Progress on the DarkSHINE Experiment

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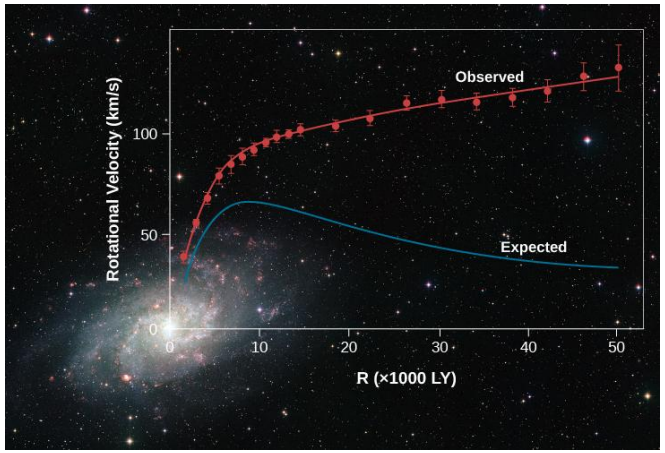
On behalf of DarkSHINE R&D Group

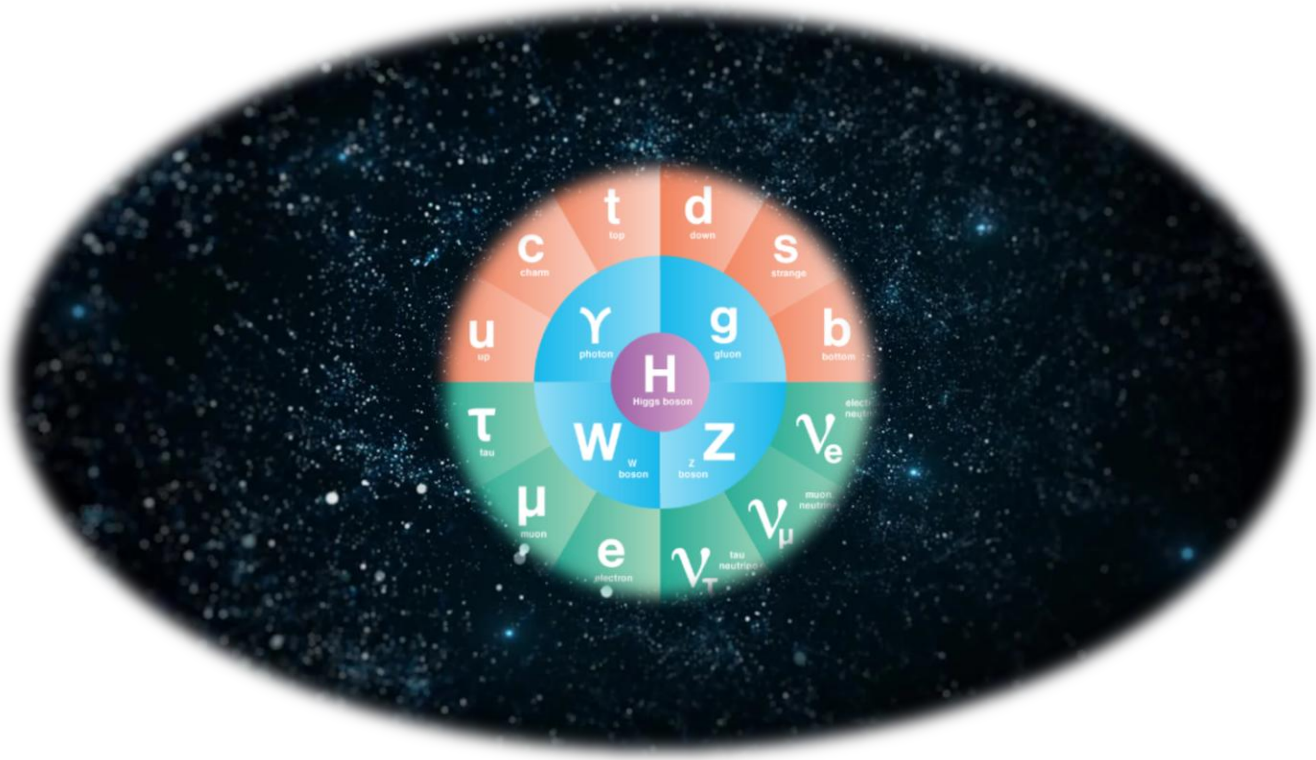
首届SHINE缪子源及其应用研讨会

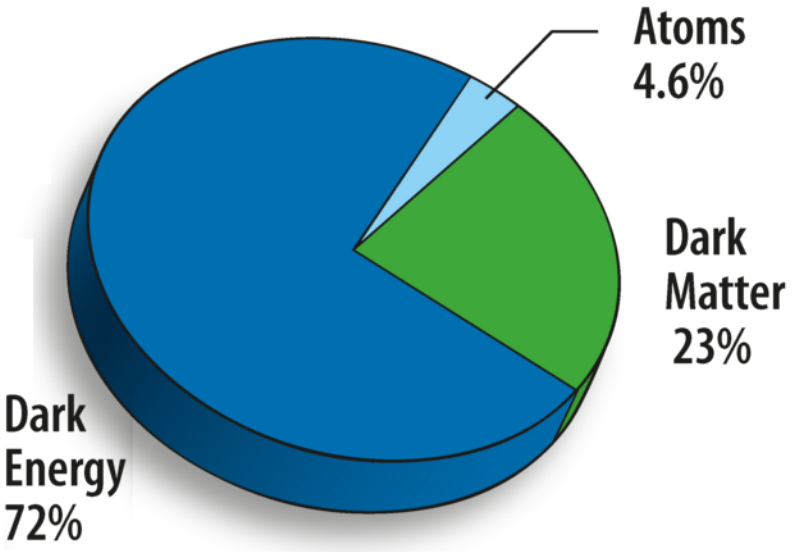
28 November, 2025

Dark Matter

- Standard Model (SM): framework for particle physics
- Beyond Standard Model: **dark matter**, dark energy, neutrino mass, …
  - Dark matter evidence from astronomical observations and gravitational effects



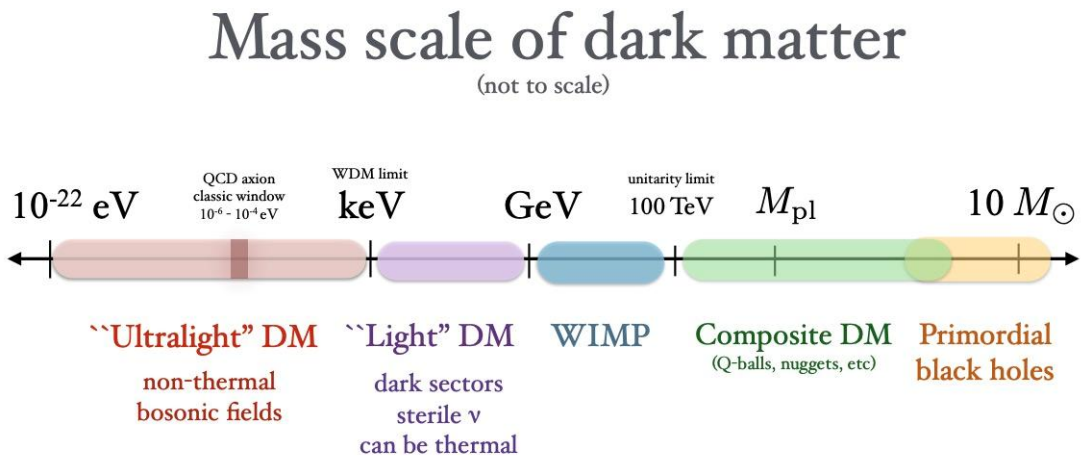




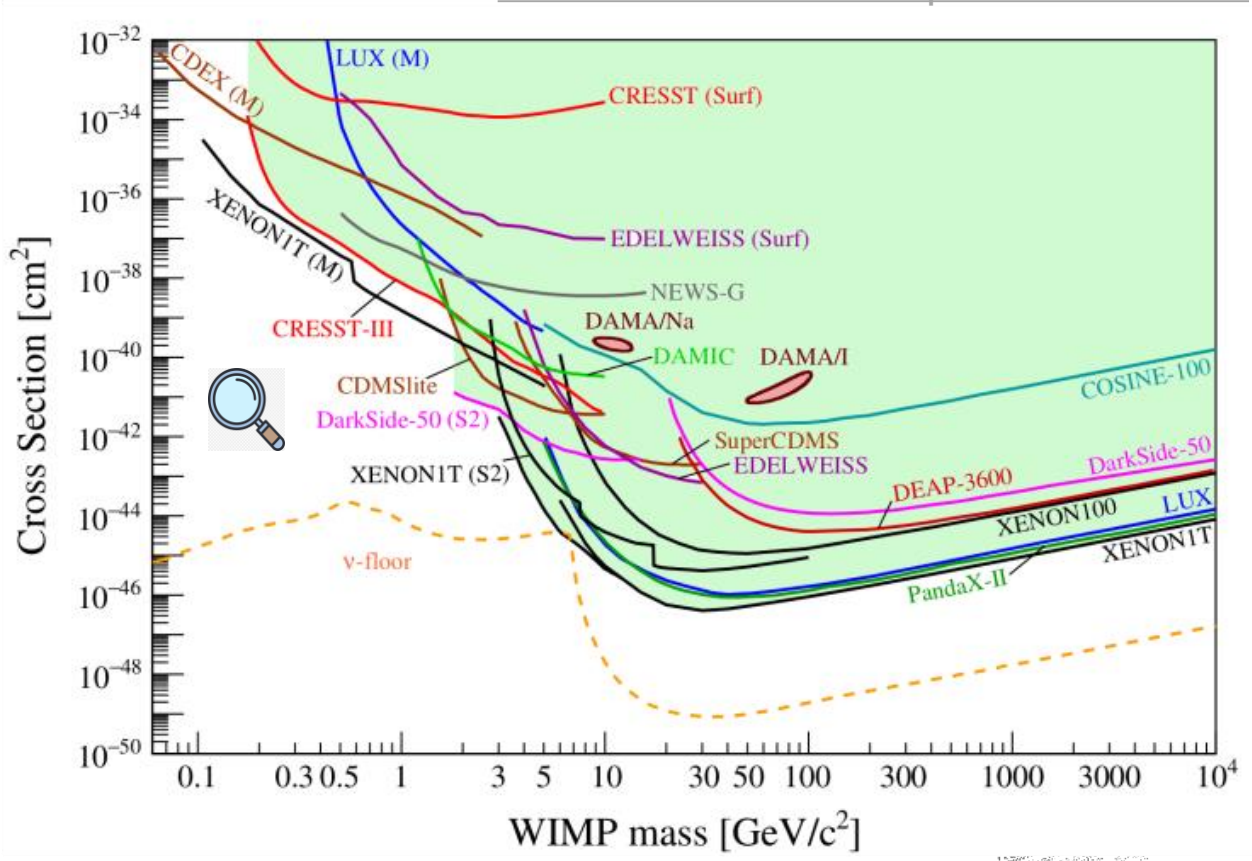
Dark Matter Candidates

- The “freeze-out” mechanism predict the mass of dark matter is mainly distributed from **MeV to tens of TeV**
  - Weakly Interacting Massive Particles (WIMP): A large parameter space ruled out in GeV~TeV mass range.
  - **Light DM: Sub-GeV mass range not fully explored yet.**

arXiv:1904.07915



APPEC Committee Report: 2104.07634



Dark Photon Theory in a Nutshell

- Dark photon: one candidate of light DM, kinetic mixing with SM photon

Introduce extra $U(1)_X$ symmetry → New Gauge Field X → Dark Photon Mediator A'

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + A_\mu j^\mu_{em} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + X_\mu j^\mu_X$$

SM Photon γ **Dark Photon A'**

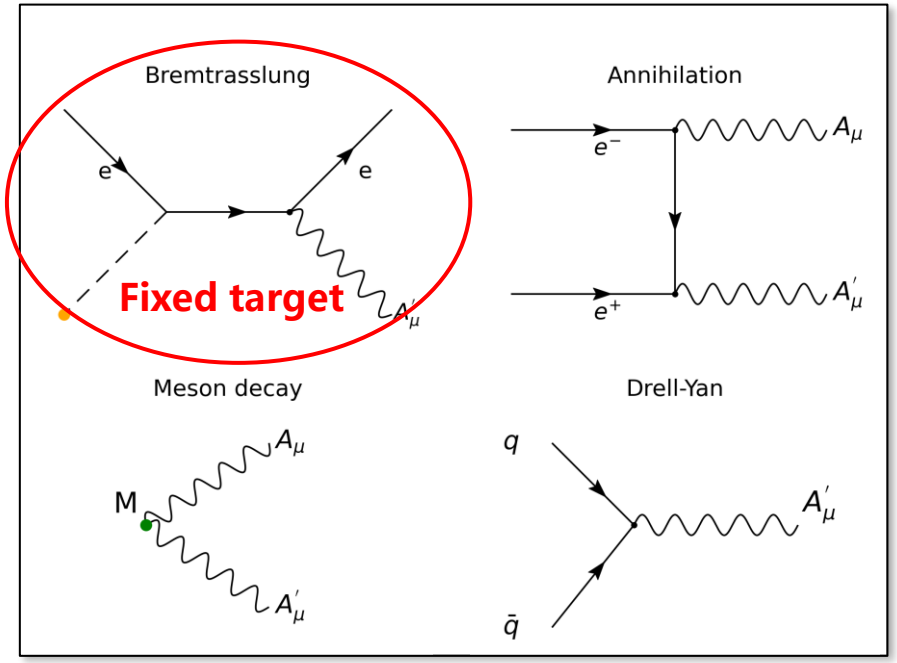
$$\varepsilon X_{\mu\nu}F^{\mu\nu}$$

- **A'& γ kin. mixing**
- **Renormalizable and Gauge Invariant**
- **Straightforward for experimental search**
  - **Free param, kin. mixing (Ɛ)、mass ($m_{A'}$)**

B. Holdom, Phys. Lett. B 166, 196 (1986)
R. Foot & X.-G. He, Phys. Lett. B 267, 509 (1991)

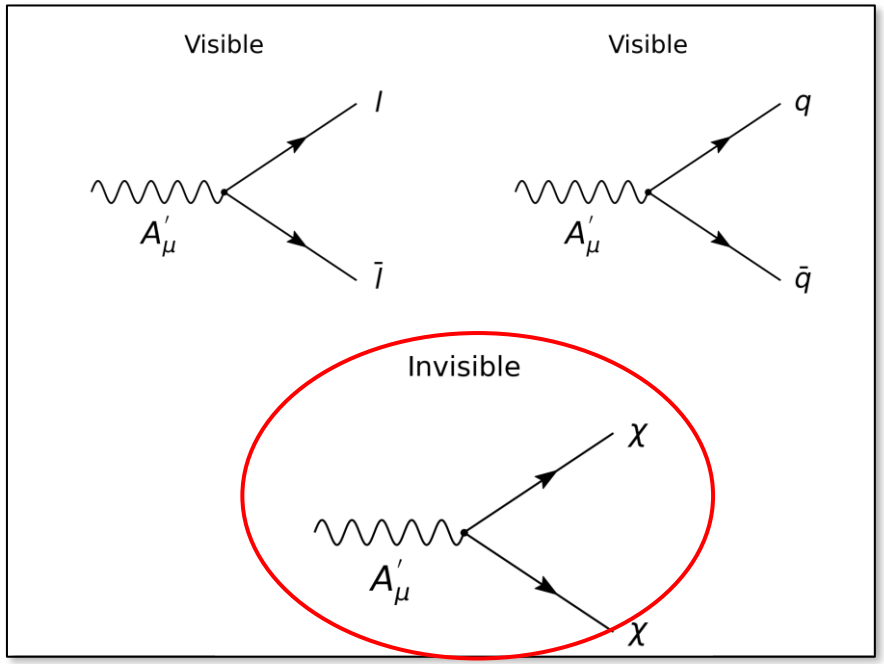
Dark Photon Production and Decay

Production



- **Bremsstrahlung, $eZ \to eZA'$ & $pZ \to pZA'$, fixed-target experiment**
- Annihilation, $e^+e^- \to A'\gamma$, e^+e^- collider
- Drell-Yan, $q\bar{q} \to A'$, hadron collider / fixed nuclear target w/ proton-beam
- Meson decay, $\pi^0 \to A'\gamma$ or $\eta \to A'\gamma$ (w/ $m_{A'} < m_{\pi,\eta}$), any experiment w/ high meson production rates

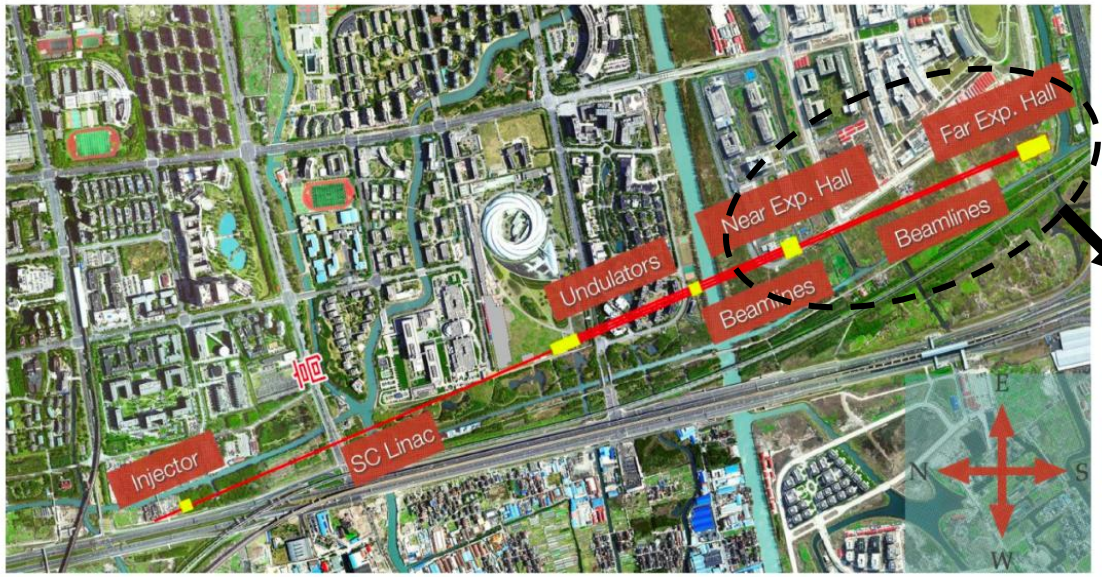
Decay

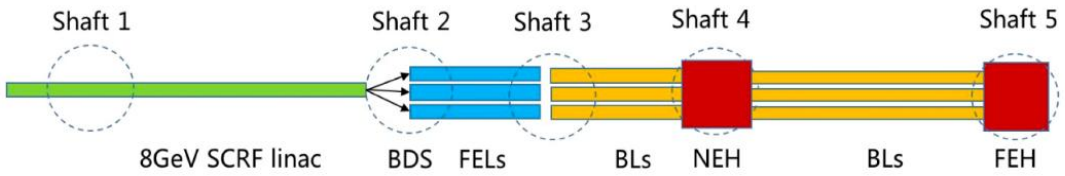


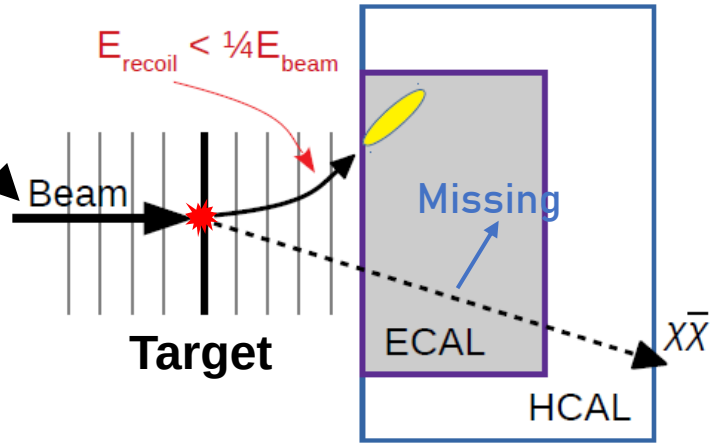
- Visible decay
  Two interaction vertices → highly suppressed
- **Invisible decay**
  Better sensitivity: one interaction vertex
  Distinctive signatures: missing E&p

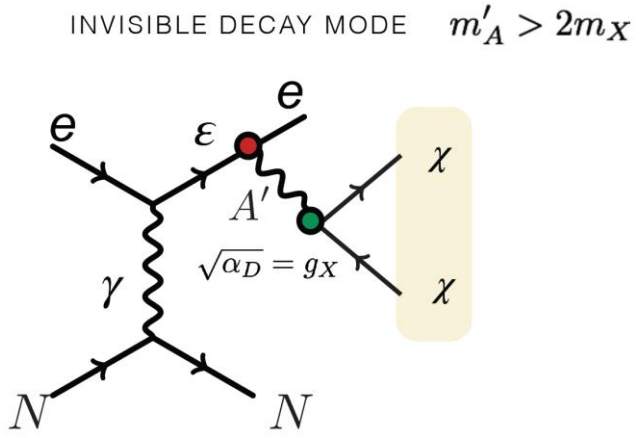
DarkSHINE Experiment Searching for Dark Photon

- **DarkSHINE**: search for **bremsstrahlung dark photon and its invisible decay**
  - Fixed-target experiment, **MHz single electron beam** (to be)provided by SHINE facility
  - Detector R&D: SJTU / FDU / USTC / SIC-CAS / IHEP





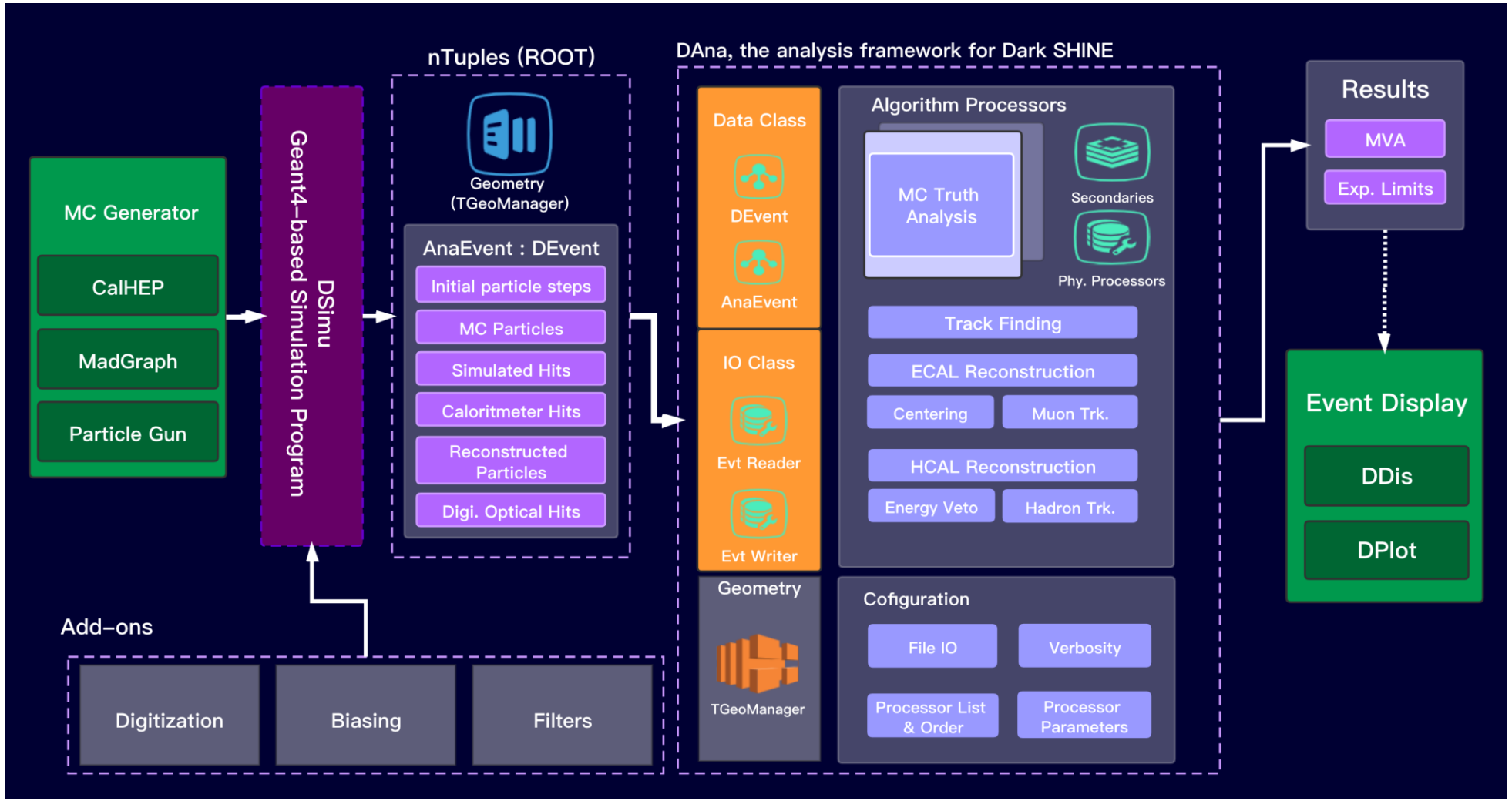




e- beam with one e- per bunch is required

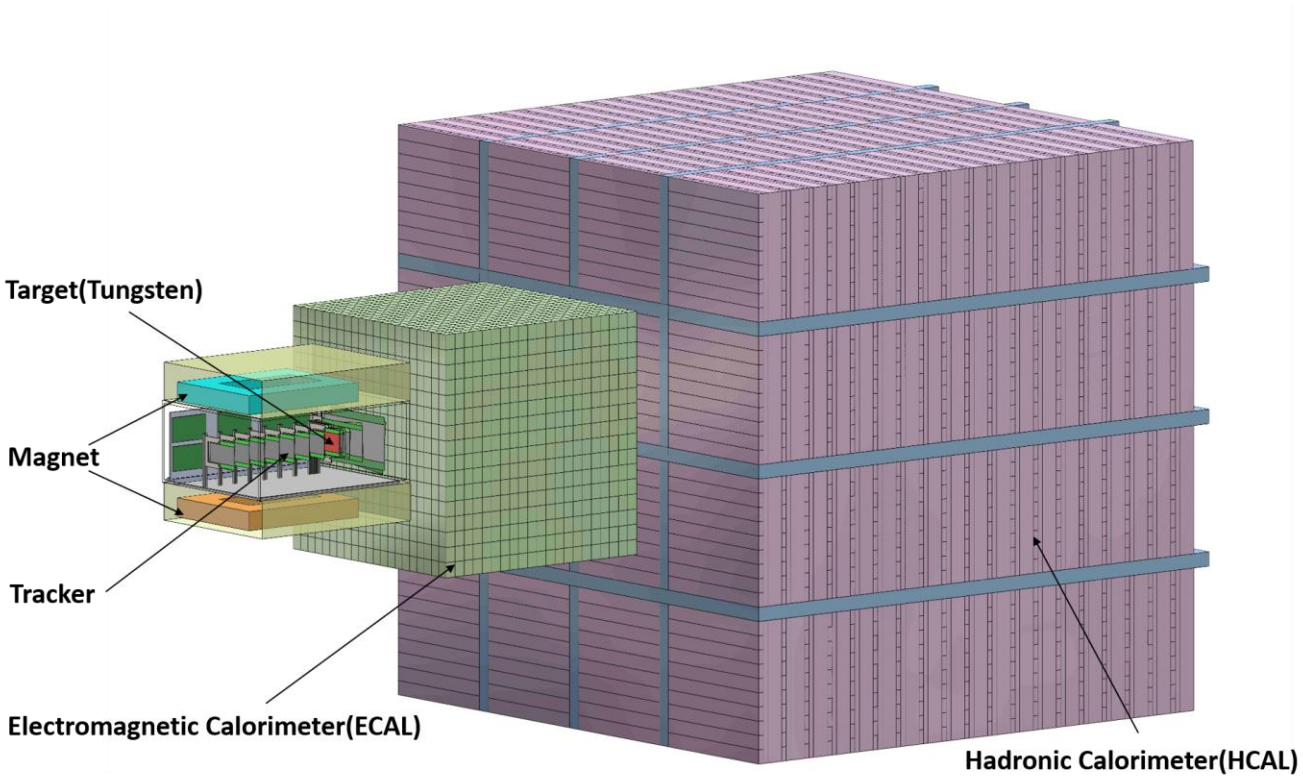
DarkSHINE Software Framework

- Integrates detector simulation, signal digitization, event reconstruction, and data analysis, etc.



Detector System Conceptual Design

DarkSHINE Baseline Design Report, arXiv: 2411.09345



Tracker: measure the track and p of charged particles

- Silicon strip sensors are arranged in an interleaved pattern
- Tagging tracker(7 layers) + recoil tracker(6 layers)
- Resolution: 10μm(horizontal), 60μm(vertical)

ECAL: measure energy of electrons and photons

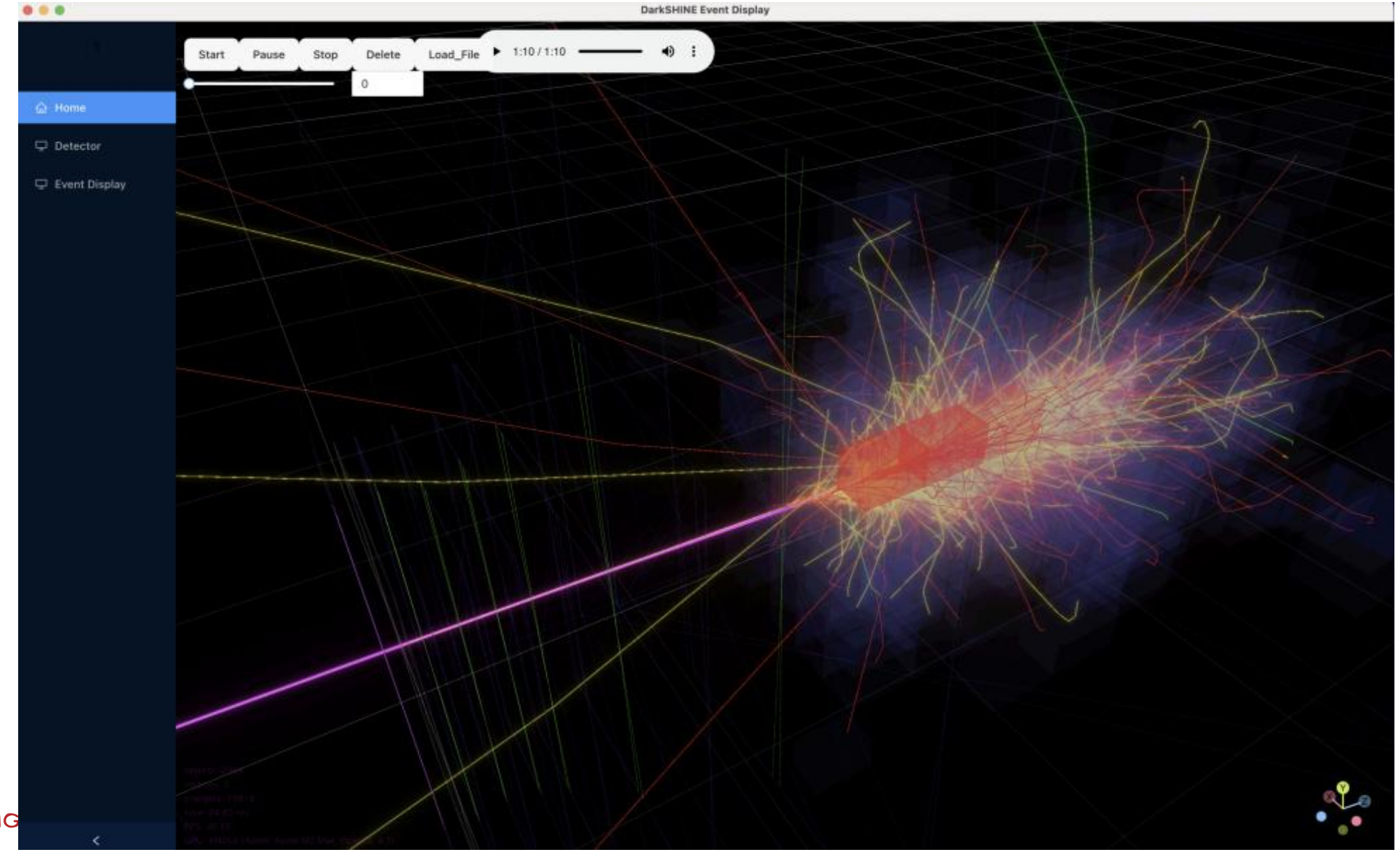
- Homogenous design with minimal EM energy leakage
- Fast response: MHz repetition rate w/o pileup
- Radiation hard: survive in ~$10^7 rad$ dose

HCAL: veto muon and hadron backgrounds

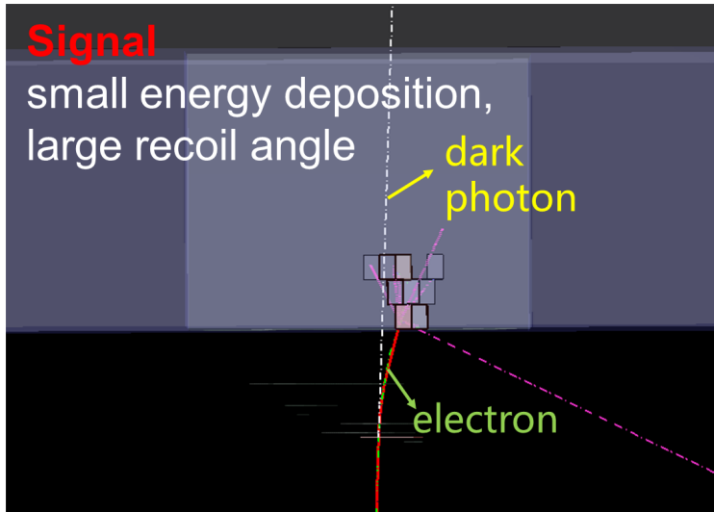
- Scintillator-absorber "sandwich" detector structure
- Small noise
- High rejection efficiency for neutron and muon

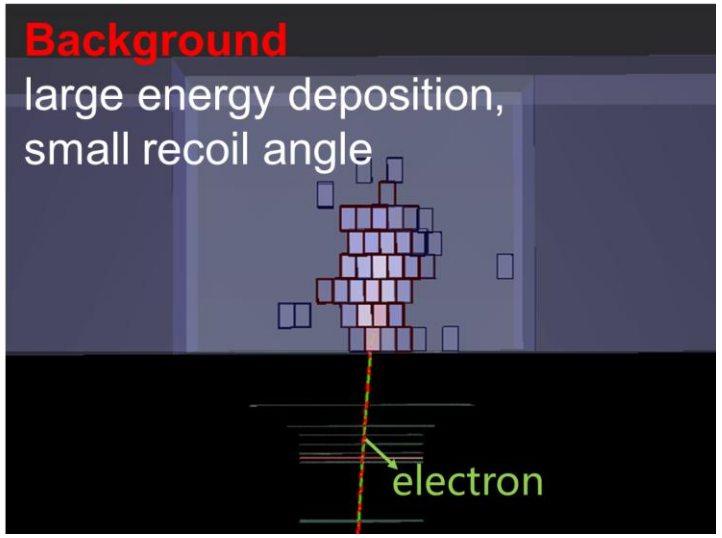
Additional system: readout electronics, trigger system, magnetic system (1.5 T), etc.

Event Display



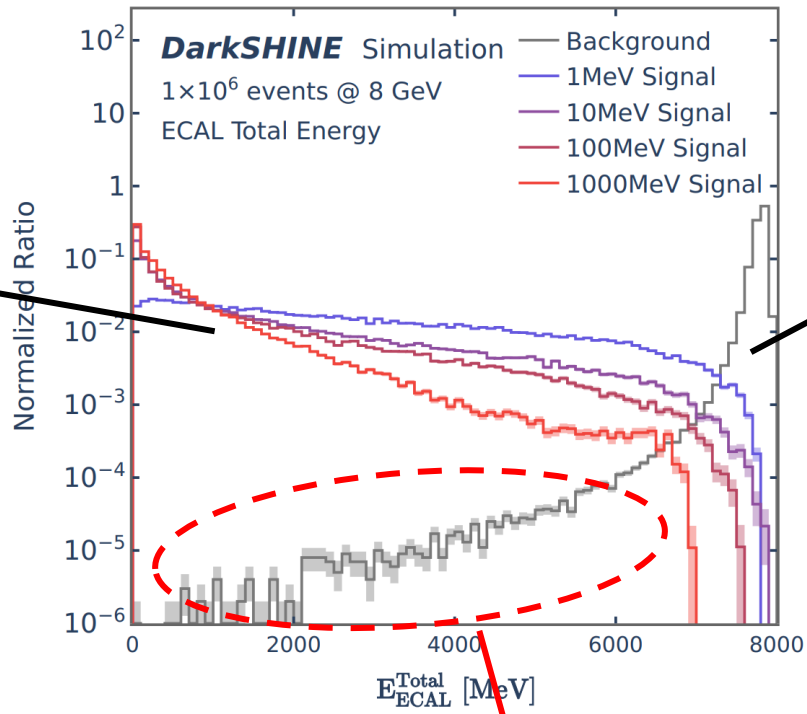
Signatures of Signal and Background





Energy deposition in ECAL

Signal:
Missing energy
(vs. 8 GeV e-)



Background:
~ 8 GeV,
full deposition

Background branching ratio

Inclusive	Bremsstrahlung	Electron-Nuclear	Photon-nuclear	Photon-to-muons
1.0	6.7×10^{-2}	3.76×10^{-6}	2.32×10^{-4}	1.64×10^{-6}

Rare backgrounds are our main focus

Physics Prospective

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

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• Article •

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https://doi.org/??

Prospective Study of Light Dark Matter Search with a Newly Proposed DarkSHINE Experiment

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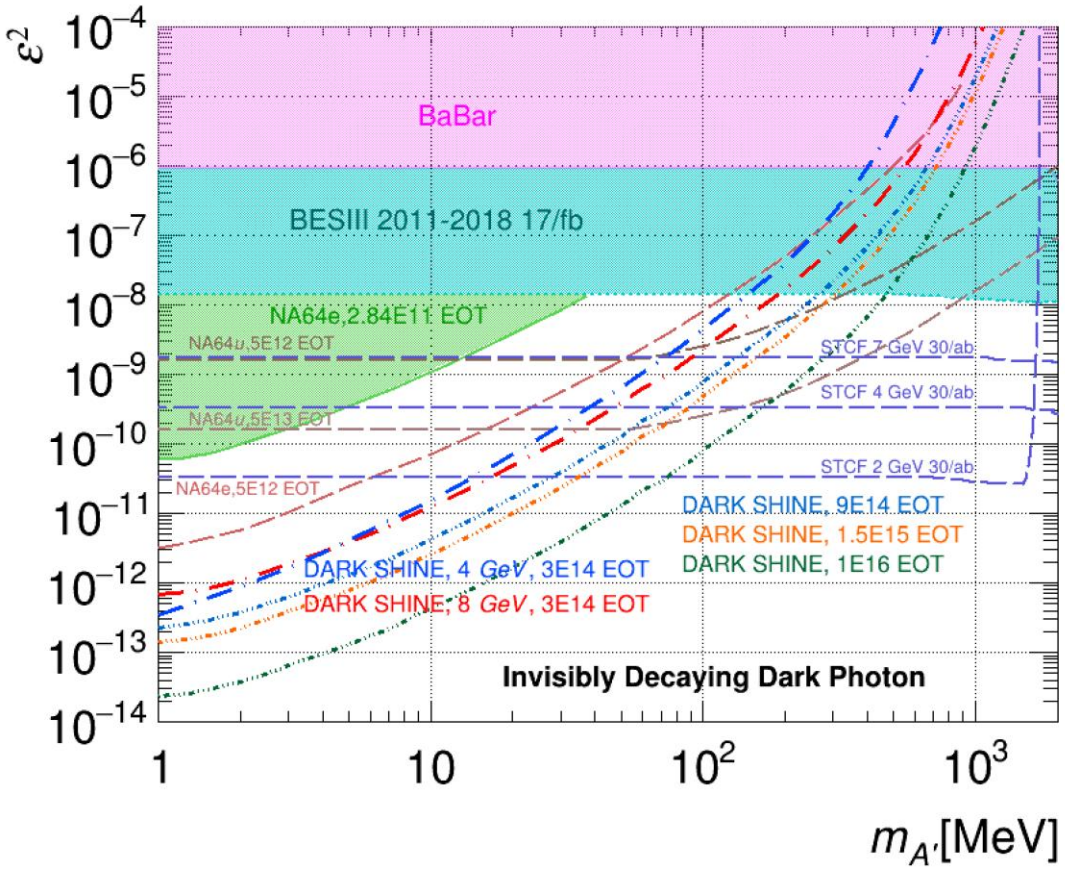
Highlight remarks

Sci. China-Phys. Mech. Astron. 66(1): 211063 (2023)

"Editor's Focus"

Sci. China-Phys. Mech. Astron. 66(1): 211061 (2023)



- Sensitivity competitive with other experiment internationally (e.g. NA64)
- Aim to deliver 10^{16} EOT stat. and cover most of the sensitivity regions of interests

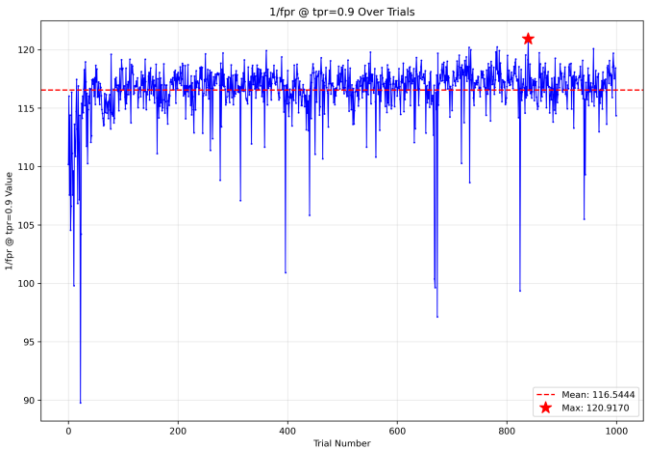
Enhance Background Rejection Through Multi-Variable-Analysis

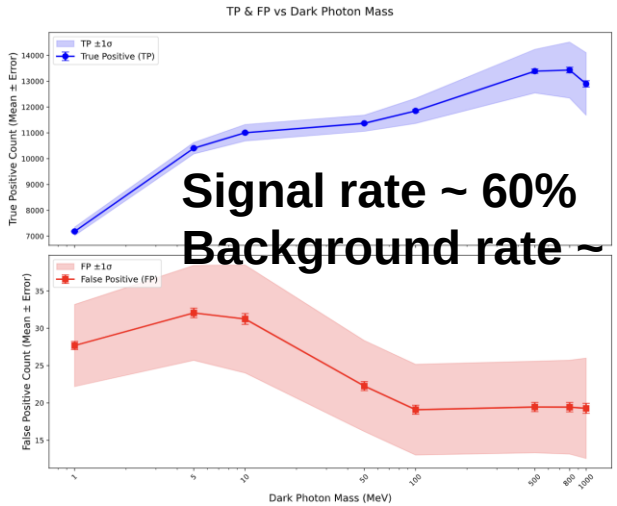
Tsung-Dao Lee Institute

- XGBoost-based analysis pipeline → **100× reduction in bkg.** (preliminary)

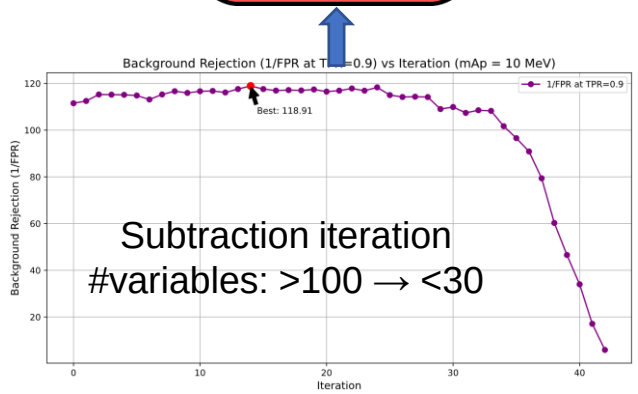
Signal ~ 10^5
Background ~ 10^{15}

DAna → Pre-selection → Hyperparameter optimization → Feature selection → Train → Yield calculation → Limit calculation

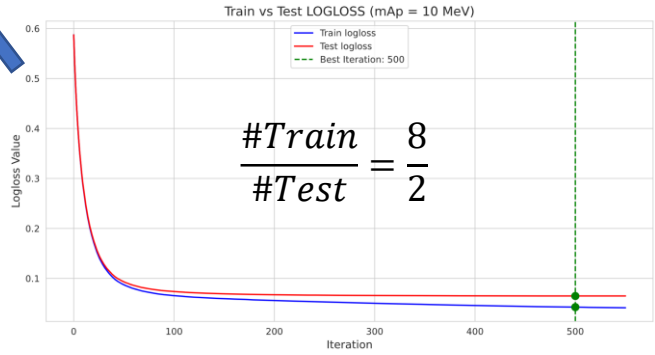




Signal rate ~ 60%
Background rate ~ $1/10^{13}$



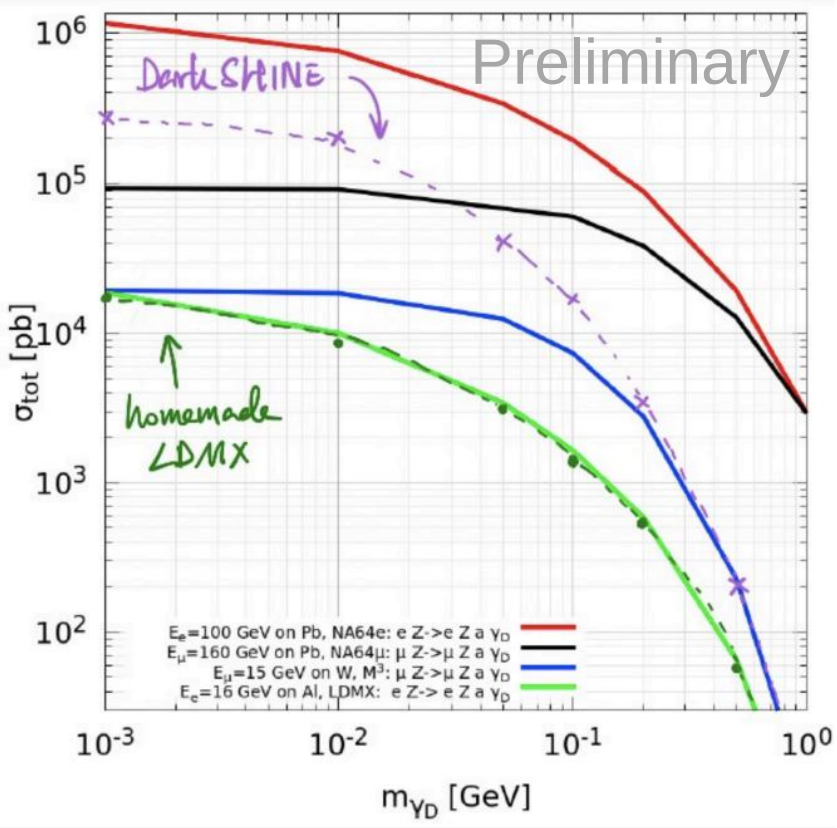
Subtraction iteration
#variables: >100 → <30



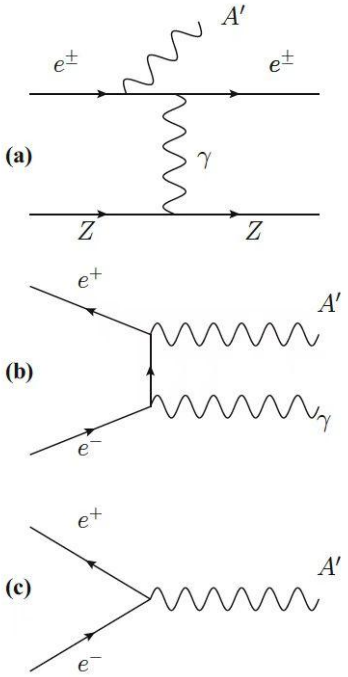
$$\frac{\#Train}{\#Test} = \frac{8}{2}$$

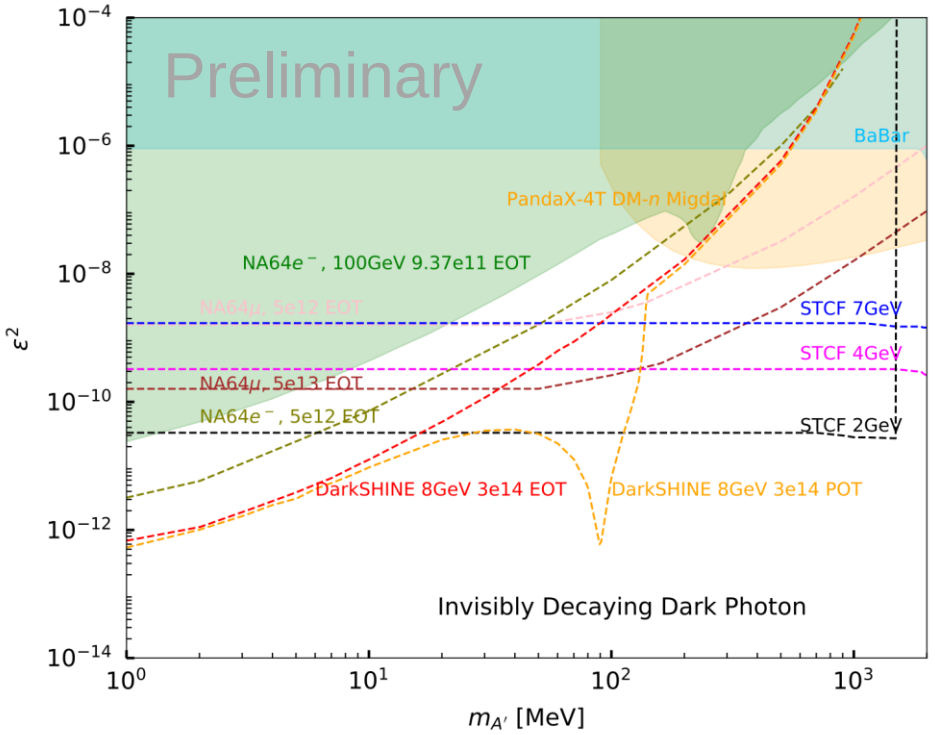
More Physics Opportunities

Minimal dark Axion-like particle portal and Axion+DP co-existence



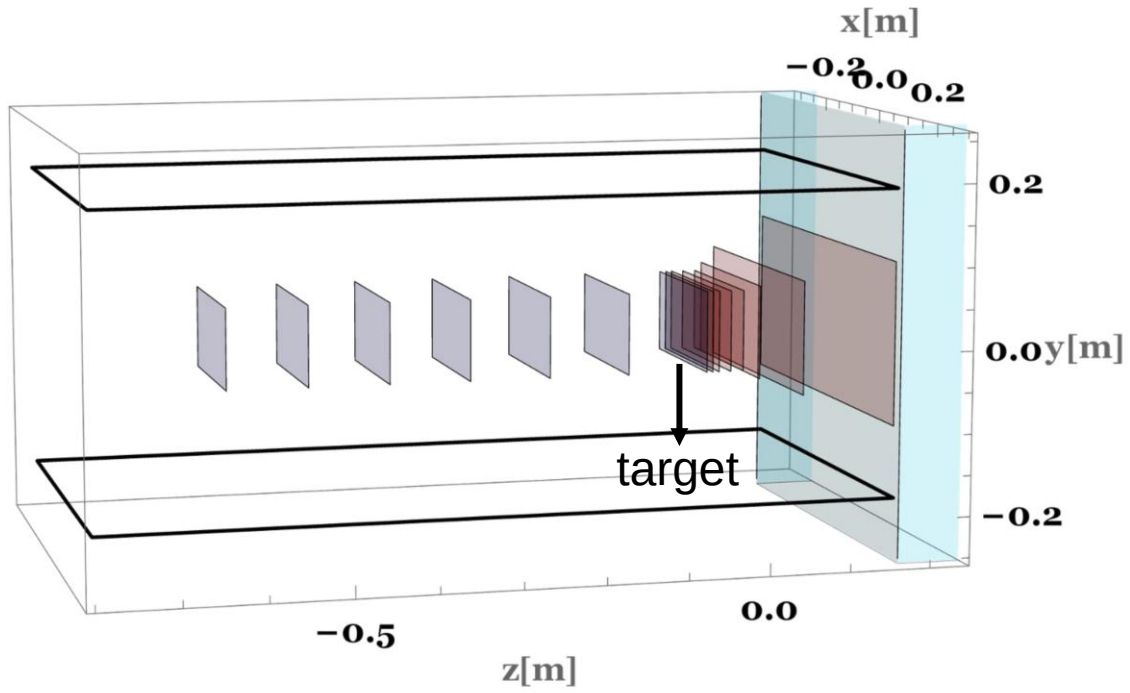
Changing from electron beam to positron beam

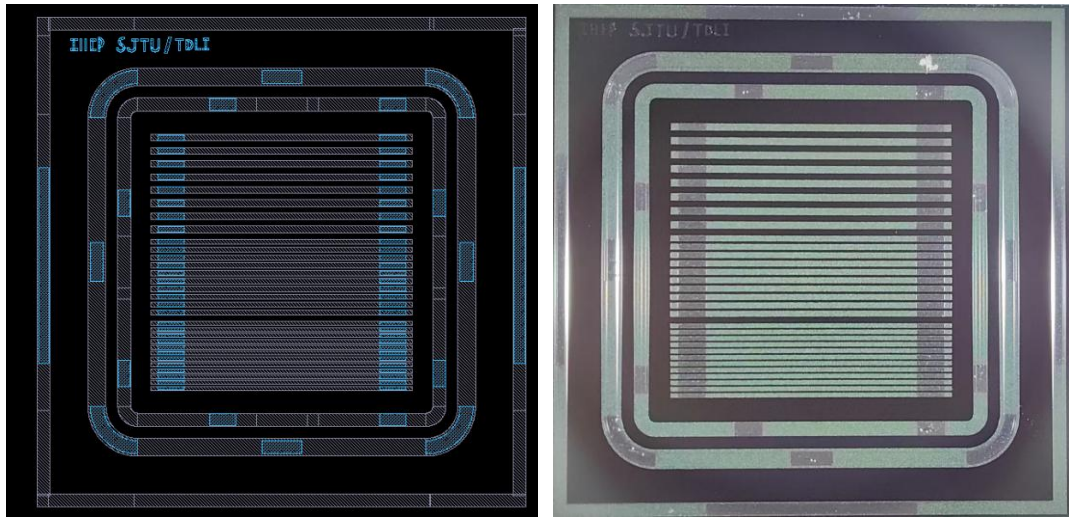




Hardware R&D: Tracking System

- Silicon strip detector in a strong magnetic field, ~10 μm position resolution
- 7 layers of tagging + 6 layers of recoil tracker, two silicon strips sensors w/ a small angle(0.1rad)



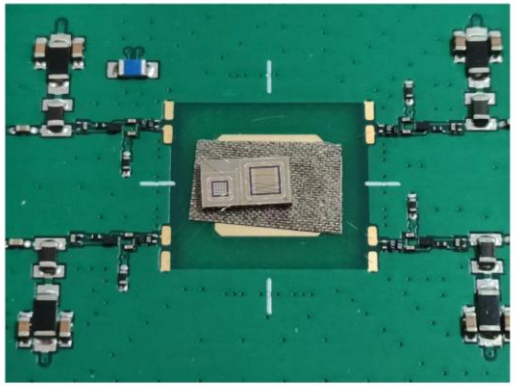


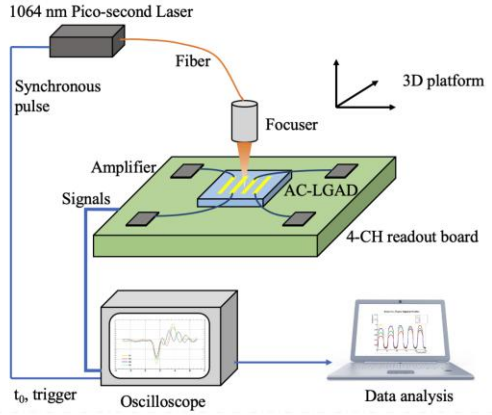
AC-LGAD silicon strip sensor 1x1 mm^2 designed, in collaboration with IHEP

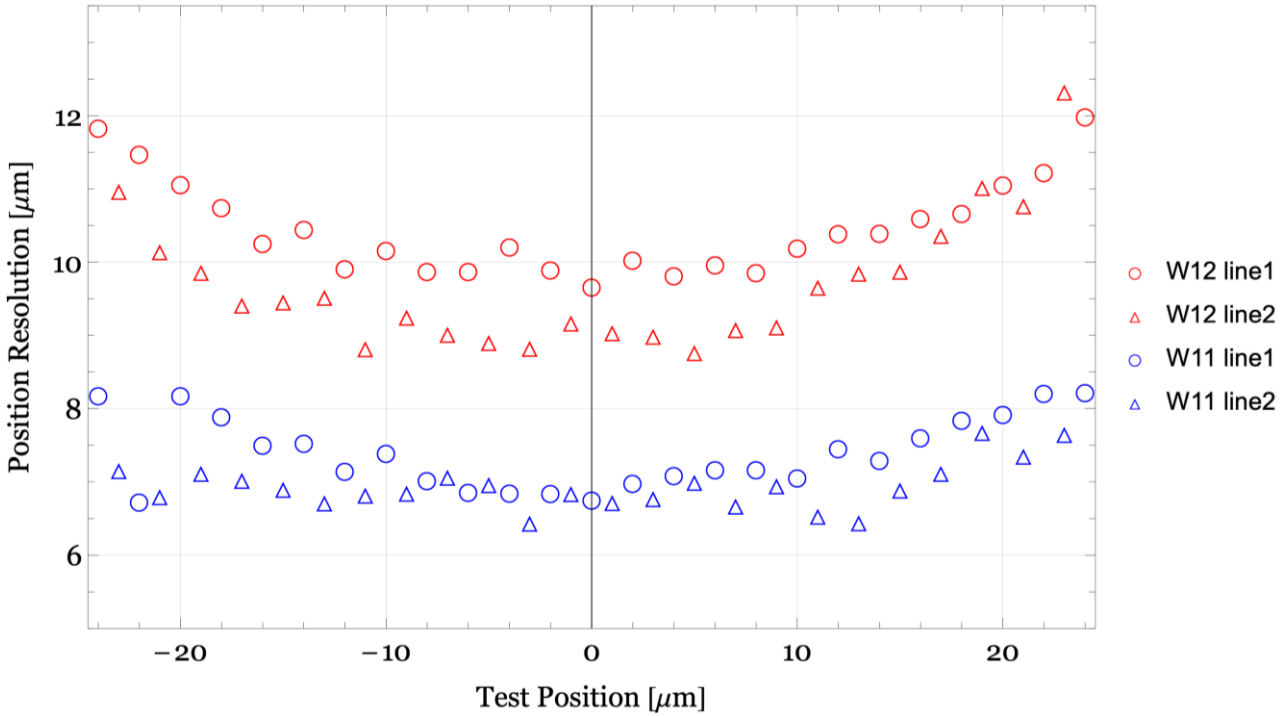
Hardware R&D: Tracking System

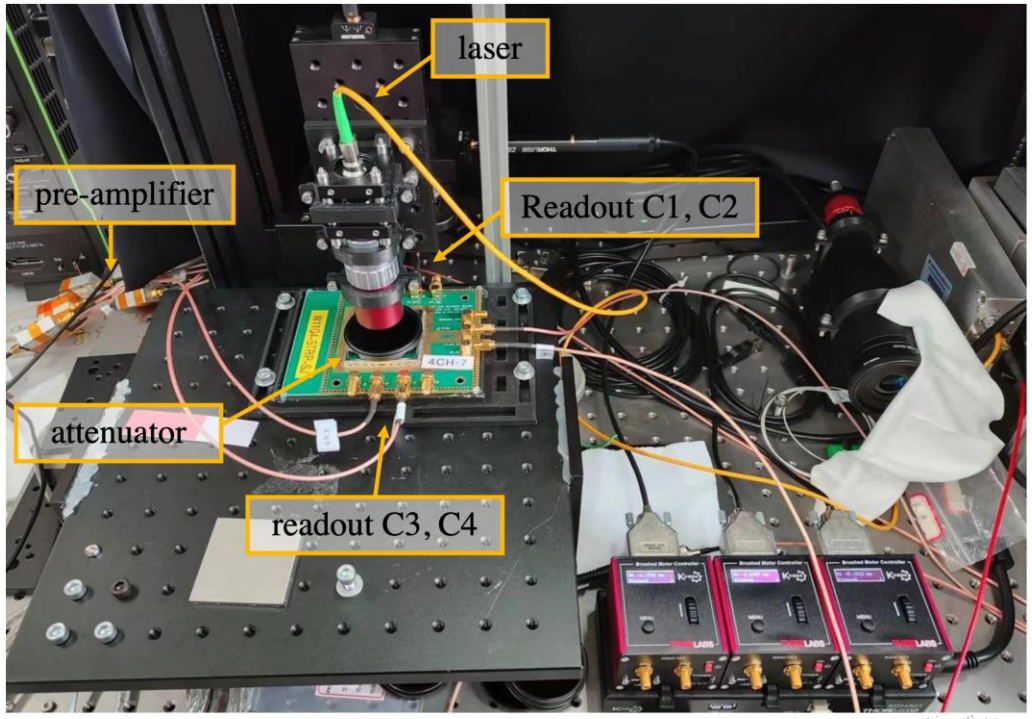
- AC-LGAD silicon strip sensor prototype tested using laser beam.
- Spatial resolution 7 μm ~ 12 μm can be achieved, with good timing resolution.

Nucl. Sci. Tech. 35, 201 (2024)



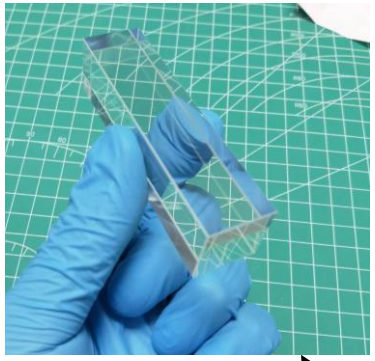






Hardware R&D: Electromagnetic Calorimeter (ECAL)

Nucl. Sci. Tech. 36, 41 (2025)

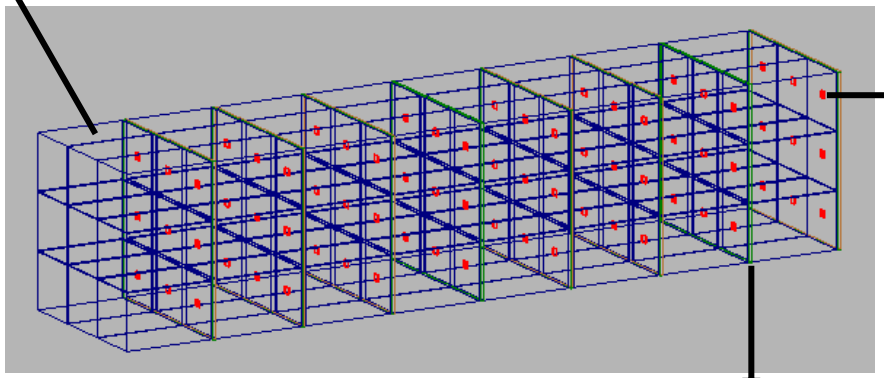


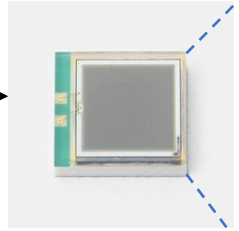
LYSO crystal scintillator

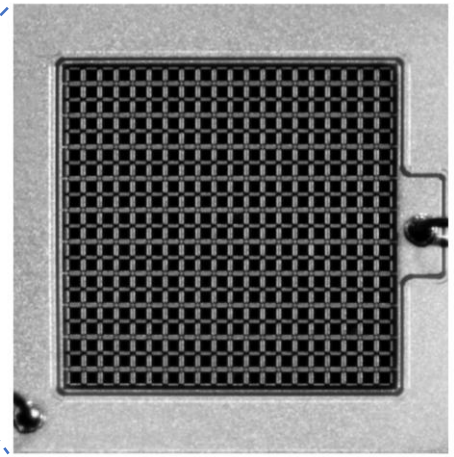
- High light yield: ~30000 ph/MeV
- Fast scintillation decay time: 40ns
- Great radiation tolerance

Other parts: mechanics, cooling system, etc.

Precise measurement on energy of electrons and photons

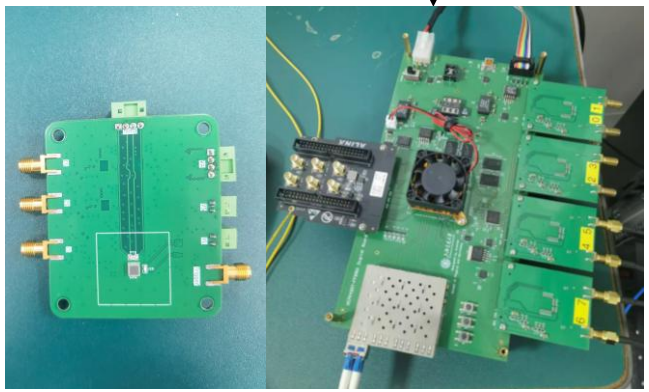






Readout electronics

- Digitization and transmission of electrical signals
- High precision, large dynamic range, high-repetition operation

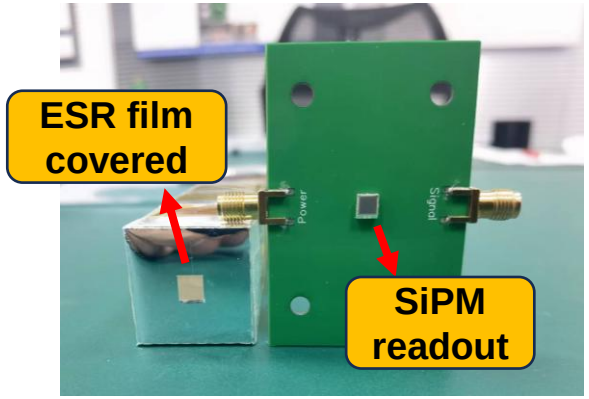


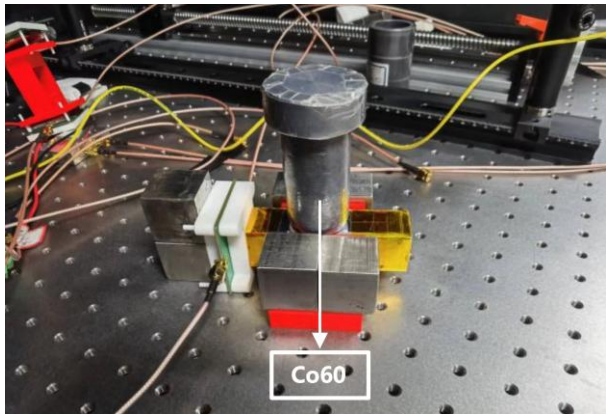
Silicon Photomultiplier (SiPM)

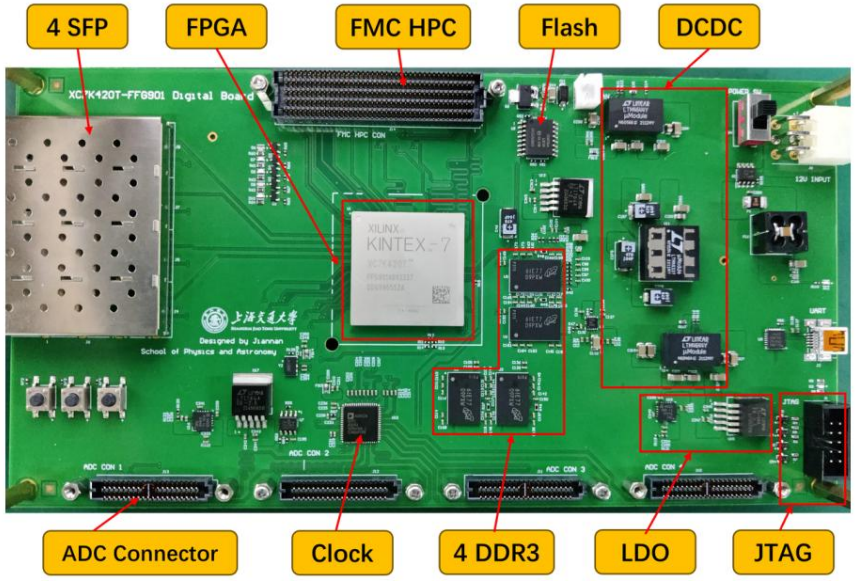
- Compact size
- Single-photon sensitivity
- Great time resolution
- Low operating voltage

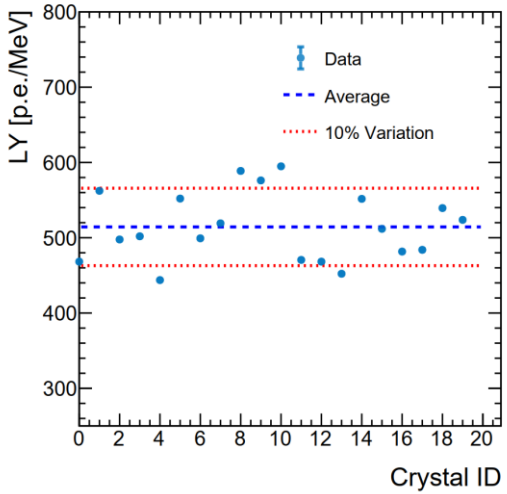
Hardware R&D: Electromagnetic Calorimeter (ECAL)

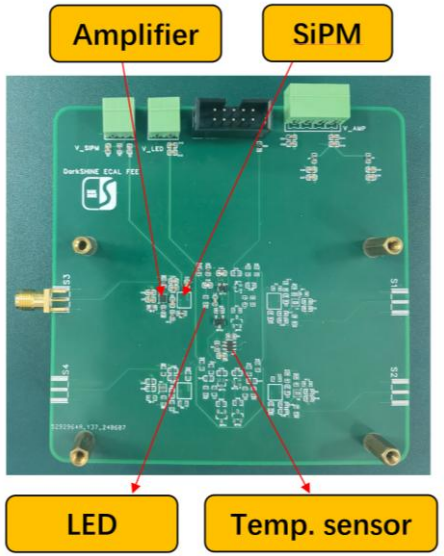
- Dedicated R&D works on crystal, SiPM and electronics

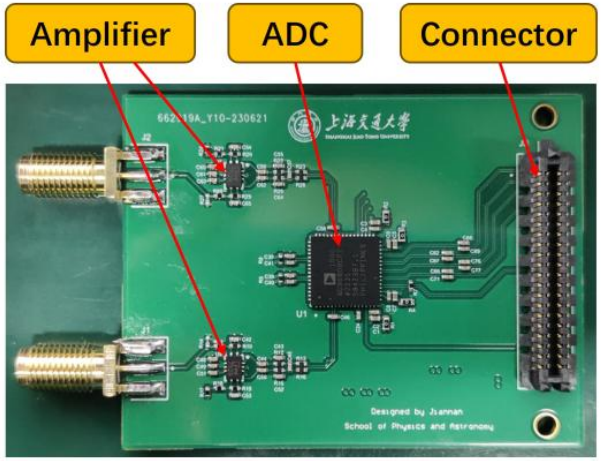




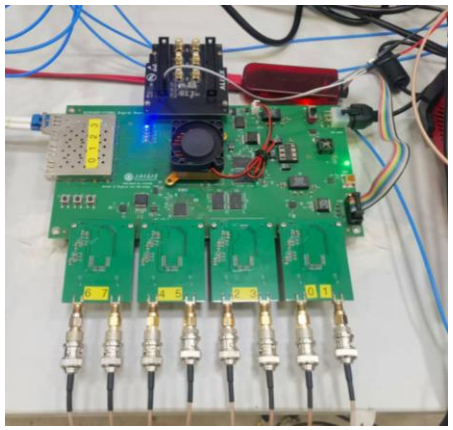


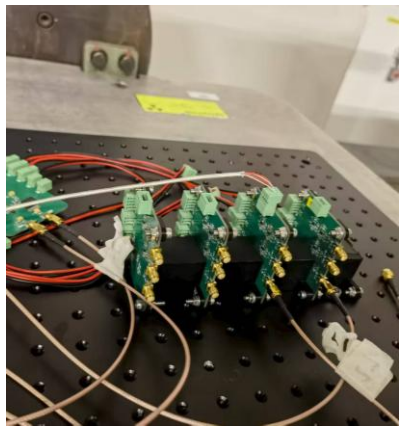






Prototype Beam Test at DESY & CERN

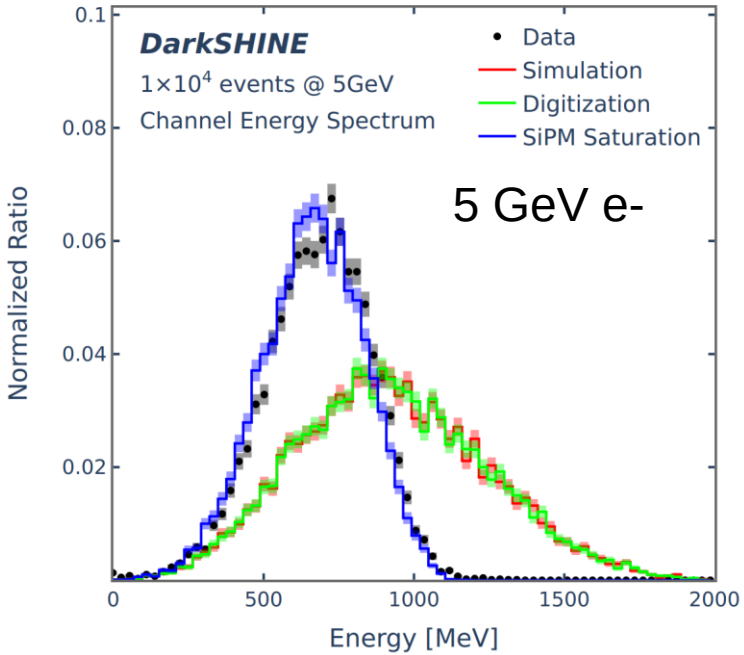




- 4-ch crystal prototype with self-designed electronics
- **1st beam test of DarkSHINE sub-detector prototype**
  - DESY (Germany) 2024, and CERN (Switzerland) 2025

June 2025 CERN PS-T9

arXiv: 2411.09345

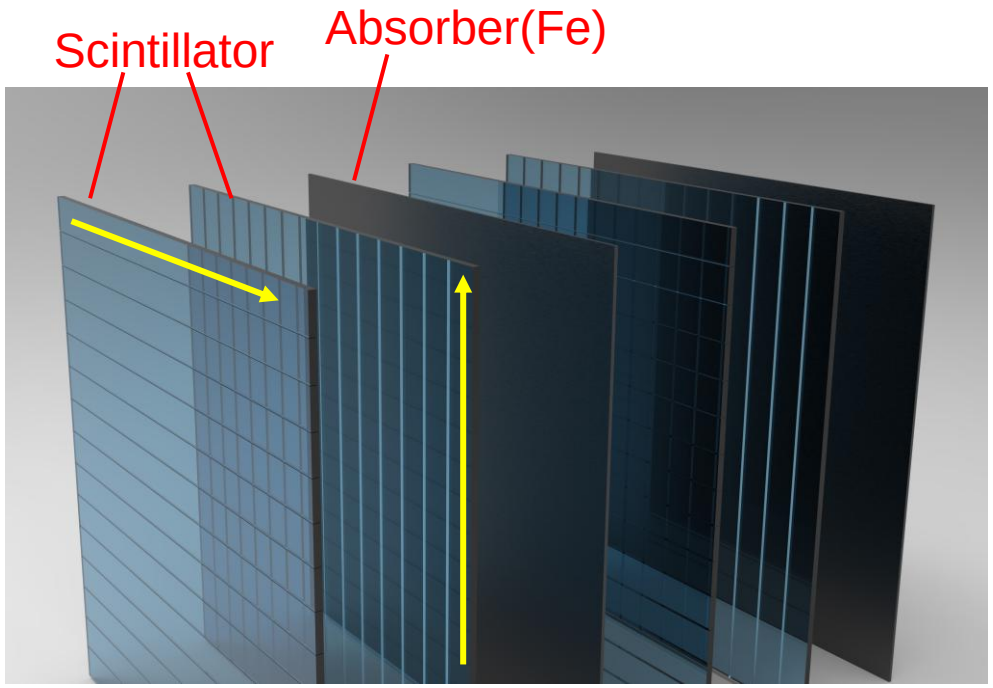


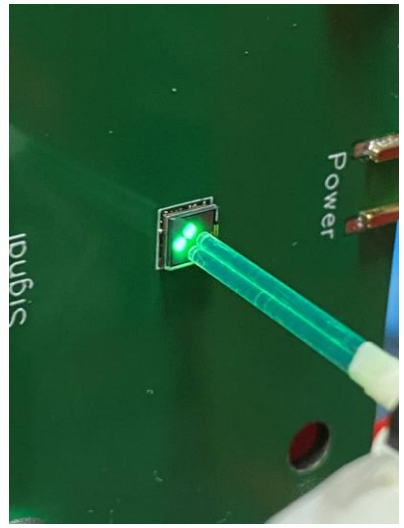
Good agreement b/w data and simulation

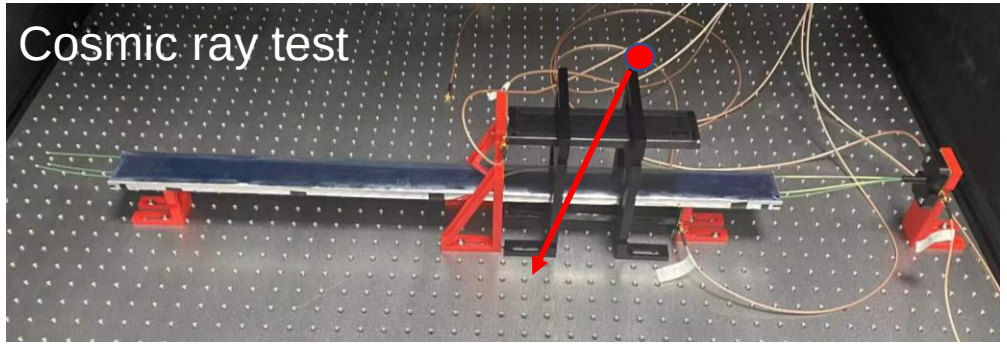
Hardware R&D: Hadronic Calorimeter (HCAL)

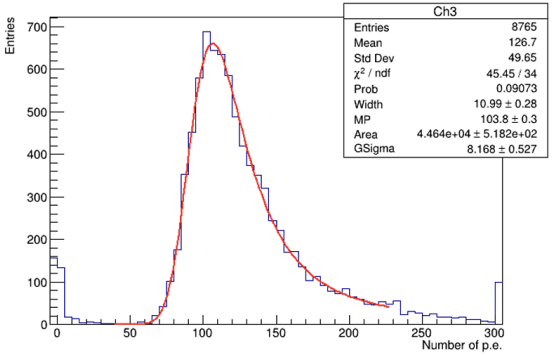
- Veto muon and hadron backgrounds
- Scintillator-Fe sampling structure
  - 1.5 m × 1.5 m x 2.5 m, ~11 λ
  - Plastic scintillator + Wavelength shift fiber + SiPM
- Good efficiency in n/p/μ detection

Nucl. Sci. Tech. 35, 148 (2024)









DarkSHINE Baseline Design Report

DarkSHINE

Baseline Design Report

Physics Prospects and Detector Technologies

Contents

Academic Activities

Dark SHINE Seasonal Workshop

22 May 2025, 09:00 → 24 May 2025, 17:10 Asia/Shanghai

Tsung-

Descrip

DarkSHINE New Physics Opportunity Mini-Forum

Saturday 2 Aug 2025, 19:30 → 21:55 Asia/Shanghai

Tsung-Dao

Haijun Yang

Liang Li (Sh

Description

09:00 → 09:30

09:30 → 10:00

10:00 → 10:30

DarkSHINE Winter Mini-Tutorial

Restricted

Saturday 8 Nov 2025, 10:00 → 18:10 Asia/Shanghai

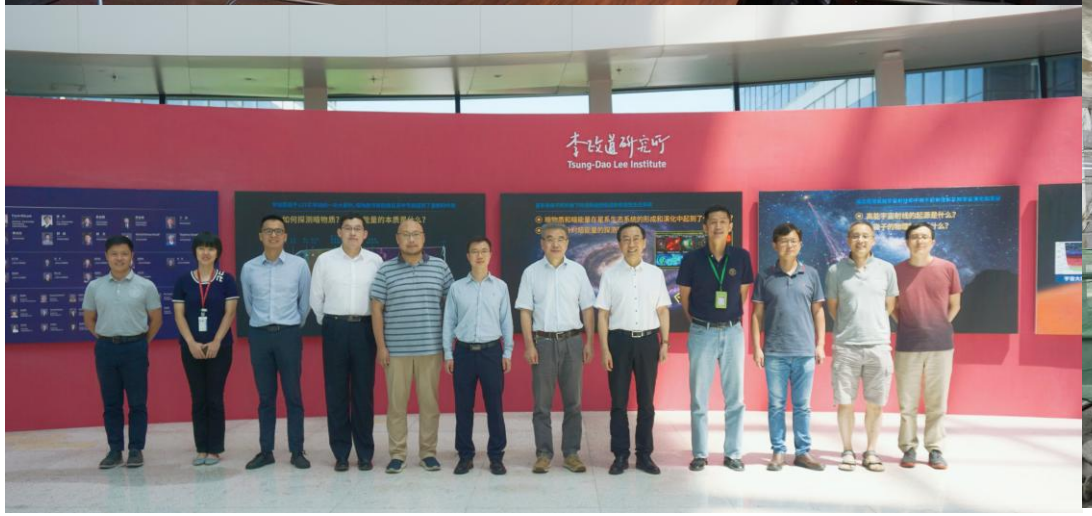
Tsung-Dao Lee Institute/N4F-N400 - meeting room (Tsung-Dao Lee Institute)

Haijun Yang (Shanghai Jiao Tong University (CN)), Shu Li (TDLI, SJTU), Kun Liu (TDLI / SJTU), Yifan Zhu, Xuliang Zhu, Haidar Mas'ud Alfanda (TDLI, SJTU)

Description Tencent meeting ID: 719270255

Password: 295188

Collaboration with SHINE



Summary

- DarkSHINE: a fixed-target experiment searching for dark photon bremsstrahlung and invisible decay via missing E/p
- Sensitivity competitive with other international experiments.
- Extensive R&D was carried out on the detector’s critical technologies
- Conceptual design report completed — submission underway

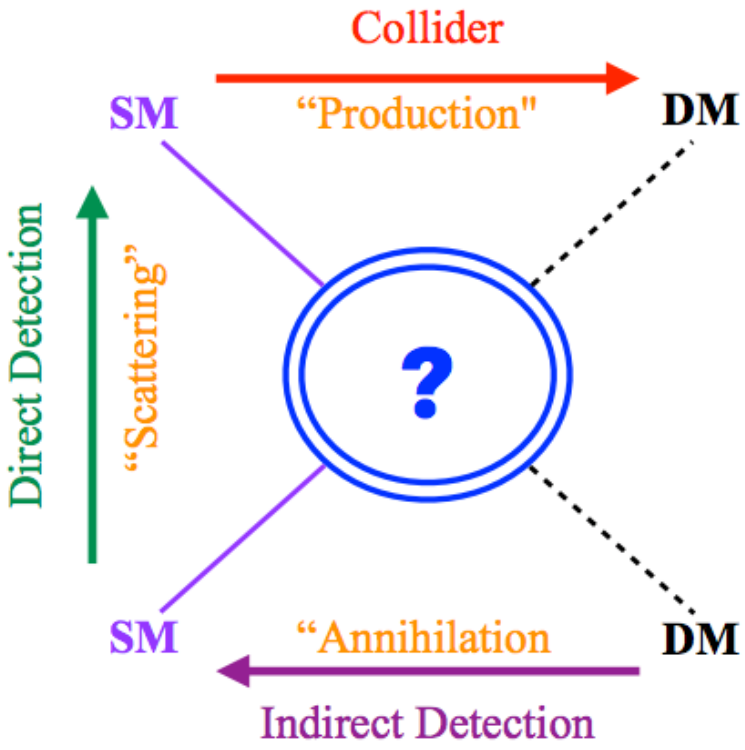
- Future: explore more physics opportunities and develop large-scale detector prototypes

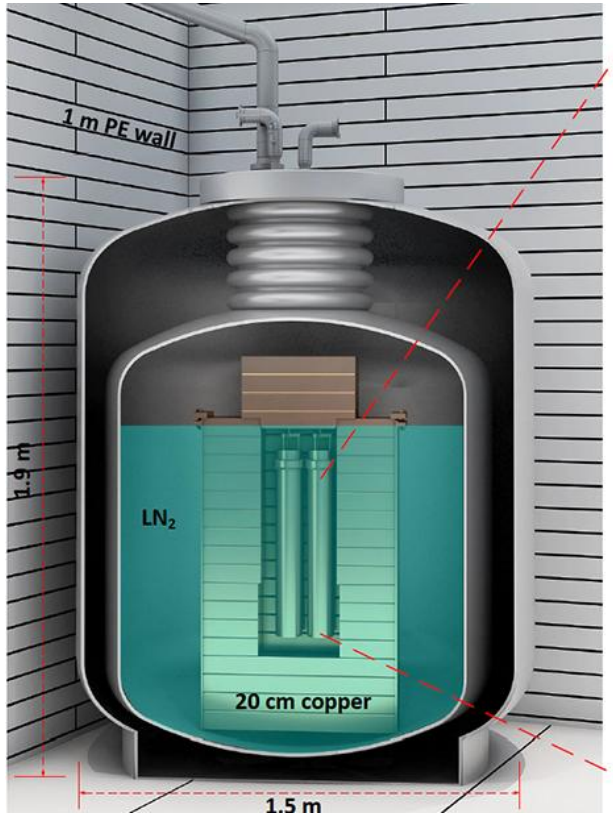
Thanks!

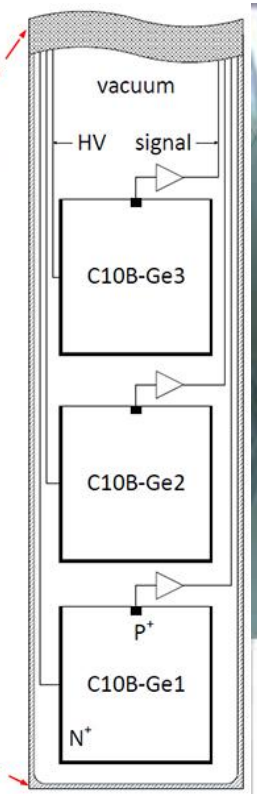
DARK SHINE

Dark Matter Direct Detections

- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (XENONnT, LZ, CDEX, PandaX, …)
- 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

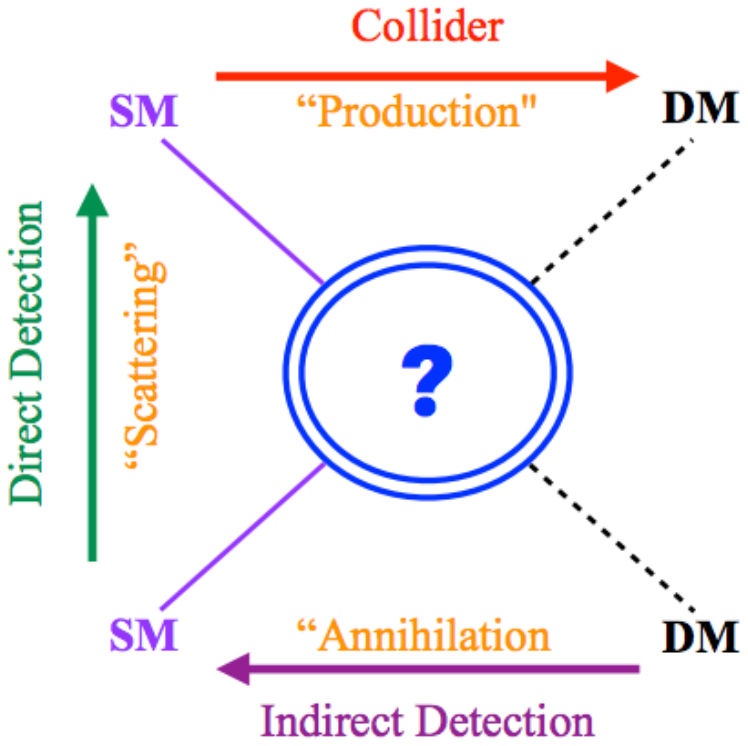


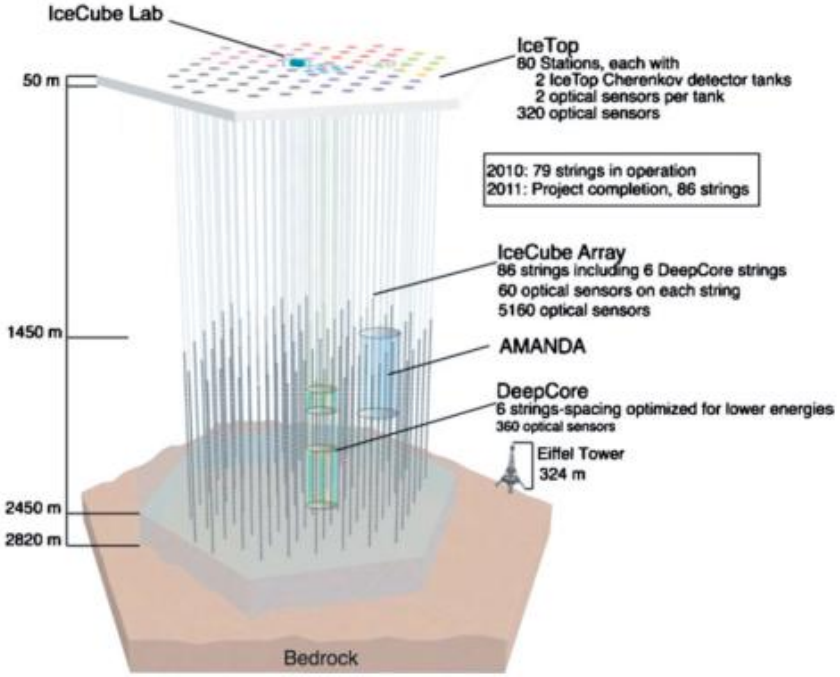




Dark Matter Indirect Detections

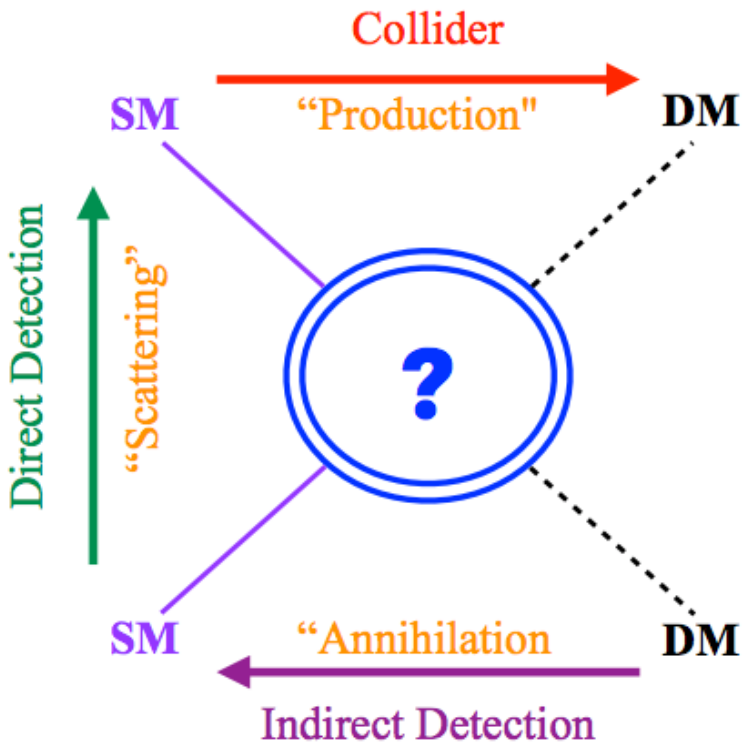
- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (XENONnT, LZ, CDEX, PandaX, …)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing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

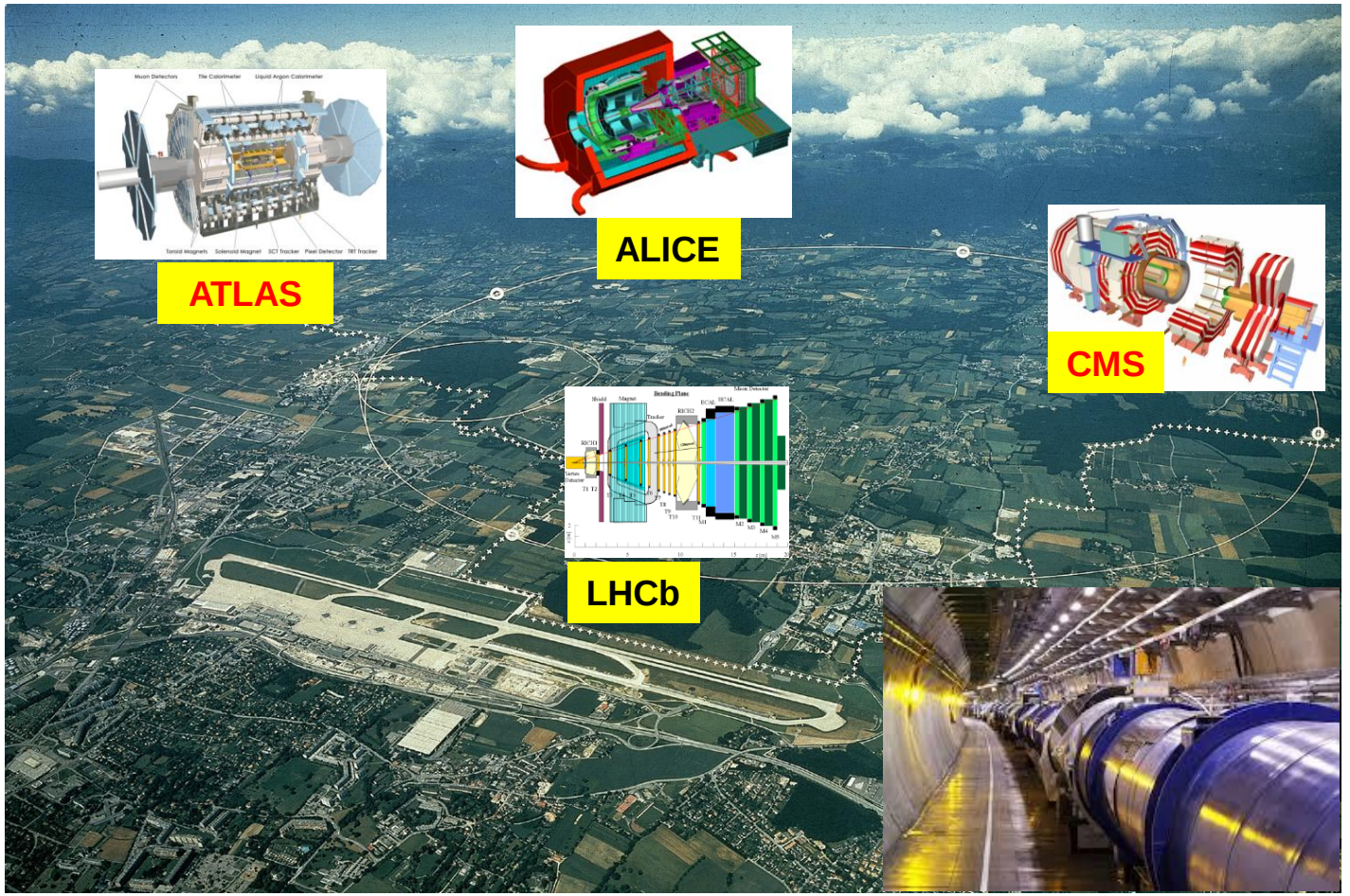




Dark Matter Collider productions

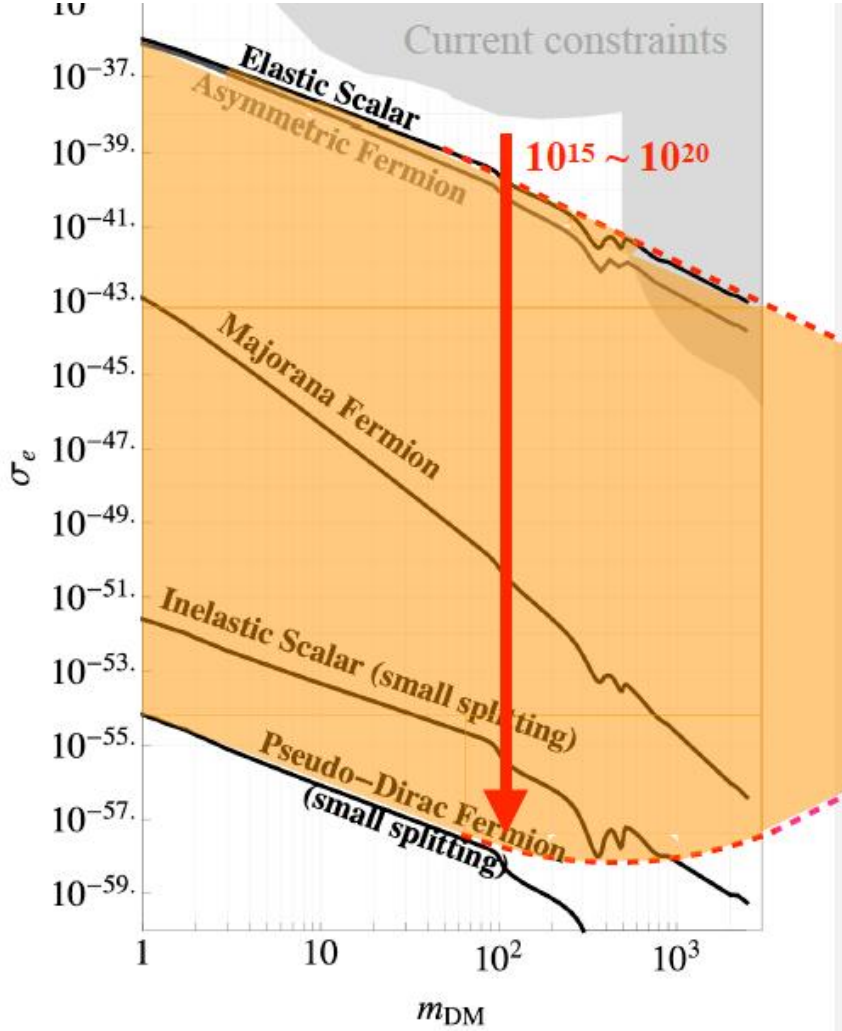
- Direct Detection (DD): nuclear recoils from DM-nuclei scattering (XENONnT, LZ, CDEX, PandaX, …)
- Indirect Detection (ID): products from DM annihilation (DAMPE, HESS, IceCube, ..)
- Colliders: DM production in high-energy collisions, focusing on the productions of a SM particle(s) (X) with large missing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



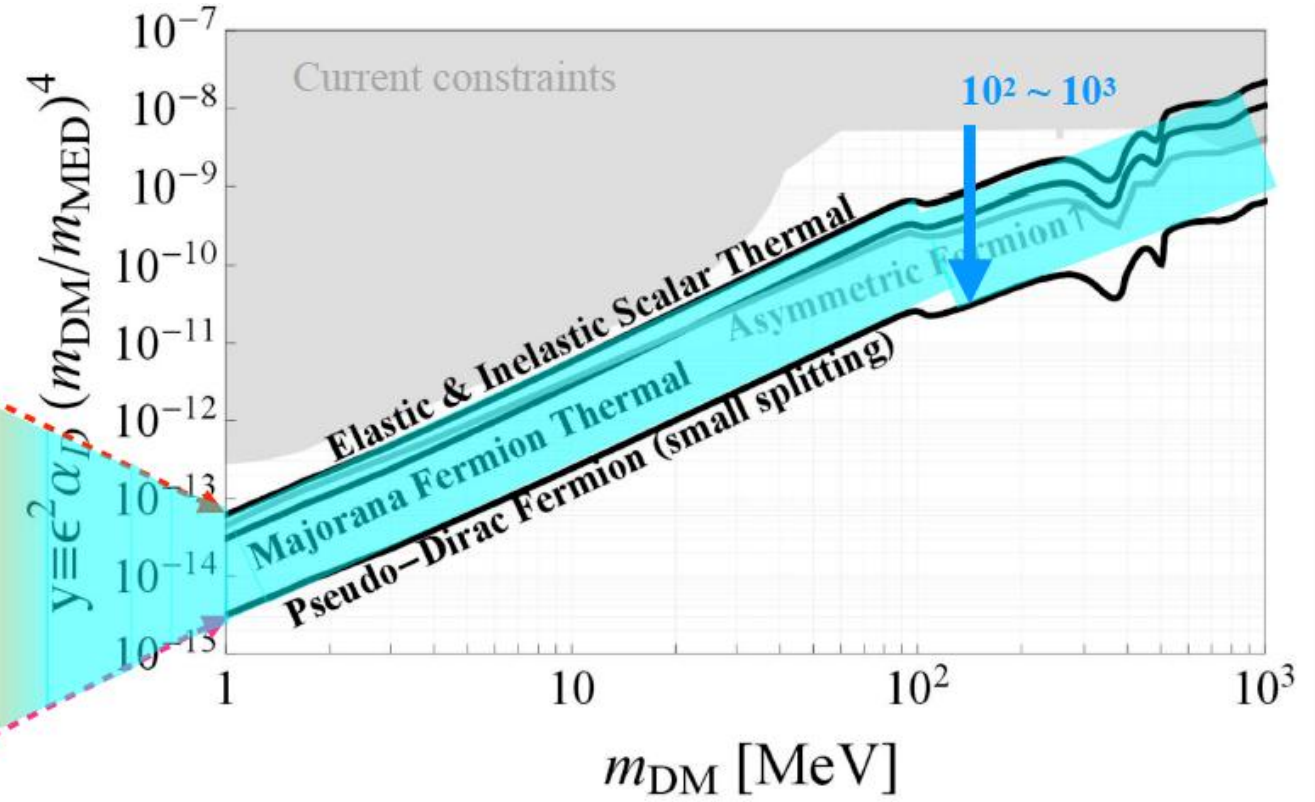


Dark Matter search at Accelerator Experiments

Direct Detection

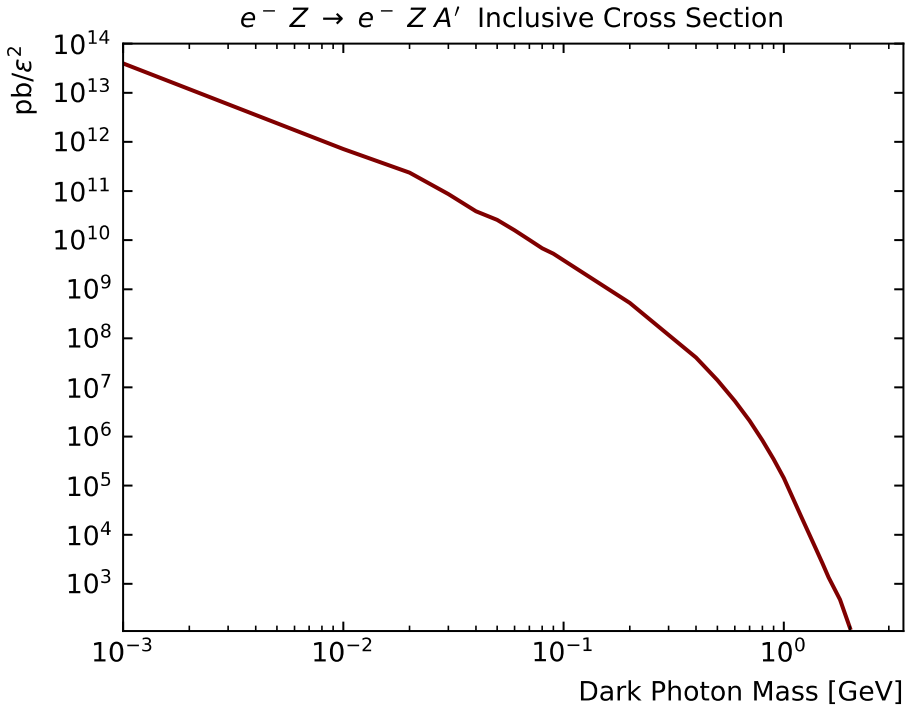


Accelerator based experiments



- 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.

Inclusive Cross Section

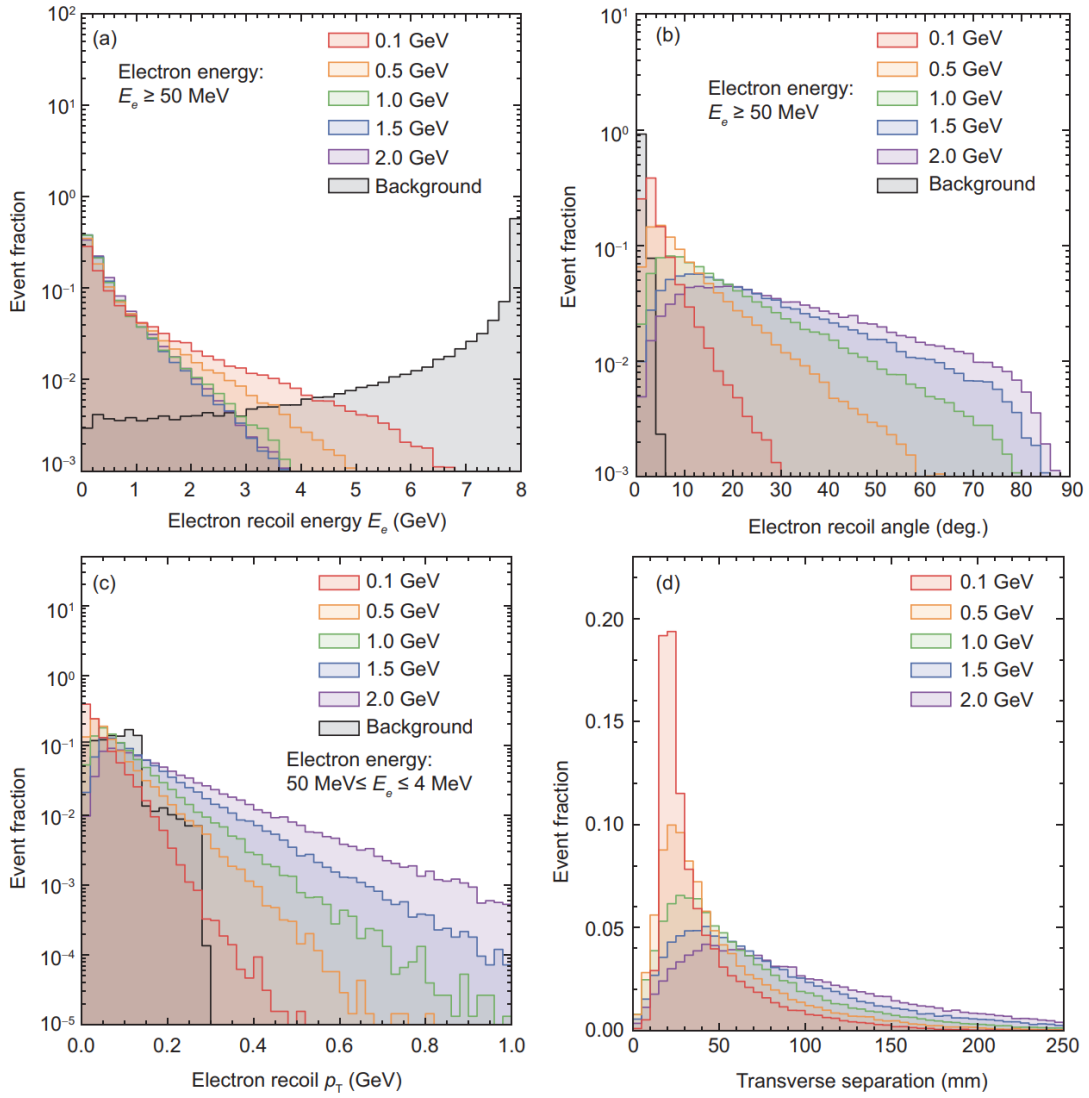


Inclusive cross-section of dark photon bremsstrahlung from electron interacting with W target, assuming $\varepsilon = 1$.

Signal & Background Features

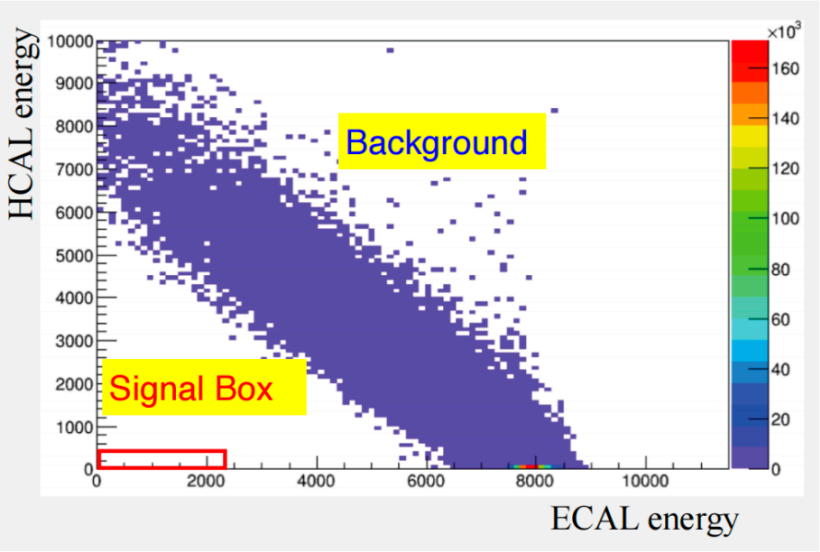
Signal
- Low recoil energy
- Large recoil angle and recoil p_T

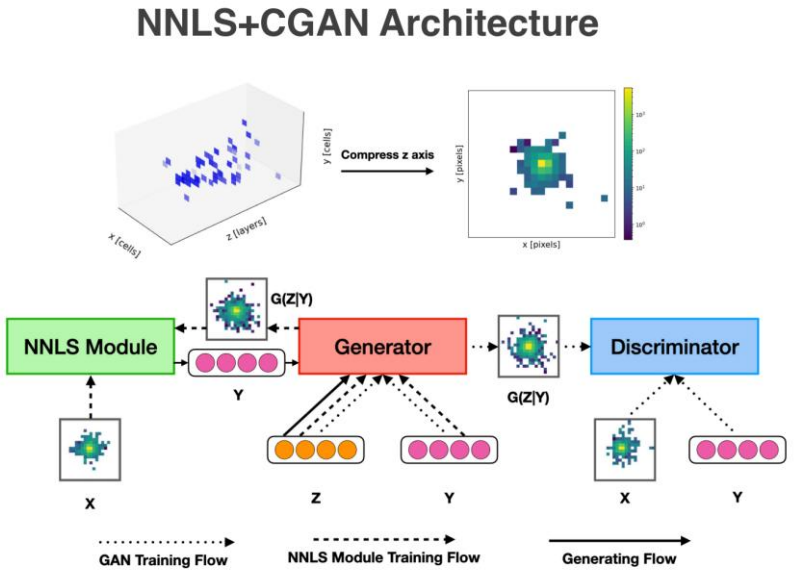
Background
- Large recoil energy
- Samll recoil angle and recoil p_T

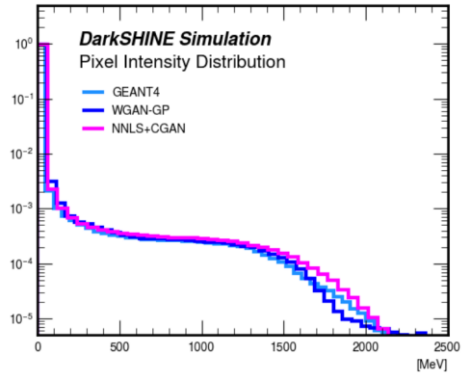


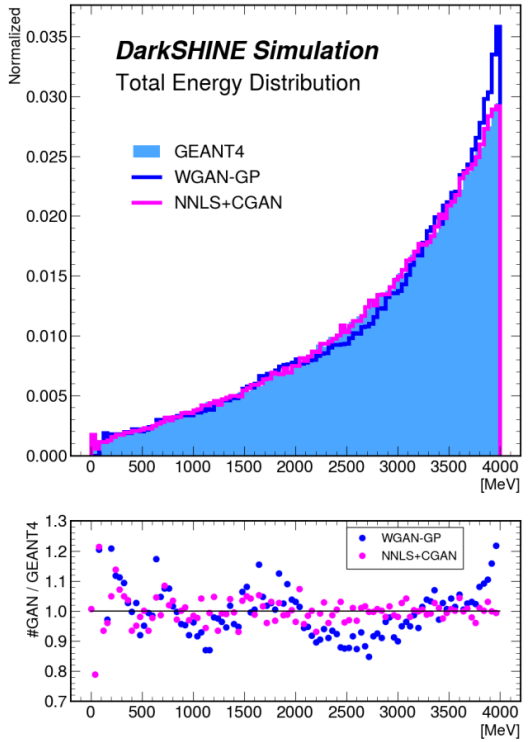
Fast Simulation with Machine Learning

- Motivation: As we increase the simulation statistical quantities, it tends to be more background events closing to signal region
  - Geant4 simulation for 3×10^{14} EOTs will consume a massive amount of resources
    - ~5ms per inclusive event. 3×10^{14} EOTs ~ 10^4 CPUs run for 5 years
  - Generation with deep learning network could save a lot of time/money
- NNLS+CGAN can work for ECAL energy data synthesis
  - $\times 10^4$ speed-up could be achieved
  - Upgrade to provided shower shape for detailed validation



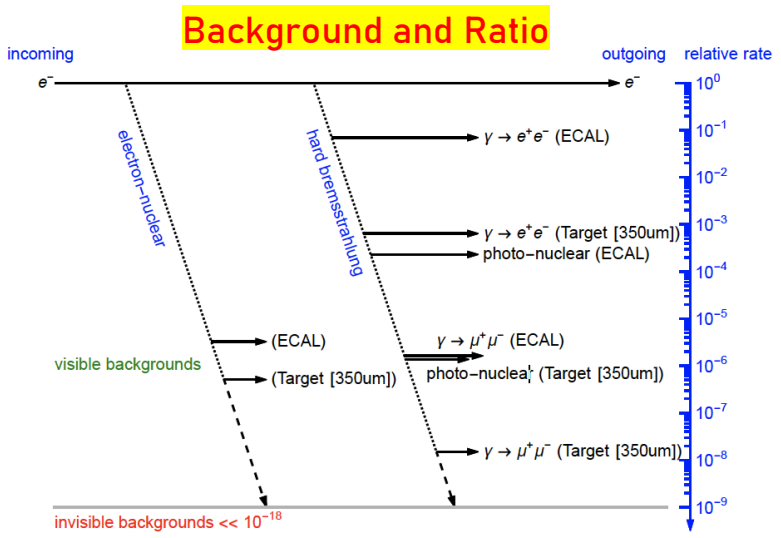


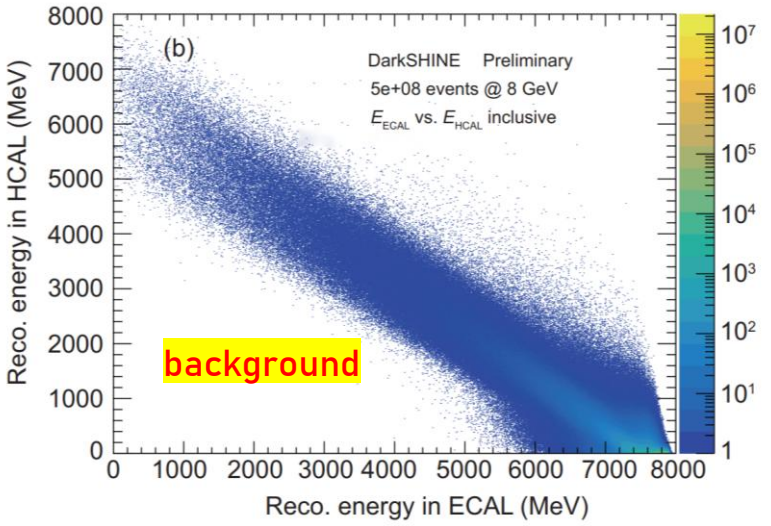


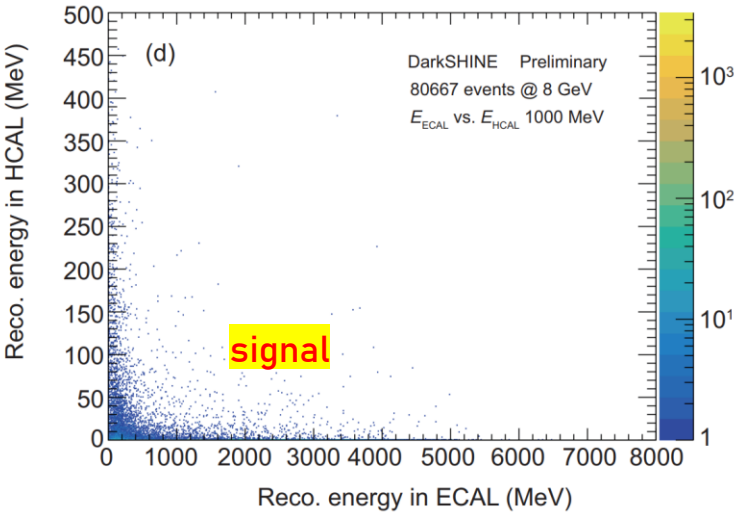


[1] Mirza M, Osindero S. Conditional generative adversarial nets[J]. arXiv preprint arXiv:1411.1784, 2014.
[2] Chen D, Plemmons R J. Nonnegativity constraints in numerical analysis[M]//The birth of numerical analysis. 2010: 109-139.

Background Rejection







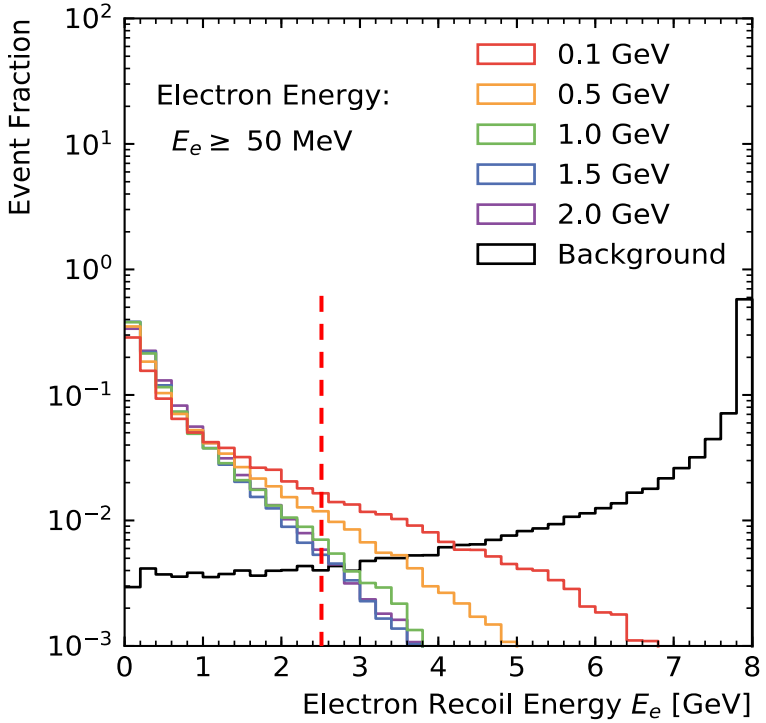
Signal region

	EN_ECAL	PN_ECAL	GMM_ECAL	EN_target	PN_target	GMM_target	Hard_brem	Inclusive
Total events	100	100	100	100	100	100	100	100
Only 1 track	58.87	70.48	87.36	5.85	5.88	$< 10^{-3}$	78.73	84.40
$p_{tag} - p_{rec} > 4$ GeV	0.0044	0.0033	0.0041	5.58	5.46	$< 10^{-5}$	70.49	4.80
$E^{total}_{HCAL} < 100$ MeV	$< 10^{-3}$	$< 10^{-3}$	0	0.30	0.72	0	69.61	4.76
$E^{MaxCell}_{HCAL} < 10$ MeV	$< 10^{-3}$	$< 10^{-3}$	0	0.13	0.27	0	65.00	4.48
$E^{MaxCell}_{HCAL} < 2$ MeV	$< 10^{-3}$	$< 10^{-3}$	0	0.058	0.095	0	58.14	4.04
$E^{total}_{ECAL} < 2.5$ GeV	0	0	0	0	0	0	0	0

Zero background can be achieved, for 2.5×10^9 inclusive EOTs and ~10^{12} rare EOTs!

Dark Photon Efficiency

- After applying all cuts in signal region, a signal efficiency of around 60% can still be achieved.



Signal loss due to the cut box