Recent progress of Dark SHINE R&D

Tong Sun on behalf of the DarkSHINE R&D team

The 5th Workshop on Frontiers of Particle Physics

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李政道研究所
TSUNG-DAO LEE INSTITUTE

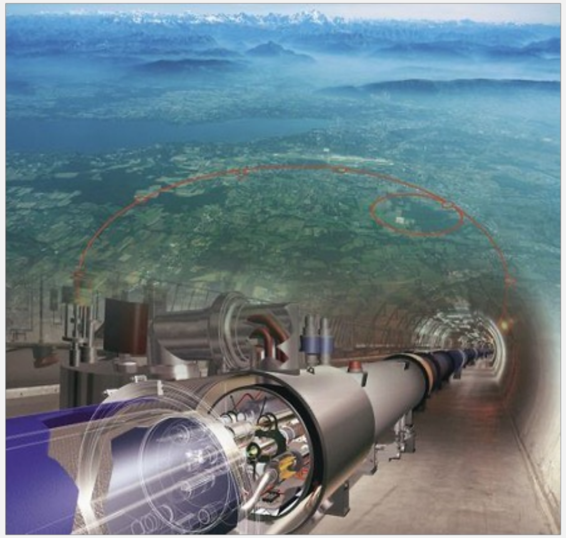
Outline

- DarkSHINE experiment motivation
- The SHINE facility and DarkSHINE Prospective Sensitivity
- DarkSHINE simulation software
- Detector R&D. status
- Summary

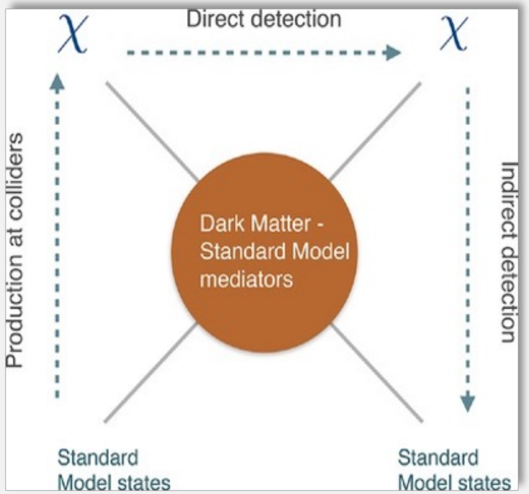
Physics motivation

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

- constituting ~25% of the universe energy content.

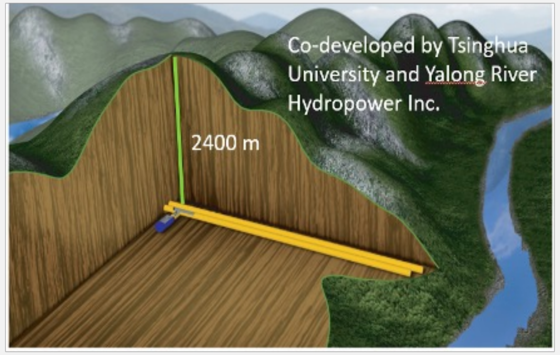


Collider experiments
(LHC, BELLE-II , BESIII etc.)



Space experiments
(DAMPE, AMS etc.)

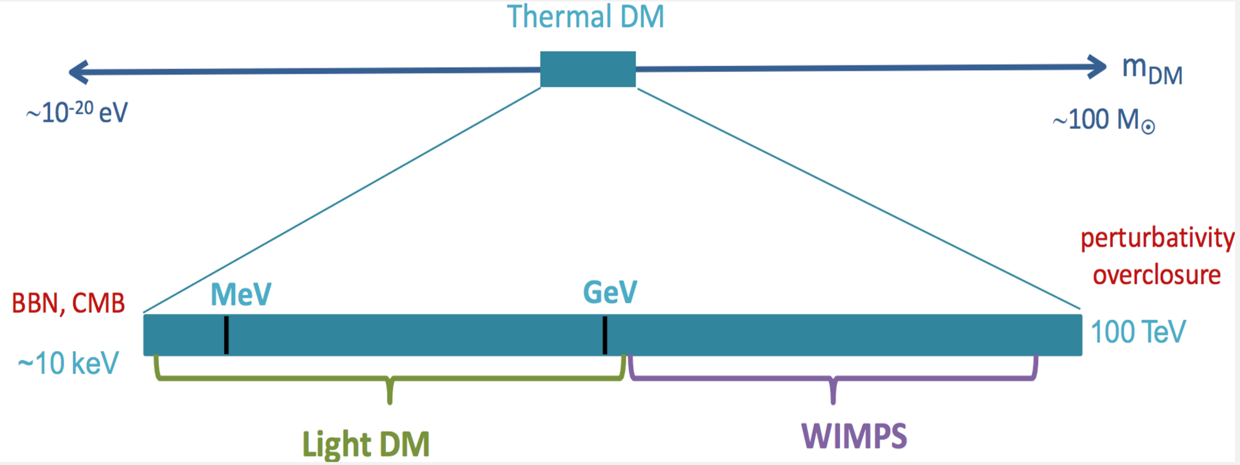
Underground experiments
(CDEX , PandaX, LUX, Xenon etc.)

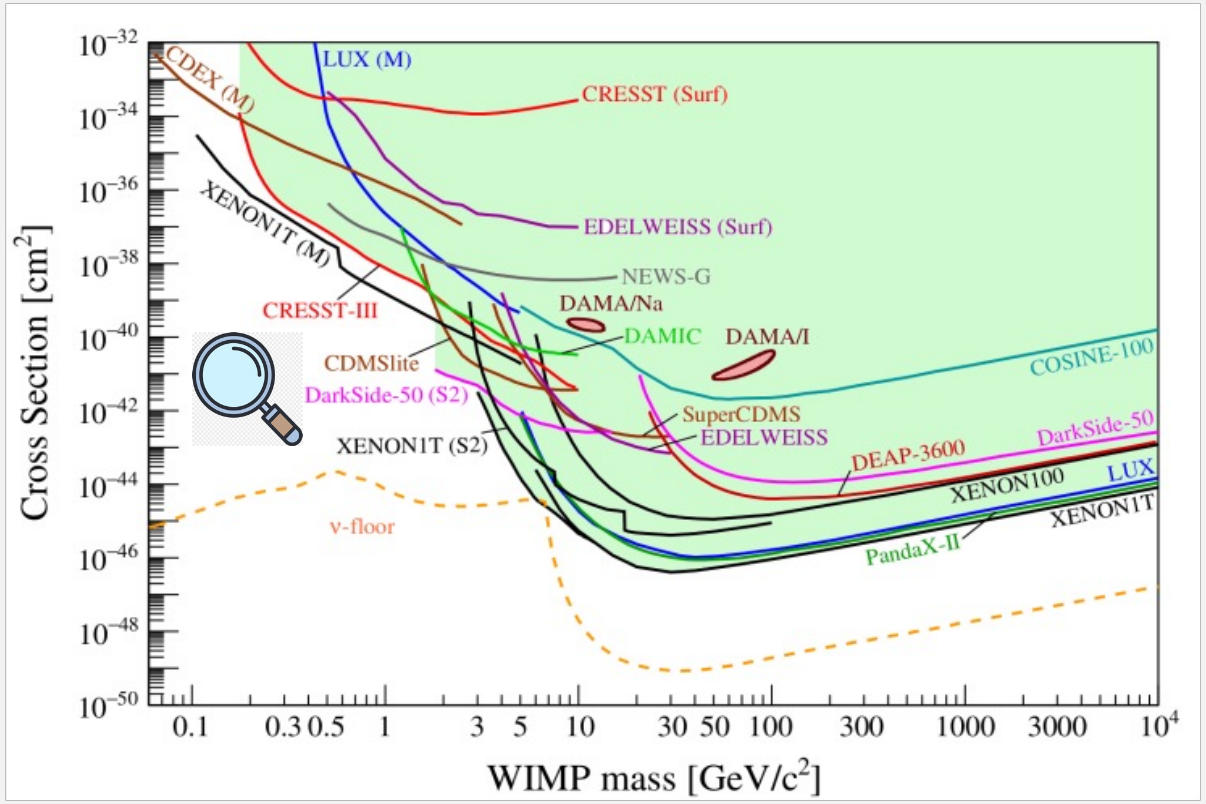


Physics motivation

The "freeze-out” mechanism predict the mass of dark matter is mainly distributed from MeV to tens of TeV

- Weakly Interacting Massive Particles (WIMP): No evidence yet. A large parameter space ruled out in GeV~TeV mass range.
- Light DM (χ): Sub-GeV mass range not fully explored yet.



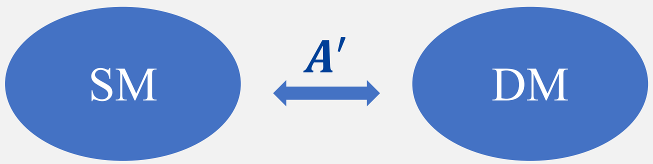


Physics motivation

Searching for sub-GeV light DM (χ):

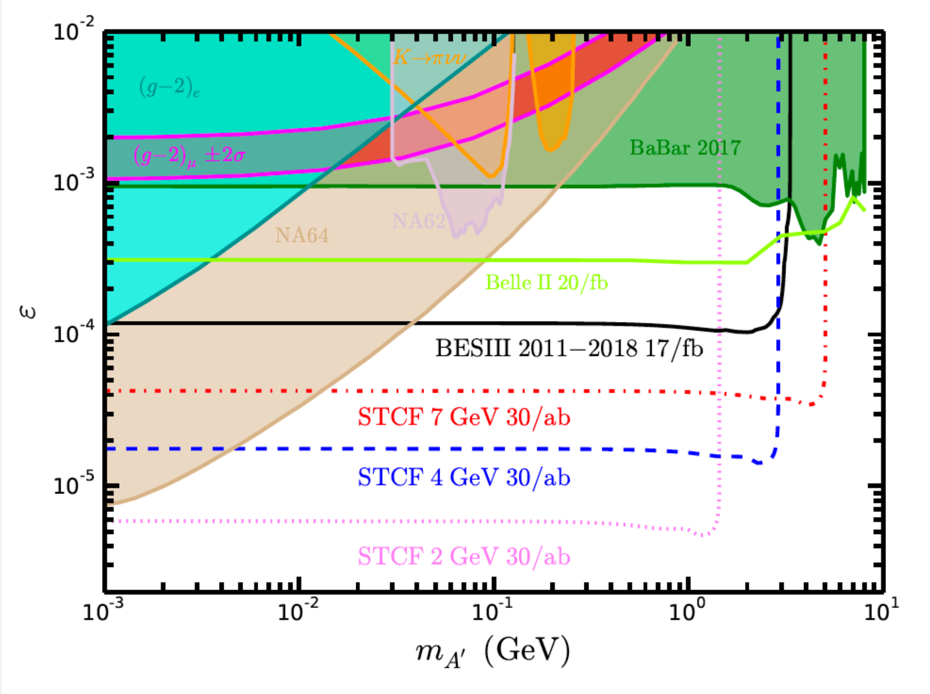
Dark Photon (A’) -an important portal between the (SM) particles and the dark matter(DM).

- Collider/accelerator-based experiments searching for dark photon: BESIII, BELL-II, NA64@CERN, etc.



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

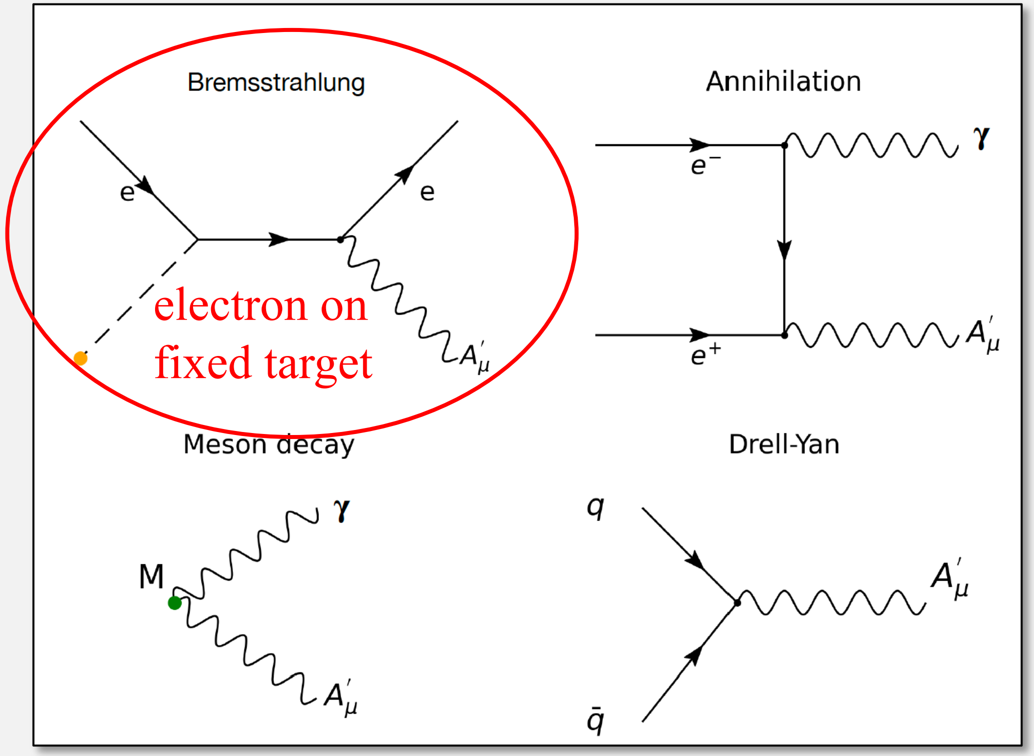
Kinetic mixing term | Field strength tensor | Dark photon field



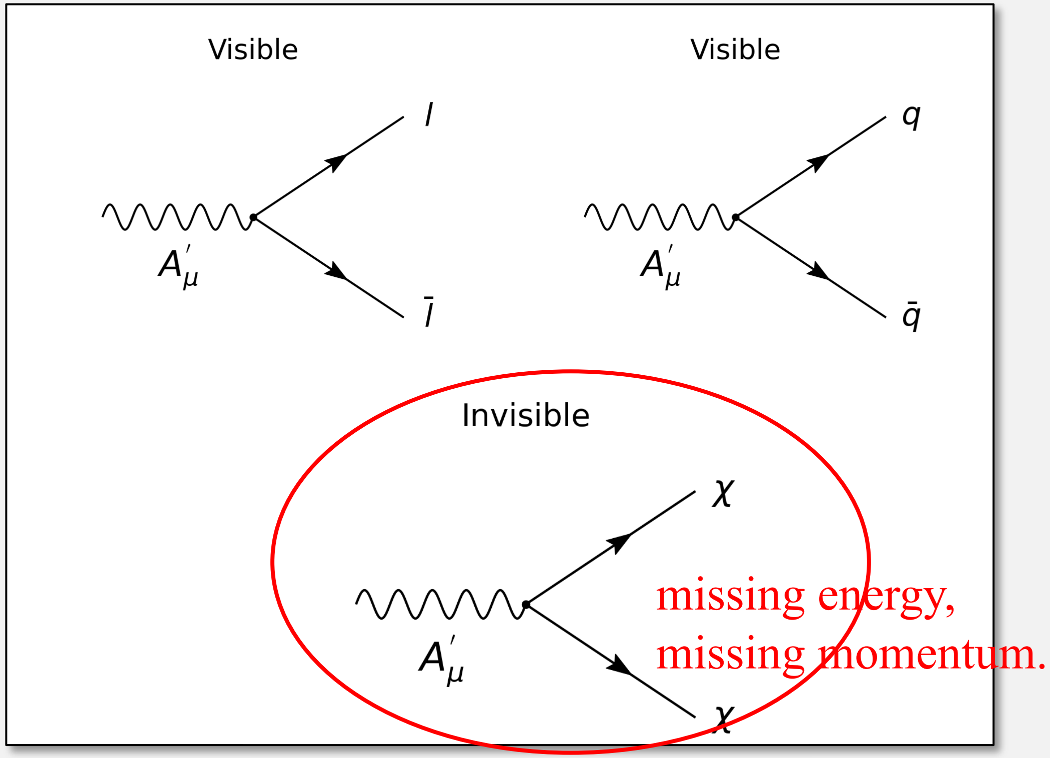
Dark Photon search sensitivity: collider vs fixed-target

Physics motivation

Processes to search for 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.

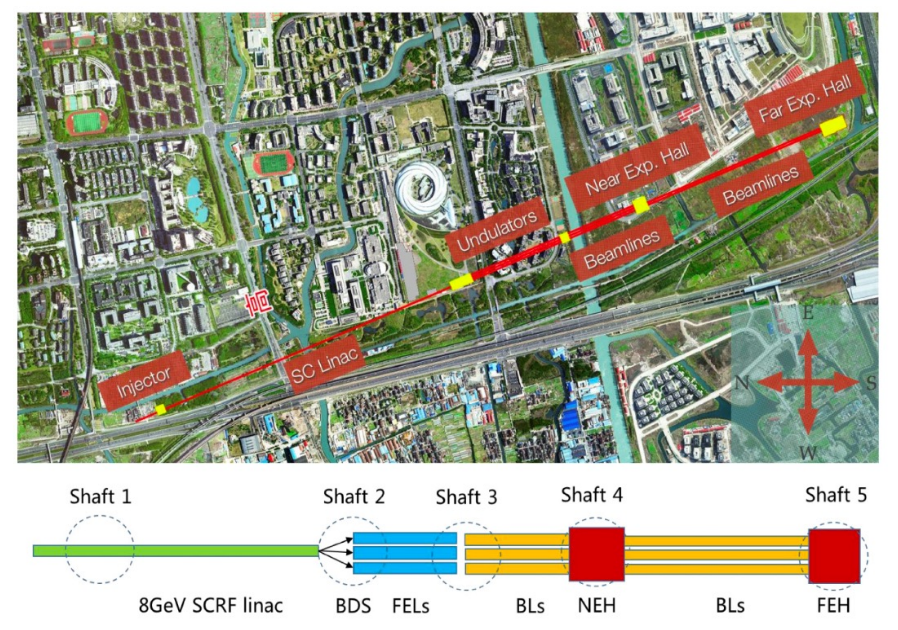
Electron source: SHINE facility

Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE) can provide high repetition rate single electron beams → with dedicated kicker to be designed and deployed.

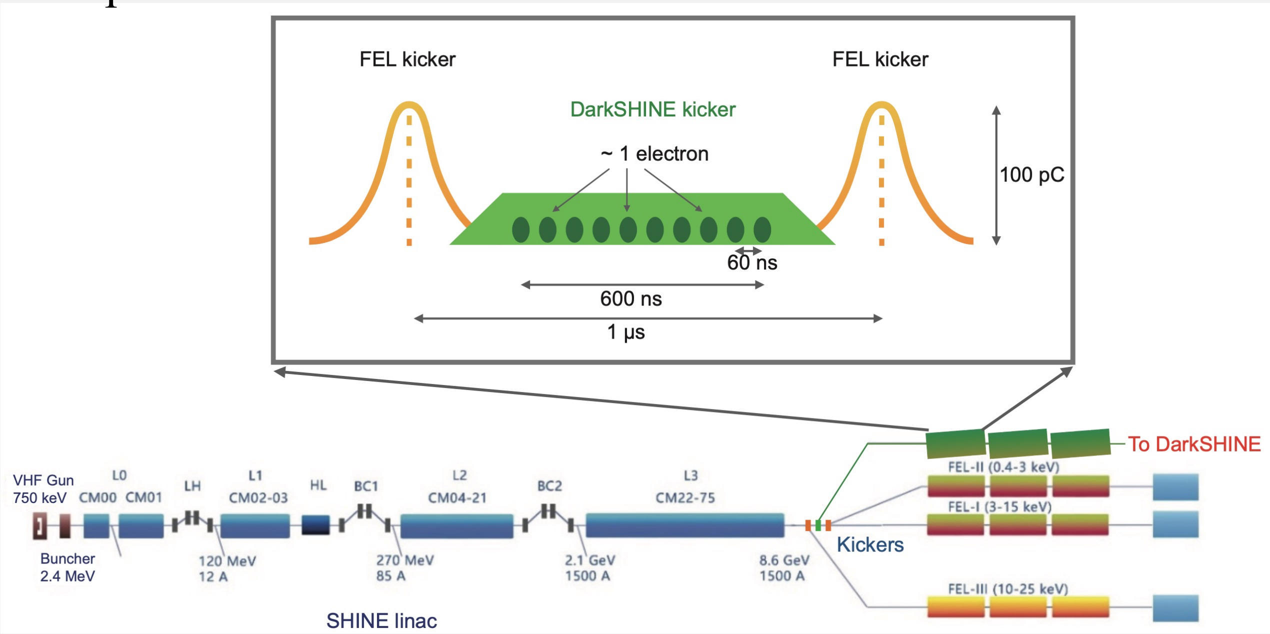
- Electron energy: **8 GeV**; Frequency: 1 MHz
  - **Expected to achieve ~3×10^{14} electrons-on-target (EOT) per year**

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

Under construction in Zhangjiang (2018-2026)

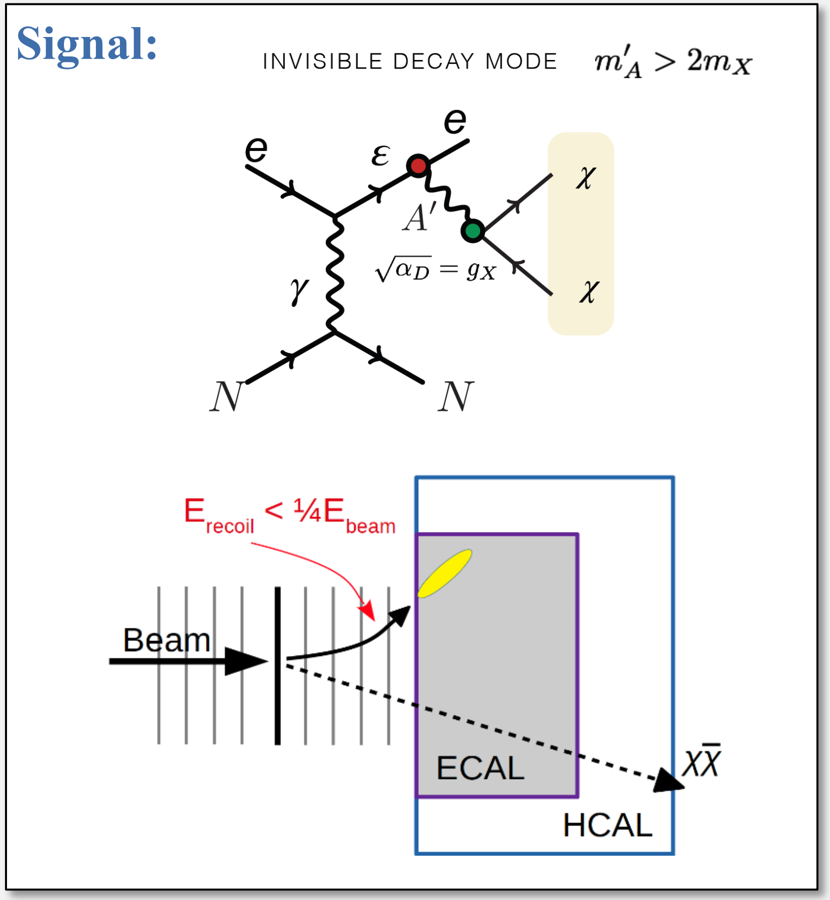


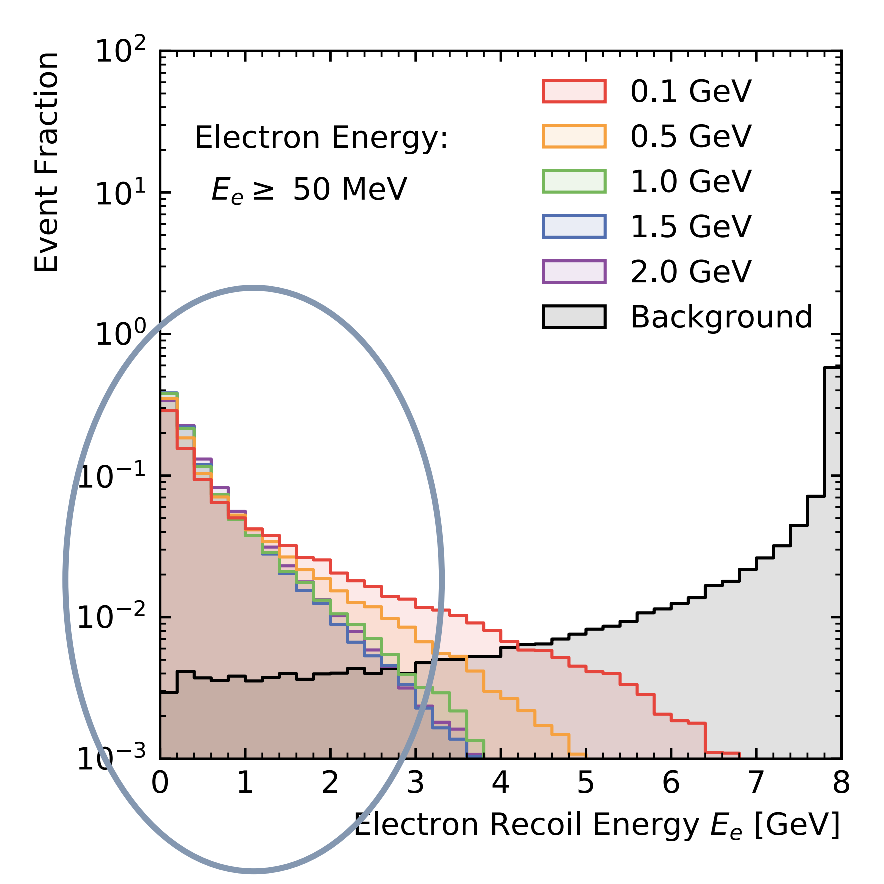
Dedicated to achieve 10MHz single electron beam with high repetition-rate kicker for Dark SHINE



Signal signature

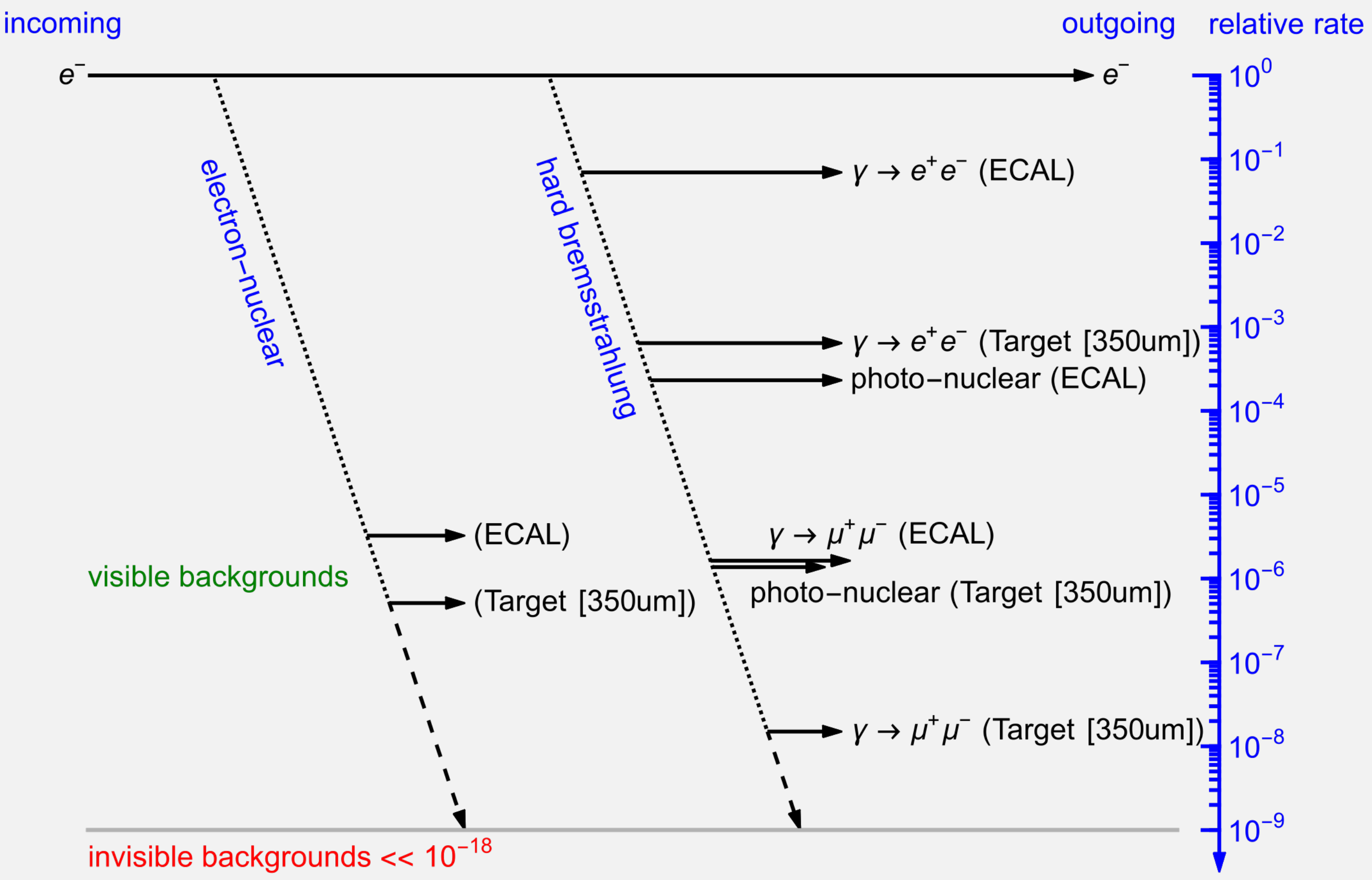
Missing particle signature: soft recoil electron, large missing energy & p_T.





Standard model barkground

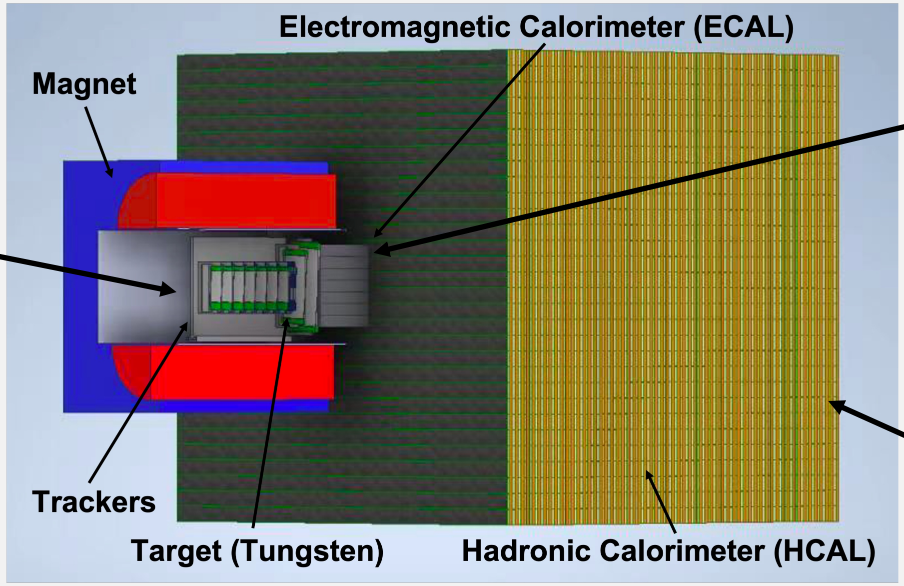
- **Leading background:**
  - **Hard bremsstrahlung**
- **Rare background processes:**
  - **Photonuclear (w. hard-brem γ)**
  - **Electronuclear**
  - **$\gamma \rightarrow \mu\mu$ (w. hard-brem γ)**
- **Irreducible but negligible:**
  - **neutrino production**



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

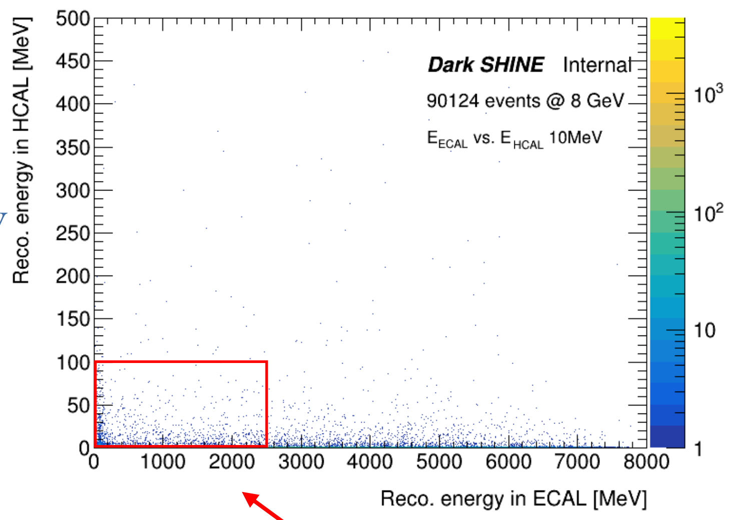
Electromagnetic calorimeter
Measure the deposited energy: electron and photon.

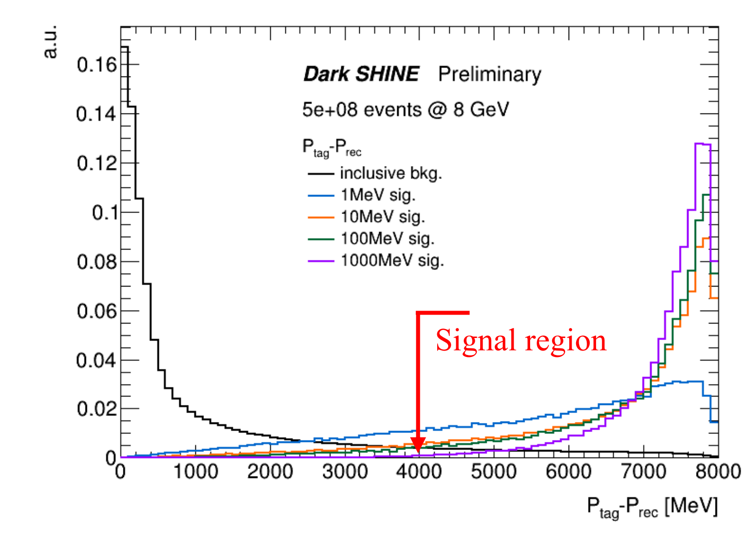
Hadronic calorimeter
Measure the deposited energy: muon and hadron backgrounds.

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

Kinematic distribution

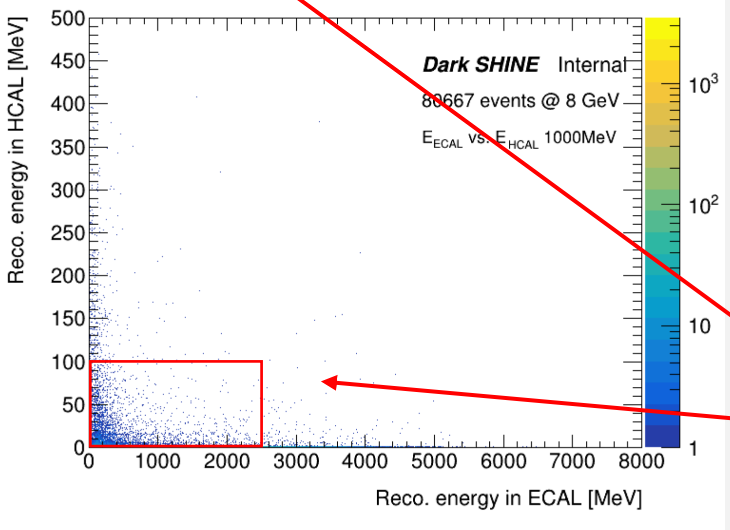
Signal
10 MeV

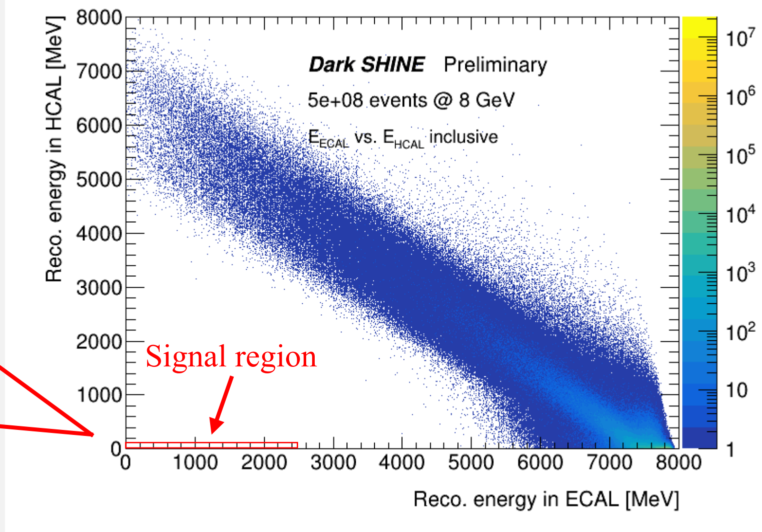




inclusive bkg.
&
signal

Signal
1 GeV





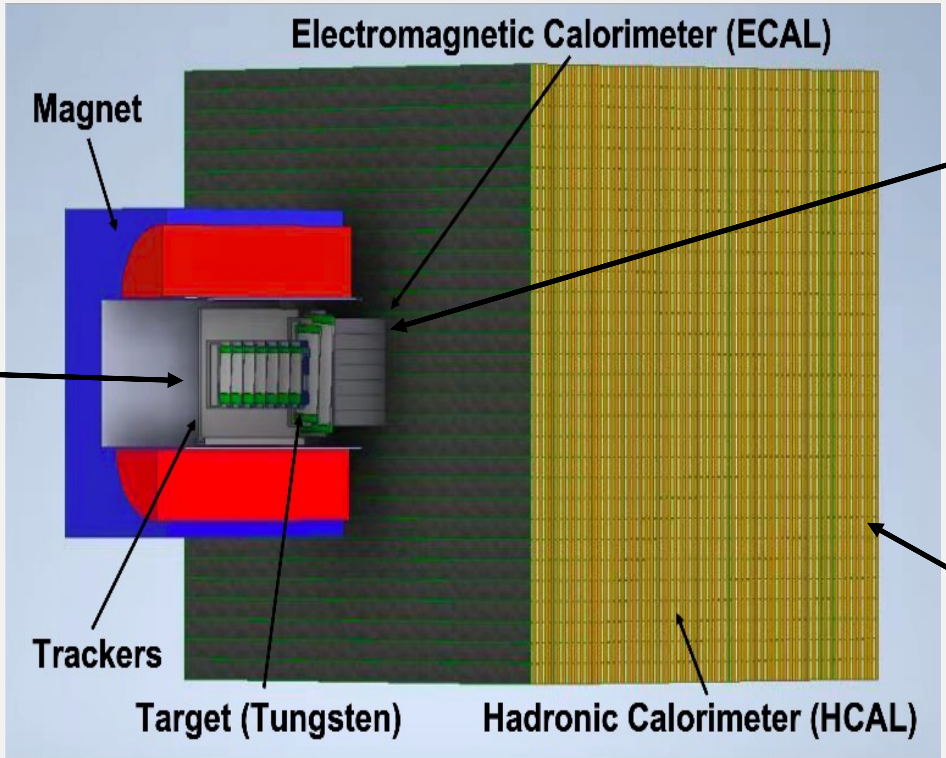
inclusive bkg.

Signal selection

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

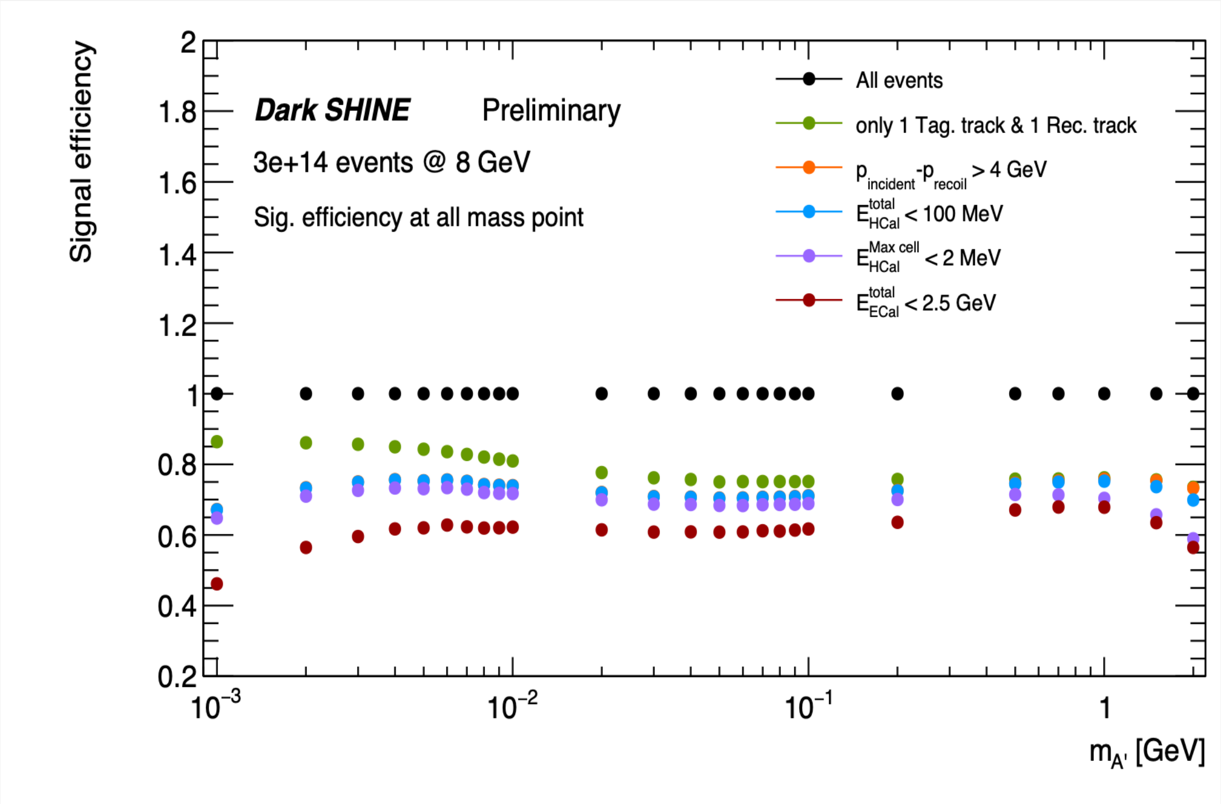
$E_{\mathrm{HCAL}}^{total} < 100$ MeV;

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

(1st round Dark SHINE analysis)

Acceptance 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 go into the HCAL directly.

Background cut-flow

Sample size:

Process	Generate Events	Branching Ratio	EOTs
Inclusive	2.5×10^9	1.0	2.5×10^9
Bremsstrahlung	1×10^7	6.70×10^{-2}	1.5×10^8
GMM_target	1×10^7	$1.5(\pm 0.5) \times 10^{-8}$	4.3×10^{14}
GMM_ECAL	1×10^7	$1.63(\pm 0.06) \times 10^{-6}$	6.0×10^{12}
PN_target	1×10^7	$1.37(\pm 0.05) \times 10^{-6}$	4.0×10^{12}
PN_ECAL	1×10^8	$2.31(\pm 0.01) \times 10^{-4}$	4.4×10^{11}
EN_target	1×10^8	$5.1(\pm 0.3) \times 10^{-7}$	1.6×10^{12}
EN_ECAL	1×10^7	$3.25(\pm 0.08) \times 10^{-6}$	1.8×10^{12}

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

Cut efficiency for each background processes:

	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%

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

Background estimation

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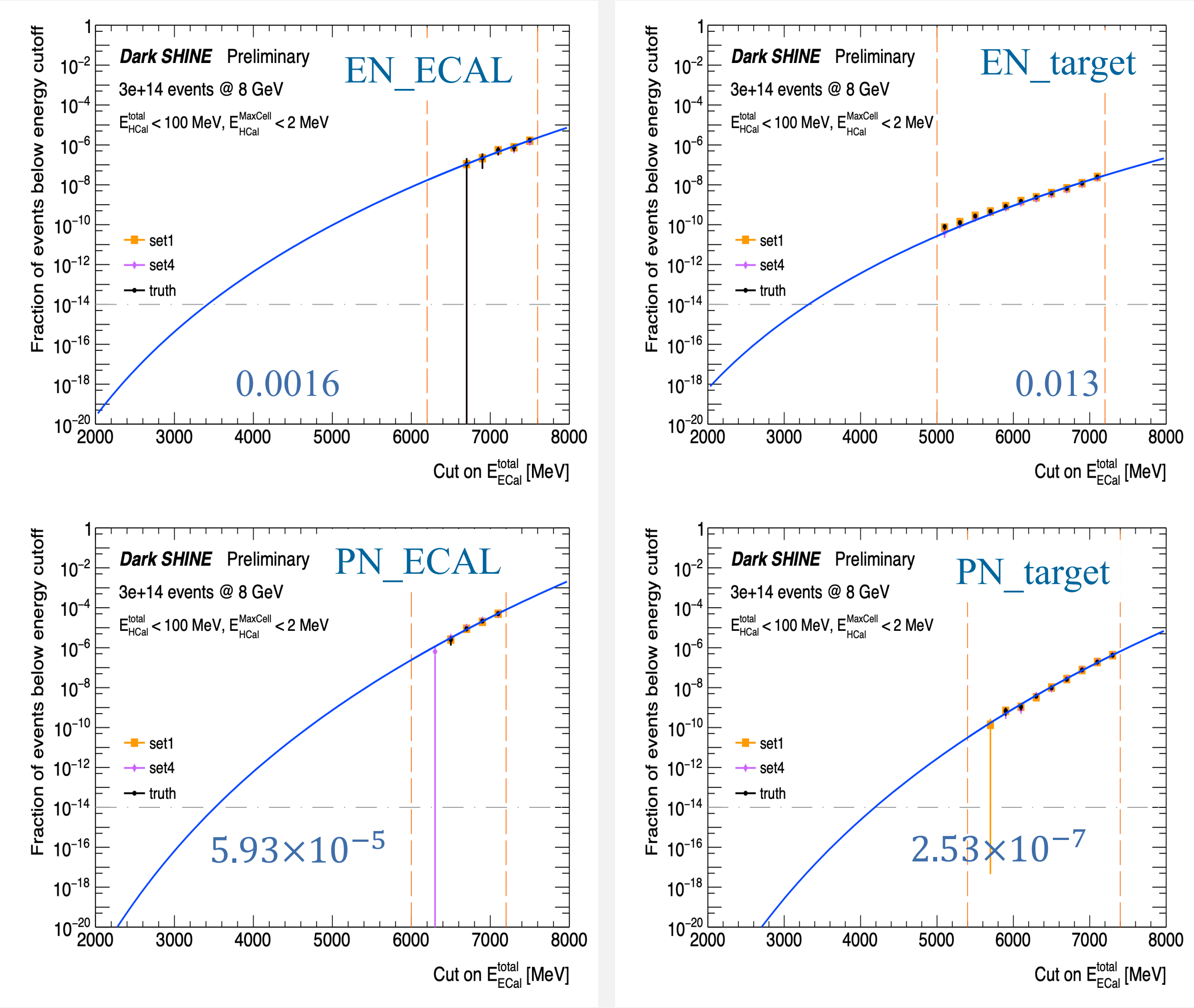

Estimate the number of background events corresponds to 3×10^{14} EOTs.

Rare bkg. production with large statistics + extrapolation method

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

- $\boldsymbol{x = 2500}$**:**
  $\boldsymbol{y}$ of the background events will survive the cut $E_{ECAL}^{total} < 2500$ MeV.

Sum: 0.015 ~3×10^{14} EOTs

Expected sensitivity

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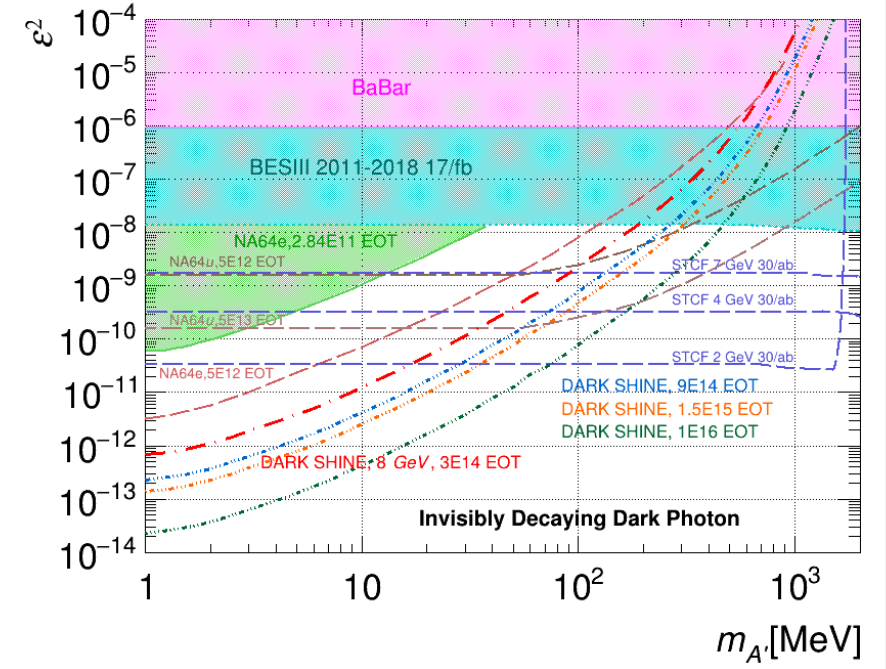
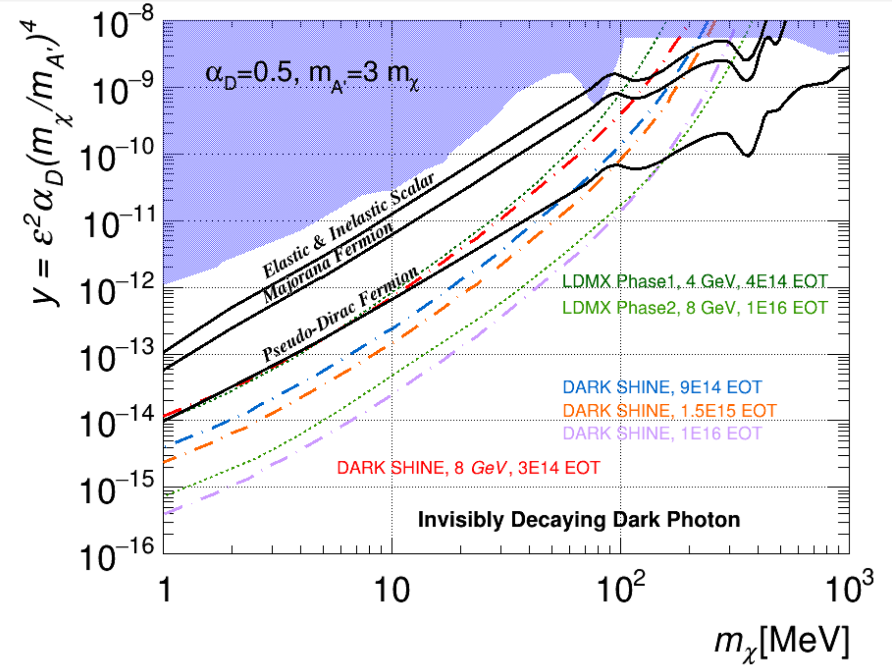
(Assuming 0.015 bkg. event/ 3×10^{14} EOTs)

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

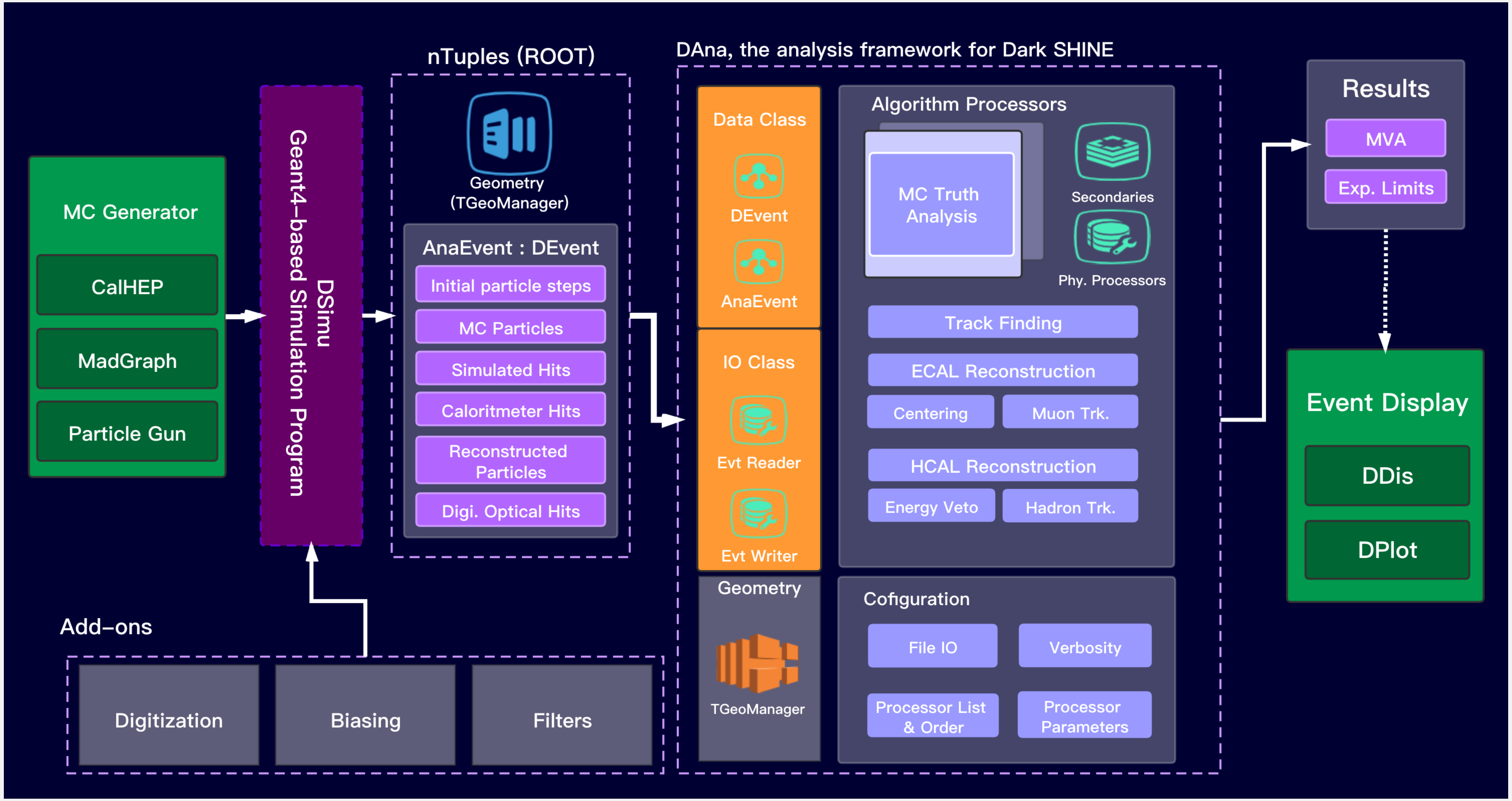




Expected 90% C.L. limit estimated with 3×10^{14} EOTs (running ~1 year), 9×10^{14} EOTs (~3 years), 1.5×10^{15} EOTs (~5 years) and 1×10^{16} EOTs (with Phase-II upgrade).

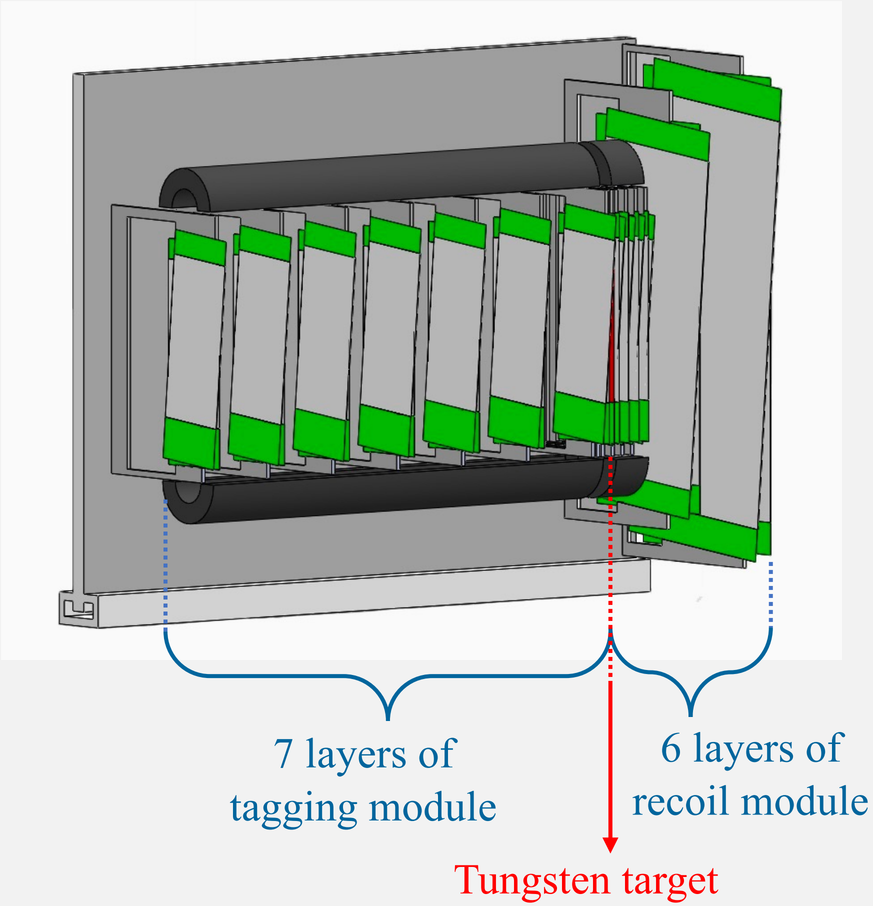
Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)

DarkSHINE simulation software



Performance optimization, Neural network integration and ACTS integration ongoing…

Hardware R&D: Tracker



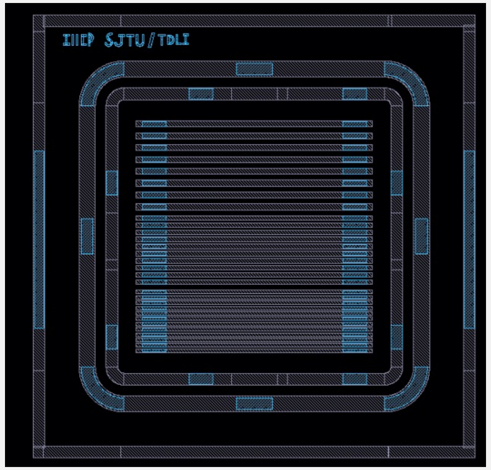
Each module: 2 layers of silicon strip sensor with a small angle (0.1rad).

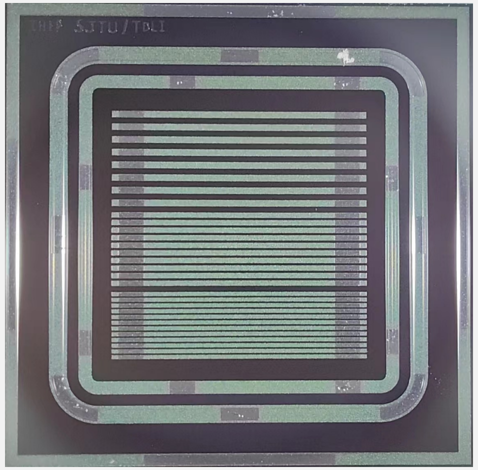
arXiv:2310.13926

Measure the track of the incident and recoil electrons.

AC-LGAD silicon strip sensor designed (1x1 mm^2) and tested in collaboration with IHEP.

position resolution: $10\mu m$ (horizontal), $60\mu m$ (vertical)





Hardware R&D: Tracker

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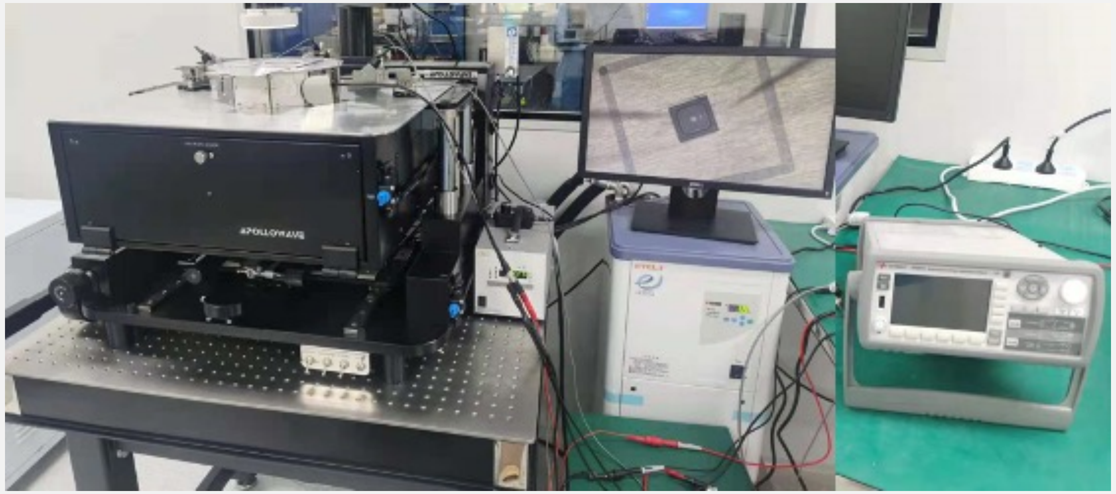
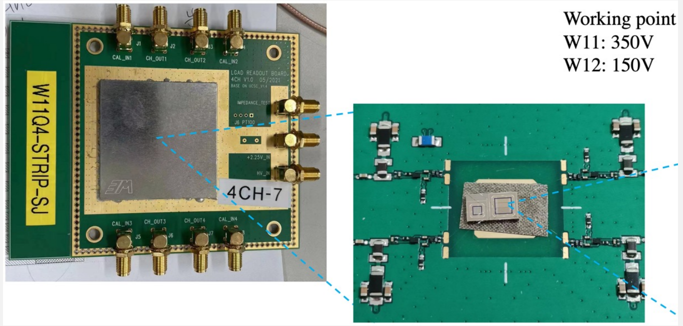
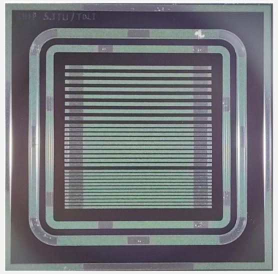
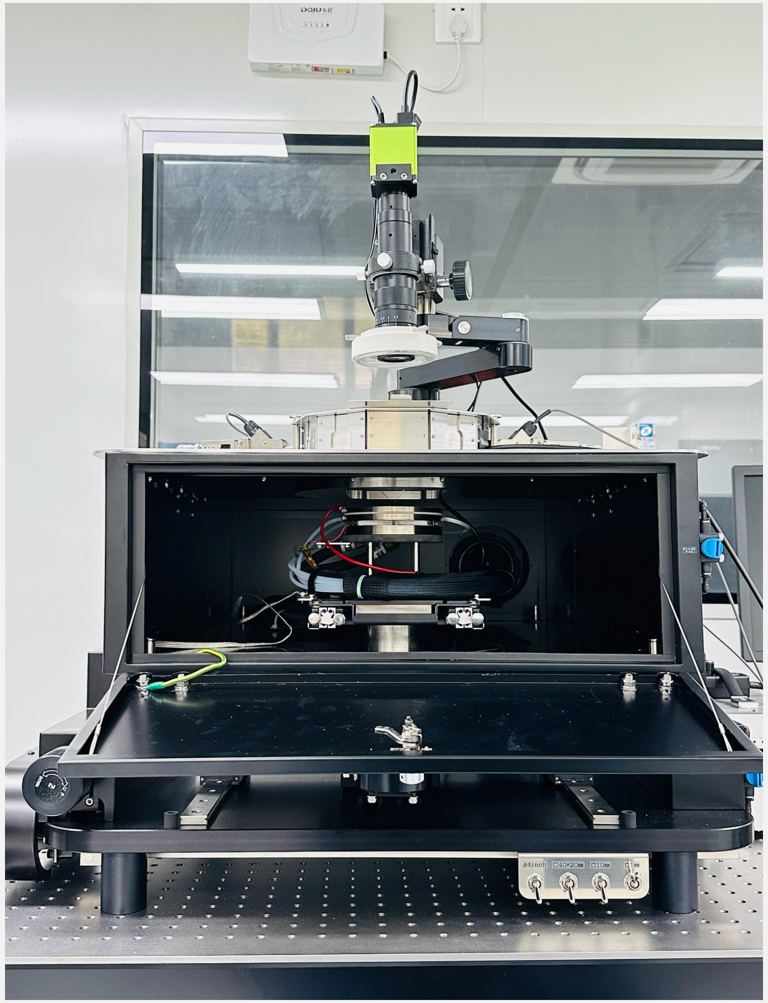
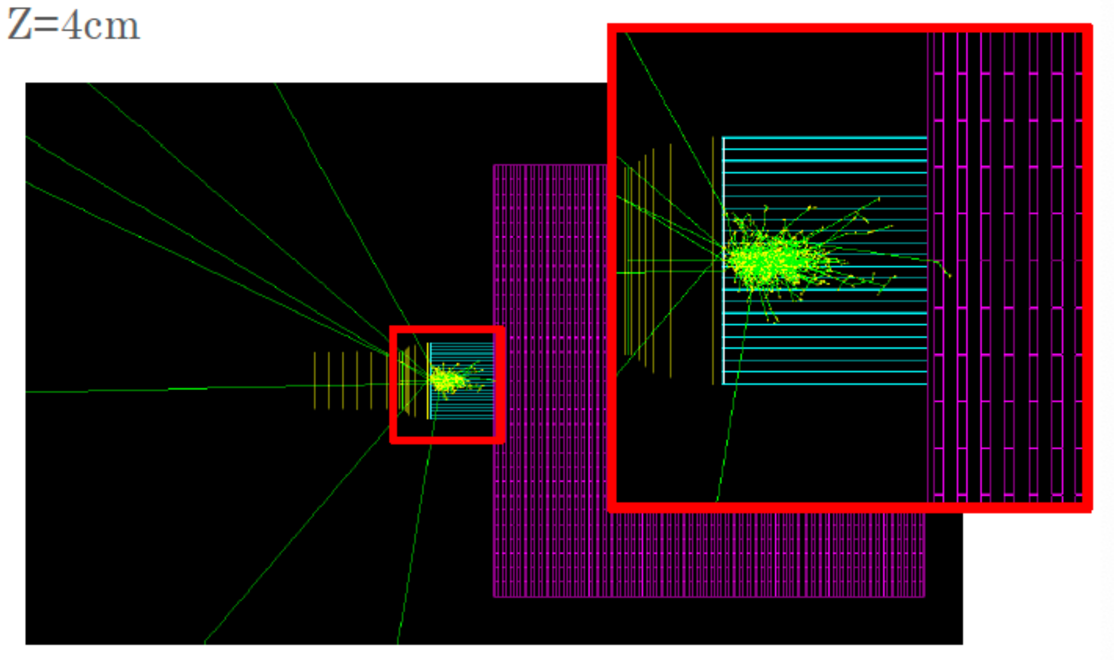


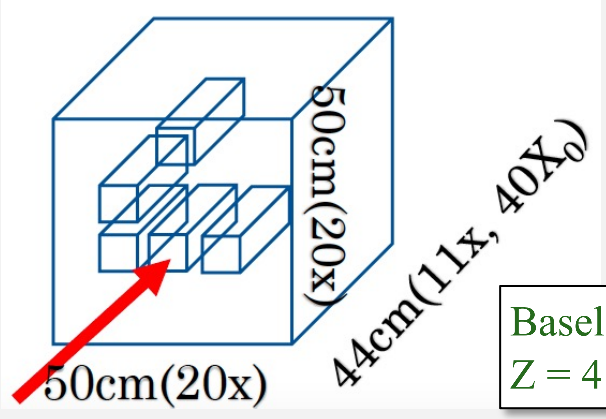






Hardware R&D: ECAL

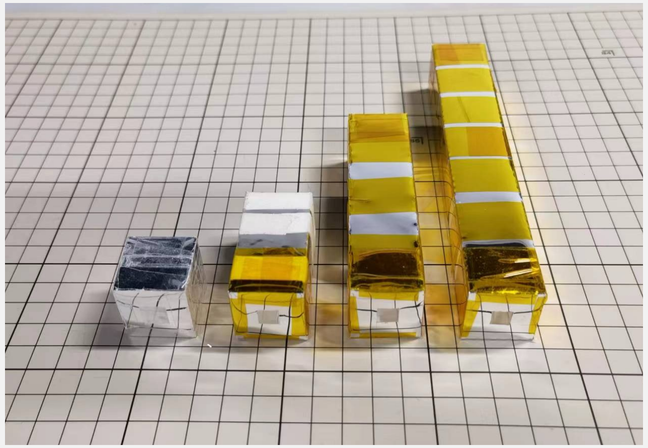




Baseline design of each crystal: X,Y = 2.5 cm,
Z = 4 cm (radiation length: 1.14 cm)

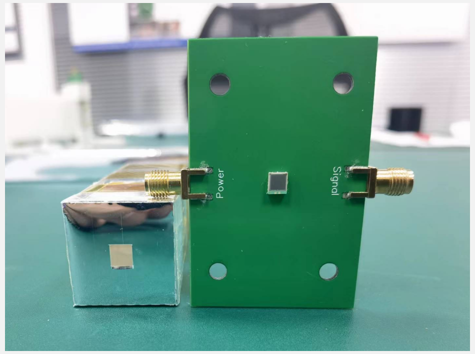
Measure the deposited energy of electron and photon.

- 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.
- More intrinsic radiation and radioactive source tests.

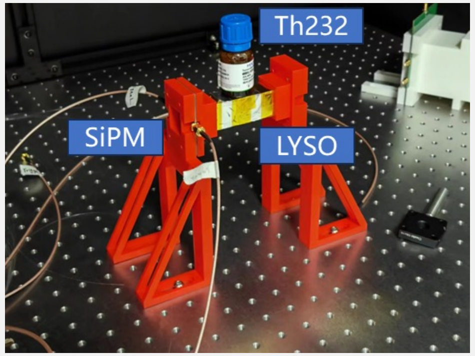


Hardware R&D: ECAL

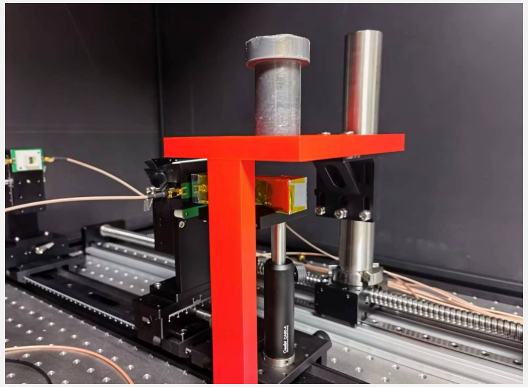
LYSO intrinsic radiation from $^{176}Lu \rightarrow {}^{176}Hf$



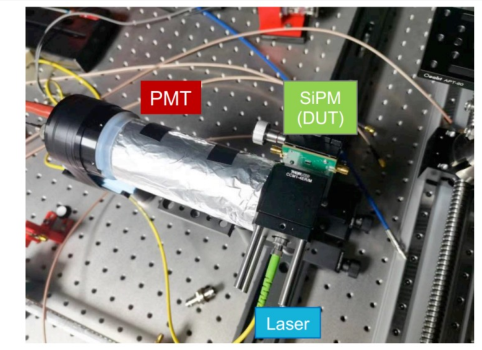
Test of unit light yield



Uniformity test with $^{60}_{27}Co$

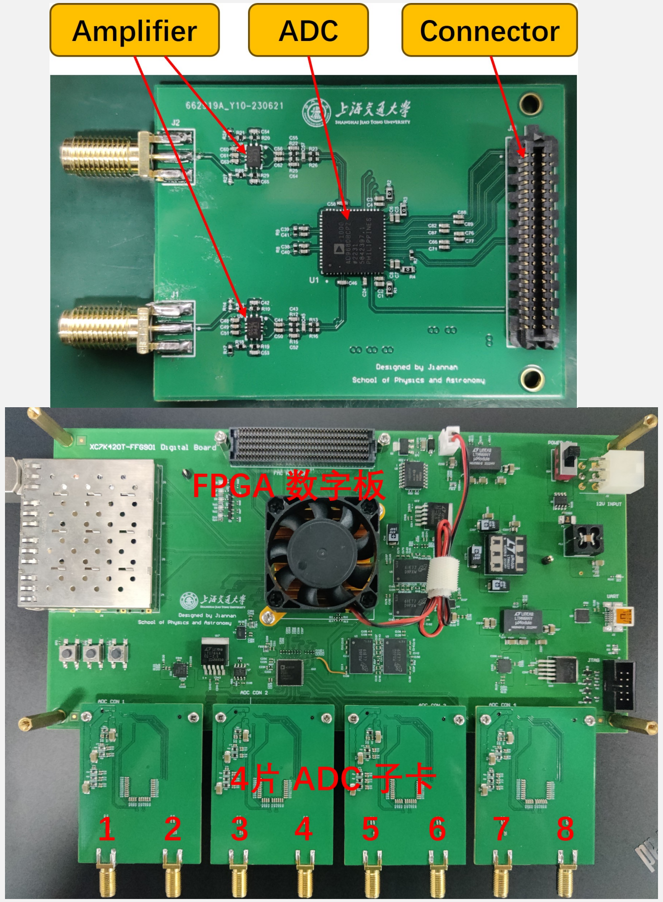


SiPM Dynamic Range Test



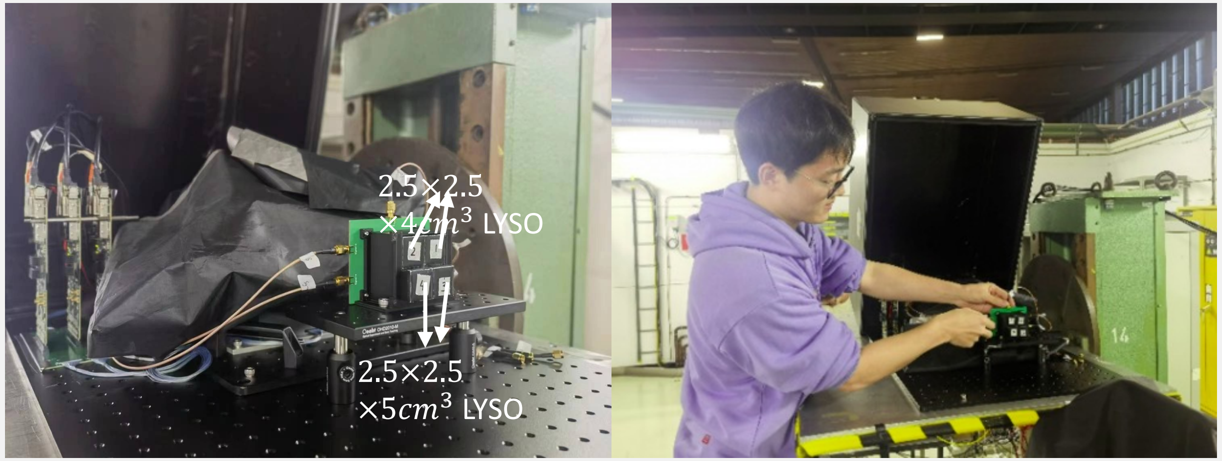
High Speed and Large Dynamic Range Readout

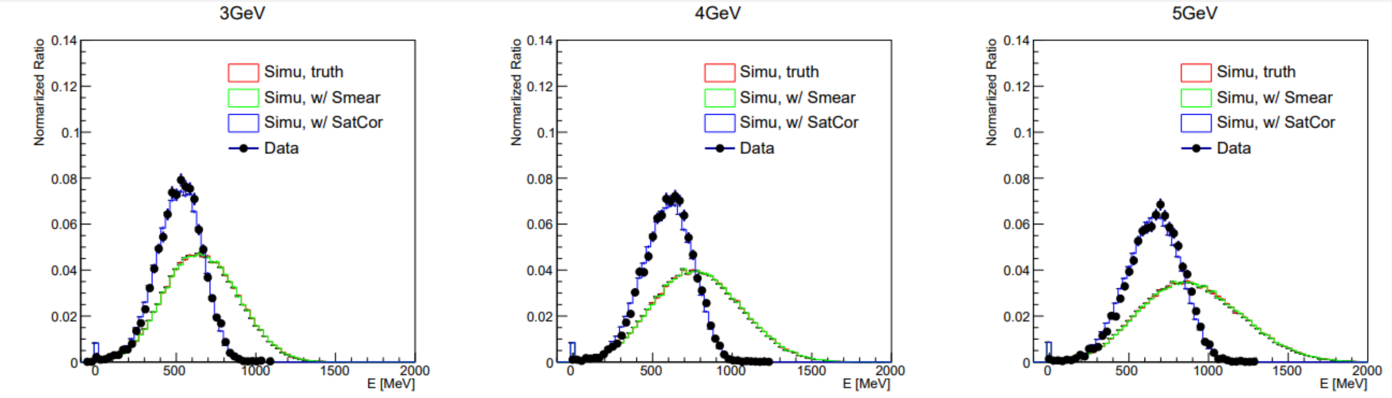
- First version readout electronics system



Hardware R&D: ECAL

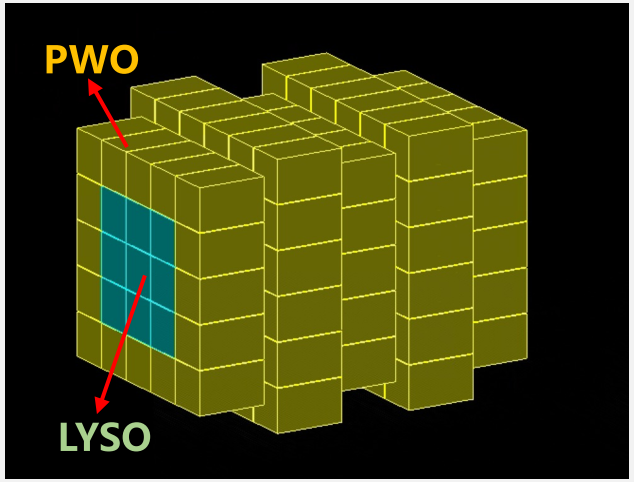
1^{st} prototype module for beam test at DESY



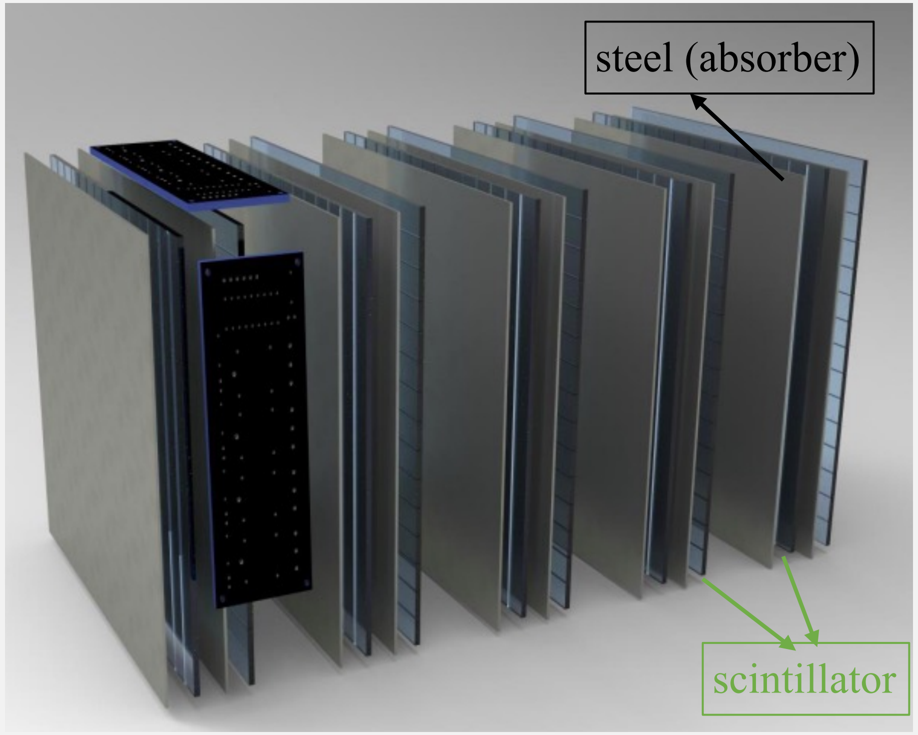


Protype design

- Motivation:
  - Performance study under high energy and high repetition beam.
  - Technical validation for the whole detector system
- Hybrid material design
  - LYSO with high radiation resistance
  - PWO with high density and more economical

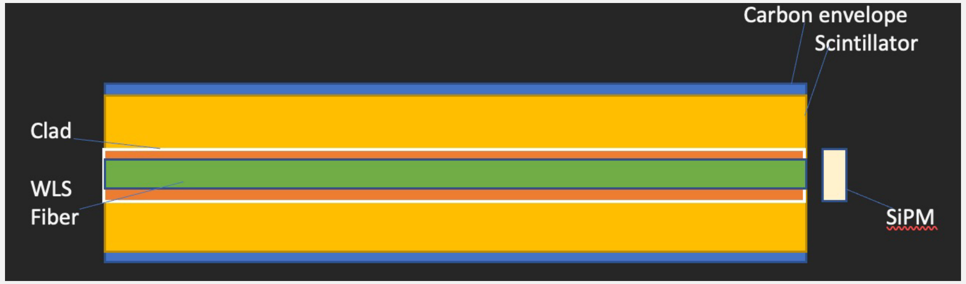


Hardware R&D: HCAL



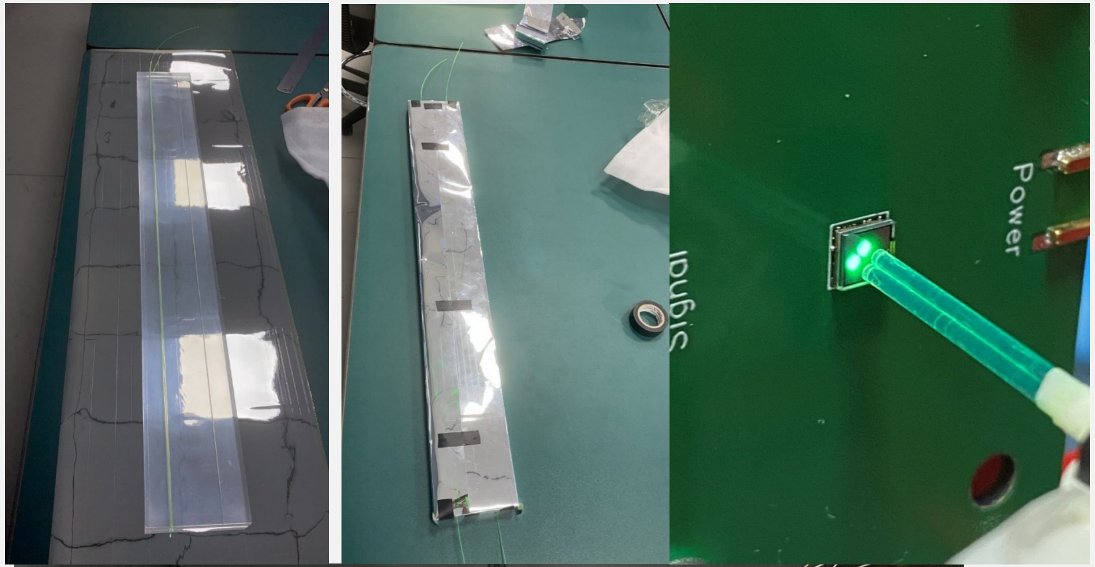
Veto backgrounds with same behavior as signal in ECAL

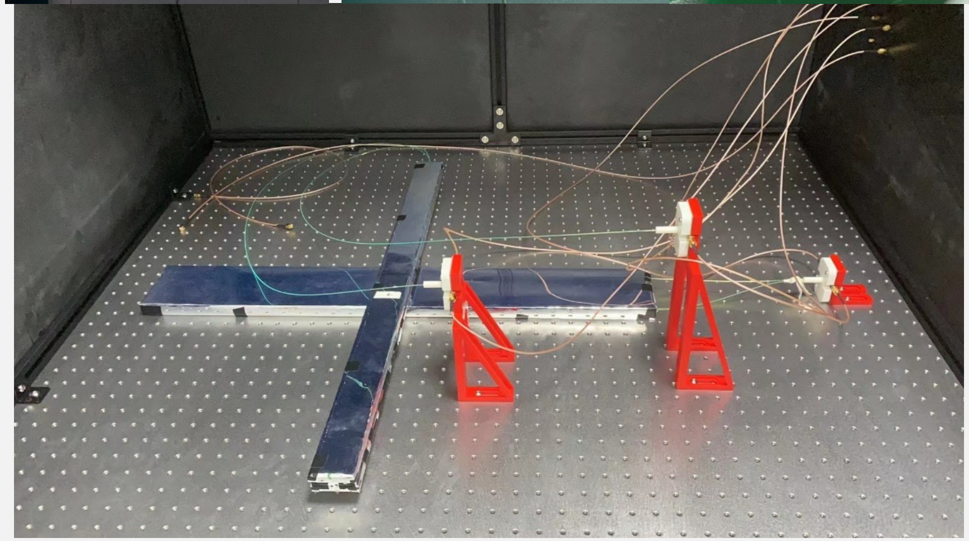
- Baseline design:1.5 m × 1.5 m (perpendicular to the beam), ~10 λ (~160 cm iron, parallel to the beam)
  - Split to 4 modules, 75 cm × 75 cm each
  - Steel absorber: 10 mm/50 mm thick, 75 cm × 75 cm
  - Plastic scintillator: 10 mm thick, 75 cm × 5 cm, 15 bars per layer per module



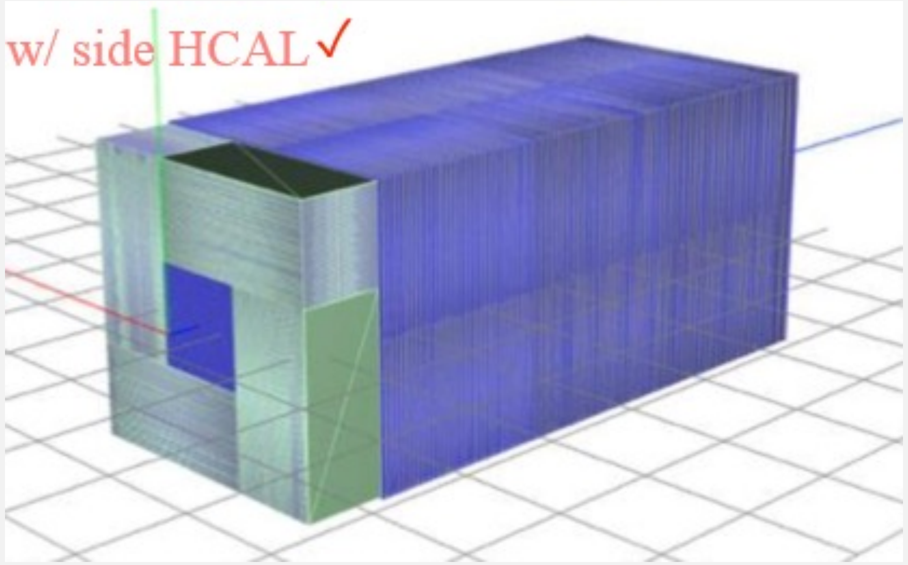
Hardware R&D: HCAL

Plastic scintillator bars are tested with radioactive source and cosmic ray source





Side-HCAL: encircling the ECAL



- **Design has been optimized**
  arXiv:2311.01780

Veto inefficiency

Particle / Energy	n	k^0	π^0	p	μ
100[MeV]	1.17E-03	3.16E-02	7.30E-06	3.07E-02	4.09E-04
500[MeV]	1.84E-05	5.40E-06	1.00E-07	8.04E-06	1.50E-05
1000[MeV]	3.70E-06	3.70E-06	1.00E-07	1.00E-07	2.00E-06
2000[MeV]	2.70E-06	1.15E-05	1.00E-07	1.00E-07	1.00E-07

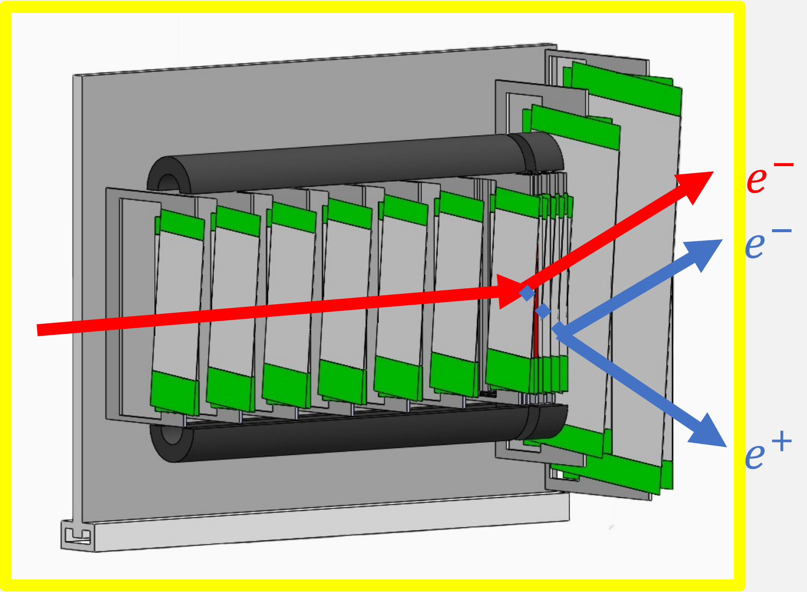
Visible Decay at DarkSHINE

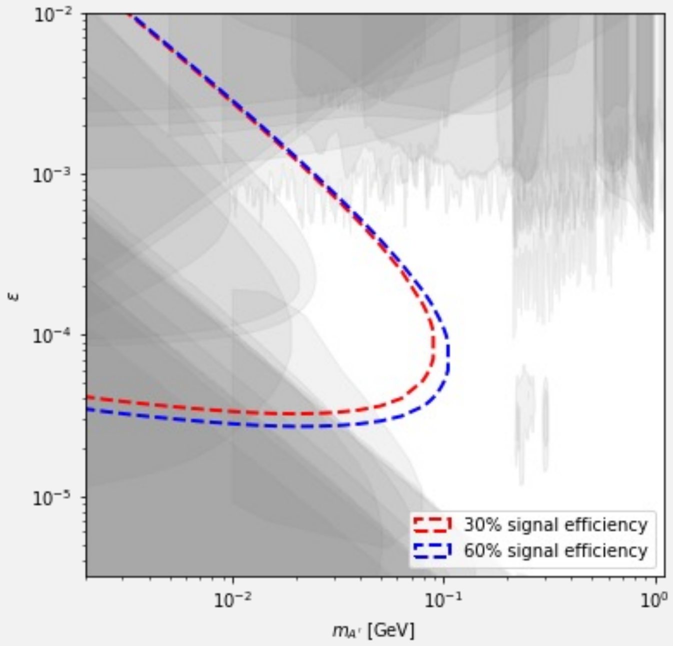
Production:

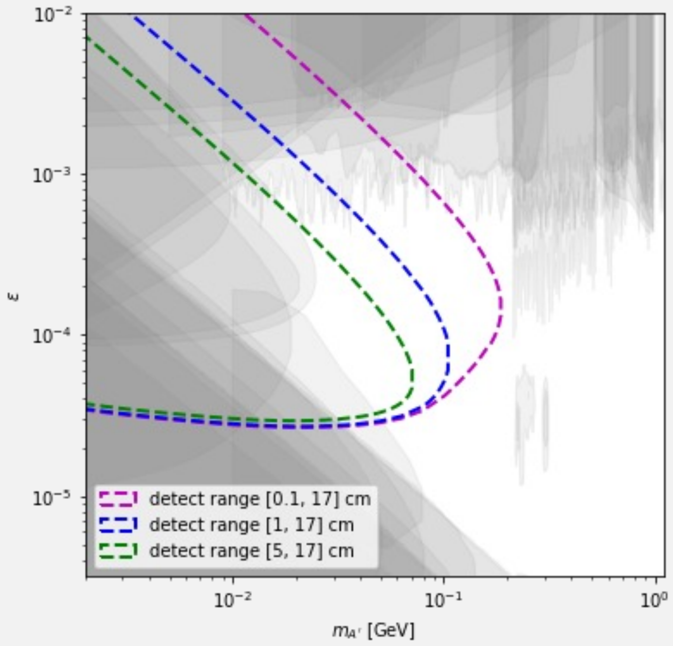
bremsstrahlung, $eZ \to eZA'$, with visible decay: $A' \to e^+e^-$

Signal Signature:

Displaced Vertex → Tracking is the crucial part.





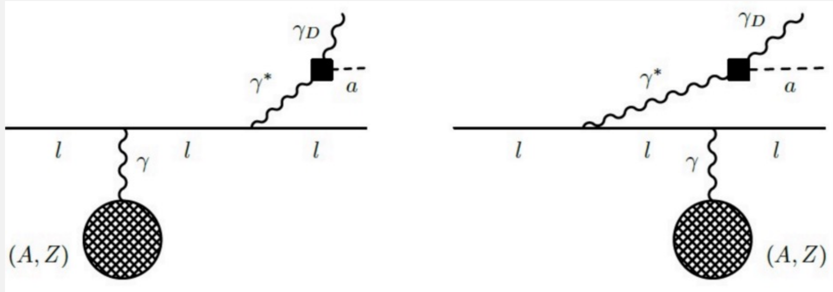


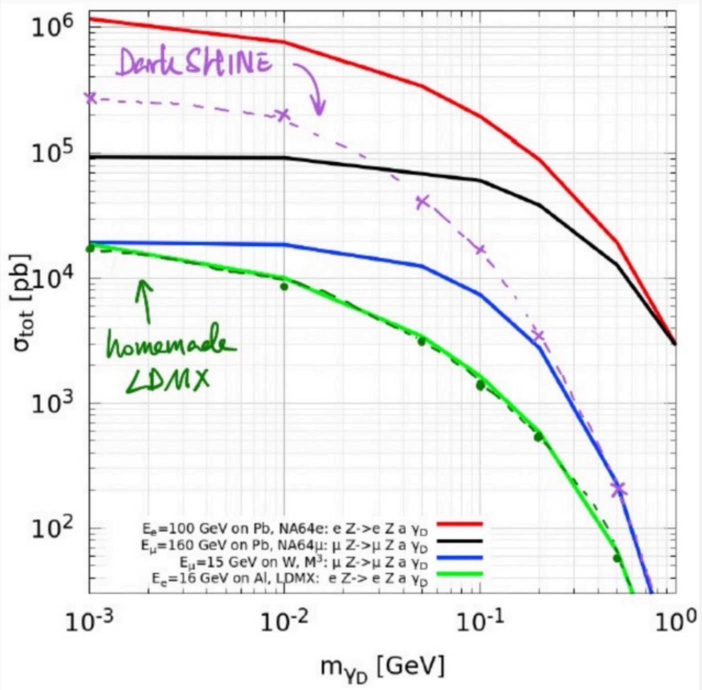
Assumption

- Detect range : [0.1/1/5, 17] cm
- Signal efficiency : 60%
- Decay channel : ee + μμ
- No. of background : 10
- EOT : 3e14
- CL : 90%

More physics opportunities at DarkSHINE

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…

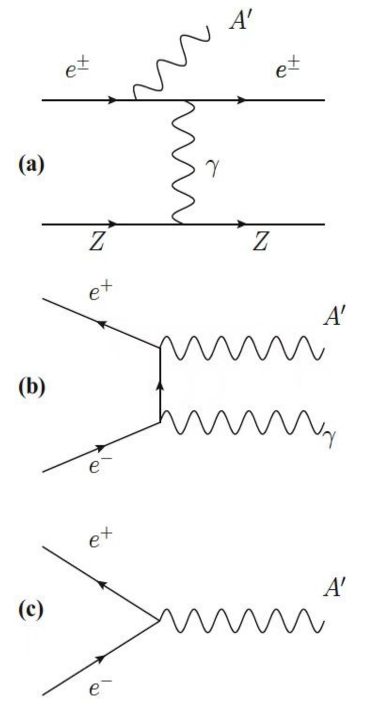
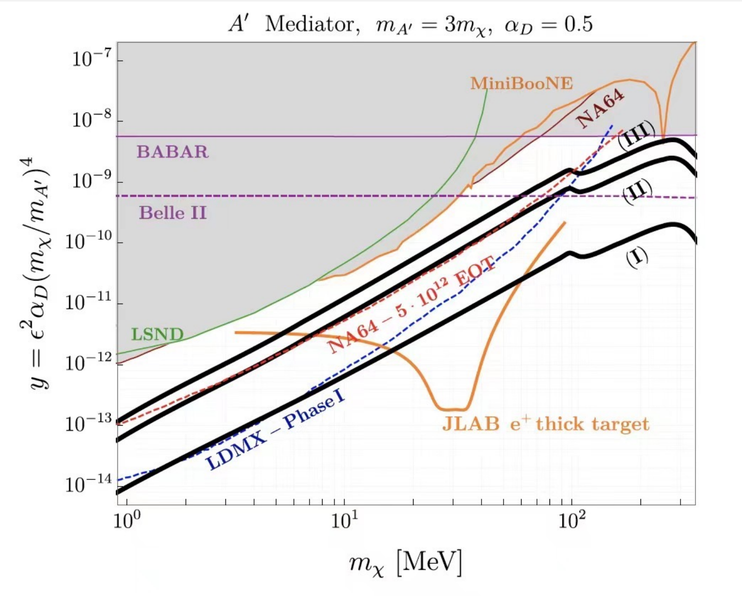


Fig. 1 Three different A' production modes in fixed target lepton beam experiments: (*a*) A'-strahlung in e^-/e^+-nucleon scattering; (*b*) A'-strahlung in e^+e^- annihilation; (*c*) resonant A' production in e^+e^- annihilation



Summary

- **First round of preliminary study for DarkSHINE has been finished:**
  - Production: bremsstrahlung, $eZ \rightarrow eZA'$, with Invisible decay: $A' \rightarrow \chi\chi$.
  - Good signal efficiency, background well suppressed.
  - Expecting competitive sensitivity.
  - Sci. China-Pay. Mech. Astron., 66(1):211062 (2023)
- **Many unit test has been done for DarkSHINE hardware and first version high speed readout electronics system has completed.**
- **Visible decay has been studied. Vertexes reconstruction with ML method and ACTs will be investigated.**
- **Fast Simulation in progress (both CPU-based and Machine-Learning based).**
- **With more physics opportunities ahead, stay tuned!**

谢 谢！