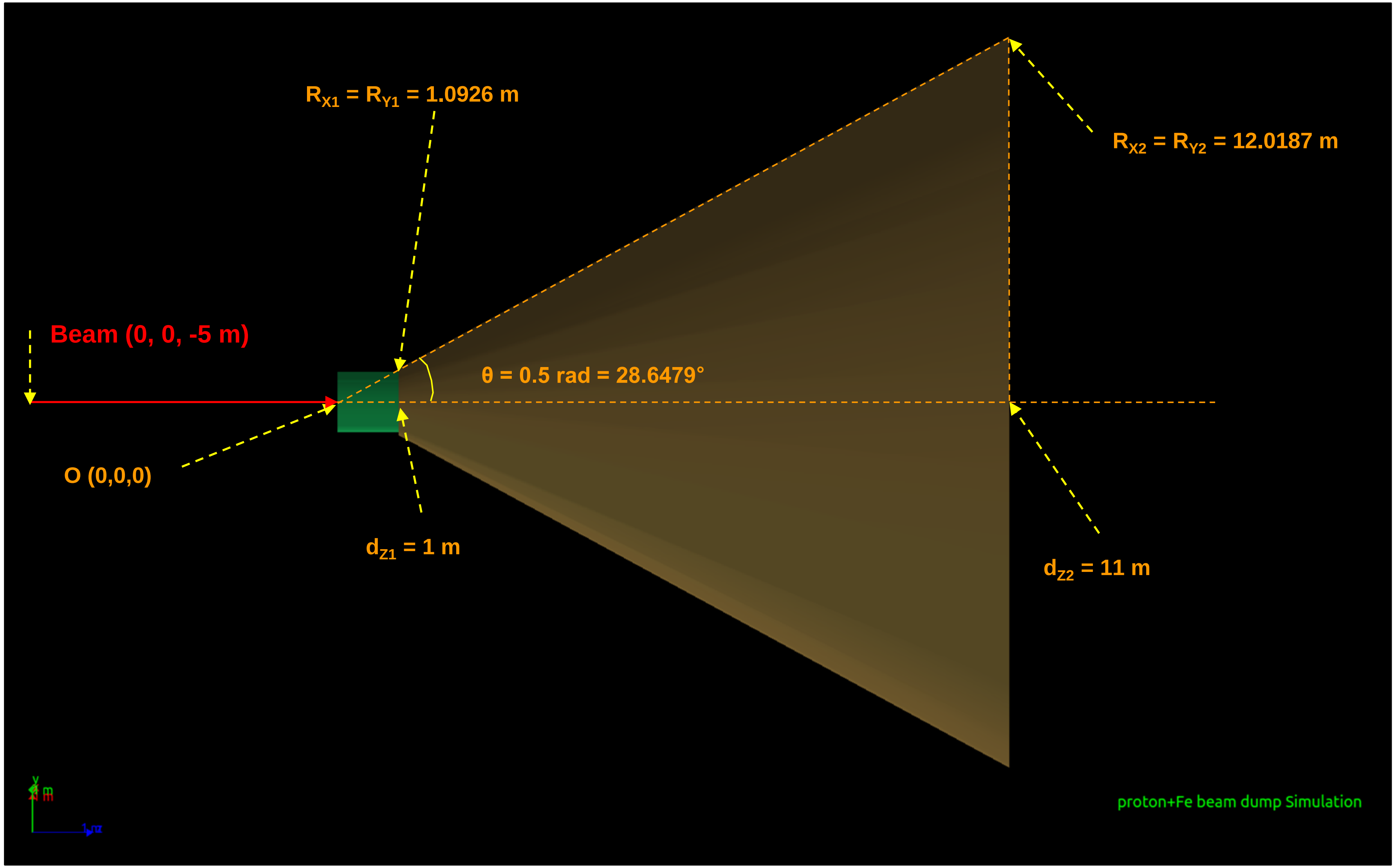








New detector geometry at DAMSA experiment



$\tan\theta = R_{Y1} / d_{Z1}$
$\Rightarrow R_{Y1} = d_{Z1} * \tan\theta = 1\text{ m} * \tan(0.5*180°/\pi)$
$= 1\text{ m} * 0.5463 = 0.5463\text{ m}$

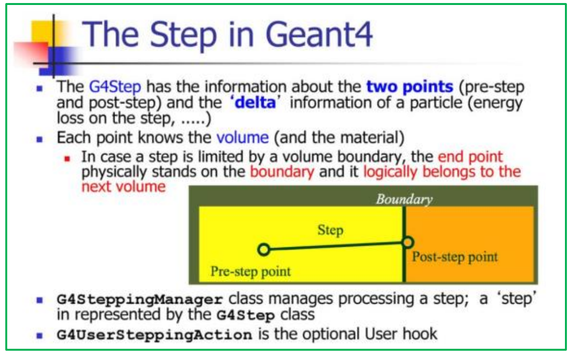
Radius at $d_{Z1} \Rightarrow R_{X1} = R_{Y1} = 0.5463$ m
Diameter at $d_{Z1} \Rightarrow D_{X1} = D_{Y1} = 2*0.5463\text{ m} = 1.0926$ m
$= 1092.6$ mm

$\tan\theta = R_{Y2} / d_{Z2}$
$\Rightarrow R_{Y2} = d_{Z2} * \tan\theta = 11\text{ m} * \tan(0.5*180°/\pi)$
$= 11\text{ m} * 0.5463 = 6.5556\text{ m}$

Radius at $d_{Z2} \Rightarrow R_{X2} = R_{Y2} = 6.0093$ m
Diameter at $d_{Z2} \Rightarrow D_{X2} = D_{Y2} = 2*6.0093\text{ m} = 12.0187$ m
$= 12018.7$ mm

Ntuple variables for beam dump simulation

Anton Lechner (CERN) Gean4: Interacting with the Geant4 Kernel



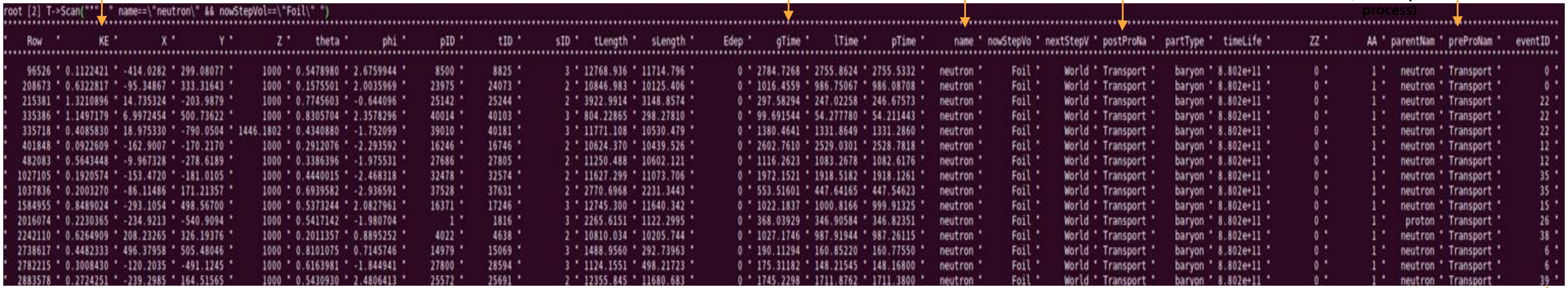
KE (MeV)

global time (gTime, ns)

particle name (name)

preProName
(Pre-step process)

postProName
(Post-step process)



```
root [2] T->Scan("*"," name==\"neutron\" && nowStepVol==\"Foil\" ")
```

Row	KE	X	Y	Z	theta	phi	pID	tID
96526	0.1122421	-414.0282	299.08077	1000	0.5478980	2.6759944	8500	8825
208673	0.6322817	-95.34867	333.31643	1000	0.1575501	2.0035969	23975	24073
215381	1.3210896	14.735324	-203.9879	1000	0.7745603	-0.644096	25142	25244
335386	1.1497179	6.9972454	500.73622	1000	0.8305704	2.3578296	40014	40103
335718	0.4085830	18.975330	-790.0504	1446.1802	0.4340880	-1.752099	39010	40181
401848	0.0922609	-162.9007	-170.2170	1000	0.2912076	-2.293592	16246	16746
482083	0.5643448	-9.967328	-278.6189	1000	0.3386396	-1.975531	27686	27805
1027105	0.1920574	-153.4720	-181.0105	1000	0.4440015	-2.468318	32478	32574
1037836	0.2003270	-86.11486	171.21357	1000	0.6939582	-2.936591	37528	37631
1584955	0.8489024	-293.1054	498.56700	1000	0.5373244	2.0827961	16371	17246
2016074	0.2230365	-234.9213	-540.9094	1000	0.5417142	-1.980704	1	1816
2242110	0.6264909	208.23265	326.19376	1000	0.2011357	0.8895252	4022	4638
2738617	0.4482333	496.37958	505.48046	1000	0.8101075	0.7145746	14979	15069
2782215	0.3008430	-120.2035	-491.1245	1000	0.6163981	-1.844941	27800	28594
2883578	0.2724251	-239.2985	164.51565	1000	0.5430930	2.4806413	25572	25691

Row	sID	tLength	sLength	Edep	gTime	lTime	pTime	name
96526	3	12768.936	11714.796	0	2784.7268	2755.8624	2755.5332	neutron
208673	2	10846.983	10125.406	0	1016.4559	986.75067	986.08708	neutron
215381	2	3922.9914	3148.8574	0	297.58294	247.02258	246.67573	neutron
335386	3	804.22865	298.27810	0	99.691544	54.277780	54.211443	neutron
335718	3	11771.108	10530.479	0	1380.4641	1331.8649	1331.2860	neutron
401848	2	10624.370	10439.526	0	2602.7610	2529.0301	2528.7818	neutron
482083	2	11250.488	10602.121	0	1116.2623	1083.2678	1082.6176	neutron
1027105	2	11627.299	11073.706	0	1972.1521	1918.5182	1918.1261	neutron
1037836	2	2770.6968	2231.3443	0	553.51601	447.64165	447.54623	neutron
1584955	3	12745.300	11640.342	0	1022.1837	1000.8166	999.91325	neutron
2016074	3	2265.6151	1122.2995	0	368.03929	346.90584	346.82351	neutron
2242110	2	10810.034	10205.744	0	1027.1746	987.91944	987.26115	neutron
2738617	3	1488.9560	292.73963	0	190.11294	160.85220	160.77550	neutron
2782215	3	1124.1551	498.21723	0	175.31182	148.21545	148.16800	neutron
2883578	2	12355.845	11680.683	0	1745.2298	1711.8762	1711.3800	neutron

Row	nowStepVo	nextStepV	postProNa	partType	timeLife	ZZ	AA	parentNam	preProNam	eventID
96526	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	0
208673	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	0
215381	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	22
335386	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	22
335718	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	22
401848	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	12
482083	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	12
1027105	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	35
1037836	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	35
1584955	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	15
2016074	Foil	World	Transport	baryon	8.802e+11	0	1	proton	Transport	26
2242110	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	38
2738617	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	6
2782215	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	6
2883578	Foil	World	Transport	baryon	8.802e+11	0	1	neutron	Transport	39

Z (mm)

Theta (rad)

Edep (MeV)

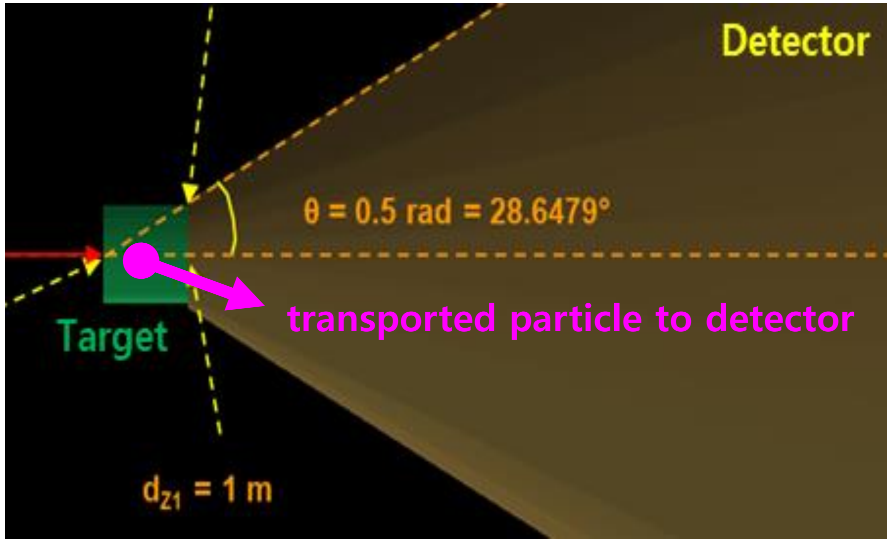
nowStepVol
(GetVolume,
Pre-step point)

nextStepVol
(GetNextVolume,
Post-step point)

parentName

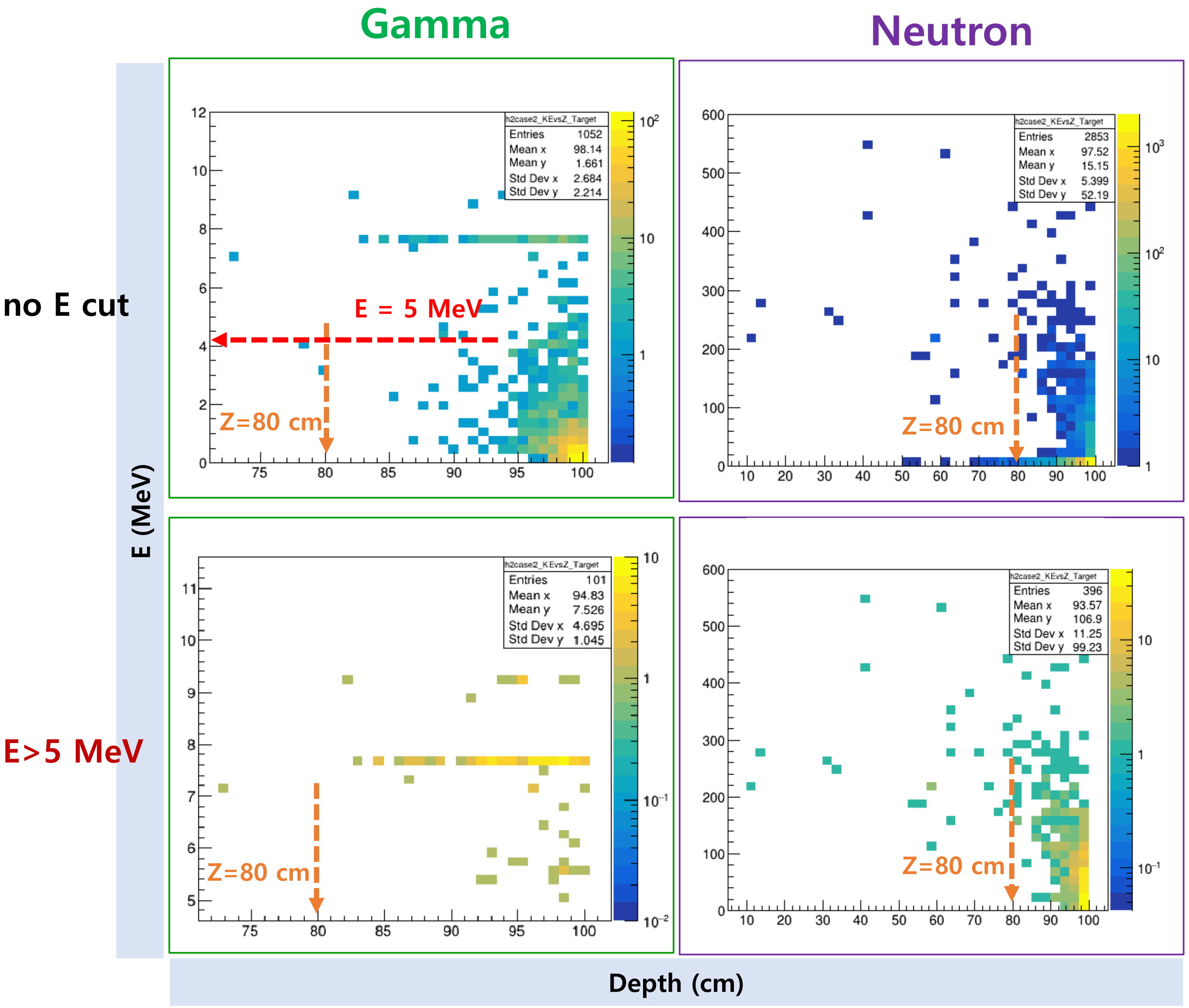
eventID

Kinetic energy cut to reduce the yield of transported particles



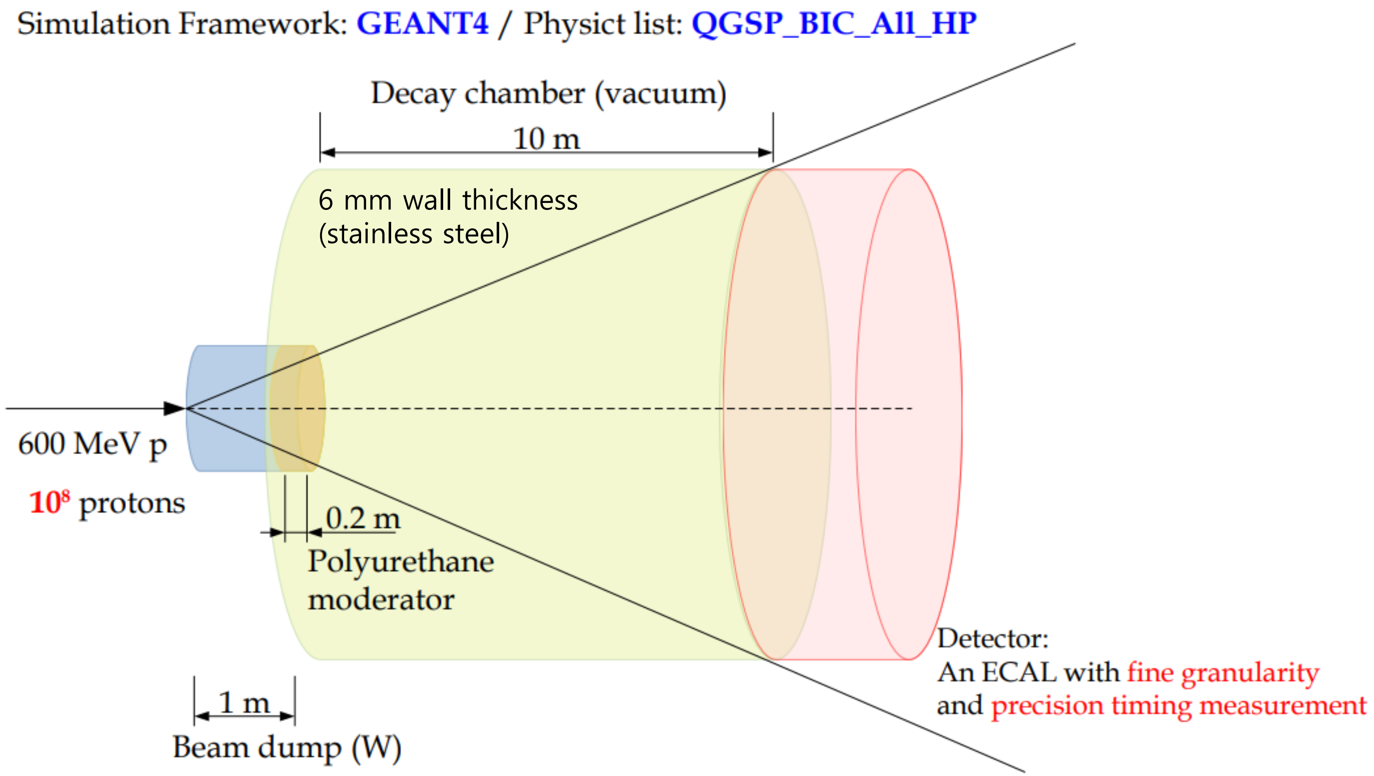
Particle name / Transportation ratio	Neutron	Gamma
no E cut	3 x 10^{-2}	1 x 10^{-2}
E > 5 MeV	4 x 10^{-3}	1 x 10^{-3}

The kinetic energy cut (E > 5 MeV) can decrease the transportation rate of neutrons and gammas up to ~10%.



Neutron-induced background mitigation study

WooYoung Jang's talk at DPF21 of APS, A neutron-induced background mitigation study for Axion-like Particle search at RAON Facilities



We provide a detector specification required to be able to reduce beam-induced background neutrons.

Primary protons 10^8 injected to dump

Two component added for mitigation study
- Neutron moderator (Polyurethane, 20 cm)
- ALP Decay chamber
  vacuum vessel with 6 mm SS wall thickness

$2.6\text{x}10^5$ neutrons enter decay chamber
 - **transportation rate = ~$2.6\text{x}10^{-3}$**

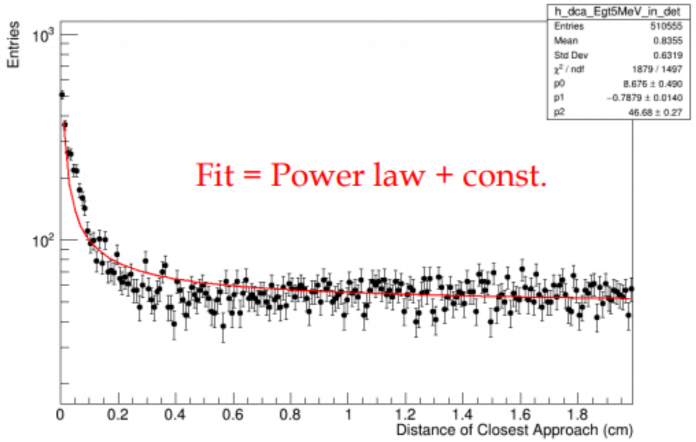
➔ $1.6\text{x}10^6$ photons produced from neutrons

➔ **$3.2\text{x}10^3$ photons with KE > 5 MeV**

Finally, **$5.1\text{x}10^5$ photon pair** combination possible

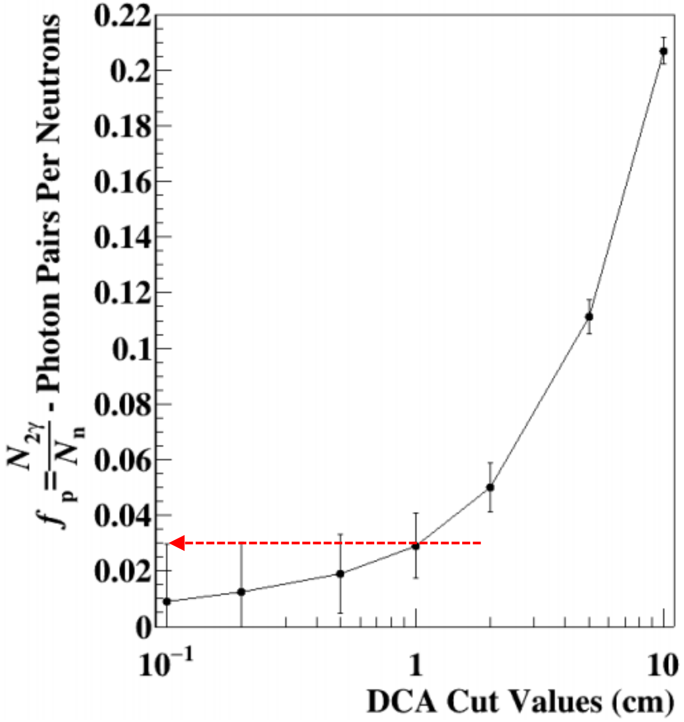
DCA cut of photon pairs

WooYoung Jang's talk at DPF21 of APS, A neutron-induced background mitigation study for Axion-like Particle search at RAON Facilities



$N_{2\gamma}/N_n$ after cut

DCA cut (cm)	$N_{2\gamma}/N_n$
<10	0.206
<5	0.111
<2	0.050
<1	0.029
<0.5	0.019
<0.2	0.012
<0.1	0.009

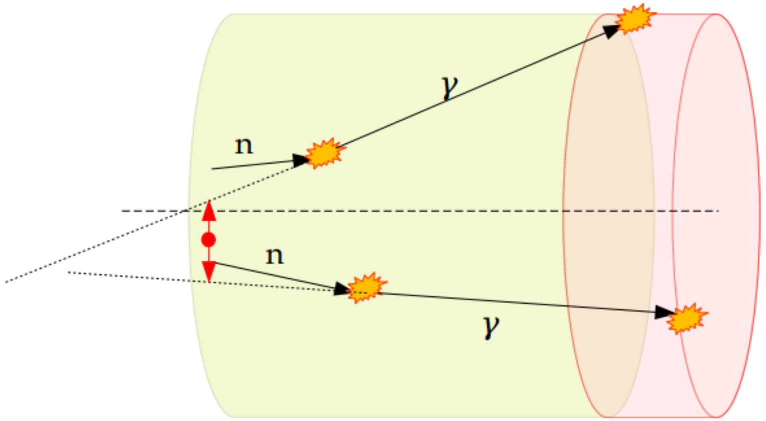


1) Distance of closest approach (DCA) of photon pairs
➔ 2.9% photon pair is survived with DCA cut (< 1 cm)

Back-tracing (vertex position) of two photon tracks

WooYoung Jang's talk at DPF21 of APS, A neutron-induced background mitigation study for Axion-like Particle search at RAON Facilities

Distances are not to scale

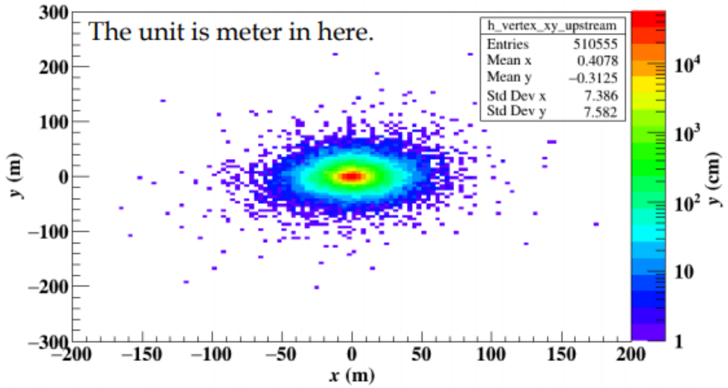


Extrapolate two photon tracks to the **upstream endcap.**

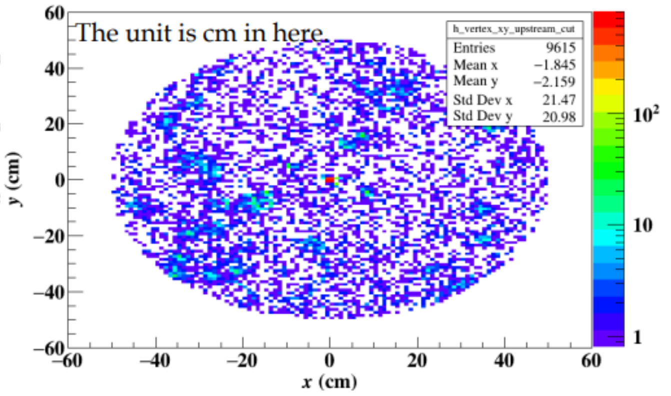
If a photon pair is identified <u>not coming from the dump,</u> **reject** the pair.

The fraction of survived photon pairs per neutrons : **~0.037**

2) Back-tracing (vertex position) of two photon tracks
➔ 3.7% photon pair is survived with back-tracing cut



before



after