TSUNG-DAO LEE INSTITUTE

DARK SHINE

Recent progress of DarkSHINE R&D

Rui Yuan

On behalf of DarkSHINE R&D Team

MEPA 2025, Nanjing

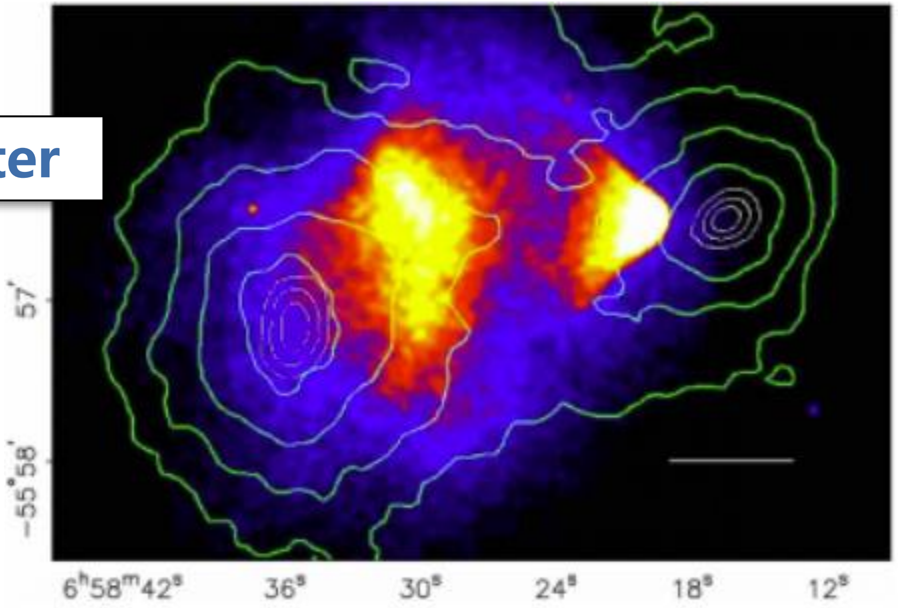
2025.04.12

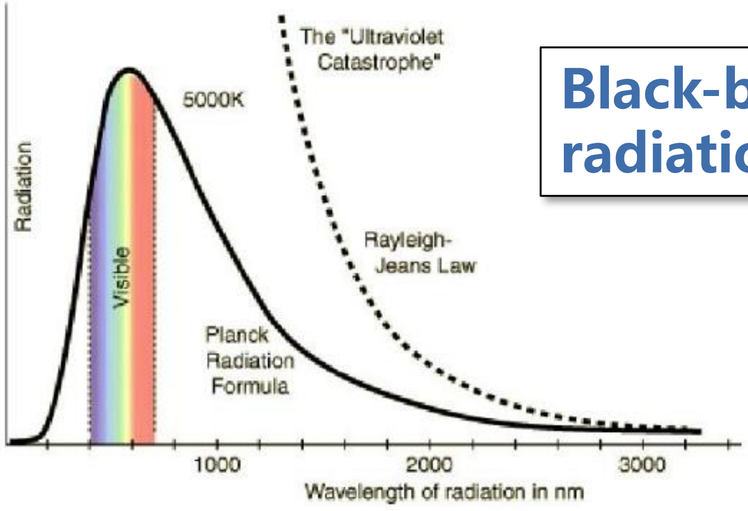
Two dark clouds over physics

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

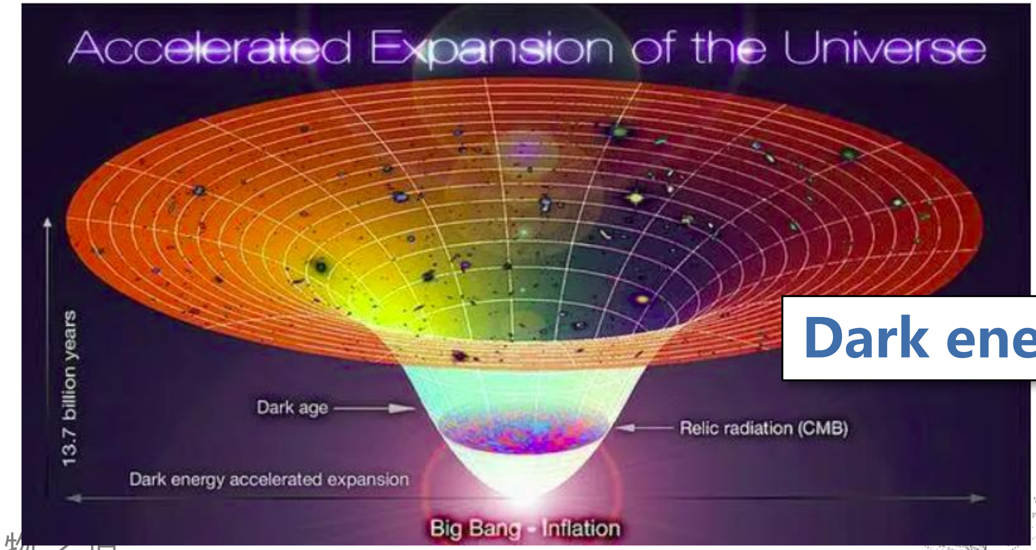
Michelson-Morley experiment

Dark matter





Black-body radiation

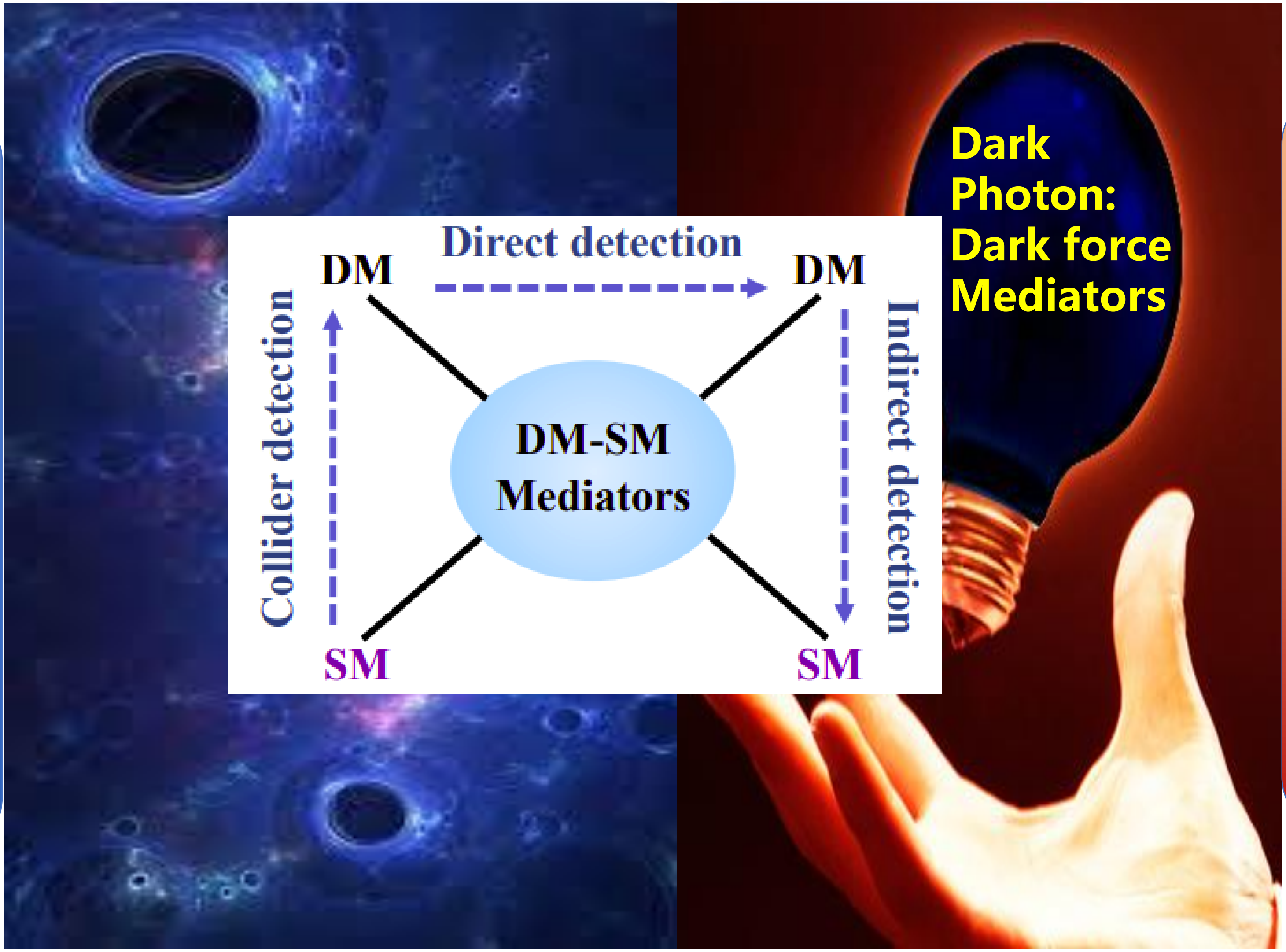


Dark energy

Dark Matter: Particle physics perspective

The world of Dark Matter

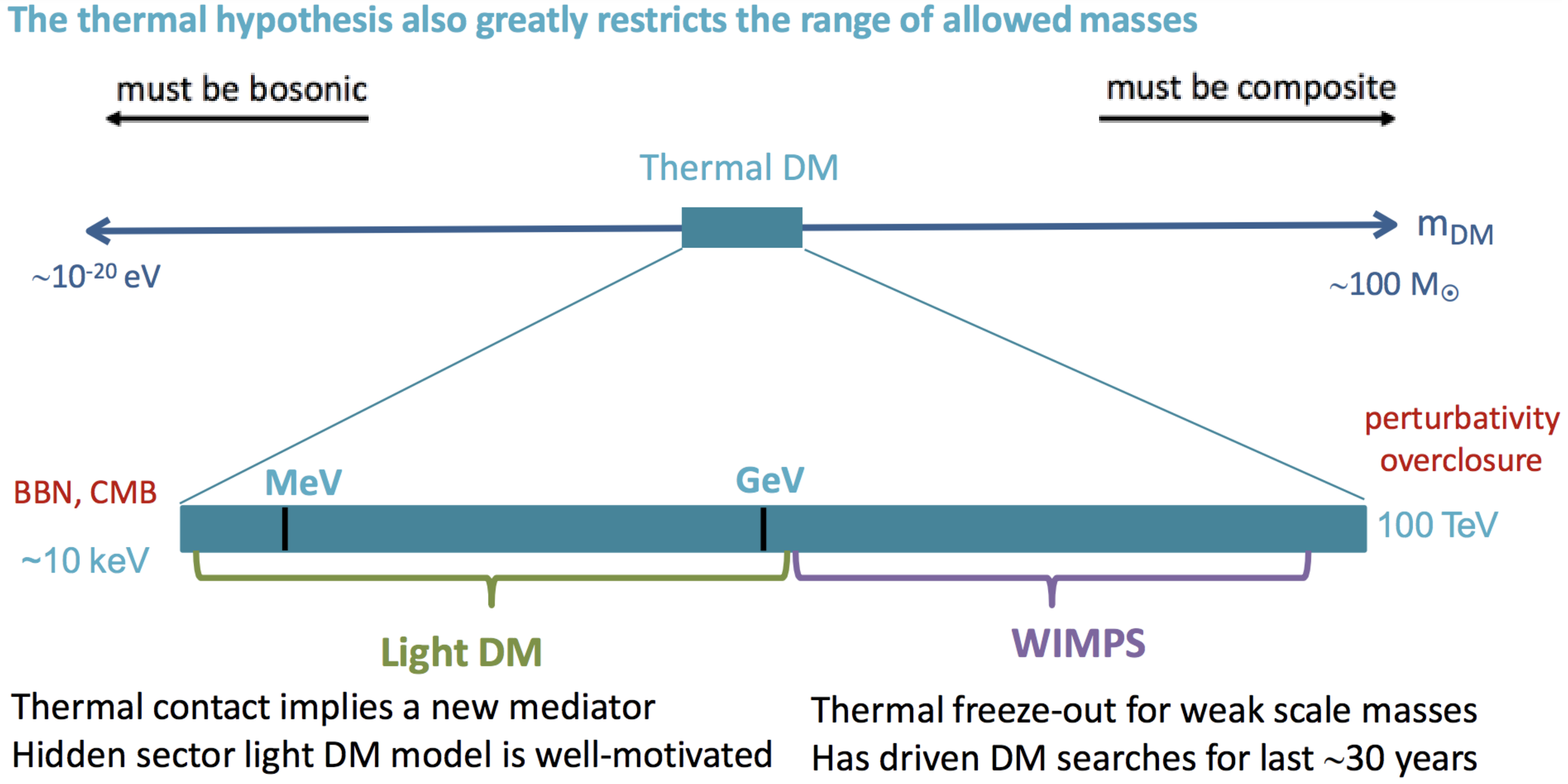
Dark Matter candidate particles



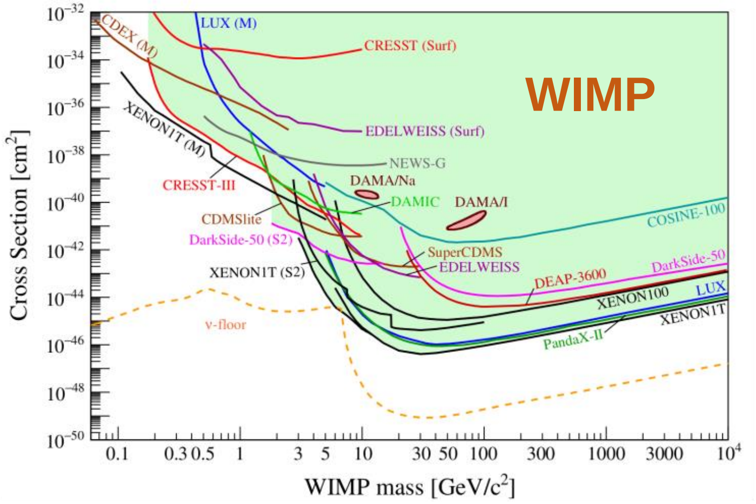
Dark Matter Mediators

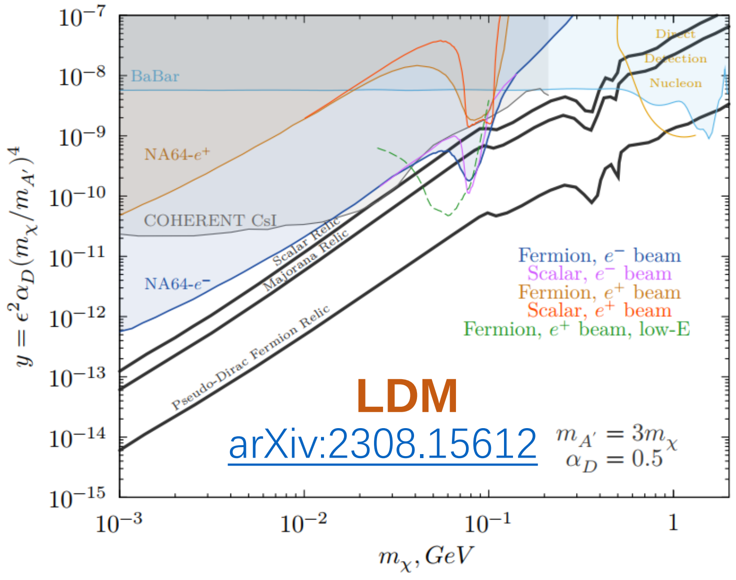
Dark Matter: Models in broad mass range

- **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)**



APPEC Committee Report: 2104.07634





Dark photon theory

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

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

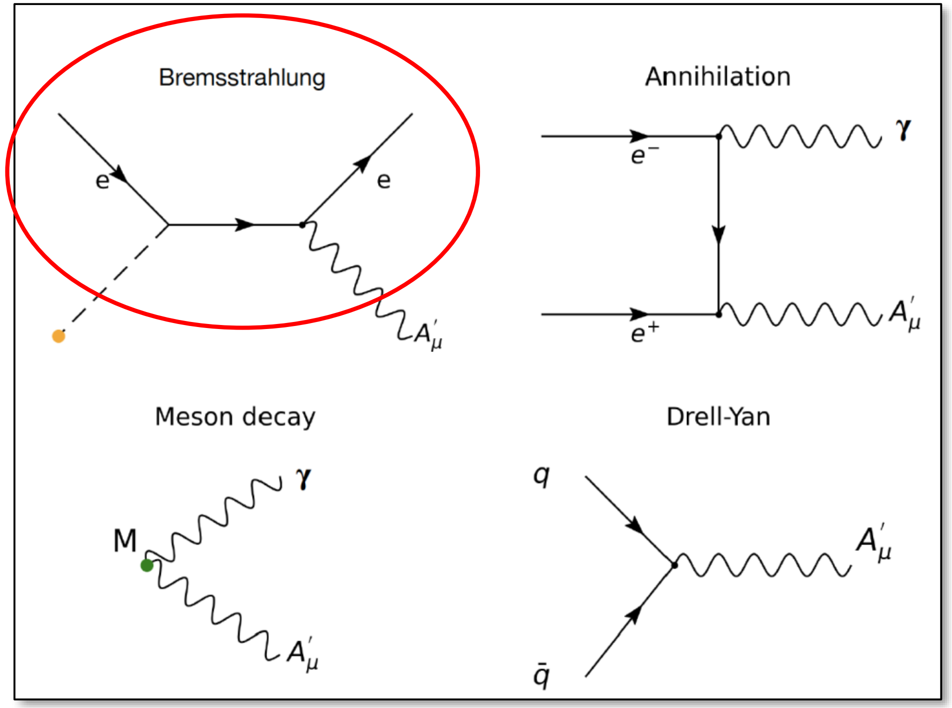
Kinetic mixing term | Field strength tensor | Dark photon field

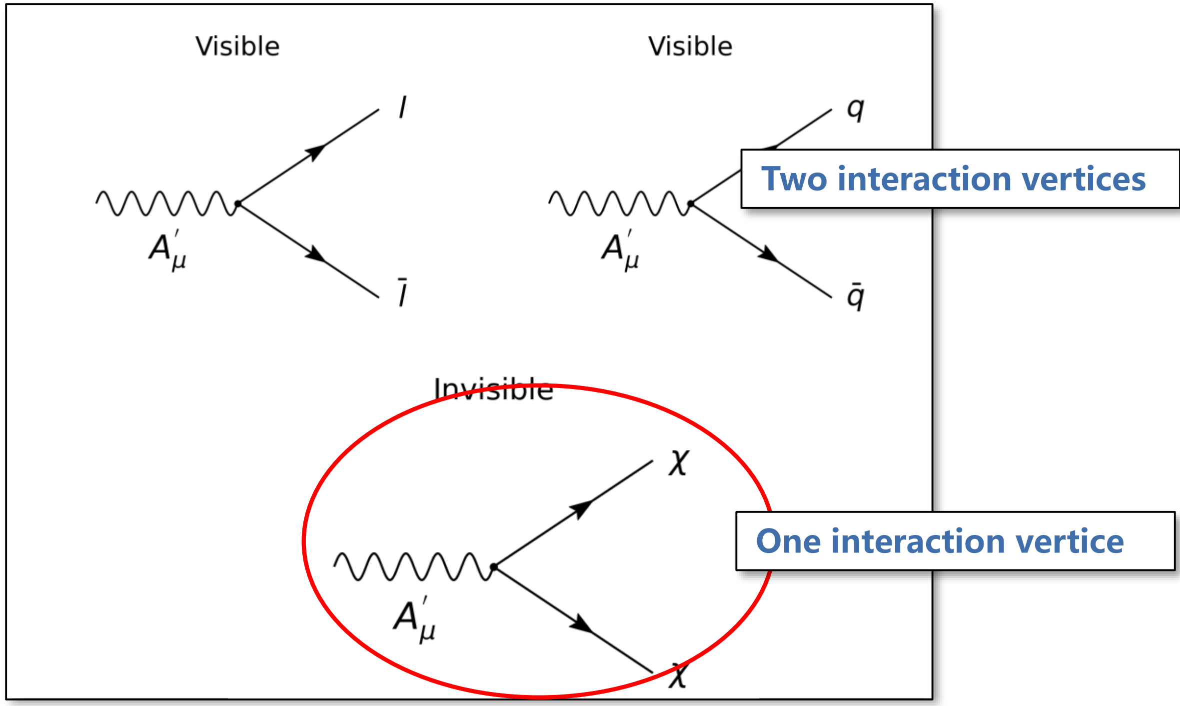
- **In the minimal Dark photon model, 3 free parameters are studied:**
  - $m_{A'}$: **Dark Photon mass**
  - ε: **Kinetic mixing parameter**
  - **Decay branching ratio: $A' \rightarrow \chi\chi$ (dark sector), could be 1 or 0**

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**



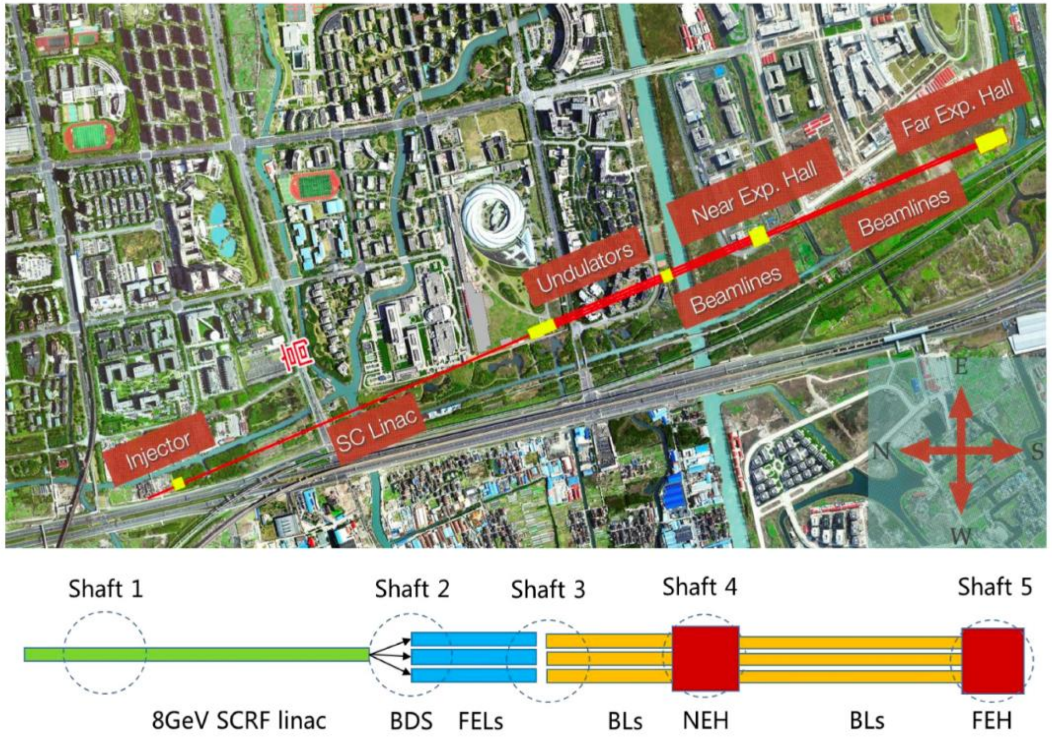


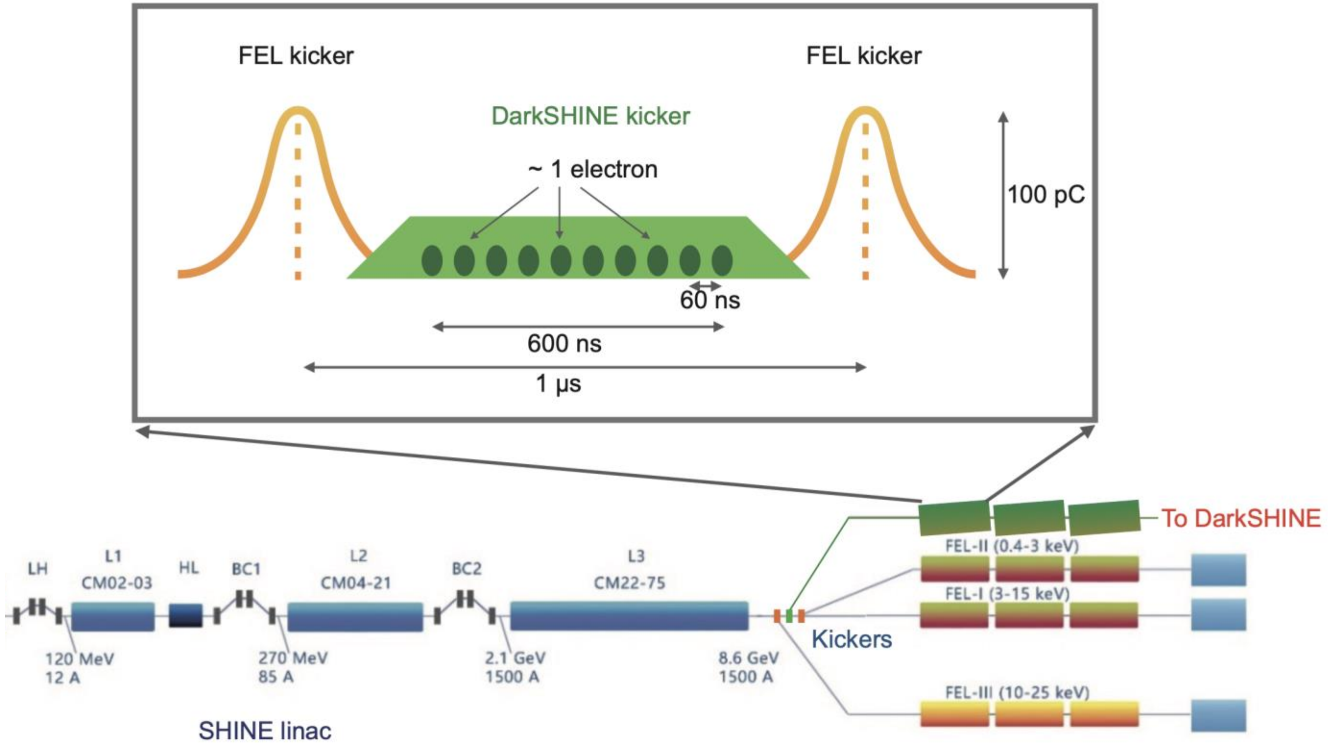
The SHINE facility

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)

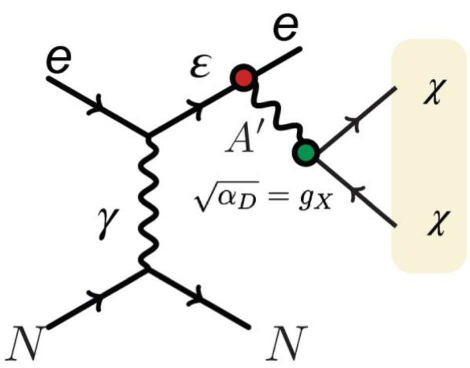
- Under construction in Zhangjiang area (2018-2026)
- Beam techniques: SARI,CAS / Shanghai Tech.
- Detector R&D: SJTU / FDU / SIC, CAS.



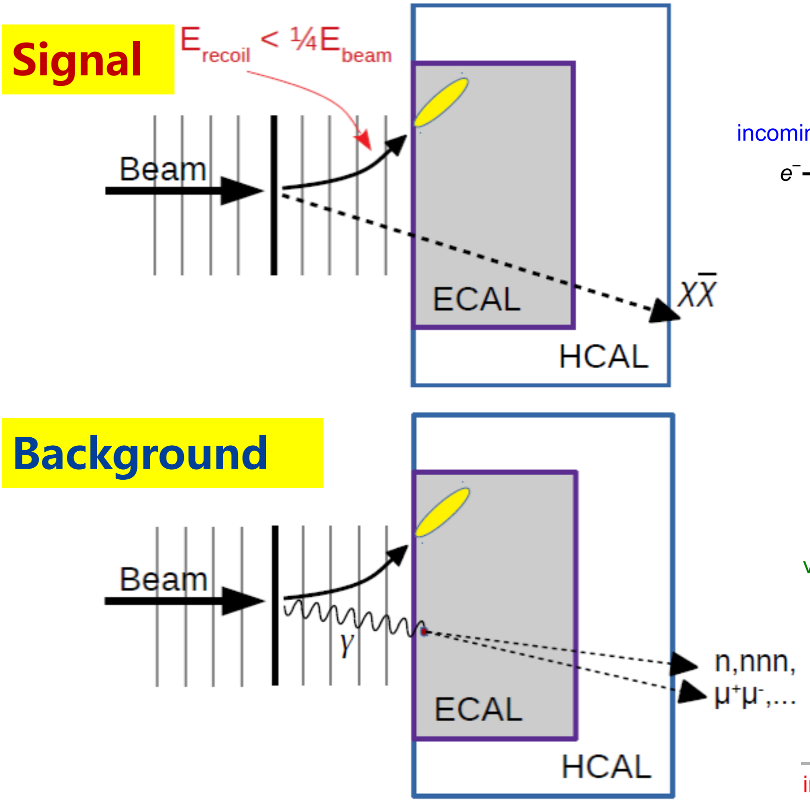


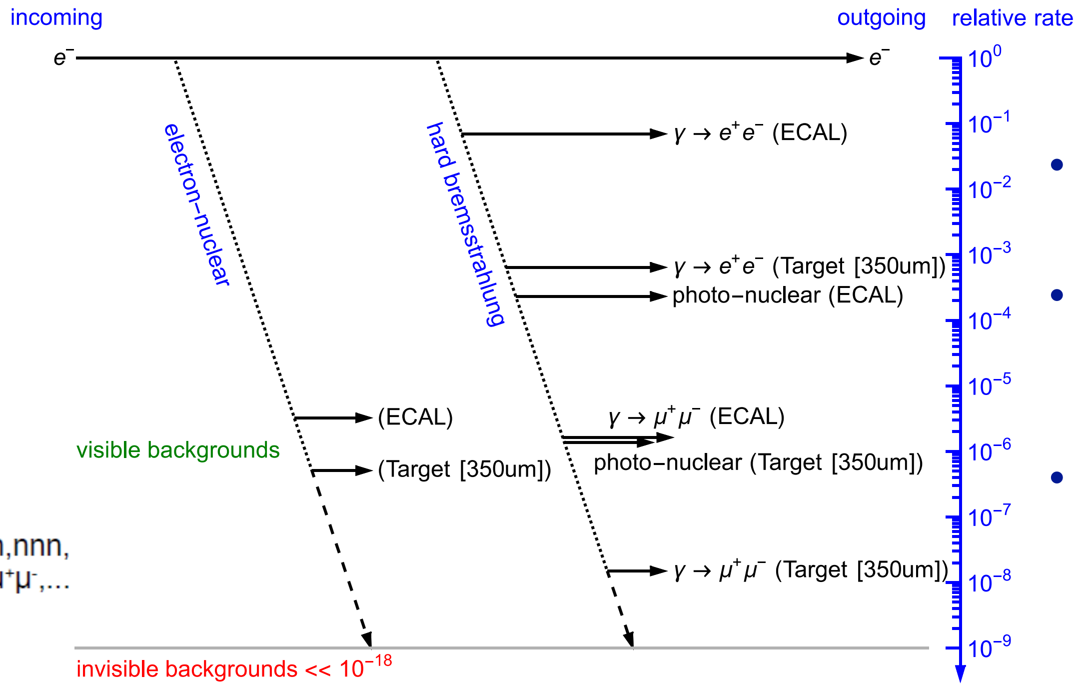
Signal and background processes

INVISIBLE DECAY MODE $m'_A > 2m_X$



- **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**



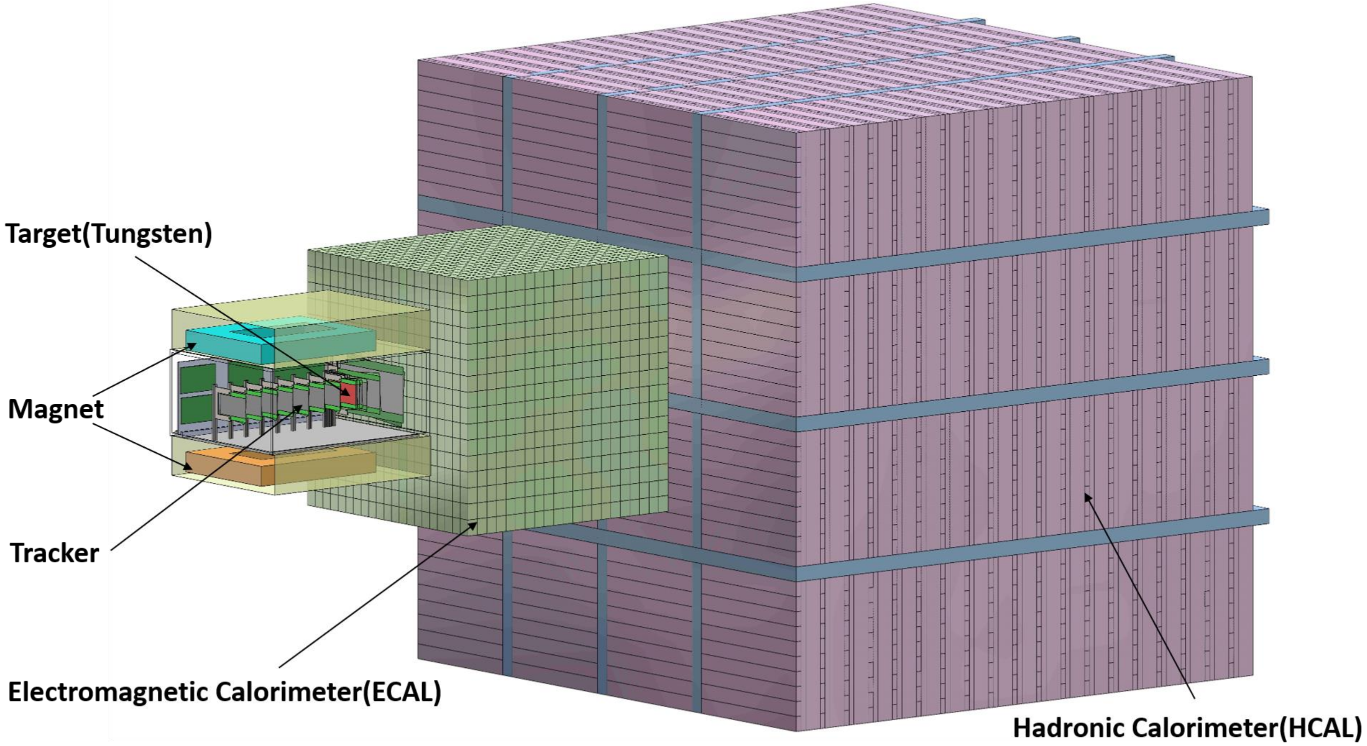


- **Leading background: γ bremsstrahlung**
- **Rare processes include: electron-nuclear, photon-nuclear, $\gamma \to \mu\mu$**
- **Neutrino production is irreducible, but negligible**

DarkSHINE detector system conceptual design

The DarkSHINE 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.



DarkSHINE detector sketch

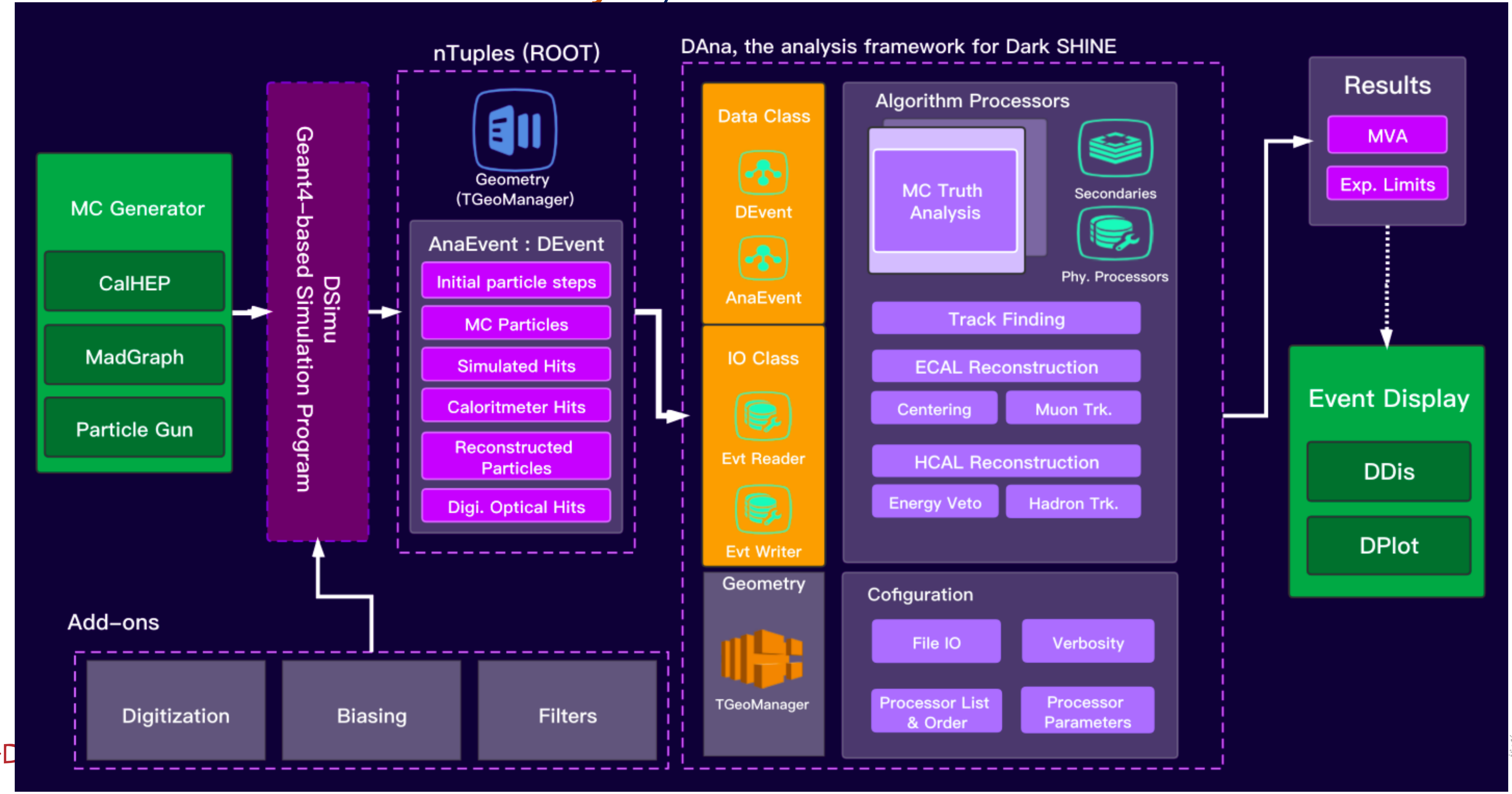
Electromagnetic calorimeter
Measure the deposited energy: electron and photon.

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 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 predicted luminosity**

SCIENCE CHINA
Physics, Mechanics & Astronomy
• Article •
Editor's Focus
January 2023 Vol. 66 No. 1: 211062
https://doi.org/10.1007/s11433-022-1983-8

Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)

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

First publication!

...ng-Bo Fu[9,10], Jun Guo[2,3], ...[2,3], Shu Li[1,2,3,4,5*], Meng Lv[7], ...ng 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]

DarkSHINE

Baseline Design Report

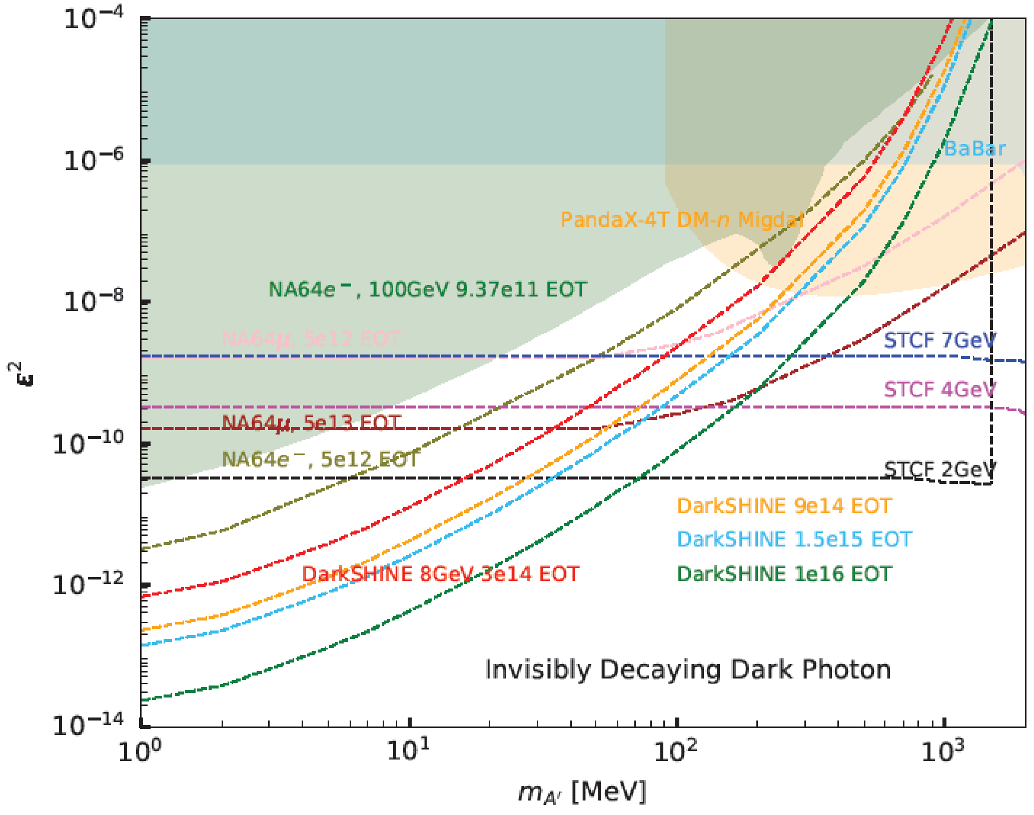
Physics Prospects and Detector Technologies

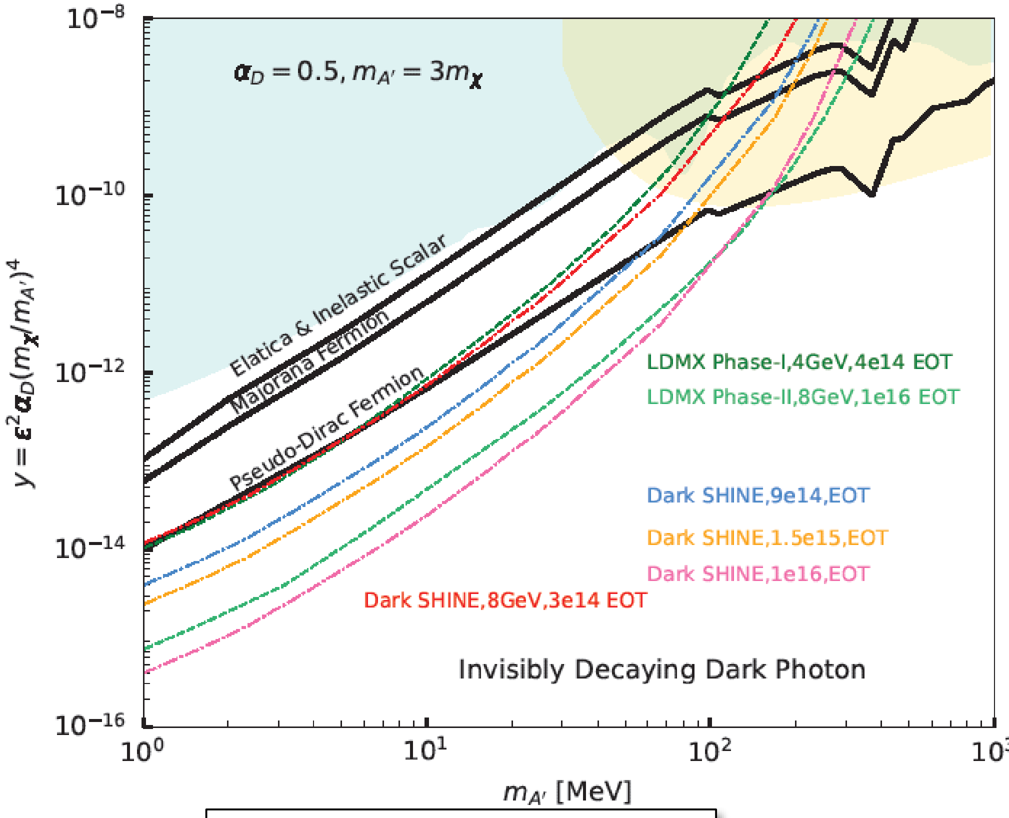
arxiv:2411.09345

Version 1

Conceptual design report!

Si-Yuan Song[2,3], Tong Sun[1,2,3], Jian-Nan Tang[2,3], Wei-Shi Wan[17,4], Dong Wang[5,4], Xiao-Long Wang[8,9], Yu-Feng Wang[1,2,3,15], Zhen Wang[1,2,3,10,11], Zi-Rui Wang[16], Wei-Hao Wu[2,3], Dao Xiang[18,19,1], Hai-Jun Yang[2,1,3], Lin Yang[1,2,3], Yong Yang[2,3], Dian Yu[1,2,3], Rui Yuan[1,2,3], Jun-Hua Zhang[1,2,3], Yu-Lei Zhang[2,3,14], ...[1,2,3], and Yi-Fan

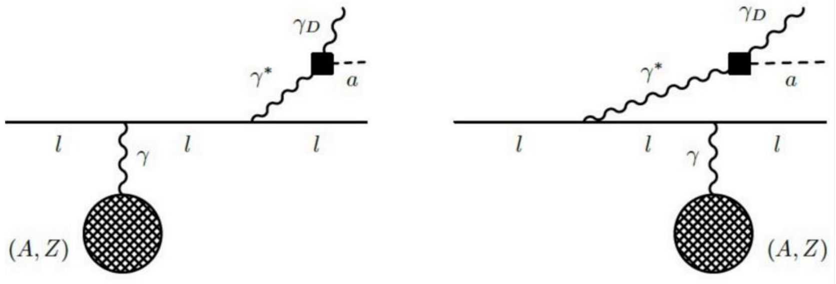


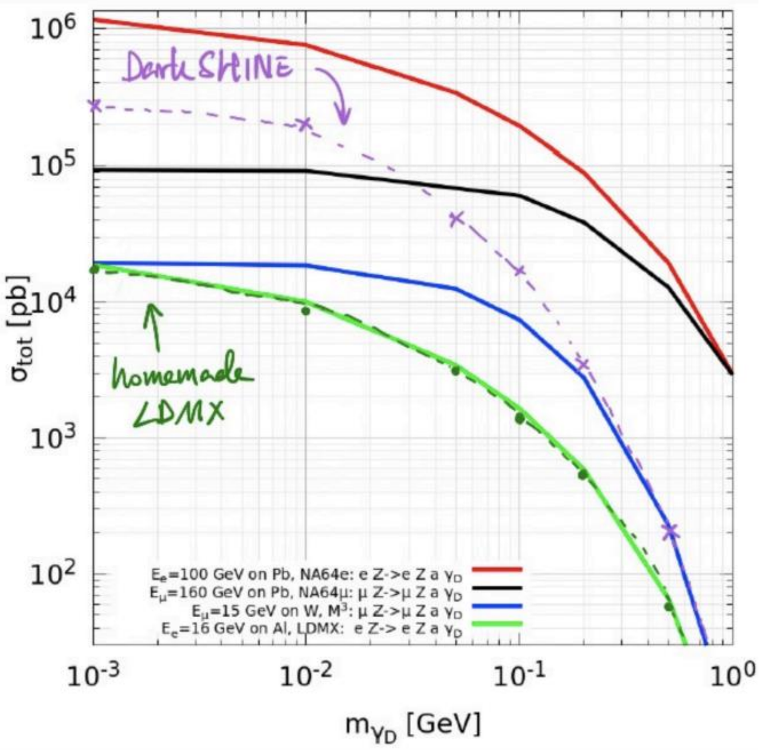


More details of this analysis

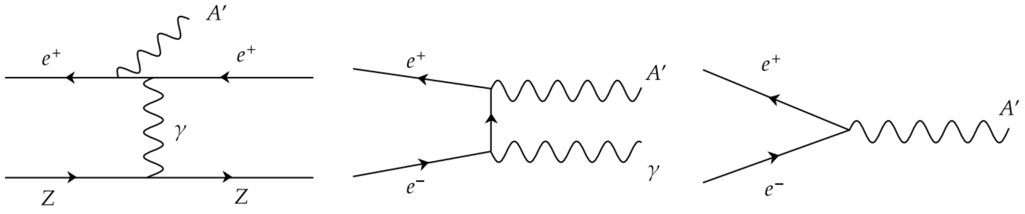
More physics opportunities…

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

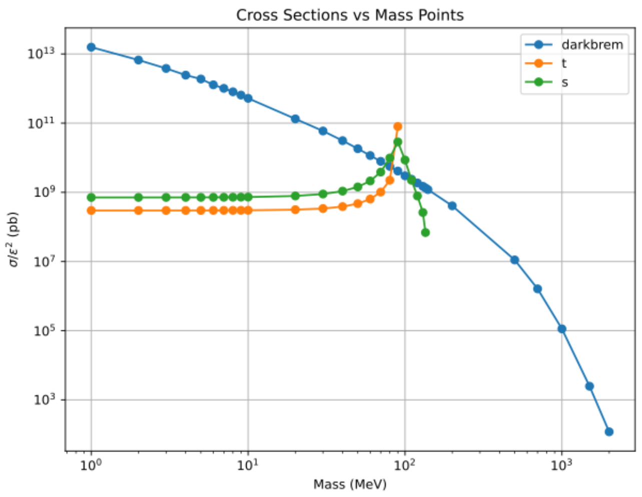




- Dramatically different sensitivity curve of Dark Photon search when changing from electron beam to positron beam
- Extra s/t-chan annihilation diagrams come into play for Dark Photon production
- SHINE can also deliver positron beam with low current…



(a) *bremsstrahlung* emission (b) non-resonant annihilation (c) resonant annihilation

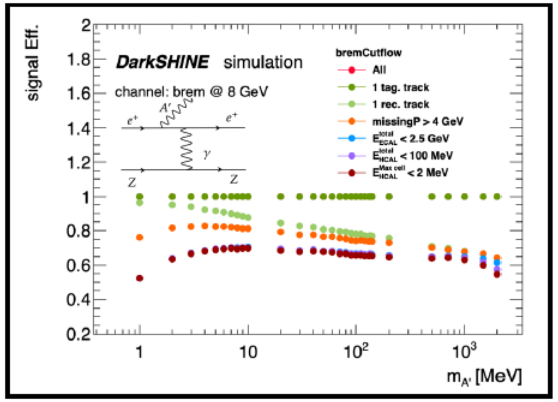


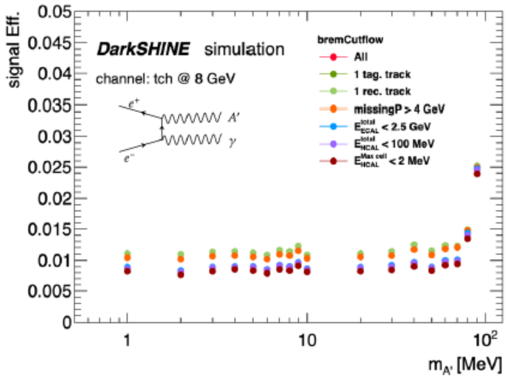
Positron-On-Target

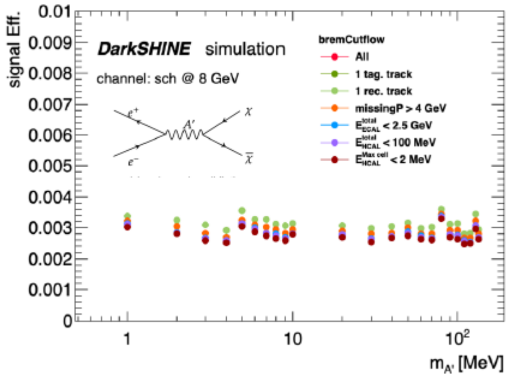
- Signal boxes for three channels are optimized
- Contamination from other signal processes are investigated
- Extrapolation method for variables' cuts, similar to the EOT analysis

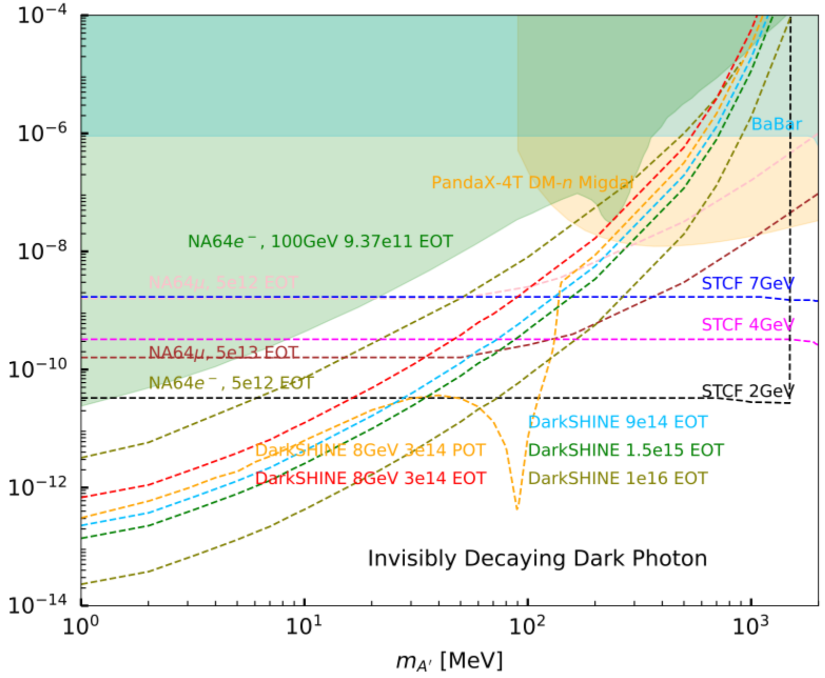
Rare process	EN_ECAL	EN_Target	PN_ECAL	PN_Target	Total
Estimated Yield	3.048E-04	3.619E-02	6.398E-02	1.204E-04	1.005952E-01

signal	N_{trk}^{tag}	N_{trk}^{rec}	$P_{missing}$	$E_{maxCell}^{ECAL}$	E_{total}^{ECAL}	E_{total}^{HCAL}	$E_{maxCell}^{HCAL}$
darkBrem	1	1	> 4GeV	-	< 2.5 GeV	< 2MeV	< 100MeV
t-channel	1	0	> 4GeV	>= 1MeV	< 2.5 GeV	< 1MeV	< 100MeV
s-channel	1	0	-	< 1MeV	-	< 1MeV	< 100MeV

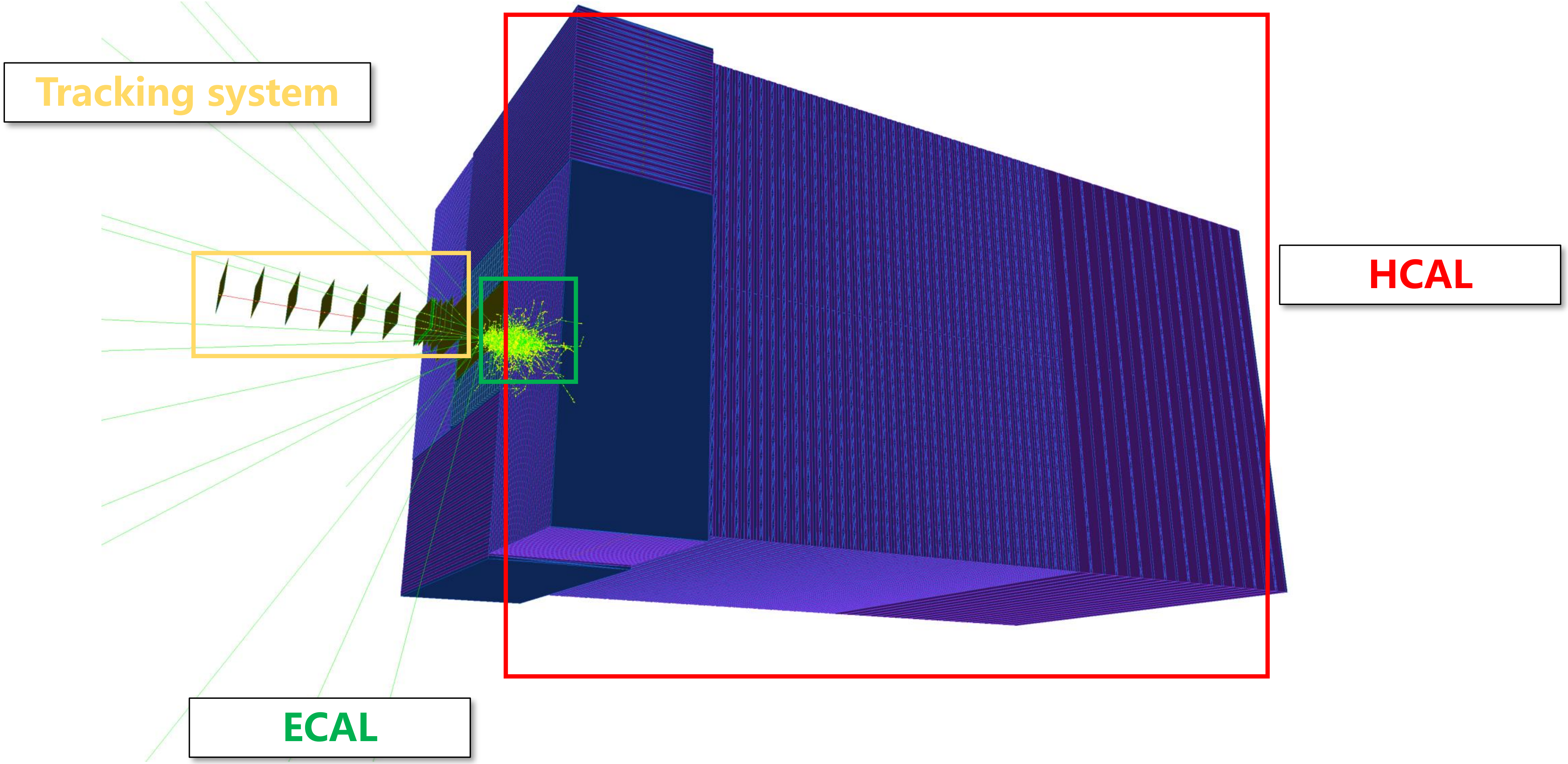






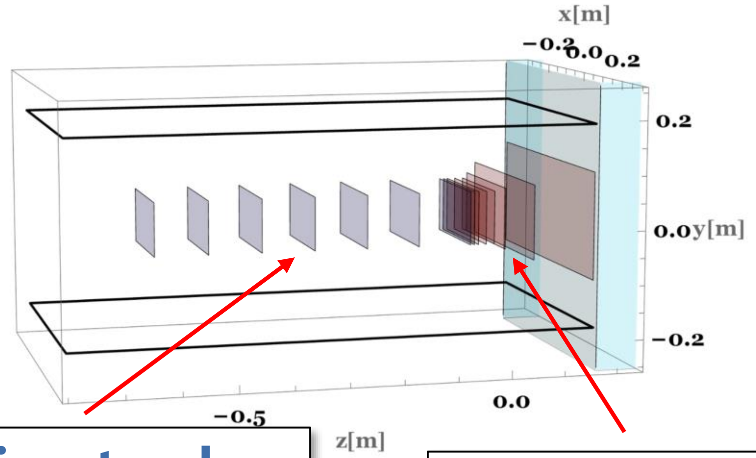


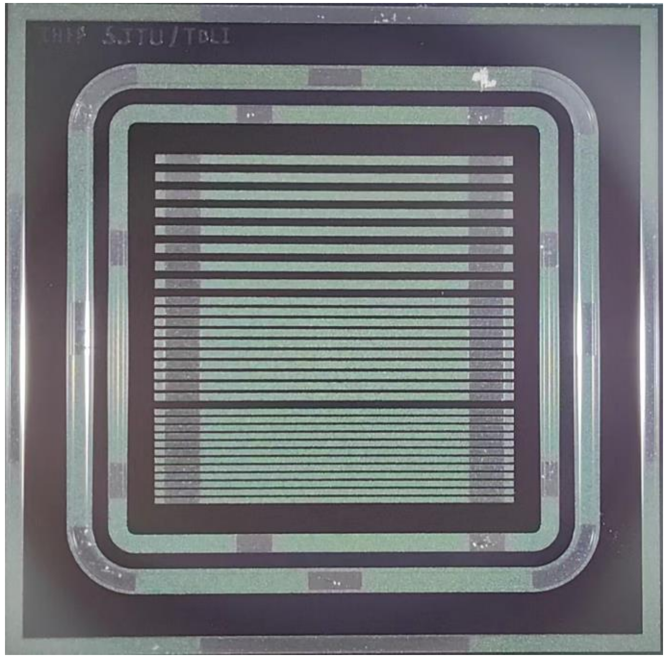
Detector R&D

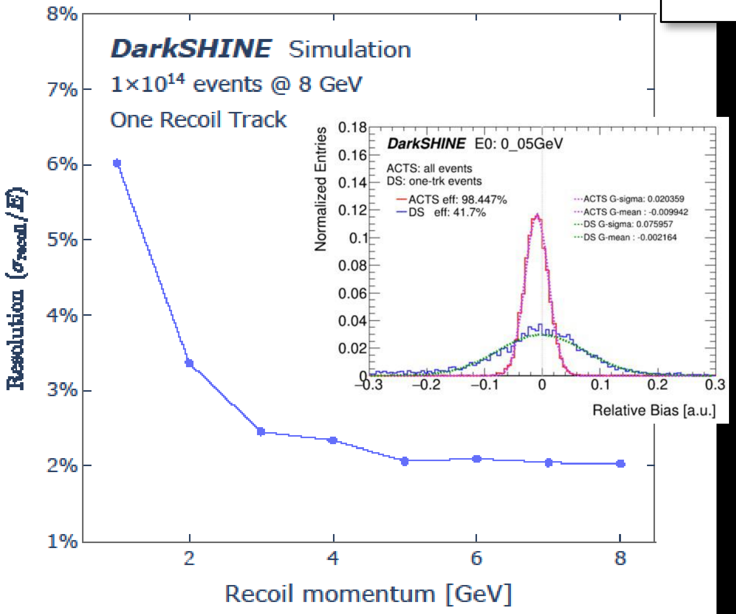


Detector R&D: Tracking system

- **7 layers of tagging tracker + 6 layers of recoil tracker**
  - **Two silicon strip sensors with a small angle (0.05 rad)**
  - **Resolution: 10 μm (horizontal), 60 μm (vertical)**
- **AC-LGAD silicon strip sensor prototype designed and tested.**







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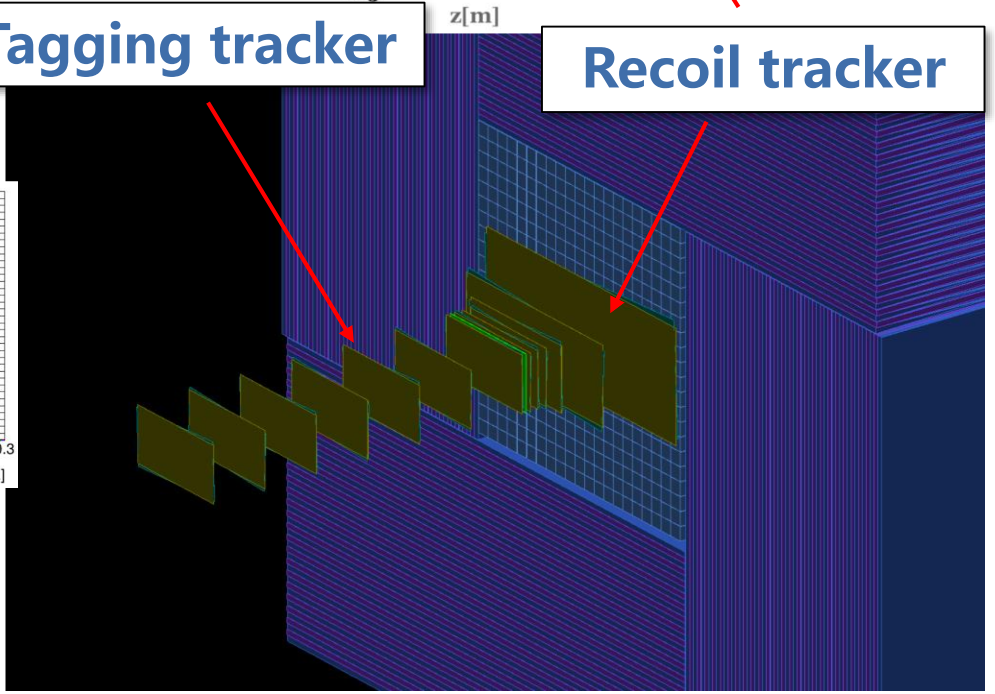
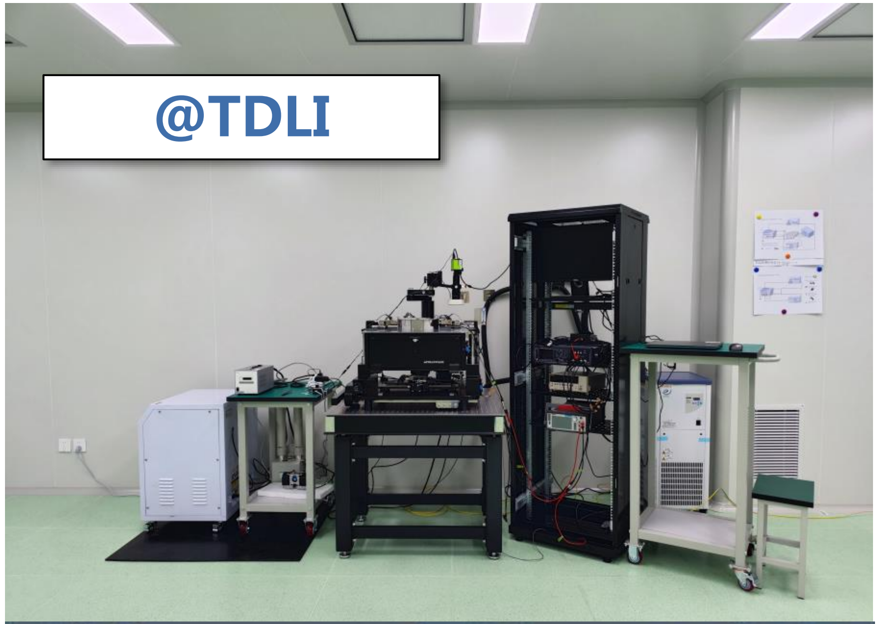
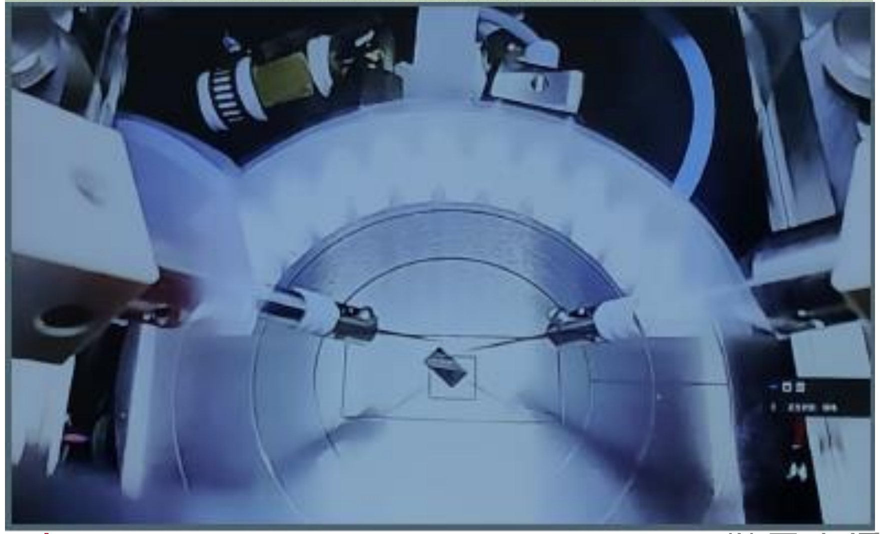
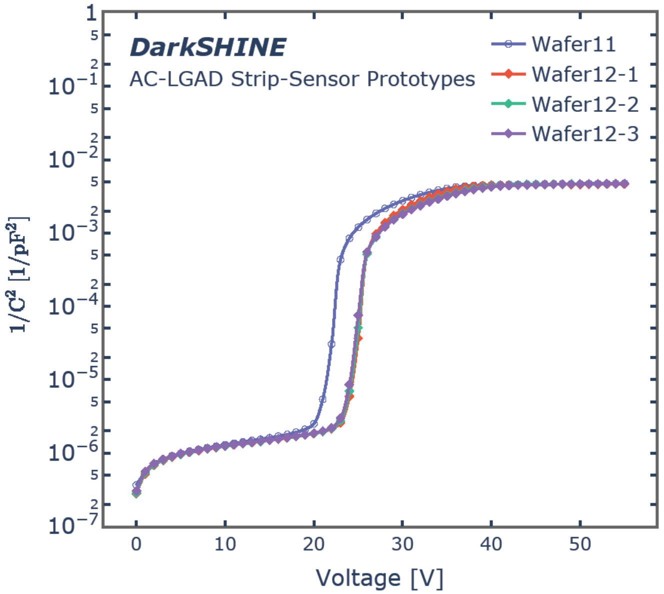
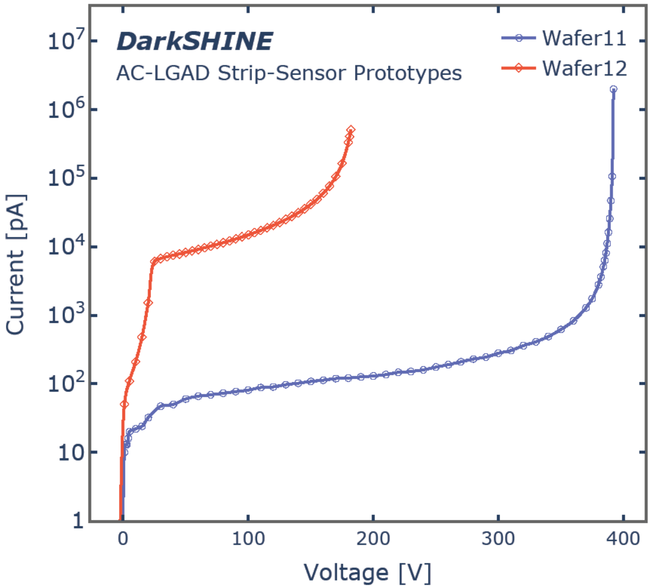


Detector R&D: Tracking system

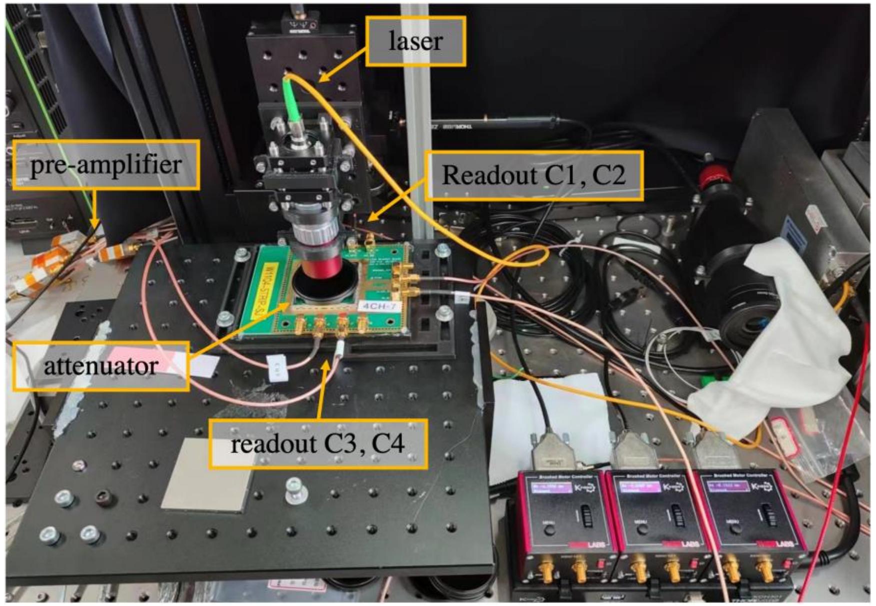


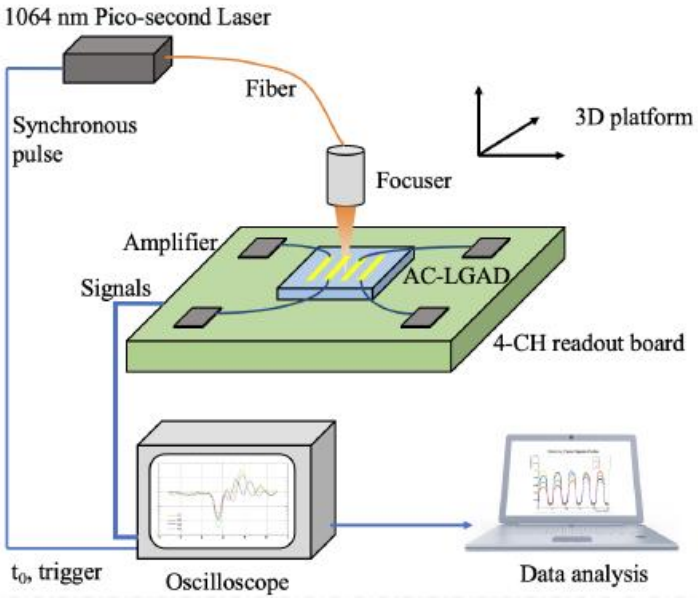


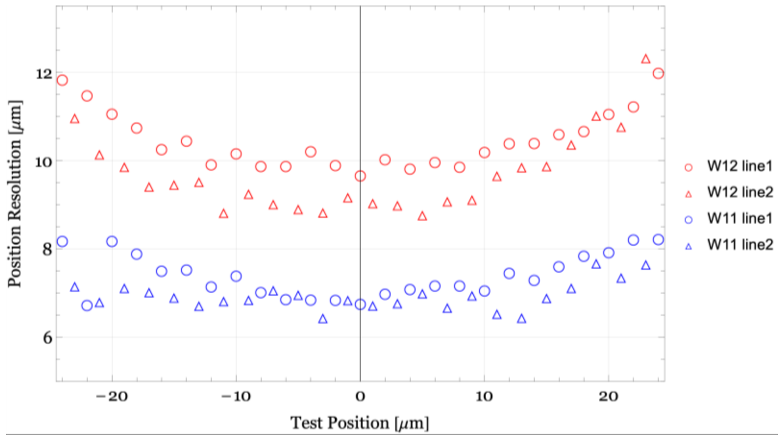


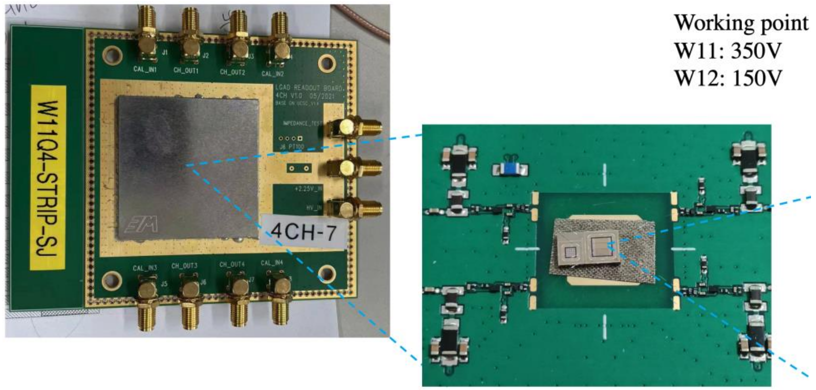


Detector R&D: Tracking system

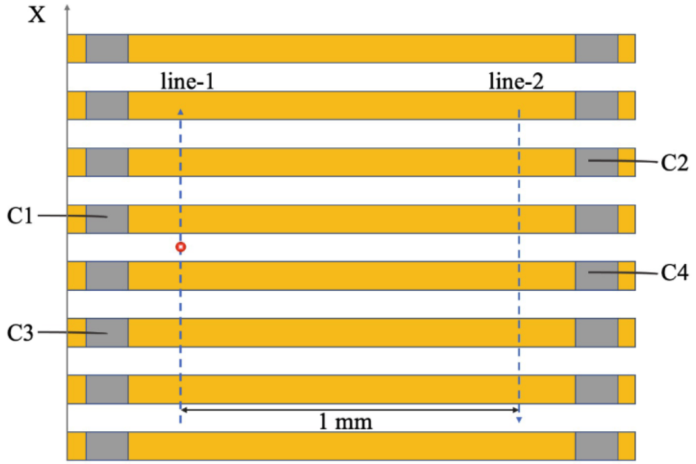


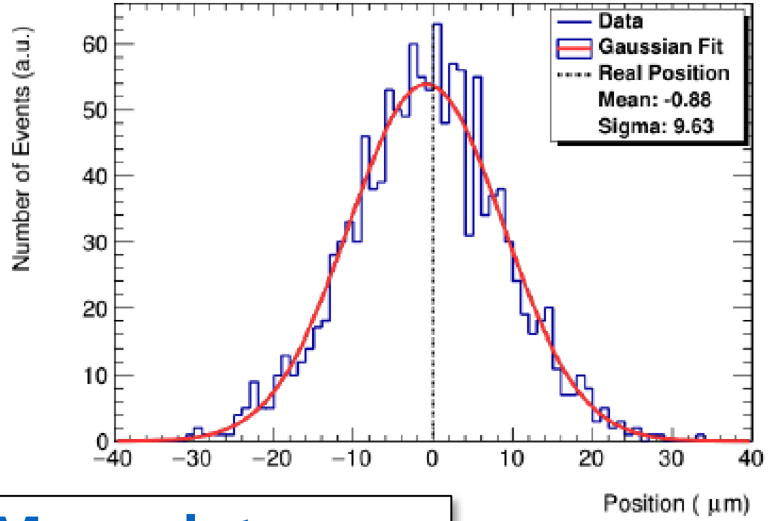






Working point
W11: 350V
W12: 150V

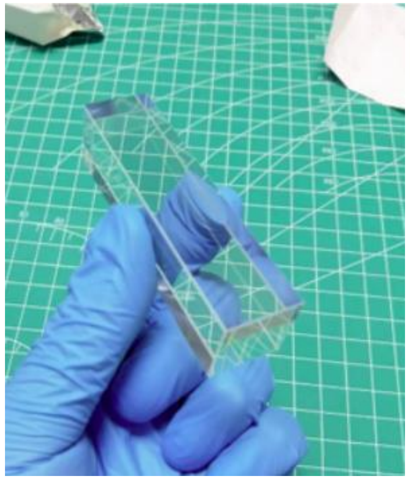


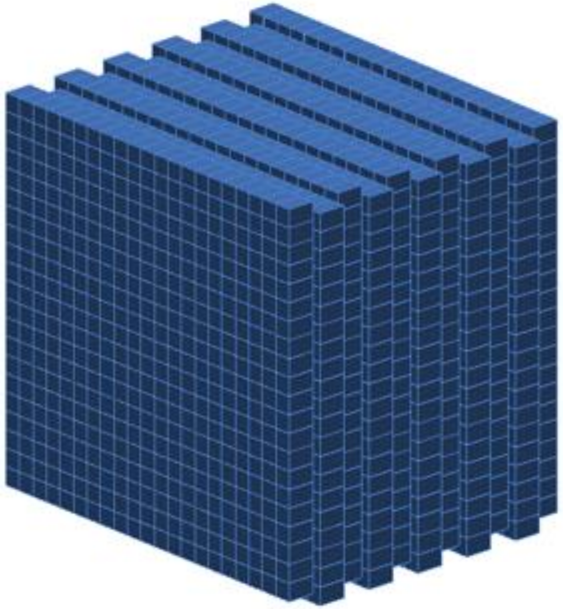


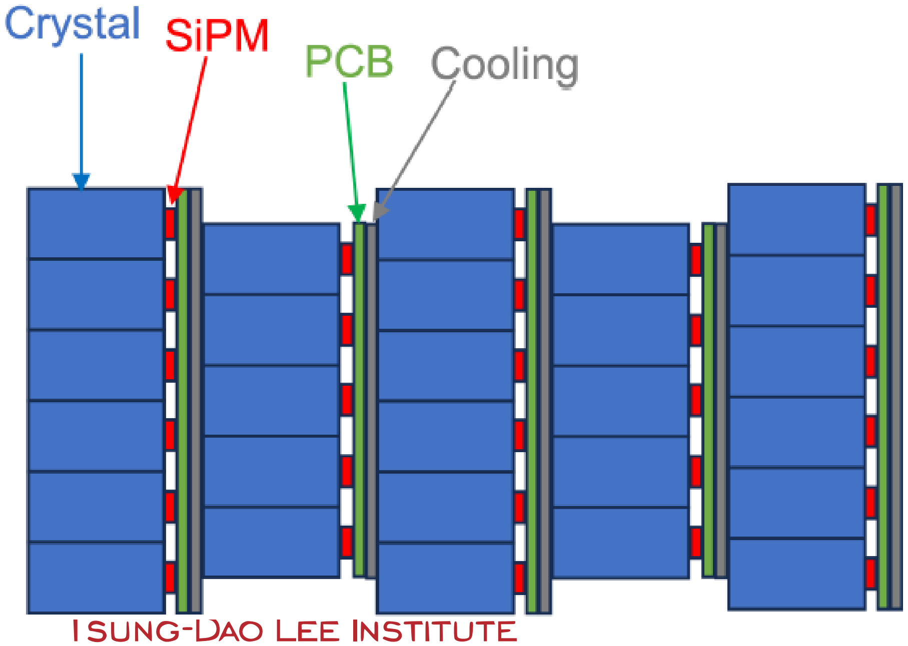
More plots

Detector R&D: ECAL

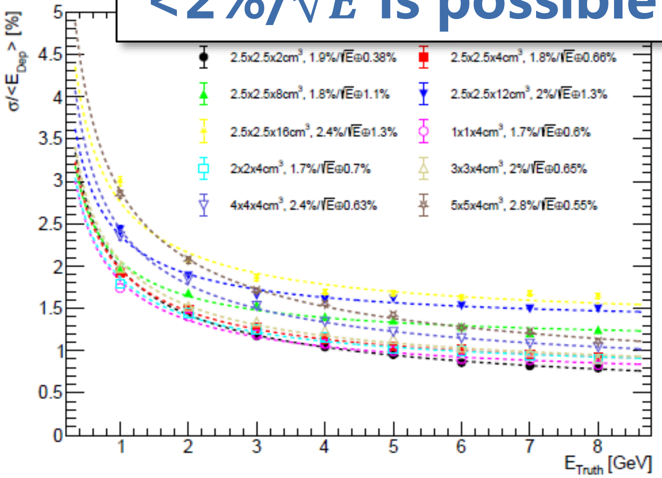
- **Deposit all the energy from electrons and photons, energy resolution ~5%**
- **Crystal Scintillator + SiPM**
  - **LYSO($Lu_{(1-x-y)}Y_{2y}Ce_{2x}SiO_5$)**
  - **21×21×11 crystals, 2.5cm×2.5cm×4cm, design has been optimized**
  - **High light yields, short decay time, good radiation resistant**

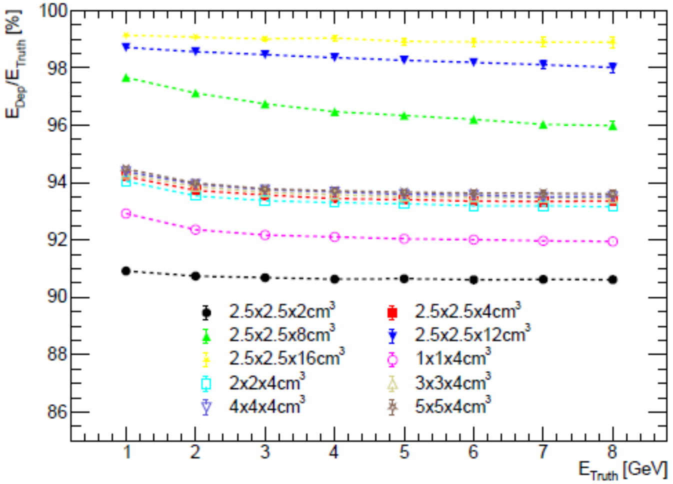






Energy resolution $<2\%/\sqrt{E}$ is possible





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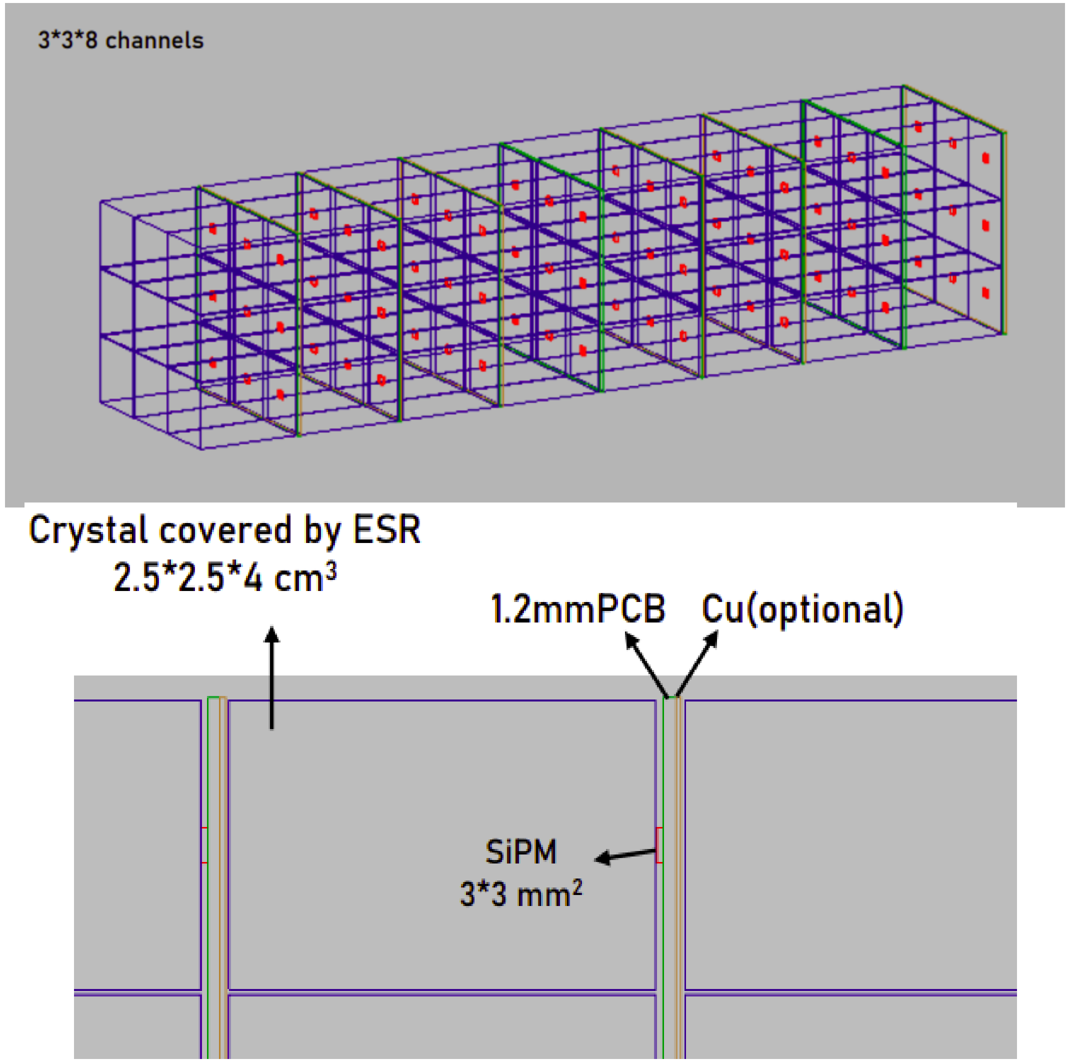
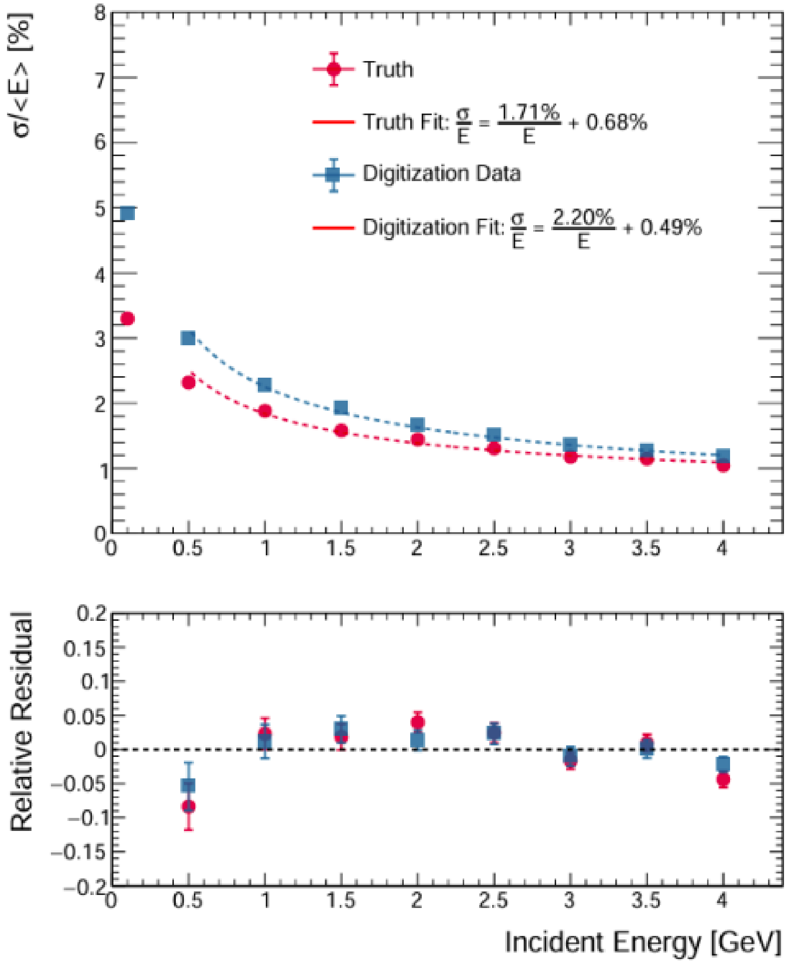
Detector R&D: ECAL prototype



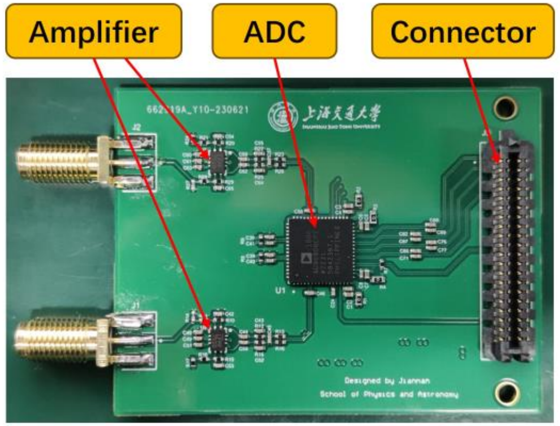
The simulated energy resolution is better than 3% at 1GeV

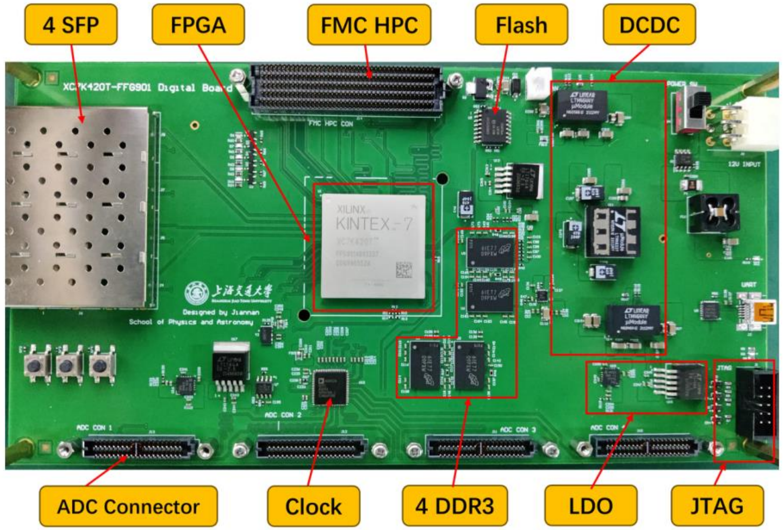


Detector R&D: ECAL prototype

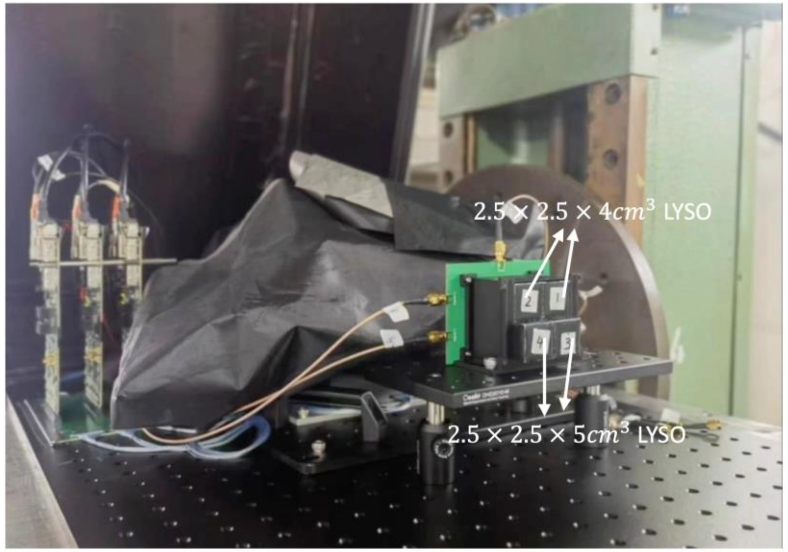
High speed and high precision ADC

ADC: AD9680, 1 GS/s, 14 bit

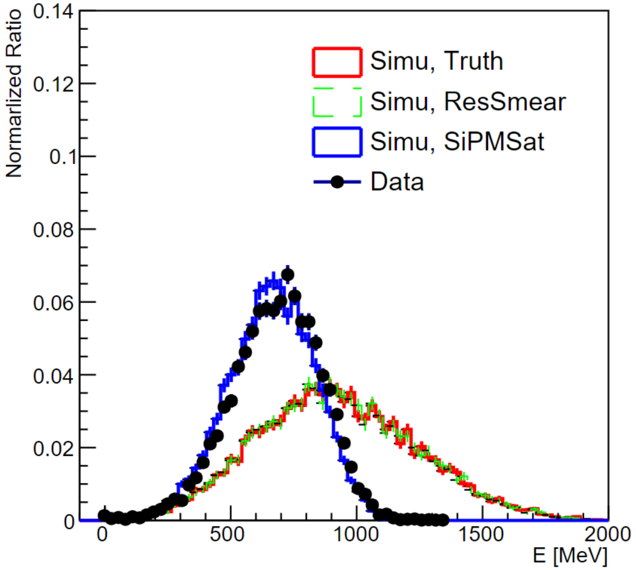




arXiv:2407.20723, submitted to JINST



DESY TB22 Oct. 2023



- **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 the sets of readout system has been further developed**
  - **1 MHz repetition rate**

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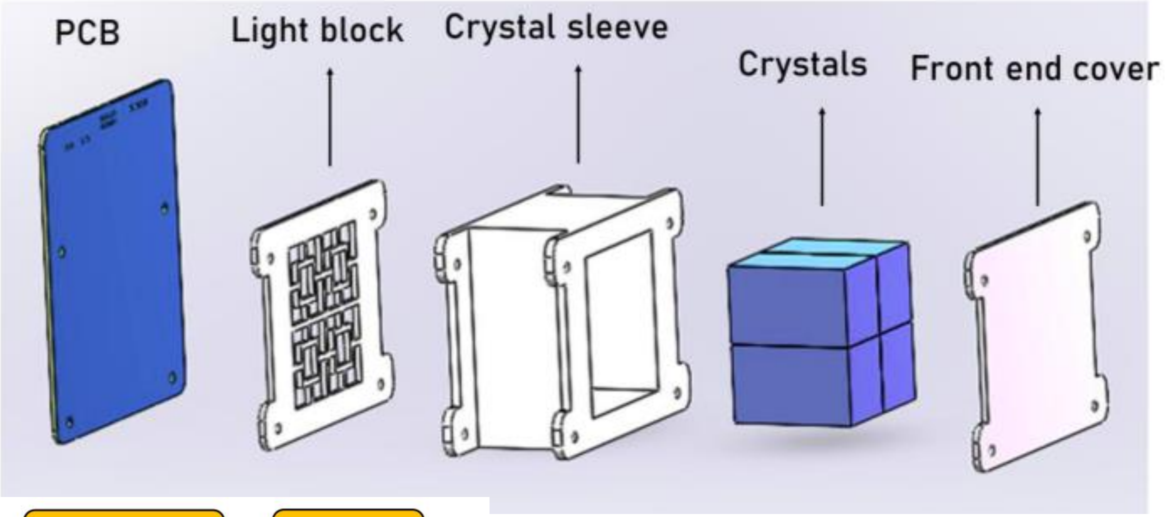
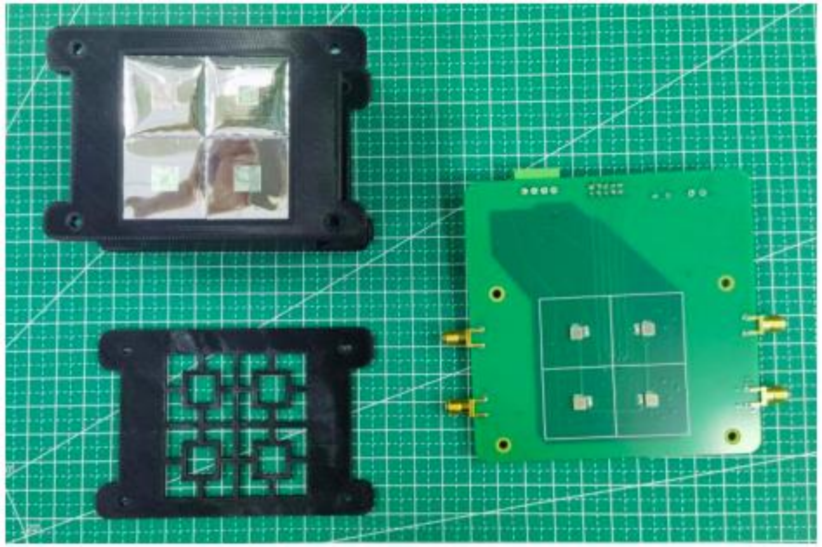
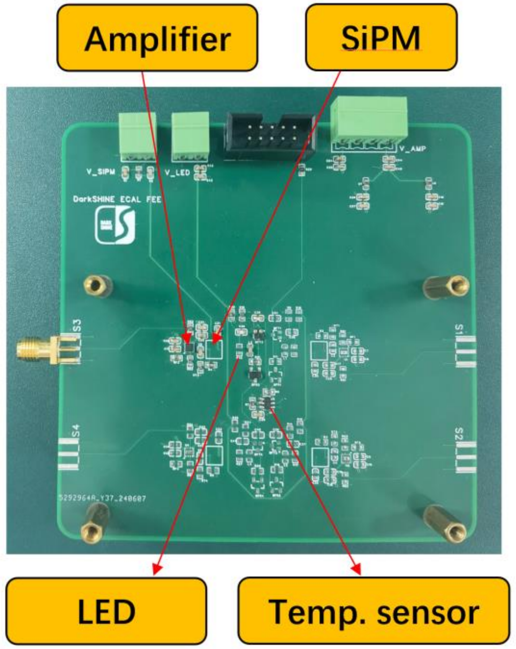
Detector R&D: ECAL prototype

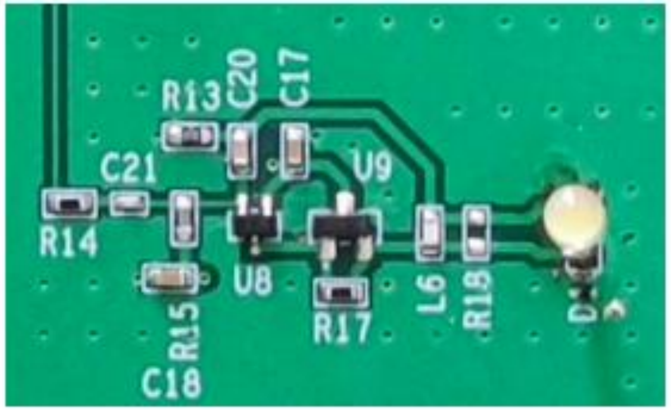






Pre-amplifier: transimpedance amplifier
- PZC + RCRC filter
- Dual output: large dynamic range

LED Driver



[More plots]

Detector R&D: HCAL

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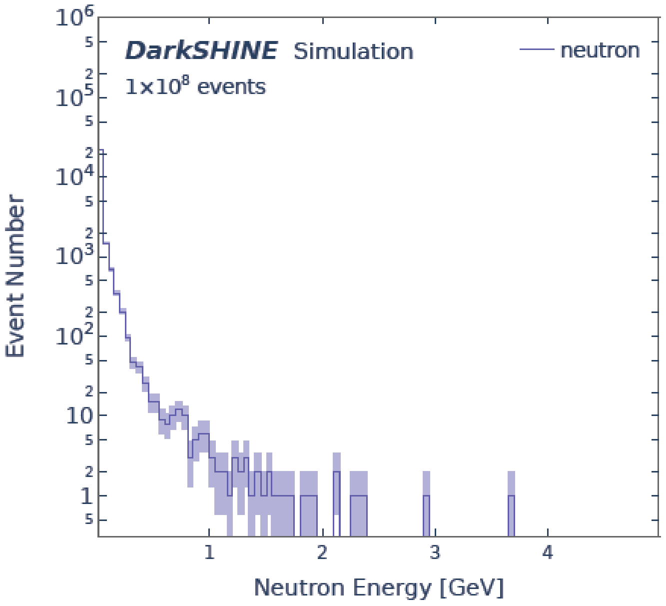
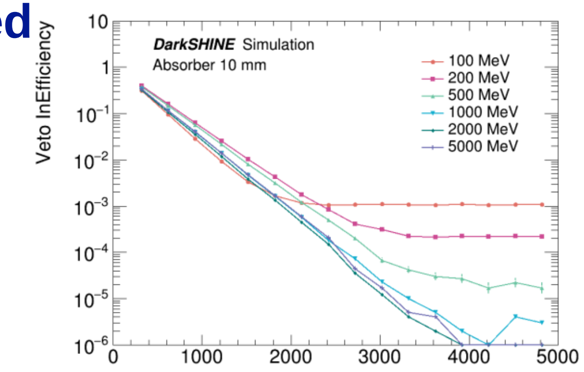
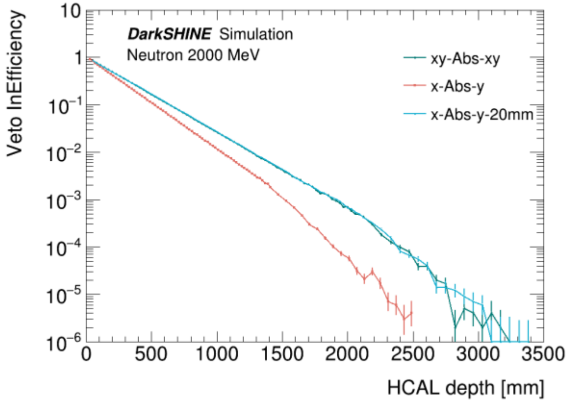
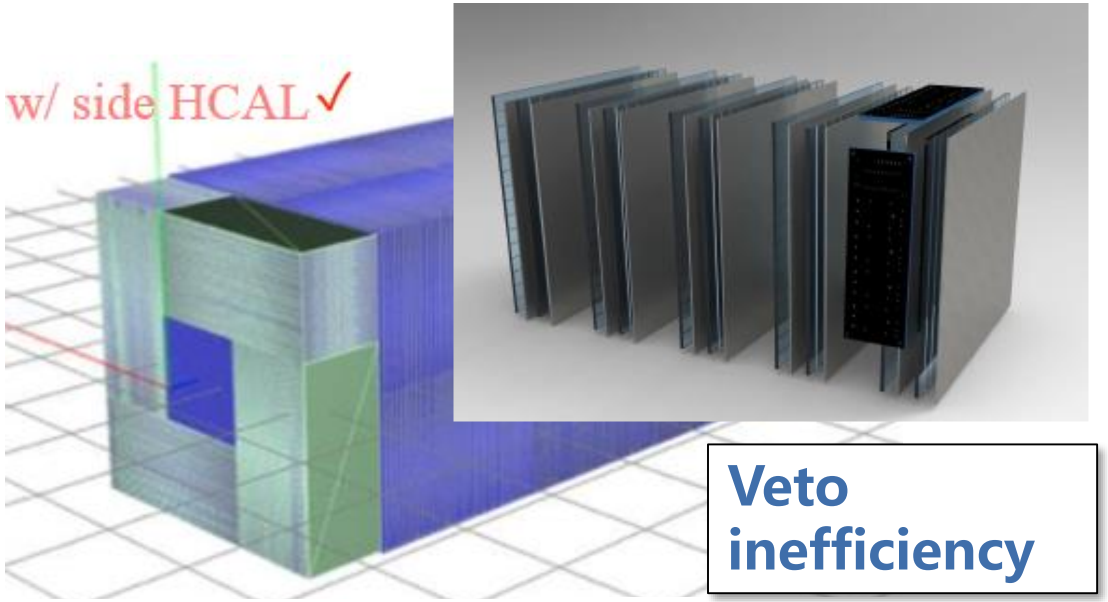
- **Veto backgrounds with same behavior as signal in ECAL**
- **1.5 m × 1.5 m (perpendicular to the beam), ~10 λ (~160 cm iron, parallel to the beam)**
  - **Split to 4 modules, 75 cm × 75 cm each**
  - **Iron absorber: 10 mm (70 layers)/50 mm (18 layers)thick, 75 cm × 75 cm**
  - **Plastic scintillator: 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**





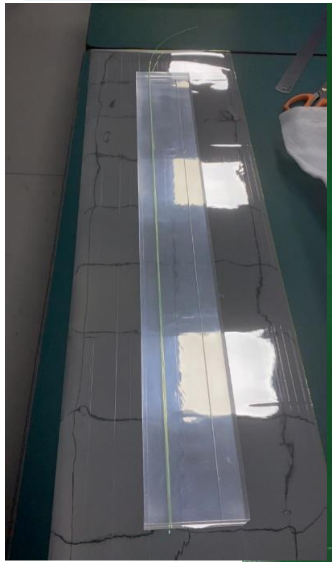
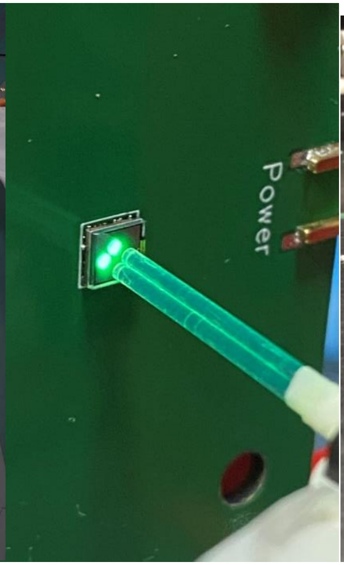


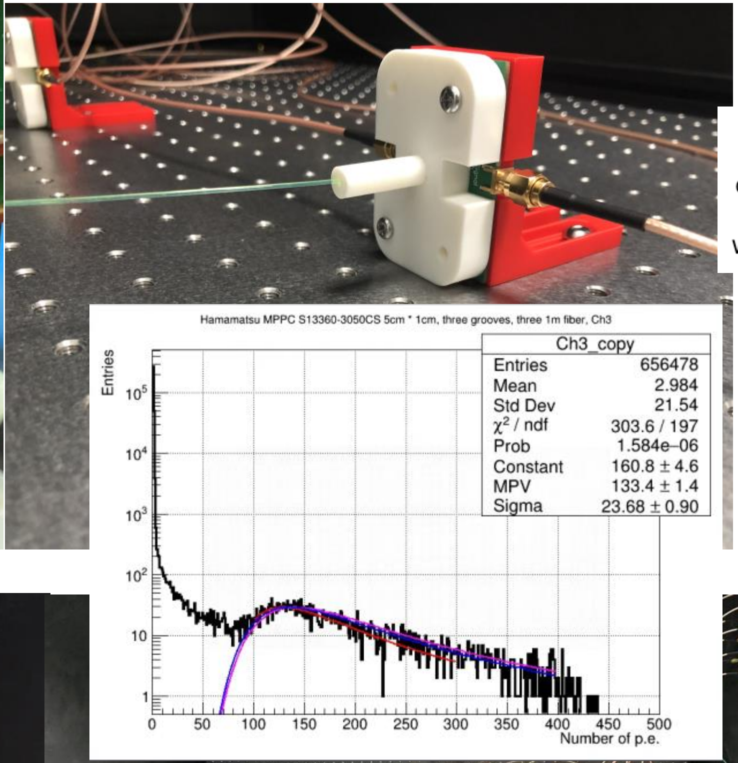


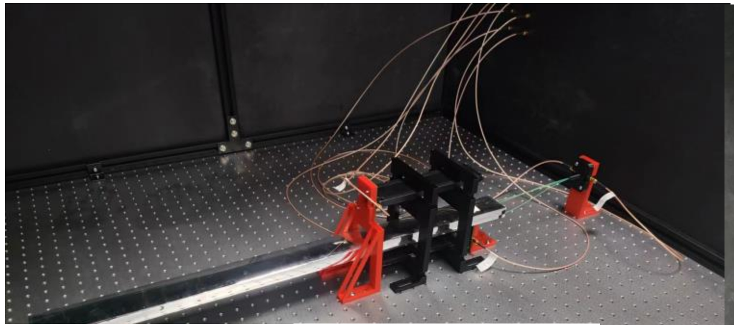
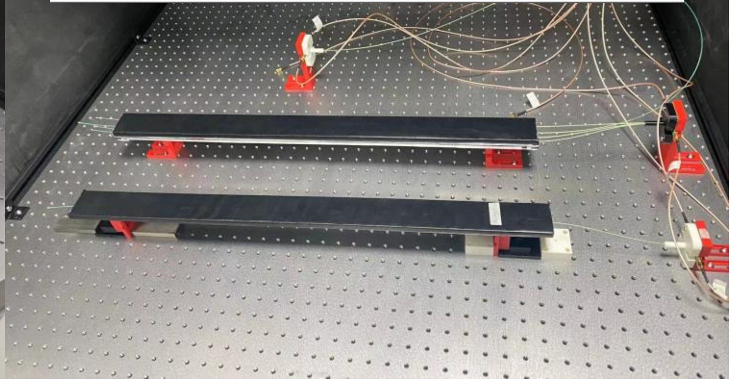
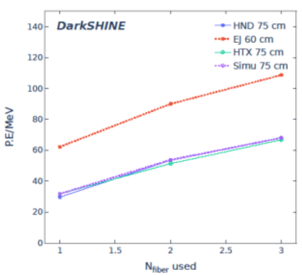
Veto inefficiency

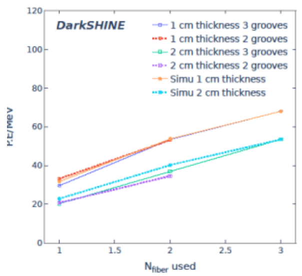
Veto InEff ×E-06	n	k^0	π^0	p	μ
100[MeV]	$1170^{+10.9}_{-10.8}$	$31600^{+55.5}_{-55.4}$	$7.30^{+0.958}_{-0.852}$	$30700^{+61.5}_{-61.3}$	$409^{+6.49}_{-6.39}$
500[MeV]	$18.4^{+1.46}_{-1.36}$	$5.40^{+0.839}_{-0.733}$	$0.1^{+0.184}_{-0}$	$8.04^{+1.34}_{-1.16}$	$15.0^{+1.33}_{-1.22}$
1000[MeV]	$3.70^{+0.714}_{-0.606}$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

Detector R&D: HCAL

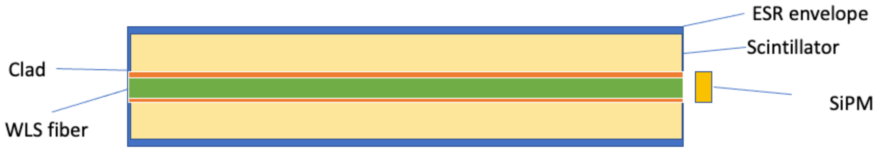





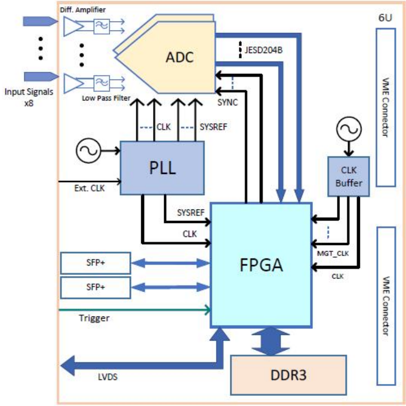




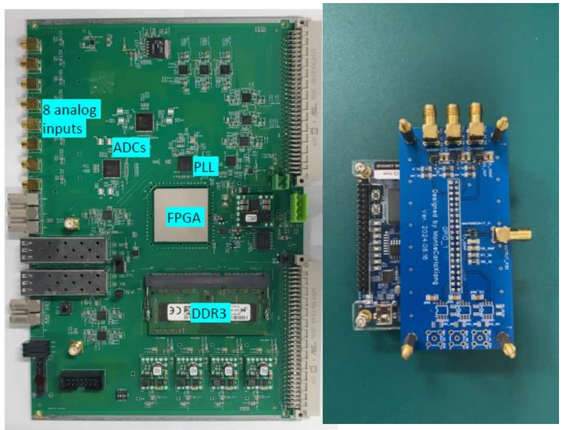


[More details]



- 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





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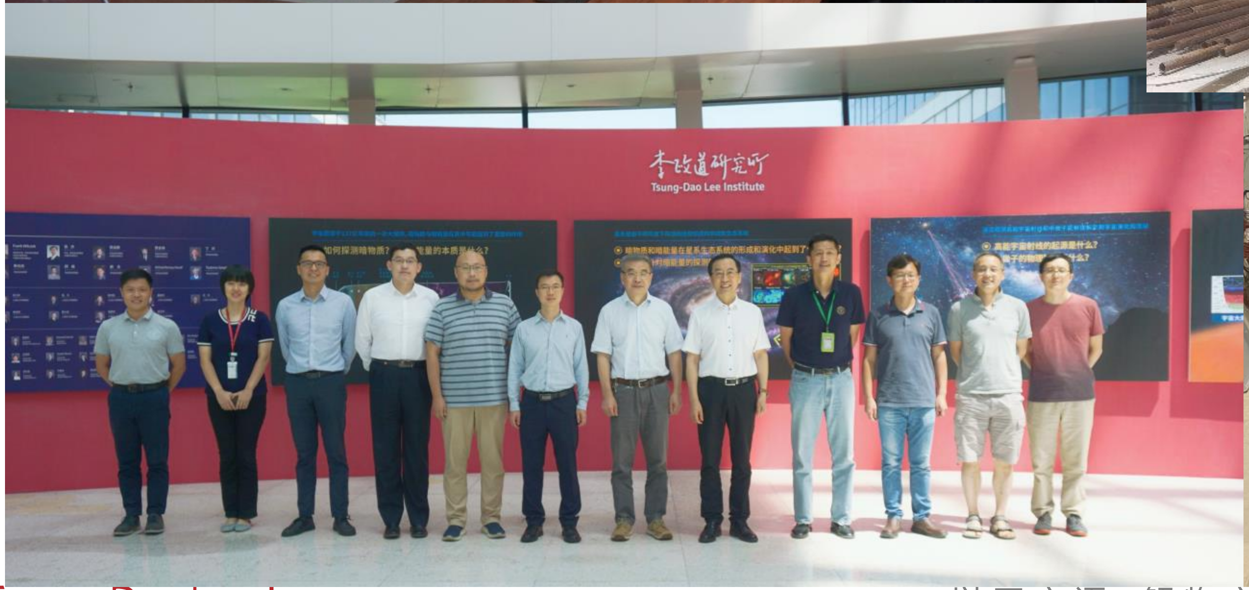
Collaboration with SHINE



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

- First round of prospective analysis sensitivity of DarkSHINE has been studied
  - Competitive sensitivity, *Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)*

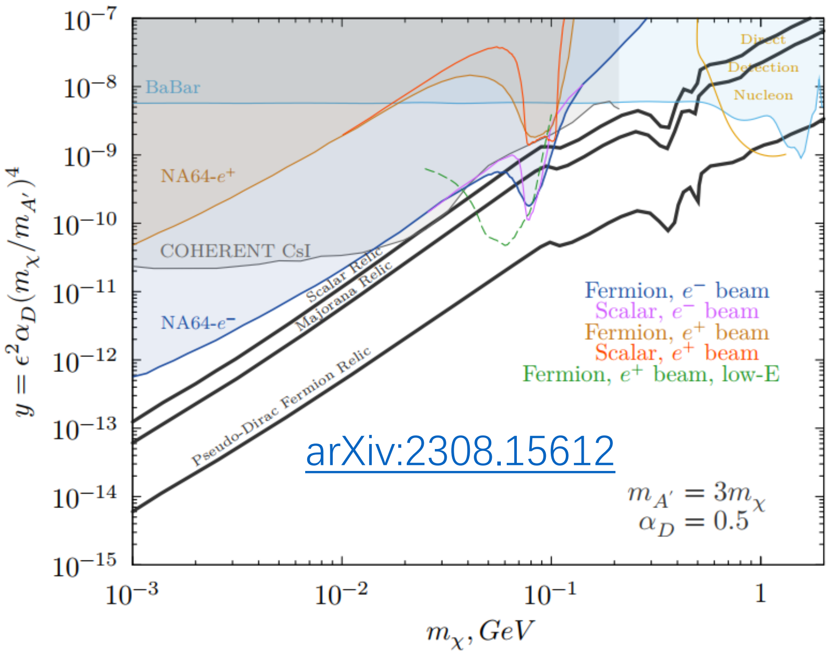
- Detector key technology R&D progress has been presented
  - Four articles have been submitted, one for each of the three sub-detectors and one for ECAL electronics, three of which have been published (HCAL, Tracking system, ECAL), and one under review (ECAL electronics)
  - Has been sponsored by NSFC (原创探索计划项目)
  - Conceptual design report is released on Arxiv

李政道研究所
TSUNG-DAO LEE INSTITUTE

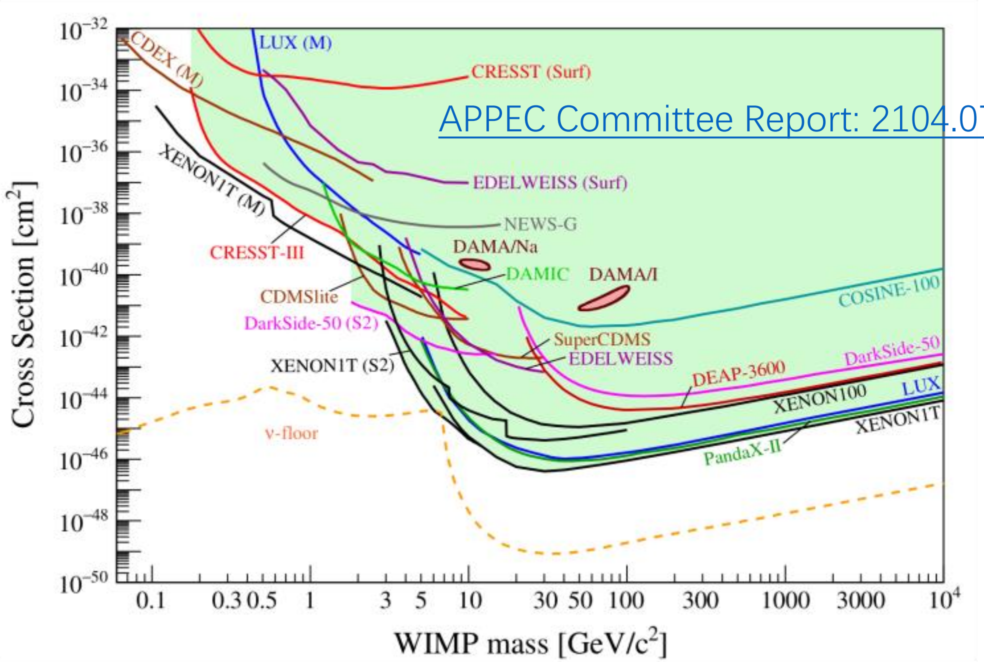
DARK SHINE

Backup

Dark Matter: Search for LDM & WIMP



arXiv:2308.15612

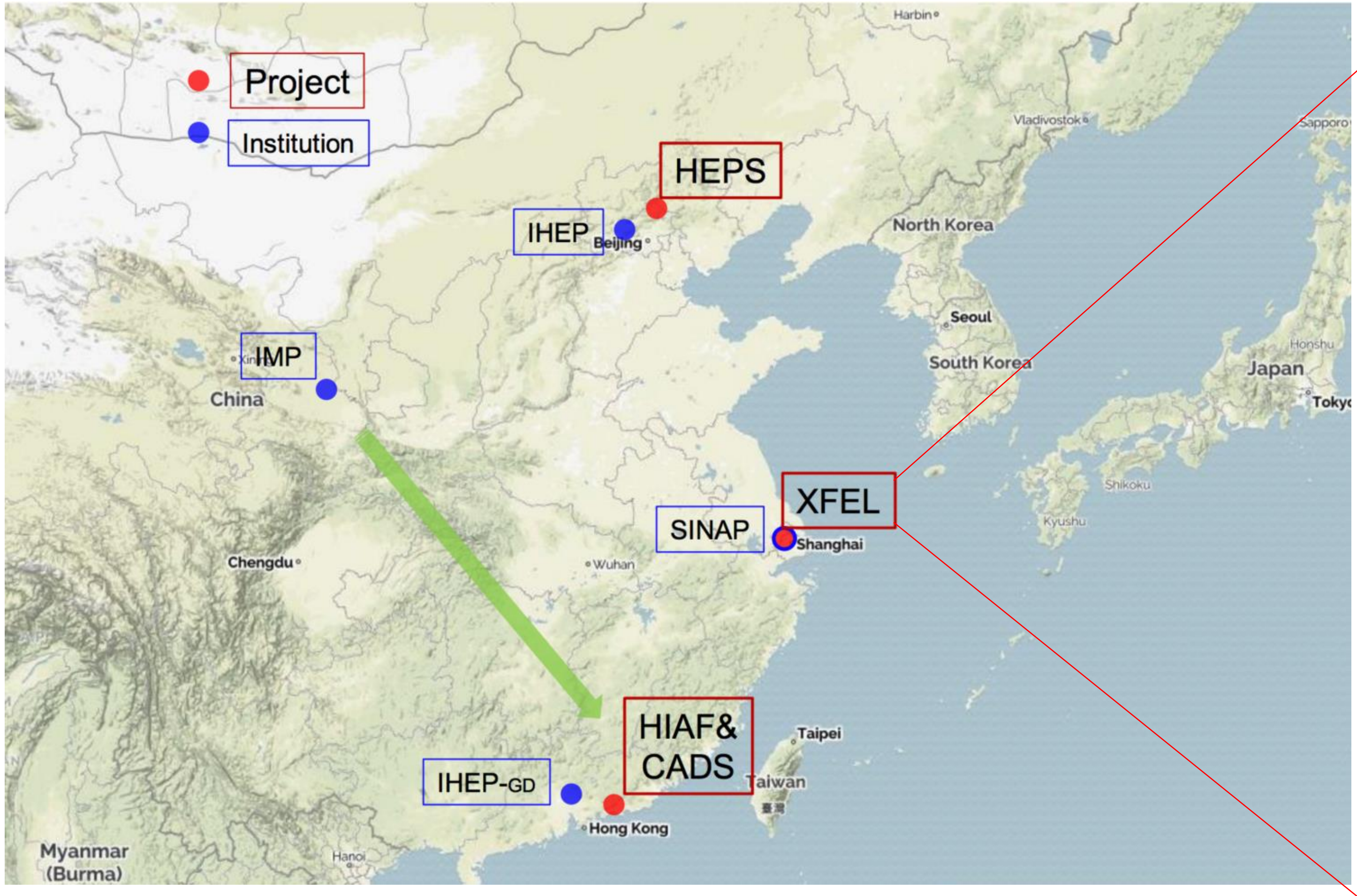


APPEC Committee Report: 2104.07634

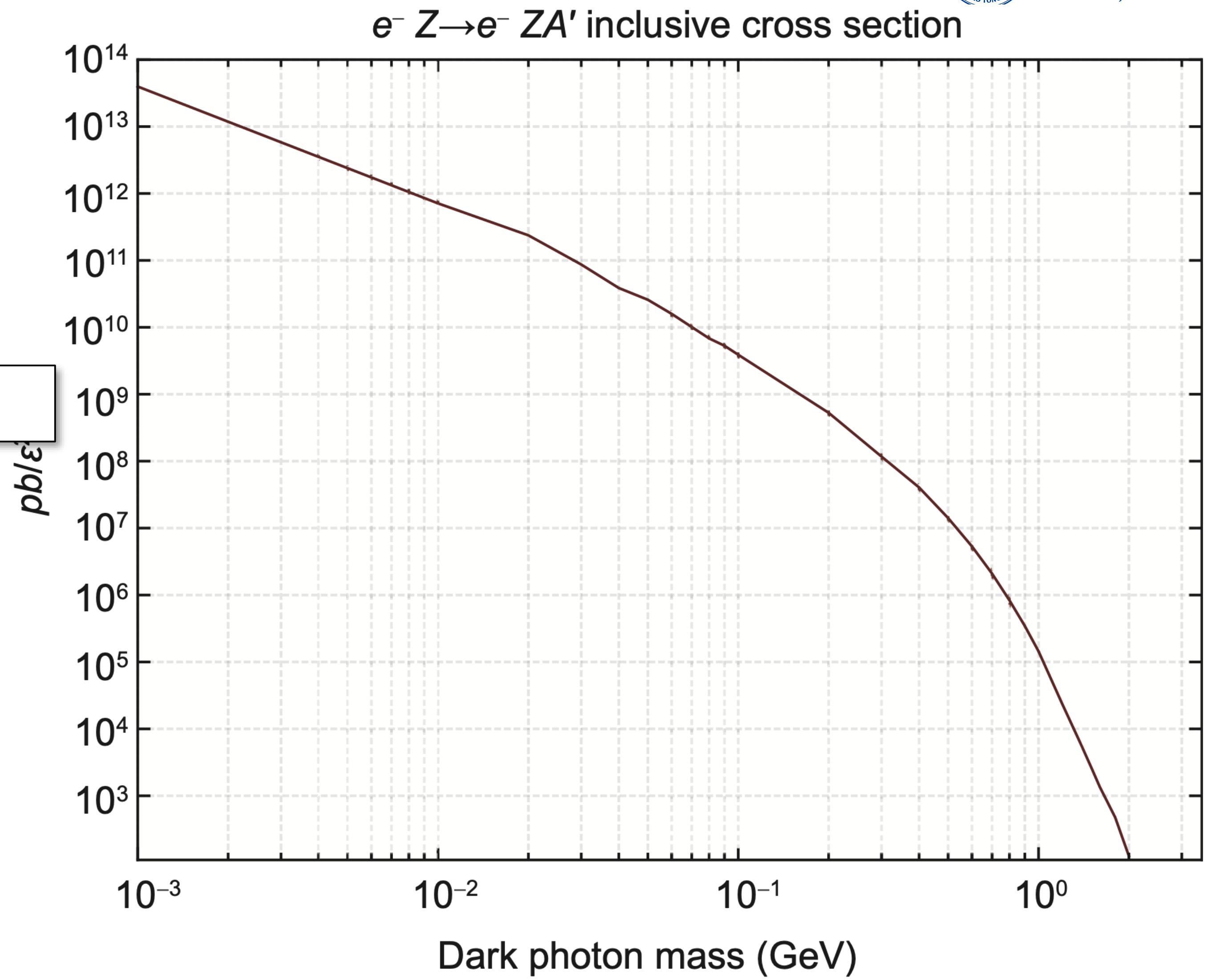
- **LDM: sub-GeV**
  - **Thermal contact implies new mediator**
  - **Beam dump/lepton-on-target experiments searching for dark photon: NA64@CERN, BESIII,BELL-II, LDMX, etc.**

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

The SHINE facility



Dark photon XS

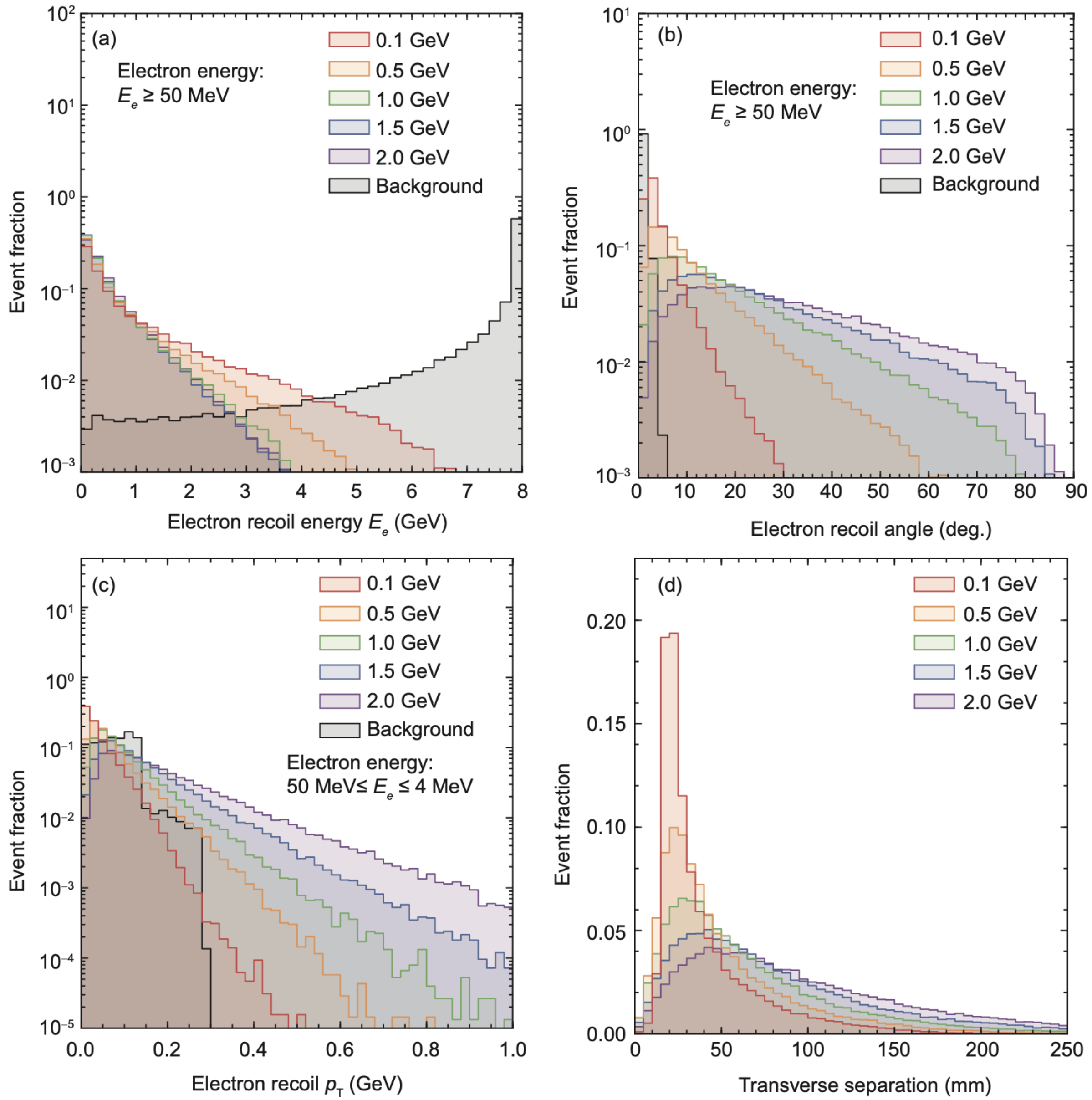


XS with $\varepsilon^2 = 1$

Signal vs. background

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

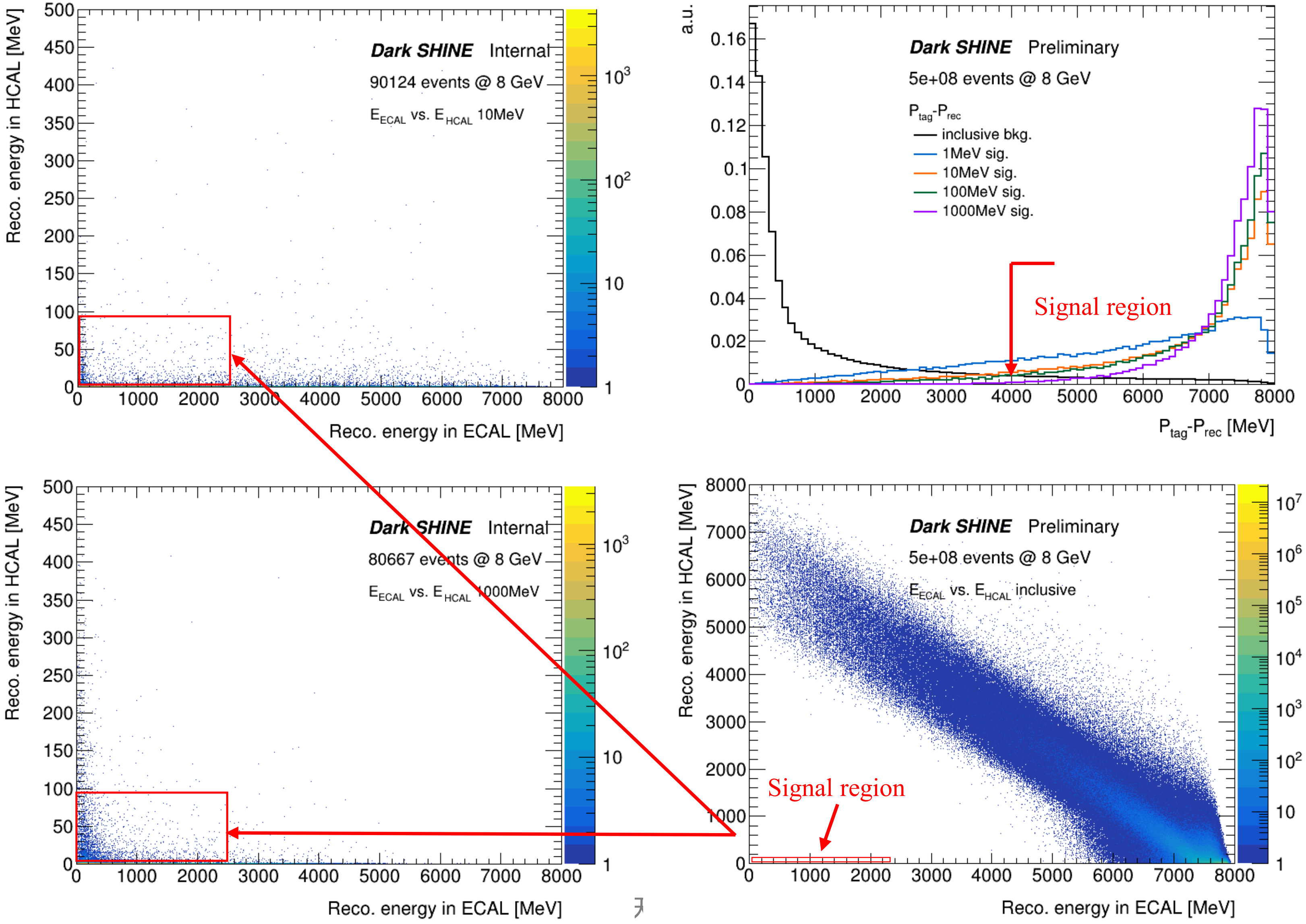
Background:
- **Small missing energy, recoil electron carries most of the momentum**
- **Small recoil electron angle**



Signal-box design

10 MeV A′

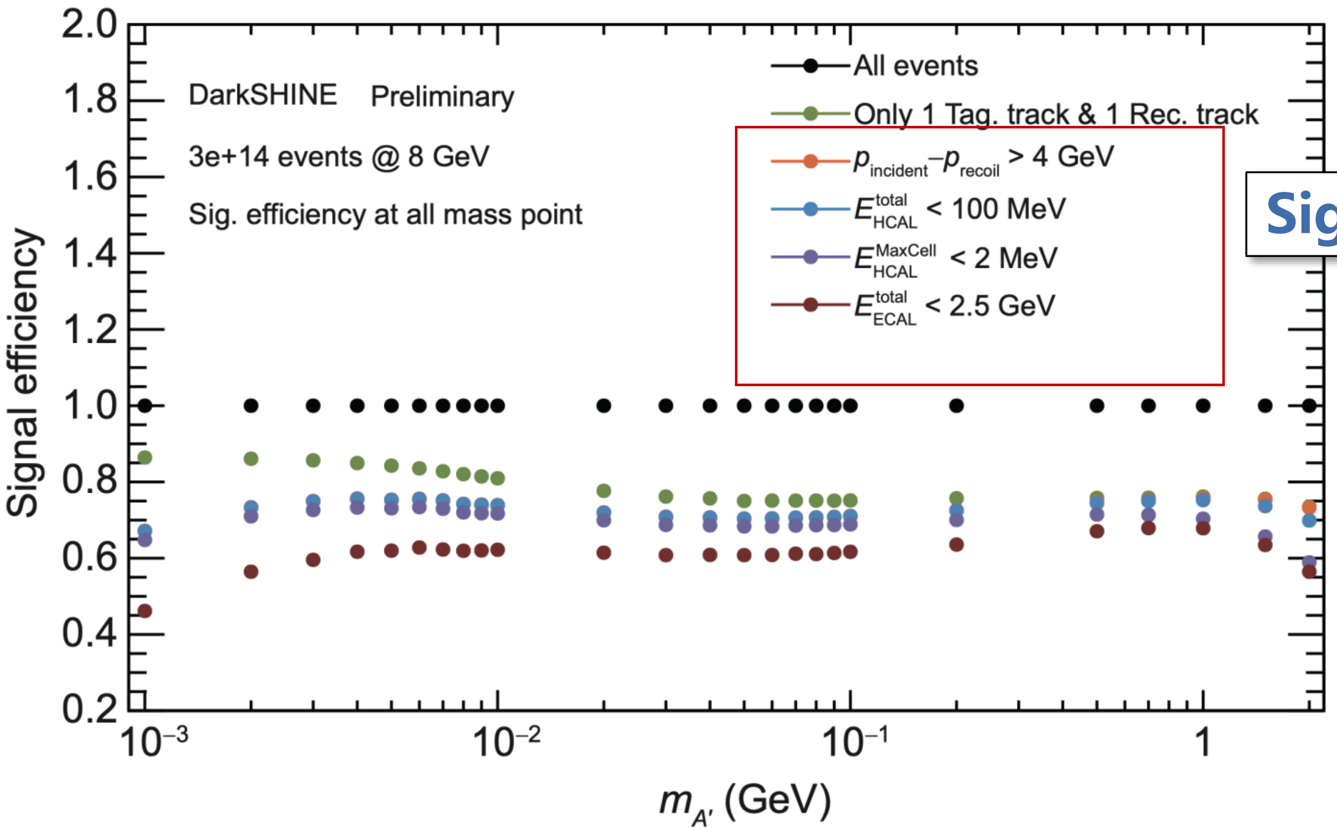
1 GeV A′



Inclusive bkg & signal

Inclusive bkg

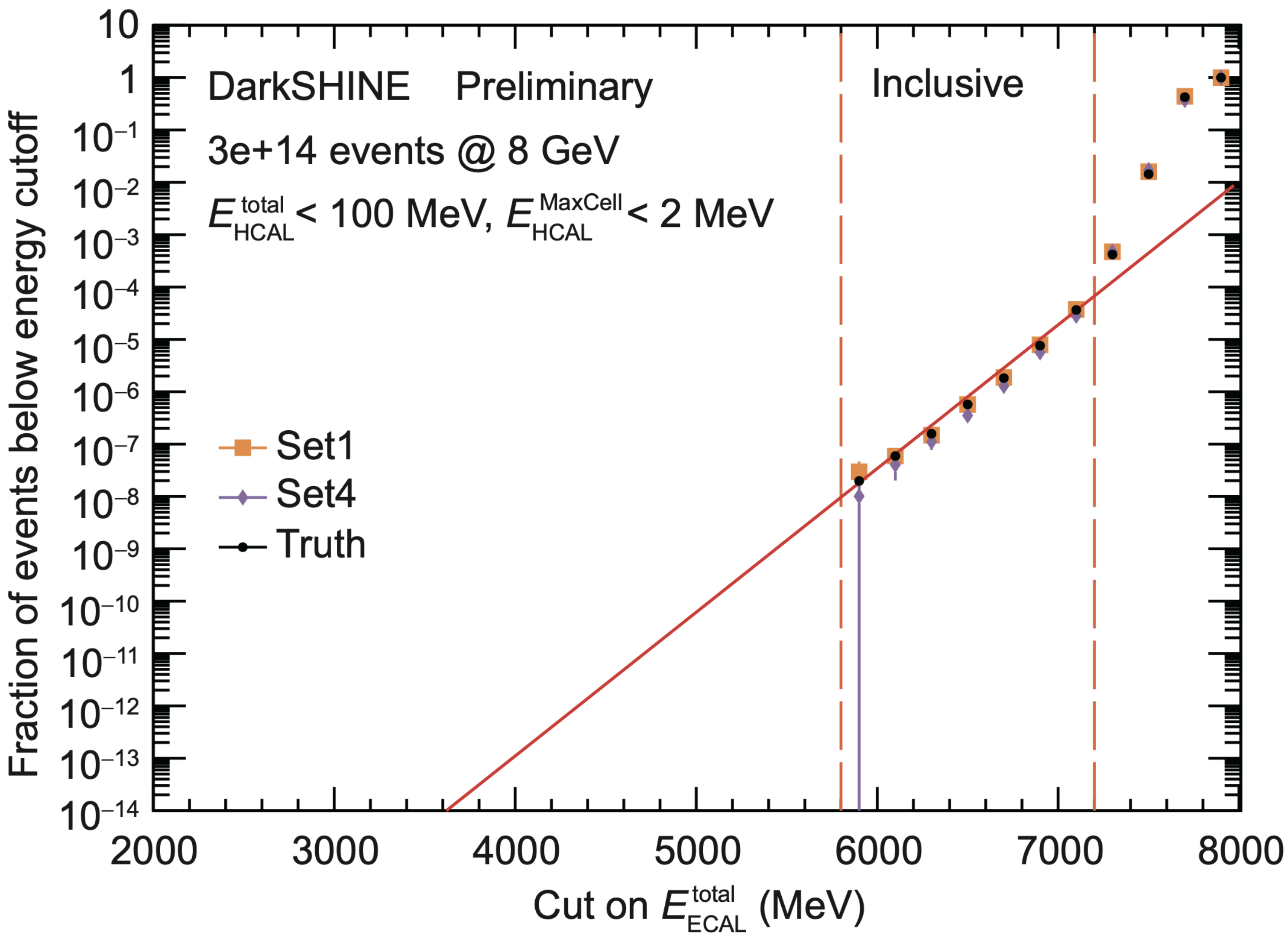
Acceptance efficiency



Signal-box selection

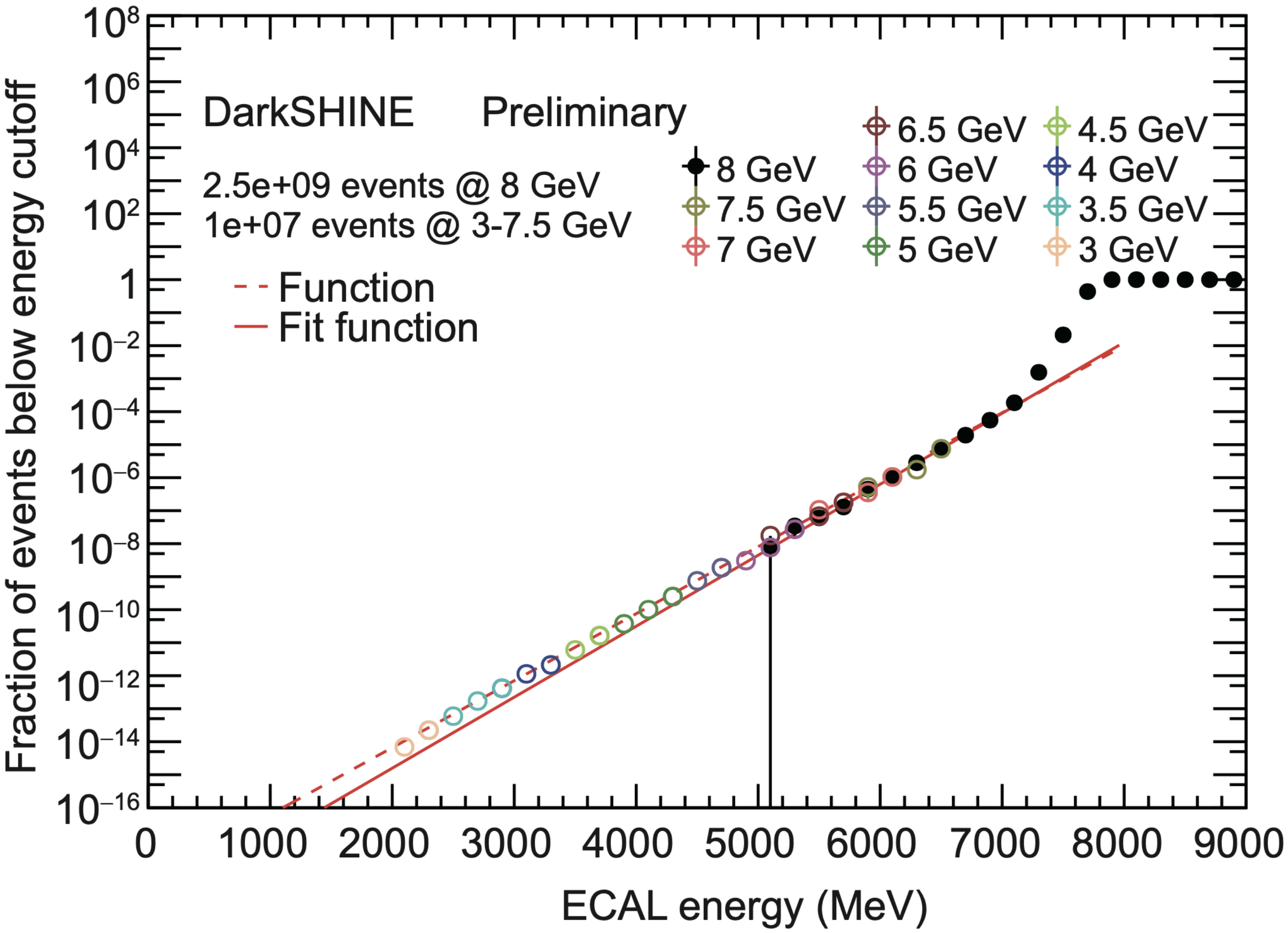
- **60% signal events survive the cut-flow, no background survive (2.5e9)**
- **Acceptance efficiency drops in:**
  - **Low-mass region of a few MeV: tight energy cuts.**
  - **High-mass region above 1 GeV: particles with large incident/recoil angle go into the HCAL directly.**

Background estimation



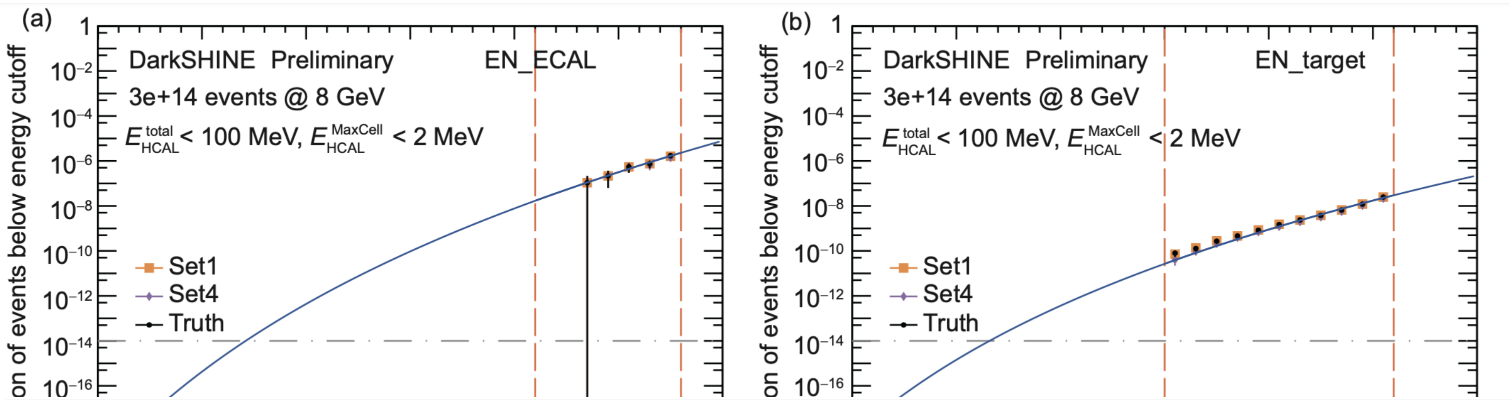
- **Expected background yields go down quickly at lower ECAL energy.**
- **In order to estimate background yields in 10^{14} EOT, extrapolation method is used**
  - **fit from inclusive background process**

Background estimation

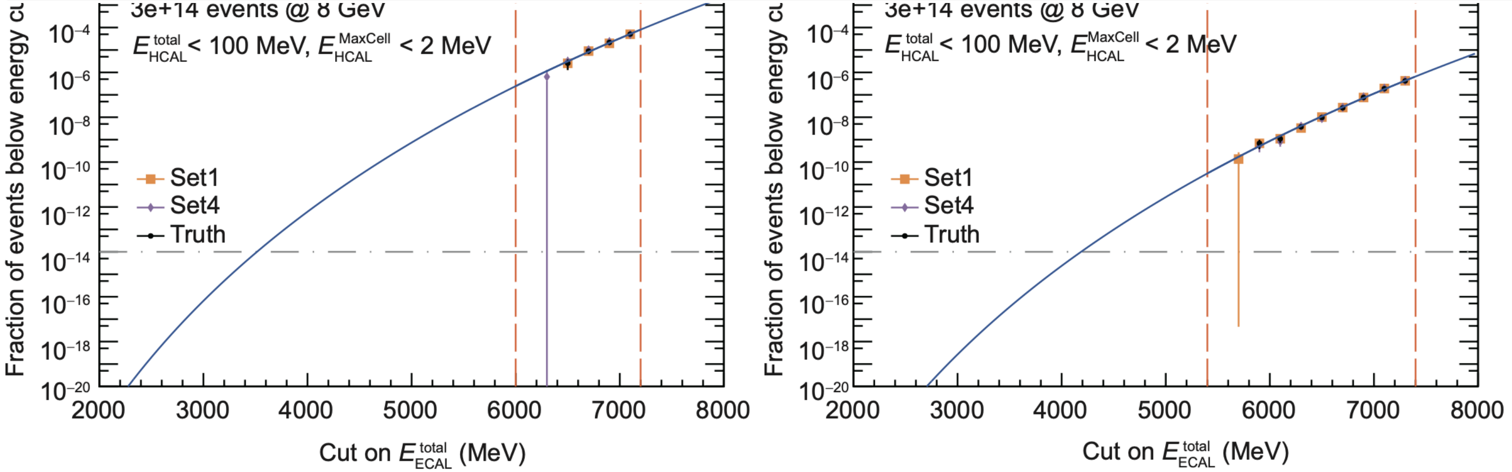


- **Expected background yields go down quickly at lower ECAL energy.**
- **In order to estimate background yields in 10^{14} EOT, extrapolation method is used**
  - **fit from inclusive background process**
  - **extrapolation from low energy samples**

Background estimation



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



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

More physics opportunities…

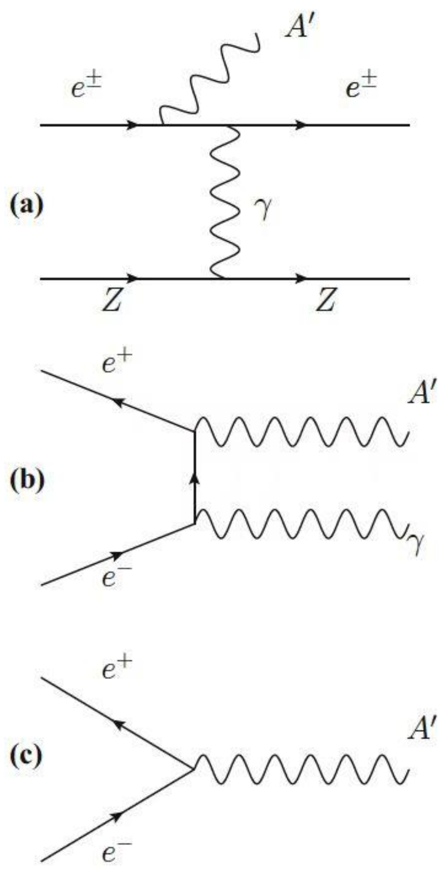
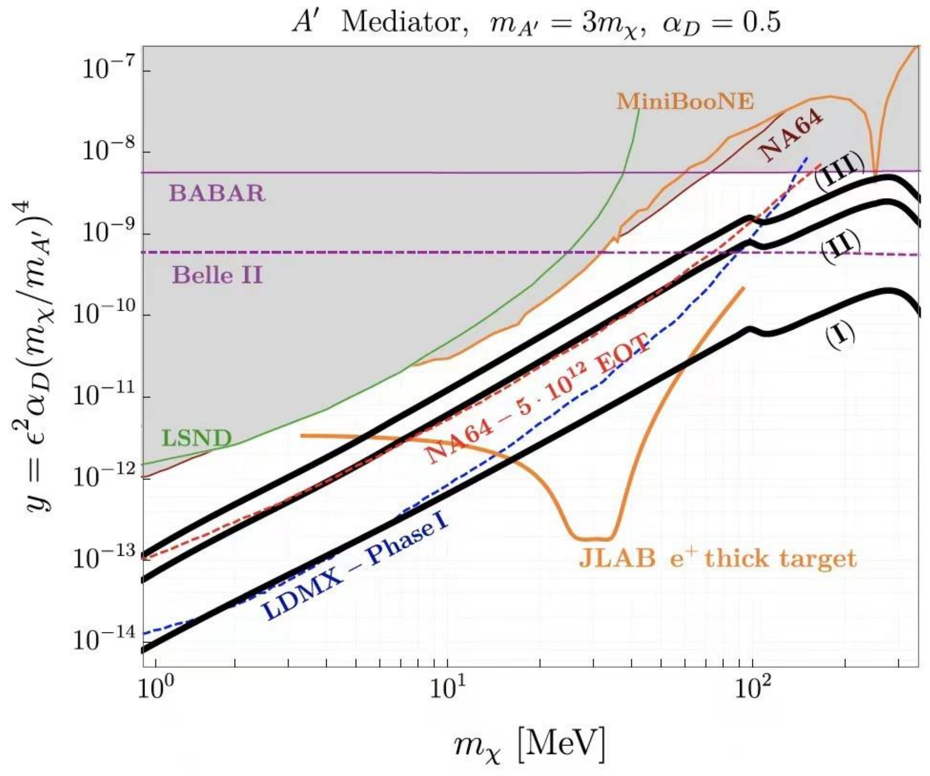


Fig. 1 Three different A' production modes in fixed target lepton beam experiments: (*a*) A'-strahlung in e^-/e^+-nucleon scattering; (*b*) A'-strahlung in e^+e^- annihilation; (*c*) resonant A' production in e^+e^- annihilation



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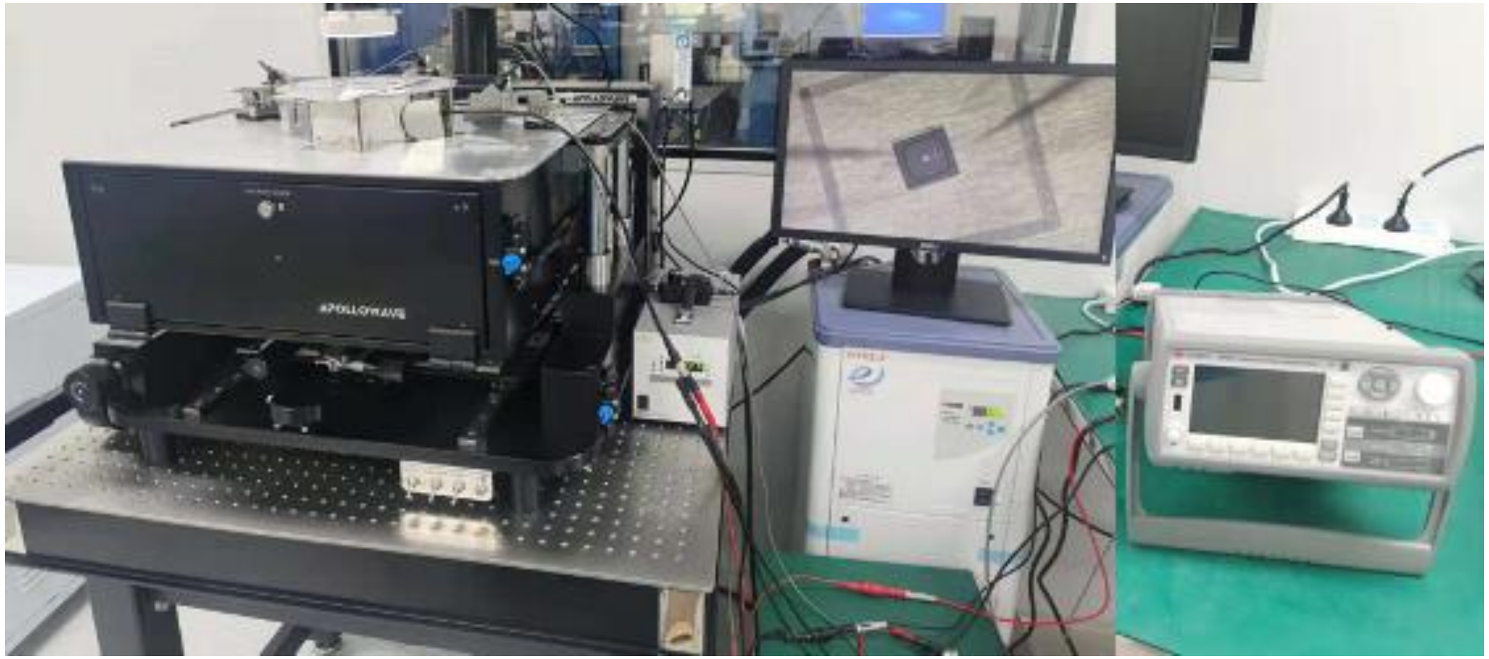
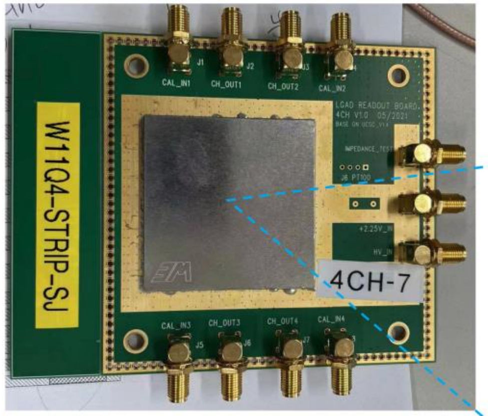
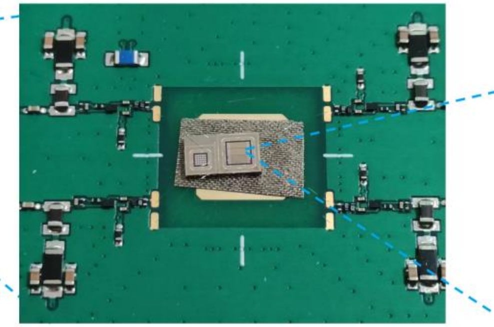
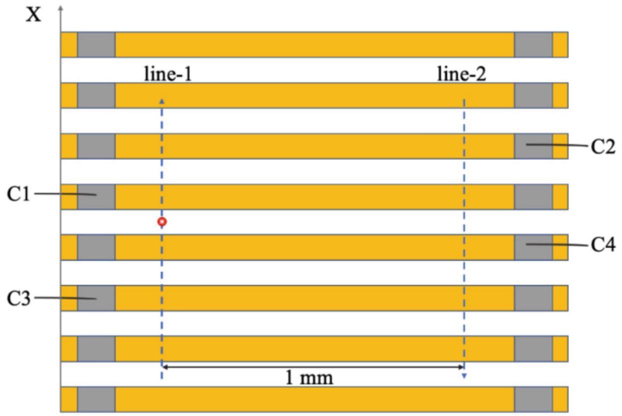
Tracking system

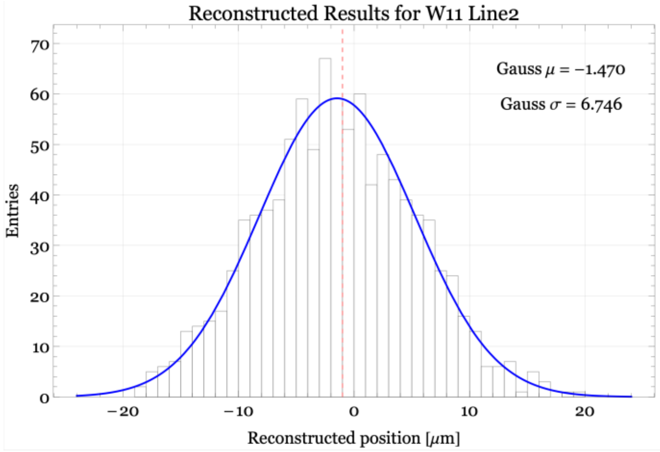


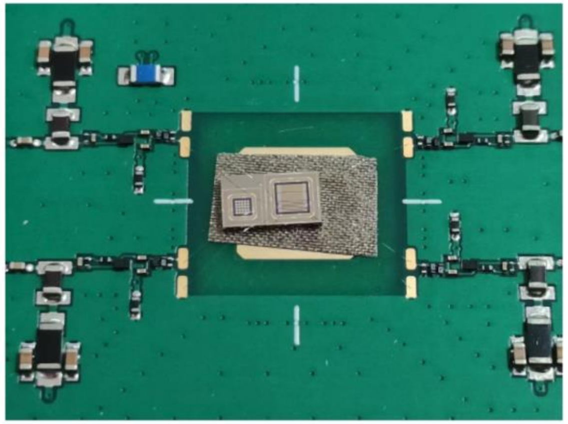


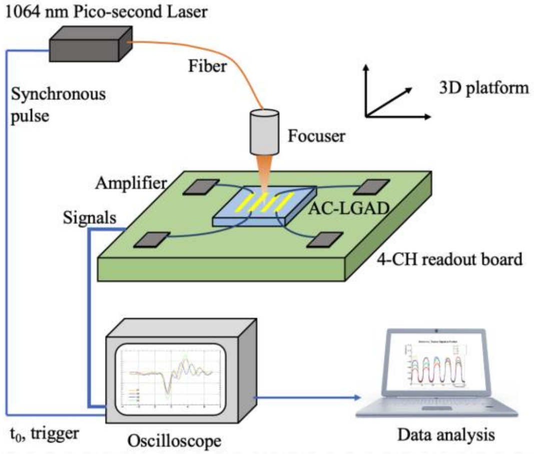
Working point
W11: 350V
W12: 150V





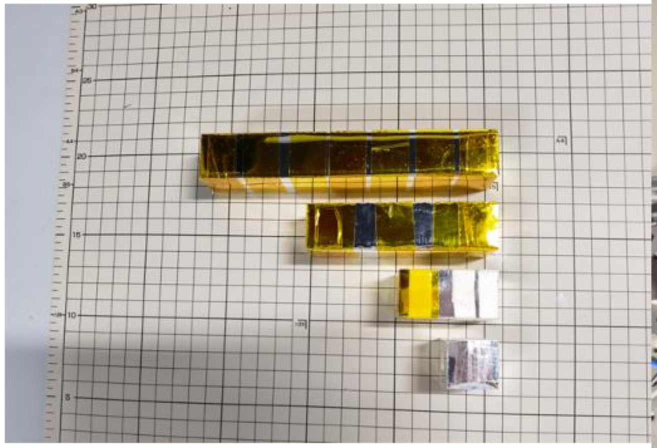




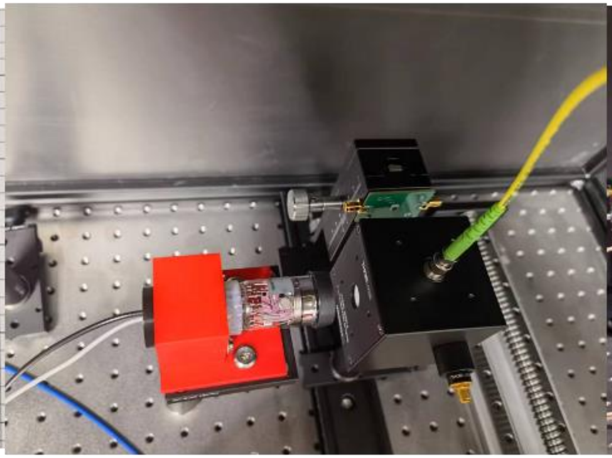


ECAL: crystal test

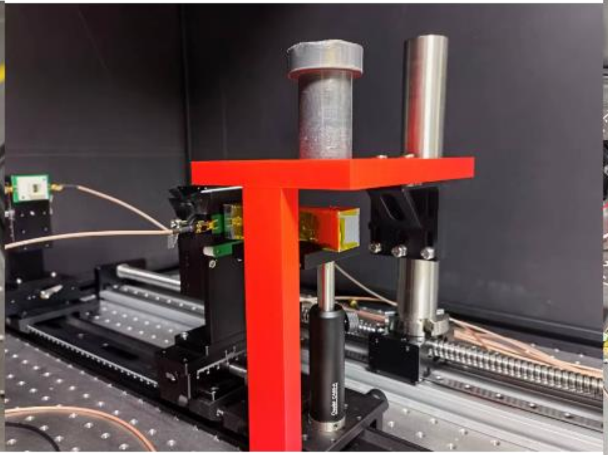
LYSO晶体切割与包裹

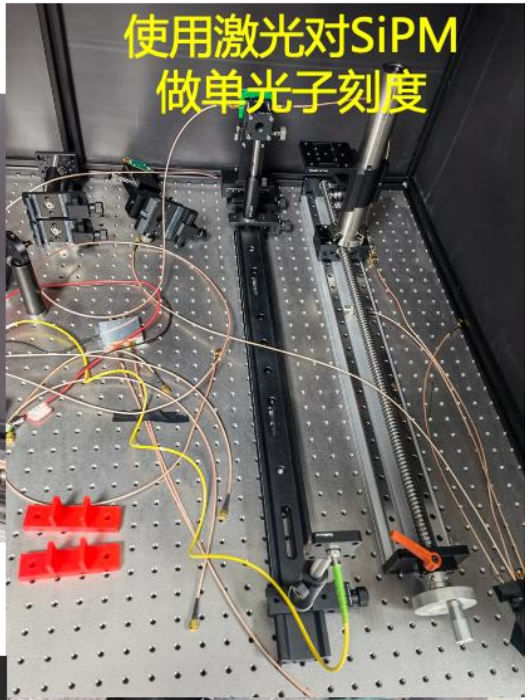


SiPM动态范围测试

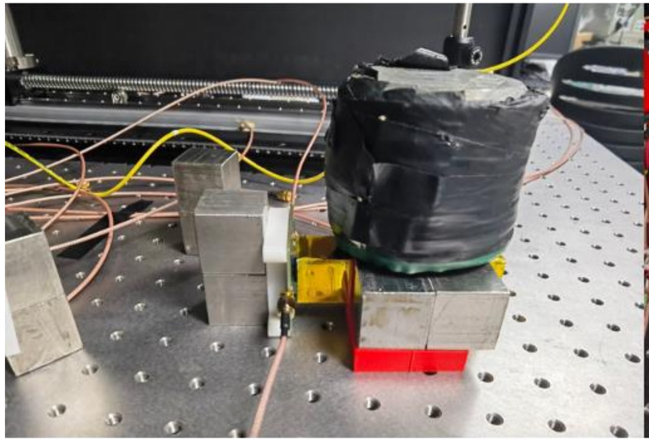


使用放射源对晶体做均匀性扫描

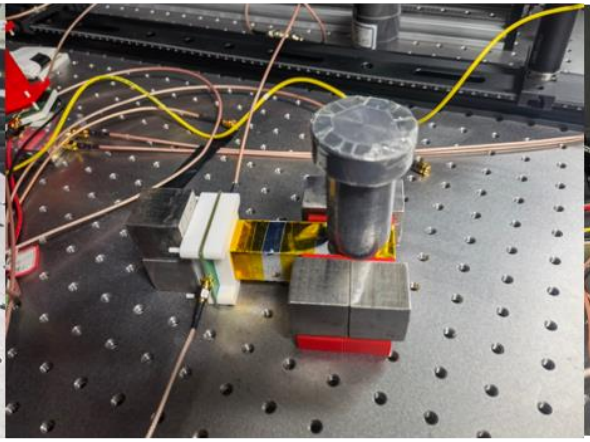




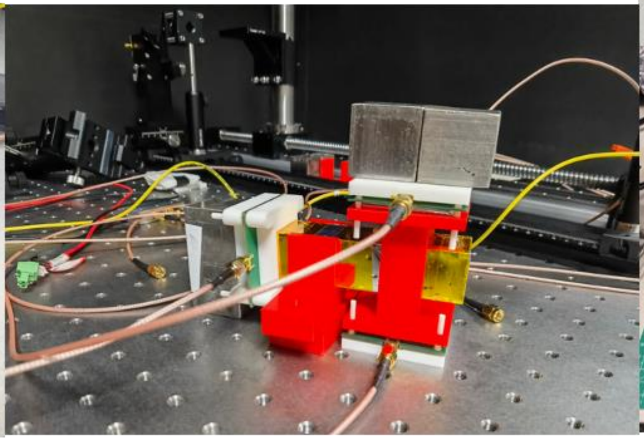
LYSO晶体^{137}Cs测试



LYSO晶体^{60}Co测试



宇宙线测试上下符合

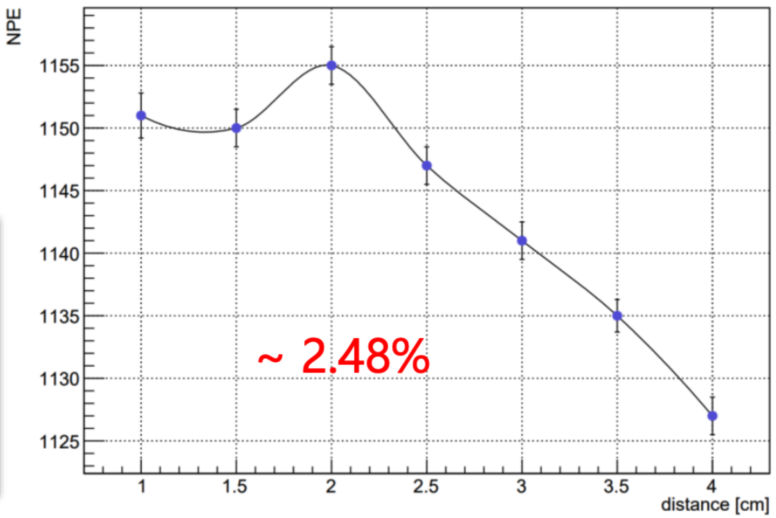


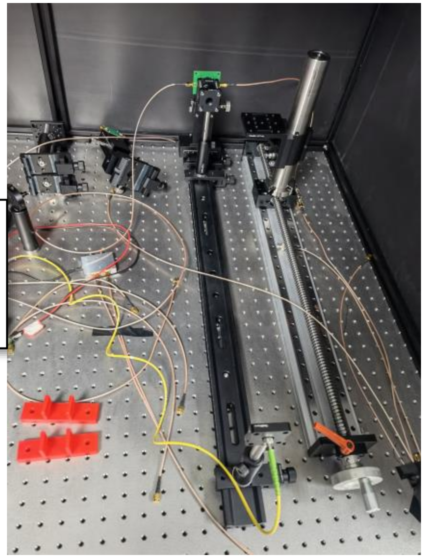
Detector R&D: Electromagnetic calorimeter

5cm LYSO

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

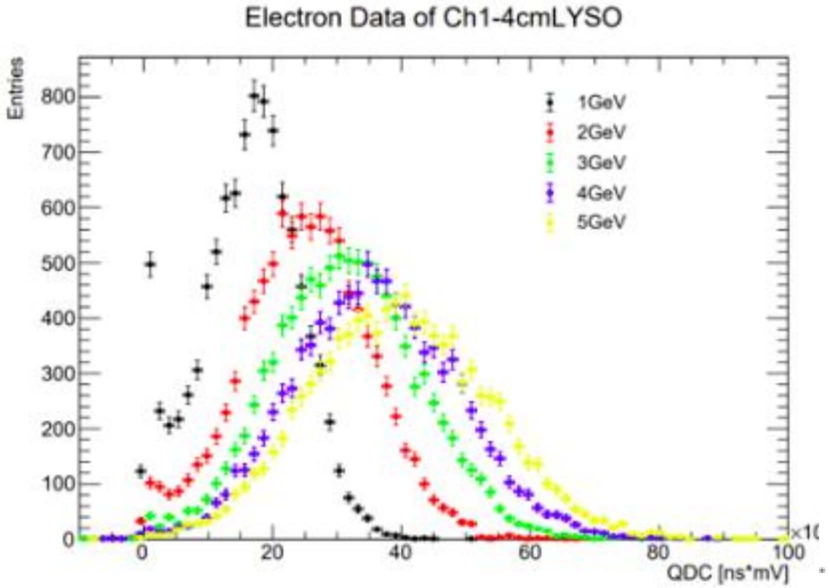
Uniformity scan with using ^{60}Co

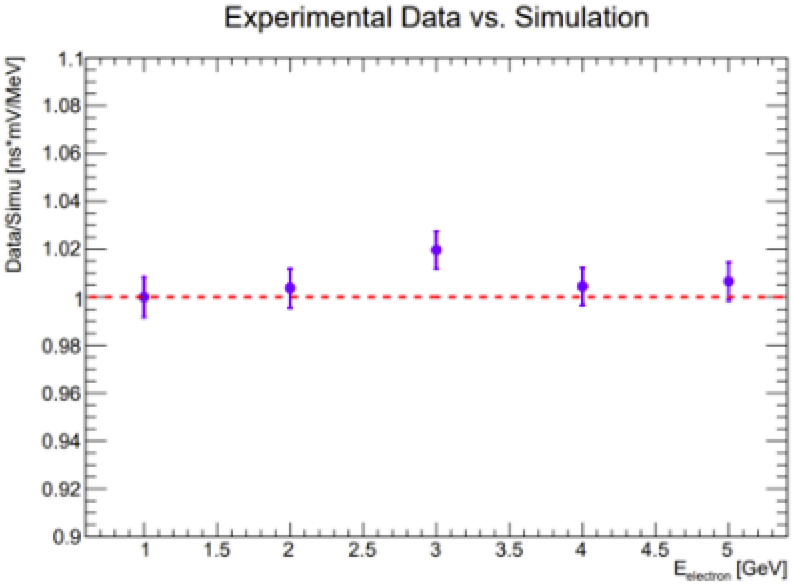




SiPM laser calibration

Beam test @Desy





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

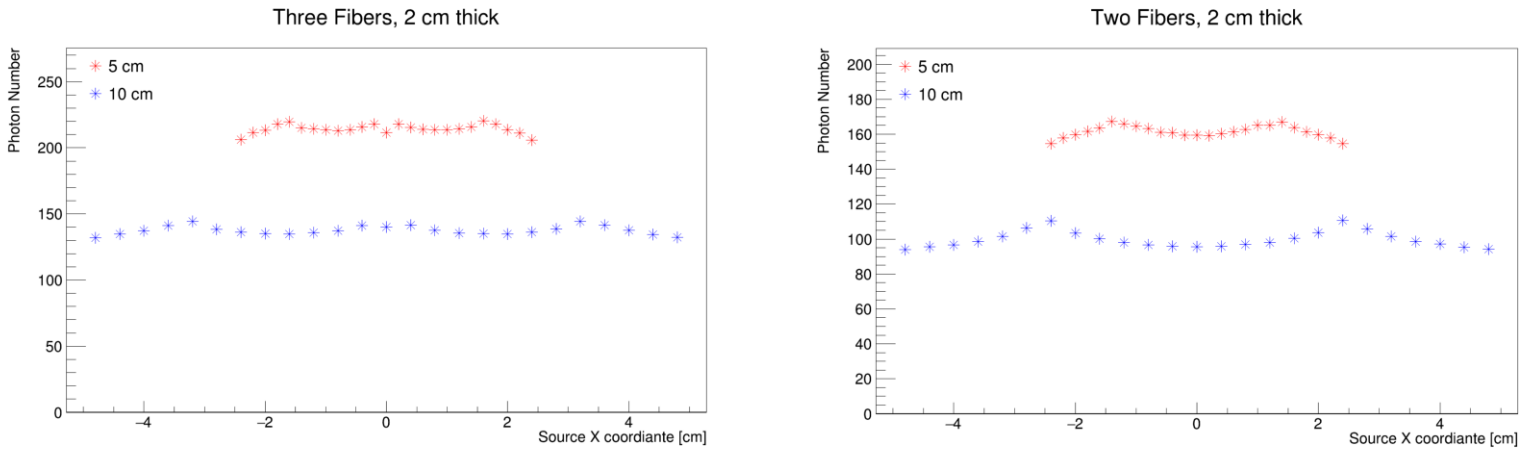
Veto InEff ×E-06	n	k^0	π^0	p	μ
100[MeV]	$1170^{+10.9}_{-10.8}$	$31600^{+55.5}_{-55.4}$	$7.30^{+0.958}_{-0.852}$	$30700^{+61.5}_{-61.3}$	$409^{+6.49}_{-6.39}$
500[MeV]	$18.4^{+1.46}_{-1.36}$	$5.40^{+0.839}_{-0.733}$	$0.1^{+0.184}_{-0}$	$8.04^{+1.34}_{-1.16}$	$15.0^{+1.33}_{-1.22}$
1000[MeV]	$3.70^{+0.714}_{-0.606}$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

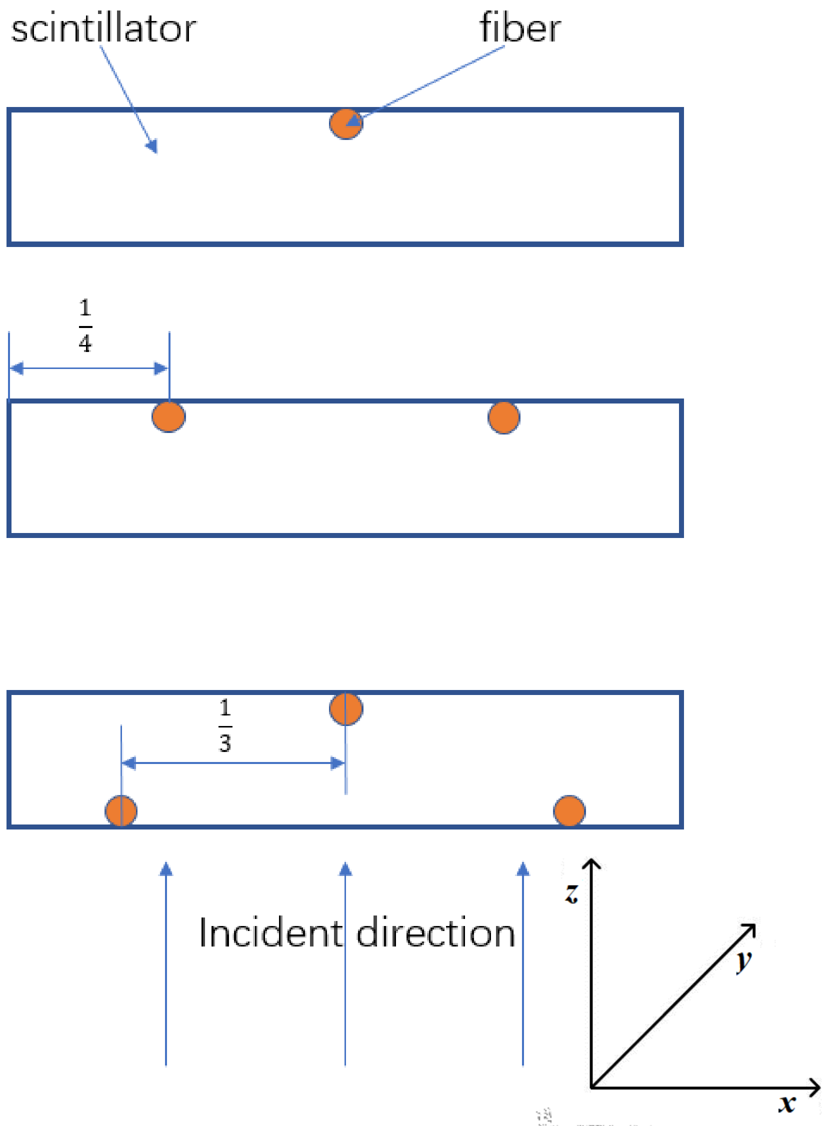
Structure \ Process	EN-target	EN-ECAL	PN-target	PN-ECAL
w/o Side HCAL	2.68E-02	3.94E-02	9.29E-02	1.24E-01
w/ Side HCAL	1.04E-03	1.09E-02	1.94E-03	3.58E-02

HCAL: Scintillator simulation

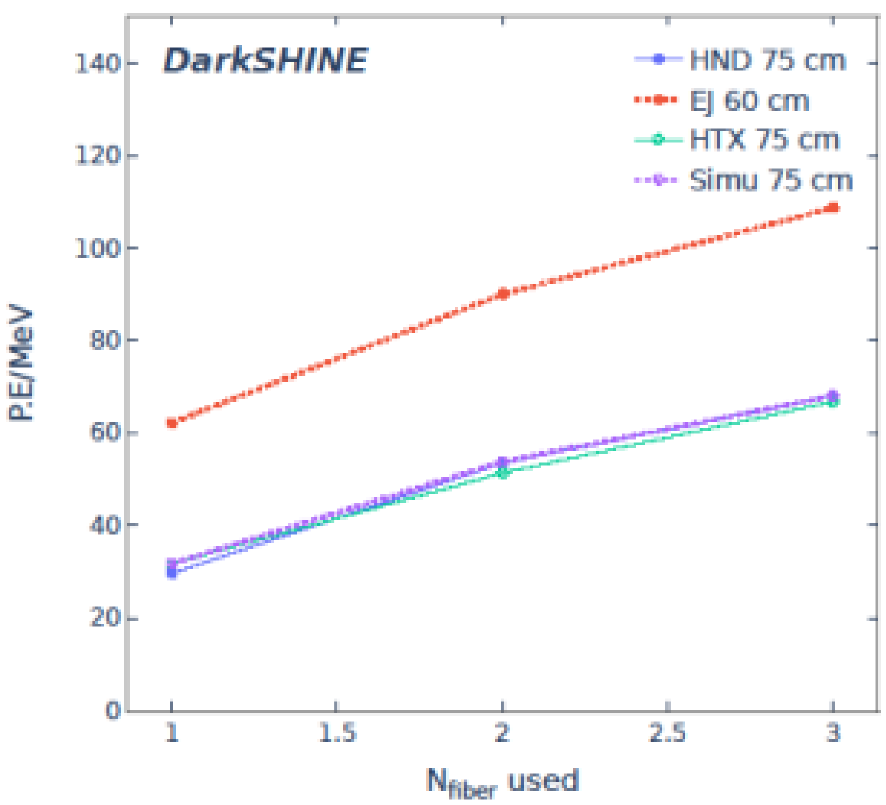
- **Scintillator size : 5/10 cm × 75 cm × 1 cm/2 cm**
- **Fiber size : 0.5 mm radius with clad**
- **Incident e^-, 100 MeV**
- **Incident position : -2.4/-4.8 cm to 2.4/4.8 cm per 0.2/0.4 cm**

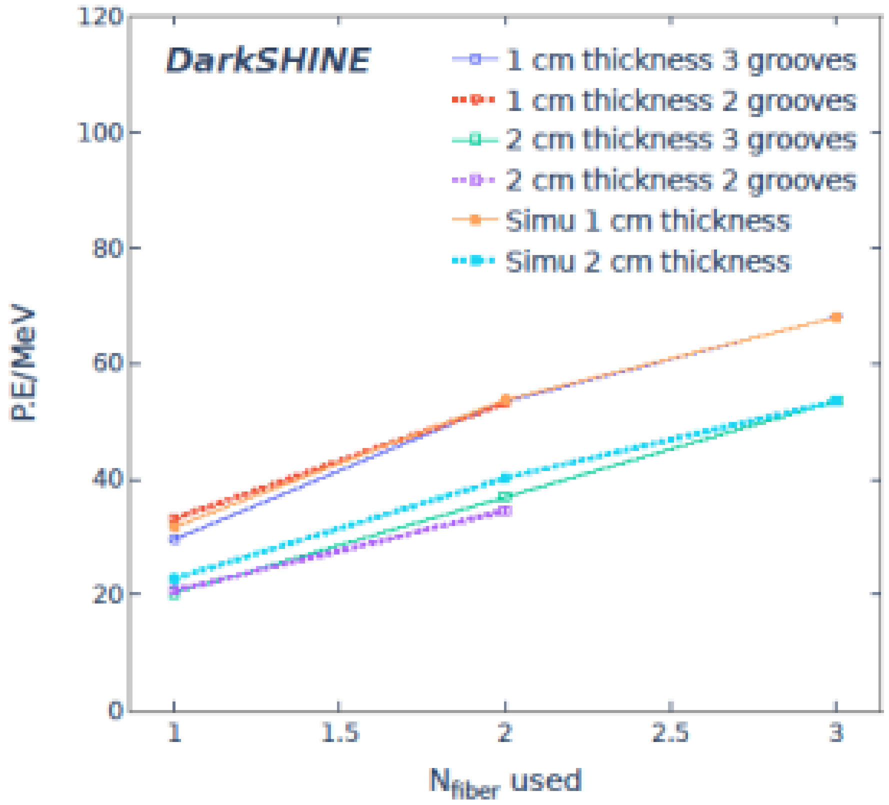


Size	1 fiber	2 fibers	3 fibers
1 cm * 5 cm	64 (60-75)	108 (100-115)	136 (130-145)
1 cm * 10 cm	38 (35-50)	69 (65-80)	92 (85-100)
2 cm * 5 cm	91 (85-100)	161 (155-170)	214 (205-220)
2 cm * 10 cm	53 (48-65)	100 (94-110)	138 (132-145)



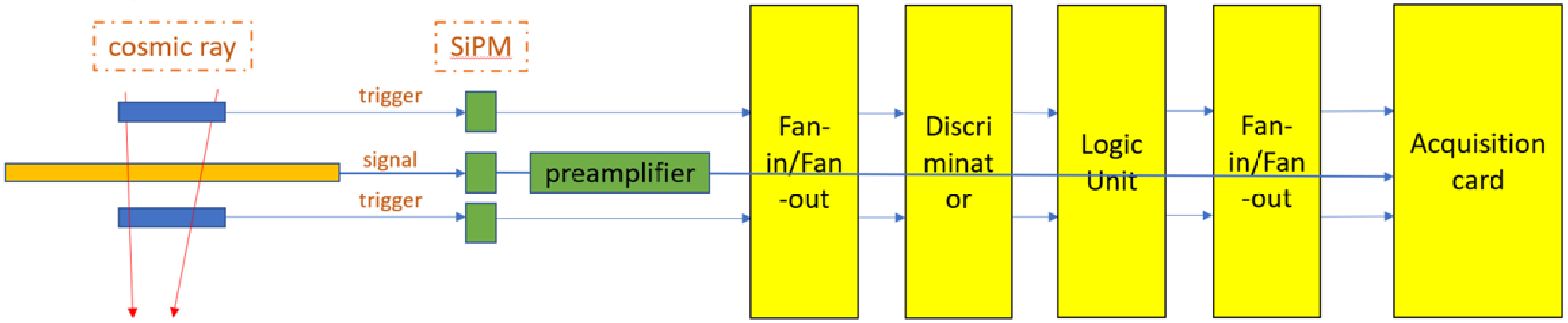
HCAL: Photon yields test results

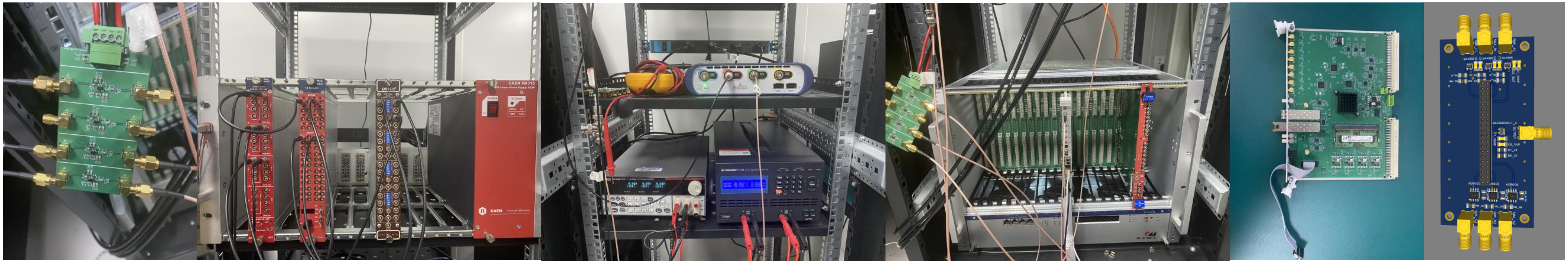




Hardware test: Electronic readout system

- **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 → 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)

Plastic scintillator noise