DarkSHINE: Dark photon fixed-target search experiment at SHINE facility

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on behalf of the DarkSHINE team

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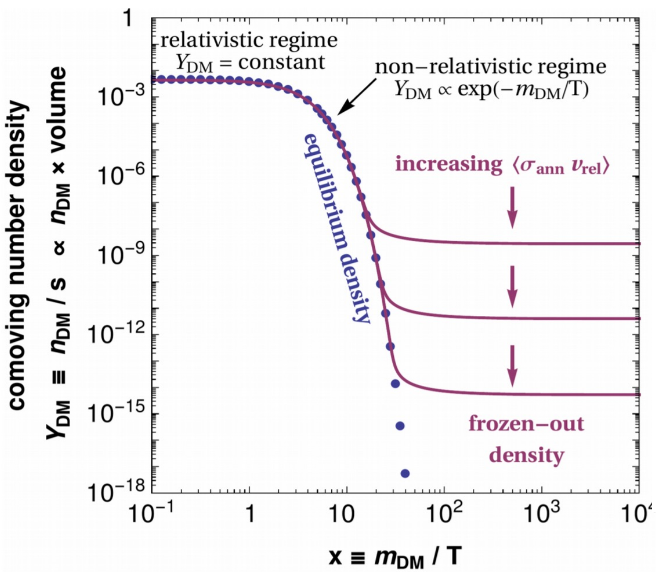
Outline

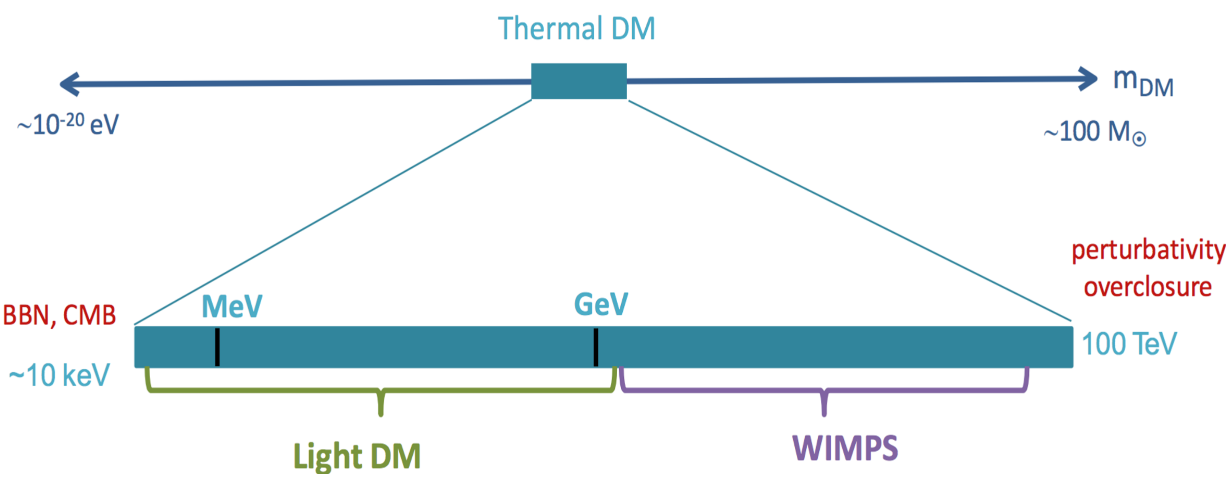
- Physics motivation
- The SHINE facility
- Detector conceptual design
- Signal and background simulation
- Prospective sensitivity
- Summary

Physics motivation

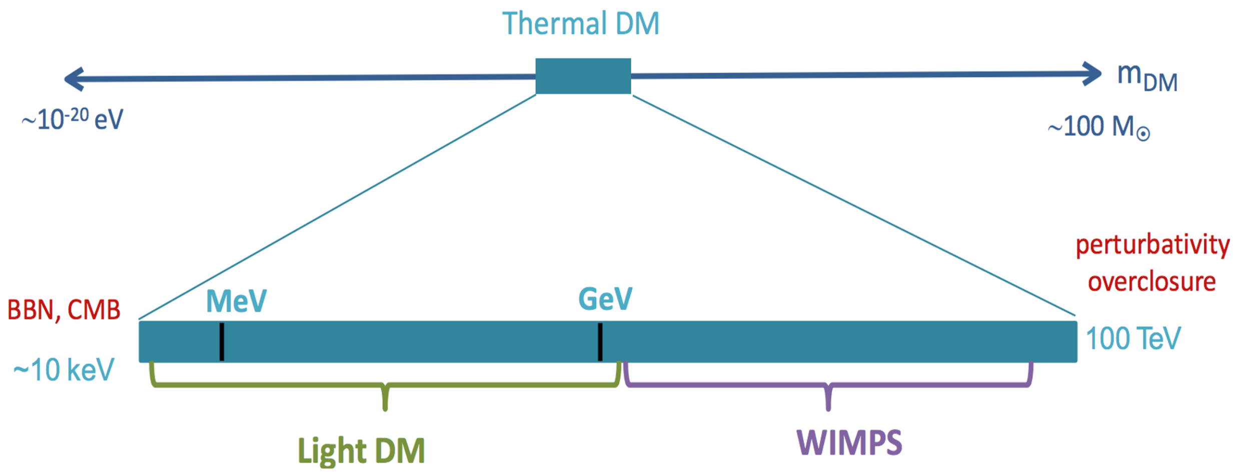
Evidence from cosmology and astronomy showing that **Dark Matter (DM)** exists in the universe.

- constituting ~25% of the universe energy content.
- one typical origin hypothesis: thermal equilibrium in the early universe.
    - Temperature drops due to the over-expansion of the universe → DM density becomes stable ("freeze-out" mechanism).





Physics motivation



Searching for light DM (χ):

Sub-GeV mass range not fully explored yet.

- New mediator implied by thermal contact: e.g., a **dark photon (A')**
  - DM interact with SM particles via the new "dark force".
  - Collider experiments searching for dark photon: NA64@CERN, BESIII, BEPCII, LDMX, etc.

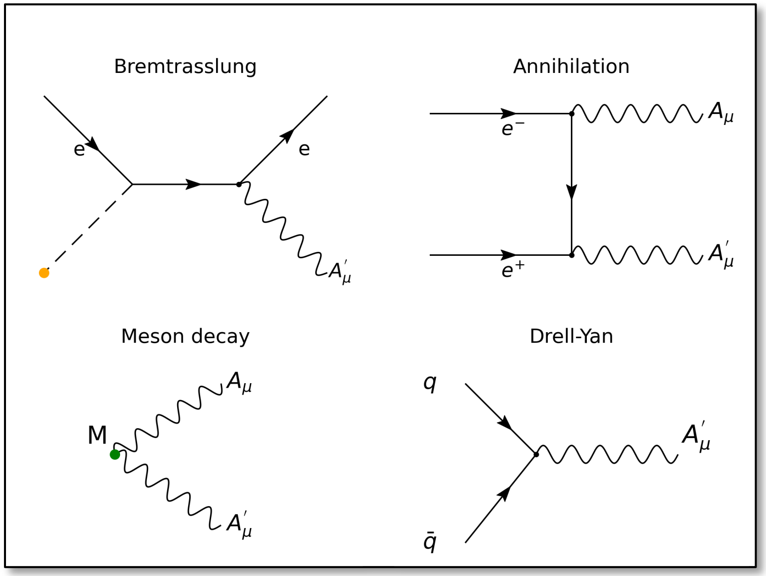
Searching for weakly interacting massive particles (WIMP):

No evidence yet. A large parameter space ruled out in GeV~TeV mass range.

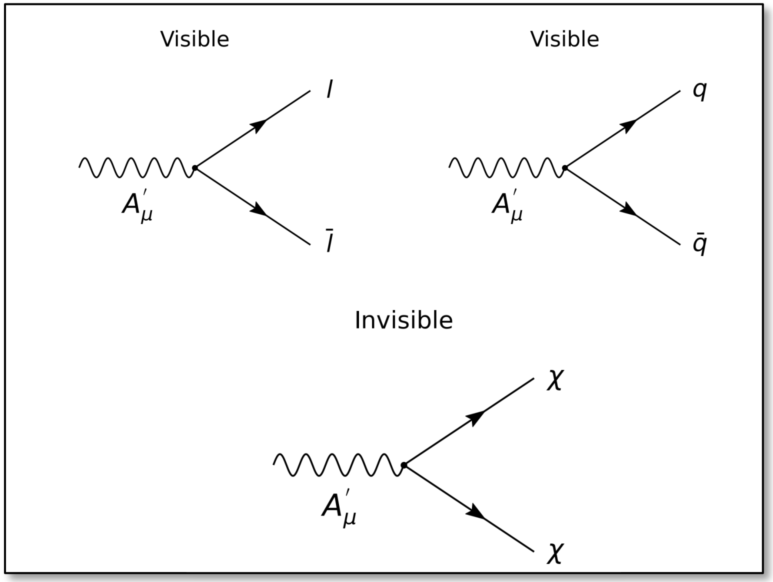
- Space experiments (DAMPE, AMS, etc.)
- Collider experiments (LHC, BELLE-II, BESIII, etc.)
- Underground experiments (PandaX, CDEX, LUX, Xenon, etc.)

Physics motivation

Search for **dark photon A'**: an important portal between the standard model (SM) particle and the dark matter.



(Dark photon production)



(dark photon decay)

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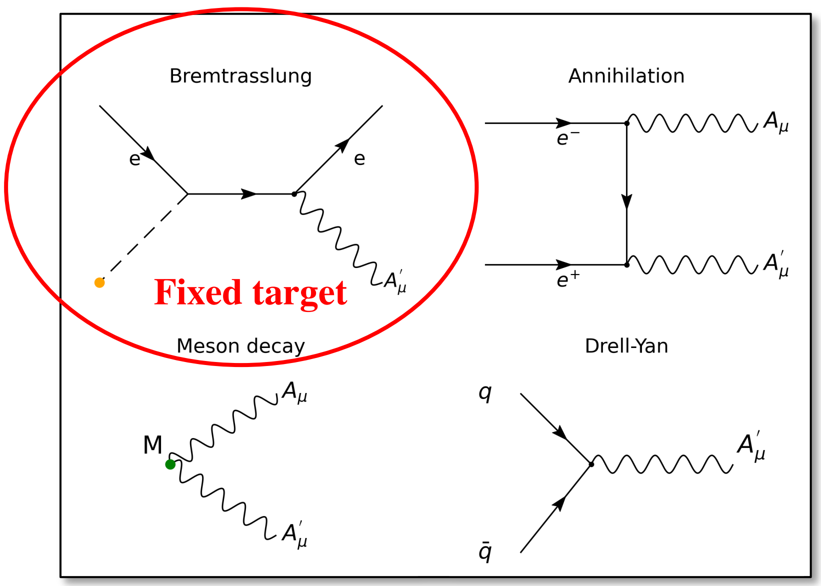
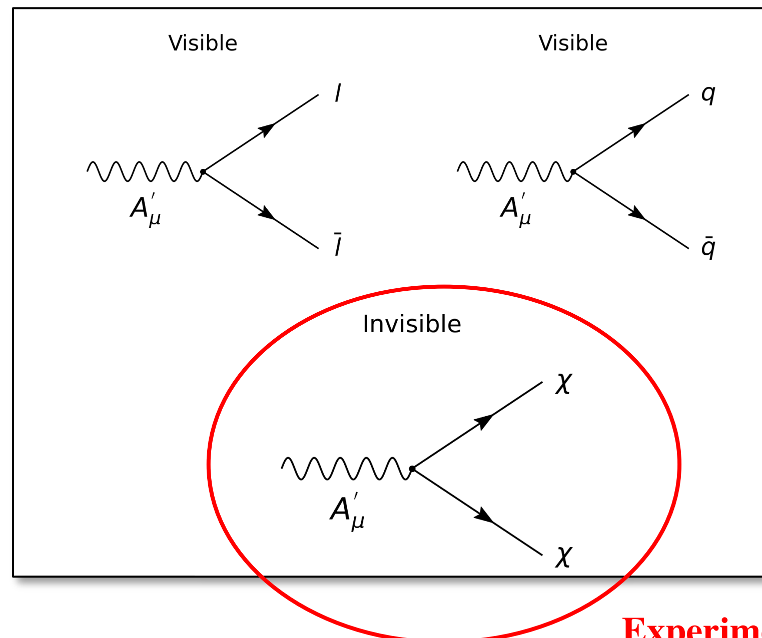


(Dark photon production)



(dark photon decay)

Experimentally: missing energy, missing momentum.

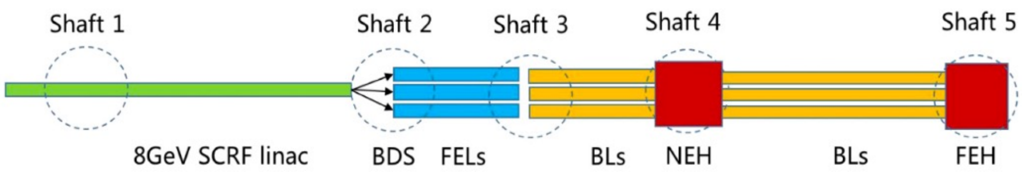
- Goal: put constraints on the kinetic mixing parameter ε.
- Challenge: small production rate → suppress bkg. from SM processes.

The SHINE facility

The high frequency single electron beam required by our experiment is provided by **SHINE** (Shanghai High Repetition-Rate XFEL and Extreme Light Facility).

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

- Electron energy: 8 GeV
- Frequency: 1 MHz
- Beam intensity: 100 pC (6.25×10^{8} electrons per bunch → too large for DarkSHINE!)



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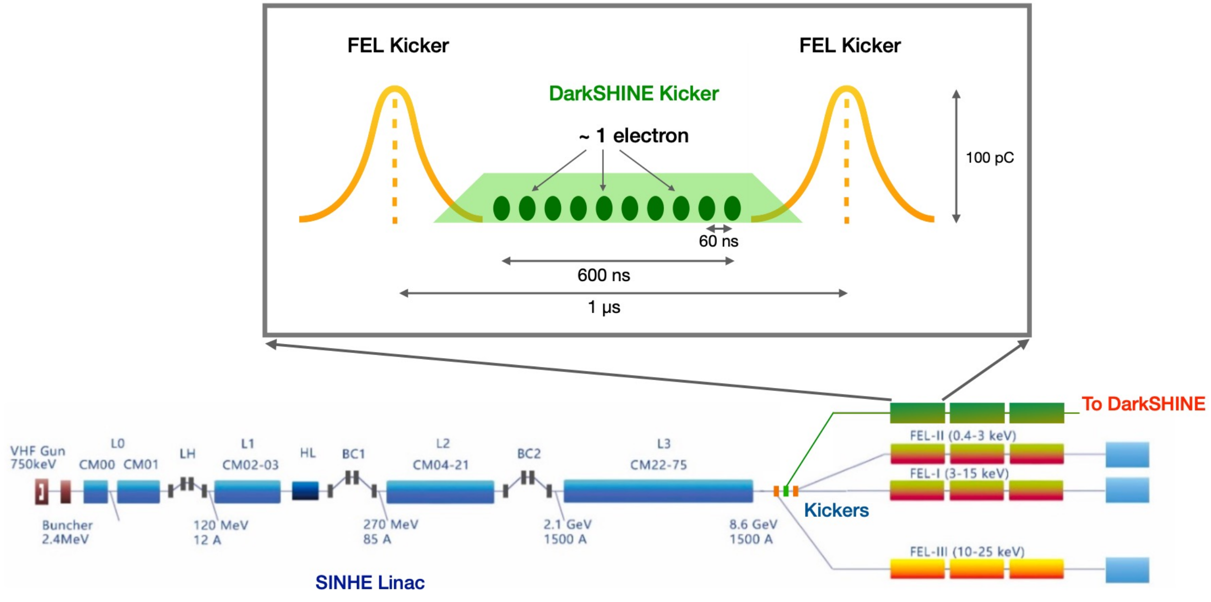
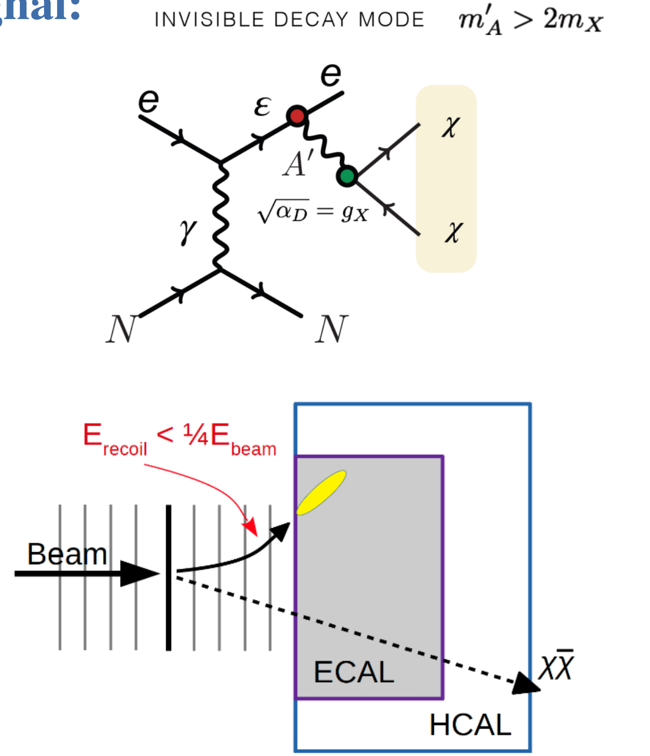


- Dedicated electron beam with one electron per bunch to be built in the SHINE linac.
- DarkSHINE kicker system to distribute these electrons, resulting in a frequency of 10 MHz, corresponds to 3×10^{14} electron on target events (EOTs) per year.

Invisible signal signature

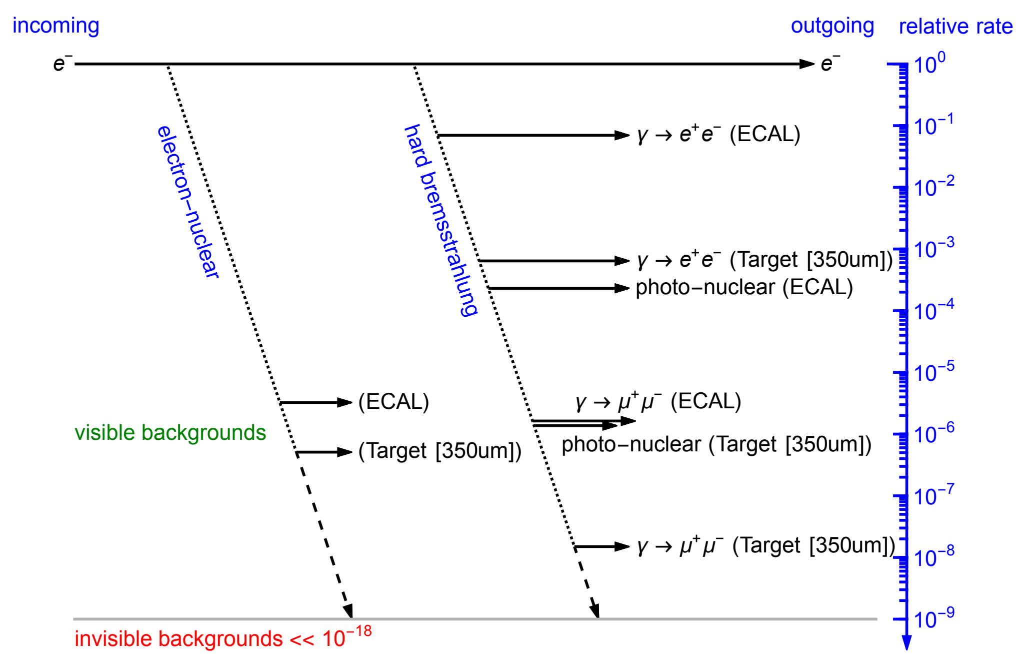
Missing particle signature: soft recoil electron, large missing energy & p_T.

Signal:



Leading background: SM photon bremsstrahlung

Rare background processes:



Invisible signal signature

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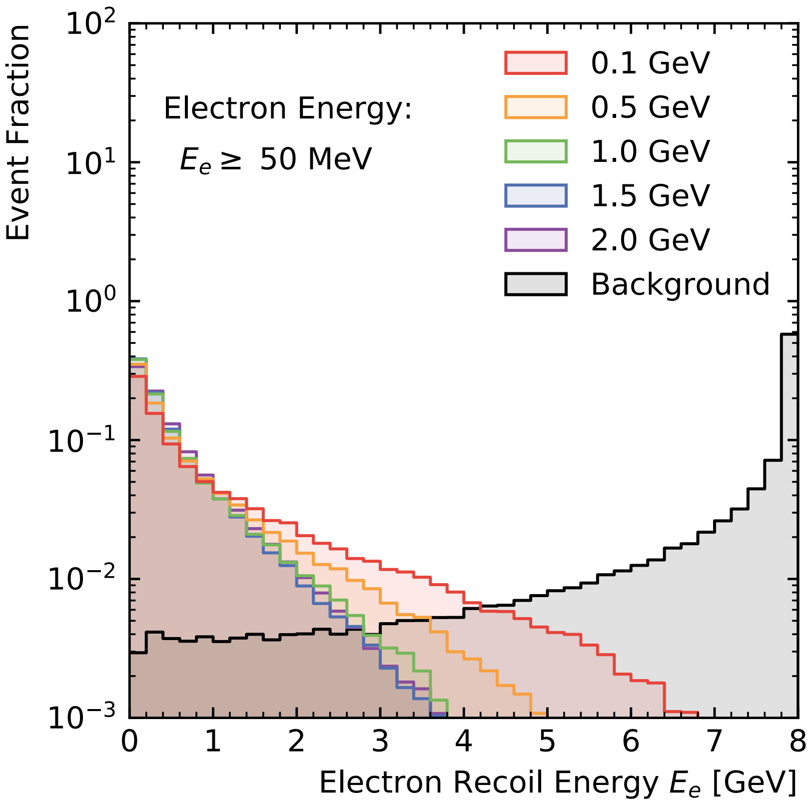
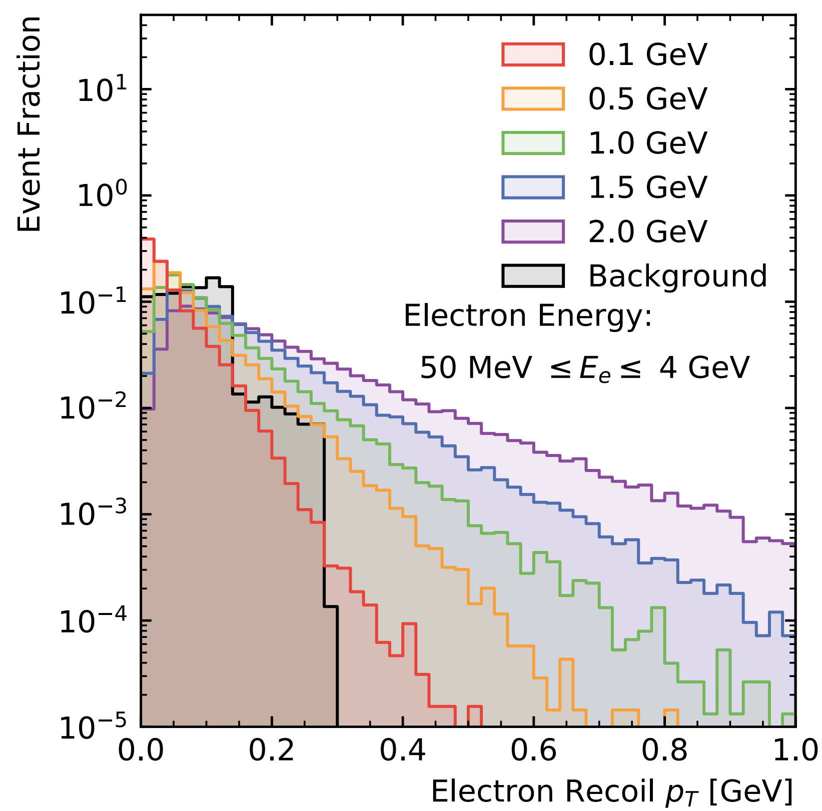


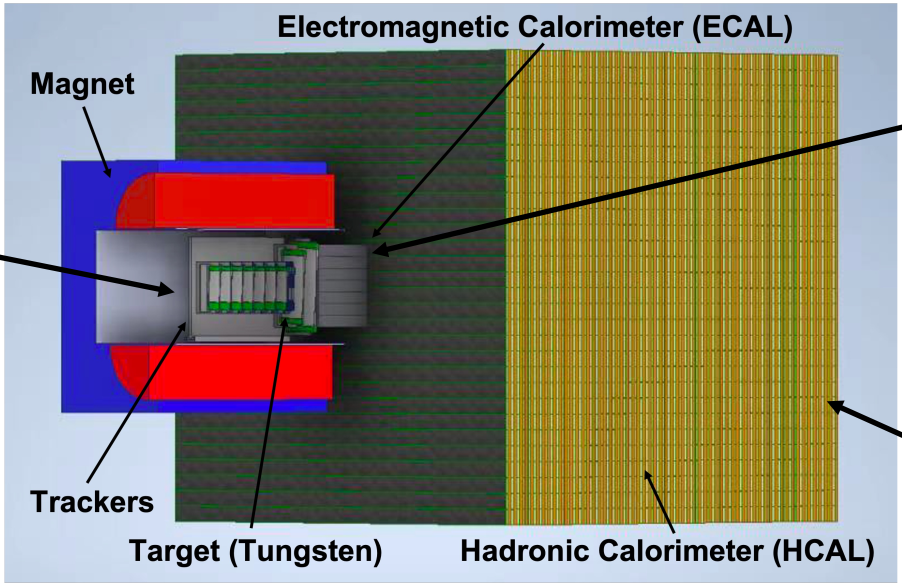
Energy brought away by A'



Reco. electron kicked in transverse momentum

Detector conceptual design

DarkSHINE detector sketch



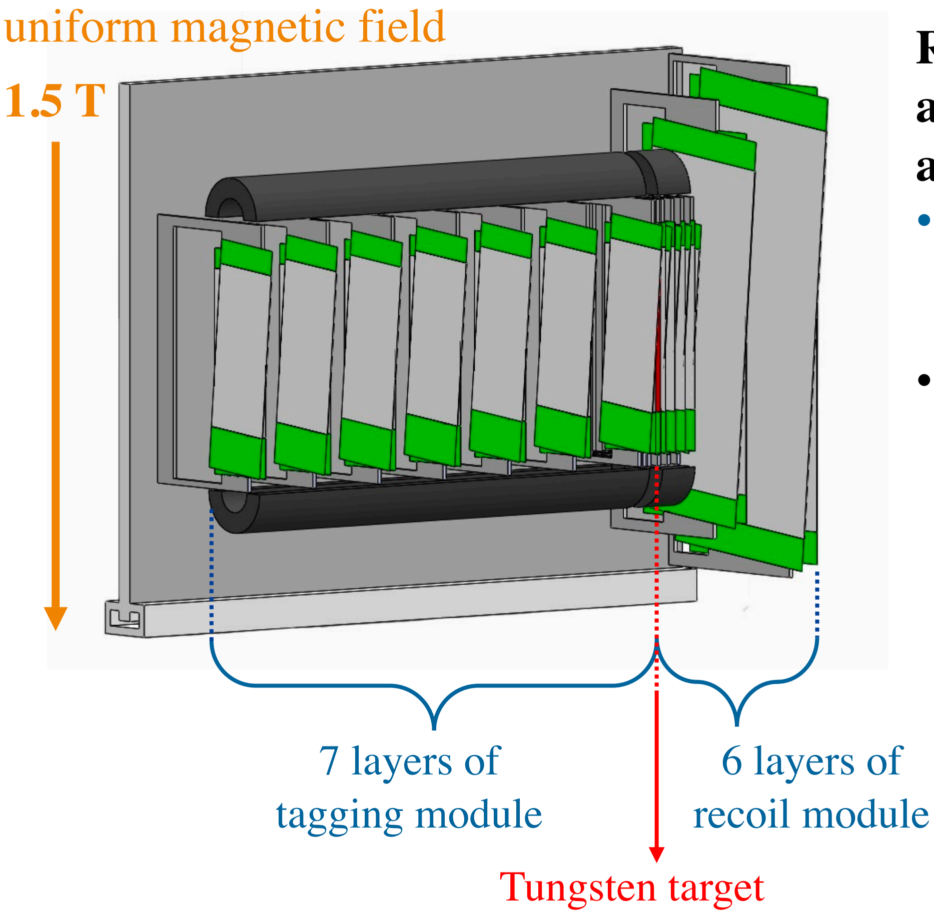
Tracking system
Measure the track of the incident and recoil electrons.

Electromagnetic calorimeter
Measure the deposited energy: electron and photon.

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

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

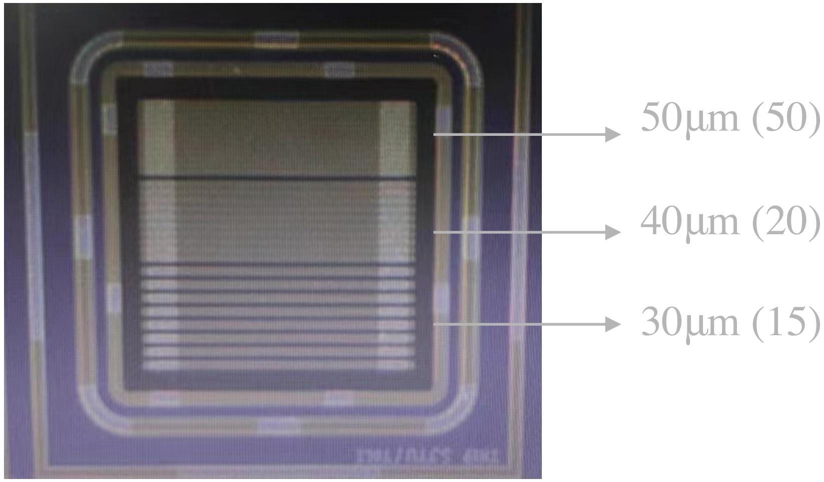
Tracker system



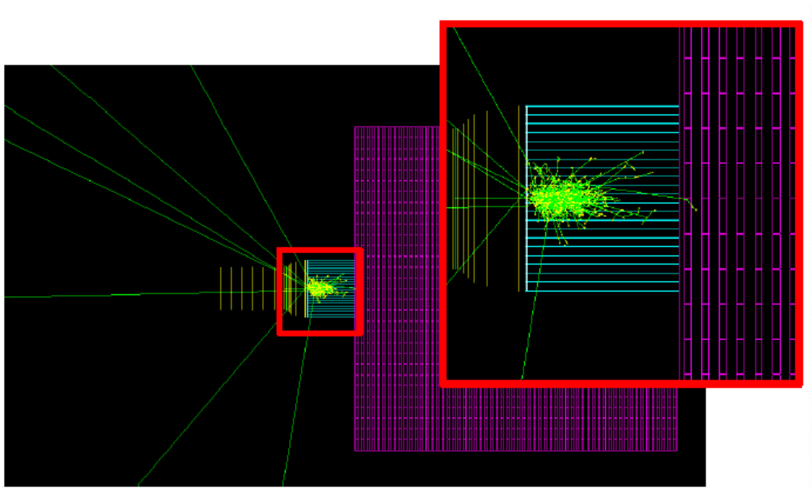
Each module: 2 layers of silicon strip sensor with a small angle (100 rad) for better position resolution.

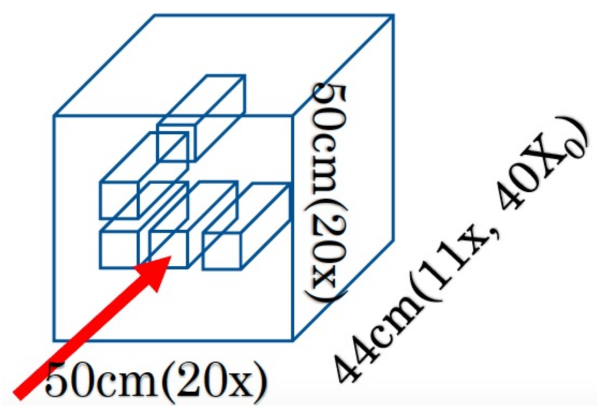
Reconstruct the track of the incident and recoil electrons, the $\gamma \rightarrow ee$ process, and the hadron/μ involved final states.

- Designed resolution:
  - Better position resolution than 10 μm.
  - Better angle resolution than 0.1%.
- Response and resolution tests with silicon strip sensor prototype ongoing.



Electromagnetic calorimeter

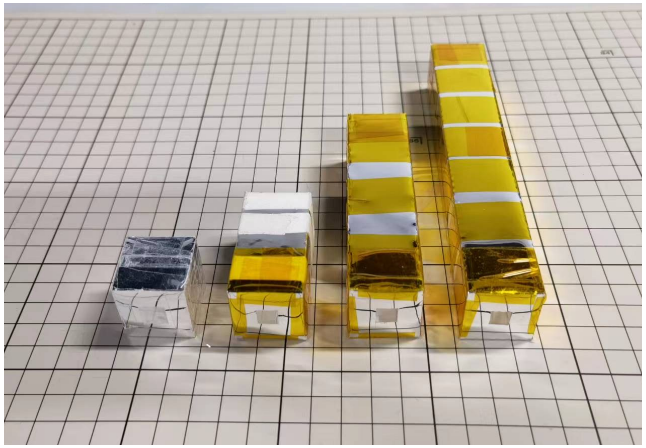




Baseline design of each crystal: X,Y = 2.5 cm, Z = 4 cm (radiation length: 1.14 cm)

Measure the deposited energy of electron and photon.

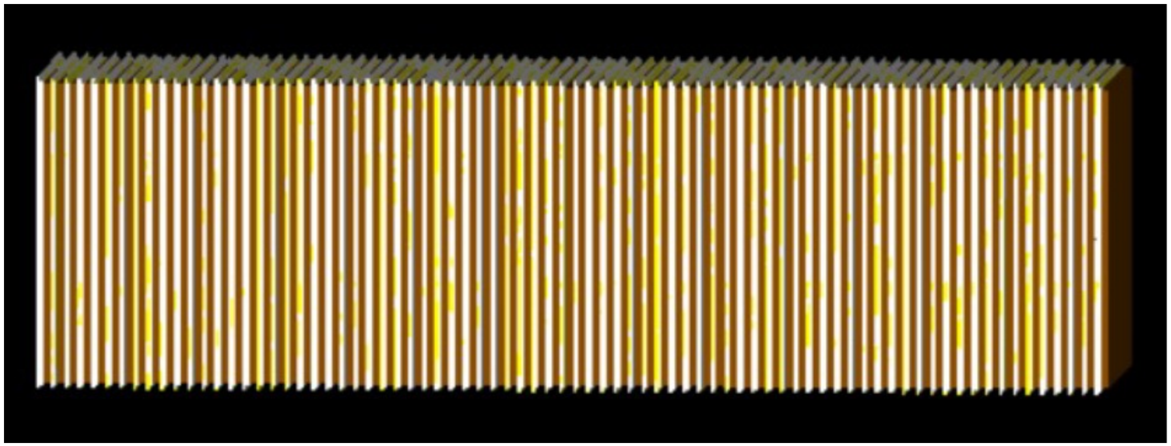
- Designed resolution: better energy resolution than 5%.
- LYSO crystal ($Lu_{(1-x-y)}Y_{2y}Ce_{2x}SiO_5$):
  - high light yield (30000 p.e/MeV) with good linearity.
  - short decay time (40 ns).
- Readout with SiPM and waveform sampling.
- Intrinsic radiation and radioactive source tests ongoing.

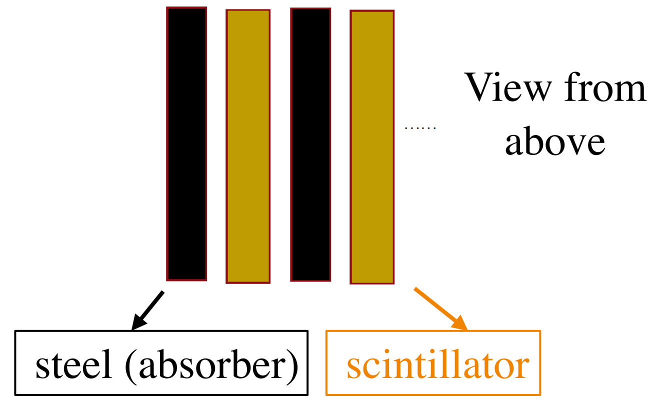


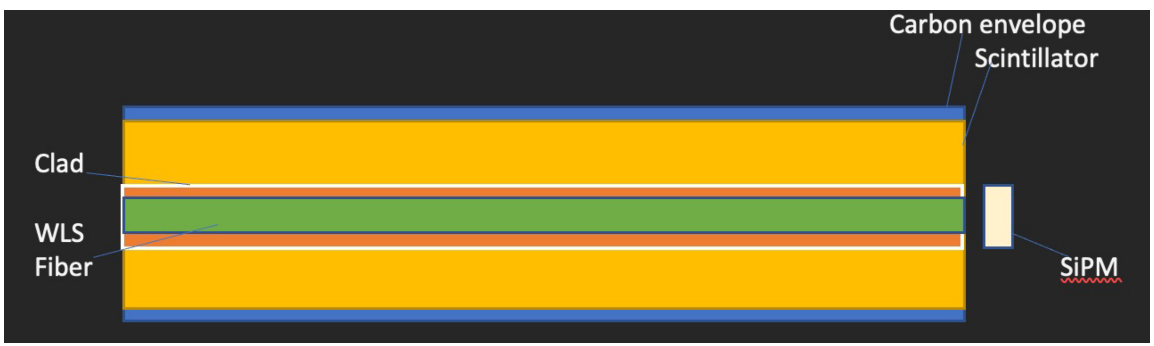
Simulation study ongoing…

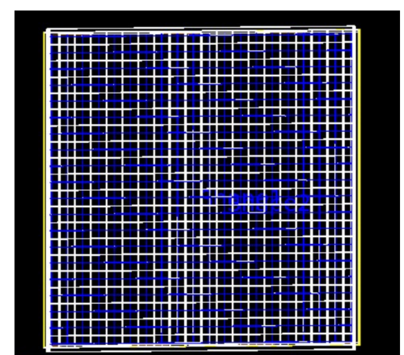
Hadronic calorimeter

Veto the muon and hadron backgrounds.









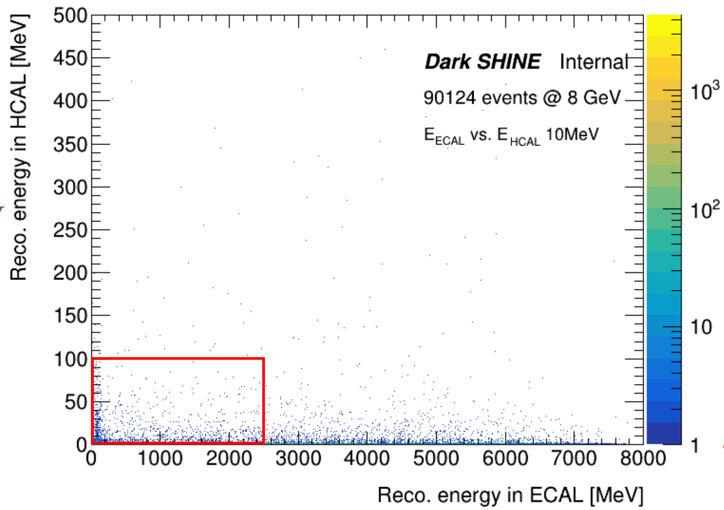
(WLS fiber in blue)

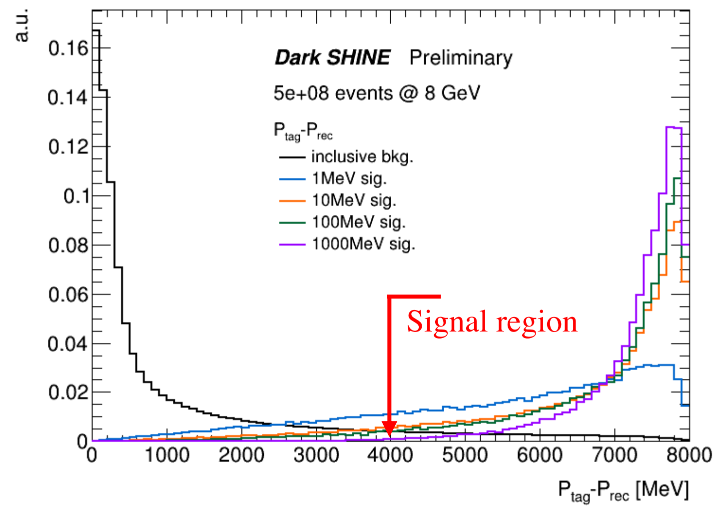
4×4×1 modules: 100×100 (cm) in x-y plane.
Each scintillator wrapped by a carbon envelope, with a wavelength shifting (WLS) fiber placed in its centre.

Simulation event display

Kinematic distributions

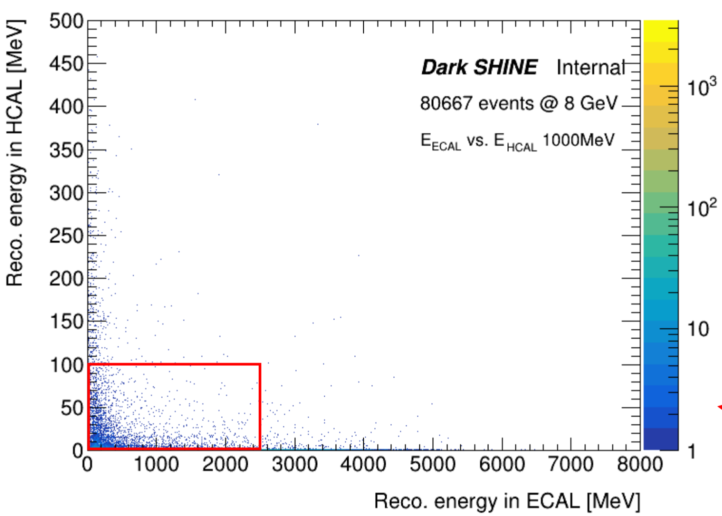
Signal 10 MeV

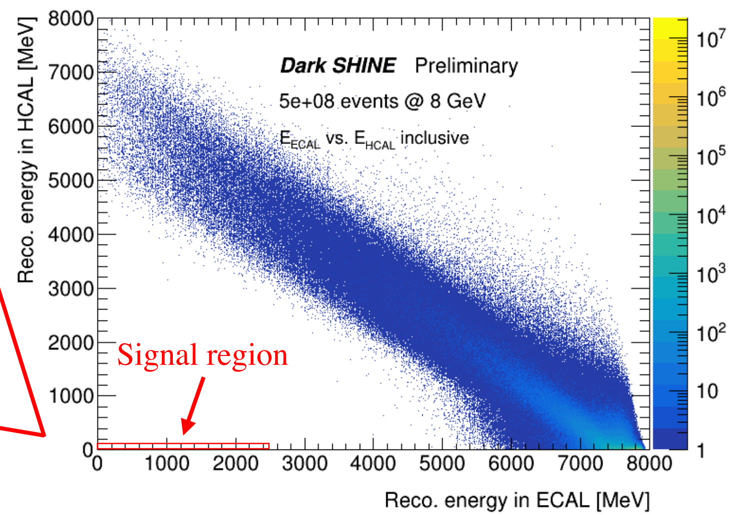




bkg. & signal

Signal 1 GeV





bkg.

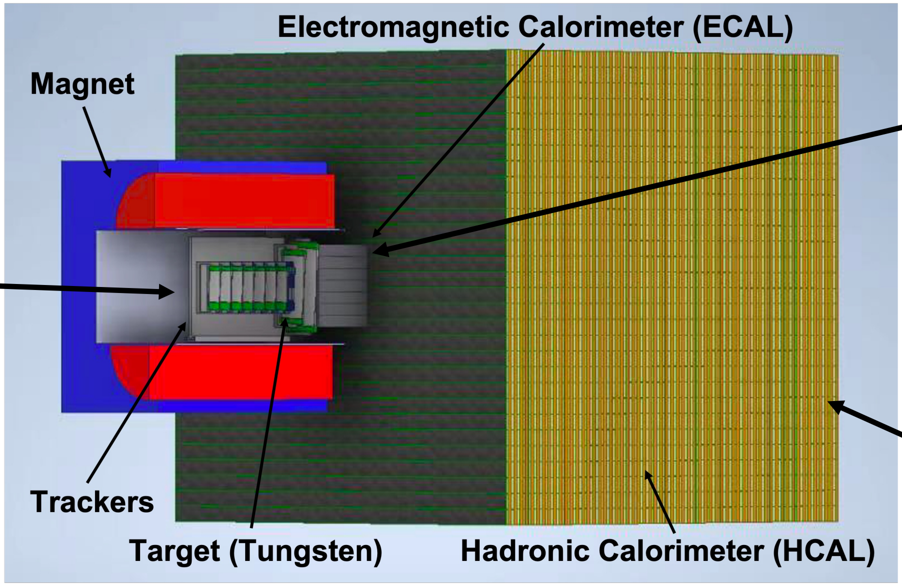
Signal region definition

Five cuts are applied to separate signal from backgrounds:

Tracking system

Only 1 incident track and 1 recoil track;

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



Electromagnetic calorimeter

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

Hadronic calorimeter

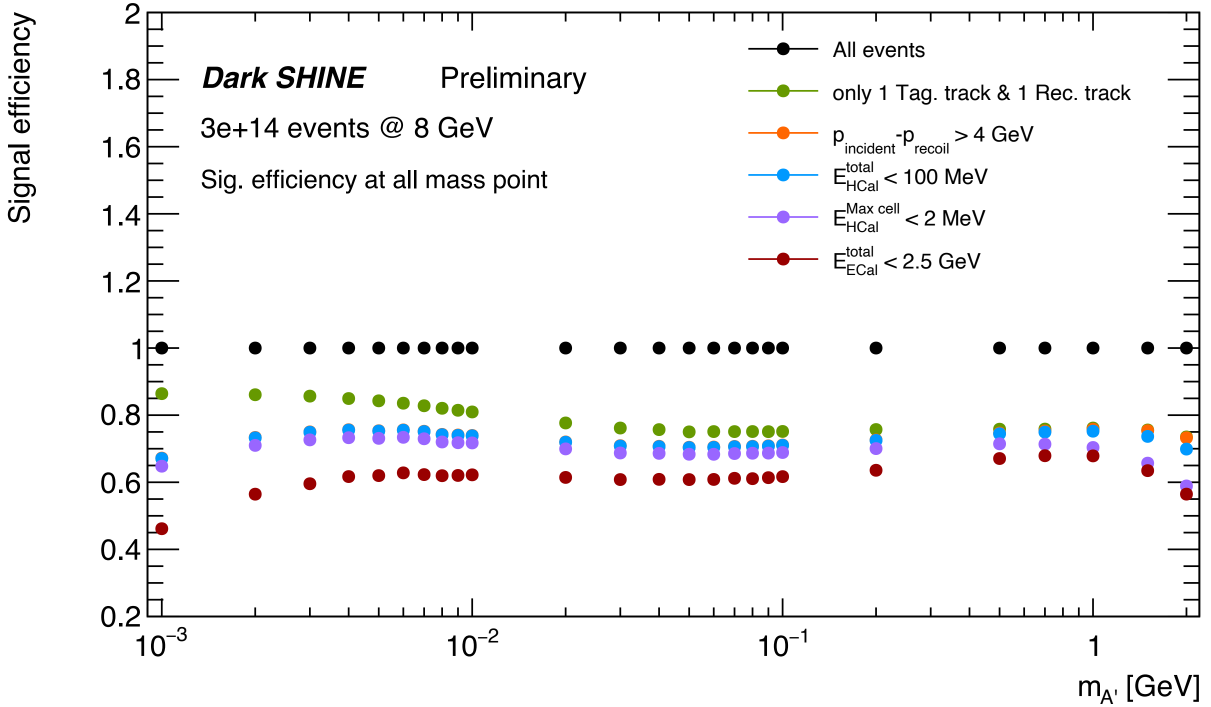
$E_{HCAL}^{total} < 100$ MeV;

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

(1st round DarkSHINE analysis)

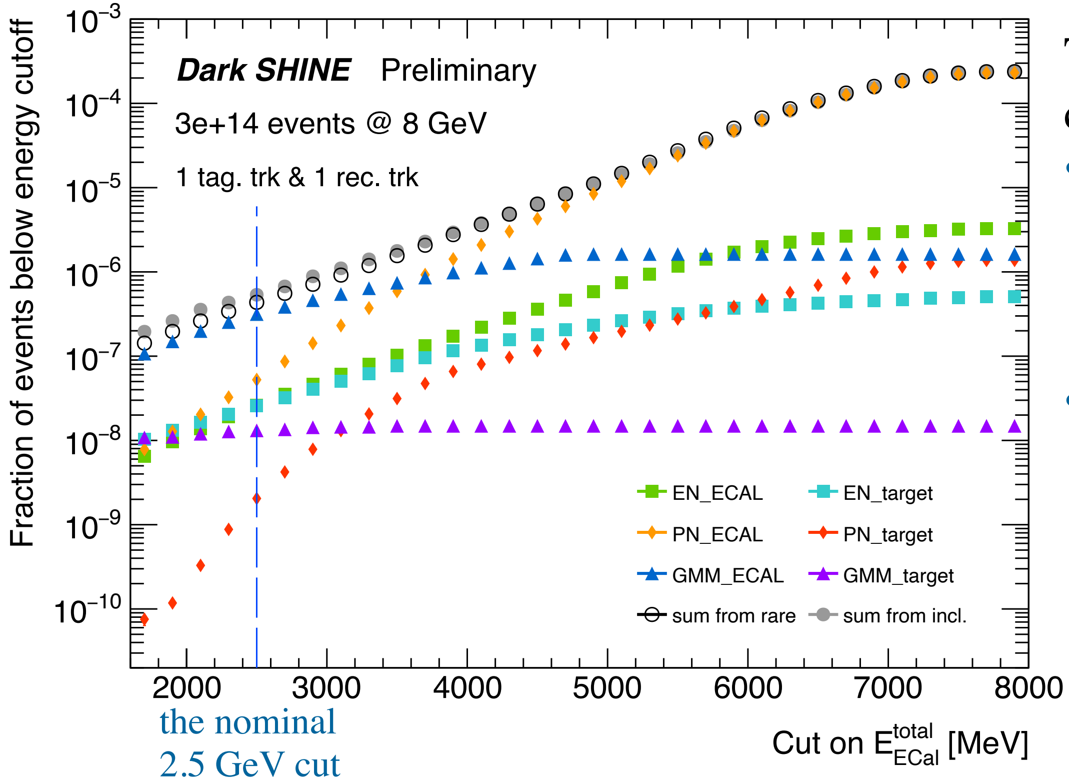
Signal efficiency

- 1×10^5 events produced for each mass point. ~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 hit directly the HCAL at simulation level.



Background estimation

- 2.5×10^{9} inclusive bkg. events produced, none of which survives the cut-flow.



Event ratio as a function of the cut value on ECAL energy.
(rare processes scaled according to branching ratio)

To estimate the number of bkg. events corresponds to 3×10^{14} EOTs:

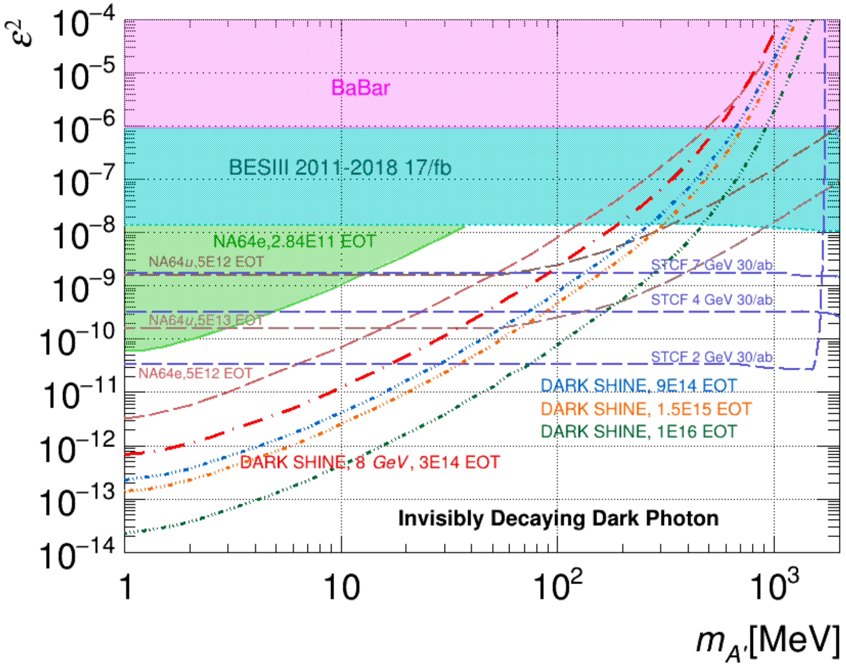
- **Dedicated rare bkg. production with large statistics.**
  - $10^{7}\sim10^{8}$ events for each process.
- **extrapolation method.**
  - expected bkg. yield can be computed from the event ratio at given ECAL energy cut.

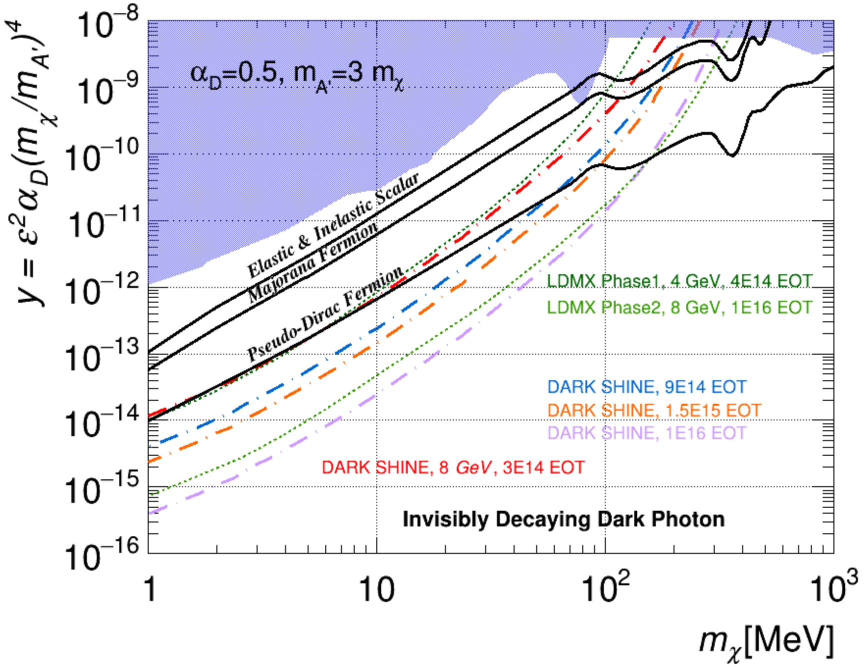
Expected total bkg. events: **0.015** (3×10^{14} EOTs).

(Assuming 0.015 bkg. event/year)

Sensitivity study

The DarkSHINE experiment will provide competitive sensitivity, which will be able to exclude most sensitive regions.





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).

Summary

DarkSHINE: a newly proposed electron-on-target experiment searching for dark photon candidate.

- Detector R&D ongoing:
  - Silicon strip sensor (tracker) & LYSO crystal (ECAL) under test.
  - HCAL simulation study ongoing.
- First round of preliminary study has been finished:
  - good signal efficiency, background well suppressed.
  - Expecting competitive sensitivity.
- Opportunities for other BSM physics in this experiment as well.

*Analysis paper submitted to Science China.
**experiment supported by "Original Exploration Program" of NSFC.

Back up

Physics motivation

Search for **dark photon A'**: an important portal between the standard model (SM) particle and the dark matter.

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

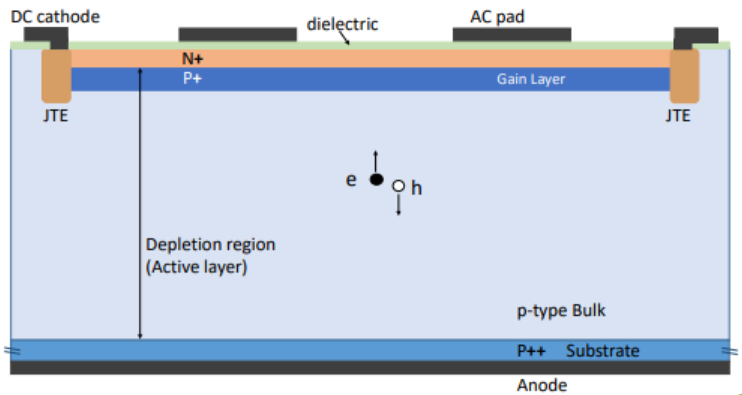
Kinetic mixing term | Field strength tensor | Dark photon field

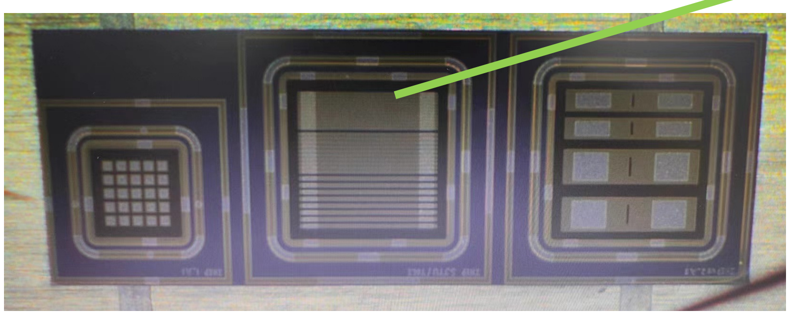
Minimal dark photon model with 3 unknown parameters:

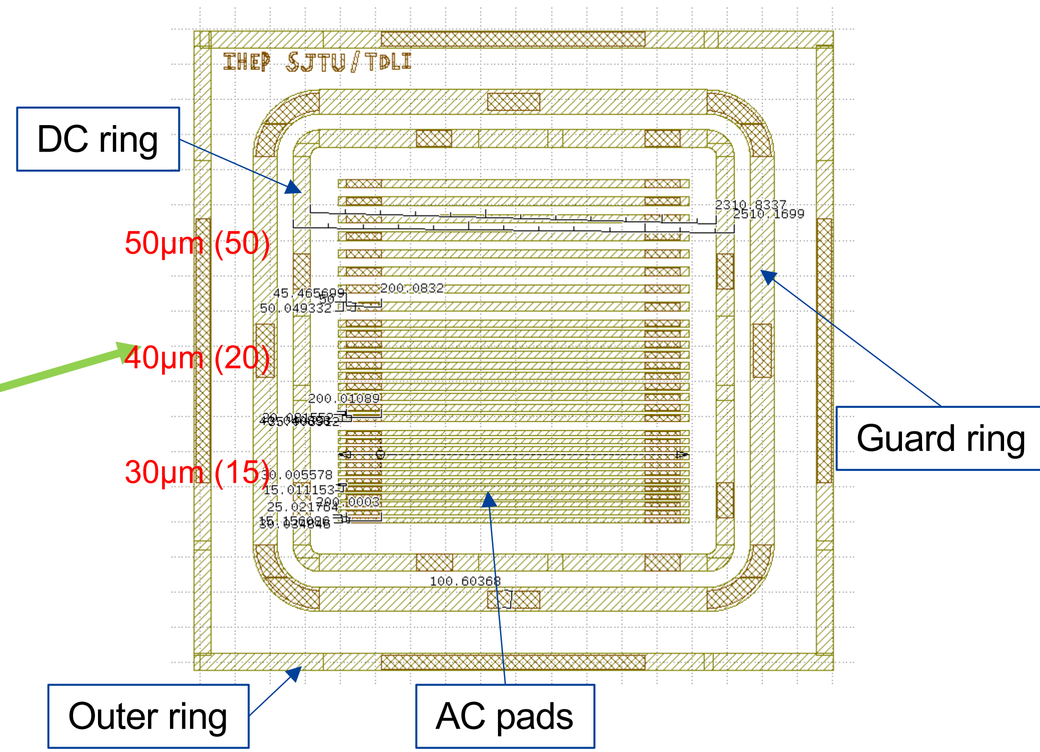
- Kinetic mixing parameter $\boldsymbol{\varepsilon}$;
  (Mixing-induced coupling suppressed relative to that of photon by factor ε)
- Dark photon mass $\boldsymbol{m_{A'}}$;
- **Decay branching ratio** (assumed to be either unity or zero) of dark photon into invisible dark sector.

arXiv:2104.10280

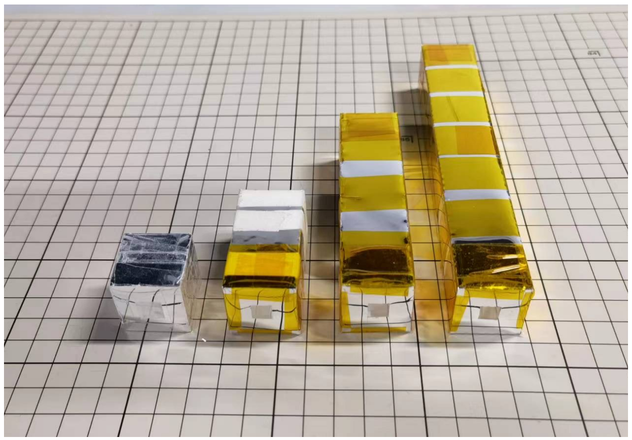
Sensor structure

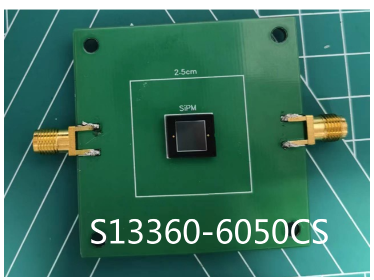


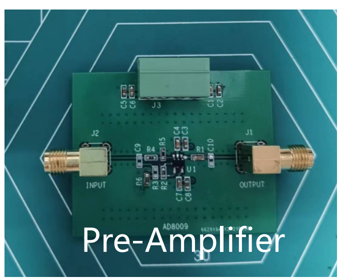




ECAL Detector Unit

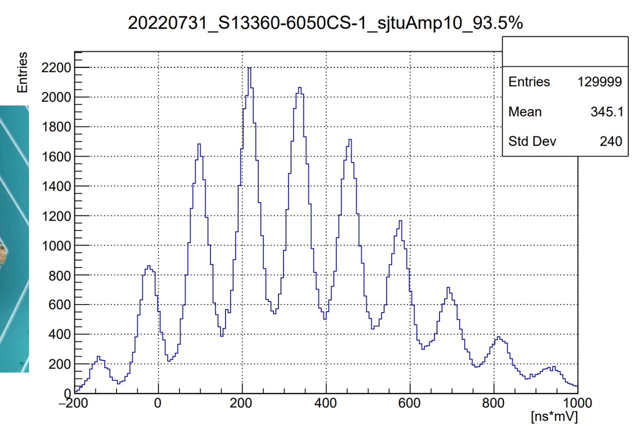


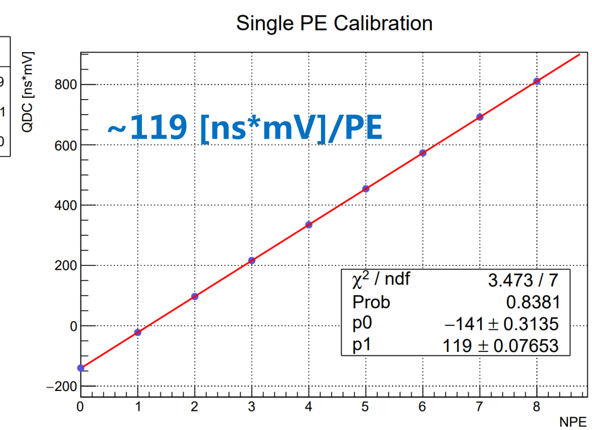




LYSO: $Lu_{(1-x-y)}Y_{2y}Ce_{2x}SiO_5$

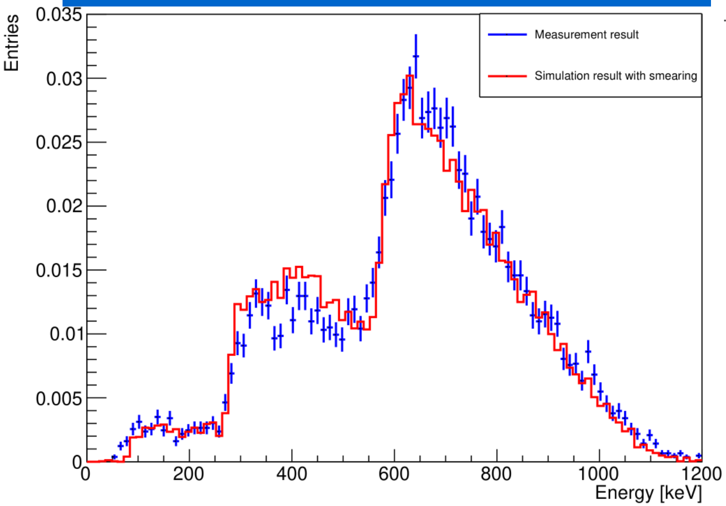
Density	Decay Time	Light Yield	Refraction Index	Radiation Length
7.2 g/cm3	40 ns	30000 p.e/MeV	1.82	1.14 cm

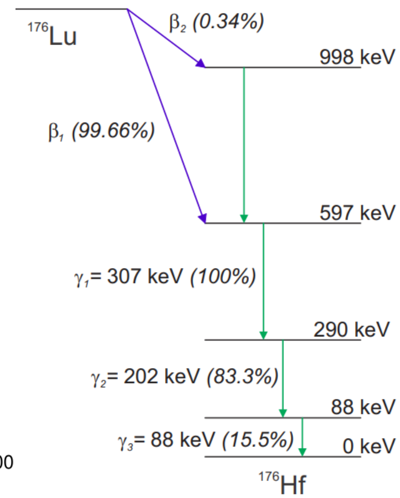




Intrinsic Radiation and Radioactive Source Test

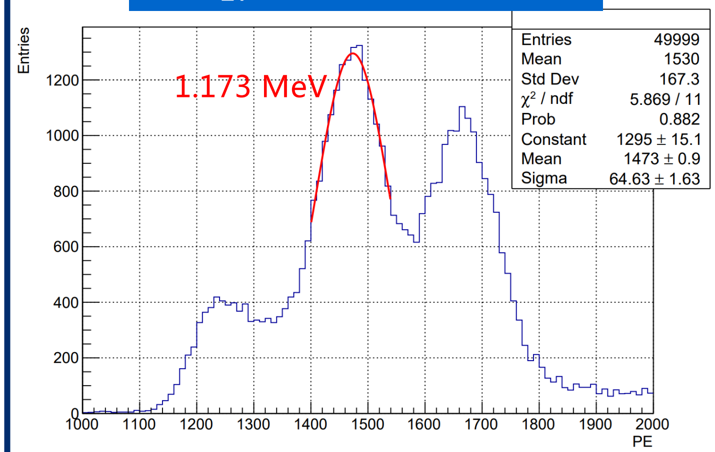
Inrinsic Radiation





- 2.5×2.5×2.5 cm^3 LYSO, HAMAMATSU MPPC S13360-6050CS
- Simulate the decay process of $^{176}_{71}Lu$ in LYSO crystal. The energy spectrum contains one beta decay and three gamma decay.

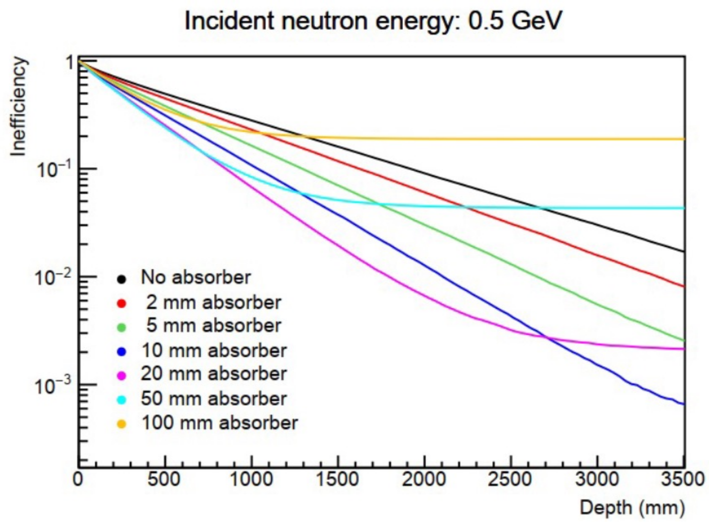
$^{60}_{27}Co$ Source Test



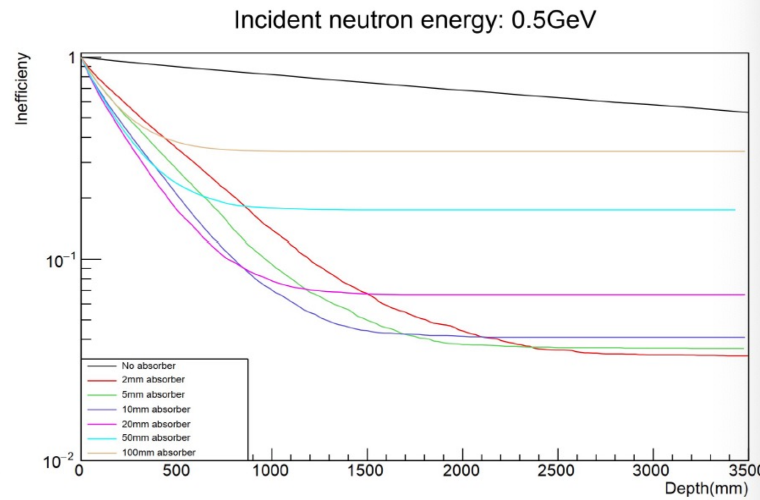
- $^{60}_{27}Co$ radioactive measurement result
- 5×2.5×2.5 cm^3 LYSO
- Light Yield: 1255.75 PE/MeV

HCAL design

Veto Inefficiency Simulation



LDMX



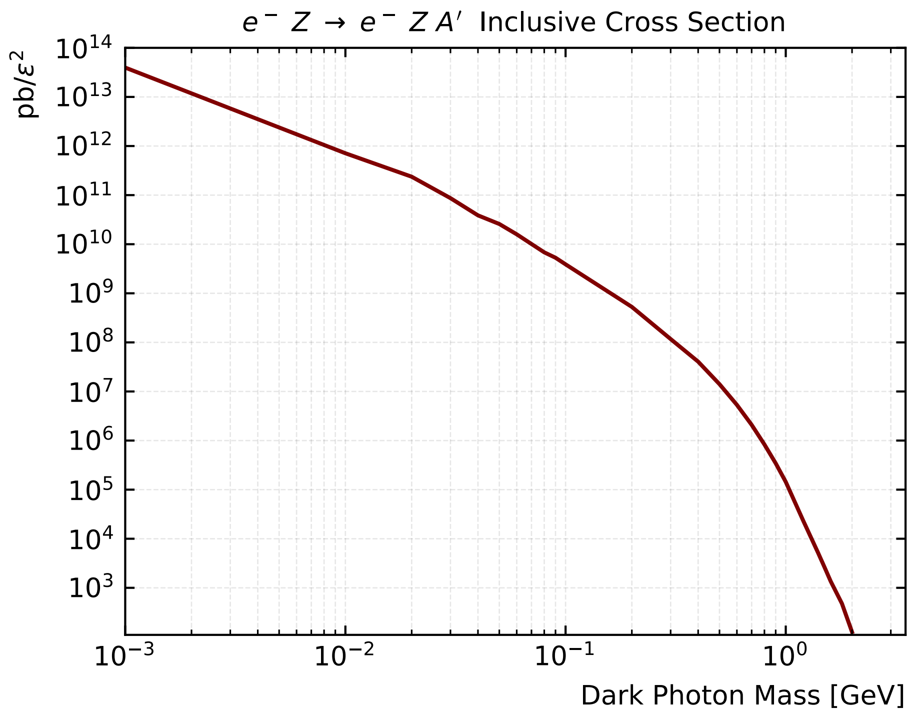
DarkShine

2-100 mm absorber ,0.5 GeV incident energy

Incident particles : 10000

Condition : Deposited energy > 1 MeV

Inclusive cross-section



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

Background cut-flow

Cut efficiency for each background processes:

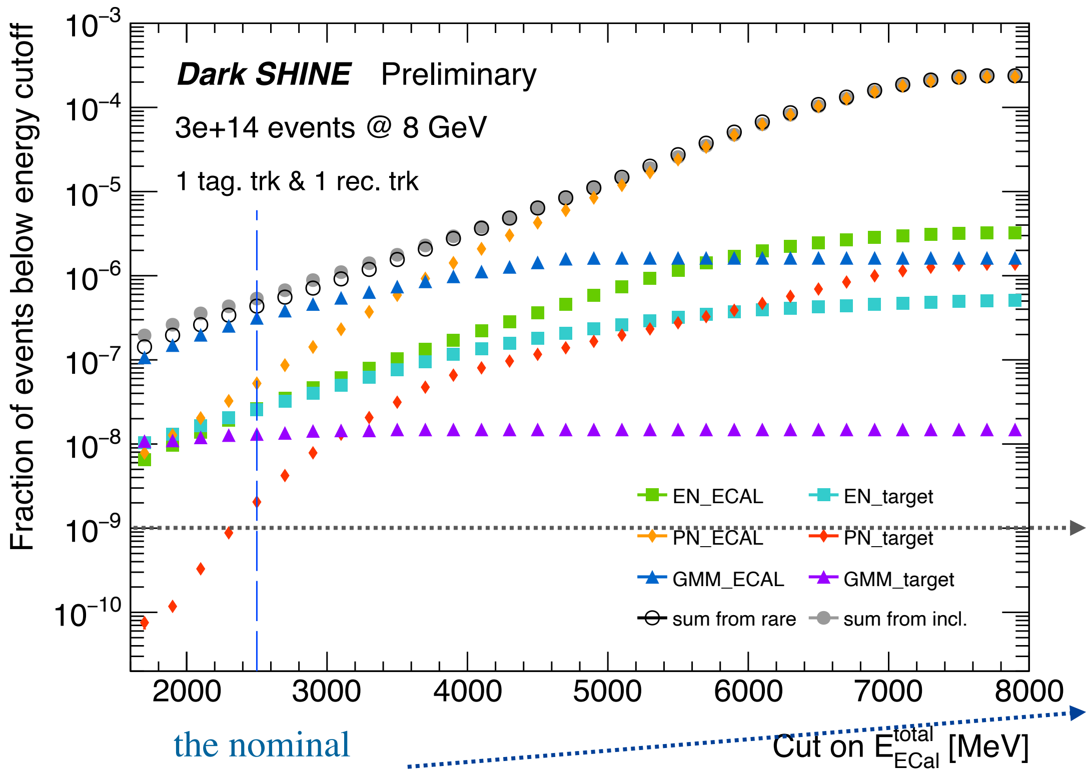
- Inclusive background: 2.5×10^{9} EOTs produced.
- Rare background: only GMM (target) process exceeds 3×10^{14} EOTs.

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}

- None of the simulated background events remains after the cut-flow.
- But what would happen with 3×10^{14} EOTs (~1 year run)?

	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%

Background estimation



the nominal 2.5 GeV cut

Event ratio as a function of the cut value on ECAL energy. (rare processes scaled according to branching ratio)

Estimate the number of background events corresponds to 3×10^{14} EOTs.

Rare bkg. production with large statistics + extrapolation method

The expected bkg. yield can be computed from the event ratio:

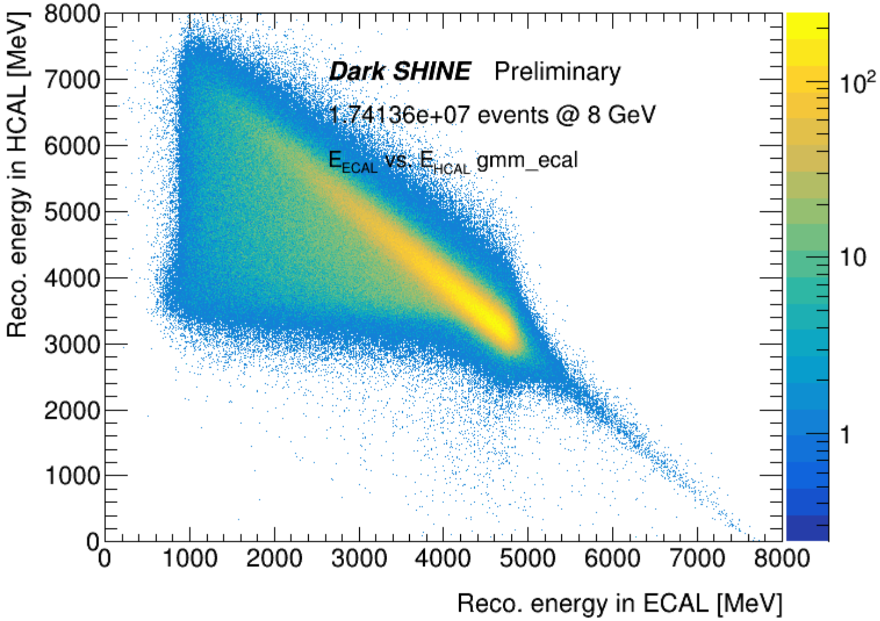
- $\boldsymbol{y = 10^{-9}}$**:**
  for 10^9 EOT, less than 1 event will remain after applying any cut tighter than $E_{ECAL}^{total} < x$ MeV.
- $\boldsymbol{x = 2500}$**:**
  y of the background events will survive the cut $E_{ECAL}^{total} < 2500$ MeV.

Extrapolation: rare processes

Not all the rare processes need further extrapolation.

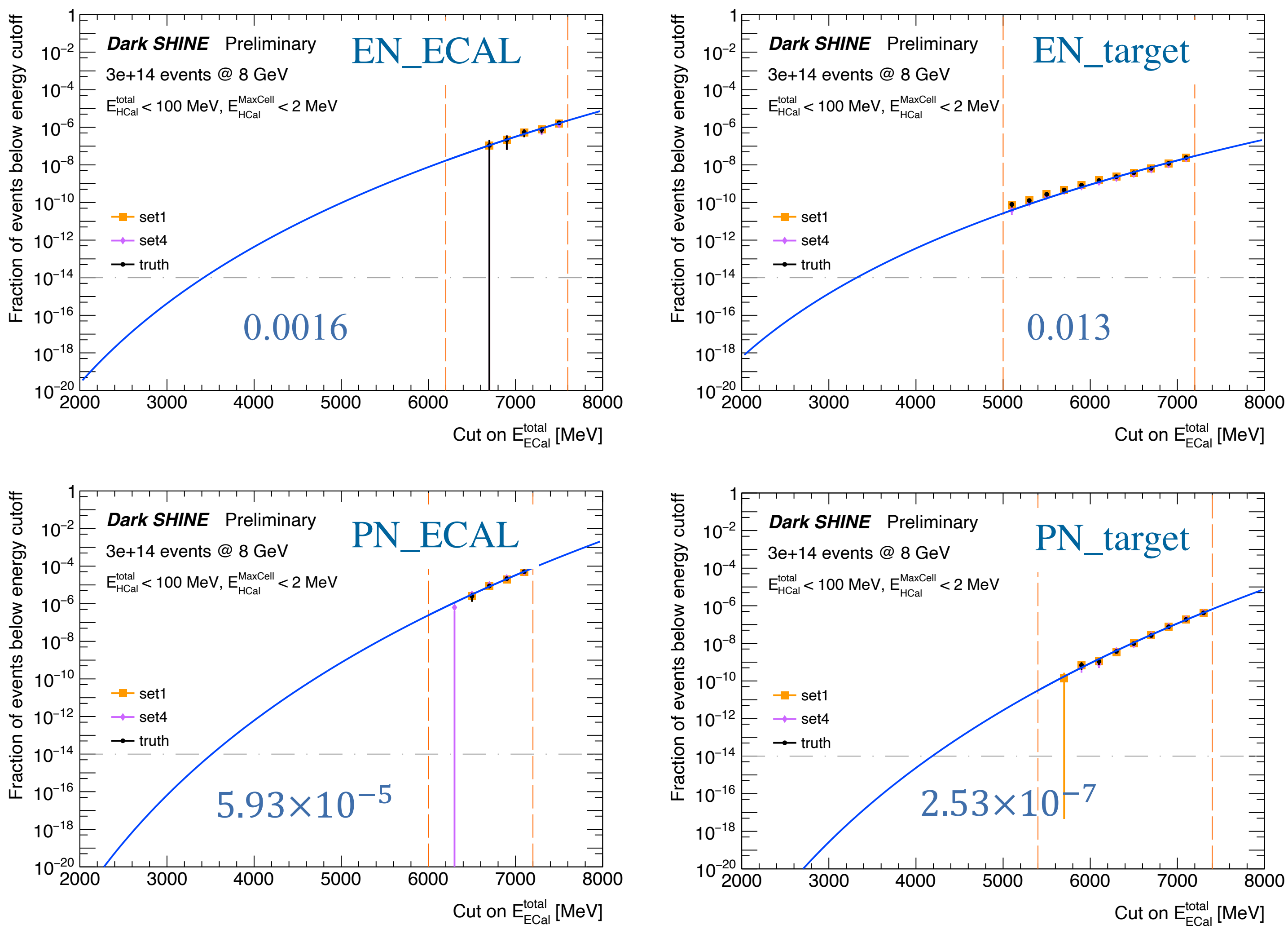
There are 6 rare background processes in total:

- EN(ECAL), PN(ECAL), **GMM(ECAL)**, EN(target), PN(target), **GMM(target)**



- Available statistics: $\sim 4.3\times10^{14}$ (target) and $\sim 6\times10^{12}$ (ECAL) EOTs considering the branching ratio.
- extrapolation method no longer applicable due to the energy distribution.
- Can always be effectively rejected by the HCAL requirement (fraction of the remaining GMM events $< 10^{-6}$).

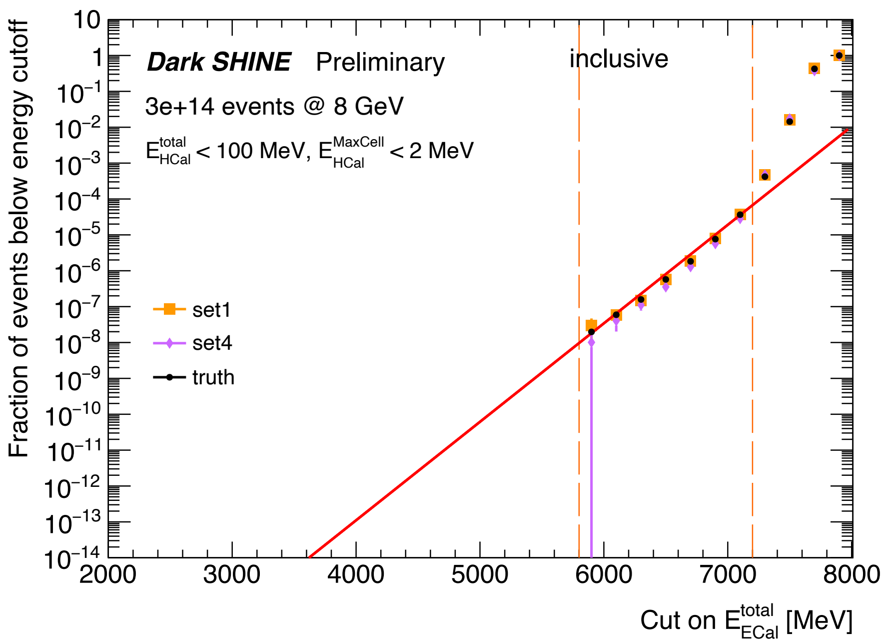
Extrapolation: rare processes

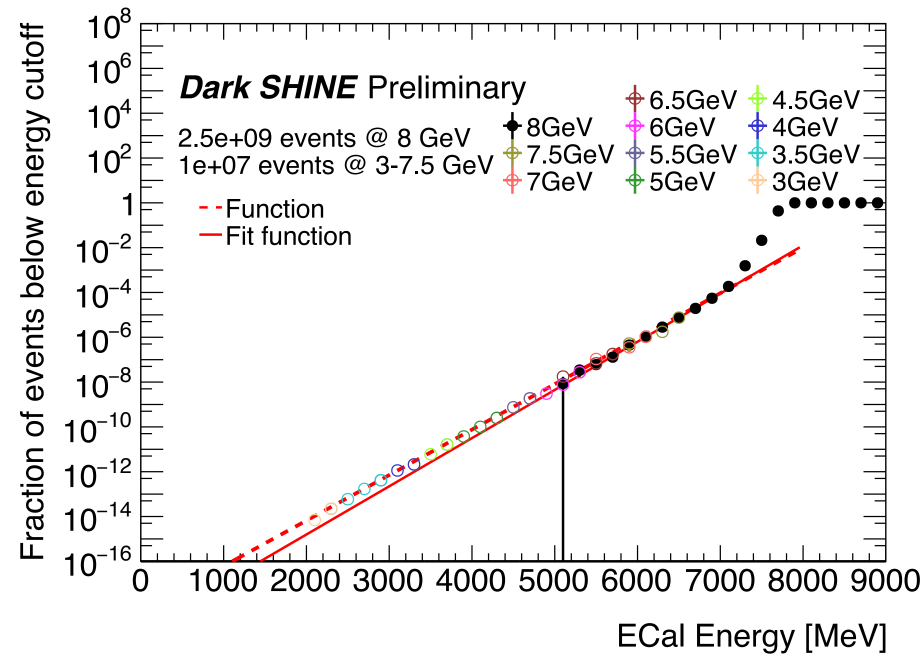


Sum: 0.015
~3×10^{14} EOTs

Validated using simulated inclusive background.

Background estimation validation





method	cut-flow	rare. extrap.	incl.- extrap.	incl. vali.	invisible
yield	0	1.5×10^{-2}	2.53×10^{-3}	9.23×10^{-3}	negligible