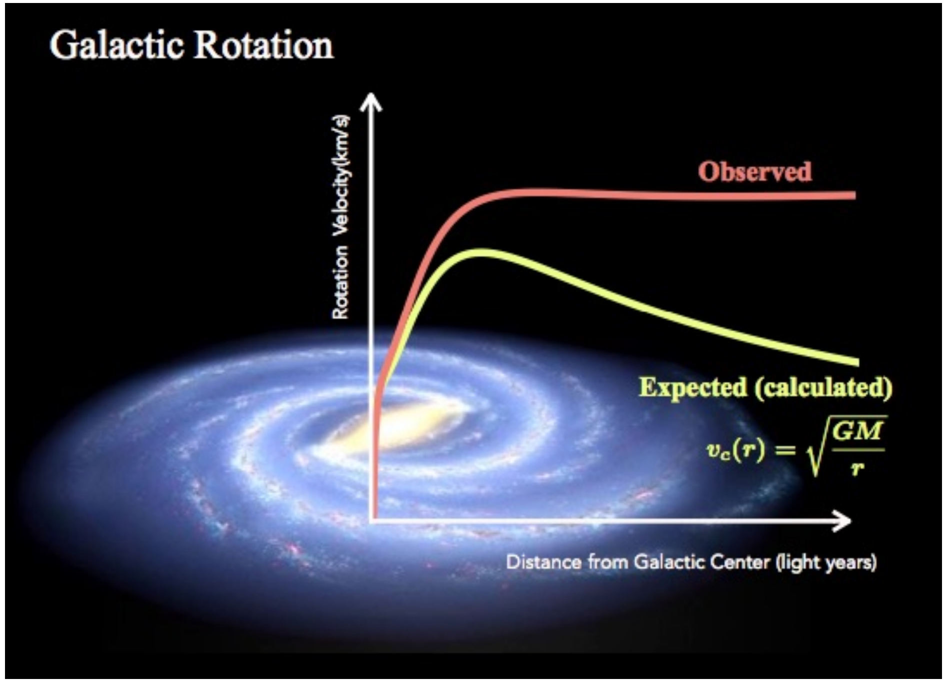
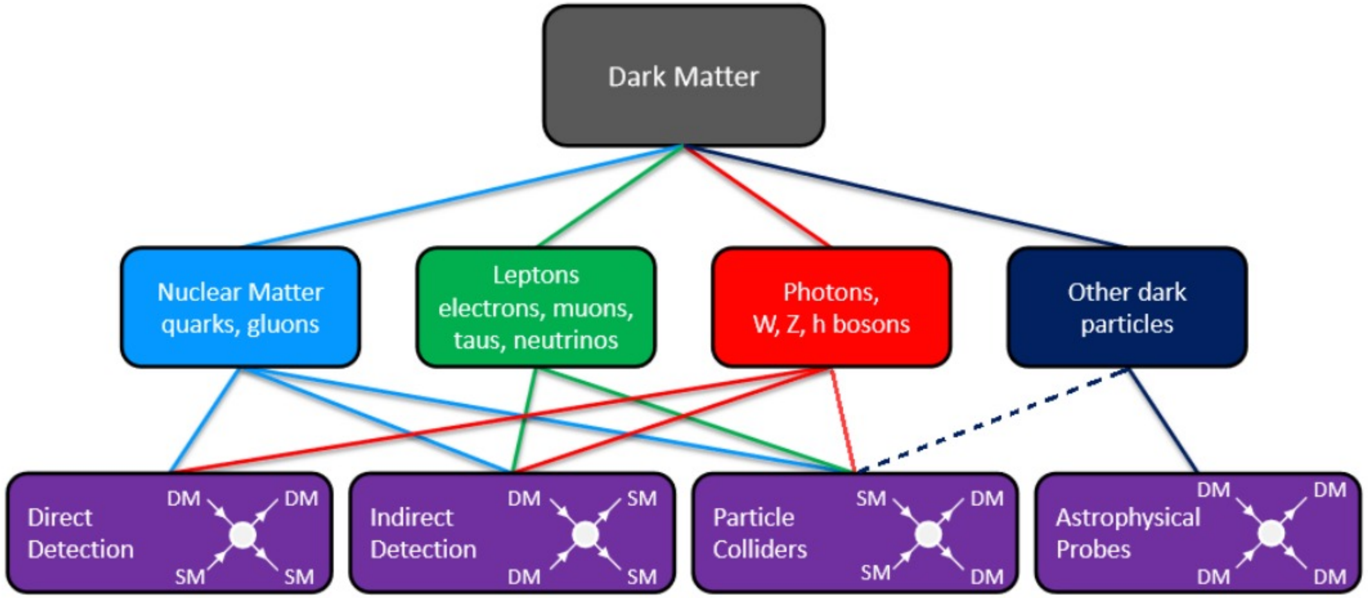
DarkSHINE – Search for Light Dark Matter at the SHINE facility in Shanghai

Danning Liu, on behalf of the DarkSHINE R&D Term

October, 2024, Moscow, Russia

Dark Matter Evidence




Dark Matter

Nuclear Matter
quarks, gluons

Leptons
electrons, muons,
taus, neutrinos

Photons,
W, Z, h bosons

Other dark
particles

Direct
Detection

Indirect
Detection

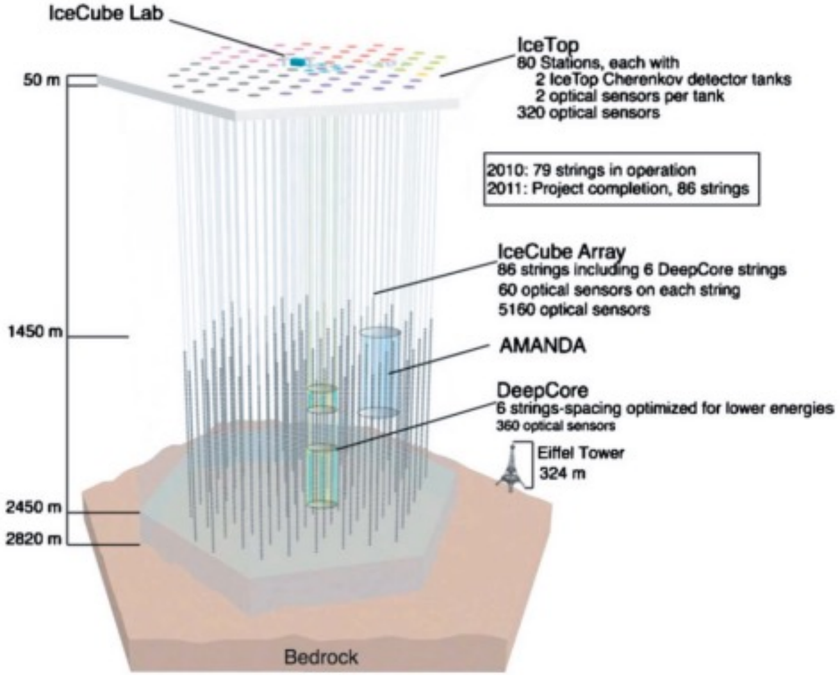
Particle
Colliders

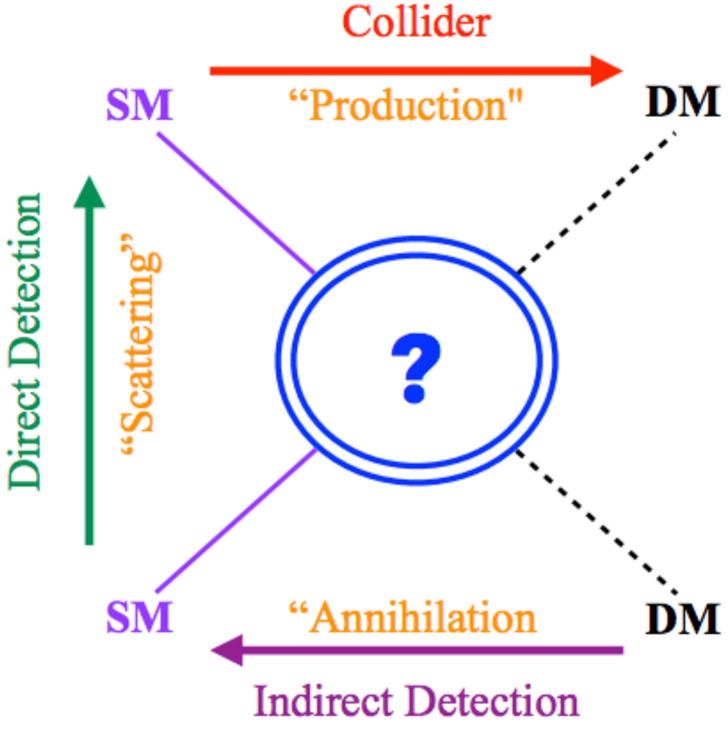
Astrophysical
Probes

- Dark Matter (DM) evidence, from astronomical observations and gravitational effects
  - Galactic rotation curves, Gravitational lensing, Cosmic Microwave Background …

Dark Matter Detection

- **Direct Detection**: nuclear recoils from DM-nuclei scattering (PandaX, XENONnT, LZ, CDEX …)
- **Indirect Detection**: products from DM annihilation (DAMPE, IceCube …)
- **Colliders**: DM production in high-energy collisions, especially focusing on the productions of a SM particle with large missing E_T

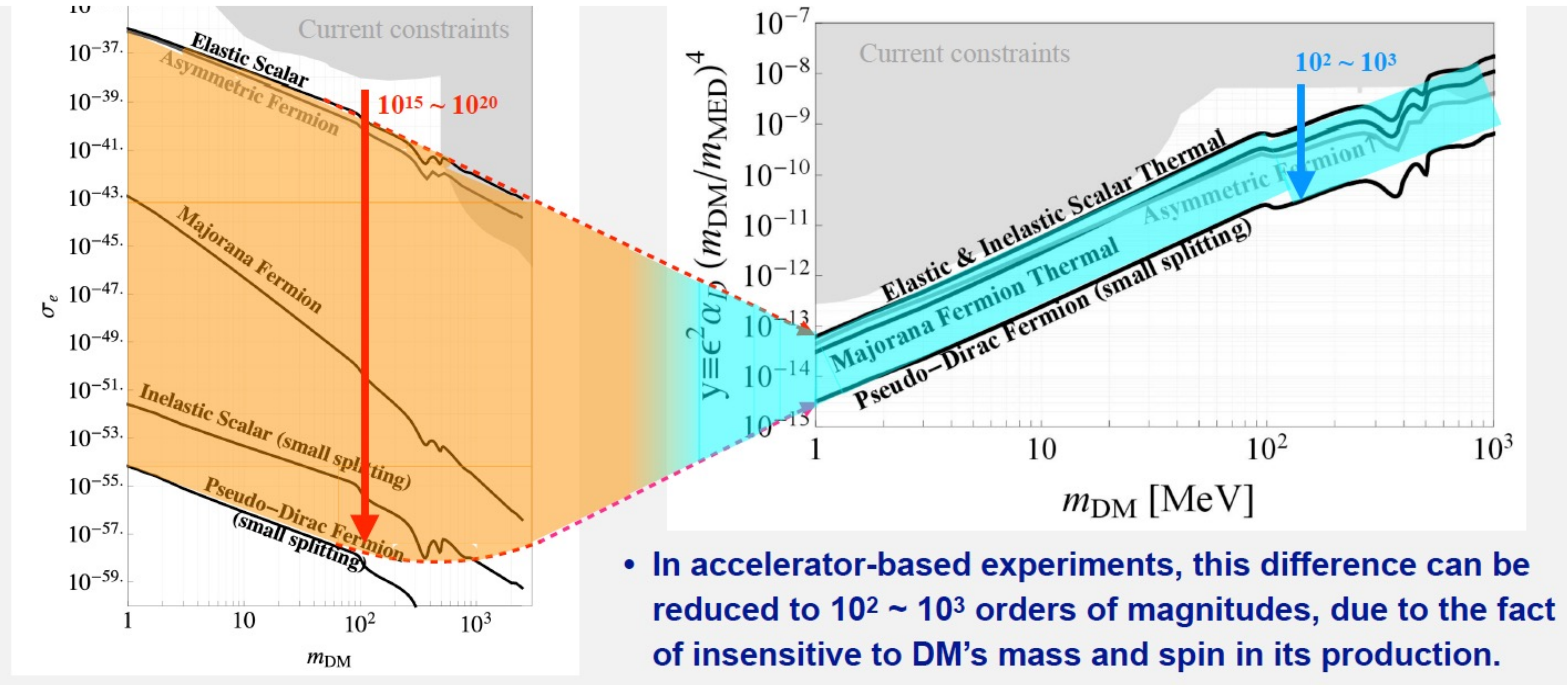




Dark Matter Search at Accelerator Experiments

Direct Detection

Accelerator based experiments



- In accelerator-based experiments, this difference can be reduced to $10^2 \sim 10^3$ orders of magnitudes, due to the fact of insensitive to DM's mass and spin in its production.

Dark Photon Theory

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

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

SM Photon γ

Dark Photon A′

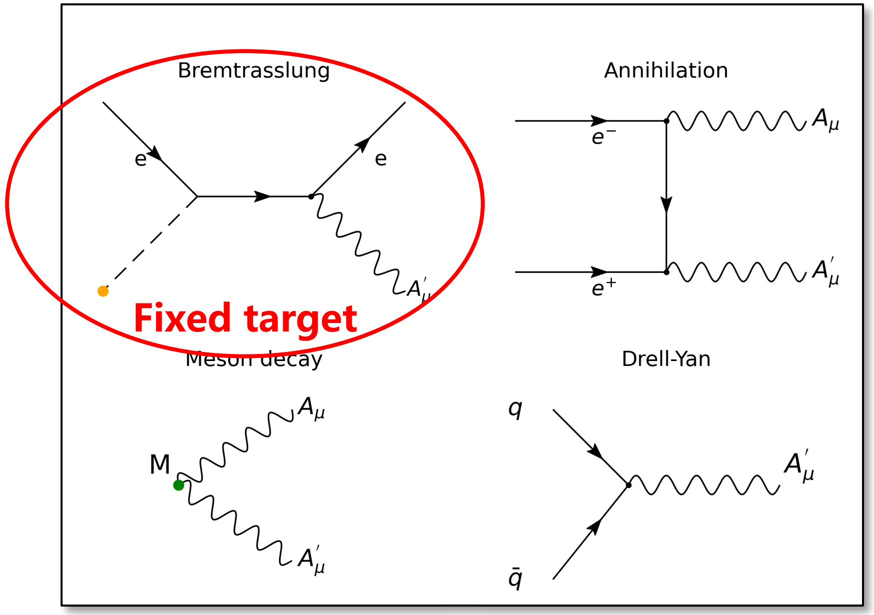
$$\varepsilon X_{\mu\nu}F^{\mu\nu}$$

- **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)

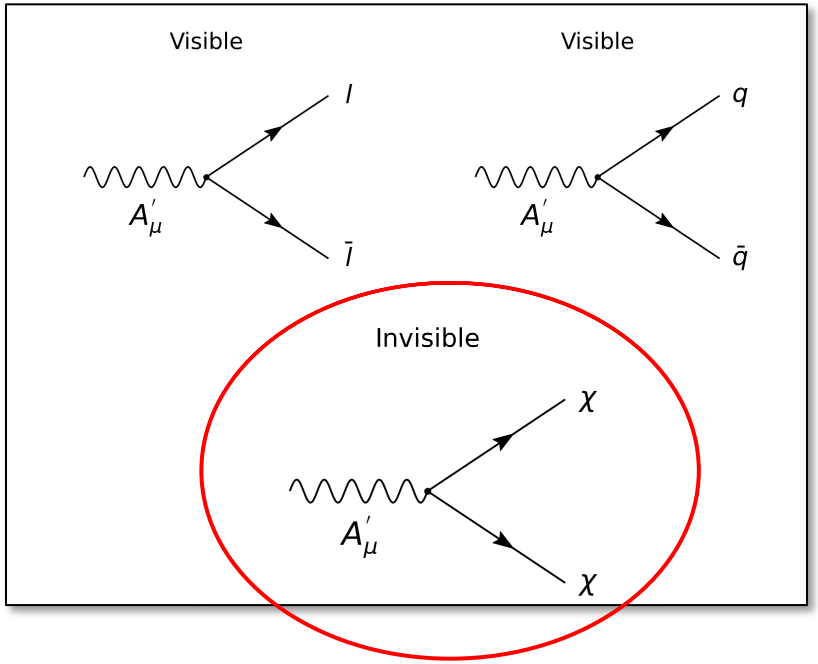
Physics Processes and Anticipated Signatures

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



Fixed target

(Dark photon production)

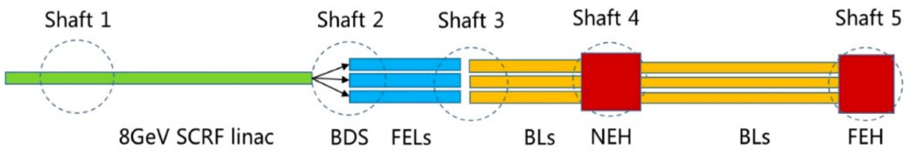


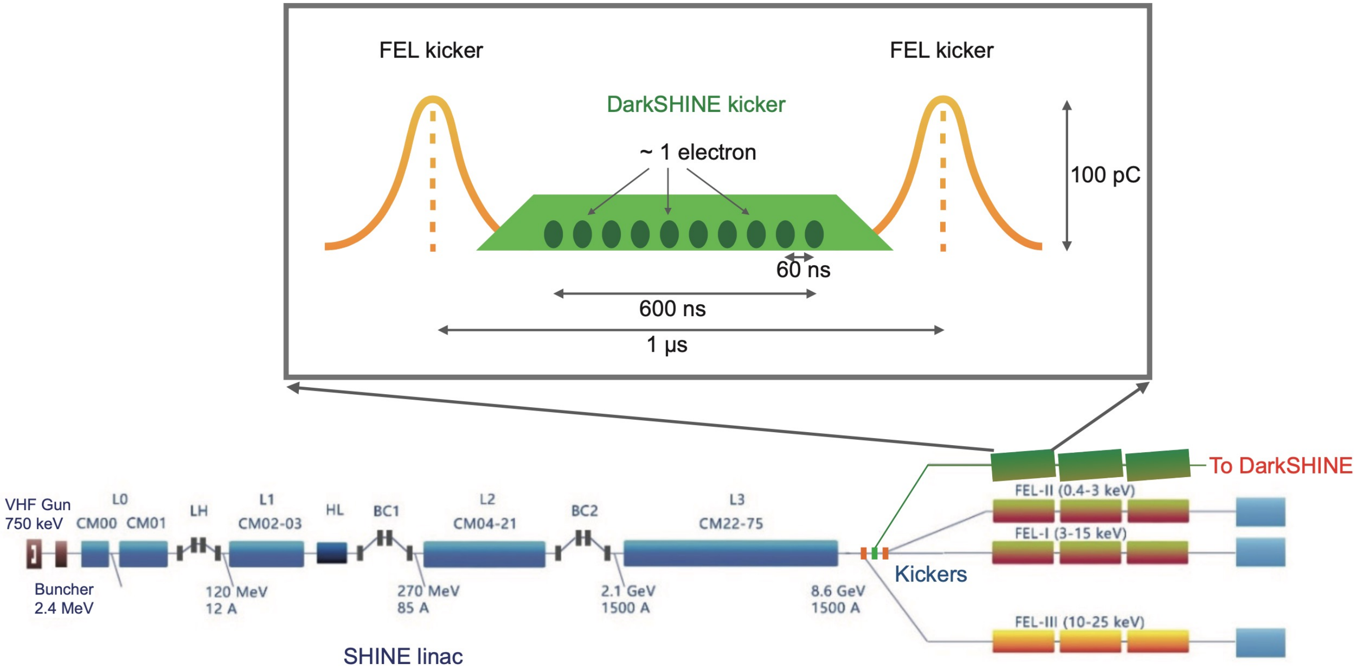
(dark photon decay)

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

The SHINE Facility

- Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE) can provide high repetition rate single electron beams → with dedicated kicker to be designed and deployed
  - Electron energy: 8 GeV, Rep. Rate: 1 MHz
  - Beam intensity: 100 pC (6.25E8 electrons/bunch)
  - ~ 3×10^{14} electrons-on-target (EOT) per year



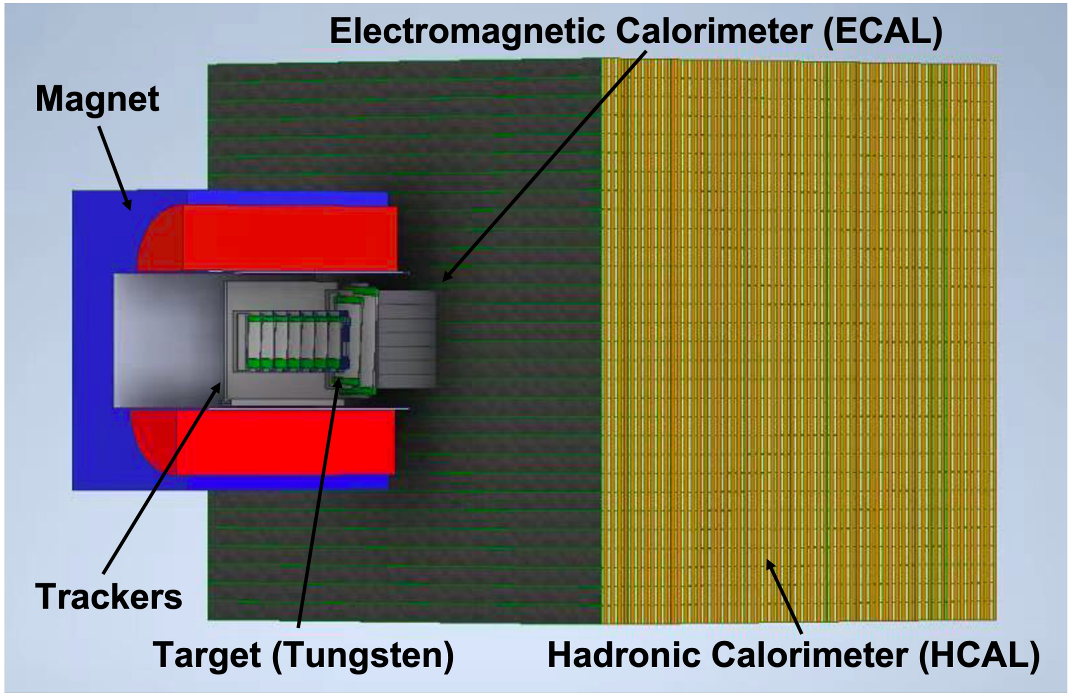


SHINE linac

DarkSHINE Experiment Conceptual Design

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

Tracking system
Measure the tracks of the incident and recoil electrons.



Dark SHINE detector sketch

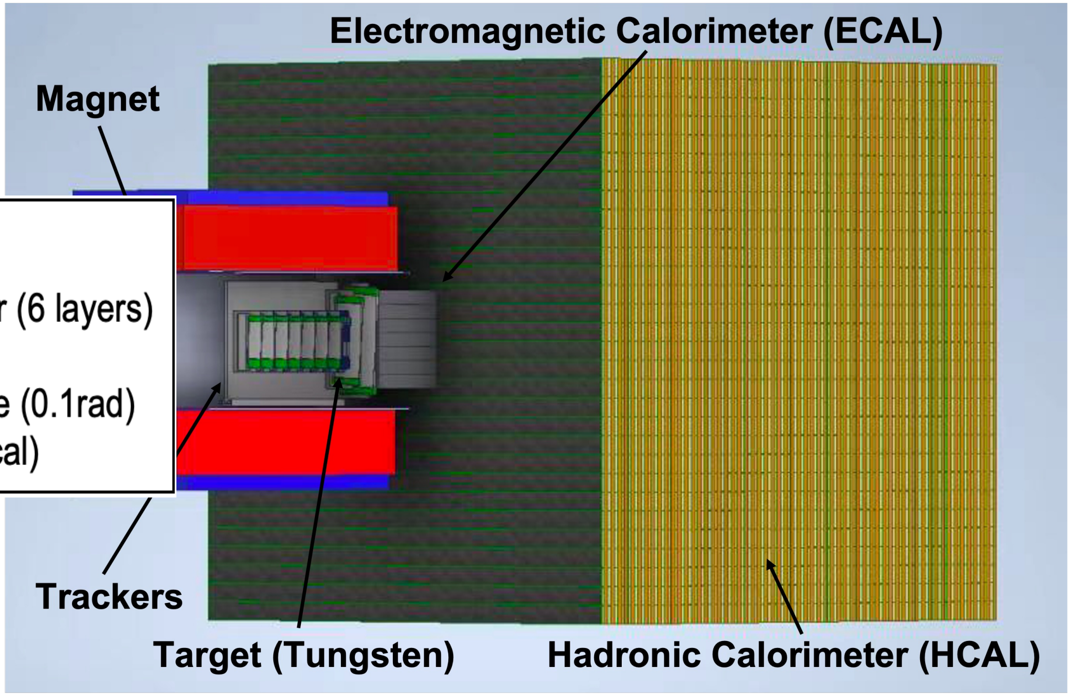
Electromagnetic calorimeter
Measure the deposited energy: electron and photon.

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

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

DarkSHINE Experiment 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



Dark SHINE detector sketch

- **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%

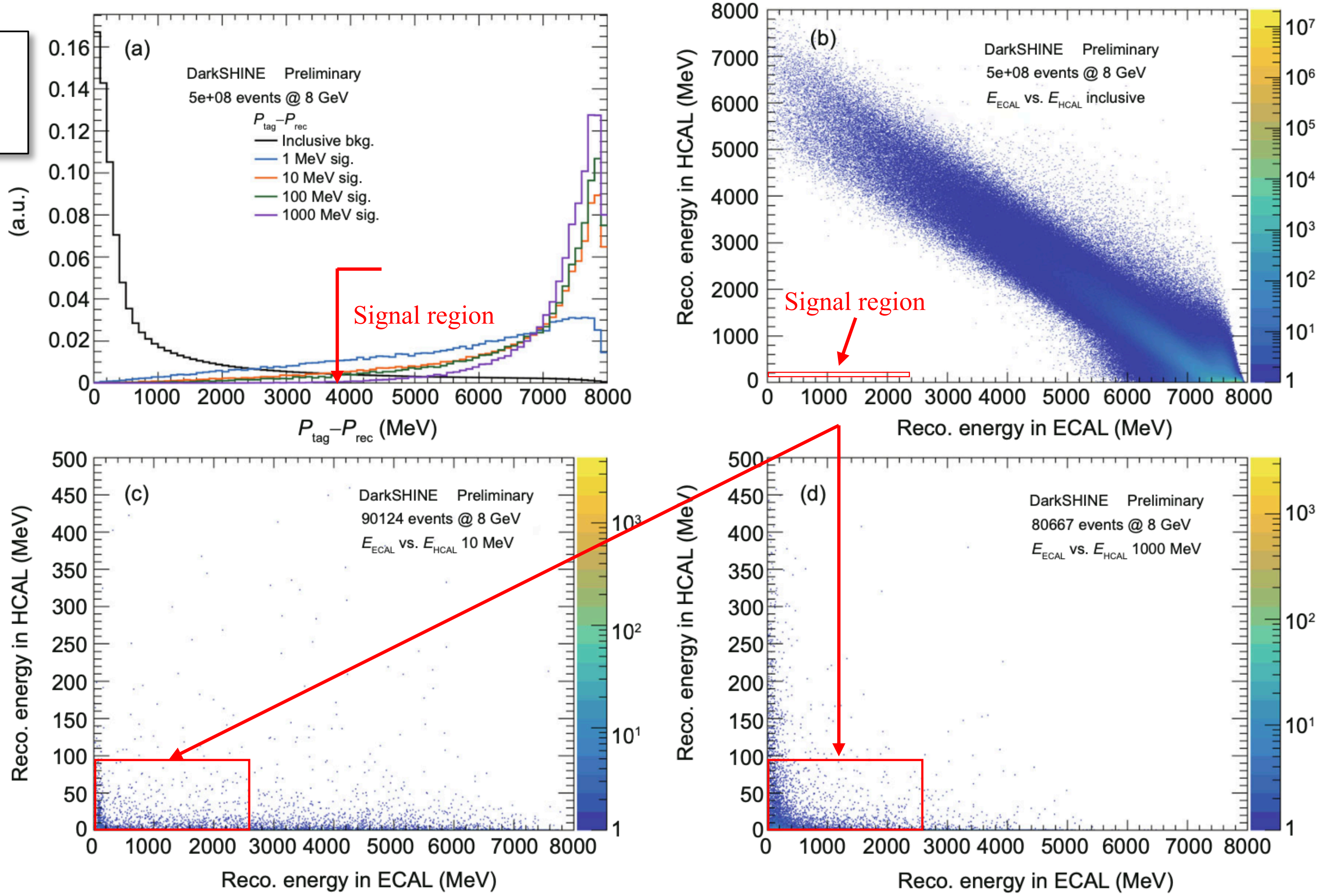
- **HCAL:**
  - Veto hadronic background
  - Scintillator w/ steel absorber
  - 4×4×1 modules

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

Determination of Signal Selections

Inclusive bkg & signal

Inclusive bkg



10 MeV A′

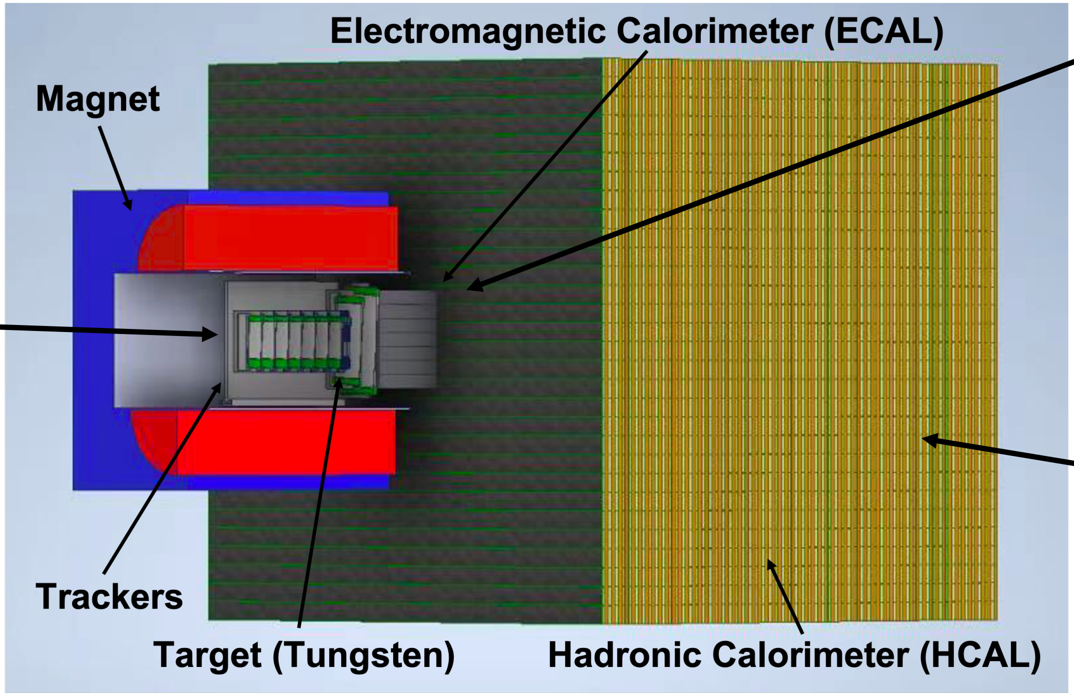
1 GeV A′

Signal Selections

Tracking system

Only 1 incident track and 1 recoil track;

$p_{inc.} - p_{rec.} > 4$ GeV.



1^{st} round Dark SHINE analysis

Electromagnetic calorimeter

$E_{ECAL}^{total} < 2.5$ GeV.

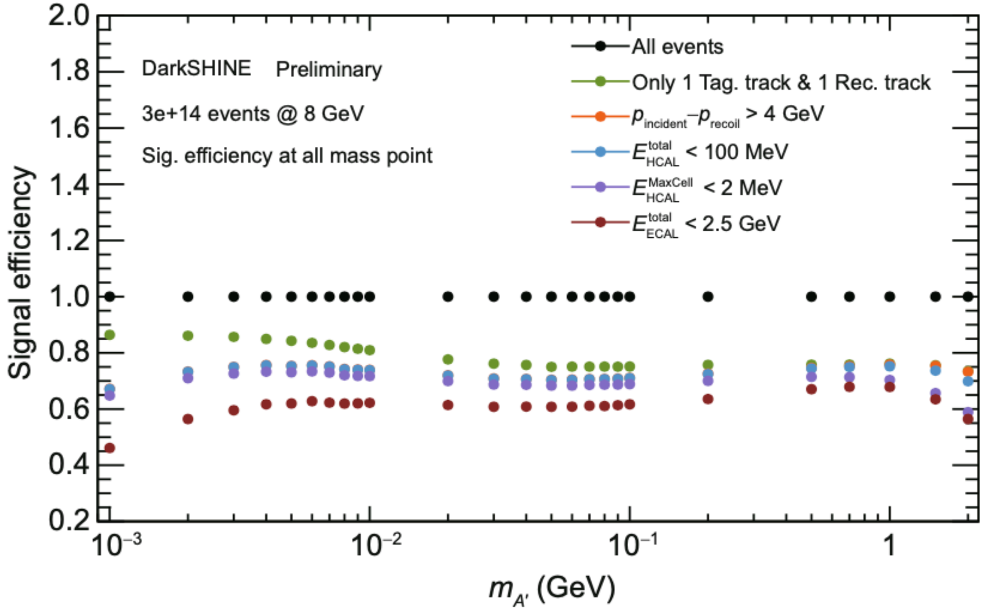
Hadronic calorimeter

$E_{\mathrm{HCAL}}^{total} < 100$ MeV;

$E_{HCAL}^{\max cell} < 2$ MeV.

Analysis Details

- Cut Efficiencies:
  - Signal Cut efficiencies as function of dark photon mass
  - 67% efficiency arrived and applied to extract significance



- Event Cutflow for each background samples on event numbers

	EN_ECAL	PN_ECAL	GMM_ECAL	EN_target	PN_target	GMM_target	Hard_brem	Inclusive
Total events	2.48×10^7	1.66×10^8	1.74×10^7	1.09×10^8	1.05×10^7	1.05×10^7	1.02×10^7	2.50×10^9
Only 1 track	1.46×10^7	1.17×10^8	1.52×10^7	6.38×10^6	6.17×10^5	77	8.03×10^6	2.11×10^9
$p_{tag} - p_{rec} > 4$ GeV	1091	5531	707	6.08×10^6	5.73×10^5	1	7.19×10^6	1.20×10^8
$E^{total}_{HCAL} < 100$ MeV	135	1348	0	322135	75501	0	1.19×10^8	2.89×10^7
$E^{MaxCell}_{HCAL} < 10$ MeV	56	676	0	141808	27949	0	1.12×10^8	2.72×10^7
$E^{MaxCell}_{HCAL} < 2$ MeV	30	363	0	63644	9999	0	1.01×10^8	2.46×10^7
$E^{total}_{ECAL} < 2.5$ GeV	0	0	0	0	0	0	0	0

< Science China > Publication with Highlights

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

SCIENCE CHINA
Physics, Mechanics & Astronomy

CrossMark

• Article •

June 2022 Vol. 63 No. 1: 000000
https://doi.org/??

Prospective Study of Light Dark Matter Search with a Newly Proposed DarkSHINE Experiment

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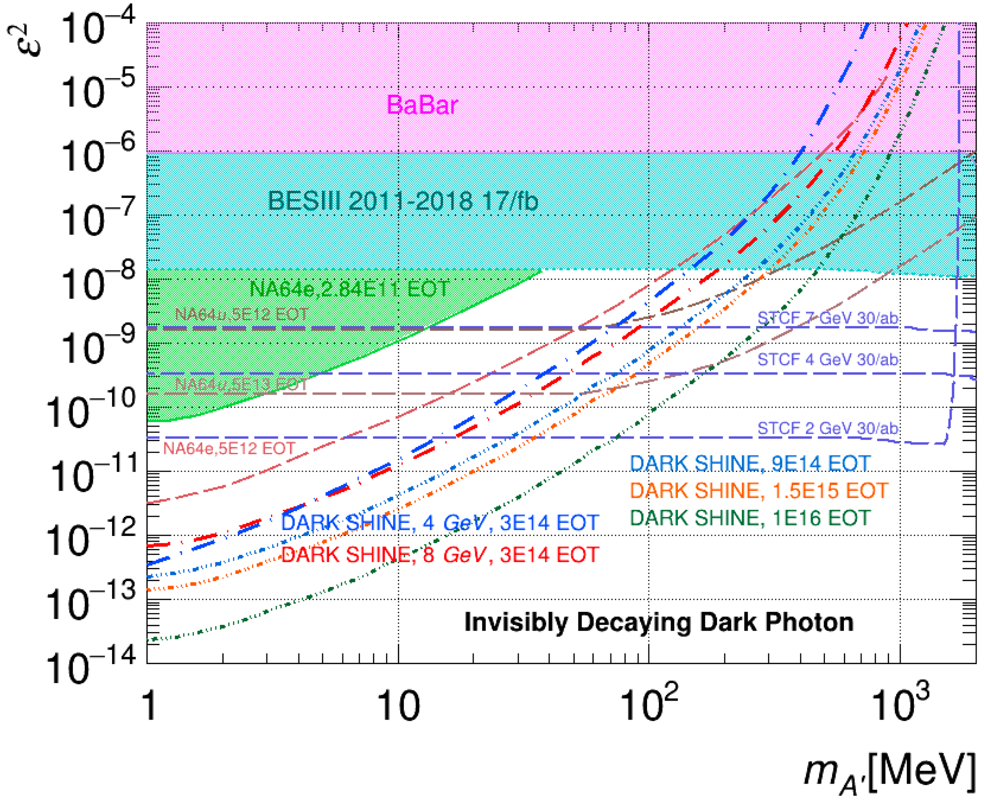


Highlight remarks

Sci. China-Phys. Mech. Astron. 66(1): 211063 (2023)

"Editor's Focus"

Sci. China-Phys. Mech. Astron. 66(1): 211061 (2023)

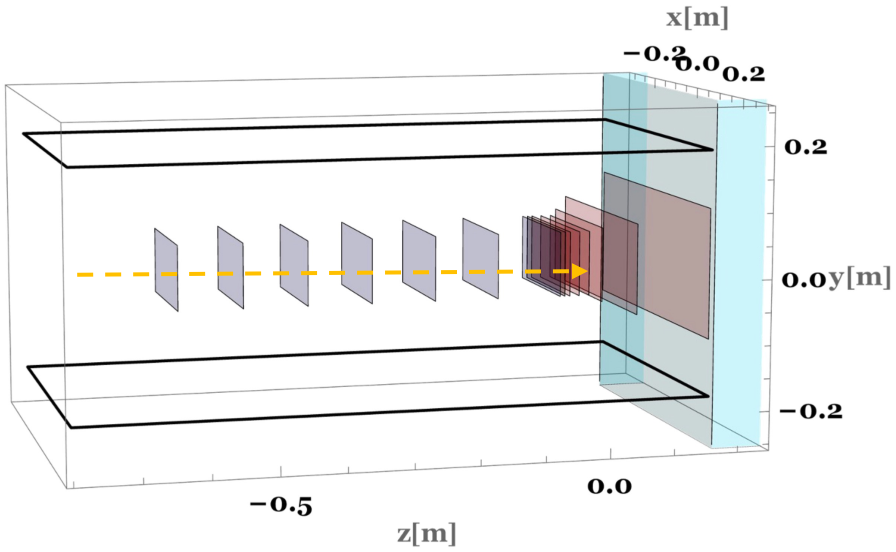
- Anticipated to have the sensitivity improved by one order of magnitude compared to other experiment (e.g. NA64)
- Aim to deliver 10^{16} EOT stat. and cover most of the sensitivity regions of interests

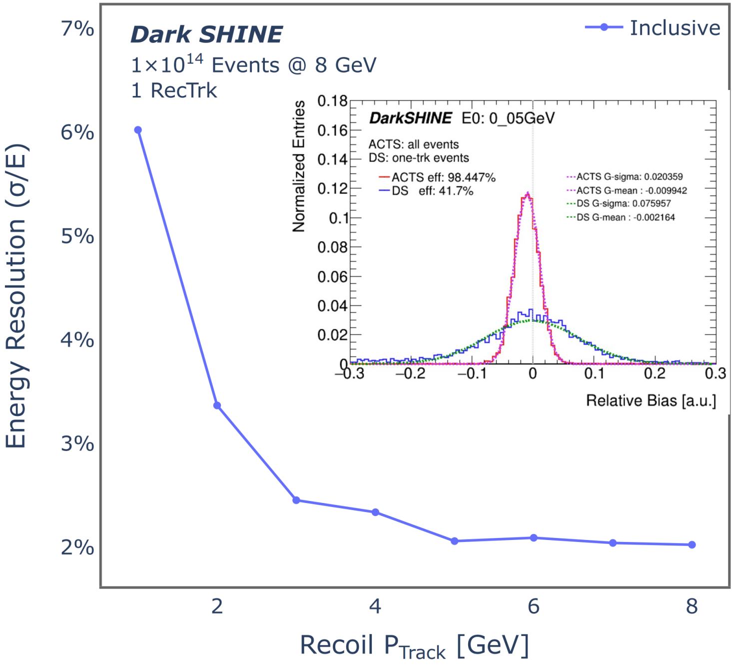
Hardware R&D: Tracking

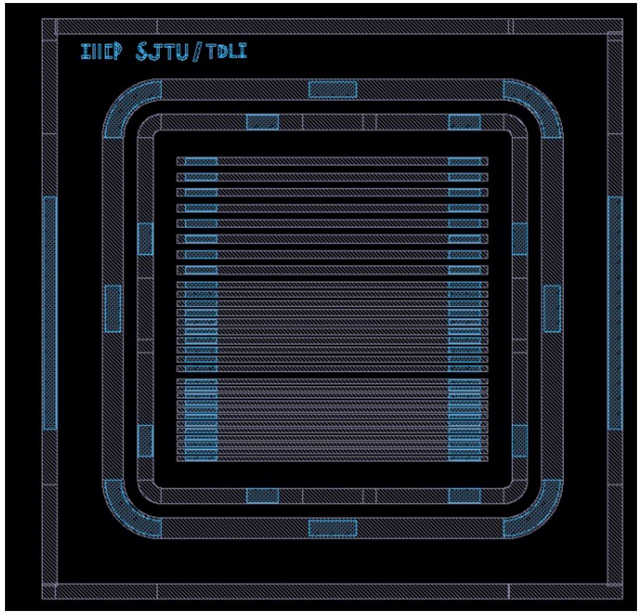
arXiv:2310.13926
Nucl Sci Tech 35, 201 (2024)

Tracker

- Incident and recoil electron tracks.
- Tagging tracker (7 layers) + recoil tracker (6 layers).
- Two silicon strip sensors w/ a small angle (0.1rad).
- Resolution: $10\mu m$(horizontal), $60\mu m$(vertical).







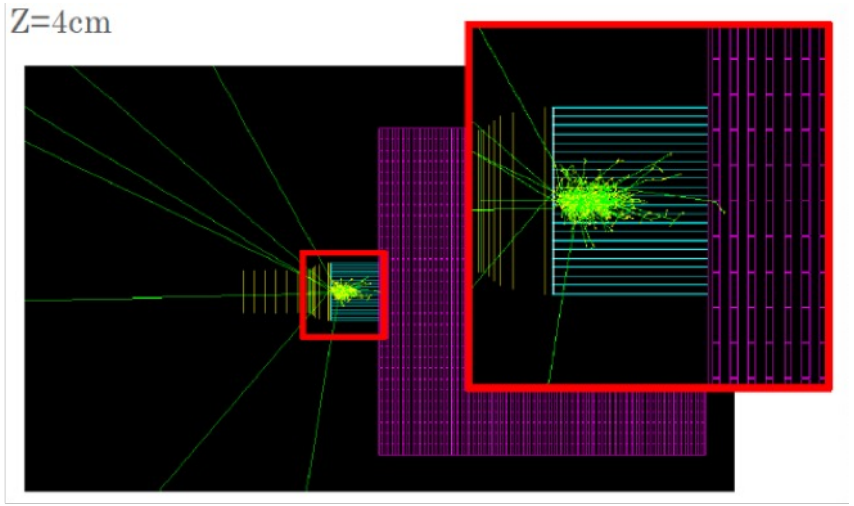
AC-LGAD silicon strip sensor 1x1 mm^2 designed, in collaboration with Prof. Zhijun Liang and Prof. Mei Zhao from IHEP.

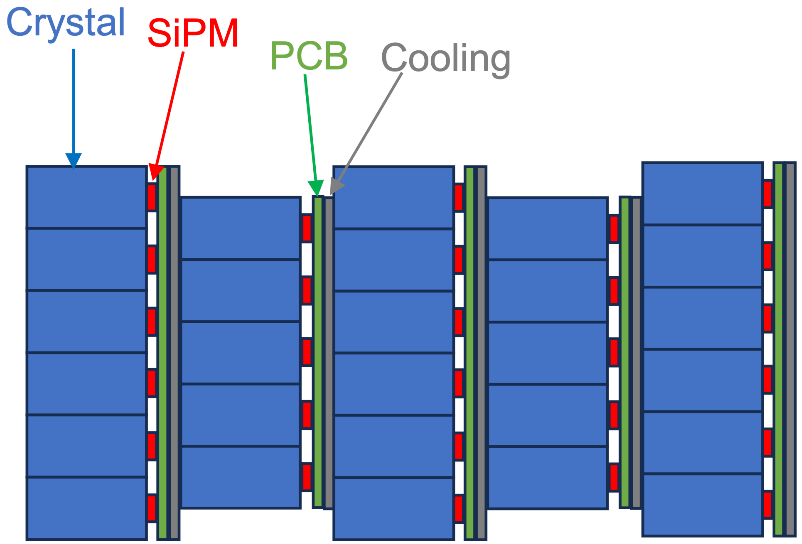
Hardware R&D: Crystal ECAL

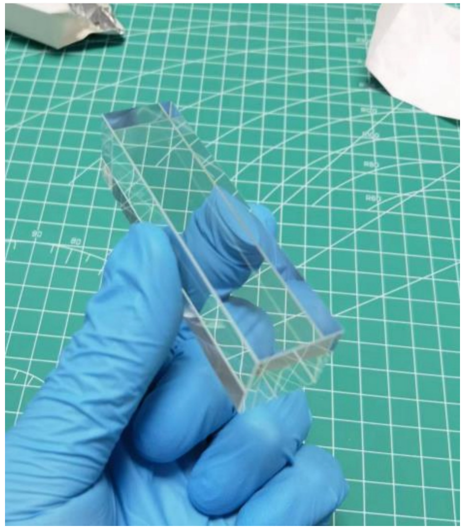
arXiv: 2407.17800
submitted to NST

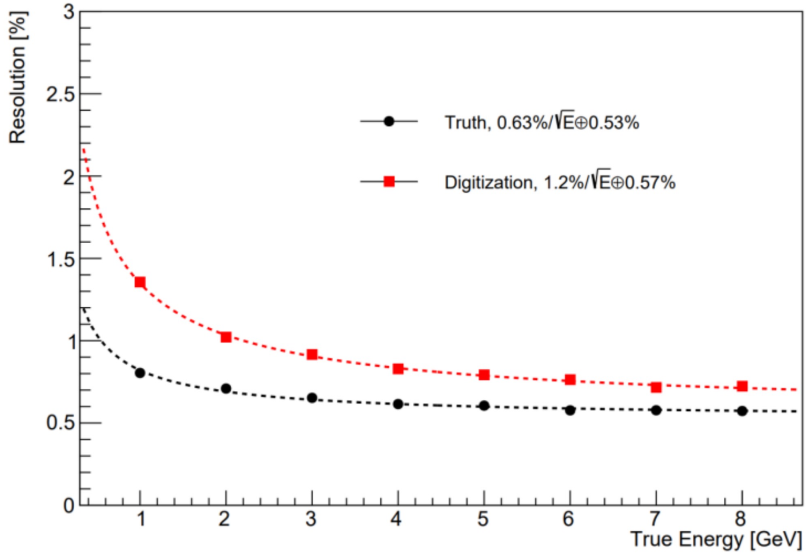
Electromagnetic Calorimeter:

- Designed resolution: better energy resolution than 5%.
- LYSO crystal ($Lu_{(1-x-y)}Y_{2y}Ce_{2x}SiO_5$):
  - High light yield (30000 p.e/MeV) with good linearity
  - Short decay time (40 ns)
- **21×21×11 crystals, 2.5cm×2.5cm×4cm**
- Readout with SiPM and waveform sampling
- More intrinsic radiation and radioactive source tests.







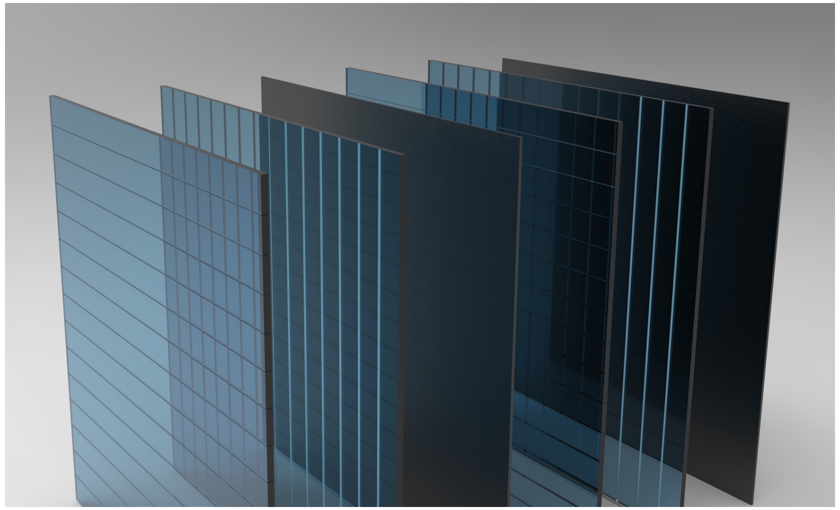


Hardware R&D: HCAL

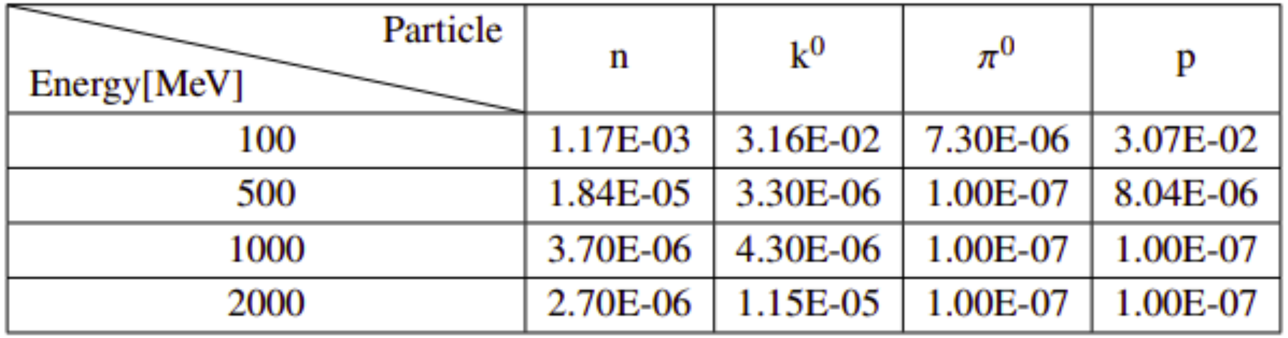
Nucl. Sci. Tech. 35, 148 (2024)

Hadronic Calorimeter:

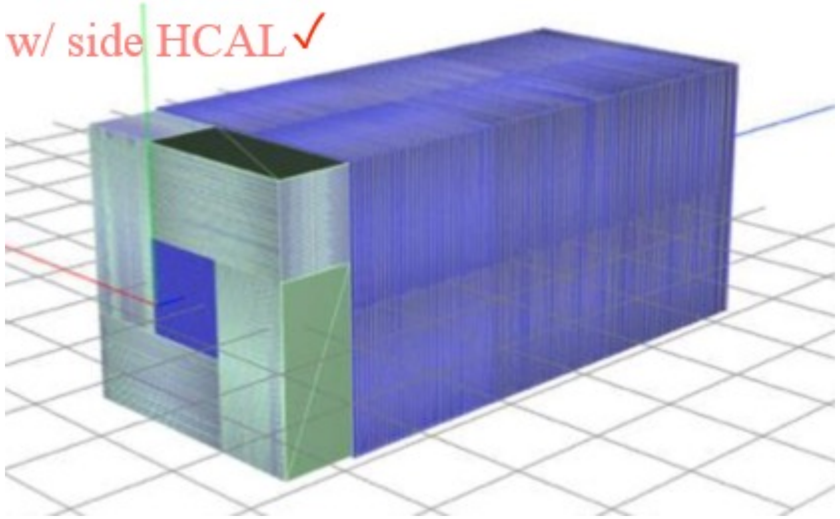
- Veto backgrounds ($1.5\times1.5\times2.5\ m^3, \sim 11\ \lambda$)
- Plastic scintillator + iron absorber
  - Plastic scintillator: 90 degree rotation between two adjacent layers
  - Wavelength shifter fiber + SiPM
- Side-HCAL: encircling the ECAL
- Design has been optimized



Veto inefficiency



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



Collaboration and Highlights at DarkSHINE

Journal Paper Publications:

- Sci. Chin.-Phys. Mech. Astron., 66(1) : 211062 (2023)
- **Nucl. Sci. Tech. 35, 148 (2024)**
- **Nucl. Sci. Tech. 35, 201 (2024)**
- arXiv:2407.17800 (submitted to NST)
- **arXiv:2407.20723 (submitted to JINST)**

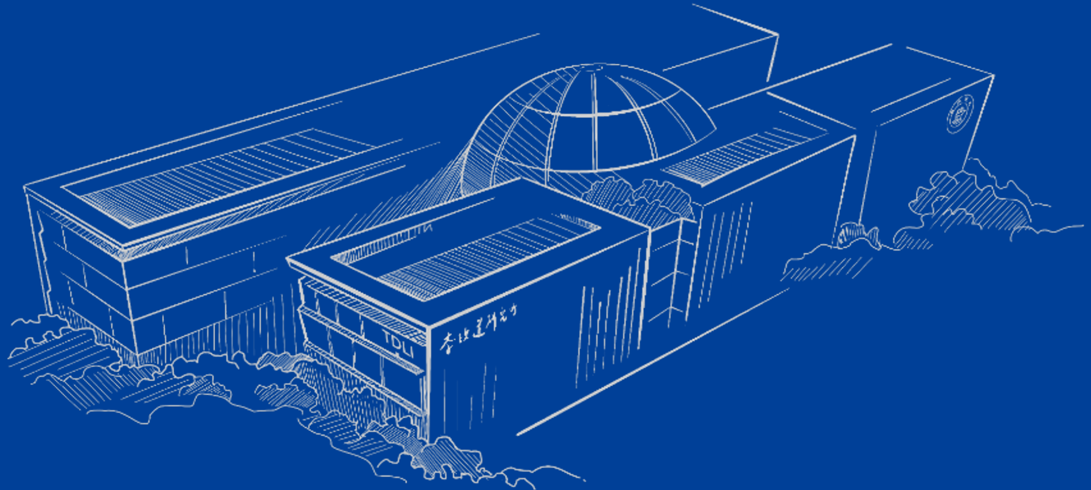
Conference Talks :

- ICHEP 2024
- Lepton Photon 2023
- Dark Matter 2023
- HKUST-IAS-HEP 2024、2023
- AEI 2023、2022
- IPAC 2023
- …

Summary

- The DarkSHINE: a fixed-target experiment searching for dark matter.
- **The DarkSHINE will be almost background free experiment**
  - Expected 0.02 background in 3x10^{14} electron-on-target (w.r.t 1 year. running)
  - Above 50% dark photon signal acceptance efficiency
- **The DarkSHINE has competitive sensitivity** (Sci. China-Pay. Mech. Astron., 66(1):211062 (2023))
  - Sensitive to most of phase space predicted by models with 3 years running
- **Detector key technology R&D studies are going on** (arXiv:2407.20723 , Nucl. Sci. Tech. 35, 148 (2024) , Nucl Sci Tech 35, 201 (2024))
- With more physics opportunities ahead, please stay tuned!

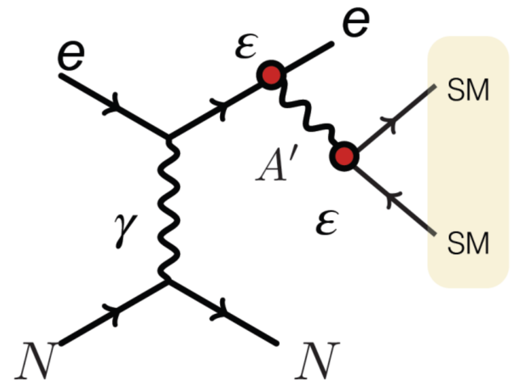
谢　谢



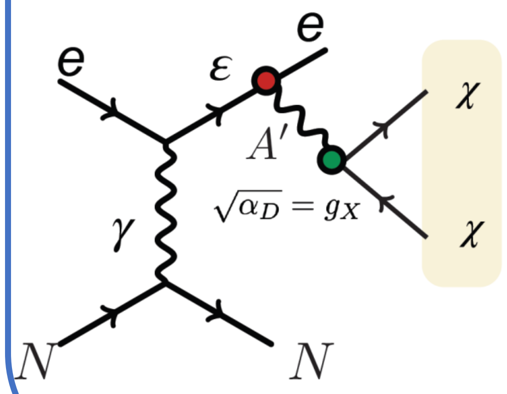
DarkSHINE Experiment Conceptual Design

Signal Topology

VISIBLE DECAY MODE $m'_A < 2m_X$



INVISIBLE DECAY MODE $m'_A > 2m_X$

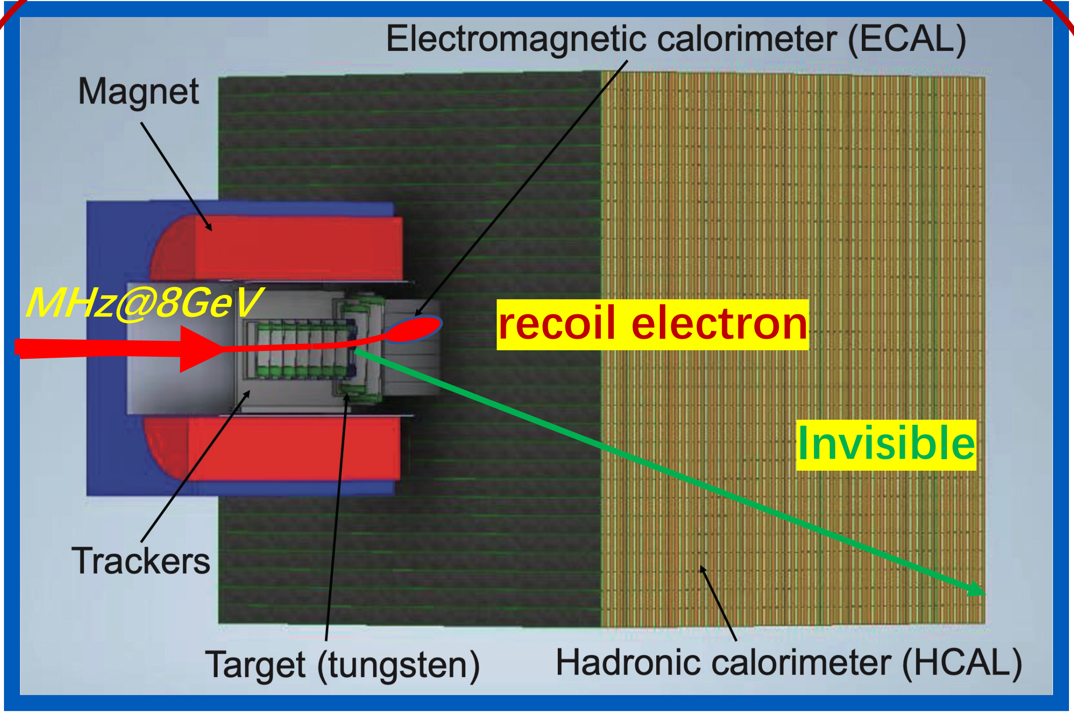


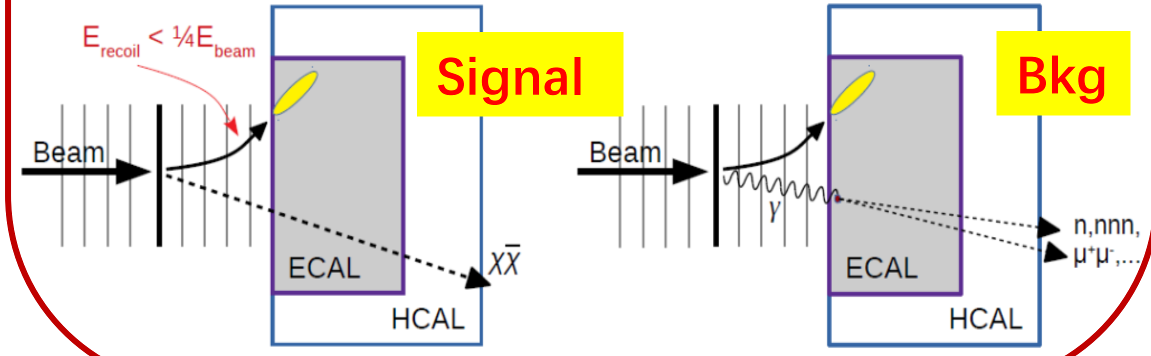
Having two interaction vertices → production rate highly suppressed

$$\boxed{N \propto \epsilon^4 \quad \ll \quad N \propto \epsilon^2(1-\epsilon^2) \approx \epsilon^2}$$

Interaction probability could be enhanced → better sensitivity

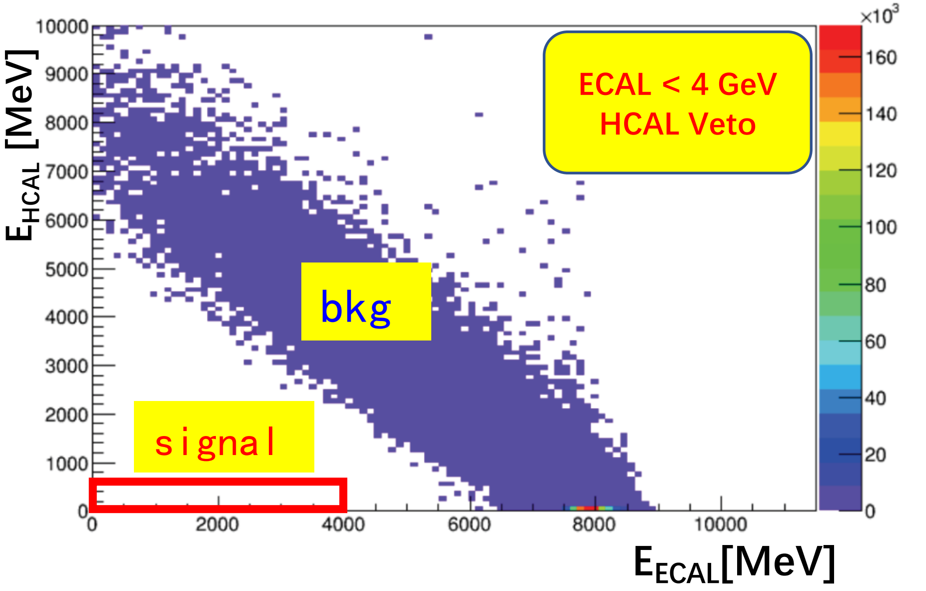
Experiment Setup

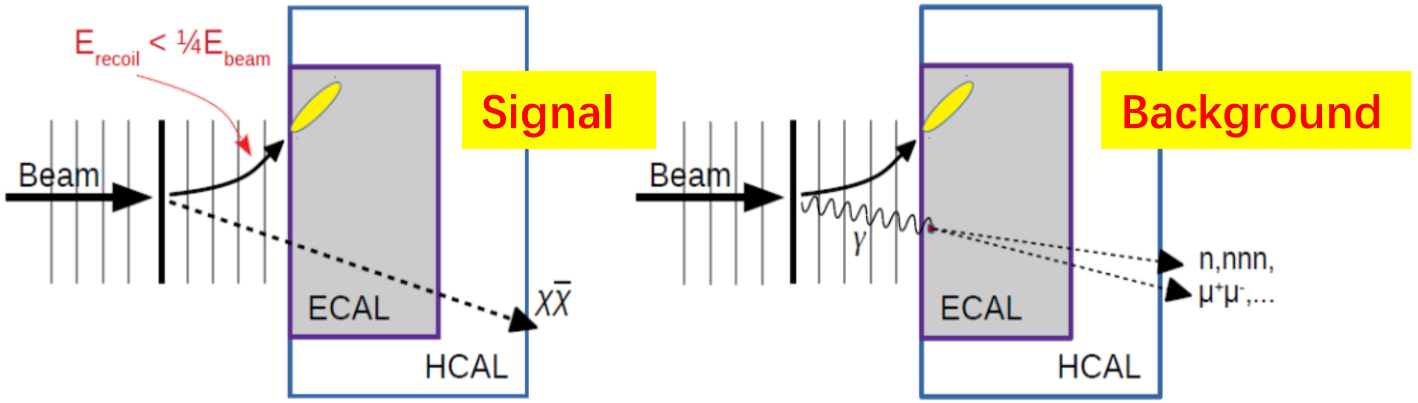


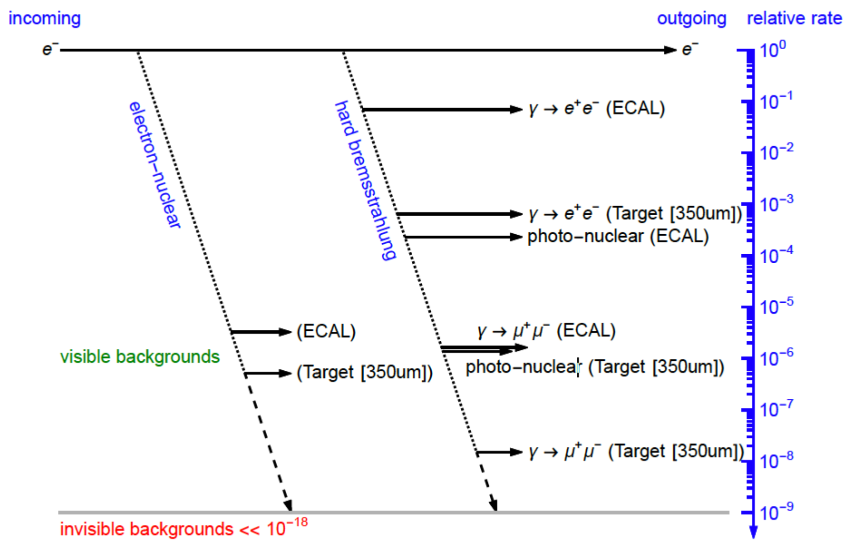


Experimental Approaches

- **High repetition rate single electron beam**
  - More striking recod of single electron-on-target event energy loss after recoiling
  - Requirements: fast detector response and readout electronics, radiation hardness to allow high e-on-target statistics
- **Energy + Momentum loss detection**
  - Synergy of high precision tracking and calorimetry

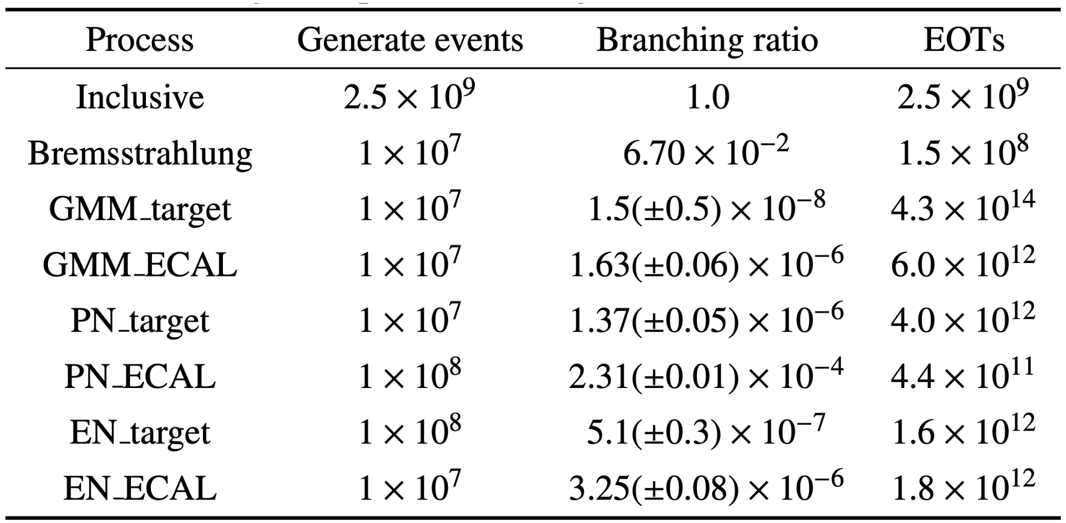






Monte Carlo Simulations

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:

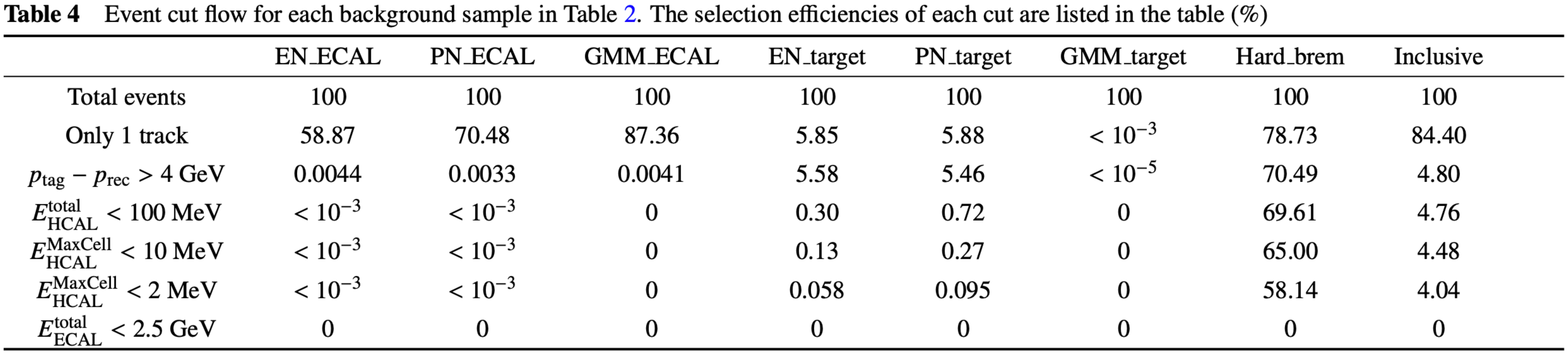
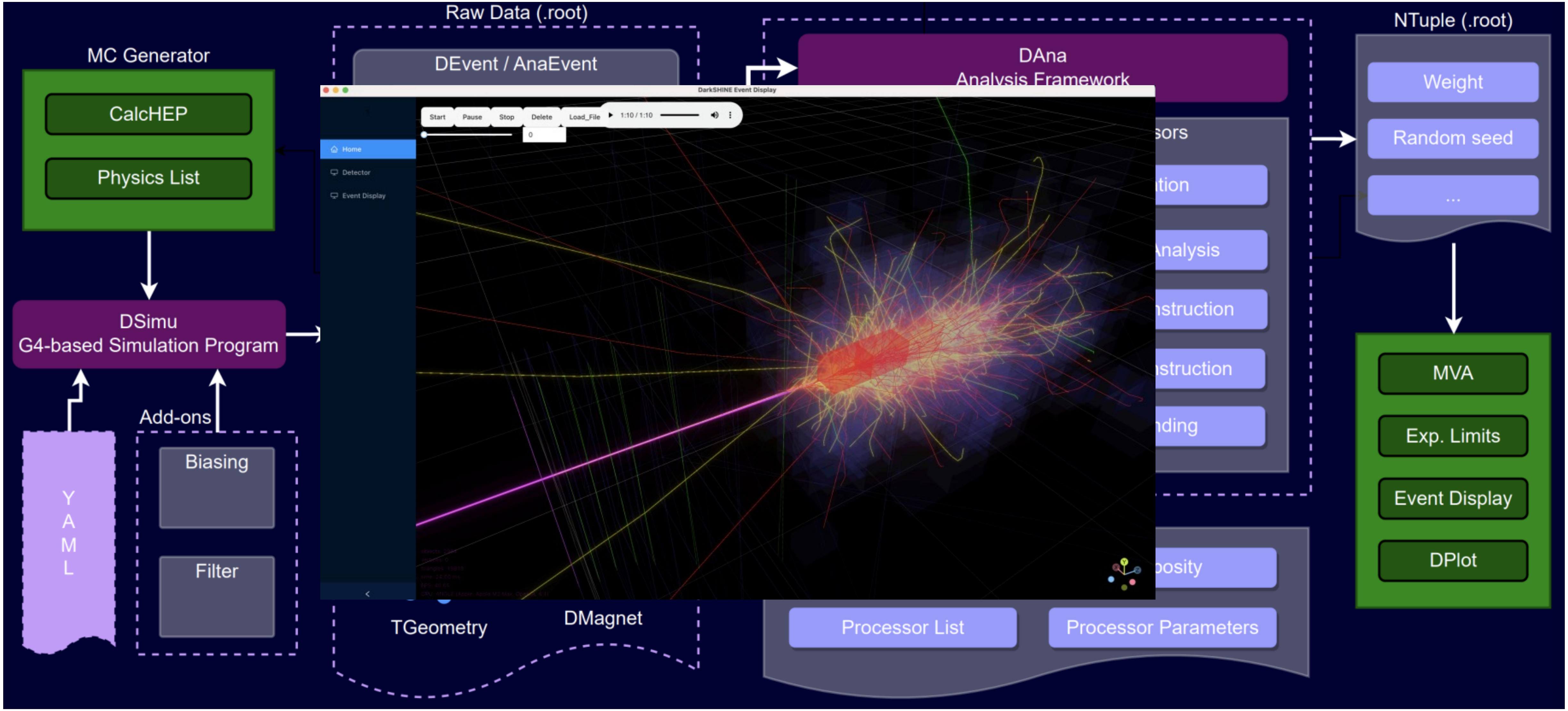


Table 4 Event cut flow for each background sample in Table 2. The selection efficiencies of each cut are listed in the table (%)

	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

Software Framework Optimization



Raw Data (.root)

DEvent / AnaEvent

MC Generator

CalcHEP

Physics List

DSimu
G4-based Simulation Program

Add-ons

Biasing

Filter

YAML

TGeometry

DMagnet

DAna
Analysis Framework

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osity

Processor List

Processor Parameters

NTuple (.root)

Weight

Random seed

...

MVA

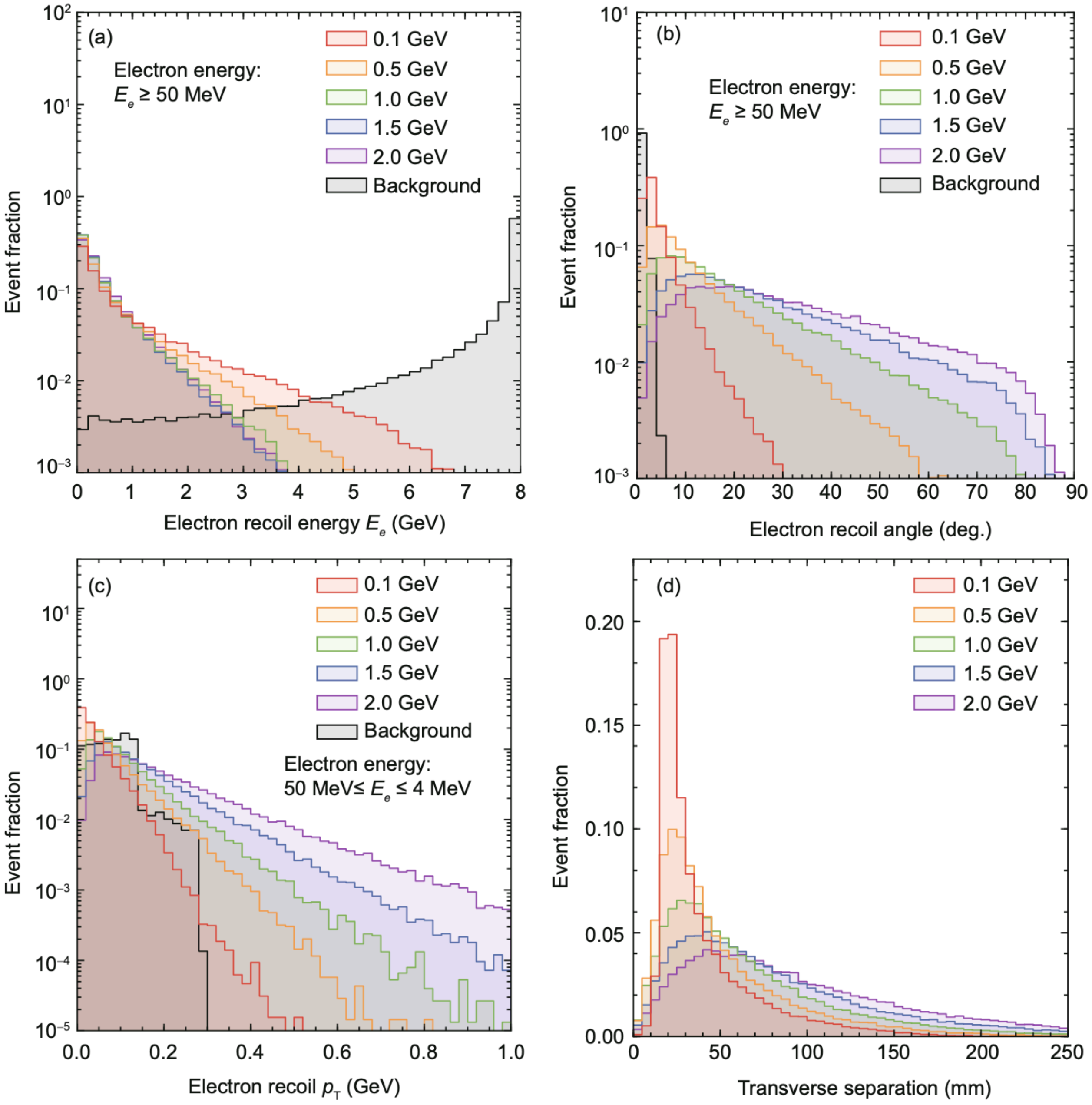
Exp. Limits

Event Display

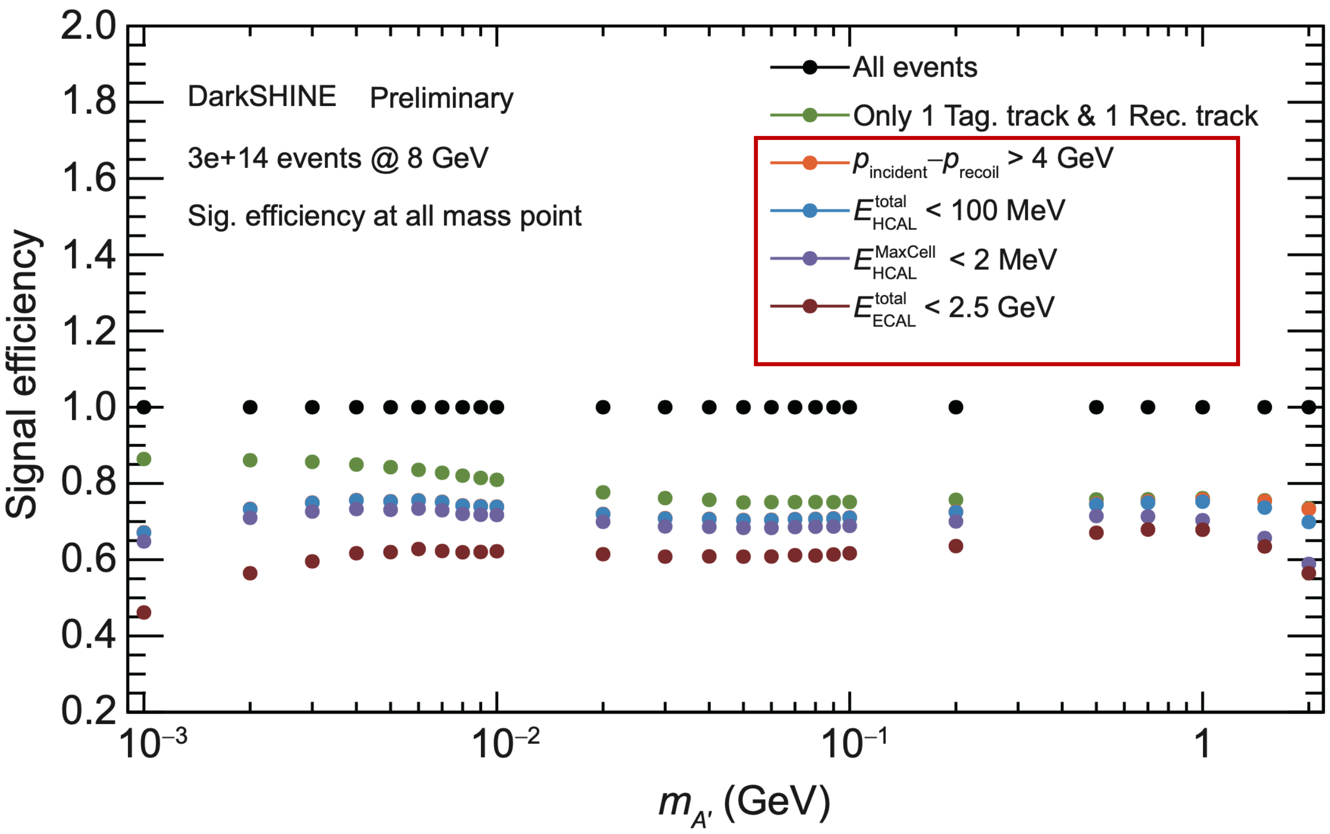
DPlot

How DM Shining at the DarkSHINE Experiment?

Other Kinematic Distributions



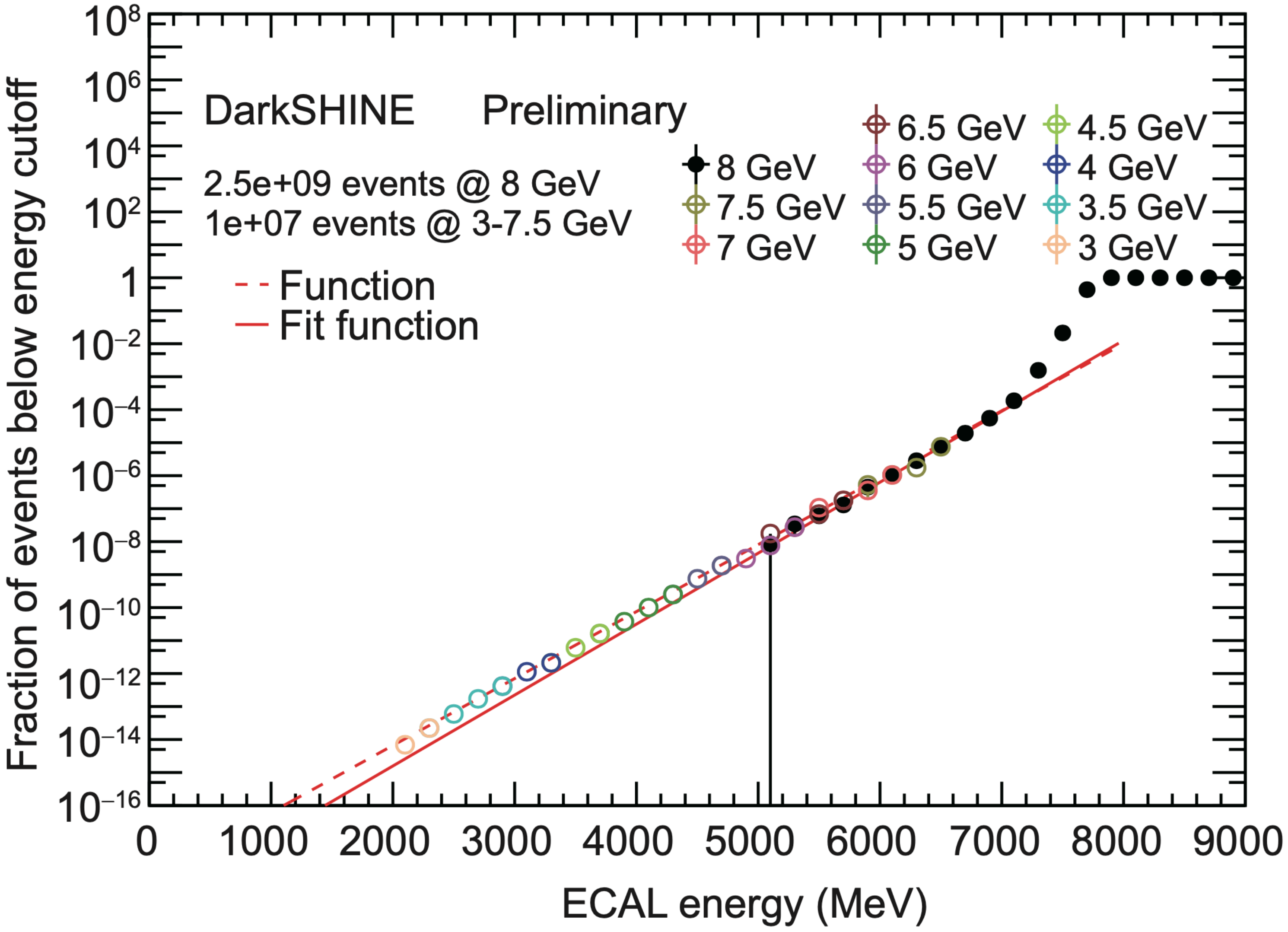
Acceptance in the Signal Region



Signal Region selections

- **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

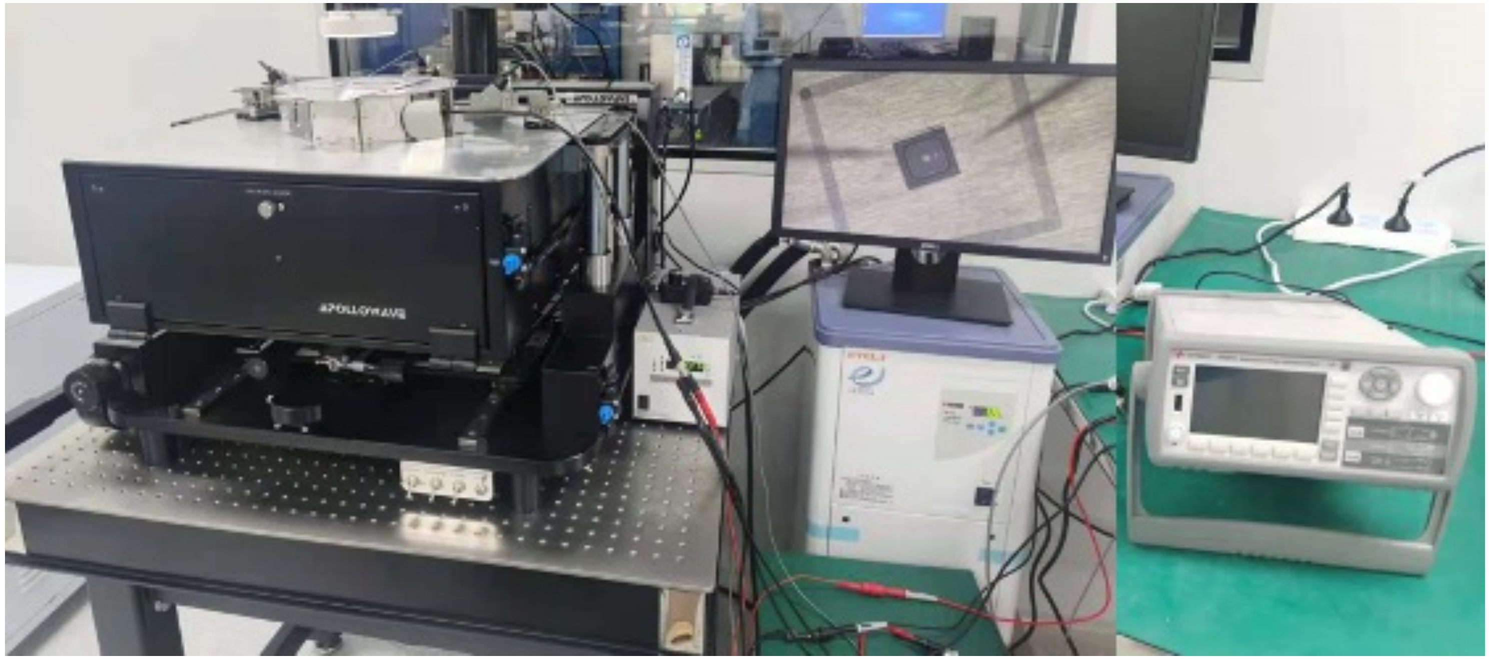


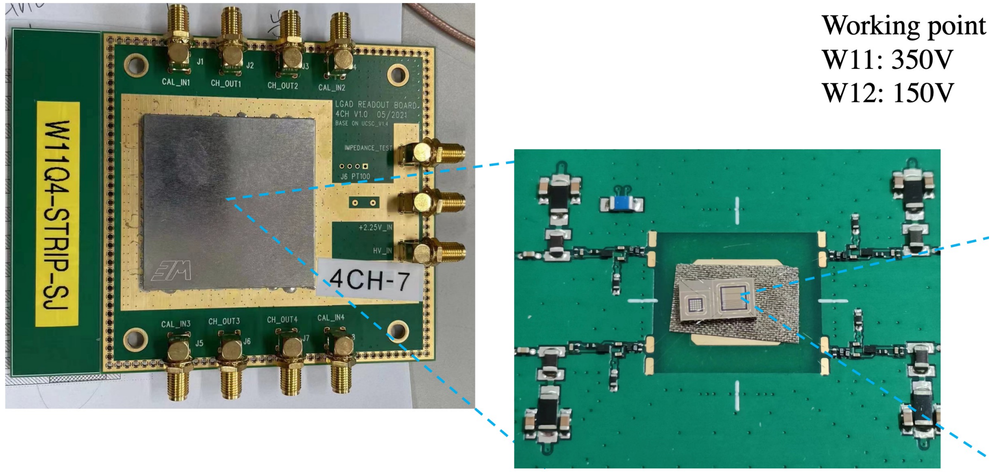
Expected background yields go down quickly at lower ECAL energy.

In order to estimate background yields in 10^{14} EOT, extrapolation method is used

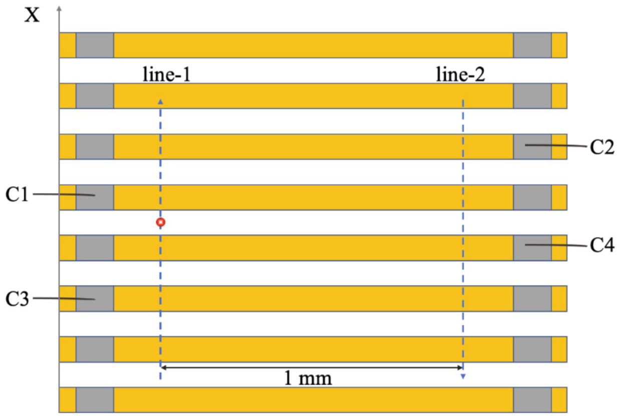
- **fit from inclusive background process**
- **extrapolation from low energy samples**

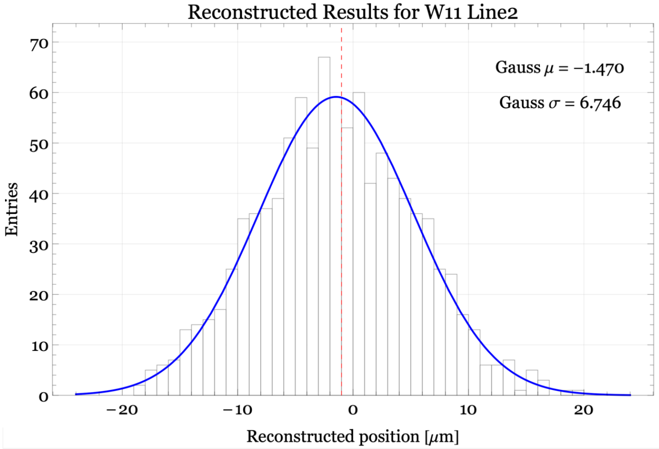
Hardware R&D: Tracking

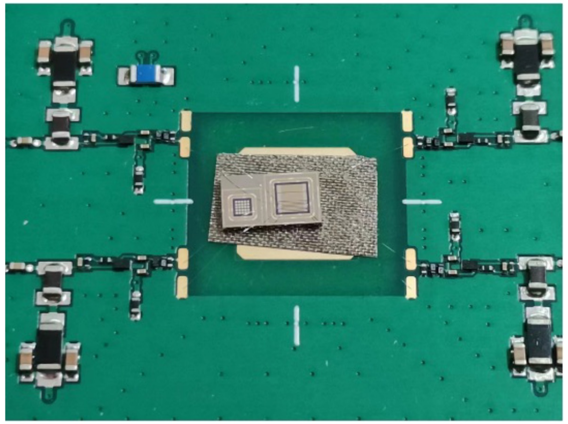


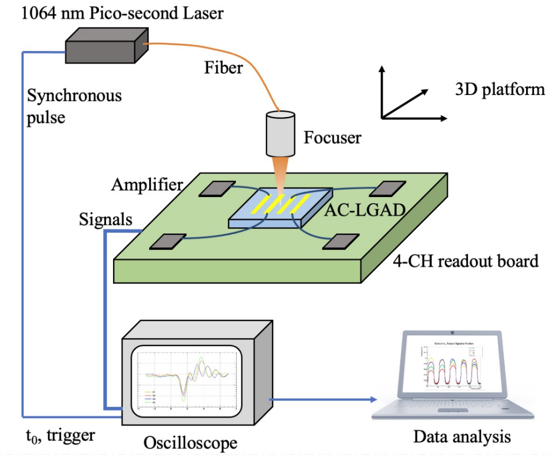


Working point
W11: 350V
W12: 150V









Hardware R&D: ECAL

- Experiments based on LYSO and SiPM

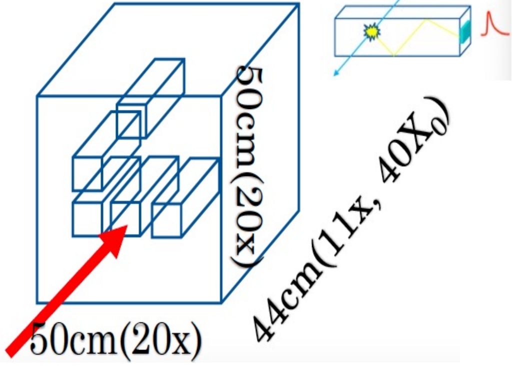
a. LYSO intrinsic radiation from $^{176}_{71}Lu \rightarrow {}^{176}_{72}Hf$

b. Uniformity test with $^{60}_{27}Co$ source

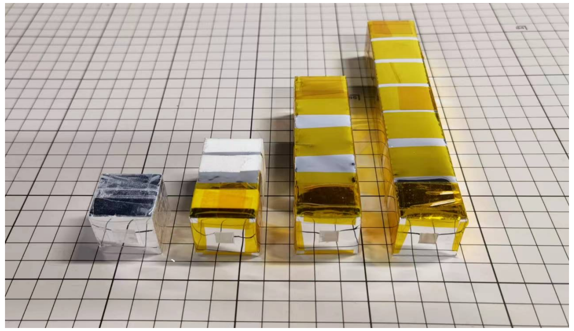
c. Cosmic ray test

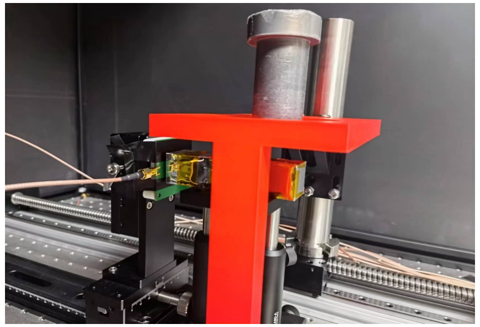
d. SiPM dynamic range test

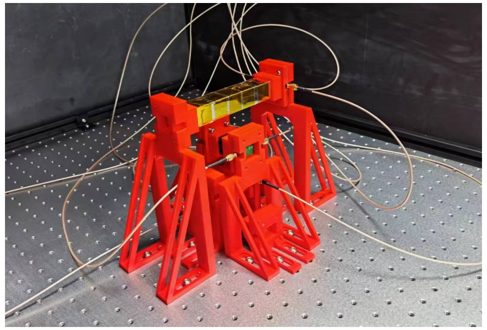
e. Light yield changed with crystal size

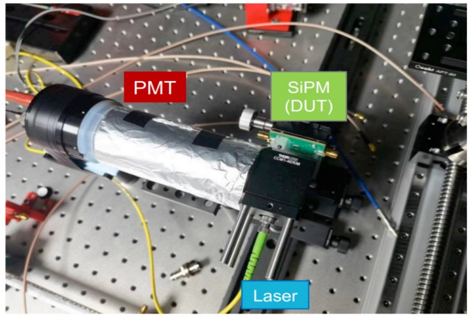


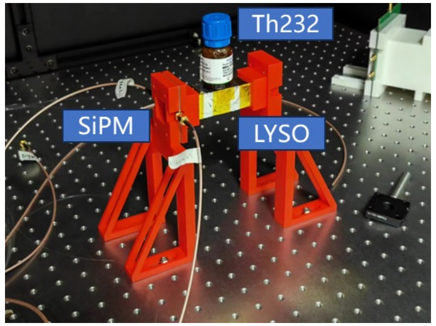
Baseline design of each crystal: X,Y = 2.5 cm, Z = 4 cm (radiation length: 1.14 cm)

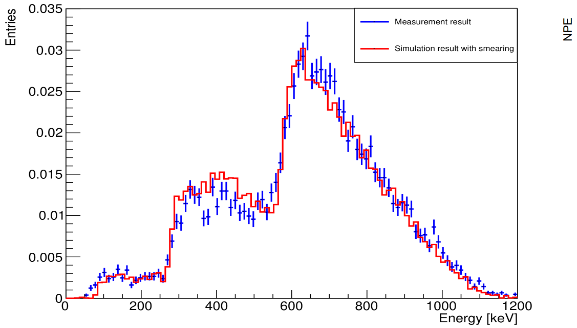


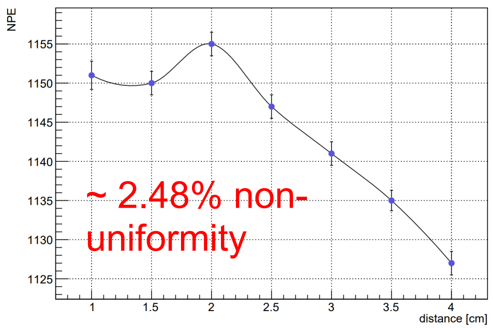




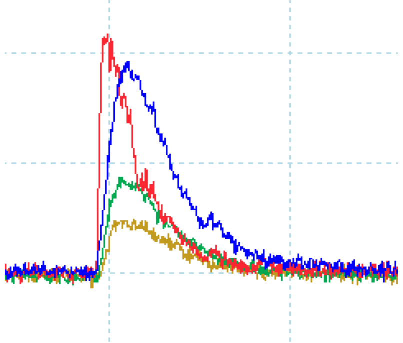


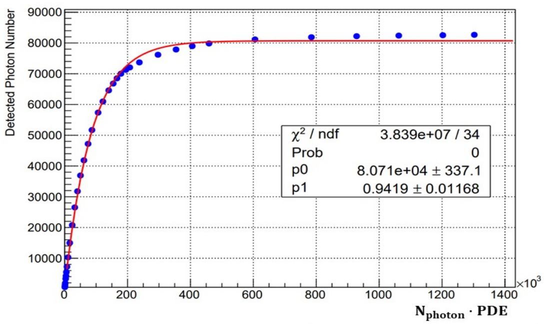


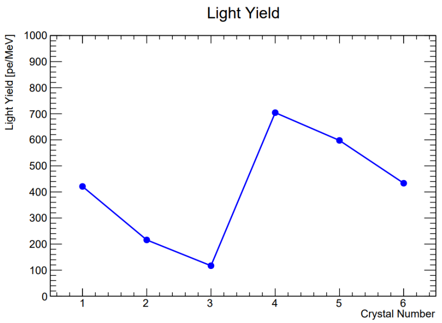




~ 2.48% non-uniformity

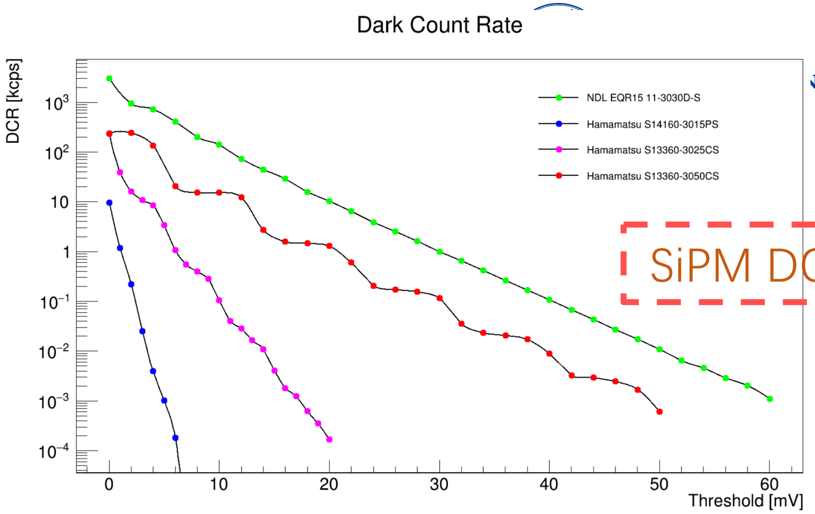




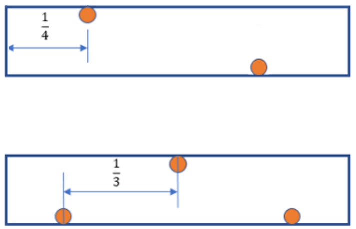


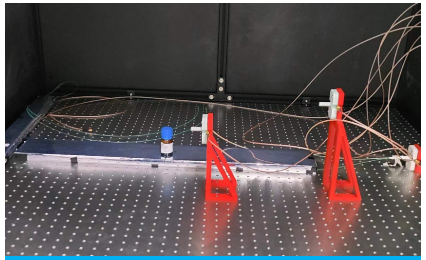
Hardware R&D: HCAL

- **Scintillator test in TDLI lab**
  - SiPMs performance are studied first, both size, gain and noise are considered, and picked one type (Hamamatsu S13360-3050, gain 1.7e6) for the rest tests
- **Radioactive source test for uniformity**
  - Very good uniformity of the scintillator along the 75 cm side



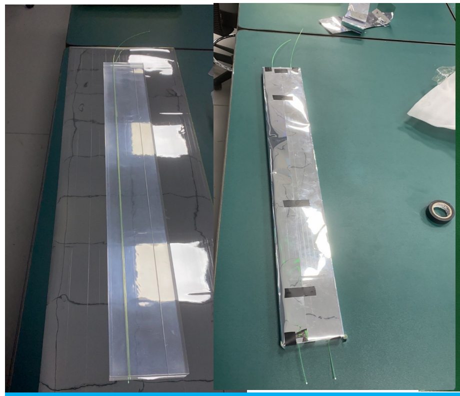
SiPM DCR test



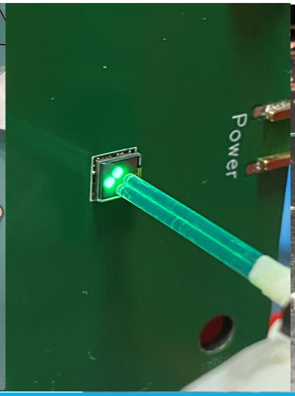


Radioactive source test

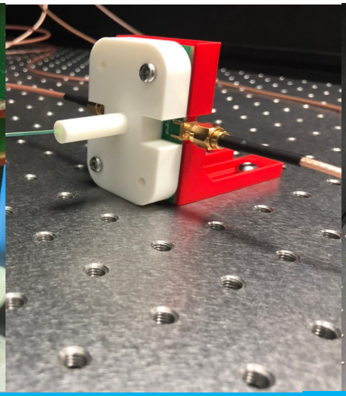
- **Cosmic ray test for photon yields**
  - Various types of scintillator are tested : sizes (75cm×5cm/10cm×1cm/2cm), number of fiber grooves/used, manufacturer/composition are tested
  - Noise test: to decide the minimal cut we could use in analysis



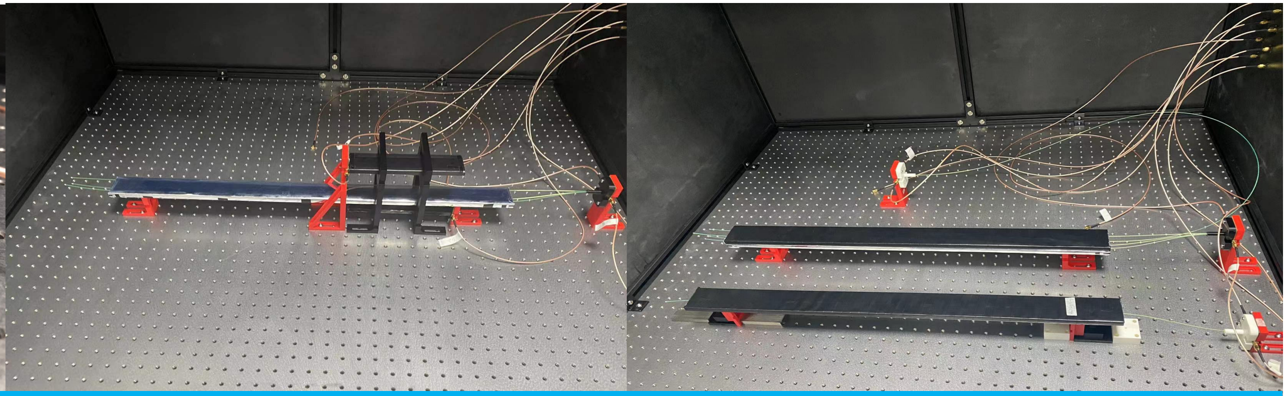
Scintillator (w/ & w/o wrap)



WLS & SiPM



Fiber collimation



Cosmic ray test: photon yields test (left) and noise test (right)

More Physical Motivations

- **Dark SHINE could explore a vast array of sub-GeV physics with unique sensitivity**
  - New force carriers coupling to electrons, decaying visibly or invisibly
  - Quasi-thermal DM, e.g. asymmetric DM or ELDER DM
  - New long-lived resonances produced in the dark sector (SIMP)
  - Freeze-in models with heavy mediators
  - Axion-like particles (ALP)
  - Milli-charged dark sector particles
  - Probe neutrino-nuclear interactions (νN) via electro-nuclear (eN) measurements and constrain nuclear models
  - …