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Recent progress of DarkSHINE R&D

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On behalf of DarkSHINE R&D Team

中国物理学会高能物理分会第十四届全国粒子
物理学术会议, Qingdao

2024.08.15



Two dark clouds over physics



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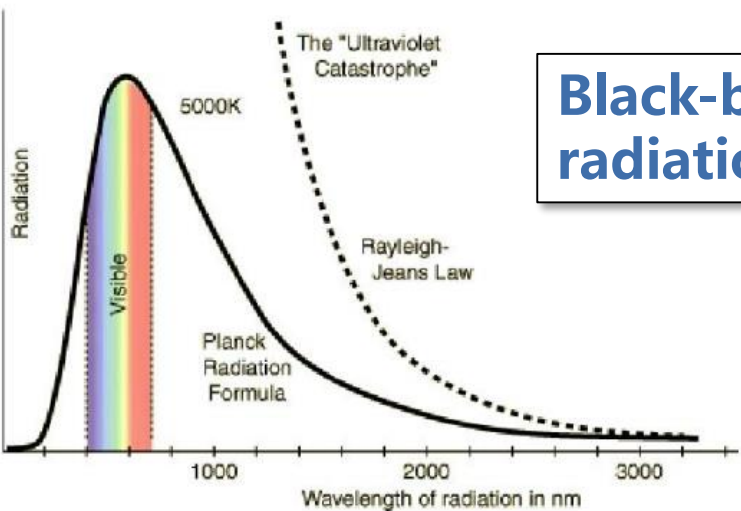
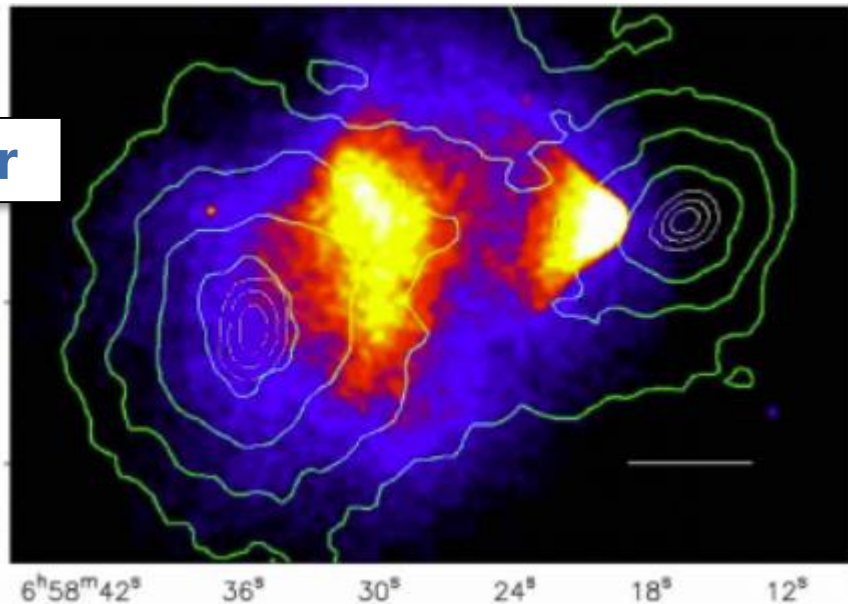
- From the 20th century to the 21st century.....



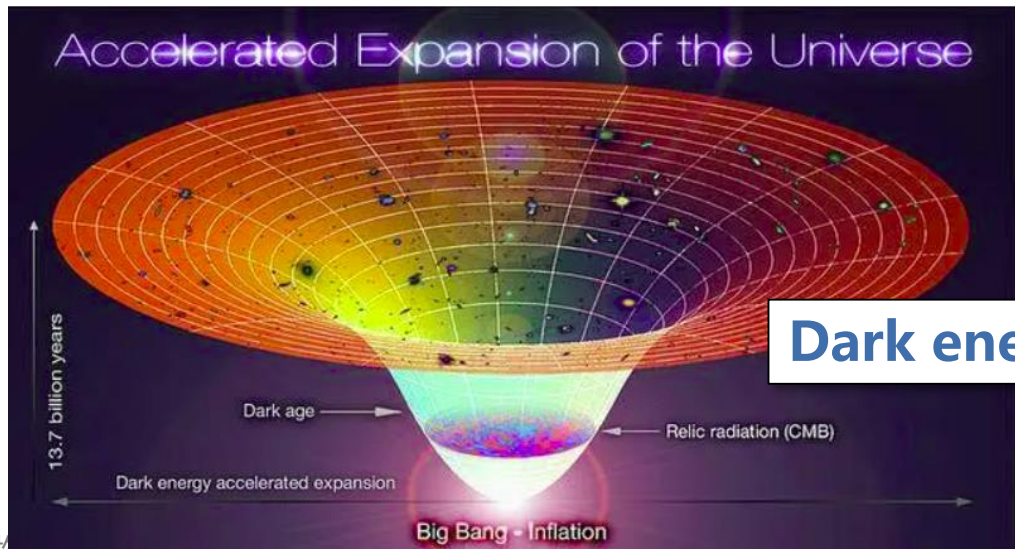
Michelson-Morley
experiment



Dark matter



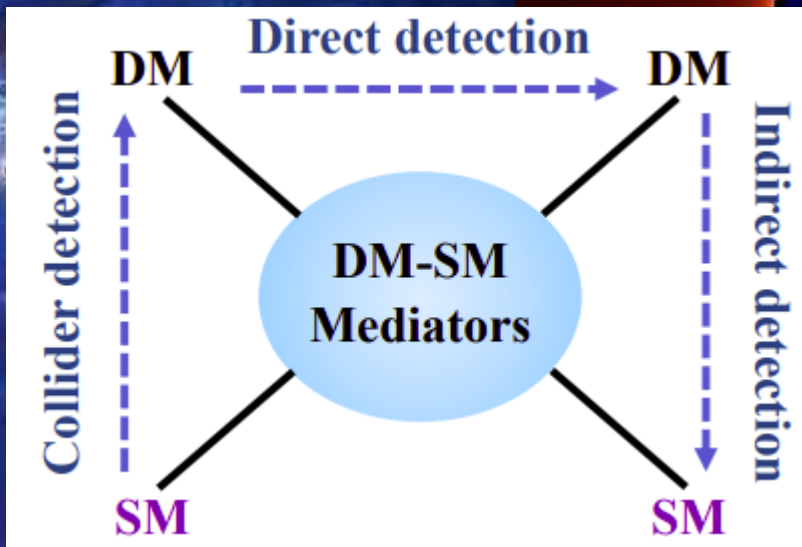
Black-body
radiation



Dark energy

The world of Dark Matter

Dark
Matter
candidate
particles



Dark
Photon:
Dark force
Mediators

Dark
Matter
Mediators

Dark Matter: Models in broad mass range



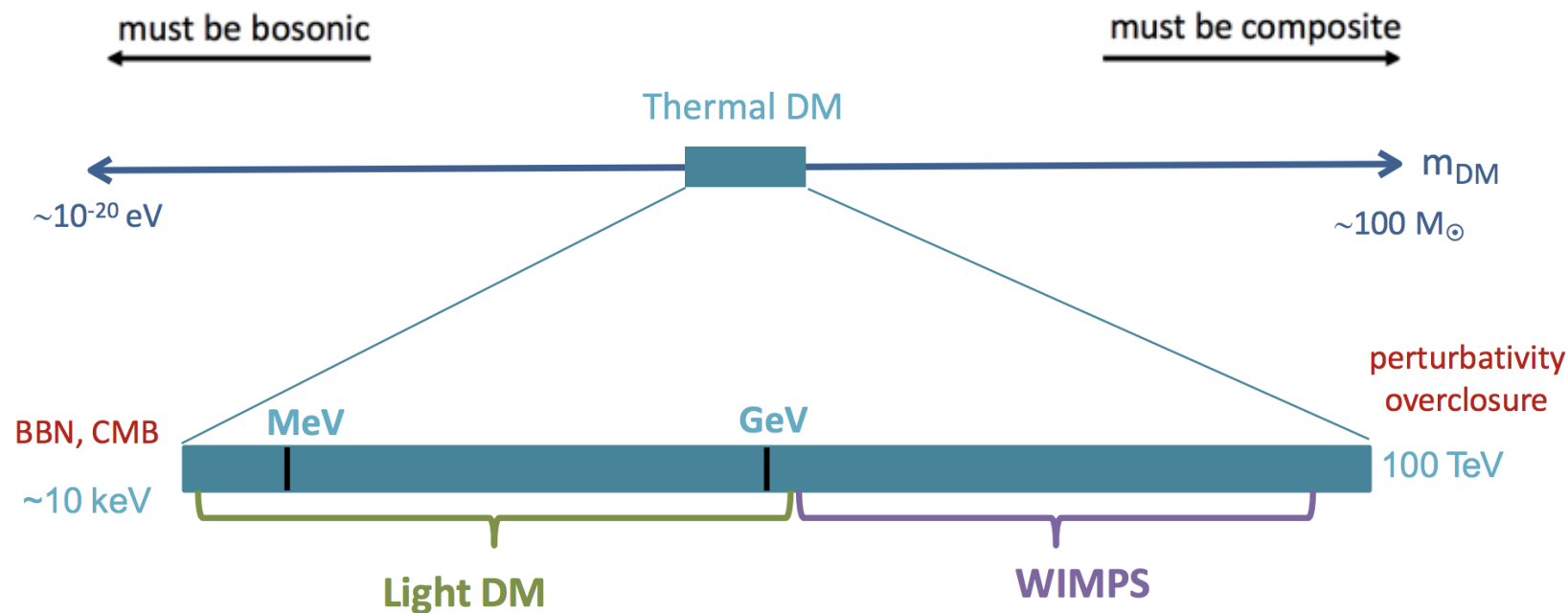
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APPEC Committee Report: 2104.07634

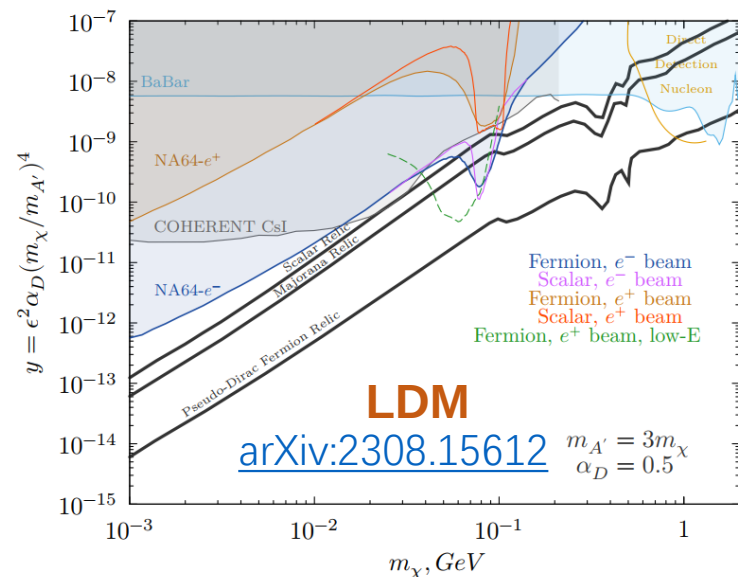
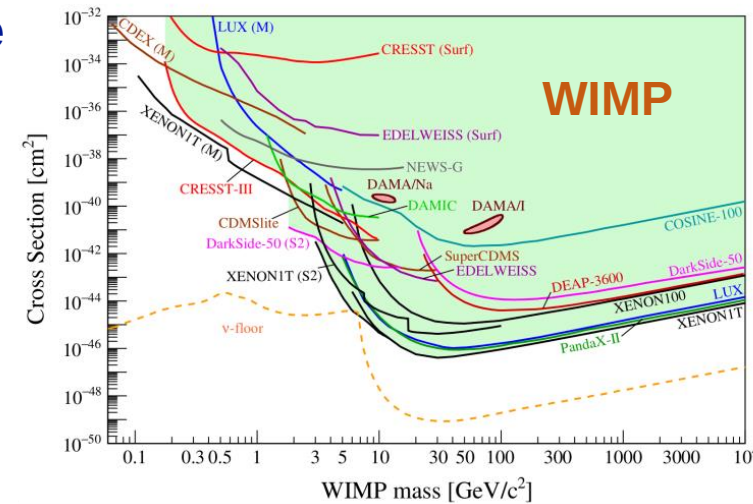
- The theory of dark matter should include the mechanisms to describe the evolution of the proportion of dark matter in the universe
 - One typical origin hypothesis: **thermal equilibrium** in the early universe, DM density become stable due to temperature drops (**freeze-out**)

The thermal hypothesis also greatly restricts the range of allowed masses



Thermal contact implies a new mediator
Hidden sector light DM model is well-motivated

Thermal freeze-out for weak scale masses
Has driven DM searches for last ~ 30 years



- Dark photon is an important portal between the standard model (SM) particles and the dark matter
 - Extra $U(1)_X$ symmetry is introduced

$$L = L_{SM} + \epsilon F^{\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'^\mu A'_\mu$$

Kinetic mixing term Field strength tensor Dark photon field

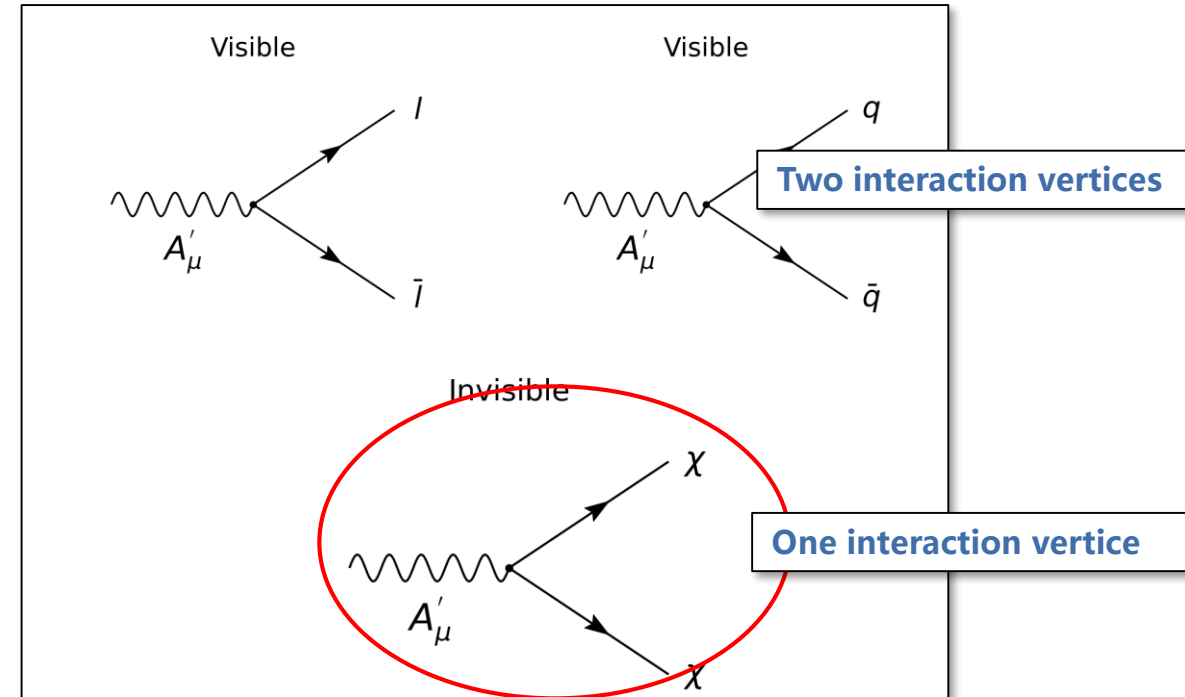
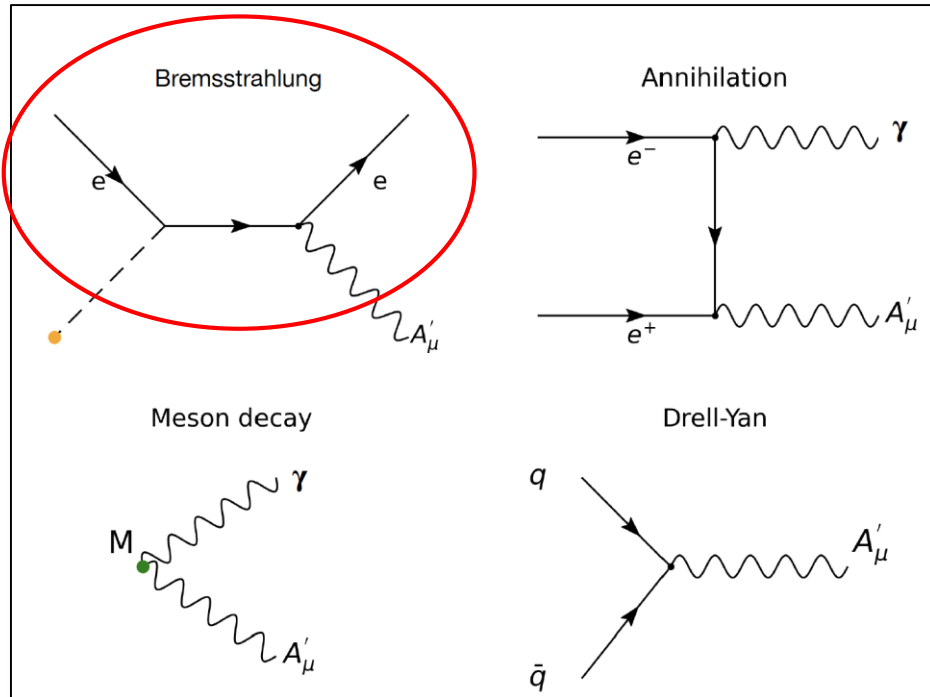
- In the minimal Dark photon model, 3 free parameters are studied:
 - $m_{A'}$: Dark Photon mass
 - ϵ : Kinetic mixing parameter
 - Decay branching ratio: $A' \rightarrow \chi\chi$ (dark sector), could be 1 or 0

[arXiv:2104.10280](https://arxiv.org/abs/2104.10280)

Search for dark photon



- Several production & decay modes
 - Bremsstrahlung production: fixed-target experiment with electron beam
 - Invisible decay mode: enhanced possibility compare to visible mode with two interaction vertices
 - **DarkSHINE**: Bremsstrahlung + invisible decay, put constraints on the kinetic mixing parameter ε



The SHINE facility

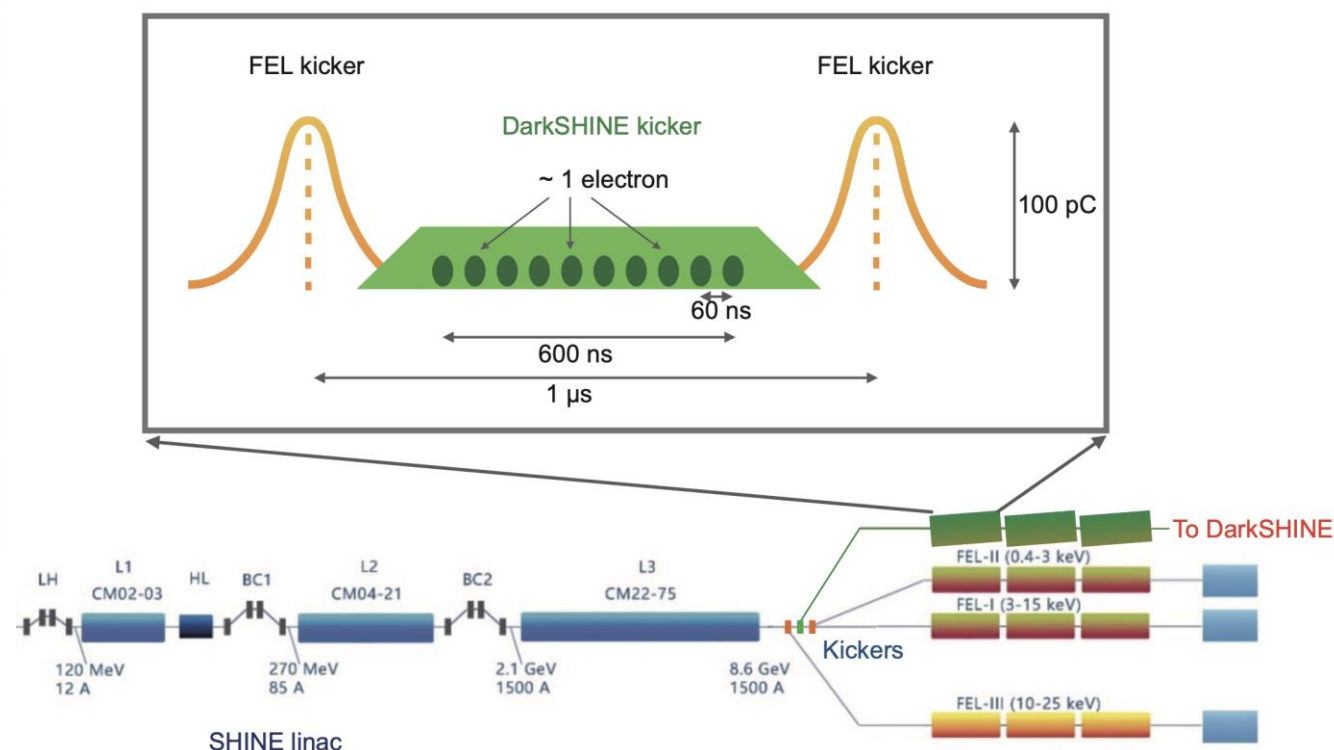
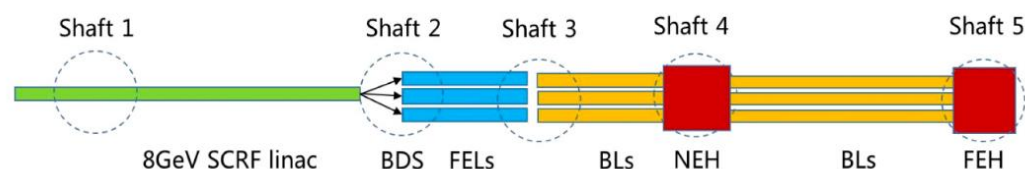


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Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE) can provide **high frequency electron beams** → **single electron** with dedicated kicker.

- Electron energy: 8 GeV, Frequency: 1MHz
- Beam intensity: 100pC (6.25E8 electrons/bunch)
- $\sim 3 \times 10^{14}$ electrons-on-target (EOT) per year.
- Under construction in Zhangjiang area (2018-2026)
- Beam techniques: SARI, CAS / Shanghai Tech.
- Detector R&D: SJTU / FDU / SIC, CAS.

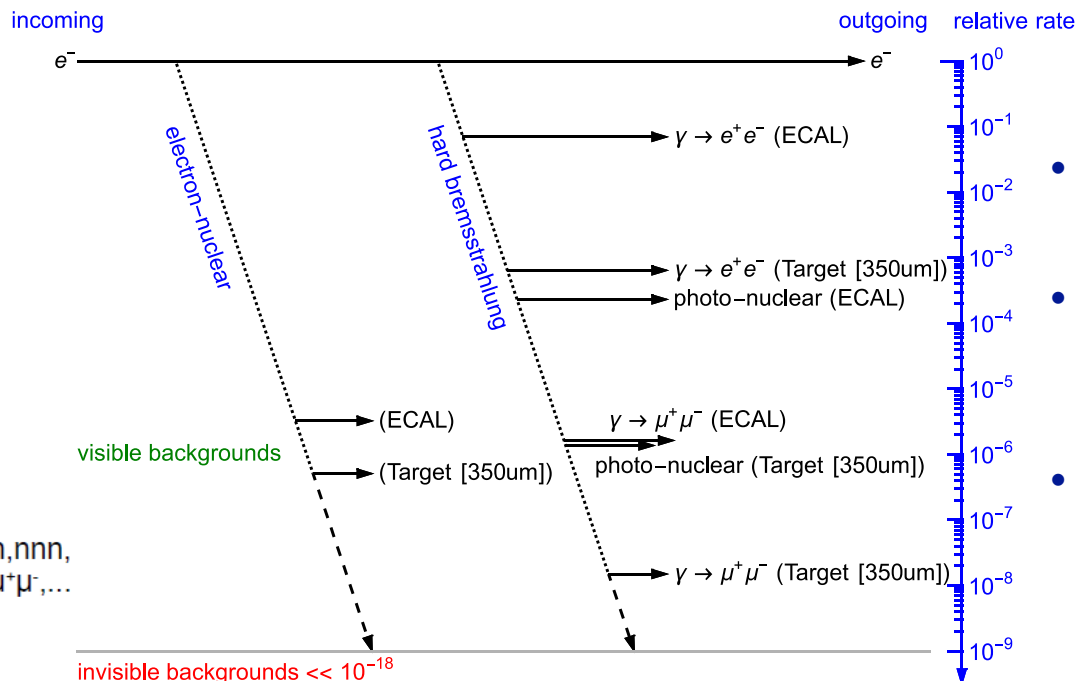
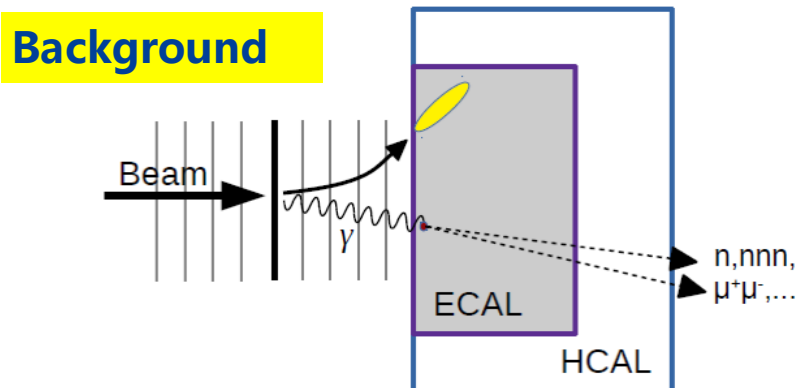
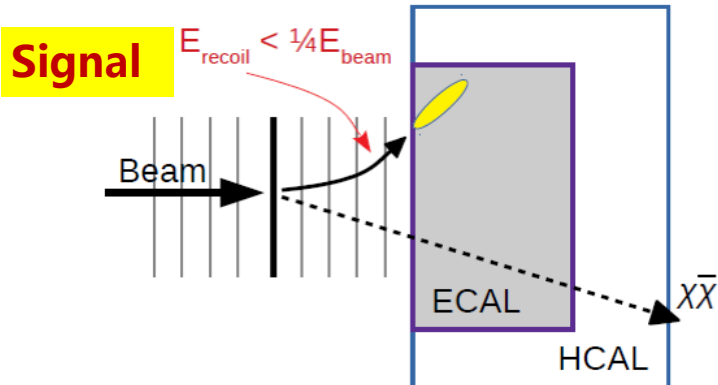
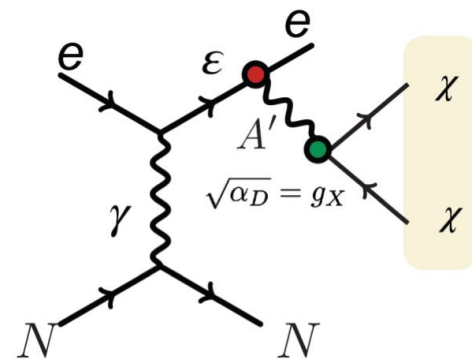


Signal and background processes



- Detector is designed based on the difference between signal and background signatures
 - Search for the final states with a soft recoil electron + large missing energy & p_T

INVISIBLE DECAY MODE $m'_A > 2m_X$



- Leading background: γ bremsstrahlung
- Rare processes include: electron-nuclear, photon-nuclear, $\gamma \rightarrow \mu\mu$
- Neutrino production is irreducible, but negligible

DarkSHINE detector system conceptual design



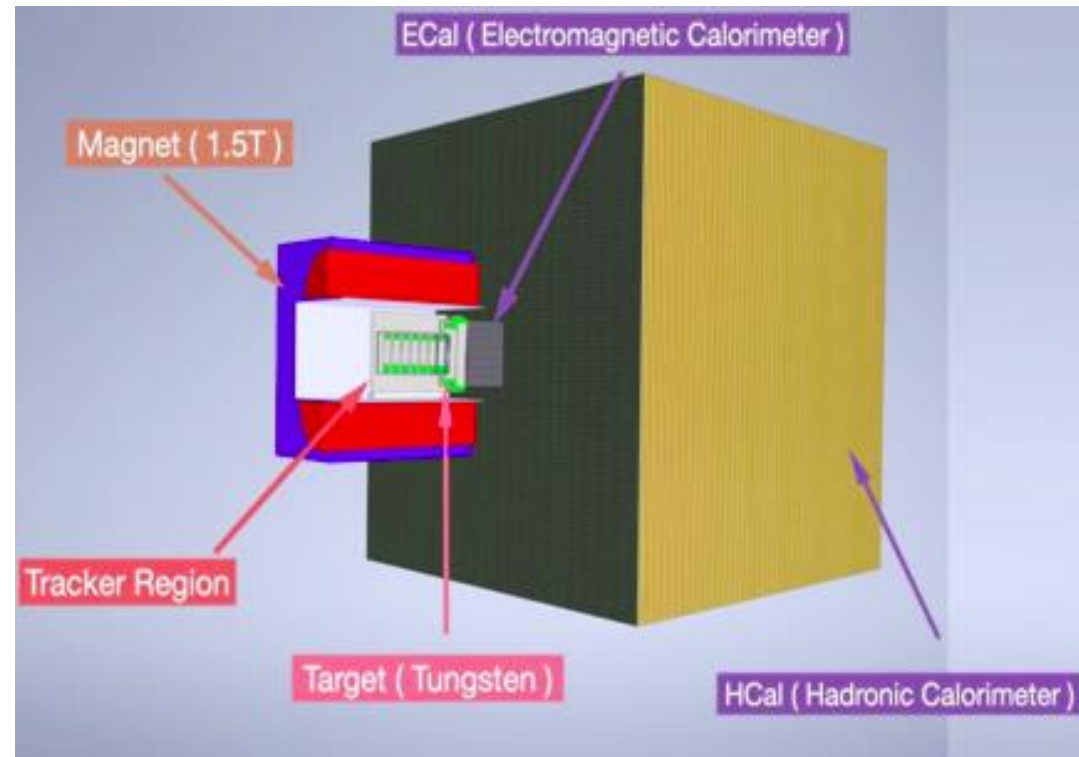
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The Dark SHINE detector hardware technical R&D is carried out in parallel to the full detector system simulation and prospective study/optimization

Tracking system

Measure the track of the incident and recoil electrons.



Electromagnetic calorimeter

Measure the deposited energy: electron and photon.

Hadronic calorimeter

Measure the deposited energy: **veto** muon and hadron backgrounds.

Dark SHINE detector sketch

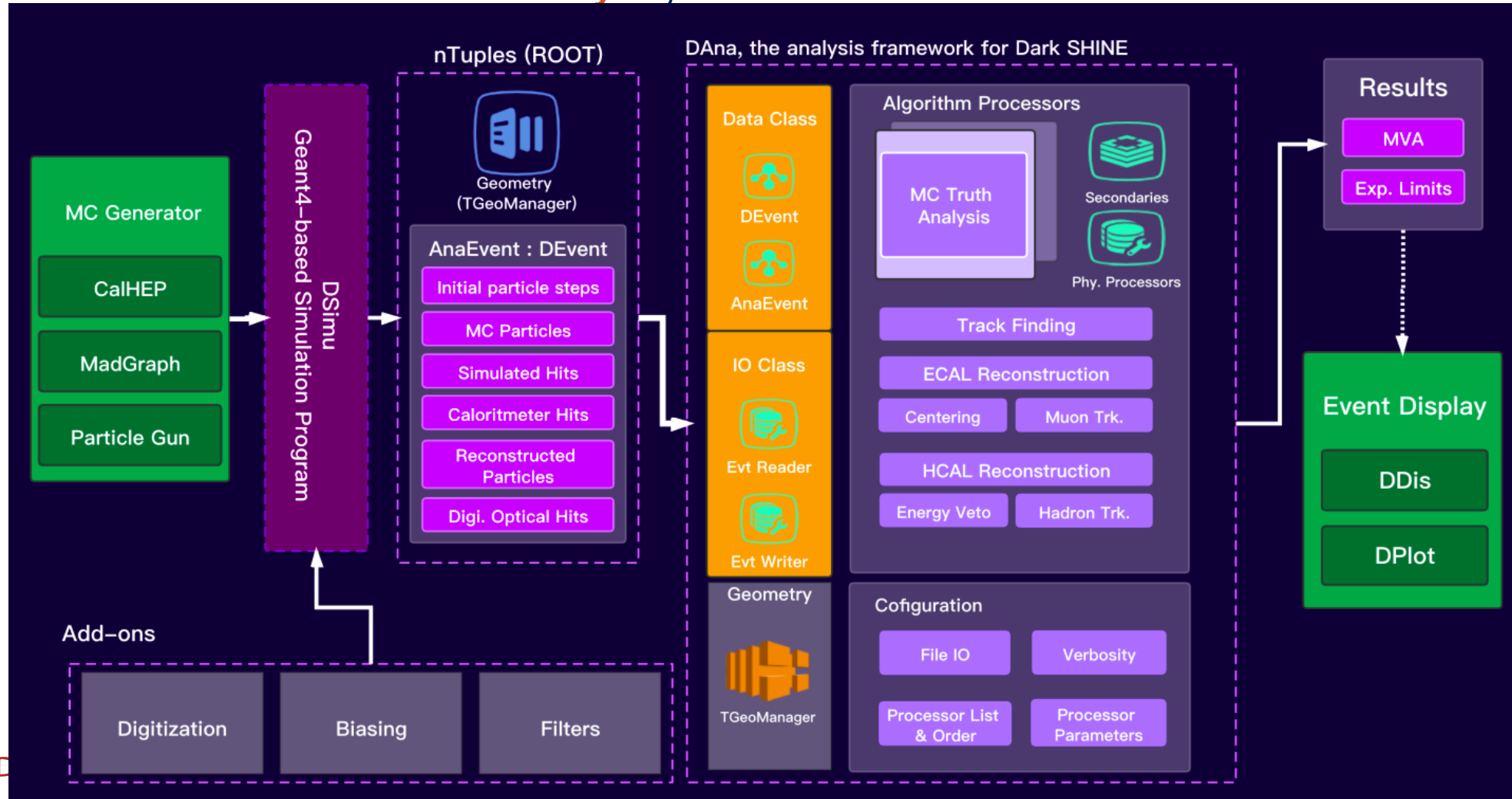
Additional system:

Readout electronics, trigger system, TDAQ, magnetic system (1.5 T), etc.

DarkSHINE simulation framework

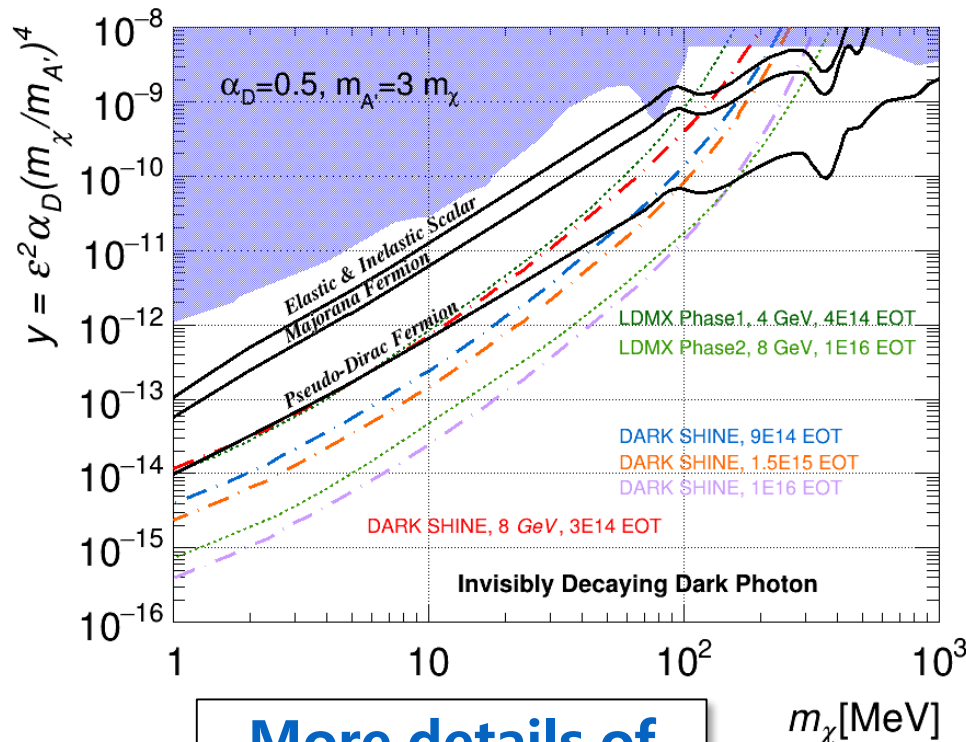
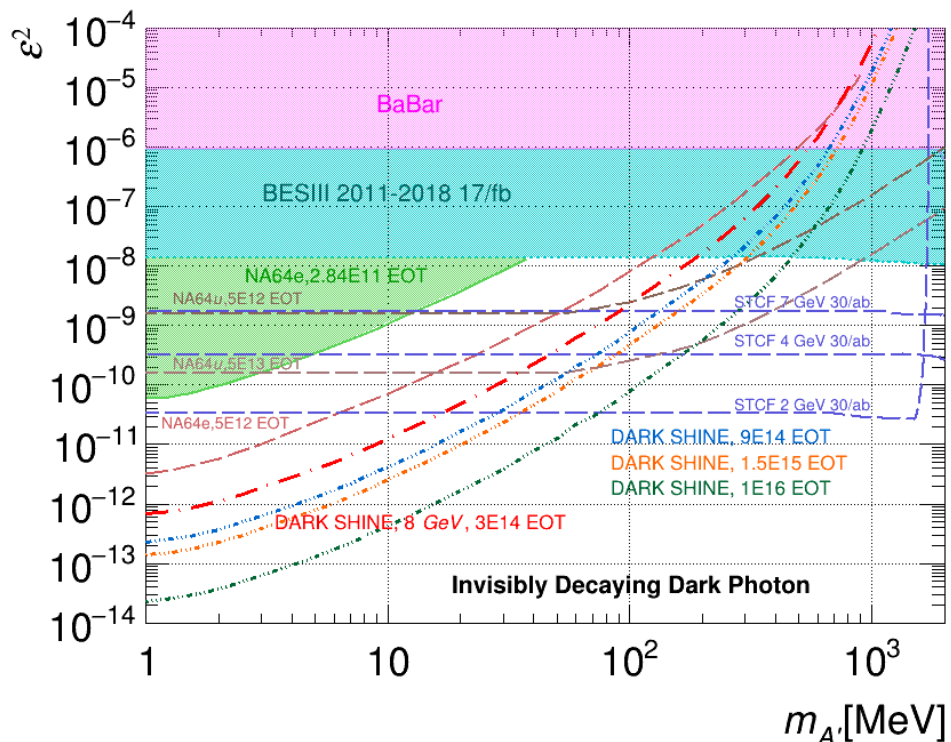


Comprehensive simulation and analysis framework that seamlessly integrates various functions, such as **detector simulation**, **electronic signal digitization**, **event display**, **event reconstruction**, and **data analysis**, based on **GEANT4** and **ACTs**.



Sensitivity study

- Prospective sensitivity is competitive
- Expected limit on the ε^2 as the function of A' mass at 90% C.L. is estimated with 3e14 EOTs (running ~1 year), 9e14 EOTs (~3 years), 1.5e15 EOTs (~5 years) and 1e16 EOTs (with Phase-II upgrade).



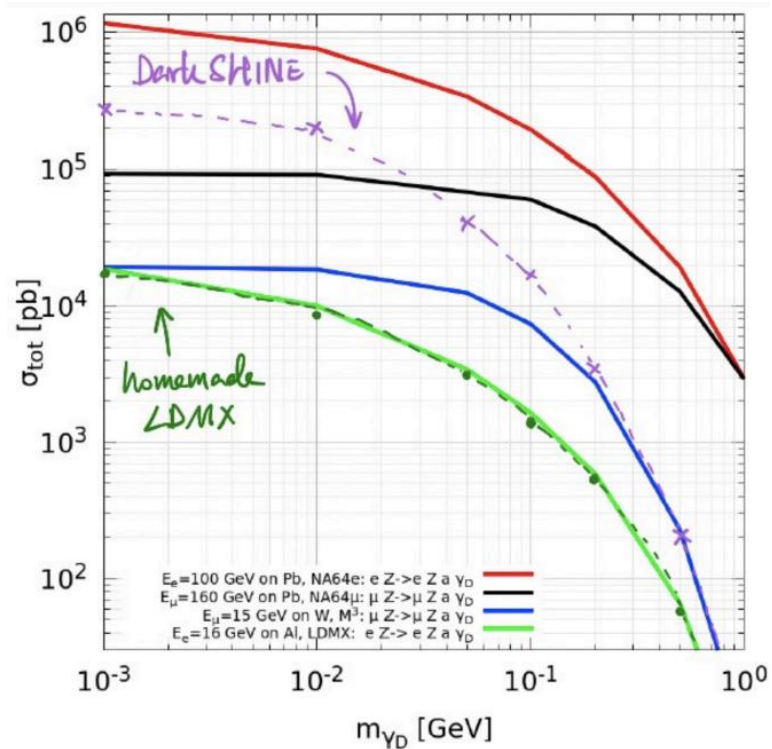
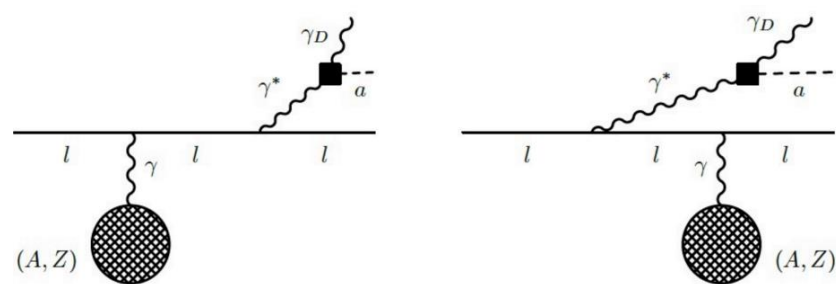
More physics opportunities...



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Minimal dark Axion-like particle portal and Axion+DP co-existence



- Dramatically different sensitivity curve of Dark Photon search when changing from electron beam to **positron** beam
- Extra s/t-chan annihilation diagrams come into play for Dark Photon production
- SHINE can also deliver **positron** beam with low current...

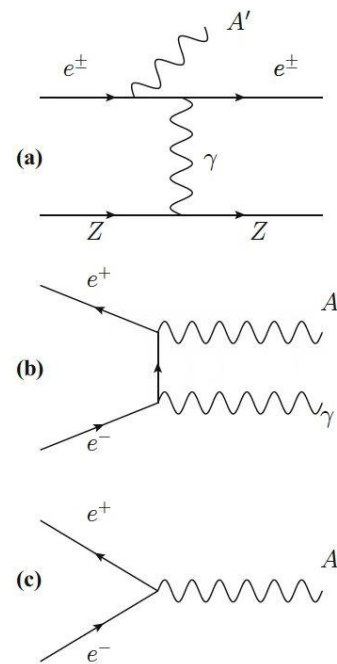
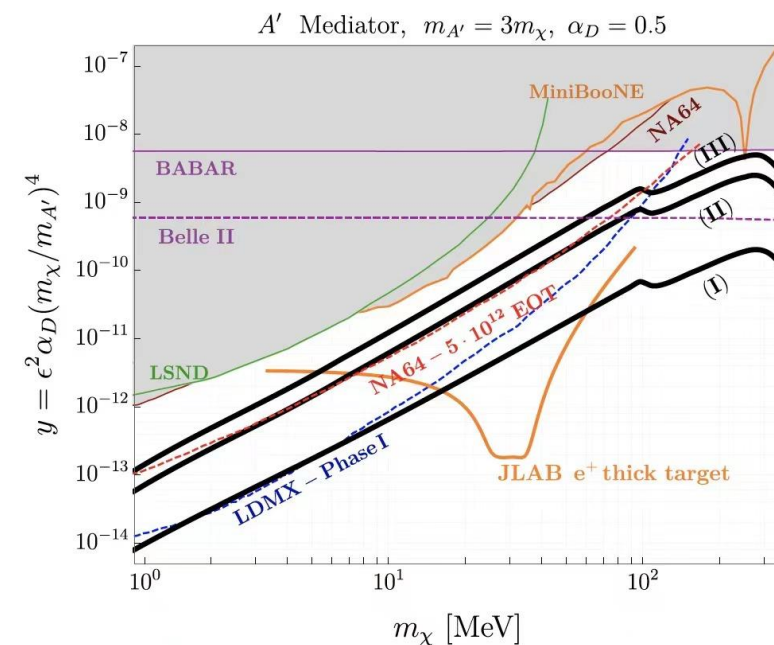


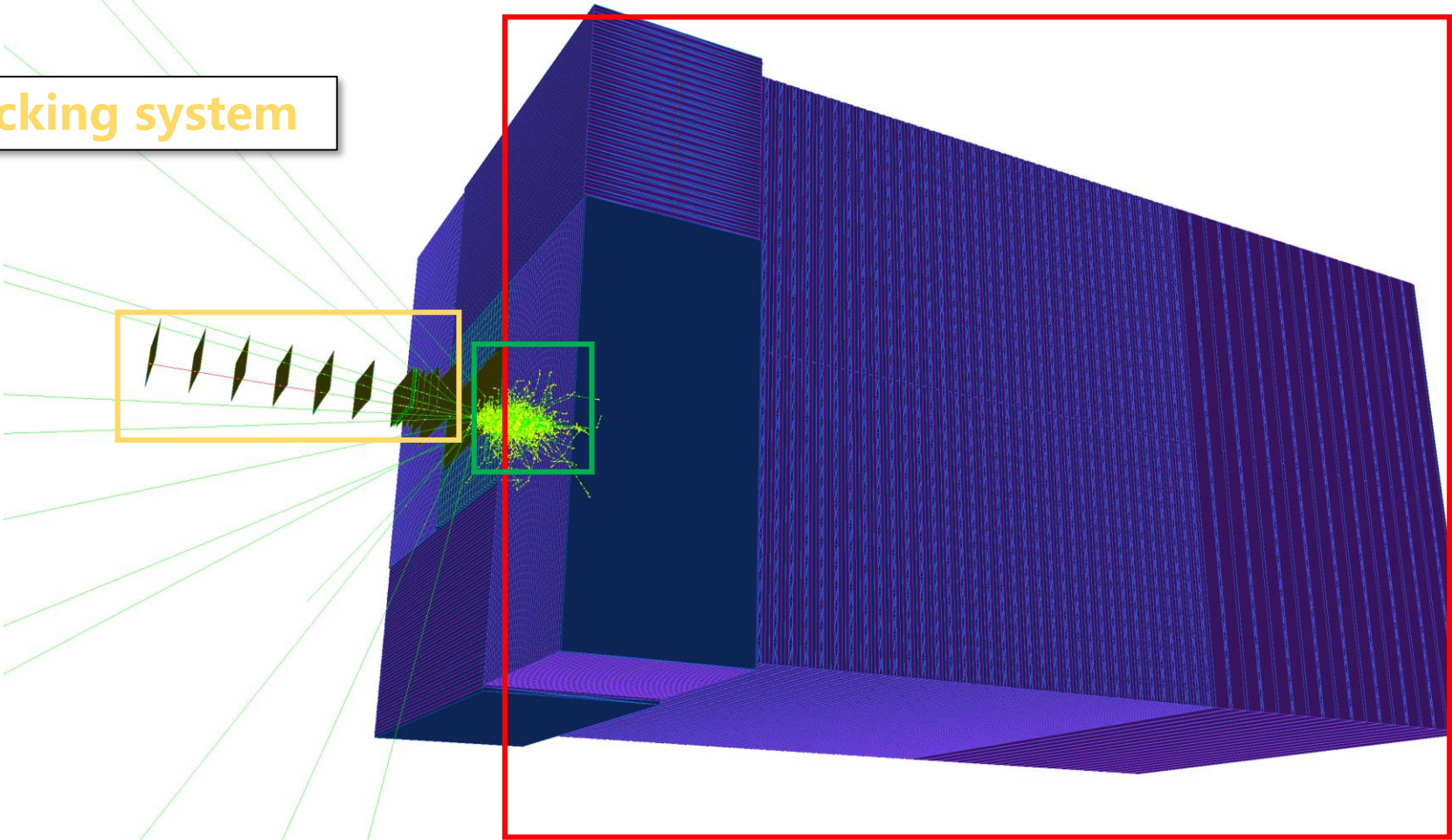
Fig. 1 Three different A' production modes in fixed target lepton beam experiments: (a) A' -strahlung in e^-/e^+ -nucleon scattering; (b) A' -strahlung in e^+e^- annihilation; (c) resonant A' production in e^+e^- annihilation



Eur. Phys. J. A (2021) 57:253



Tracking system



HCAL

ECAL

Detector R&D: Tracking system



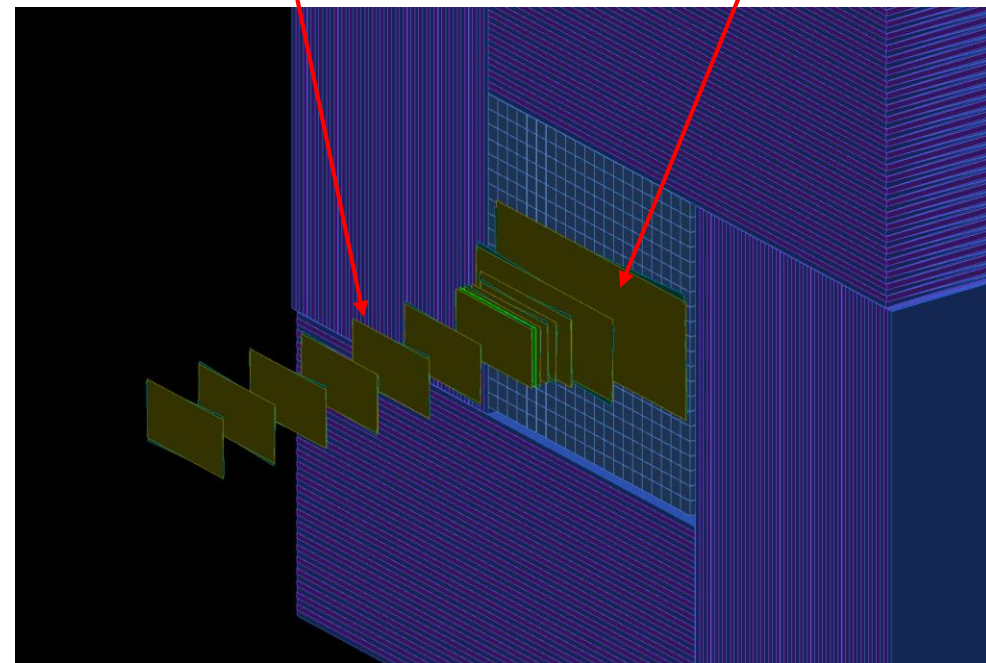
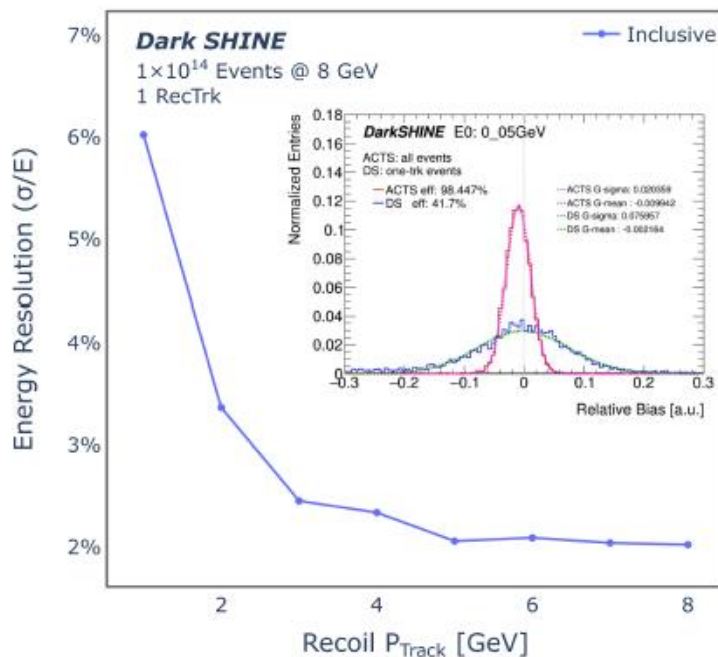
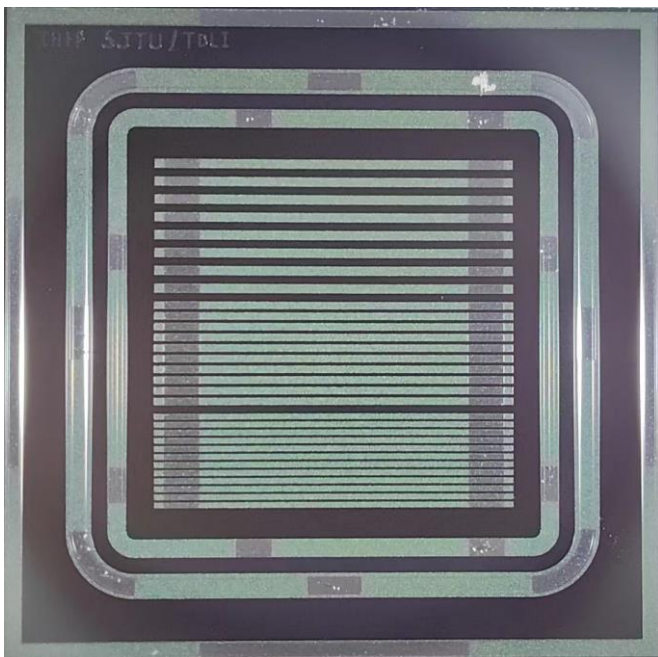
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- 7 layers of tagging tracker + 6 layers of recoil tracker
 - Two silicon strip sensors with a small angle (0.1 rad)
 - Resolution: 10 μm (horizontal), 60 μm (vertical)
- AC-LGAD silicon strip sensor prototype designed and tested.

Tagging tracker

Recoil tracker

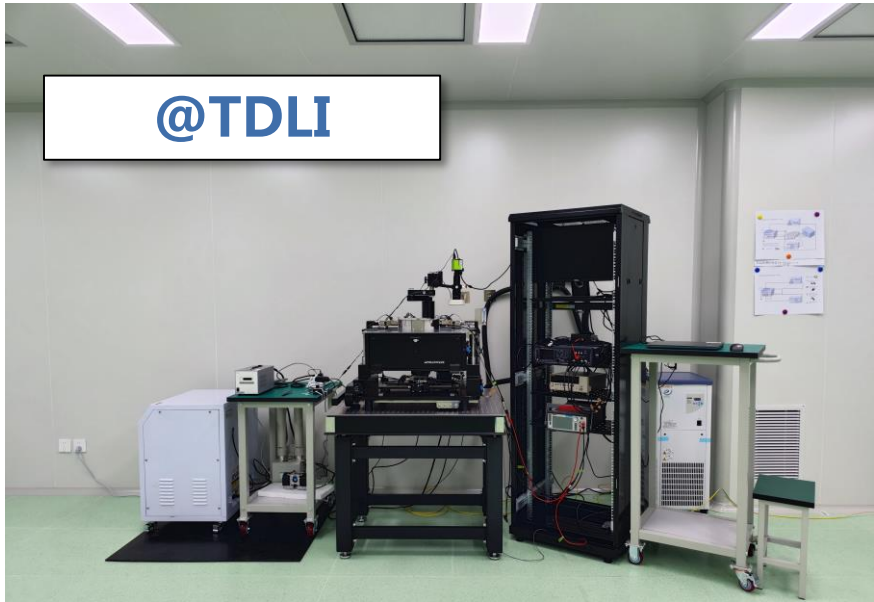


Detector R&D: Tracking system

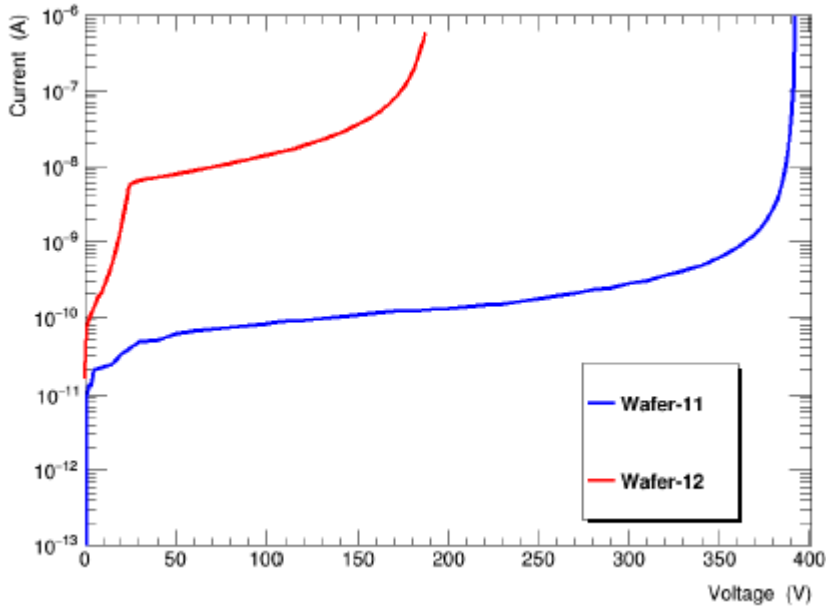
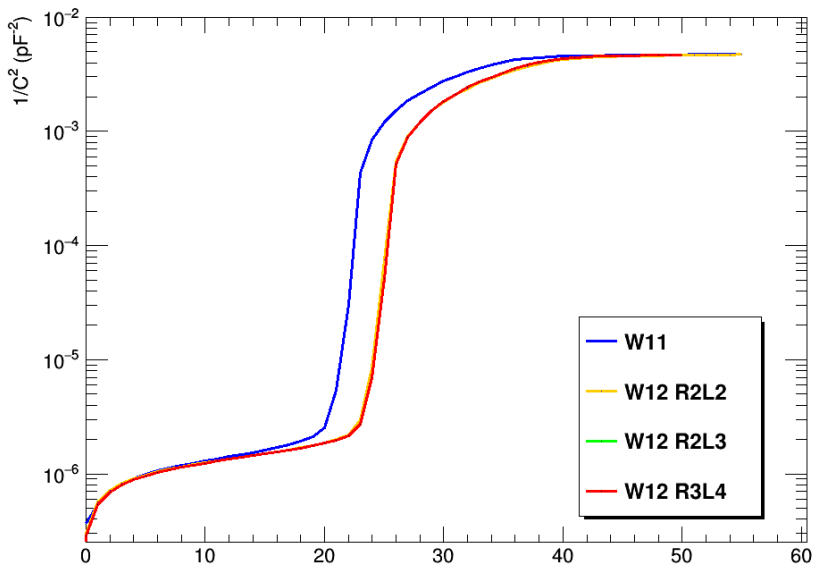


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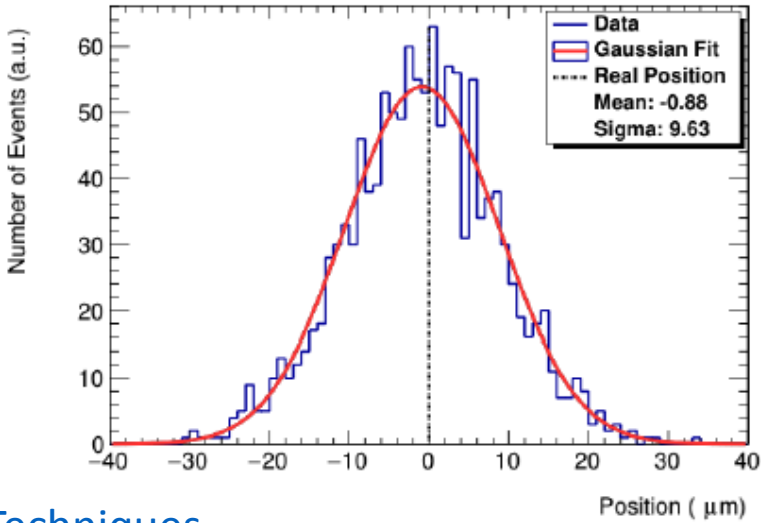
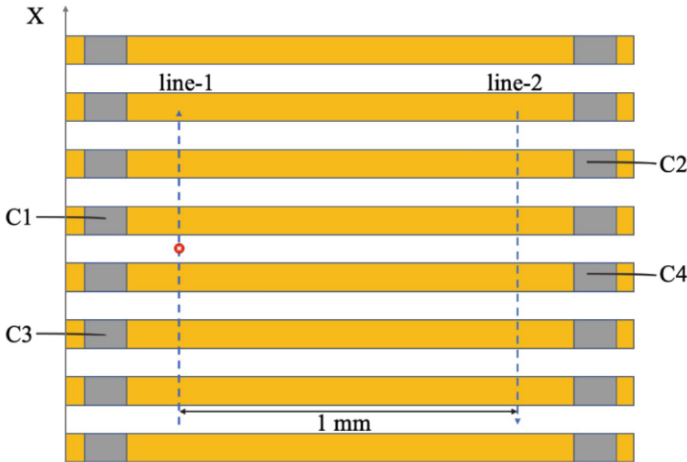
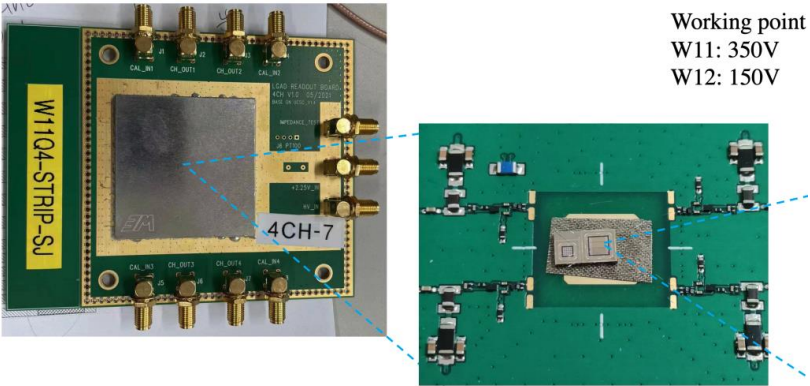
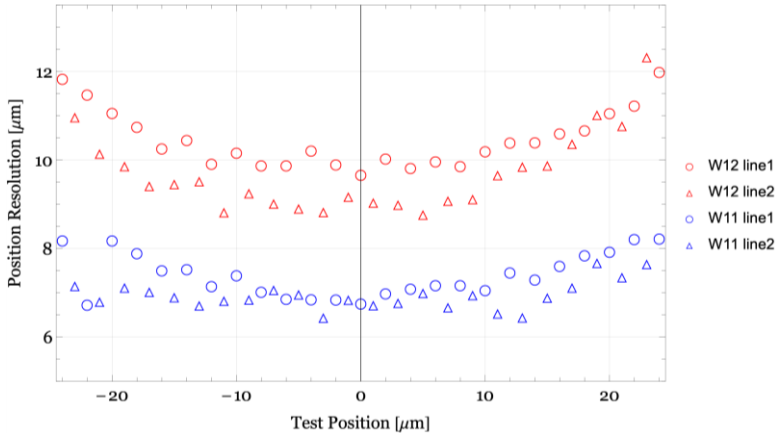
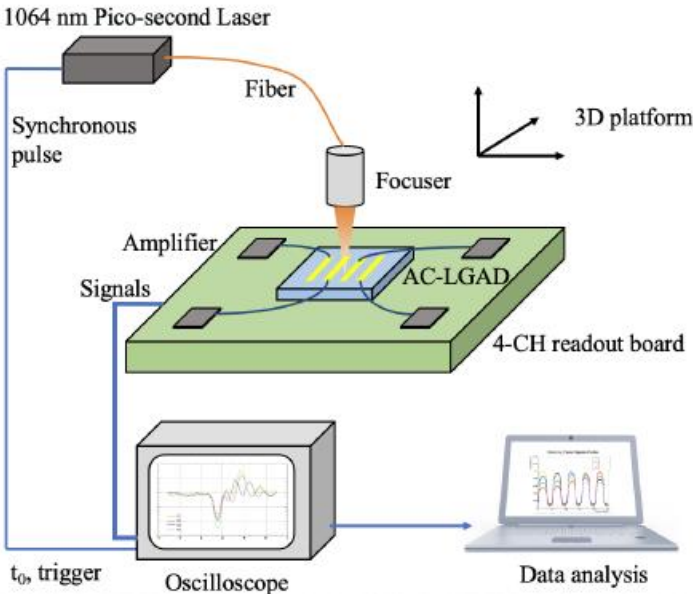
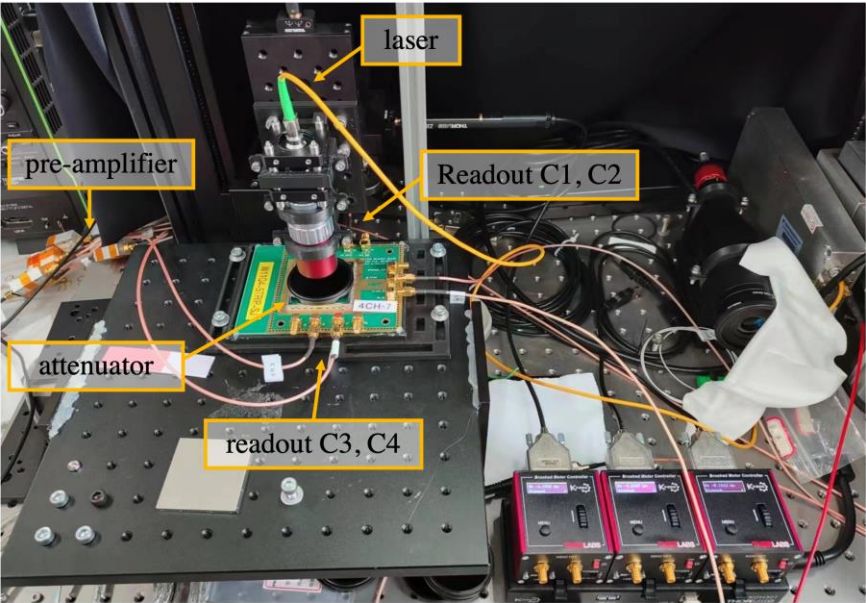
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More details on the poster No. 5-06



Detector R&D: Tracking system



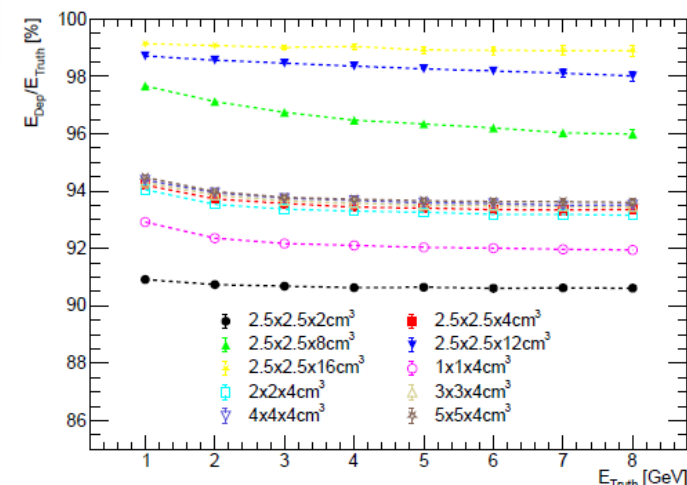
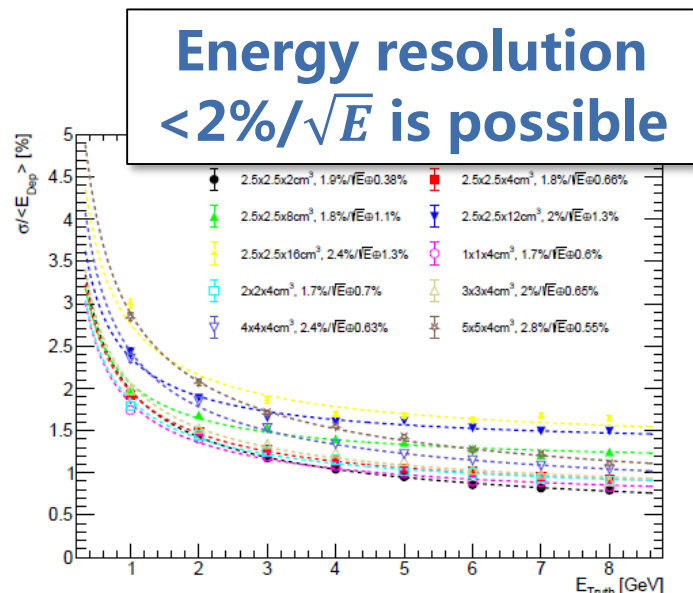
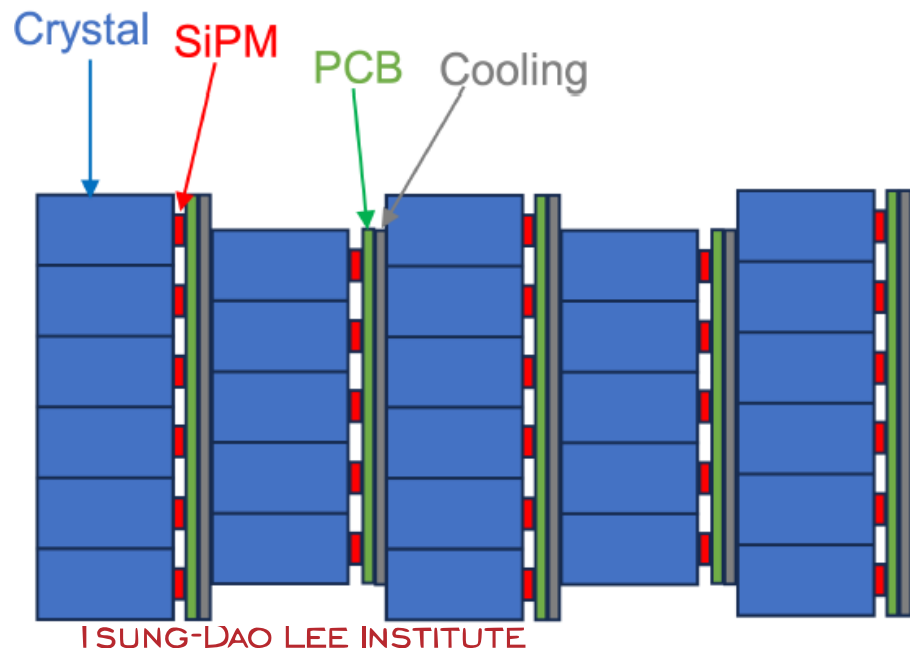
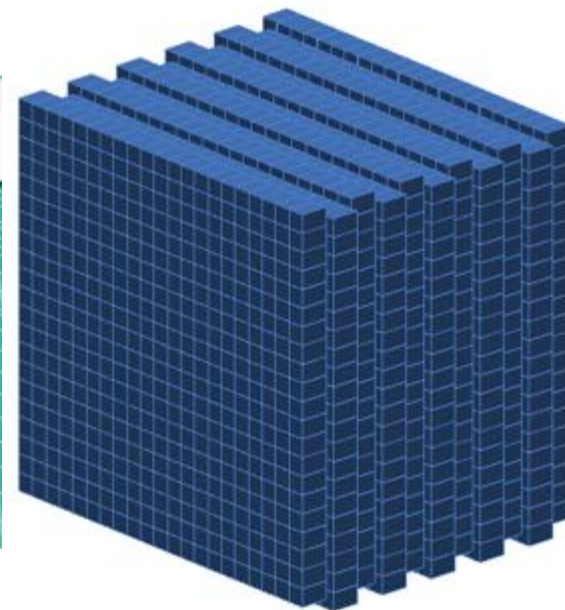
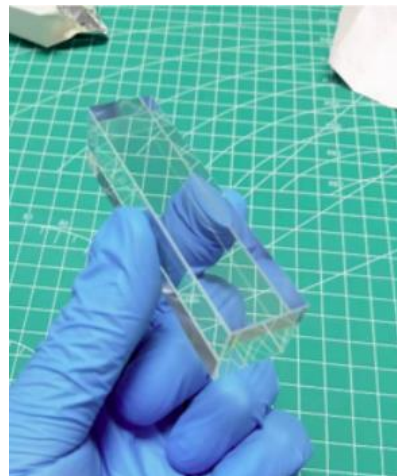
Detector R&D: Electromagnetic calorimeter



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- Deposit all the energy from electrons and photons, energy resolution $\sim 5\%$
- Crystal Scintillator + SiPM
 - $\text{LYSO}(\text{Lu}_{(1-x-y)}\text{Y}_{2y}\text{Ce}_{2x}\text{SiO}_5)$
 - $21 \times 21 \times 11$ crystals, $2.5\text{cm} \times 2.5\text{cm} \times 4\text{cm}$, design has been optimized
 - High light yields, short decay time, good radiation resistant



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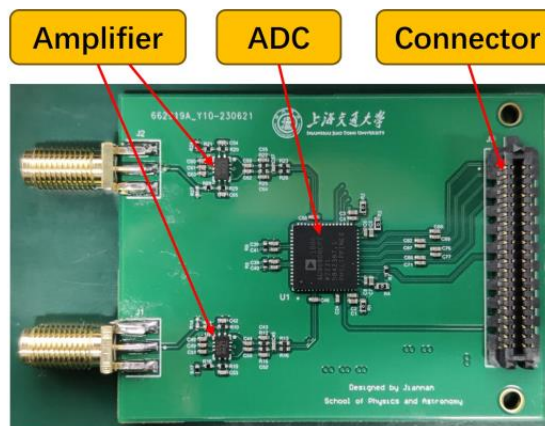
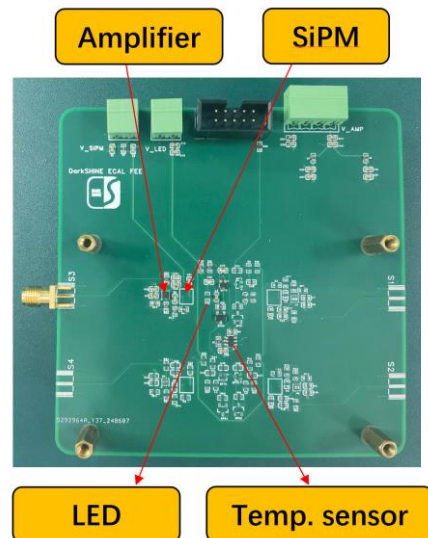
arXiv:2407.17800, submitted to Nuclear Science and Techniques

Detector R&D: Electromagnetic calorimeter

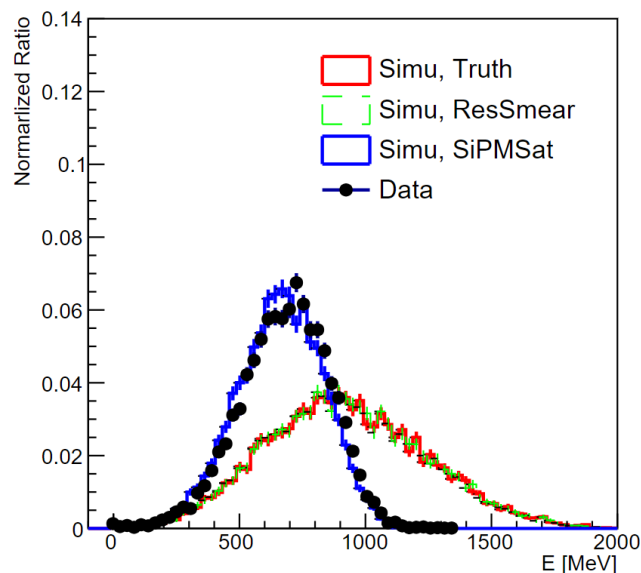
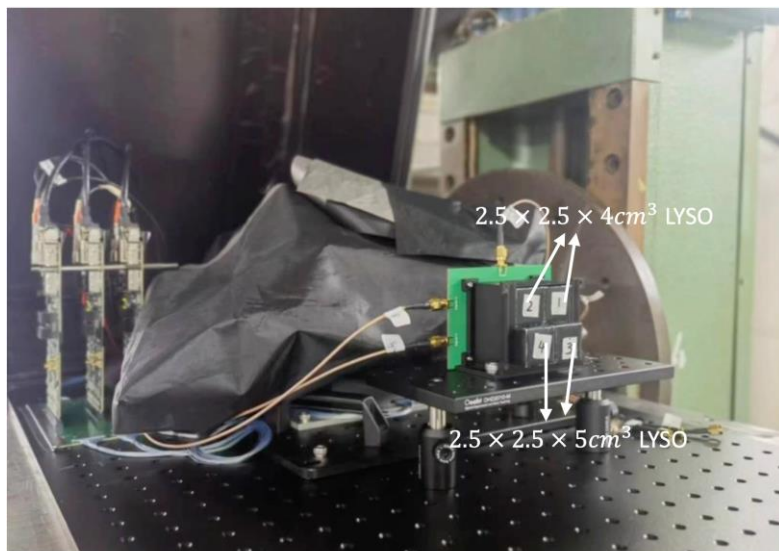
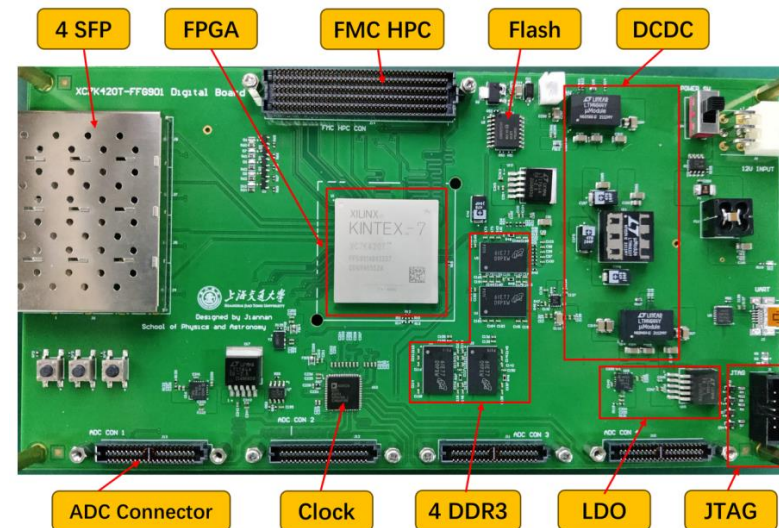


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5GeV



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- LYSO unit test has been done
- 1st prototype module for beam test (2x2 LYSO) at DESY (Many thanks to CEPC Calorimeter group!)
- New read-out has been designed and is under testing

More details on the poster
No. 5-17

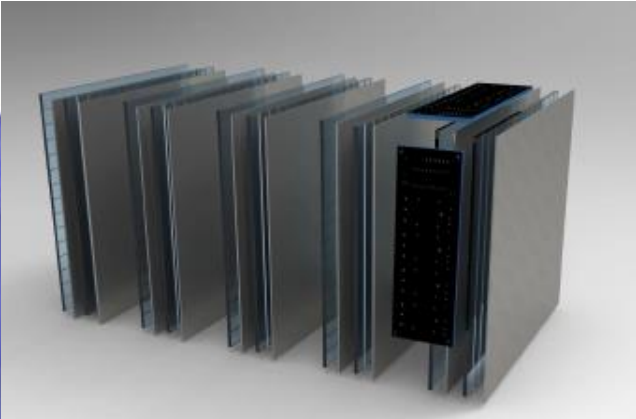
DESY TB22 Oct. 2023

Detector R&D: Hadronic calorimeter



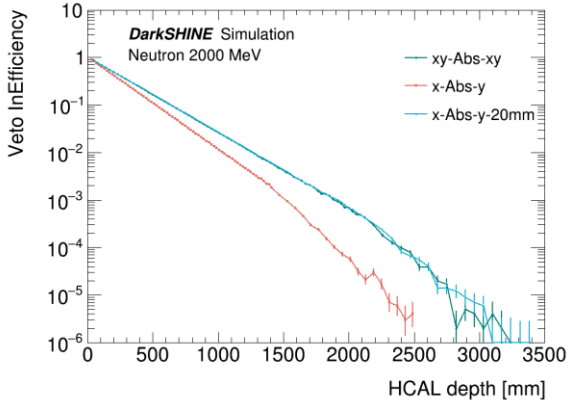
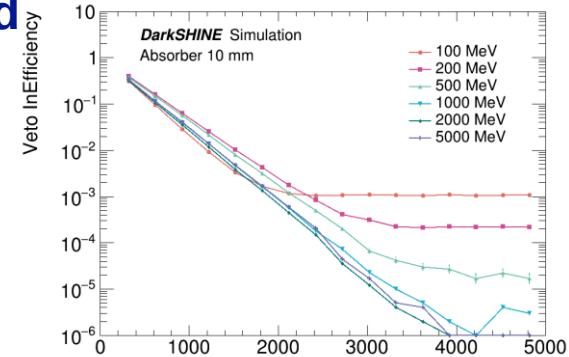
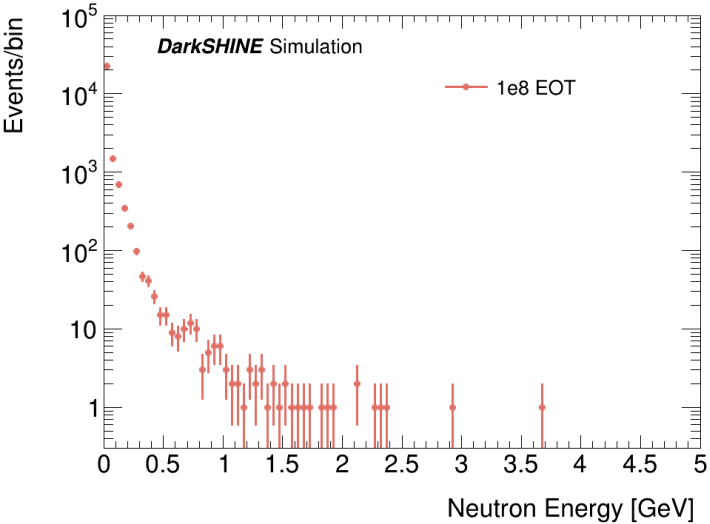
[arXiv:2311.01780](https://arxiv.org/abs/2311.01780), accepted by Nuclear Science and Techniques

- Veto backgrounds with same behavior as signal in ECAL
- 1.5 m × 1.5 m (perpendicular to the beam), ~10 λ (~160 cm iron, parallel to the beam)
 - Split to 4 modules, 75 cm × 75 cm each
 - Iron absorber: 10 mm (70 layers)/50 mm (18 layers) thick, 75 cm × 75 cm
 - Plastic scintillator: 10 mm thick, 75 cm × 5 cm, 15 bars per layer per module
 - 90 degree rotation between 2 adjacent layers
 - Wavelength shift fiber + SiPM
- Side-HCAL: encircling the ECAL
- Design has been optimized



w/ side HCAL ✓

Veto inefficiency



Veto InEff × E-06	n	k ⁰
100[MeV]	1170 ^{+10.9} _{-10.8}	31600 ^{+55.5} _{-55.4}
500[MeV]	18.4 ^{+1.46} _{-1.36}	5.40 ^{+0.839} _{-0.733}
1000[MeV]	3.70 ^{+0.714} _{-0.606}	3.70 ^{+0.714} _{-0.606}
2000[MeV]	2.70 ^{+0.626} _{-0.516}	11.5 ^{+1.19} _{-1.08}

π ⁰	p	μ
7.30 ^{+0.958} _{-0.852}	30700 ^{+61.5} _{-61.3}	409 ^{+6.49} _{-6.39}
0.1 ^{+0.184} ₋₀	8.04 ^{+1.34} _{-1.16}	15.0 ^{+1.33} _{-1.22}
0.1 ^{+0.184} ₋₀	0.1 ^{+0.958} ₋₀	2.00 ^{+0.555} _{-0.443}
0.1 ^{+0.188} ₋₀	0.1 ^{+2.78} ₋₀	0.1 ^{+0.184} ₋₀

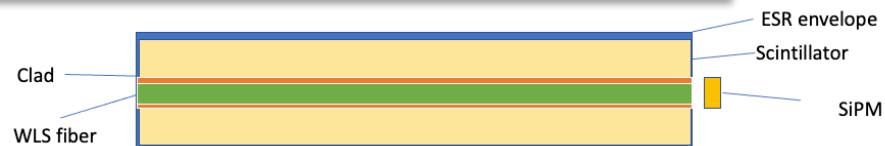
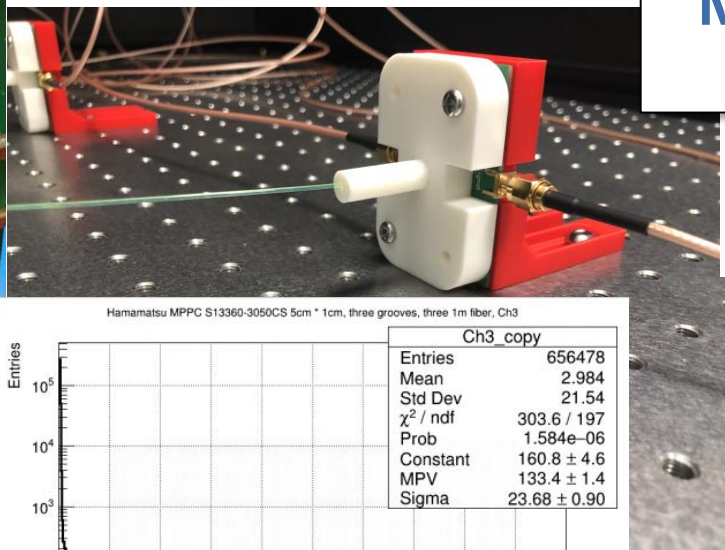
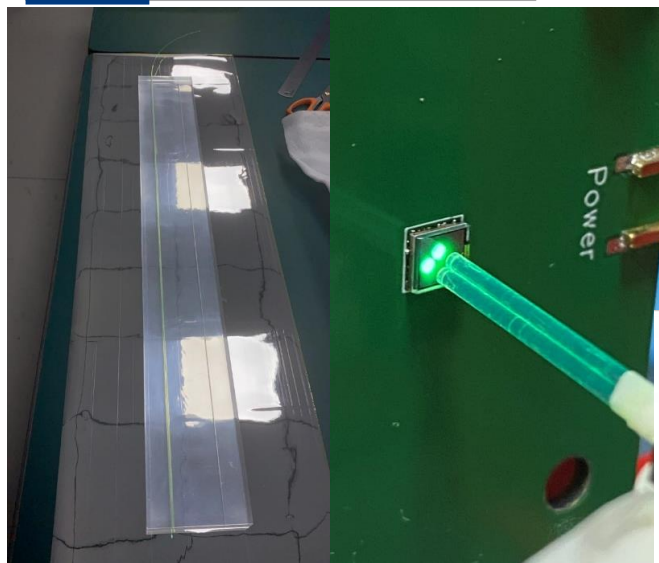
Detector R&D: Hadronic calorimeter



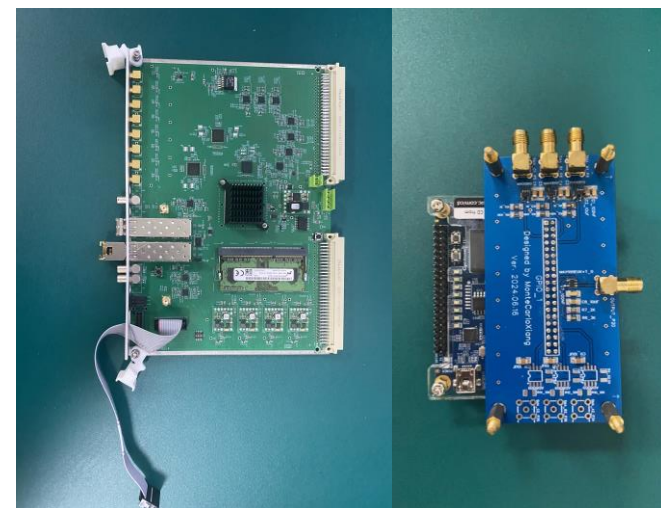
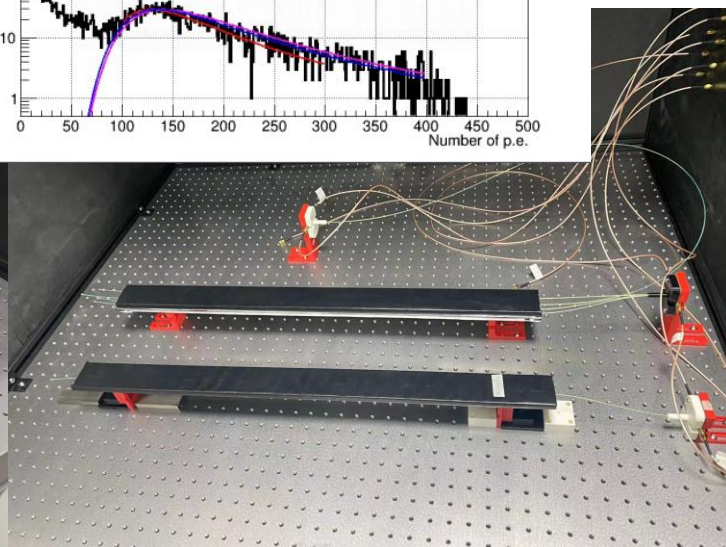
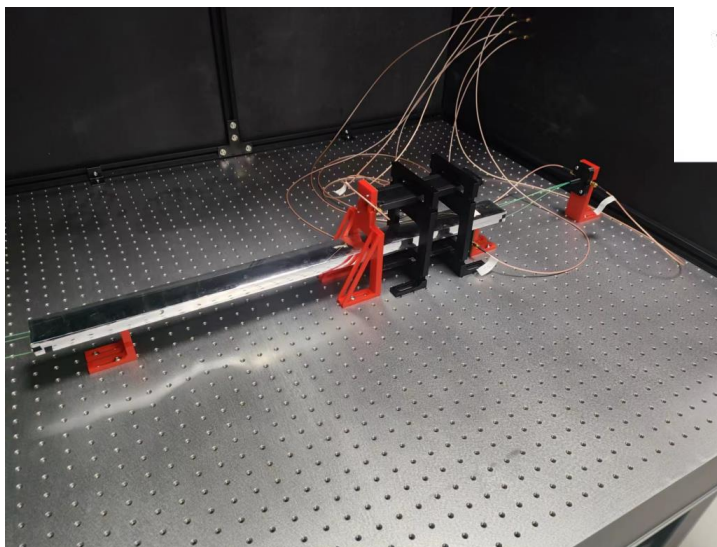
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More details in the HCAL- focused talk



- Plastic scintillator bars are tested with radioactive source and cosmic ray source
 - P.E test & noise test
- The fiber and SiPM are coupled with support and collimation structures

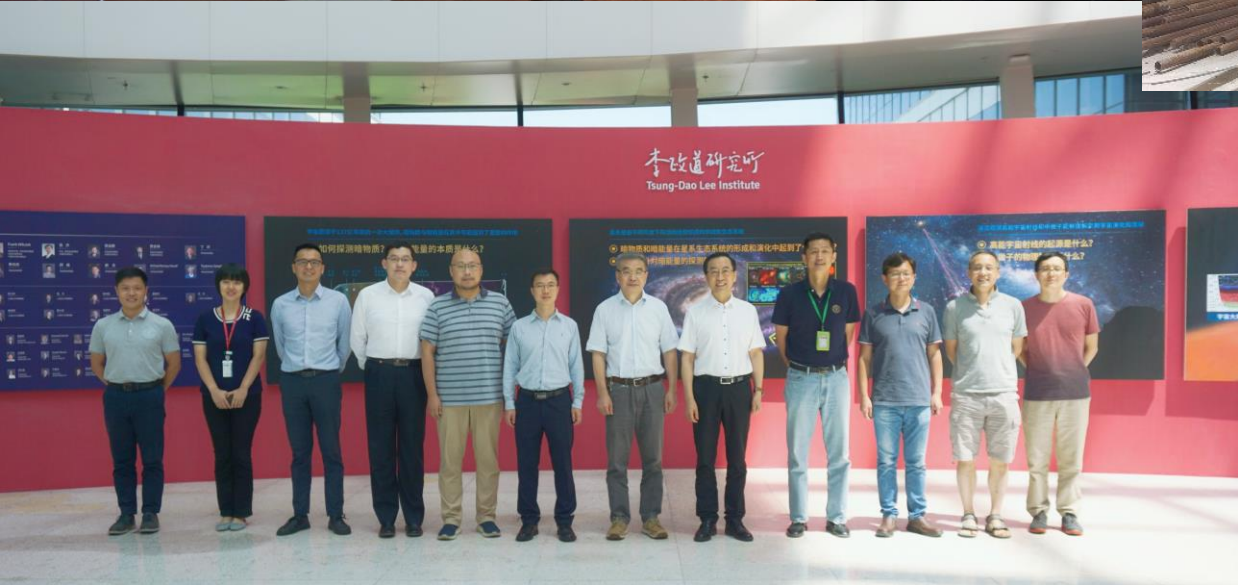


Collaboration with SHINE



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- The DarkSHINE experiment is a fixed target experiment using an electron beam to search for light dark matter, and has the potential for searching for more BSM particles
- First round of prospective analysis sensitivity of DarkSHINE has been studied
 - Competitive sensitivity, [Sci. China-Phys. Mech. Astron., 66\(1\): 211062 \(2023\)](#)
- Detector key technology R&D progress has been presented
 - Three articles have been submitted, one for each sub-detector, and two of them have been accepted
 - Has been sponsored by NSFC (原创探索计划项目)
 - Aiming for a conceptual design report



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Backup

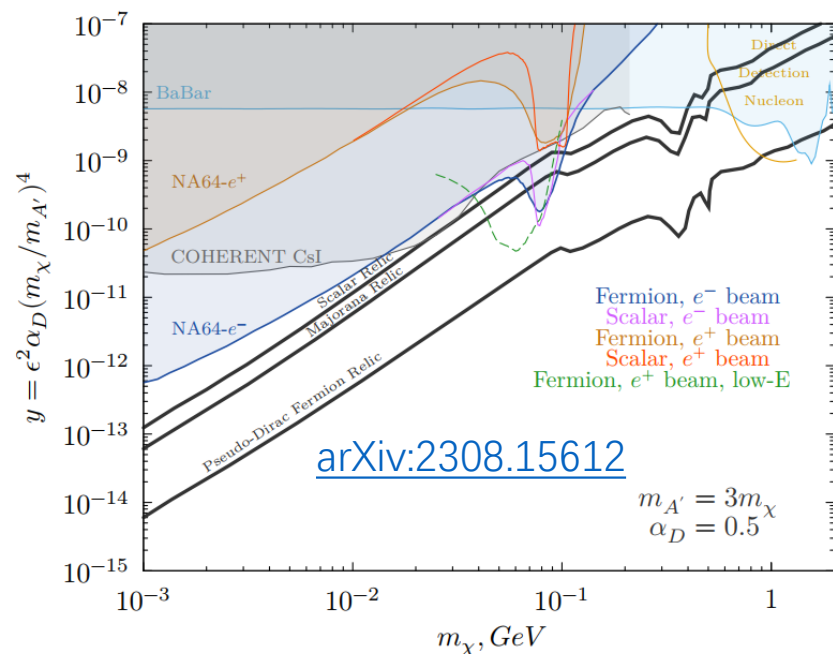


Dark Matter: Search for LDM & WIMP



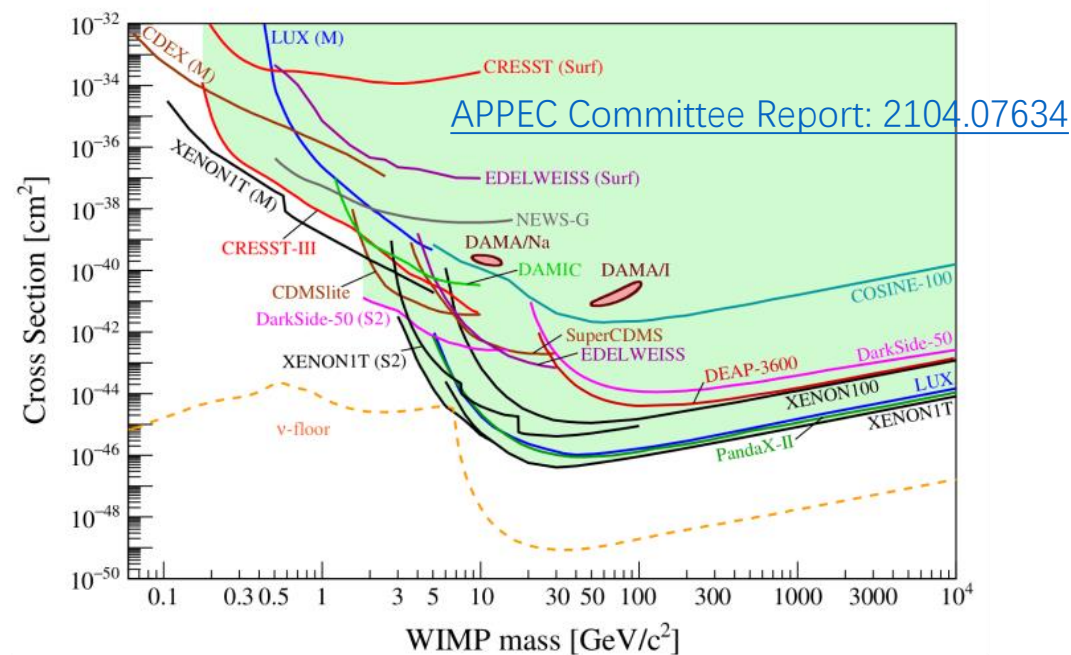
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• LDM: sub-GeV

- Thermal contact implies **new mediator**
- Beam dump/lepton-on-target experiments searching for dark photon: **NA64@CERN, BESIII, BELL-II, LDMX, etc.**



• WIMPs: GeV ~ TeV

- Space experiments (**DAMPE, AMS, etc.**)
- Collider experiments (**LHC, BELLE-II, BESIII, etc.**)
- Underground experiments (**PandaX, CDEX, LUX, Xenon, etc.**)

The SHINE facility



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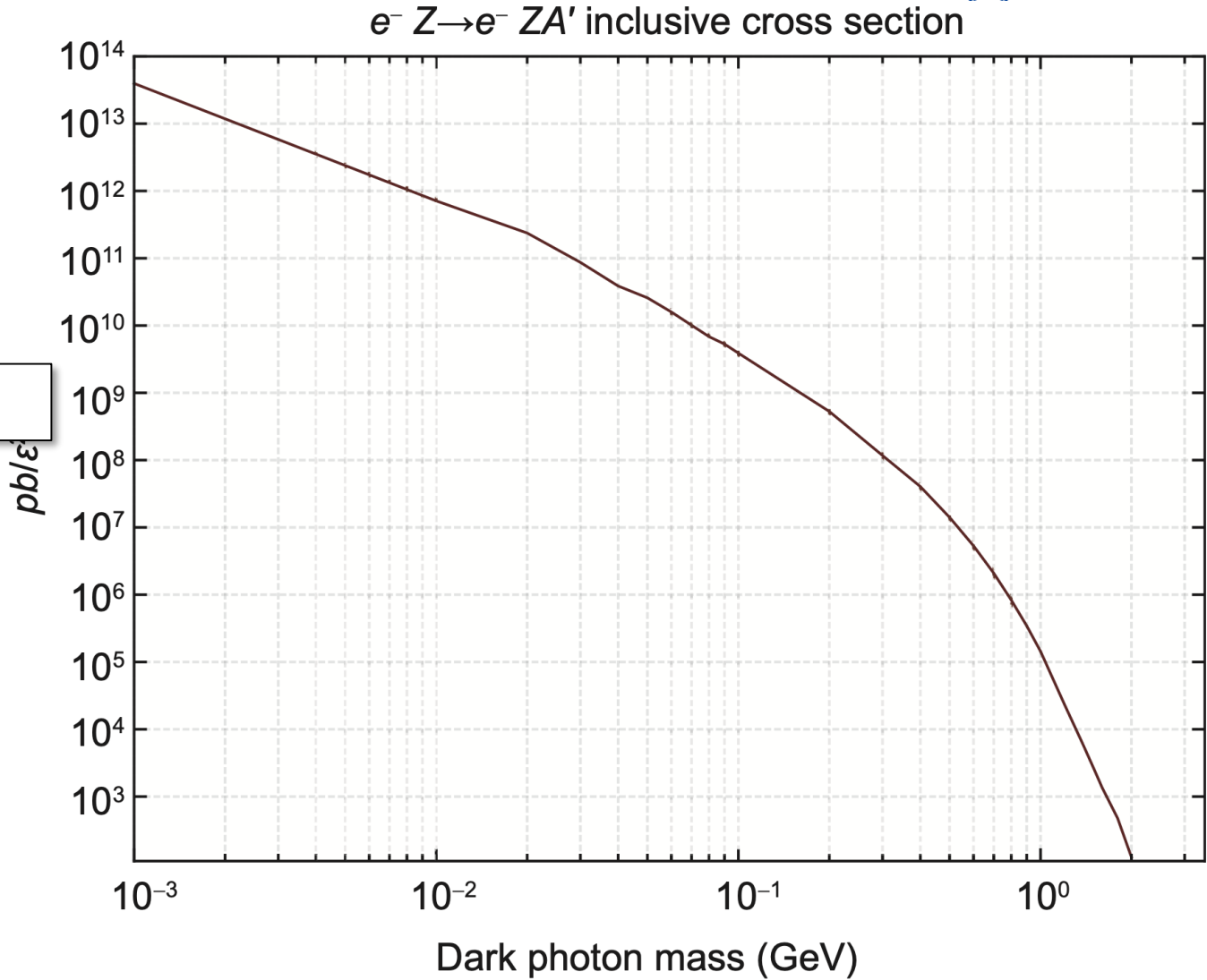
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Dark photon XS



XS with $\epsilon^2 = 1$



Signal vs. background



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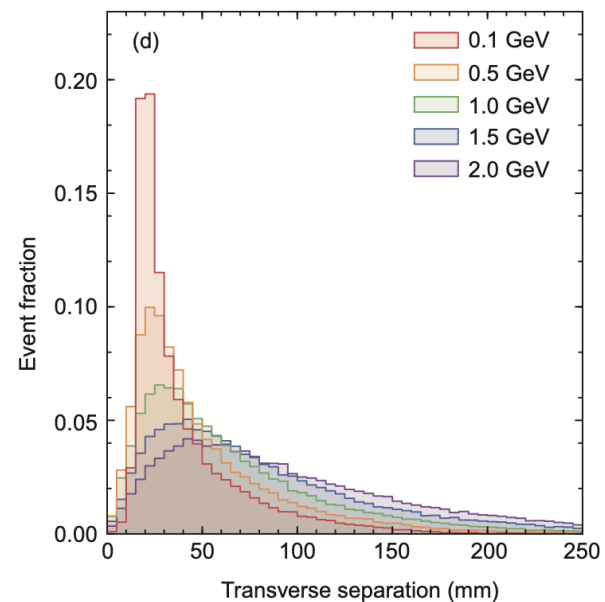
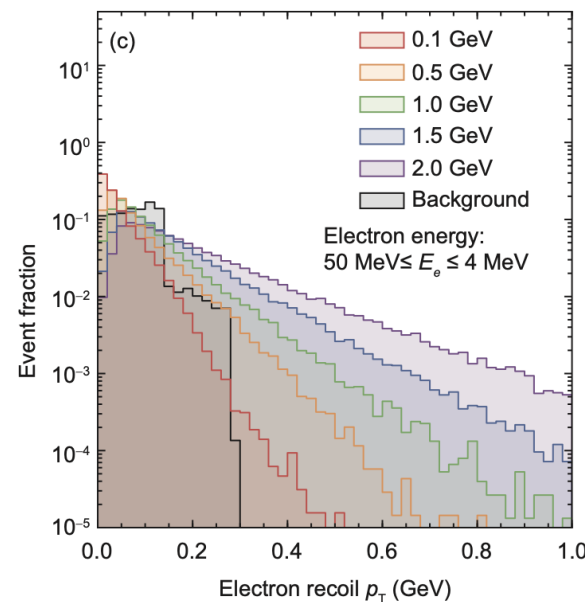
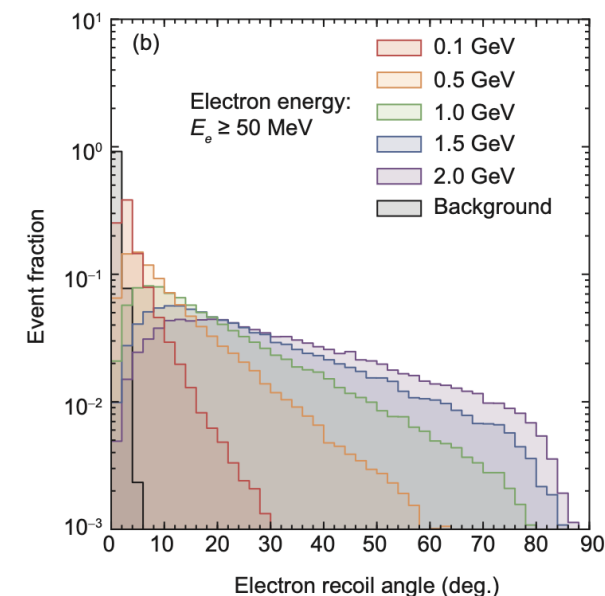
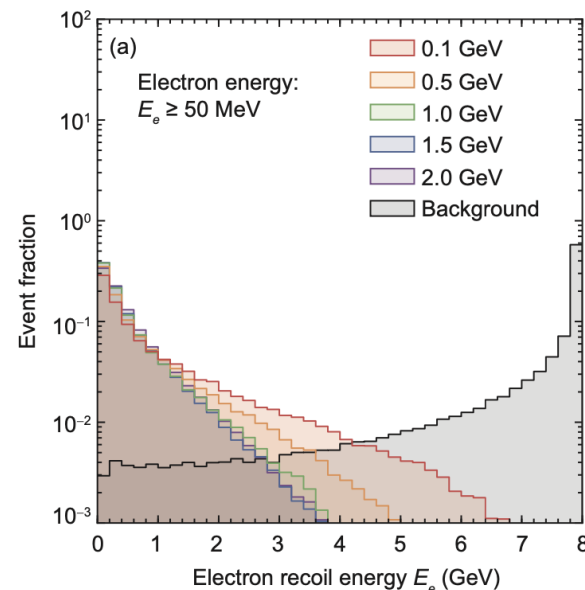
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Signal:

- Low momentum of recoil electron
- Recoil electron angle has on average value

Background:

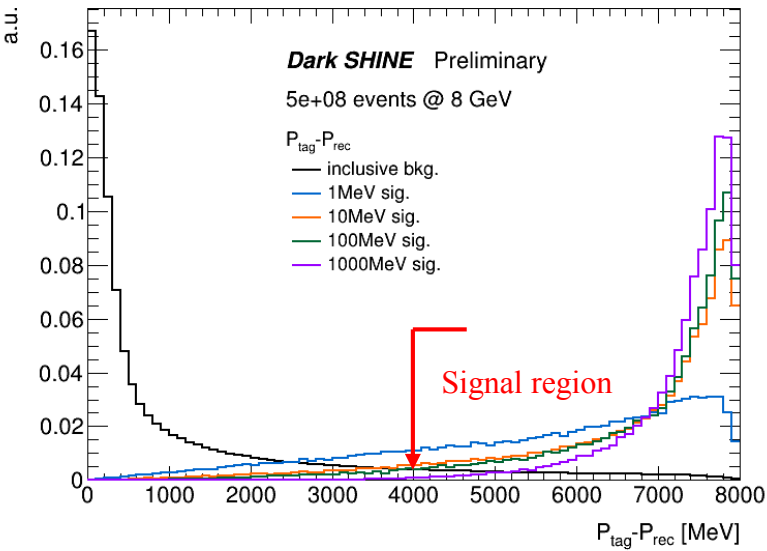
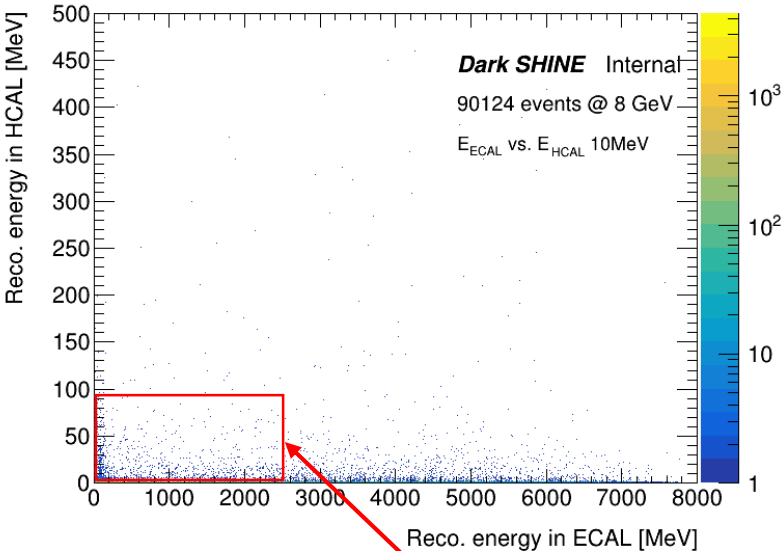
- Small missing energy, recoil electron carries most of the momentum
- Small recoil electron angle



Signal-box design

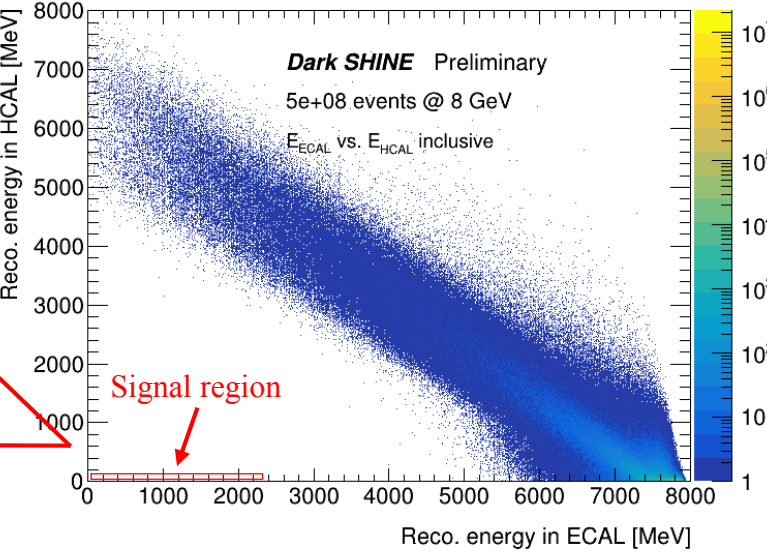
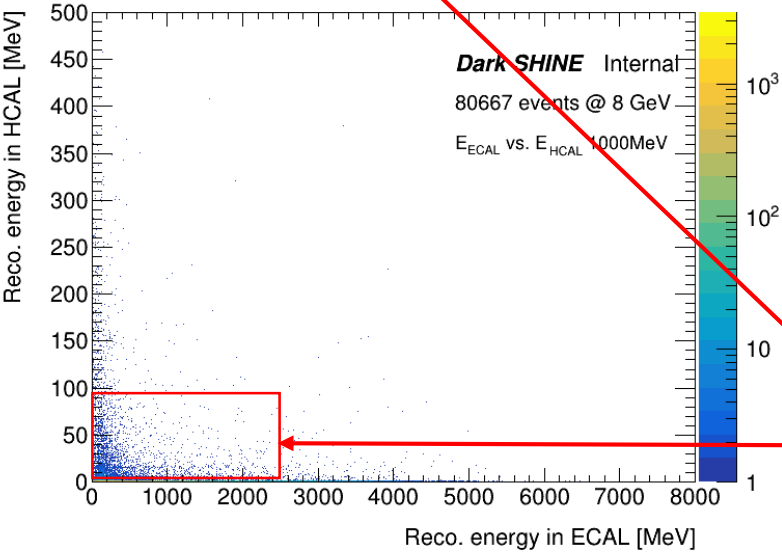


10 MeV A'



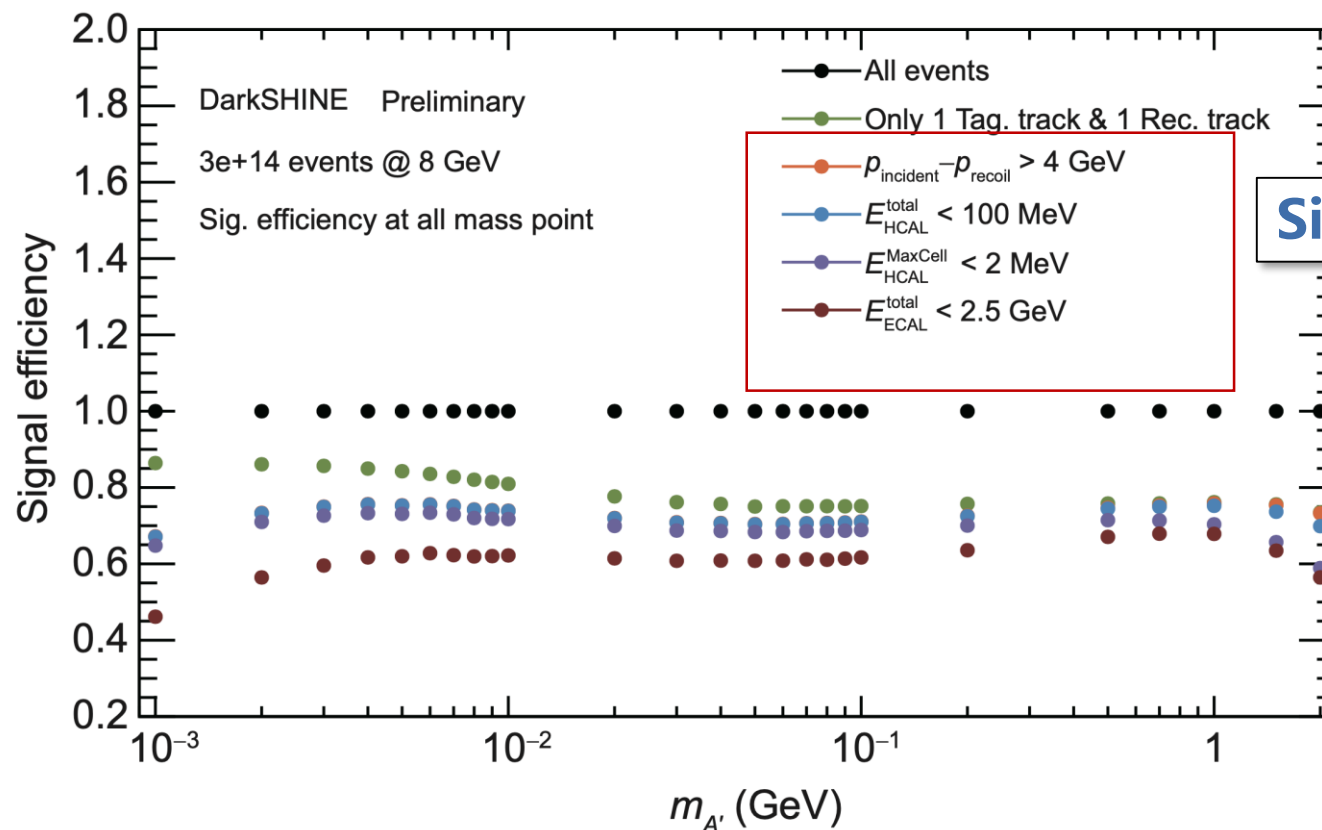
Inclusive bkg
& signal

1 GeV A'



Inclusive bkg

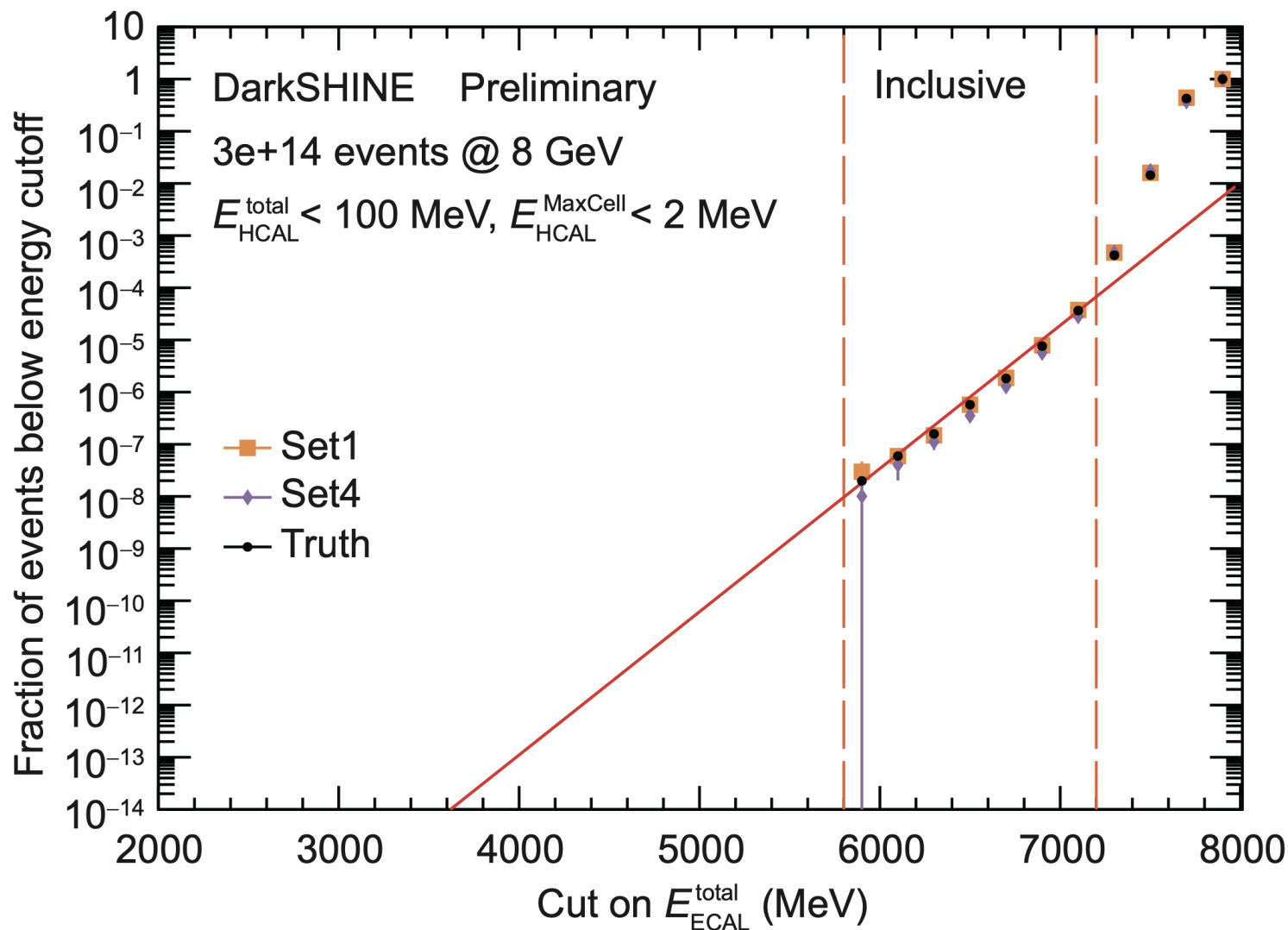
Acceptance efficiency



Signal-box selection

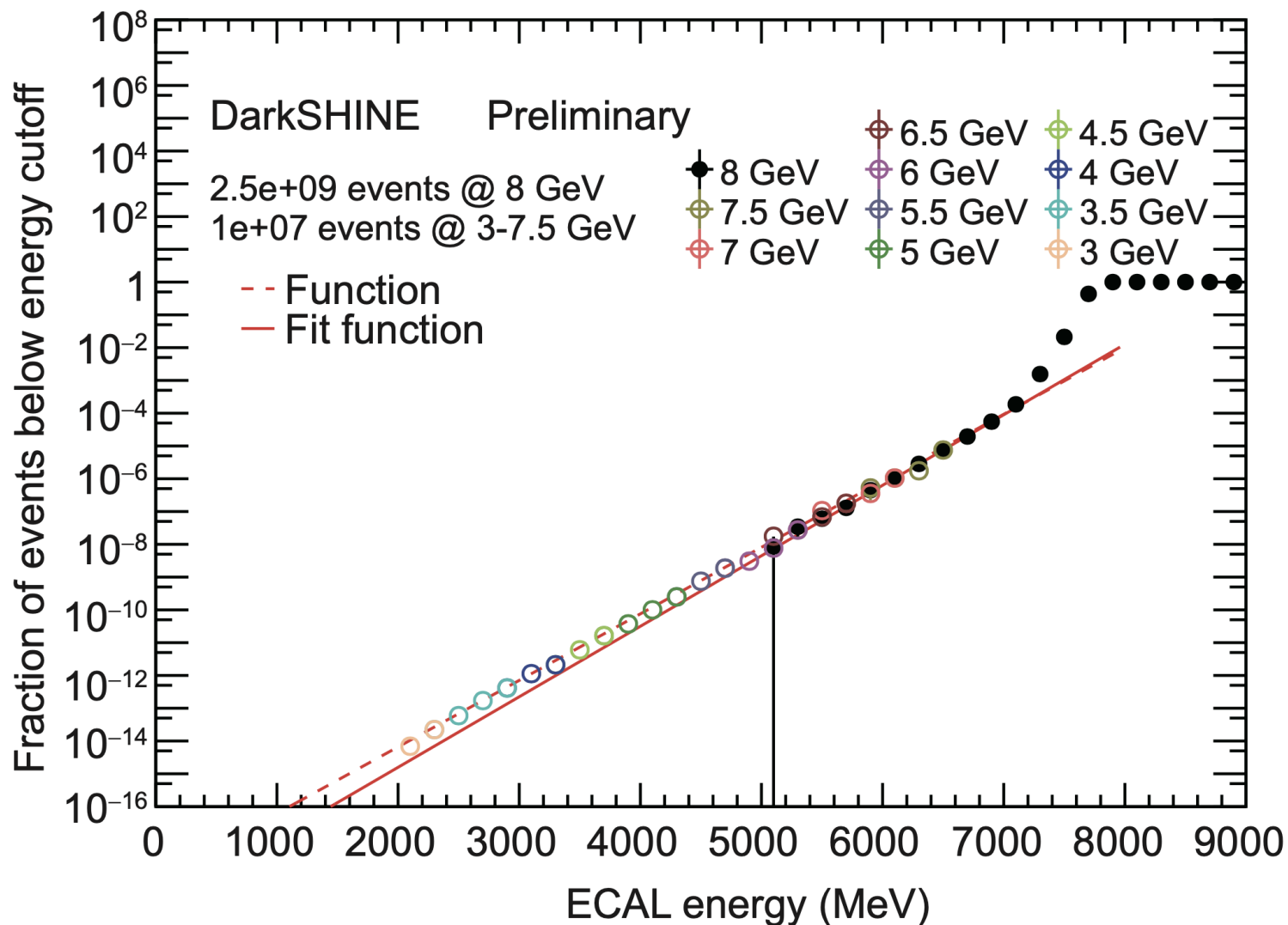
- 60% signal events survive the cut-flow, no background survive (2.5e9)
- Acceptance efficiency drops in:
 - **Low-mass** region of a few MeV: tight energy cuts.
 - **High-mass** region above 1 GeV: particles with large incident/recoil angle go into the HCAL directly.

Background estimation



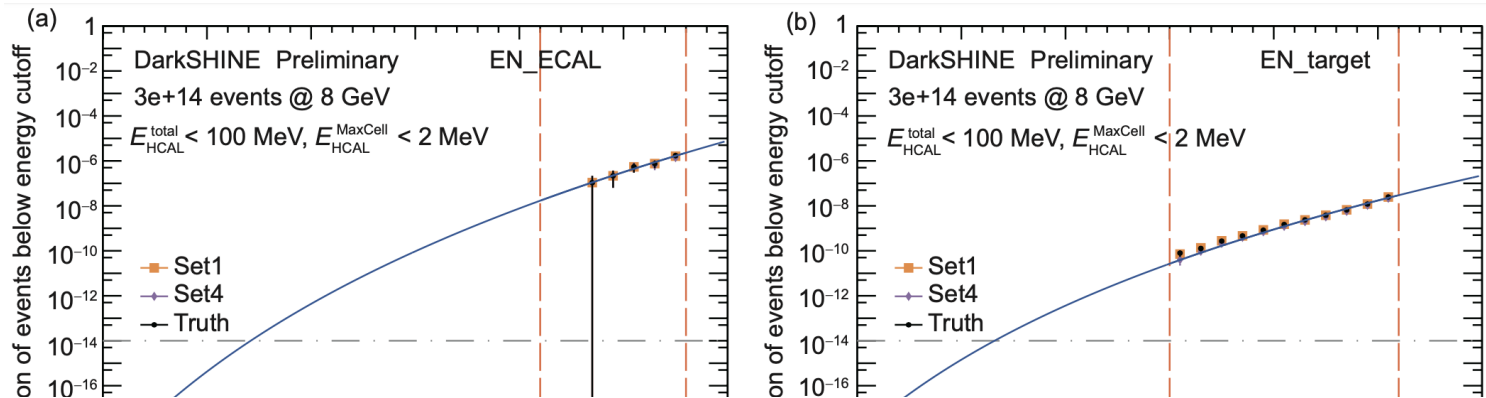
- Expected background yields go down quickly at lower ECAL energy.
- In order to estimate background yields in 10^{14} EOT, extrapolation method is used
 - fit from inclusive background process

Background estimation



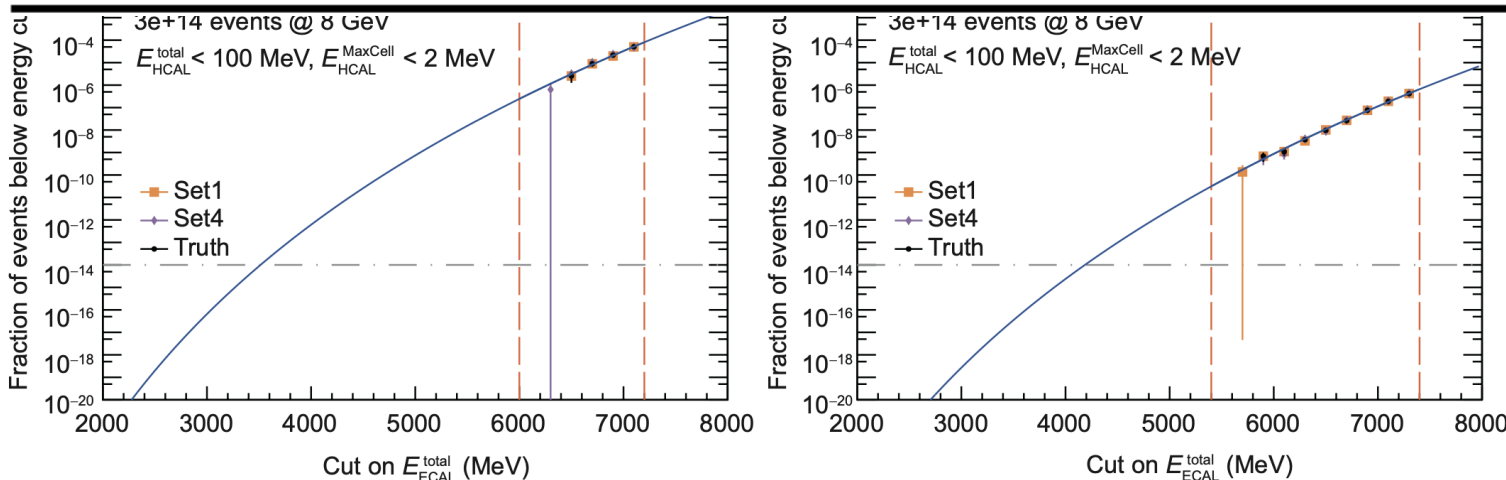
- Expected background yields go down quickly at lower ECAL energy.
- In order to estimate background yields in 10^{14} EOT, extrapolation method is used
 - fit from inclusive background process
 - extrapolation from low energy samples

Background estimation



- Expected background yields go down quickly at lower ECAL energy.
- In order to estimate background yields in

Method	Cut flow	Rare. extra.	Incl.- extra.	Incl. vali.	Invisible
Yield	0	1.5×10^{-2}	2.53×10^{-3}	9.23×10^{-3}	negligible



background process

- extrapolation from low energy samples
- fit from each rare background process

The DarkSHINE simulation

Simulated background statistics:

Process	Generate events	Branching ratio	EOTs
Inclusive	2.5×10^9	1.0	2.5×10^9
Bremsstrahlung	1×10^7	6.70×10^{-2}	1.5×10^8
GMM_target	1×10^7	$1.5(\pm 0.5) \times 10^{-8}$	4.3×10^{14}
GMM_ECAL	1×10^7	$1.63(\pm 0.06) \times 10^{-6}$	6.0×10^{12}
PN_target	1×10^7	$1.37(\pm 0.05) \times 10^{-6}$	4.0×10^{12}
PN_ECAL	1×10^8	$2.31(\pm 0.01) \times 10^{-4}$	4.4×10^{11}
EN_target	1×10^8	$5.1(\pm 0.3) \times 10^{-7}$	1.6×10^{12}
EN_ECAL	1×10^7	$3.25(\pm 0.08) \times 10^{-6}$	1.8×10^{12}

Event cut-flow of each background process:

Table 4 Event cut flow for each background sample in Table 2. The selection efficiencies of each cut are listed in the table (%)

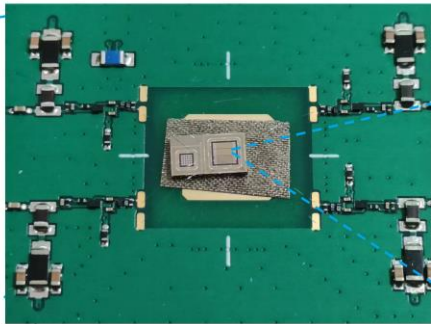
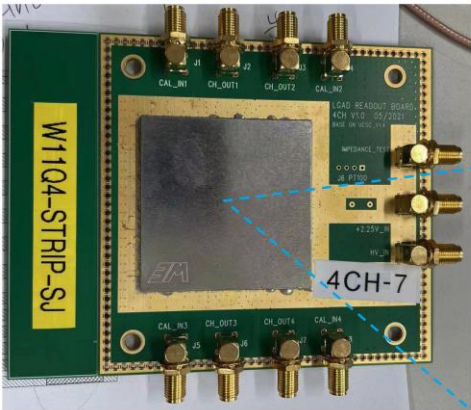
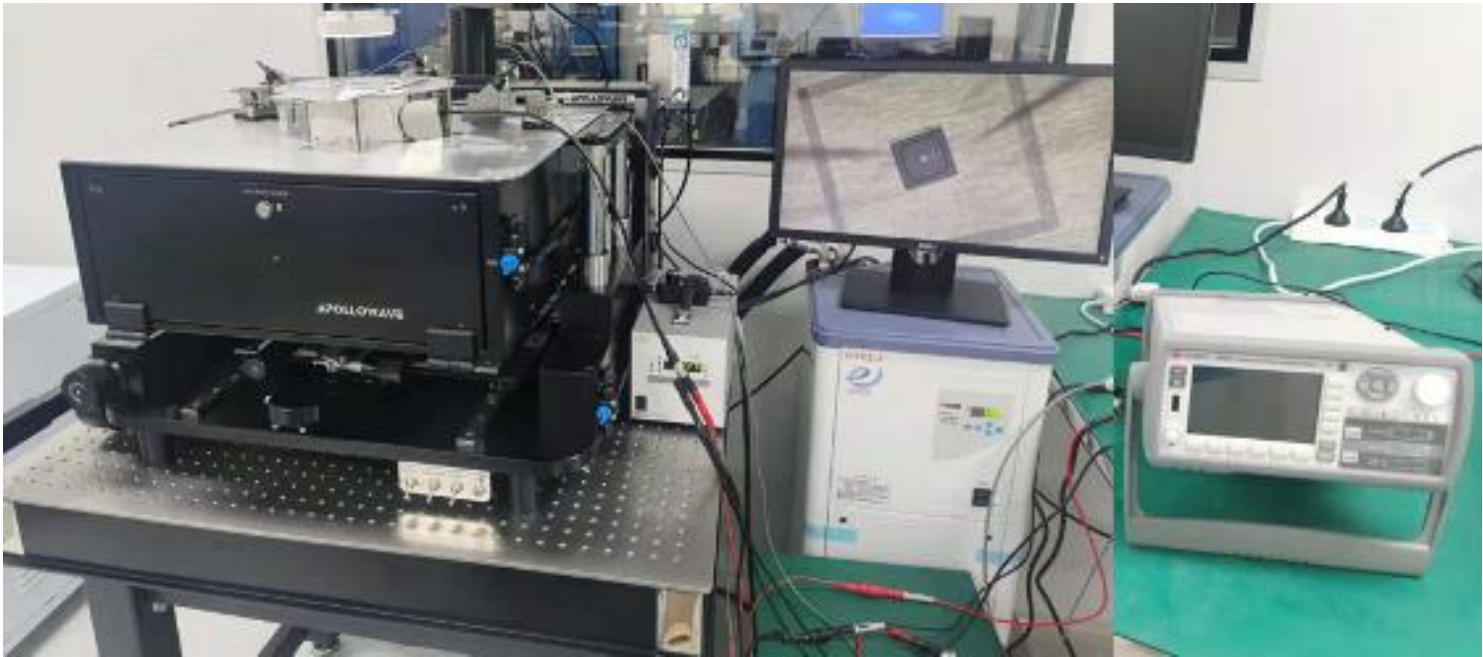
	EN_ECAL	PN_ECAL	GMM_ECAL	EN_target	PN_target	GMM_target	Hard_brem	Inclusive
Total events	100	100	100	100	100	100	100	100
Only 1 track	58.87	70.48	87.36	5.85	5.88	$< 10^{-3}$	78.73	84.40
$p_{\text{tag}} - p_{\text{rec}} > 4 \text{ GeV}$	0.0044	0.0033	0.0041	5.58	5.46	$< 10^{-5}$	70.49	4.80
$E_{\text{HCAL}}^{\text{total}} < 100 \text{ MeV}$	$< 10^{-3}$	$< 10^{-3}$	0	0.30	0.72	0	69.61	4.76
$E_{\text{HCAL}}^{\text{MaxCell}} < 10 \text{ MeV}$	$< 10^{-3}$	$< 10^{-3}$	0	0.13	0.27	0	65.00	4.48
$E_{\text{HCAL}}^{\text{MaxCell}} < 2 \text{ MeV}$	$< 10^{-3}$	$< 10^{-3}$	0	0.058	0.095	0	58.14	4.04
$E_{\text{ECAL}}^{\text{total}} < 2.5 \text{ GeV}$	0	0	0	0	0	0	0	0

Tracking system

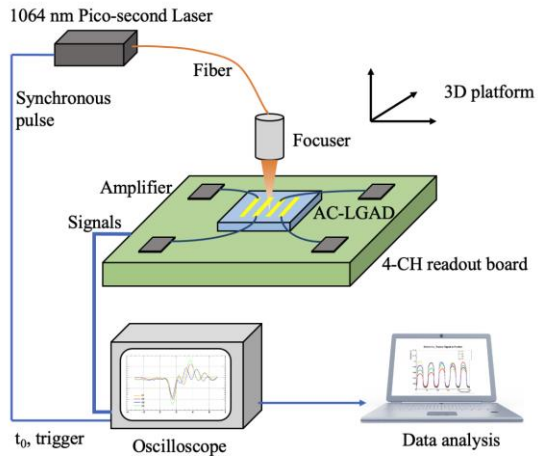
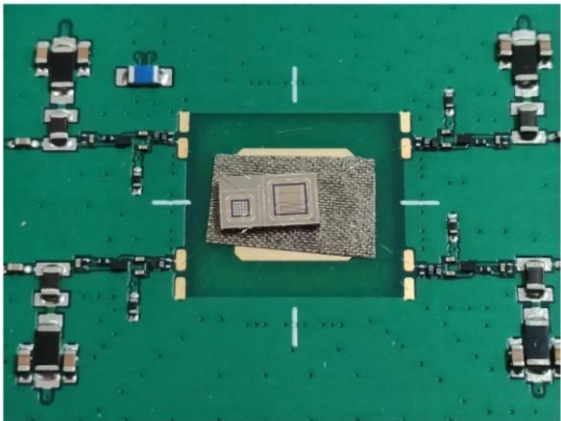
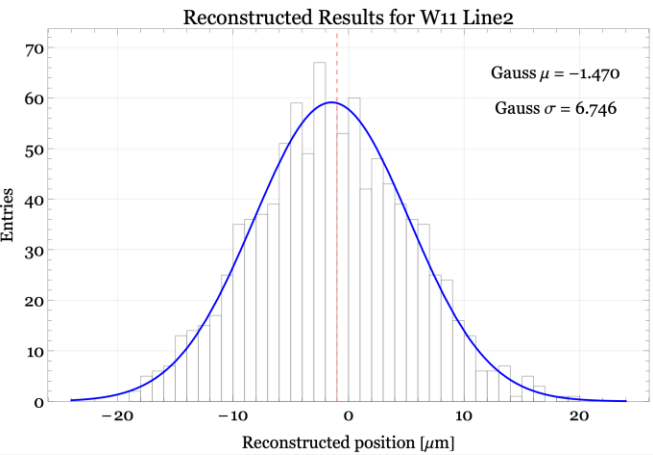
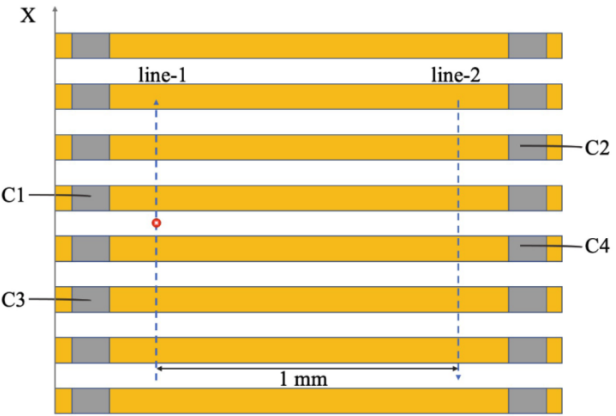


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Working point
W11: 350V
W12: 150V



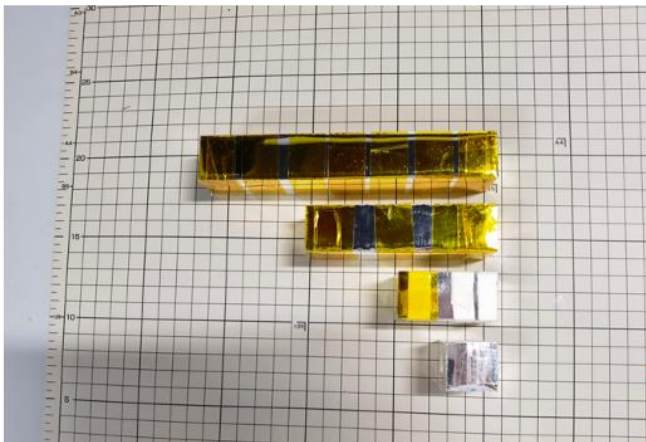
ECAL: crystal test



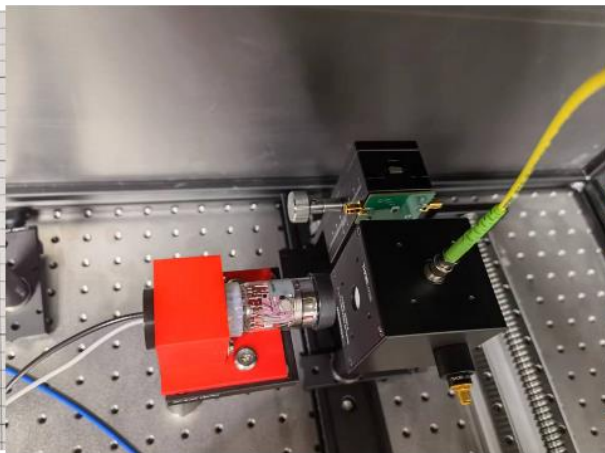
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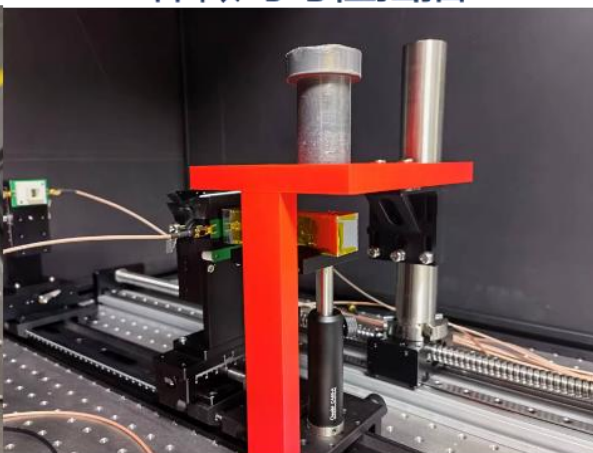
LYSO晶体切割与包裹



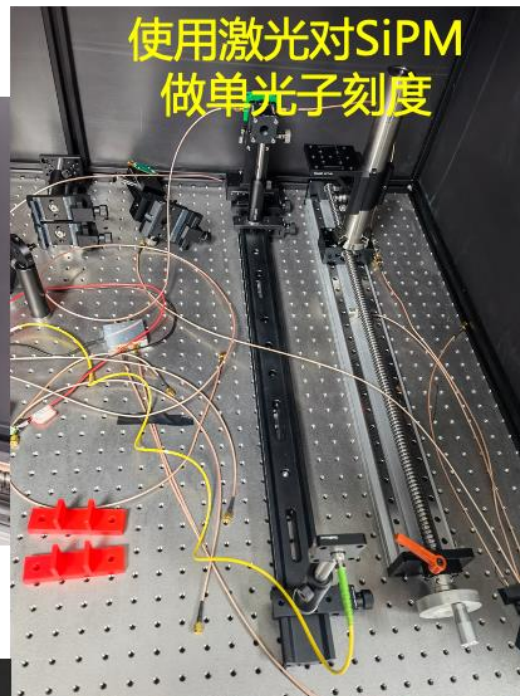
SiPM动态范围测试



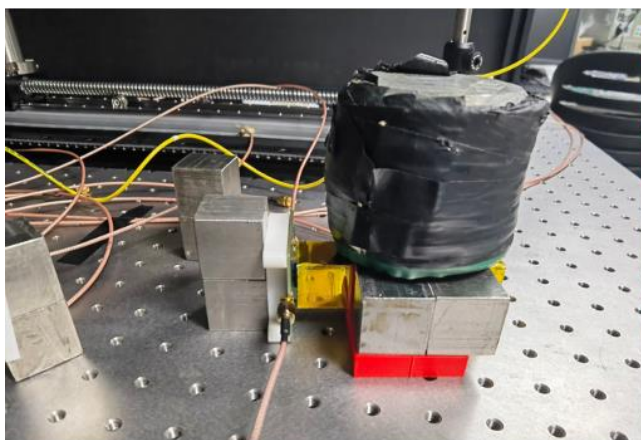
使用放射源对晶体做均匀性扫描



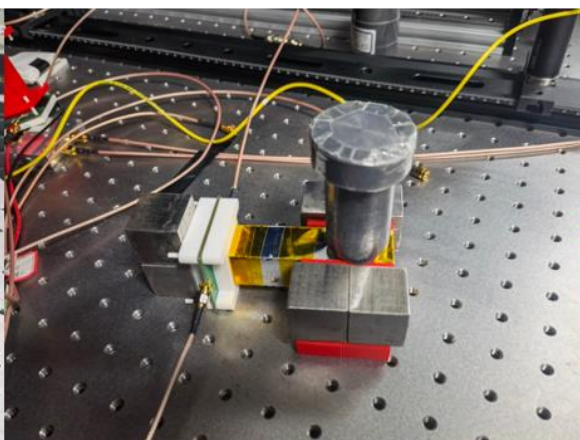
使用激光对SiPM做单光子刻度



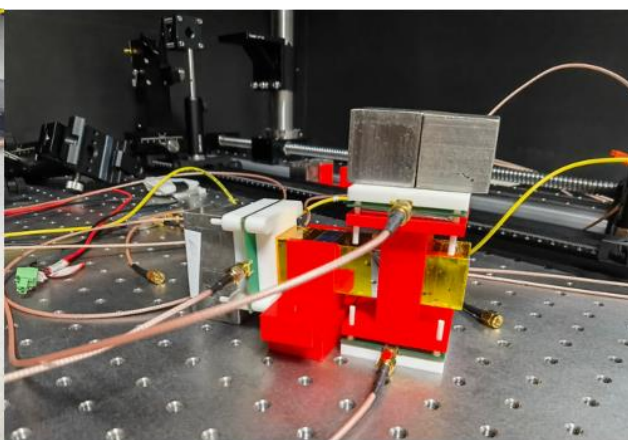
LYSO晶体 ^{137}Cs 测试



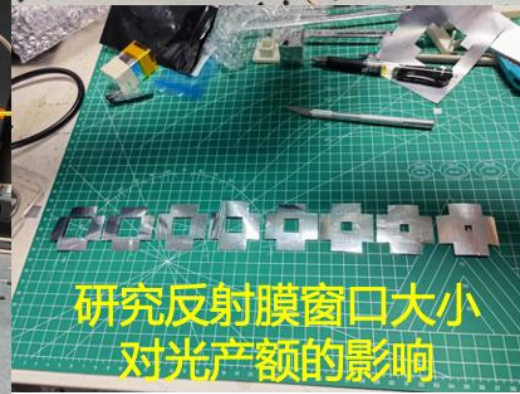
LYSO晶体 ^{60}Co 测试



宇宙线测试上下符合



研究反射膜窗口大小对光产额的影响



Detector R&D: Electromagnetic calorimeter

5cm LYSO

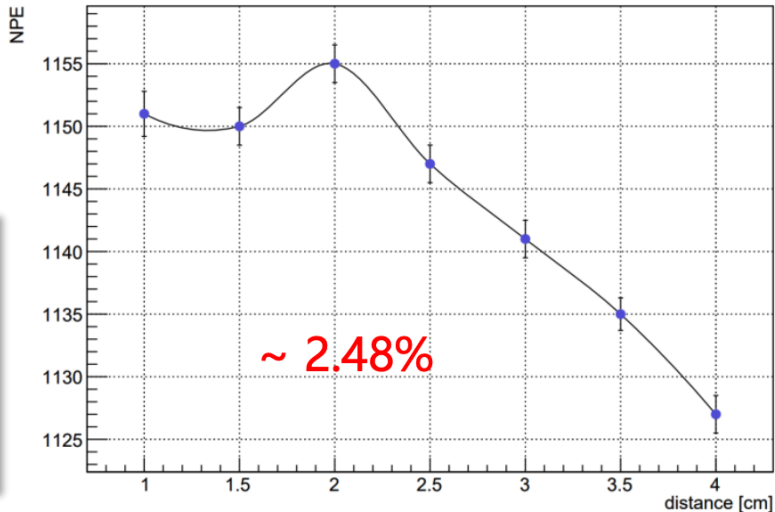


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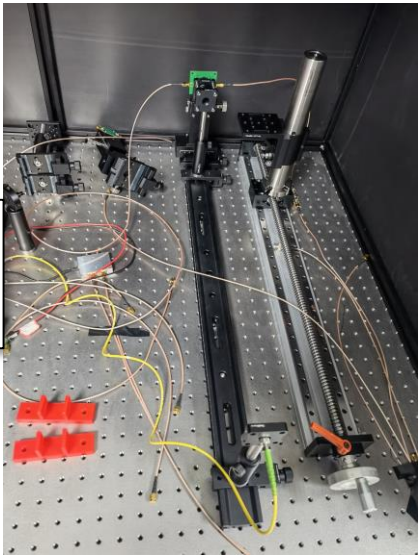
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Uniformity
scan with
using ^{60}Co

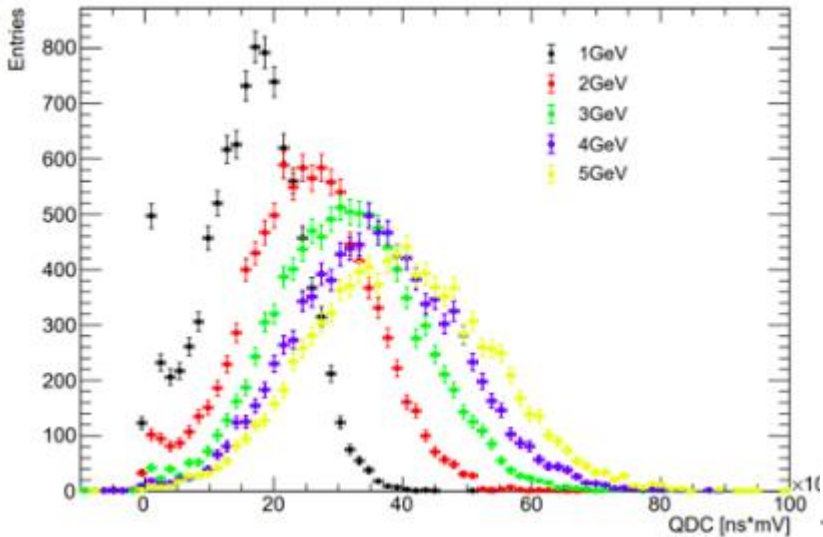


SiPM laser
calibration

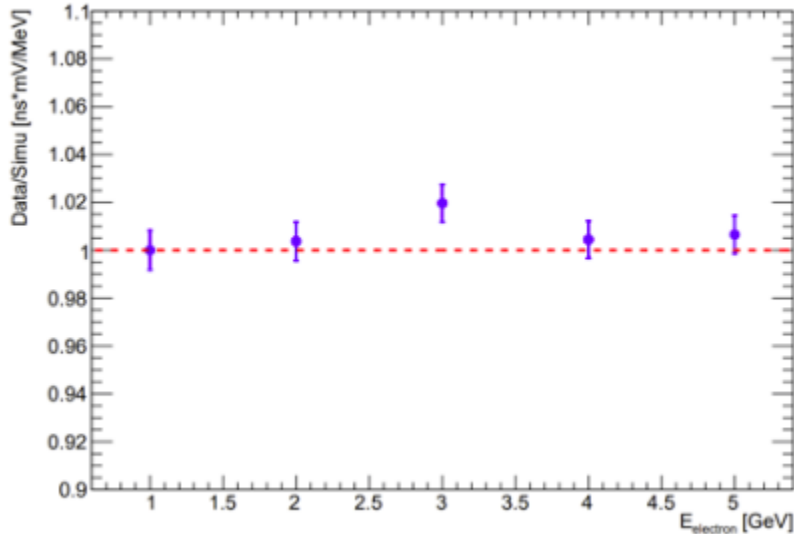


Beam test
@Desy

Electron Data of Ch1-4cmLYSO



Experimental Data vs. Simulation



HCAL: Simulation optimized



- Several conclusions are obtained:
 - Size is reduced from 4 m × 4 m × 4 m to 1.5 m × 1.5 m × 10λ
 - Performance is good enough with weight restriction
 - Use thin absorber + thick absorber can have best veto inEff for both low energy (100 MeV) neutron and high energy neutron (> 1 GeV)
 - 1 scintillator layer + 1 absorber layer is enough
 - Long edge of the scintillator strip is along the X-axis/Y-axis in odd/even layer to cover the gap (wrapper)
 - Side-HCAL is needed: surround ECAL, sensitive plane perpendicular to ECAL

• Neutral hadron veto inEff

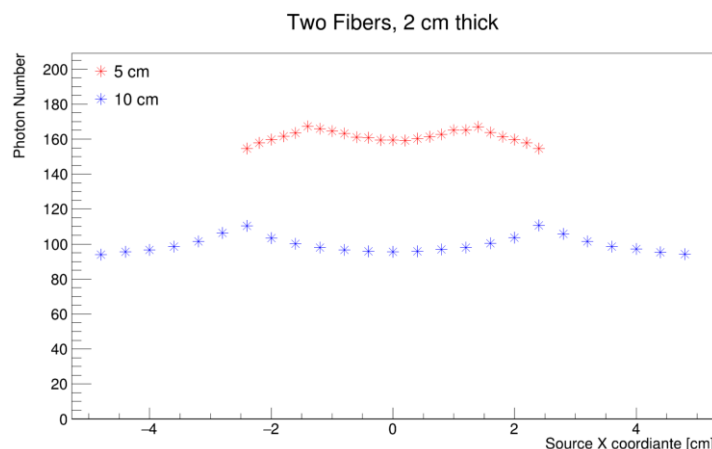
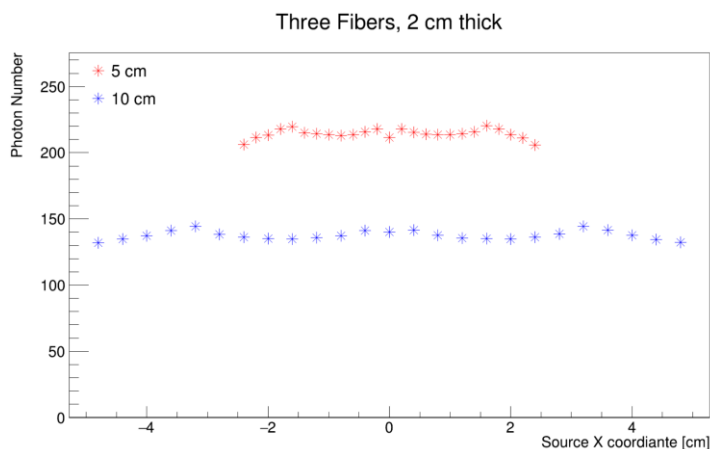
Veto InEff × E-06	n	k^0	π^0	p	μ
100[MeV]	$1170^{+10.9}_{-10.8}$	$31600^{+55.5}_{-55.4}$	$7.30^{+0.958}_{-0.852}$	$30700^{+61.5}_{-61.3}$	$409^{+6.49}_{-6.39}$
500[MeV]	$18.4^{+1.46}_{-1.36}$	$5.40^{+0.839}_{-0.733}$	$0.1^{+0.184}_{-0}$	$8.04^{+1.34}_{-1.16}$	$15.0^{+1.33}_{-1.22}$
1000[MeV]	$3.70^{+0.714}_{-0.606}$	$3.70^{+0.714}_{-0.606}$	$0.1^{+0.184}_{-0}$	$0.1^{+0.958}_{-0}$	$2.00^{+0.555}_{-0.443}$
2000[MeV]	$2.70^{+0.626}_{-0.516}$	$11.5^{+1.19}_{-1.08}$	$0.1^{+0.188}_{-0}$	$0.1^{+2.78}_{-0}$	$0.1^{+0.184}_{-0}$

• Events veto inEff

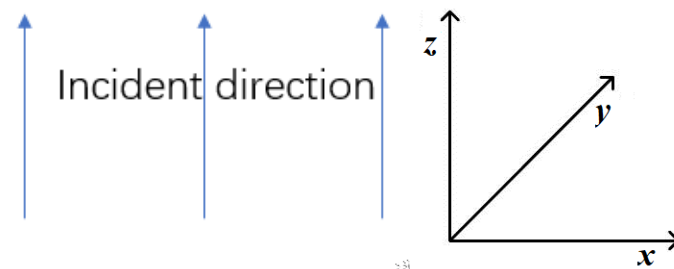
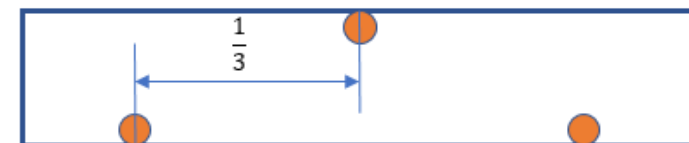
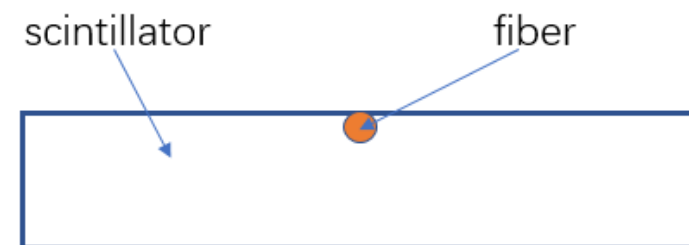
Process Structure	EN-target	EN-ECAL	PN-target	PN-ECAL
w/o Side HCAL	2.68E-02	3.94E-02	9.29E-02	1.24E-01
w/ Side HCAL	1.04E-03	1.09E-02	1.94E-03	3.58E-02

HCAL: Scintillator simulation

- Scintillator size : 5/10 cm × 75 cm × 1 cm/2 cm
- Fiber size : 0.5 mm radius with clad
- Incident e^- , 100 MeV
- Incident position : -2.4/-4.8 cm to 2.4/4.8 cm per 0.2/0.4 cm



Size	1 fiber	2 fibers	3 fibers
1 cm * 5 cm	64 (60-75)	108 (100-115)	136 (130-145)
1 cm * 10 cm	38 (35-50)	69 (65-80)	92 (85-100)
2 cm * 5 cm	91 (85-100)	161 (155-170)	214 (205-220)
2 cm * 10 cm	53 (48-65)	100 (94-110)	138 (132-145)



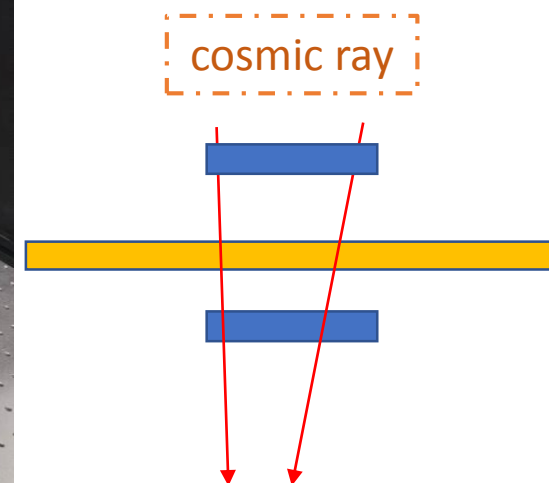
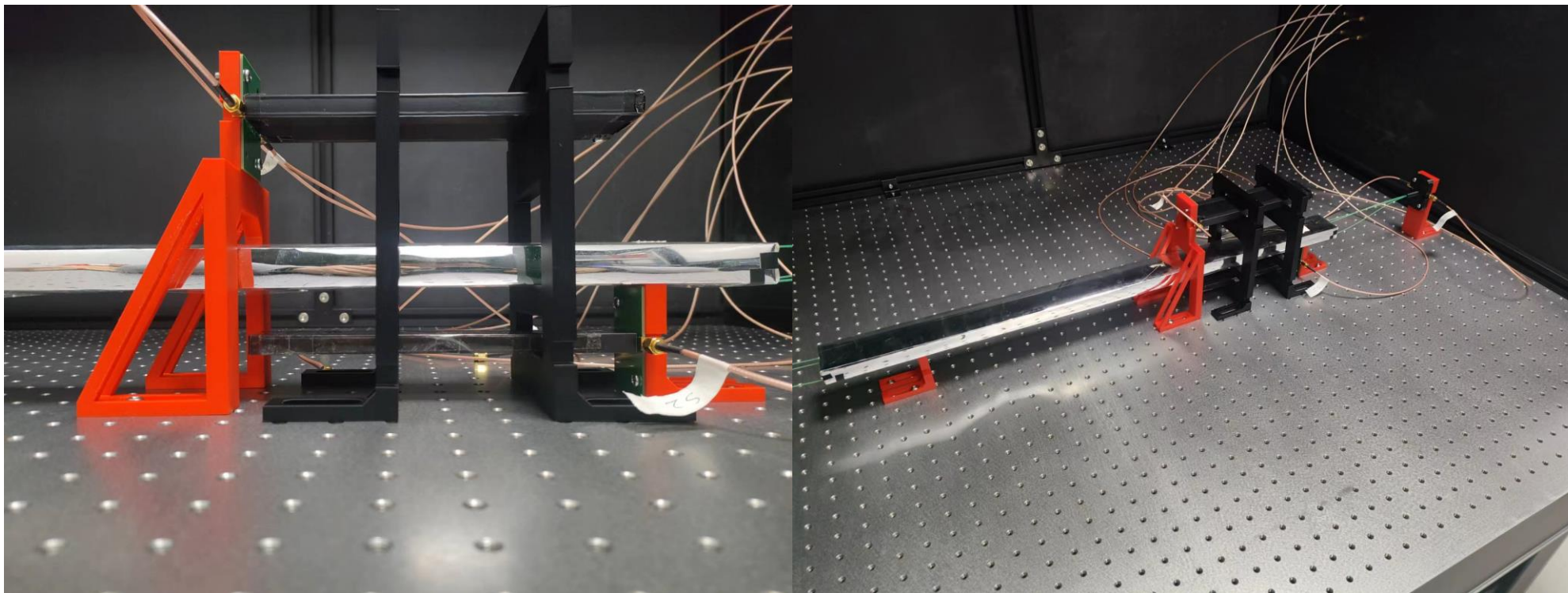
HCAL: Photon yields test platform



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- Two small scintillator + one long bar
 - Trigger size : 20 cm × 5 cm × 1 cm
 - The long bar is tested
 - Coincidence trigger, top & bottom of them should pass the related threshold



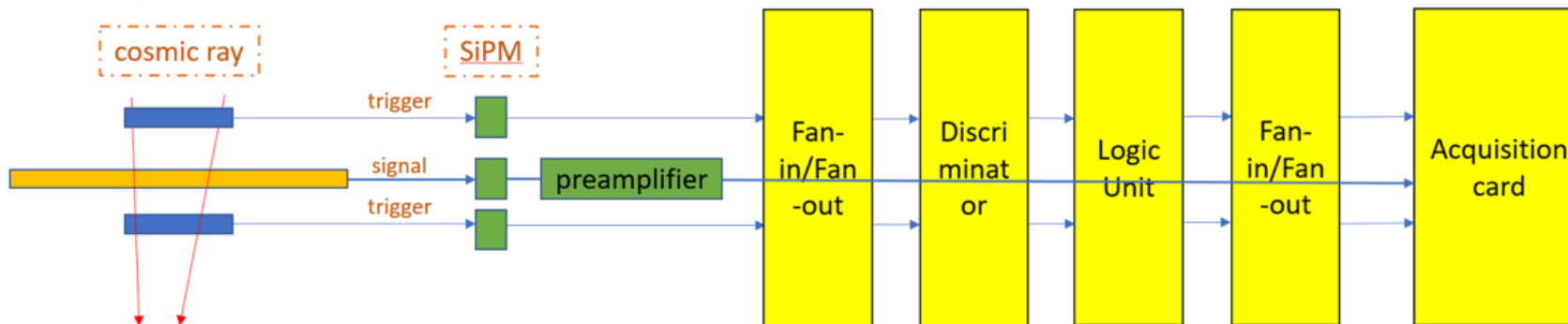
Hardware test: Electronic readout system



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- The electronic readout system was constructed and tested
- Test the acquisition card designed by Prof. Yang Yong



Dark Photon Theory in a nutshell

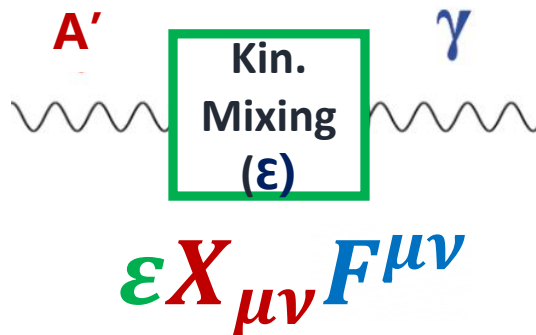


Introduce extra $U(1)_X$ symmetry $\rightarrow$ New Gauge Field $X \rightarrow$ Dark Photon Mediator A'
 $U(1)_{em} \rightarrow U(1)_{em} \times U(1)_X$

$$\mathcal{L} = \underbrace{-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + A_\mu j_{em}^\mu}_{\text{SM Photon } \gamma} \underbrace{-\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + X_\mu j_X^\mu}_{\text{Dark Photon } A'}$$

SM Photon γ

Dark Photon A'



- A' & γ kin. mixing
- Renormalizable and Gauge Invariant
- Straightforward for experimental search
- Free param, kin. mixing (ϵ), mass ($m_{A'}$)

B. Holdom, Phys. Lett. B 166, 196 (1986)

R. Foot & X.-G. He, Phys. Lett. B 267, 509 (1991)