李政道研究所
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The DarkSHINE Experiment R&D Status

Searching for dark photon to light dark matter invisible decay

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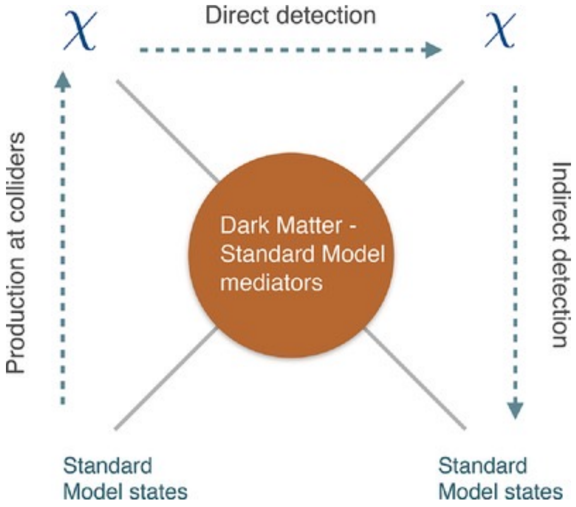
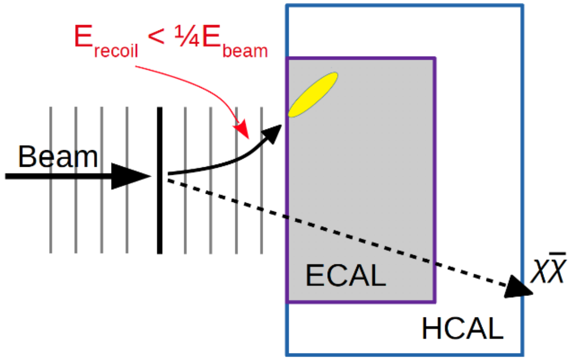
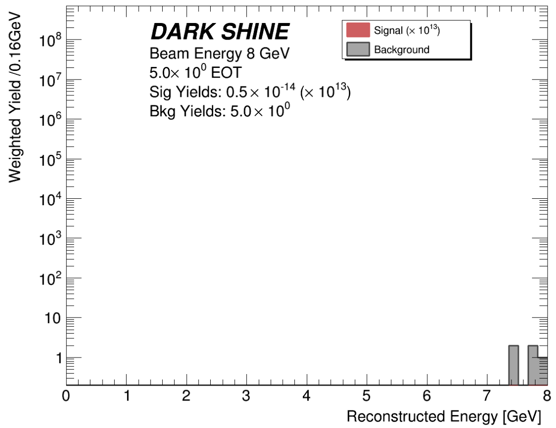
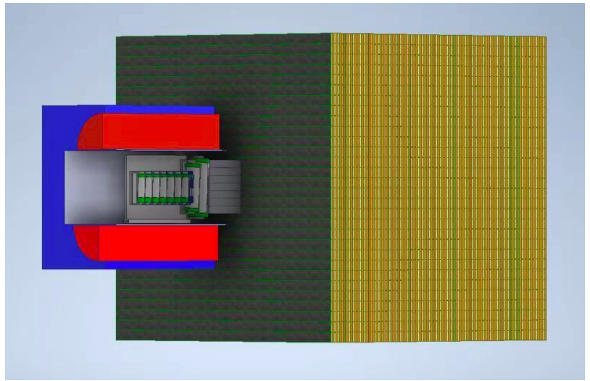
Outline

- **Physics motivation**
- **The SHINE facility introduction**
- **The detector conceptual design**
- **Prospective studies in simulation**
- **Detector R&D status**
- **Summary**

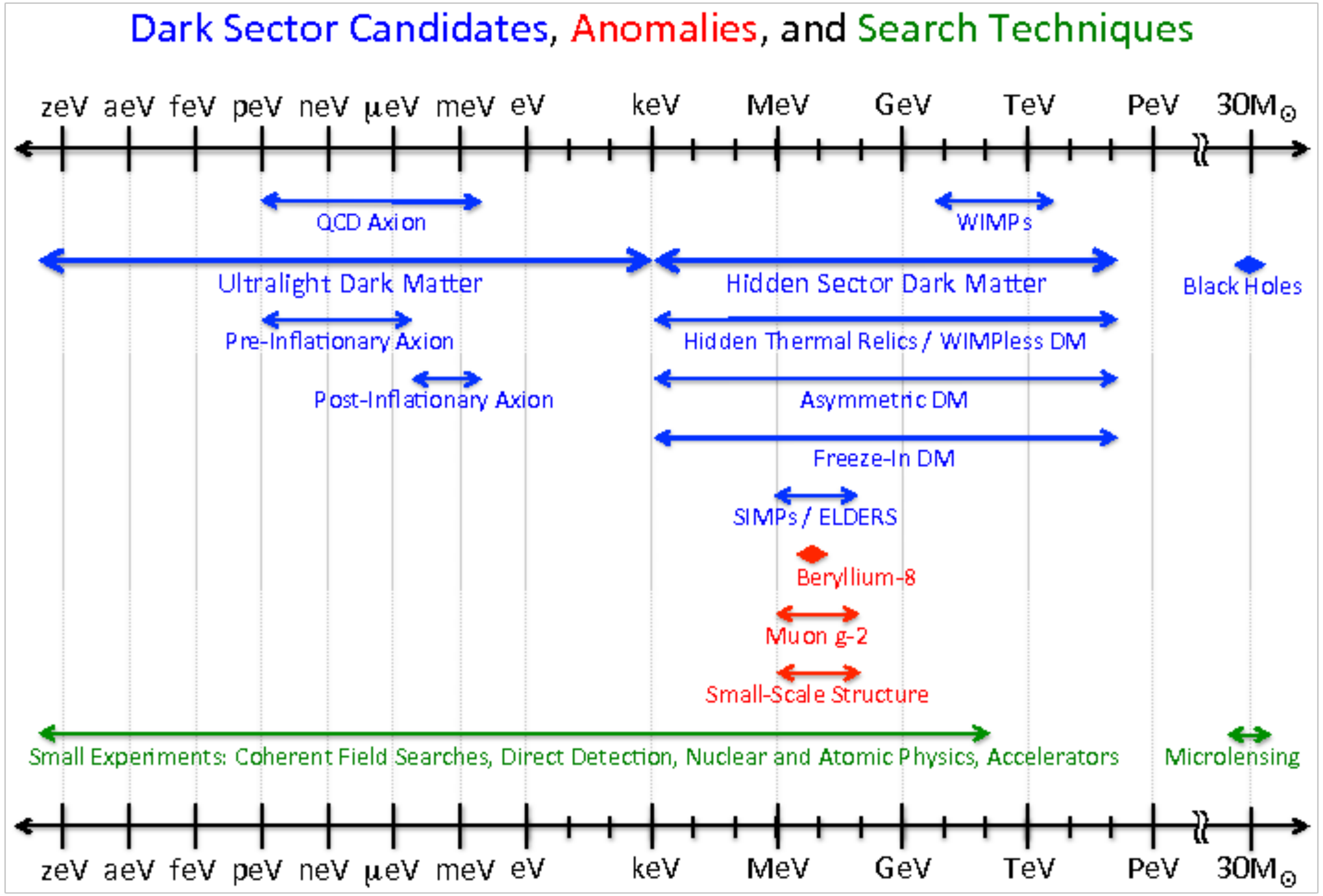






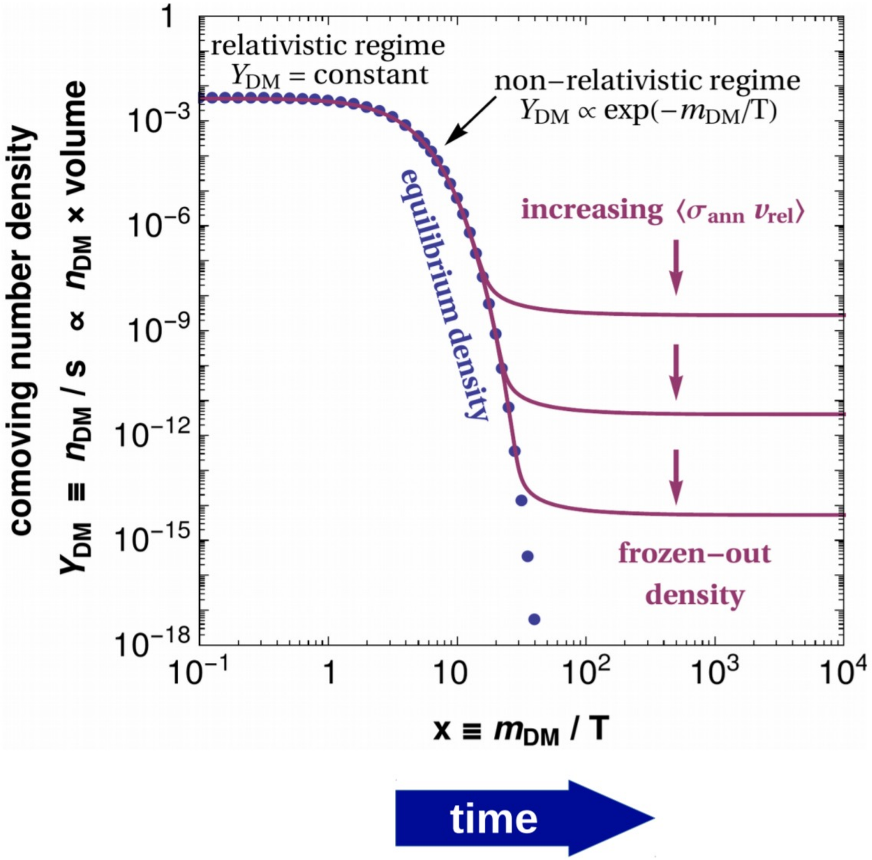


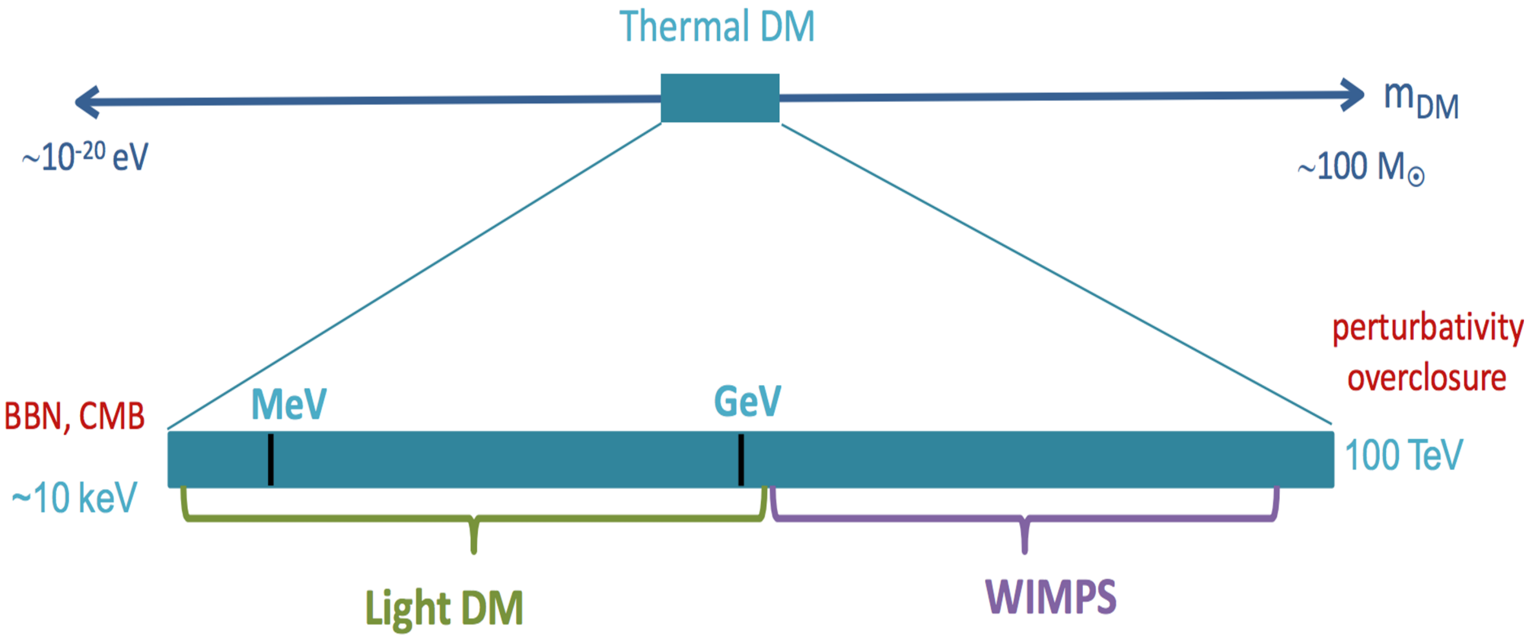
- **Dark Matter can exist in wide mass range, from Ultralight "Fuzzy DM" to Primordial Black Holes.**



arXiv: 1707.04591; arXiv:1810.01668

Physics Motivation – search for light dark matter





Thermal contact implies a new mediator
Hidden sector light DM model is well-motivated

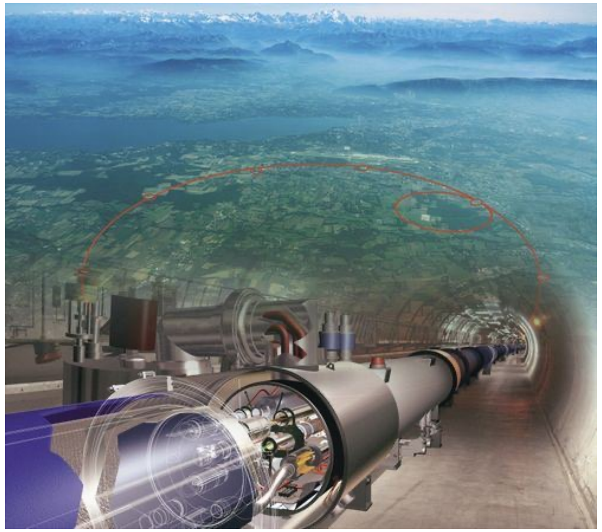
Thermal freeze-out for weak scale masses
Has driven DM searches for last ~30 years

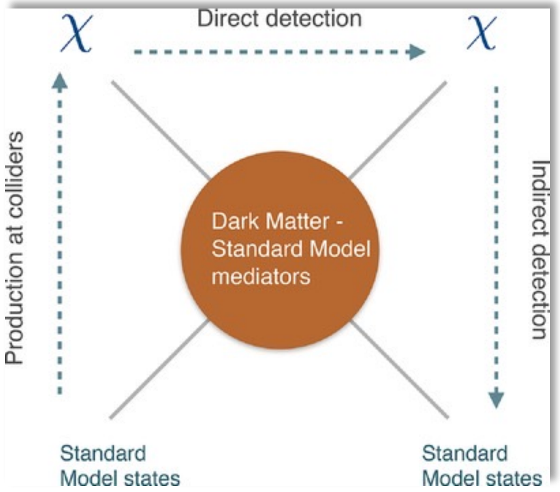
- **In order to explain the presence of Dark Matter constituting ~ 27% of the energy content of the universe, the "Freeze-out" mechanism allows mass range of Dark Matter: MeV ~ 10s TeV.**

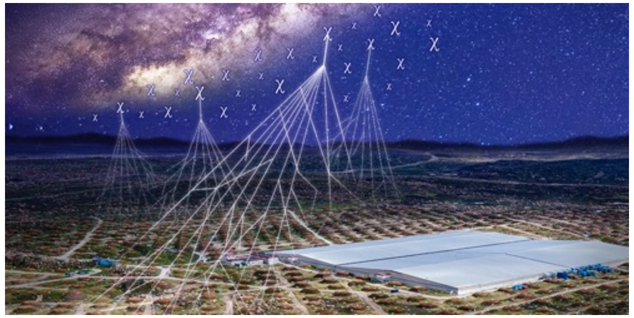
Physics Motivation – search general strategy

MeV $\sim m_e$ GeV $\sim m_p$ $m_{Z,h}$ $\sim$ 10s TeV

$\Delta N_{\rm eff}$ LDM "WIMPs" $\Omega_\chi > \Omega_{\rm DM}$

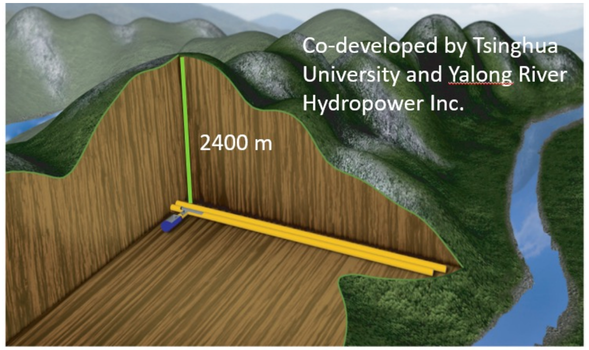


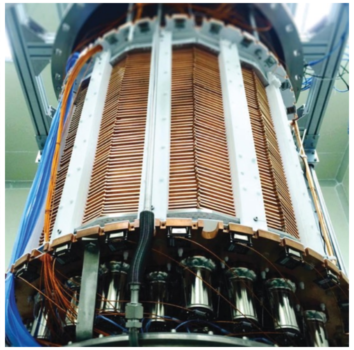




Collider experiments
(LHC, BELLE-II , BESIII etc.)

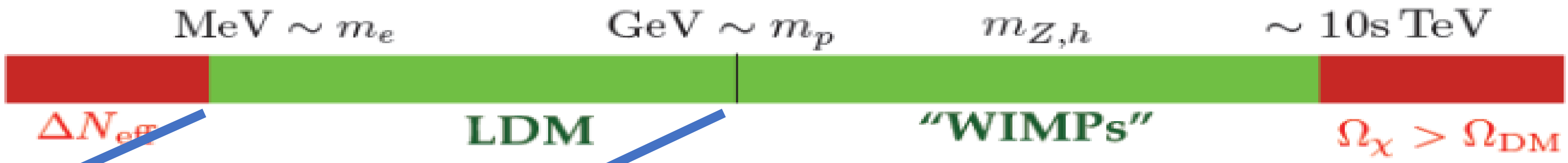
Underground experiments
(CDEX, PandaX, Xenon etc.)

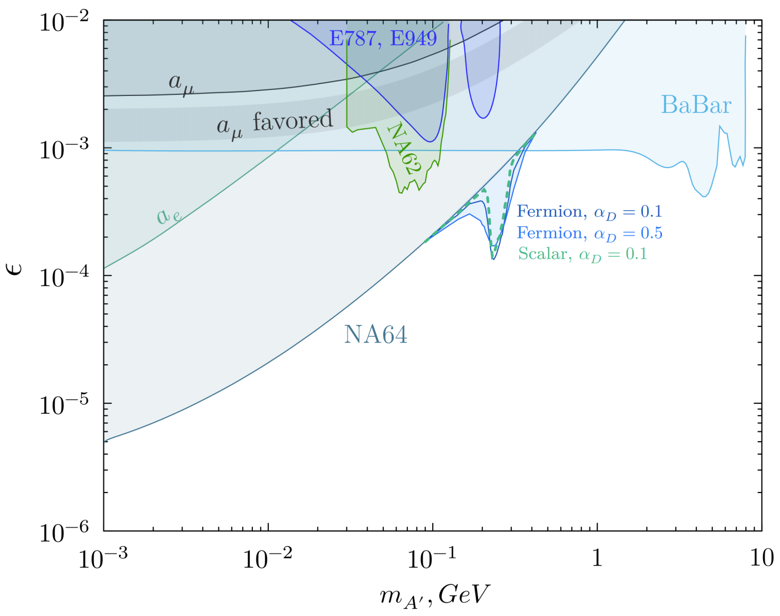


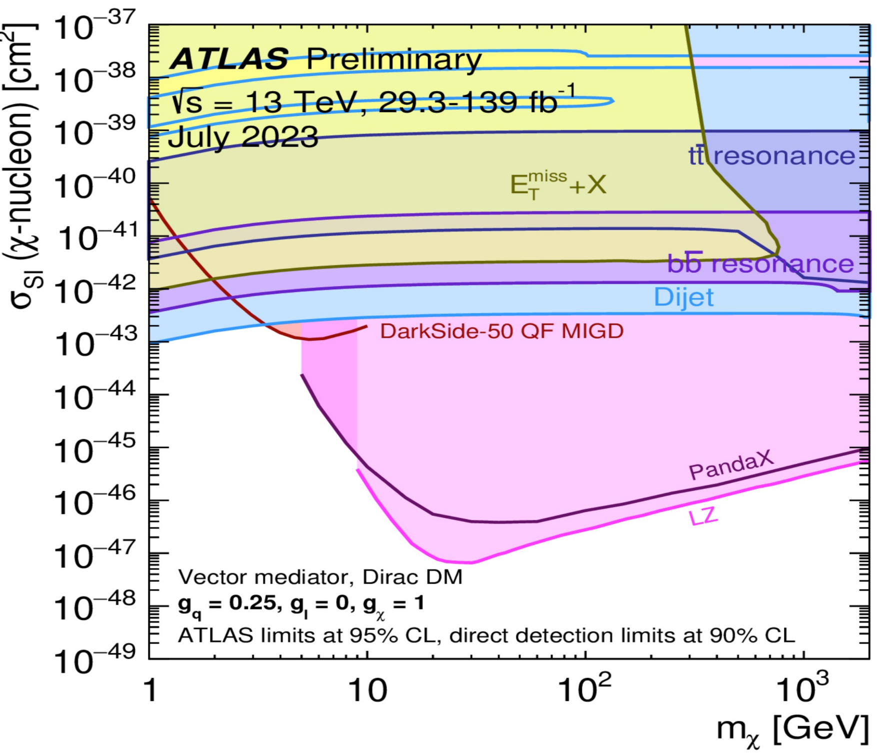


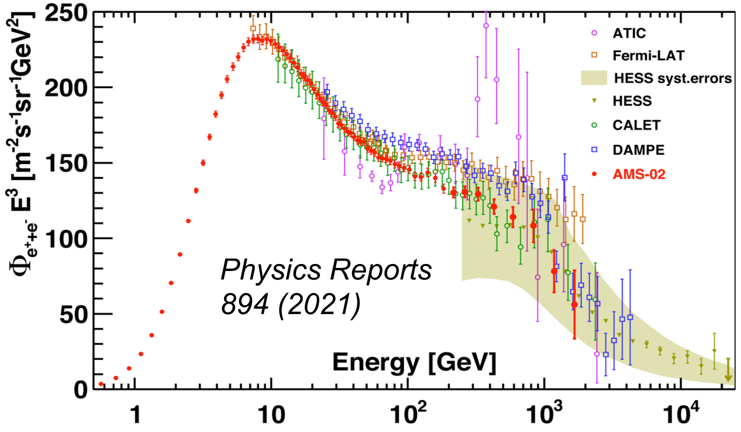
Space experiments
(DAMPE, AMS etc.)
and LHAASO etc.

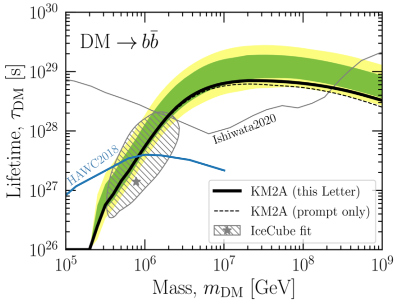
Physics Motivation – experimental search results

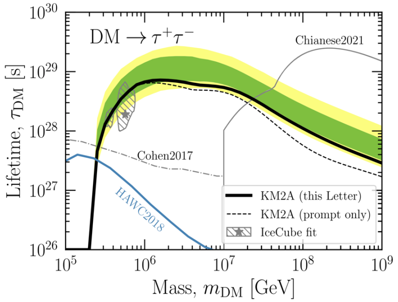






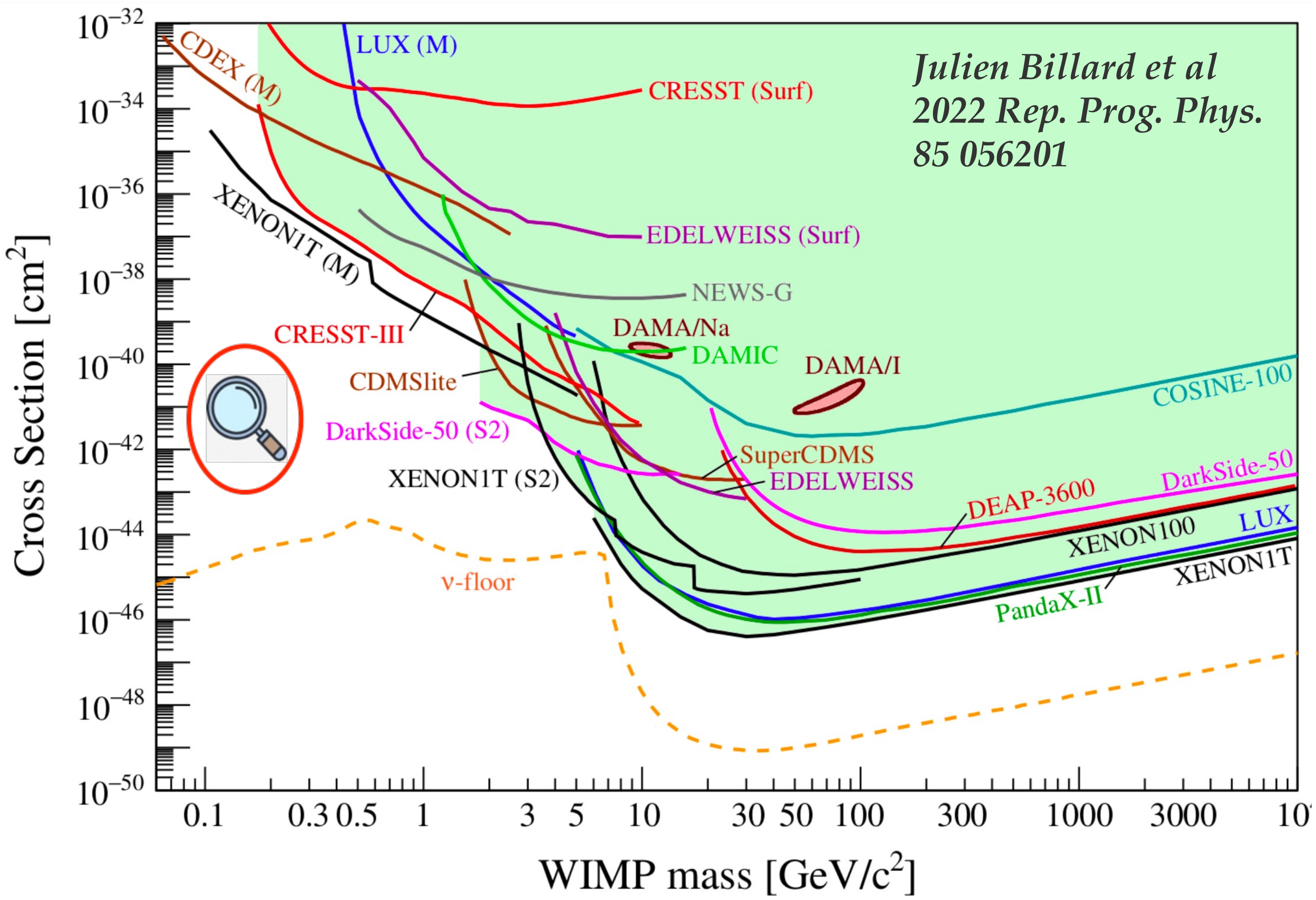






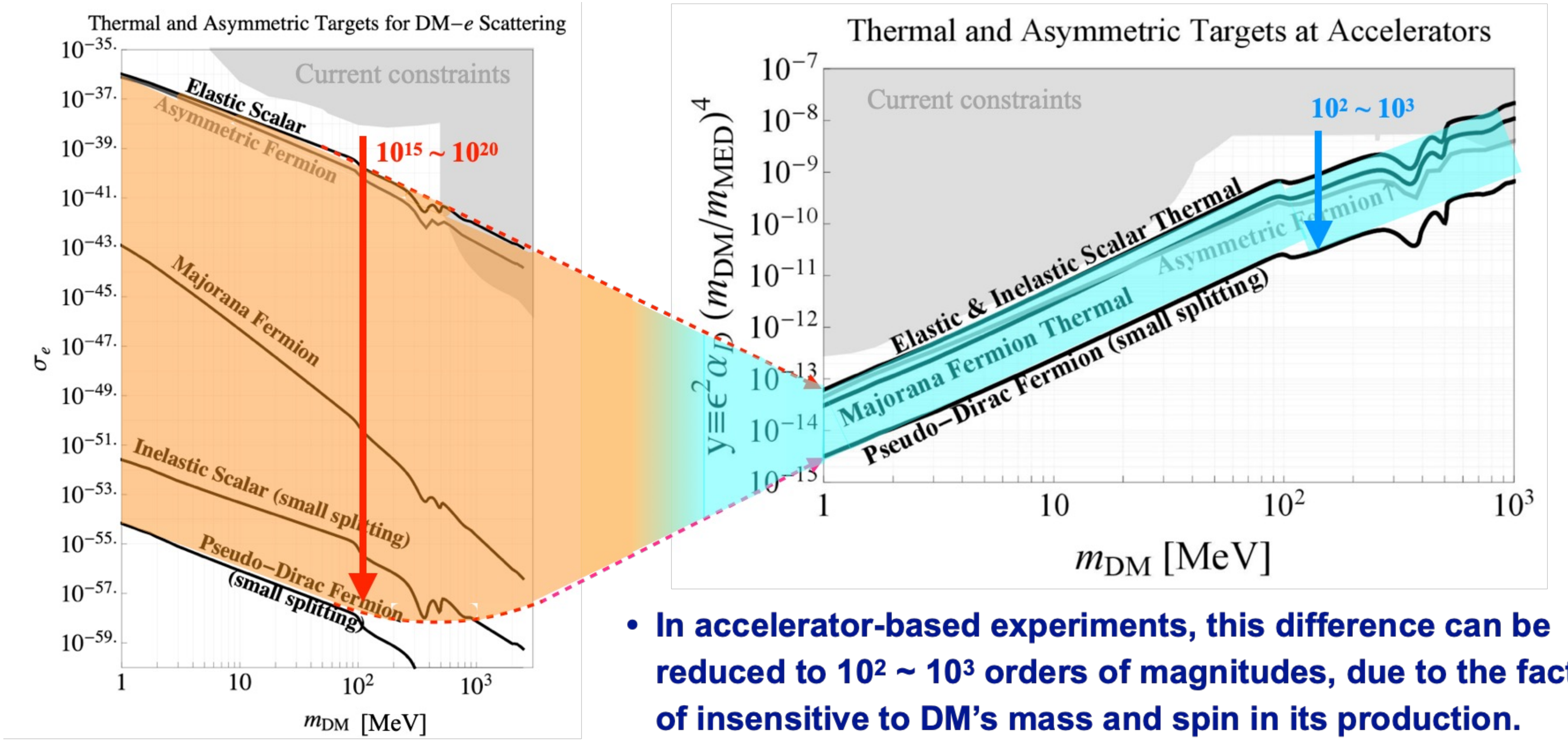
PRL 129, 261103

Physics Motivation – search for light dark matter



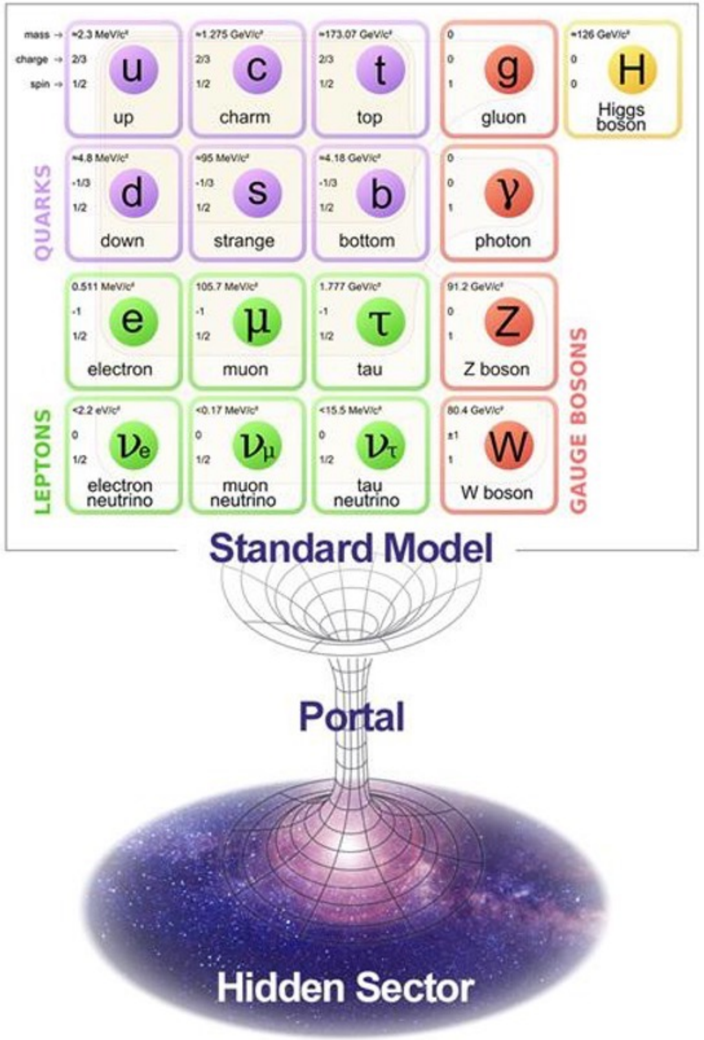
- **Competitive experiments world-wide have been hunting for dark matter candidates from GeV to 10s TeV mass range.**
- **Sub-GeV regime less explored by direct search experiments.**
- **Alternative approaches have been proposed at this regime.**

Physics Motivation – search for light dark matter



- **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.**

Physics Motivation – search for light dark matter



How Dark Matter may interact with Ordinary Matter?

Dark Matter — Mediator — Standard Model

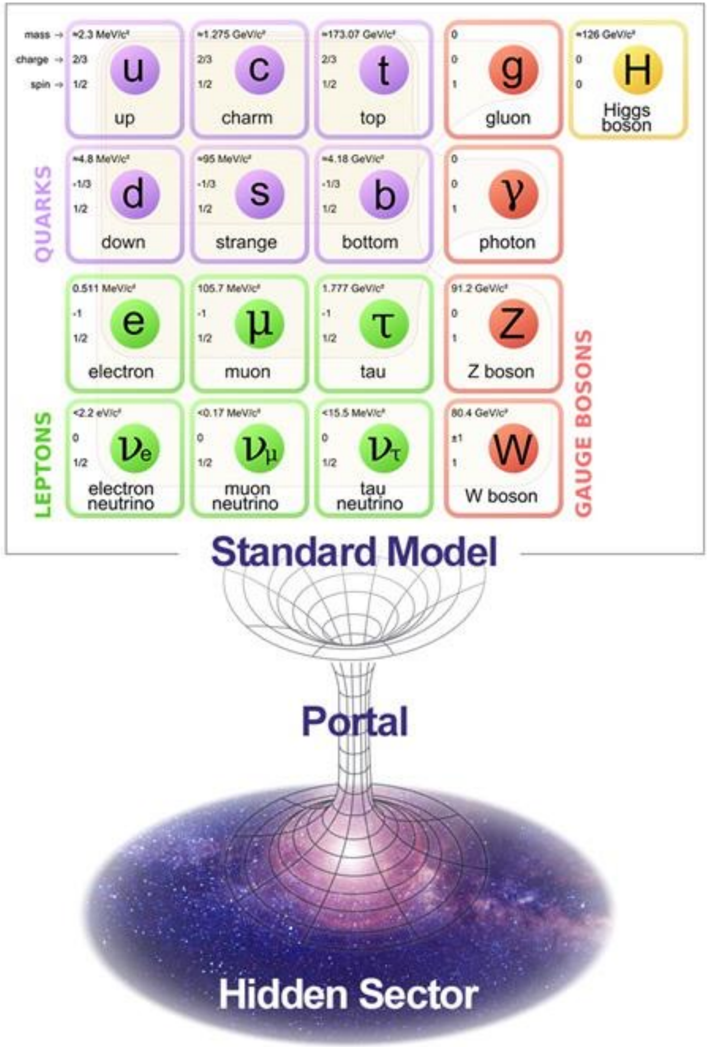
4 Renormalizable "Portals"

Portal	Operator		Portal	Operator	
Axion	$\frac{1}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a$	Axion/ALP	**Higgs**	$\lambda H^2 S^2 + \mu H^2 S$	Exotic Higgs decay?
Vector	$\epsilon F^{Y,\mu\nu} F'_{\mu\nu}$	Dark photon	**Neutrino**	$\kappa (HL) N$	Sterile neutrino?

Dark Matter — Dark Photon — ϵ — Kinetic Mixing — Standard Model

New force carried by massive vector boson: dark photon

Physics Motivation – search for dark photon



- **Search for the mediator, like dark photon, opens an alternative way to shed light on the dark world.**
- **The dark photon can be predicted by introducing extra U(1)$_x$ gauge group ➔ new gauge field X ➔ dark photon A'.**

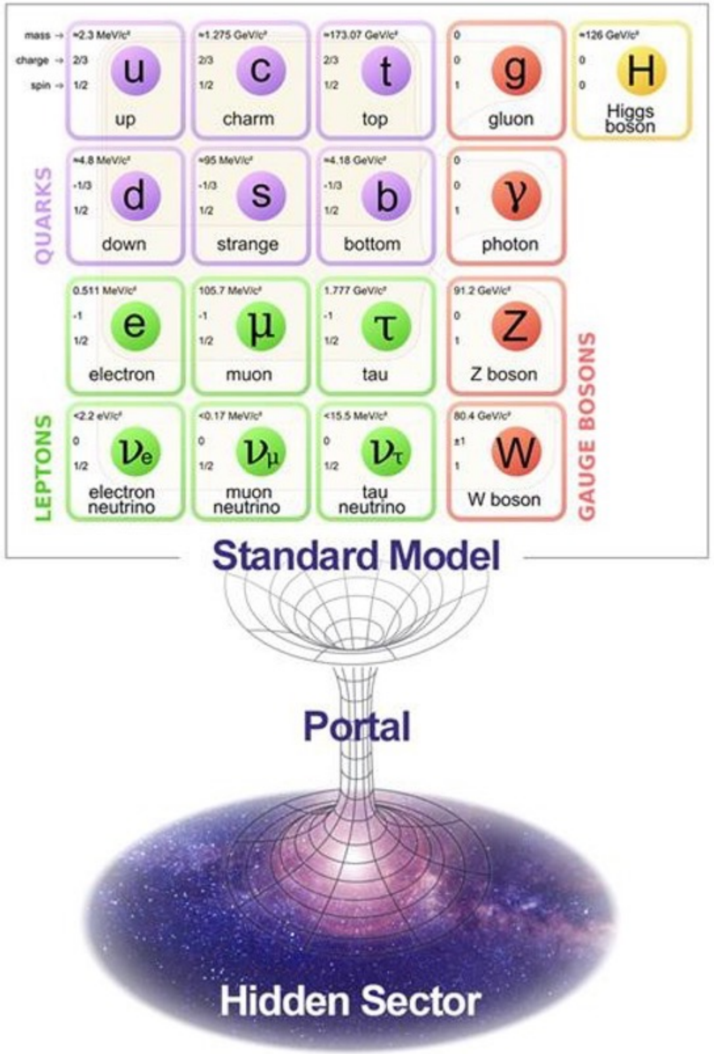
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + A_\mu j^\mu_{em} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + X_\mu j^\mu_X$$

The SM γ terms

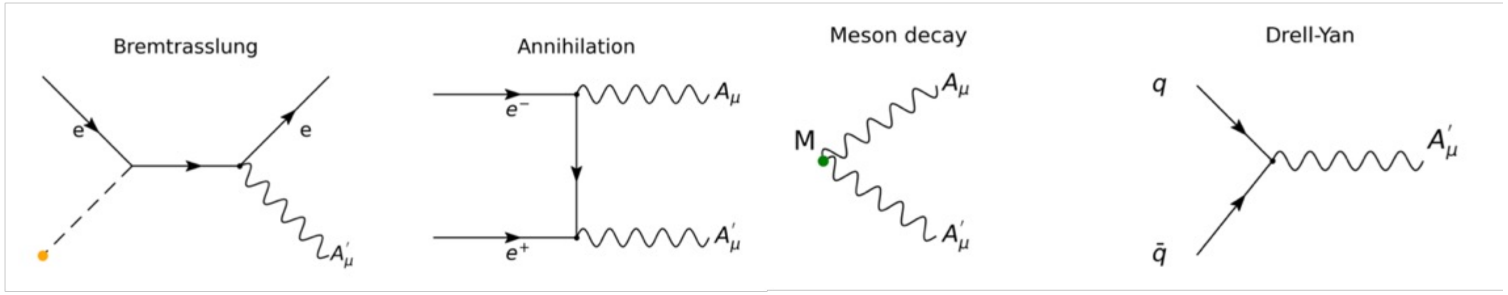
Interactions between the photon and dark photon via kinetic mixing.

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

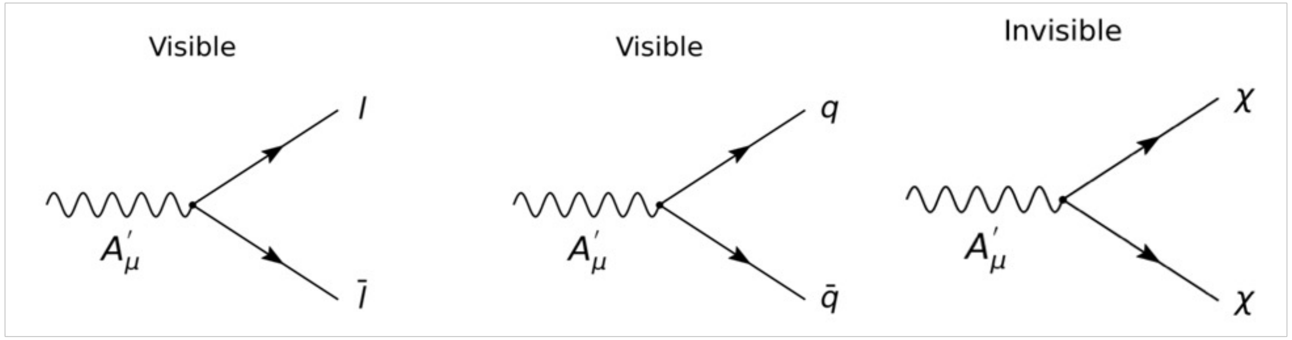
Physics Motivation – search for dark photon



- **Dark photon production modes: Bremsstrahlung, Annihilation, Meson decay and Drell-Yan process**



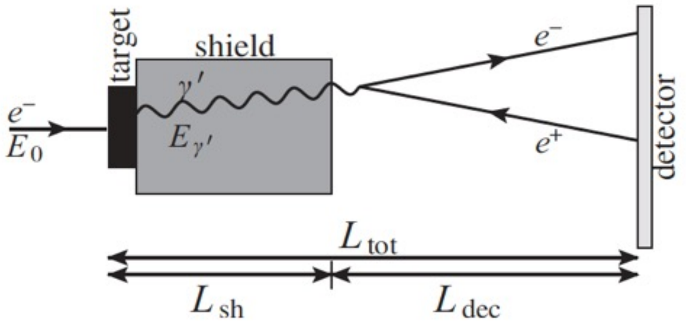
- **Dark photon decay channels: visible and invisible decays**



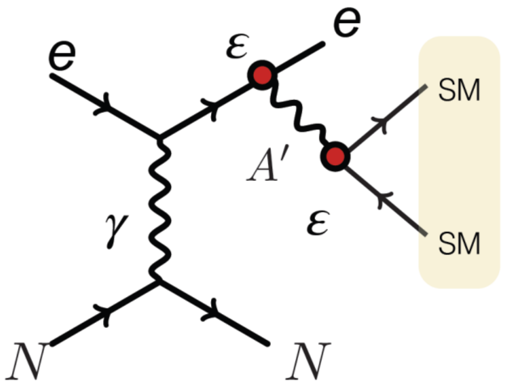
Physics Motivation – search for dark photon

- Dark photon can be produced via electron-nuclei interaction (electron-on-target).
- Two ways of detection, via its
  - **Visible decay**

    Having two interaction vertices → production rate highly supressed



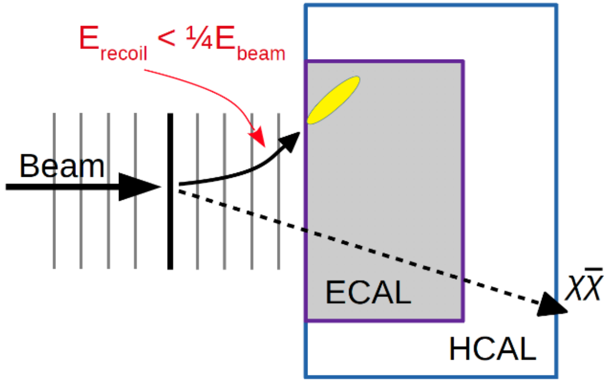
VISIBLE DECAY MODE $m'_A < 2m_X$



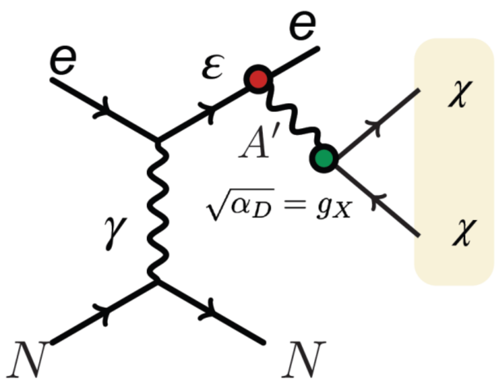
$$N \propto \epsilon^4 \quad \ll \quad N \propto \epsilon^2(1-\epsilon^2) \approx \epsilon^2$$

  - **Invisible decay**

    Interaction probability could be enhanced → better sensitivity!

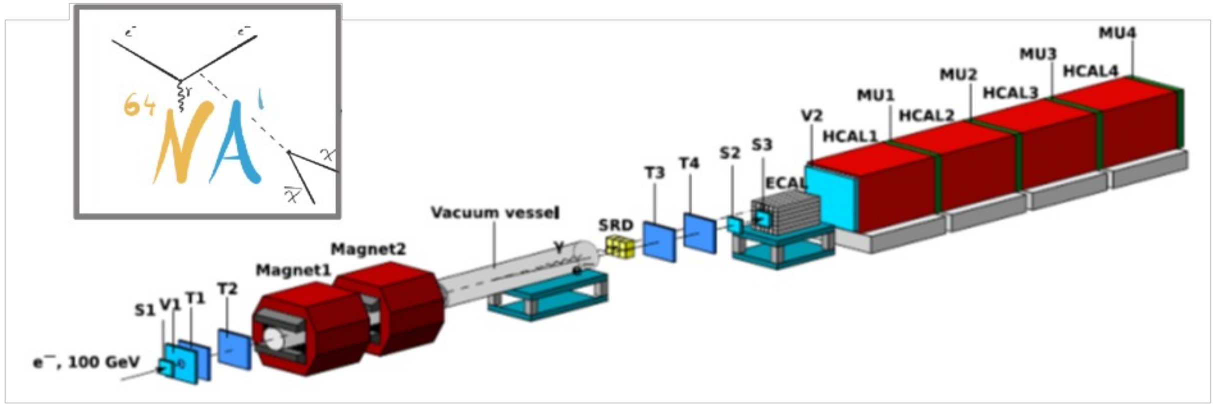


INVISIBLE DECAY MODE $m'_A > 2m_X$

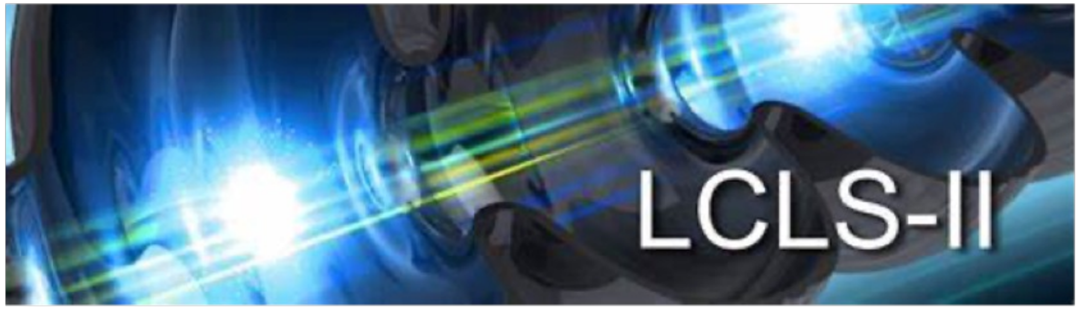


Searching for Dark Photon Invisible Decay

- **Searches at collider and beam-dump experiment:**
  - Missing mass (BESIII, Belle-II etc.)
  - Missing energy (NA64)



- **A new approach looking at missing momentum**
  - Single electron on target
  - High frequency electron beam
  - “Missing momentum” information



arXiv: 1912.05535

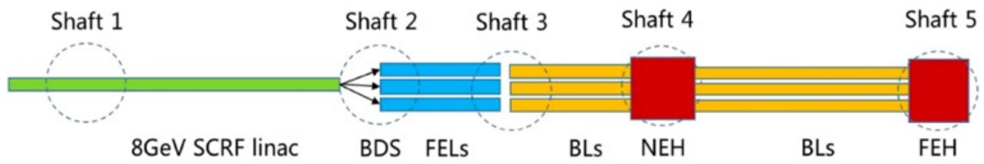
➡ **Light Dark Matter eXperiment (LDMX) at LCLS-II SLAC (R&D)**

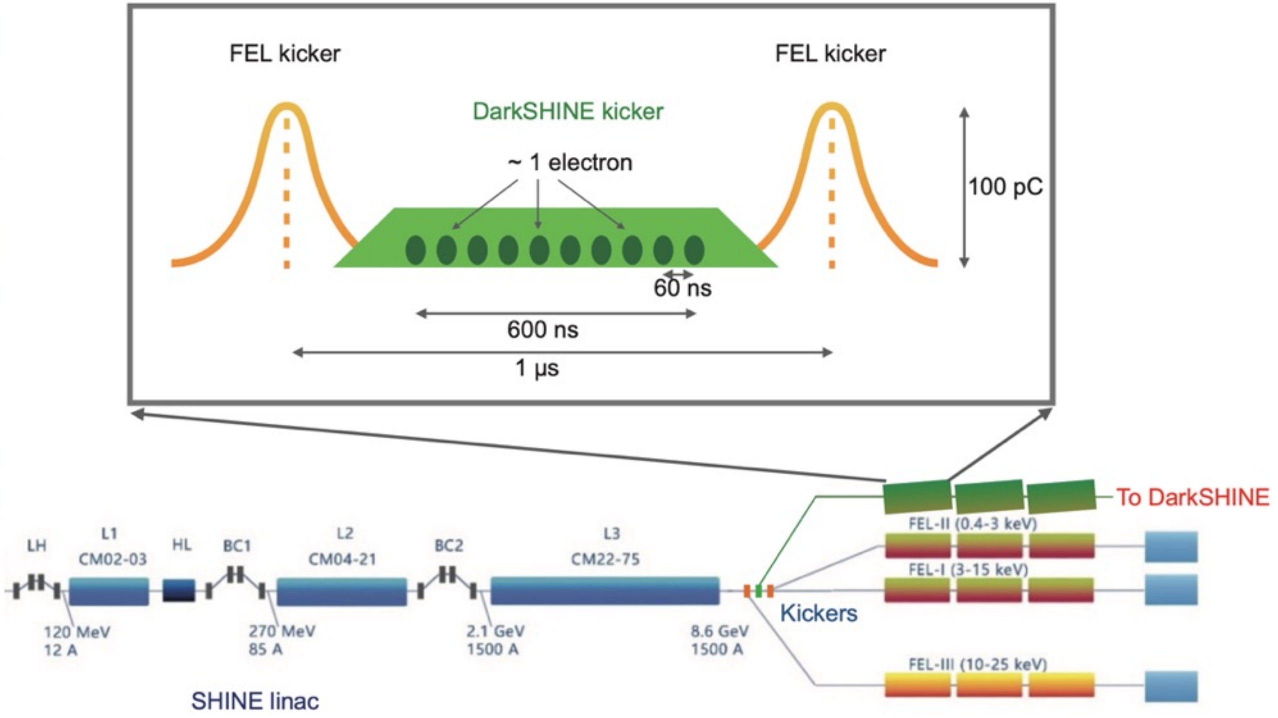
➡ **DarkSHINE experiment at SHINE facility, Shanghai (R&D)**

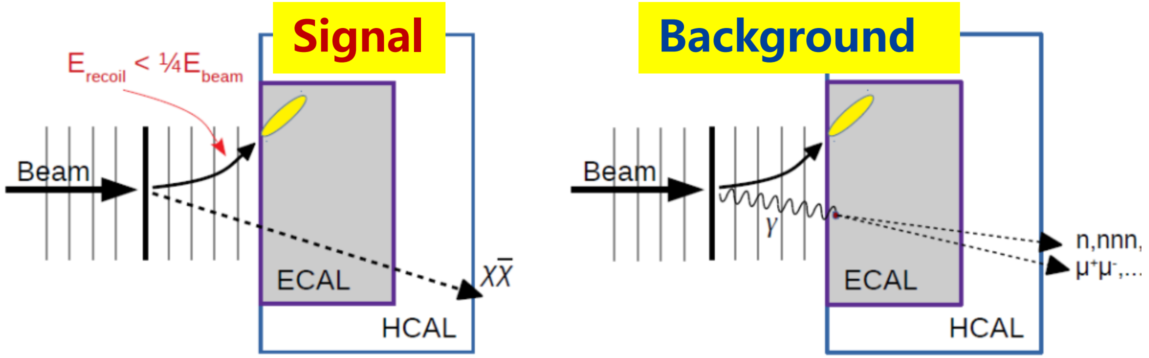
The SHINE Facility Introduction

Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE) can provide high frequency electron beams → single electron with dedicated kicker.

- **Electron energy: 8 GeV, Frequency: 1MHz**
- **Beam intensity: 100pC (6.25E8 electrons/bunch)**
- **~3x10^{14} electrons-on-target (EOT) per year.**
- **Under construction in Zhangjiang area (2018-2026)**
- **Beam techniques: SARI,CAS / Shanghai Tech.**
- **Detector R&D: SJTU / FDU / SIC, CAS.**



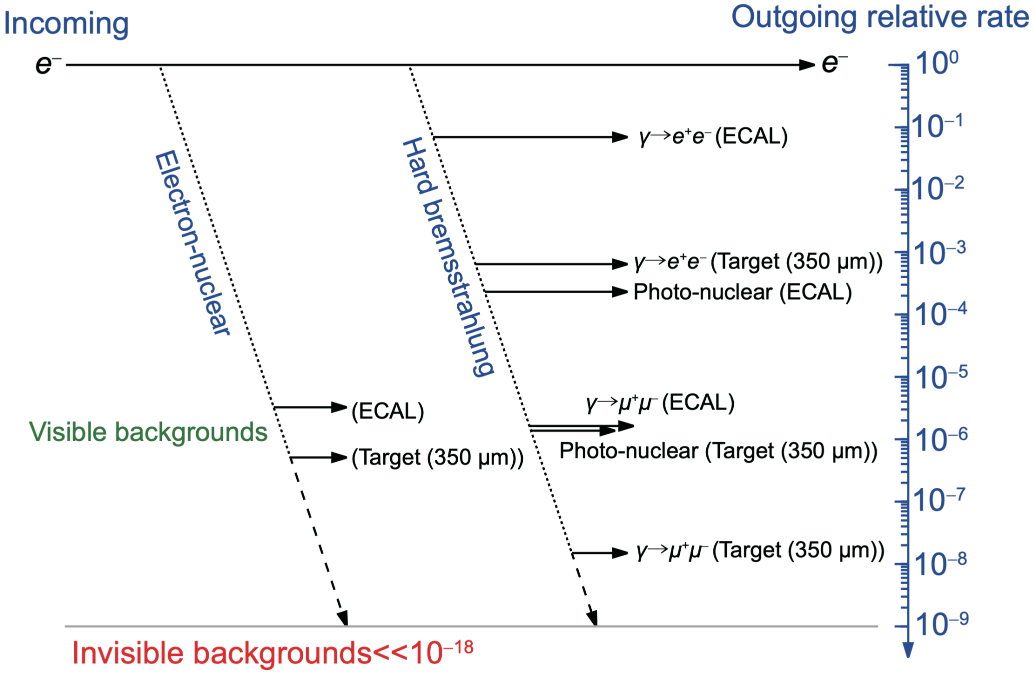


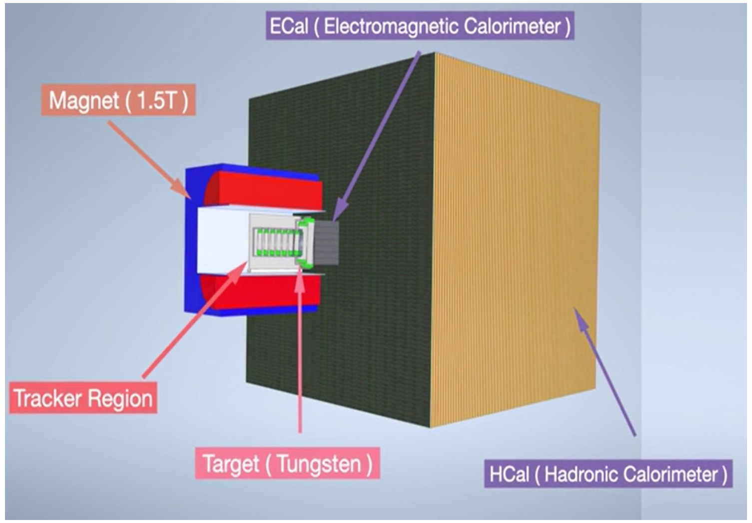


The DarkSHINE detector conceptual design:

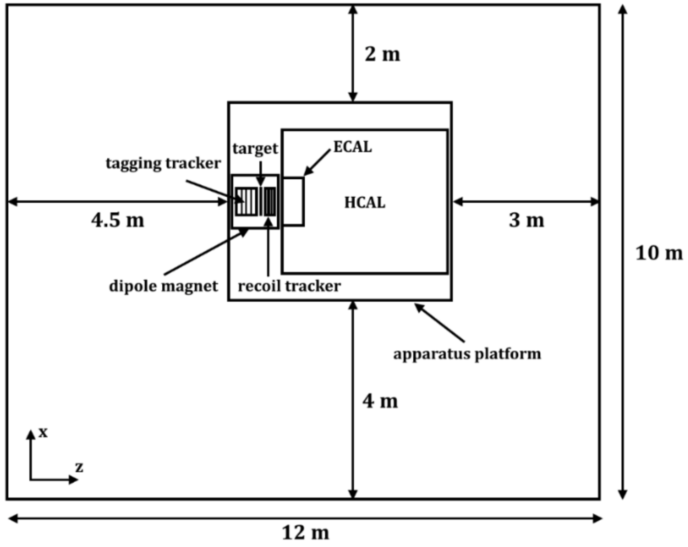
- **Silicon tracker:** incident and recoil electrons
- **EM Calo.:** electron and photon energy reco.
- **Hadron Calo.:** veto muon and hadron bkgs.
- Readout electronics, trigger system, TDAQ etc.

Main processes produced in electron-on-target





The DarkSHINE detector design



Experiment hall design

The DarkSHINE Simulation Framework

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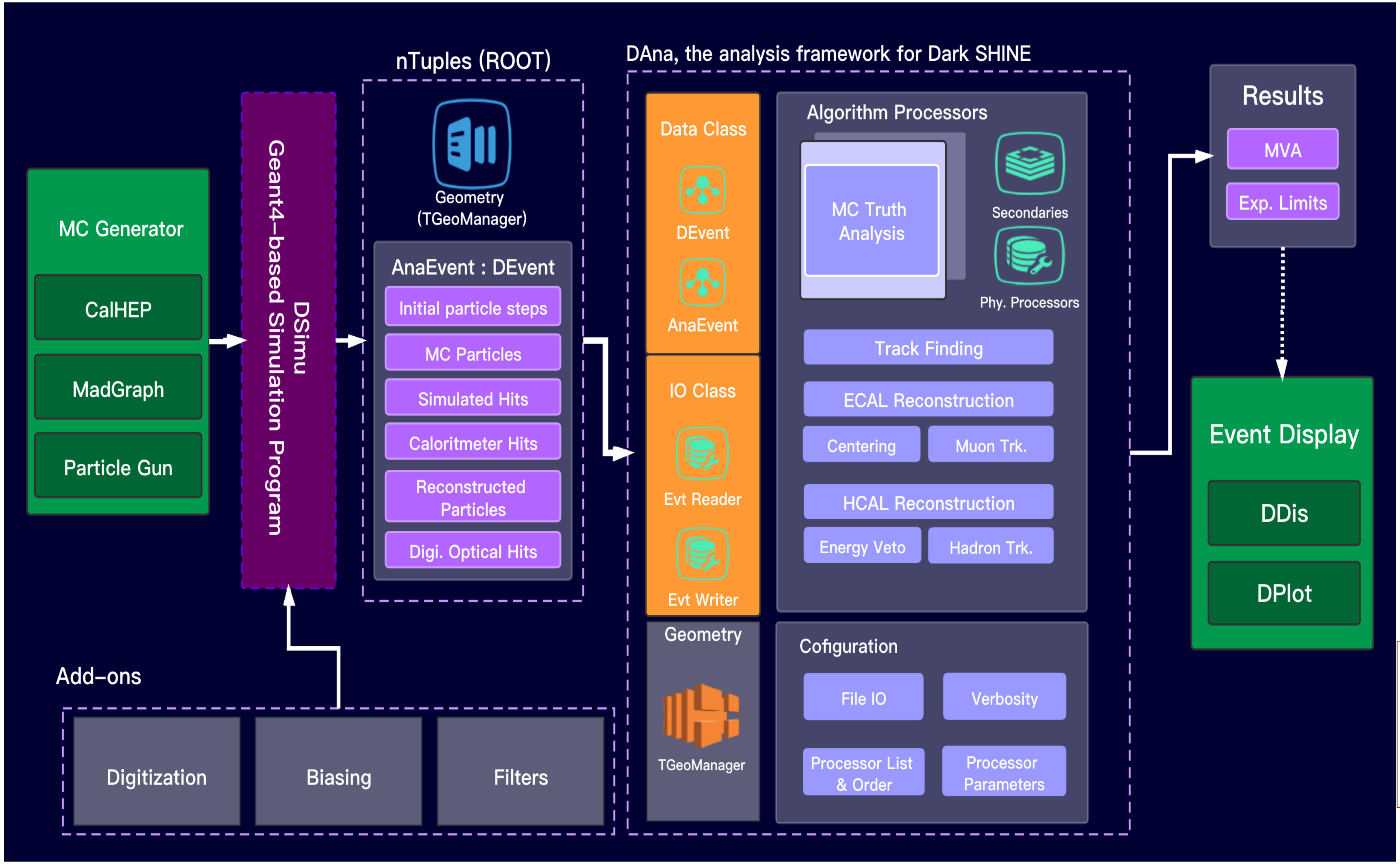
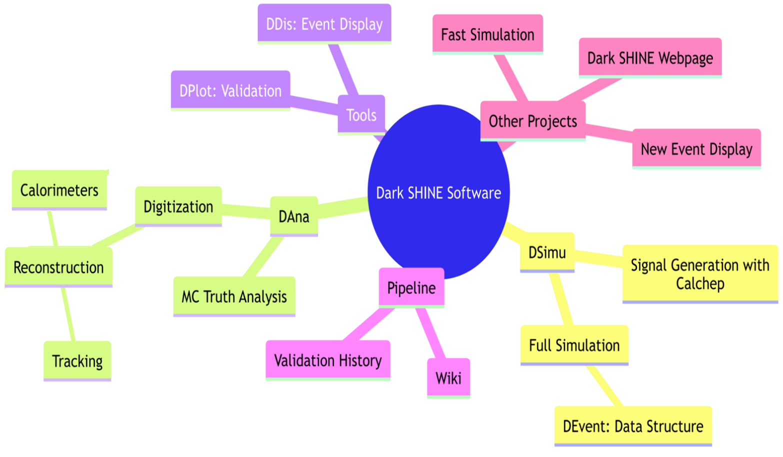
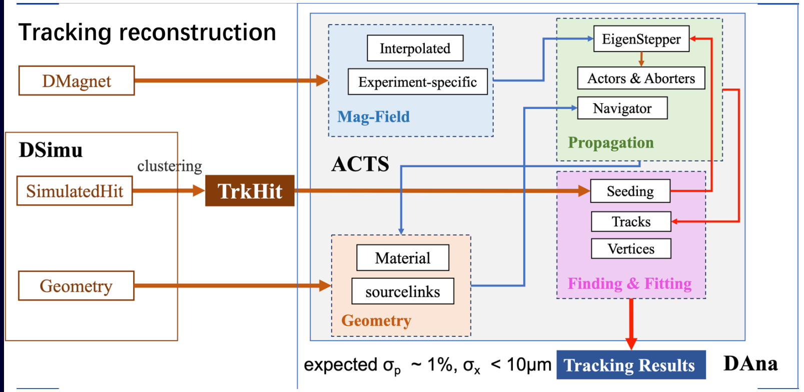
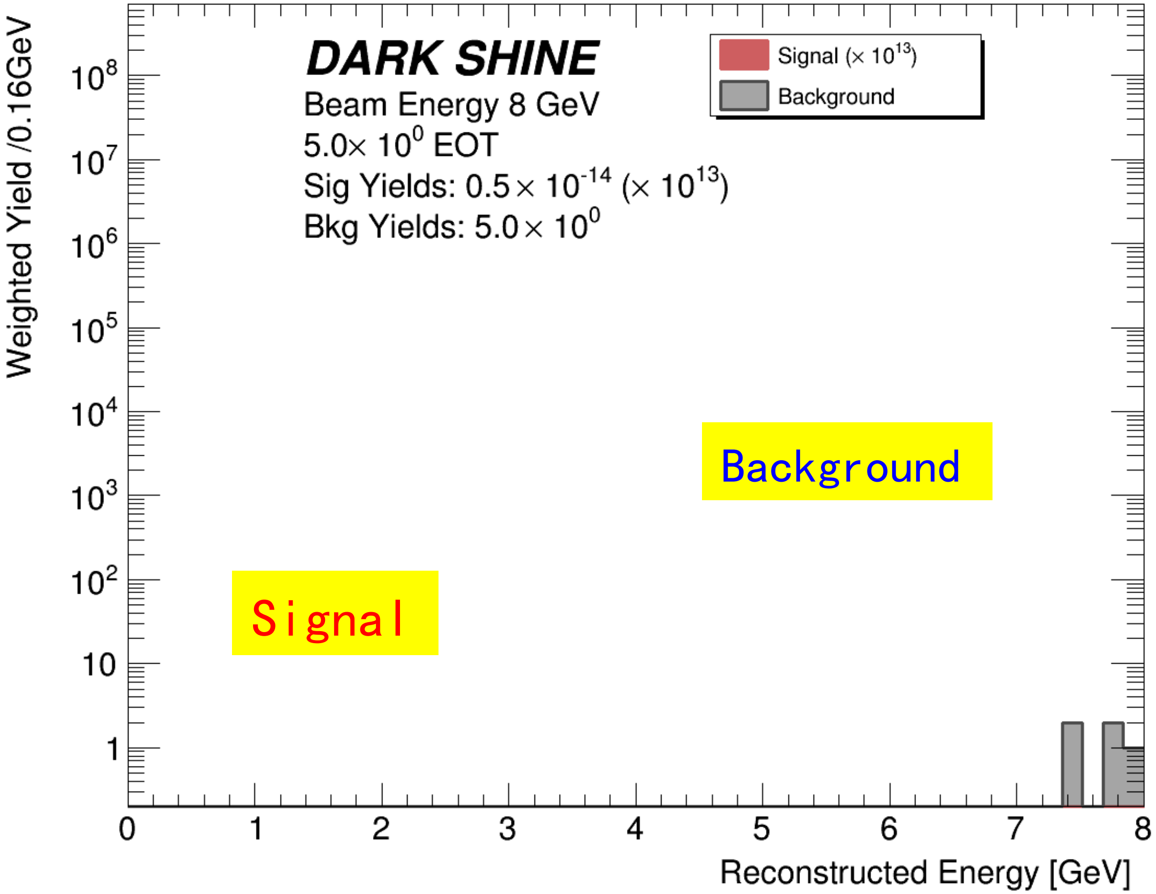
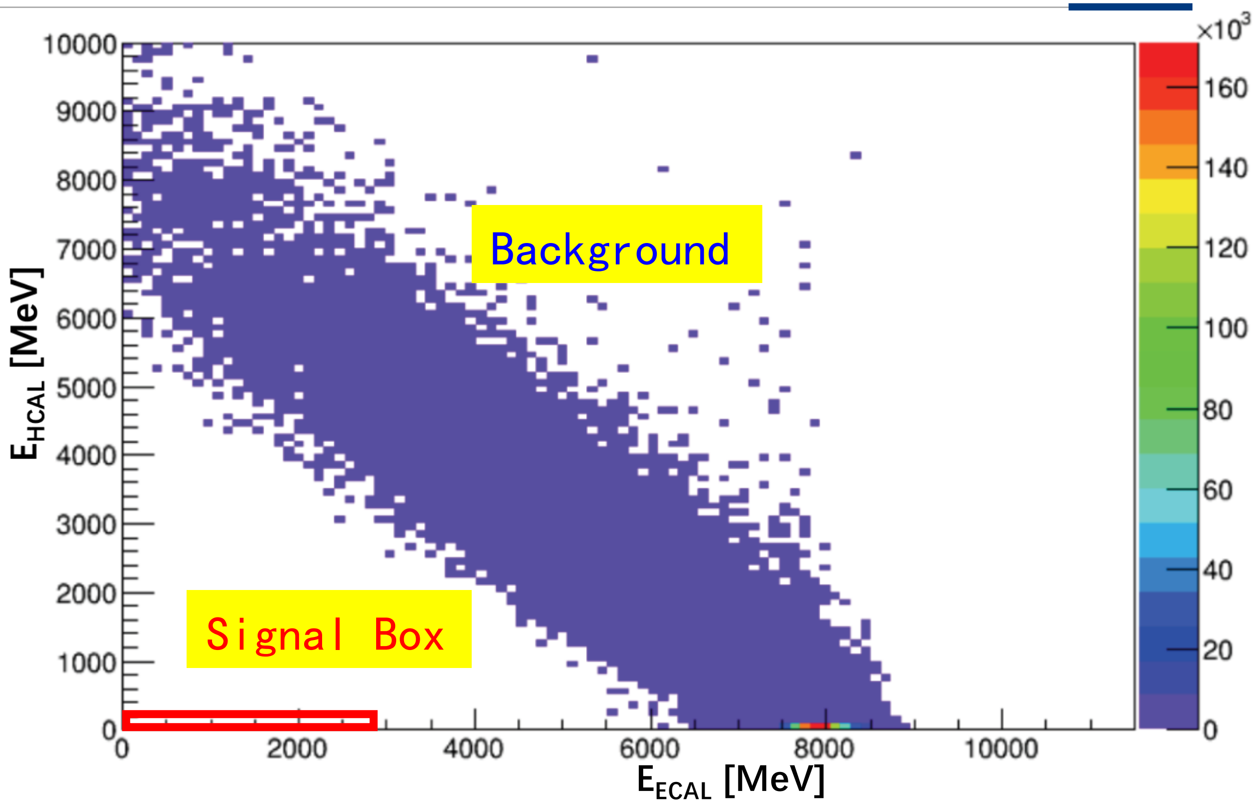






The DarkSHINE Experiment Simulation

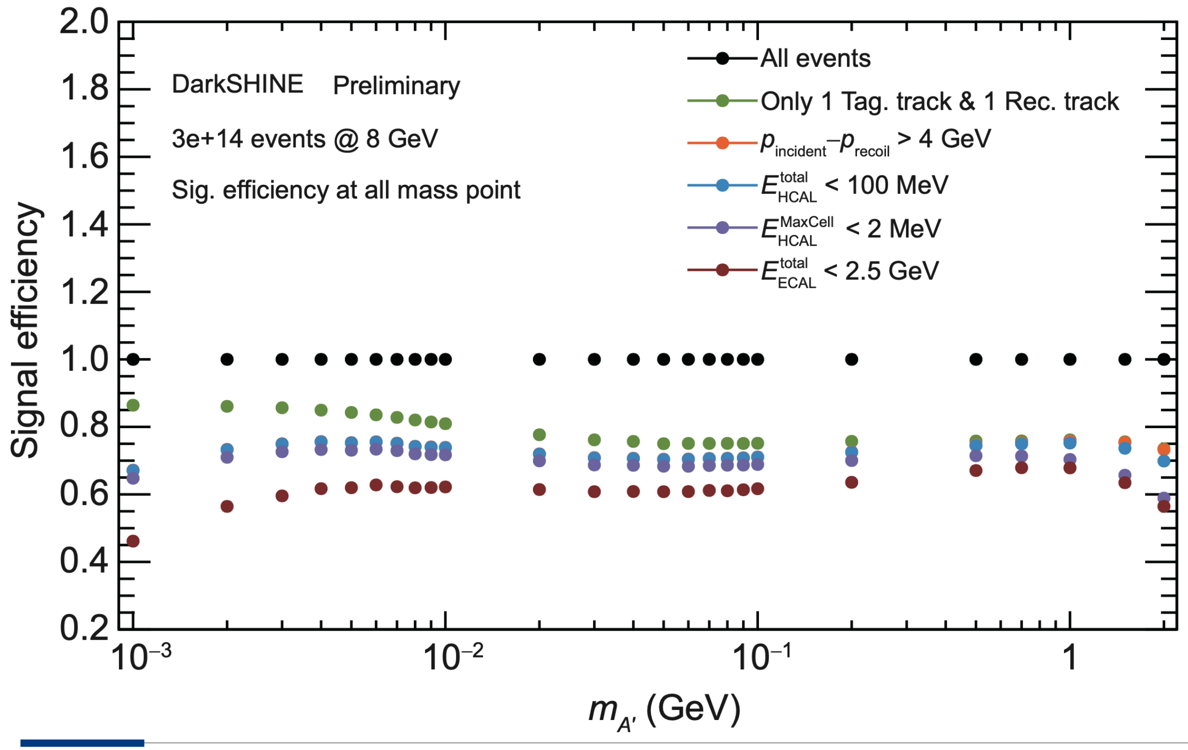


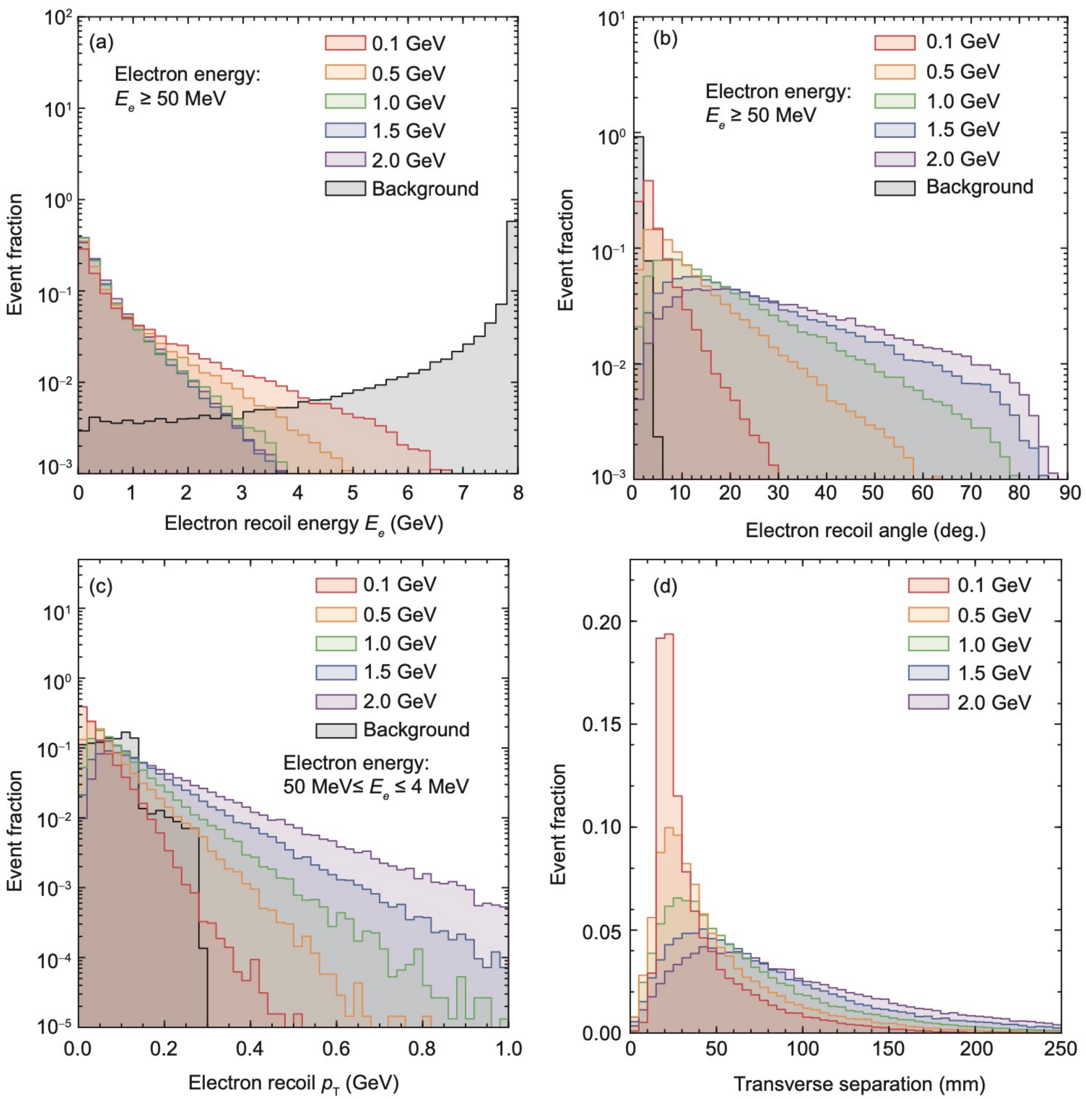


- **Signal region definition (preliminary):**
  1. Exact one track in tagging and recoil tracker
  2. Momentum of $p_{incident} - p_{recoil} > 4\ GeV$
  3. ECAL deposited total energy < 2.5 GeV
  4. HCAL deposited total energy < 100 MeV
  5. HCAL max cell energy < 2 MeV.

The DarkSHINE Simulation

- **Kinematic distributions of the signal and inclusive background (right) and signal acceptance efficiency:**





The DarkSHINE Simulation

- **Simulated background statistics** ☞
  - Cost a lot computer time
  - Biasing techniques to produce rare process
- **Cut-flow of each backgroud process**

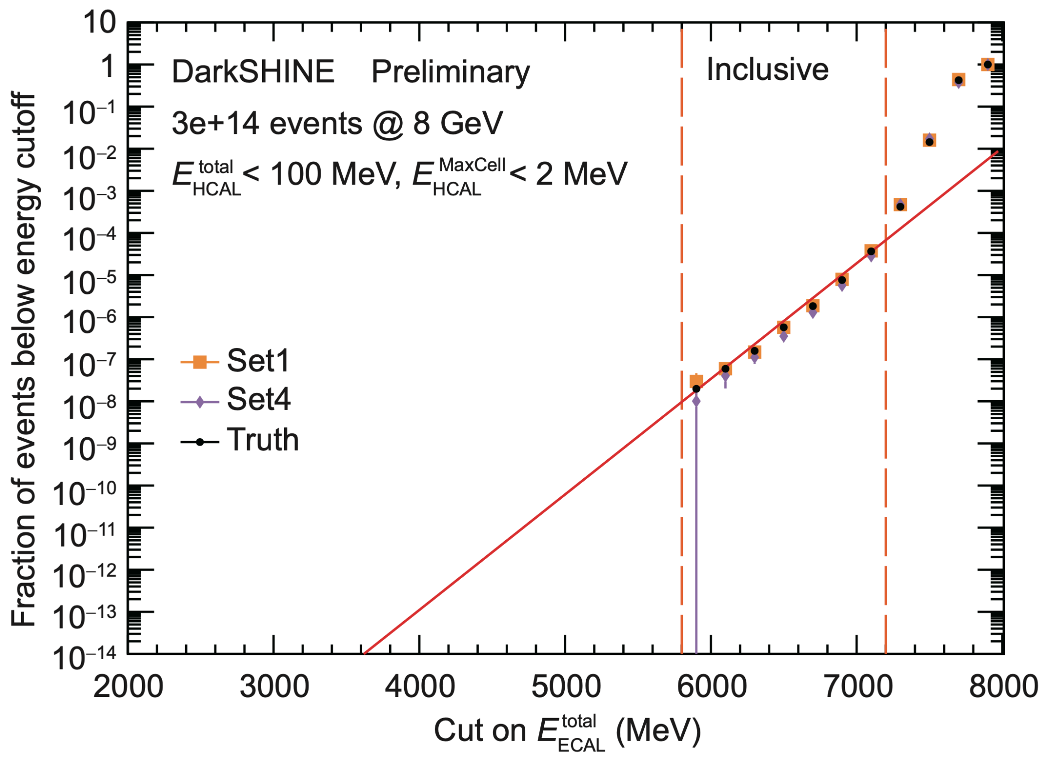
☟

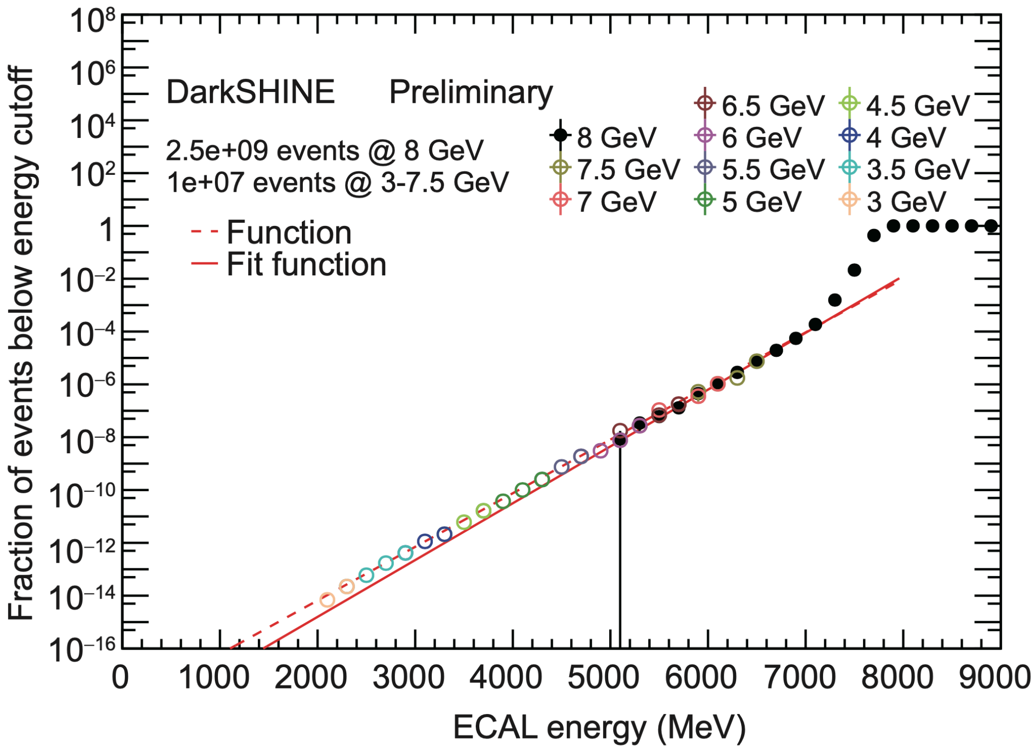
Process	Generate events	Branching ratio	EOTs
Inclusive	2.5×10^9	1.0	2.5×10^9
Bremsstrahlung	1×10^7	6.70×10^{-2}	1.5×10^8
GMM_target	1×10^7	$1.5(\pm 0.5) \times 10^{-8}$	4.3×10^{14}
GMM_ECAL	1×10^7	$1.63(\pm 0.06) \times 10^{-6}$	6.0×10^{12}
PN_target	1×10^7	$1.37(\pm 0.05) \times 10^{-6}$	4.0×10^{12}
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}

	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

The DarkSHINE Background Estimates

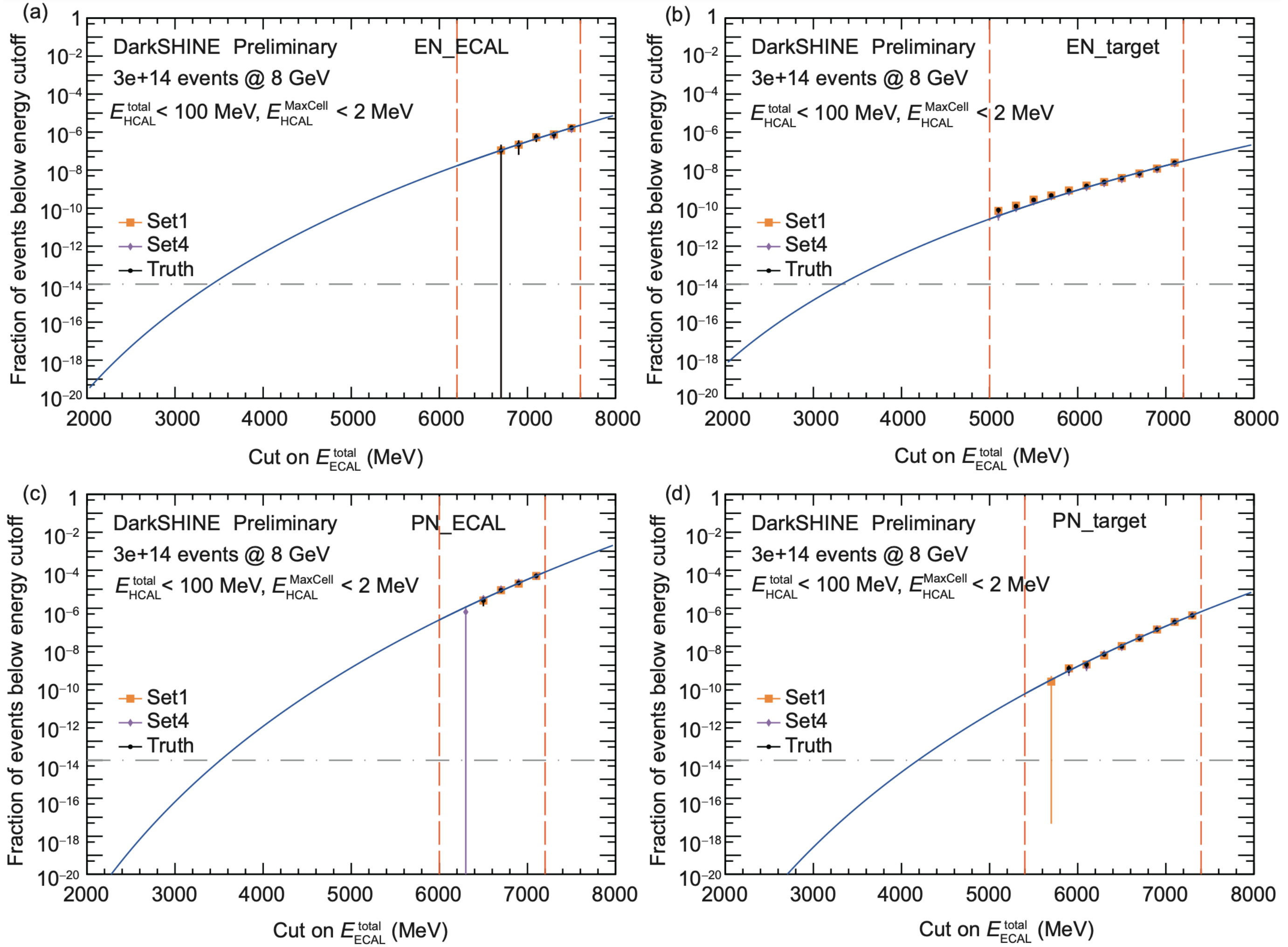
- To estimate background yields in 3×10^{14} EOTs, extrapolation method is used
  - Left: fit from inclusive background process
  - Right: extrapolation from low energy electron-fixed-target samples





The DarkSHINE Background Estimates

- **To estimate background yields in 3x10^14 EOTs, fit from each rare process**

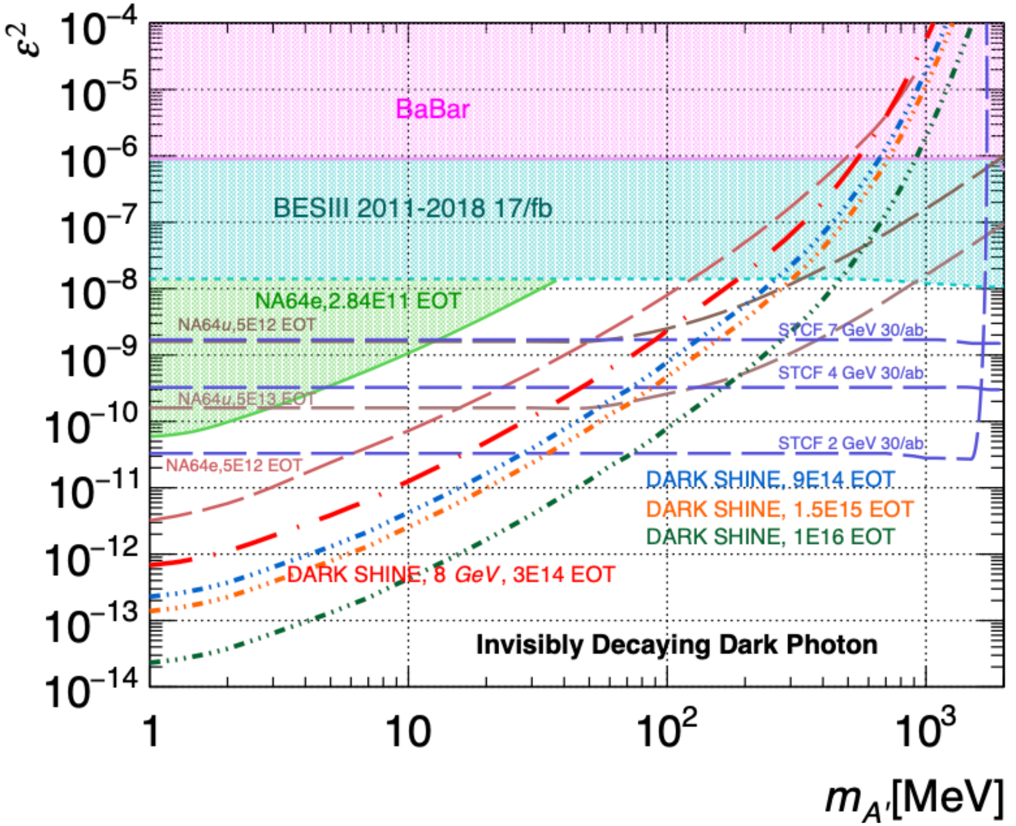


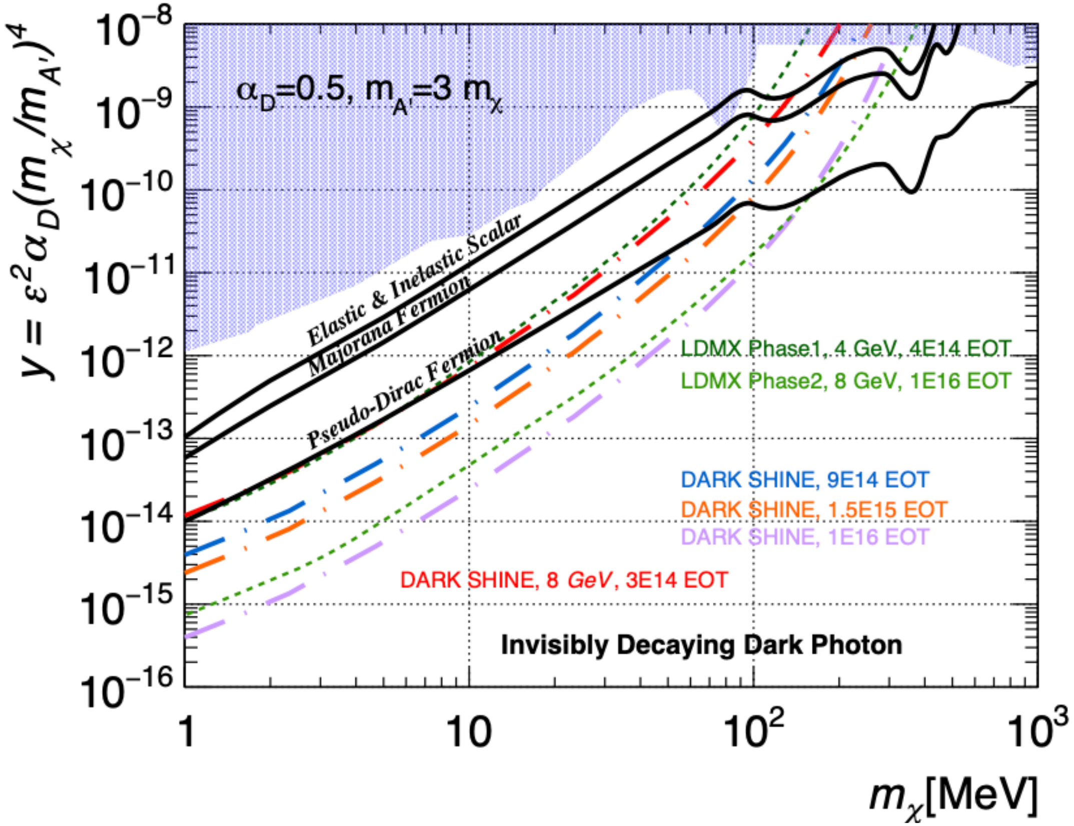
Background w.r.t 3x10^14 EOT:

Method	Expectation in signal region
Cut flow	0
Inclusive fit	9.23×10^{-3}
Low energy extrapolation	2.53×10^{-3}
Rare processes fit	1.5×10^{-2}

The DarkSHINE Projected Sensitivity

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

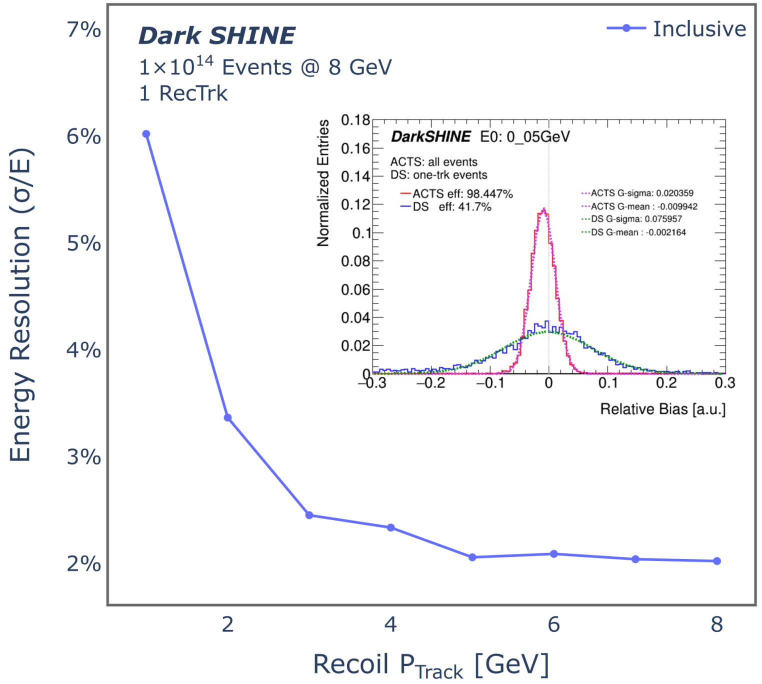


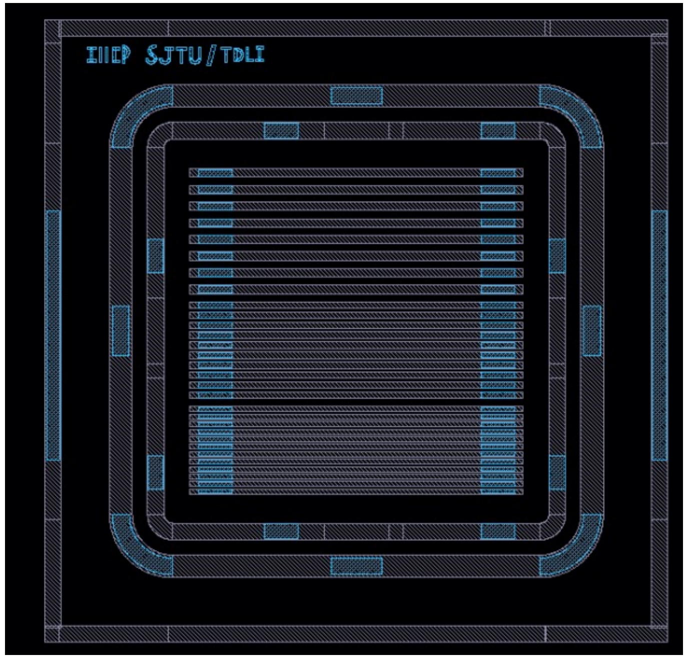


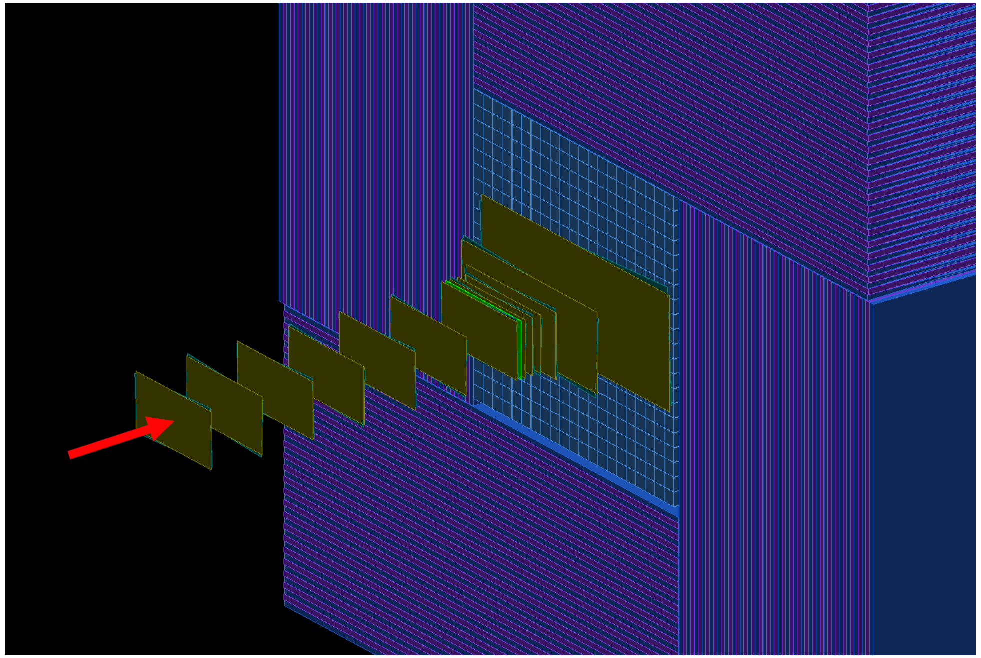
- **The DarkSHINE experiment can provide competitive results which will be sensitive to most of phase space predicted by models, with 9x10^{14} EOTs (running ~3 years).**

The DarkSHINE Detector R&D

- **Tracker:**
  - Tagging tracker (7 layers) + recoil tracker (6 layers)
  - Incident and recoil electron tracks
  - Two silicon strip sensors w/ a small angle (0.1rad)
  - Resolution: 10 μm(horizontal), 60 μm(vertical)

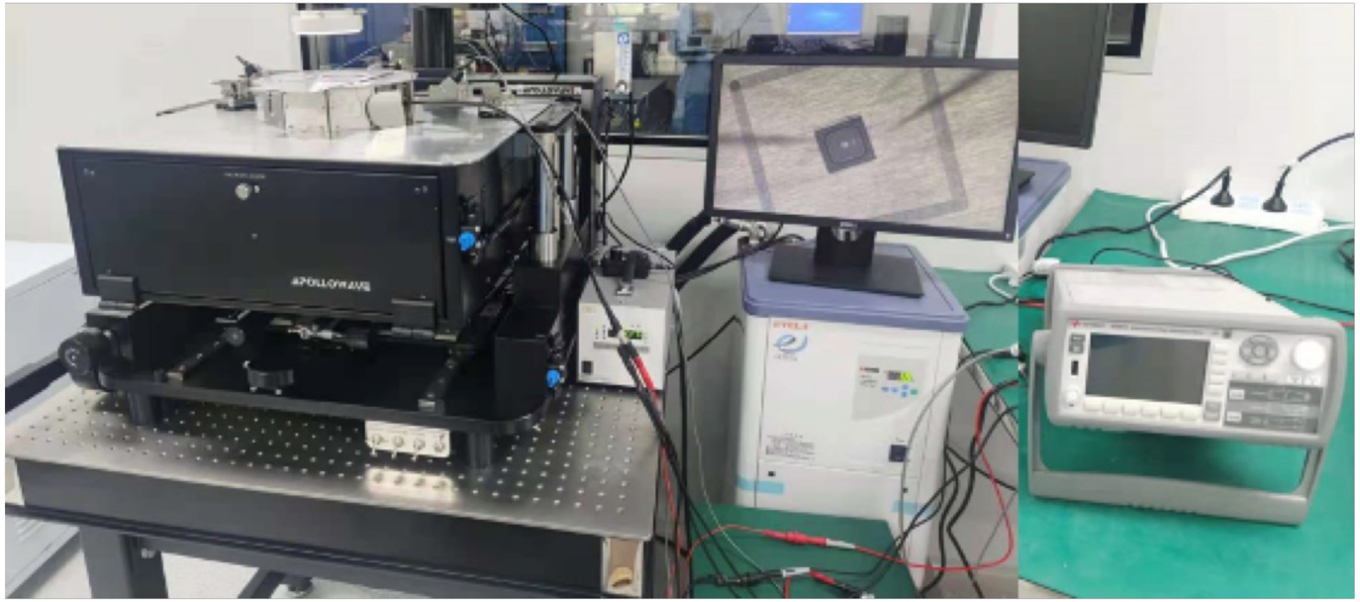


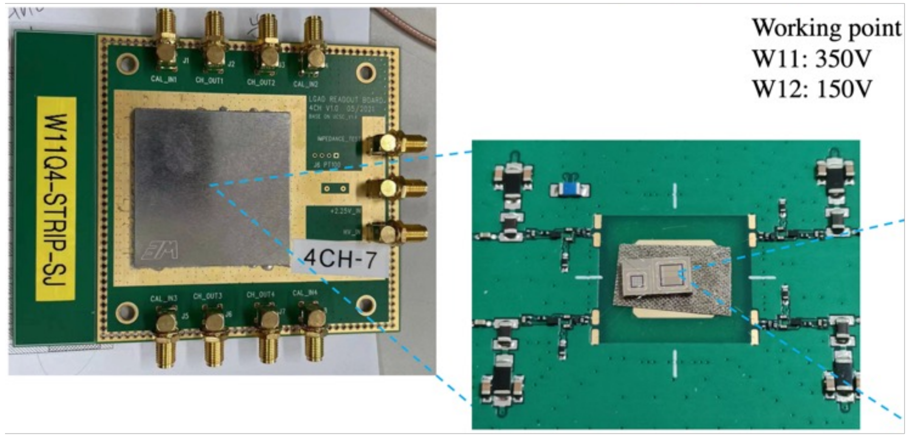


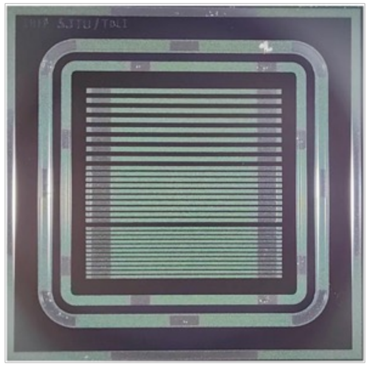


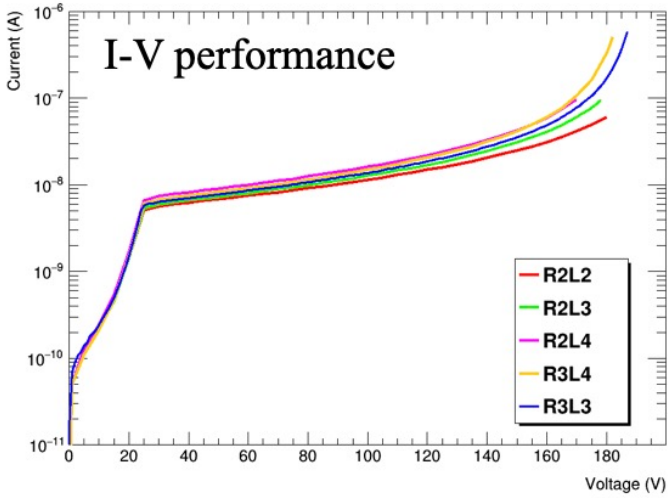
AC-LGAD silicon strip sensor $1\text{x}1\ \text{mm}^2$ designed, in collaboration with Prof.Zhijun Liang and Prof.Mei Zhao from IHEP.

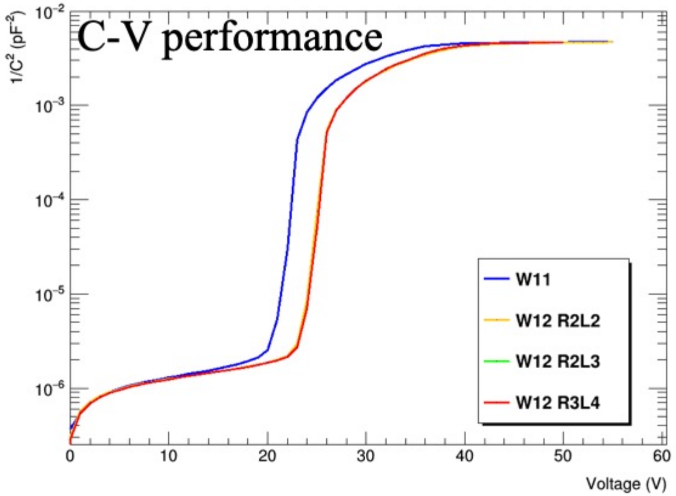
The DarkSHINE Detector R&D





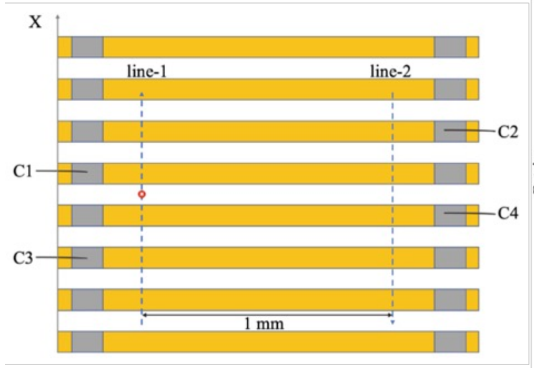


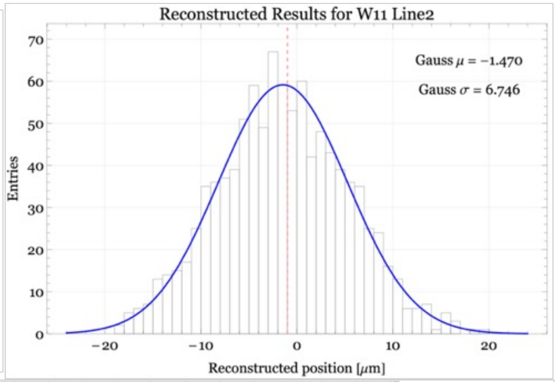


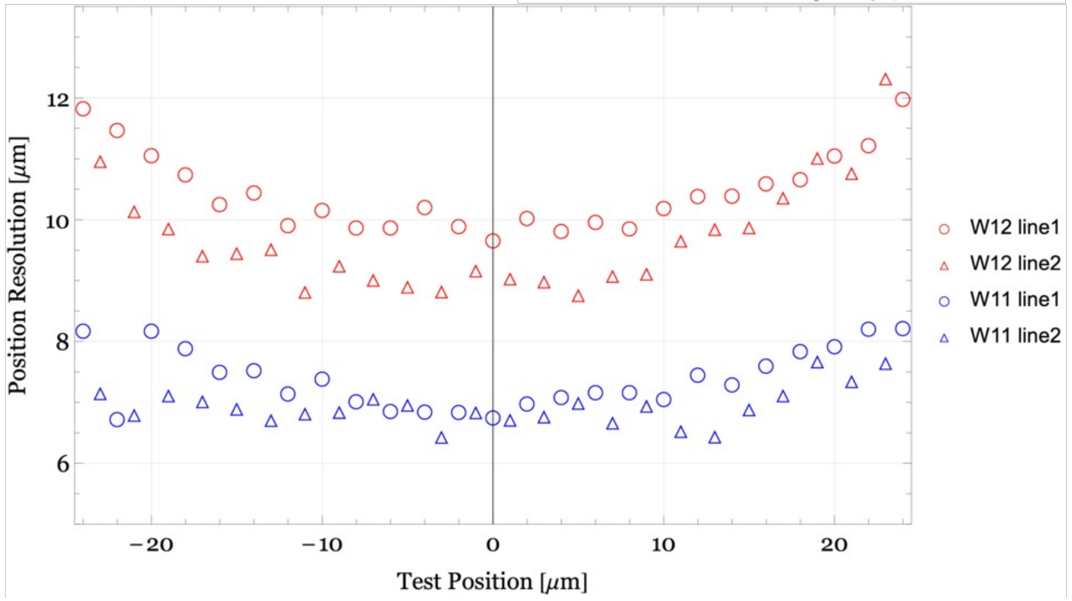


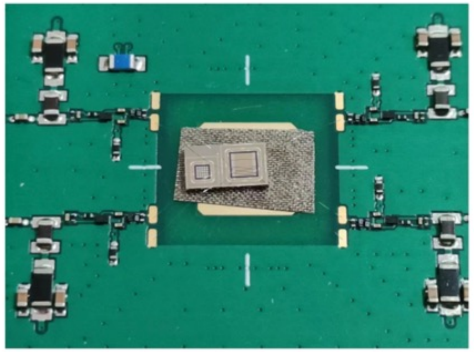
The DarkSHINE Detector R&D

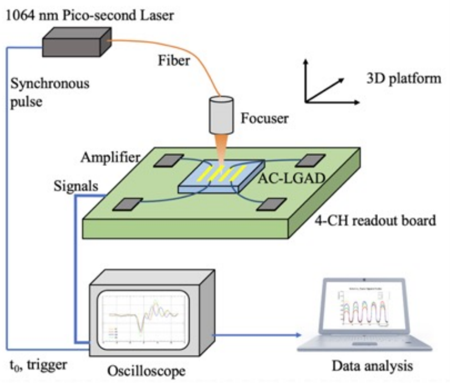
- **Position resolution can reach to 7 ~ 12 μm.**

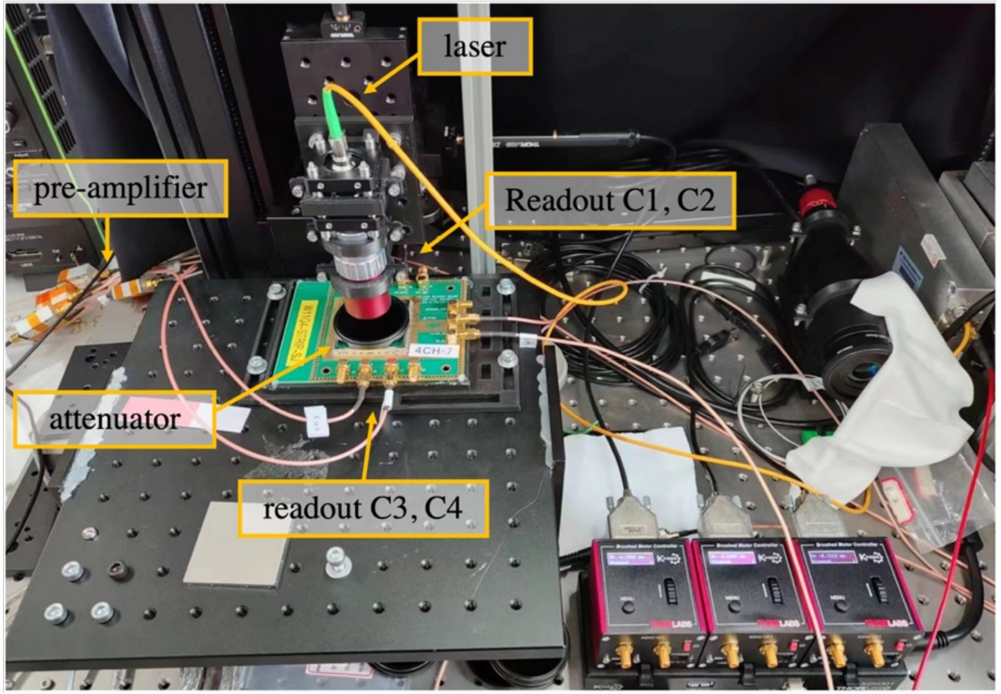












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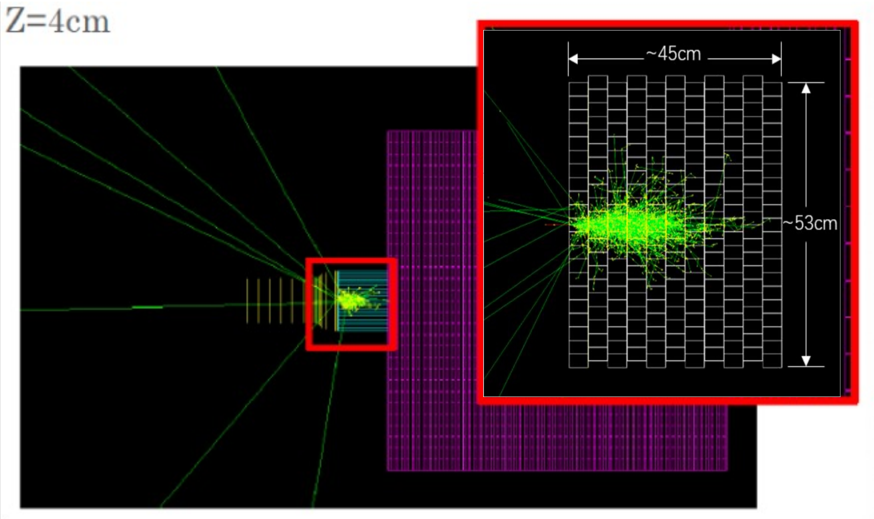
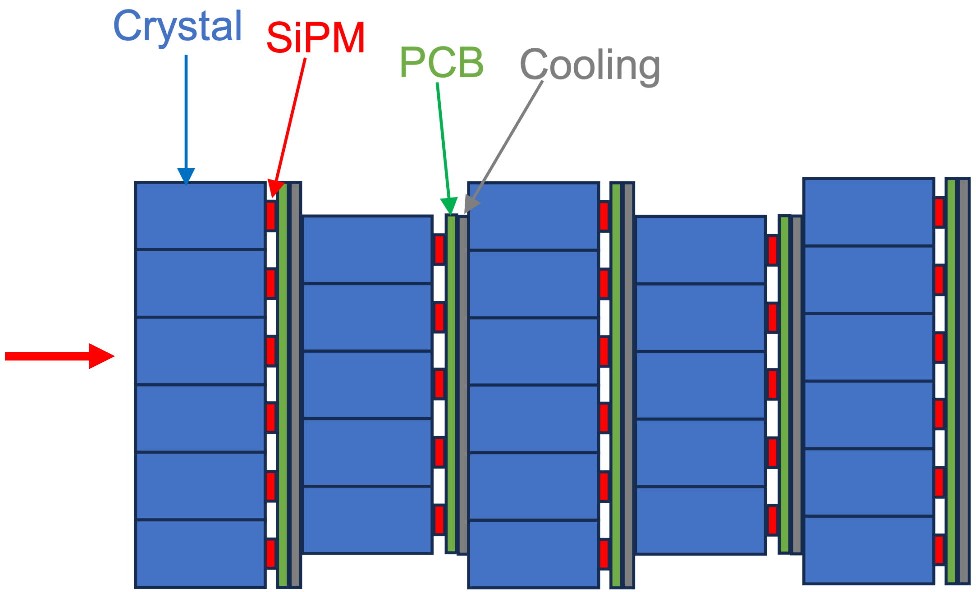
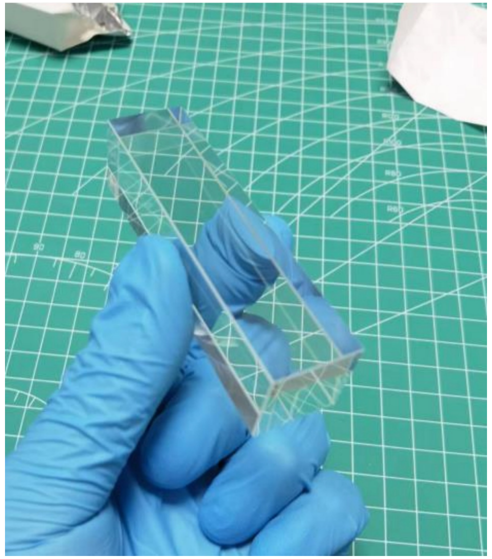
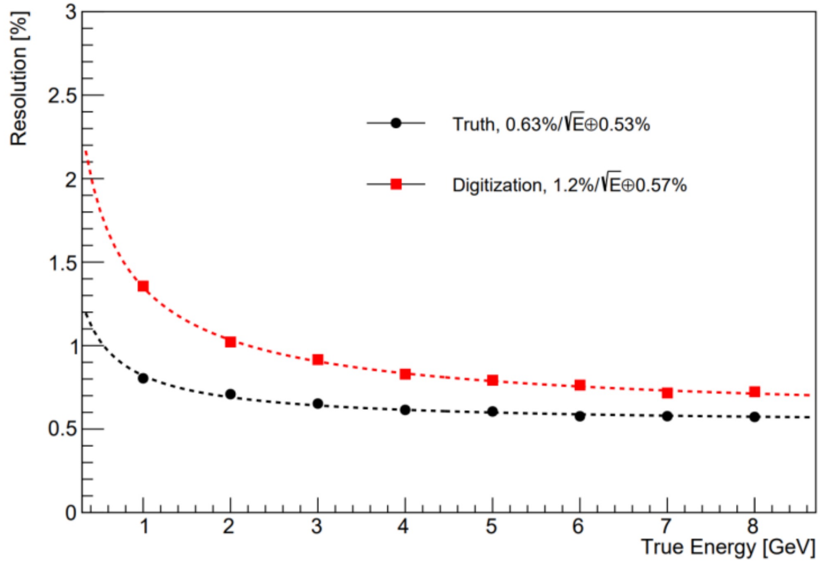
Electromagnetic Calorimeter:

- 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)
- **21×21×11 crystals, 2.5cm×2.5cm×4cm**
- Readout with SiPM and waveform sampling
- More intrinsic radiation and radioactive source tests.





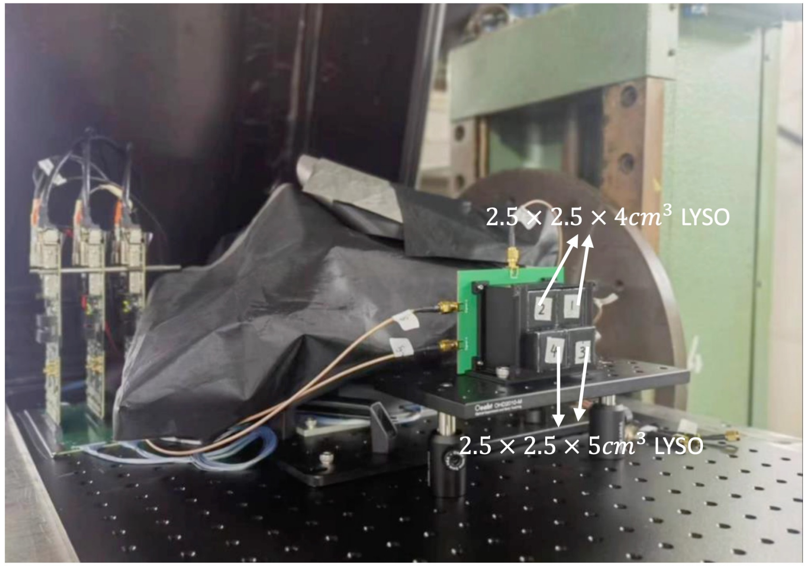




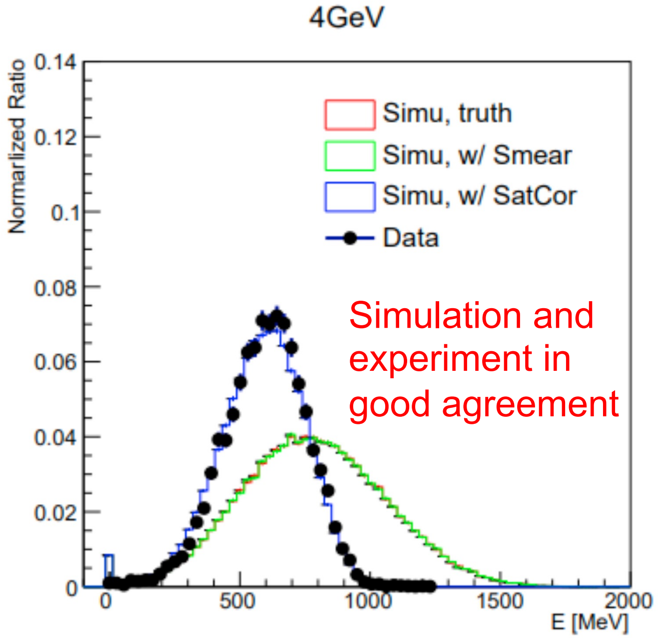
The DarkSHINE Detector R&D

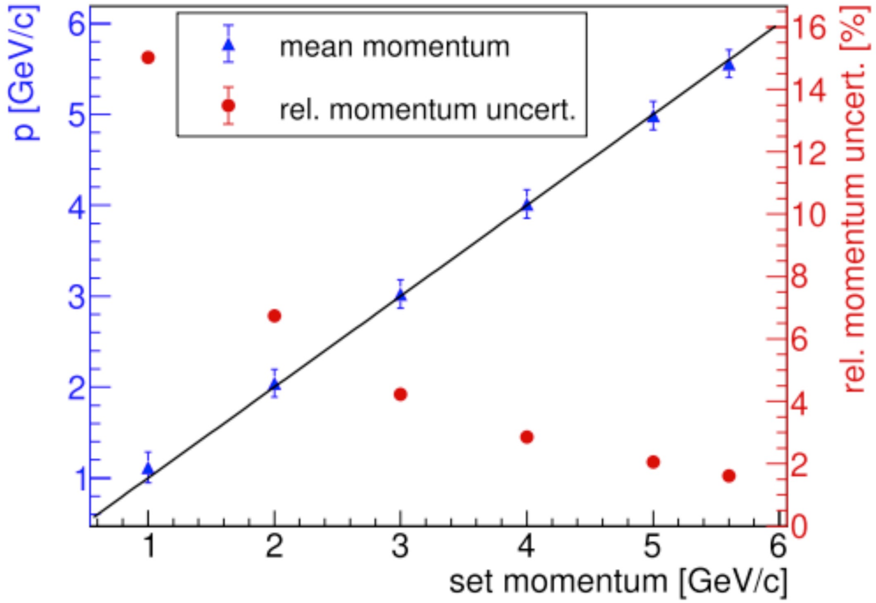
- **Motivation:**
  - Performance study under high energy and high repetition beam.
  - Technical validation for the whole detector system
- Prototype conceptual design: hybrid materials with LYSO as core scintillator, and PWO as outer scintillator
- **1st prototype module for beam test (2x2 LYSO) at DESY**
- **Energy resolution is better than 3% (244ch). Very low energy leakage below 2.5 GeV.**

Many thanks to CEPC Calorimeter group!



DESY TB22 Oct. 2023





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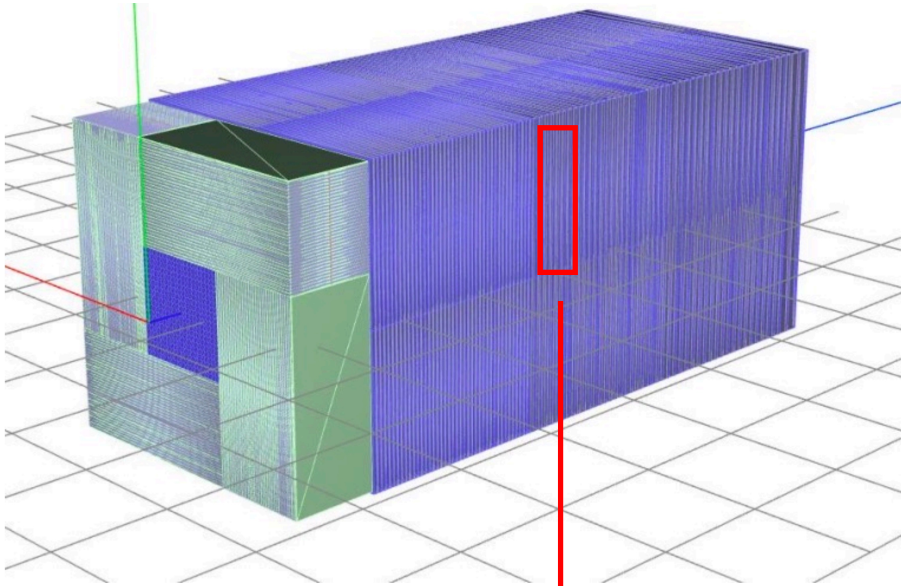
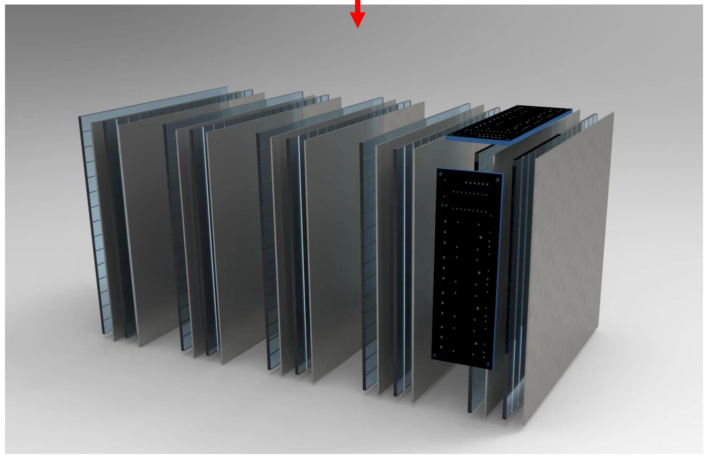
Hadronic Calorimeter:

- Veto backgrounds with same behavior as signal in ECAL
- 1.5 m x 1.5m x 2.5 m (perpendicular to the beam)
  - Split to 4 modules: 75 cm x 75 cm each
  - Plastic scintillator
    - 10 mm thick, 75cm x 5cm, 15 bars per module
    - 90 degree rotation between 2 adjacent layers
    - Wavelength shift fiber + SiPM
  - Iron absorber: 10 mm/ 50 mm thick, 75cm x 75cm
- Side-HCAL: encircling the ECAL



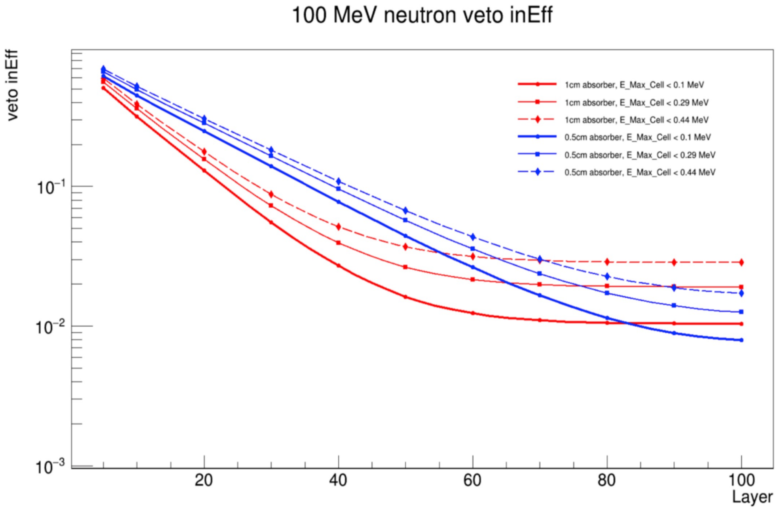
Veto inefficiency on hadrons

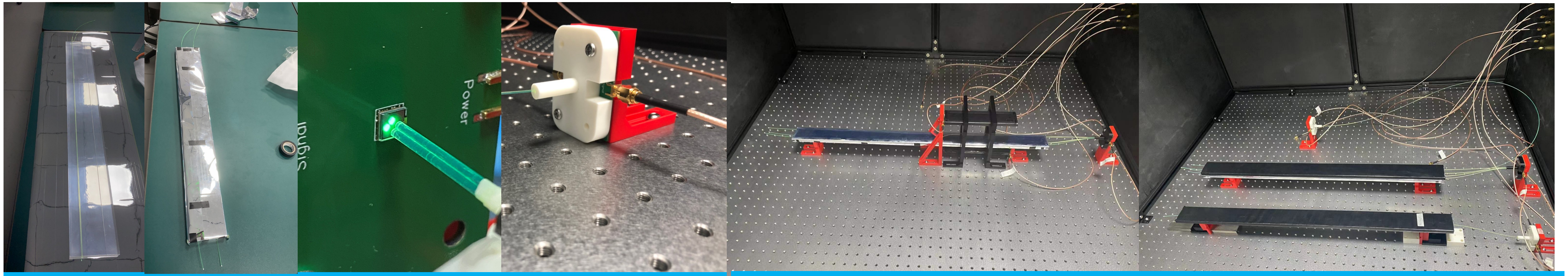
Energy[MeV] \ Particle	n	k^0	π^0	p
100	1.17E-03	3.16E-02	7.30E-06	3.07E-02
500	1.84E-05	3.30E-06	1.00E-07	8.04E-06
1000	3.70E-06	4.30E-06	1.00E-07	1.00E-07
2000	2.70E-06	1.15E-05	1.00E-07	1.00E-07



The DarkSHINE Detector R&D

- **Scintillator test at TDLI lab**
  - SiPMs performance are studied first, both size, gain and noise are considered, and picked one type (Hamamatsu S13360-3050, gain 1.7e6) for the rest tests
- **Radioactive source test for uniformity:** good uniformity with 75 cm
- **Cosmic ray test for photon yields**
  - Various types of scintillator are tested: : sizes, number of fiber grooves/used, manufacturer/composition (on-going)





Scintillator (w/ & w/o wrap) | WLS & SiPM | Fiber collimation | Cosmic ray test: photon yields test (left) and noise test (right)

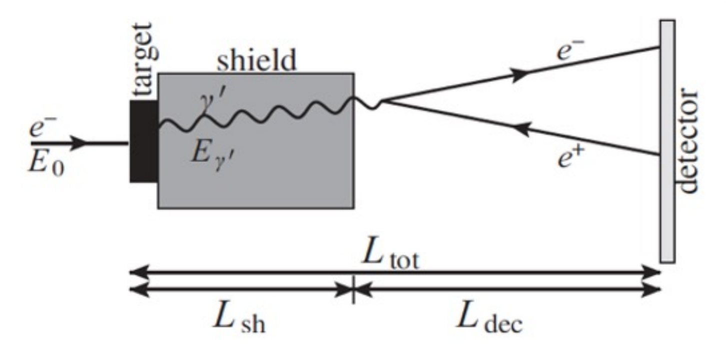
Summary

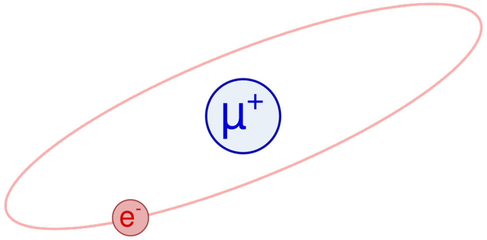
- The DarkSHINE: a fixed-target experiment searching for dark photon to light dark matter
- **The DarkSHINE will be almost background free experiment**
  - Expected 0.02 background in 3×10^{14} electron-on-target (w.r.t 1 year. running)
  - Above 50% dark photon signal acceptance efficiency
- **The DarkSHINE has competitive sensitivity** (Sci. China-Pay. Mech. Astron., 66(1):211062 (2023))
  - Sensitive to most of phase space predicted by models with 3 years running
- Detector key technology R&D has been sponsored by NSFC "原创探索计划项目".

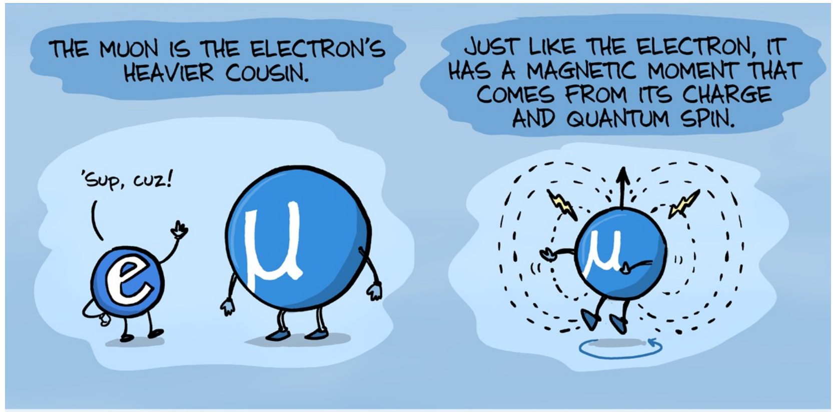

DARK
SHINE
Thanks so much for your support
to the DarkSHINE Experiment!

More physics opportunities at the DarkSHINE

- Searching for dark photon in visible decay channels
- Probing invisible vector meson decays
  - Phys. Rev. D 105, 035036 (2022)
- Millicharges, Axion-like particles, Minimal U(1) gauge bosons, light new leptophilic scalar particles
  - Phys. Rev. D 99, 075001 (2019)
- Searching for “true muonium”(缪子偶素) $\mu^+\mu^-$ bound state
- The DarkSHINE can be a compact muon source
  - 150,000 $\mu^+\mu^-$ pairs per bunch at 10 MHz
- …

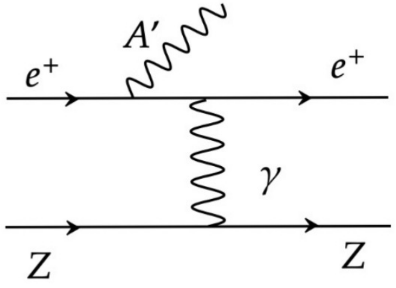




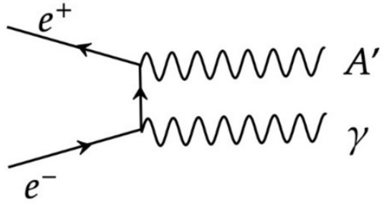


More physics opportunities at the DarkSHINE

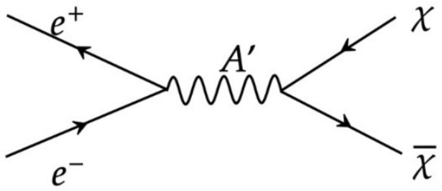
- **Positron on fixed-target experiment has great sensitivity at dedicated mass:**



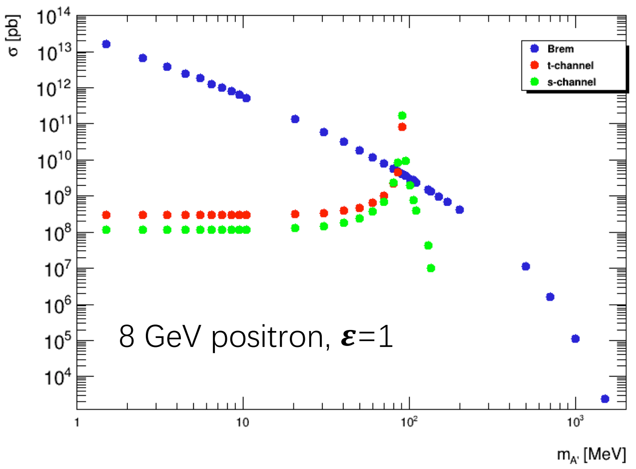
(a) bremsstrahlung

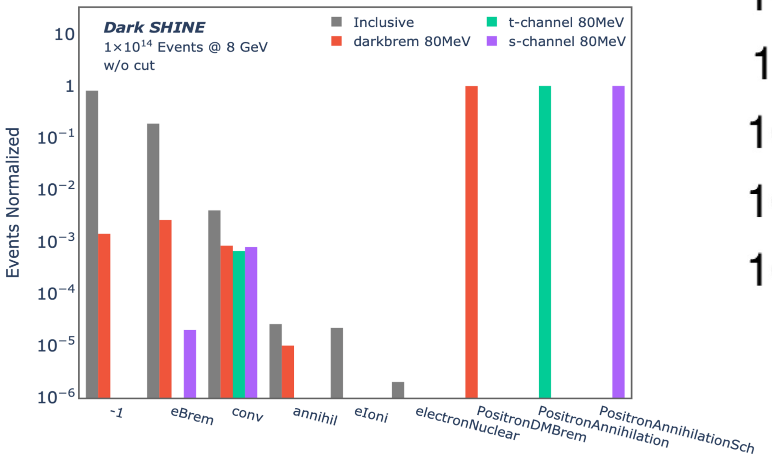


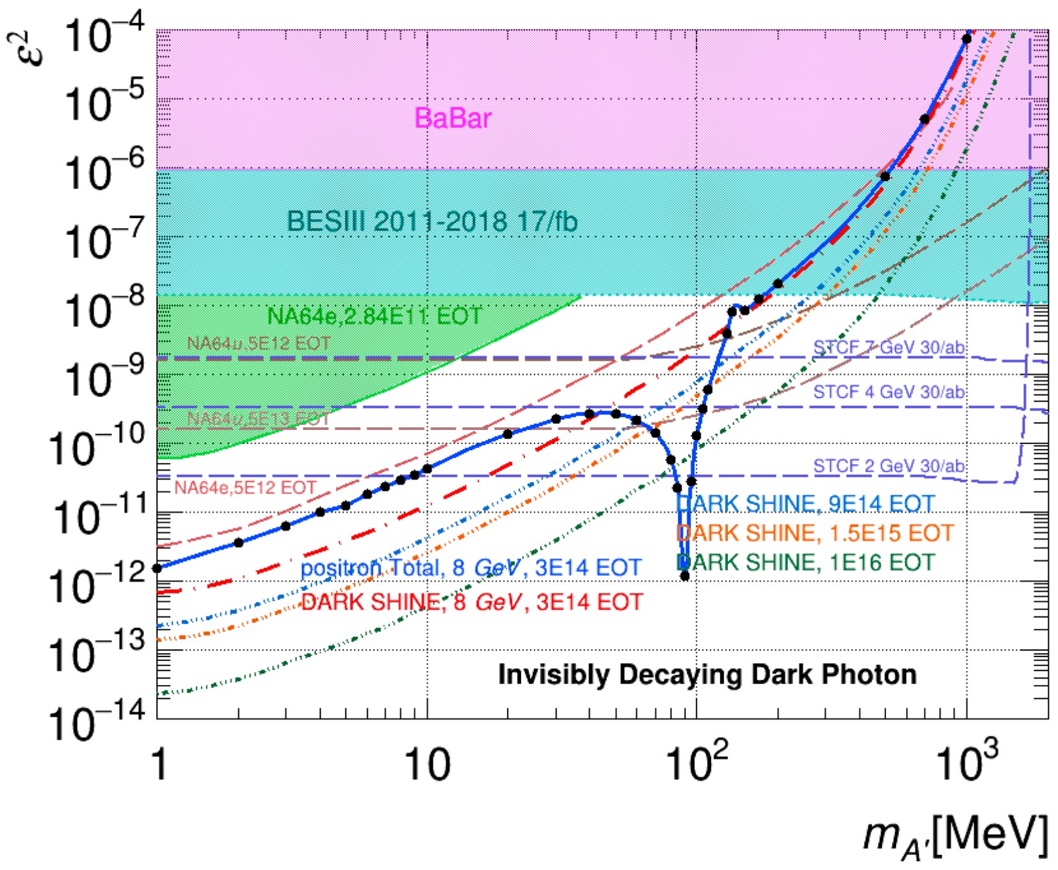
(b) t-channel annihilation



(c) s-channel annihilation







Alternative beam energy and target at DarkSHINE

- **Left: dark photon production cross sections with different target materials**
- **Right: projected sensitivity with 4 GeV electron beam (very preliminary)**