DarkSHINE: a new initiative to search for light dark matter at SHINE facility

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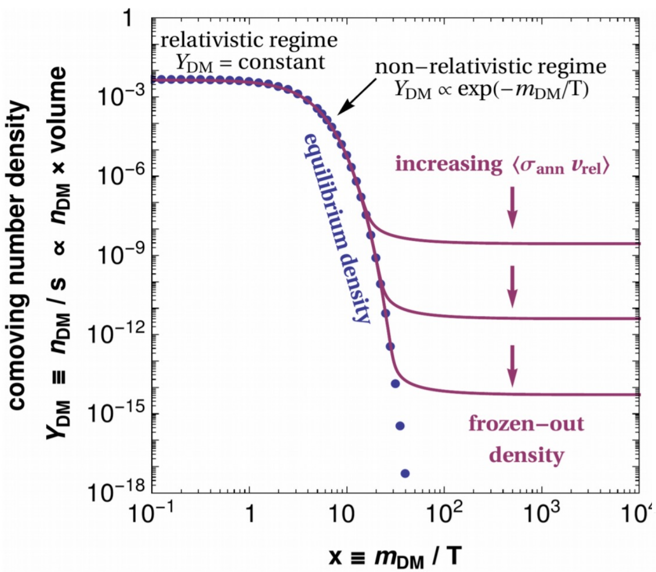
Outline

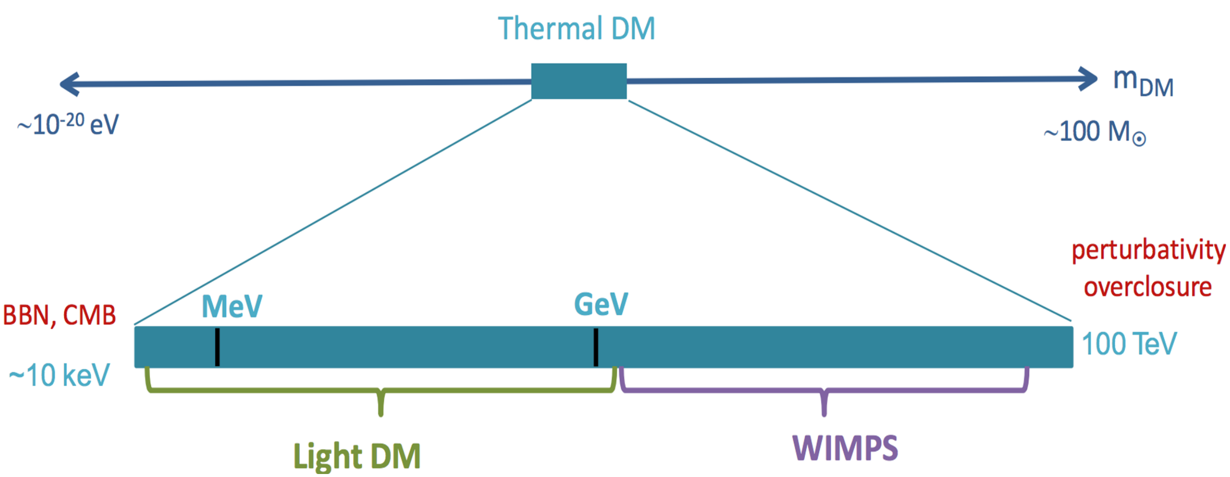
- Physics motivation
- The SHINE facility
- DarkSHINE simulation
- Prospective sensitivity
- Summary

Physics motivation

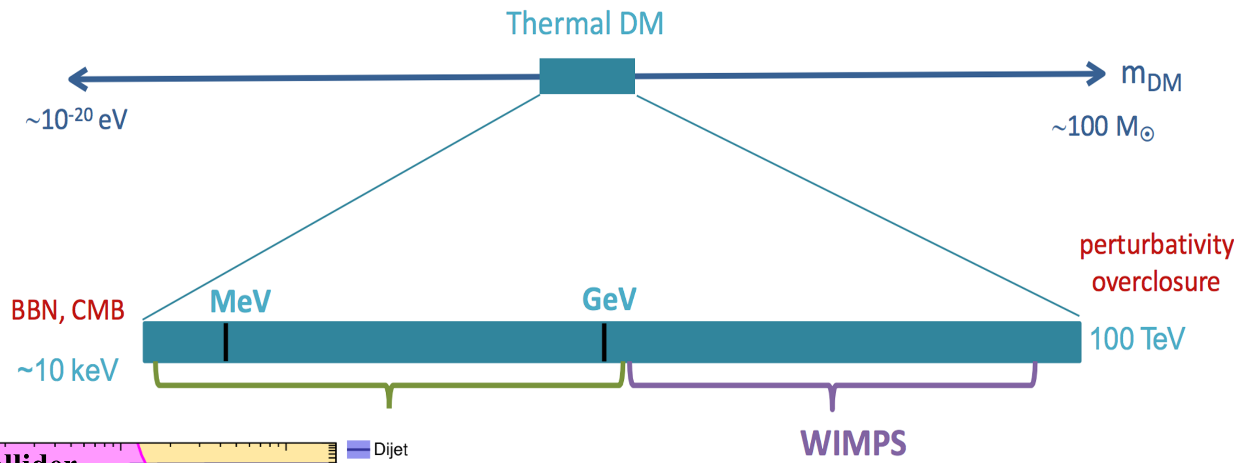
Evidence from cosmology and astronomy showing that **Dark Matter (DM)** exists in the universe.

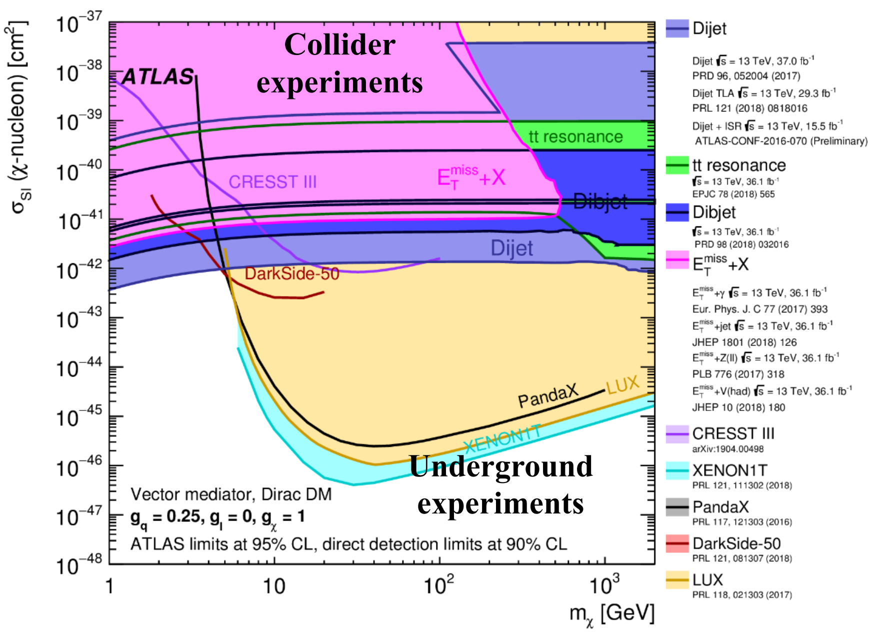
- constituting ~25% of the universe energy content.
- one typical origin hypothesis: thermal equilibrium in the early universe.
  - Temperature drops due to the over-expansion of the universe → DM density becomes stable ("freeze-out" mechanism).





Physics motivation



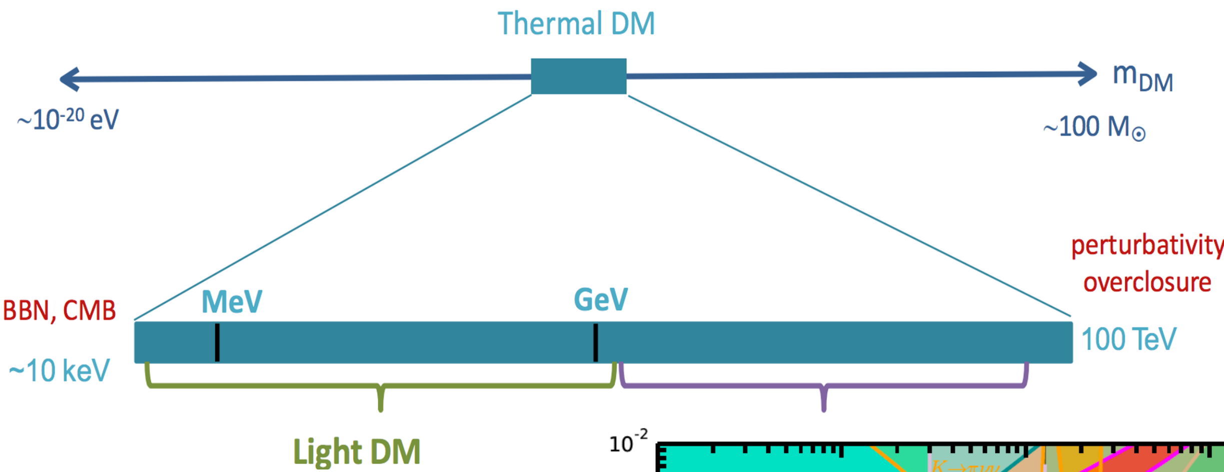


Searching for weakly interacting massive particles (WIMP):

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.)

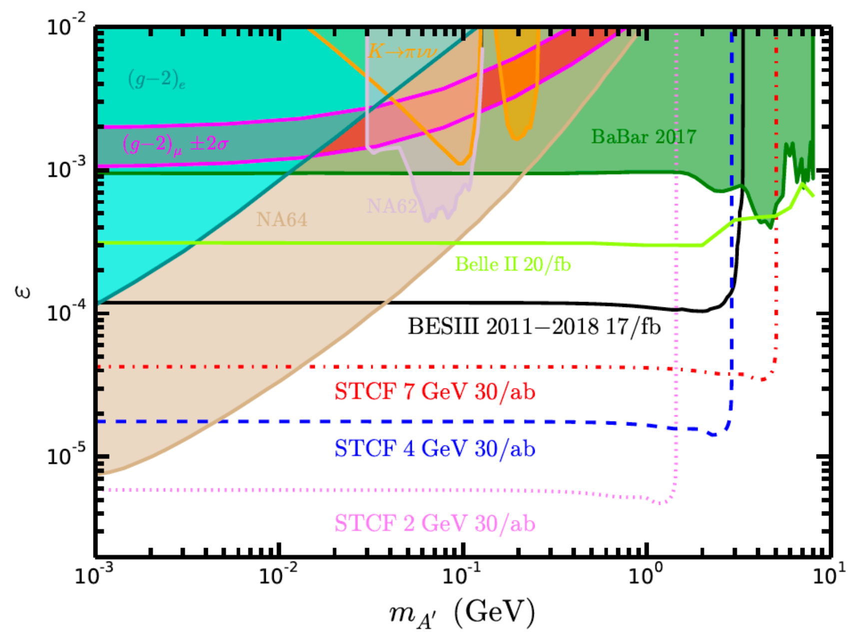
Physics motivation



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".
  - Beam dump/lepton-on-target experiments searching for dark photon: NA64@CERN, BESIII,BELL-II, LDMX, etc.



Dark photon theory in a nutshell

Introduce extra $U(1)_X$ symmetry → New gauge field X → dark mediator A'

$U(1)_{em}$ → $U(1)_{em} \times U(1)_X$

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

Kinetic mixing term | Field strength tensor | Dark photon field

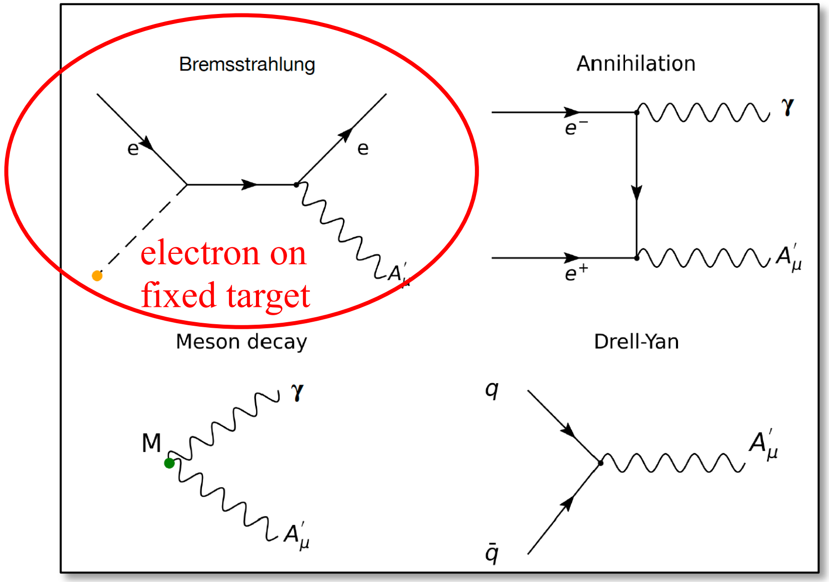
Minimal dark photon model with 3 unknown parameters:

- 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 decaying into invisible dark sector.

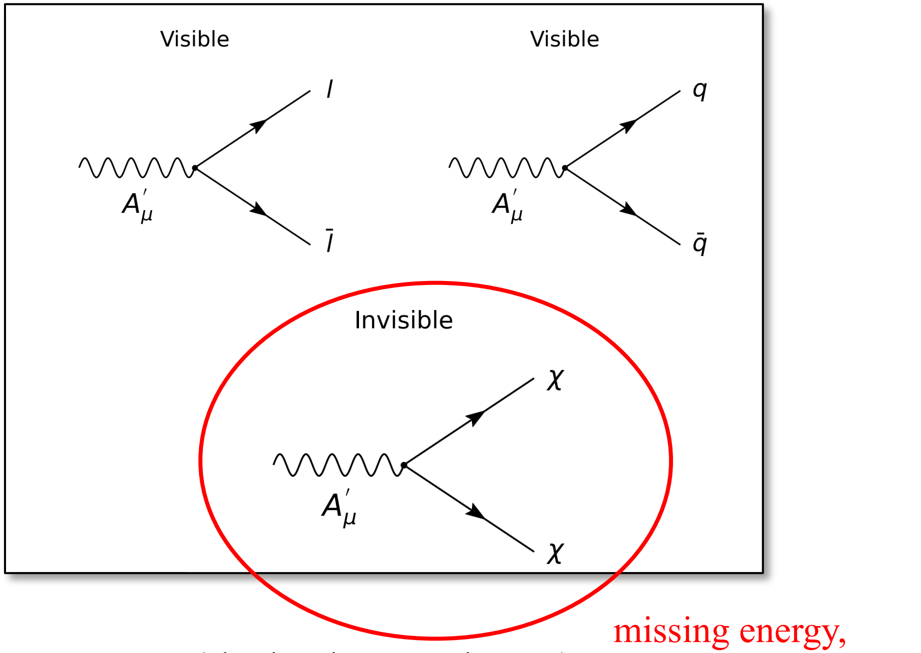
arXiv:2104.10280

Dark photon production & decay

Physics processes and anticipated signatures concerning the dark photon A':



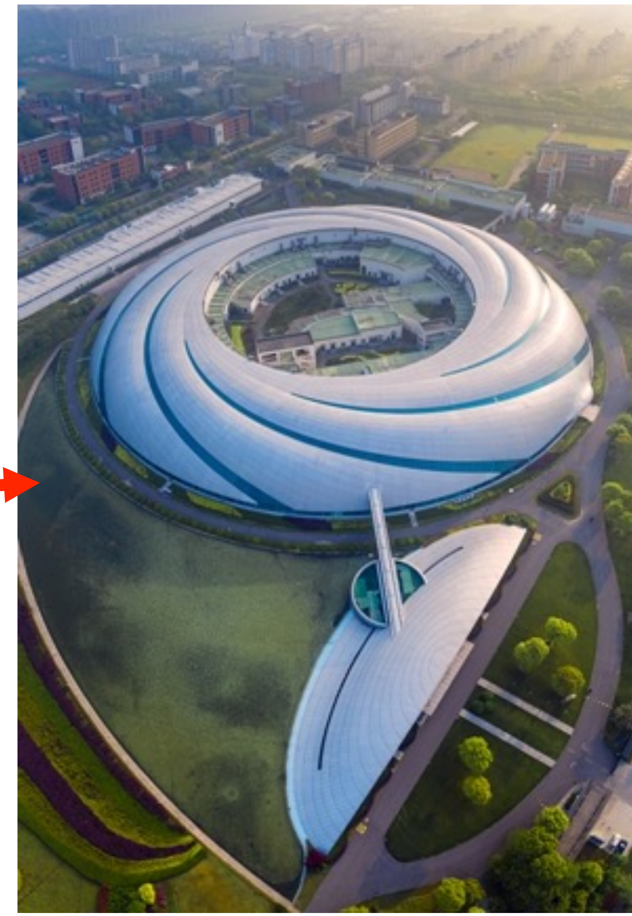
(Dark photon production)



(dark photon decay)

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

Electron source: SHINE facility



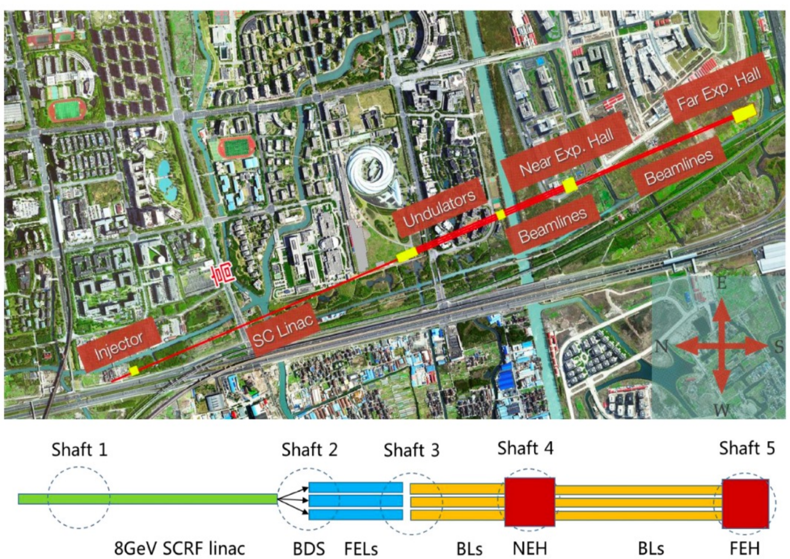
Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE)
@ Zhangjaing area, Shanghai

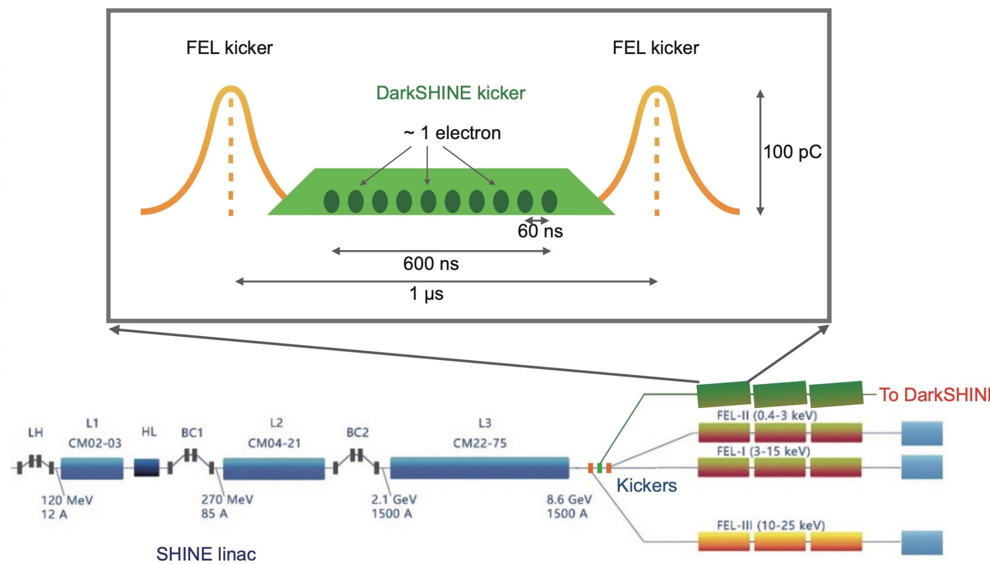
Electron source: SHINE facility

The **SHINE** facility can provide **high repetition rate single electron beams**
→ with dedicated kicker to be designed and deployed.

- Electron energy: **8 GeV**; Frequency: 1 MHz
- Beam intensity: 100 pC (6.25e8 electrons/bunch)
- **~3×10^{14} electrons-on-target (EOT) per year**

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

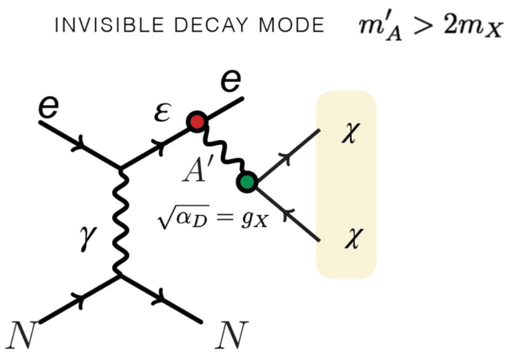


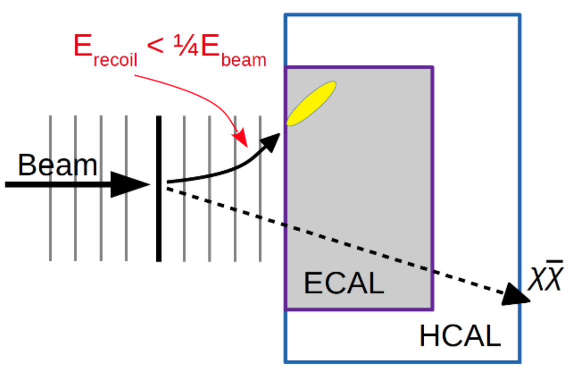


Invisible signal signature

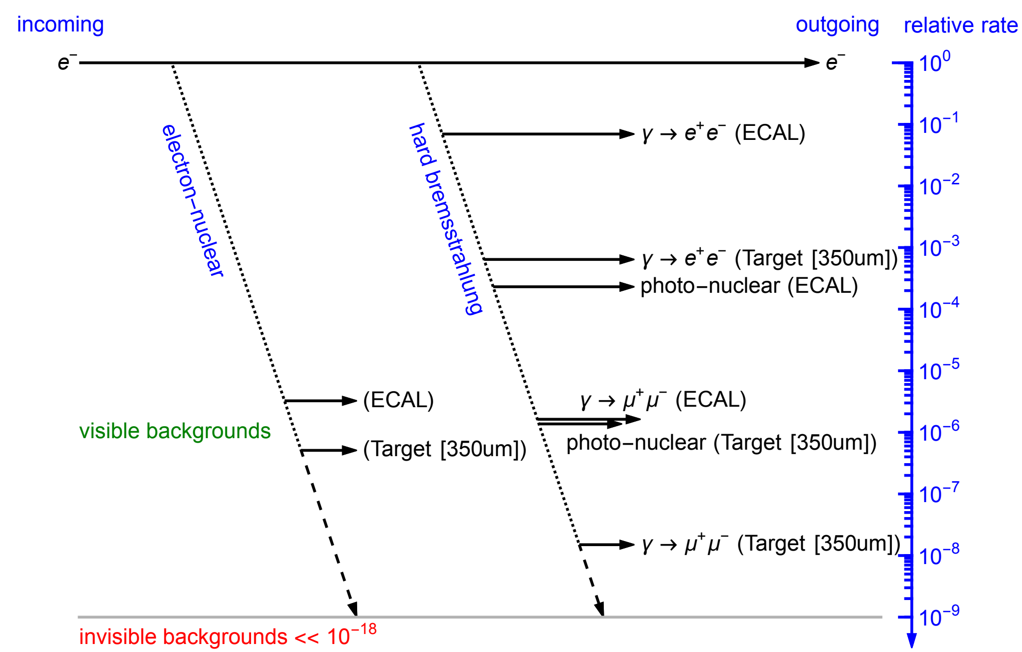
Missing particle signature: soft recoil electron, large missing energy & p_T.

Signal:





- **Leading background:** SM photon bremsstrahlung
- **Rare background processes:**

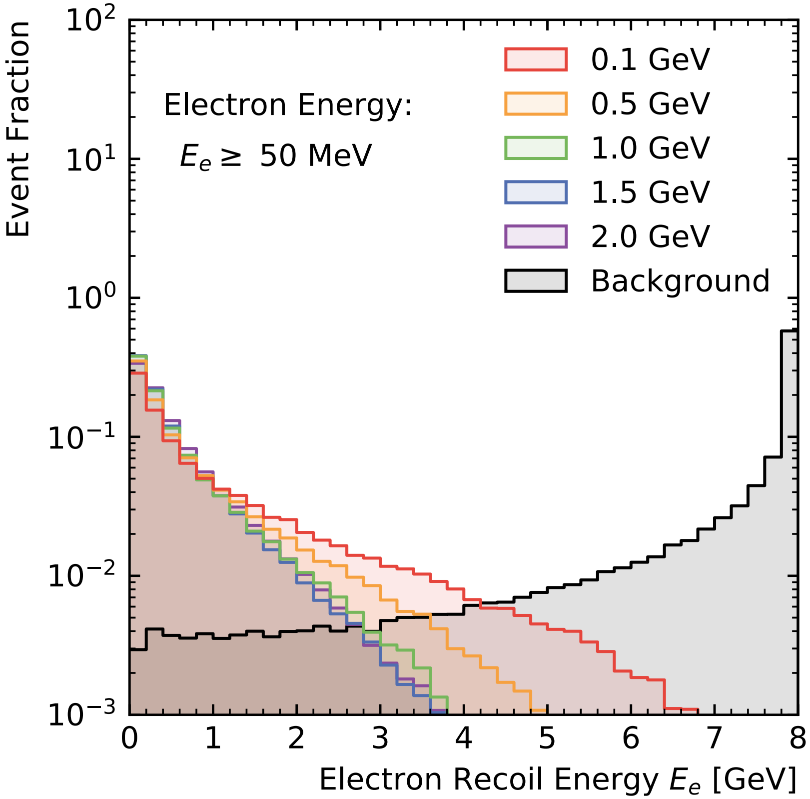


- **Irreducible but negligible:** neutrino production

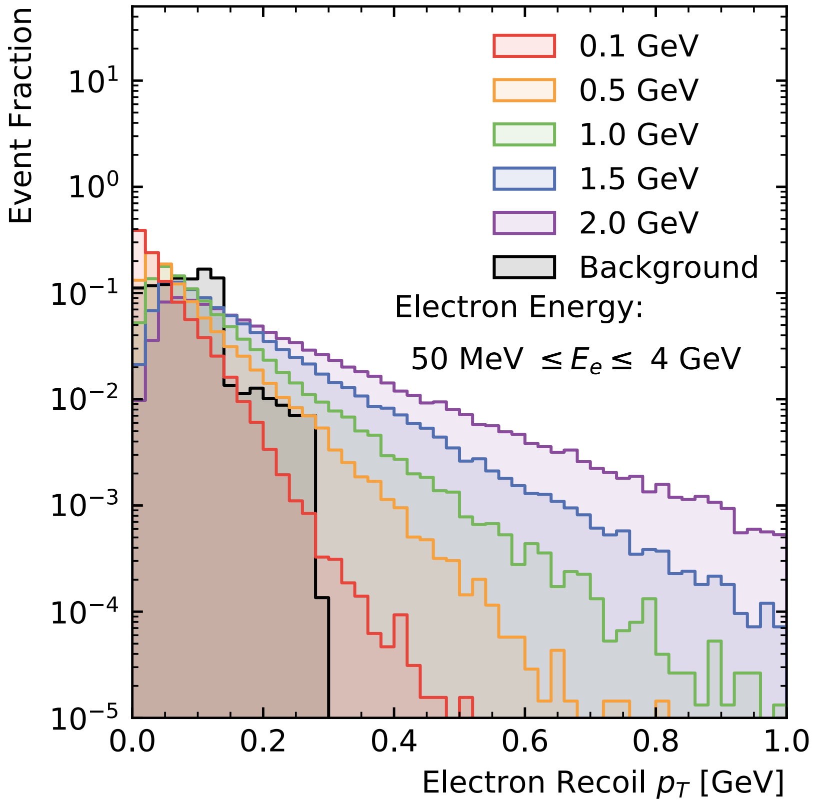
Events generated with calcHEP

Invisible signal signature

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



Energy brought away by A'

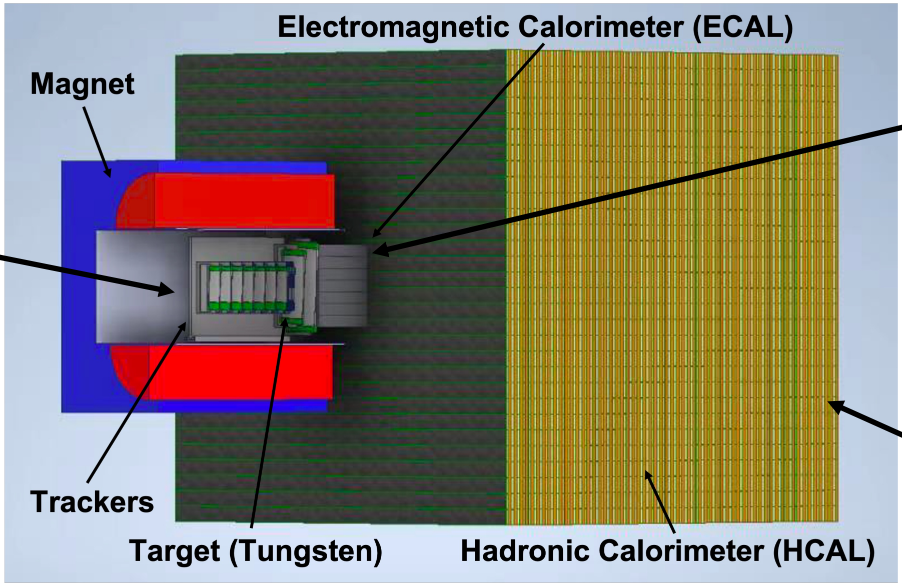


Reco. electron kicked in transverse momentum

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.

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



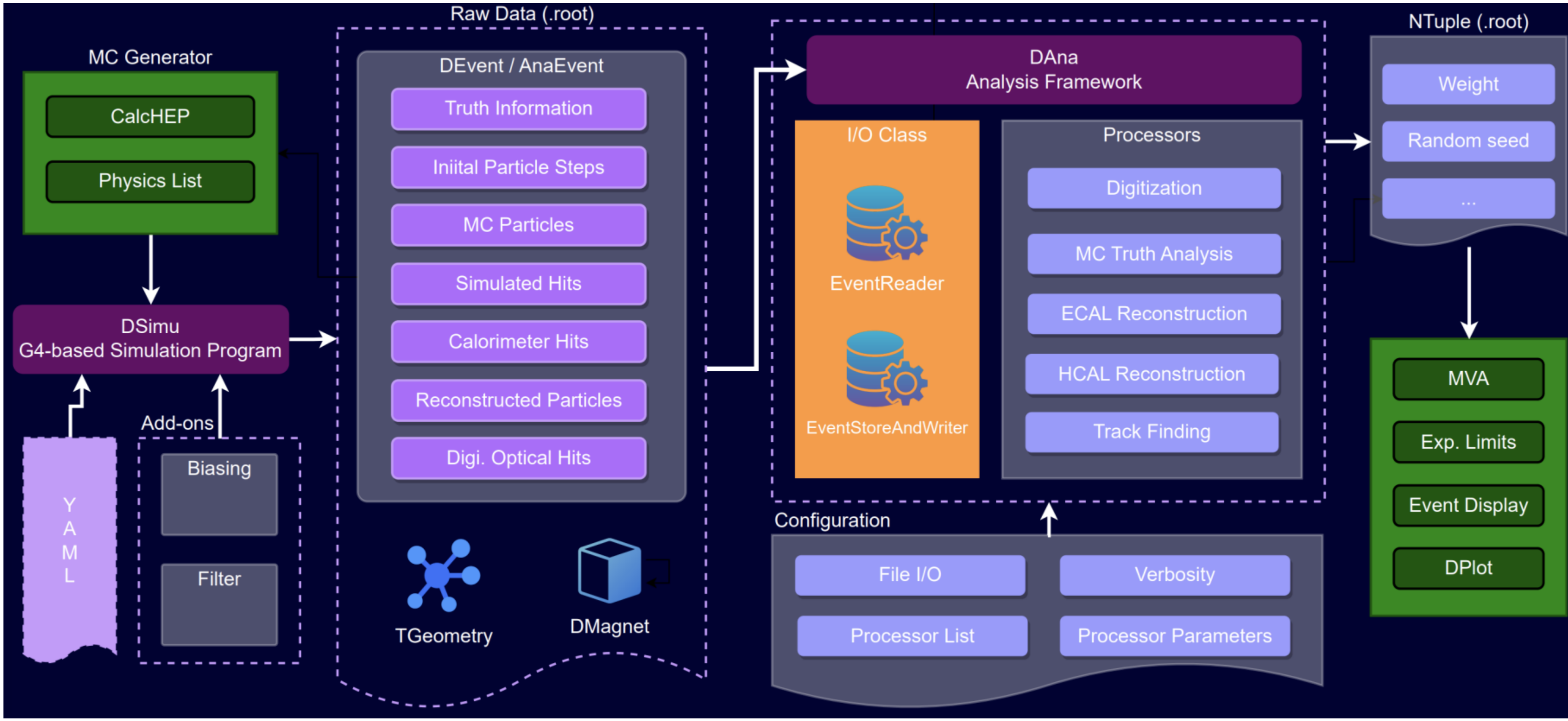
DarkSHINE detector sketch

Electromagnetic calorimeter
Measure the deposited energy: electron and photon.

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

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

DarkSHINE simulation framework

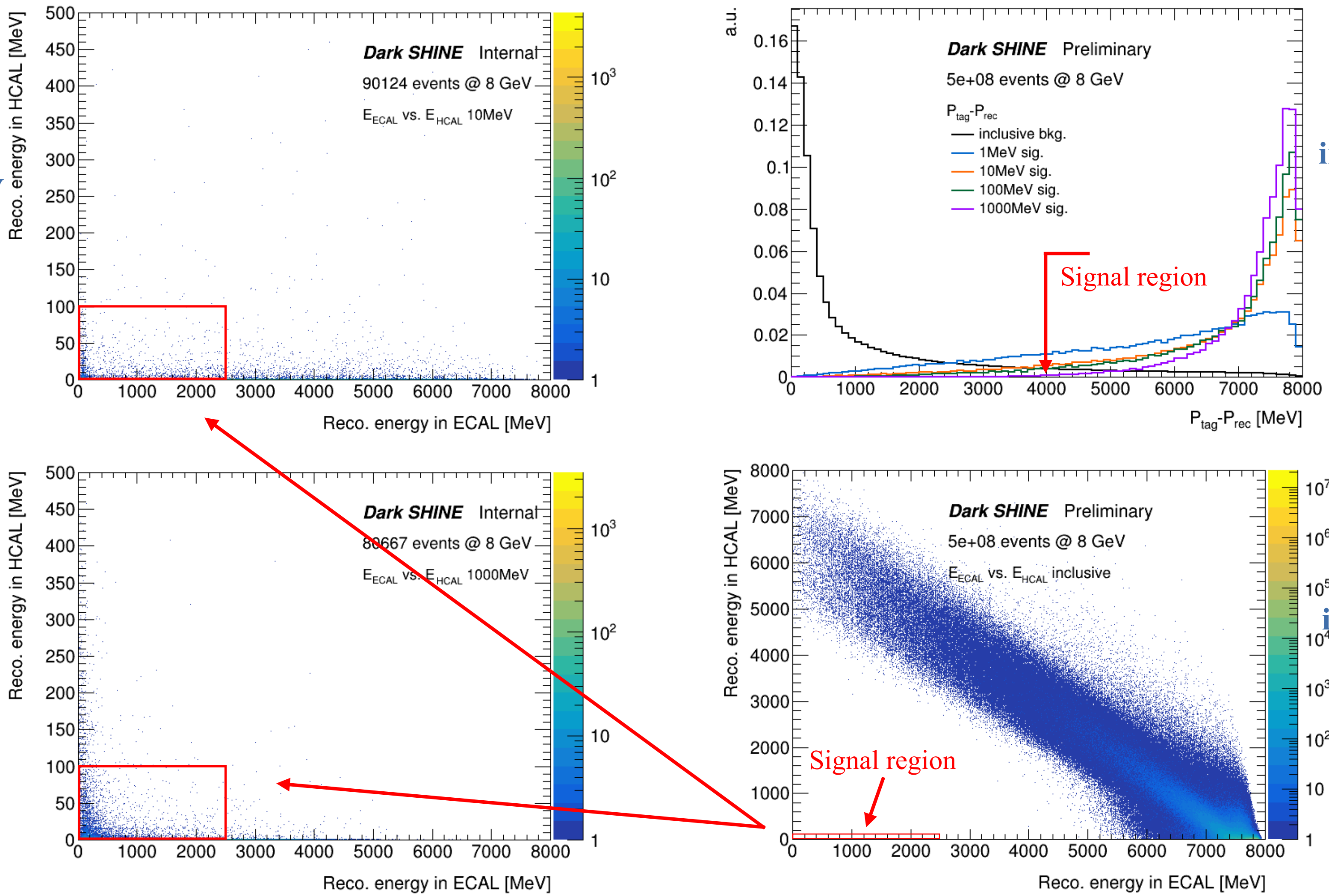


- Based on GEANT4 v10.6.0: event simulation, reconstruction and display.
- Optimization and machine learning implementation ongoing…

Kinematic distributions

Signal
10 MeV

Signal
1 GeV

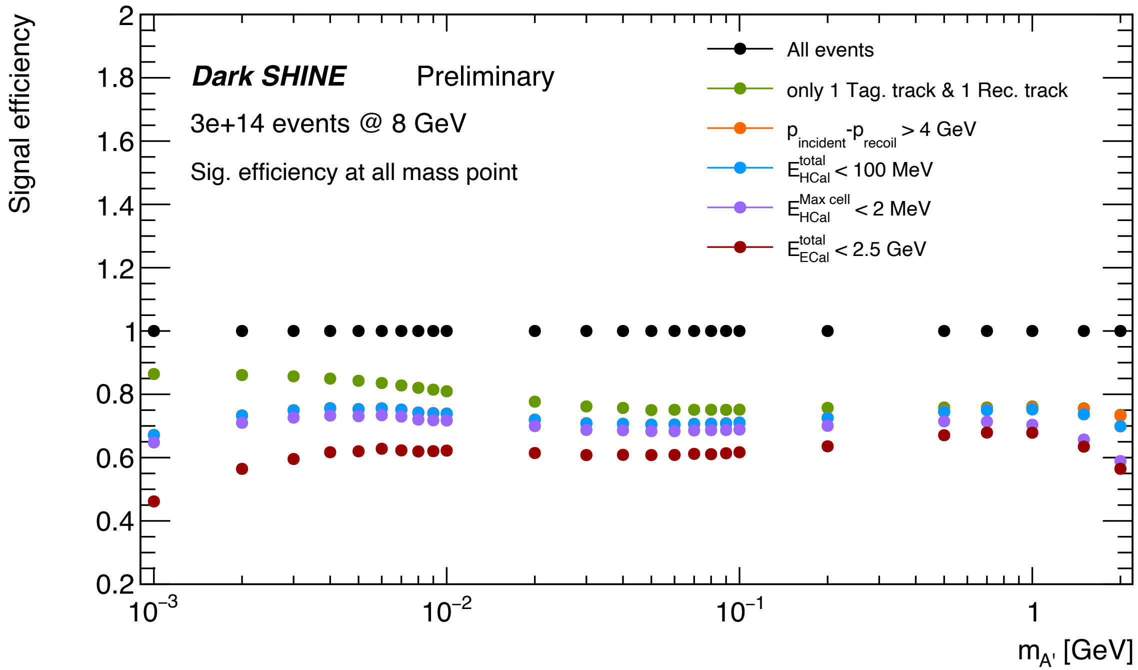


inclusive bkg.
&
signal

inclusive bkg.

Acceptance efficiency

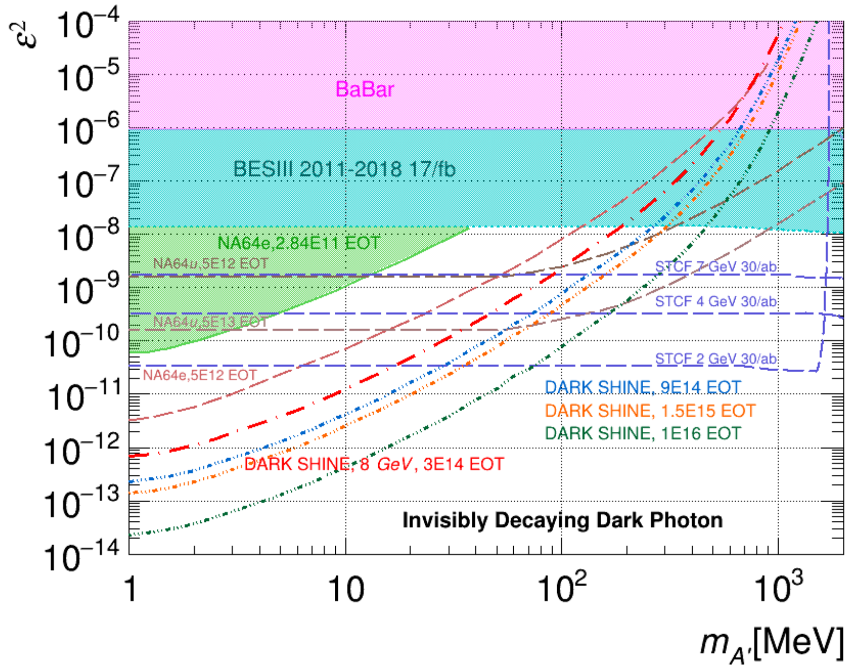
- 2.5e9 inclusive bkg. events and 1e7~1e8 rare bkg. events produced for better background estimation. None of which survives the cut-flow.
- ~60% signal events survive the cut-flow. Efficiency drops in:
  - Low-mass region of a few MeV: tight energy cuts.
  - High-mass region above 1 GeV: particles with large incident/recoil angle go into the HCAL directly.

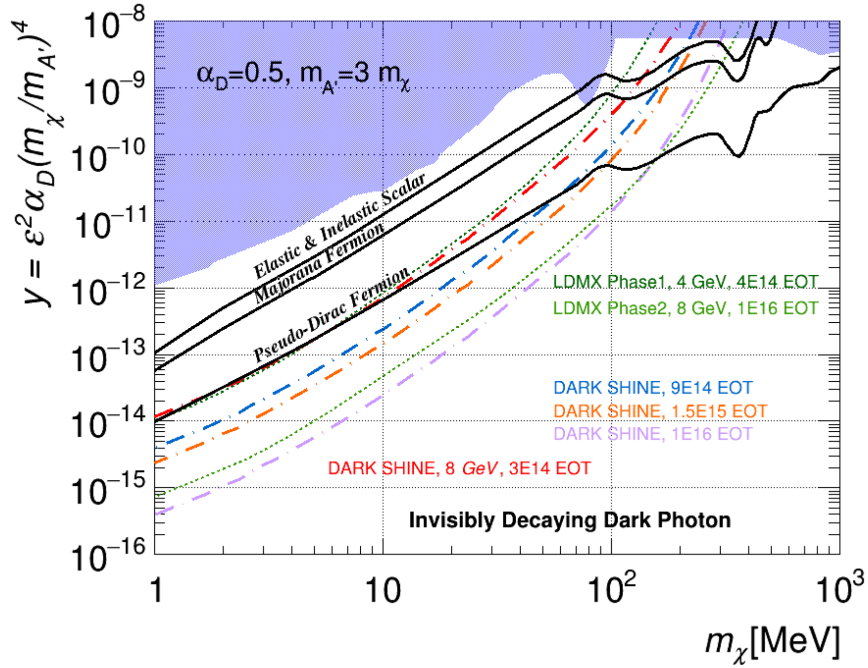


(Assuming 0.015 bkg. event/ 3×10^{14} EOTs)

Expective sensitivity comparison

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

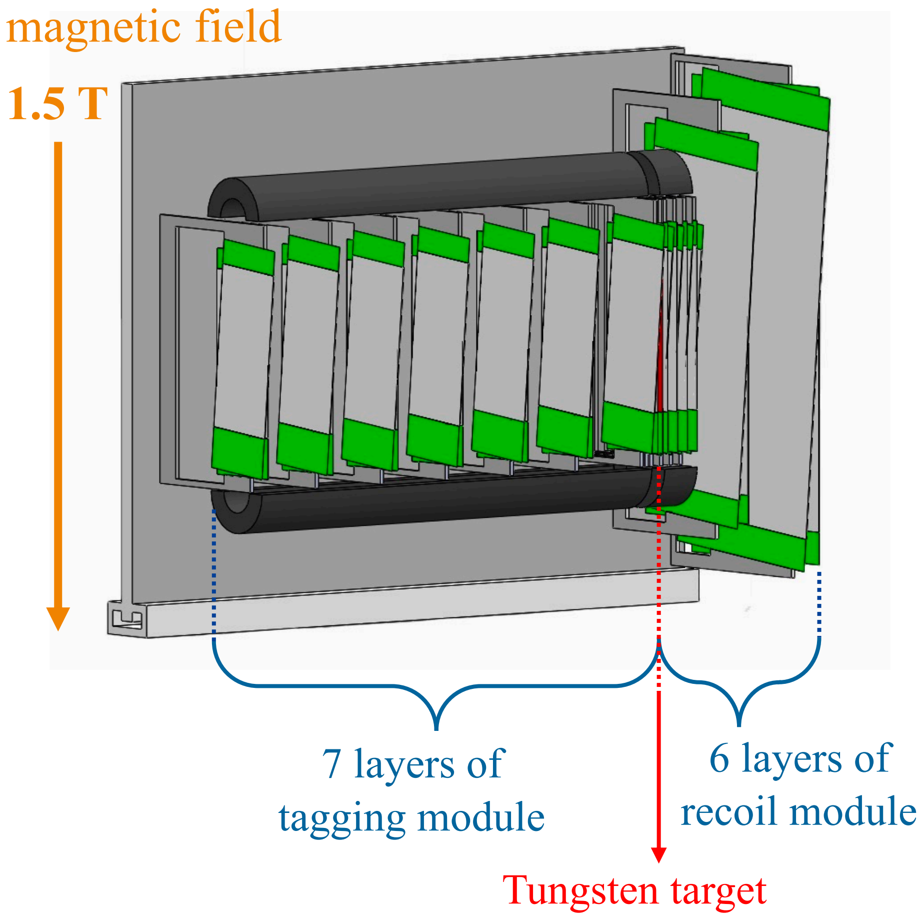




Expected 90% C.L. limit estimated with 3×10^{14} EOTs (running ~1 year), 9×10^{14} EOTs (~3 years), 1.5×10^{15} EOTs (~5 years) and 1×10^{16} EOTs (with Phase-II upgrade).

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

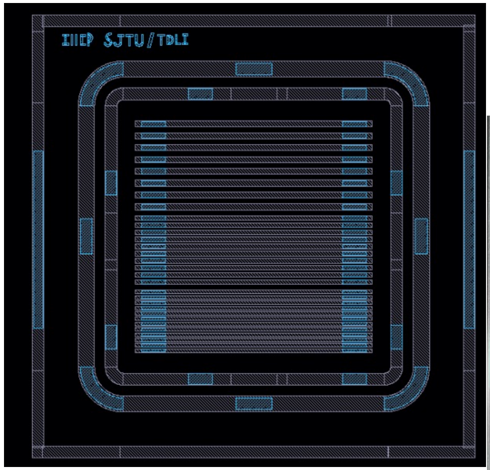
Detector R&D: tracking system

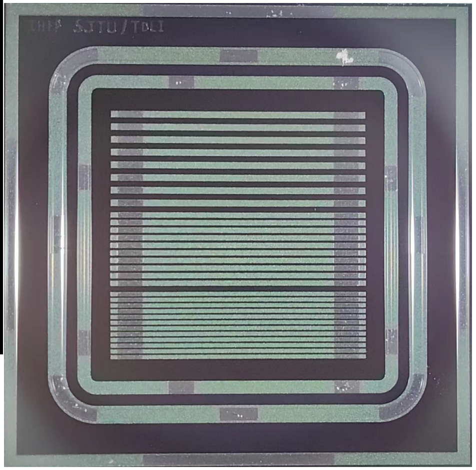


Each module: 2 layers of silicon strip sensor with a small angle (100 mrad).

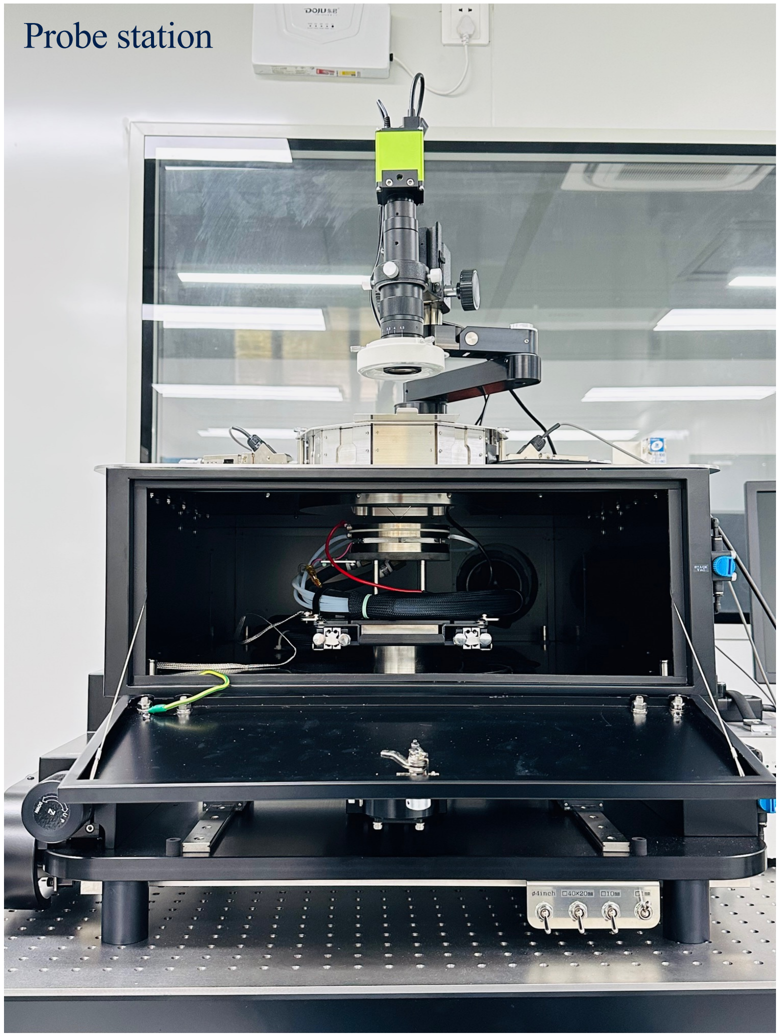
AC-LGAD silicon strip sensor prototype designed (1x1 mm^2) and tested in collaboration with Prof. Zhijun Liang and Prof. Mei Zhao from IHEP.

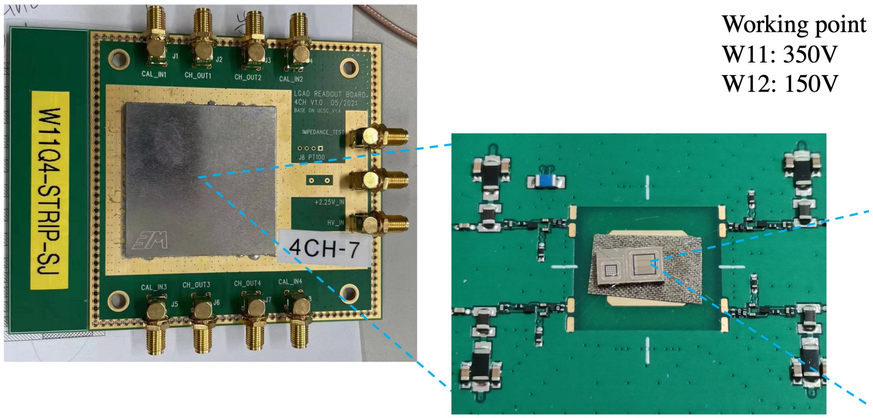
- Designed resolution:
  - Better position resolution than 10 μm.
  - Better angle resolution than 0.1%.



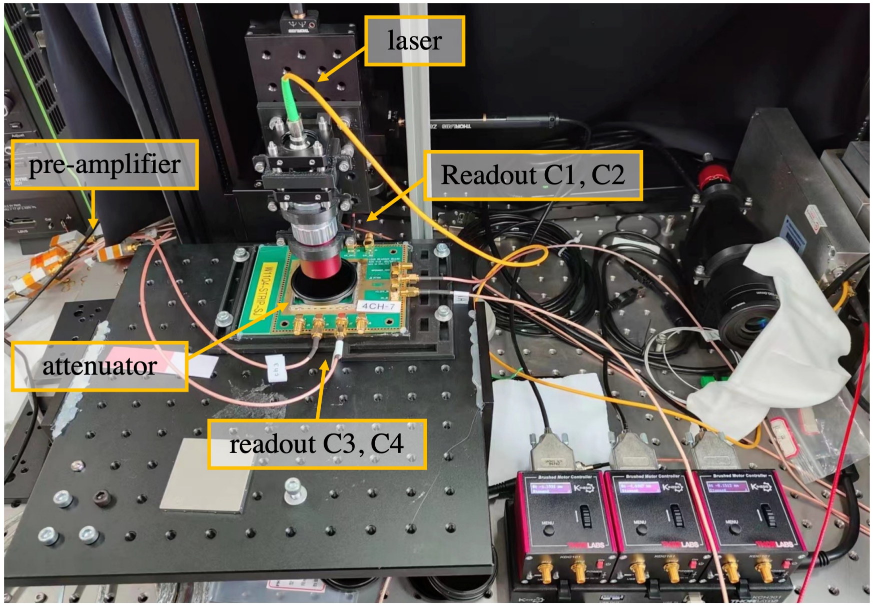


Detector R&D: tracking system

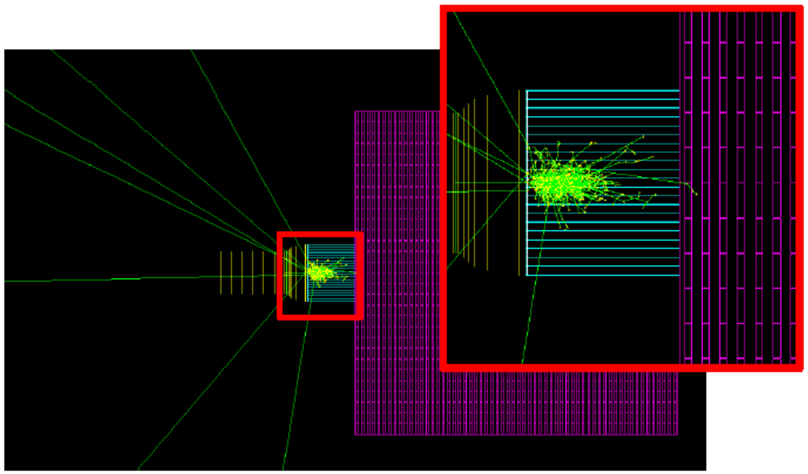


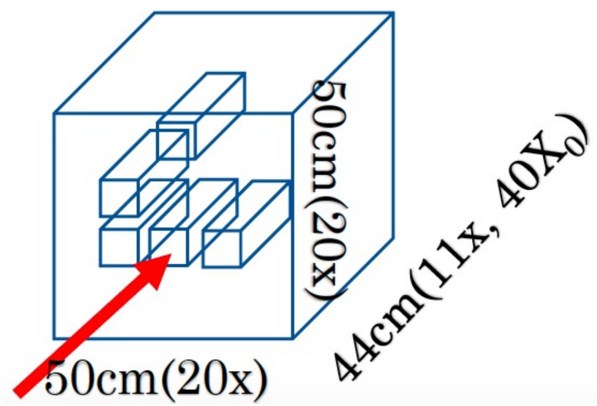


Working point
W11: 350V
W12: 150V



Detector R&D: electromagnetic calorimeter

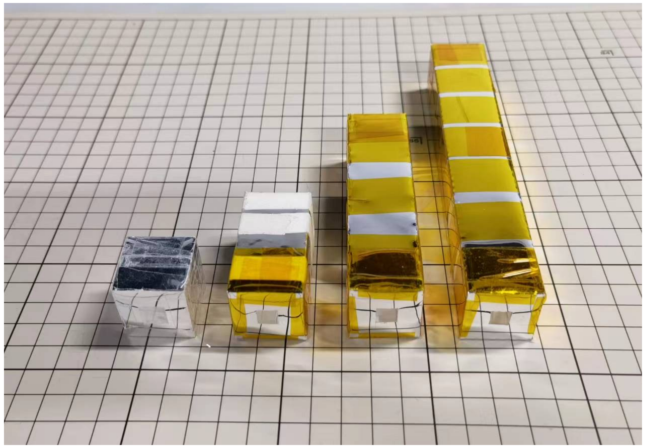




Baseline design of each crystal: X,Y = 2.5 cm, Z = 4 cm (radiation length: 1.14 cm)

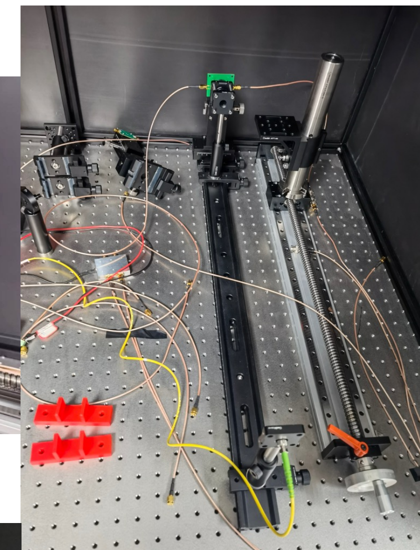
Measure the deposited energy of electron and photon.

- 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.

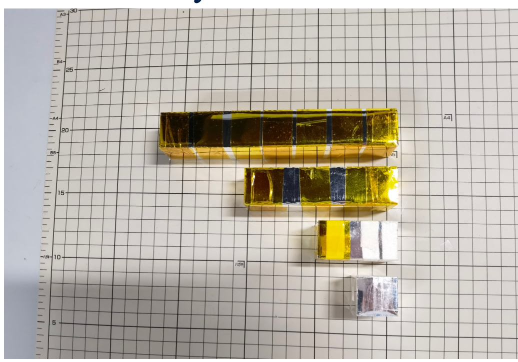


Detector R&D: electromagnetic calorimeter

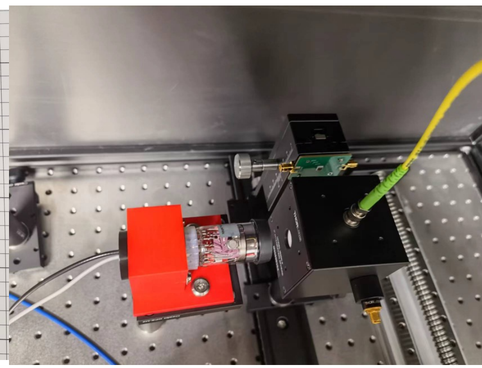
SiPM laser calibration



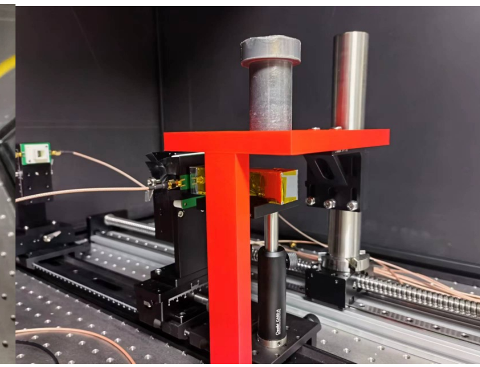
LYSO crystal elements



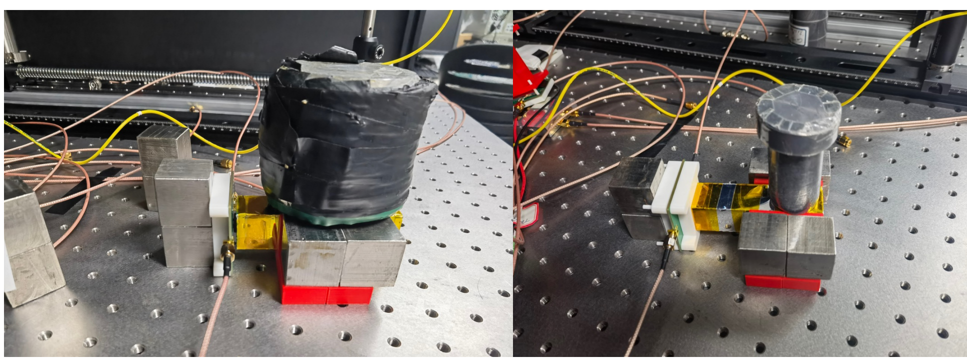
SiPM test



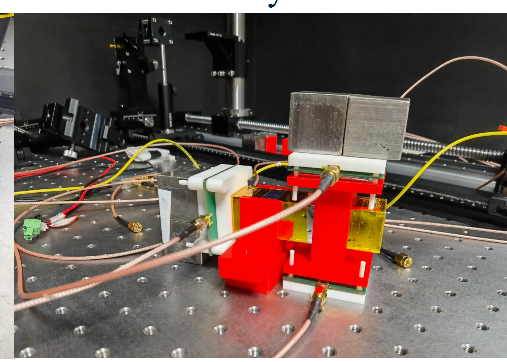
Uniformity scan

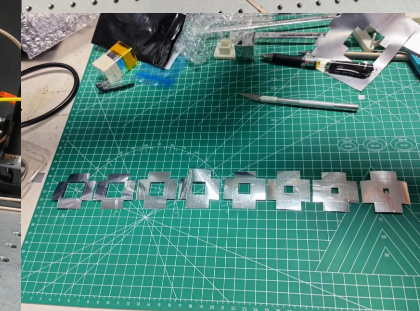


LYSO test w/ ^{137}Cs and ^{60}Co



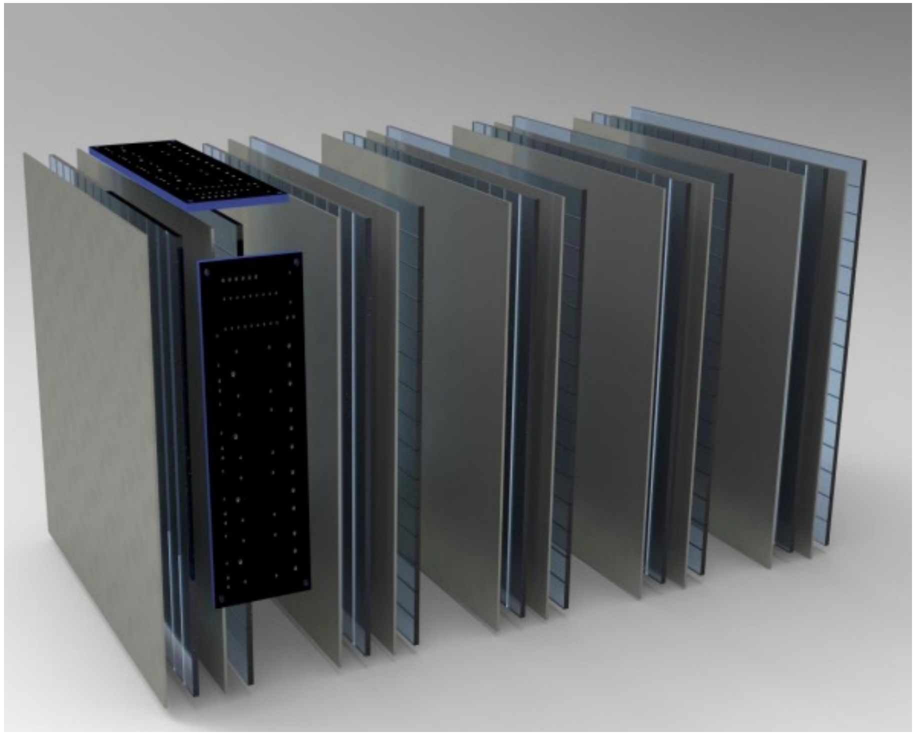
Cosmic ray test





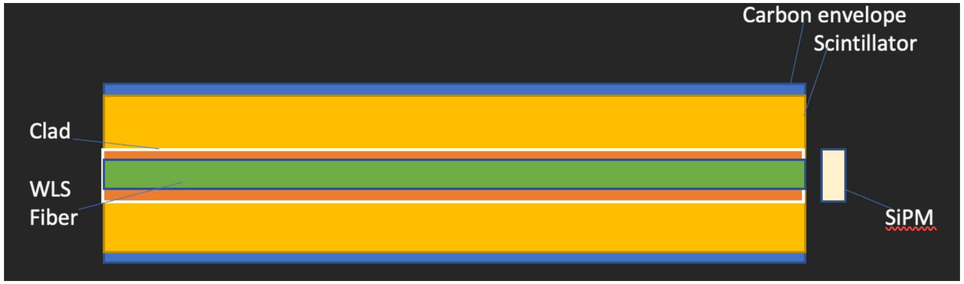
Reflection and light yield investigation

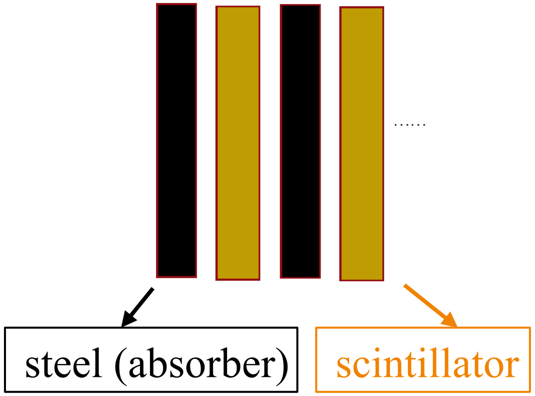
Detector R&D: hadronic calorimeter



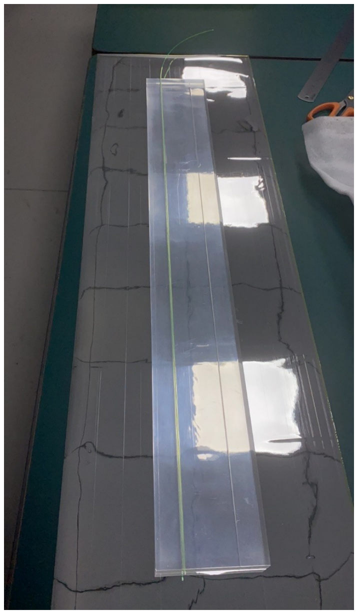
Veto backgrounds with same behavior as signal in ECAL

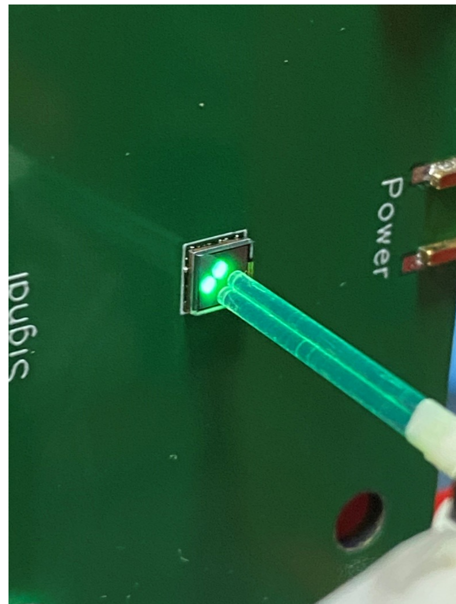
- 1.5 m × 1.5 m (perpendicular to the beam), ~10 λ (~160 cm iron, parallel to the beam)
- Split to 4 modules, 75 cm × 75 cm each
- Iron absorber: 10 mm/50 mm thick, 75 cm × 75 cm
- Plastic scintillator: 10 mm thick, 75 cm × 5 cm, 15 bars per layer per module
    - Each scintillator: wavelength shift fiber + SiPM



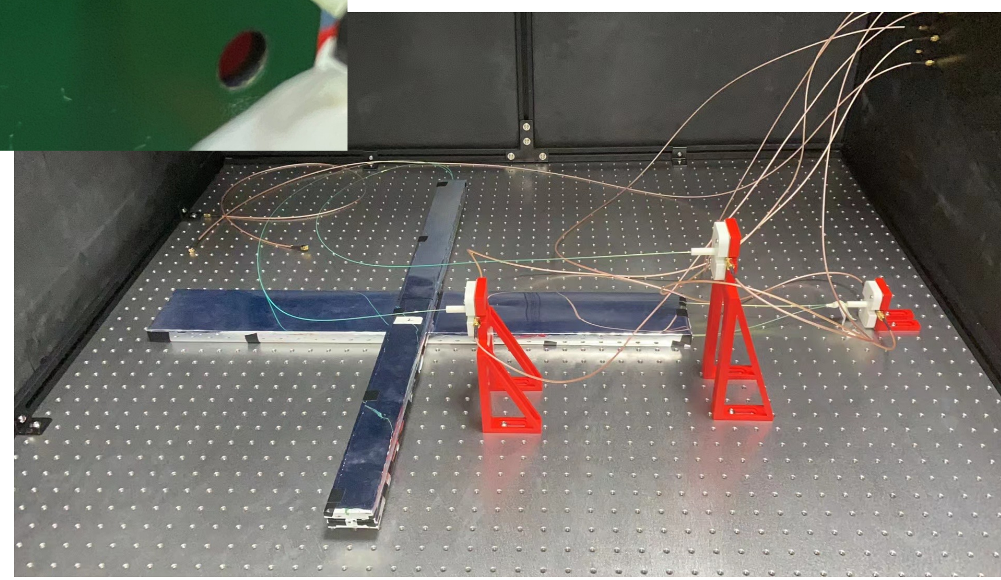


Detector R&D: hadronic calorimeter





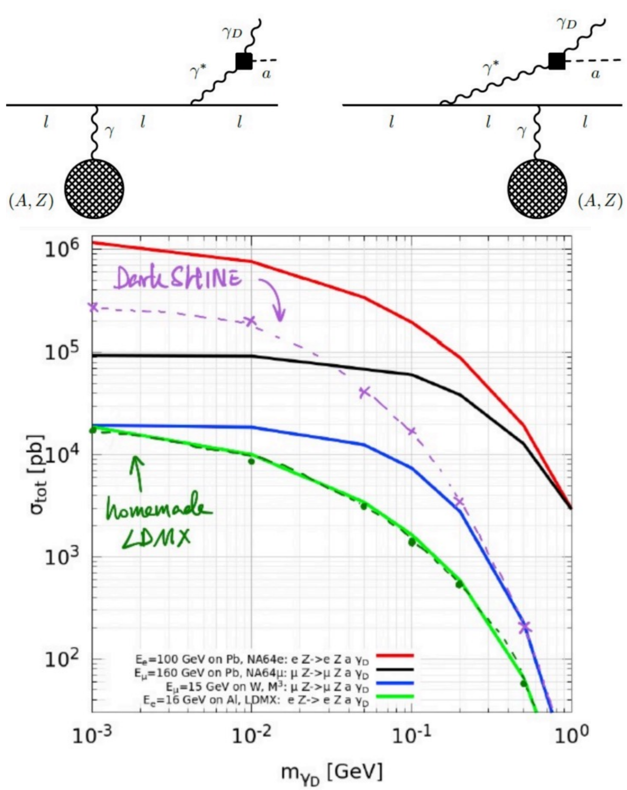
Tested with radioactive source and cosmic ray source.



Scintillator: HND-S2 (高能科迪) polystyrene
WLS: Kurary, d=1 mm, reflector on one side
SiPM: EQR15 11-3030D-S, 3 mm × 3 mm, 40000 microcell
Wrapper: 80 mm ESR

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…

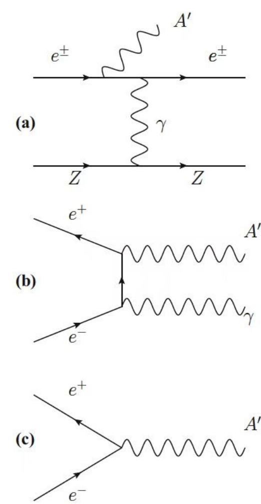
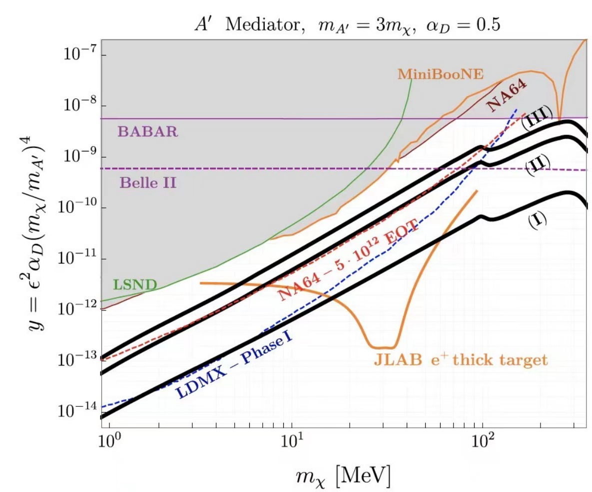


Fig. 1 Three different A' production modes in fixed target lepton beam experiments: (*a*) A'-strahlung in e^-/e^+-nucleon scattering; (*b*) A'-strahlung in e^+e^- annihilation; (*c*) resonant A' production in e^+e^- annihilation



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

Summary

DarkSHINE: a fixed-target experiment searching for dark photon.

- almost background-free: expected 0.02 background from 1 yr. running.
- above 50% dark photon signal acceptance efficiency.

DarkSHINE has competitive sensitivity.

- Sensitive to most of the light dark matter models with 3 yrs running.
  (Sci. China-Pay. Mech. Astron., 66(1):211062 (2023))

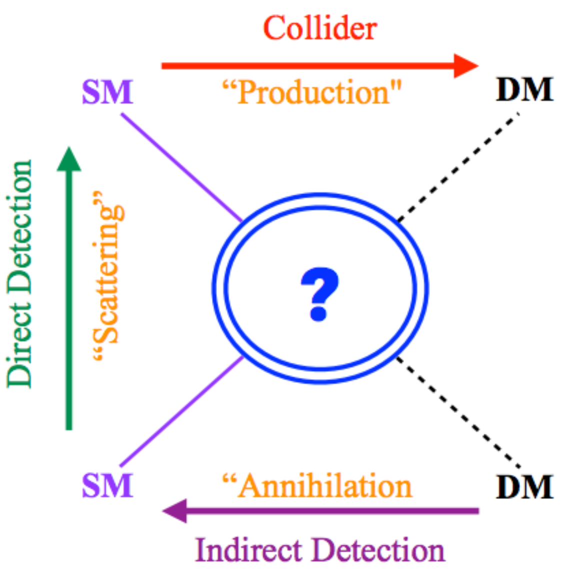
Detector key technology R&D ongoing, sponsored by NSFC (原创探索计划项目).

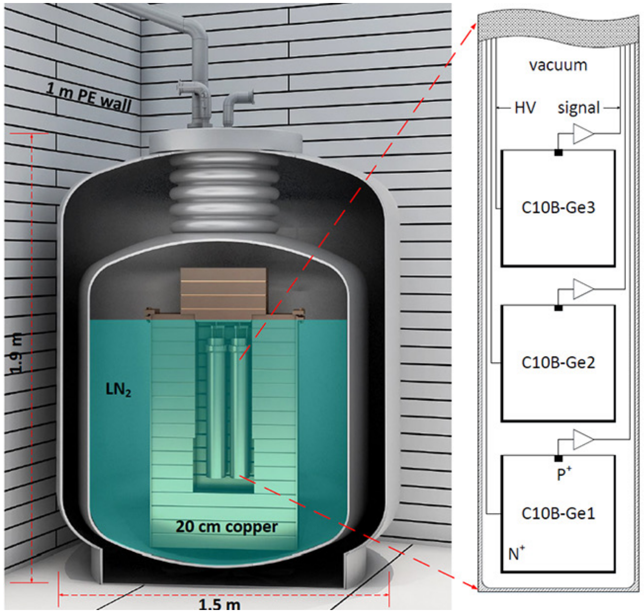
With more physics opportunities ahead, stay tuned! ☺

Collaboration with SHINE

Dark Matter Direct Detections

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





Dark Matter Indirect Detections

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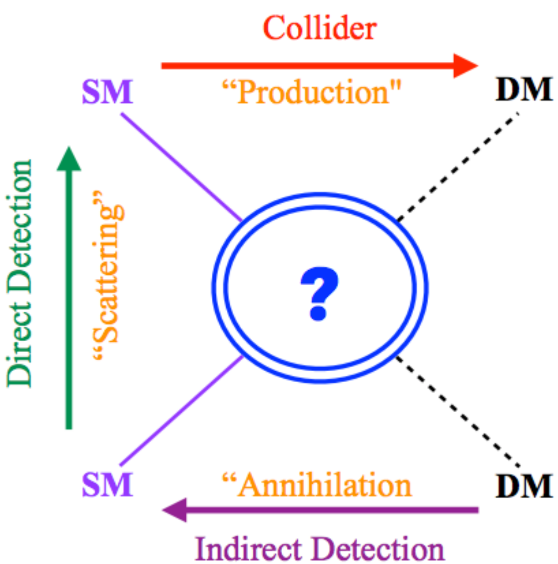
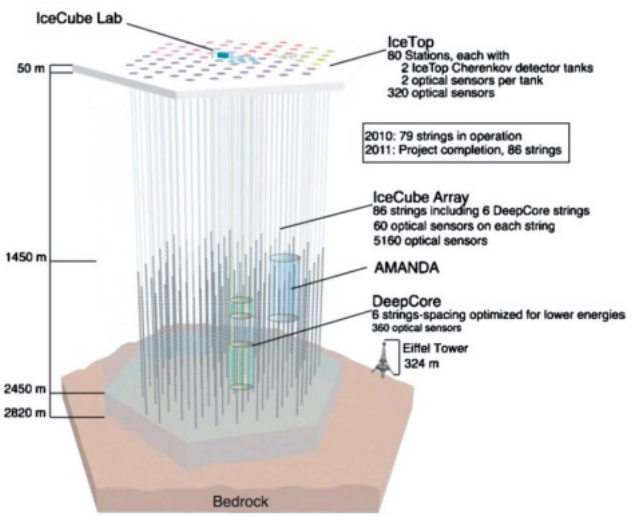
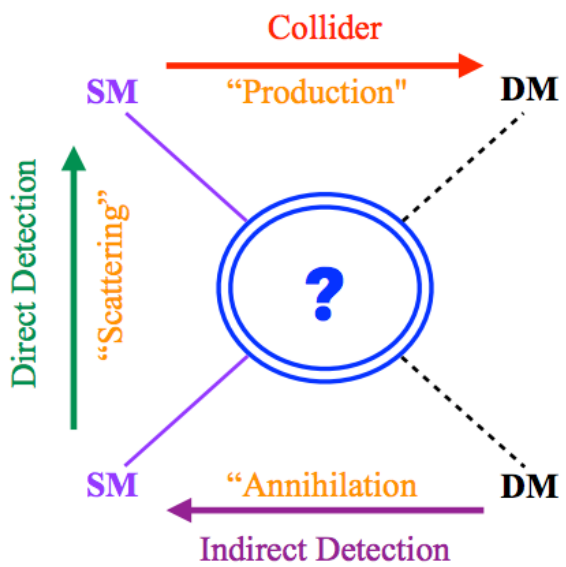
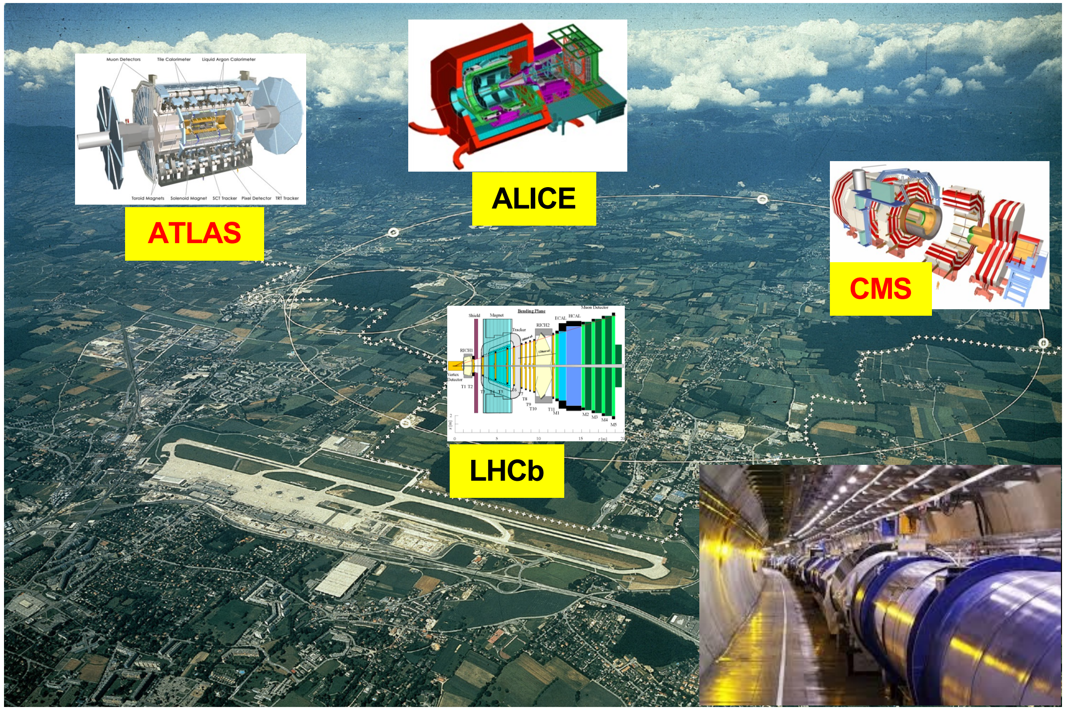




Dark Matter Collider productions

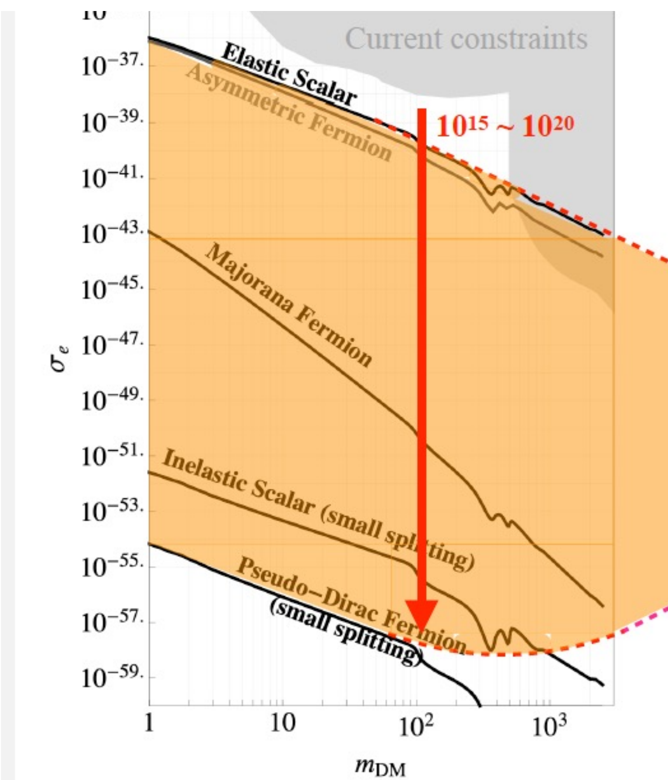
- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (CDEX, PandaX, LZ, XenonNT, ...)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing E_T



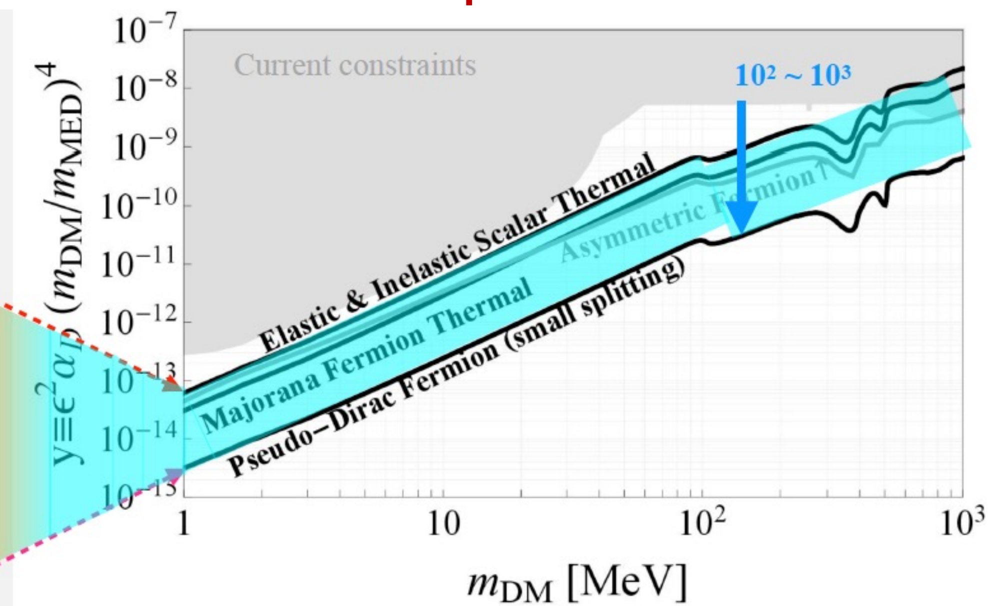


Dark Matter search at Accelerator Experiments

Direct Detection

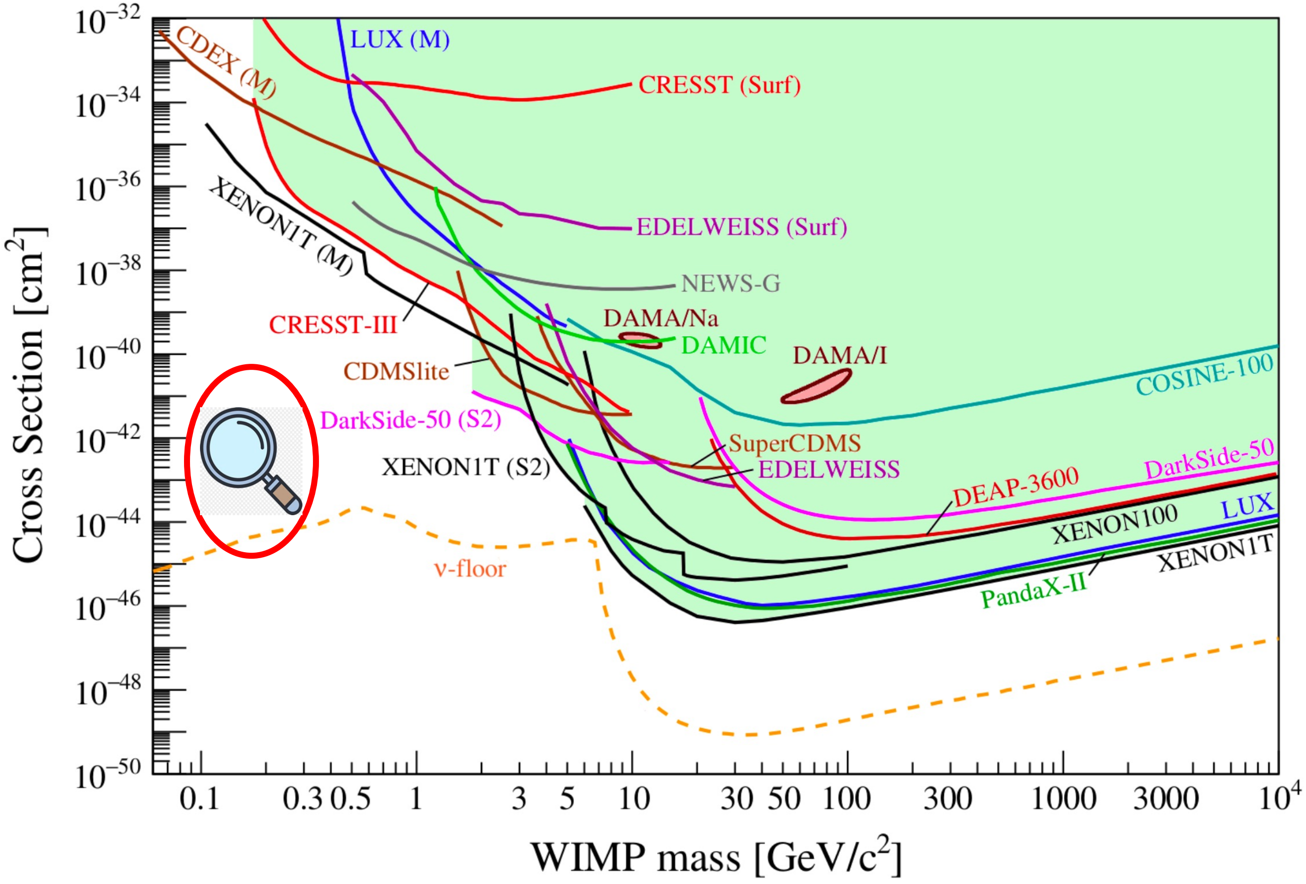


Accelerator based experiments



- 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.

Light DM searches need further exploration



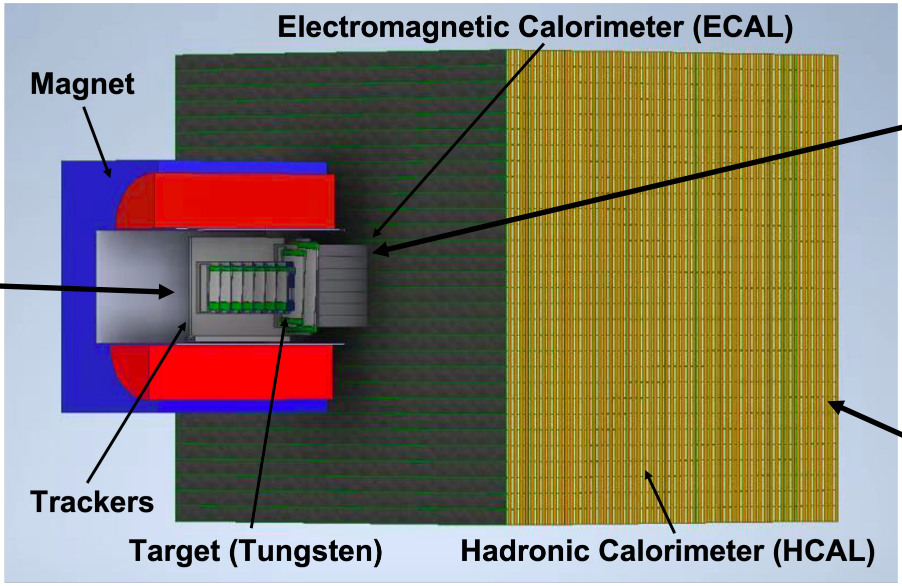
Signal region definition

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.

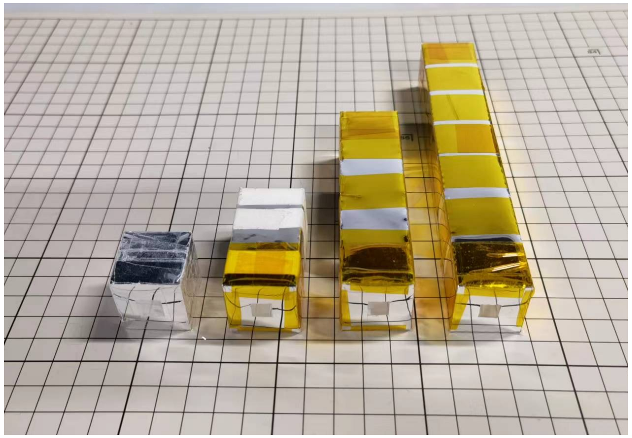
Hadronic calorimeter

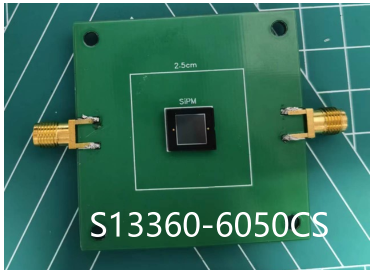
$E_{HCAL}^{total} < 100$ MeV;

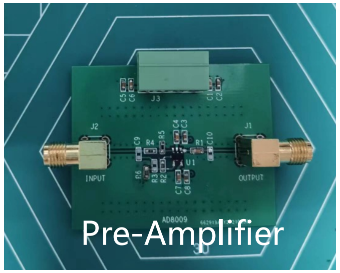
$E_{HCAL}^{max\ cell} < 2$ MeV.

(1st round DarkSHINE analysis)

ECAL Detector Unit

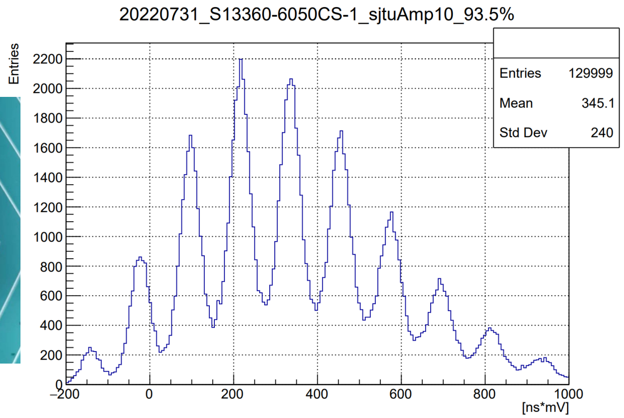


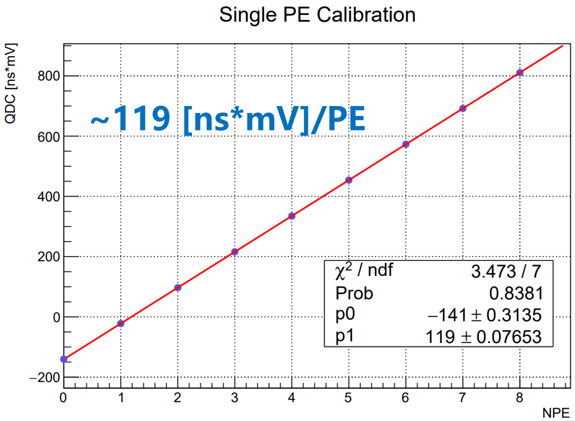




LYSO: $Lu_{(1-x-y)}Y_{2y}Ce_{2x}SiO_5$

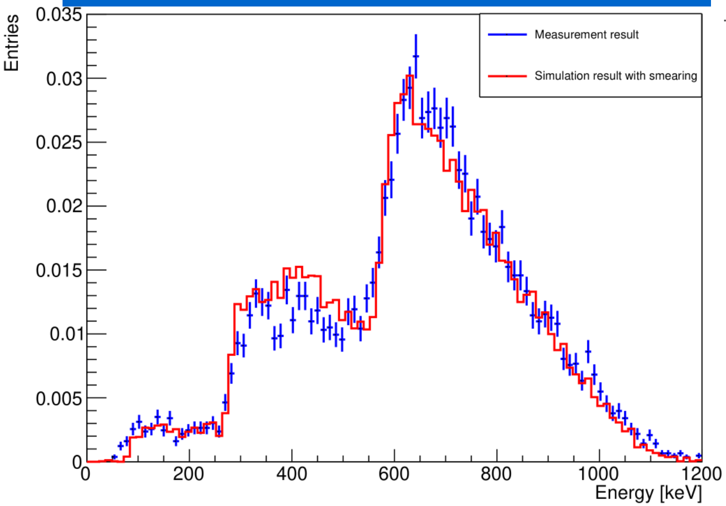
Density	Decay Time	Light Yield	Refraction Index	Radiation Length
7.2 g/cm3	40 ns	30000 p.e/MeV	1.82	1.14 cm

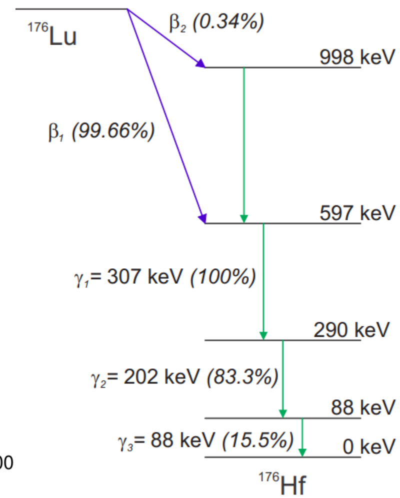




Intrinsic Radiation and Radioactive Source Test

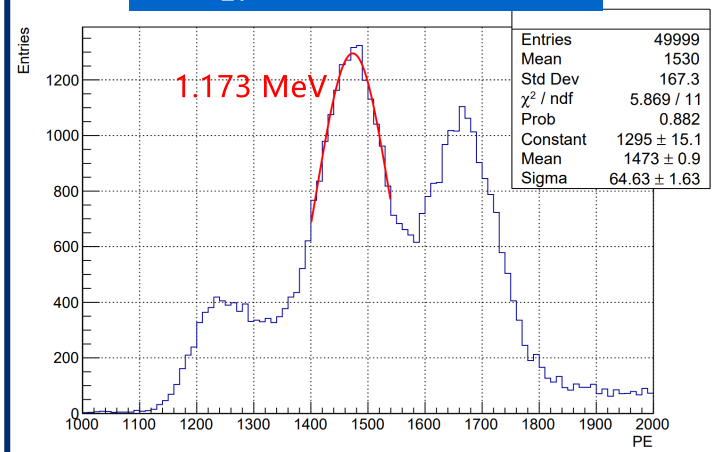
Inrinsic Radiation





- 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

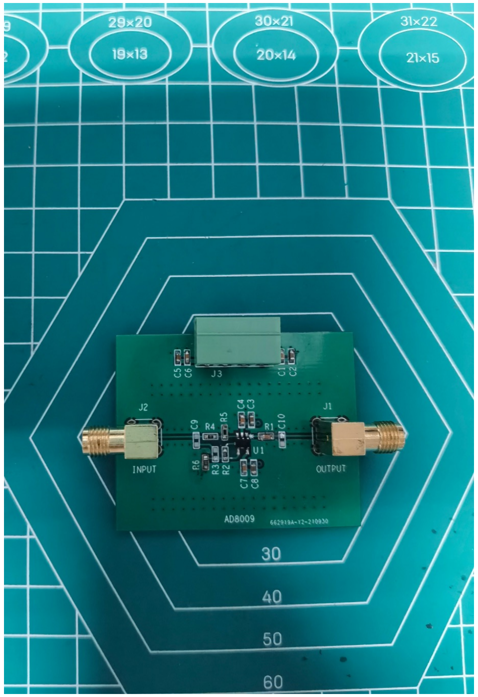


- $^{60}_{27}Co$ radioactive measurement result
- 5×2.5×2.5 cm^3 LYSO
- Light Yield: 1255.75 PE/MeV

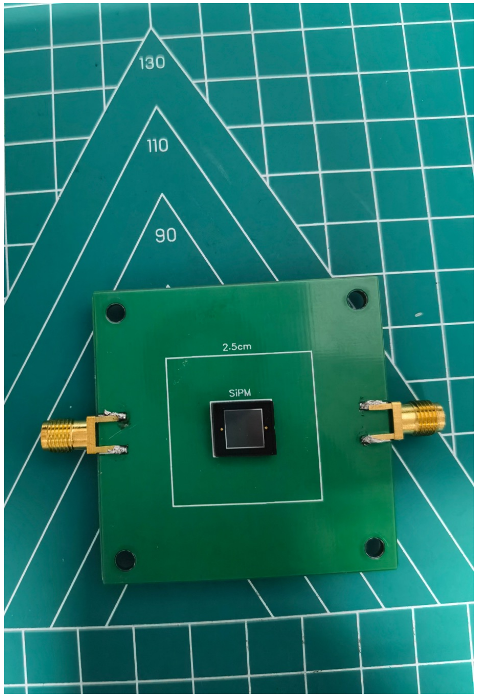
Detector R&D: ECAL readout system

Crystal ECAL readout electronics:

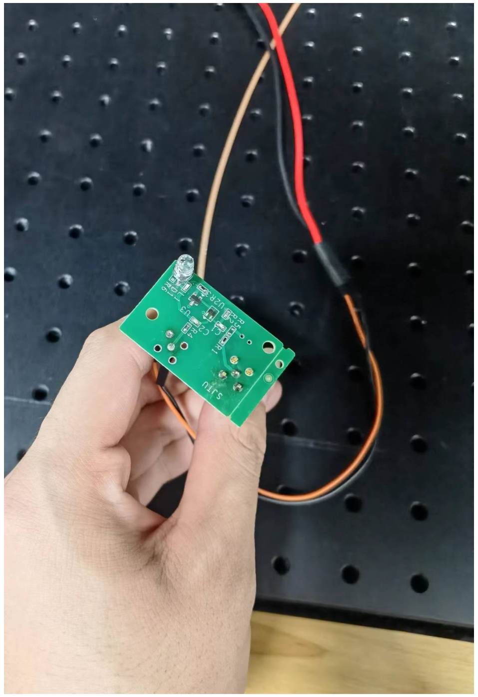
Pre-Amp



SiPM

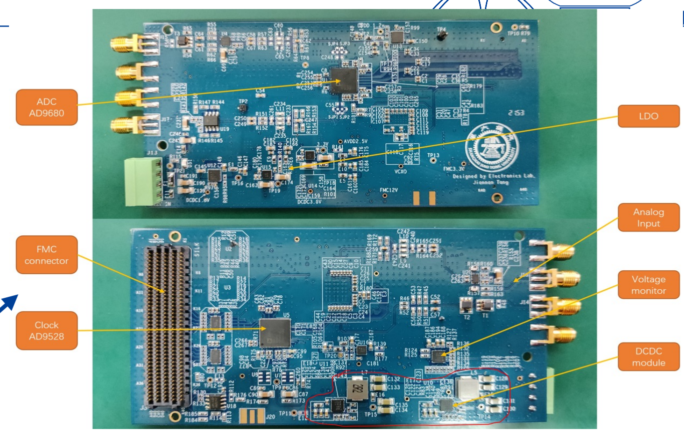


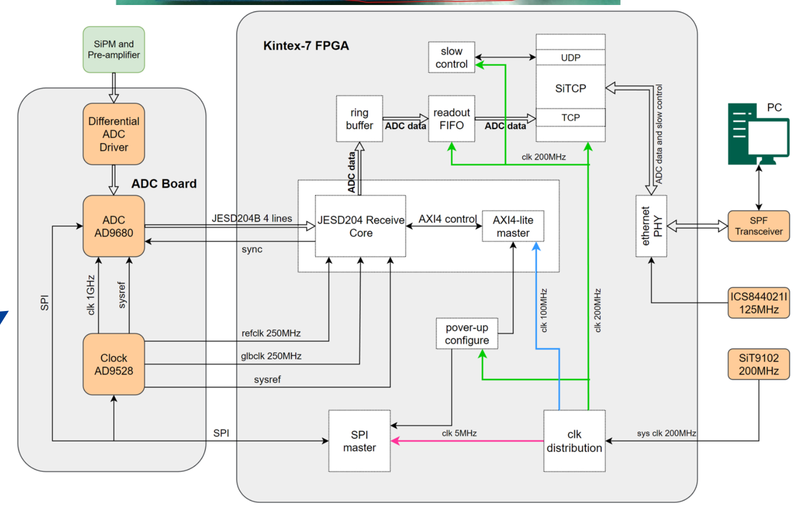
LED driver



Design scheme

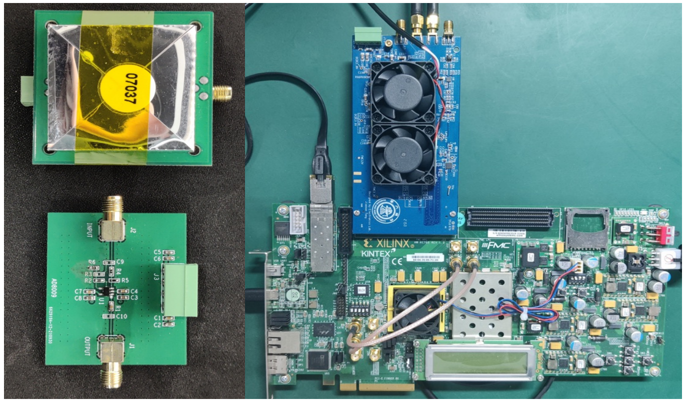
- **Ecal used SiPM to detect photon**
- **SiPM**
  - Width : tens of nanoseconds
  - Rising edge : about 2-3 nanoseconds
  - Requirement : higher sample rate ~ GSPS
- **ADC chip : AD9680 (from ADI)**
  - Sanple rate : 1GSPS
  - Resolution : 14 bits 1.7Vpp 0.1038mV/LSB
  - 2 channels/piece, 2GHz input bandwidth
- **ADC Mezzanine Card (picture)**
  - ADC : AD9680
  - Clock : AD9528
  - FMC HPC connector to the FPGA board
- **Data transfer and processing**
  - Kintex-7 KC705 board
  - ADC DAQ system block diagram

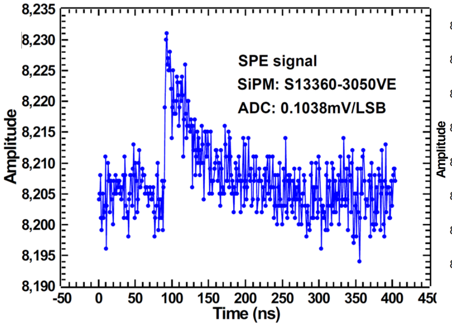




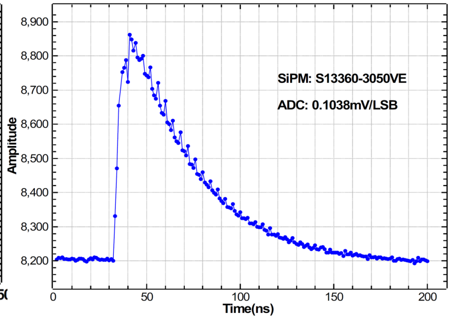
Test results

- Test the performance of ADC
  - 10.3MHz standard sine wave
  - SNR = 58.4dB , ENOB = 9.4bit
  - SFDR = 75.8dB
- Test with SiPM input
  - Analog input :
    - Cosmic ray + SiPM (S13360-3050VE) + plastic scintillator
  - ADC board : Full-bandwidth 1GSPS
- Test results
  - Waveform of an SPE signal and a cosmic ray signal
  - Amplitude of SPE signal : ~ 42 LSB, 4.4mV
  - Noise level : about 10 LSB, 1mV





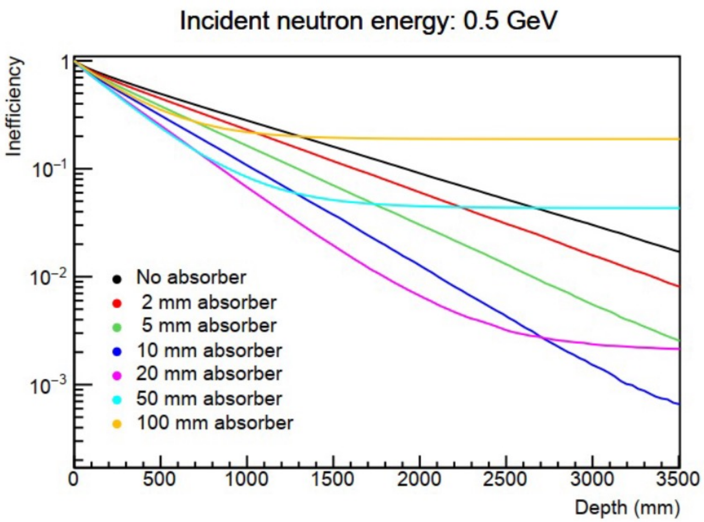
An SPE signal



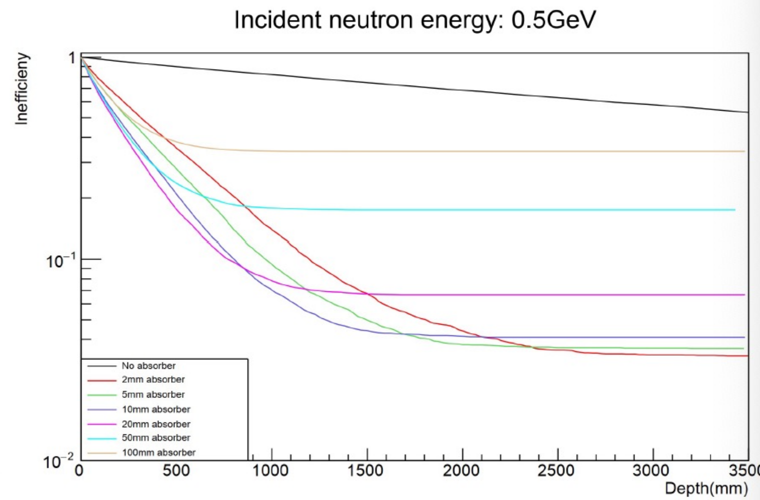
A cosmic ray signal

HCAL design

Veto Inefficiency Simulation



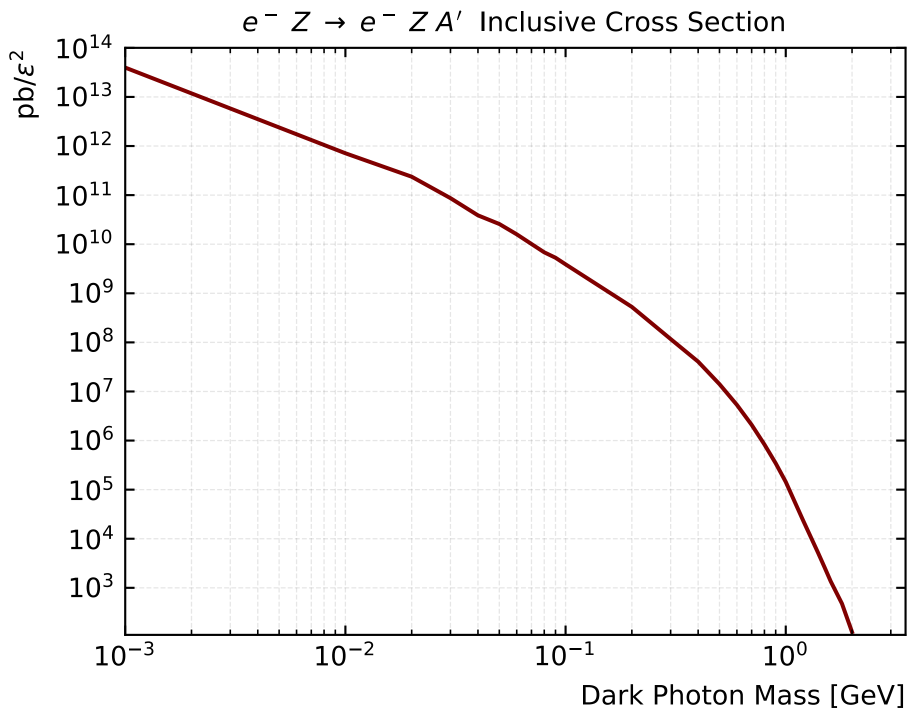
LDMX



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:

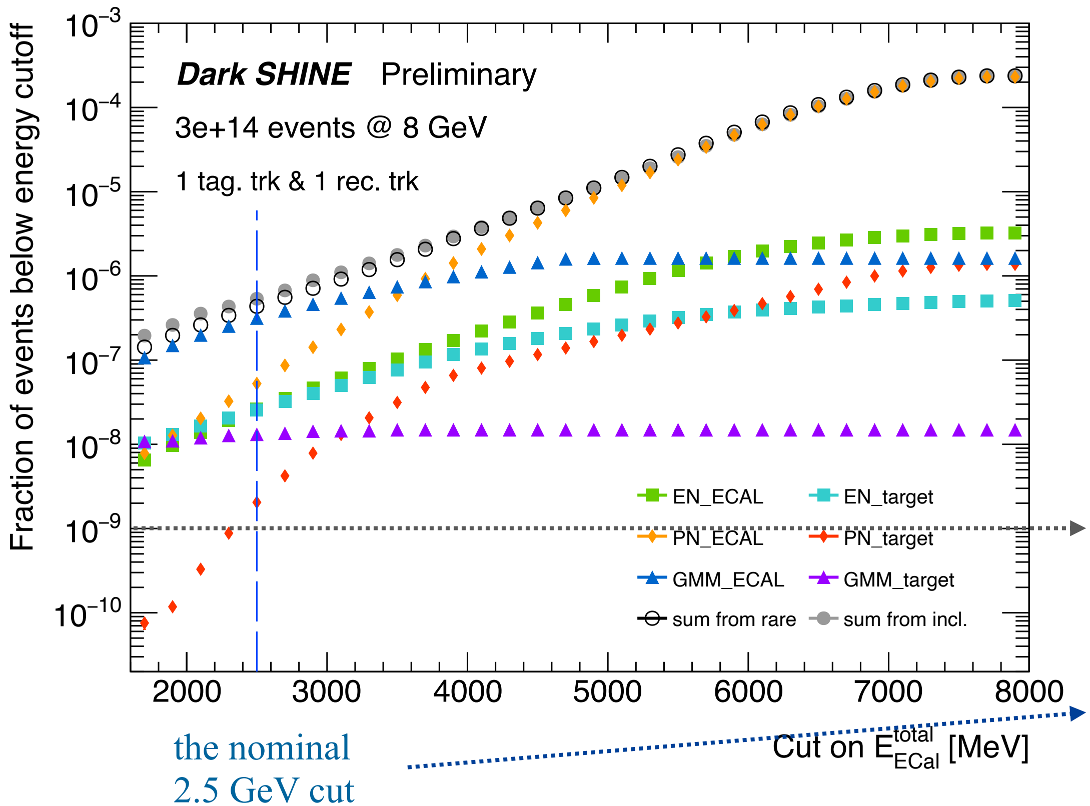
- Inclusive background: 2.5×10^9 EOTs produced.
- Rare background: only GMM (target) process exceeds 3×10^{14} EOTs.

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



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:

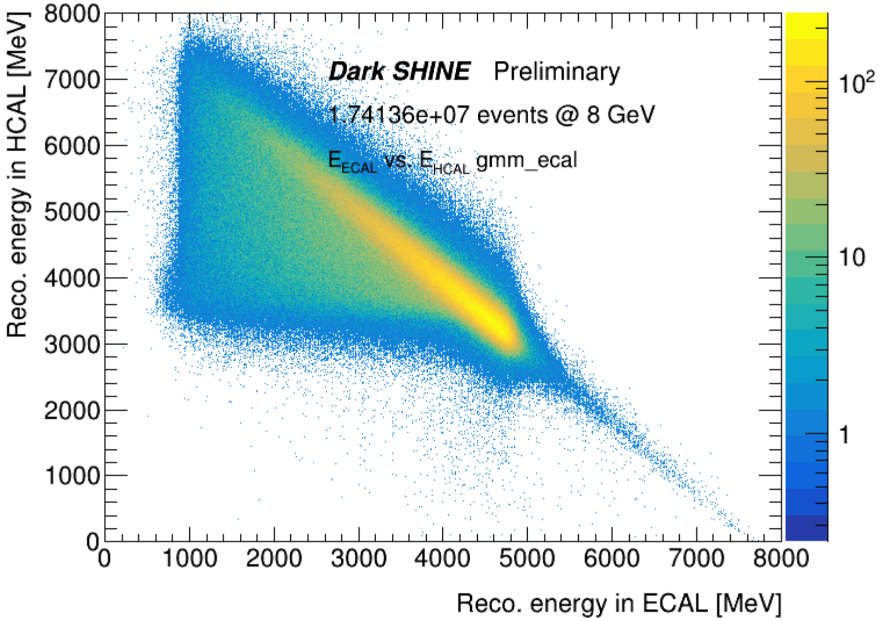
- $\boldsymbol{y = 10^{-9}}$:
  for 10^9 EOT, less than 1 event will remain after applying any cut tighter than $E_{ECAL}^{total} < x$ MeV.
- $\boldsymbol{x = 2500}$:
  y of the background events will survive the cut $E_{ECAL}^{total} < 2500$ MeV.

Extrapolation: rare processes

Not all the rare processes need further extrapolation.

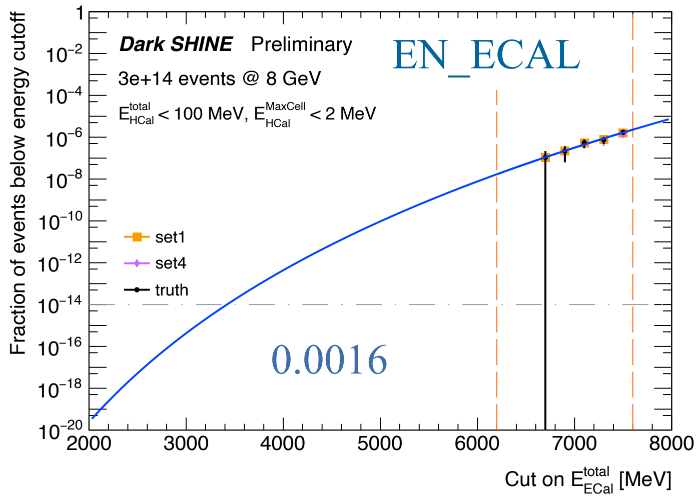
There are 6 rare background processes in total:

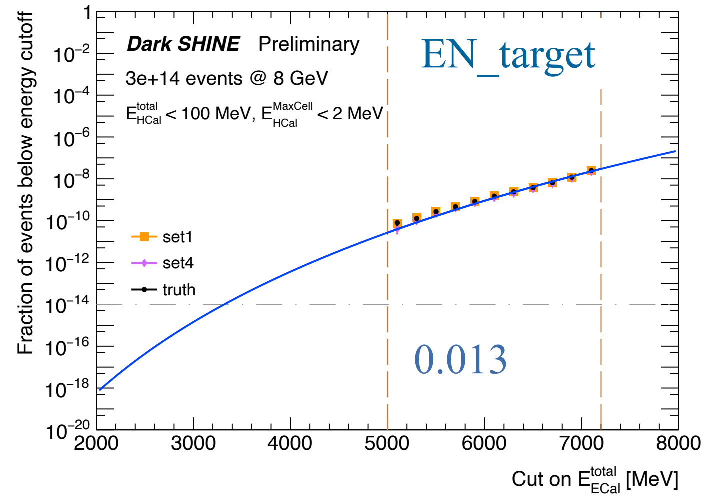
- EN(ECAL), PN(ECAL), **GMM(ECAL)**, EN(target), PN(target), **GMM(target)**

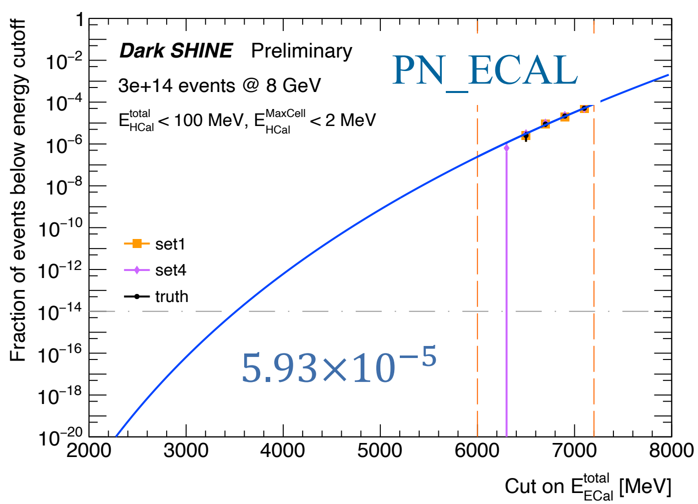


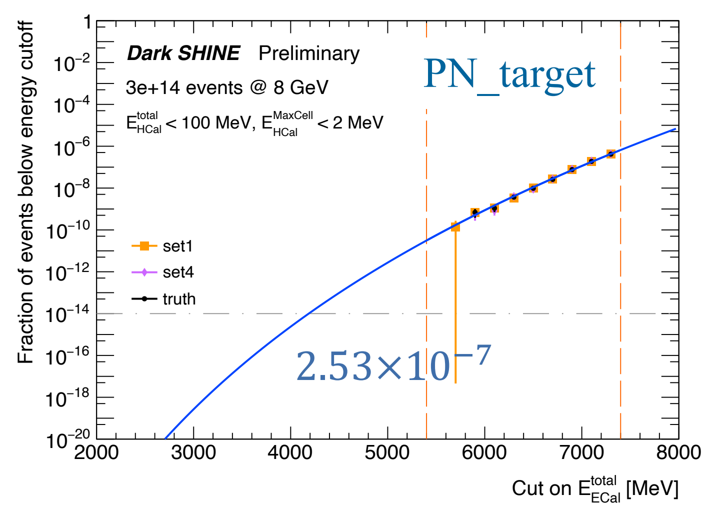
- Available statistics: $\sim 4.3\times 10^{14}$ (target) and $\sim 6\times 10^{12}$ (ECAL) EOTs considering the branching ratio.
- extrapolation method no longer applicable due to the energy distribution.
- Can always be effectively rejected by the HCAL requirement (fraction of the remaining GMM events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

Extrapolation: rare processes







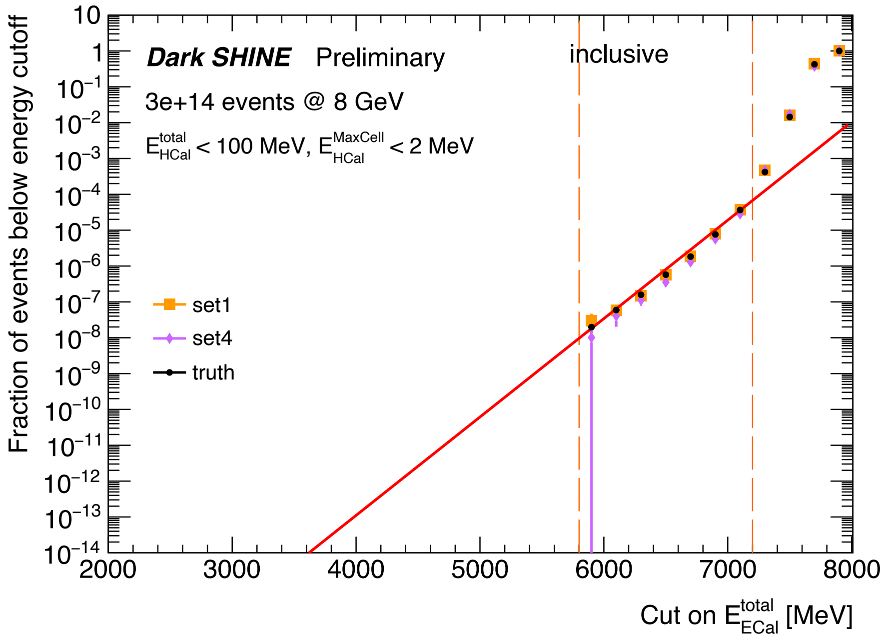


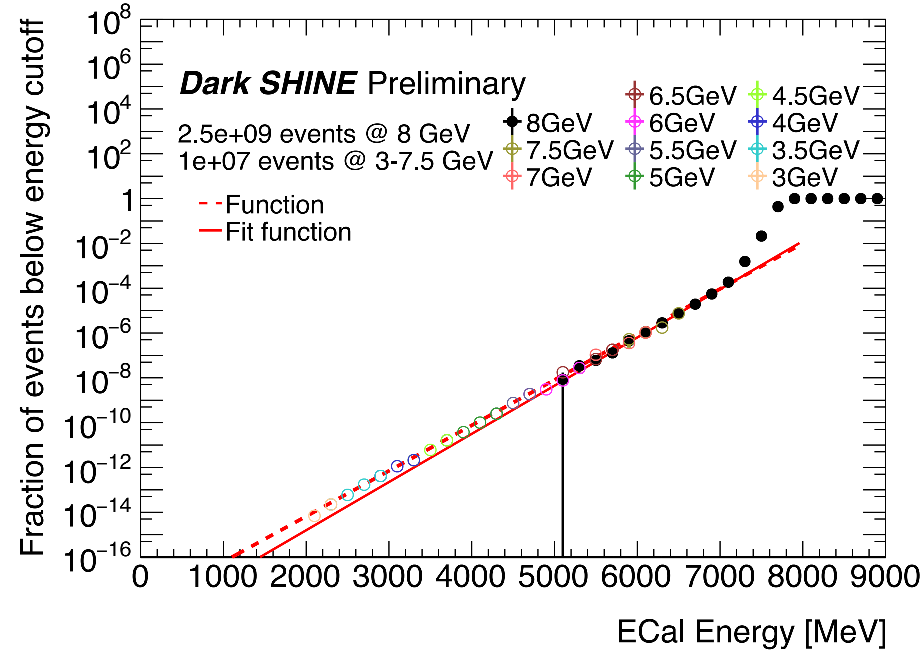
Sum: 0.015

~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