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

Jing Chen

on behalf of the DarkSHINE team

MEPA2022, Hefei China

2022.12.17

李政道研究所

Tsung-Dao Lee Institute

DARK SHINE

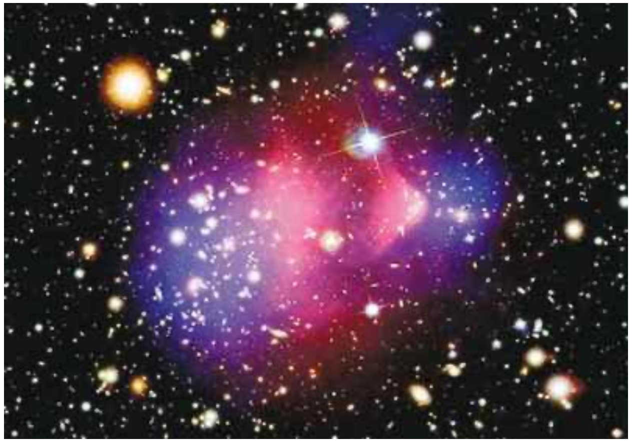
上海交通大學

SHANGHAI JIAO TONG UNIVERSITY

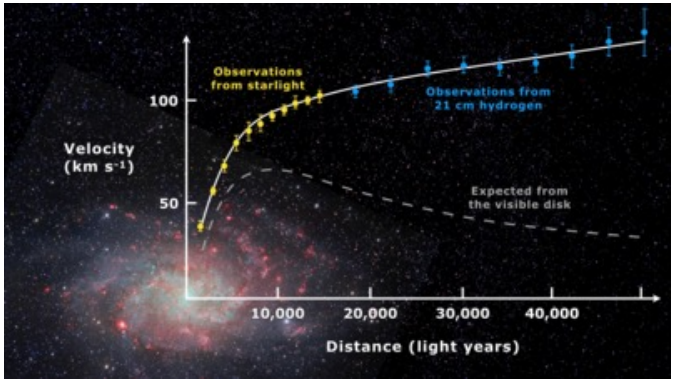
Evidence of dark matter

Gravitational Lensing

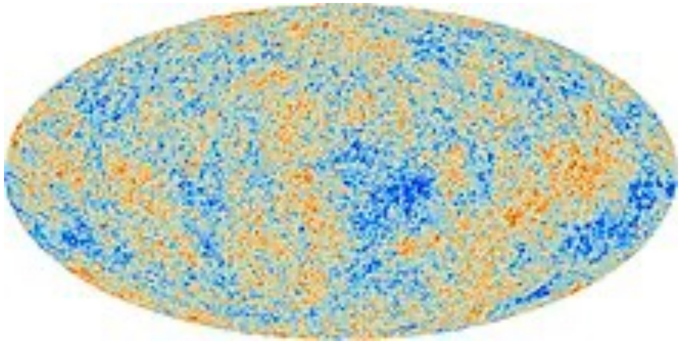
The Bullet Cluster



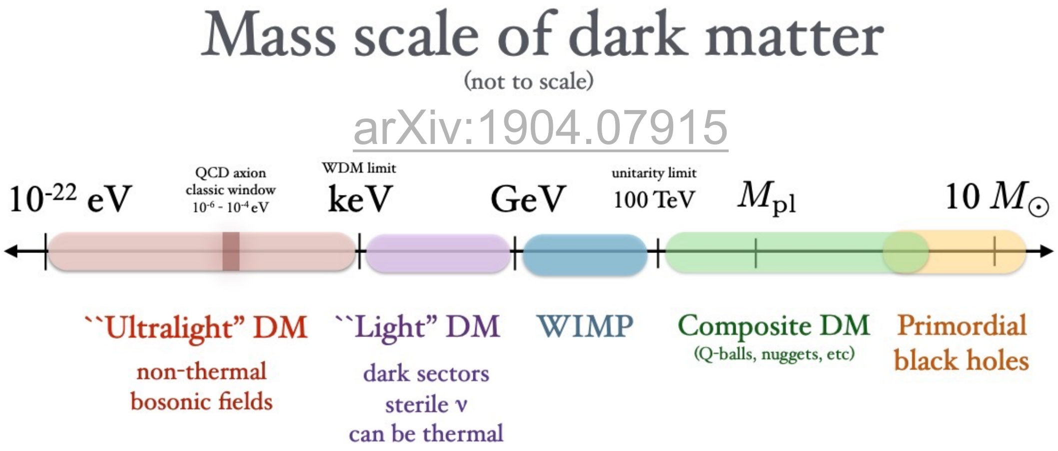
Rotation Curve



Cosmic Microwave Background



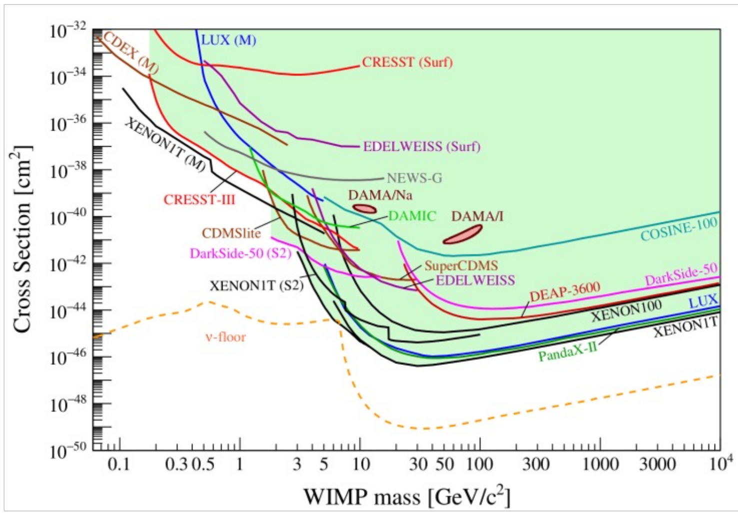
Dark matter candidates



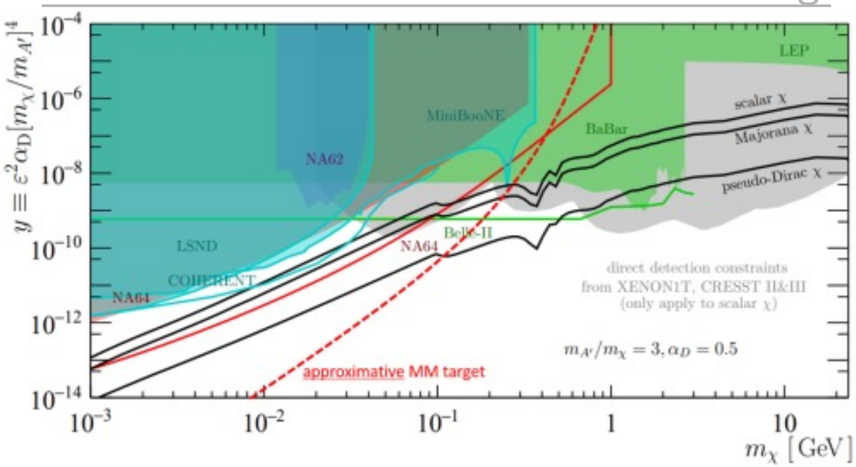
- Dark Matter can exist in **wide mass range**, from Ultralight DM to Primordial Black Holes.
- Dark matter is the mysterious substance that makes up roughly a quarter of the Universe.

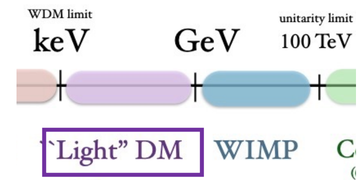
Dark matter candidates

APPEC Committee Report: 2104.07634



2022 CALICE collaboration meeting





- Experimental search:

  - Space experiments: **DAMPE, AMS etc.**
  - Collider experiments: **LHC, BELLE-II , BESIII etc.**
  - Underground experiments: **CDEX, PandaX, LUX, Xenon etc.**

- **Searching for light DM:**

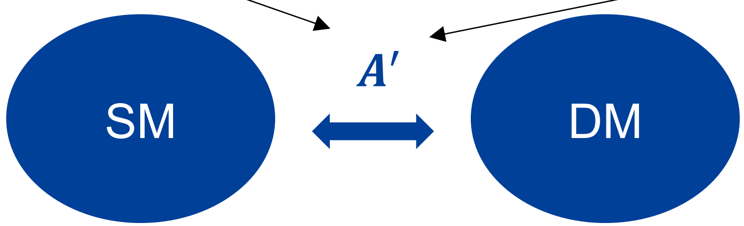
  - Sub-GeV mass range is not fully explored yet.
  - Dark photon A':
    1. Dark matter particles may interact with other dark matter particles via a new force mediated by A'.
    2. Collider/accelerator-based experiments searching for dark photon: NA64@CERN, BESIII, BEPCII, LDMX, Lohengrin, etc.

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 $\boldsymbol{\varepsilon}$



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

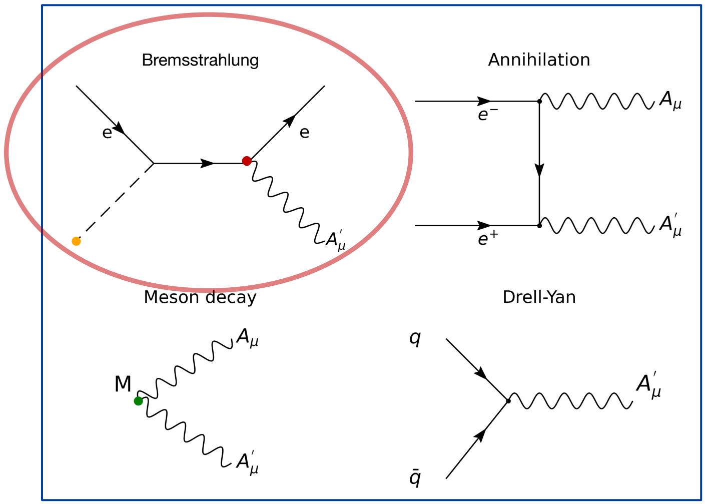
Kinetic mixing term | Field strength tensor | Dark photon field

- 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.
  $\boldsymbol{m_{A'}}$: dark photon mass.
  Decay branching ratio of $A' \to \chi\chi$ (assumed to be 1 or 0)

arXiv:2104.10280

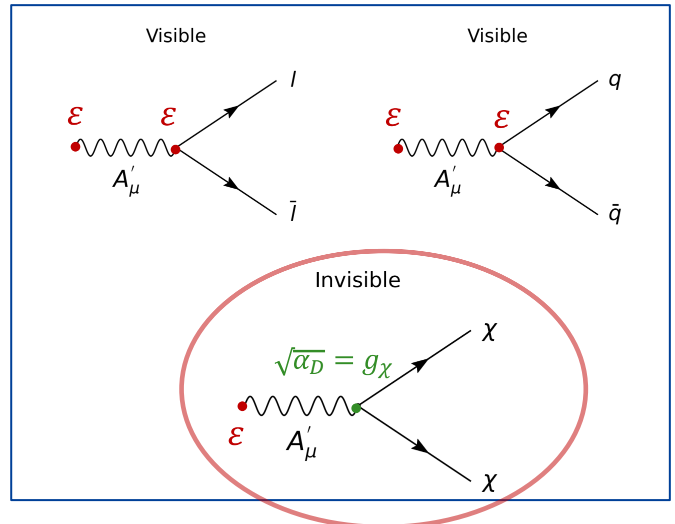
Search for dark photon

- 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

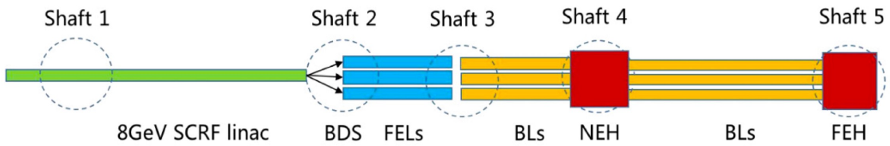
- DarkSHINE:

  - **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:

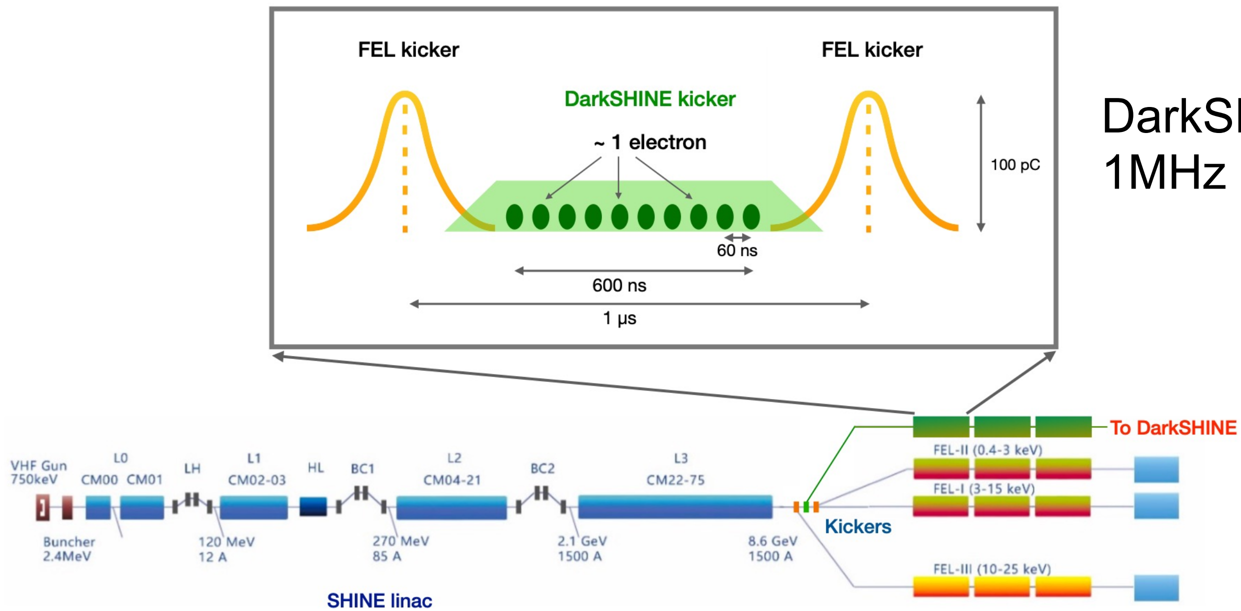
  - Under construction in Zhangjiang area, Shanghai (2018-2026).
  - $E_{beam} = 8GeV$ with frequency 1MHz
  - Beam intensity: 6.25×10^{8} electrons per bunch

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



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

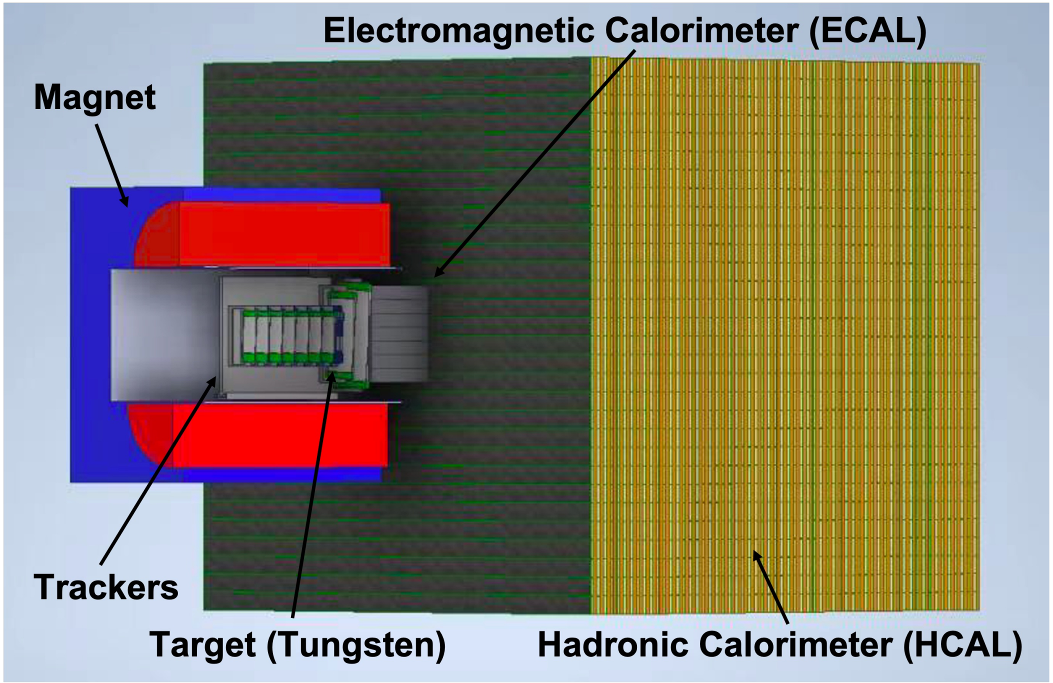
DarkSHINE Kicker

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

DarkSHINE detector



- **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: 10%

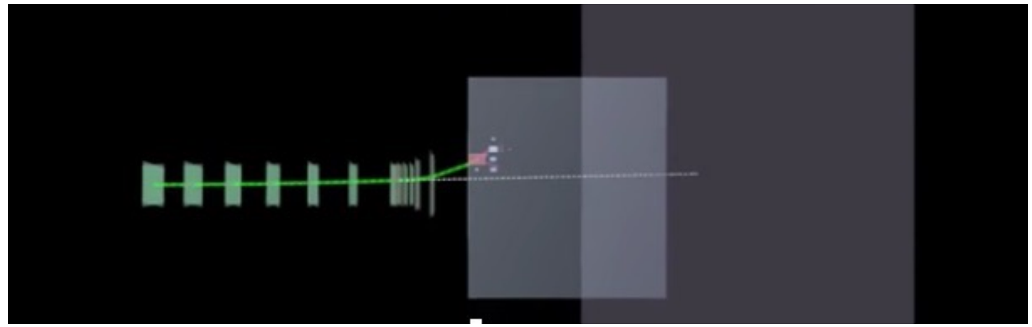
- **HCAL:**
  - Veto hadronic background
  - Scintillator w/ steel absorber
  - $4\times4\times1$ modules

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

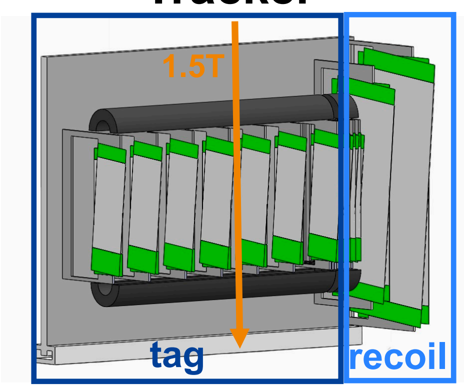
- **Tracker:**
  - Tagging tracker (7 layers) + recoil tracker (6 layers)
  - Incident and recoil electron tracks
  - Two silicon strip sensors w/ a small angle (0.1rad)
  - Resolution: $6\mu m$(horizontal), $60\mu m$(vertical)

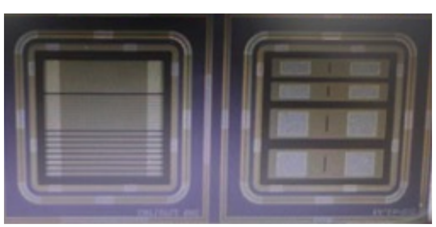
Detector R&D

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



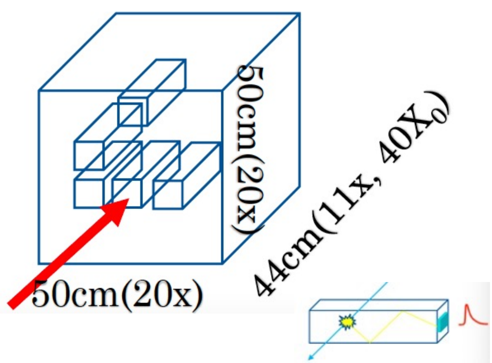
Tracker

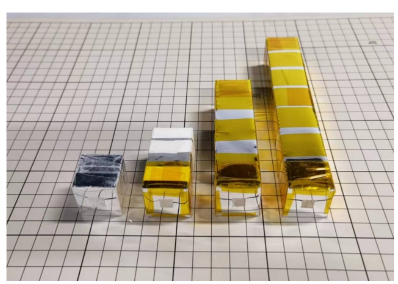




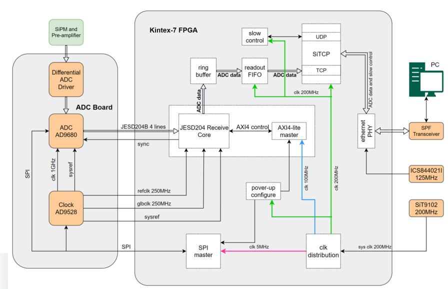
silicon strip sensor prototype

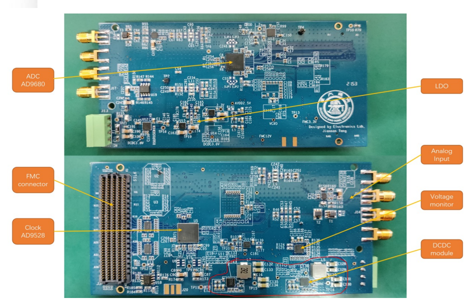
ECAL



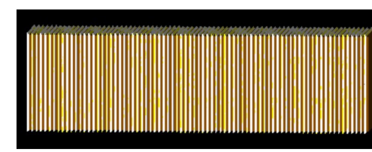


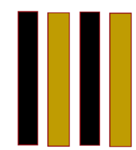
Readout electronics





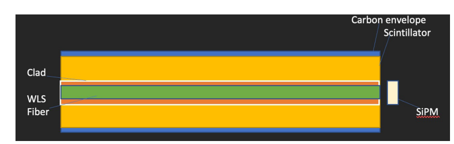
HCAL





steel

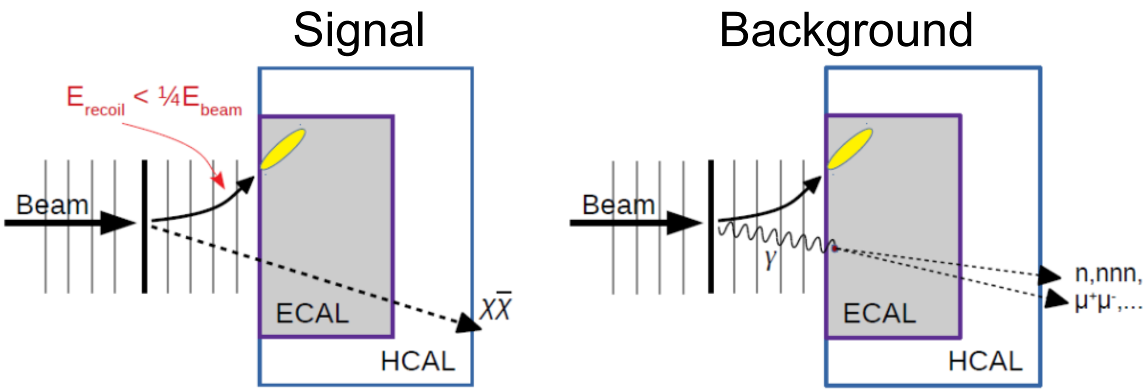
scintillator



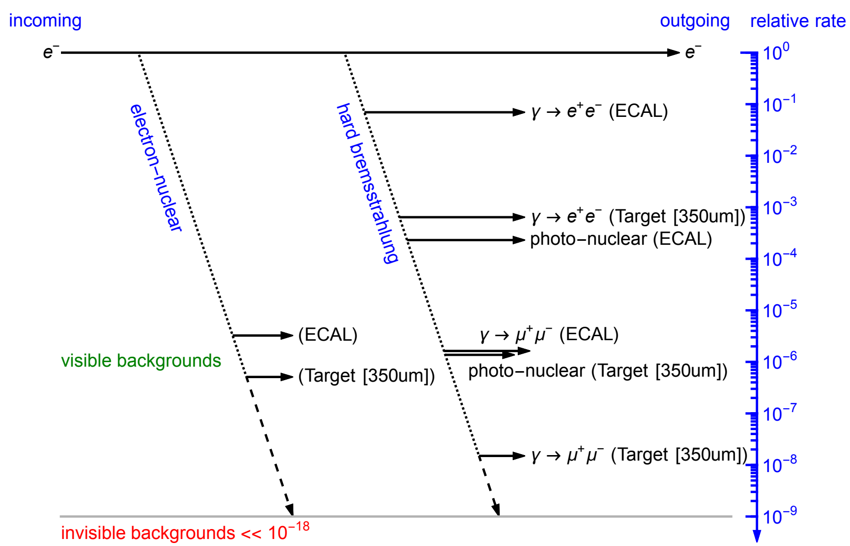
Signal & background

- 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

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}

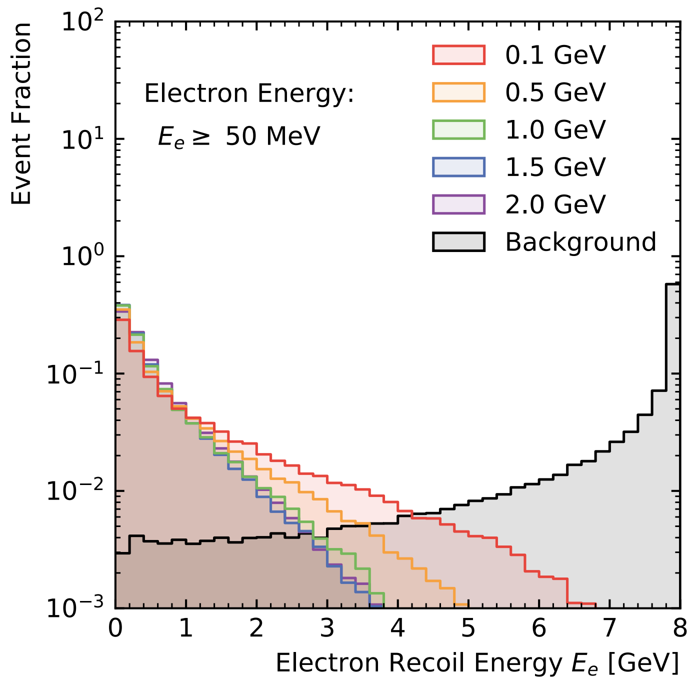
Simulation

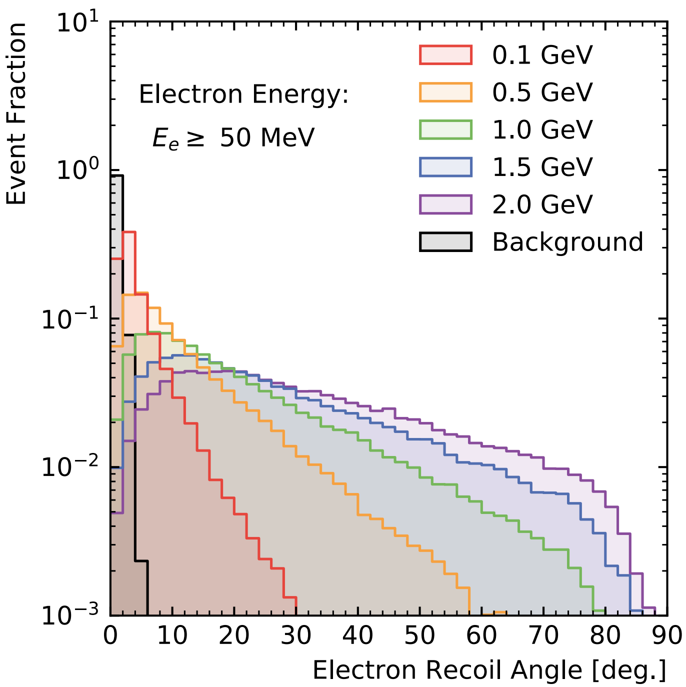
Signal

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

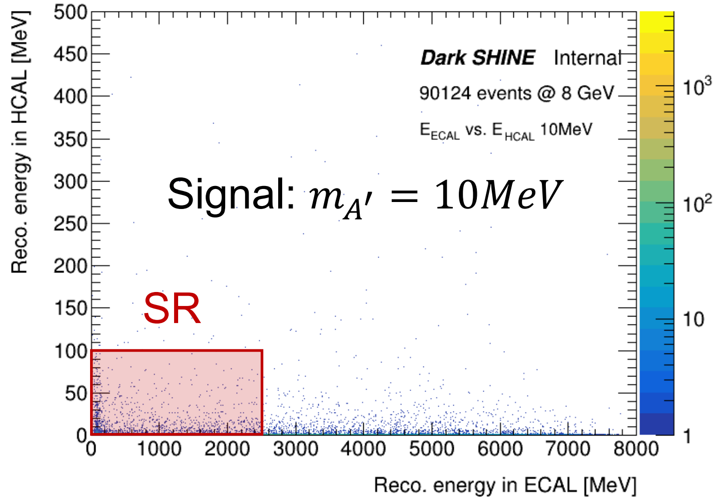
Background

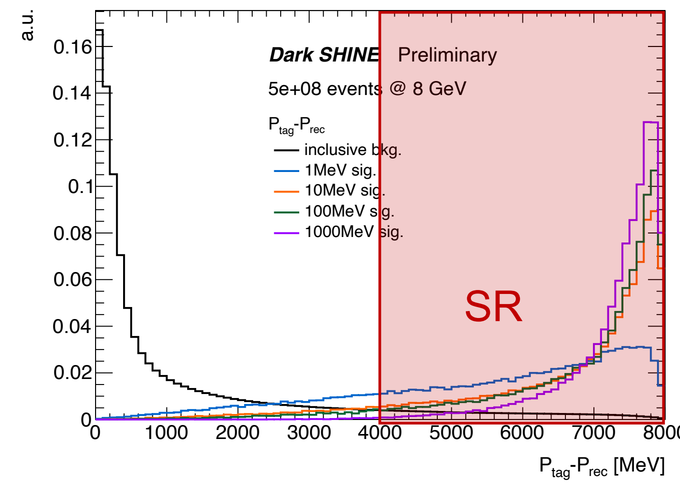
- Recoil electron carry most of the incident momentum
- Recoil electron angle small

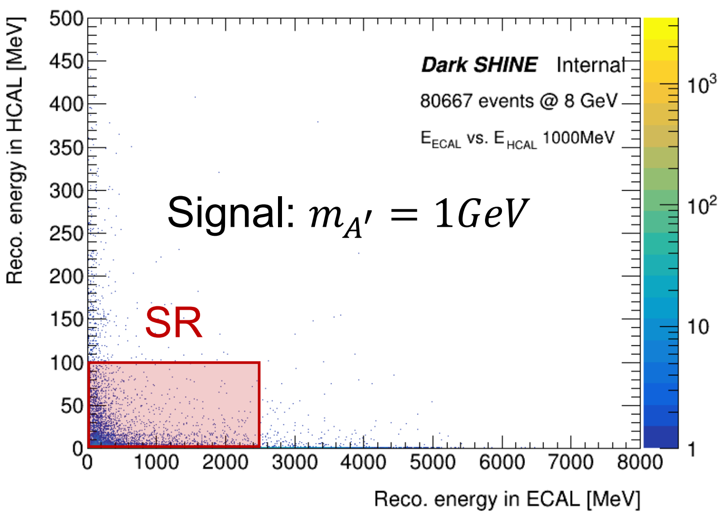


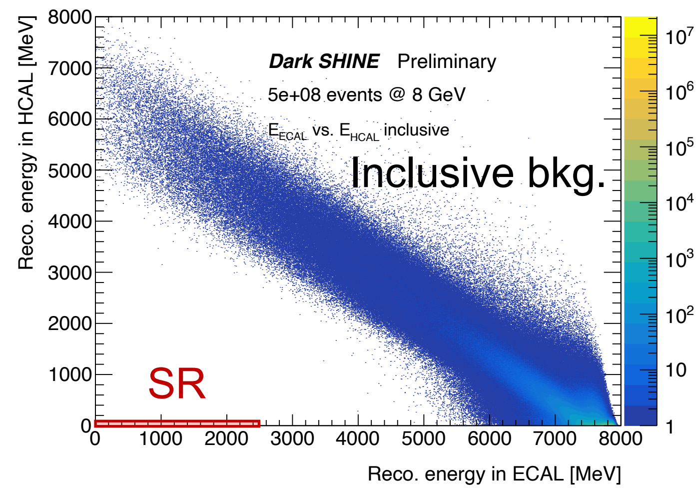


ECAL energy vs. HCAL energy







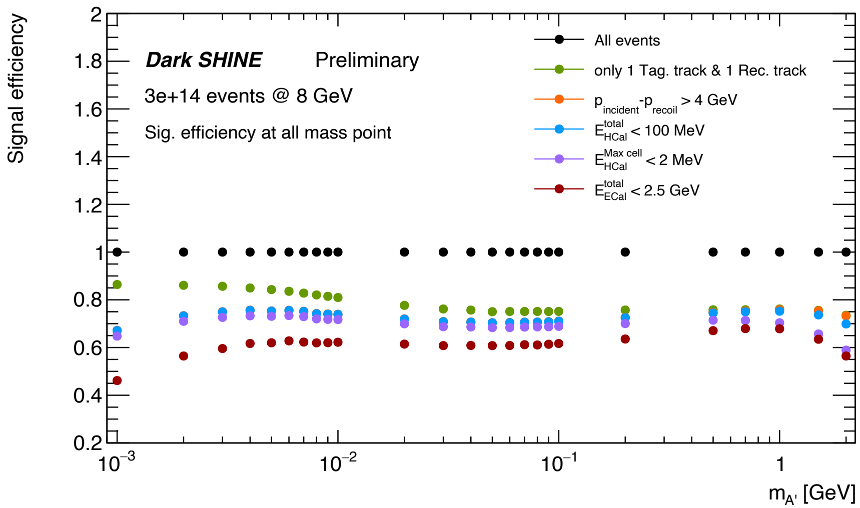


Signal region

- Signal region definition:

number of the reconstructed tracks, $N_{trk}^{tag,rec} = 1$;
missing momentum of electron, $p_{tag} - p_{rec} > 4$ GeV;
total energy reconstructed in ECAL, $E_{ECAL}^{total} < 2.5$ GeV;
total energy reconstructed in HCAL, $E_{HCAL}^{total} < 0.1$ GeV;
max. cell energy in HCAL, $E_{HCAL}^{MaxCell} < 2$ MeV.

- Signal efficiency:



- 25 mass points are produced.

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

- 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

- 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%
$E^{total}_{HCAL} < 100$ 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%

- 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

⇨ $> 3 \times 10^{14}$ EOTs (1year run)

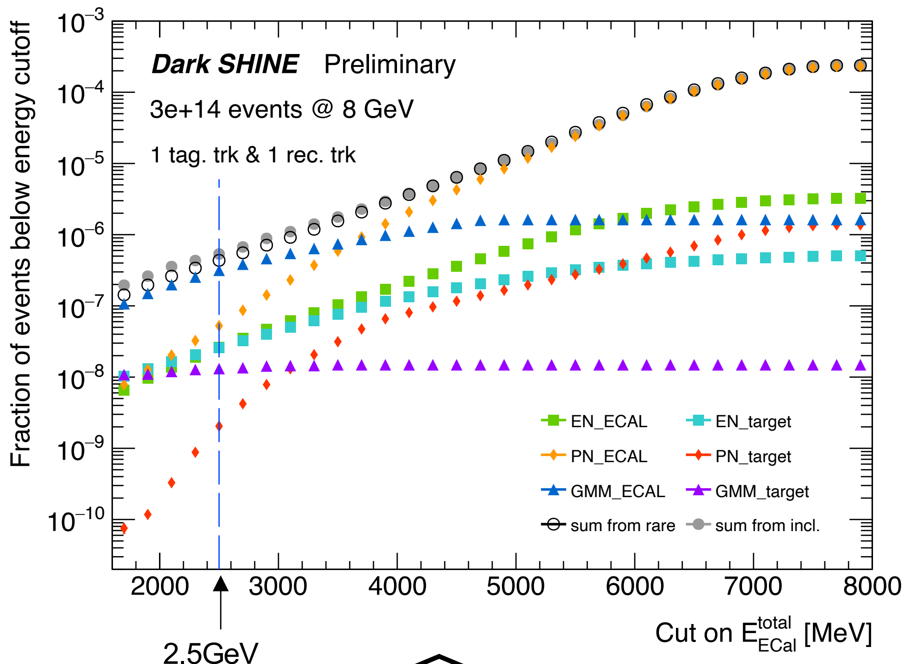
Lack of statistics!

⇩

Extrapolate from fit results

No background events left after SR selection.

Background estimation

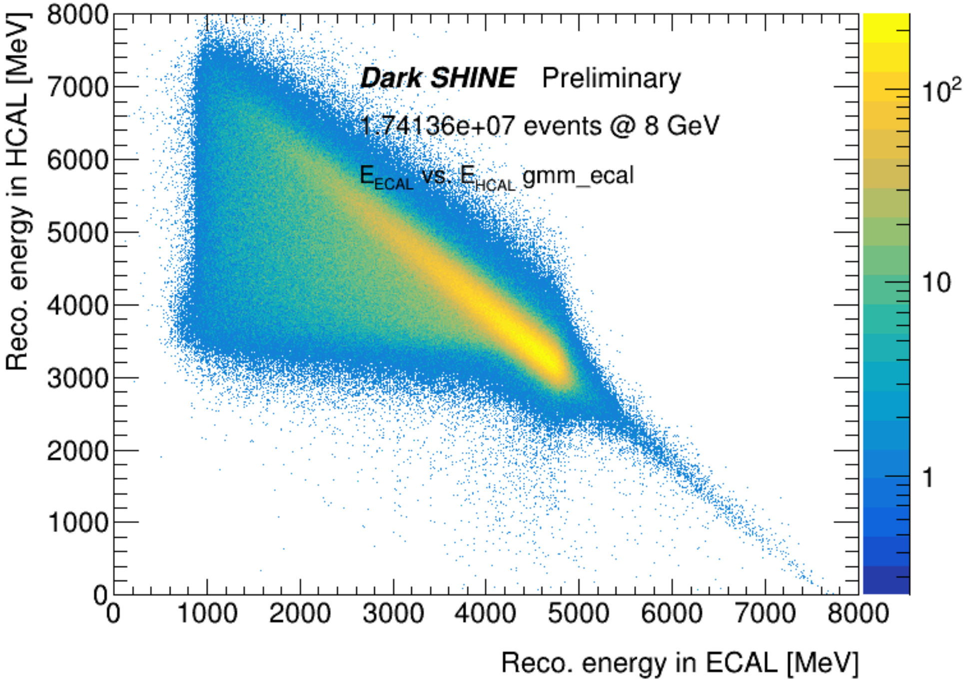


rare processes scaled according to the corresponding branching ratio.

- **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})

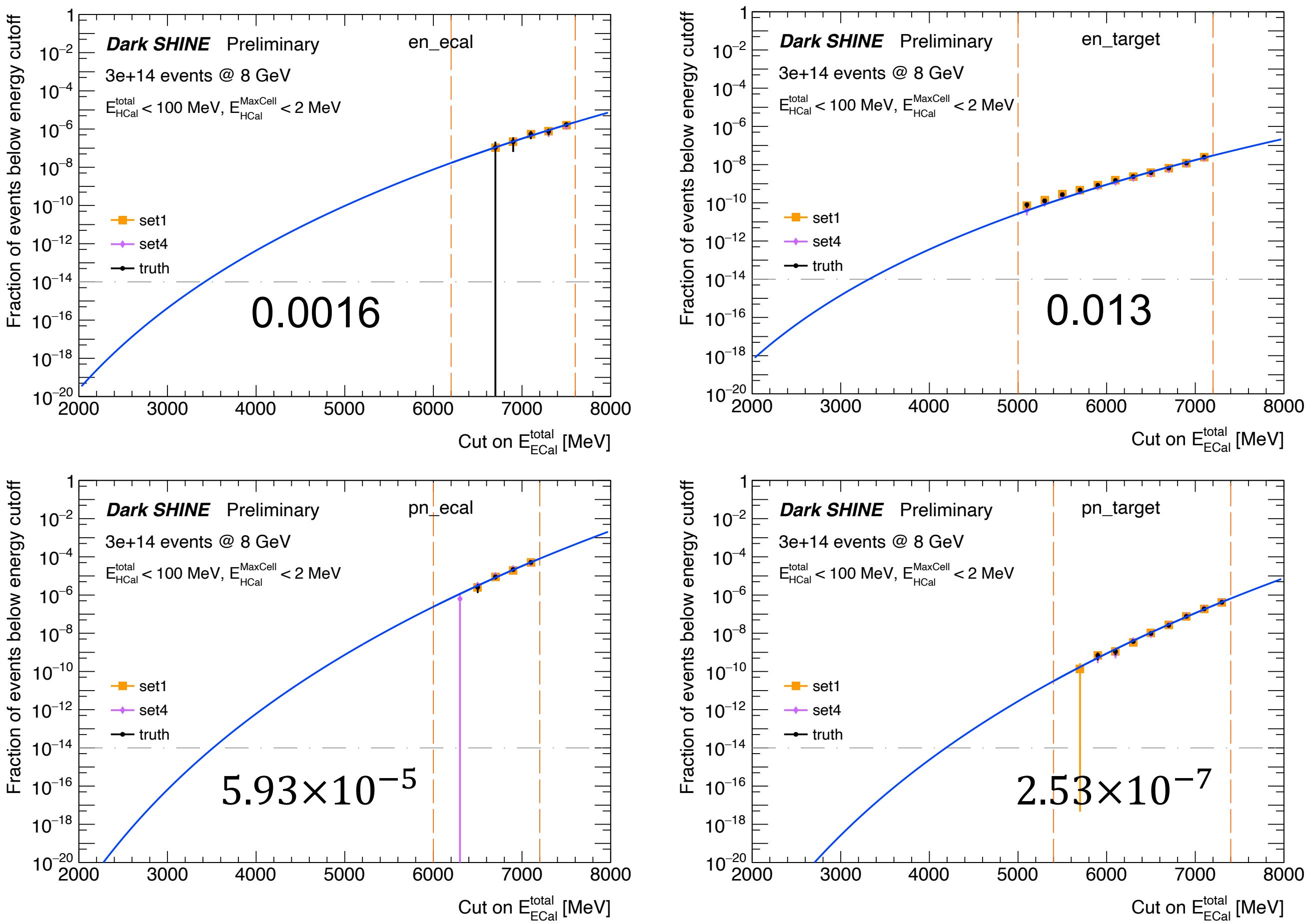
- Don't need to further extrapolation on:

  GMM_target – **enough statistics**

  GMM_ECAL – **can reject by HCAl requirements**

Background estimation

- **Extrapolation from rare processes simulation**



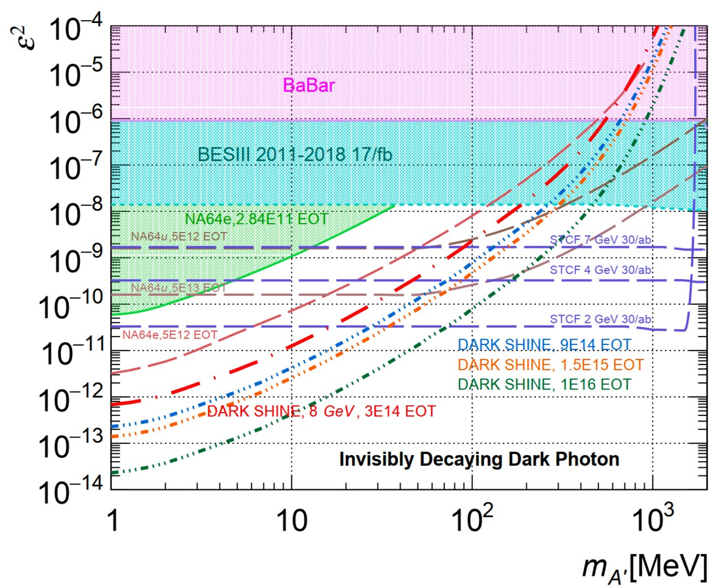
3×10^{14}EOTs

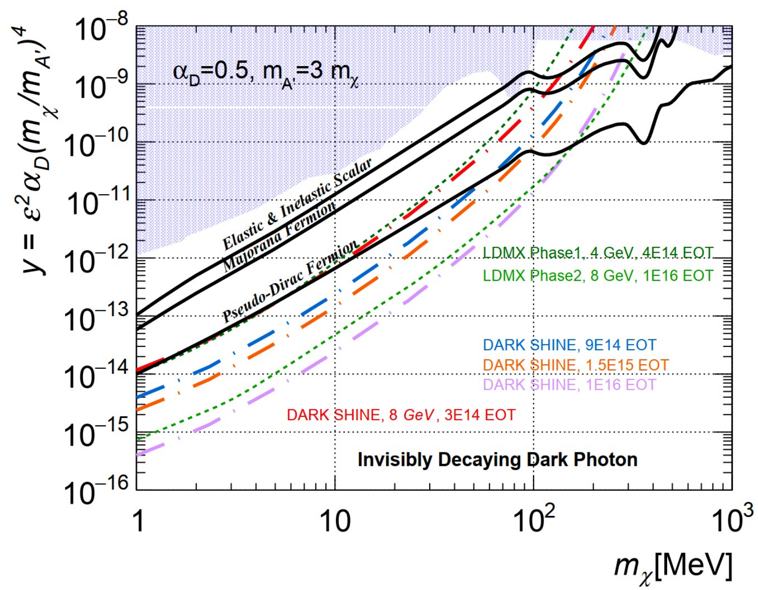
⇕

Bkg. Events:
0.015

Sensitivity study

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





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

Summary

- DarkSHINE: a fixed-target experiment to search for light dark matter.
- Detector R&D ongoing.
- First round of **preliminary study** has been finished:

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

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

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

- Track, missing momentum, deposit energy in ECAL and HCAL: good signal efficiency, background well suppressed (~0.015 bkg. event expected for 1 year operation).

- Expecting competitive sensitivity.

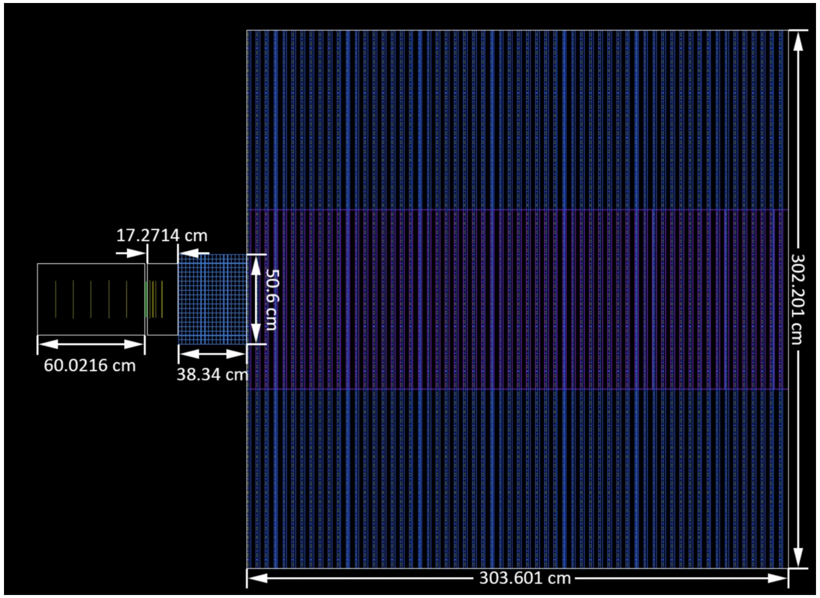
- Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)


LOVE
lovelove LOVE
LOVE LOVE
LOVE love
LOVELOVE
lovelove
LOVE
INI HERO

Backup

Event display

DarkSHINE detector



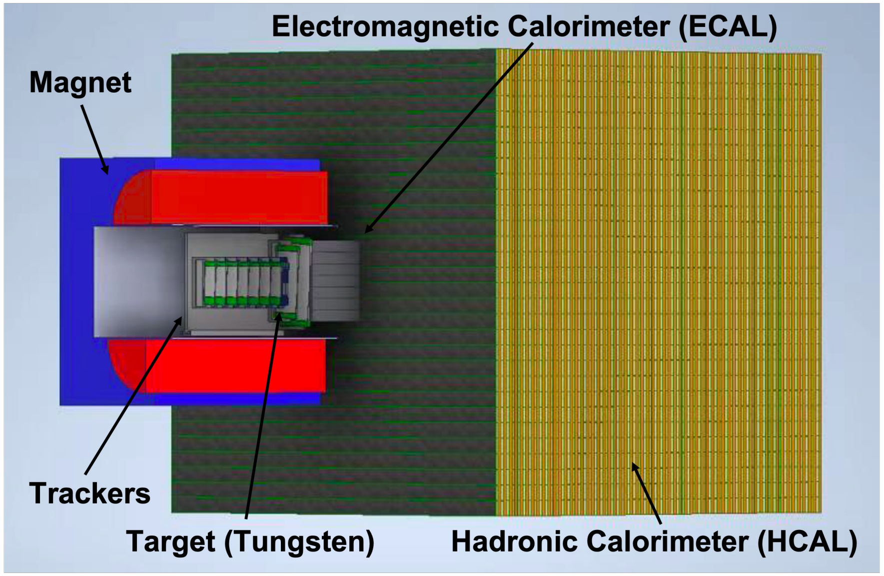
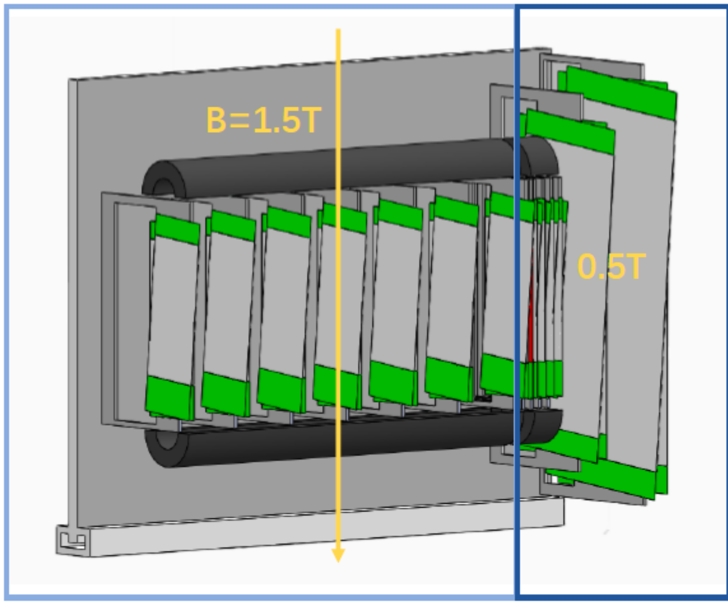


Table 1 The detector geometry overview.

Node	Centre (mm)	Size (mm)			Arrangement	Comments
	z	x	y	z		
Tagging Tracker	-307.783	200	400	600.216	7 layers	Second layer rotation: 0.1 rad
Target	0	100	200	0.35		
Recoil Tracker	94.032	500	800	172.714	6 layers	Second layer rotation: 0.1 rad
ECAL	408.539	506	506	454.3	$20 \times 20 \times 11$ cells	
HCAL	2660.69	4029.51	4029.51	4048.01	$4 \times 4 \times 1$ modules	

Tracker design

- Silicon tracker geometry



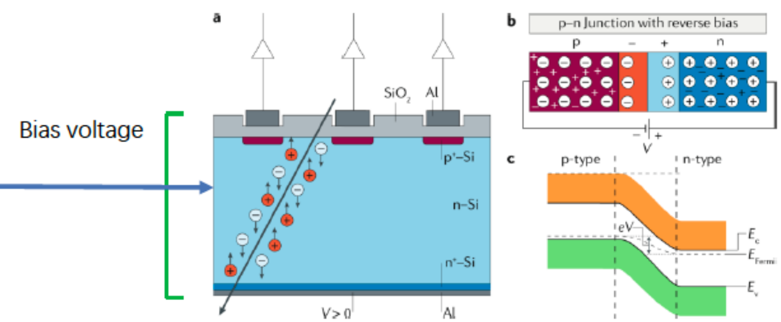
Tag tracker

Recoil tracker

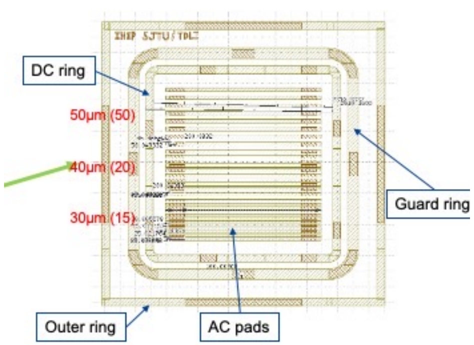
Tag tracker							
Z position/mm	-607.5	-507.5	-407.5	-307.5	-207.5	-107.5	-7.5
X size/mm	100	100	100	100	100	100	100
Y size/mm	200	200	200	200	200	200	200

Recoil tracker						
Z position/mm	7.5	22.5	38.5	53.5	89.5	180.5
X size/mm	100	100	100	120	180	250
Y size/mm	200	200	200	230	280	400

Z thickness ~100μm, 0.001λ
Resolution x: ~6μm, y: ~60μm

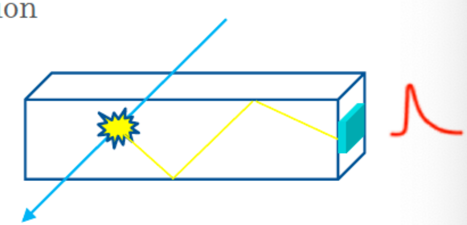


doi.org/10.1038/s42254-019-0081-z

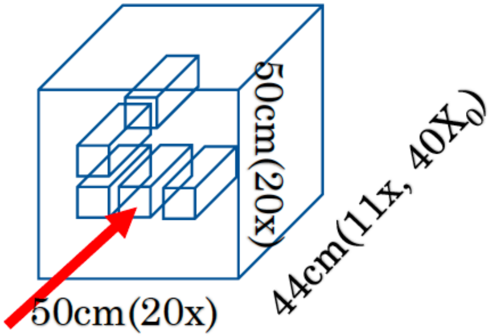


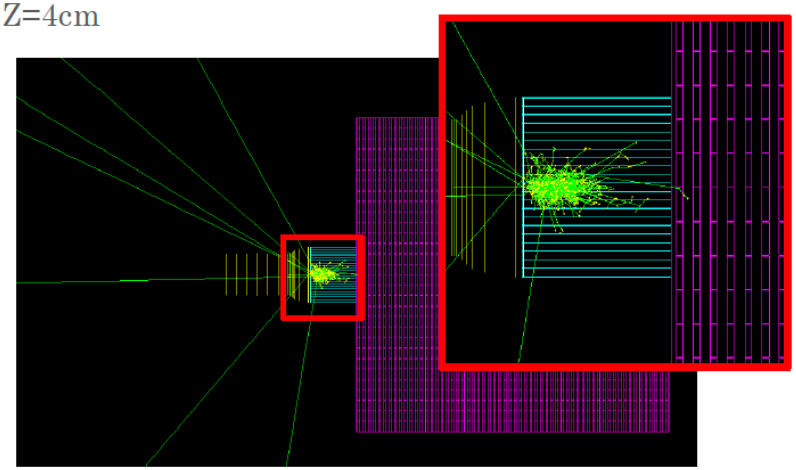
Calorimeter Design (ECAL)

- **Cubic design** of crystal for the electronic calorimeter
  - Z segmentation for 3D shower reconstruction and (potential) PID
  - Potential PFA combined with tracker: location resolution and better track regression
- Readout with SiPM(light sensor) and waveform sampling
  - Wide dynamic range and abundant models for different application
  - Compact size and (relatively) easy to drive
  - High repeated rate and strictly zero integral/dead time with fast ADC&DAQ

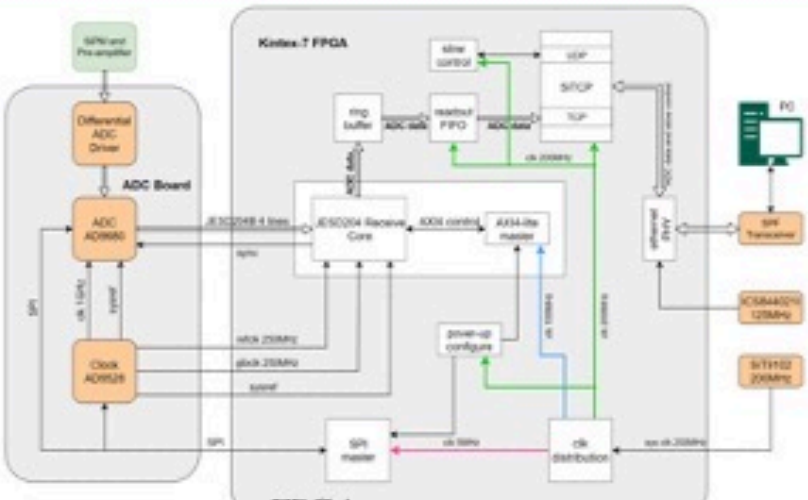


- **LYSO crystal** chosen as baseline design with XY=2.5cm Z=4cm
  - High light yield with good linearity
  - Radiation hard and short decay time

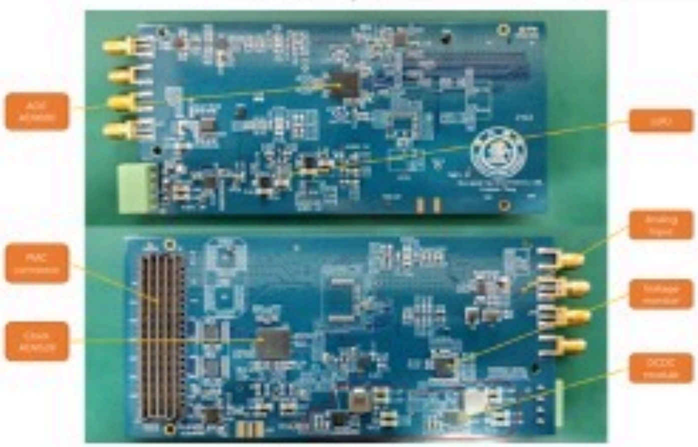




Detector R&D: ECAL readout system



FPGA



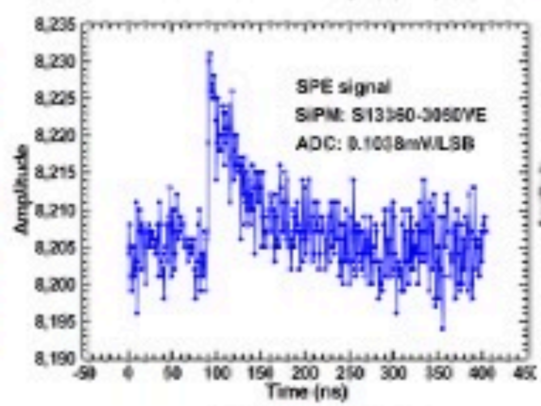
ADC board

Photons from ECAL crystal are detected using SiPM + fast readout system.

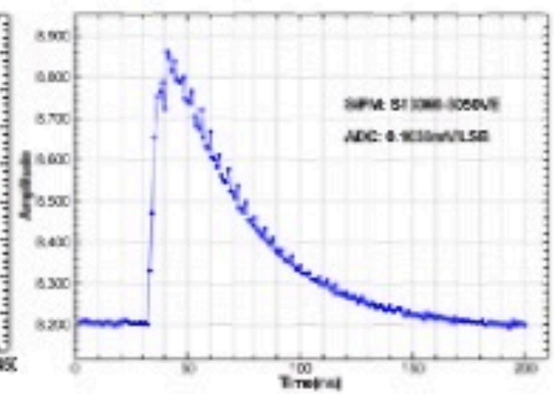
- SiPM (width~10s ns, rising edge ~2ns)
- ADC chip (AD9680 from ADI)
- ADC Mezzanine Card
- Data transfer and processing

AEI workshop

- ADC performance has been tested.
  - Analog input: Cosmic ray + SiPM (S13360-3050VE) + plastic scintillator
  - Amplitude of SPE signal : ~42 LSB, 4.4mV
  - Noise level : ~10 LSB, 1mV

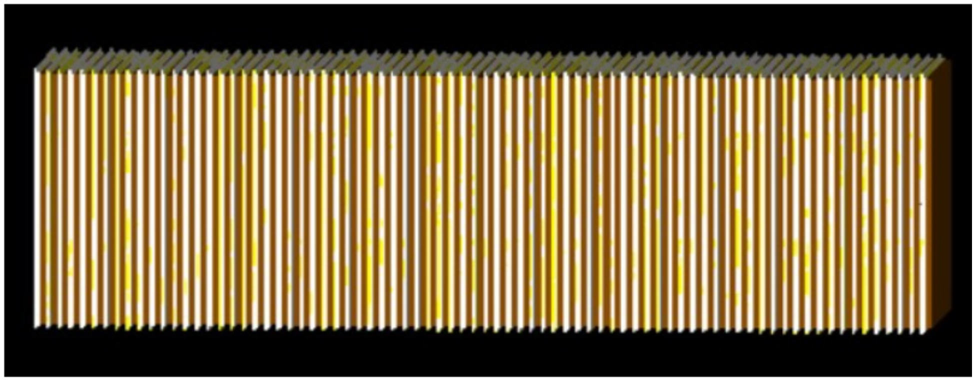


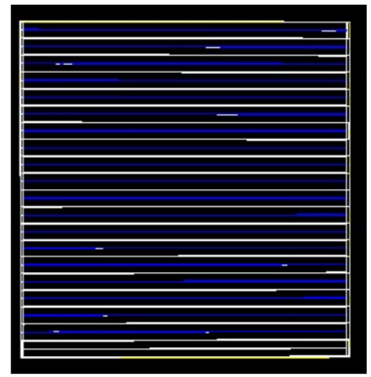
An SPE signal

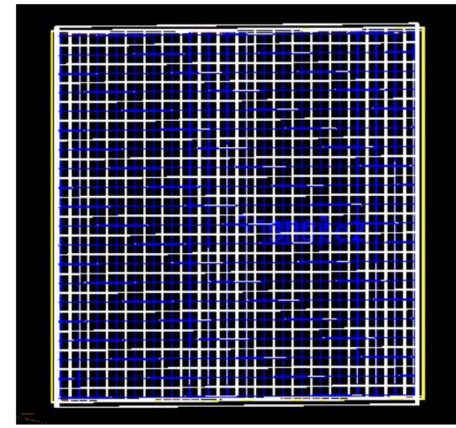


A cosmic ray signal

HCAL design



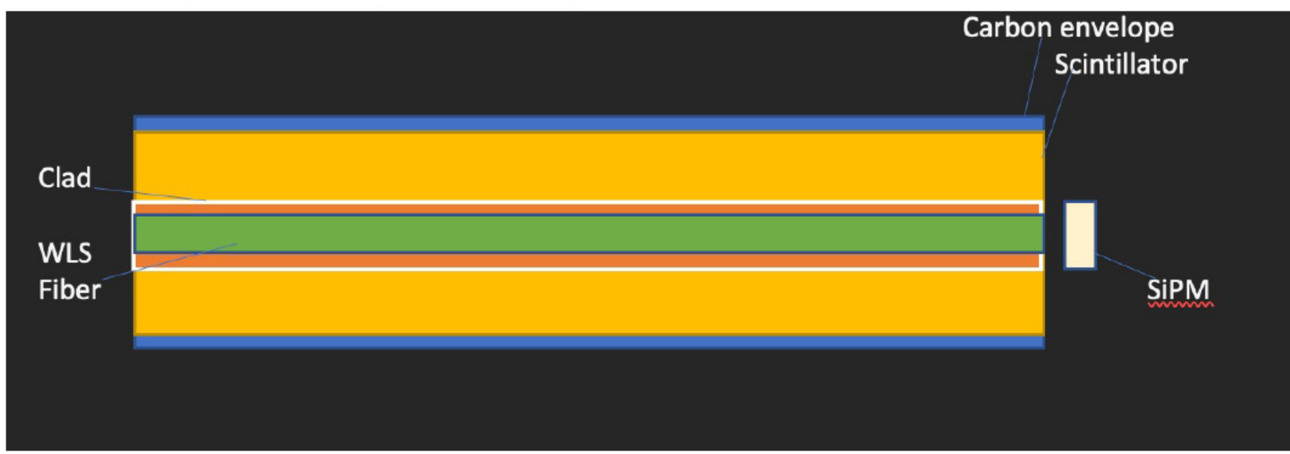




xy crossing

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.

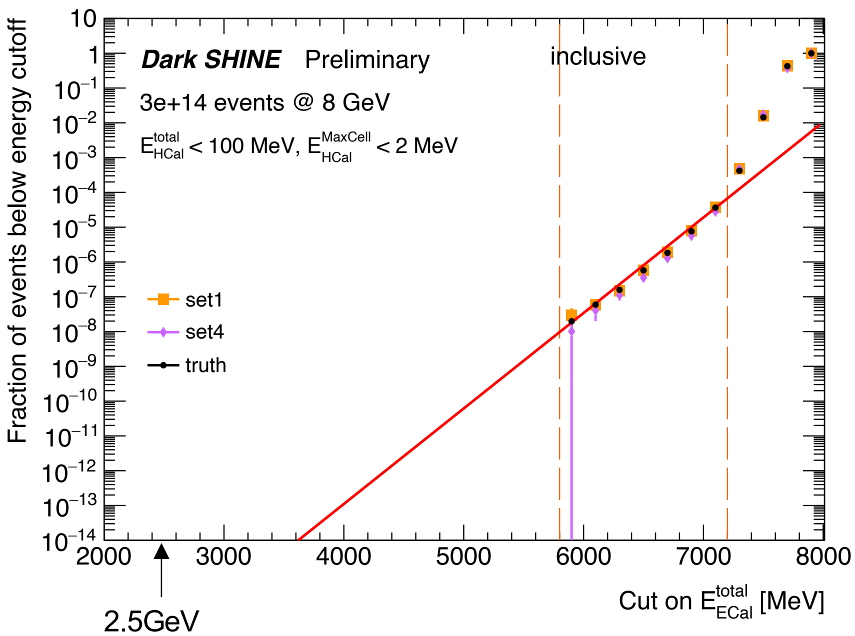


Veto the muon and hadron backgrounds.

- 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.

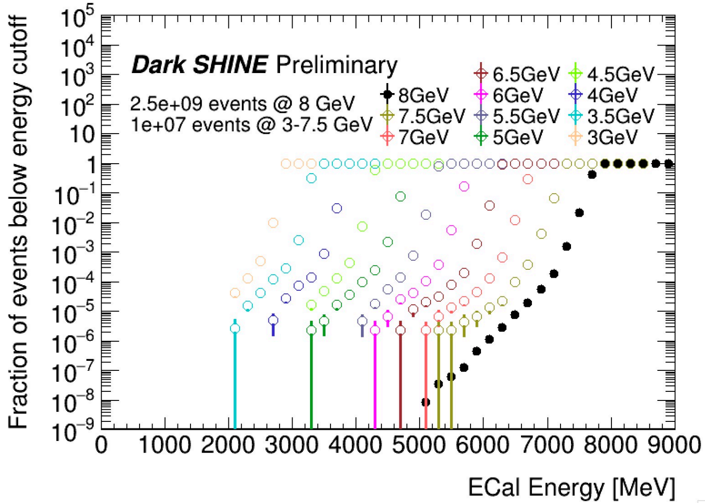
Event yield (3×10^{14}EOTs):

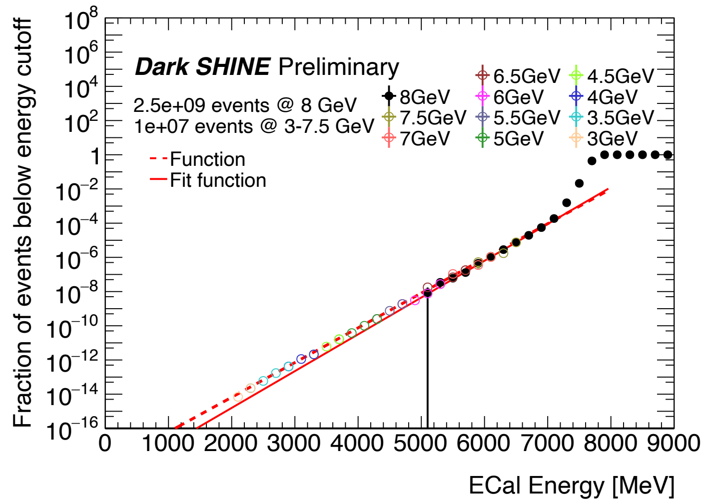
$$\mathbf{2.53\times10^{-3}}$$

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

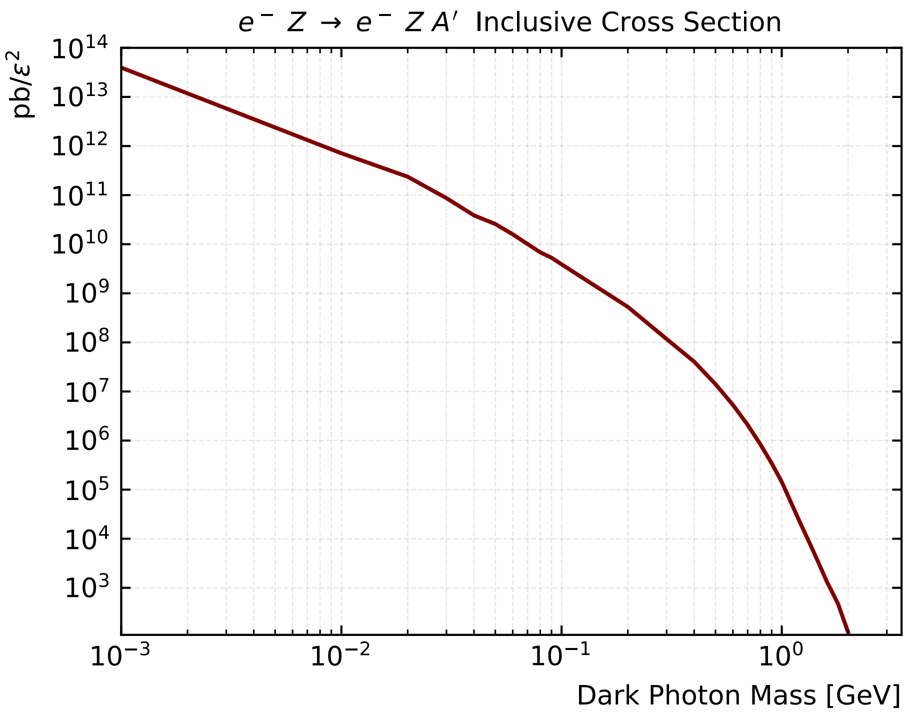
- Neutrino productions:

  - 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 ⨁ 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 ⨁ 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 ⨁ CCQE	charge-current exchange
estimated yield	0.3	0.3

Inclusive cross-section



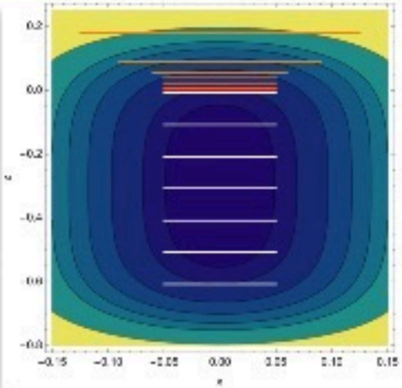
Inclusive cross-section of dark photon bremsstrahlung from electron interacting with W target, assuming $\varepsilon = 1$.

What's next?

Many interesting tasks ongoing after the 1st round of prospective study based on truth information:

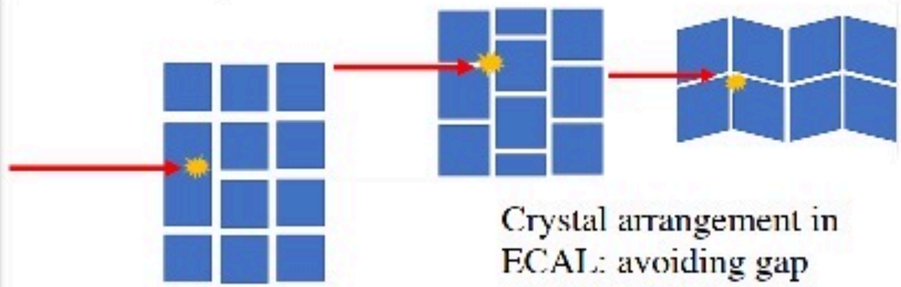
- Detector design optimization
  - strip sensor width, nonuniform magnetic field, calorimeter layout, radiation damage control, supporting structure & detector gap region, …
- Analysis using reco-level information
  - track reconstruction from strip info., cell clustering, track-cell matching, machine learning application…
- Other signal model?
  - visible decay mode, axion-like particle, …

We're stepping into the real world!

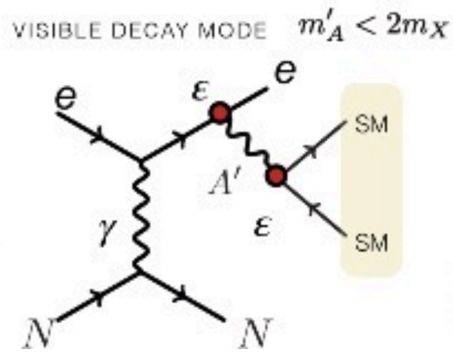


Nonuniform magnetic field: optimization for better track fitting and acceptance region.

AEI workshop

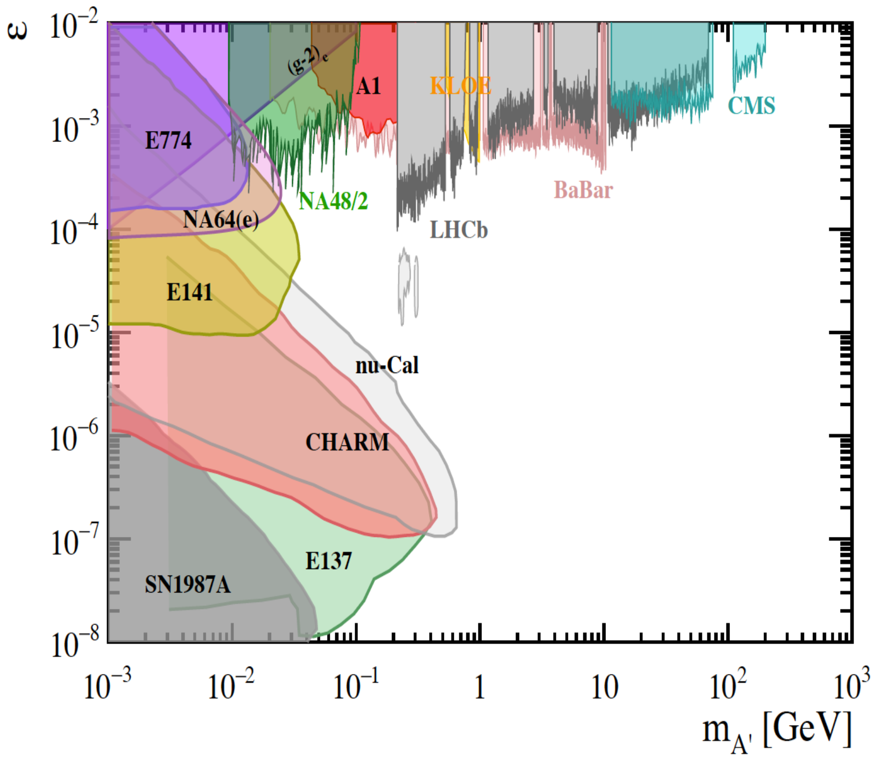


Crystal arrangement in ECAL: avoiding gap region; increased complexity in shower shape reconstruction.

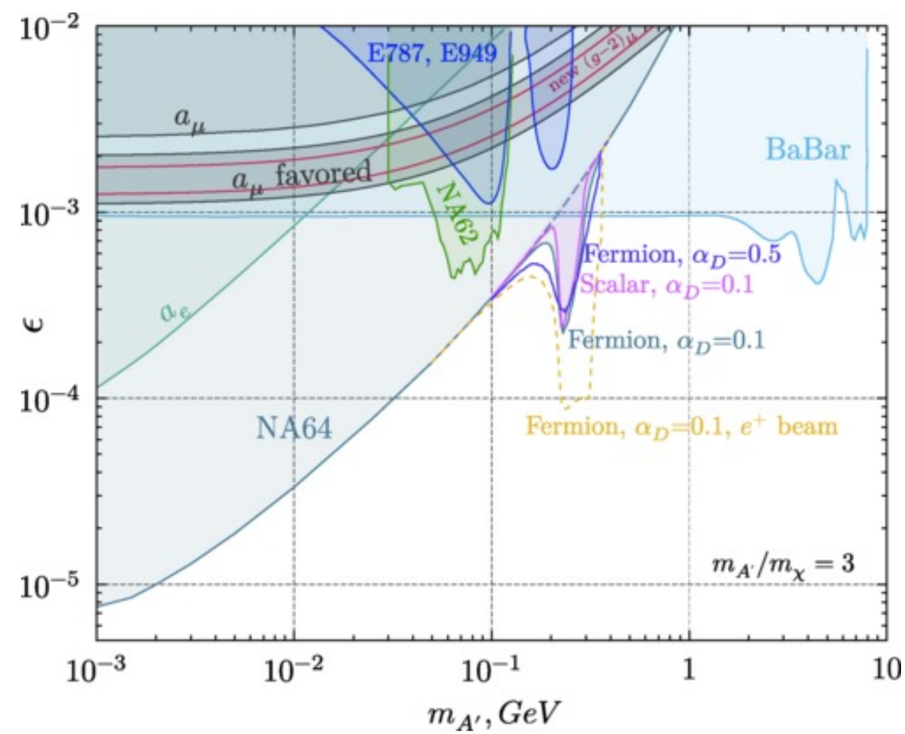


Visible decay of dark photon: no more missing energy, requiring better event reconstruction.

Dark photon search experimental results



arXiv: 1707.04591



Phys. Rev. D 104, L091701 (**2021**)

Plan

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

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

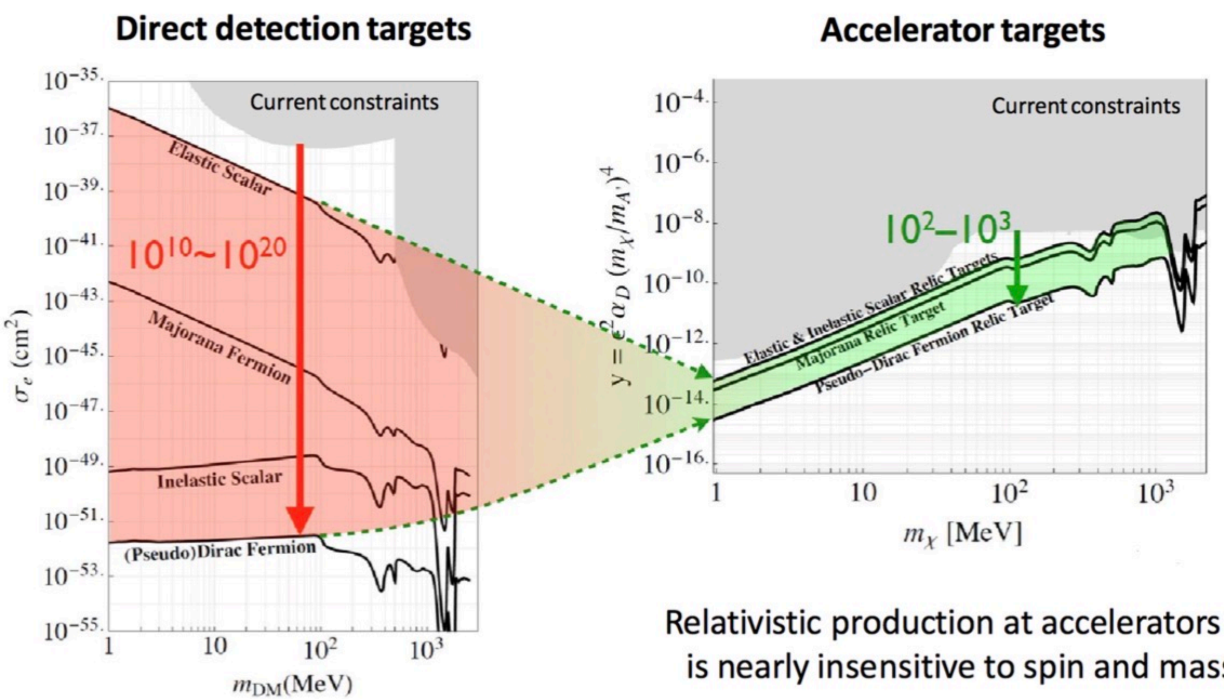
2024 In-lab technical demonstration of detector prototypes; overall **conceptual design report** of **DarkSHINE detector system** and the preliminary **beamline conceptual design report**.

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

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

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

Why need accelerator-based program?



Relativistic production at accelerators is nearly insensitive to spin and mass

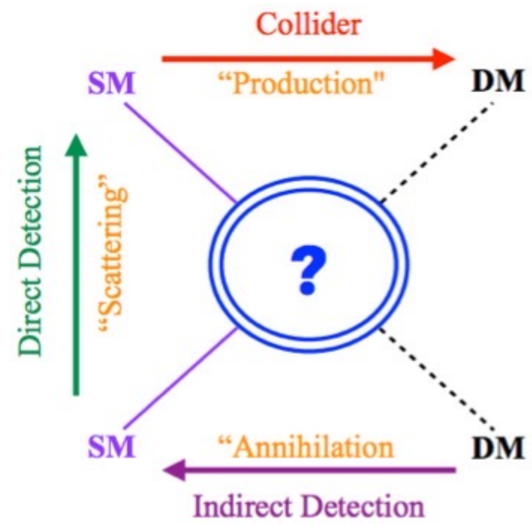
arXiv:1707.04591

- 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