李政道研究所
TSUNG-DAO LEE INSTITUTE

DARK SHINE

DarkSHINE
—A new initiative for Dark Photon search at SHINE facility

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On behalf of Dark SHINE R&D Team

第五届粒子物理天问论坛 , Changsha

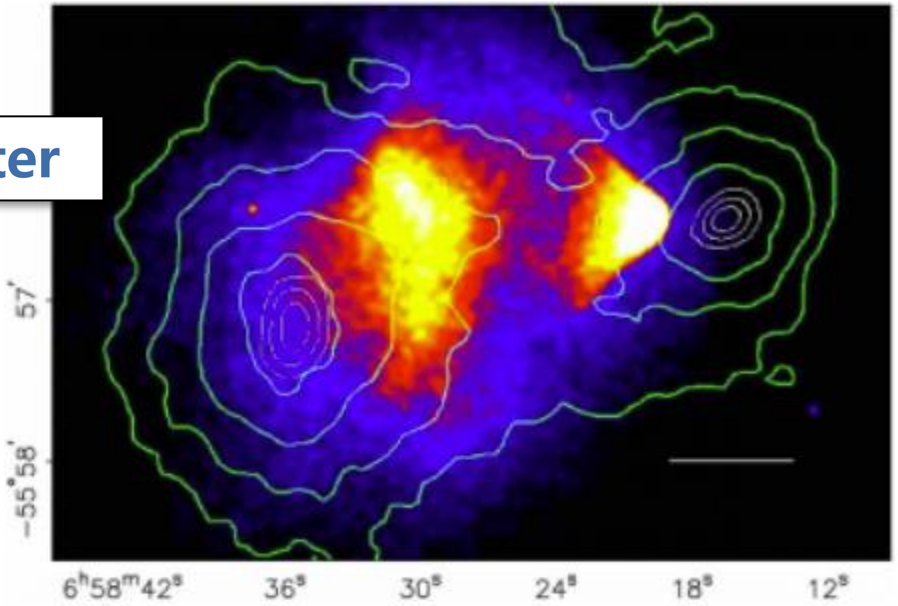
2023.11.12

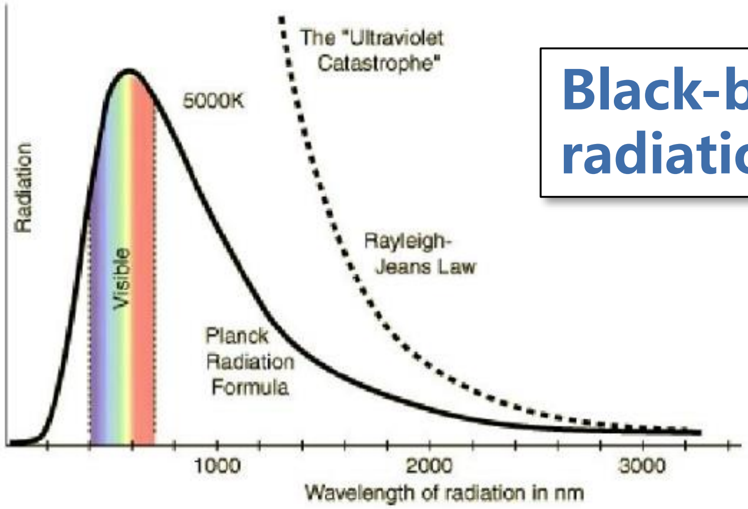
Two dark clouds over physics

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

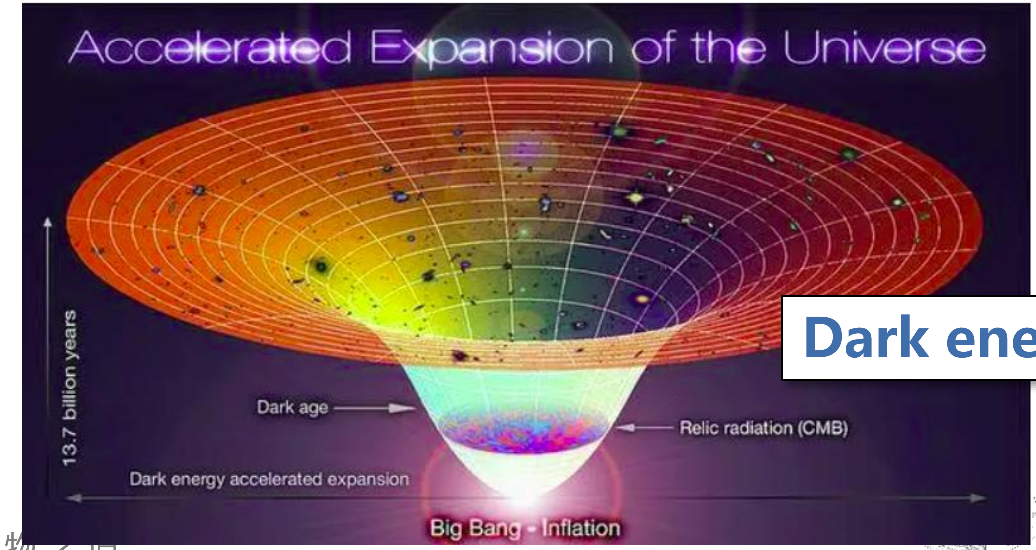
Michelson-Morley experiment

Dark matter





Black-body radiation

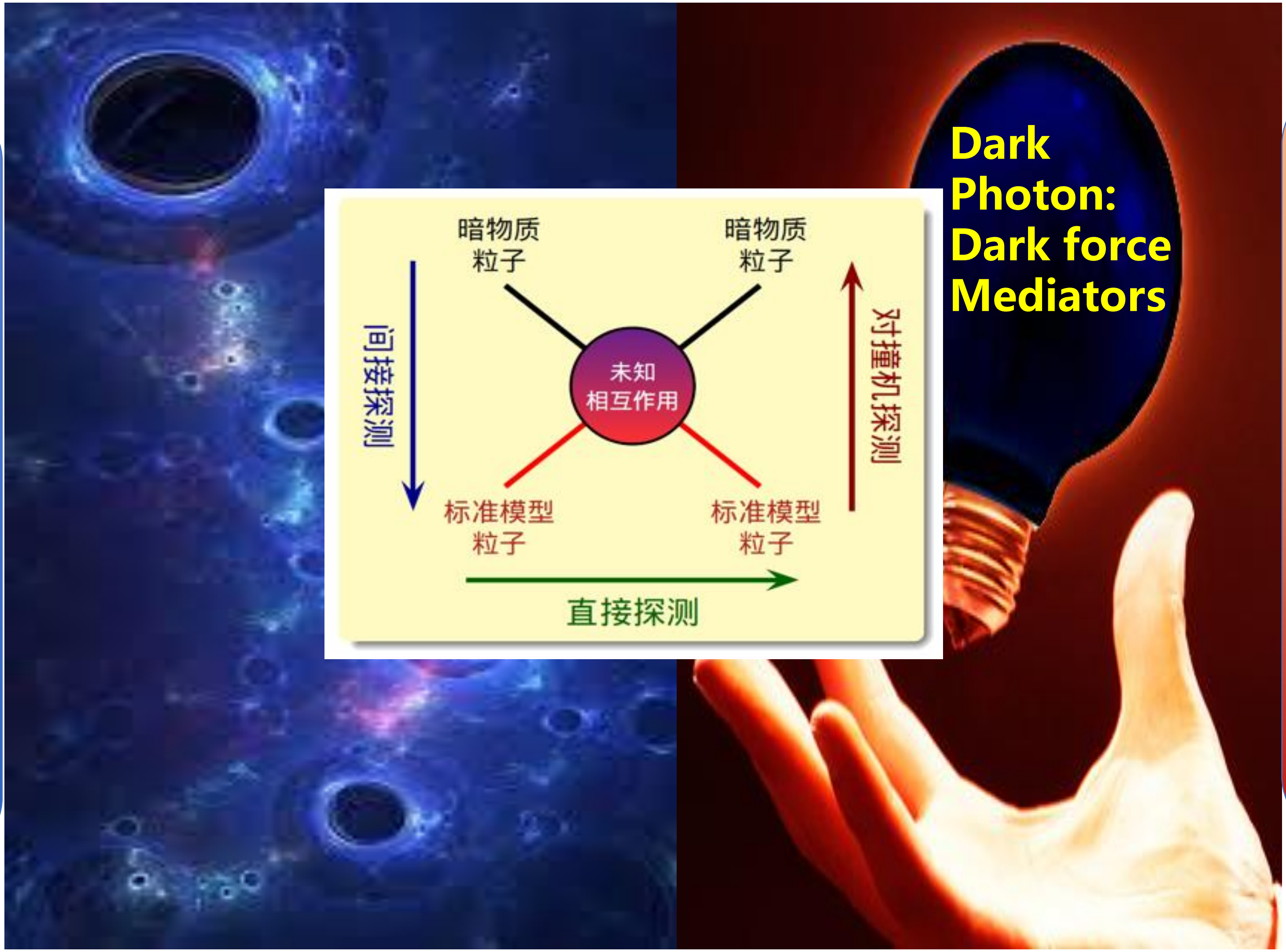


Dark energy

Dark Matter: Particle physics perspective

The world of Dark Matter

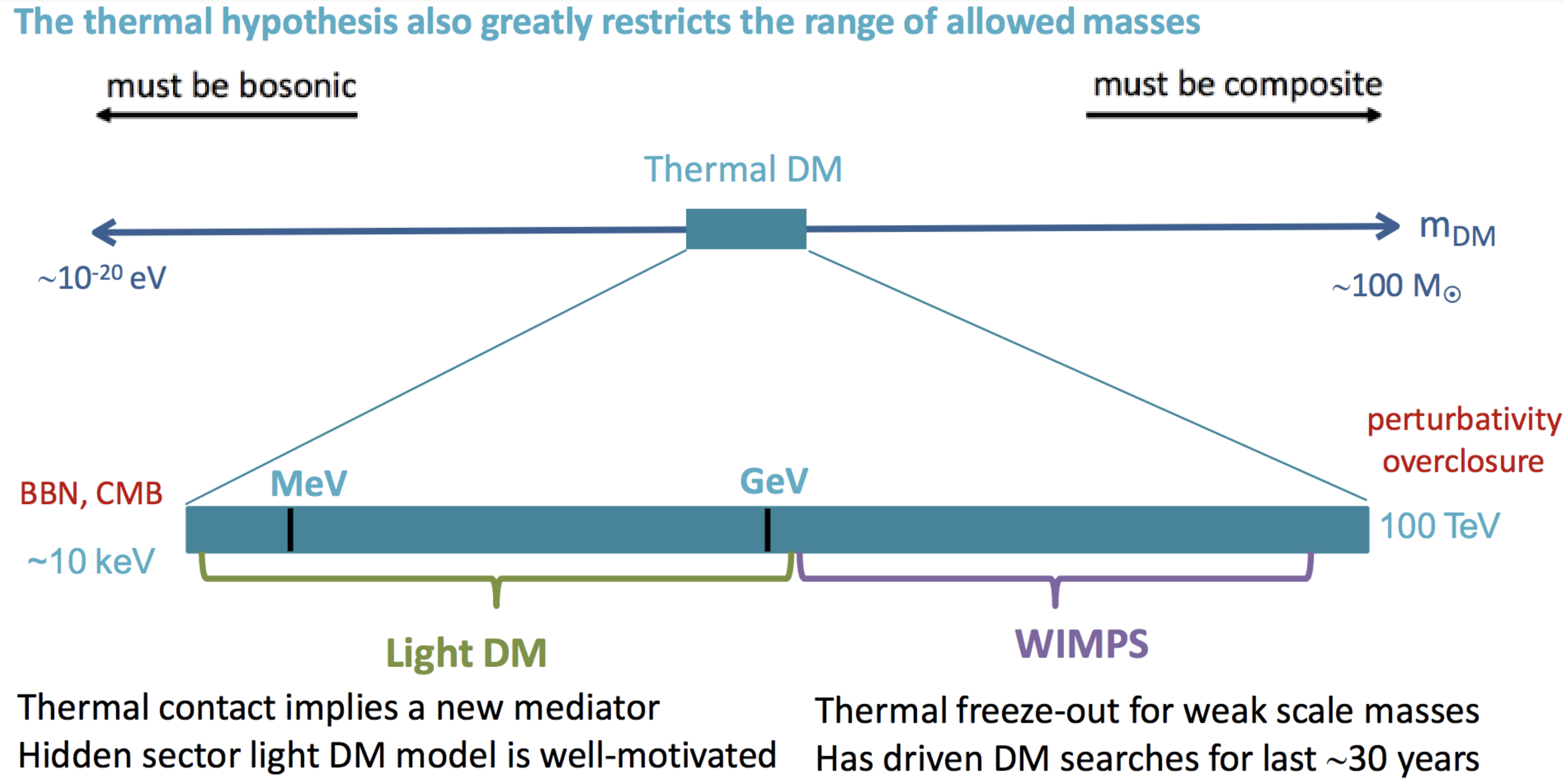
Dark Matter candidate particles

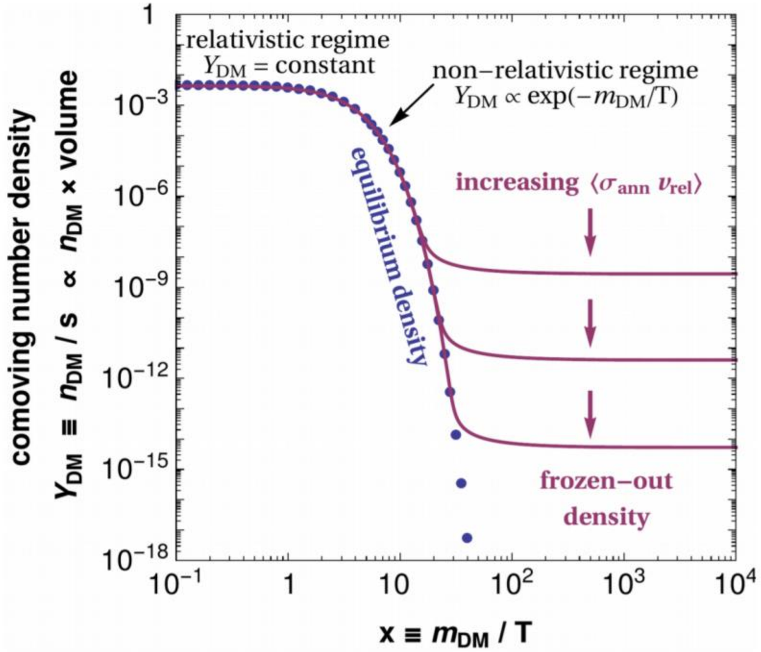


Dark Matter Mediators

Dark Matter: models in broad mass range

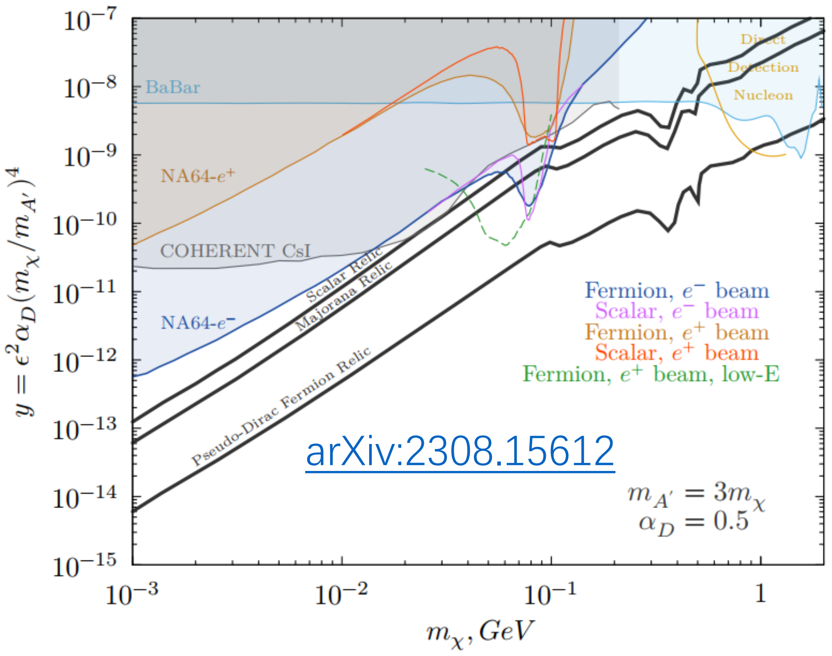
- **Dark matter is about five to six times the amount of visible matter**
- **The theory of dark matter should include the mechanisms to describe the evolution of the proportion of dark matter in the universe**
    - **One typical origin hypothesis: thermal equilibrium in the early universe, DM density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



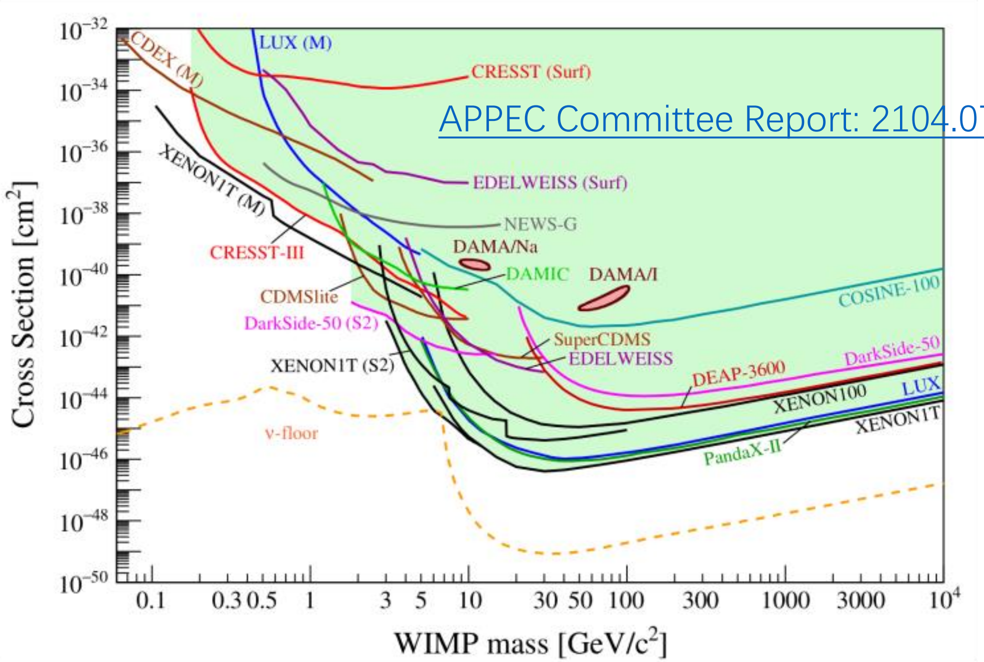


Dark Matter: Search for LDM & WIMP

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY | 李政道研究所 Tsung-Dao Lee Institute



arXiv:2308.15612



APPEC Committee Report: 2104.07634

- **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.)**

Dark photon theory

- **Dark photon is the mediator to transfer the interaction between DM particles and SM particles by mixing with photon**
  - **Extra $U(1)_X$ symmetry is introduced**

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

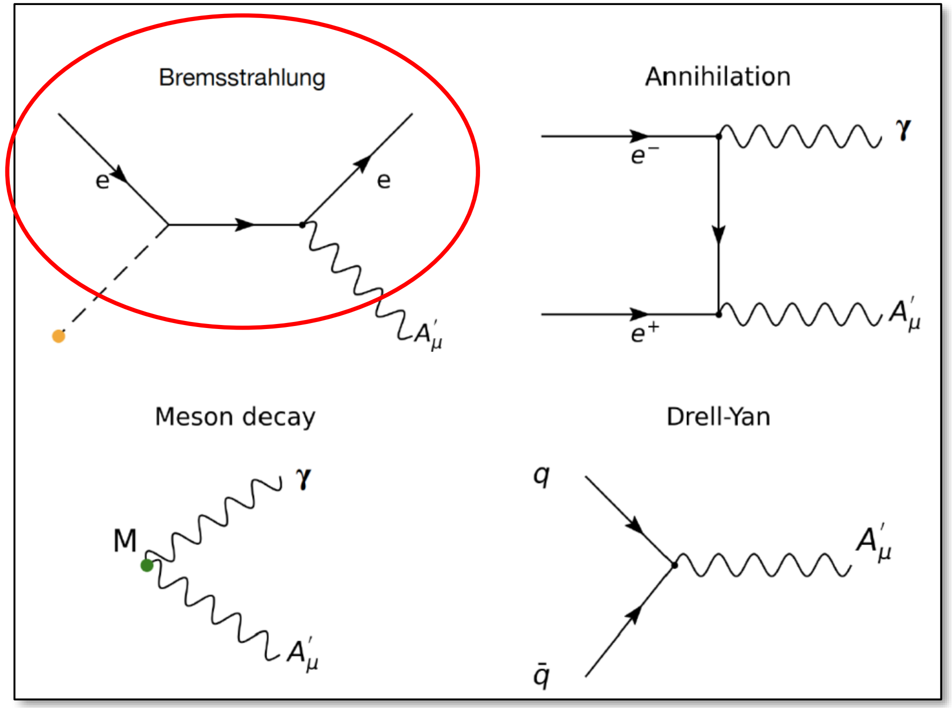
Kinetic mixing term | Field strength tensor | Dark photon field

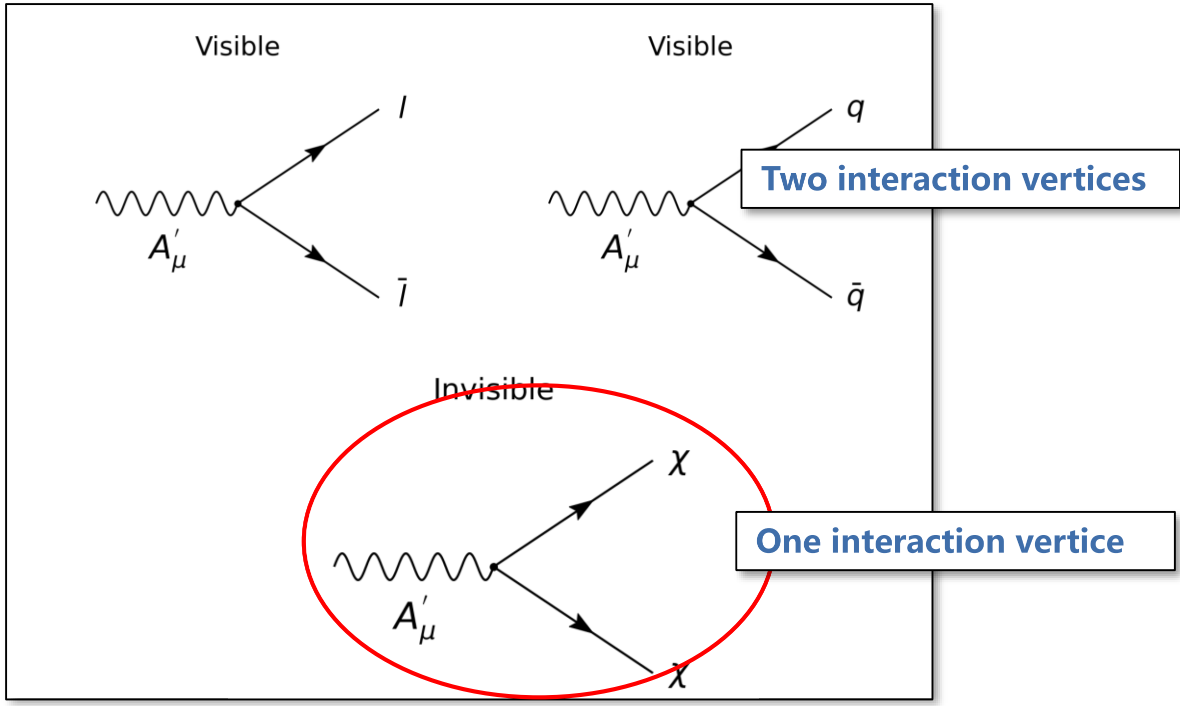
- **In the minimal Dark photon model, 3 free parameters are studied:**
  - $m_{A'}$: **Dark Photon mass**
  - ε: **Kinetic mixing parameter**
  - **Decay branching ratio:** $A' \rightarrow \chi\chi$ **(dark sector), could be 1 or 0**

arXiv:2104.10280

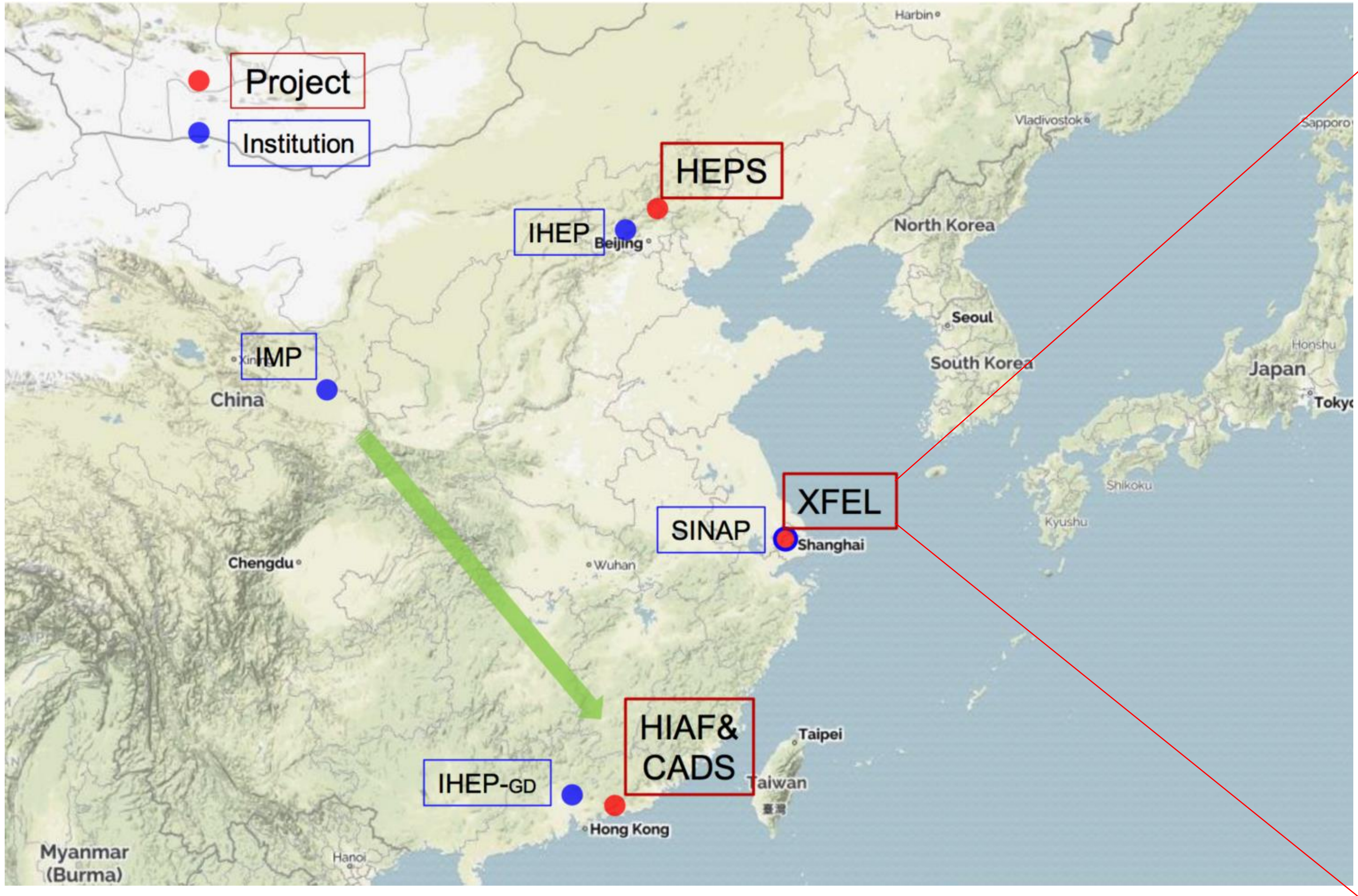
Search for dark photon

- **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

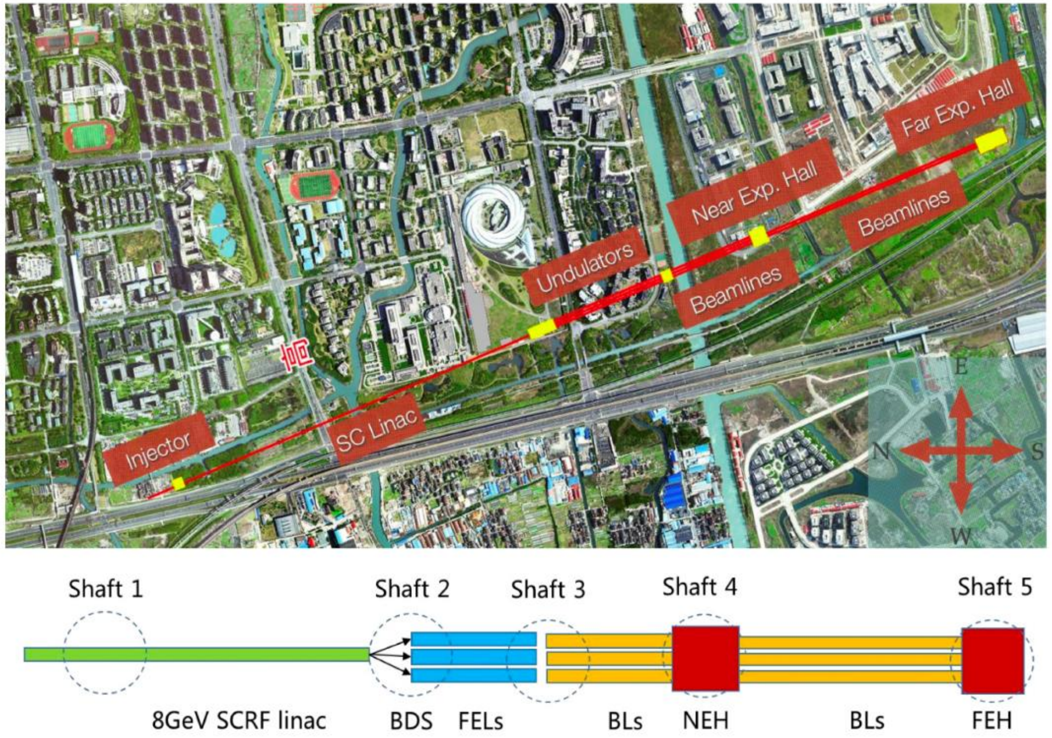


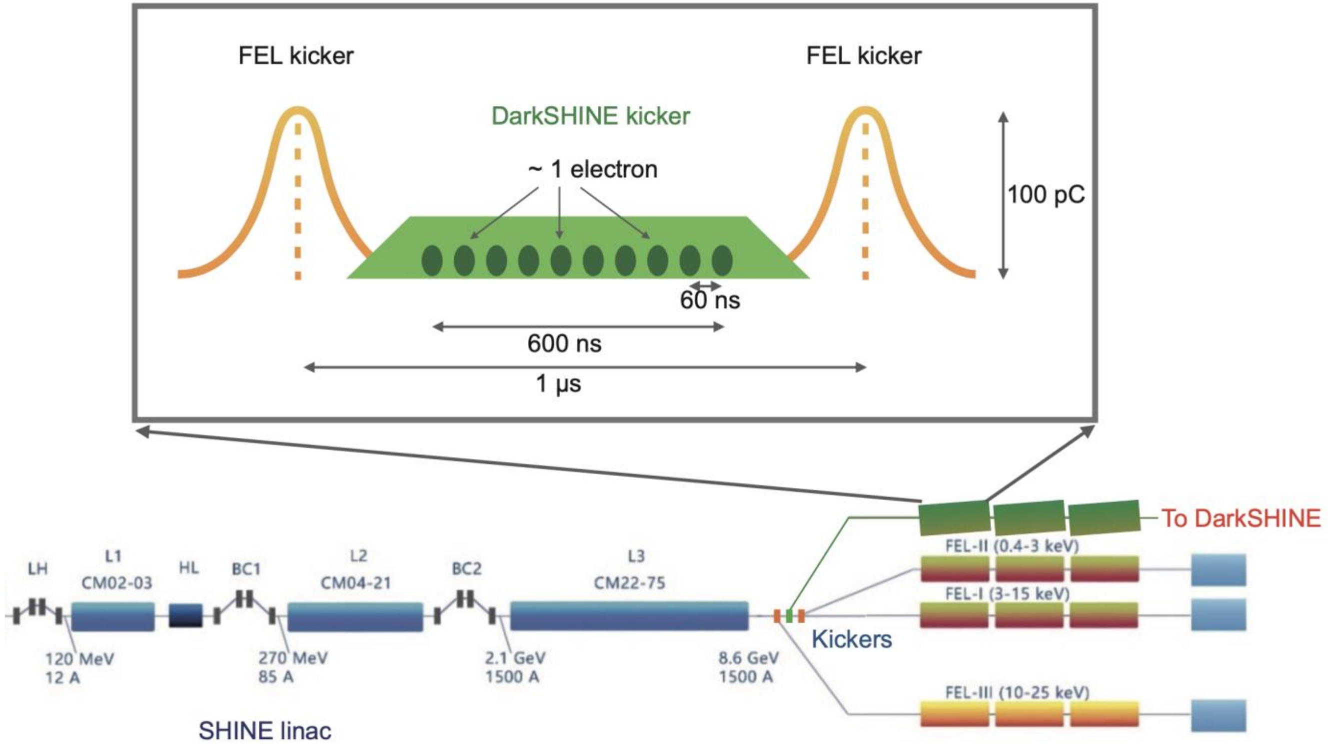
The SHINE facility

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)
- ~3x10^{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.

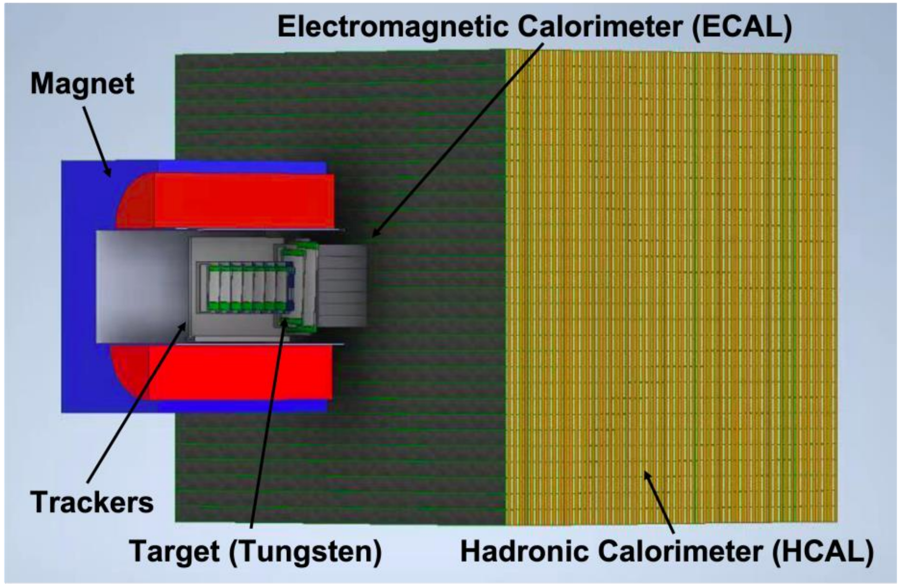




DarkSHINE detector system conceptual design

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.



Dark SHINE detector sketch

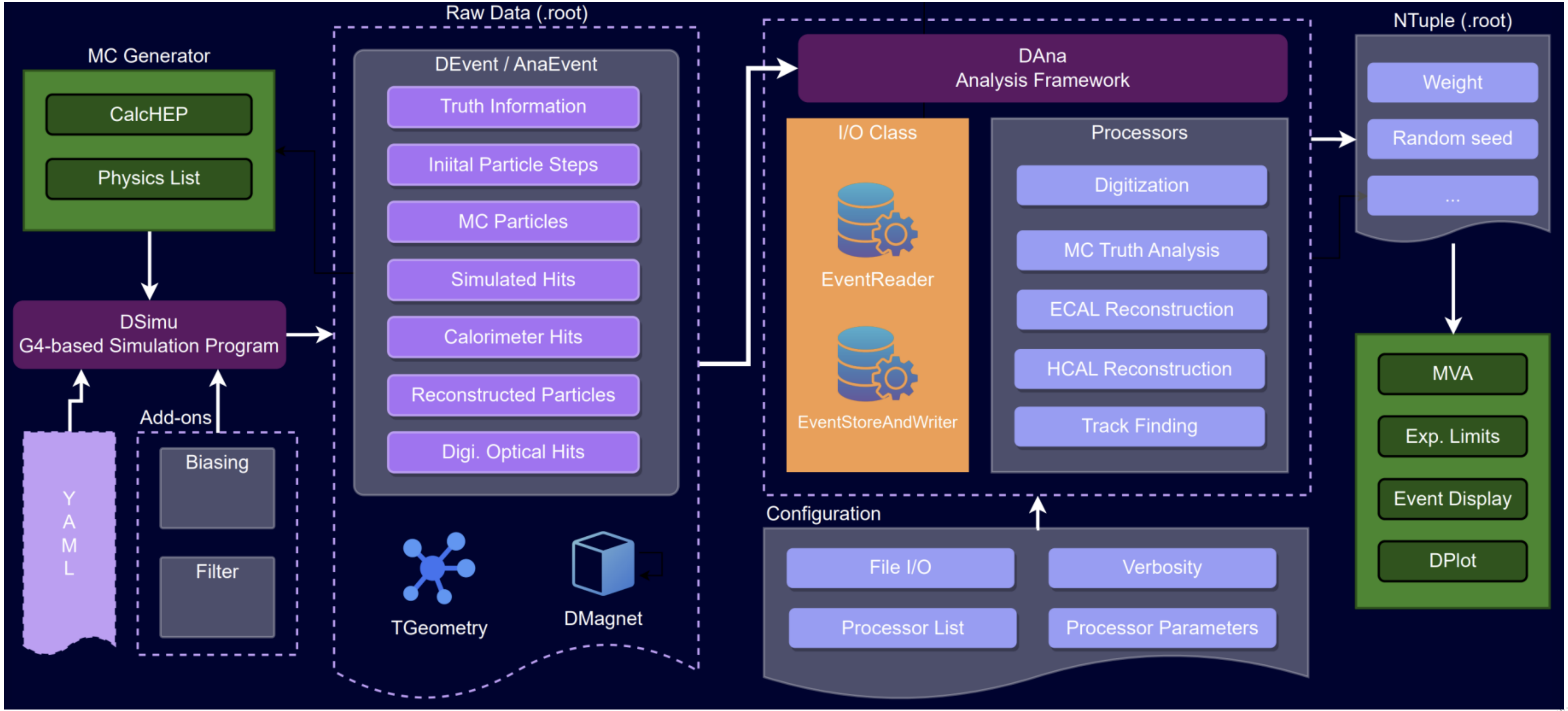
Electromagnetic calorimeter
Measure the deposited energy: electron and photon.

Hadronic calorimeter
Measure the deposited energy: veto muon and hadron backgrounds.

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

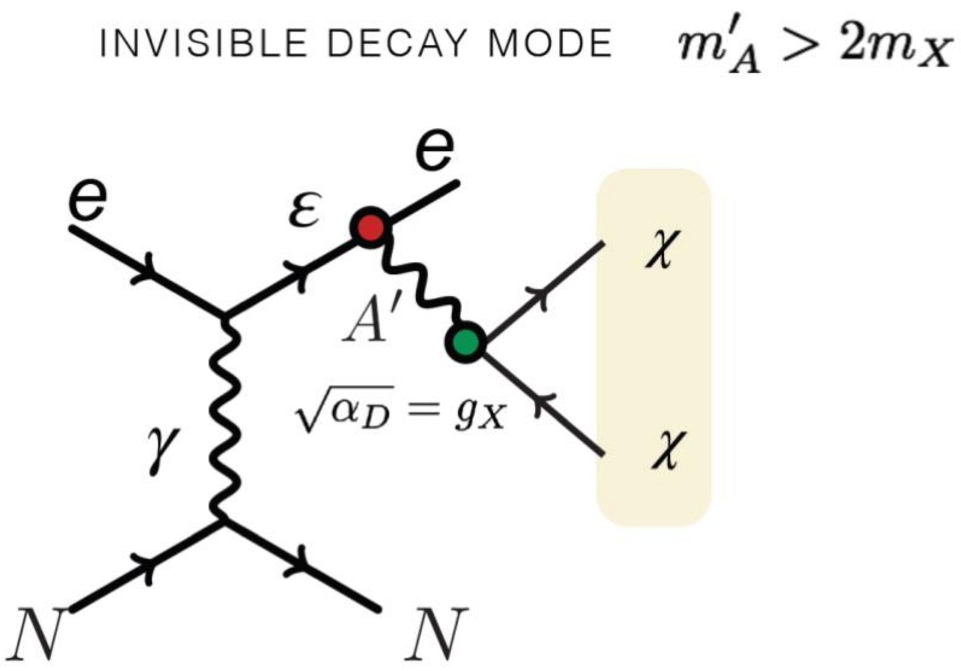
DarkSHINE simulation framework

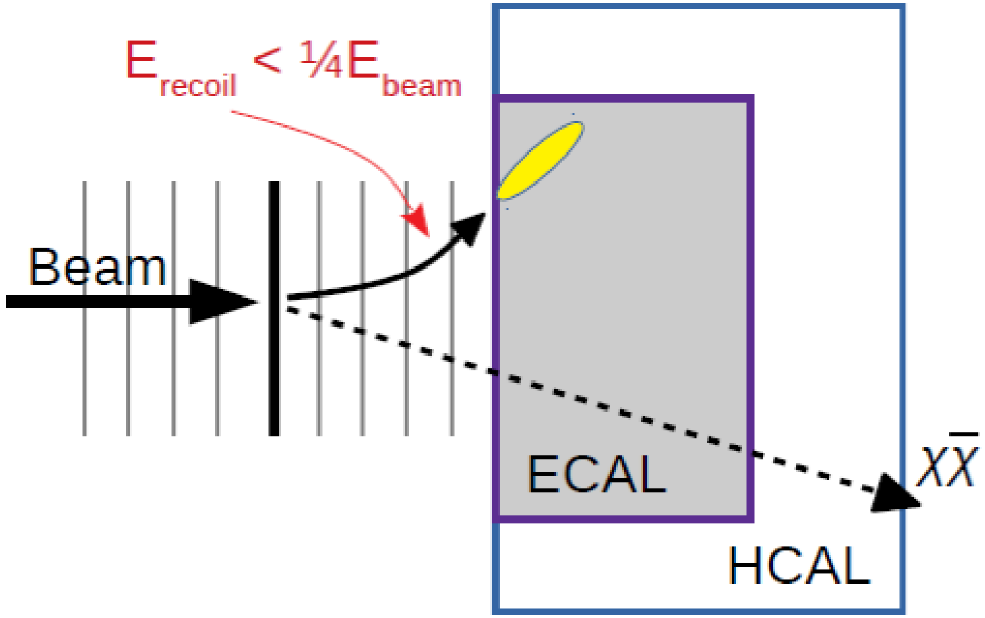
Comprehensive simulation and analysis framework that seamlessly integrates various functions, such as detector simulation, electronic signal digitization, event display, event reconstruction, and data analysis, based on GEANT4 10.6.1



Signal Signature

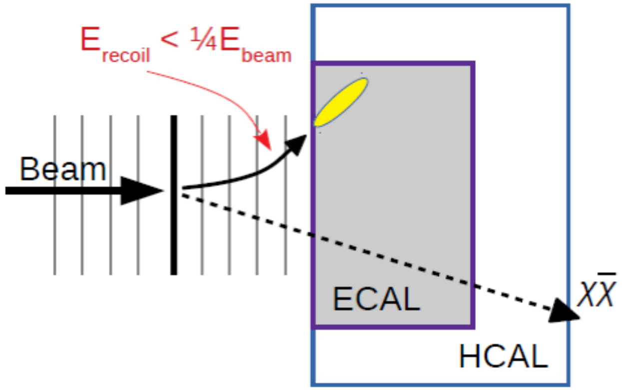
- **Detector is designed based on the difference between signal and background signatures**
  - **Search for the final states with a soft recoil electron + large missing energy & p_T**



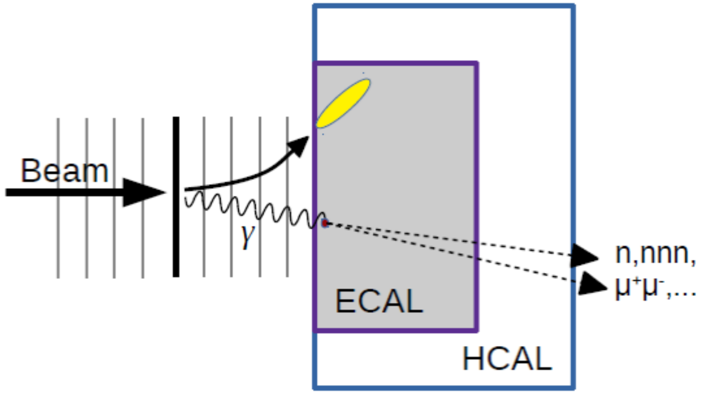


Background processes

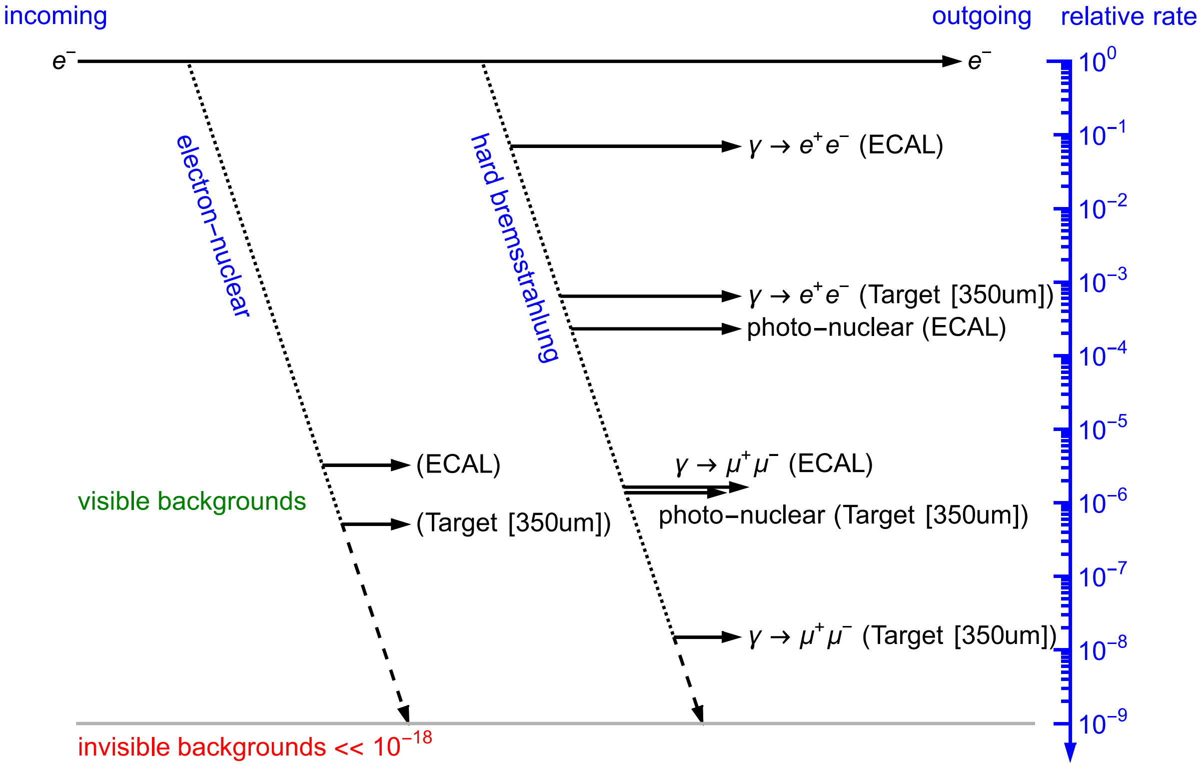
Signal



Background



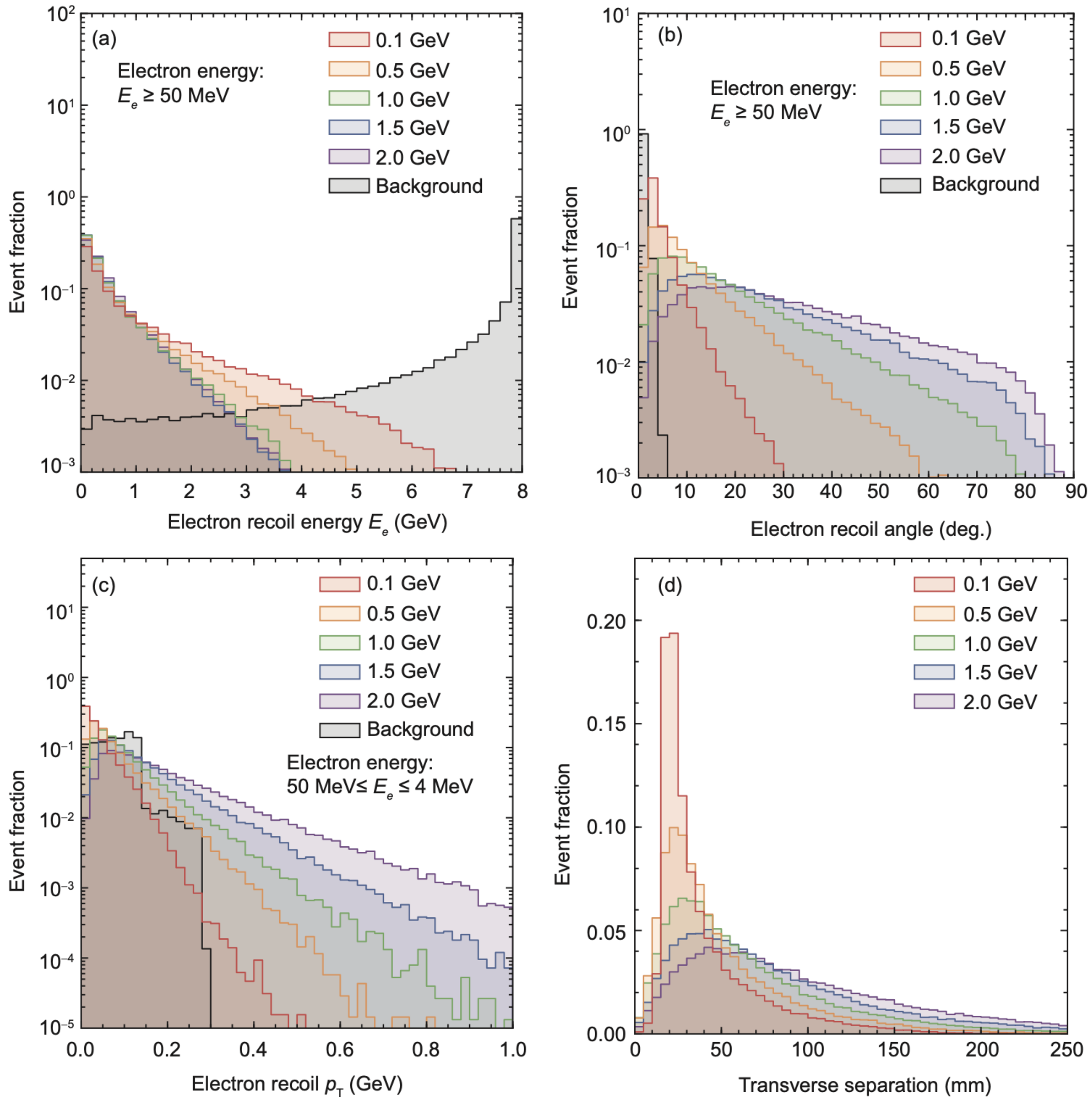
- **Leading background: γ bremsstrahlung**
- **Rare processes include: electron-nuclear, photon-nuclear, γ → μμ**
- **Neutrino production is irreducible, but negligible**



Signal vs. background

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

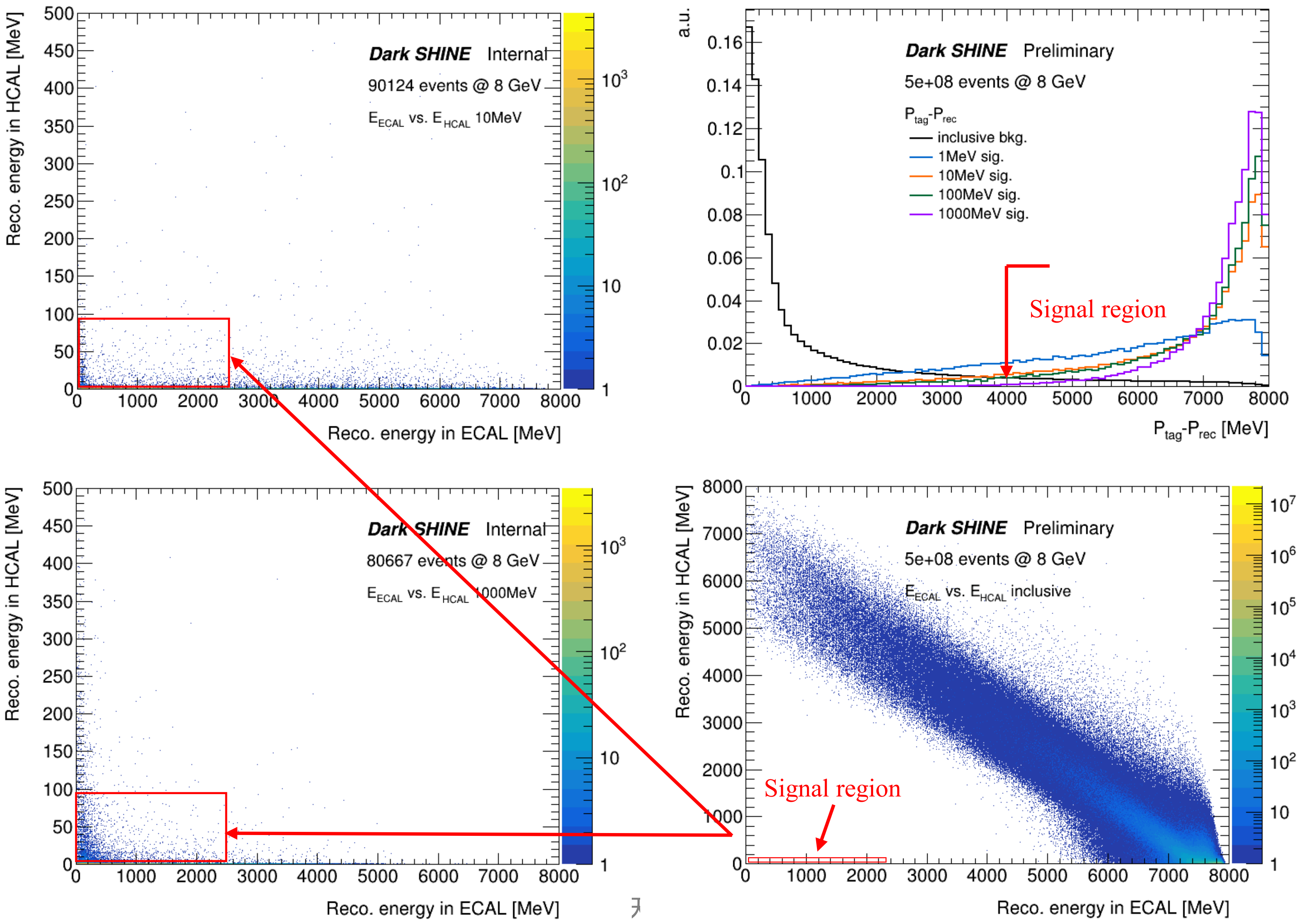
Background:
- Small missing energy, recoil electron carries most of the momentum
- Small recoil electron angle



Signal-box design

10 MeV A′

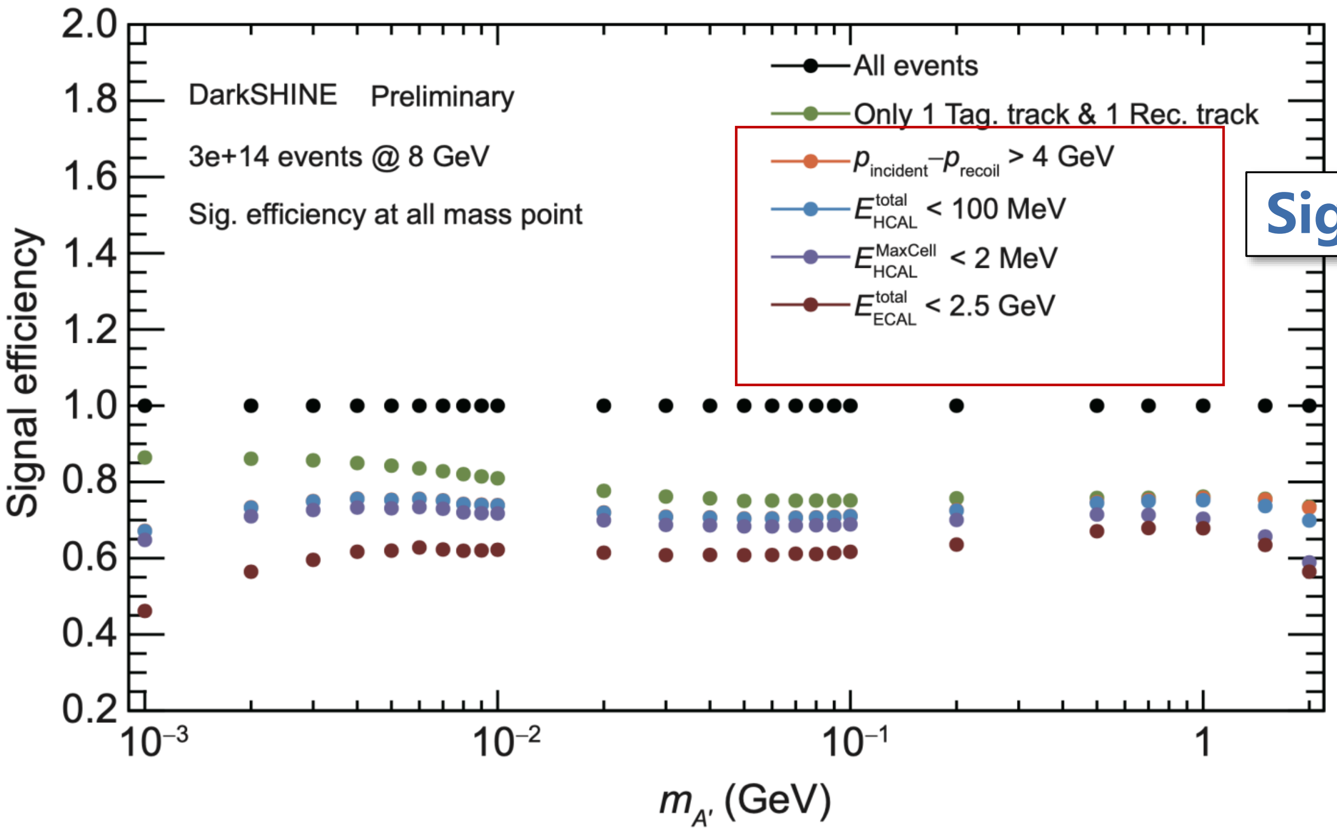
1 GeV A′



Inclusive bkg & signal

Inclusive bkg

Acceptance efficiency

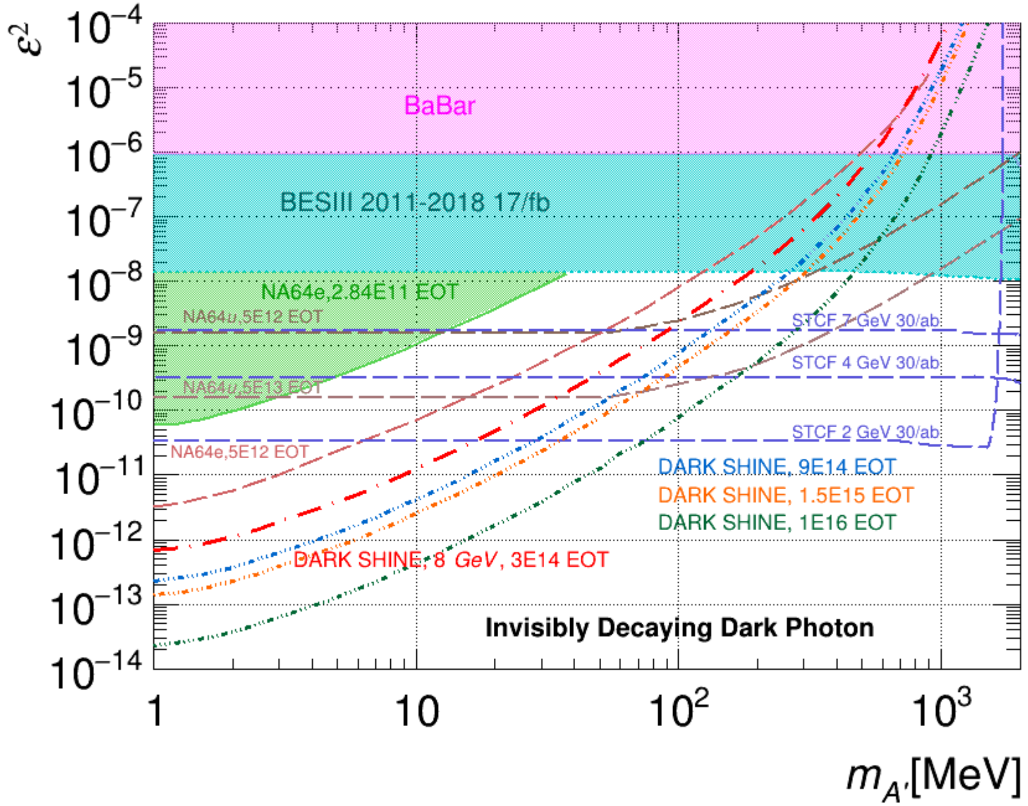


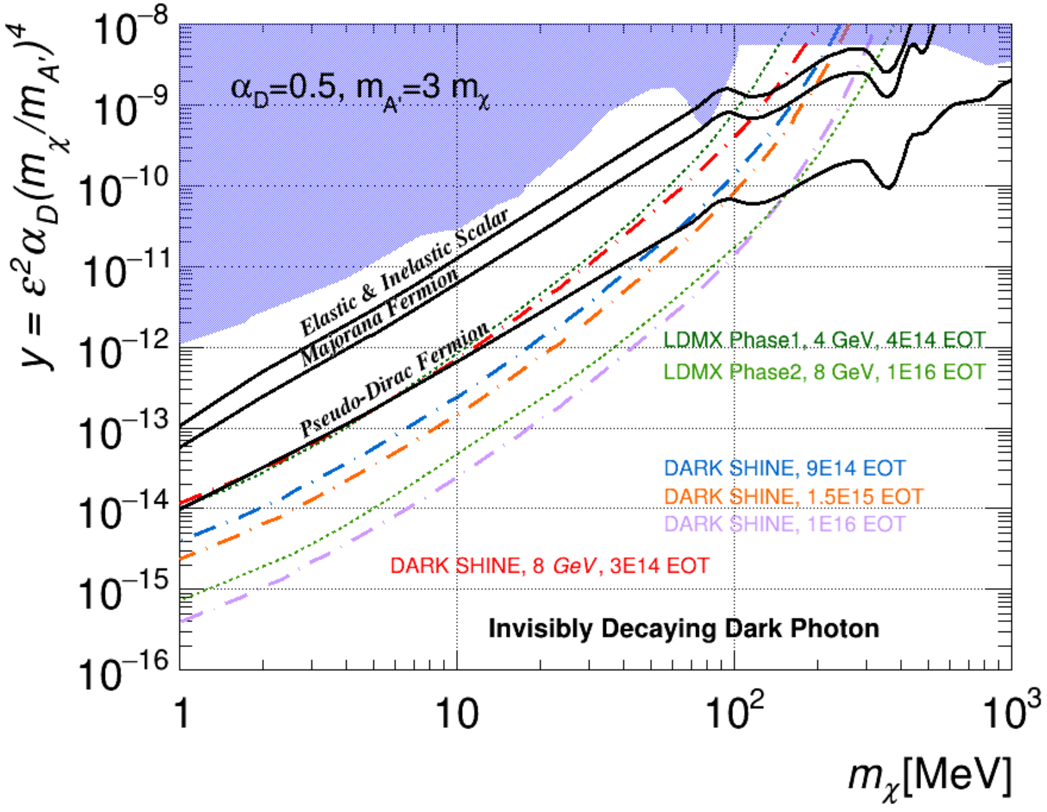
Signal-box selection

- **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.**

Sensitivity

- **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).**





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Physics, Mechanics & Astronomy

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• **Article** •
Editor's Focus

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Editor's Focus

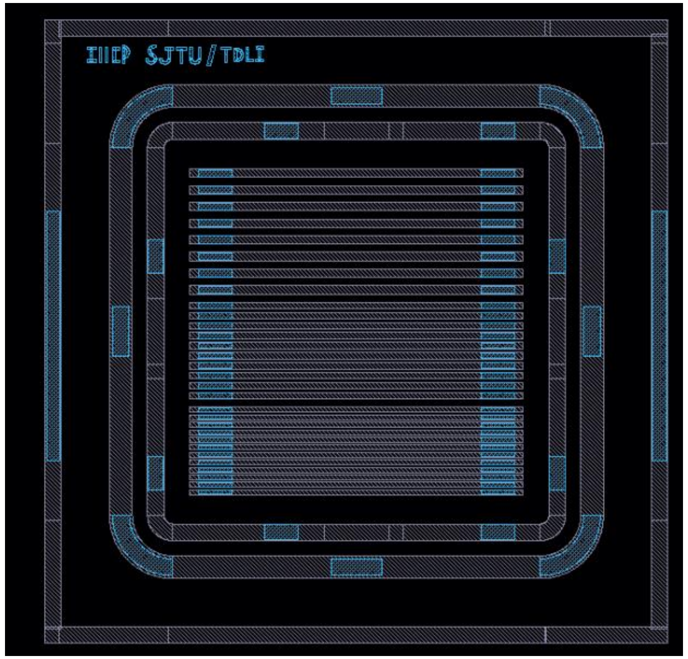
Prospective study of light dark matter search with a newly proposed DarkSHINE experiment

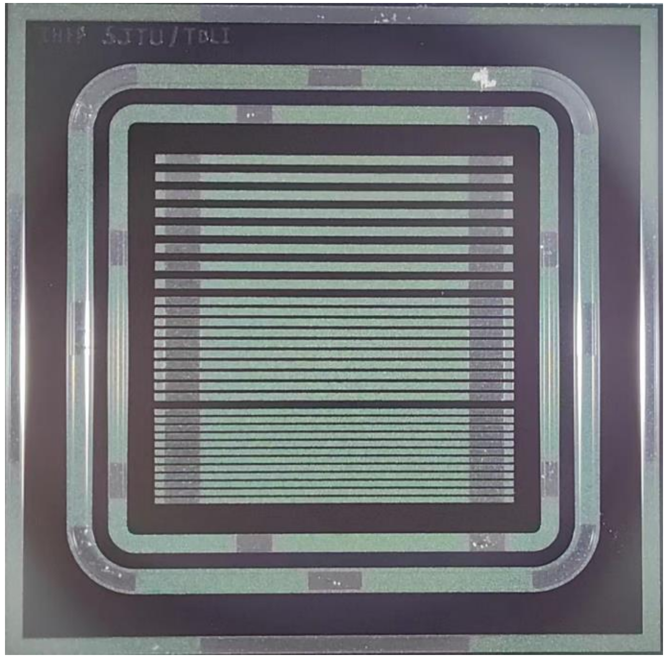
Jing Chen[1,2,3†], Ji-Yuan Chen[2,3], Jun-Feng Chen[8], Xiang Chen[2,3], Chang-Bo Fu[9,10], Jun Guo[2,3], Le He[6], Zheng-Ting He[1,14], Kim Siang Khaw[1,2,3], Jia-Lin Li[2,3], Liang Li[2,3], Shu Li[1,2,3,4,5*], Meng Lv[7], Dan-Ning Liu[1,2,3], Han-Qing Liu[2,3], Kun Liu[1,2,3*], Qi-Bin Liu[1,2,3], Yang Liu[1,2,3], Ze-Jia Lu[2,3], Cen Mo[2,3], Si-Yuan Song[2,3], Xiao-Long Wang[9,10], Yu-Feng Wang[1,2,3†], Zhen Wang[1,2,3], Zi-Rui Wang[13], Wei-Hao Wu[2,3], Dao Xiang[1,11,12], Hai-Jun Yang[1,2,3*], Jun-Hua Zhang[1,2,3], Yu-Lei Zhang[2,3†], Zhi-Yu Zhao[1,2,3], Xu-Liang Zhu[1,2,3], Chun-Xiang Zhu[2,3], and Yi-Fan Zhu[2,3]

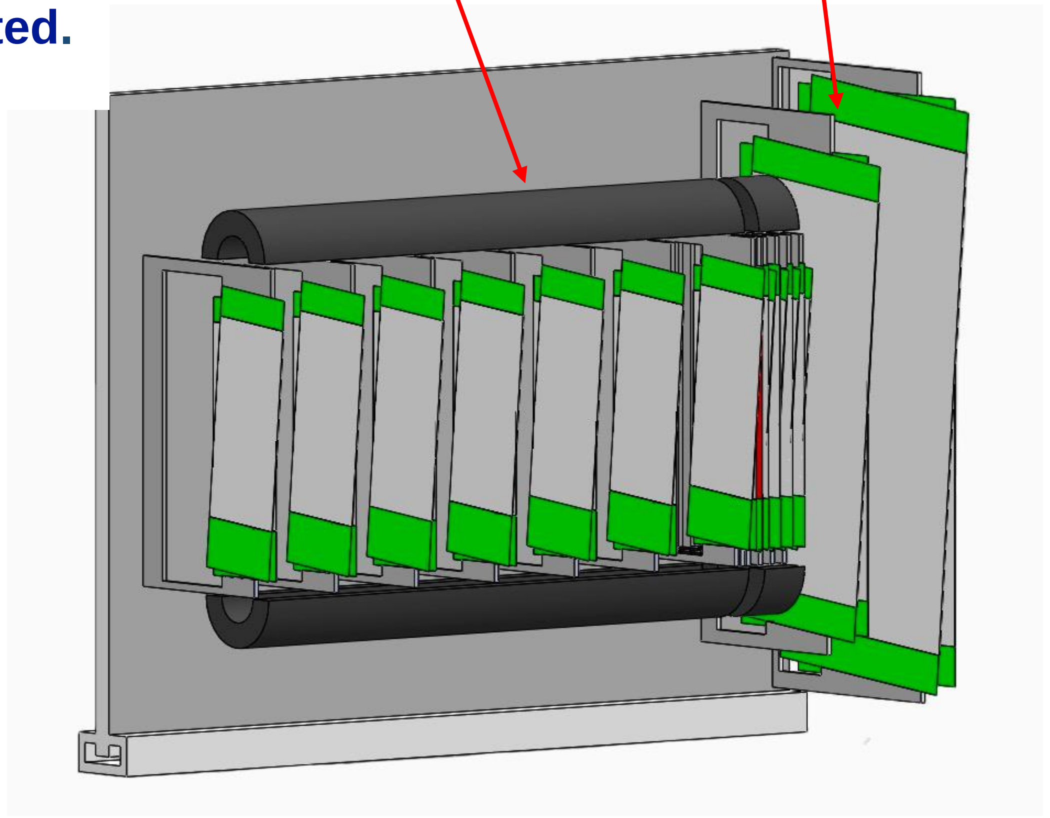
Tracking system

- 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)
- AC-LGAD silicon strip sensor prototype designed and tested.

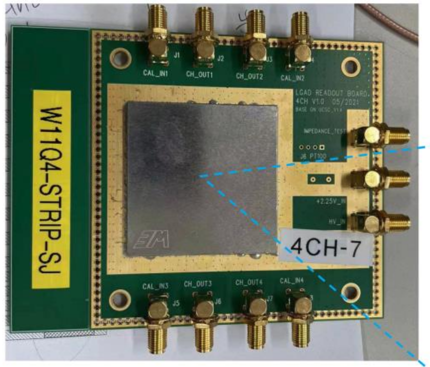
arXiv:2310.13926



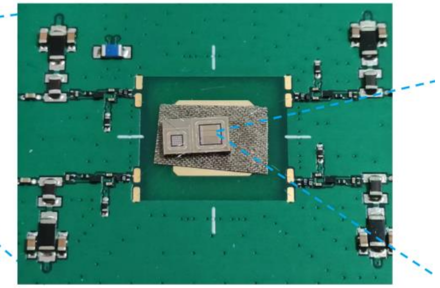


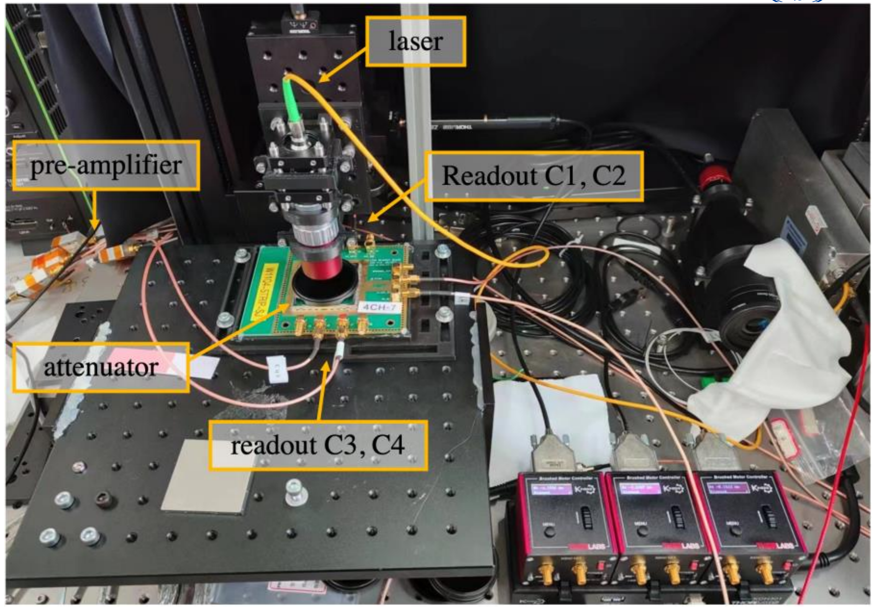


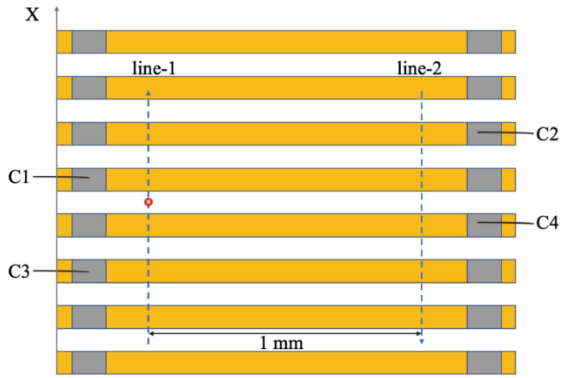
Tracking system

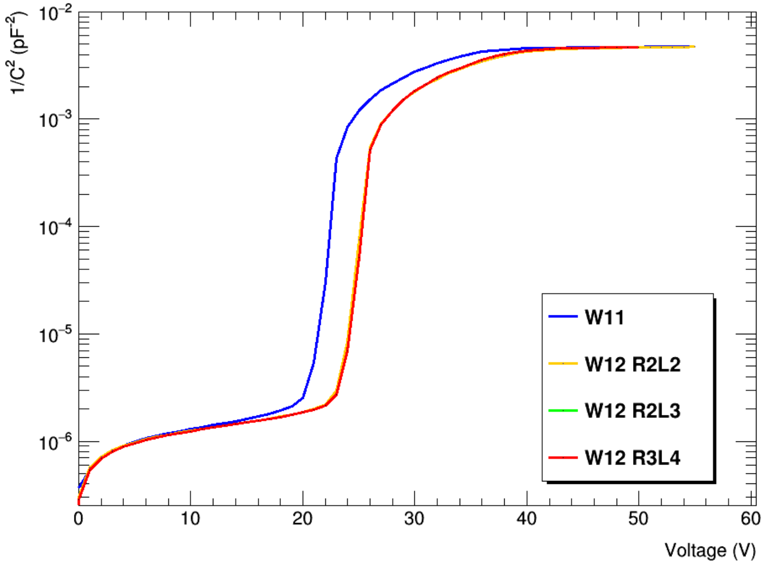


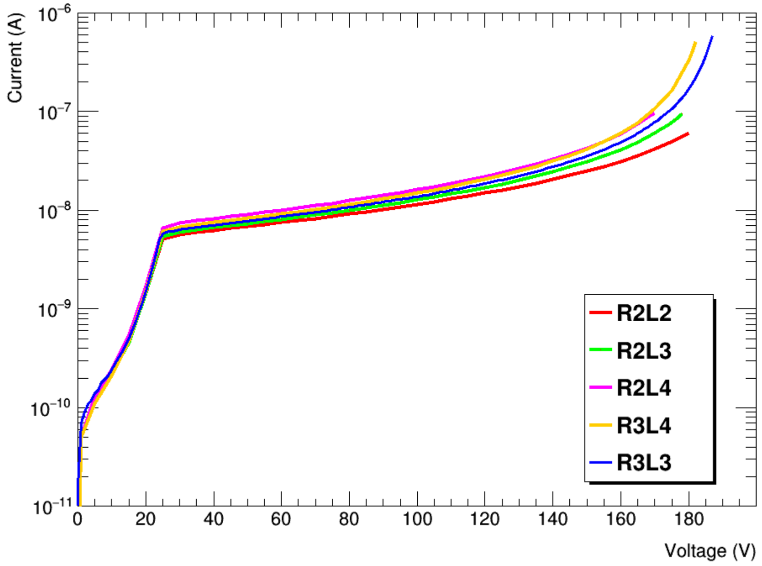
Working point
W11: 350V
W12: 150V

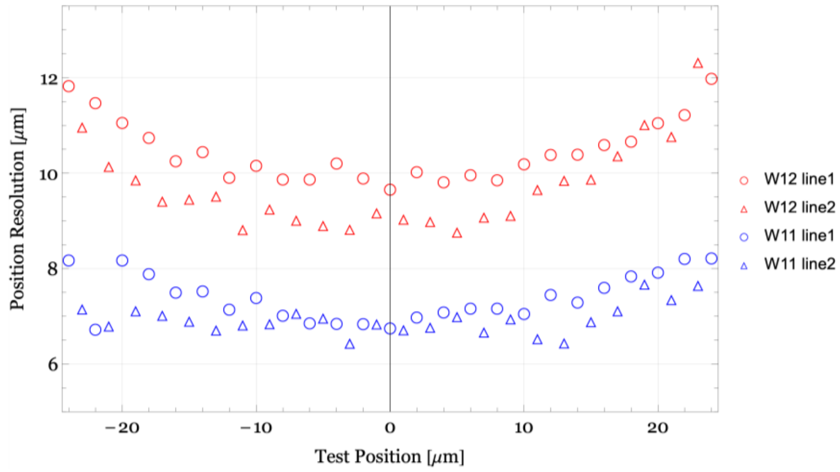






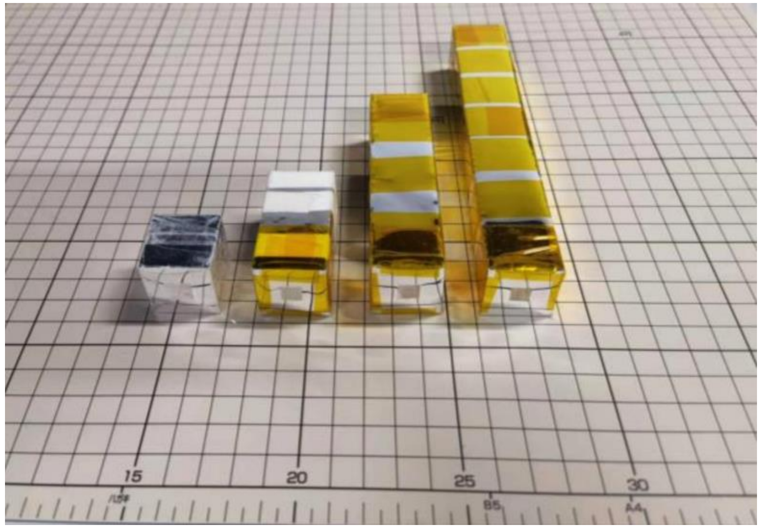


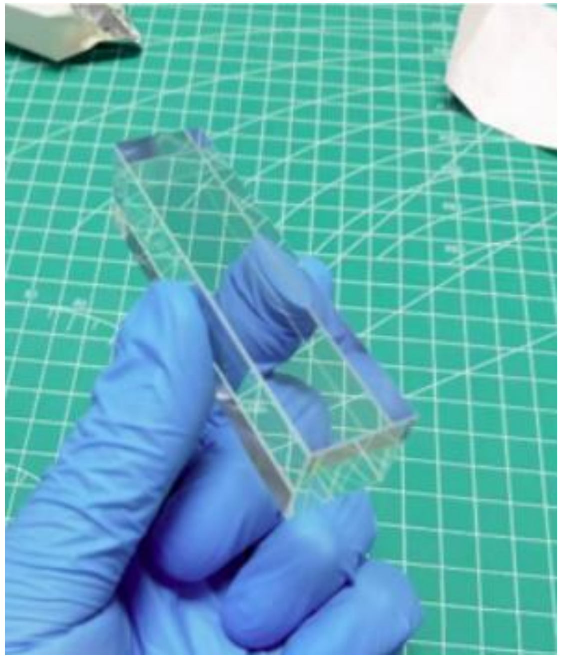


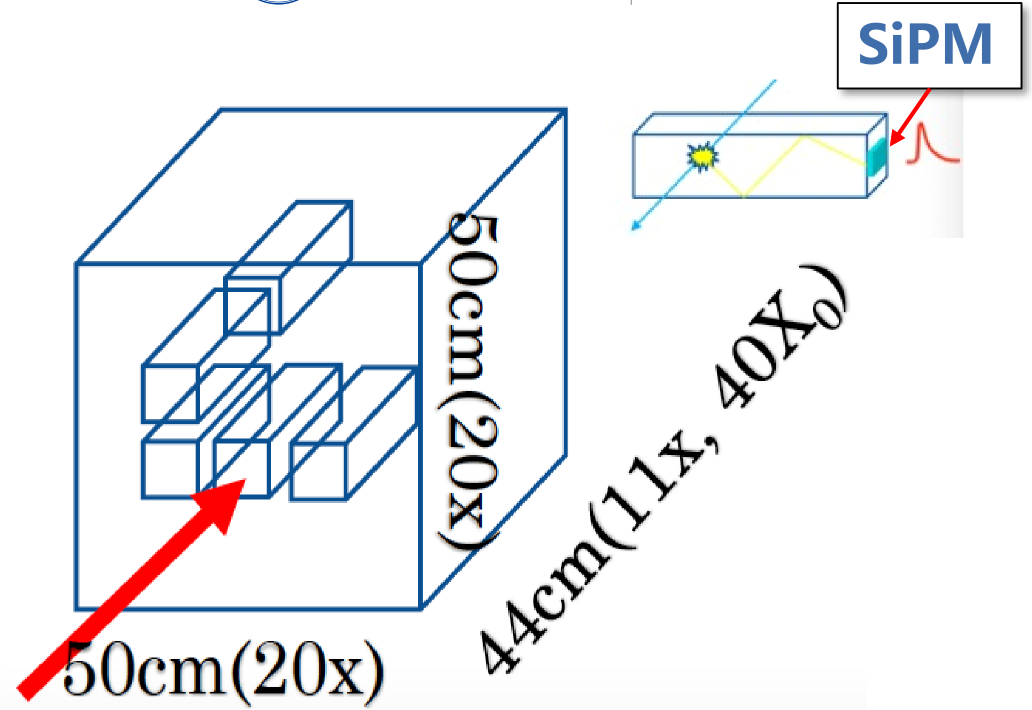


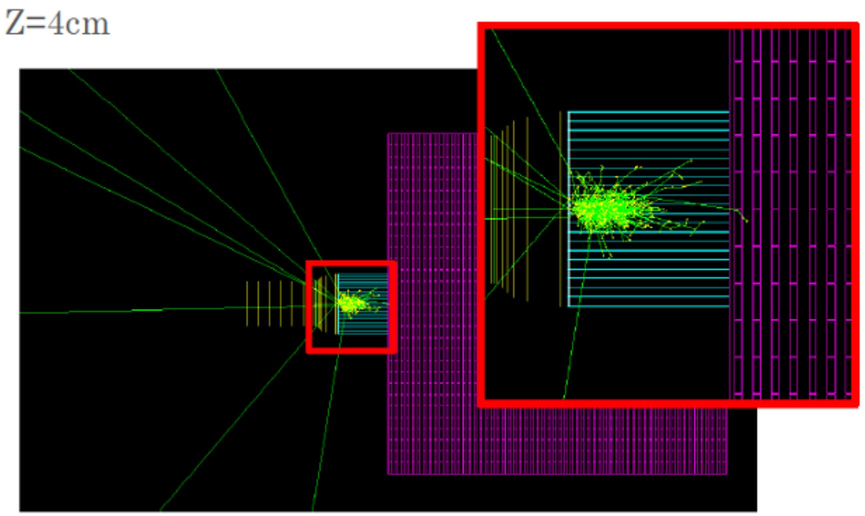
Electromagnetic calorimeter

- **Deposit all the energy from electrons and photons**
- **Crystal Scintillator + SiPM**
  - **LYSO(Ce),**
  - **20×20×11 crystals, 2.5cm×2.5cm×4cm**
  - **High light yields, short decay time , good radiation resistant**
- **Module has been tested in DESY**





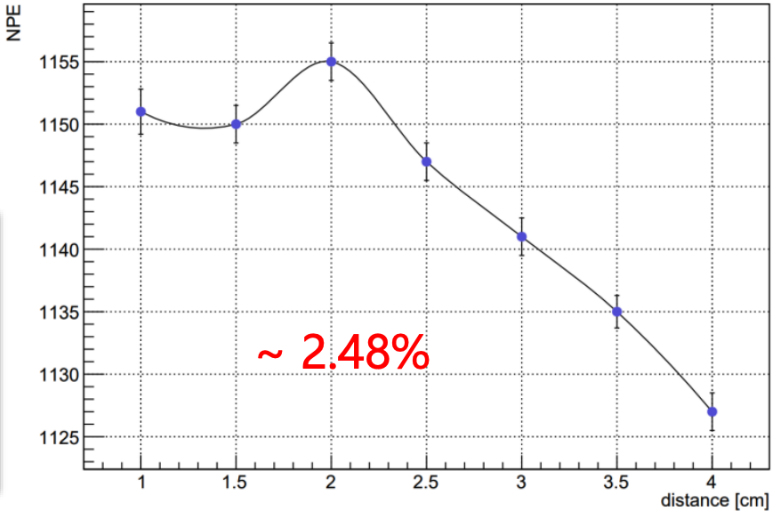




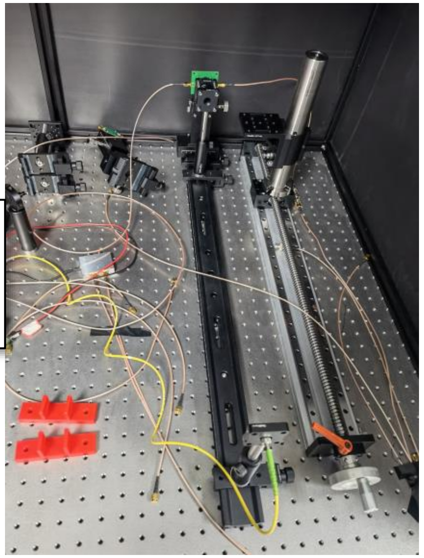
Electromagnetic calorimeter

5cm LYSO

Uniformity scan with using ^{60}Co

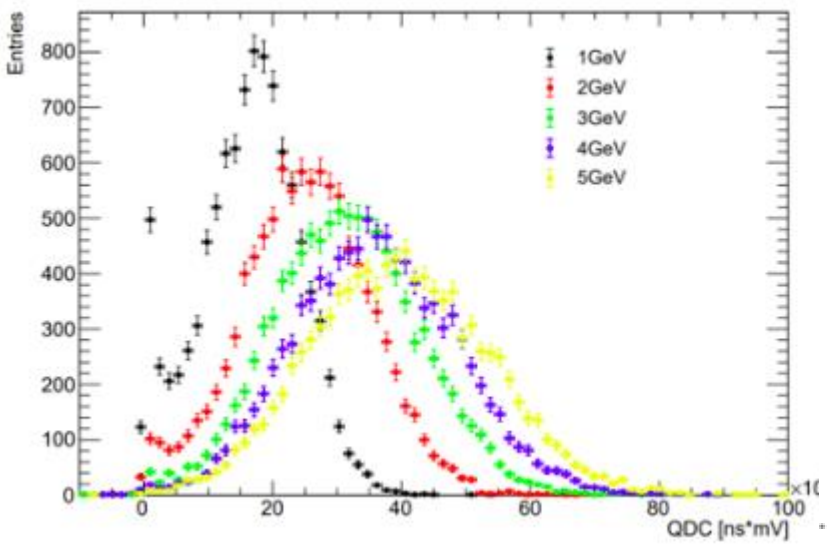


SiPM laser calibration

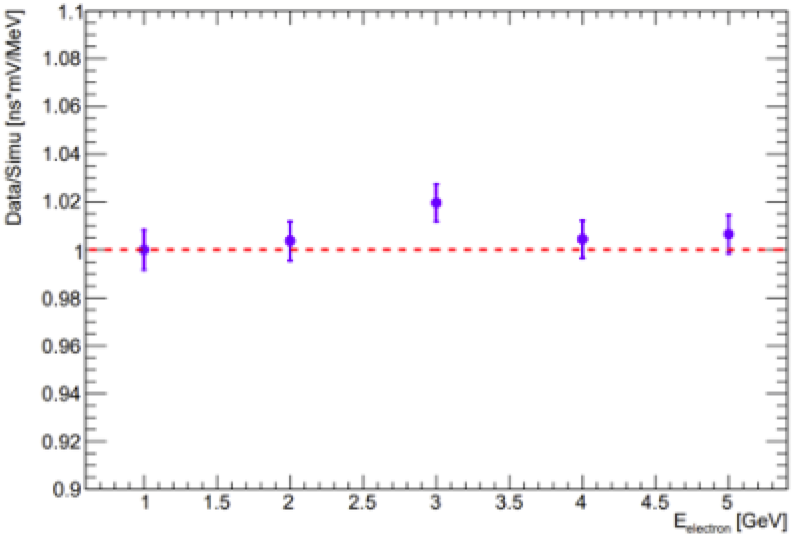


Beam test @Desy

Electron Data of Ch1-4cmLYSO

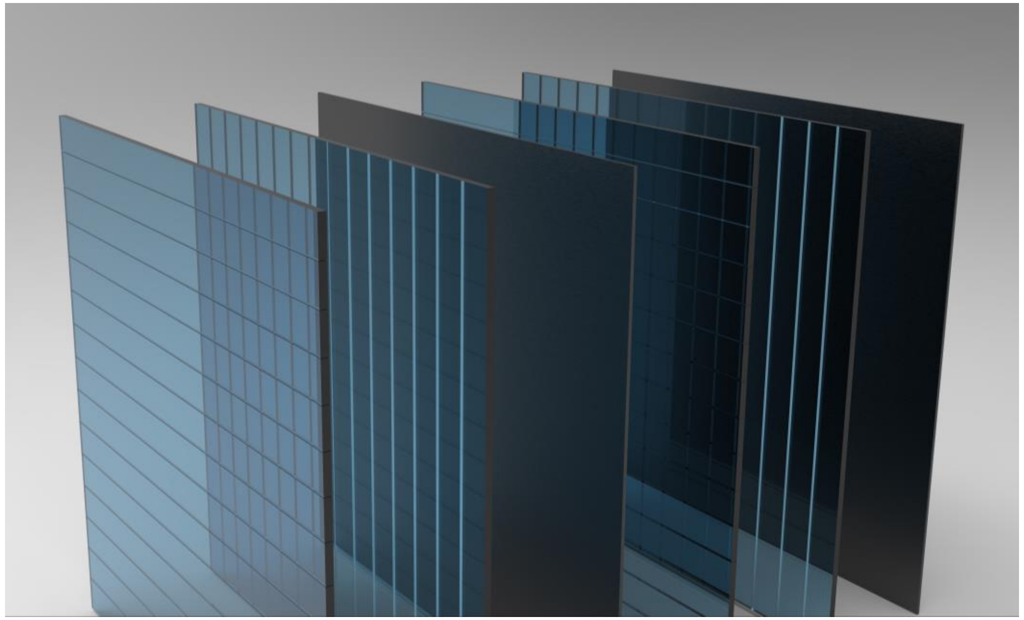


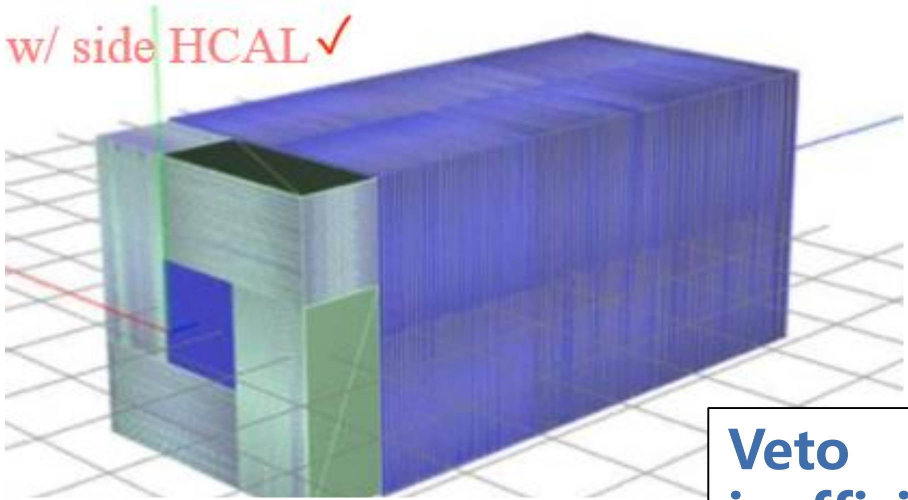
Experimental Data vs. Simulation



Hadronic calorimeter

- **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/50 mm 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** arXiv:2311.01780

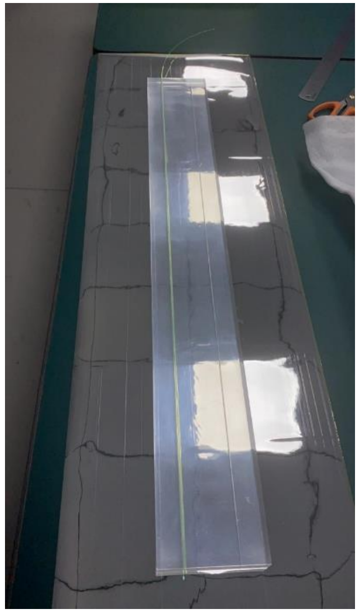


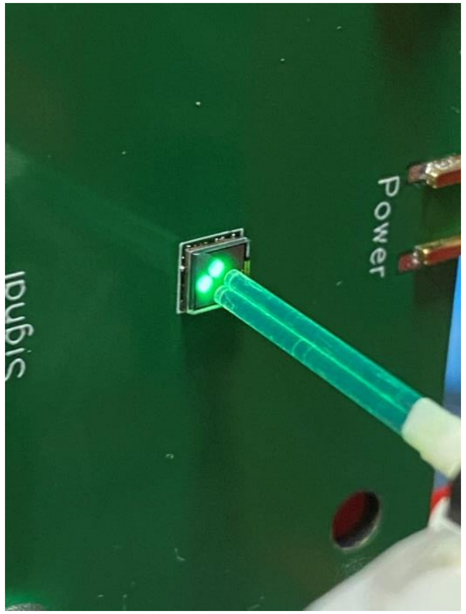


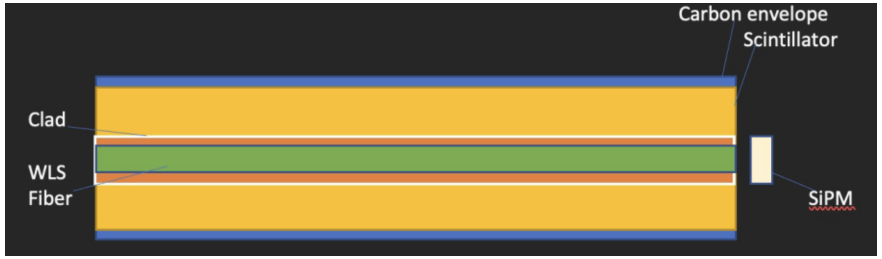
Veto inefficiency

Energy[MeV] \ Particle	n	k^0	π^0	p
100	1.17E-03	3.16E-02	7.30E-06	3.07E-02
500	1.84E-05	3.30E-06	1.00E-07	8.04E-06
1000	3.70E-06	4.30E-06	1.00E-07	1.00E-07
2000	2.70E-06	1.15E-05	1.00E-07	1.00E-07

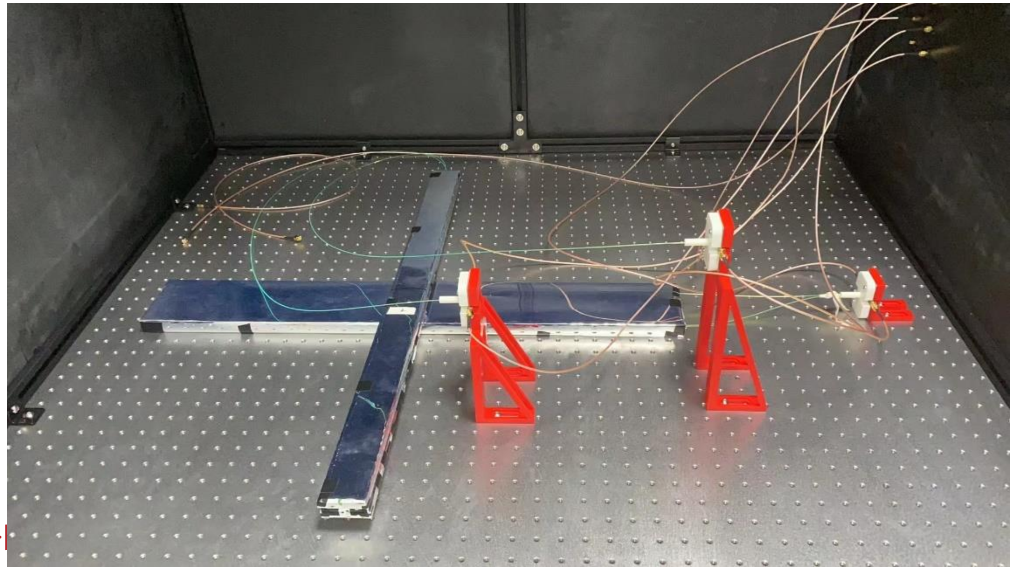
Hadronic calorimeter

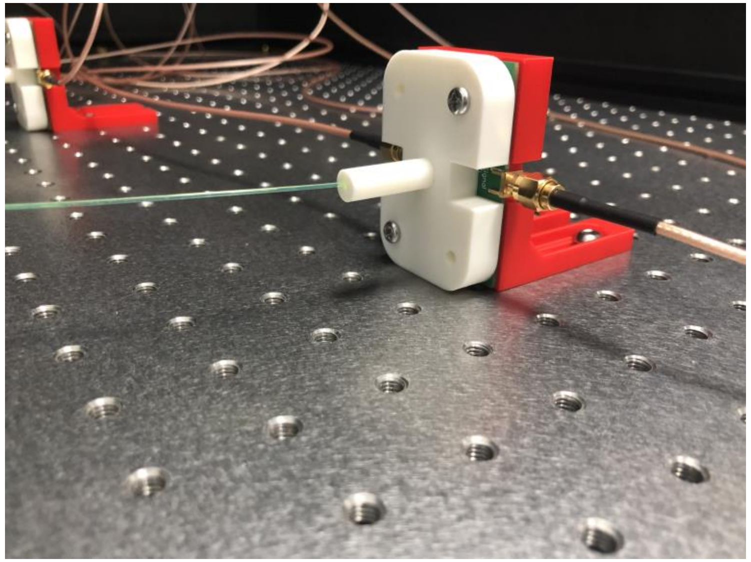






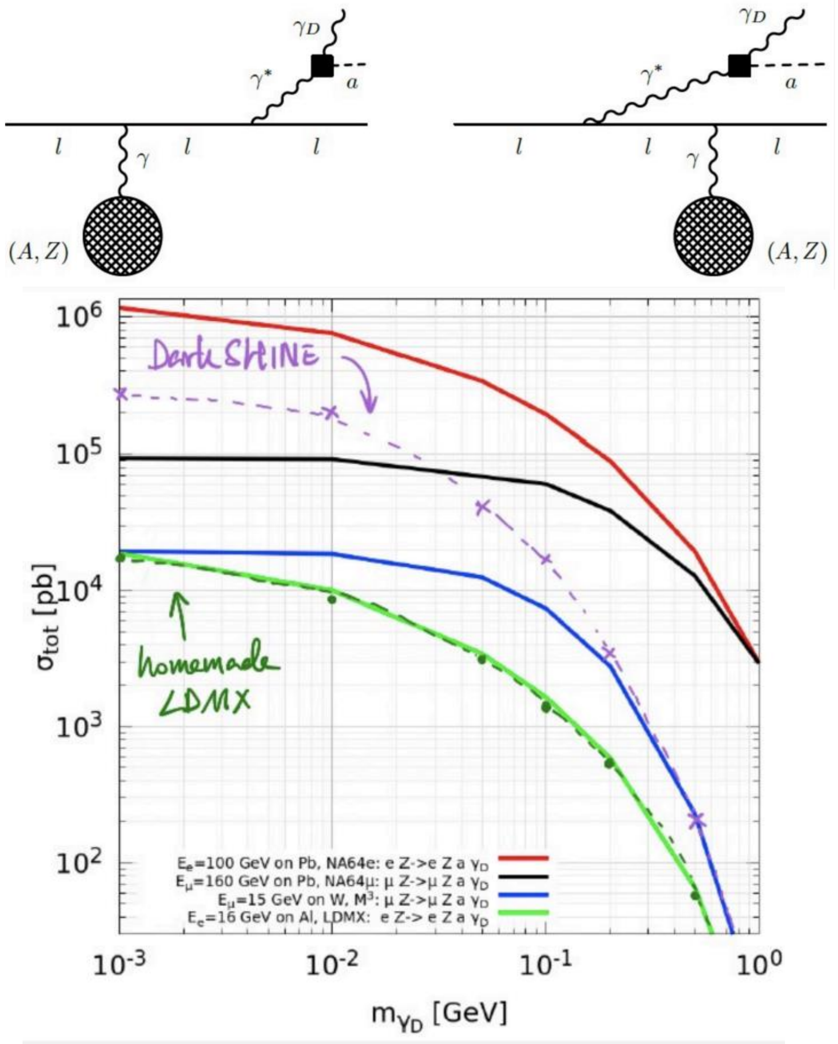
- **Plastic scintillator bars are tested with radioactive source and cosmic ray source.**
- **The fiber and SiPM are coupled with support and collimation structures**





More Physics Opportunities…

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…

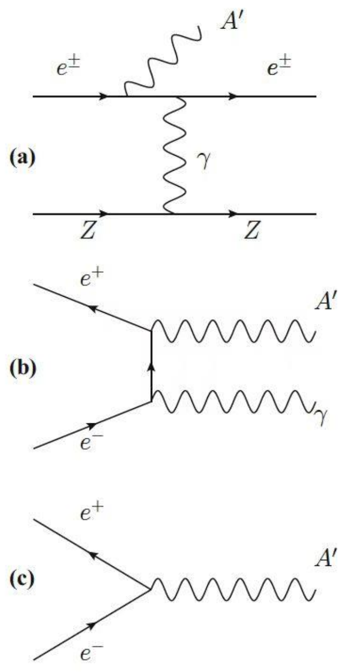
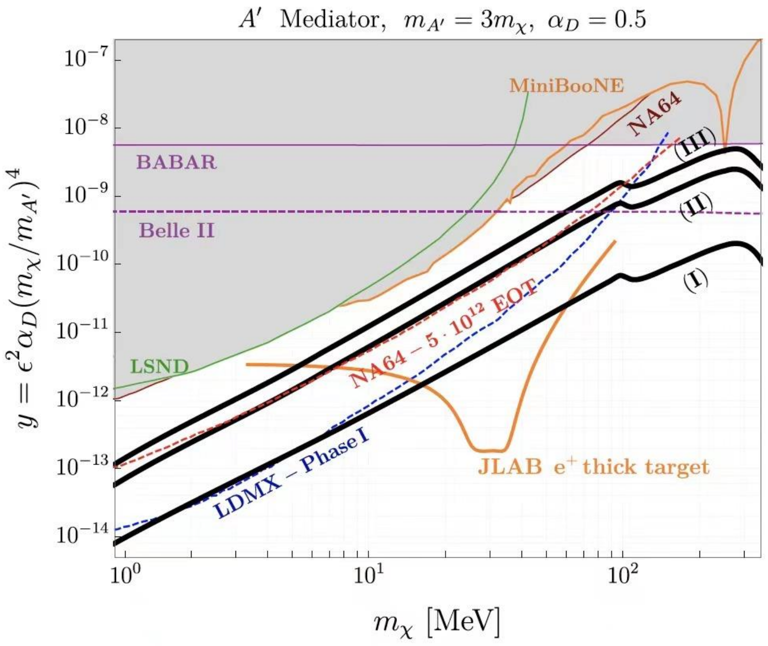


Fig. 1 Three different A' production modes in fixed target lepton beam experiments: (*a*) A'-strahlung in e^-/e^+-nucleon scattering; (*b*) A'-strahlung in e^+e^- annihilation; (*c*) resonant A' production in e^+e^- annihilation



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Summary

- **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**

- **Prospective analysis sensitivity of DarkSHINE is presented**
  - **Almost background free, expected 0.02 background from 3e14 electron-on-target (w.r.t 1 yr running)**
  - **Above 50% dark photon acceptance efficiency**
  - **Competitive sensitivity,** *Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)*

- **Detector key technology R&D has been sponsored by NSFC (原创探索计划项目)**

Backup

Plan

2022 1st **simulation studies** of detector system; establish DarkSHINE collaboration formally with SHINE facility (start the R&D work on the beamline).

2023 **R&D** of the **calorimeter systems, tracker system, magnet** and **mechanical supporting layout**; determine 1st **conceptual design** of DarkSHINE **beamline**.

2024 In-lab technical demonstration of detector prototypes; overall **conceptual design report** of **DarkSHINE detector system** and the preliminary **beamline conceptual design report**.

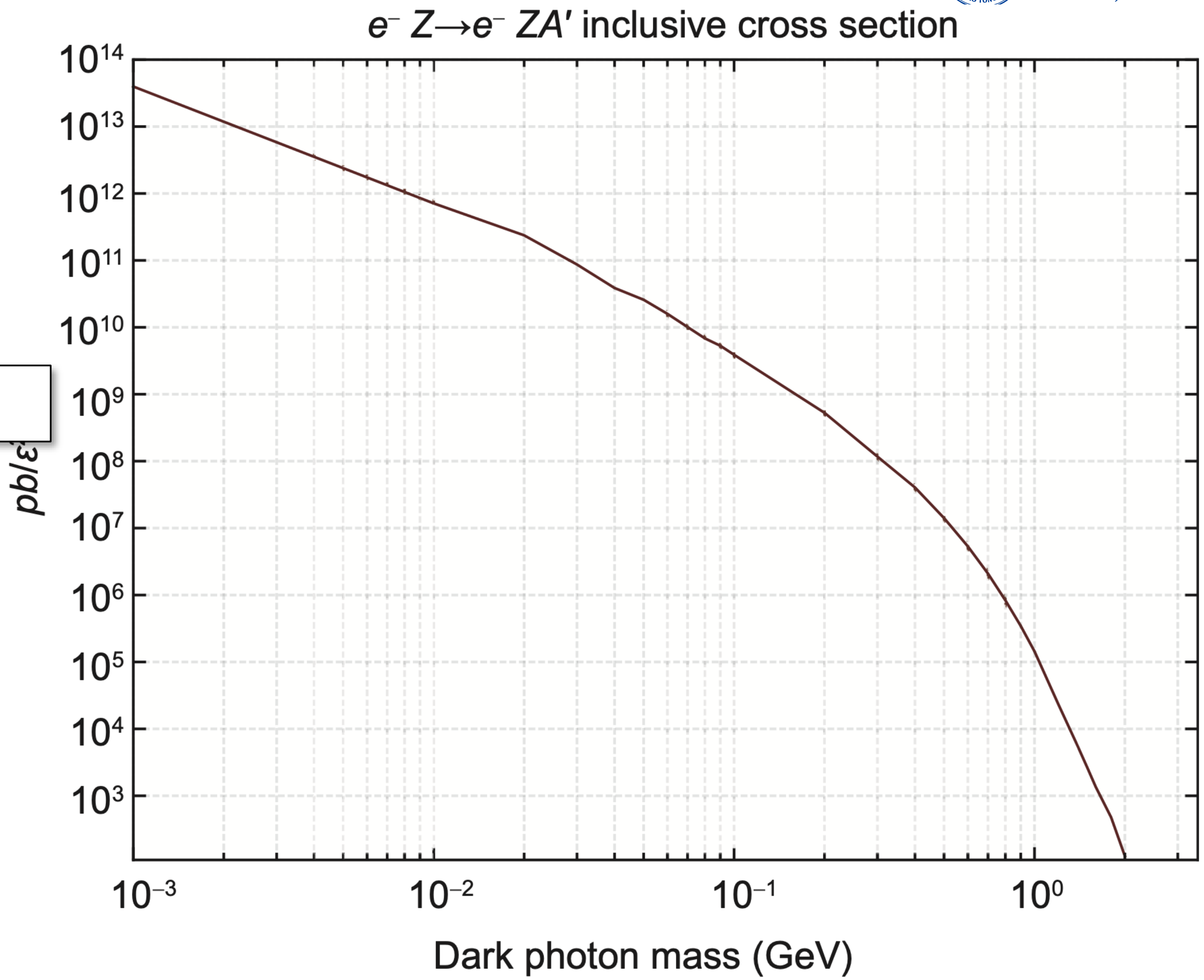
2025 **Sub-detector** prototyping; **cosmic** tests and **beam** tests.

2026 Start the **construction** of the DarkSHINE beamline and detector systems.

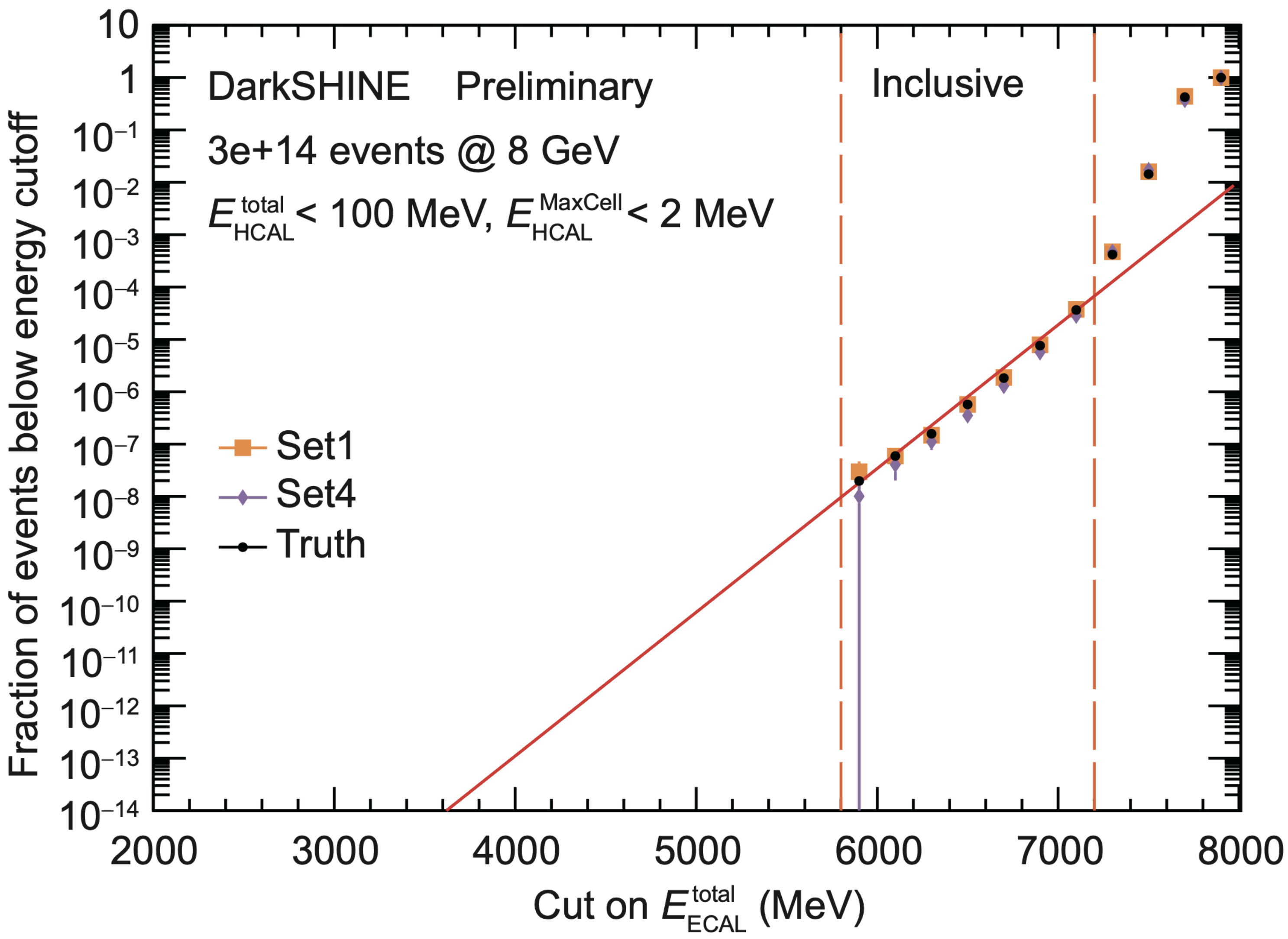
2028 1st **commissioning** of the overall DarkSHINE experiment at the accomplished SHINE facility and dedicated DarkSHINE specific beamline.

Dark photon XS

XS with $\varepsilon^2 = 1$

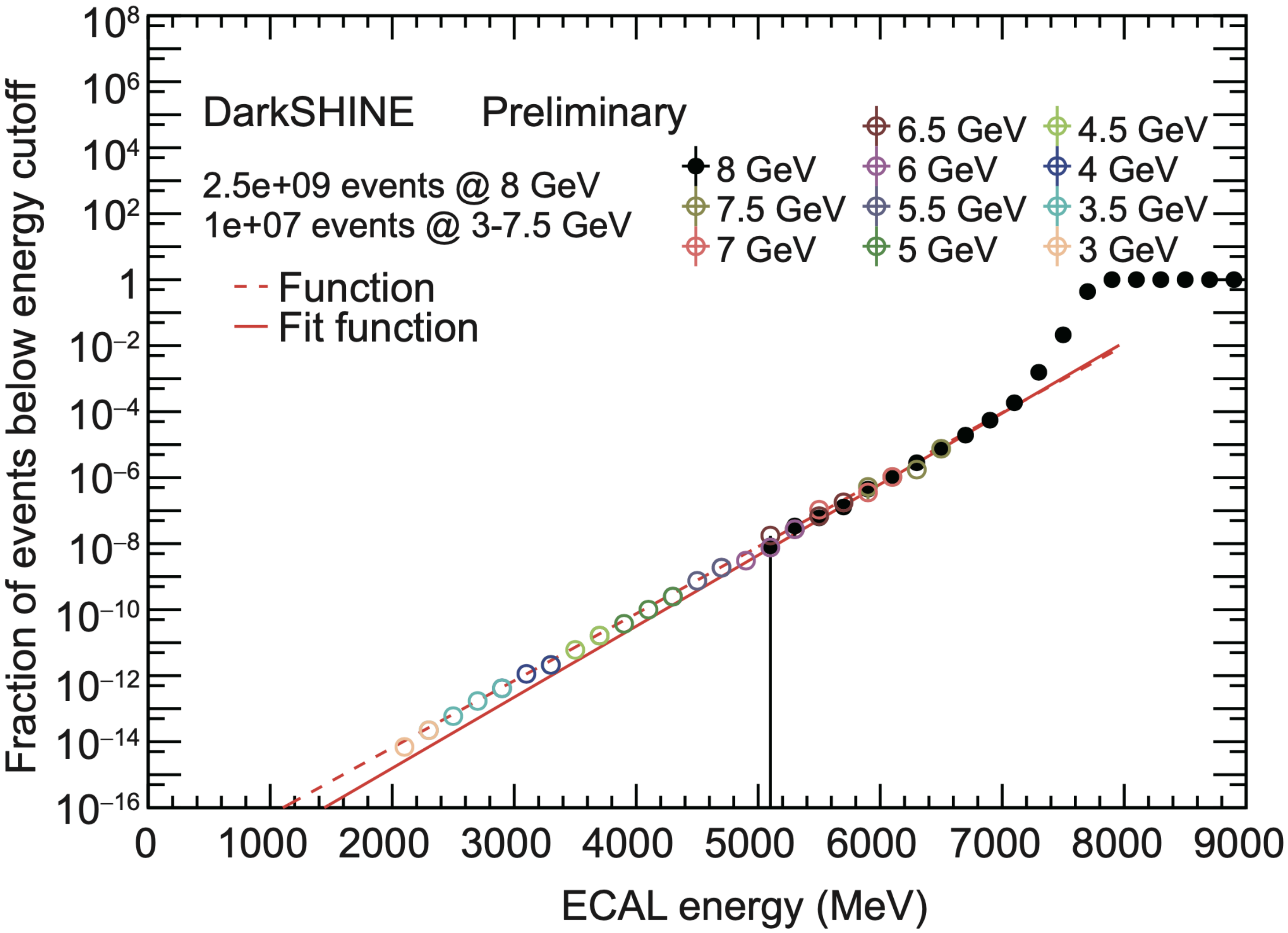


Background estimation



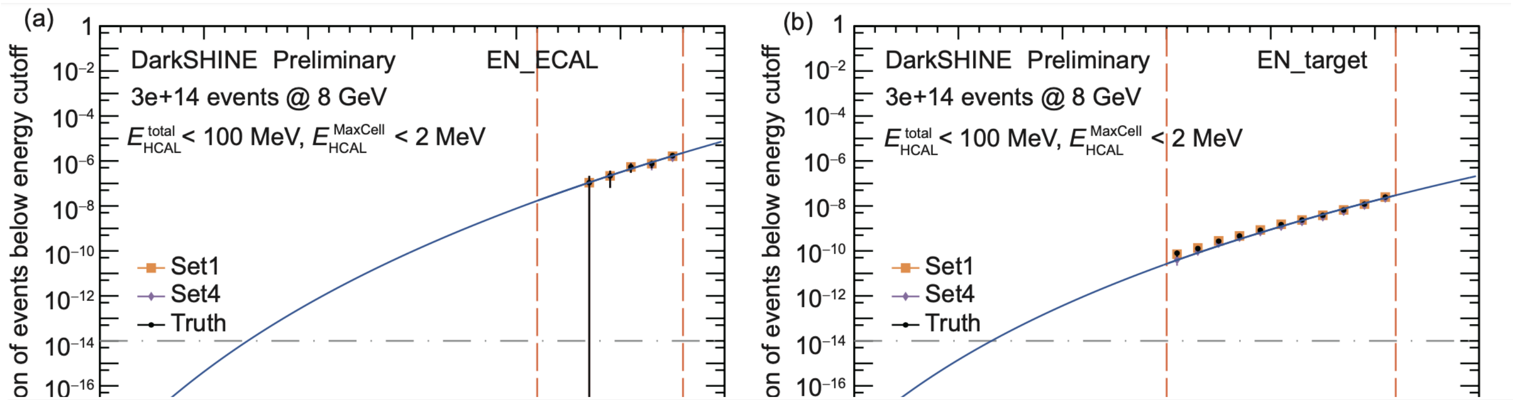
- **Expected background yields go down quickly at lower ECAL energy.**
- **In order to estimate background yields in 10^{14} EOT, extrapolation method is used**
  - **fit from inclusive background process**

Background estimation



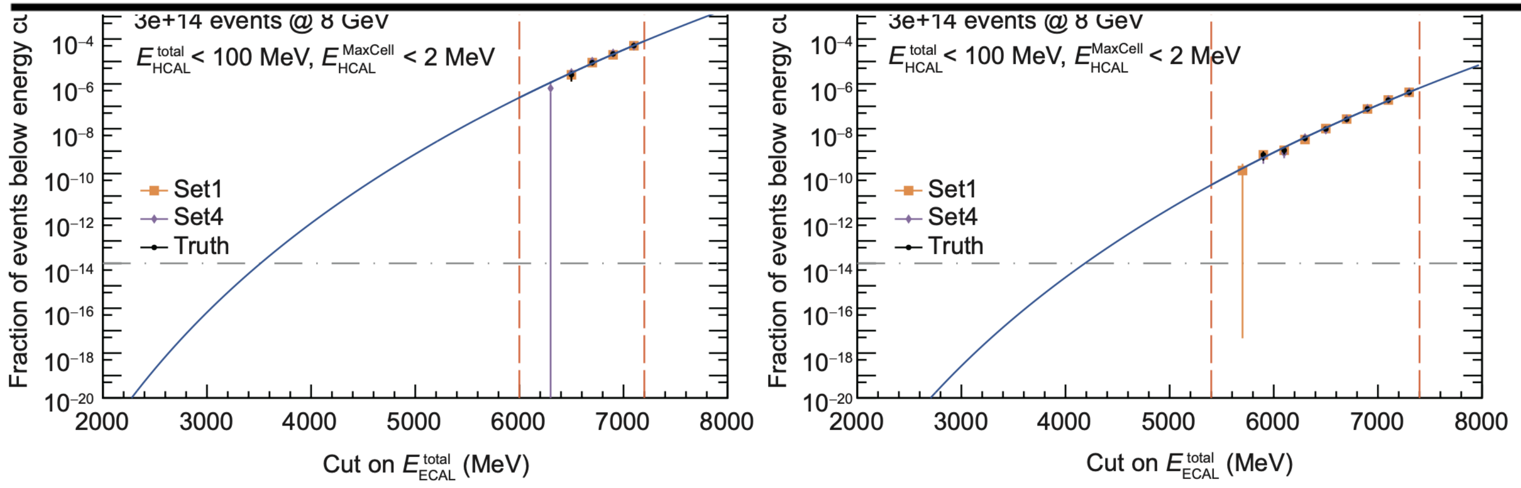
- **Expected background yields go down quickly at lower ECAL energy.**
- **In order to estimate background yields in 10^{14} EOT, extrapolation method is used**
  - **fit from inclusive background process**
  - **extrapolation from low energy samples**

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



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

The DarkSHINE simulation

Simulated background statistics:

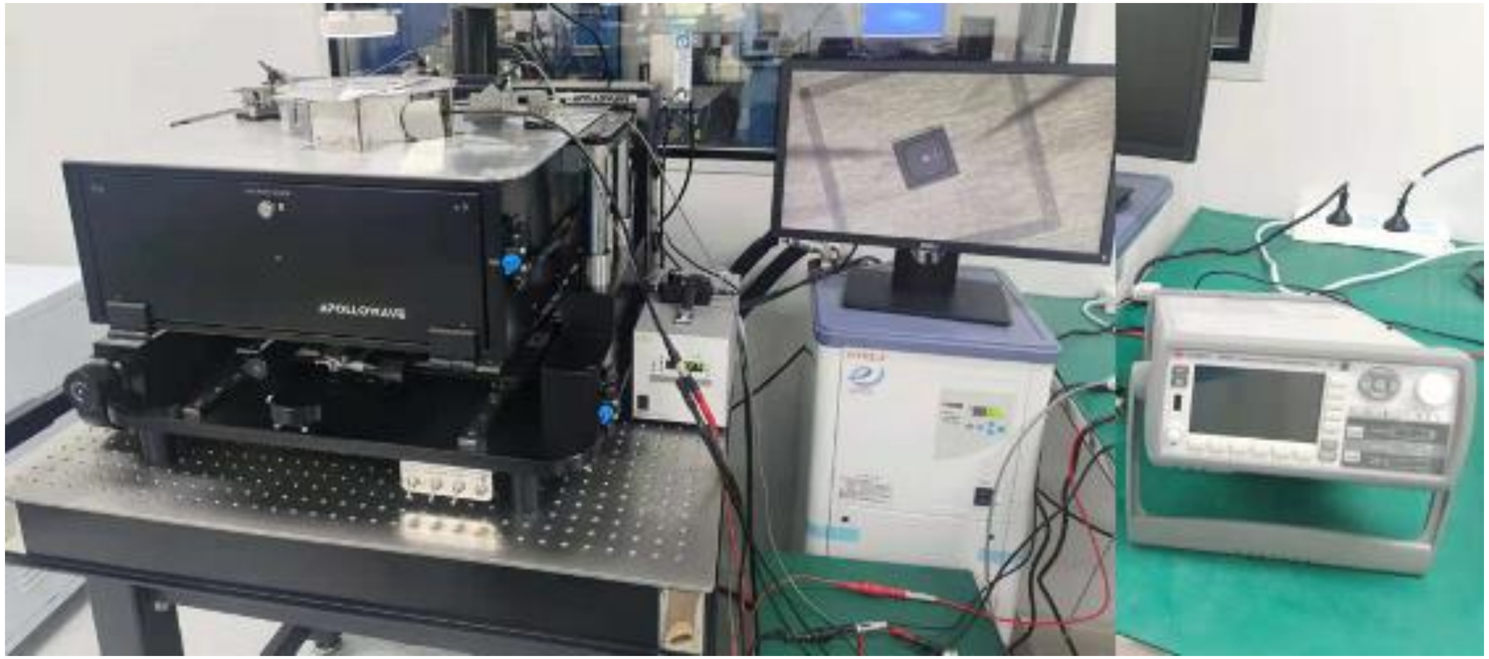
Process	Generate events	Branching ratio	EOTs
Inclusive	2.5×10^9	1.0	2.5×10^9
Bremsstrahlung	1×10^7	6.70×10^{-2}	1.5×10^8
GMM_target	1×10^7	$1.5(\pm 0.5) \times 10^{-8}$	4.3×10^{14}
GMM_ECAL	1×10^7	$1.63(\pm 0.06) \times 10^{-6}$	6.0×10^{12}
PN_target	1×10^7	$1.37(\pm 0.05) \times 10^{-6}$	4.0×10^{12}
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}

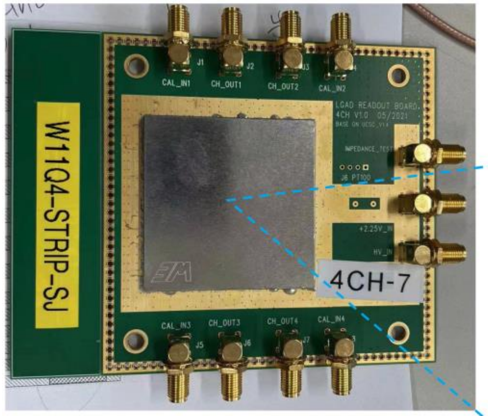
Event cut-flow of each background process:

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

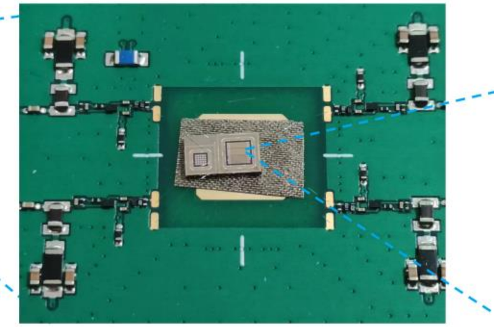
	EN_ECAL	PN_ECAL	GMM_ECAL	EN_target	PN_target	GMM_target	Hard_brem	Inclusive
Total events	100	100	100	100	100	100	100	100
Only 1 track	58.87	70.48	87.36	5.85	5.88	$< 10^{-3}$	78.73	84.40
$p_{\text{tag}} - p_{\text{rec}} > 4$ GeV	0.0044	0.0033	0.0041	5.58	5.46	$< 10^{-5}$	70.49	4.80
$E_{\text{HCAL}}^{\text{total}}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

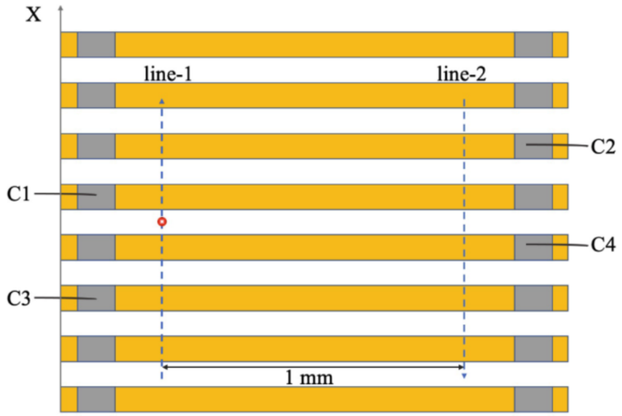
Tracking system

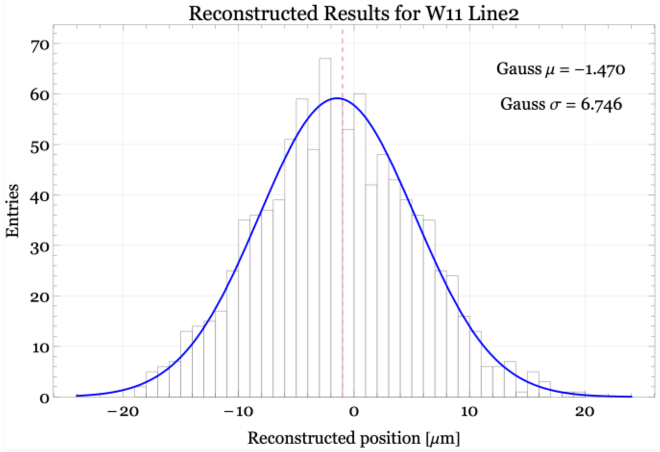


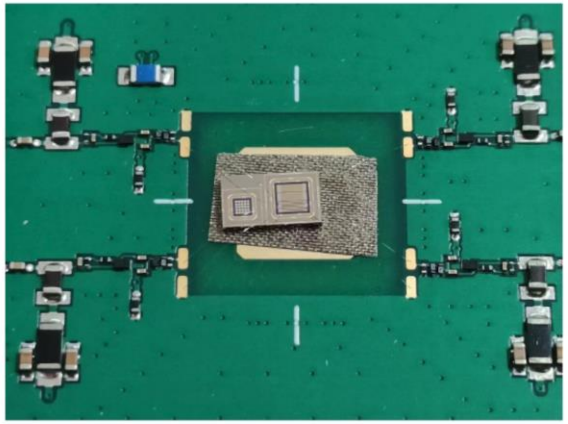


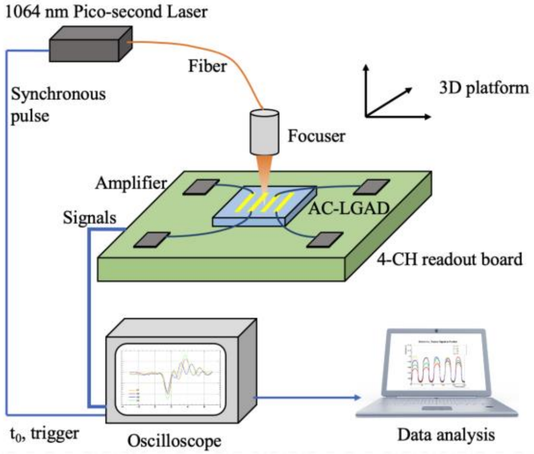
Working point
W11: 350V
W12: 150V





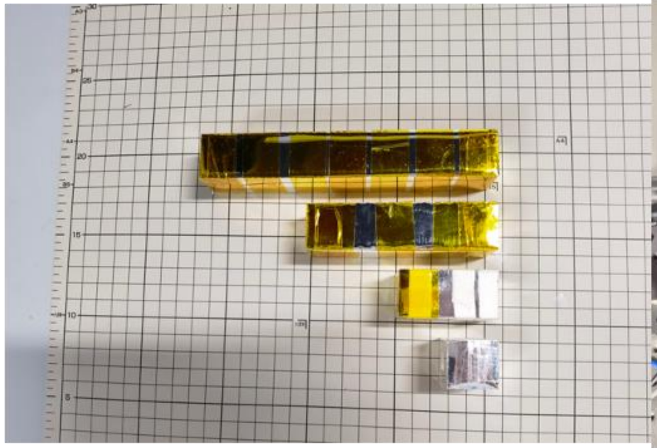




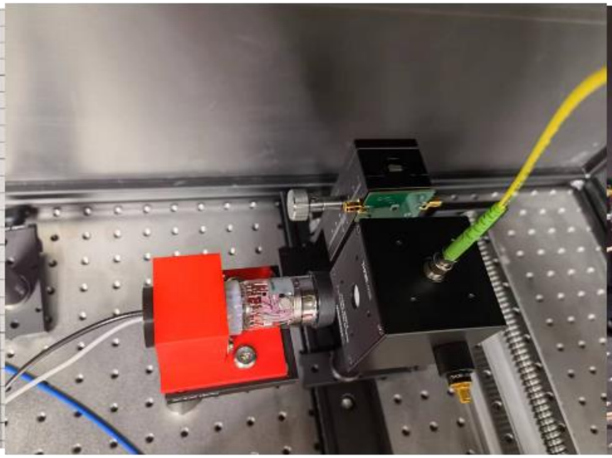


ECAL: crystal test

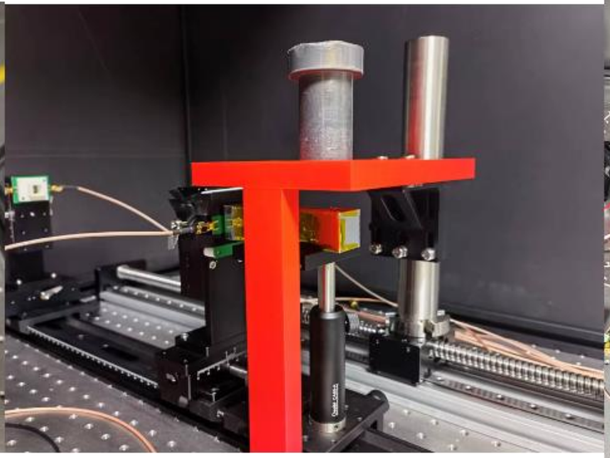
LYSO晶体切割与包裹

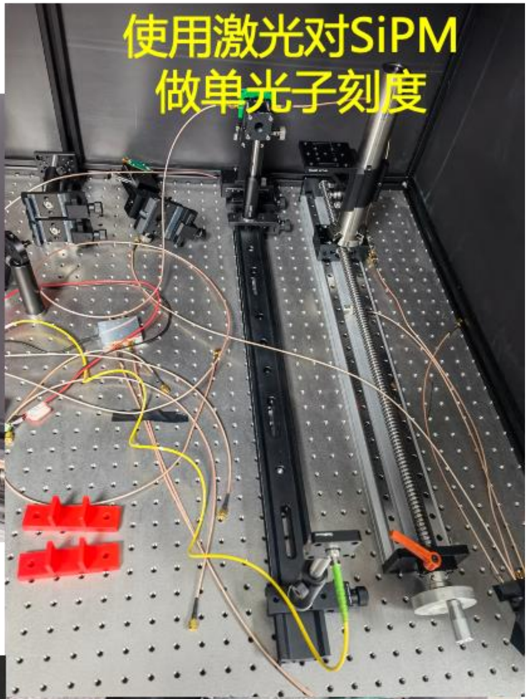


SiPM动态范围测试

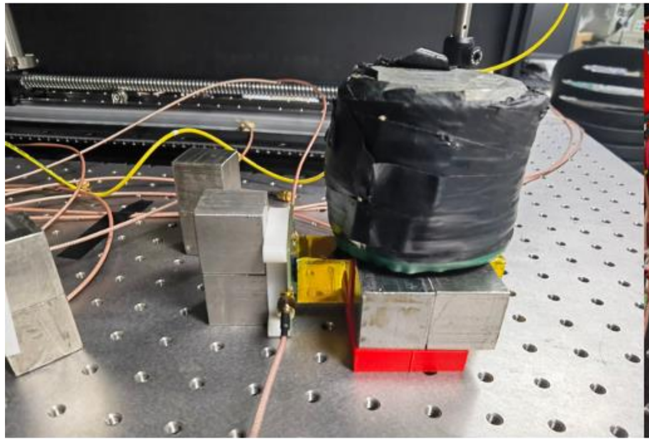


使用放射源对晶体做均匀性扫描

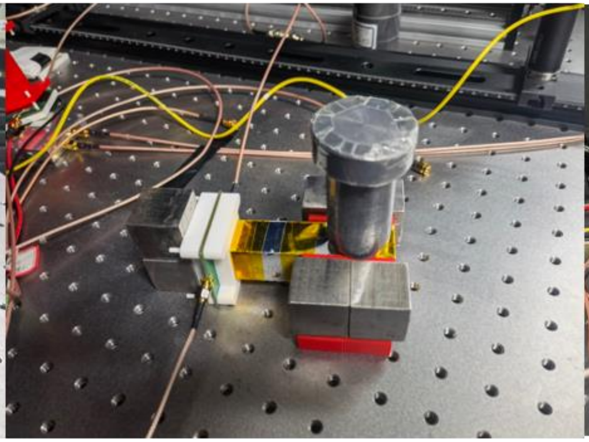




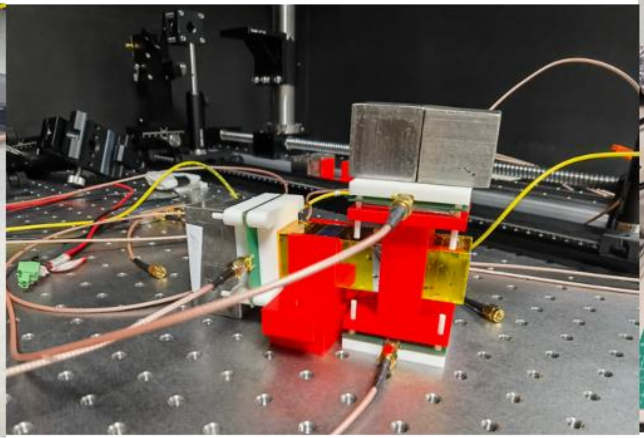
LYSO晶体^{137}Cs测试



LYSO晶体^{60}Co测试



宇宙线测试上下符合



HCAL: Simulation optimized

上海交通大学 SHANGHAI JIAO TONG UNIVERSITY | 李政道研究所 Tsung-Dao Lee Institute

- **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**

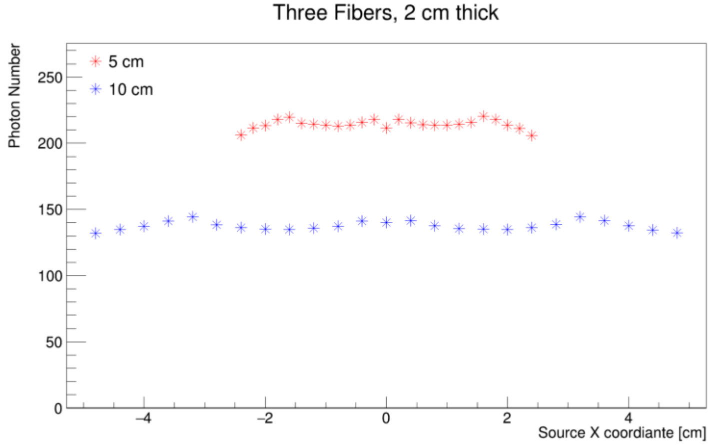
Energy[MeV] \ Particle	n	k^0	π^0	p
100	1.17E-03	3.16E-02	7.30E-06	3.07E-02
500	1.84E-05	3.30E-06	1.00E-07	8.04E-06
1000	3.70E-06	4.30E-06	1.00E-07	1.00E-07
2000	2.70E-06	1.15E-05	1.00E-07	1.00E-07

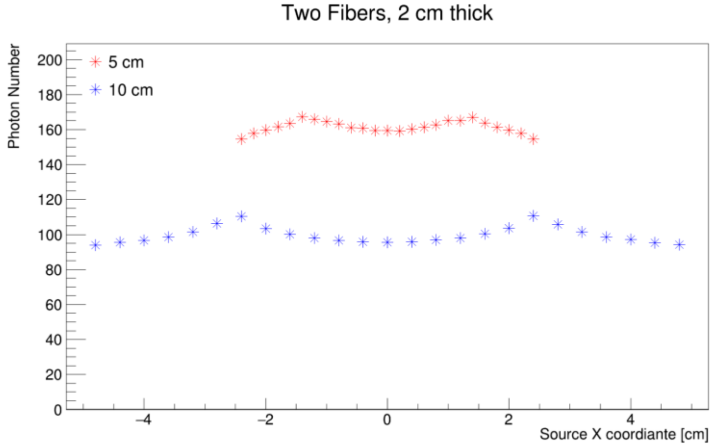
- **Events veto inEff**

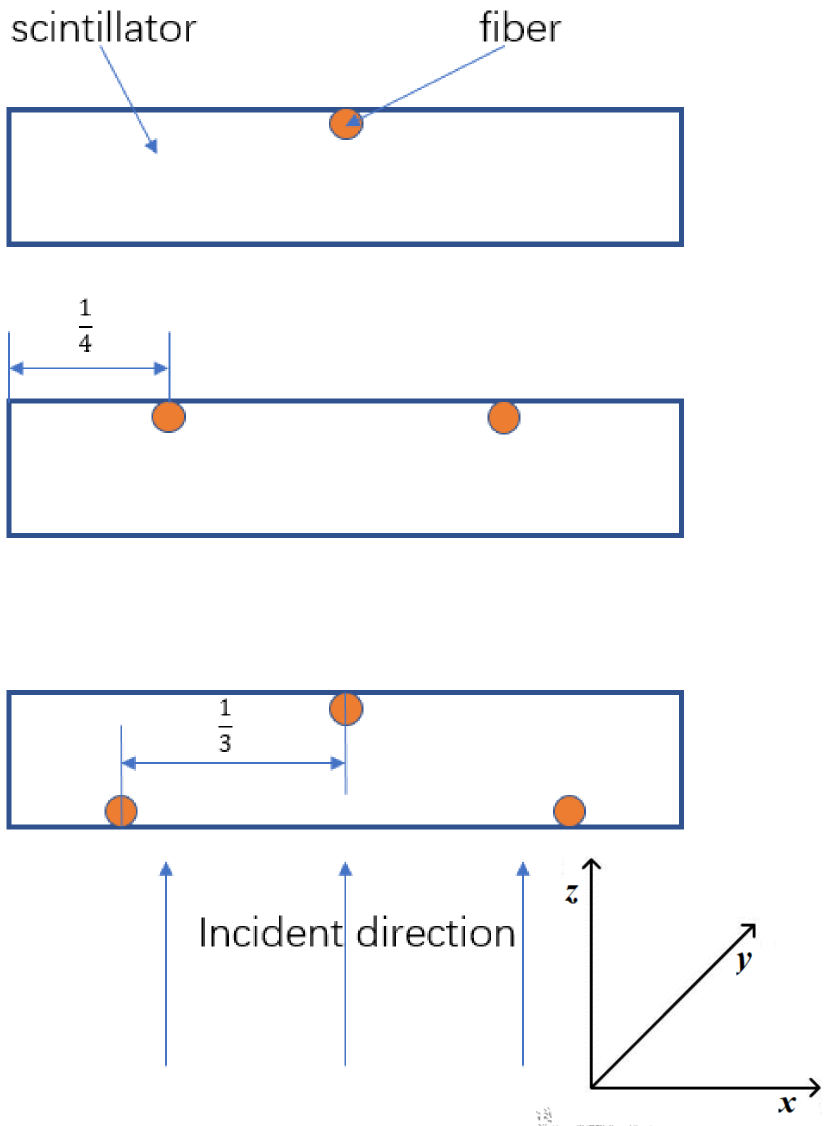
Structure \ Process	EN-target	EN-ECAL	PN-target	PN-ECAL
x-abs-y-noside	2.68E-02	3.94E-02	9.29E-02	1.24E-01
x-abs-y-side	1.04E-03	1.09E-02	1.94E-03	3.58E-02

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**



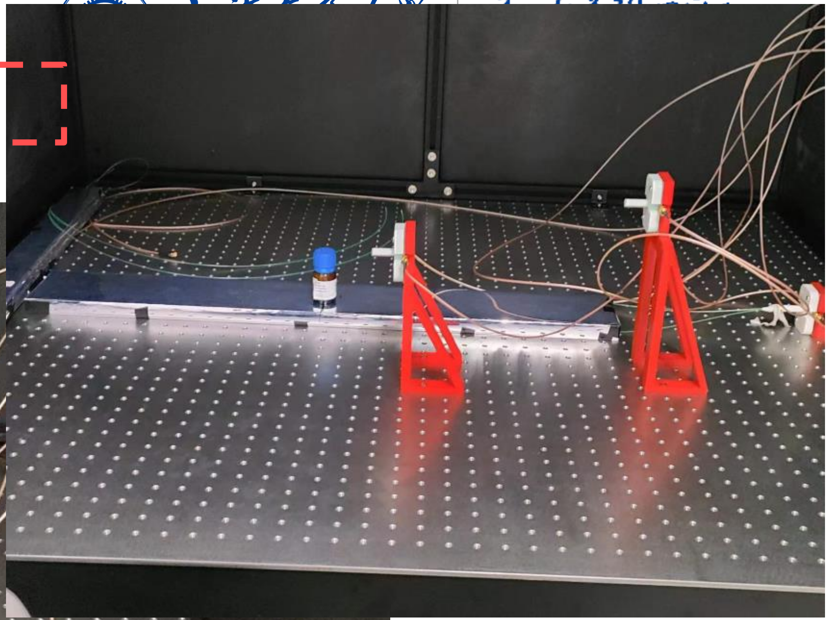




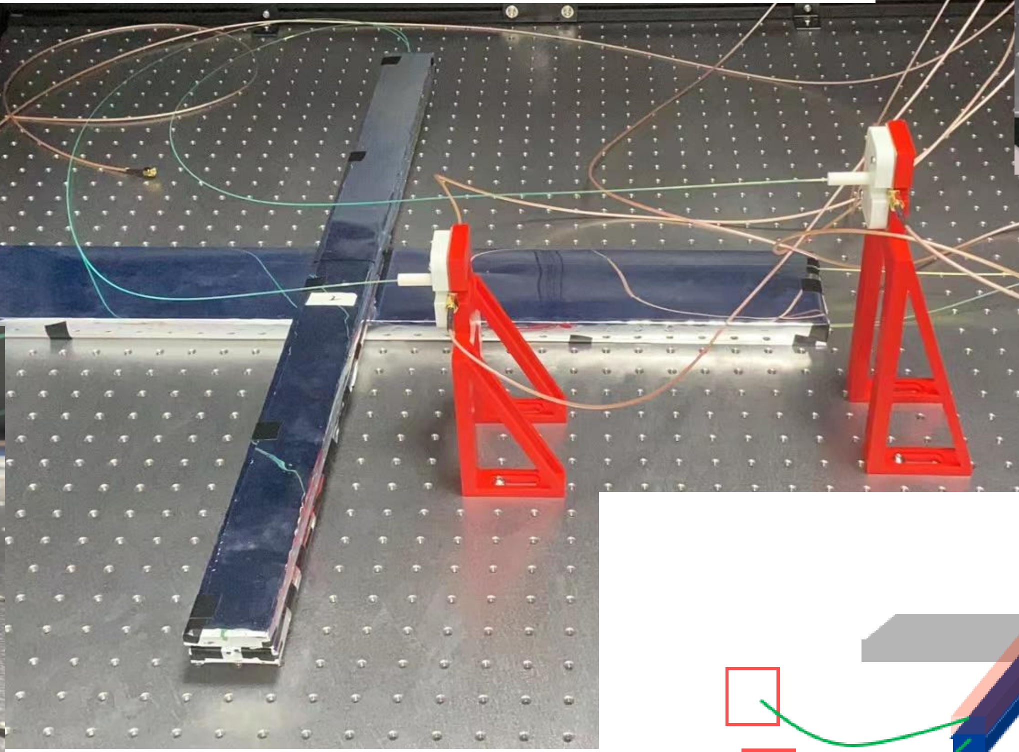
Size	1 fiber	2 fibers	3 fibers
1 cm * 5 cm	64 (60-75)	108 (100-115)	136 (130-145)
1 cm * 10 cm	38 (35-50)	69 (65-80)	92 (85-100)
2 cm * 5 cm	91 (85-100)	161 (155-170)	214 (205-220)
2 cm * 10 cm	53 (48-65)	100 (94-110)	138 (132-145)

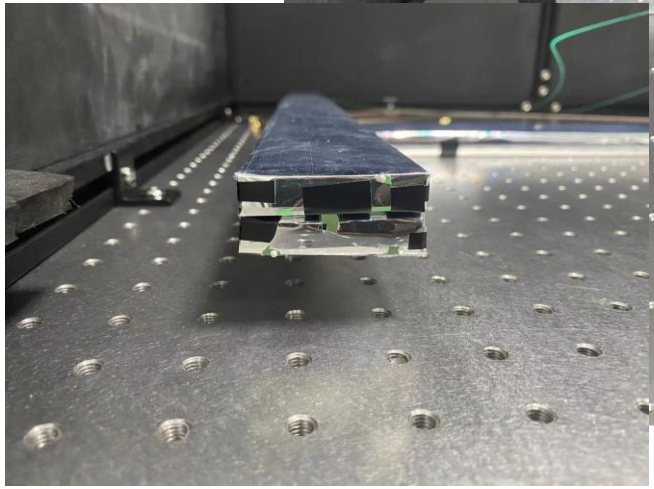
HCAL: Scintillator test Platform

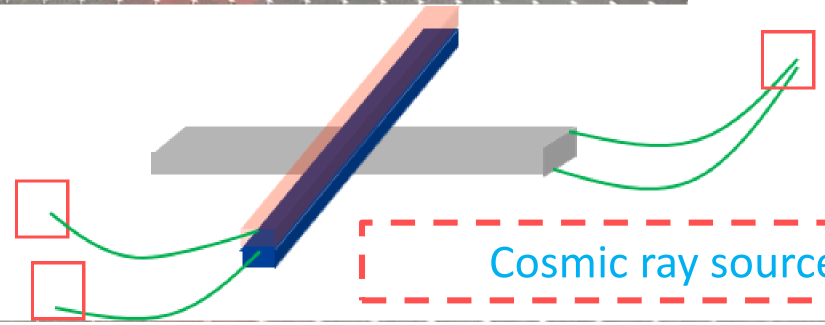
Radioactive source



- **Scintillator: HND-S2 (高能科迪) polystyrene**
  - **Several sizes are studied: width/thickness/grooves are varied**
- **WLS: Kurary, d=1 mm, reflector on one side**
- **SiPM: EQR15 11-3030D-S, 3.0 mm × 3.0 mm, 40000 microcell**
- **Wrapper: 80 um ESR**







Cosmic ray source

Dark Photon Theory in a nutshell

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY | 李政道研究所 Tsung-Dao Lee Institute

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

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + A_\mu j^\mu_{em} - \frac{1}{4} X_{\mu\nu}X^{\mu\nu} + X_\mu j^\mu_X$$

SM Photon γ **Dark Photon A'**

$$\varepsilon X_{\mu\nu}F^{\mu\nu}$$

- **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)