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

Yufeng Wang on behalf of the DarkSHINE team

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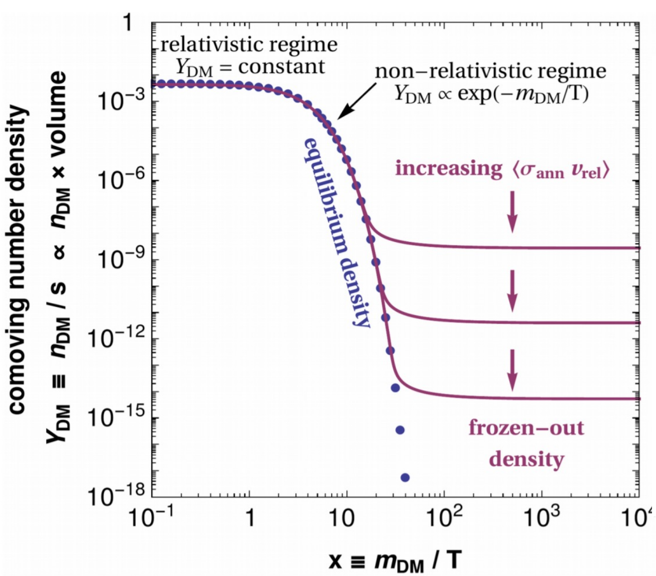
Outline

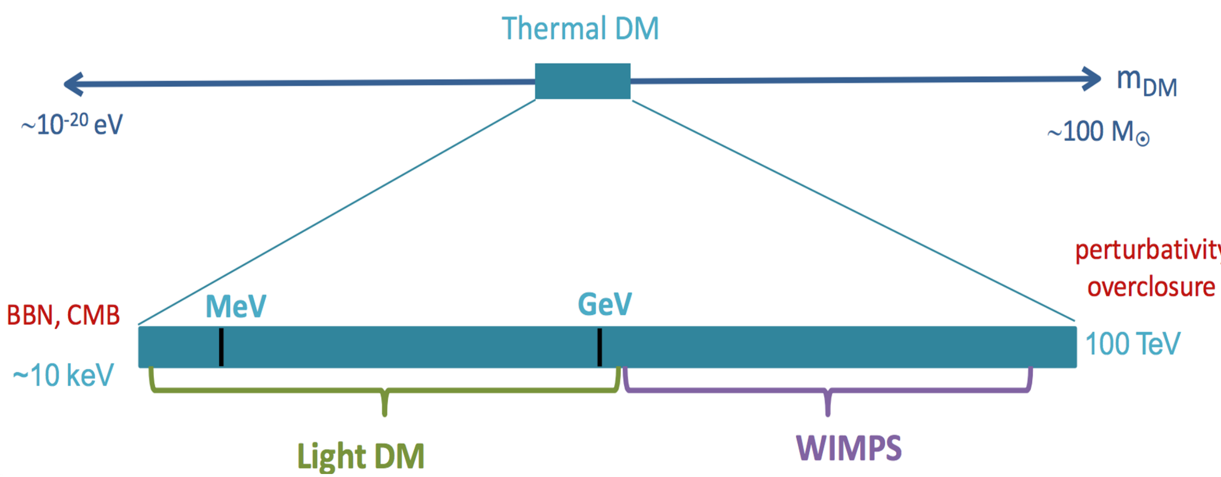
- Physics motivation
- The SHINE facility
- Detector conceptual design
- Signal and background simulation
- Prospective sensitivity
- Summary

Physics motivation

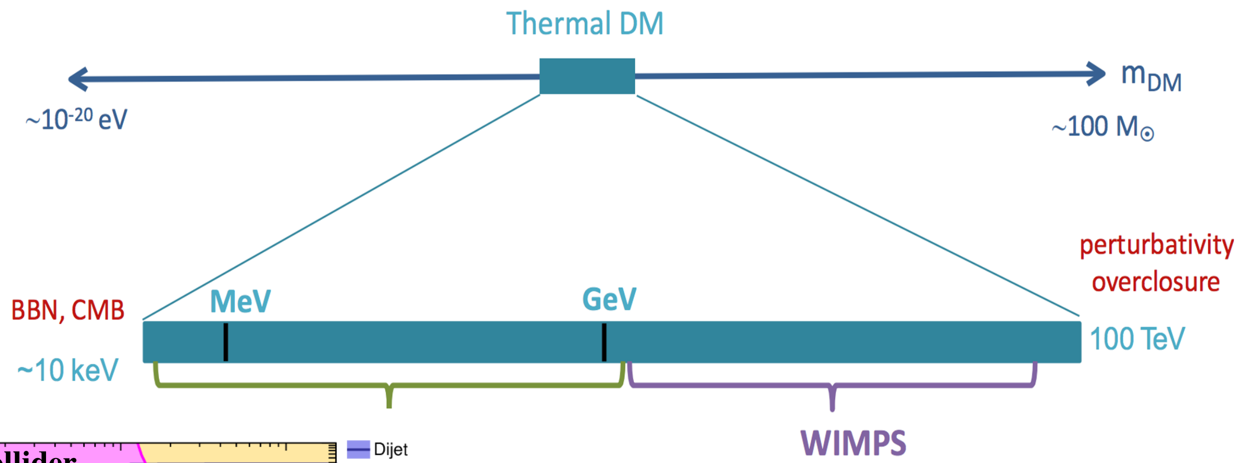
Evidence from cosmology and astronomy showing that **Dark Matter (DM)** exists in the universe.

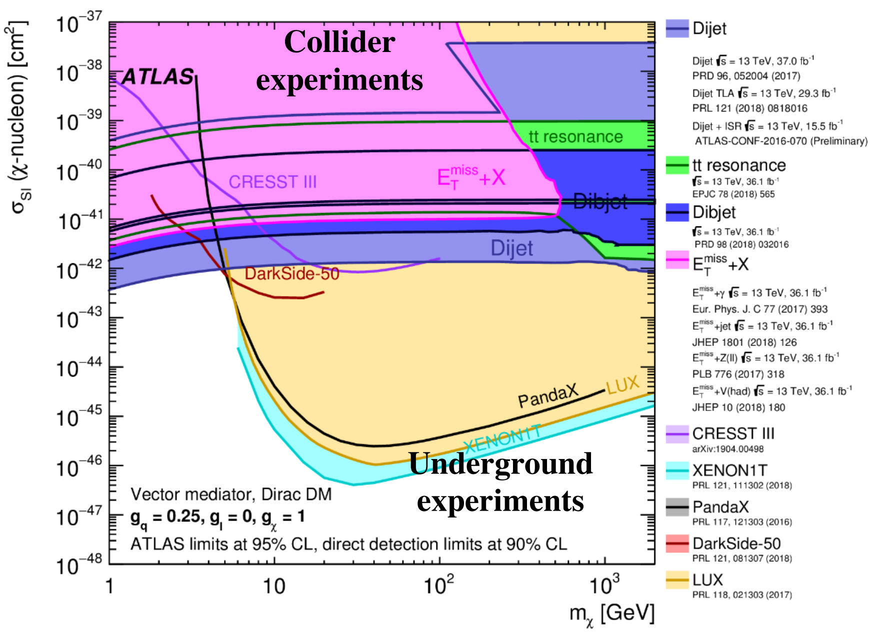
- constituting ~25% of the universe energy content.
- one typical origin hypothesis: thermal equilibrium in the early universe.
  - Temperature drops due to the over-expansion of the universe → DM density becomes stable ("freeze-out" mechanism).





Physics motivation



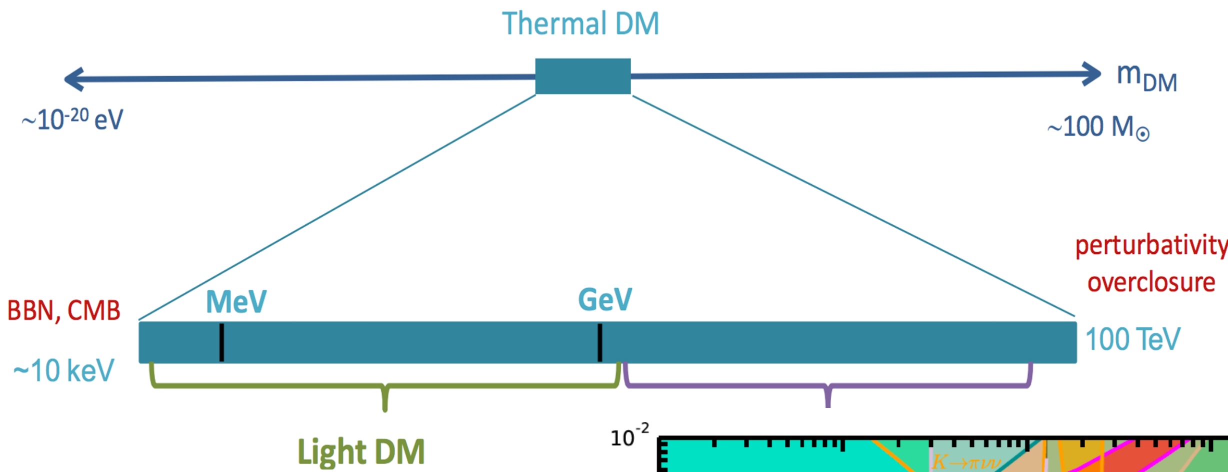


Searching for weakly interacting massive particles (WIMP):

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.)

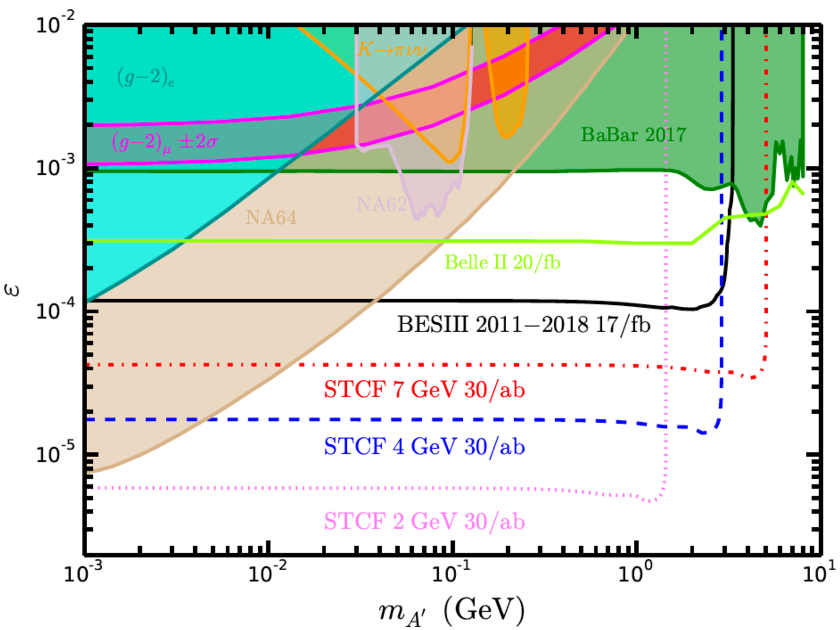
Physics motivation



Searching for light DM (χ):

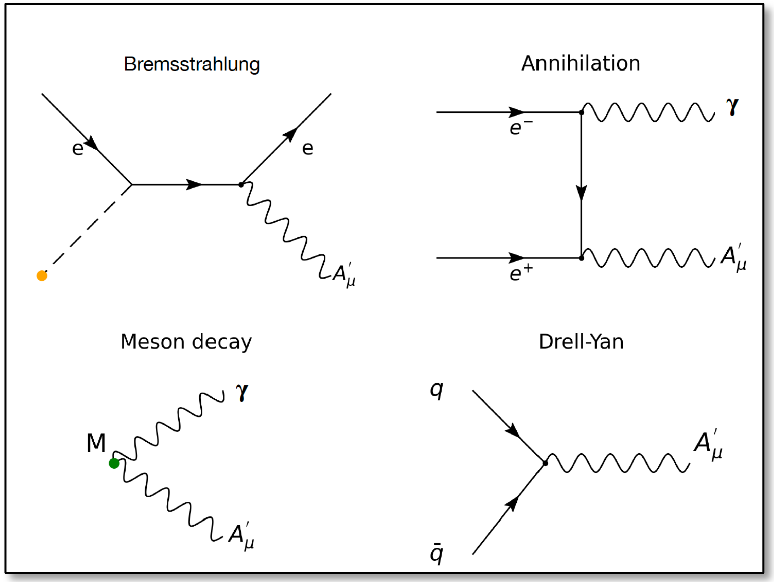
Sub-GeV mass range not fully explored yet.

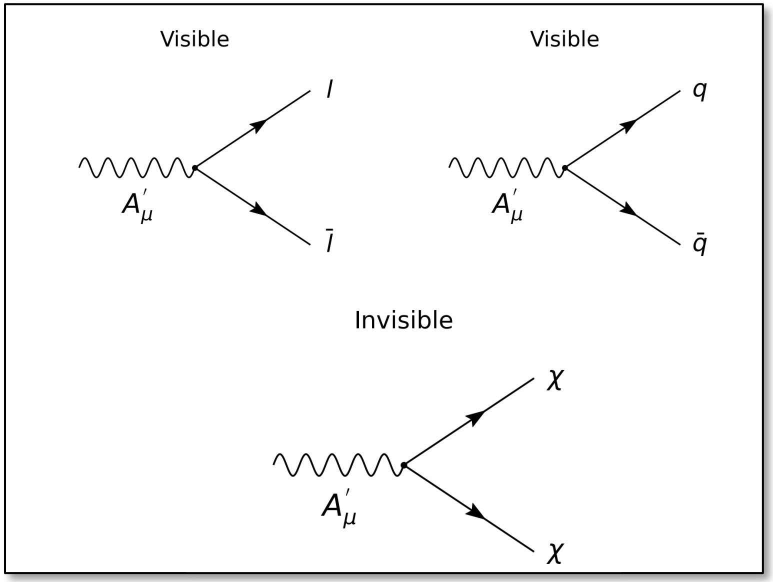
- New mediator implied by thermal contact: e.g., a **dark photon (A')**
  - DM interact with SM particles via the new "dark force".
  - Collider/accelerator-based experiments searching for dark photon: NA64@CERN, BESIII, BEPCII, LDMX, etc.



Physics motivation

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



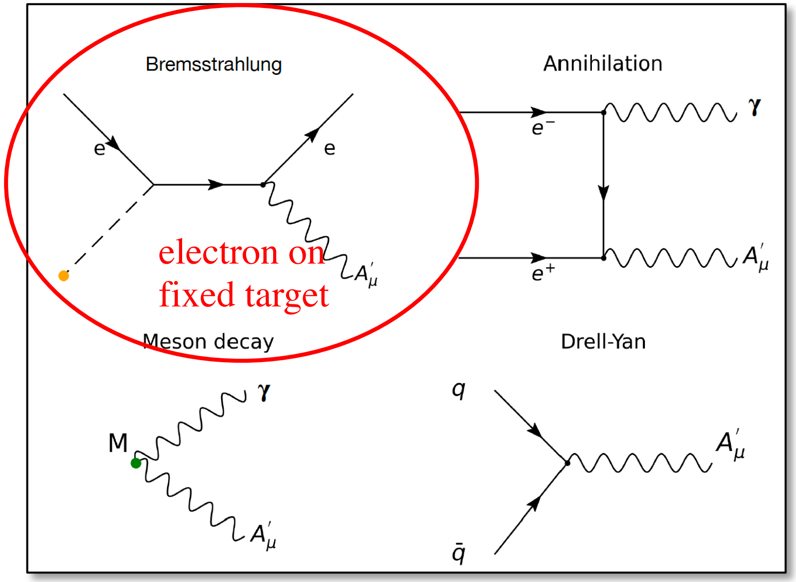


(Dark photon production)

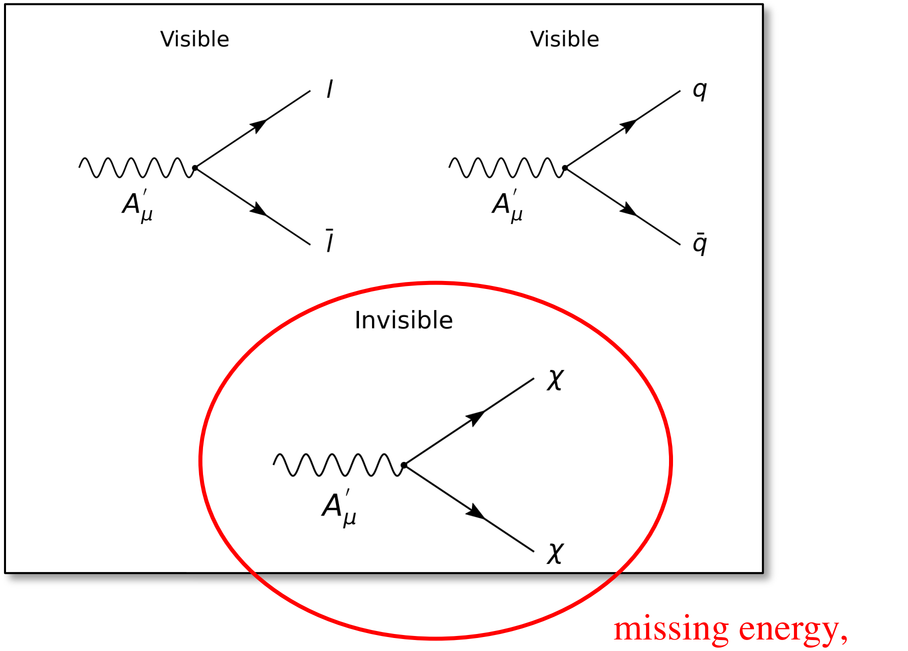
(dark photon decay)

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)

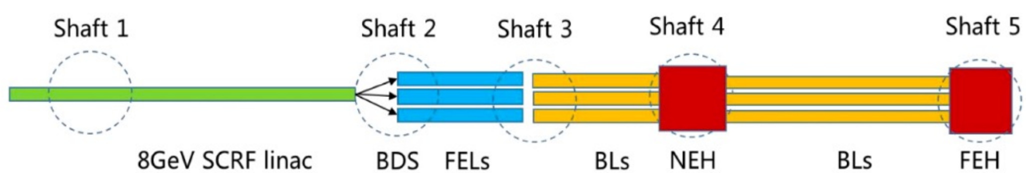
- Goal: put constraints on the kinetic mixing parameter ε.
- Challenge: small production rate → suppress bkg. from SM processes.

The SHINE facility

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

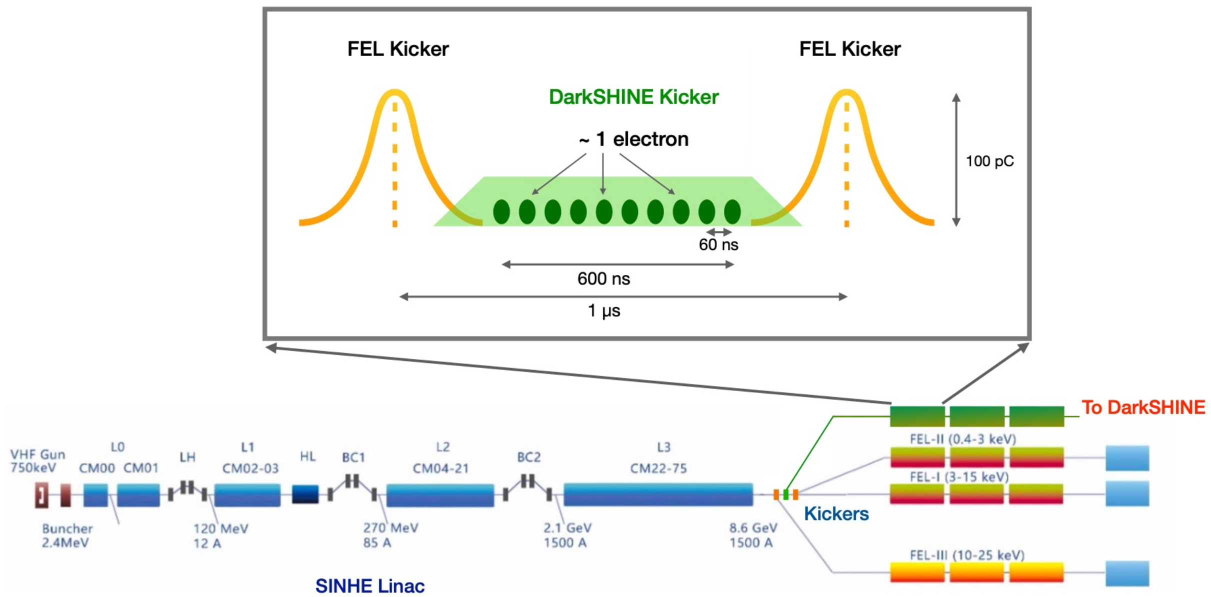
- Under construction in Zhangjiang area, Shanghai (2018-2026).
  - Beam techniques: SARI, CAS/Shanghai Tech.
  - Detector R&D: SJTU/FDU/SIC, CAS.

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



The SHINE facility

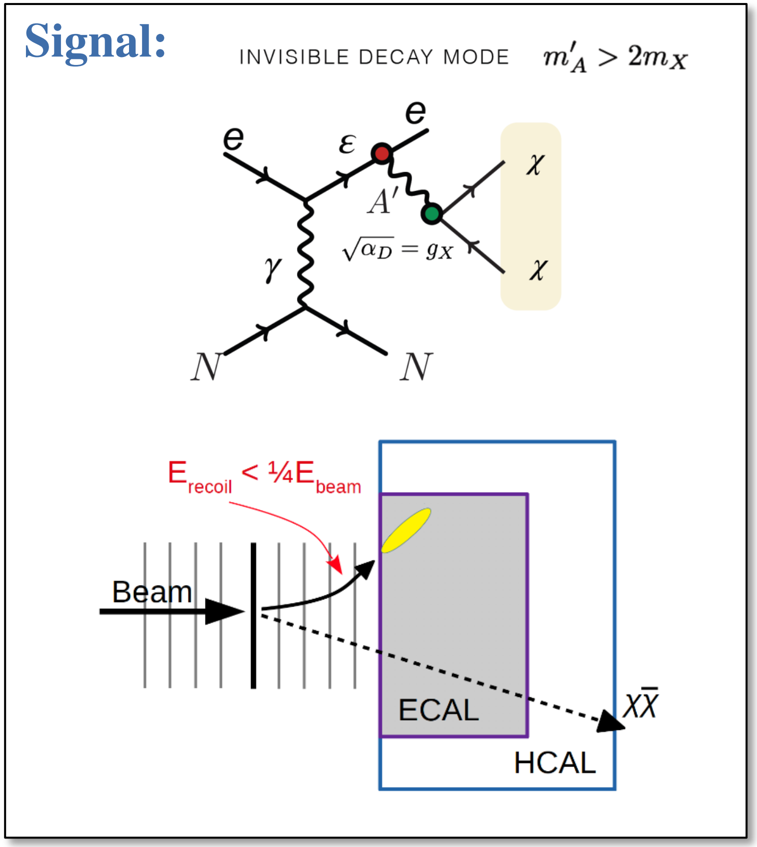
Idea of obtaining the single electron beam:



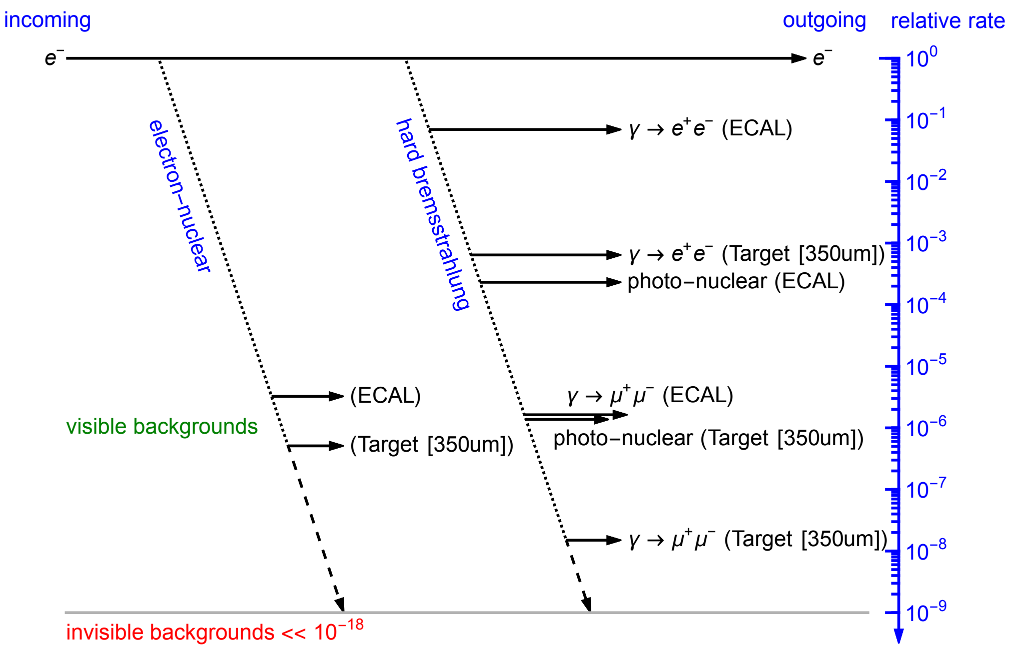
- Dedicated electron beam with one electron per bunch to be built in the SHINE linac.
- DarkSHINE kicker system to distribute these electrons, resulting in a frequency of 1~10 MHz, corresponds to $\mathbf{3\times10^{14}}$ electron on target events (EOTs) per year.

Invisible signal signature

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



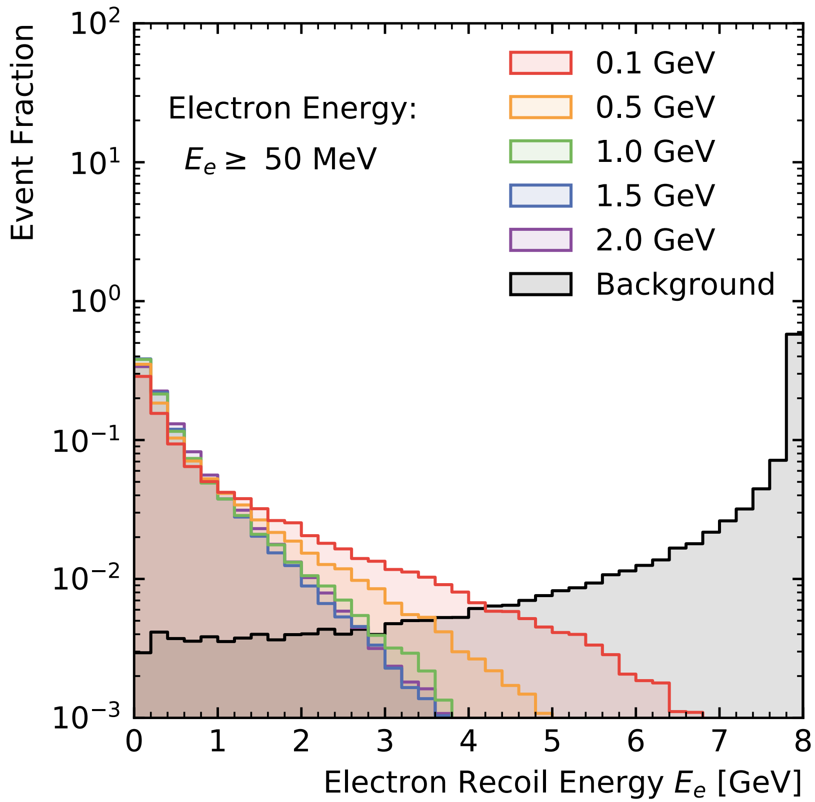
- **Leading background:** SM photon bremsstrahlung
- **Rare background processes:**



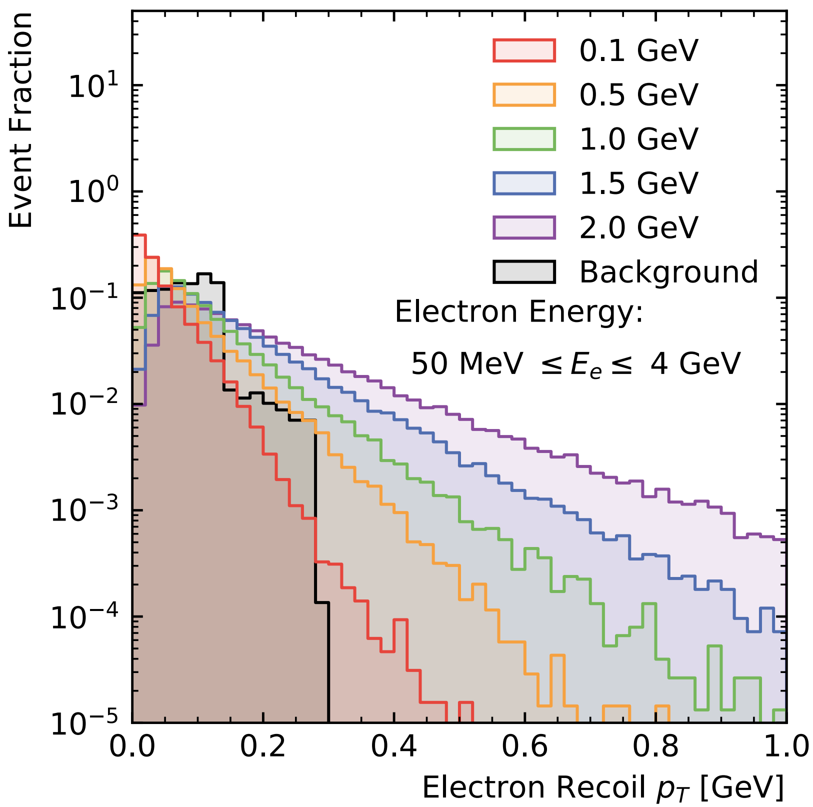
- **Irreducible but negligible:** neutrino production

Invisible signal signature

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



Energy brought away by A'

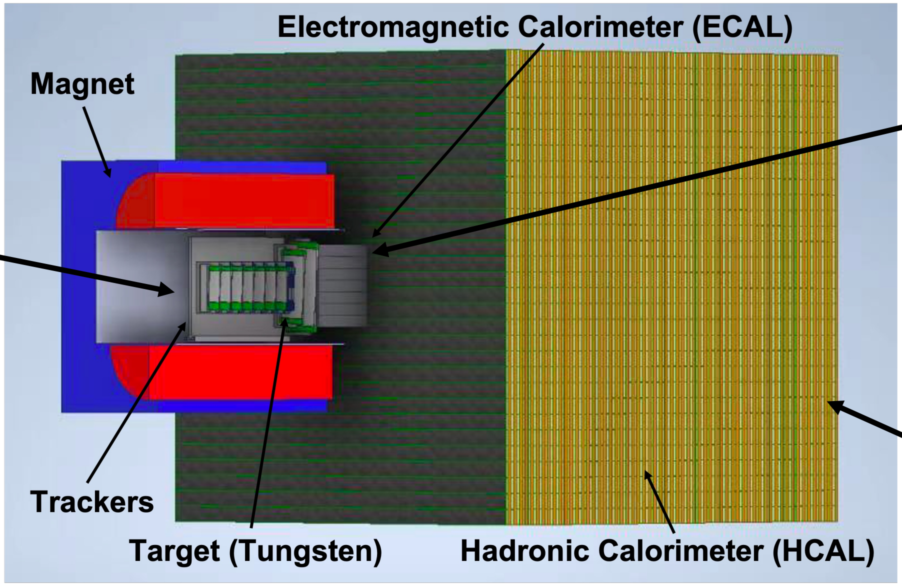


Reco. electron kicked in transverse momentum

Detector conceptual design

The DarkSHINE detector R&D is carried out at the same time while the simulation-based prospective study ongoing.

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



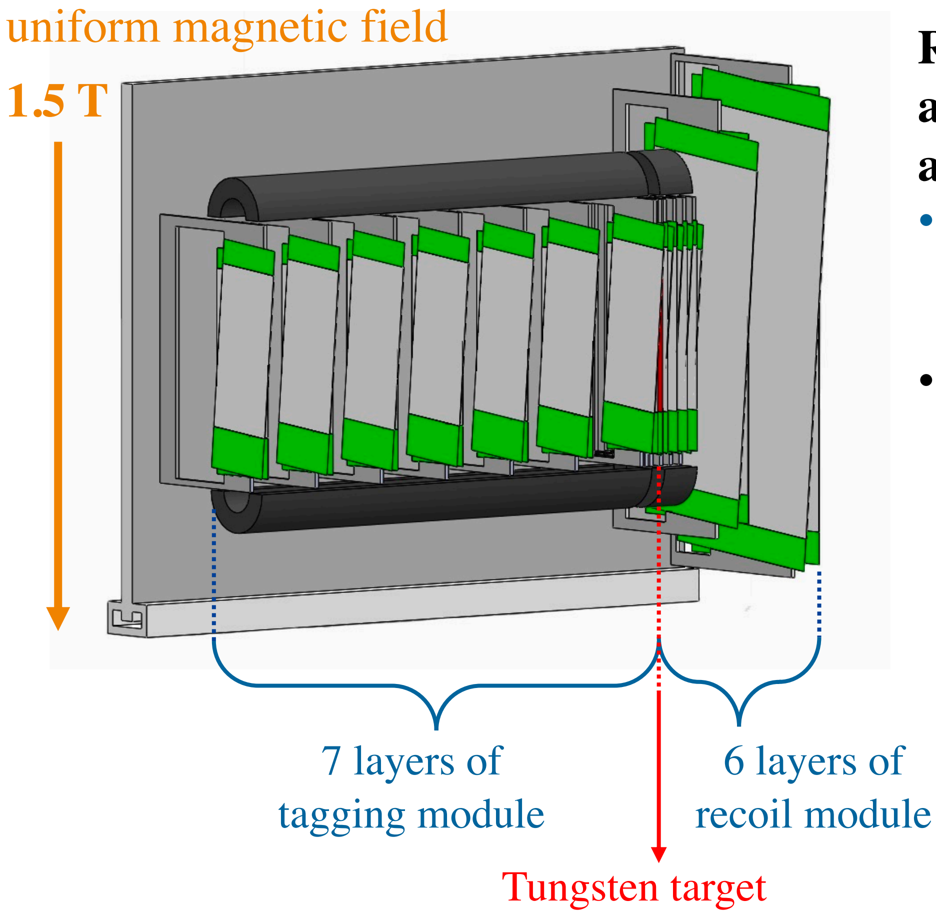
DarkSHINE detector sketch

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.

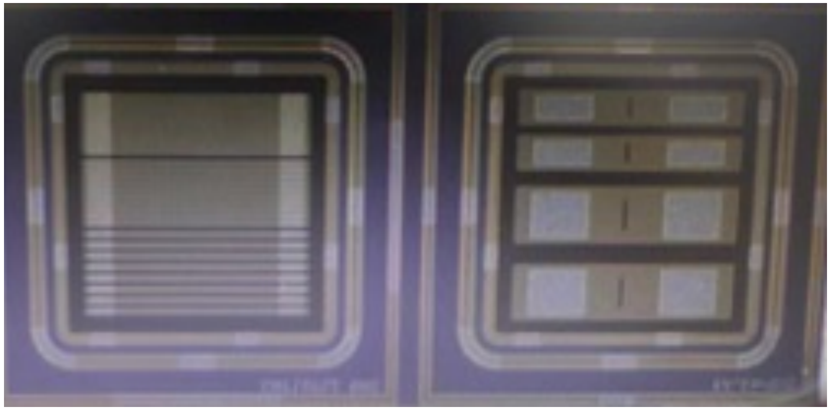
Detector R&D: tracker system



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

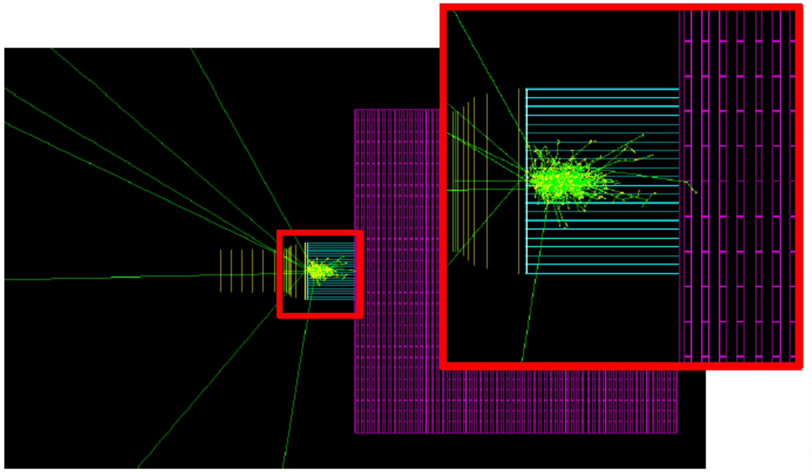
Reconstruct the track of the incident and recoil electrons, the $\gamma \to ee$ process, and the hadron/μ involved final states.

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



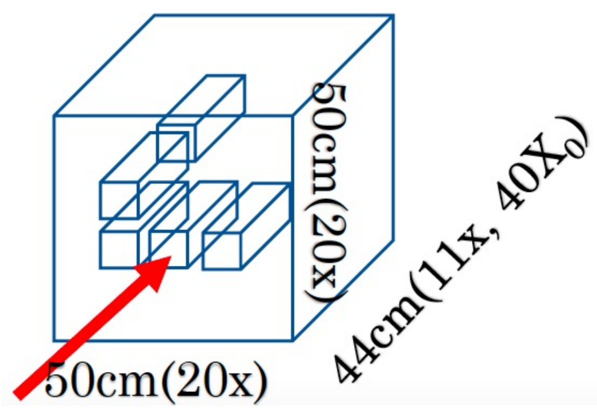
uniform thin strip | nonuniform wide strip

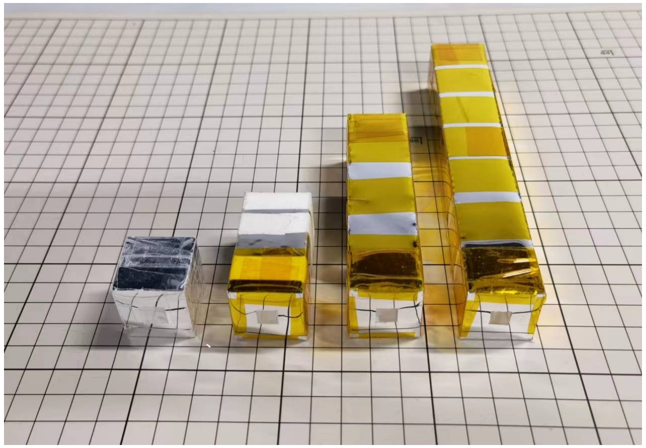
Detector R&D: electromagnetic calorimeter



Measure the deposited energy of electron and photon.

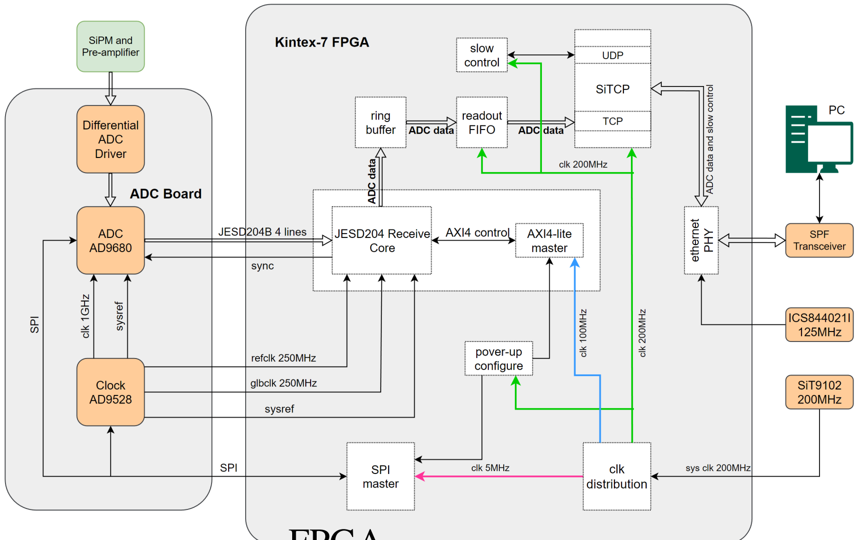
- Designed resolution: better energy resolution than 5%.
- LYSO crystal ($Lu_{(1-x-y)}Y_{2y}Ce_{2x}SiO_5$):
  - high light yield (30000 p.e/MeV) with good linearity.
  - short decay time (40 ns).
- Readout with SiPM and waveform sampling.
- Intrinsic radiation and radioactive source tests ongoing.





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

Detector R&D: ECAL readout system

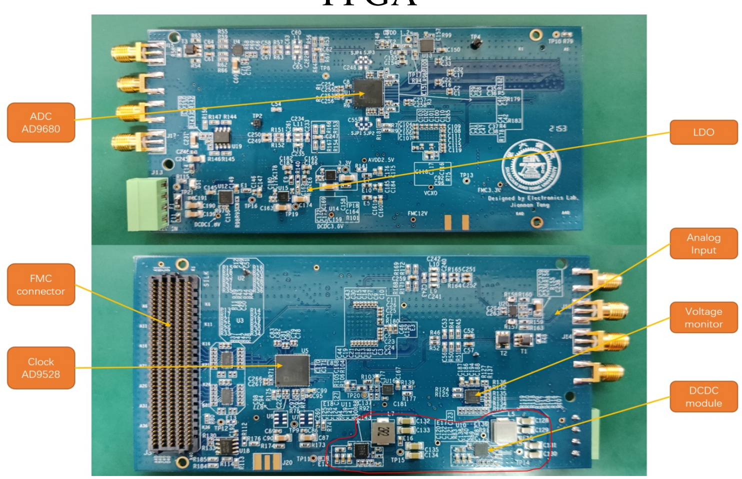


FPGA

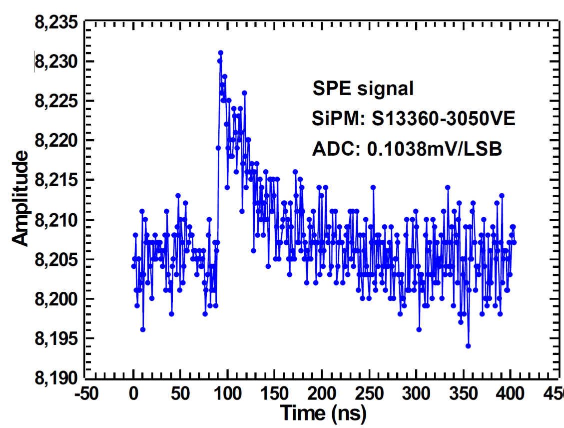
Photons from ECAL crystal are detected using SiPM + fast readout system.

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

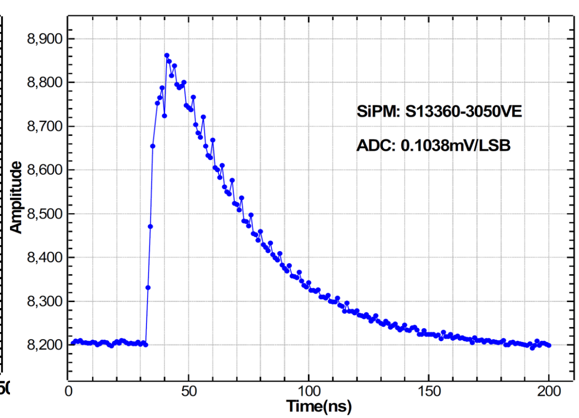
- ADC performance has been tested.
  - Analog input: Cosmic ray + SiPM (S13360-3050VE) + plastic scintillator
  - Amplitude of SPE signal : ~42 LSB, 4.4mV
  - Noise level : ~10 LSB, 1mV



ADC board

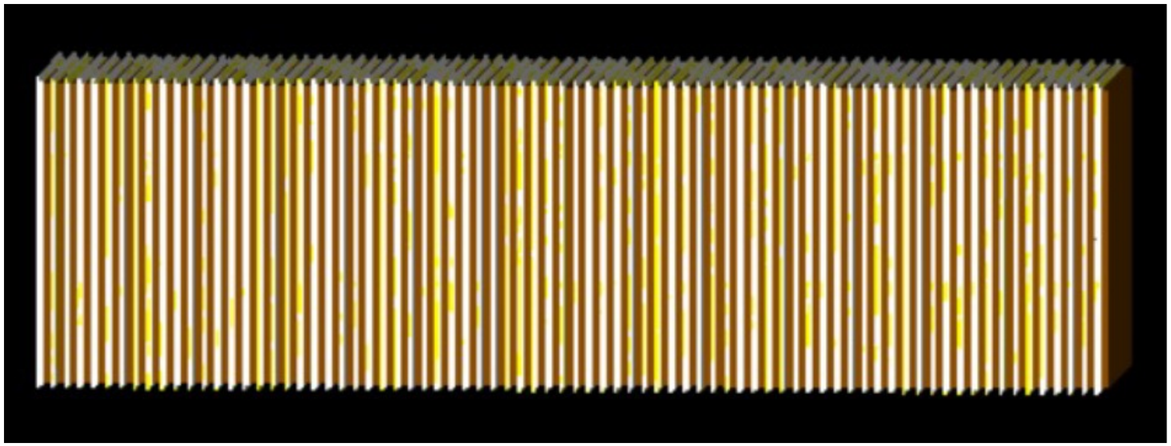


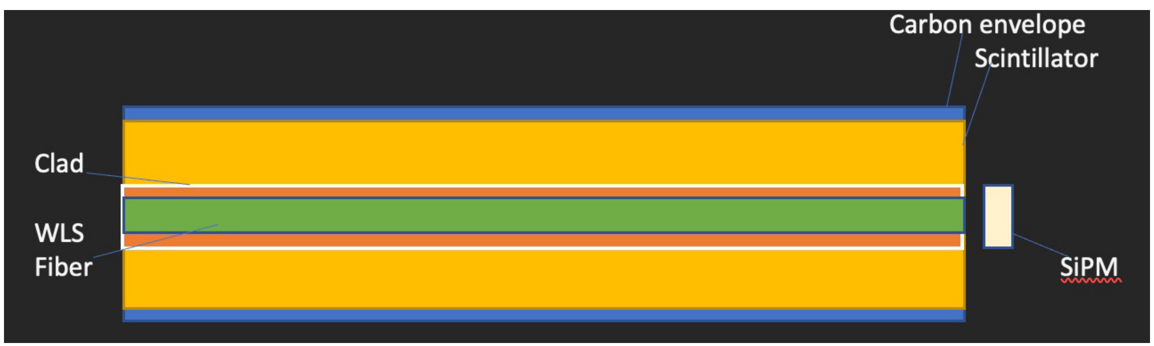
An SPE signal



A cosmic ray signal

Detector R&D: hadronic calorimeter

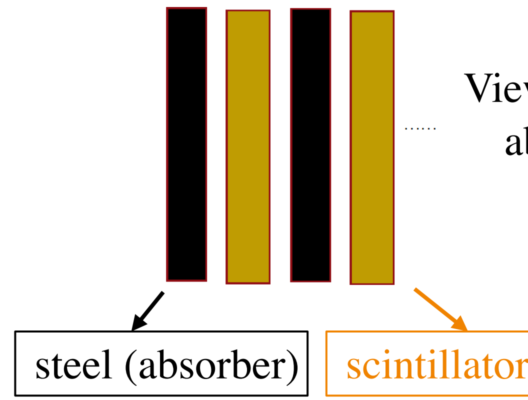




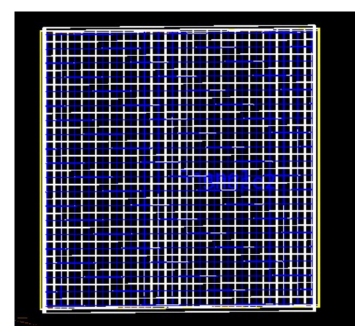
4×4×1 modules: 100×100 (cm) in x-y plane.
Each scintillator wrapped by a carbon envelope, with a wavelength shifting (WLS) fiber placed in its centre.

Veto the muon and hadron backgrounds.

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



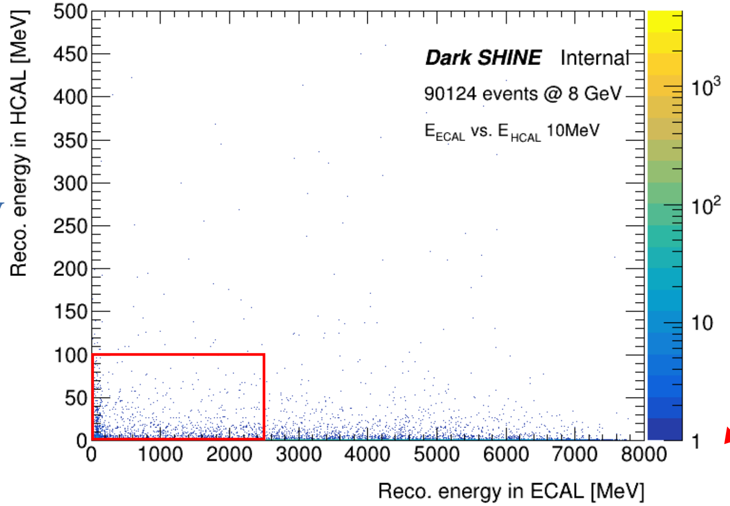
View from above

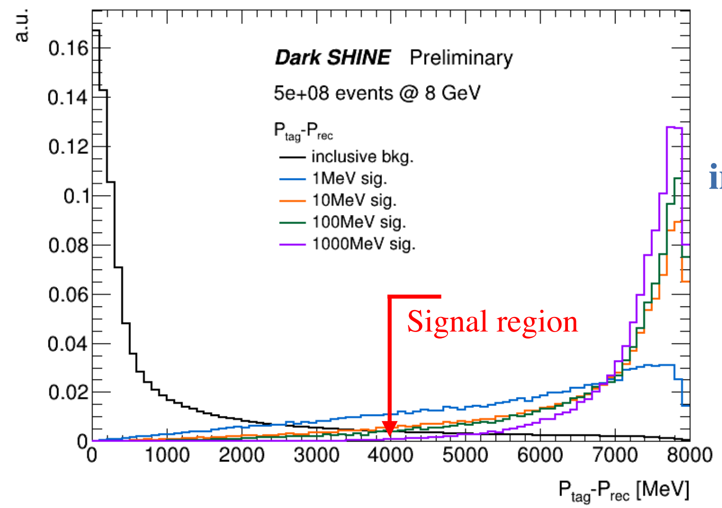


View of x-y crossing

Kinematic distributions

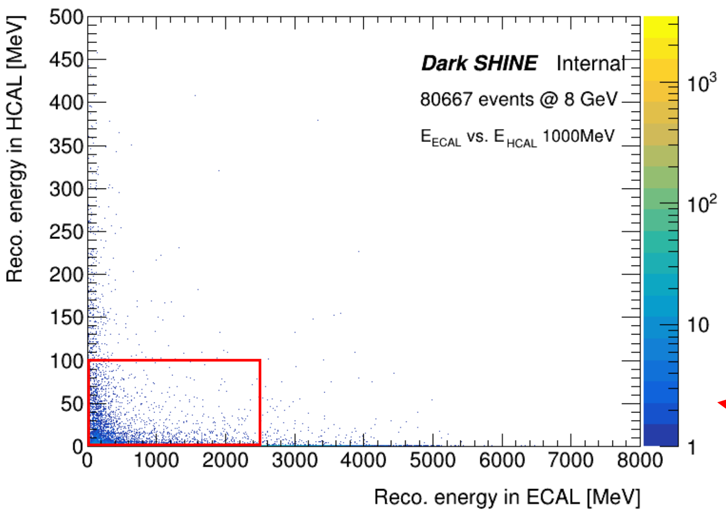
Signal
10 MeV

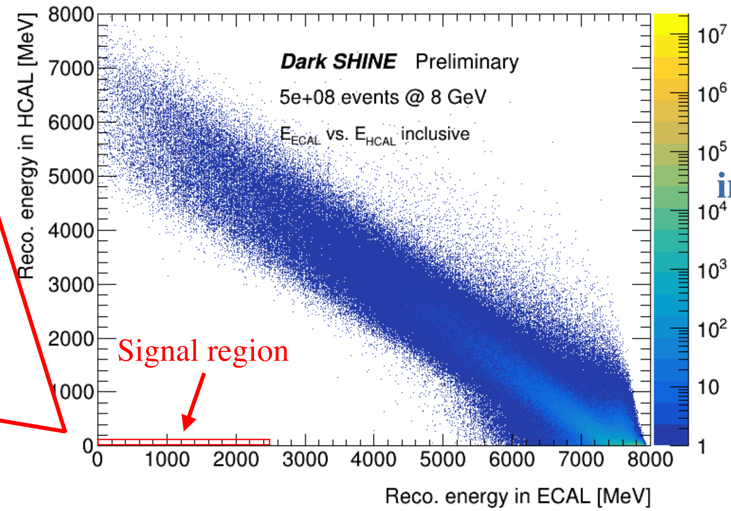




inclusive bkg.
&
signal

Signal
1 GeV





inclusive bkg.

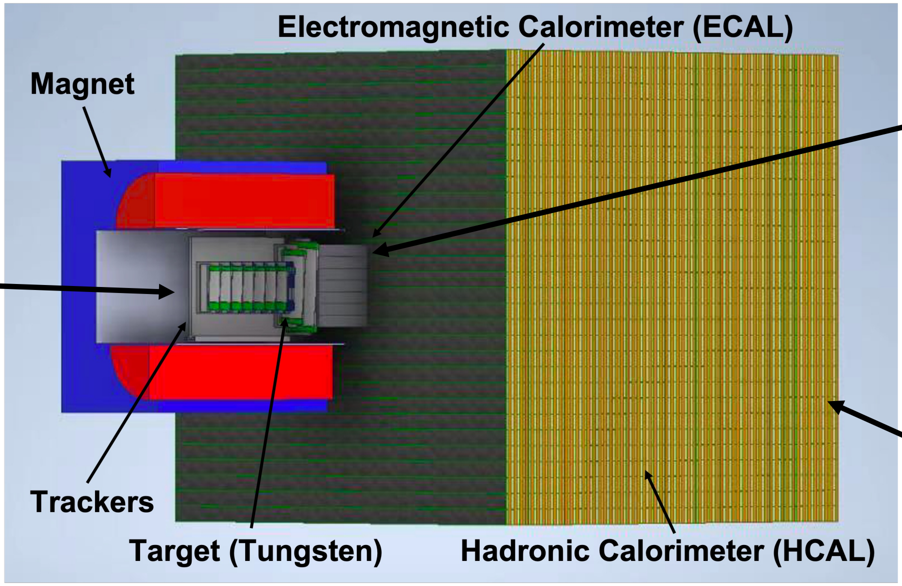
Signal region definition

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

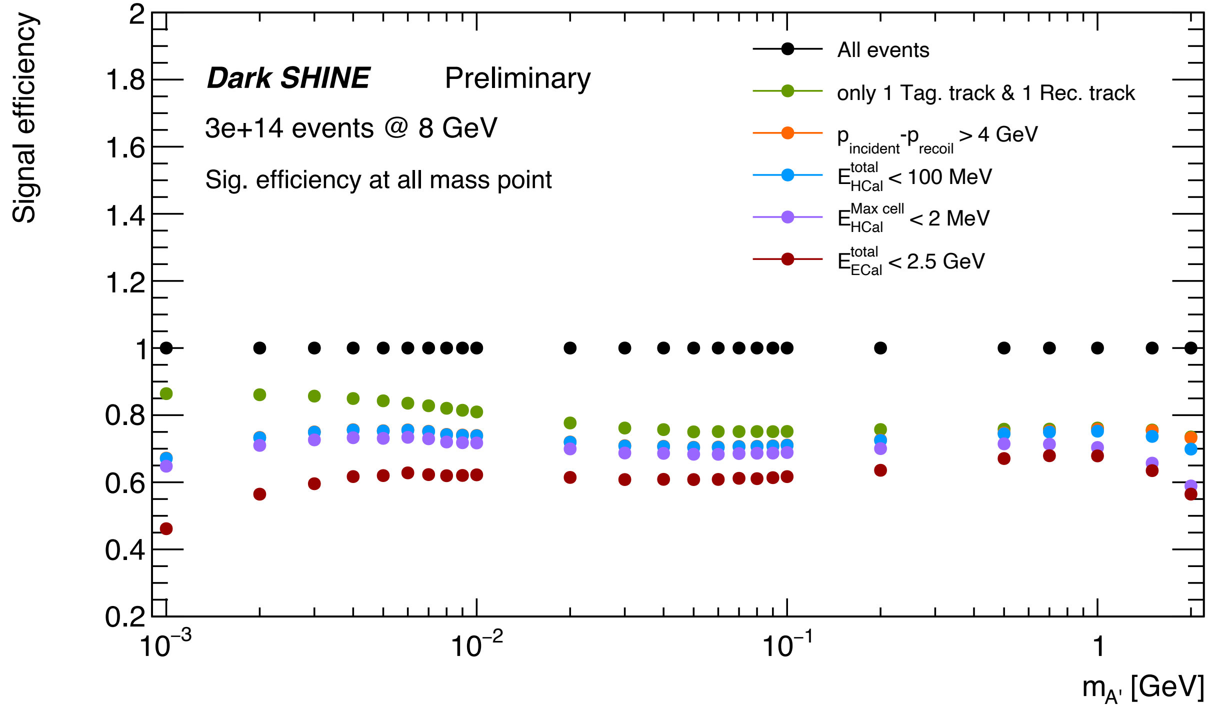
$E_{HCAL}^{total} < 100$ MeV;

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

(1st round DarkSHINE analysis)

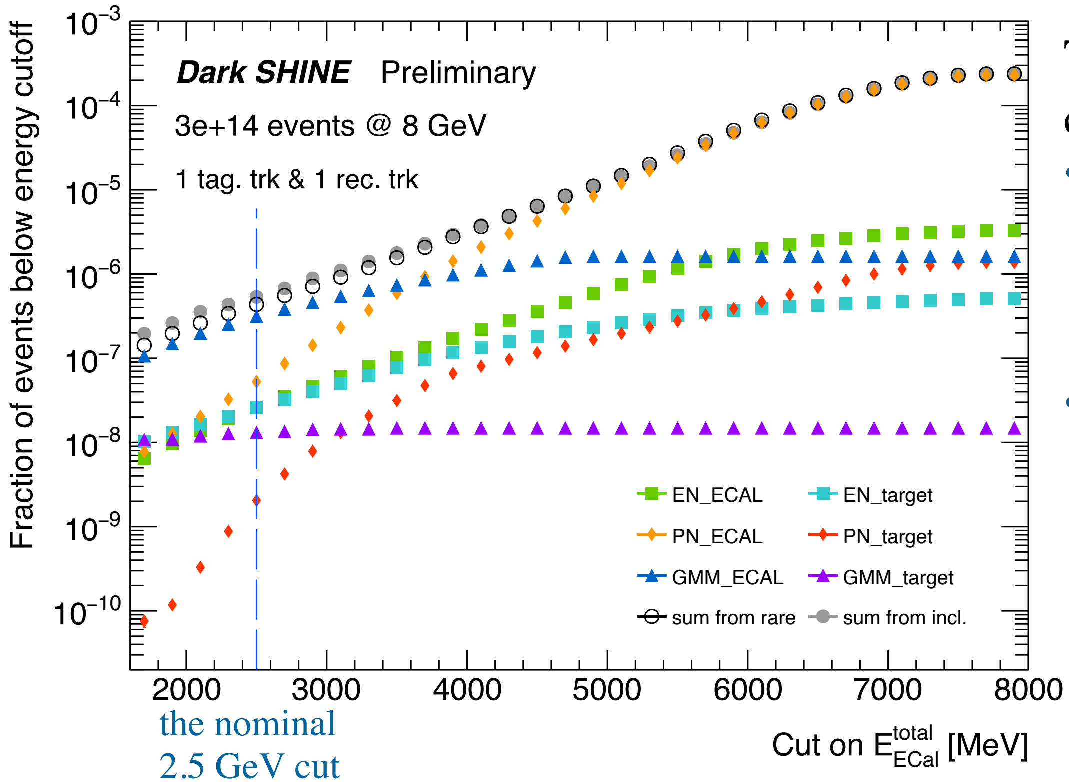
Signal efficiency

- ~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.



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)

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 computed from the event ratio at given ECAL energy cut.

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

Simulation study summary

- All simulated samples are produced based on the baseline geometry described before, with:
  - Incident electron energy of 8 GeV
  - DarkSHINE software (based on GEANT4 v10.6.0, characterized by the DarkSHINE detector)
- After applying the analysis cuts,
  - Expected total background yield: 0.015 bkg. event/ 3×10^{14} EOTs
  - Irreducible background: neglected

➢ Inclusive background sample and rare background process production →

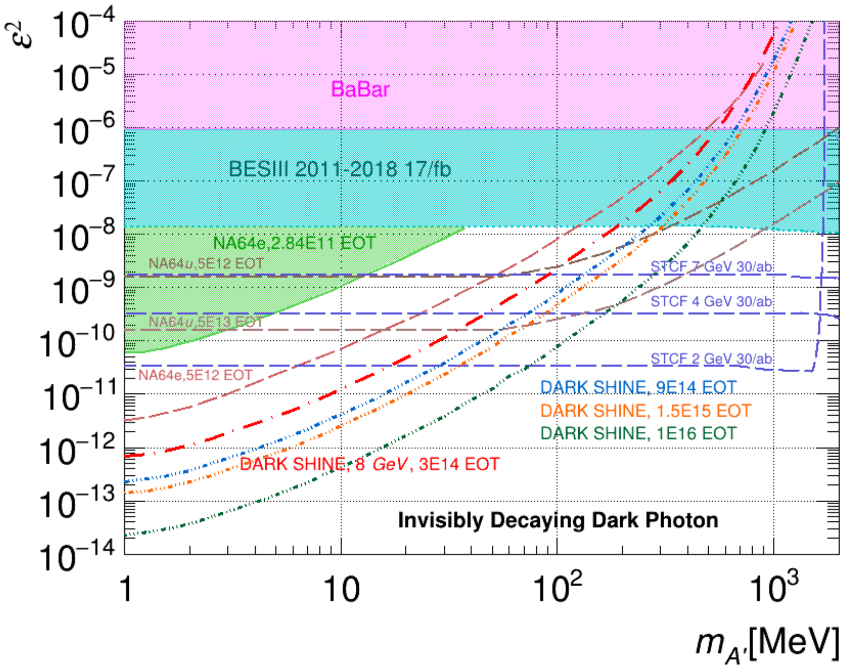
➢ signal sample: 1×10^{5} EOTs for each mass point (23 dark photon mass points in total).

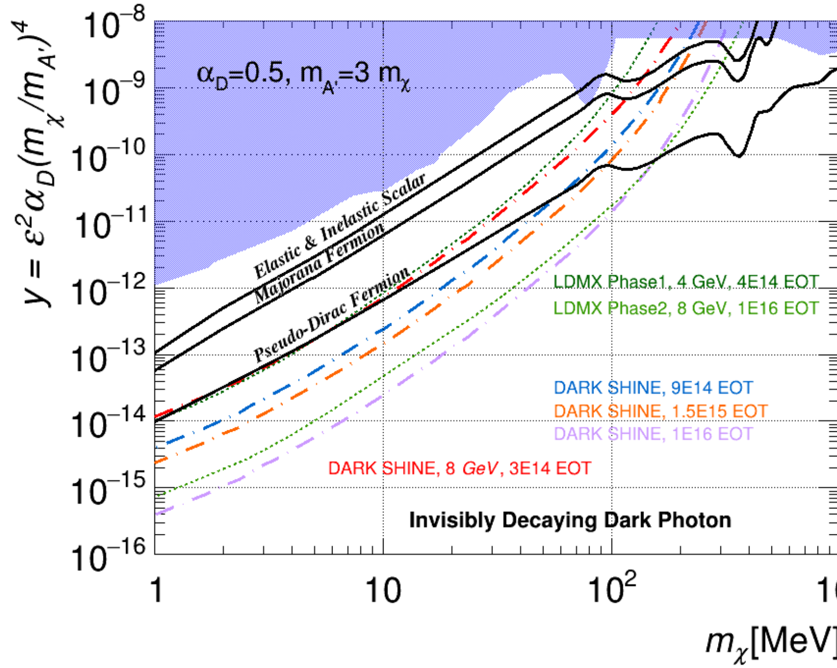
Process	Generate Events	Branching Ratio	EOTs
Inclusive	2.5×10^{9}	1.0	2.5×10^{9}
Bremsstrahlung	1×10^{7}	6.70×10^{-2}	1.5×10^{8}
GMM_target	1×10^{7}	$1.5(\pm0.5)\times10^{-8}$	4.3×10^{14}
GMM_ECAL	1×10^{7}	$1.63(\pm0.06)\times10^{-6}$	6.0×10^{12}
PN_target	1×10^{7}	$1.37(\pm0.05)\times10^{-6}$	4.0×10^{12}
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}

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

Expective sensitivity

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).

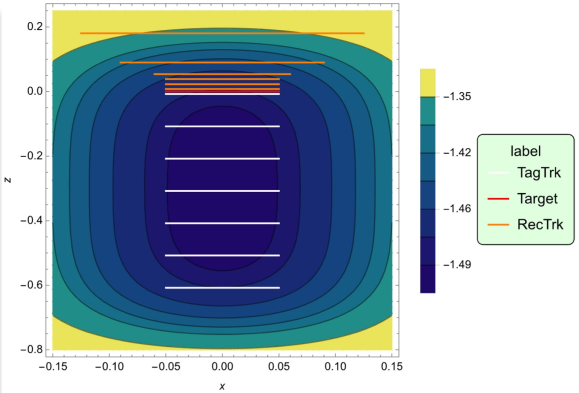
Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)

What's next?

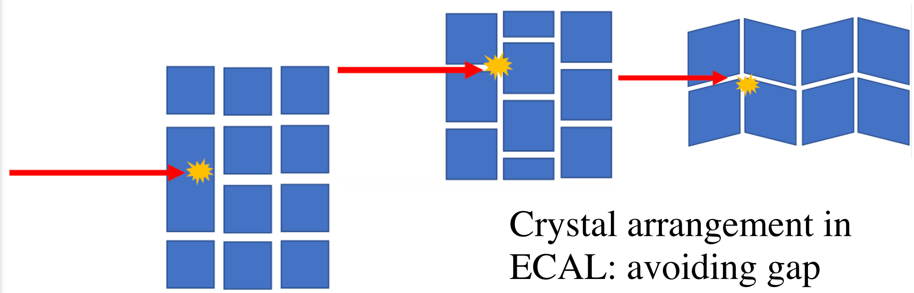
Many interesting tasks ongoing after the 1st round of prospective study based on truth information:

- 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, …

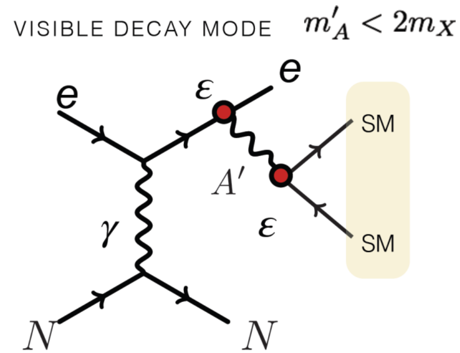
We're stepping into the real world!



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



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.

Conclusion

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

- **Detector R&D ongoing.**
  - strip sensor prototype & LYSO crystal
  - SiPM and fast readout system
  - HCAL simulation study
- **First prospective study published.**
  - good signal efficiency, background well suppressed.
  - expecting competitive sensitivity.
- **Further analysis started.**

- **Stay tuned! ☺**

Timeline

- **2022:** first simulation studies of detector system; establish the DarkSHINE collaboration with SHINE facility.
- **2023:** calorimeter and tracker systems R&D, magnet and mechanical supporting layout, first conceptual beamline design.
- **2024:** In-lab technical demonstration of detector prototypes, overall conceptual design of detector system, preliminary beamline conceptual design.
- **2025:** finish up sub-detector prototyping; cosmic tests and beam tests.
- **2026:** DarkSHINE beamline and detector systems construction.
- **2028:** first commissioning of the overall DarkSHINE experiment at the accomplished SHINE facility.

Back up

Simulation event display

The 1st round of prospective study based on truth information has been finished.

Physics motivation

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

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

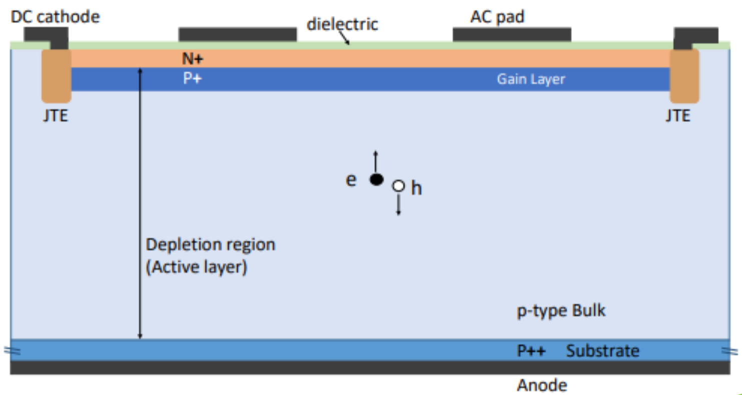
Kinetic mixing term | Field strength tensor | Dark photon field

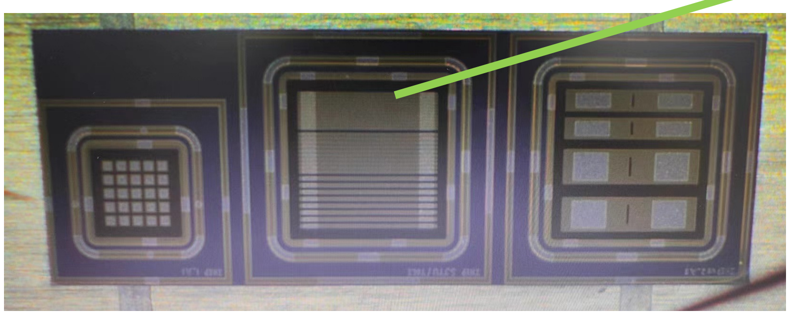
Minimal dark photon model with 3 unknown parameters:

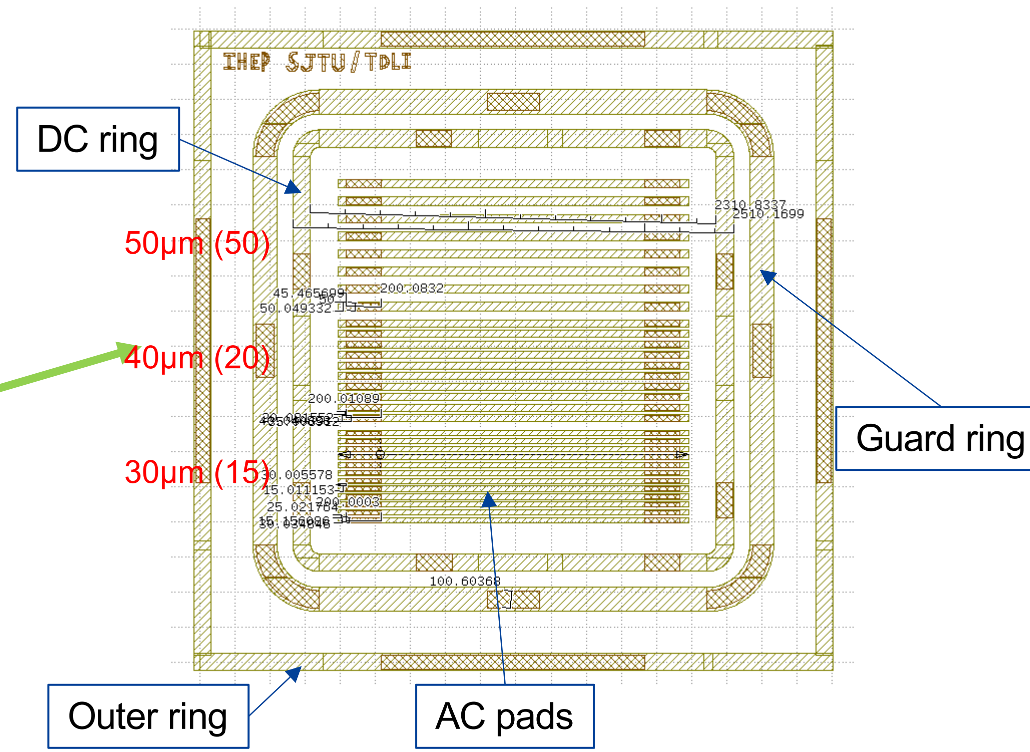
- Kinetic mixing parameter $\boldsymbol{\varepsilon}$;
  (Mixing-induced coupling suppressed relative to that of photon by factor ε)
- Dark photon mass $\boldsymbol{m_{A'}}$;
- **Decay branching ratio** (assumed to be either unity or zero) of dark photon into invisible dark sector.

arXiv:2104.10280

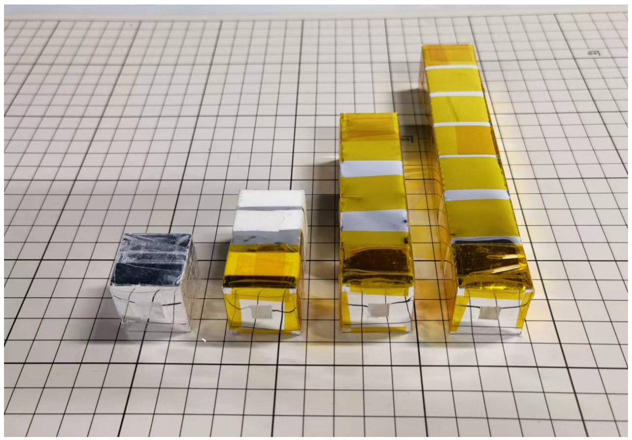
Sensor structure

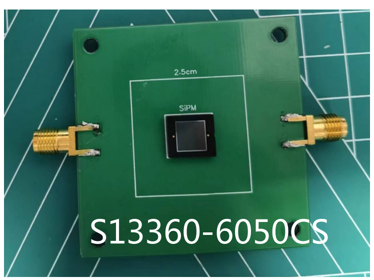


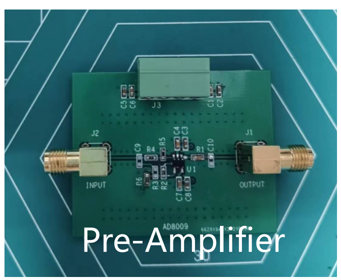




ECAL Detector Unit

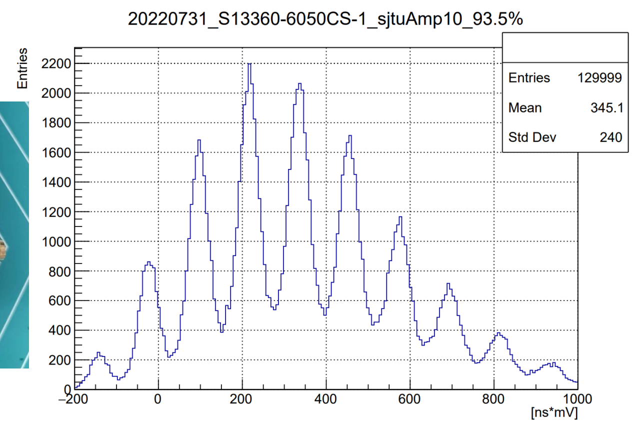


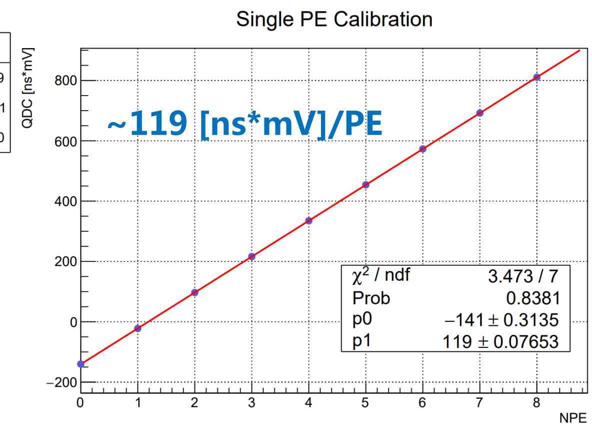




LYSO: $Lu_{(1-x-y)}Y_{2y}Ce_{2x}SiO_5$

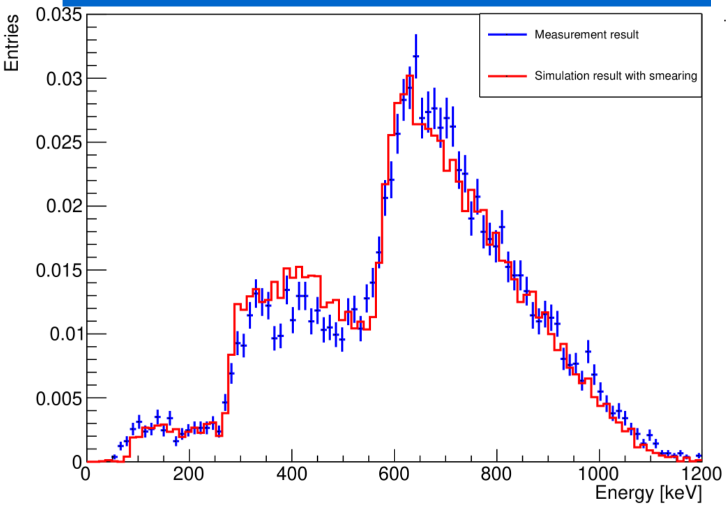
Density	Decay Time	Light Yield	Refraction Index	Radiation Length
7.2 g/cm3	40 ns	30000 p.e/MeV	1.82	1.14 cm

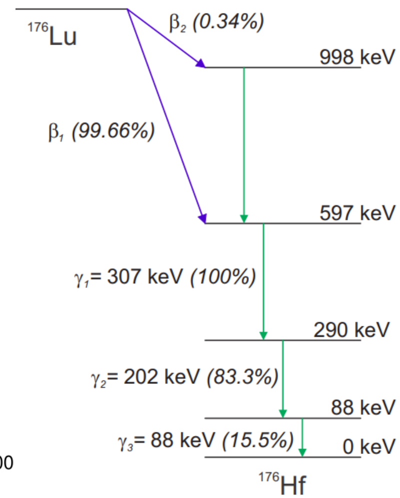




Intrinsic Radiation and Radioactive Source Test

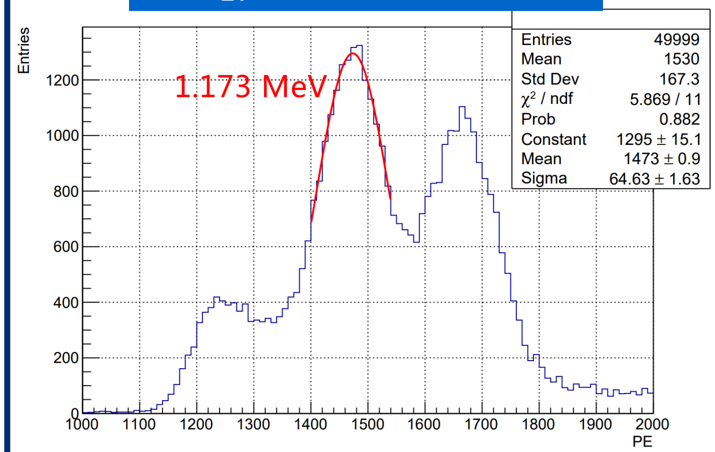
Inrinsic Radiation





- 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.

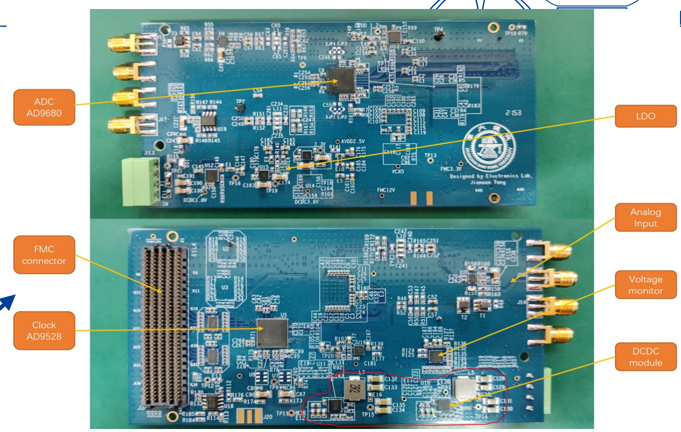
$^{60}_{27}Co$ Source Test

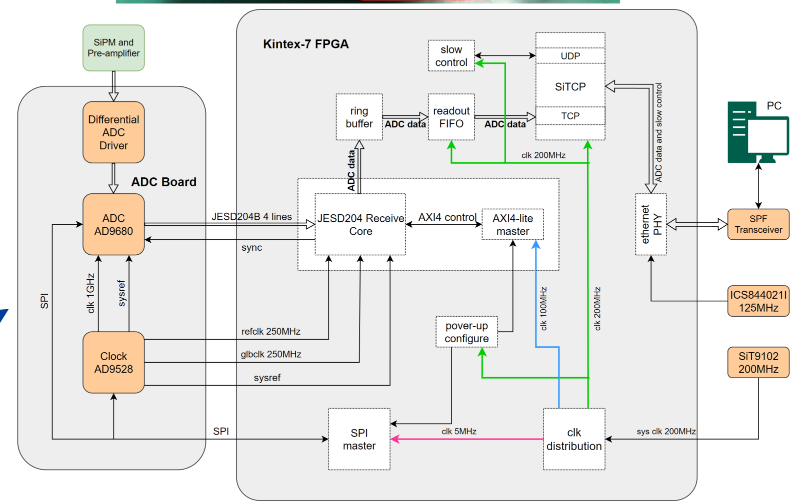


- $^{60}_{27}Co$ radioactive measurement result
- 5×2.5×2.5 cm^3 LYSO
- Light Yield: 1255.75 PE/MeV

Design scheme

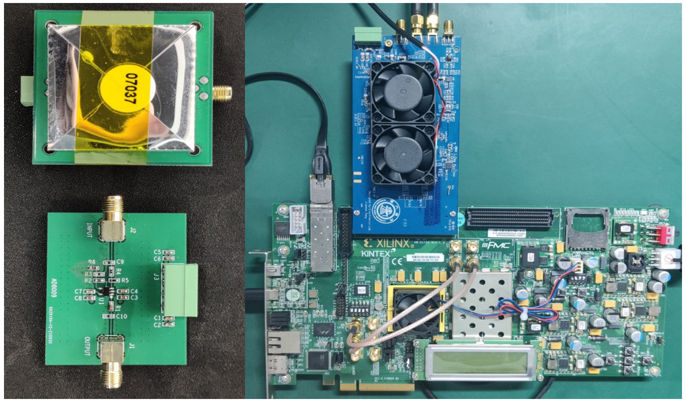
- **Ecal** used **SiPM** to detect photon
- SiPM
  - Width : tens of nanoseconds
  - Rising edge : about 2-3 nanoseconds
  - Requirement : higher sample rate ~ GSPS
- ADC chip : AD9680 (from ADI)
  - Sanple rate : 1GSPS
  - Resolution : 14 bits 1.7Vpp 0.1038mV/LSB
  - 2 channels/piece, 2GHz input bandwidth
- 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

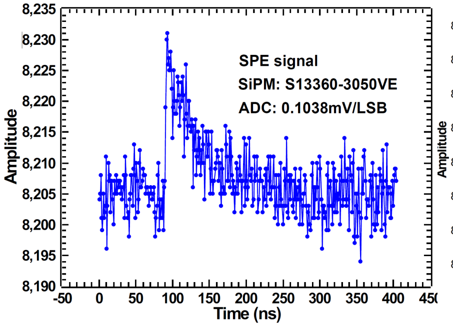




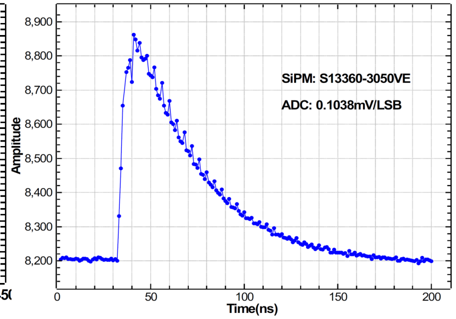
Test results

- 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





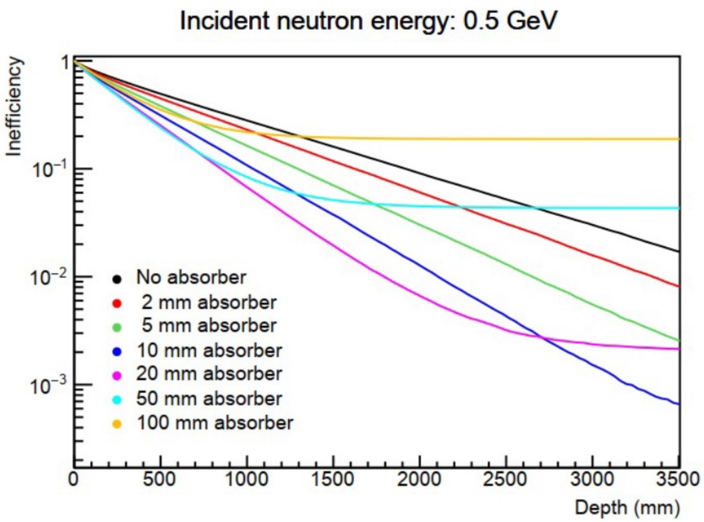
An SPE signal



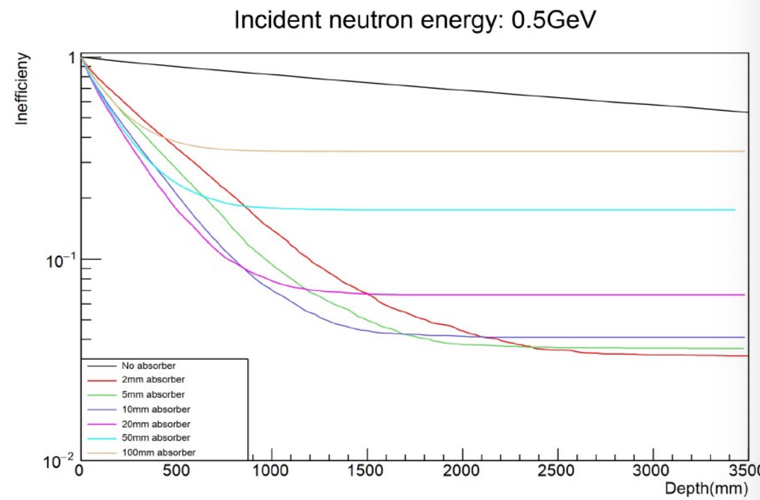
A cosmic ray signal

HCAL design

Veto Inefficiency Simulation



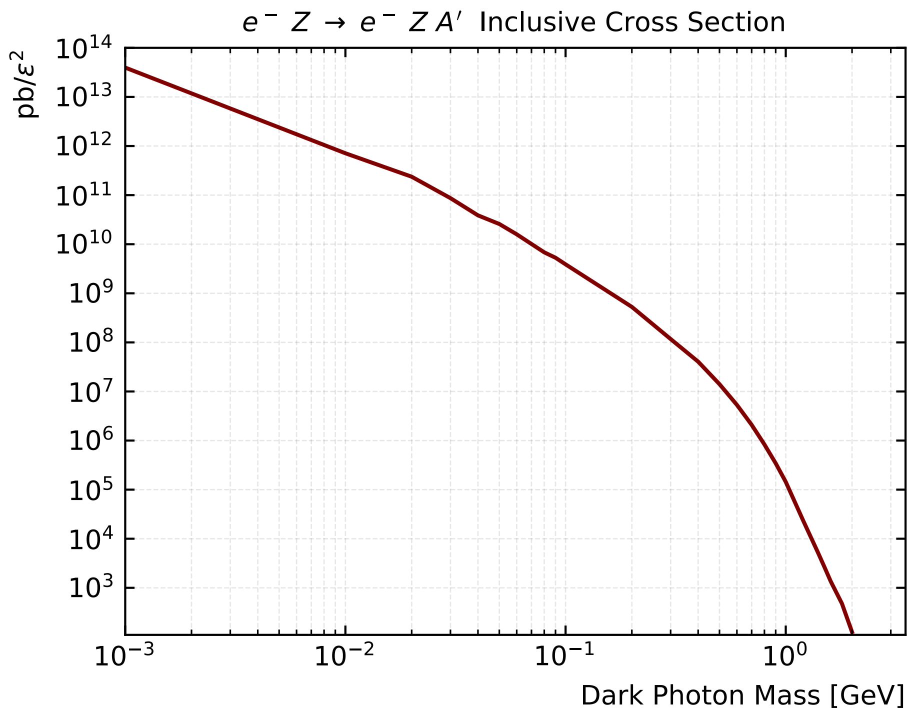
LDMX



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:

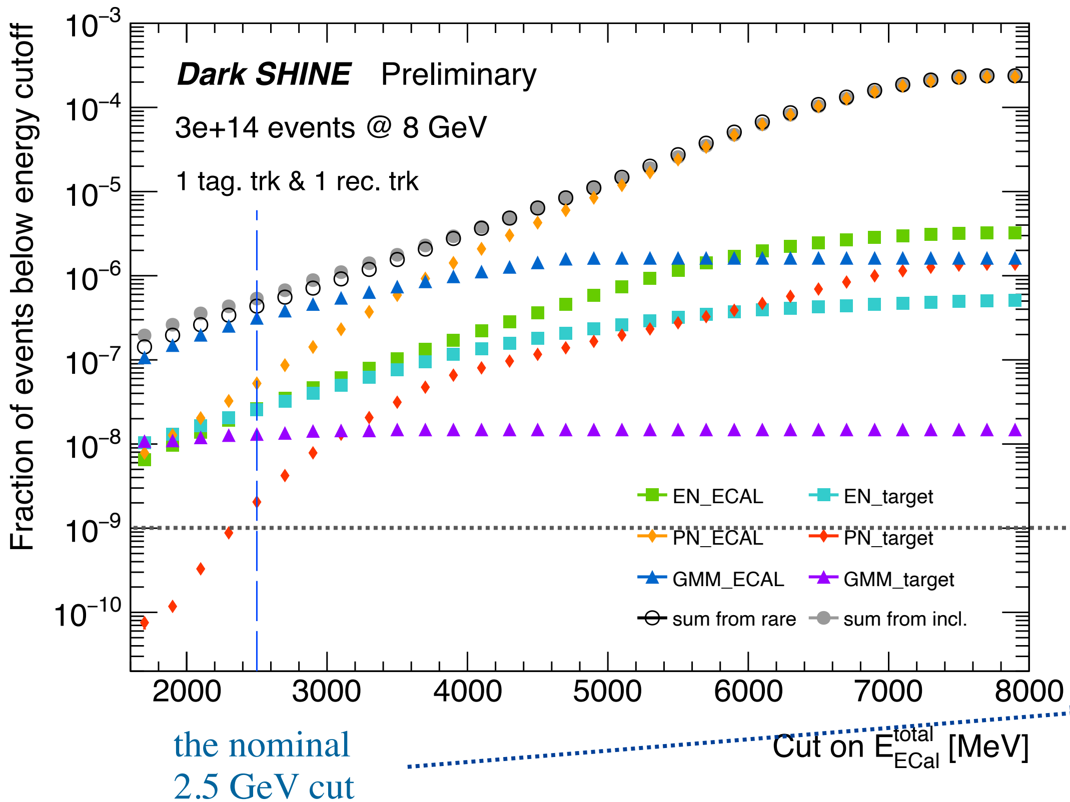
- Inclusive background: 2.5×10^{9} EOTs produced.
- Rare background: only GMM (target) process exceeds 3×10^{14} EOTs.

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:

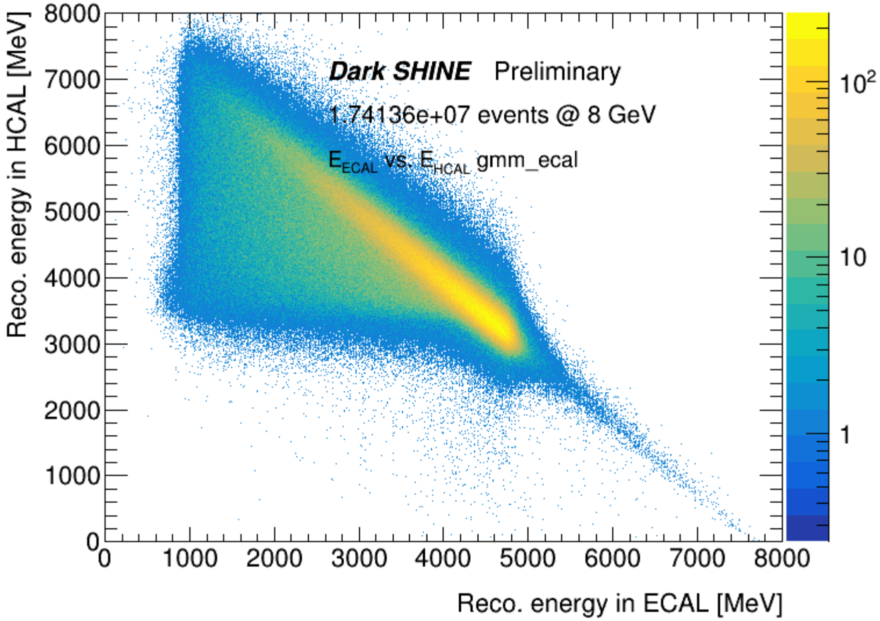
- $\boldsymbol{y = 10^{-9}}$:
  for 10^9 EOT, less than 1 event will remain after applying any cut tighter than $E_{ECAL}^{total} < x$ MeV.
- $\boldsymbol{x = 2500}$:
  y of the background events will survive the cut $E_{ECAL}^{total} < 2500$ MeV.

Extrapolation: rare processes

Not all the rare processes need further extrapolation.

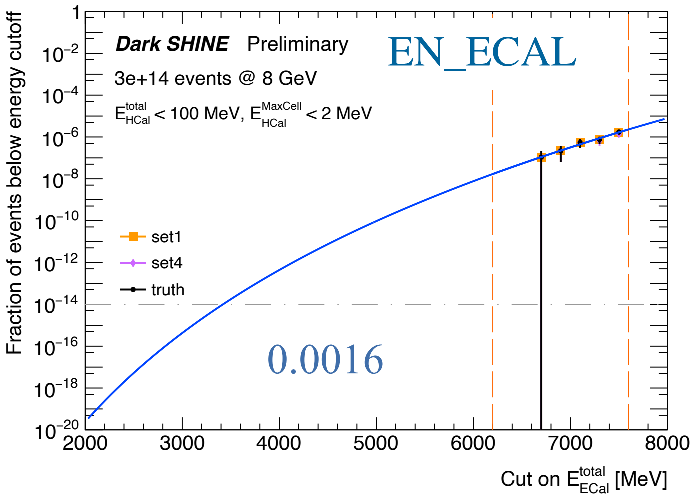
There are 6 rare background processes in total:

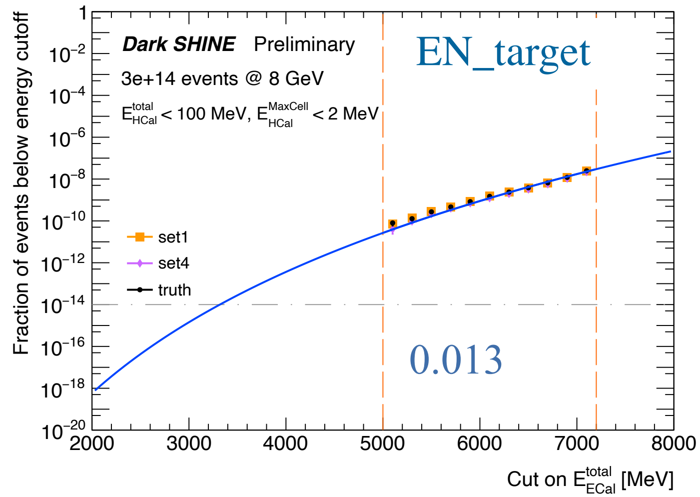
- EN(ECAL), PN(ECAL), **GMM(ECAL)**, EN(target), PN(target), **GMM(target)**

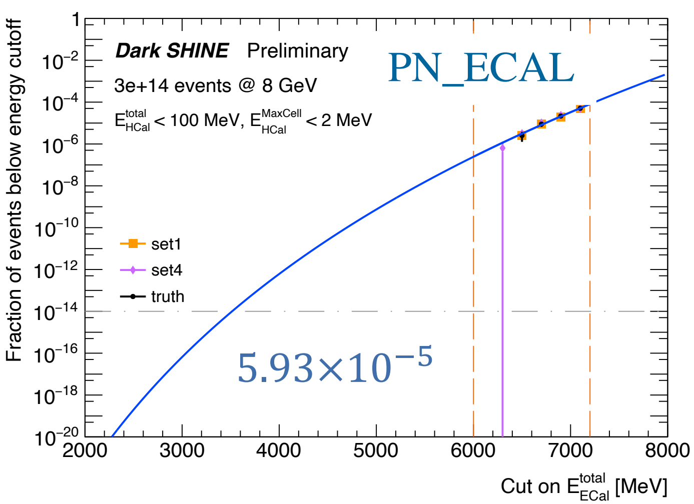


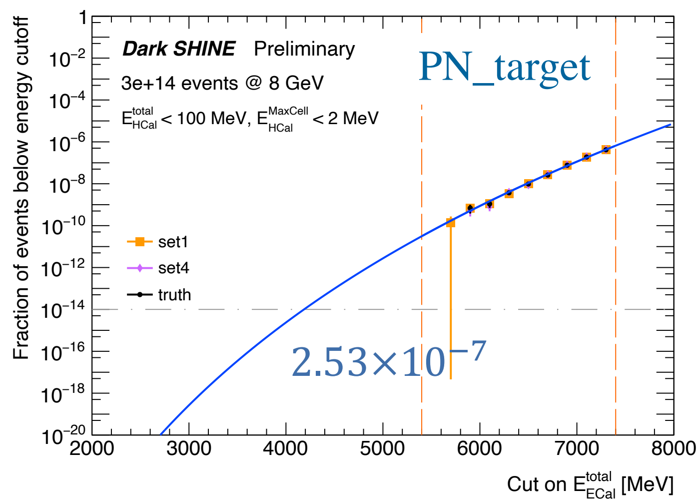
- Available statistics: $\sim 4.3\times10^{14}$ (target) and $\sim 6\times10^{12}$ (ECAL) EOTs considering the branching ratio.
- extrapolation method no longer applicable due to the energy distribution.
- Can always be effectively rejected by the HCAL requirement (fraction of the remaining GMM events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

Extrapolation: rare processes







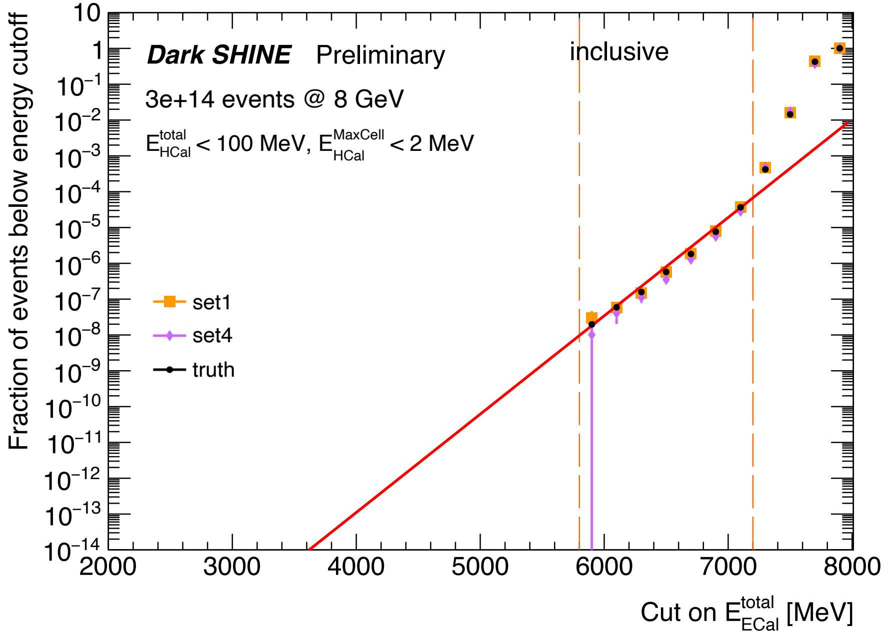


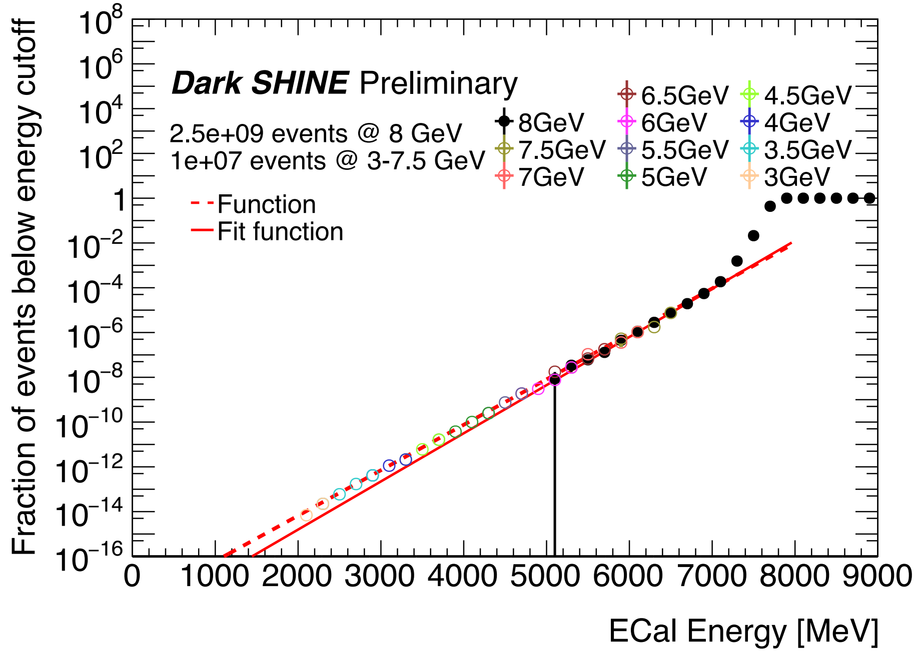
Sum: 0.015

~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