DarkSHINE – Search for Light Dark Matter Mediator at the SHINE facility

Jing Chen

On behalf of DarkSHINE R&D team

第十七届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会

2024.07.14

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Tsung-Dao Lee Institute

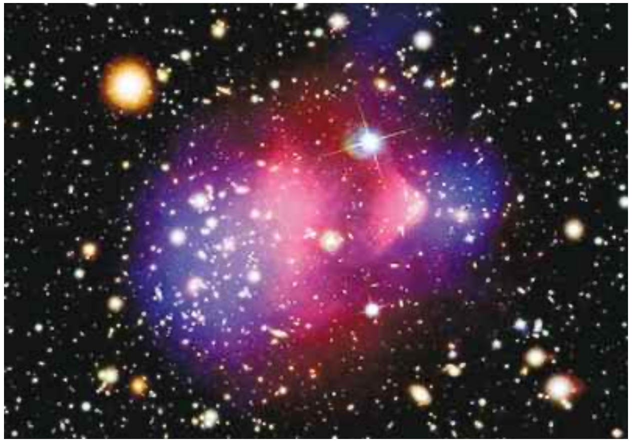
DARK SHINE

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

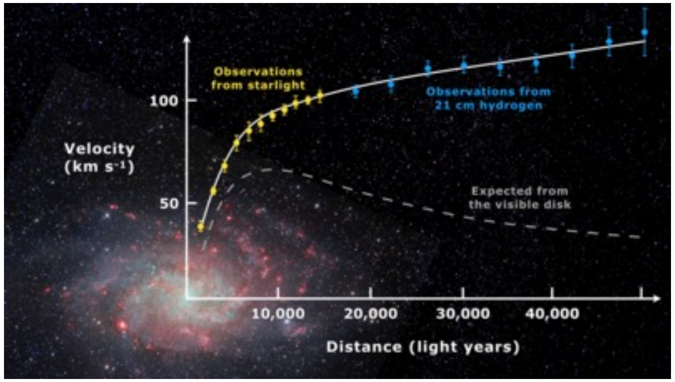
Evidence of dark matter

Gravitational Lensing

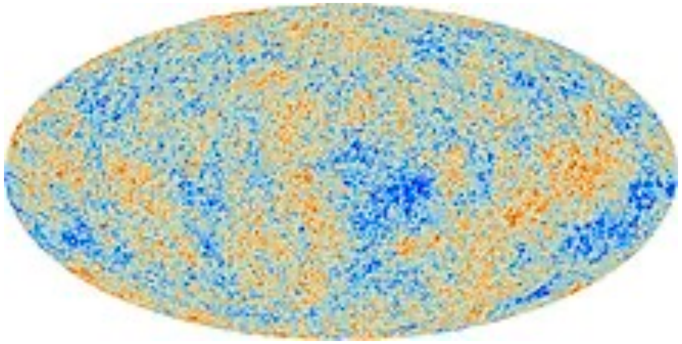
The Bullet Cluster



Rotation Curve



Cosmic Microwave Background



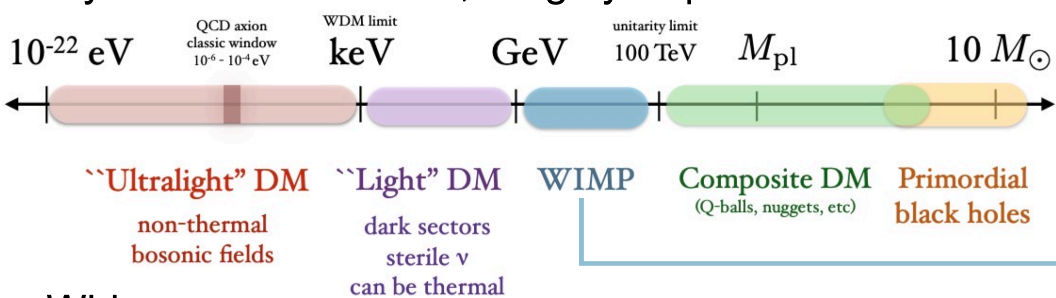
Dark matter candidates

arXiv:1904.07915

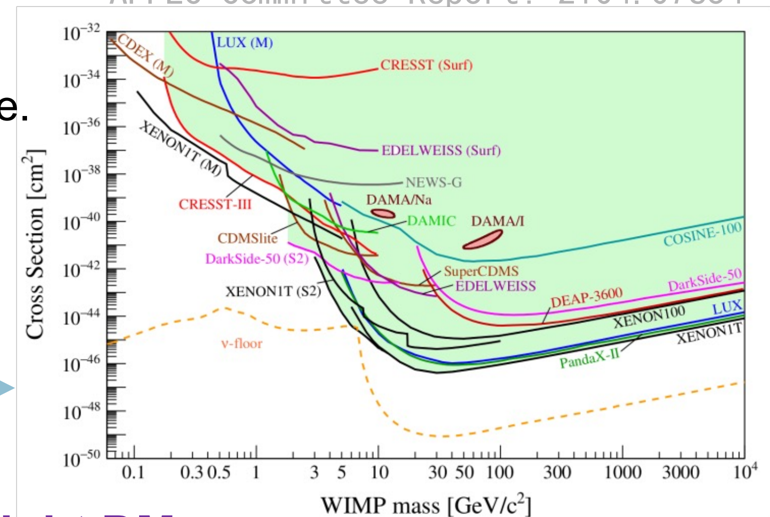
Mass scale of dark matter

(not to scale)

- Mysterious substance, roughly a quarter of the Universe.

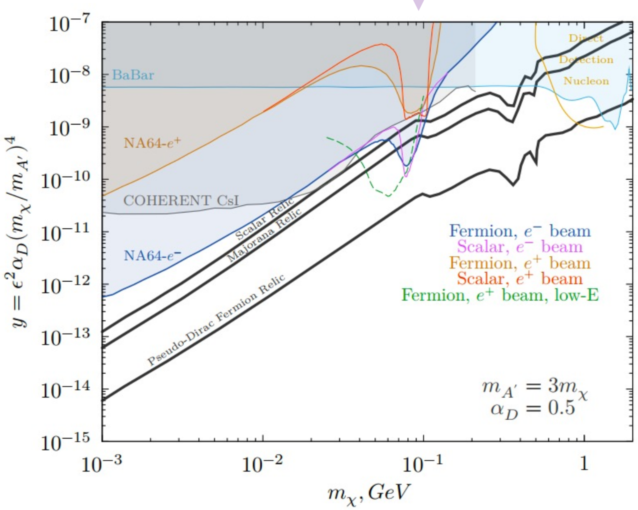


APPEC Committee Report: 2104.07634



- Wide mass range.

arXiv:2308.15612



- **Searching for light DM:**

  - Dark photon A':

    1. Dark matter particles may interact with other dark matter particles via a new force mediated by A'.

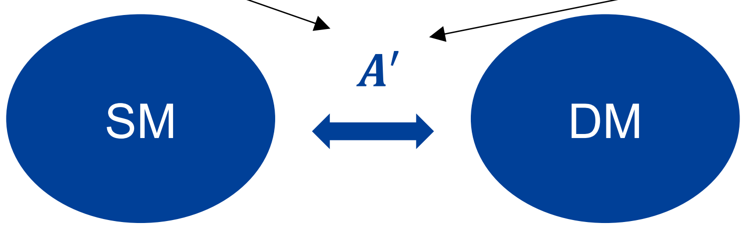
    2. Collider/accelerator-based experiments searching for dark photon: NA64@CERN, BESIII, BEPCII, LDMX, etc.

Search for dark photon

- Dark photon is an important portal between the standard model (SM) particles and the dark matter.

not couple directly to SM particles

obtain a small coupling to the EM current due to $\boldsymbol{\varepsilon}$



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

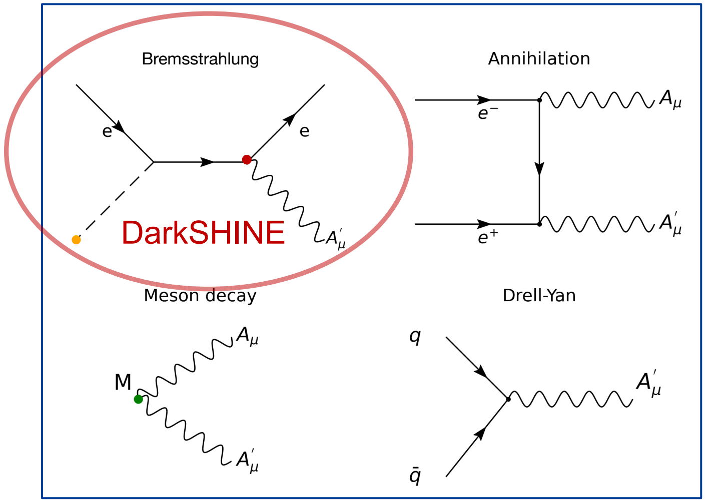
Kinetic mixing term | Field strength tensor | Dark photon field

- DarkSHINE is an experiment based on the minimal dark-photon model with 3 unknown parameters:
  $\boldsymbol{\varepsilon}$: kinetic mixing between the SM hypercharge and A' field strength tensors.
  $\boldsymbol{m}_{\boldsymbol{A'}}$: dark photon mass.
  Decay branching ratio of $A' \to \chi\chi$ (assumed to be 1 or 0)

arXiv:2104.10280

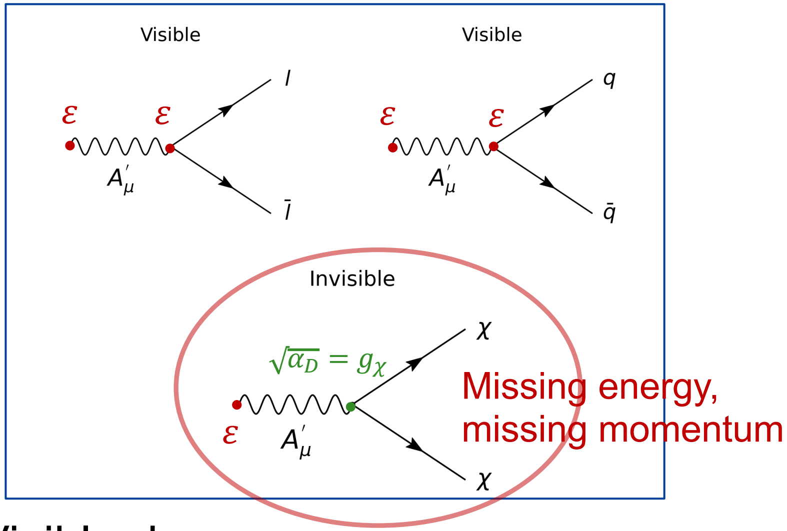
Search for dark photon

- A' production:



- Bremsstrahlung, $eZ \to eZA'$ & $pZ \to pZA'$, fixed-target experiment
- Annihilation, $e^+e^- \to A'\gamma$, e^+e^- collider
- Drell-Yan, $q\bar{q} \to A'$, hadron collider / fixed nuclear target w/ proton-beam
- Meson decay, $\pi^0 \to A'\gamma$ or $\eta \to A'\gamma$ (w/ $m_{A'} < m_{\pi,\eta}$), any experiment w/ high meson production rates

- A' decay:



- Visible decay

Two interaction vertices → production rate highly suppressed

- Invisible decay

One interaction vertice → interaction probability enhanced

Better sensitivity!

The SHINE facility

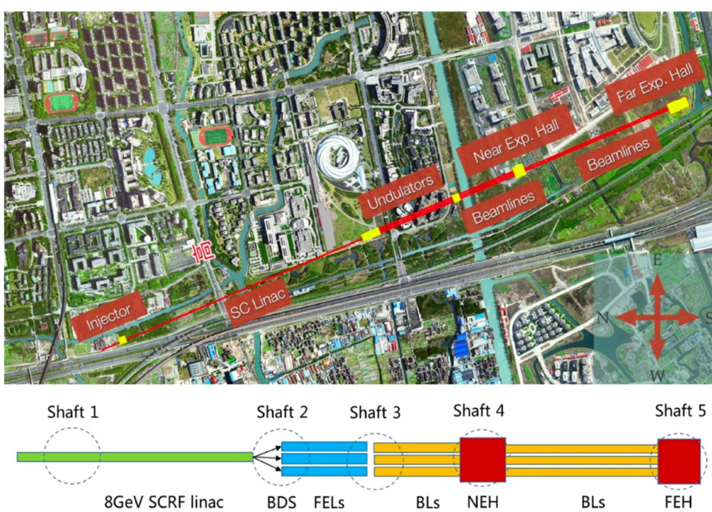
- DarkSHINE:

  - **Fixed-target** experiment w/ high frequency **single electron beam** provided by Shanghai High Repetition-Rate XFEL and Extreme Light Facility(**SHINE**)
  - Invisible decay: $m_{A'} > 2m_{\chi}$, **missing energy / missing momentum**
  - Search for A' in $[m_{A'}, \varepsilon]$ parameter space

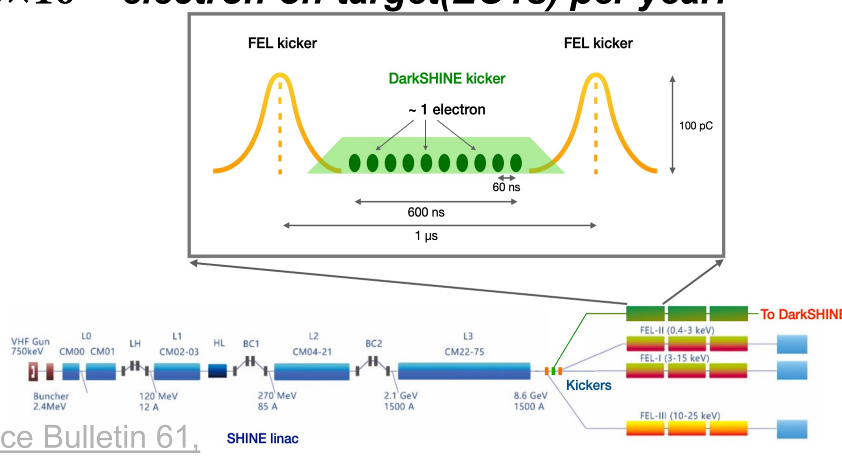
- The SHINE:

  - Under construction in Zhangjiang area, Shanghai (2018-2026).
  - $E_{beam} = 8GeV$ with frequency 1MHz, beam intensity: $6.25{\times}10^{8}$ electrons/bunch

$3{\times}10^{14}$ *electron-on-target(EOTs) per year!*



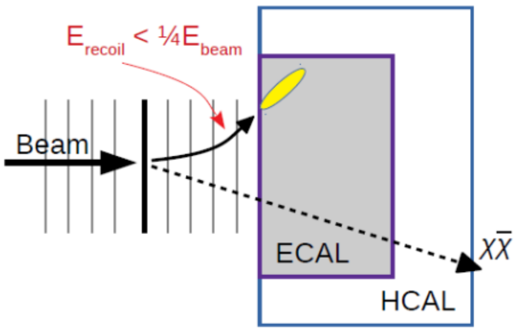
Science Bulletin 61, 117(2016), 720-727

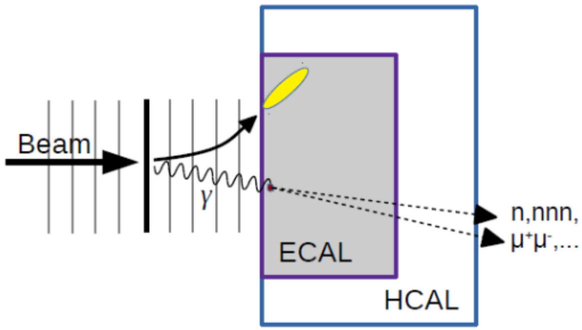


Signal & background signatures

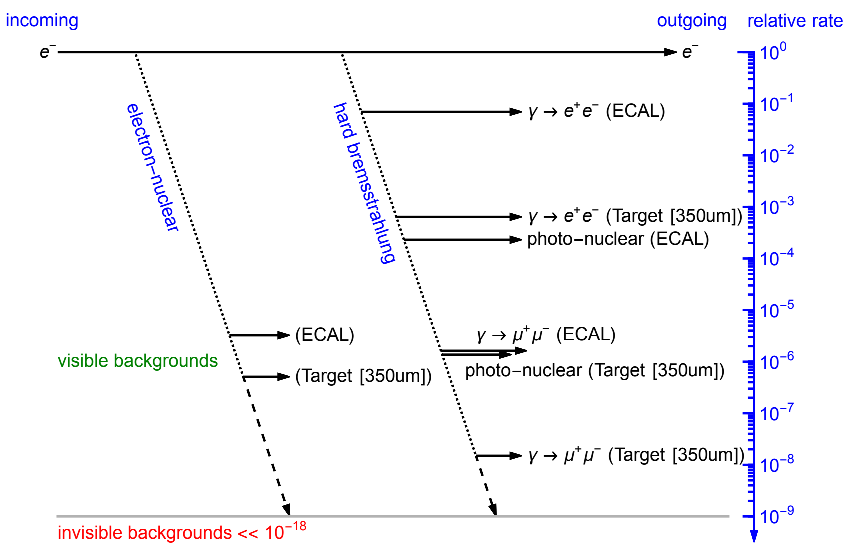
- Signal signature:

  Most of the incident momentum is transferred to A'.





- Major background processes:



Leading background:

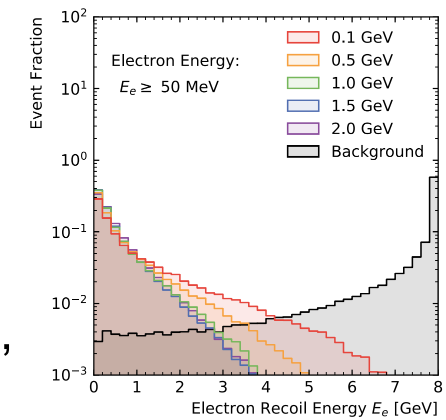
photon bremsstrahlung

Rare processes:

photon-nuclear, $\gamma \to \mu\mu$, electron-nuclear

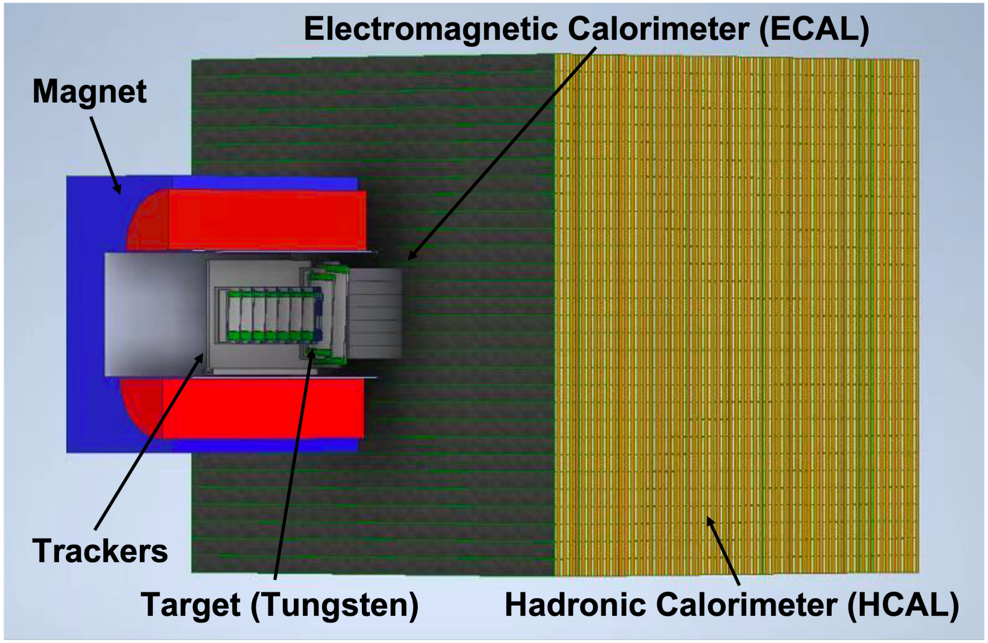
Invisible background:

Neutrino productions



Detector 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.



- **Electromagnetic calorimeter**

  - Measure the deposited energy: electron & photon

- **Hadronic calorimeter**

  - Measure the deposited energy: muon & hadron backgrounds

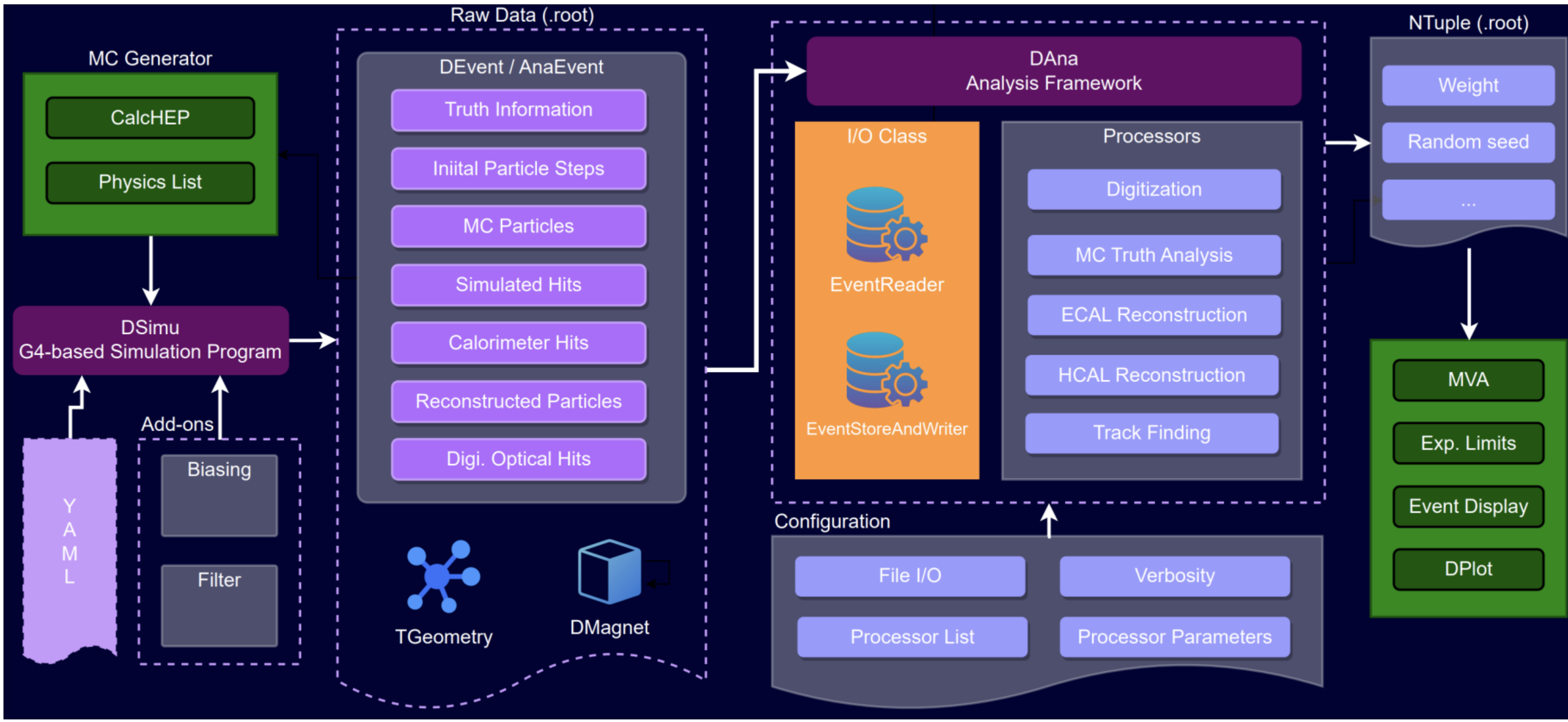
- **Tracking system**

  - Incident and recoil electron tracks

- **Additional system:**

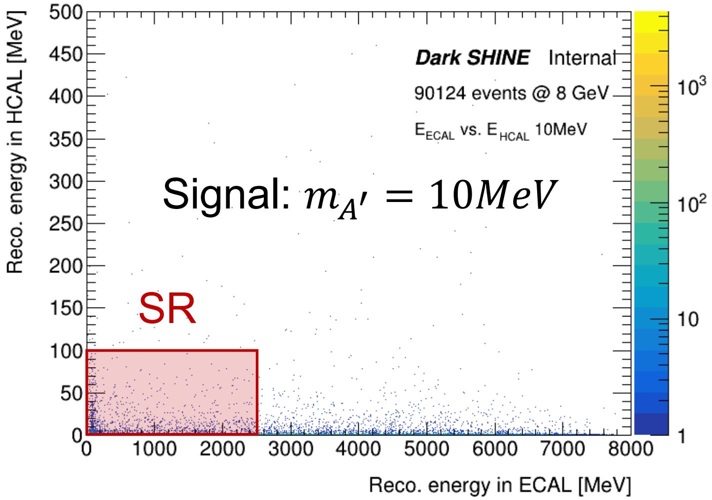
  - Readout electronics, trigger system, TDAQ, magnetic system (1.5T)

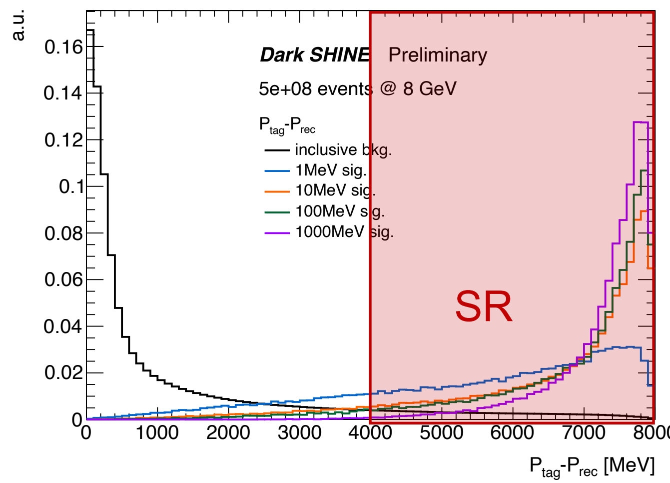
Software framework

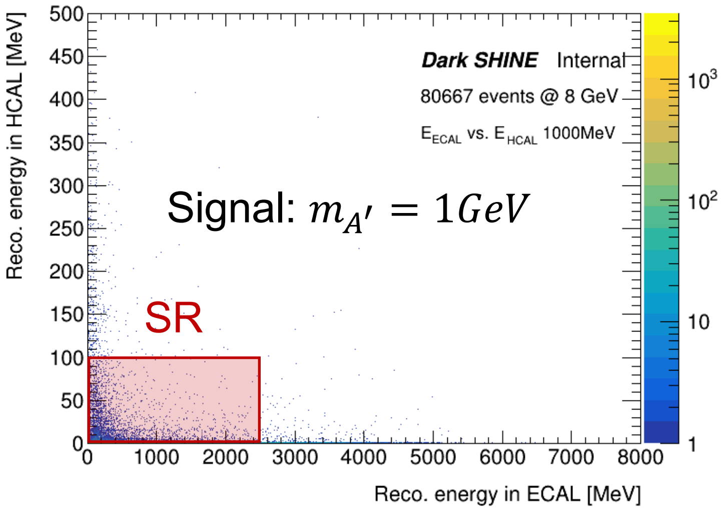


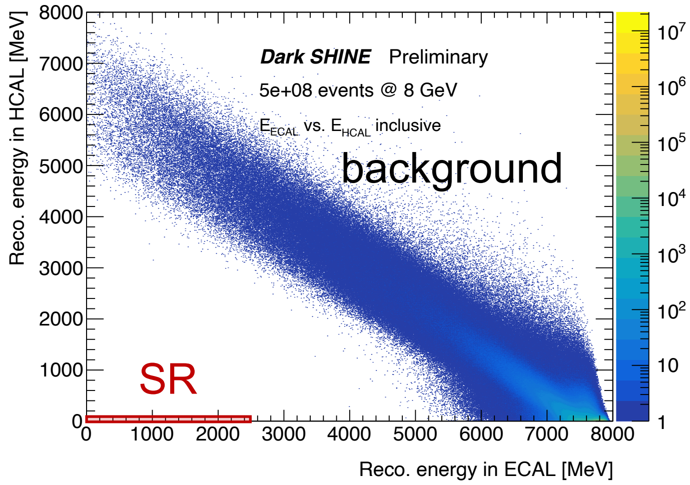
- Based on GEANT4 v10.6.1: event simulation, reconstruction and display.
- Optimization and machine learning implementation ongoing…

ECAL energy vs. HCAL energy



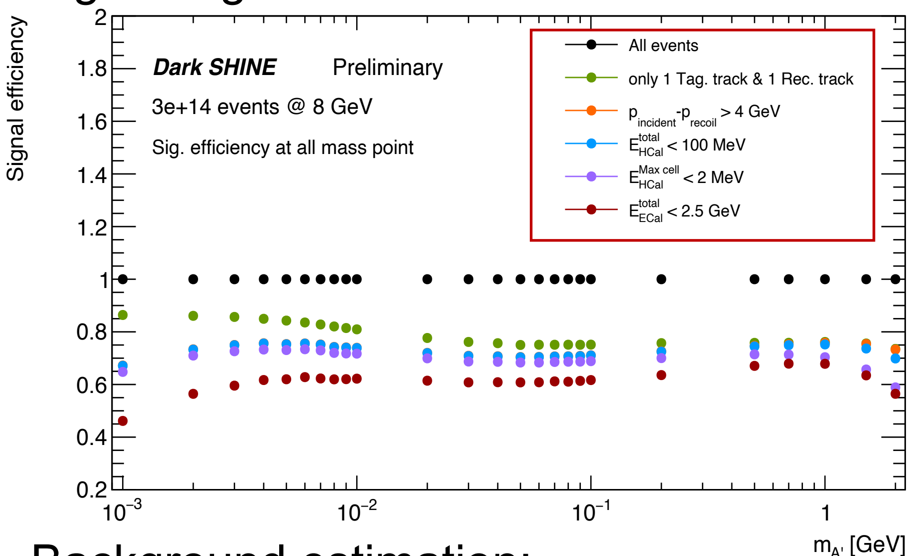






Signal efficiency & background estimation

- Signal region selections:



- Efficiency drops:

  Low-mass region of a few MeV: tight missingP cuts.

  High-mass region above 1 GeV: particles with large incident/recoil angle go into the HCAL directly.

- Around 60% signal events survive the cut-flow.

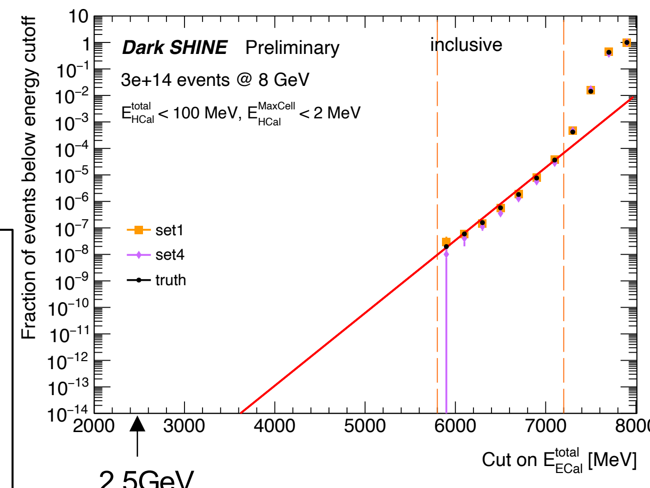
- Background estimation:

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

Extrapolate from rare processes simulation.

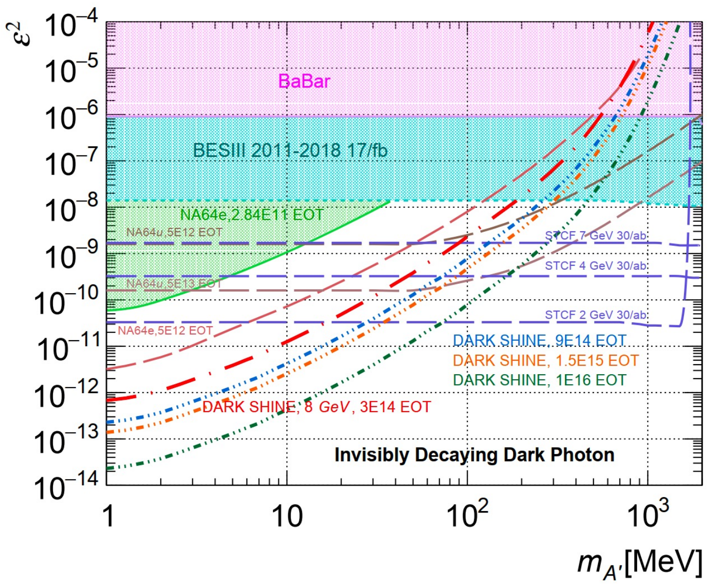
Extrapolate from inclusive background simulation.

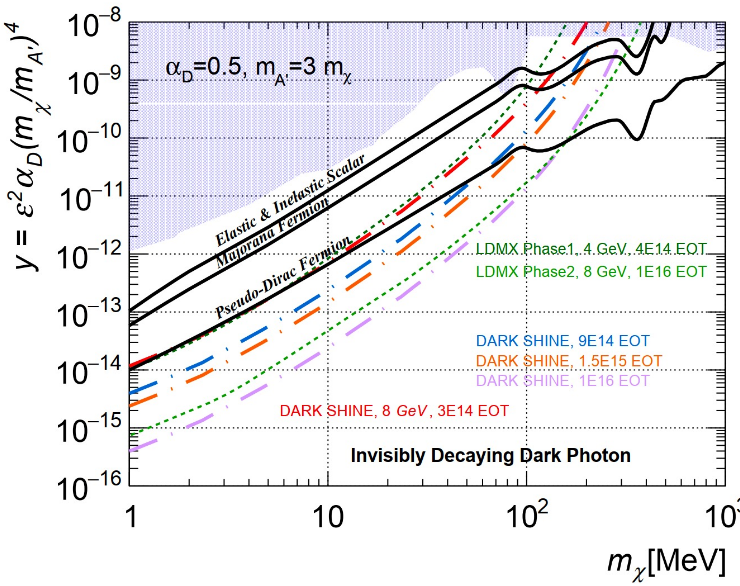
Validate Inclu.-extra: Scale low E_{beam} events to match the shoulder with $E_{beam} = 8$ GeV events.



Sensitivity study

- Expected 90% C.L. limit estimated with 3×10^{14} EOTs (running ~1 year), 9×10^{14} EOTs (~3 years), 1.5×10^{15} EOTs (~5 years) and 1×10^{16} EOTs (with Phase-II upgrade).



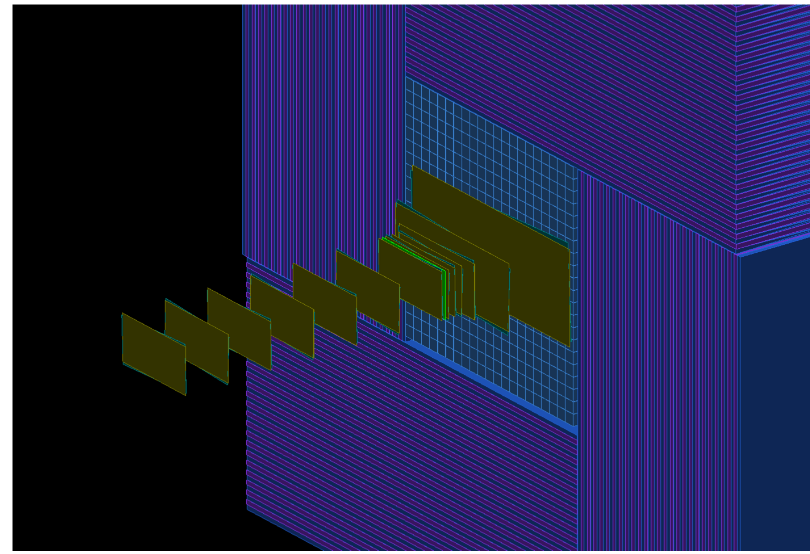


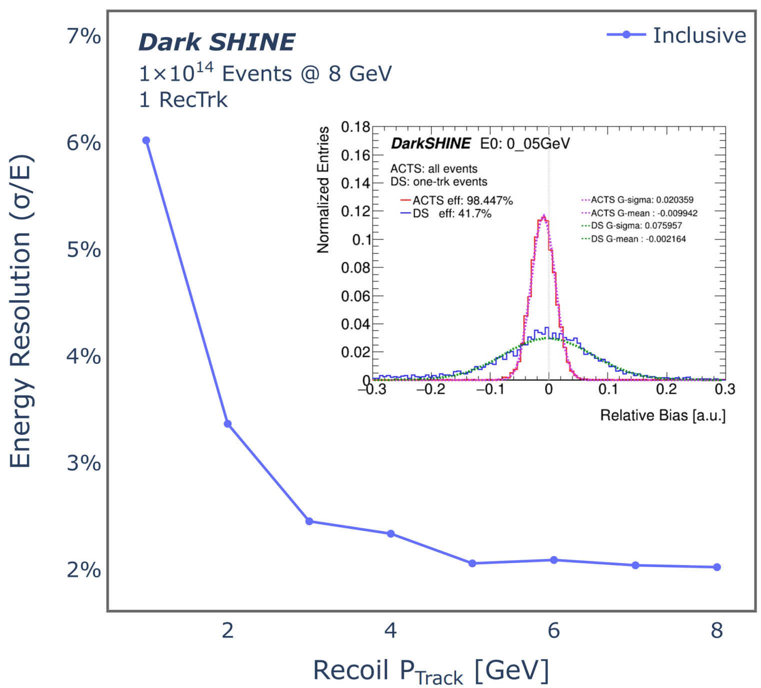
- Comparing with other experiments, DarkSHINE can provide competitive sensitivity.

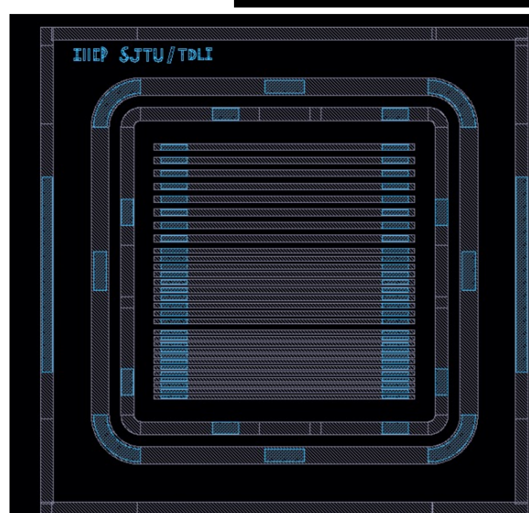
Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)

Detector R&D: tracking system

- Incident and recoil electron tracks.
- Tagging tracker (7 layers) + recoil tracker (6 layers).
- Two silicon strip sensors w/ a small angle (0.1rad).
- Resolution: $6\mu m$(horizontal), $60\mu m$(vertical).

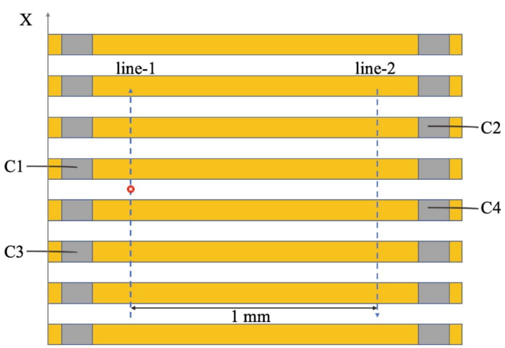


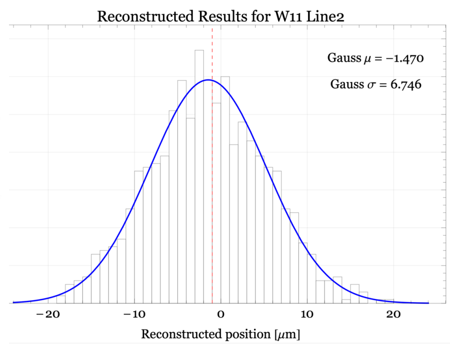


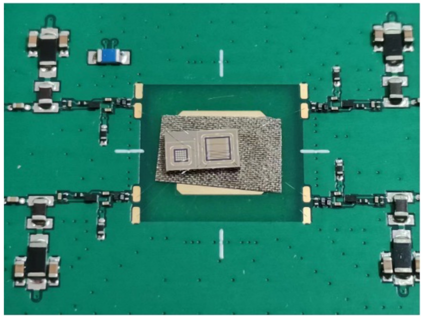


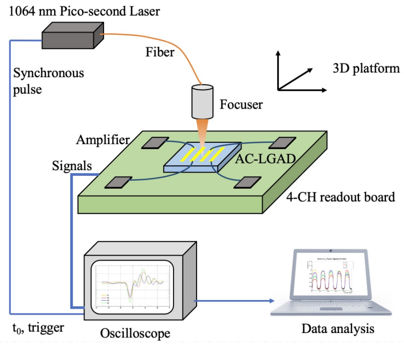
AC-LGAD silicon strip sensor $1\times1mm^2$ designed, in collaboration with Prof.Zhijun Liang and Prof.Mei Zhao from IHEP.

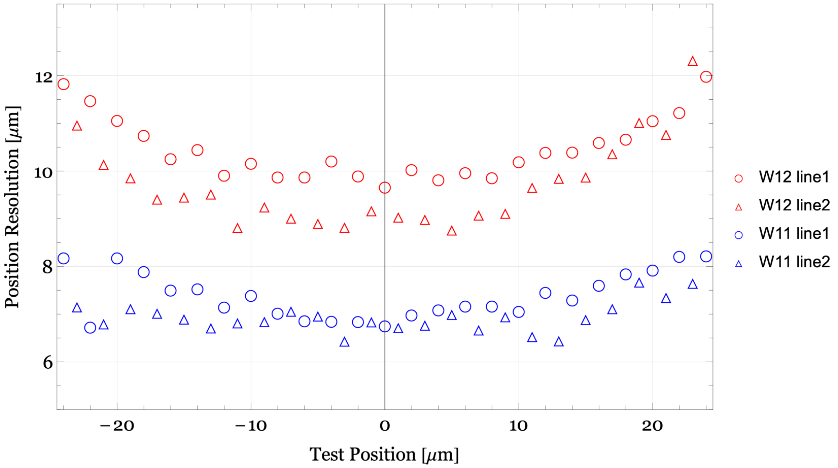
Detector R&D: tracking system

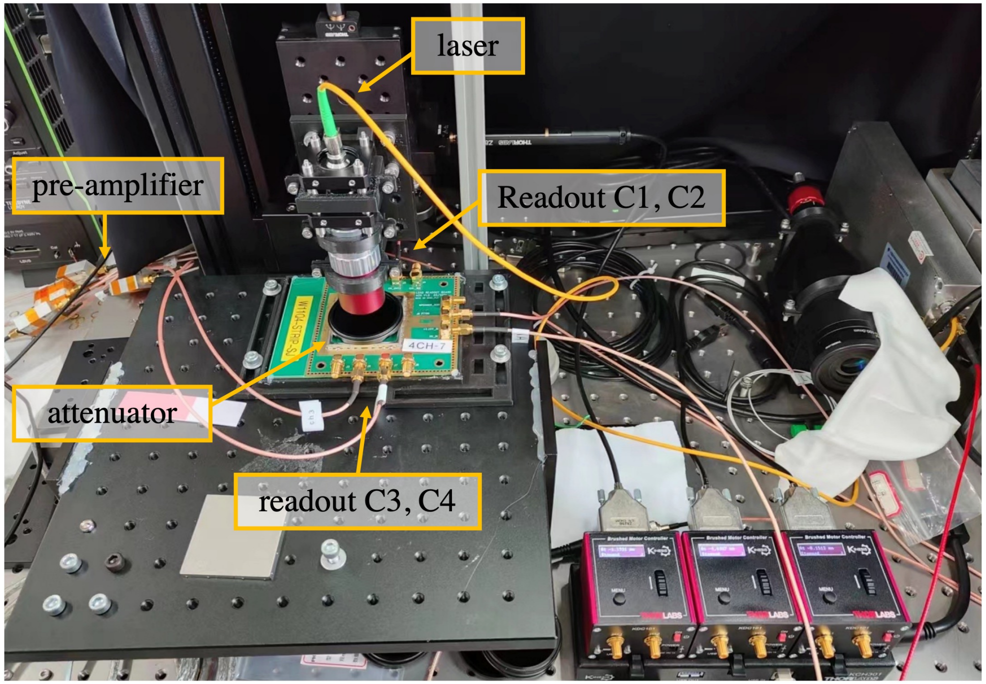












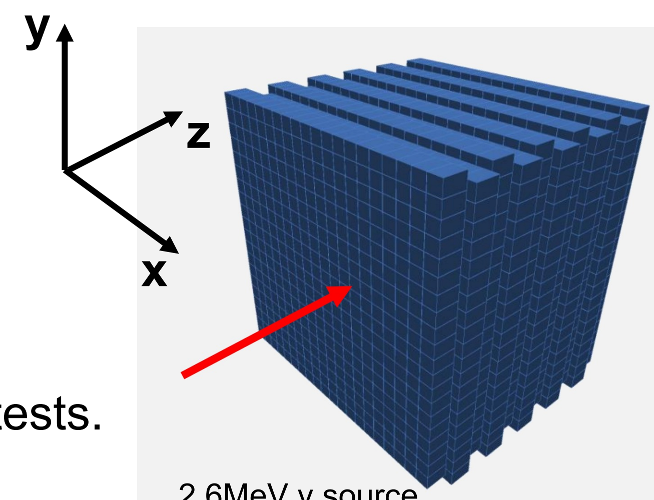
arXiv:2310.13926 (submitted to NST)

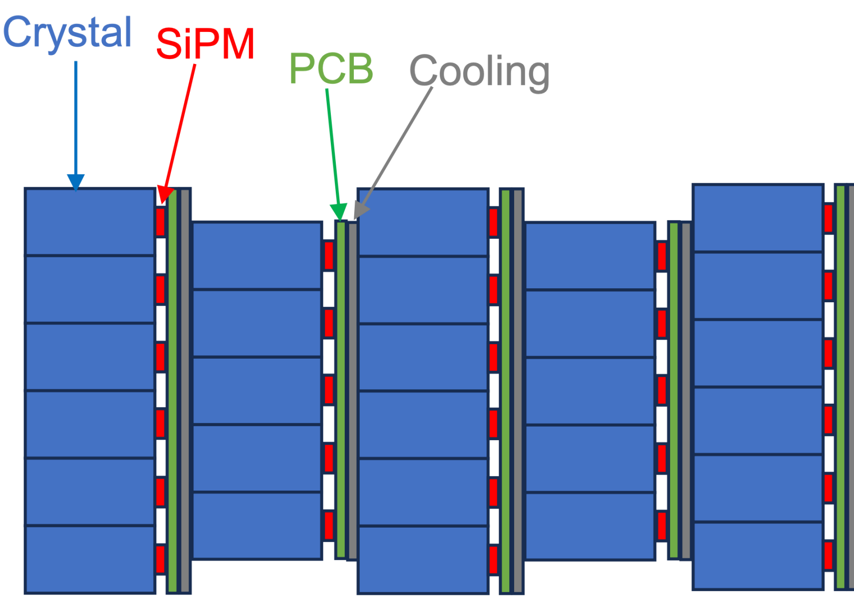
Detector R&D: ECAL

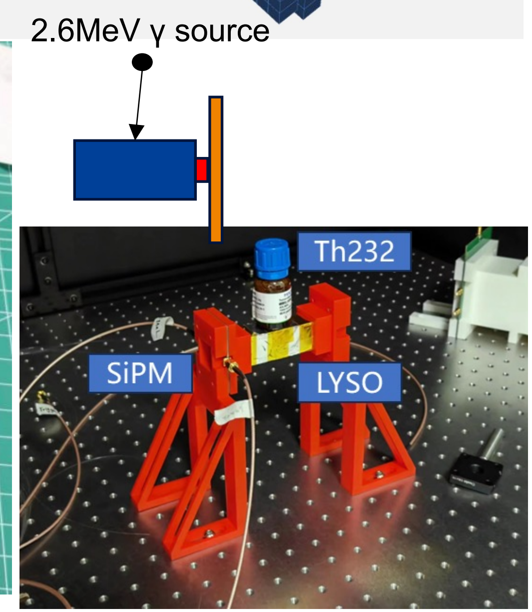
- Measure the deposited energy of e & γ.
- $2.5\times2.5\times4cm^2$LYSO, $20\times20\times11$crystals.
- Designed resolution: energy resolution ~ 5%.
- LYSO crystal ($Lu_{(1-x-y)}Y_{2y}Ce_{2x}SiO_5$):

  high light yield (30000 p.e/MeV), short decay time (40 ns), low electronic noise, good radiation resistant.

- More intrinsic radiation and radioactive source tests.

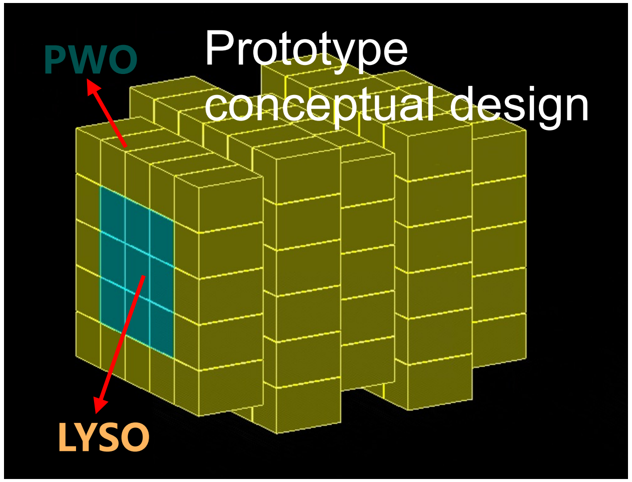


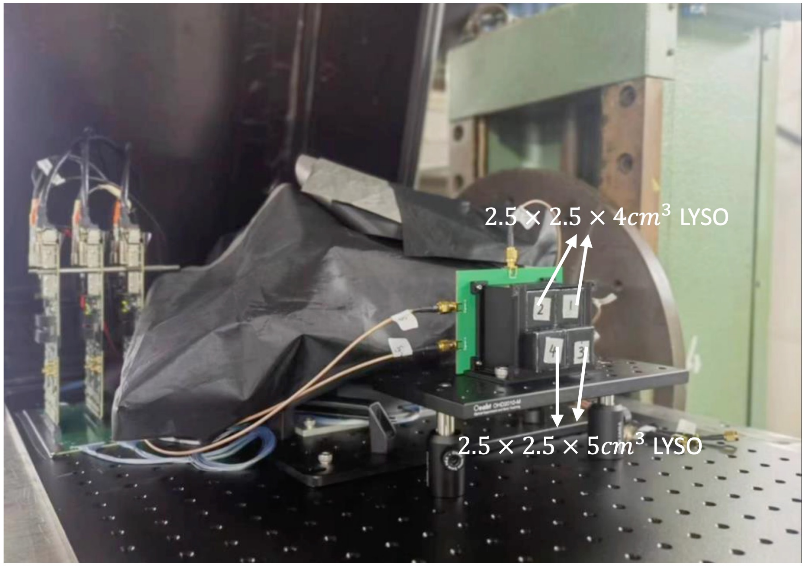




Detector R&D: ECAL

- Motivation:
  - Performance study under high energy and high repetition beam.
  - Technical validation for the whole detector system.
- Energy resolution is better than 3%. Very low energy leakage below 2.5 GeV.

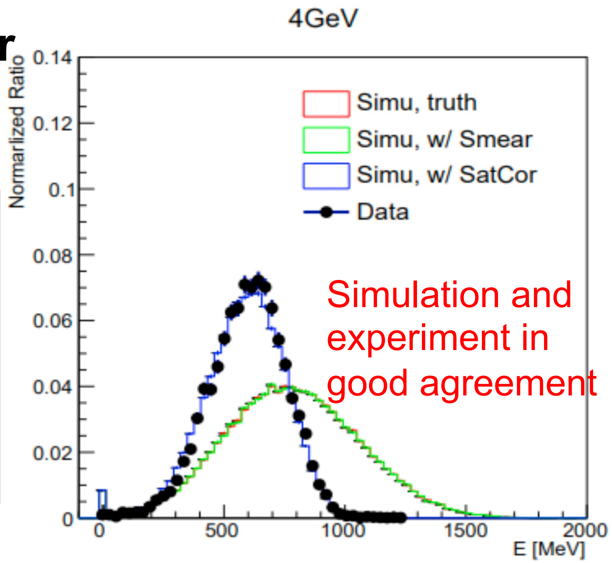




DESY TB22 Oct. 2023

Many thanks to CEPC Calorimeter group!

1st prototype module for beam test (2x2 LYSO) at DESY

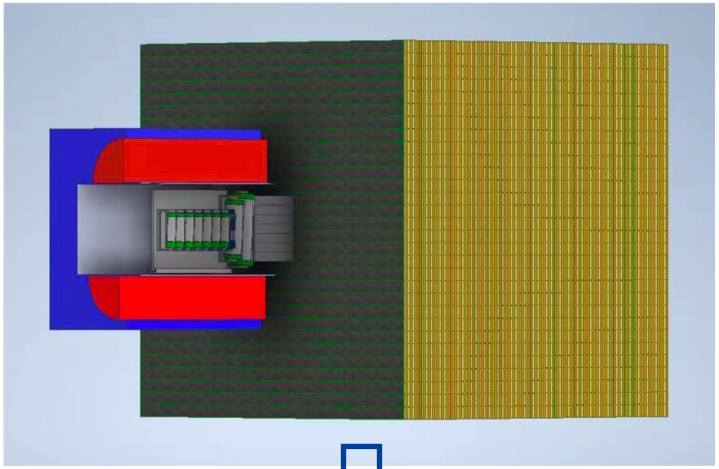


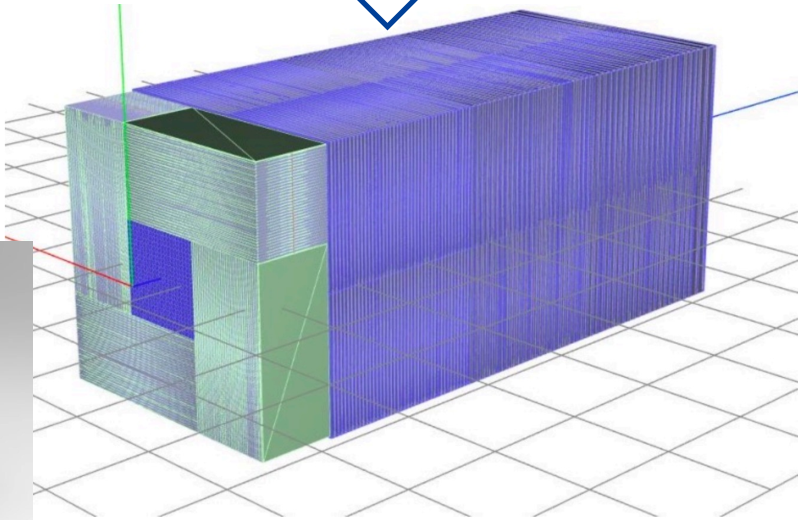
Detector R&D: HCAL

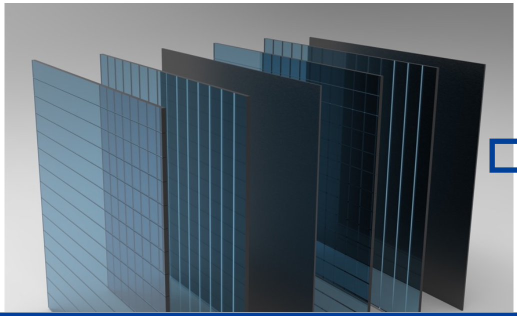
arXiv:2311.01780 (accepted by NST)

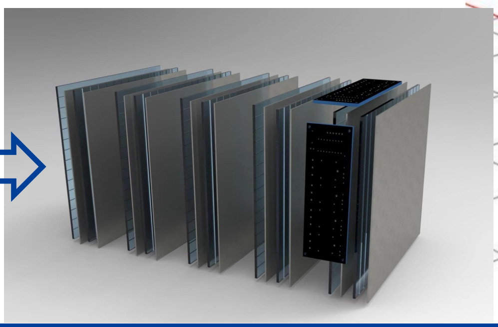
- Measure the deposited energy of muon & hadron backgrounds.
- Main HCAL: $1.5\text{m}\times 1.5m\times 2.5m$, < 30tons

  - 2×2 module (10 layers of absorber + scintillator).
  - Iron absorber: $75cm\times 75cm$ (10mm/50mm thick).
  - Plastic scintillator: $75\text{cm}\times 5cm\times 1cm$, 15 bars per layer per module. 90 degree rotation between 2 adjacent layers. Wavelength shift fiber + SiPM.
  - 2sides read-out.
- Side-HCAL: encircling the ECAL



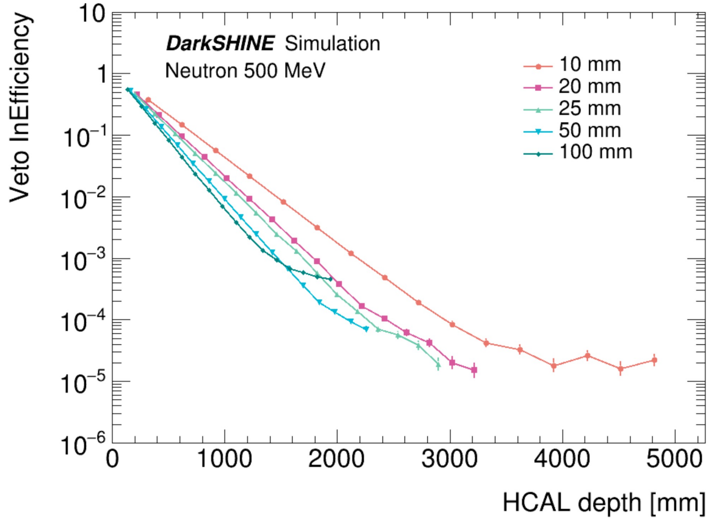


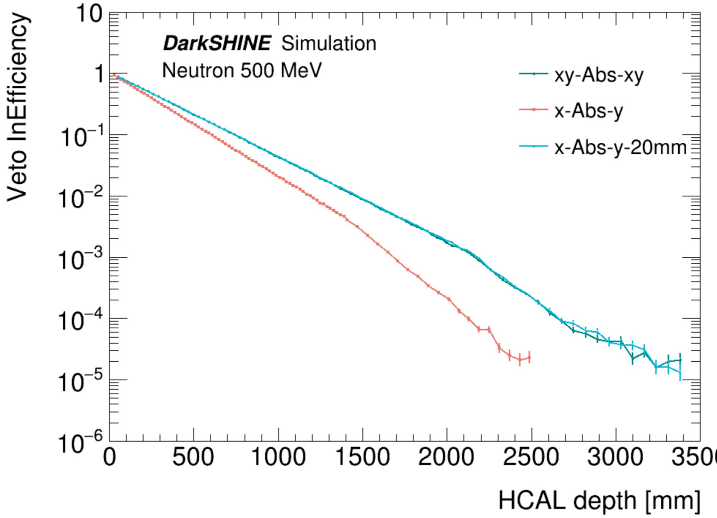




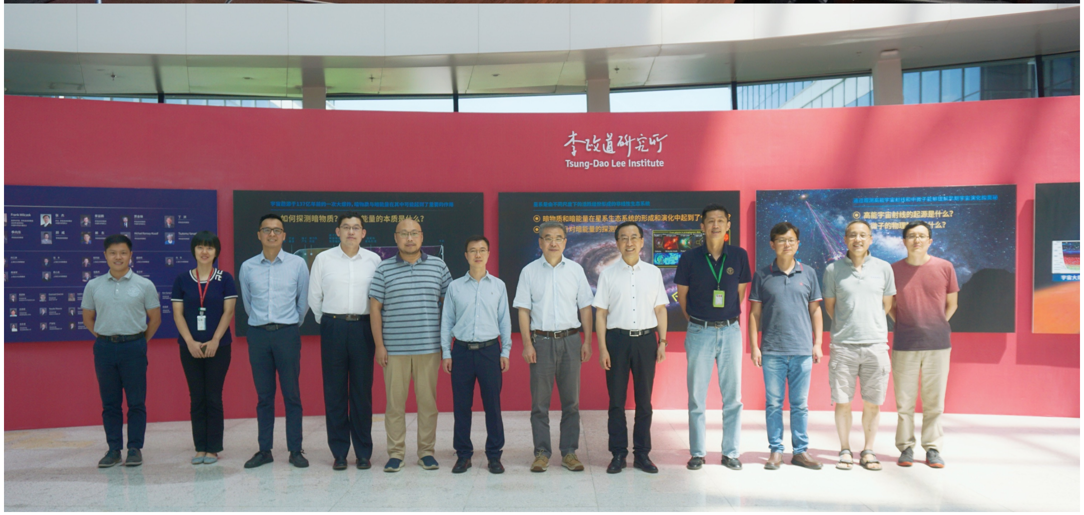
Detector R&D: HCAL

- **HCAL optimization to reduce veto inefficiency**
  - Main backgrounds: neutral hadrons, muons from bremsstrahlung photon.
  - Optimization for total weight (mainly from iron) and cost (mainly from scintillator).
- Transverse dimensions: 1.5 m x 1.5 m, with ~ 10 λ iron absorbing layers along the beam direction.
- Optimized structure: 1 cm thickness iron for the first 70 layers, 5 cm thick for the last 18 layers, 1 cm thick plastic scintillator.



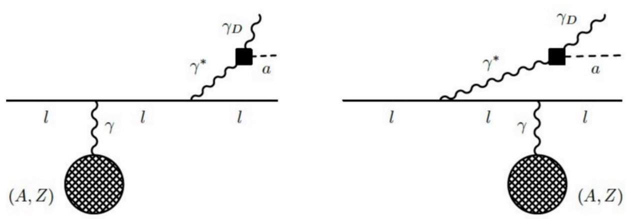


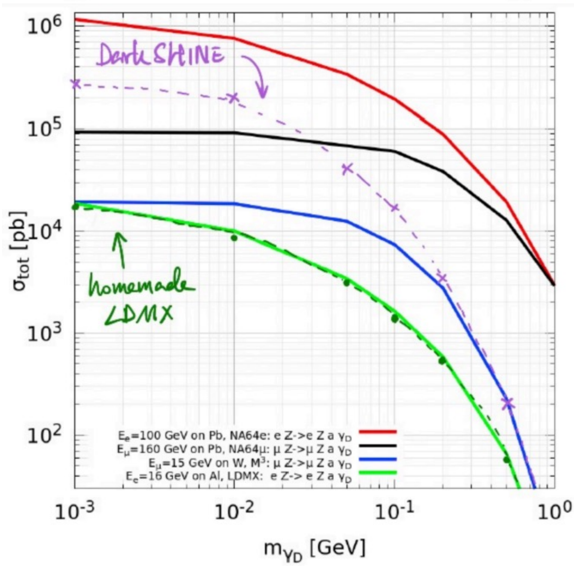
Collaboration with SHINE



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-channel annihilation diagrams come into play for Dark Photon production.
- SHINE can also deliver positron beam with low current…

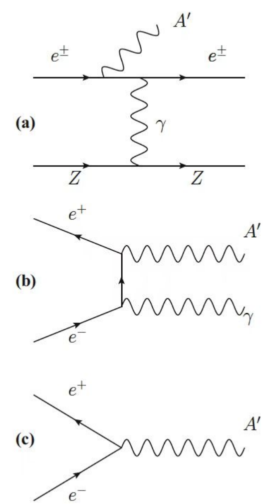
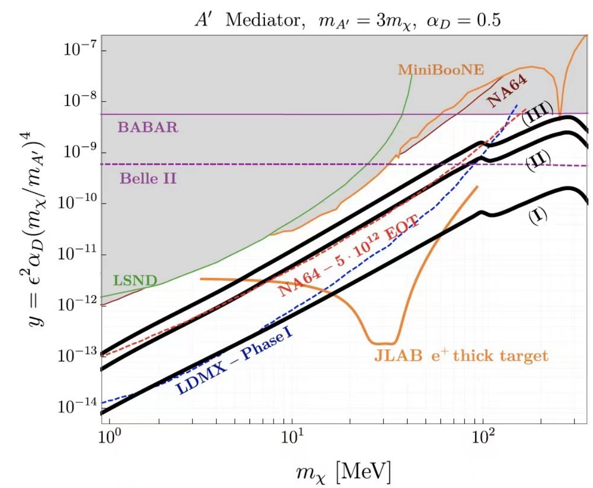


Fig. 1 Three different A' production modes in fixed target lepton beam experiments: (*a*) A'-strahlung in e^-/e^+-nucleon scattering; (*b*) A'-strahlung in e^+e^- annihilation; (*c*) resonant A' production in e^+e^- annihilation



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

Summary

- DarkSHINE: a fixed-target experiment to search for light dark matter mediator.
- First round of **preliminary study** has been finished:

  - Production: bremsstrahlung, $eZ \to eZA'$.

  - Invisible decay: $A' \to \chi\chi$.

  - Most of the incident momentum is transferred to A'.

  - Good signal efficiency, background well suppressed.

  - Expecting competitive sensitivity.

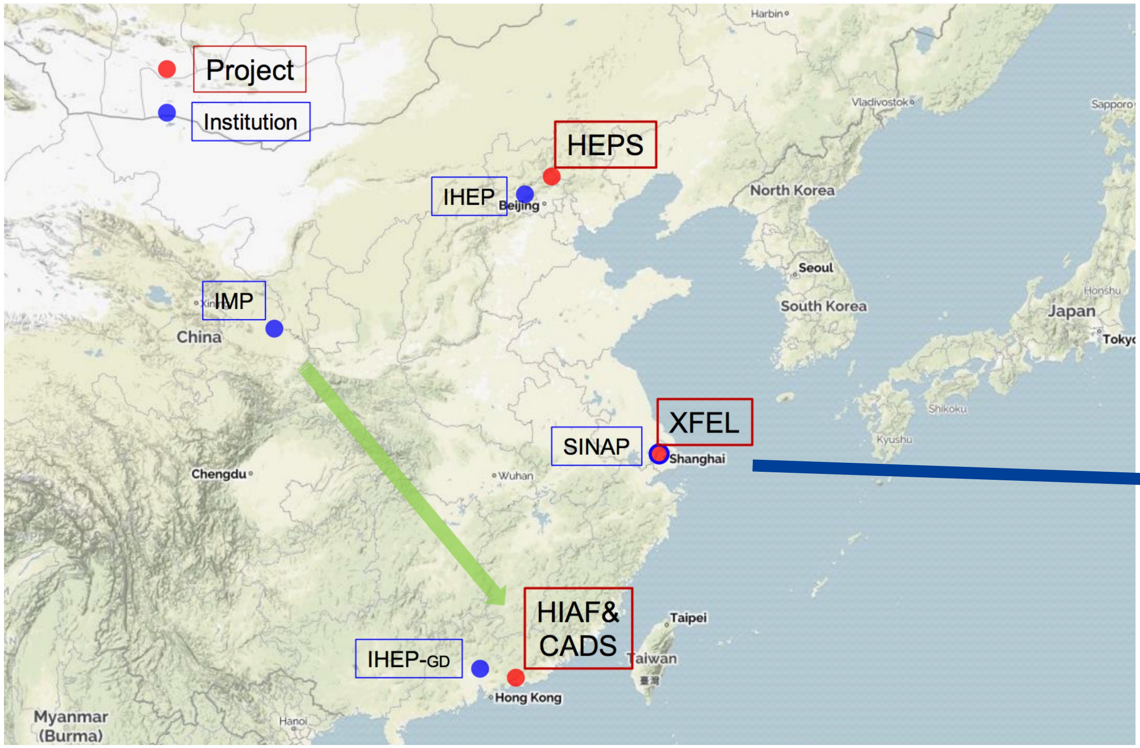
  - Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)

- Detector R&D ongoing. (arXiv:2310.13926 , arXiv:2311.01780)
- With more physics opportunities ahead, stay tuned!

谢谢！

Backup

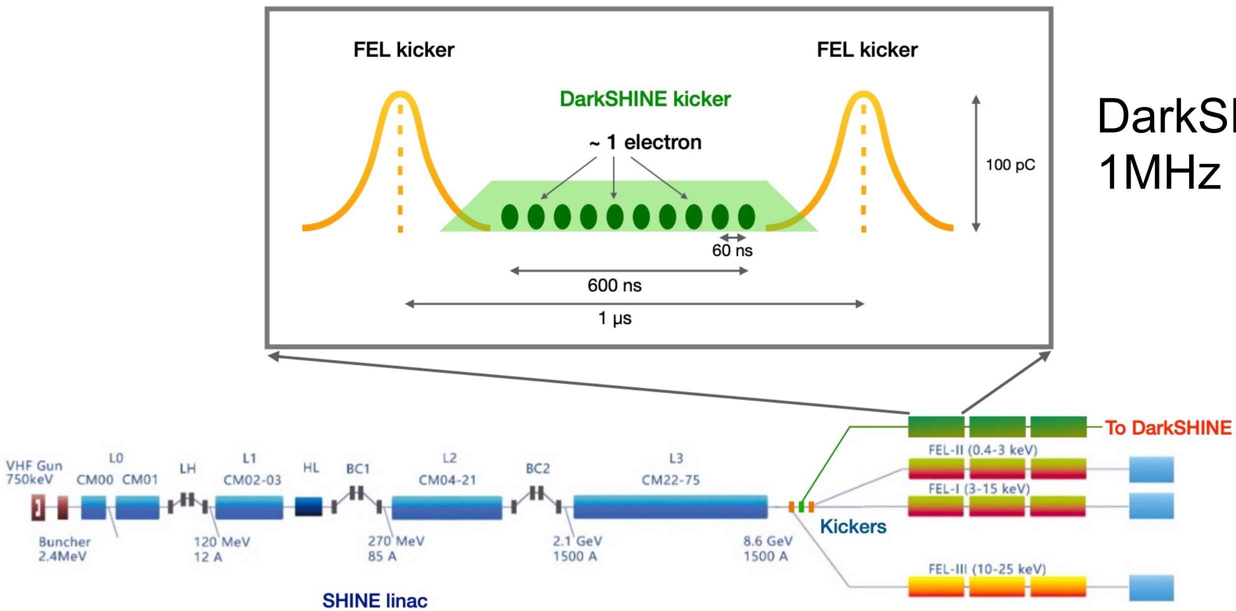
The SHINE facility



Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE)
@ Zhangjaing area, Shanghai

The SHINE facility

Single electron beam is needed for DarkSHINE.



DarkSHINE Kicker:
1MHz → 10MHz

3×10^{14} electron-on-target(EOTs) per year!

FEL kicker	DarkSHINE Kicker

1300 buckets provided by 1.3GHz microwave

100pC in one bucket
6.25×10^{8} electrons per bunch

electron beam w/ one electron per bunch

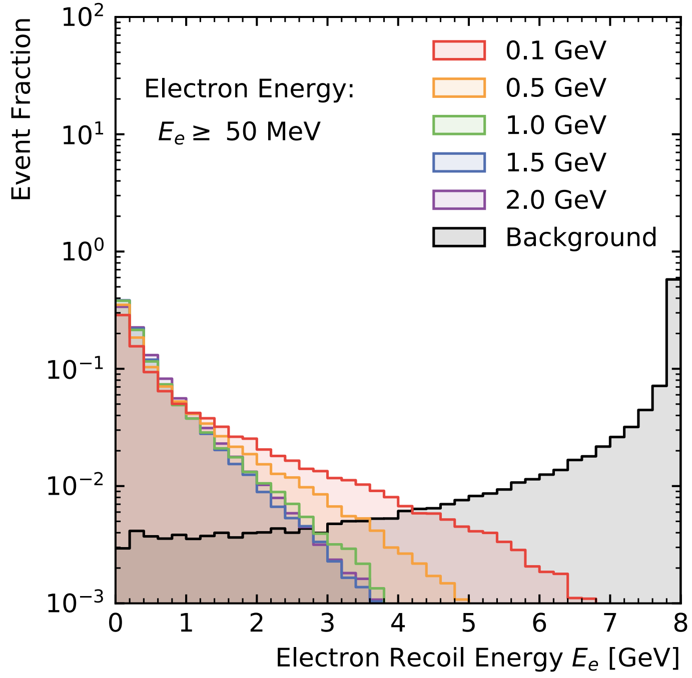
Signal & background signatures

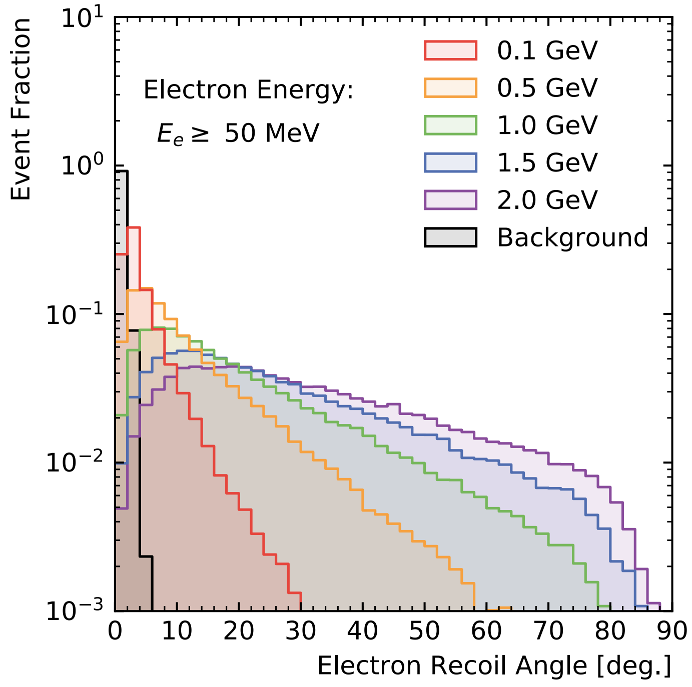
Signal

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

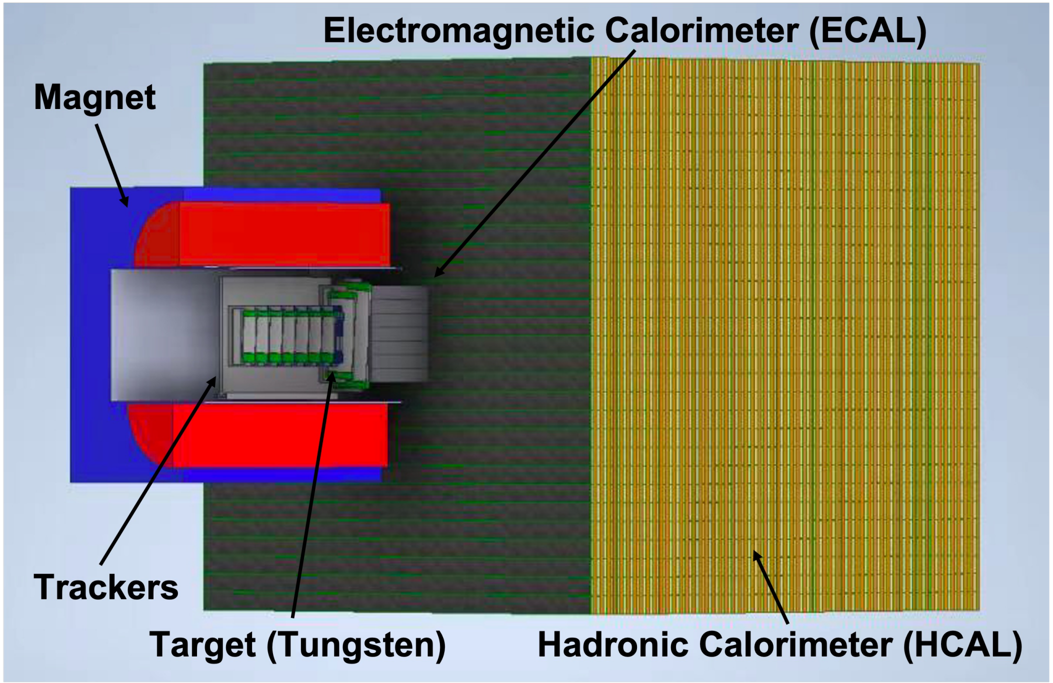
Background

- Recoil electron carries most of the incident momentum
- Recoil electron angle small





Detector conceptual design



- **Tracker:**
  - Tagging tracker (7 layers) + recoil tracker (6 layers)
  - Incident and recoil electron tracks
  - Two silicon strip sensors w/ a small angle (0.1rad)
  - Resolution: $6\mu m$(horizontal), $60\mu m$(vertical)

- **ECAL:**
  - Electron & photon
  - Scintillator: LYSO(Ce)

    high light yield (30000 p.e/MeV), fast decay time (40 ns), low electronic noise
  - $20\times20\times11$ crystals

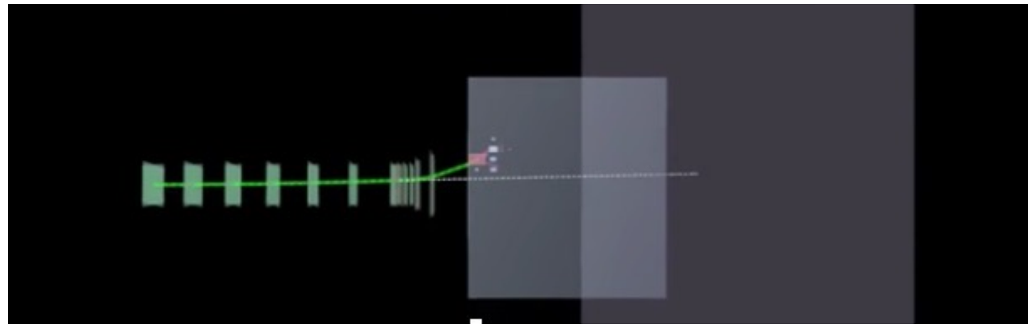
    $2.5\times2.5\times4cm^3$
  - Energy resolution of LYSO: 5%

- **HCAL:**
  - Veto muon & hadron backgrounds
  - Scintillator w/ steel absorber
  - $4\times4\times1$ modules

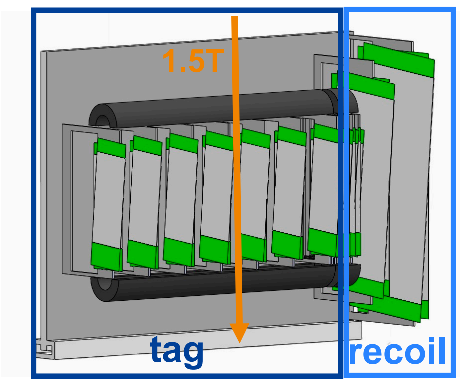
- **Additional system:**
  - Magnet:1.5T magnetic field
  - Readout electronics

Detector R&D

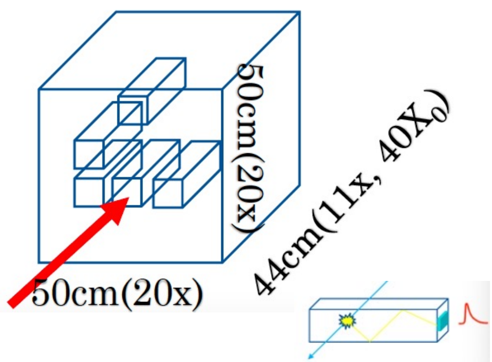
If an electron interacts with tungsten target and produce a dark photon …



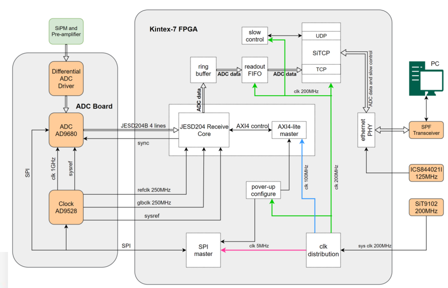
Tracker



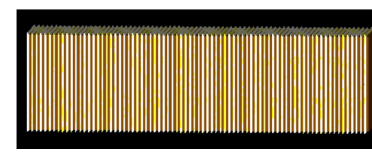
ECAL

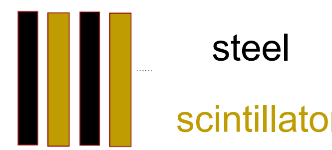


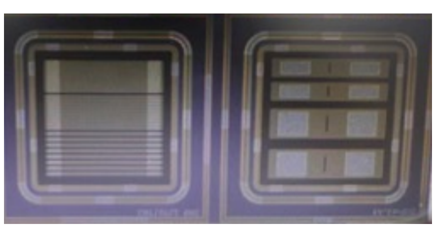
Readout electronics



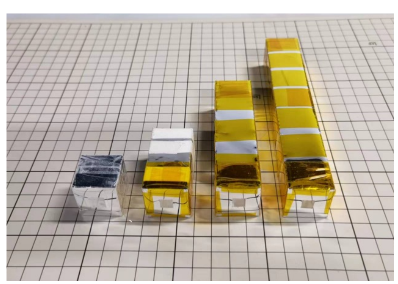
HCAL

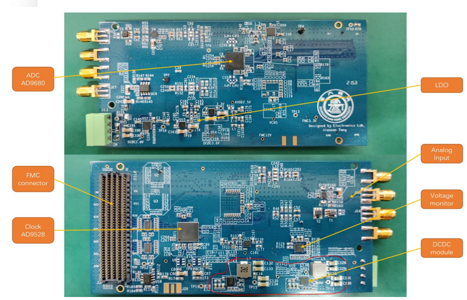






silicon strip sensor prototype





MC samples

- Signal samples:

  - Dark photon mass:1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 500, 700, 1000, 1500, 2000 MeV.
  - 1×10^5 events in each sample.

- Background samples:

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	$1.5(\pm0.5)\times10^{-8}$	4.3×10^{14}
GMM_ECAL	1×10^7	$1.63(\pm0.06)\times10^{-6}$	6.0×10^{12}
PN_target	1×10^7	$1.37(\pm0.05)\times10^{-6}$	4.0×10^{12}
PN_ECAL	1×10^8	$2.31(\pm0.01)\times10^{-4}$	4.4×10^{11}
EN_target	1×10^8	$5.1(\pm0.3)\times10^{-7}$	1.6×10^{12}
EN_ECAL	1×10^7	$3.25(\pm0.08)\times10^{-6}$	1.8×10^{12}

Background estimation

- Cut-flow:

	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%
$E_{HCAL}^{total} < 100$ MeV	$< 10^{-3}$%	$< 10^{-3}$%	0%	0.30%	0.72%	0%	69.61%	4.76%
$E_{HCAL}^{MaxCell} < 10$ MeV	$< 10^{-3}$%	$< 10^{-3}$%	0%	0.13%	0.27%	0%	65.00%	4.48%
$E_{HCAL}^{MaxCell} < 2$ MeV	$< 10^{-3}$%	$< 10^{-3}$%	0%	0.058%	0.095%	0%	58.14%	4.04%
$E_{ECAL}^{total} < 2.5$ GeV	0%	0%	0%	0%	0%	0%	0%	0%

- EOTs:

Process	EOTs
Inclusive	2.5×10^9
Bremsstrahlung	1.5×10^8
GMM_target	4.3×10^{14}
GMM_ECAL	6.0×10^{12}
PN_target	4.0×10^{12}
PN_ECAL	4.4×10^{11}
EN_target	1.6×10^{12}
EN_ECAL	1.8×10^{12}

⇨ Inclusive background: 2.5×10^9 EOTs

⇨ $> 3\times10^{14}$ EOTs (1year run)

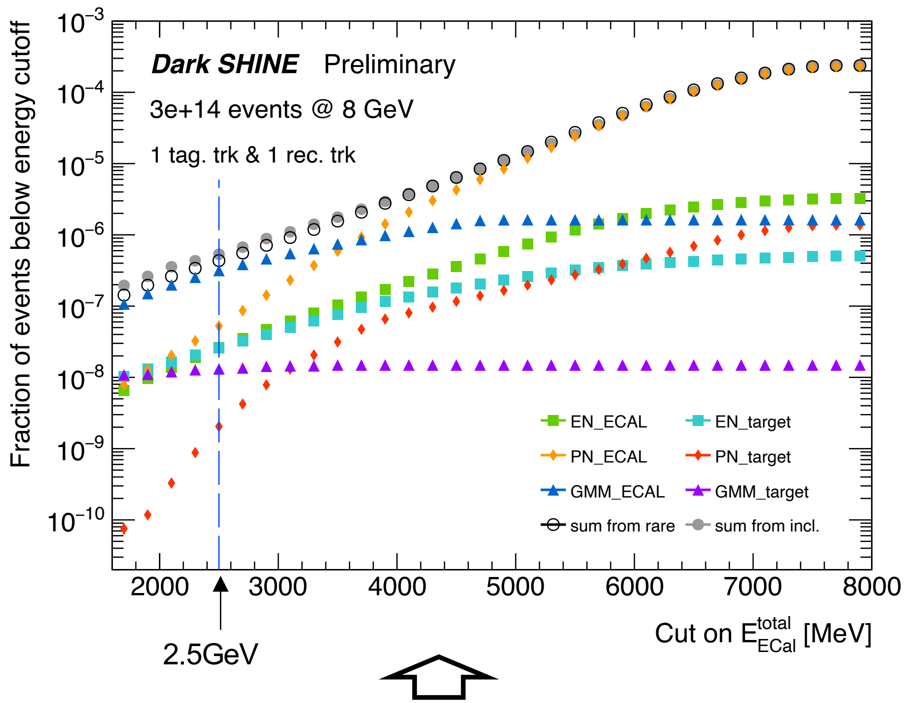
Lack of statistics!

⇩

Extrapolate from fit results

No background events left after SR selection.

Background estimation

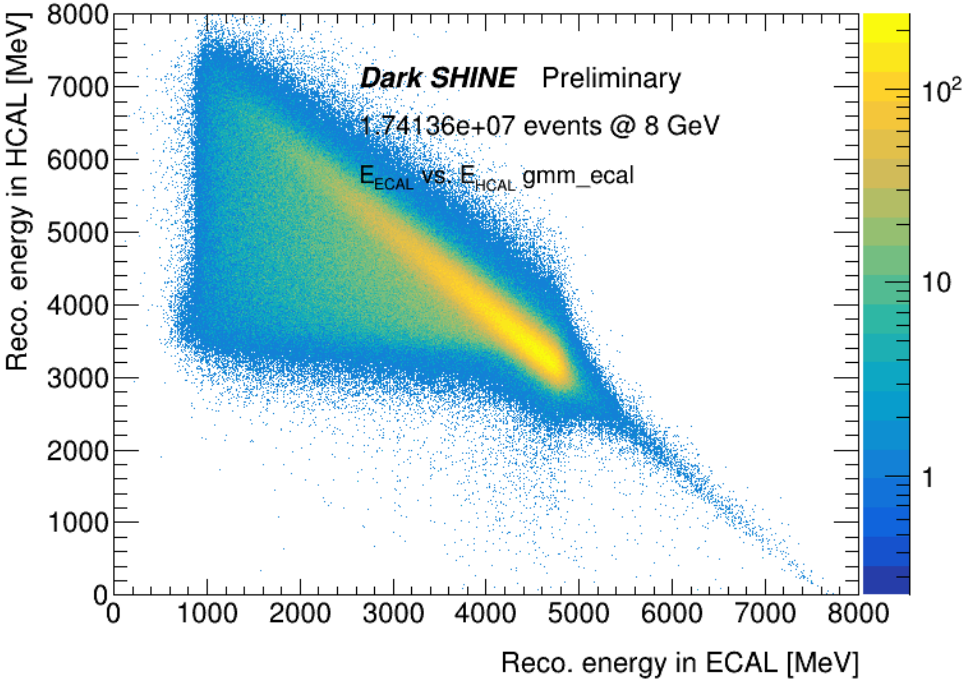


rare processes scaled according to the corresponding branching ratio.

- **Extrapolate from rare processes simulation.**
- Rare processes background samples are produced with larger statistics.
- Fit the fraction of events below energy cutoff in other rare processes (EN_ECAL, EN_target, PN_ECAL, PN_target).

Background estimation

- **Extrapolate from rare processes simulation.**
- Estimate the number of background events corresponds to $\mathbf{3 \times 10^{14}}$ EOTs.



GMM_target:

4.3×10^{14}EOTs > 3×10^{14}EOTs

GMM_ECAL:

6.0×10^{12}EOTs

Energy carried by the muon pair

HCAL requirements can highly suppress these events (fraction of the remaining GMM events < 10^{-6})

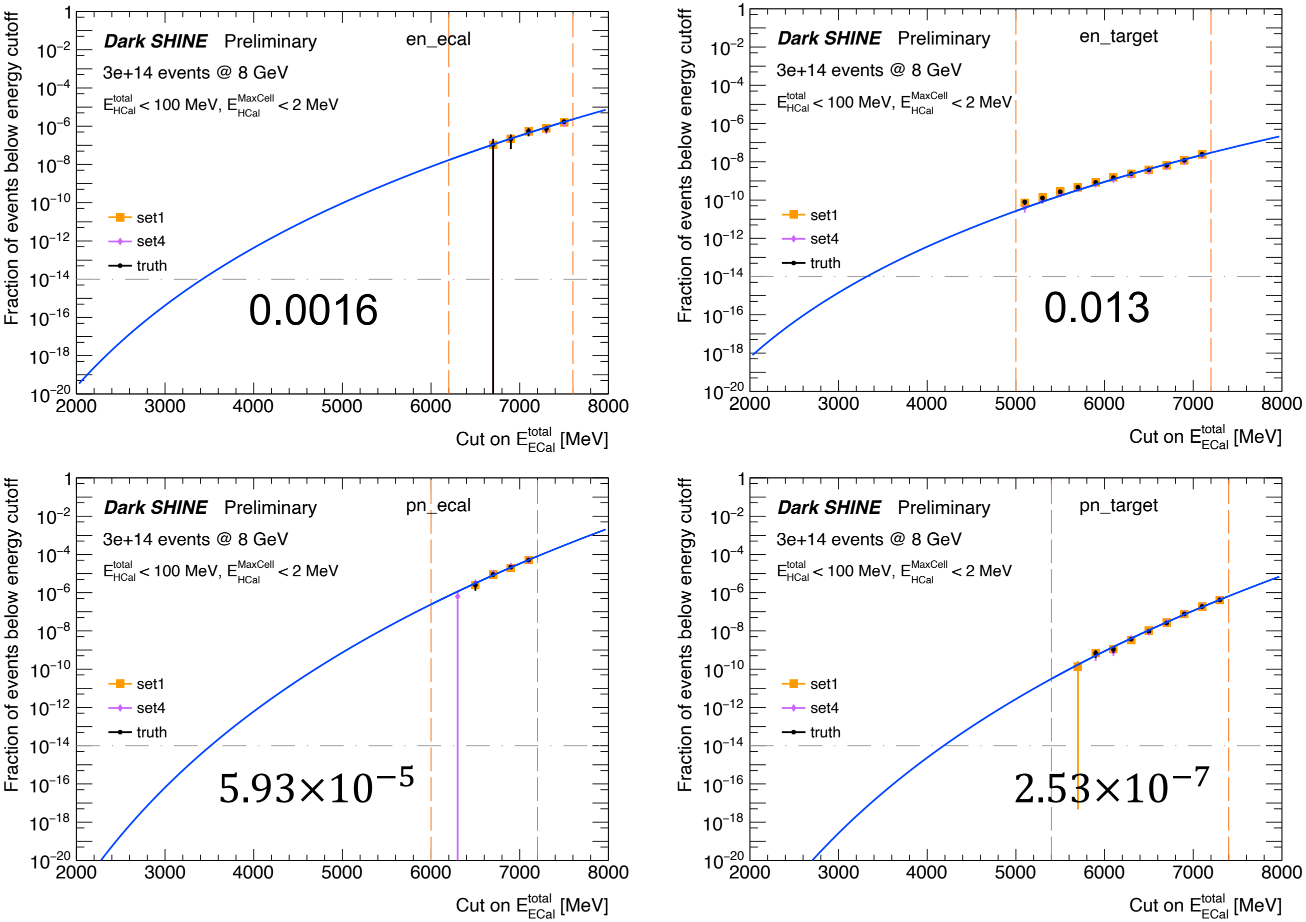
- Don't need to further extrapolation on:

GMM_target – **enough statistics**

GMM_ECAL – **can reject by HCAl requirements**

Background estimation

- **Extrapolation from rare processes simulation**



3×10^{14}EOTs

⇕

Bkg. Events:
0.015

1st publication

SCIENCE CHINA
Physics, Mechanics & Astronomy

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• Article •
Editor's Focus

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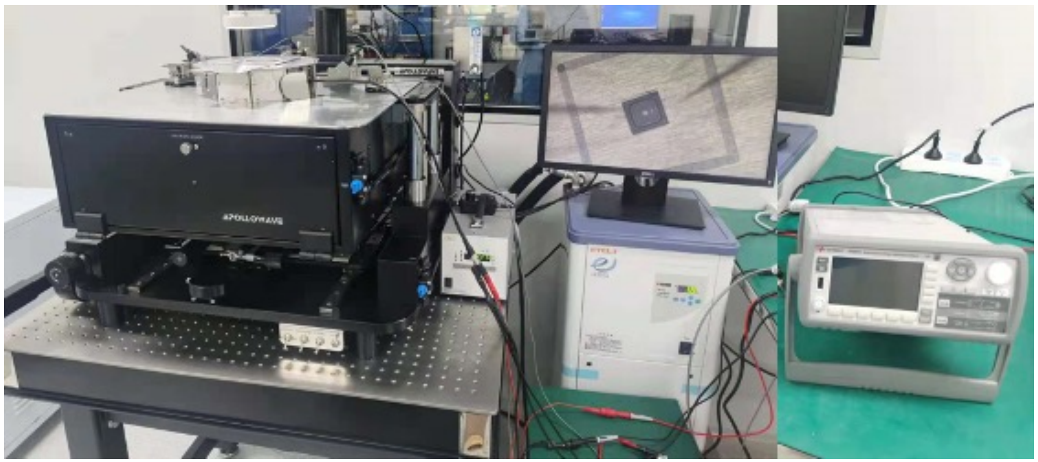
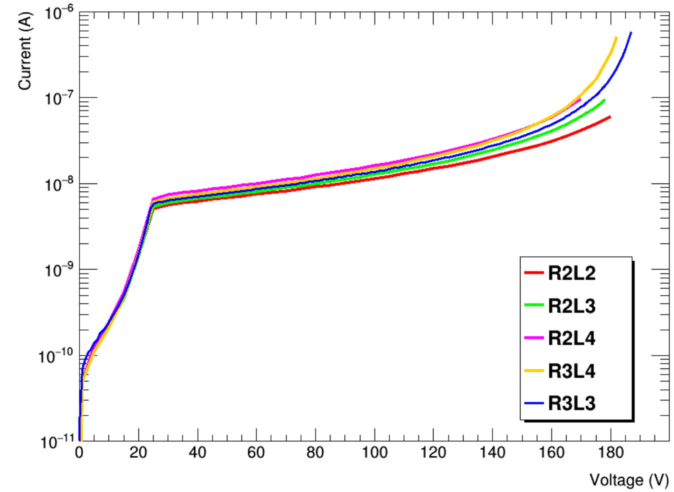
Editor's Focus

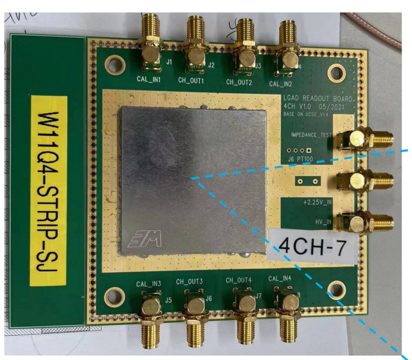
Prospective study of light dark matter search with a newly proposed DarkSHINE experiment

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]

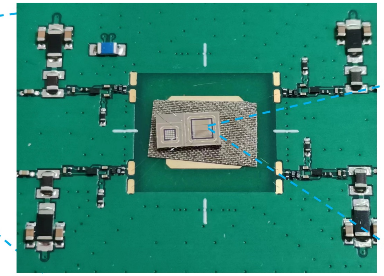
Detector R&D: tracking system

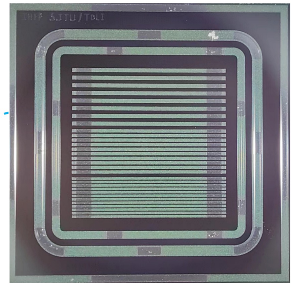


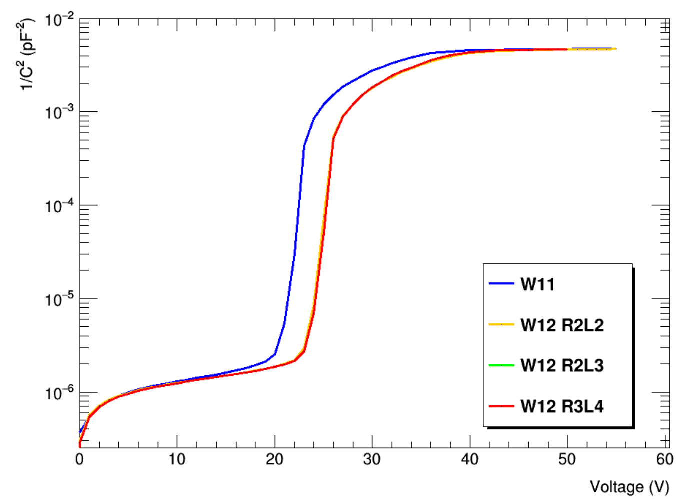




Working point
W11: 350V
W12: 150V







Detector R&D: tracking system

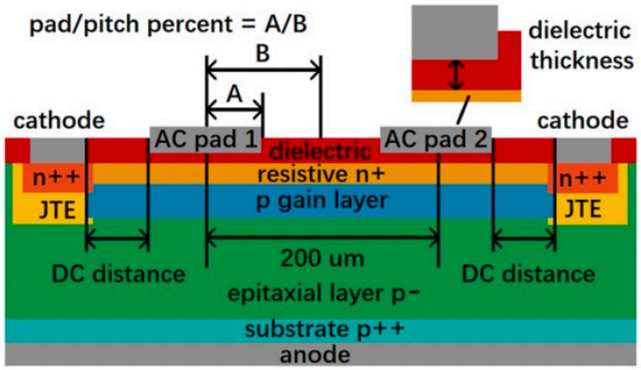
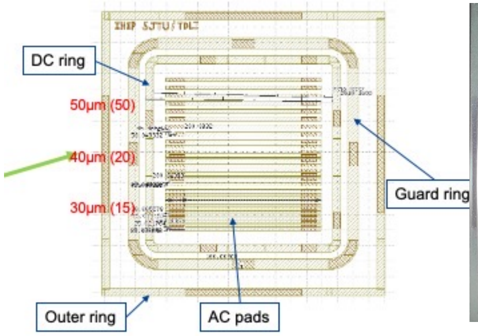
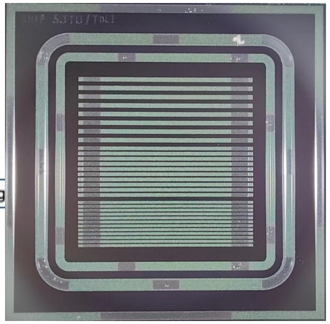


Figure 1. Sketch of AC-LGADs with 2 AC pads (not to scale).

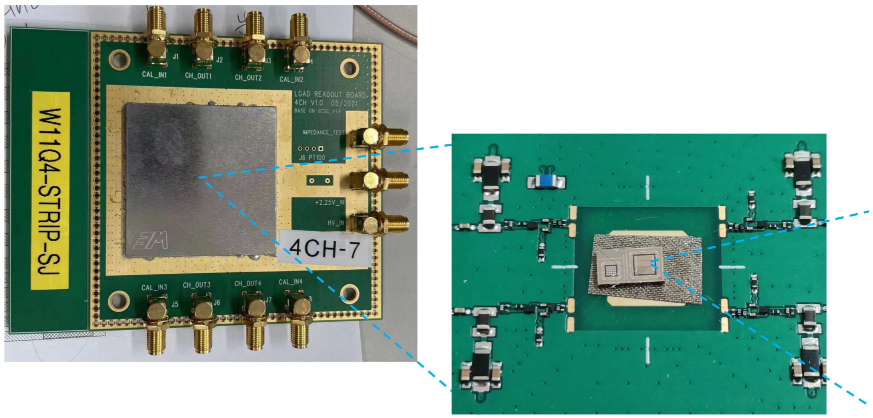
- Each module: 2 layers of silicon strip sensors with a small angle (0.1rad) for better position resolution.
- Designed resolution: 10μm.
- AC-LGAD silicon strip sensor prototype designed (1×1 mm^2) and tested in collaboration with IHEP.

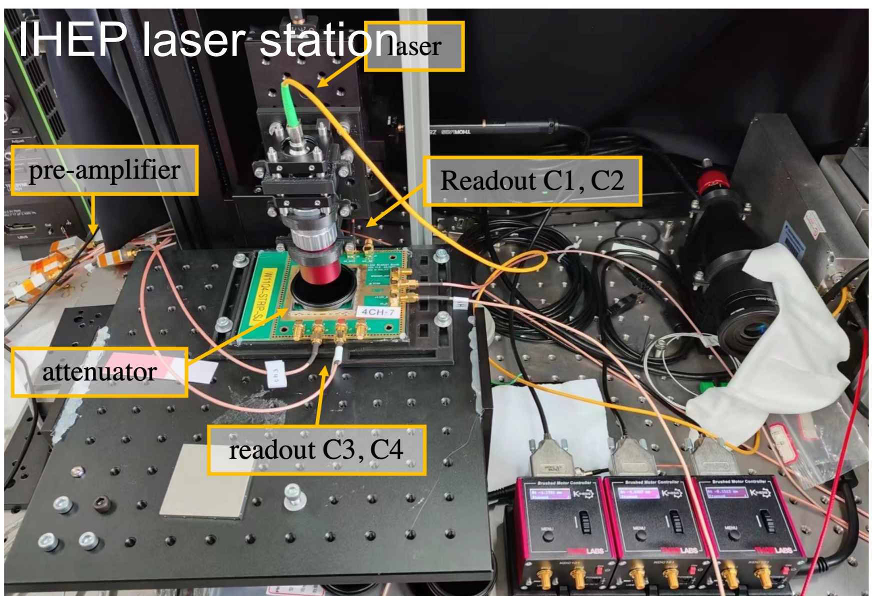


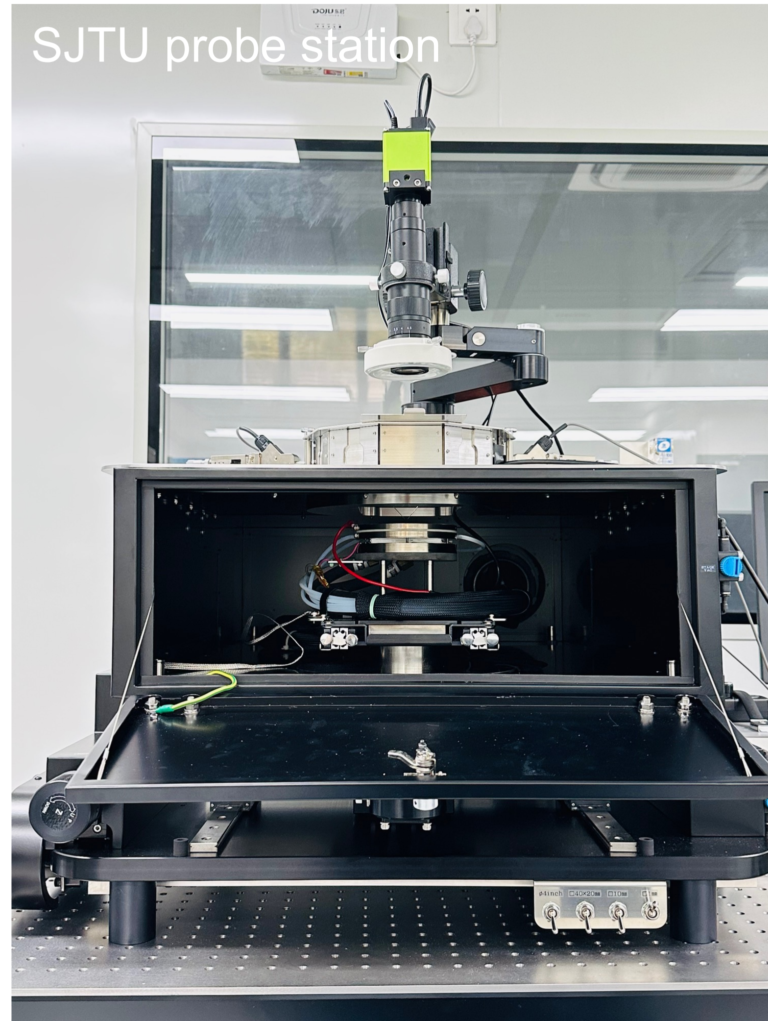


AC-coupled Low Gain Avalanche Detector (AC-LGAD) offers exceptional timing performance (response time ~ 1ns) and spatial resolution (6.5μm ~8.2 μm).

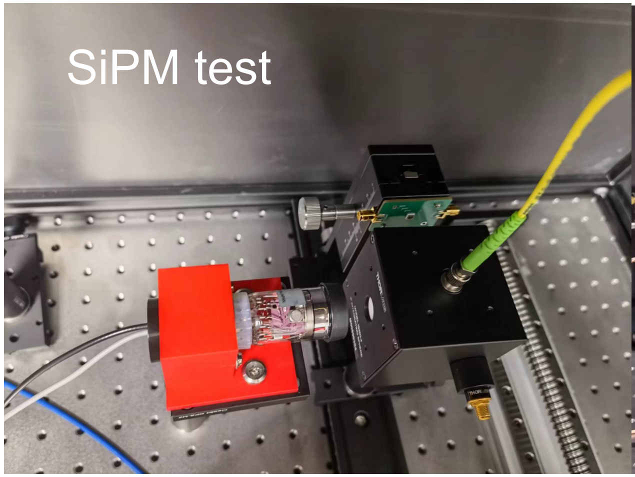
Detector R&D: tracking system

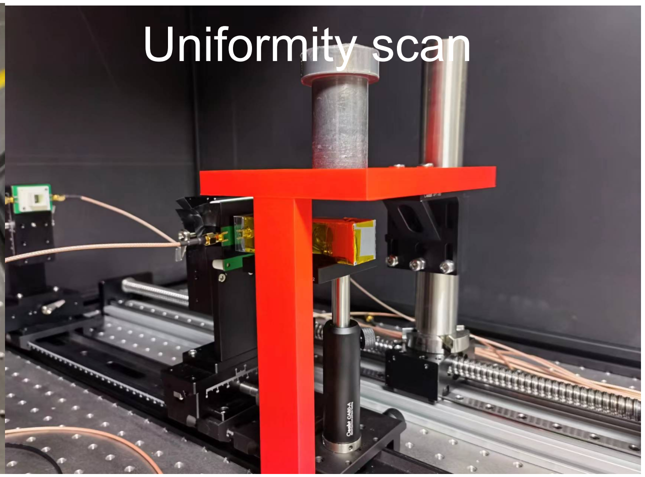


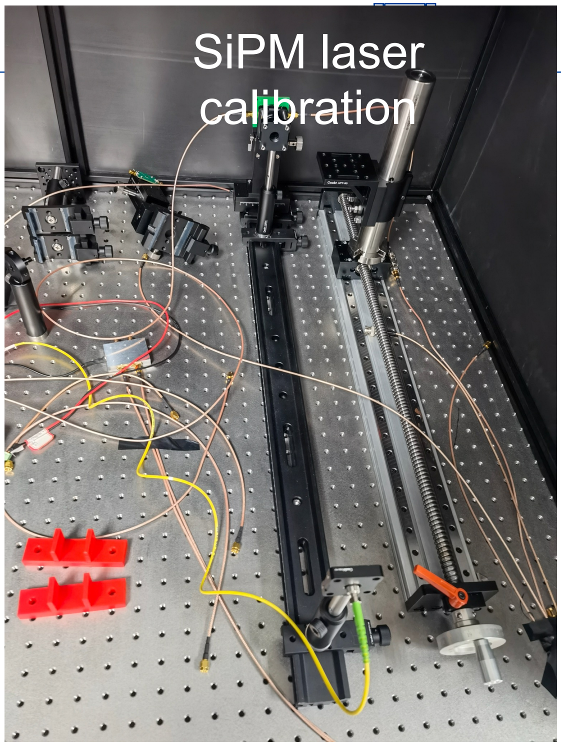


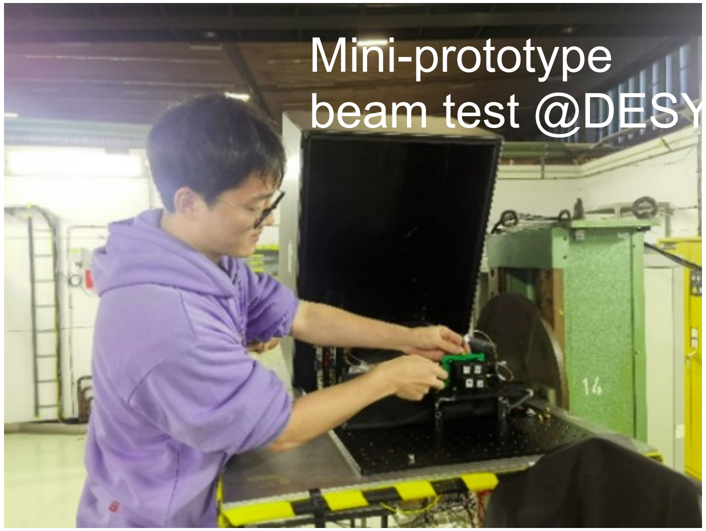


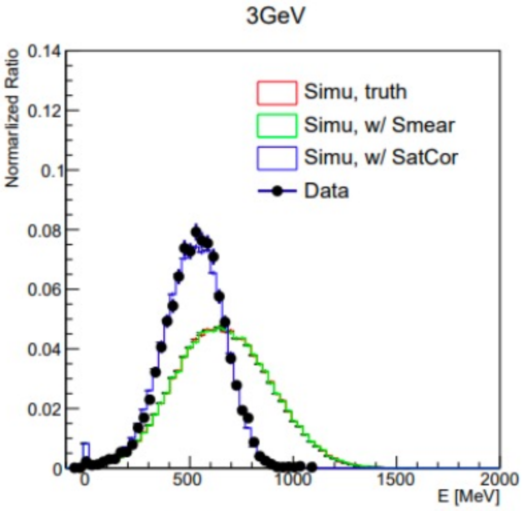
Detector R&D: ECAL



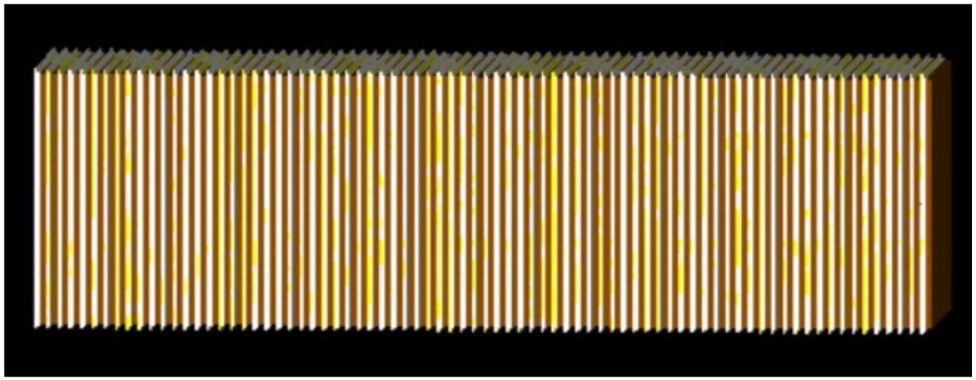


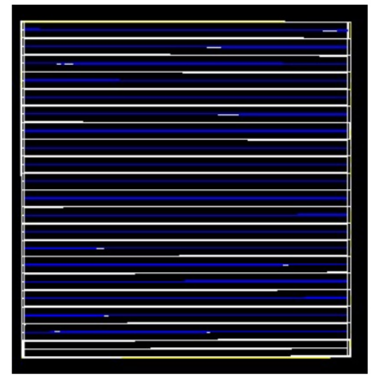


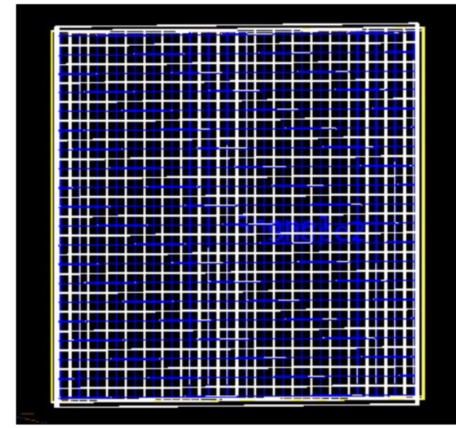




HCAL design



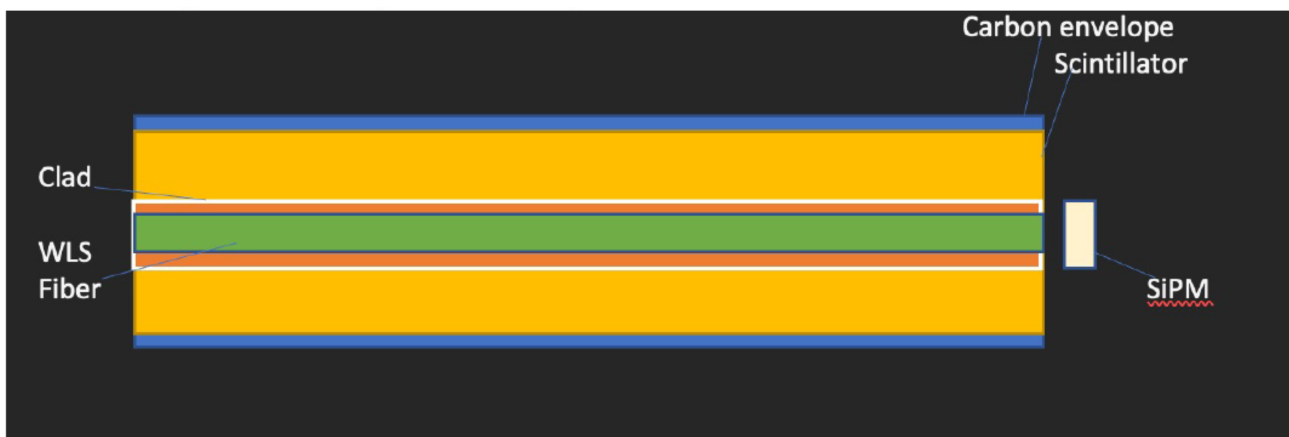




xy crossing

Parameter for the whole HCAL
X:100cm
Y:100cm
Z:360cm

Each scintillator wrapped by a carbon envelope, with a wavelength shifting (WLS) fiber placed in its center.

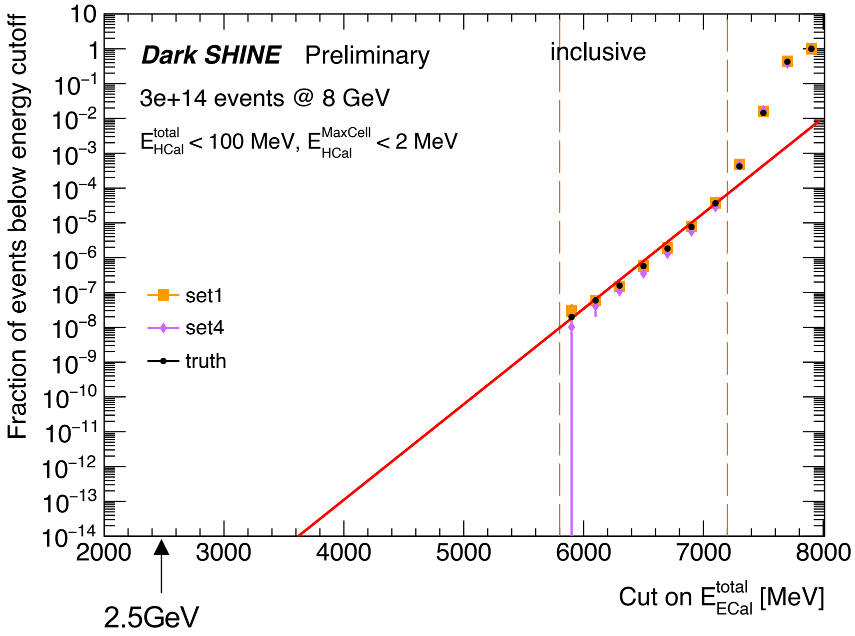


Veto the muon and hadron backgrounds.

- Simulation study ongoing with inject particles of different type and energy.

Background estimation

- Fit the fraction of events below energy cutoff as a function of cut values on ECAL energy.
- **Extrapolate from inclusive background simulation.**
- Validation from inclusive background simulation.
- Extrapolate from rare processes simulation.



$y = 10^{-14}$: less than one background event left w/ ECAL energy cut.

Extrapolate from the fit results.

Lack of statistics in low "cut on E_{ECal}^{total}" region.

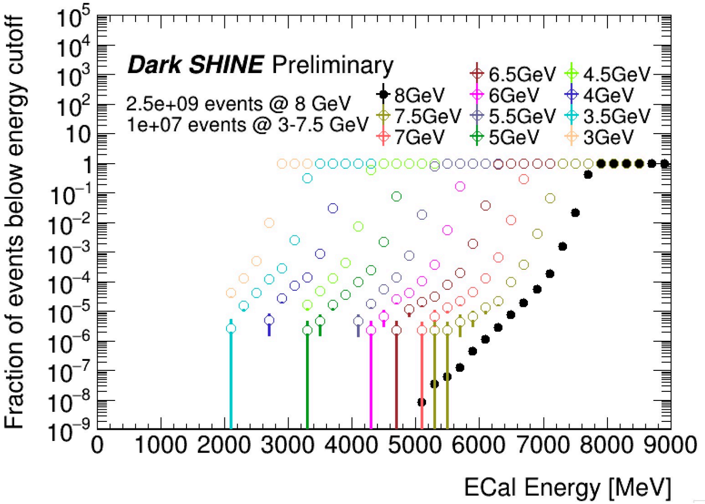
Event yield (3×10^{14}EOTs):

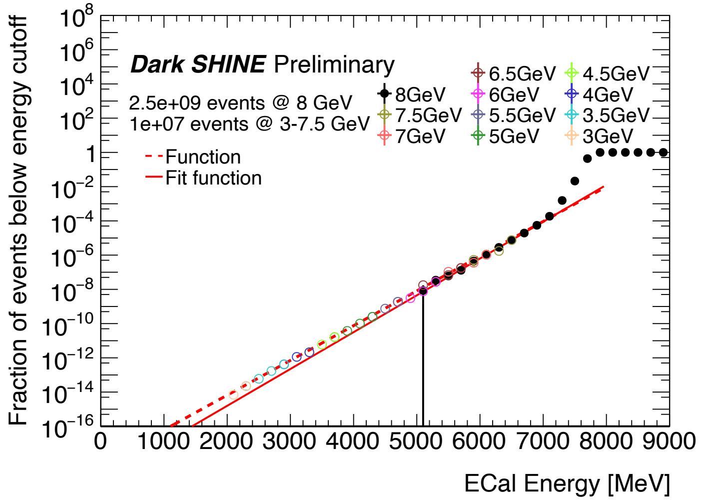
$$\mathbf{2.53\times10^{-3}}$$

Background estimation

- **Validation from inclusive background simulation.**
- Statistics is limited in $E_{beam} = 8\text{GeV}$ inclusive samples.
- In extrapolation of inclusive background simulation, the fit range is far away from the final E_{ECal}^{total} cut (2.5 GeV).
- Inclusive samples with E_{beam} from 3 – 7.5 GeV are used to estimate events in low E_{ECal}^{total}.
- Scale low E_{beam} events to match the shoulder with $E_{beam} = 8$ GeV events.
- **Event yield from direct extrapolation(3×10^{14}EOTs):**

$$N_{100,2} = 3\times10^{14}\times N_{100,20}\cdot\frac{N_{fit,100,2}}{N_{fit,100,20}}$$
$$= \mathbf{9.23\times10^{-3}}$$





Invisible background

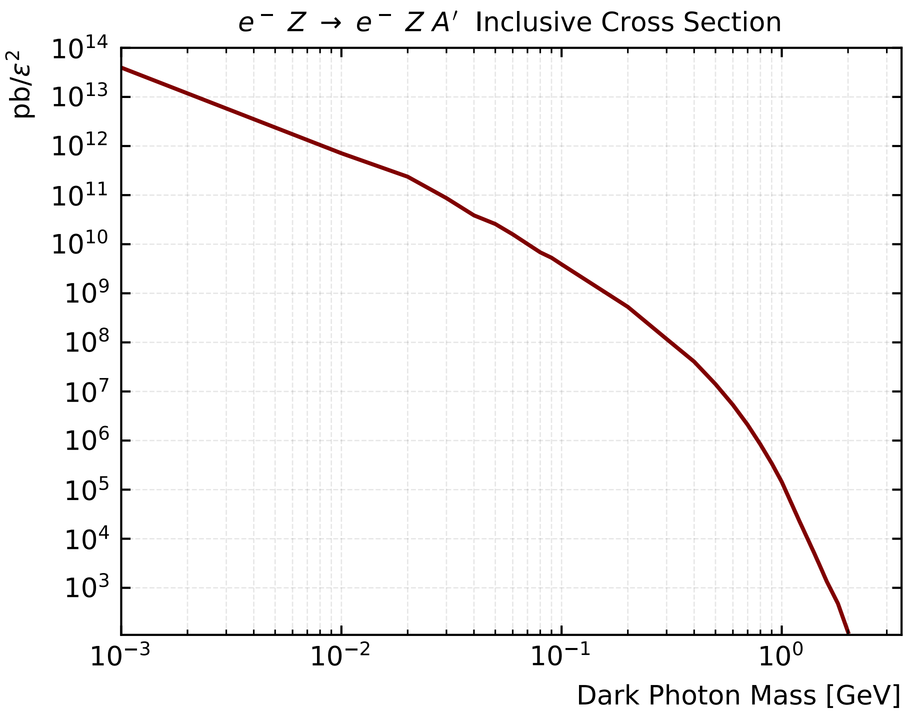
- Neutrino productions:

  - Moller scattering $e^-e^- \to e^-e^-$ followed by charged-current quasi-elastic (CCQE) reaction $e^-p \to \nu_e n$.
  - Neutrino pair production $e^-N \to e^-N\nu\bar{\nu}$.
  - Bremsstrahlung $\bigoplus$ CCQE and charge-current exchange with exclusive $e^-p \to \nu n\pi_0$. No recoil electron, track requirement can remove these processes.

Table 6 Expected invisible background production corresponds to 3×10^{14} EOTs, estimated from different irreducible reaction scenarios. The Bremsstrahlung $\bigoplus$ CCQE and the charge-current exchange productions can be effectively rejected by the one-track requirement.

irreducible reaction	Moller scattering	neutrino pair production
estimated yield	3×10^{-4}	$< 1.8 \times 10^{-5}$
irreducible reaction	Bremsstrahlung $\bigoplus$ CCQE	charge-current exchange
estimated yield	0.3	0.3

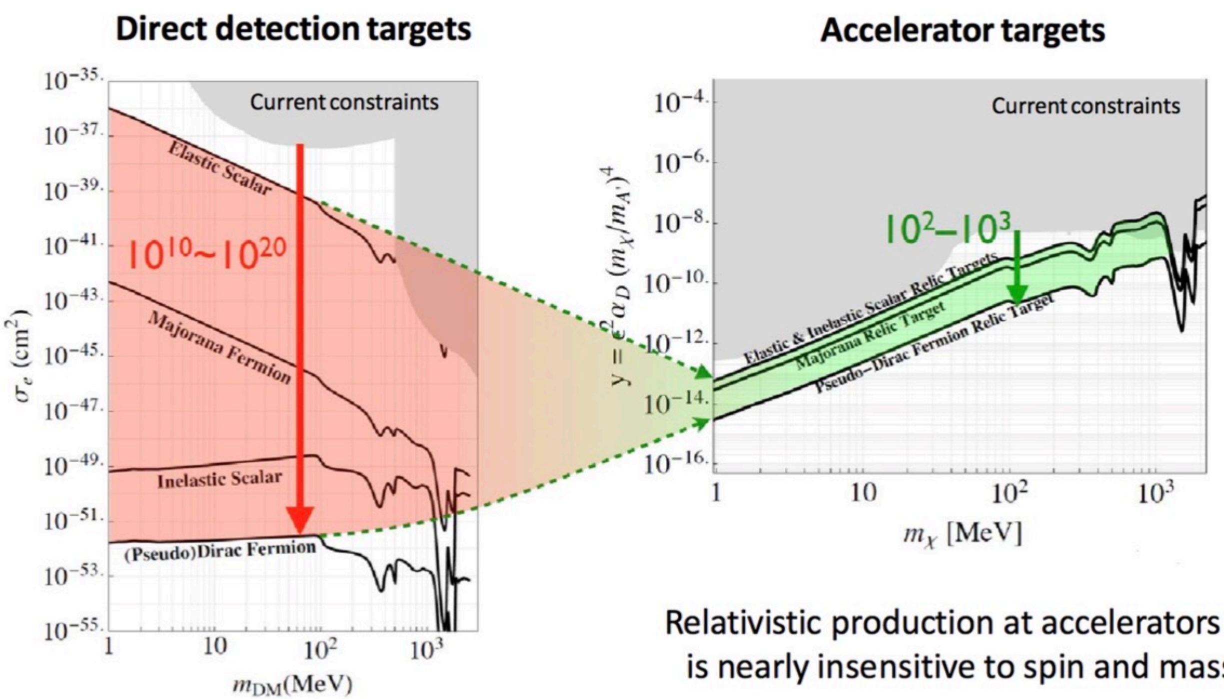
Inclusive cross-section



Inclusive cross-section of dark photon bremsstrahlung from electron interacting with W target, assuming $\varepsilon = 1$.

$$N_{sig} = \sigma_{A'} \times 0.1 X_0 \times L \times N_A / M_W \times 10^{-36} \times \varepsilon^2$$

Why need accelerator-based program?



Relativistic production at accelerators is nearly insensitive to spin and mass

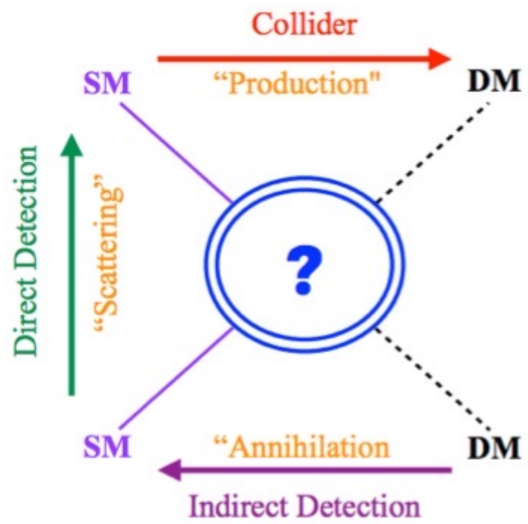
arXiv:1707.04591

- Accelerator-based experiments are much less sensitive to the details of the DM particle nature than direct detection experiments.
- Predictions with different theoretical models $\sim 10^2 - 10^3$.

⇧

Easy to carry out simultaneous verification in experiments.

Dark matter detection



- Direct Detection: nuclear recoils from DM-nuclei scattering
- Indirect Detection: products from DM annihilation
- Colliders: DM production in high-energy collisions