李政道研究所
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Recent progress of DarkSHINE R&D

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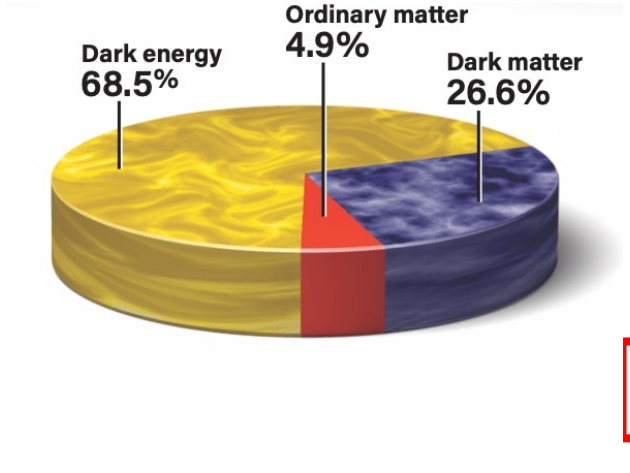
On behalf of the DarkSHINE R&D Team

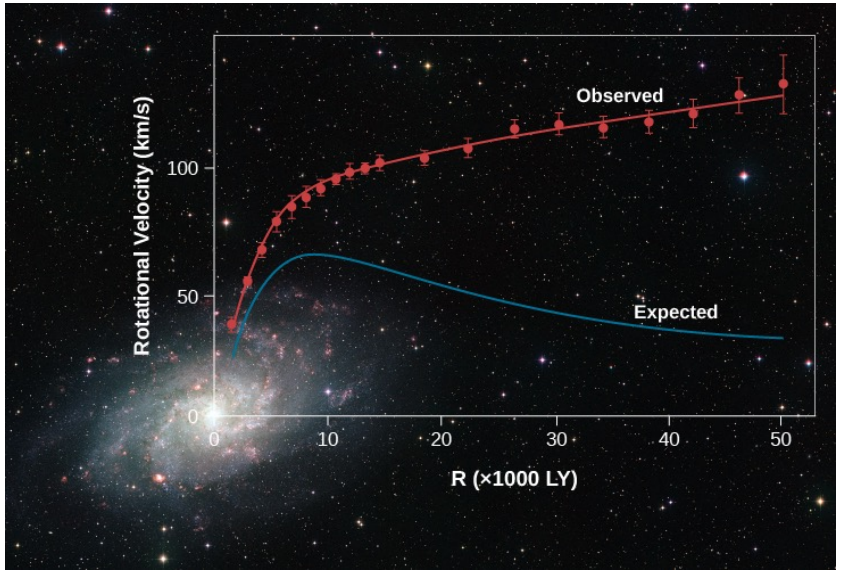
Axion 2025, Nanjing
2025.07.28

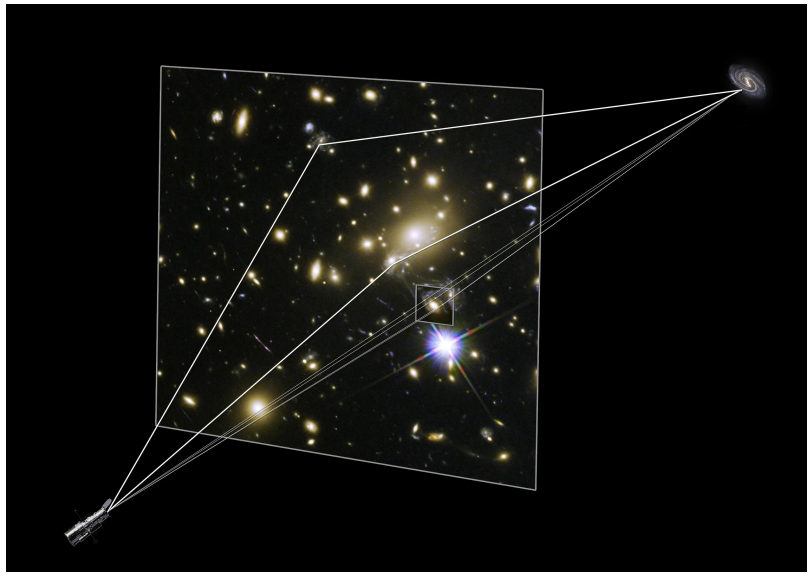
Dark Matter Evidence

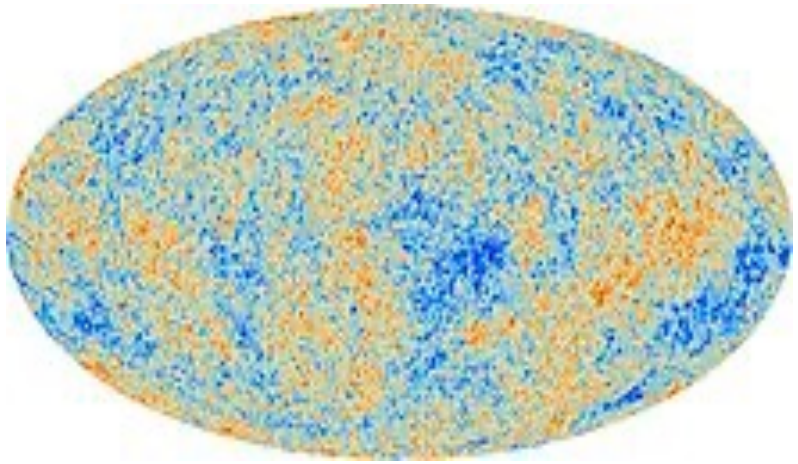
- Dark matter evidence from astronomical observations and gravitational effects:
  - Galactic rotation curves, Gravitational lensing, Cosmic Microwave Background anisotropies, …



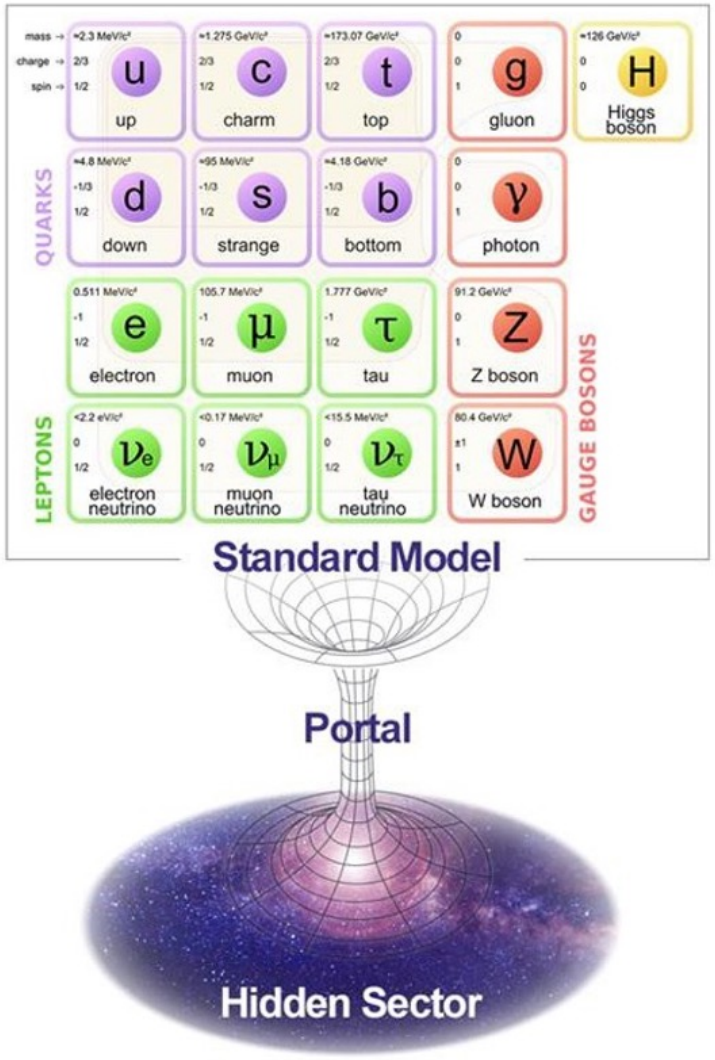
Dark matter exist!







Massive dark photon as new force carrier



How Dark Matter may interact with Ordinary Matter?

Dark Matter — Mediator — Standard Model

4 Renormalizable "Portals"

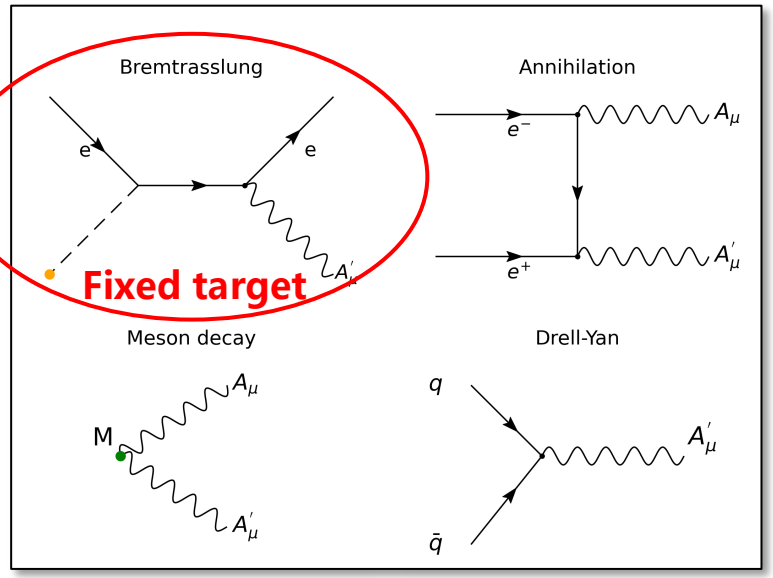
Axion	$\frac{1}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a$	Axion/ALP	**Higgs**	$\lambda H^2 S^2 + \mu H^2 S$	Exotic Higgs decay?
Vector	$\epsilon F^{Y,\mu\nu} F'_{\mu\nu}$	Dark photon	**Neutrino**	$\kappa (HL) N$	Sterile neutrino?

Dark Matter — Dark Photon — ϵ — Kinetic Mixing — Standard Model

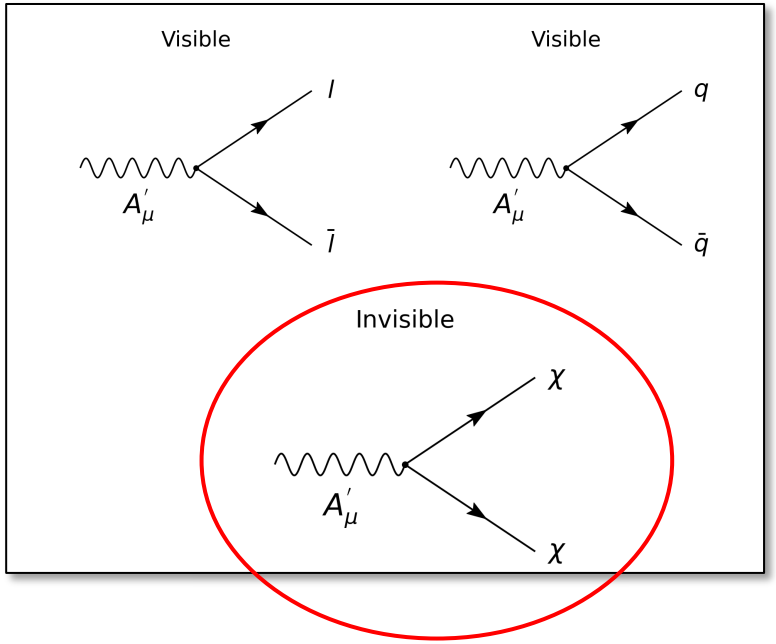
New force carried by massive vector boson: dark photon

Physics process and anticipated signatures

Processes to search for **dark photon A':** Bremsstrahlung, Annihilation, Meson decay and Drell-Yan process



(Dark photon production)



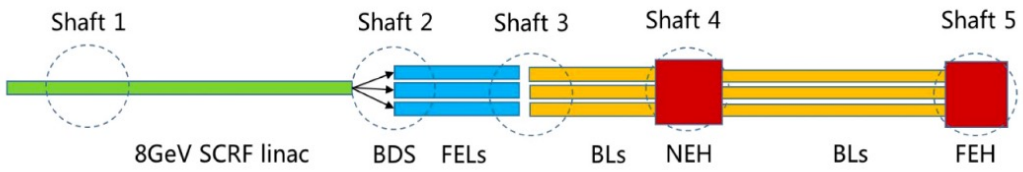
(dark photon decay)

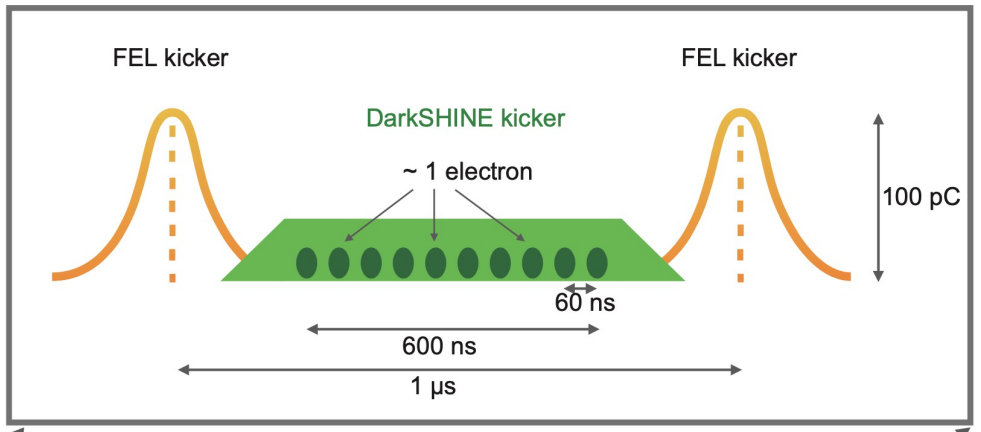
- **Goal:** put constraints on the kinetic mixing parameter ε.
- **Challenge:** small production rate → suppress bkg. from SM processes.
- **Experimental signatures:** missing energy, missing momentum
- **DarkSHINE: Bremsstrahlung + invisible decay**

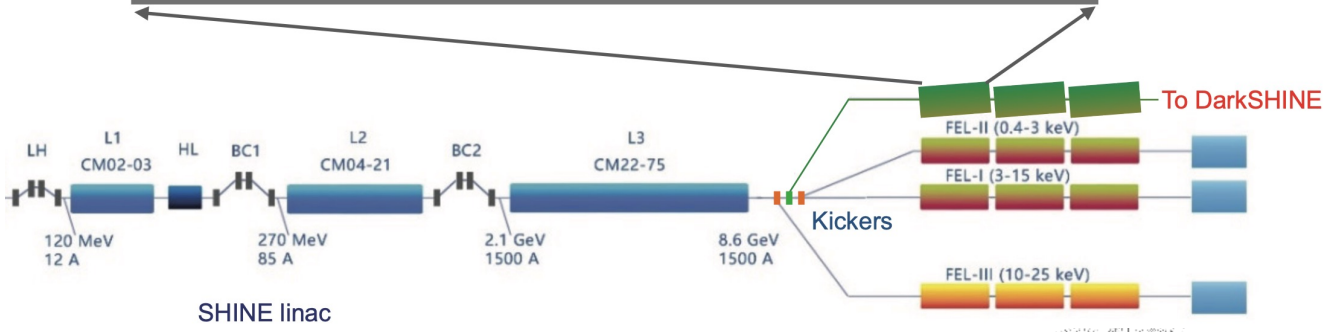
DarkSHINE experimental approaches

- **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**
- **~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**



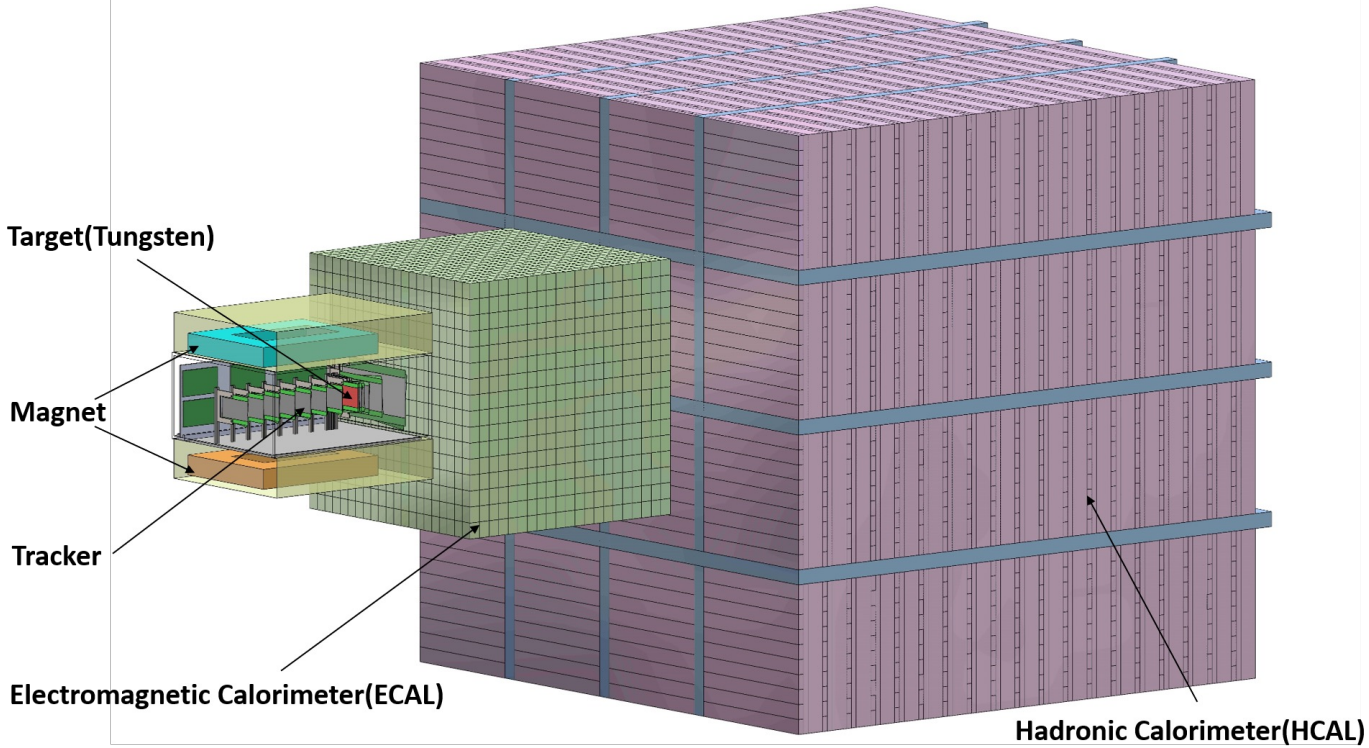




DarkSHINE detector system conceptual design

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

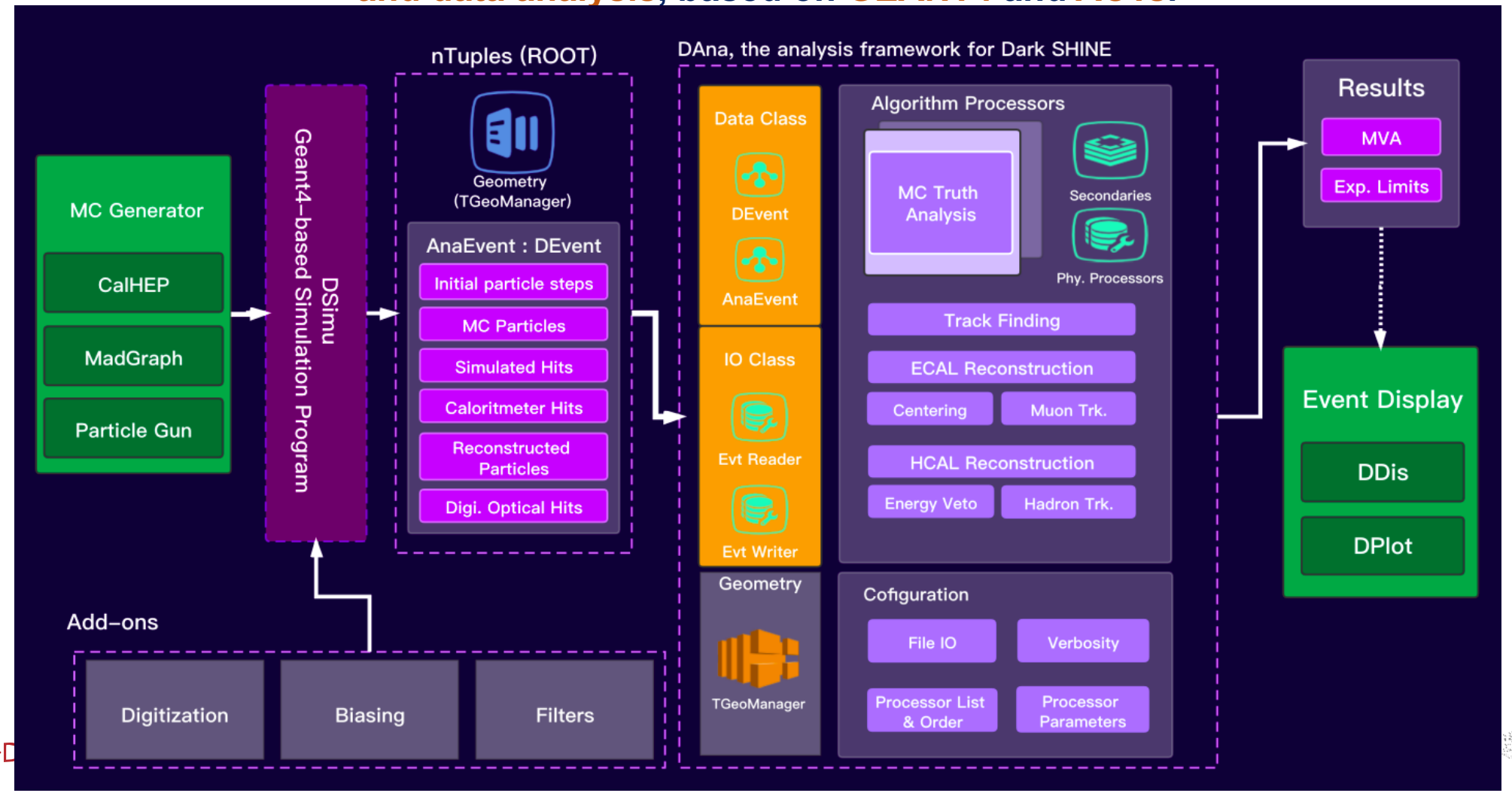
Electromagnetic calorimeter
Measure the deposited energy: electron and photon.

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

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

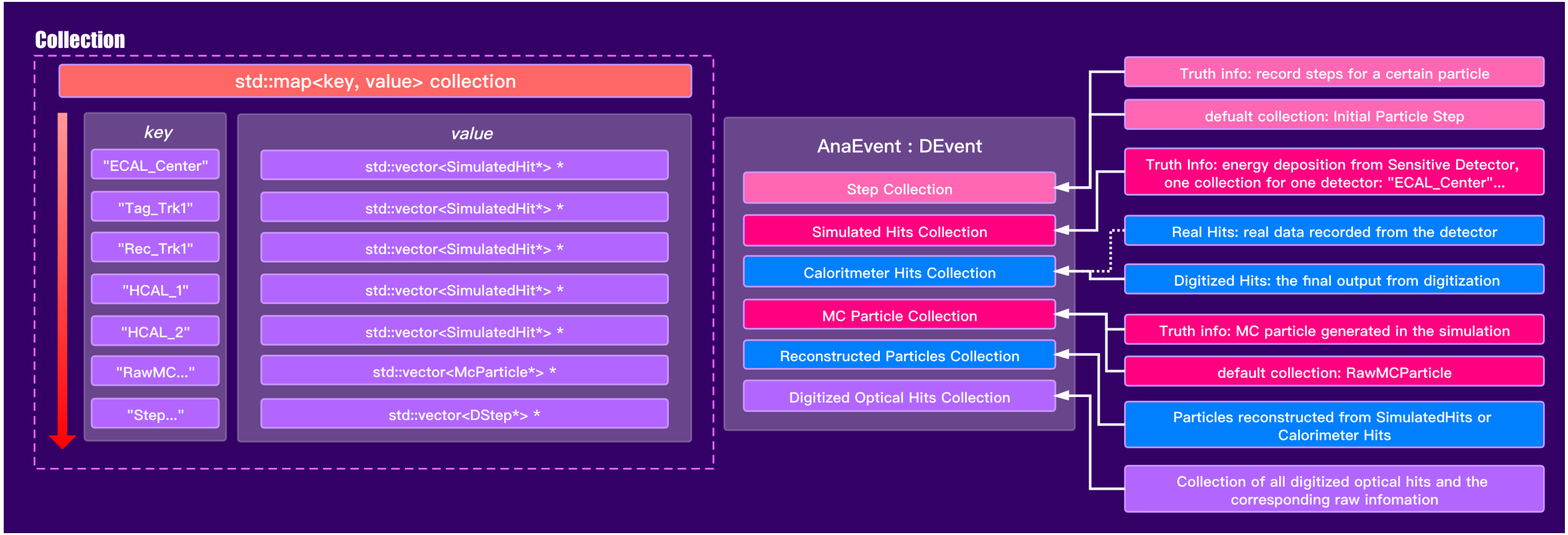
DarkSHINE simulation framework

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.



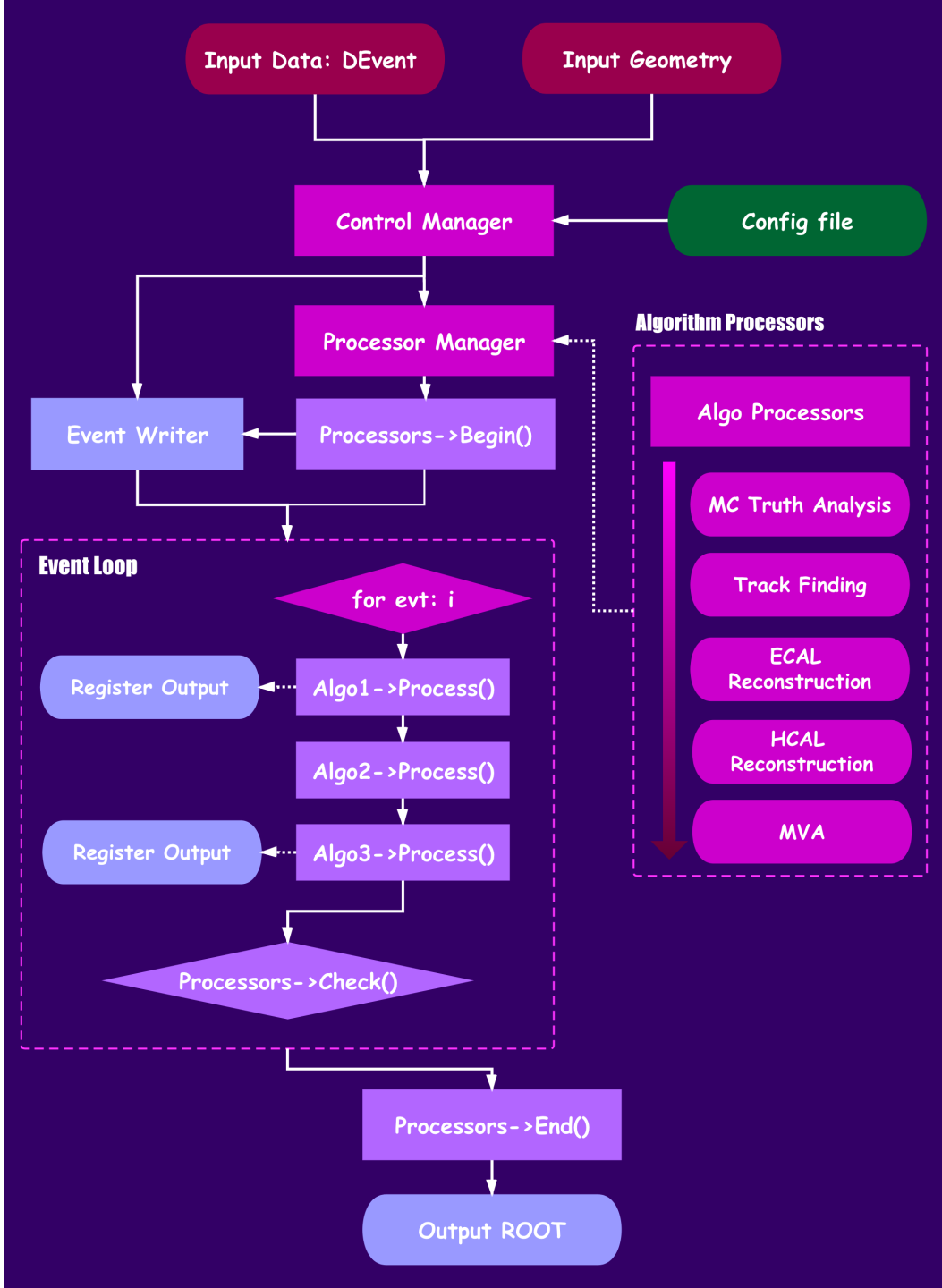
Event Data Model (DEvent)

- Customized event data structure based on ROOT
- Optimized ***data class*** & memory, w/ ***memory alignment*** : 60.1 KB/event → minimum 13.7 KB/event



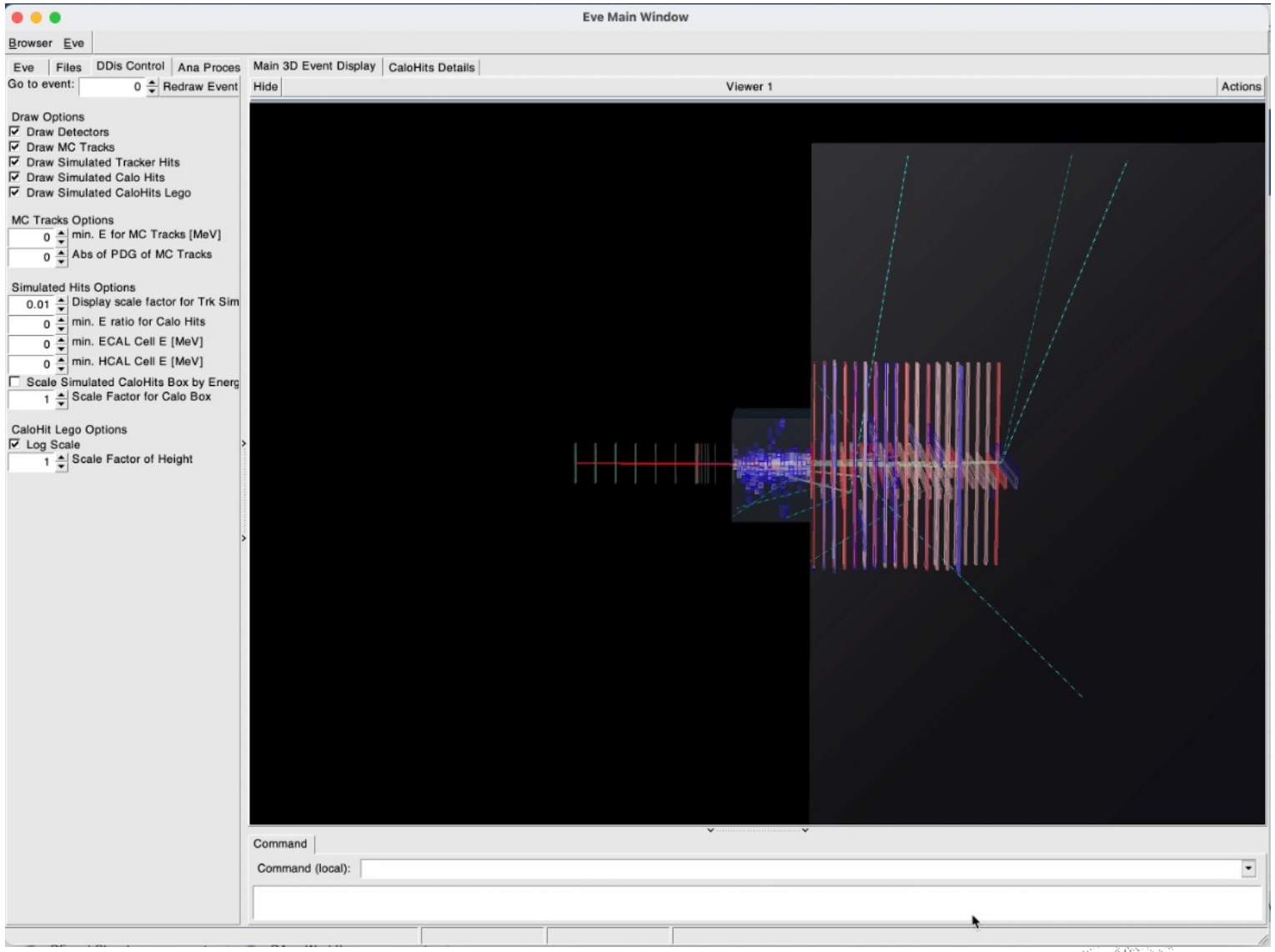
Reconstruction and Analysis (DAna)

- **Reconstruction and Analysis Framework for DarkSHINE Software**
- **Algorithm Processors:**
  - Called subsequently
  - Analyzed data can be shared within the event
- **Featured processors:**
  - MC Truth Analysis
  - Digitizer
  - Track Reconstruction
  - ECAL Reconstruction
  - HCAL Reconstruction
  - Data Exporter for Machine Learning



Event Display

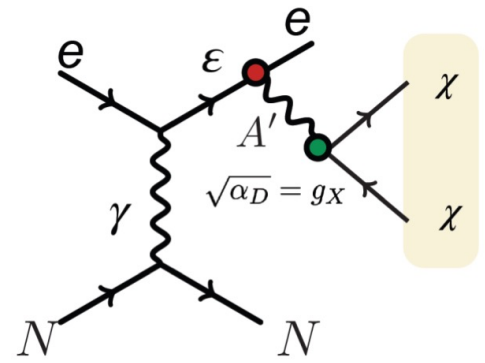
- Event Display for DarkSHINE Software based on QT and ROOT
- Read Geometry and Event Collection from output of **DSimu**
- Draw event one by one
- Customized draw options
- Support online algorithm processors



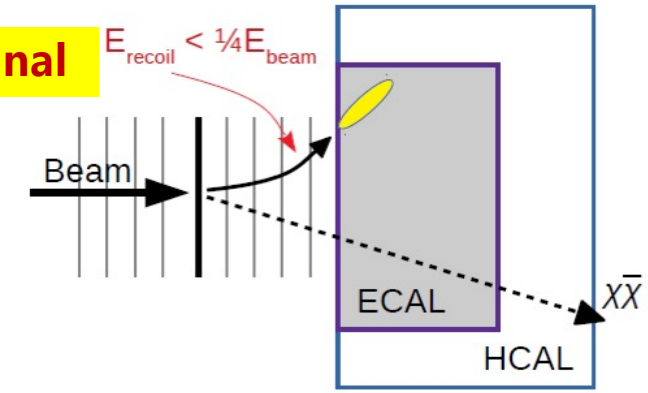
Signal and background processes

INVISIBLE DECAY MODE $m'_A > 2m_X$

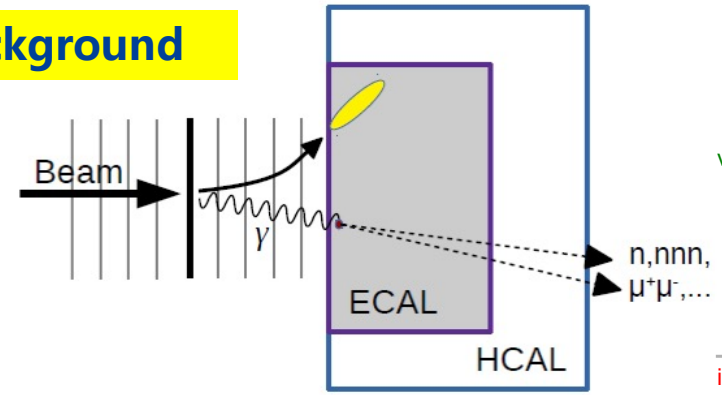
- **Detector is designed based on the difference between signal and background signatures**
  - **Search for the final states with a soft recoil electron + large missing energy & p_T**

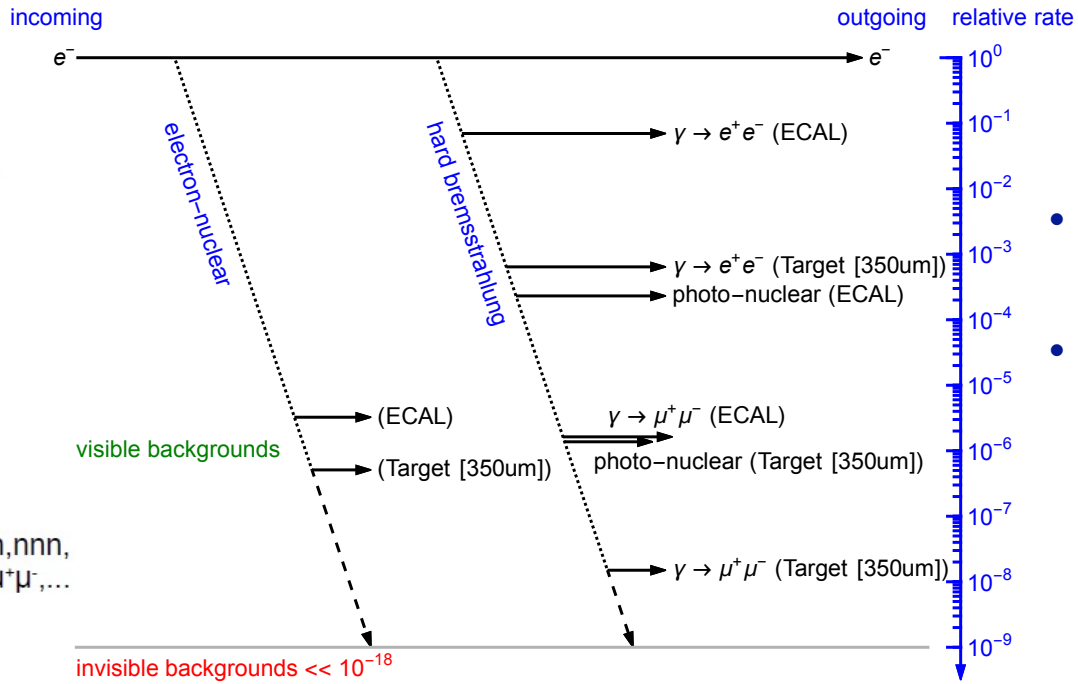


Signal



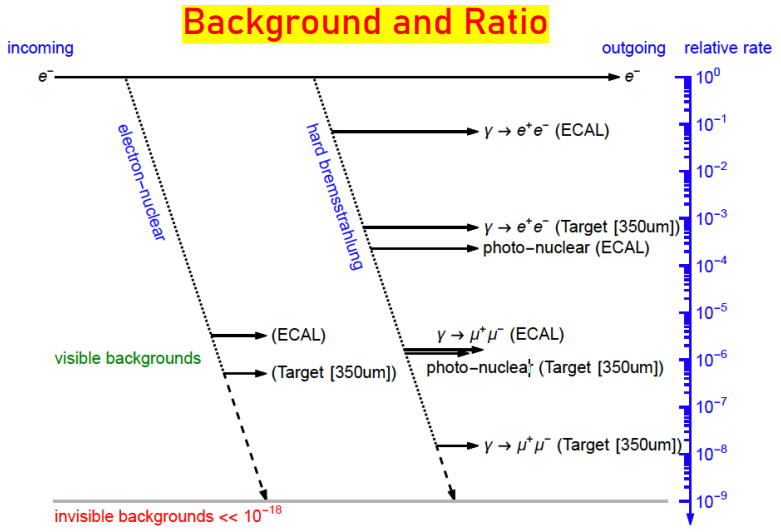
Background

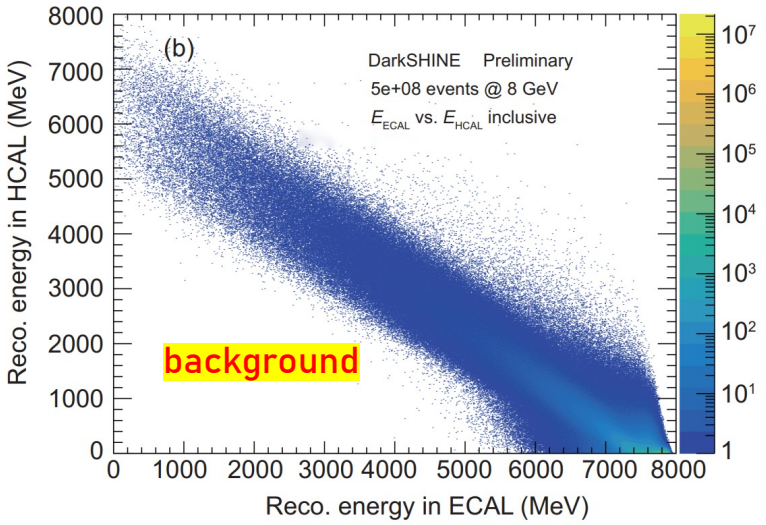


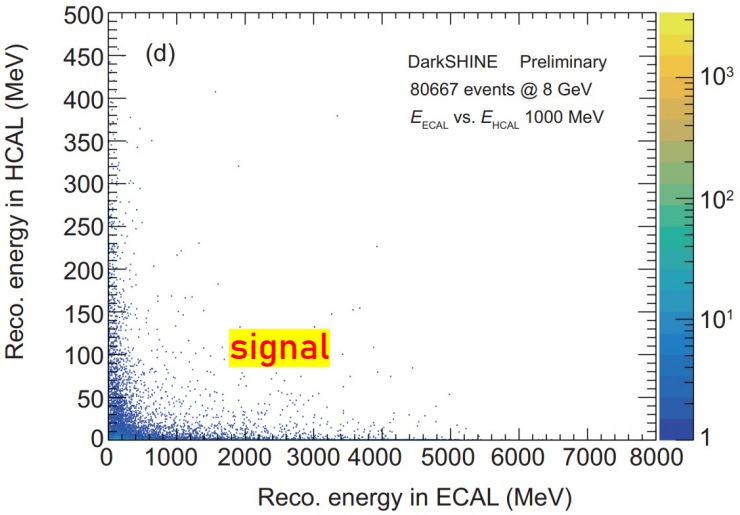


- **Leading background: γ bremsstrahlung**
- **Rare processes include: electron-nuclear, photon-nuclear, γ → μμ**

Background Rejection







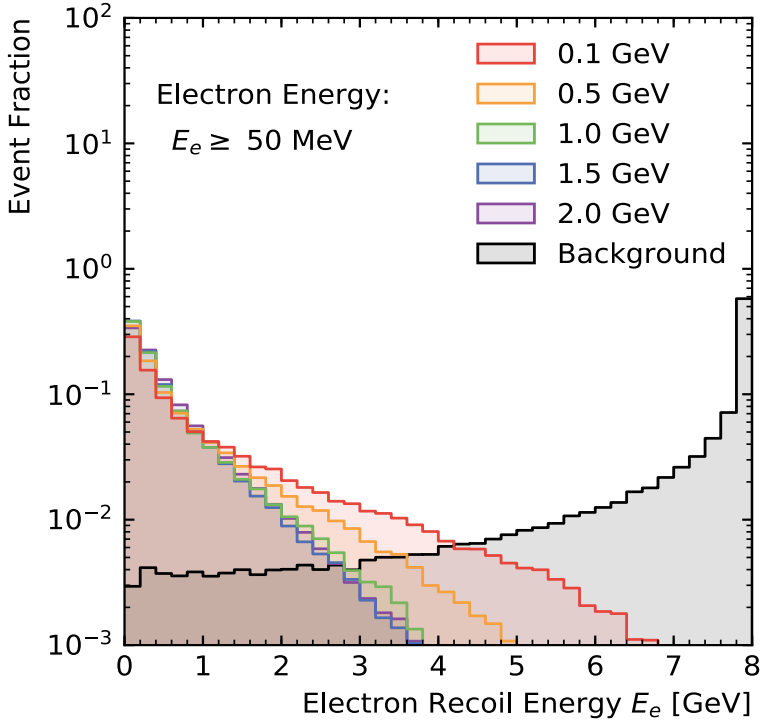
Signal region

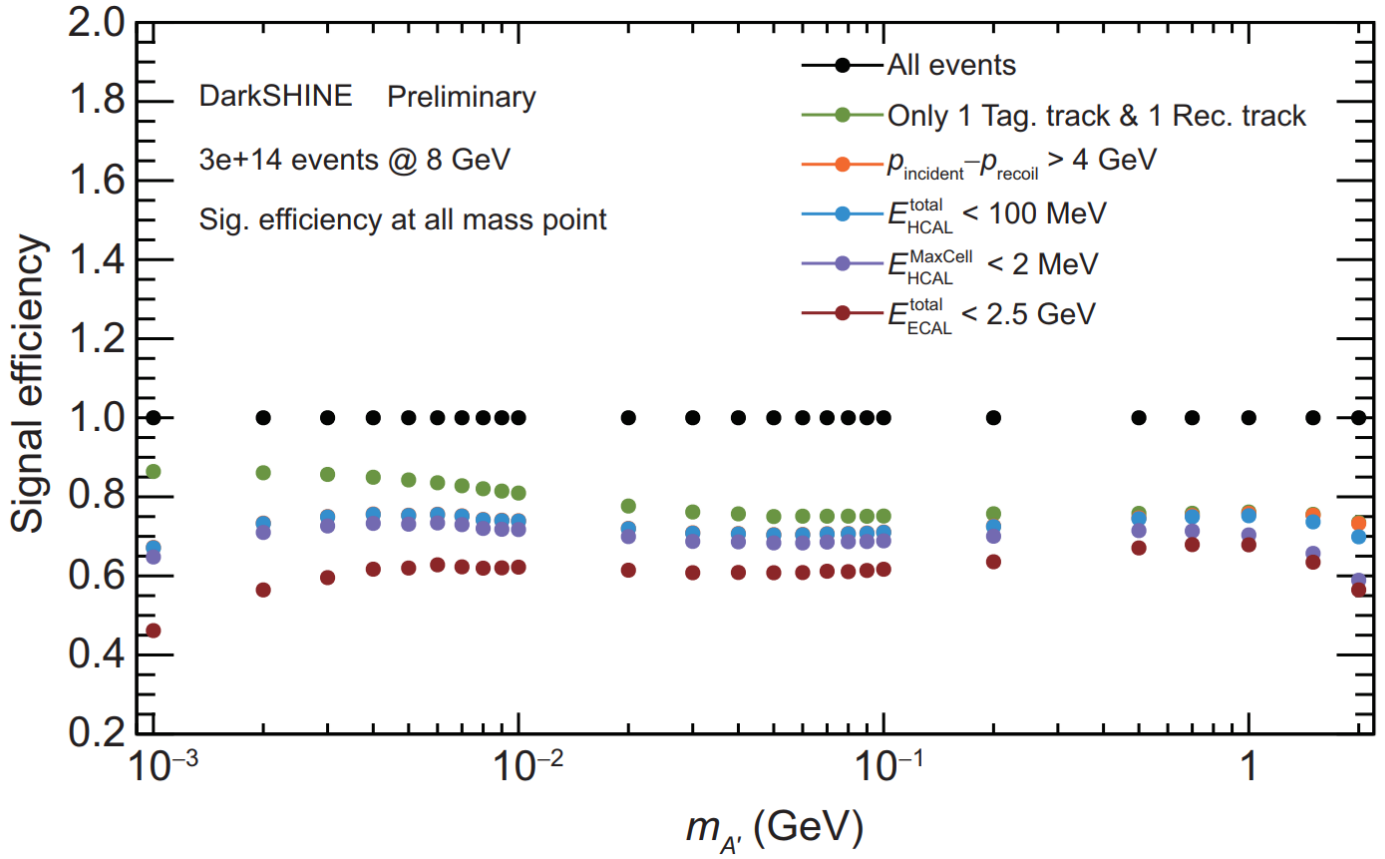
	EN_ECAL	PN_ECAL	GMM_ECAL	EN_target	PN_target	GMM_target	Hard_brem	Inclusive
Total events	100	100	100	100	100	100	100	100
Only 1 track	58.87	70.48	87.36	5.85	5.88	$< 10^{-3}$	78.73	84.40
$p_{tag} - p_{rec} > 4$ GeV	0.0044	0.0033	0.0041	5.58	5.46	$< 10^{-5}$	70.49	4.80
$E^{total}_{HCAL} < 100$ MeV	$< 10^{-3}$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

Zero background can be achieved, for 2.5×10^{9} inclusive EOTs and ~10^{12} rare EOTs!

Dark Photon Efficiency

- After applying all cuts in signal region, a signal efficiency of around 60% can still be achieved.





Sensitivity study

- **Prospective sensitivity is competitive**
- **Expected limit on the ε^2 as a function of A' mass at 90% C.L. is estimated with predicted luminosity**

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Physics, Mechanics & Astronomy
• Article •
Editor's Focus
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https://doi.org/10.1007/s11433-022-1983-8
Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)
Editor's Focus

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

First publication!

Jun Guo[2,3], [3,4,5*], Meng Lv[7], Ze-Jia Lu[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

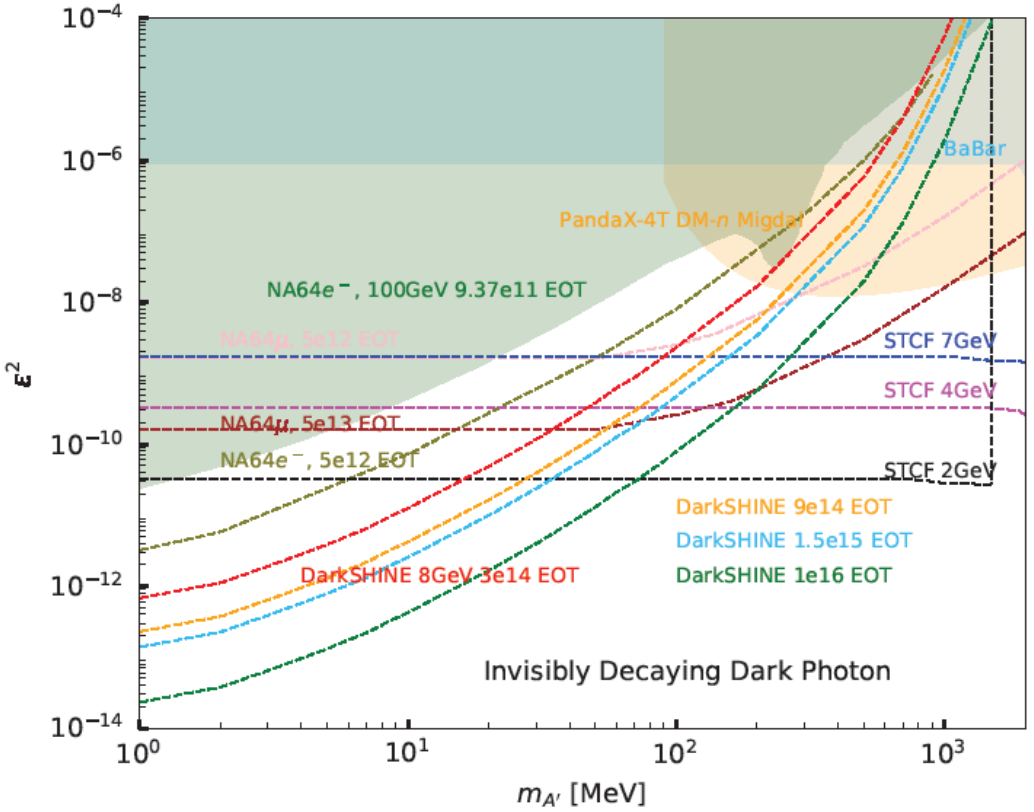
Baseline Design Report

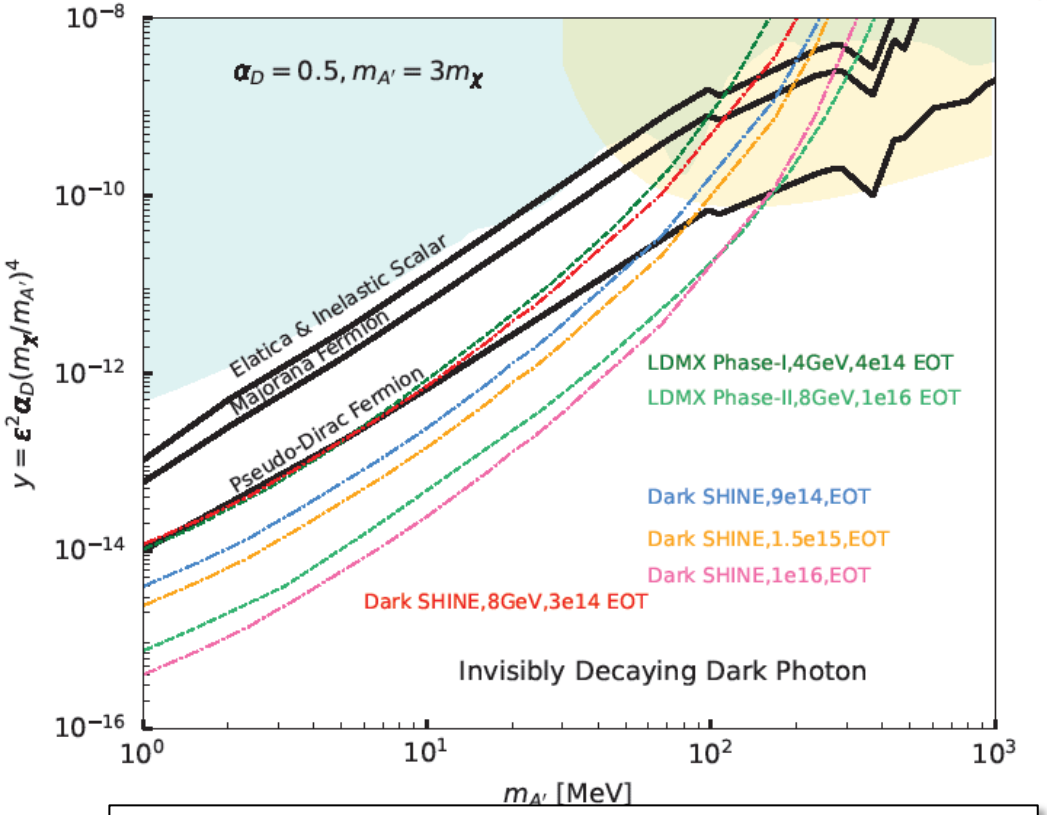
Physics Prospects and Detector Technologies

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[5,9], 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



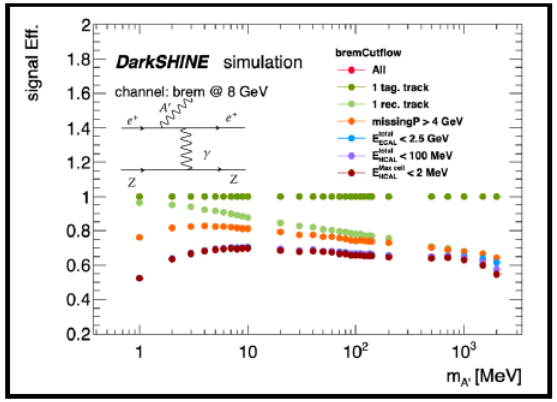


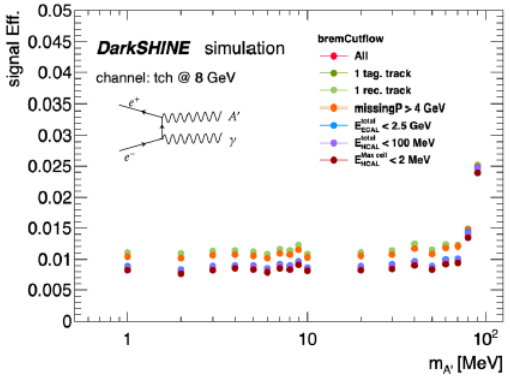
Competitive sensitivity compared with other experiments

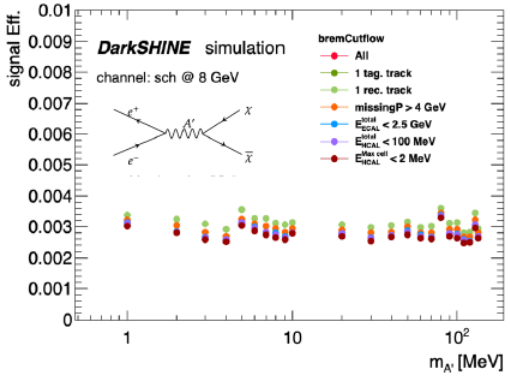
More physics opportunity: Positron-on-Target

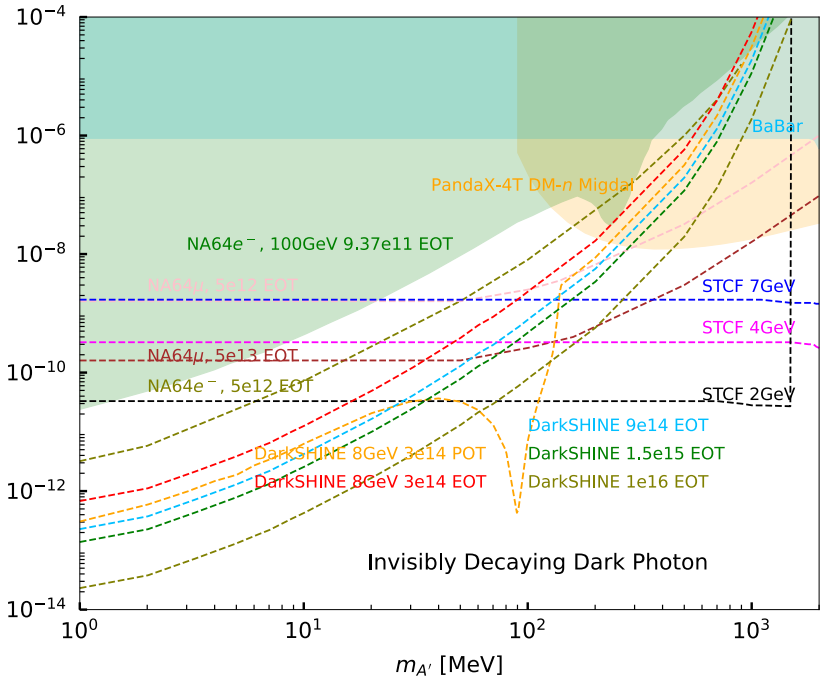
- SHINE can also deliver positron beam with low current
- Signal boxes for three channels are optimized
- Contamination from other signal processes are investigated
- Extrapolation method for variables' cuts, similar to the EOT analysis

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

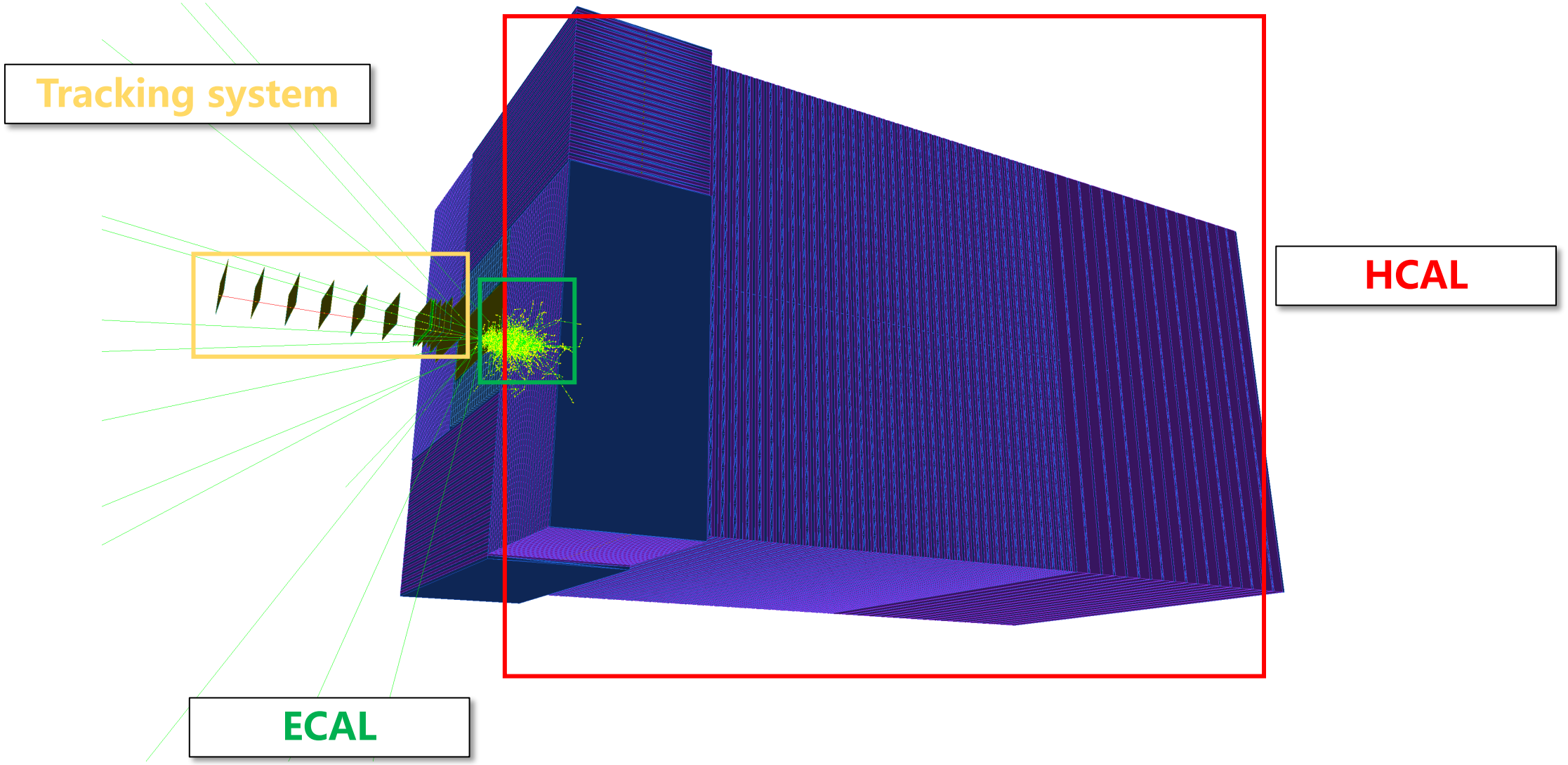






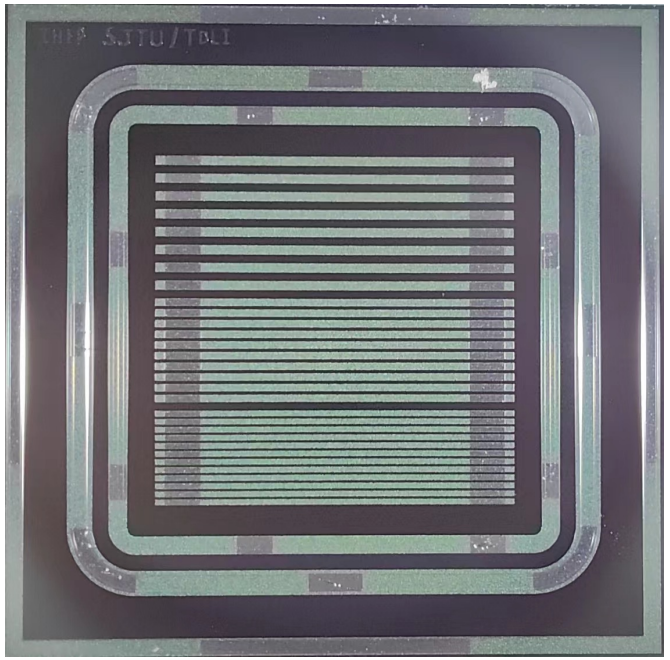


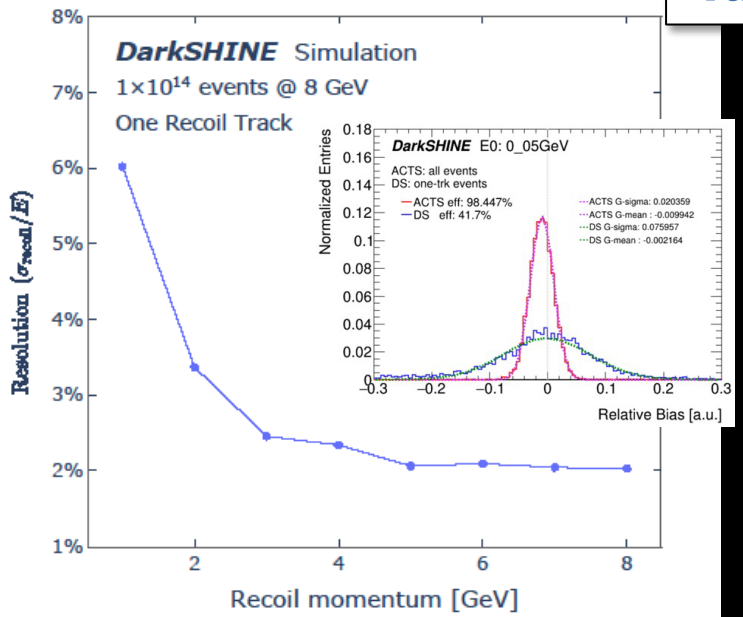
Detector R&D



Detector R&D: Tracking system

- Silicon strips detector under strong magnetic field, ~10 μm position resolution
- 7 layers of tagging + 6 layers of recoil tracker, two silicon strips sensors for each layer
- AC-coupled low-gain avalanche diode (AC-LGAD) silicon strip sensor 1x1 mm^2 for performance study





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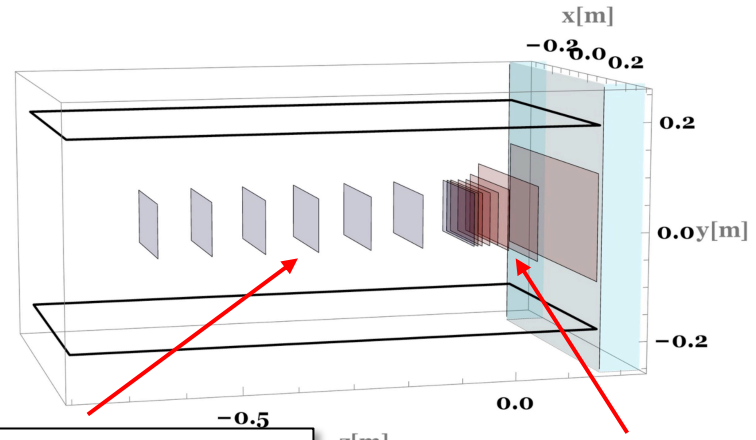
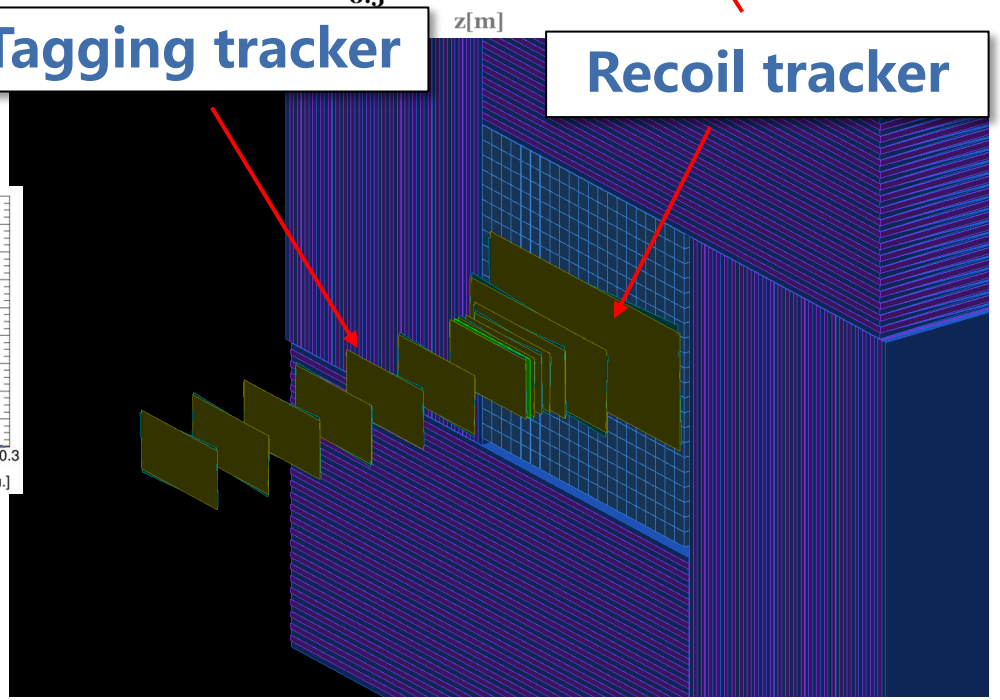
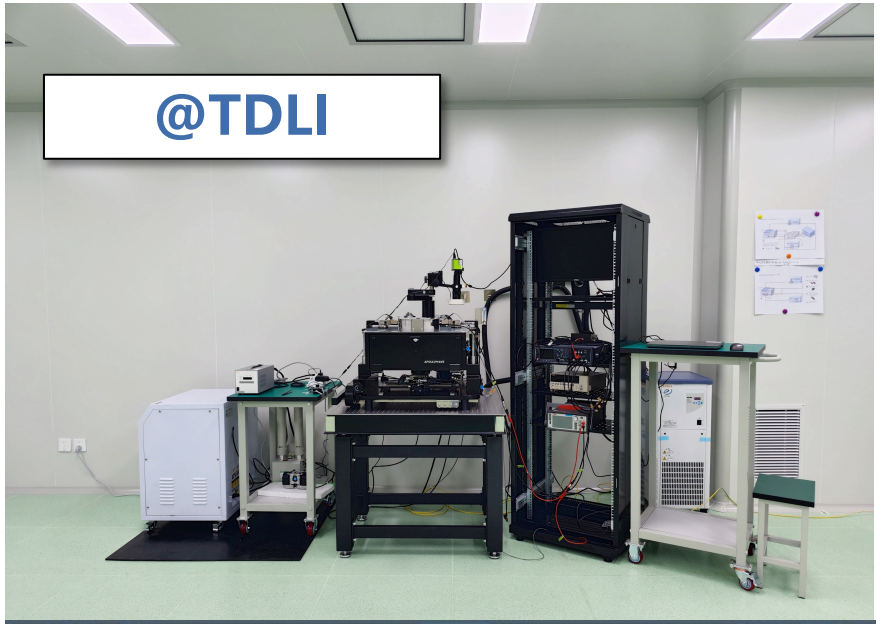
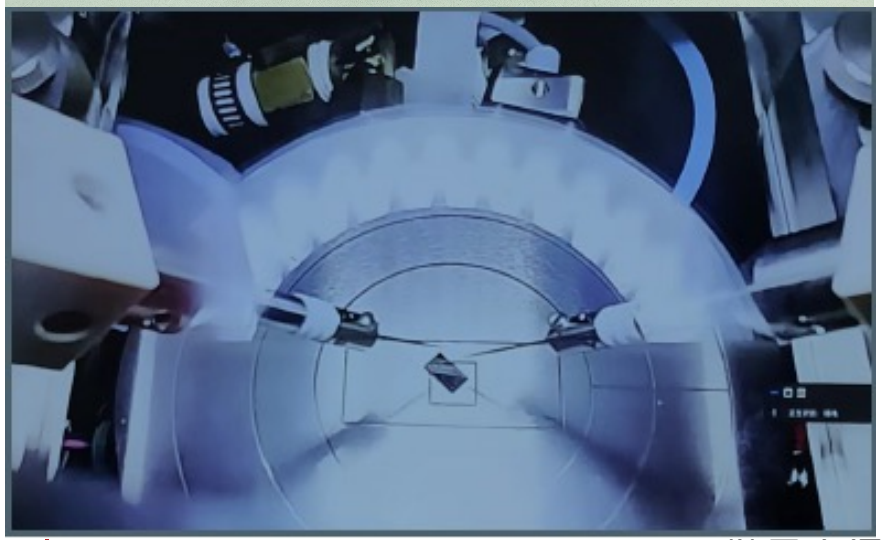


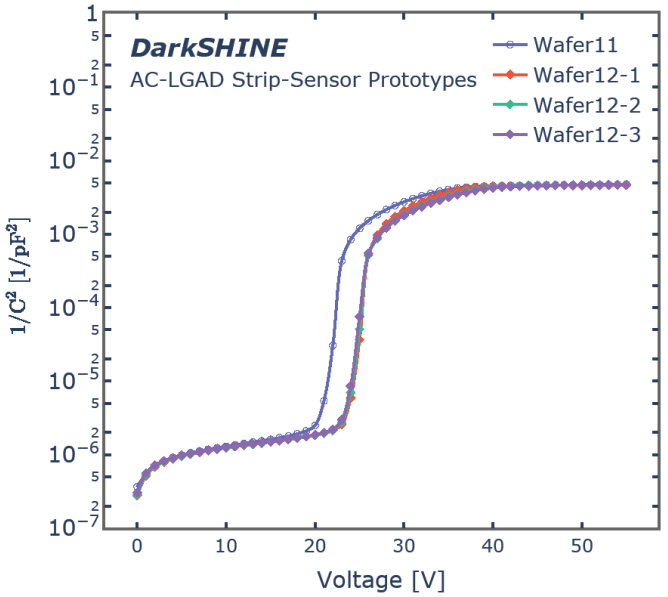


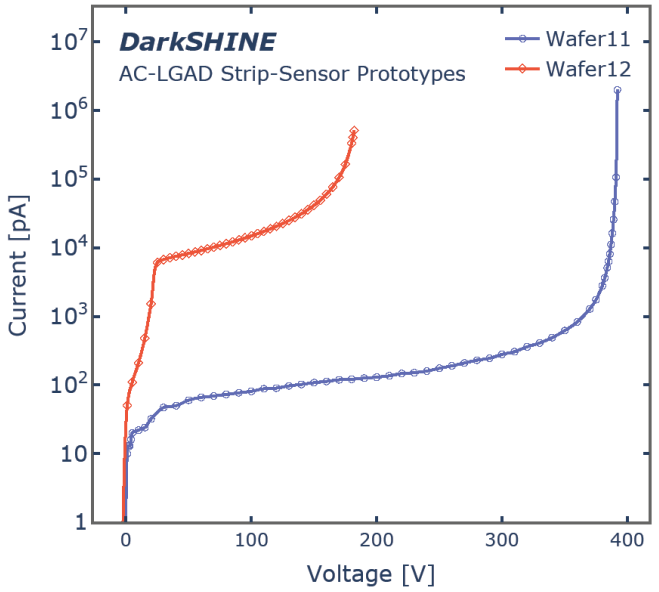
Detector R&D: Tracking system





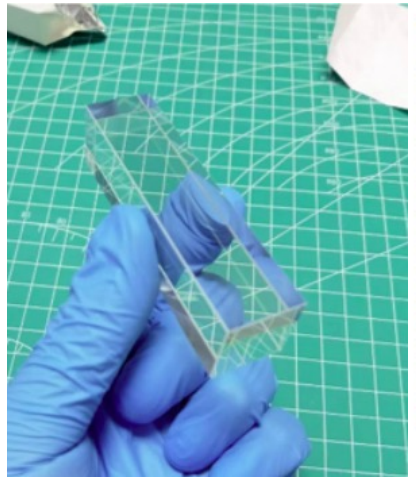
More plots

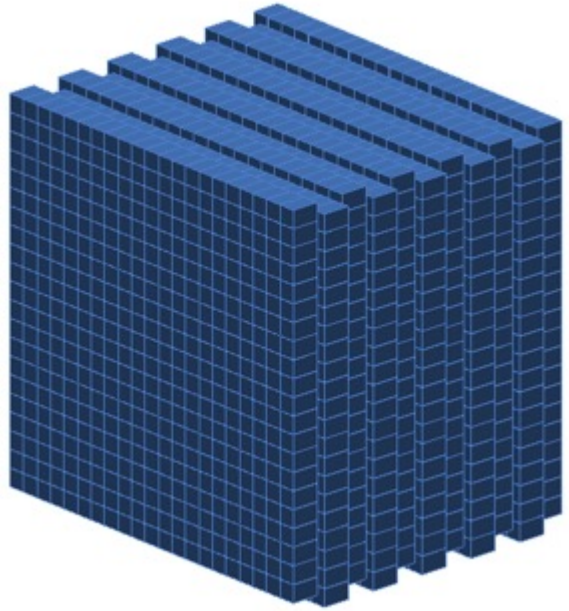


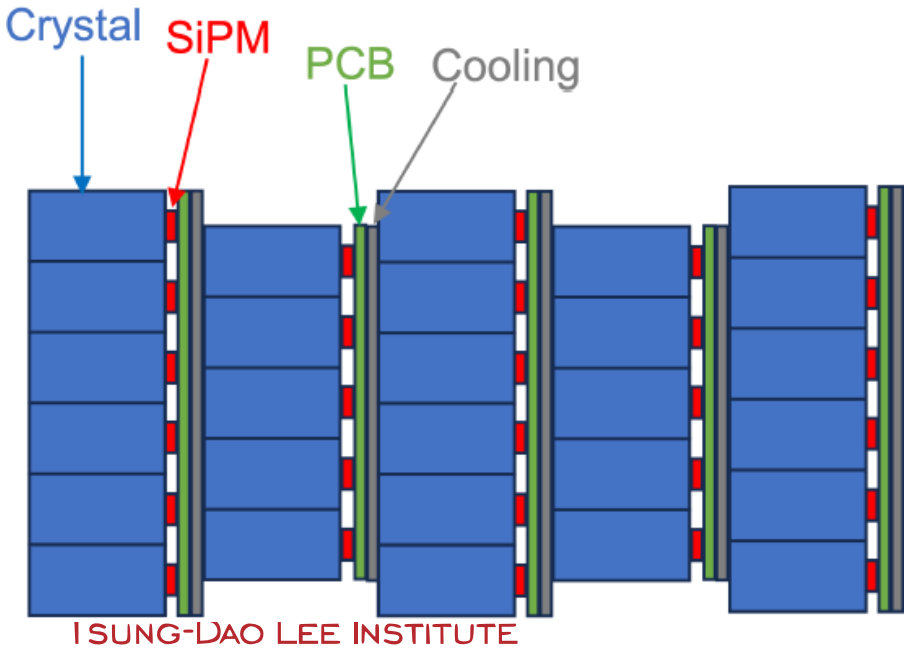


The Electromagnetic Calorimeter and performance

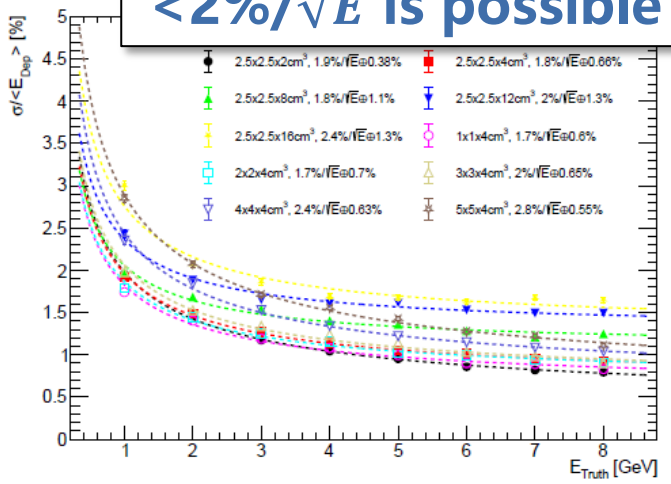
- **Crystal Scintillator + SiPM**
  - **LYSO ($Lu_{(1-x-y)}Y_{2y}Ce_{2x}SiO_5$)**
  - **21×21×11 crystals, 2.5cm×2.5cm×4cm, design has been optimized**
  - **High light yields, short decay time, good radiation resistant**
- **Module has been tested in DESY**

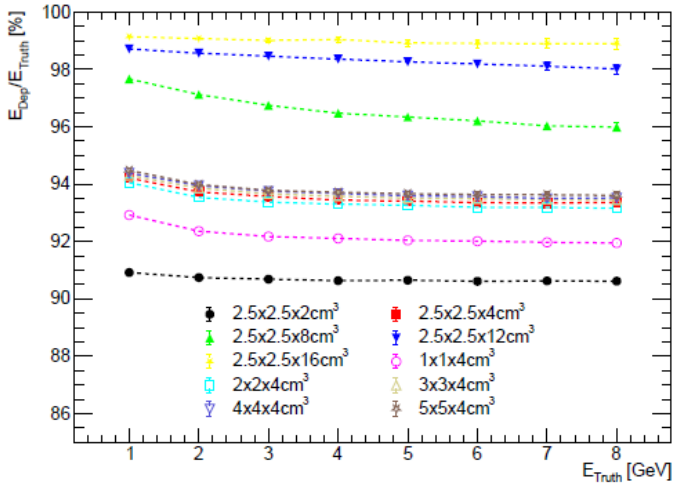






Energy resolution <2%/$\sqrt{E}$ is possible





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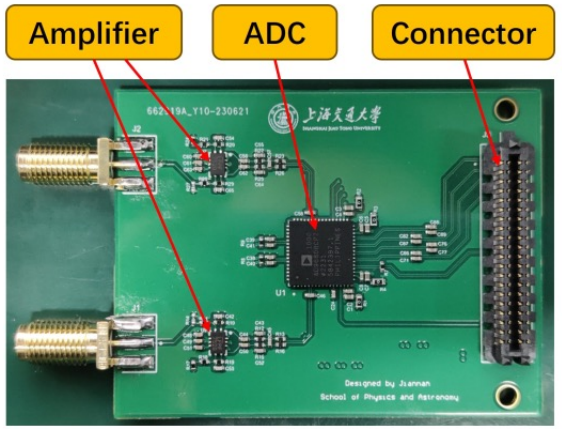
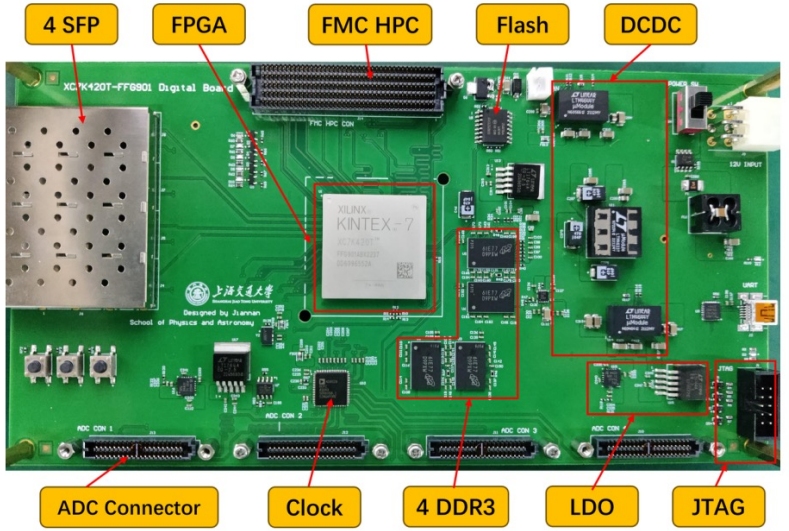
Detector R&D: ECAL prototype

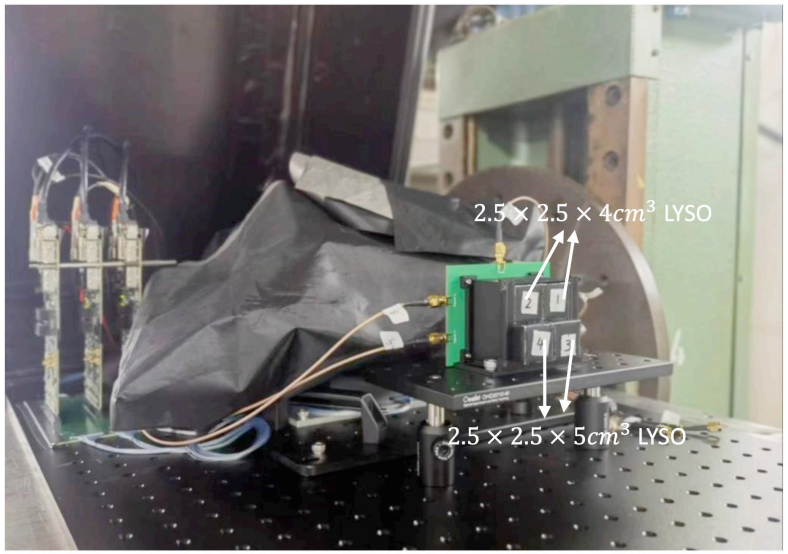
High speed and high precision ADC

ADC: AD9680,

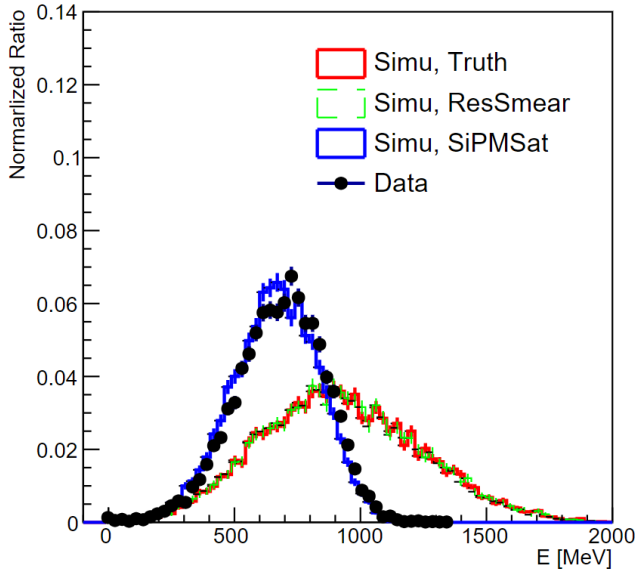
1 GS/s, 14 bit







5GeV



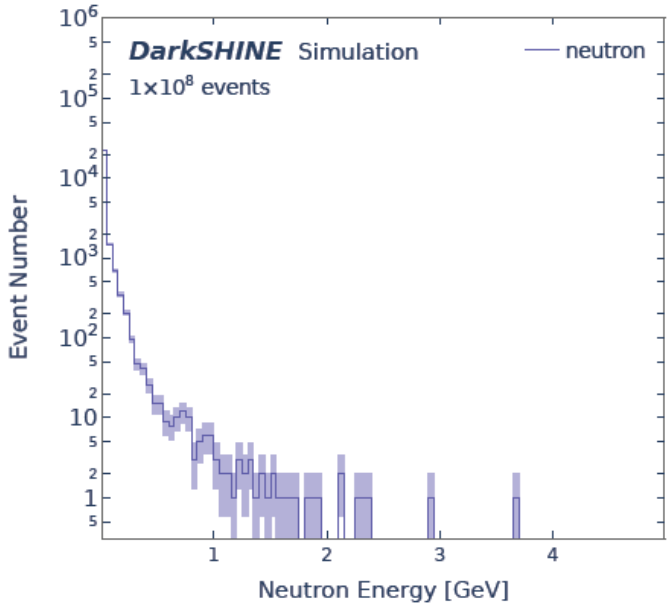
arXiv:2407.20723, submitted to JINST

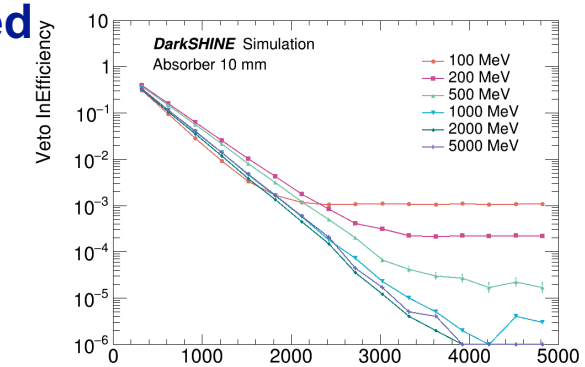
- **LYSO unit test has been done**
- **1st prototype module for beam test (2x2 LYSO) at DESY**
- **New read-out has been designed and the sets of readout system has been further developed**
  - **1 MHz repetition rate**

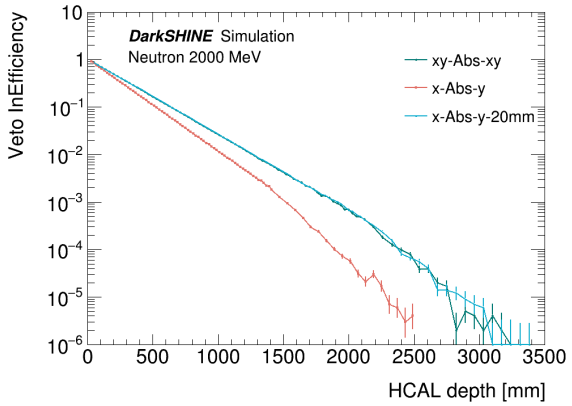
The Hadronic Calorimeter and performance

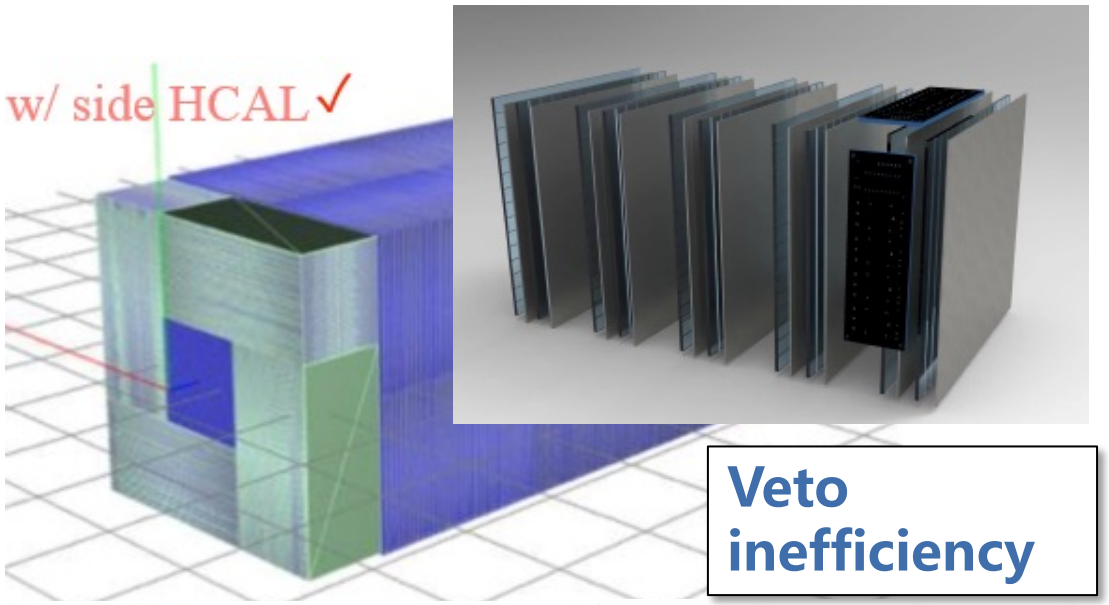
Nucl.Sci.Tech. 35 (2024) 9, 148

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

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: *arxiv:2411.09345*
  - ***With data collection by 2026 and more physics opportunities ahead, stay tuned!***

Thanks for listening!

Backup

Dark Photon Theory in a nutshell

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

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

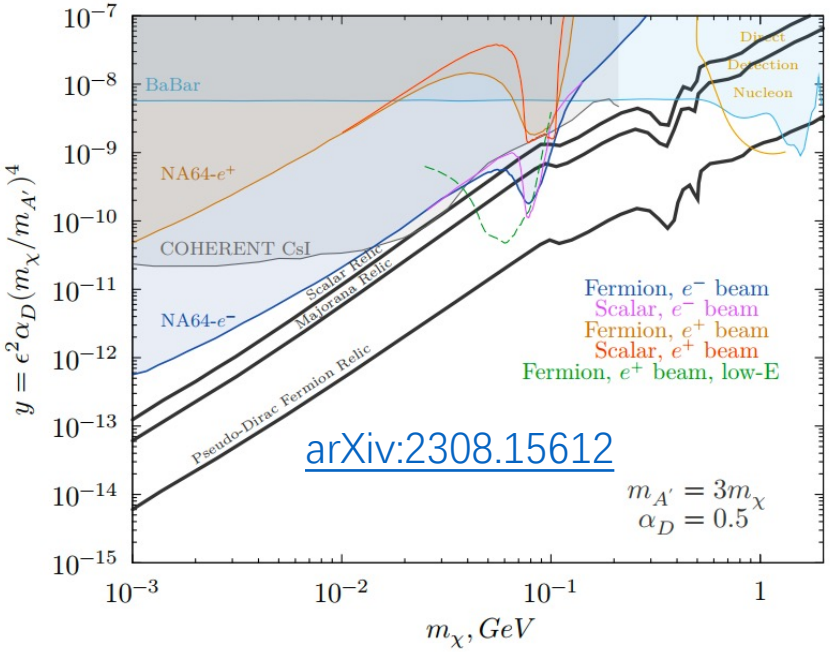
SM Photon γ **Dark Photon A′**

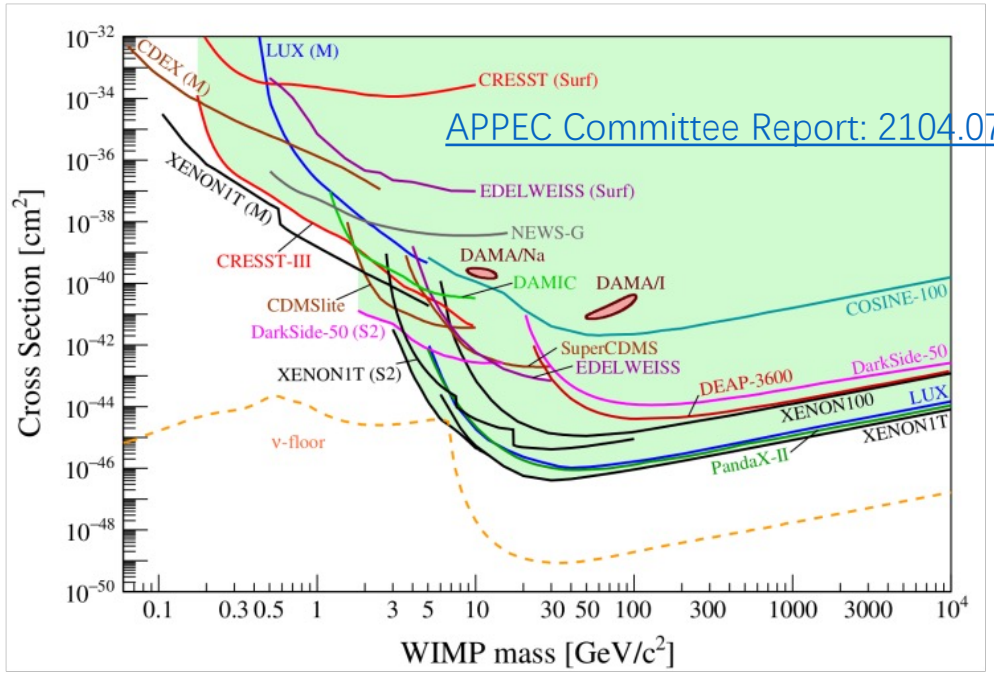
$$\varepsilon X_{\mu\nu}F^{\mu\nu}$$

- 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)

Dark Matter: Search for LDM & WIMP



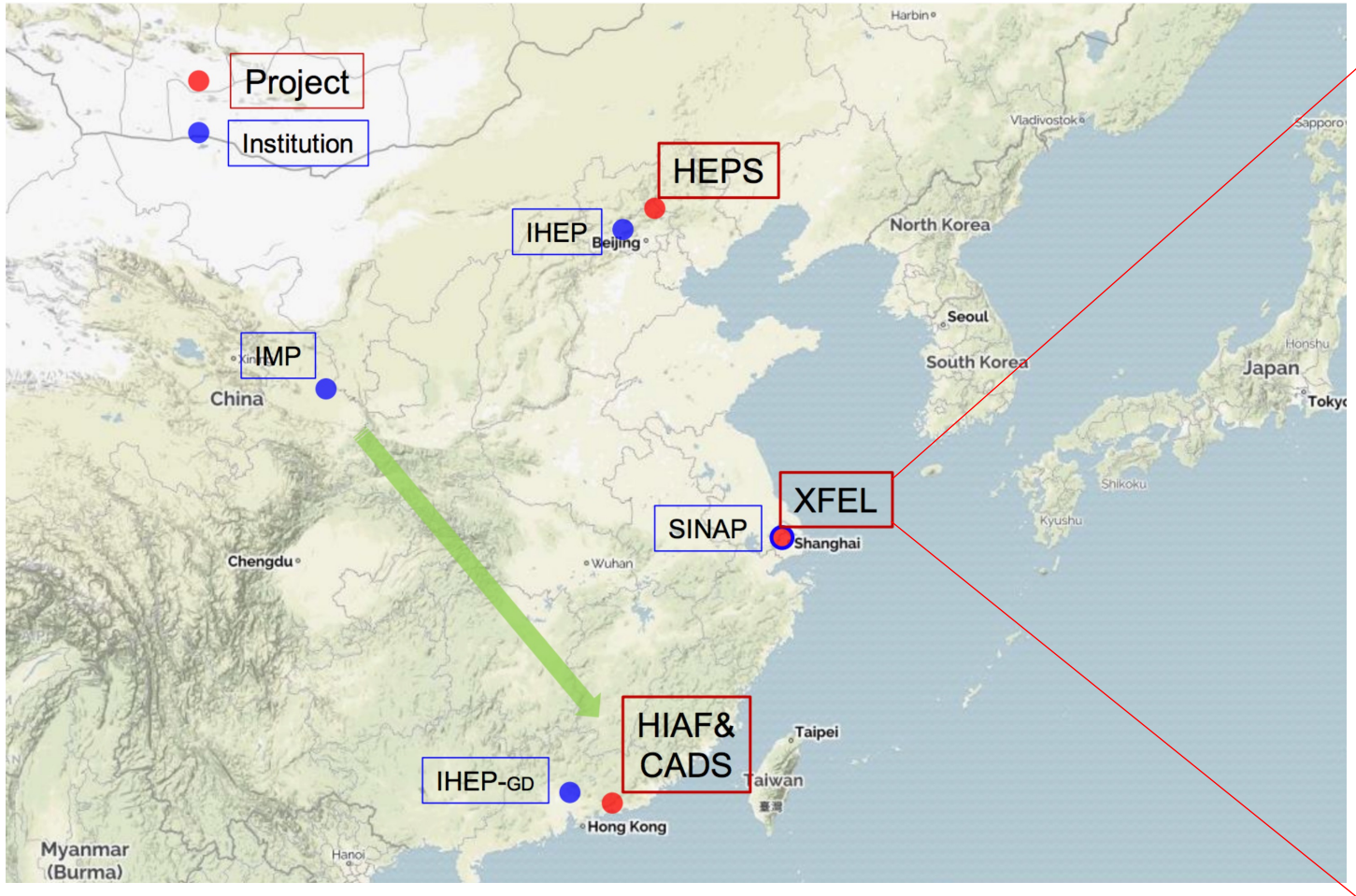


APPEC Committee Report: 2104.07634

- **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.**

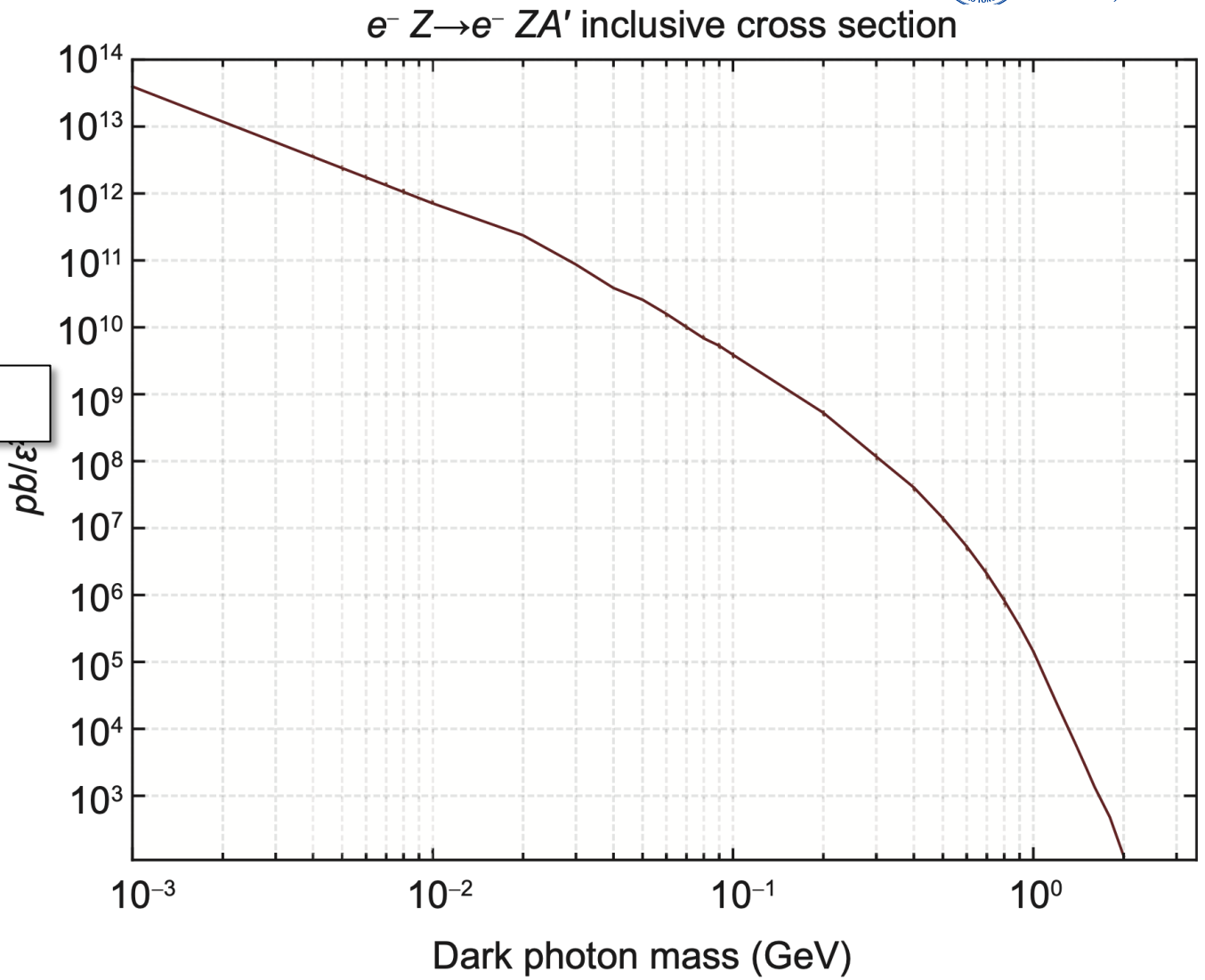
- **WIMPs: GeV ~ TeV**
  - **Space experiments (DAMPE, AMS, etc.)**
  - **Collider experiments (LHC, BELLE-II, BESIII, etc.)**
  - **Underground experiments (PandaX, CDEX, LUX, Xenon, etc.)**

The SHINE facility



Dark photon XS

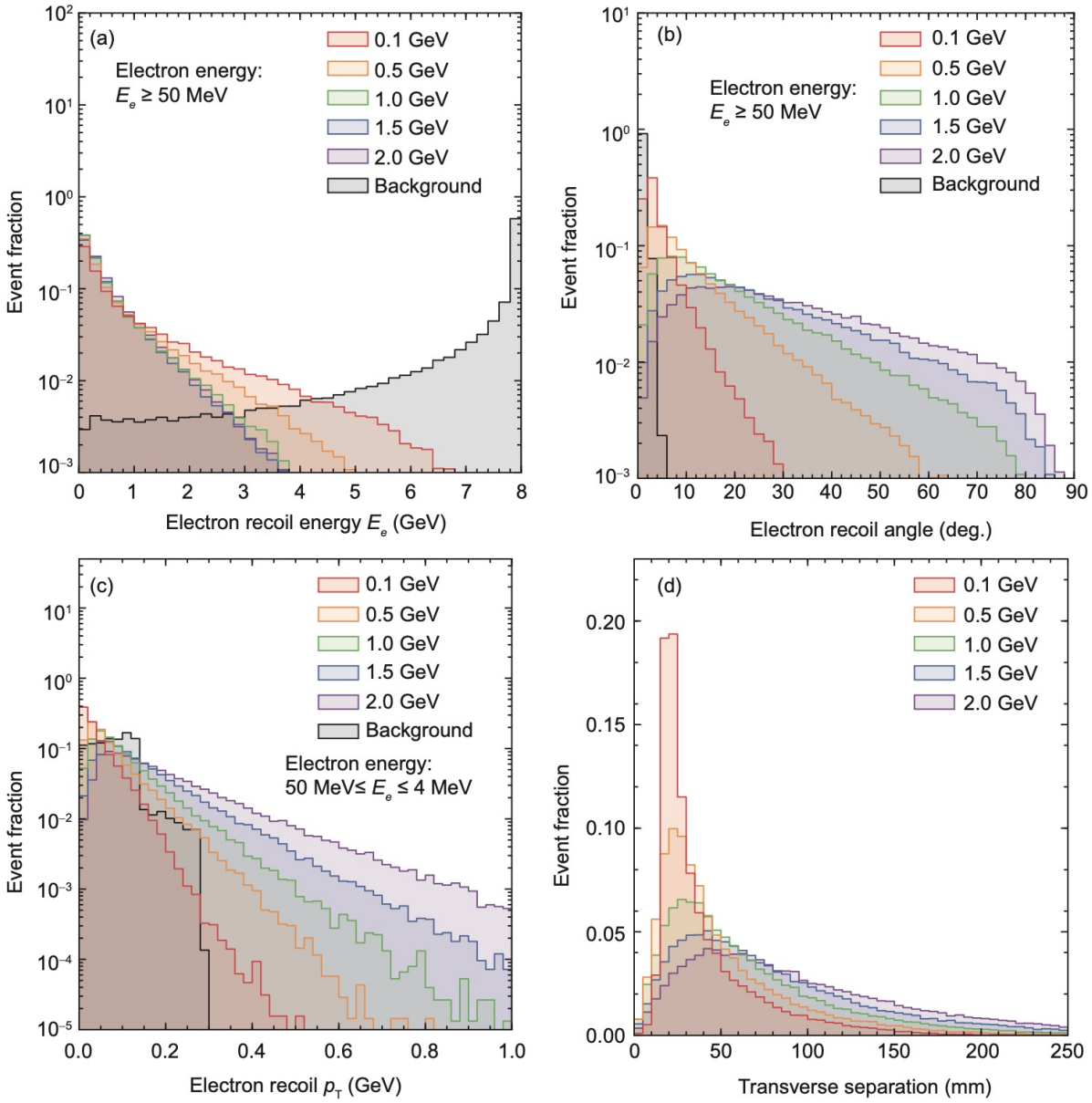
XS with $\varepsilon^2 = 1$



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



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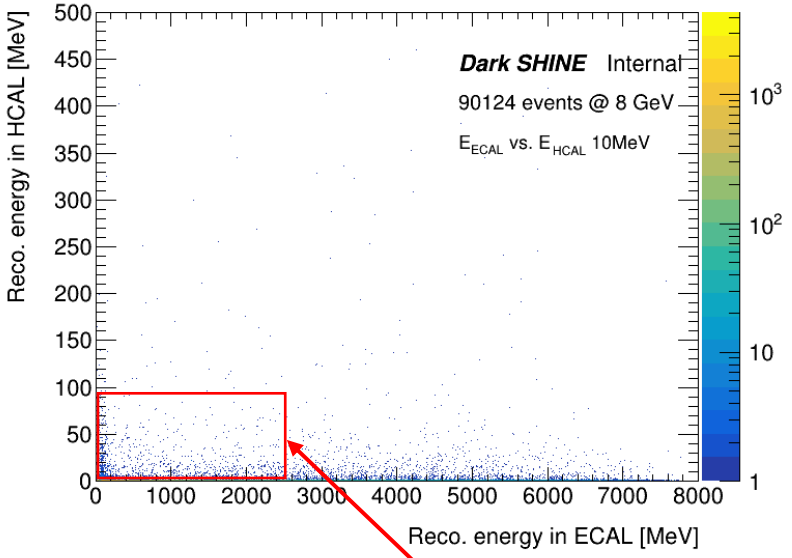
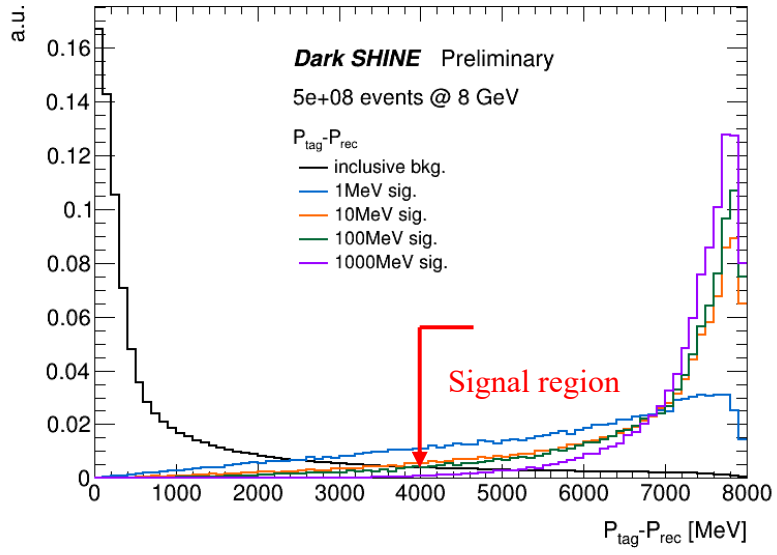
Signal-box design

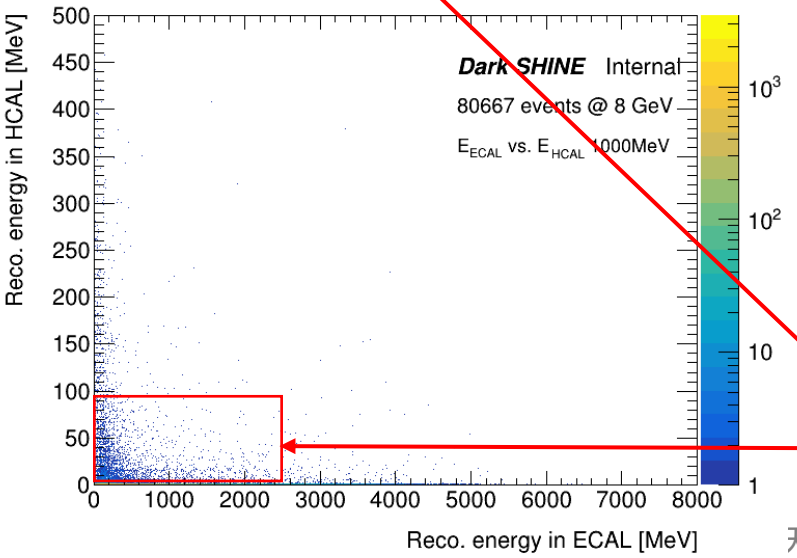
10 MeV A′

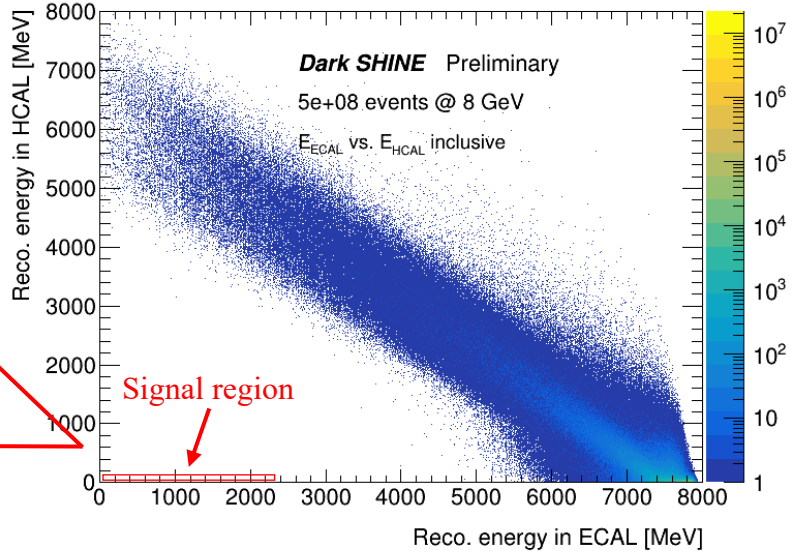




Inclusive bkg & signal

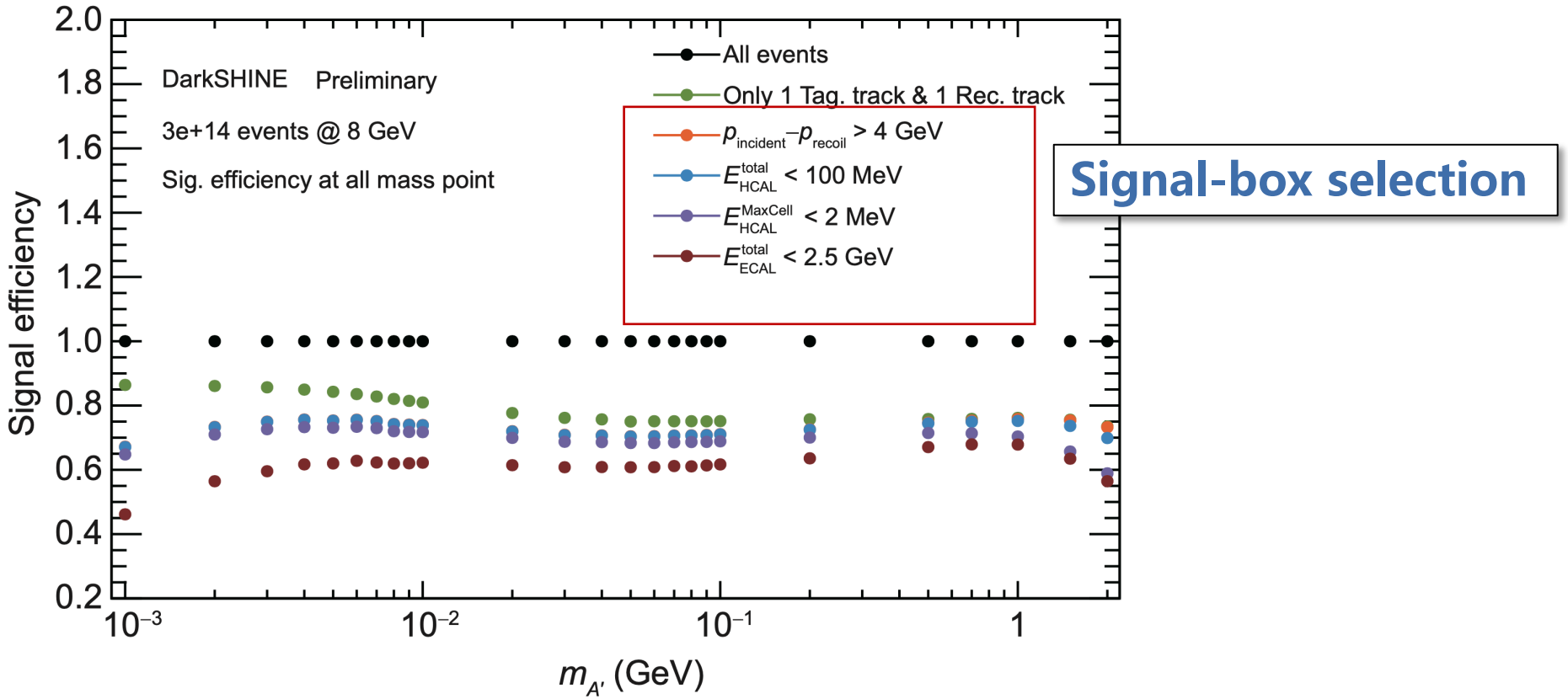
1 GeV A′





Inclusive bkg

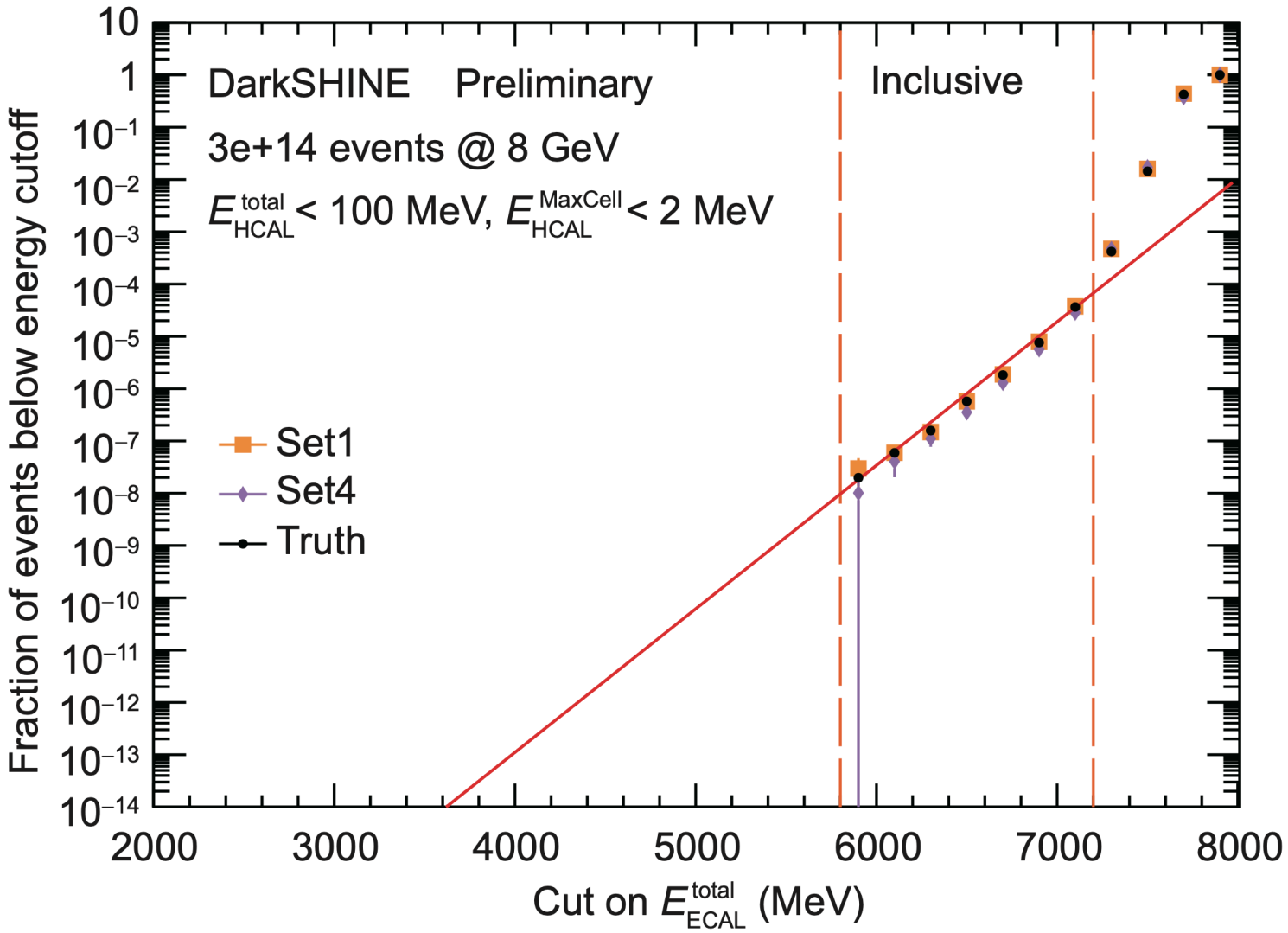
Acceptance efficiency



Signal-box selection

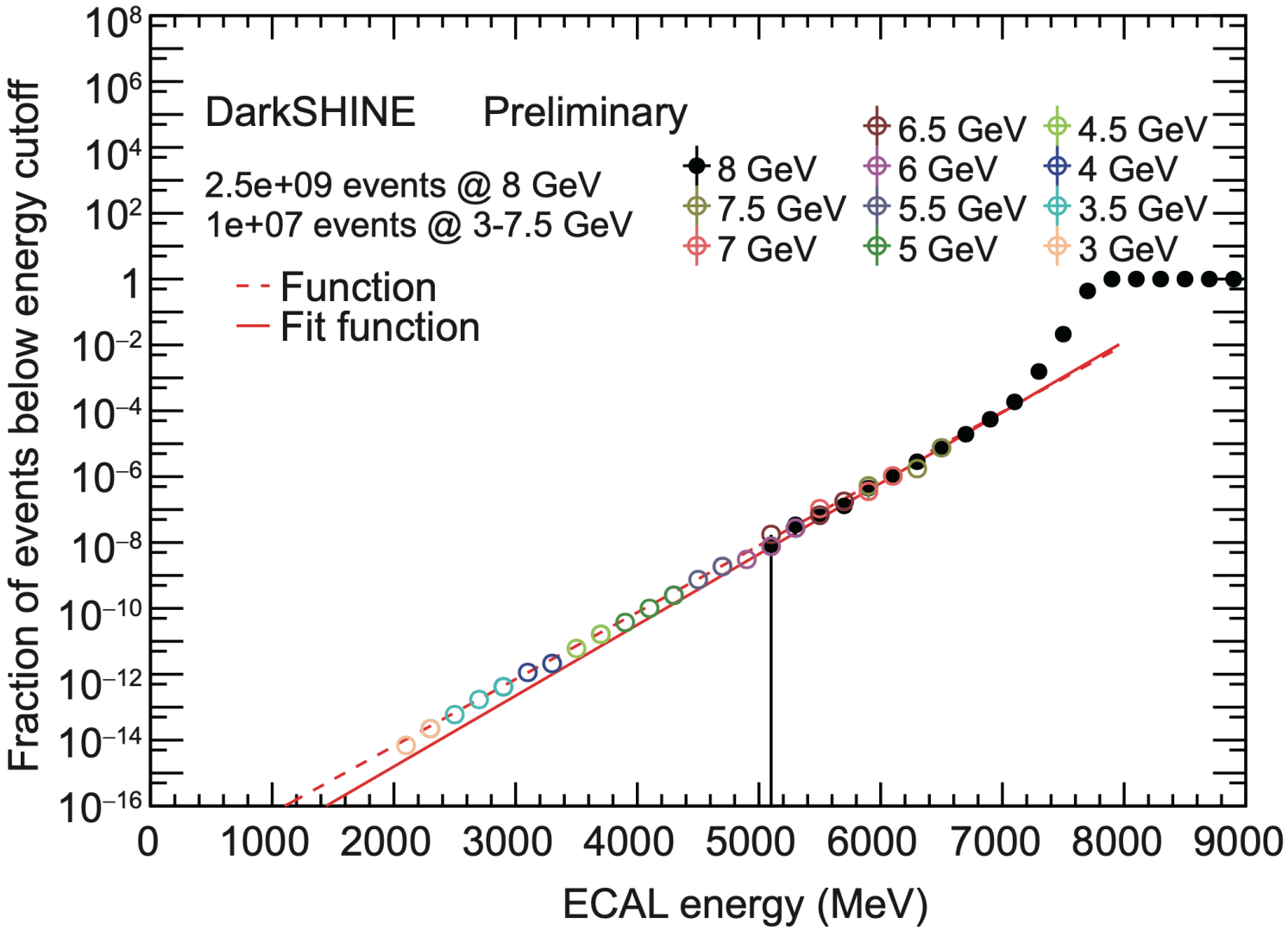
- **60% signal events survive the cut-flow, no background survive (2.5e9)**
- **Acceptance efficiency drops in:**
  - **Low-mass region of a few MeV: tight energy cuts.**
  - **High-mass region above 1 GeV: particles with large incident/recoil angle go into the HCAL directly.**

Background estimation



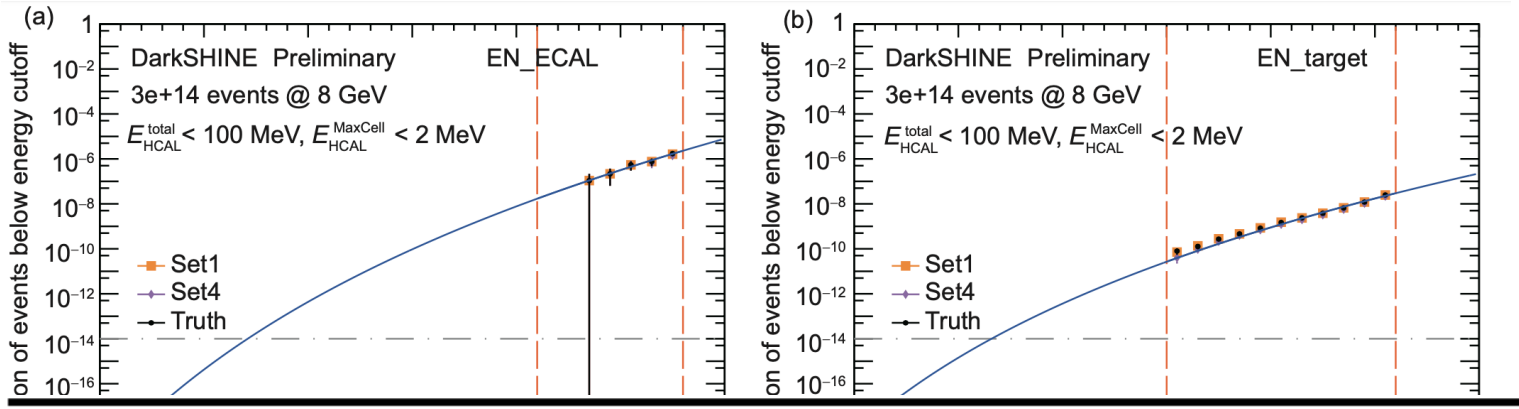
- **Expected background yields go down quickly at lower ECAL energy.**
- **In order to estimate background yields in 10^{14} EOT, extrapolation method is used**
  - **fit from inclusive background process**

Background estimation



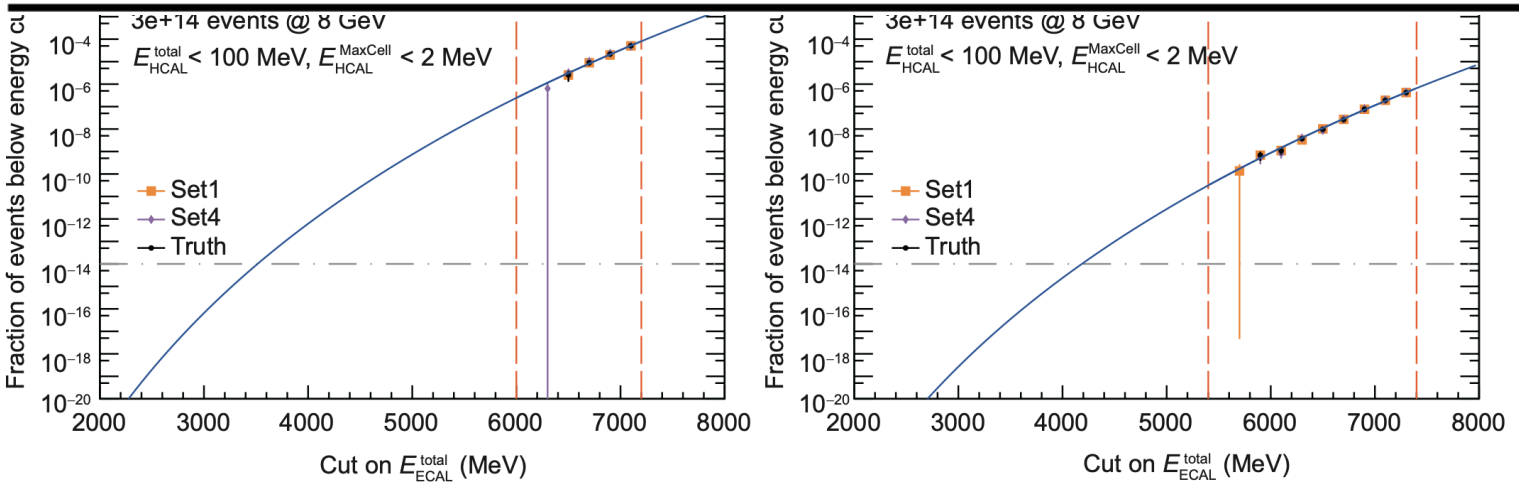
- **Expected background yields go down quickly at lower ECAL energy.**
- **In order to estimate background yields in 10^{14} EOT, extrapolation method is used**
  - **fit from inclusive background process**
  - **extrapolation from low energy samples**

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



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

More physics opportunities…

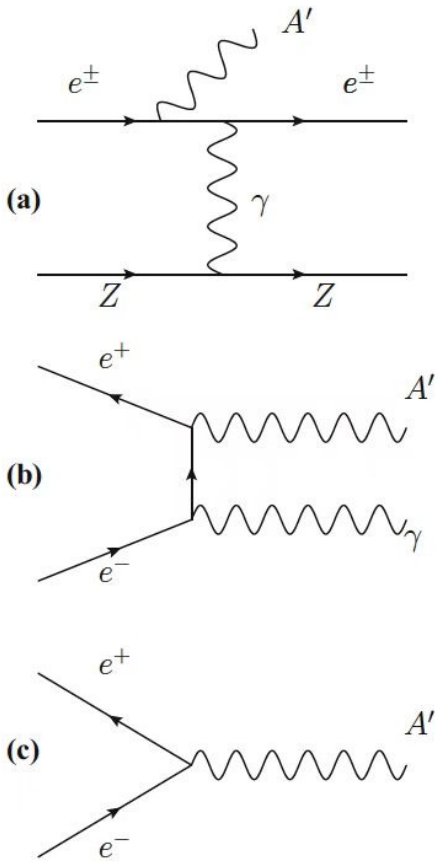
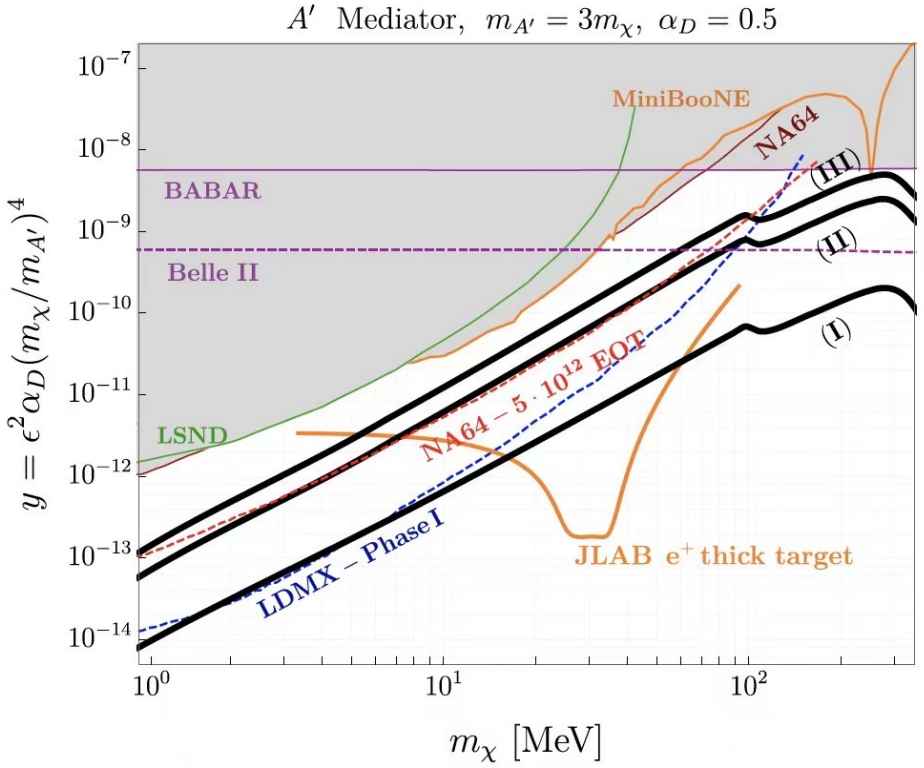


Fig. 1 Three different A' production modes in fixed target lepton beam experiments: (*a*) A'-strahlung in e^-/e^+-nucleon scattering; (*b*) A'-strahlung in e^+e^- annihilation; (*c*) resonant A' production in e^+e^- annihilation



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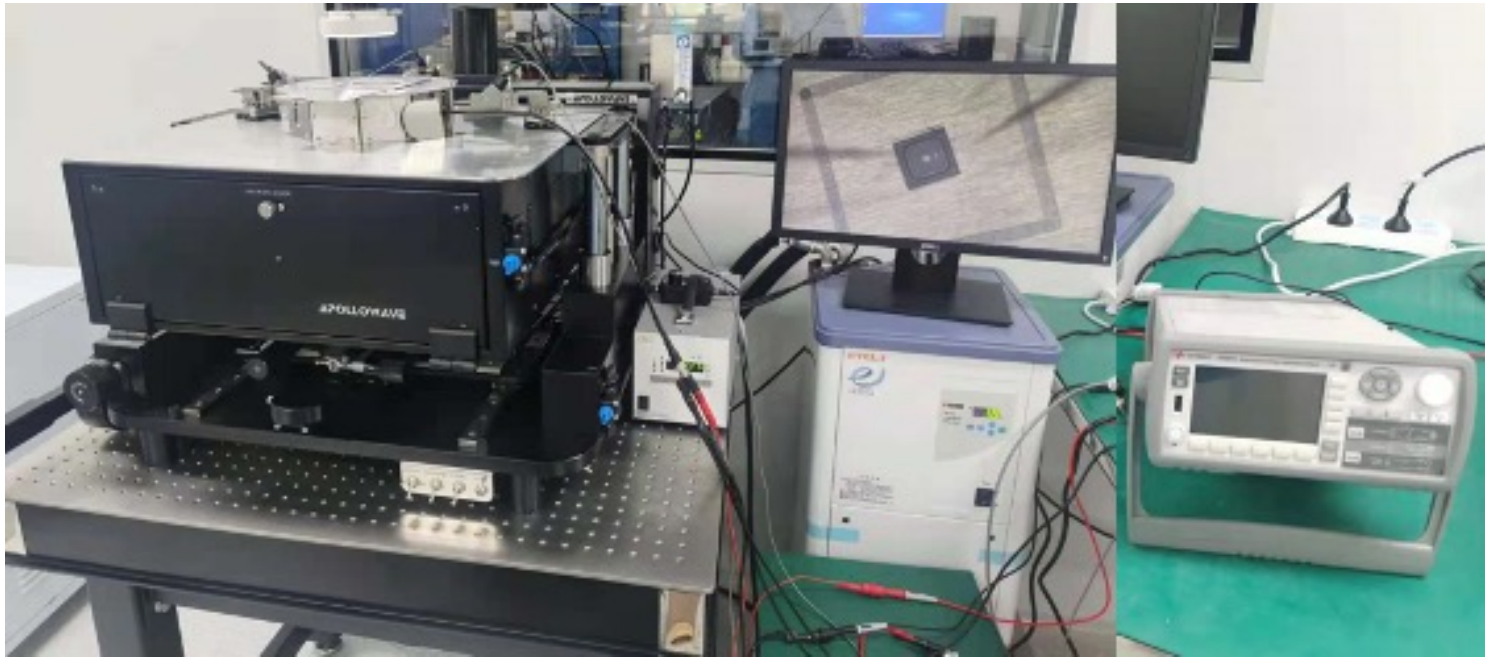
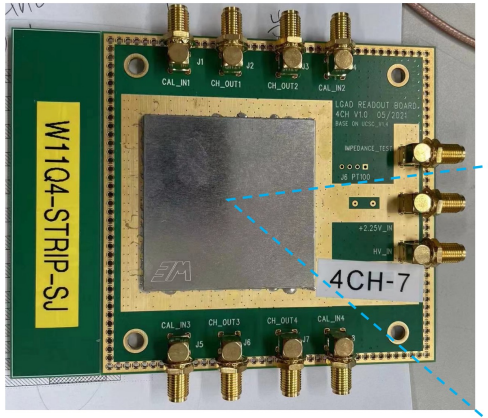
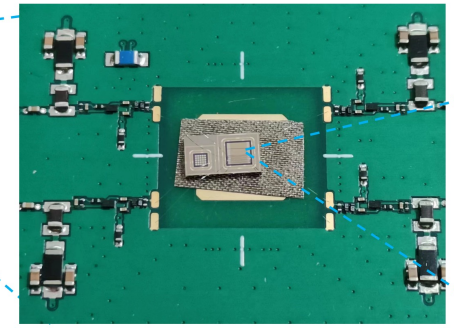
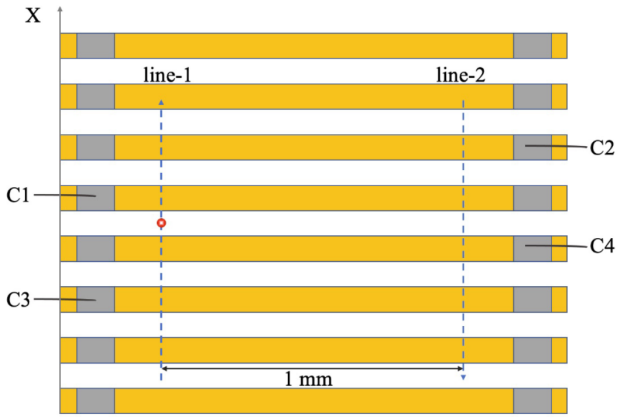
Tracking system

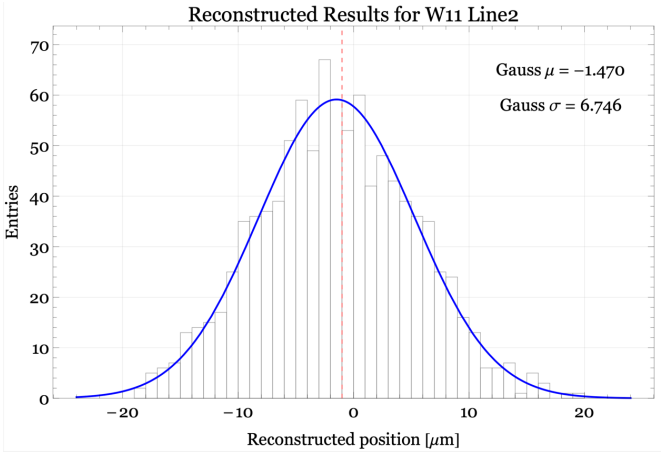


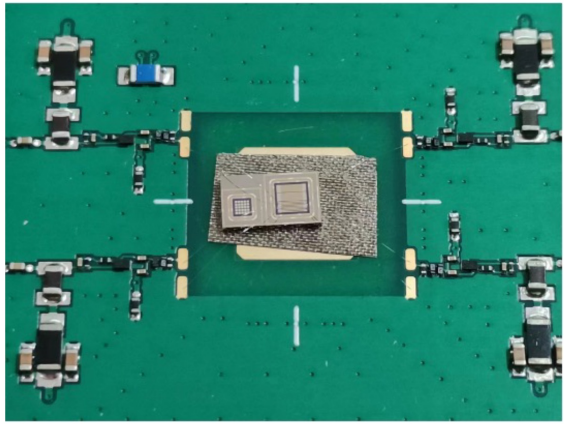


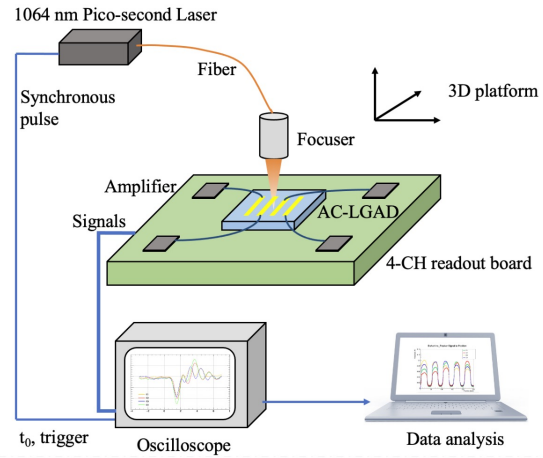


Working point
W11: 350V
W12: 150V



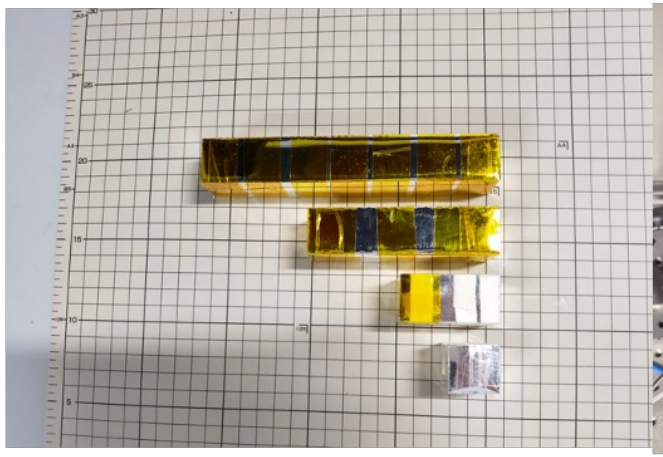




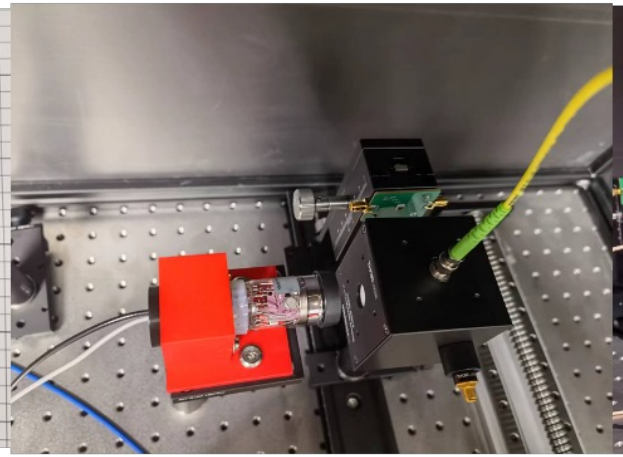


ECAL: crystal test

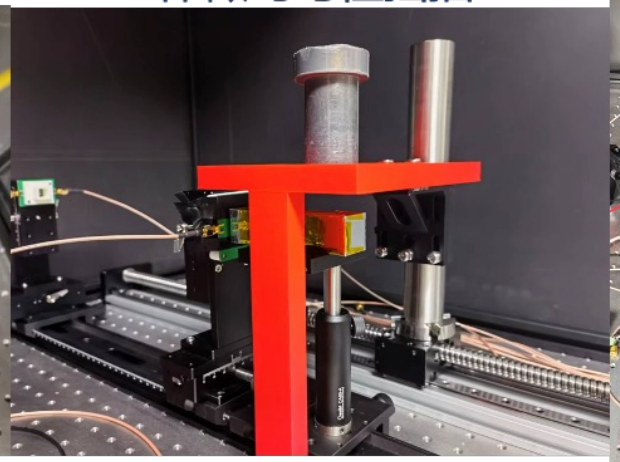
LYSO晶体切割与包裹



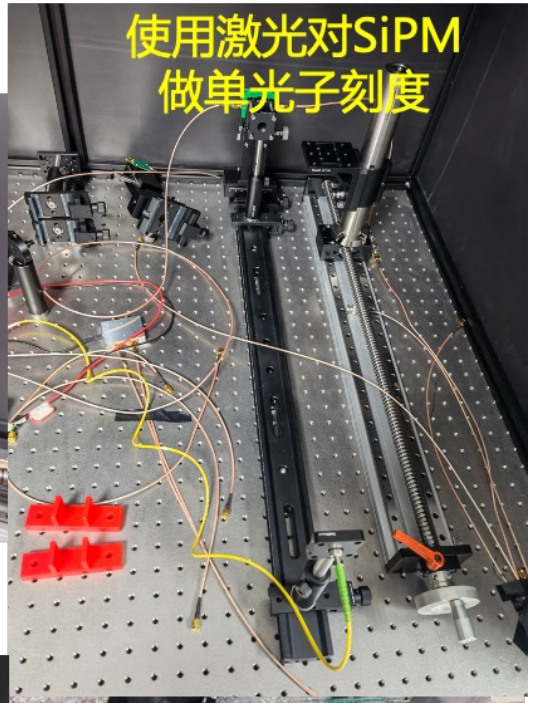
SiPM动态范围测试



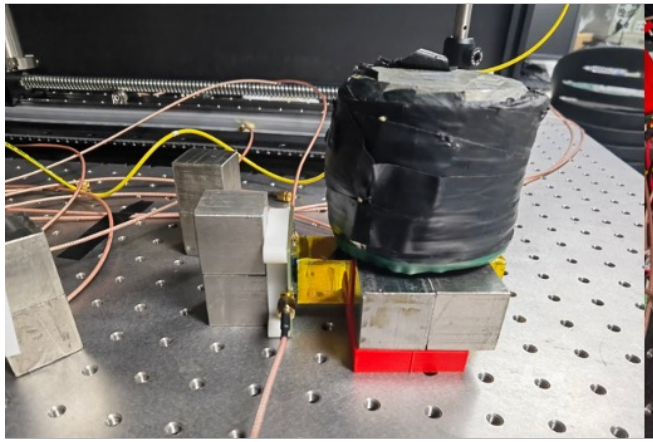
使用放射源对晶体做均匀性扫描



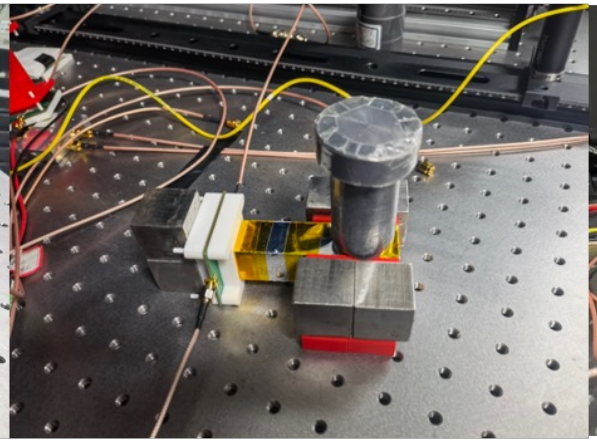
使用激光对SiPM做单光子刻度



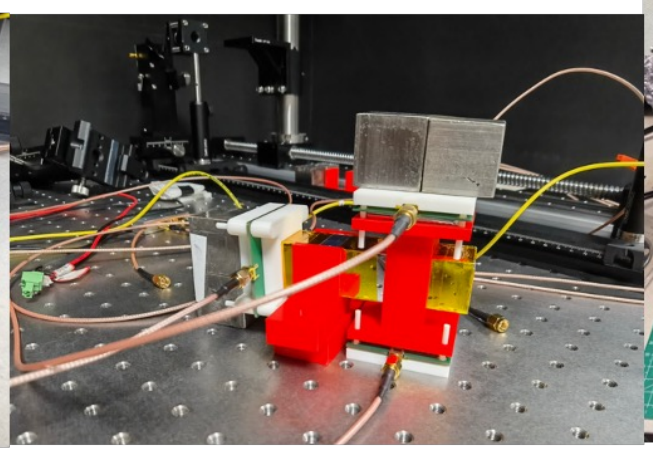
LYSO晶体^{137}Cs测试



LYSO晶体^{60}Co测试



宇宙线测试上下符合

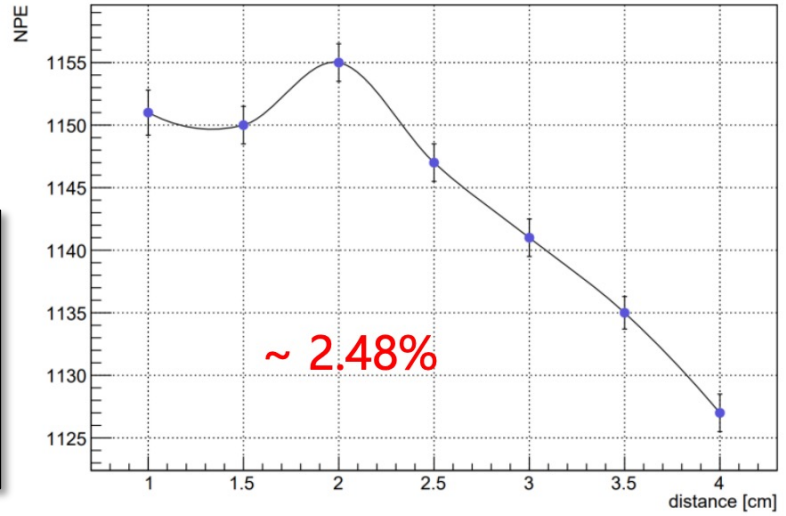


研究反射膜窗口大小对光产额的影响

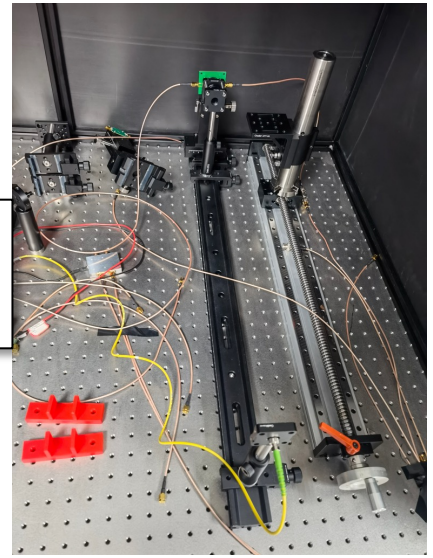
Detector R&D: Electromagnetic calorimeter

5cm LYSO

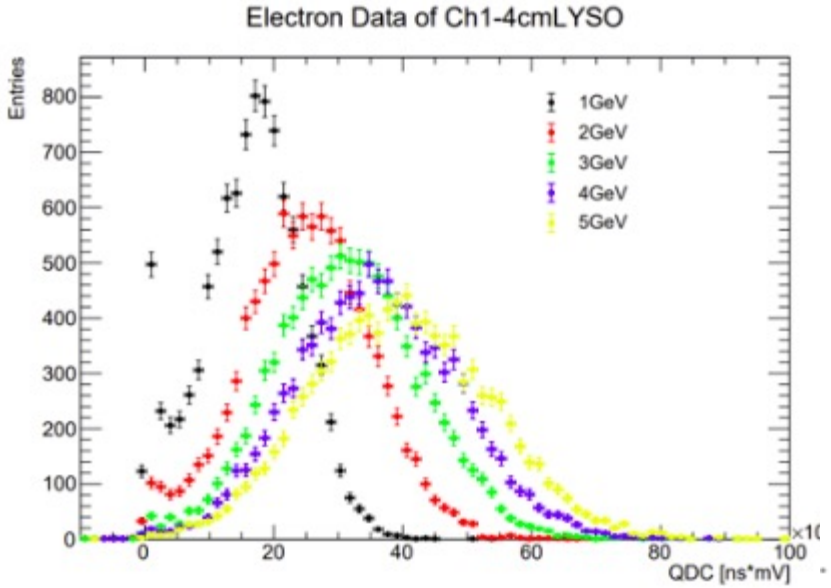
Uniformity scan with using ^{60}Co

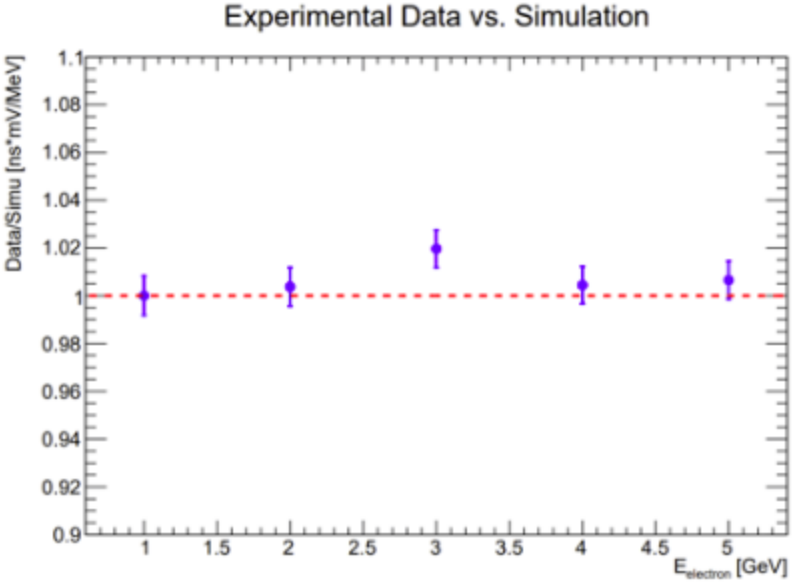


SiPM laser calibration

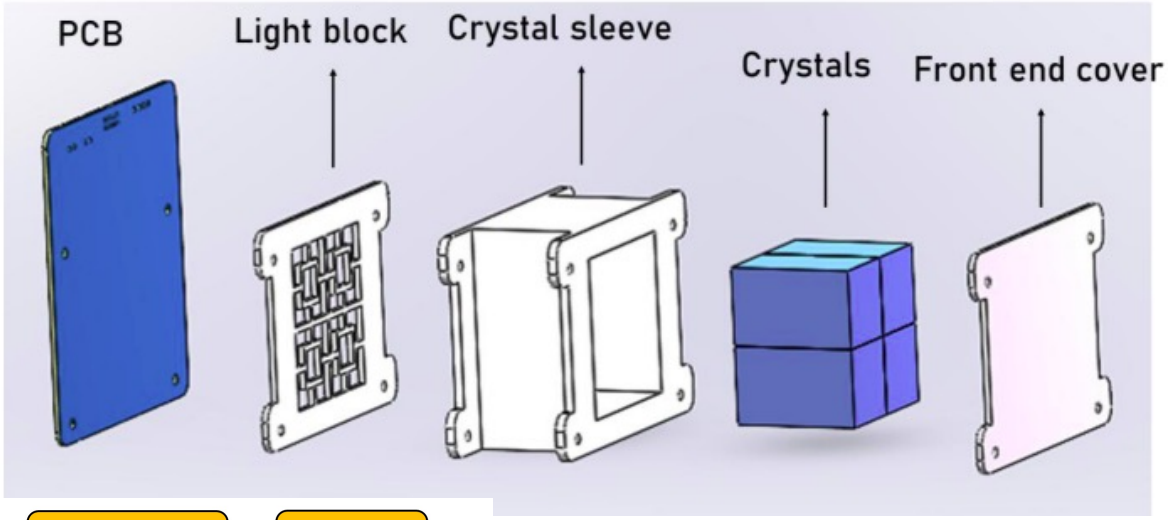


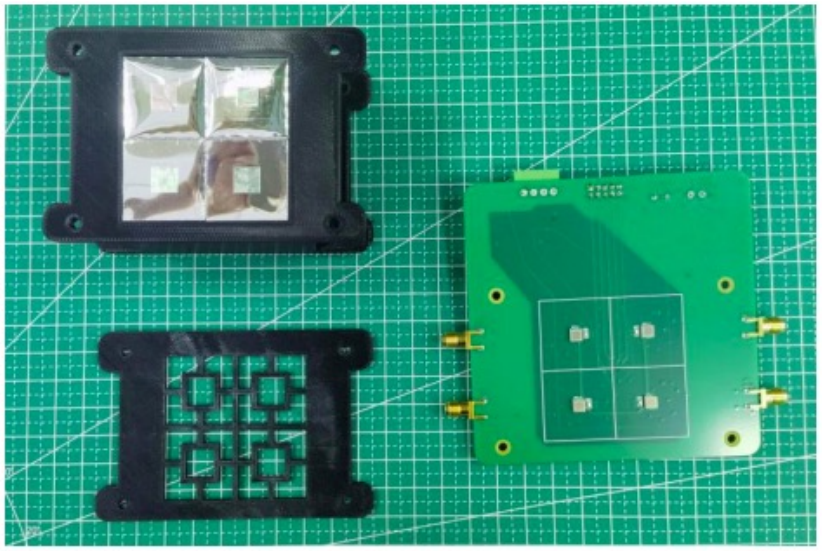
Beam test @Desy

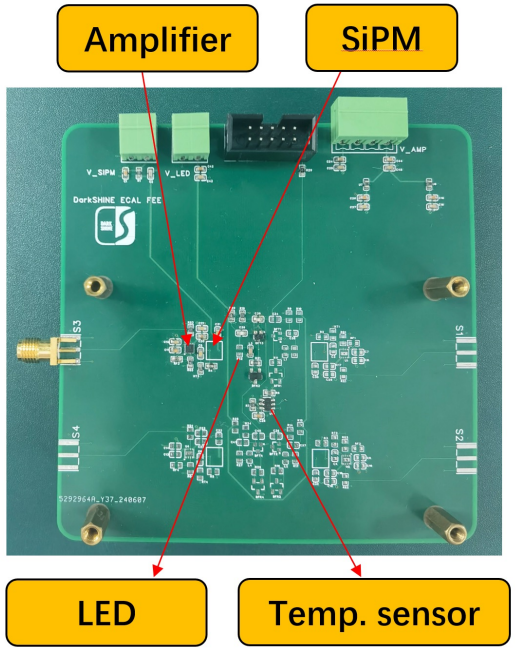




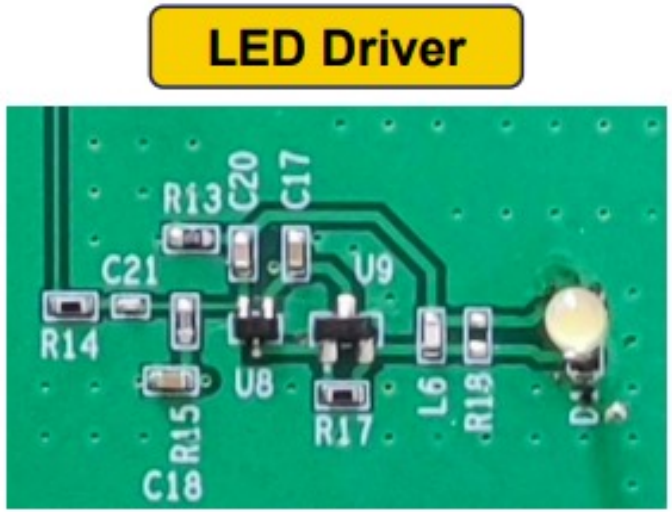
Detector R&D: ECAL prototype



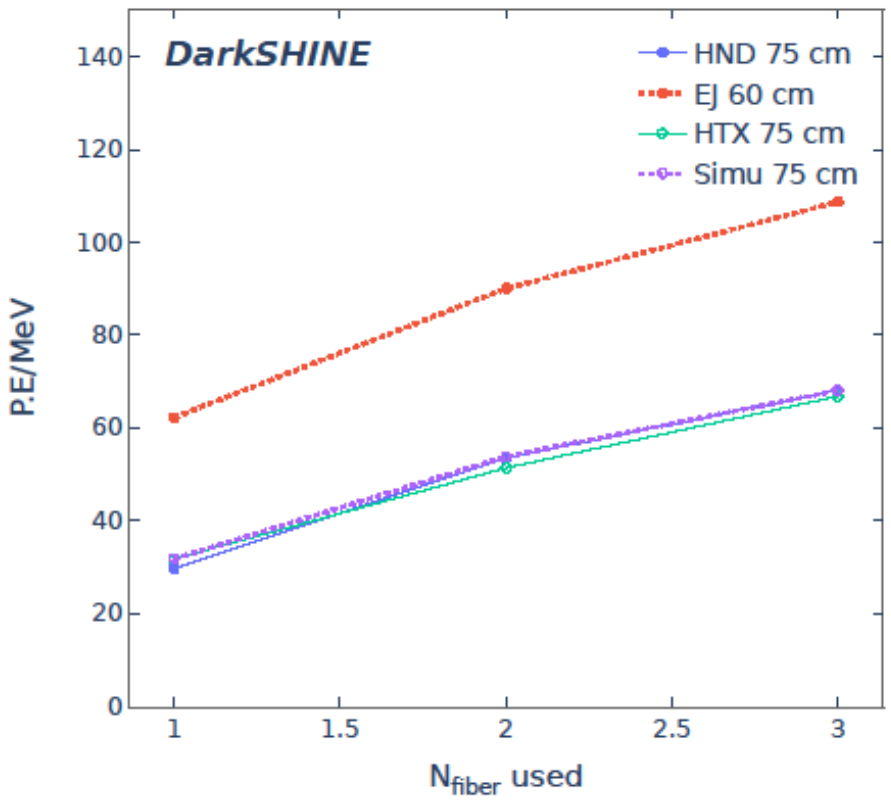


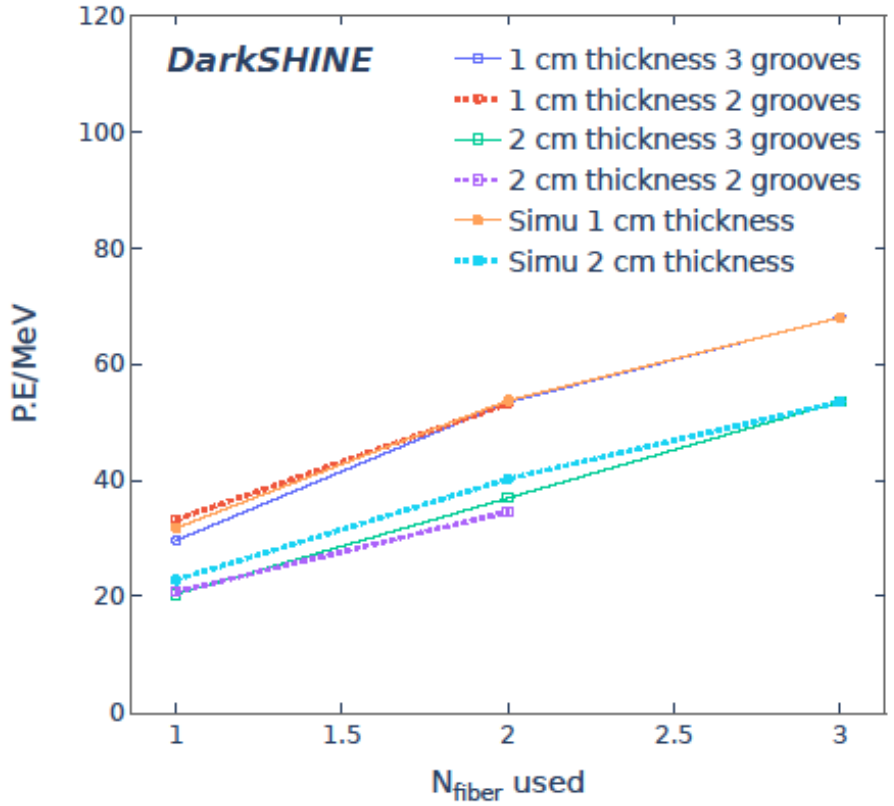


Pre-amplifier: transimpedance amplifier
- **PZC + RCRC filter**
- **Dual output: large dynamic range**



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