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Simulation and Scintillator Test for DarkSHINE Hadronic calorimeter

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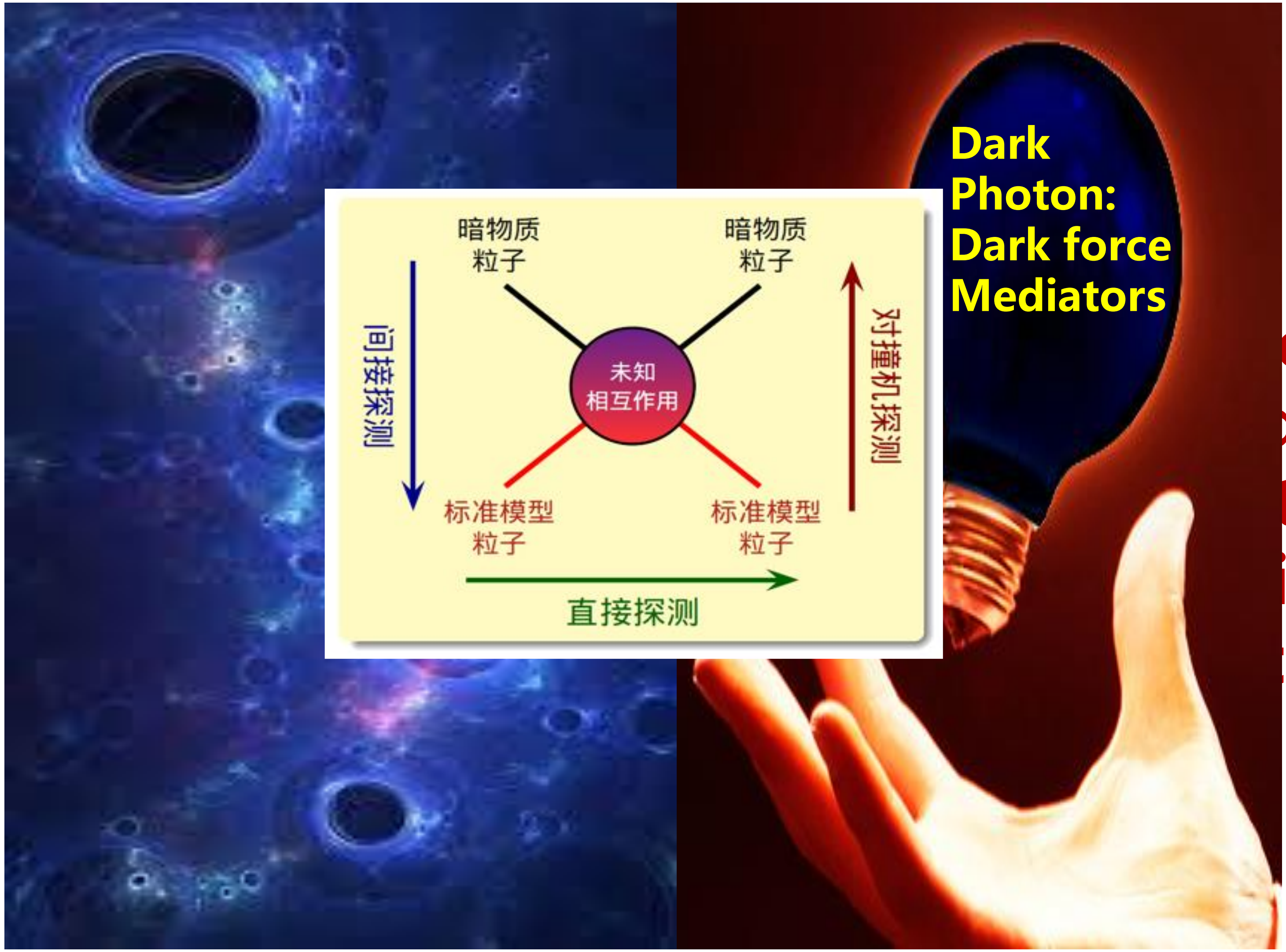
On behalf of Dark SHINE R&D Team

Searching for Dark Force Mediators

The world of Dark Matter

Dark Matter candidate particles

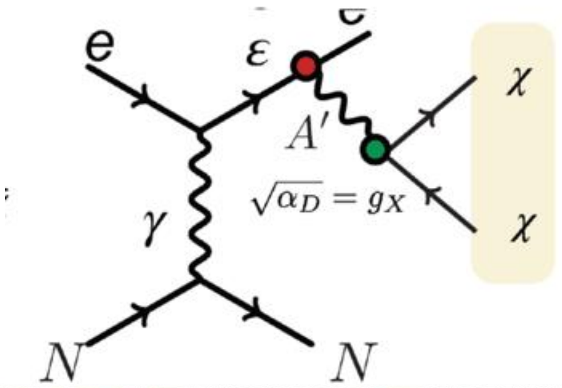


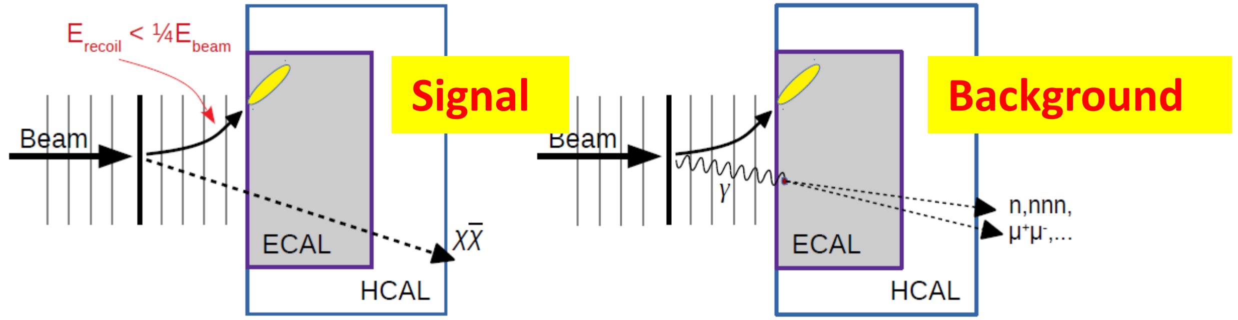
Dark Matter Mediators

DarkSHINE Introduction

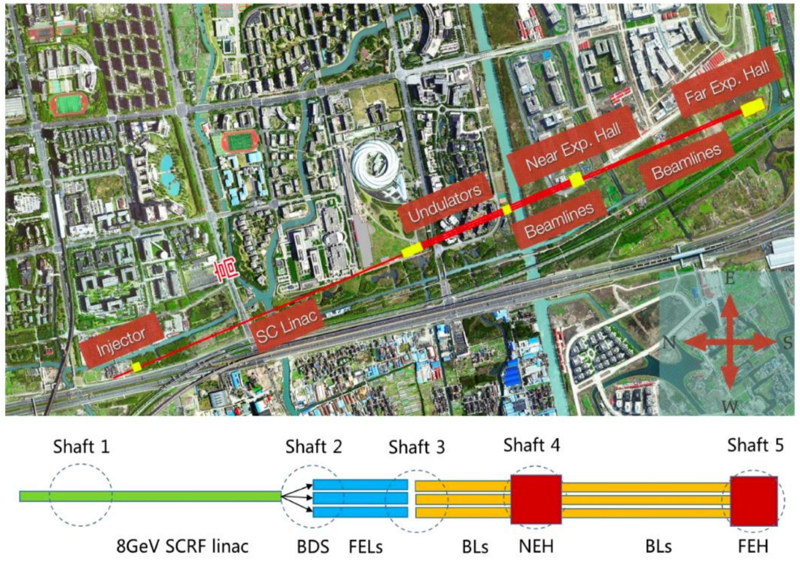
- **DarkSHINE searches the dark photon via invisible mode**
  - **Dark Photon can be produced in electron-nuclei interaction (electron-on-target), and then decay to dark matter particle**
  - **Target + Tracker + ECAL + HCAL**
  - **Single electron on target, $\sim 3 \times e^{14}$ EOT/year**
  - **Energy + Momentum loss detection**
  - **Veto background with big missing energy in ECAL**

INVISIBLE DECAY MODE $m'_A > 2m_\chi$





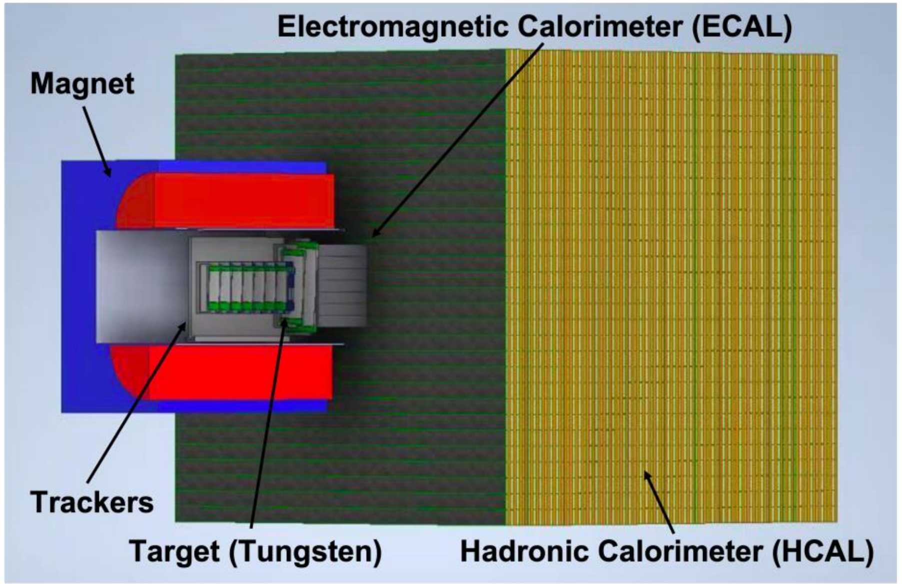
Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE) can provide 8 GeV high repetition rate single electron beams



Detector system 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.



Dark SHINE detector sketch

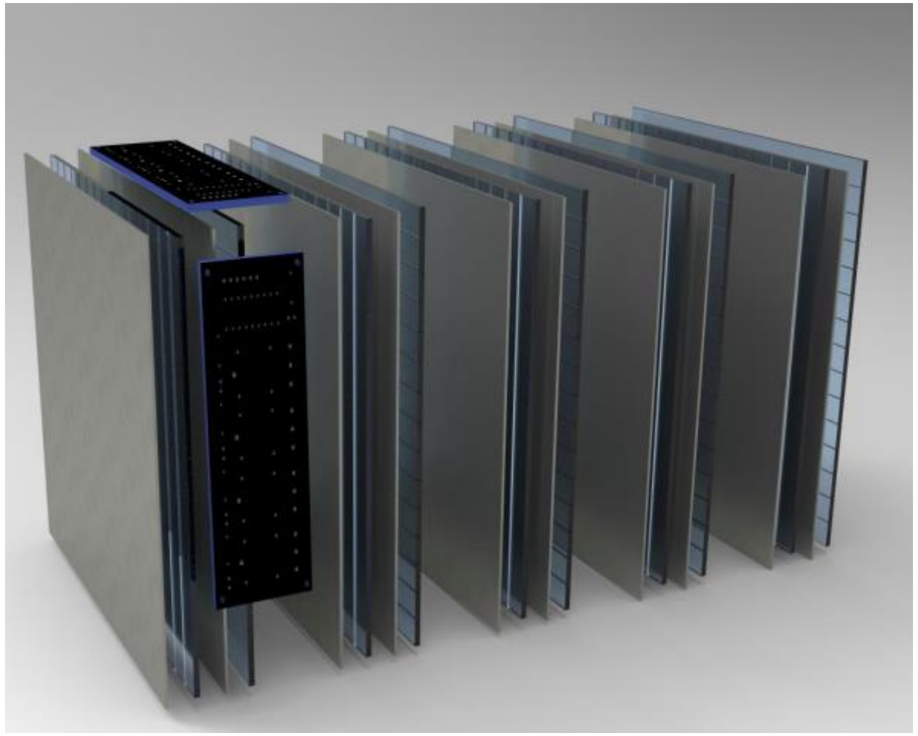
Electromagnetic calorimeter
Measure the deposited energy: electron and photon.

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

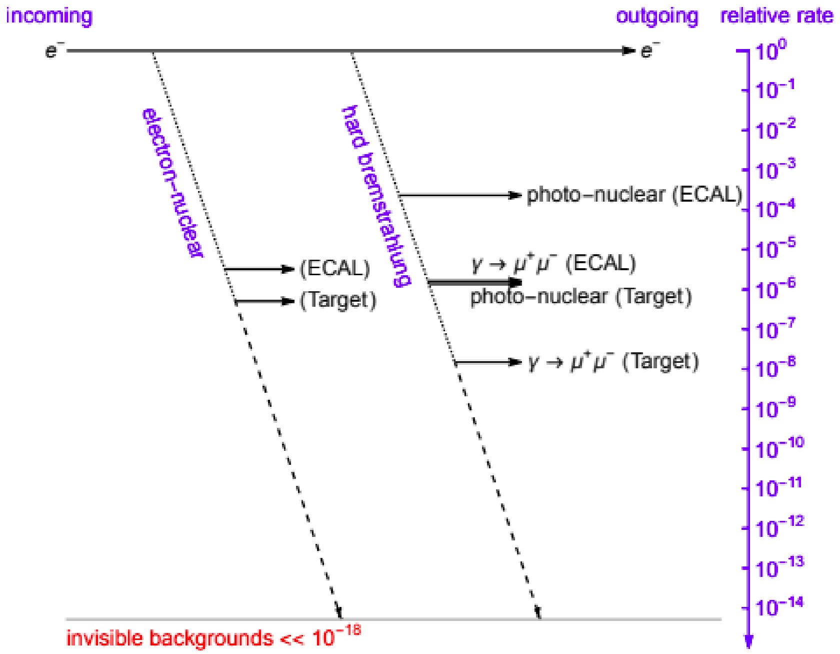
Additional system:
Readout electronics, trigger system, TDAQ, magnetic system (1.5 T), etc.

Hadronic Calorimeter

- **Veto backgrounds with same behavior as signal in ECAL**
- **1.5 m × 1.5 m (perpendicular to the beam), ~10 λ (~160 cm iron, parallel to the beam)**
  - Split to 4 modules, 75 cm × 75 cm each
  - Iron absorber: 10 mm/50 mm thick， 75 cm × 75 cm
  - Plastic scintillator: 10 mm thick, 75 cm × 5 cm, 15 bars per layer per module
    - 90 degree rotation between 2 adjacent layers
    - Wavelength shift fiber + SiPM



- **Leading background:** SM bremsstrahlung
- **Rare background processes**
- **Irreducible but negligible:** neutrino production

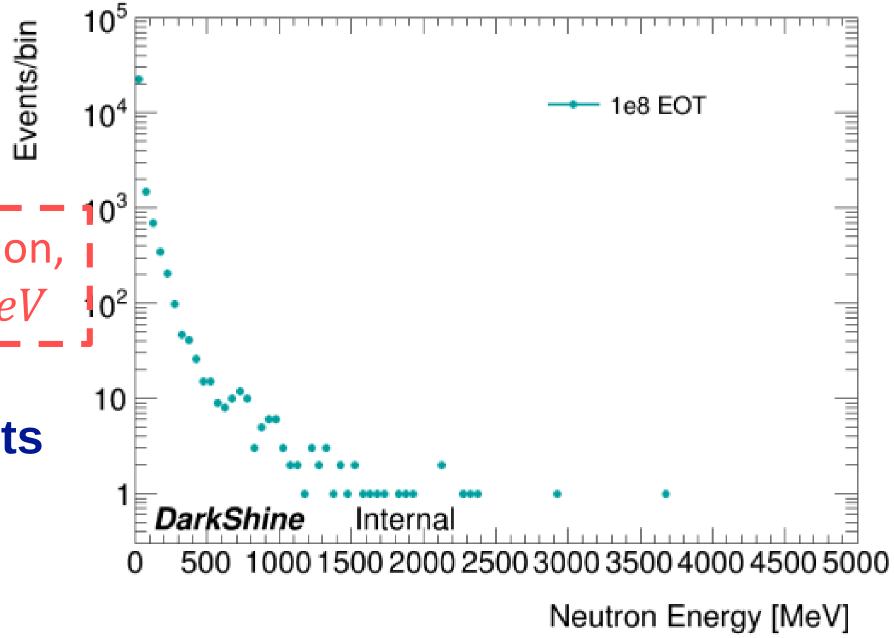


HCAL: Simulation

- **Simulation is implemented with GEANT4-based framework**
- **Use neutral hadron rejection efficiency as the index**
  - **Define veto inefficiency: ratio of hadrons/events that can not be rejected by HCAL cuts**
    - $E_{Total}^{HCAL} < 30\ MeV\ \&\&\ E_{Max-cell}^{HCAL} < 0.1\ MeV$ **not veto**
  - **Veto inEff** $\geq 1e^{-6}$ **can suppress backgrounds to unit level in** $\sim 3 \times e^{14}$

Process	Neutron	Proton	Pion	Kaon
ElectronNuclear	73.42%	21.52%	4.64%	0.42%
PhotonNuclear	64.95%	18.56%	14.43%	2.06%

Neutron Energy distribution, with cut: $E^{ECAL} < 2.5\ GeV$



- **Two types simulation**
  - **Electron-on-target & full detector simulation -> Veto events**
  - **Neutron & HCAL only -> Veto neutrons**

HCAL: Simulation Results

- **Several conclusions are obtained:**
  - **Size is reduced from 4 m × 4 m × 4 m to 1.5 m × 1.5 m × 10λ**
    - **Performance is good enough with weight restriction**
  - **Better veto inefficiency with both 10mm and 50mm absorbers**
  - **1 scintillator layer + 1 absorber layer is enough**
  - **Adjacent scintillator layers are perpendicular to avoid potential energy leakage**
  - **Side-HCAL is needed: surround ECAL, sensitive plane perpendicular to ECAL**
- **Neutral hadron veto inEff**

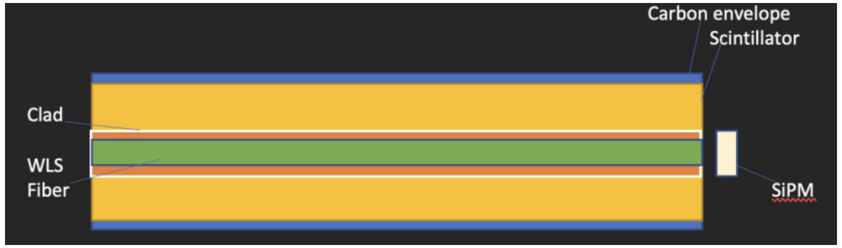
Energy[MeV] \ Particle	Neutron	Kaon	Pion	Proton
100	7.30E-04	3.27E-02	1.08E-05	4.94E-02
500	1.97E-05	7.80E-06	1.00E-07	3.90E-06
1000	1.90E-06	1.30E-06	1.00E-07	1.00E-07
2000	5.00E-07	4.80E-06	1.00E-07	1.00E-07

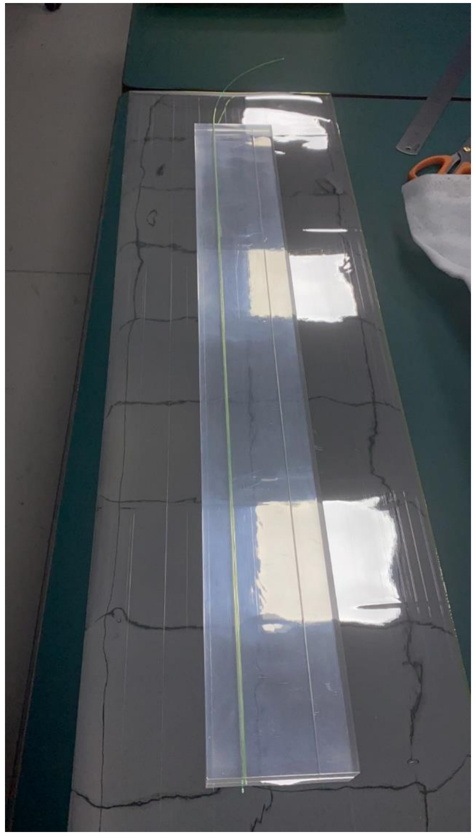
- **Events veto inEff**

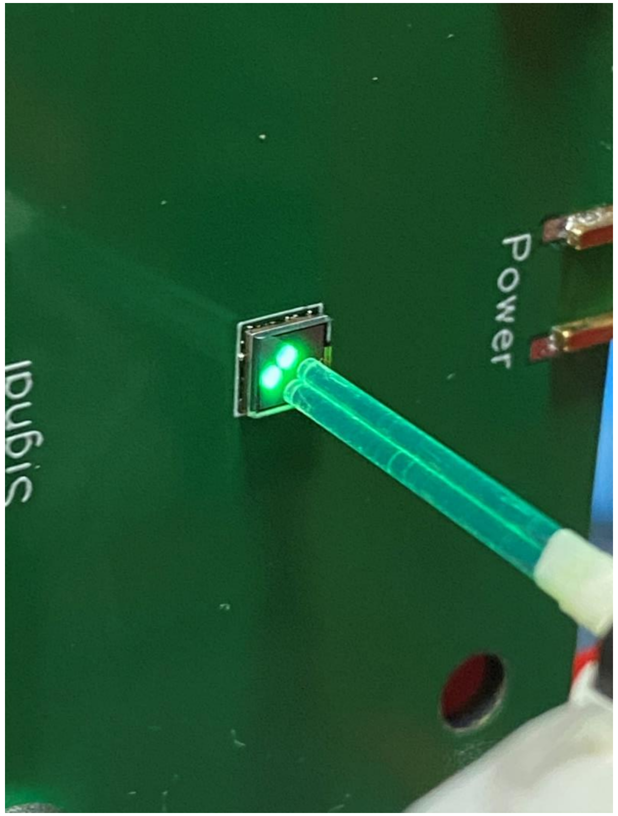
Structure \ Process	entarget	enecal	pntarget	pnecal
x-abs-y-noside	2.17E-02	3.50E-02	7.84E-02	1.09E-01
x-abs-y-side-2cm	8.92E-04	9.46E-03	1.80E-03	3.01E-02
x-abs-y-side	1.06E-03	1.01E-02	1.82E-03	3.15E-02
xy-abs-xy-side	1.06E-03	1.01E-02	1.82E-03	3.15E-02

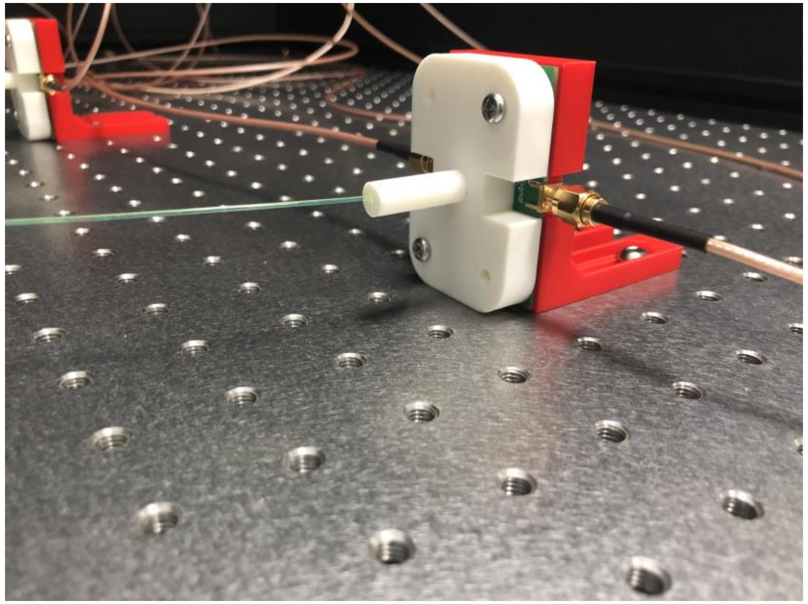
Scintillator Test

- **Scintillator: HND-S2 (高能科迪) polystyrene**
  - **Several sizes are studied: width/thickness/grooves are varied**
- **WLS: Kurary, d=1 mm, reflector on one side**
- **SiPM: NDL EQR15 11-3030D-S, 3.0 mm × 3.0 mm, 40000 microcell**
- **Wrapper: 80 um ESR**



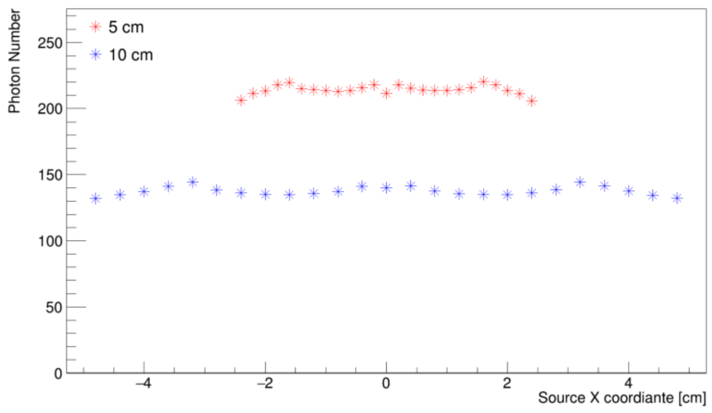


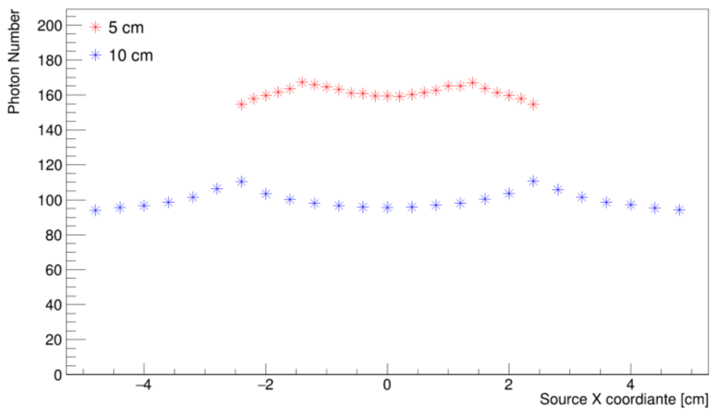


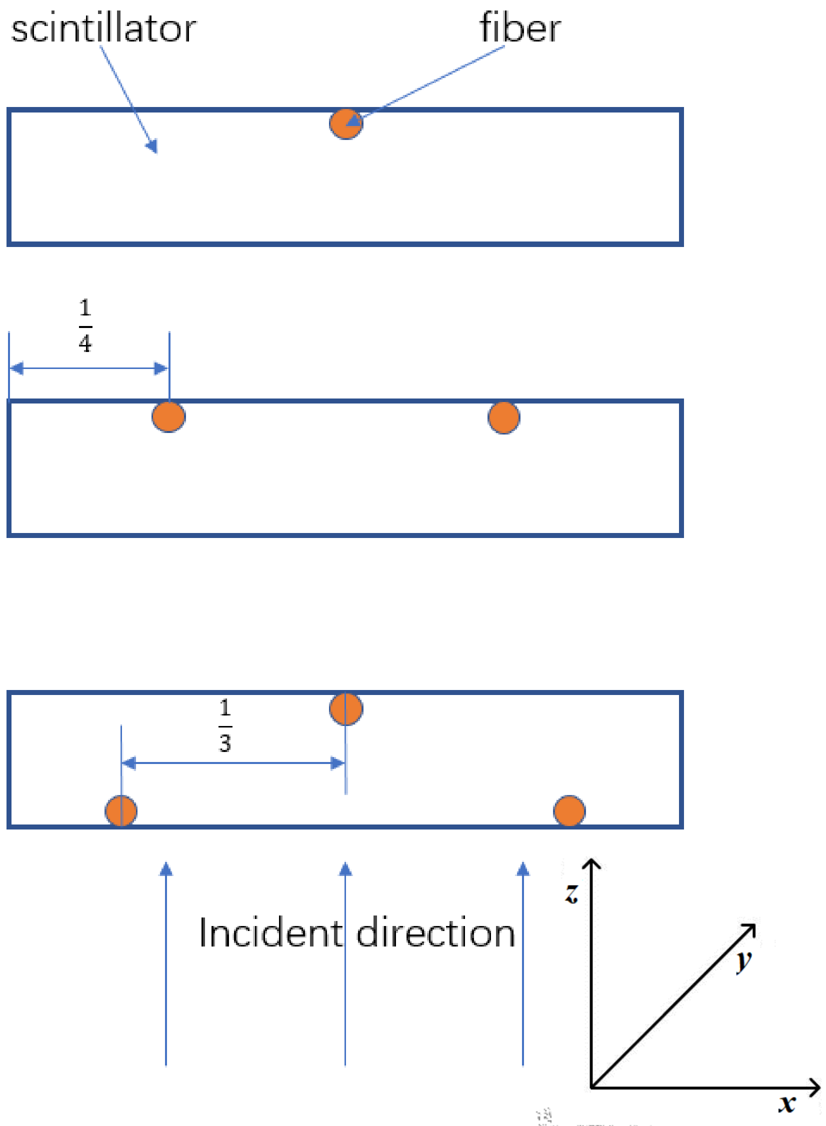


Scintillator Test: Simulation

- **Scintillator size : 5/10 cm × 75 cm × 1 cm/2 cm**
- **Fiber size : 0.5 mm radius with clad**
- **Incident e^{-}, 100 MeV**
- **Incident position : -2.4/-4.8 cm to 2.4/4.8 cm per 0.2/0.4 cm**



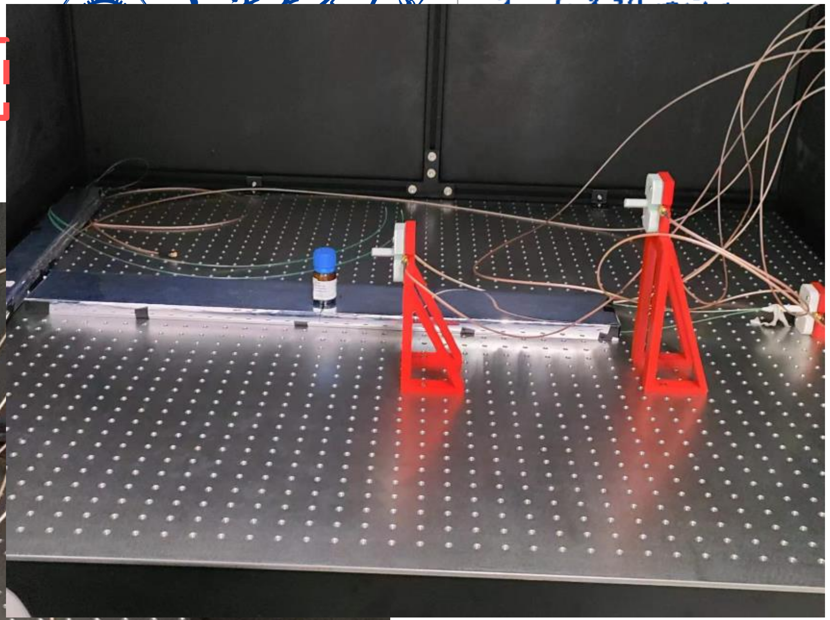


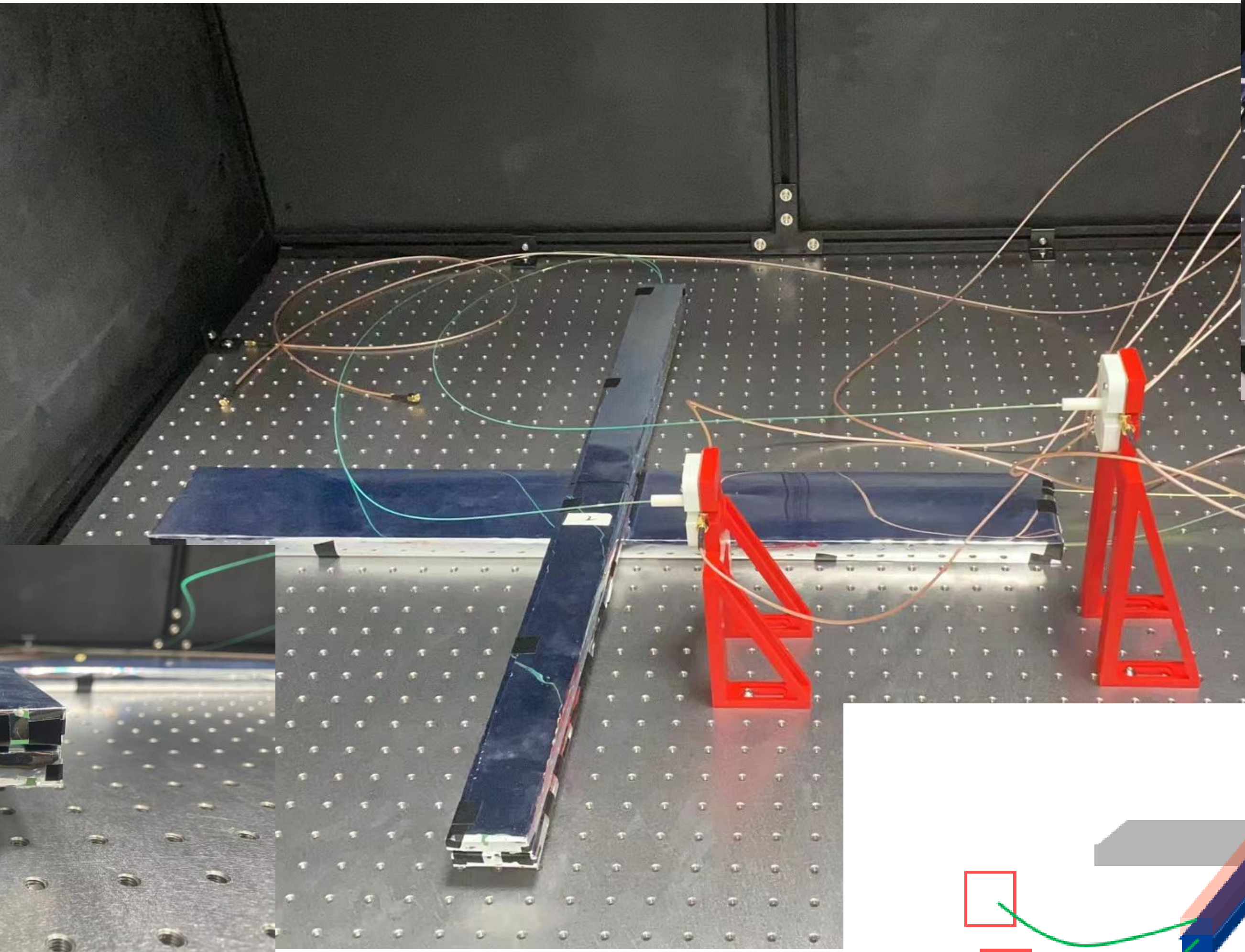


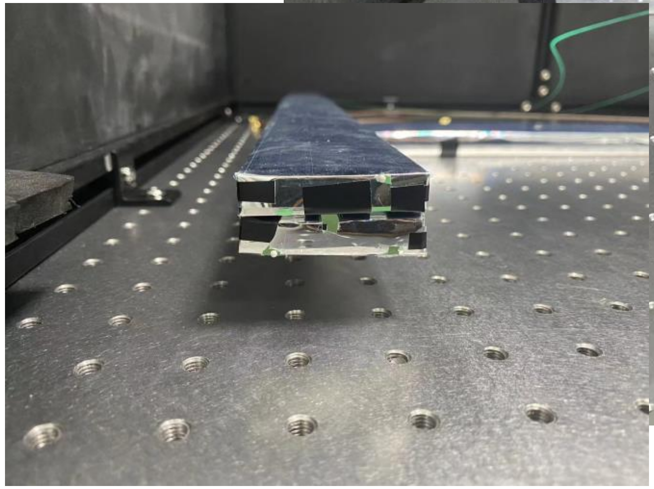
Size	1 fiber	2 fibers	3 fibers
1 cm * 5 cm	64 (60-75)	108 (100-115)	136 (130-145)
1 cm * 10 cm	38 (35-50)	69 (65-80)	92 (85-100)
2 cm * 5 cm	91 (85-100)	161 (155-170)	214 (205-220)
2 cm * 10 cm	53 (48-65)	100 (94-110)	138 (132-145)

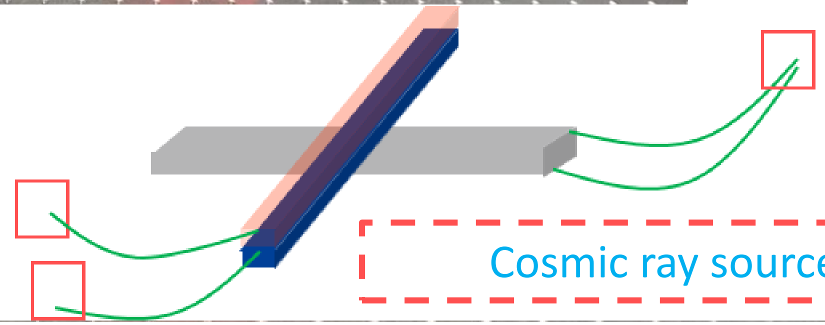
Scintillator Test: Platform

Radioactive source



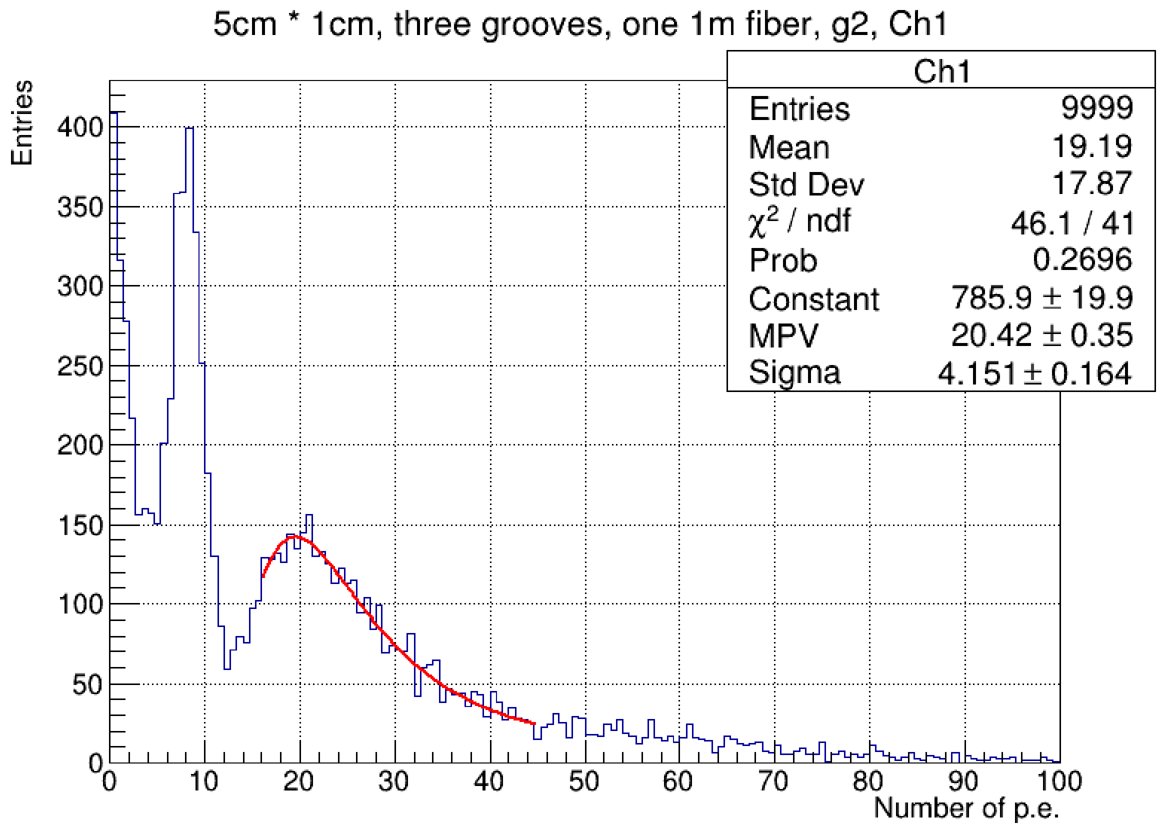






Cosmic ray source

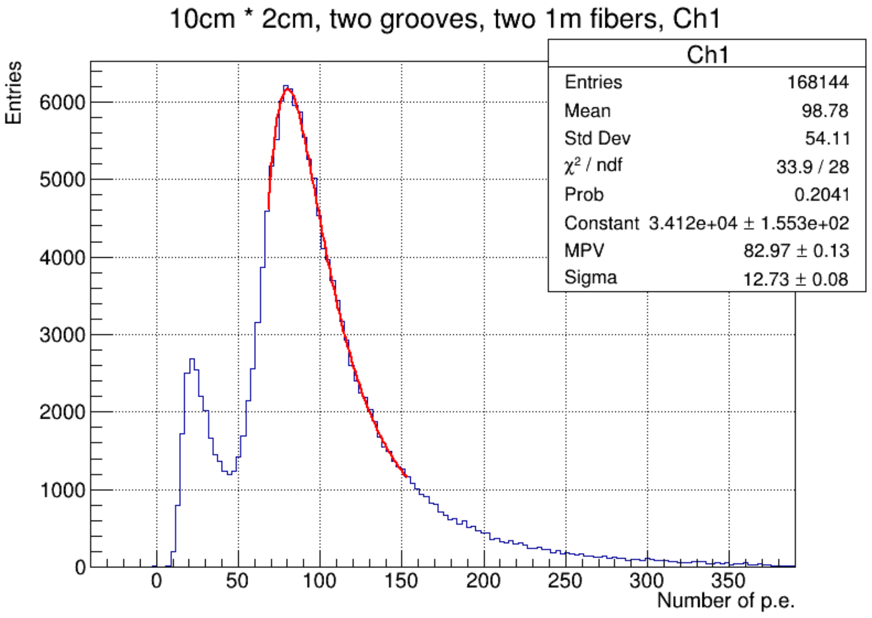
Scintillator Test: Noise



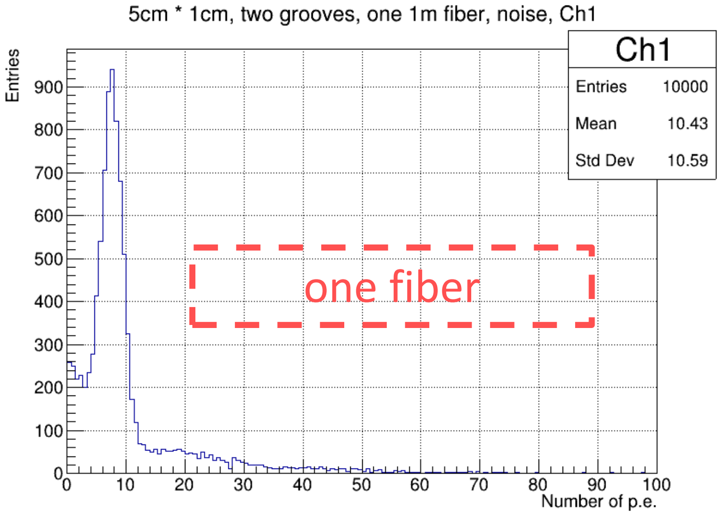
- **Noise test: 1 scintillator bar, self-trigger**
- **3 types of noise are observed**
  - **Electronic**
  - **SiPM**
  - **Scintillator**

Scintillator Test: Noise

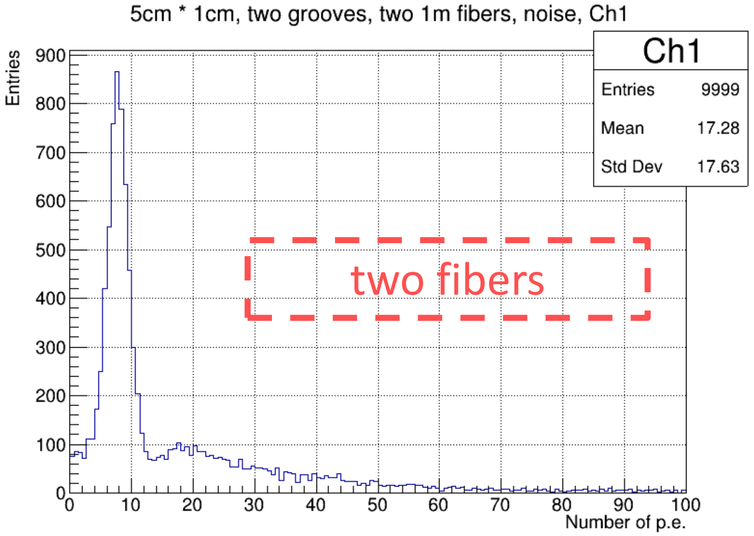
- **Several things learnt:**
  - **Electronic noise can be suppressed by raising the threshold (but need more time for cosmic ray test)**
  - **Scintillator noises are consistent among different choices of scintillator size/fiber&grooves**
    - **Two fiber won't amplify the scintillator noise (very slightly), and can separate the signal and noise**



Coincidence Triggered



Self-triggered

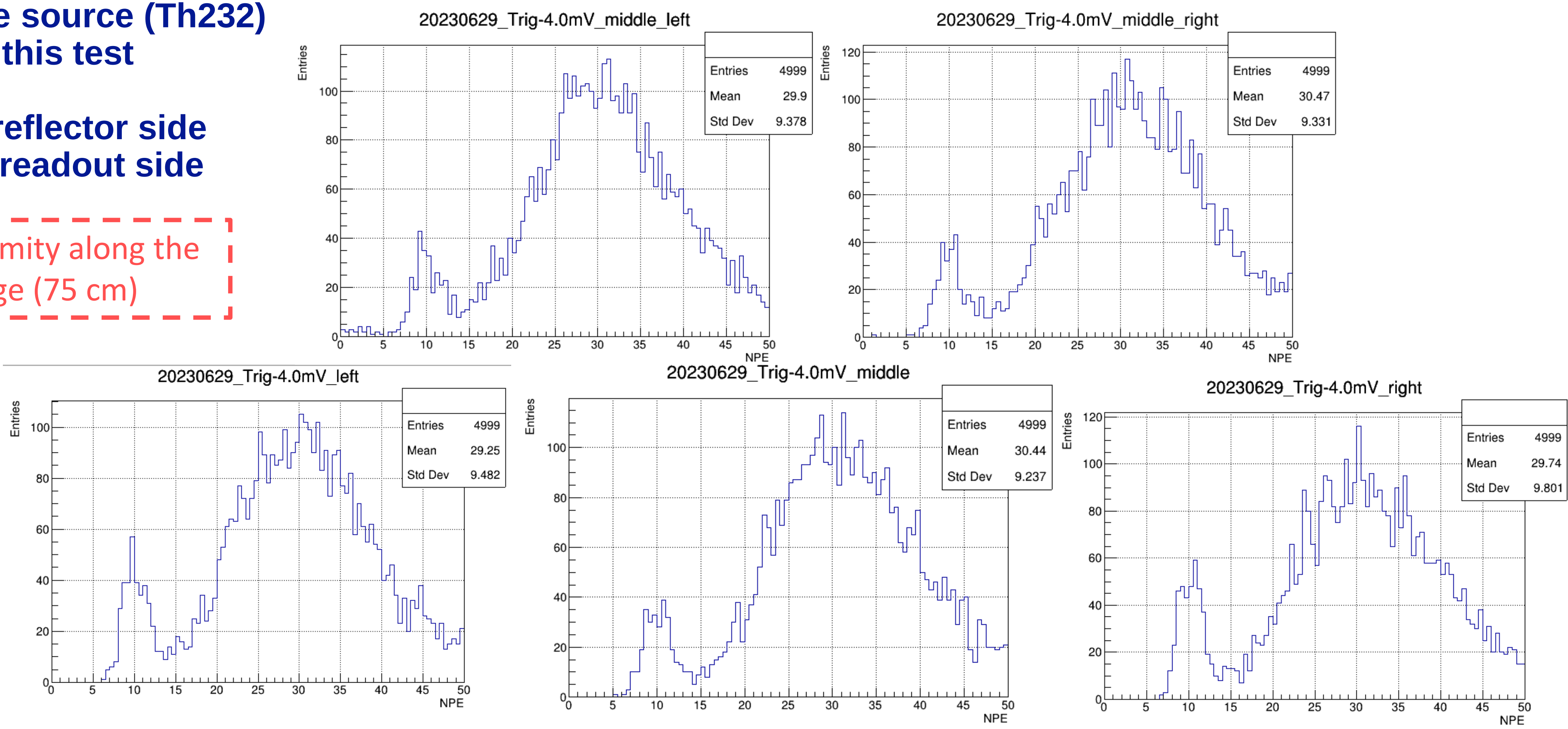


Self-triggered

Scintillator Test: Uniformity

- **Radioactive source (Th232) is used for this test**
- **Left is the reflector side right is the readout side**

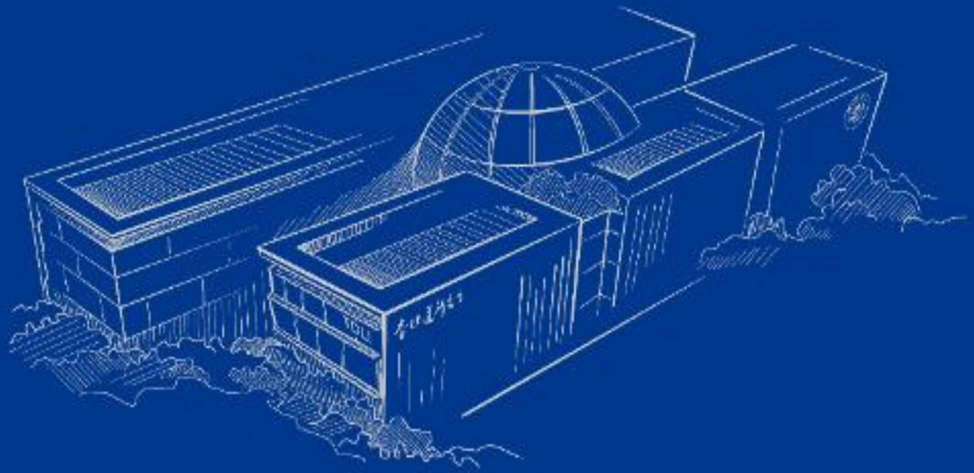
Good Uniformity along the long edge (75 cm)



Summary

- DarkSHINE experiment is a fixed target experiment using an electron beam, and the primary purpose is to search for dark photon, brief introduction is given.
- DarkSHINE HCAL uses a design of iron absorber + plastic scintillator, and the photons are collected by WLS and SiPM. The design has been optimized and the results of the simulation study is illustrated.
- Scintillator test is on-going, current results of noise and uniformity are shown, photon yields of different size will be obtained soonish

谢谢 ！



HCAL Simulation: Transverse Size

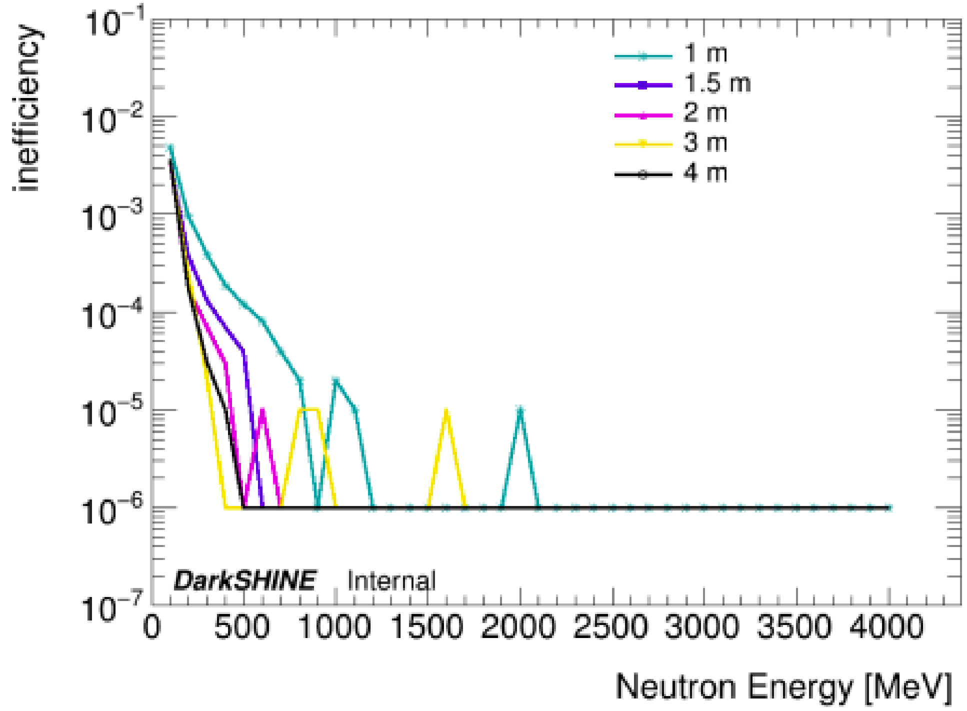


Figure 5. Veto inefficiency as a function of different incident neutron energies. Larger size HCAL is showing better veto power as expected due to its capability of acceptance compared with smaller size HCAL designs. To satisfy the weighting limits of the SHINE facility, we decided to use 1.5 m as the final design.

HCAL Simulation: Absorber thickness study

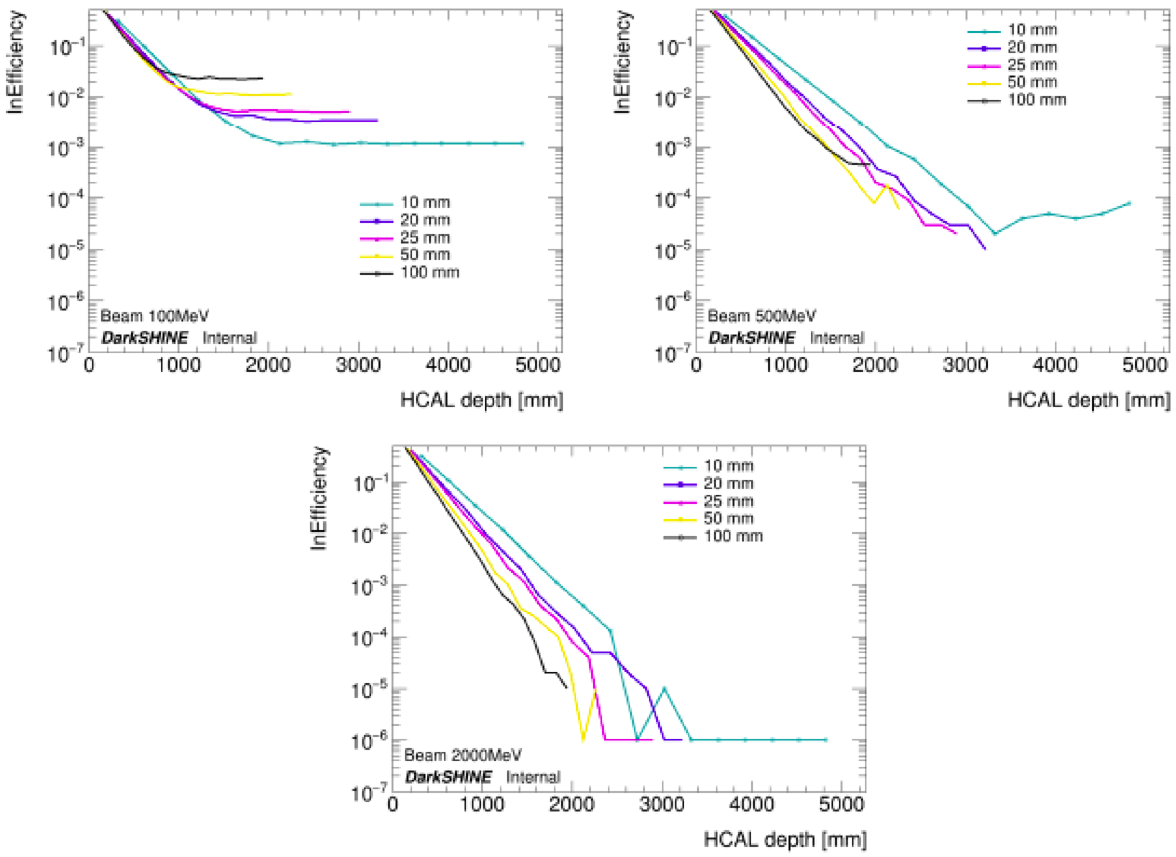


Figure 6. Veto inefficiency as a function of detector depth for different absorber thickness. 100,500 and 2000 MeV neutrons are generated to hit towards hadronic calorimeter at its center.Thick absorber thickness would be able to veto neutrons in small depth range.

HCAL Simulation: Absorber thickness study

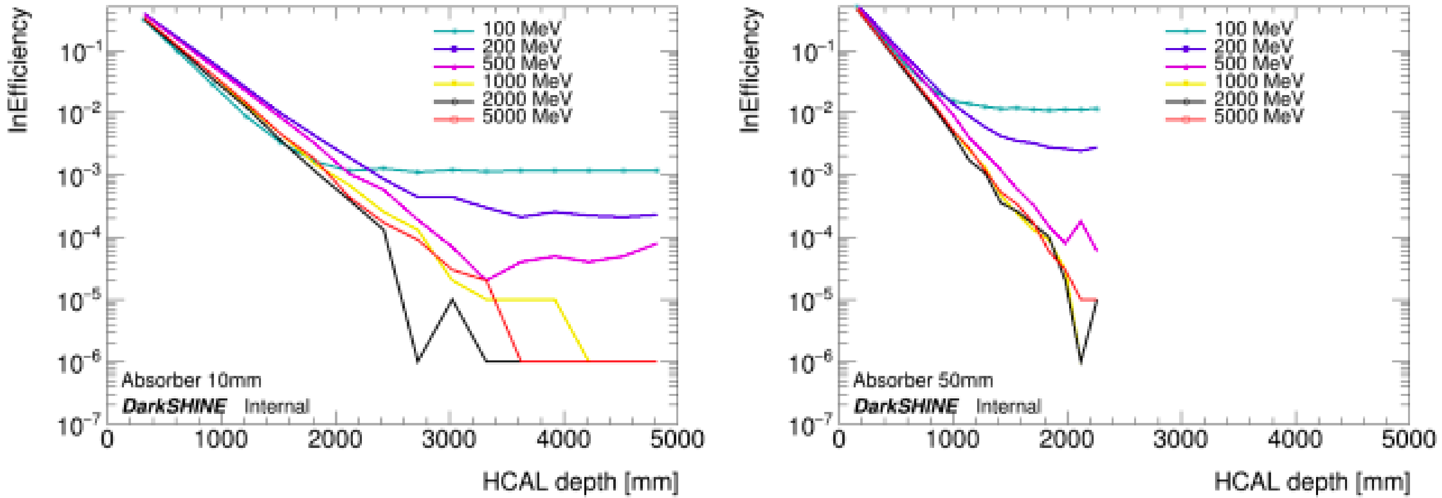


Figure 7. Veto inefficiency as a function of detector depth for different beam energy. Different absorber thickness are selected, Left figure is showing effects for 10 mm absorber detectors and right hand side figure is showing effects on 50 mm absorbers.

HCAL Simulation: Scintillator Layer design

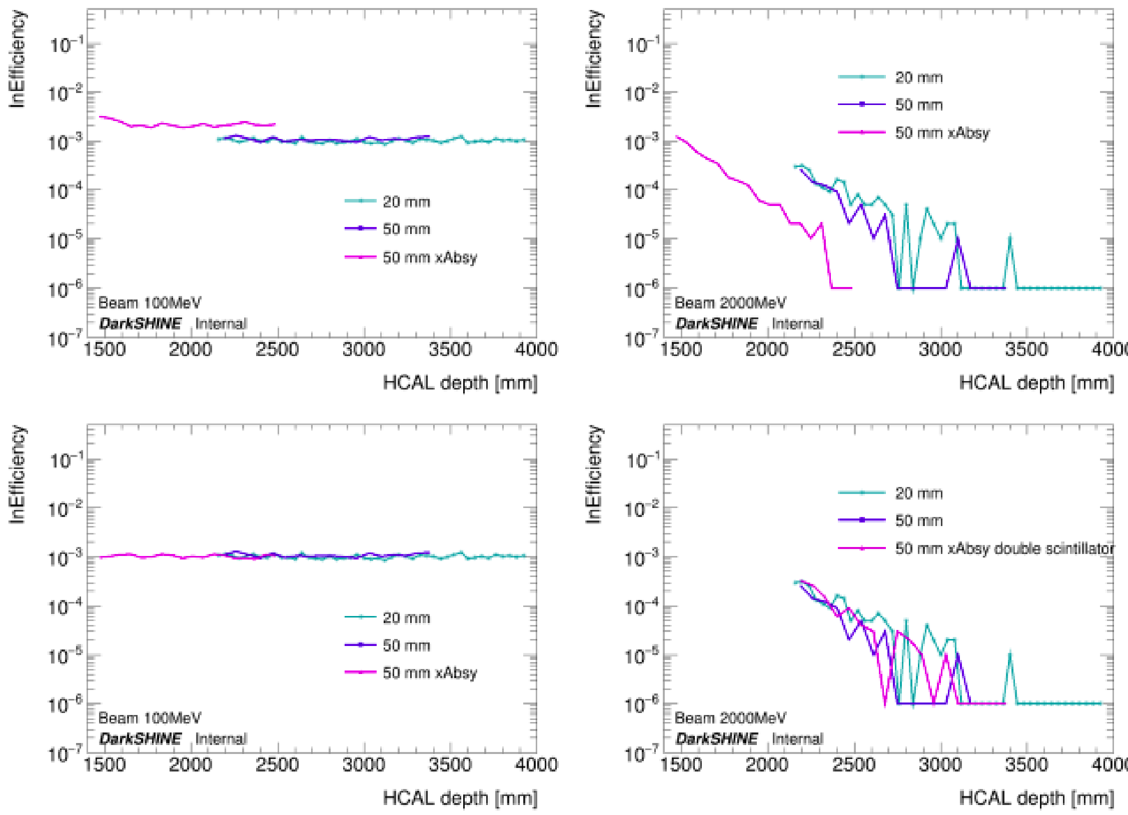
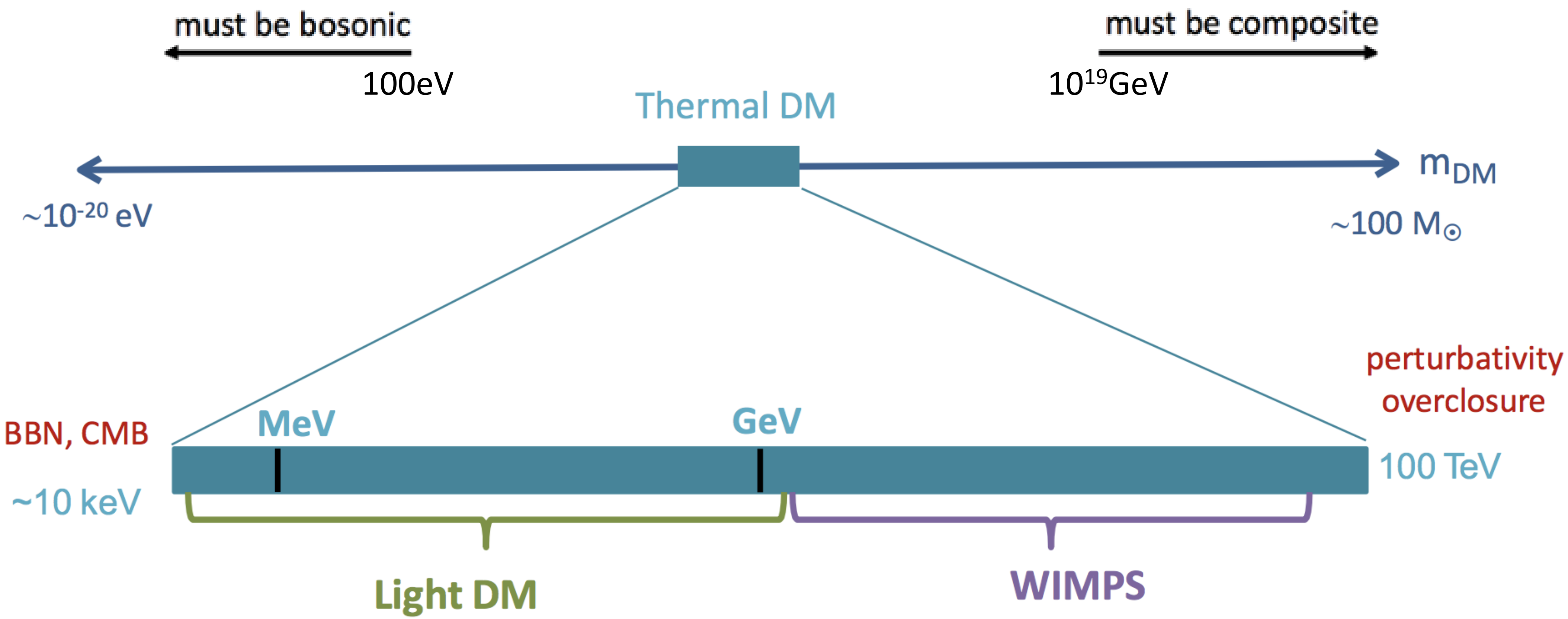


Figure 8. Veto inefficiency as a function of detector depth for different absorber thickness and scintillator strategy. 100 and 2000 MeV neutrons are generated to hit towards hadronic calorimeter at its center. Top two plots show the case that scintillator is 1 cm thick, while that in the bottom two plots is 2 cm.

Dark Matter Mystery: broad mass range

The thermal hypothesis also greatly restricts the range of allowed masses



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

Dark Photon Theory in a nutshell

Introduce extra $U(1)_X$ symmetry → New Gauge Field X → Dark Photon Mediator A'
$U(1)_{em}$ → $U(1)_{em} \times U(1)_X$

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

SM Photon γ **Dark Photon A'**

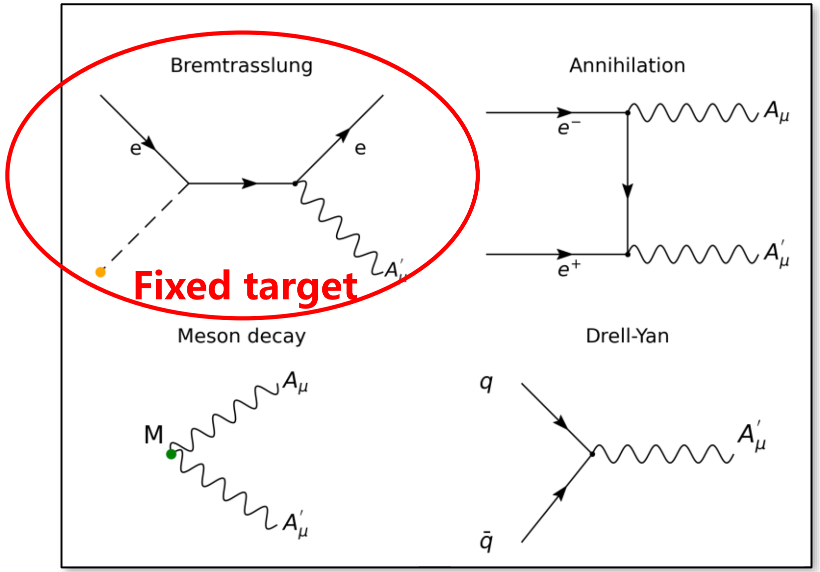
$$\varepsilon X_{\mu\nu} F^{\mu\nu}$$

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

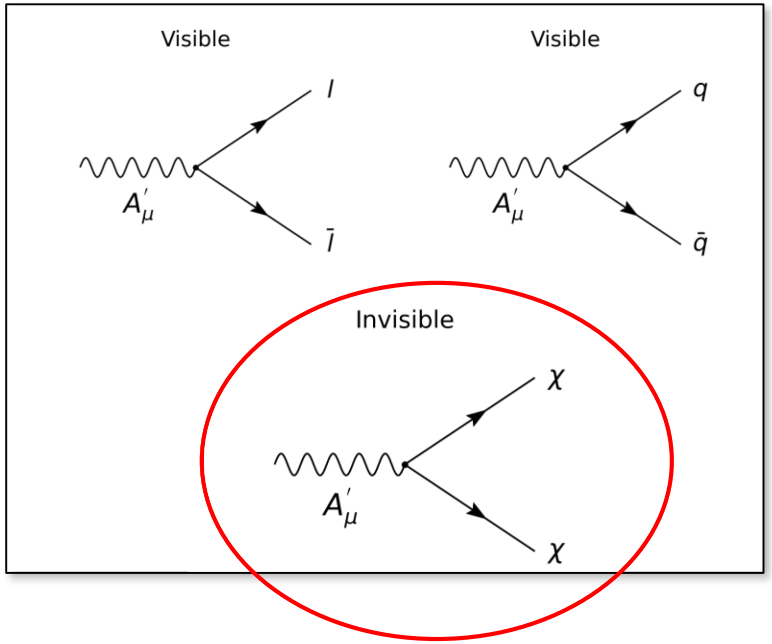
B. Holdom, Phys. Lett. B 166, 196 (1986)
R. Foot & X.-G. He, Phys. Lett. B 267, 509 (1991)

Physics process and anticipated signatures

Processes to search for **dark photon A'** : Bremsstrahlung, Annihilation, Meson decay and Drell-Yan process



(Dark photon production)

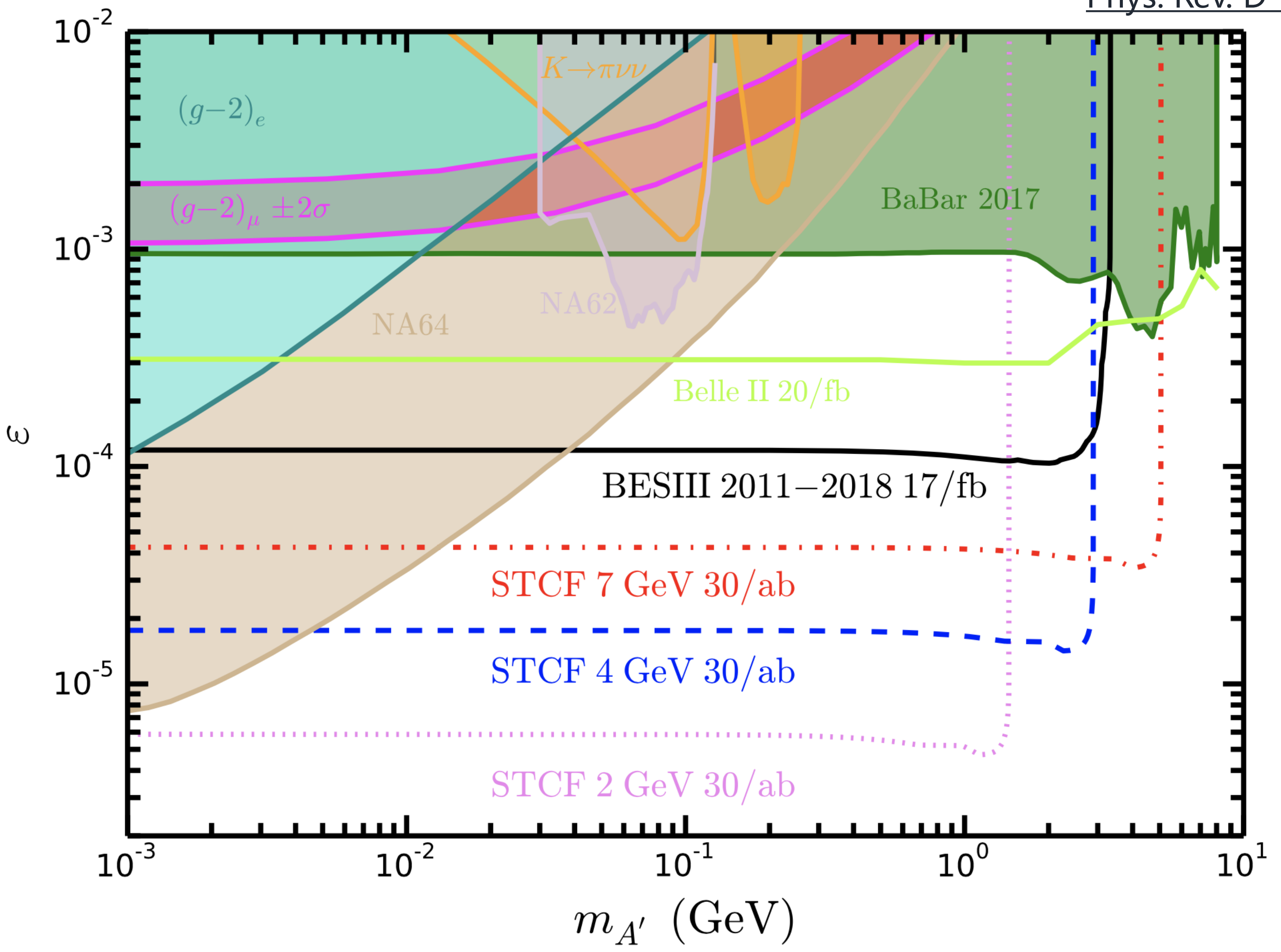


(dark photon decay)

- **Goal:** put constraints on the kinetic mixing parameter ε.
- **Challenge:** small production rate → suppress bkg. from SM processes.
- **Experimental signatures:** missing energy, missing momentum.

Dark Photon search sensitivity: collider vs fixed-target

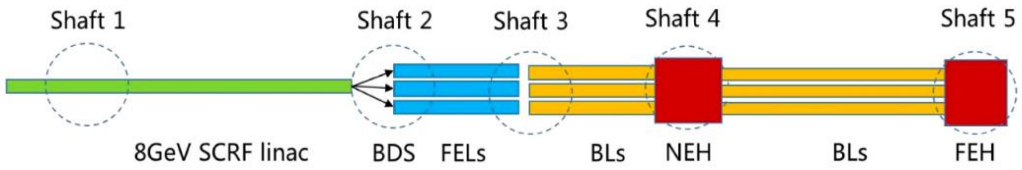
Phys. Rev. D 100, 115016 (2019)

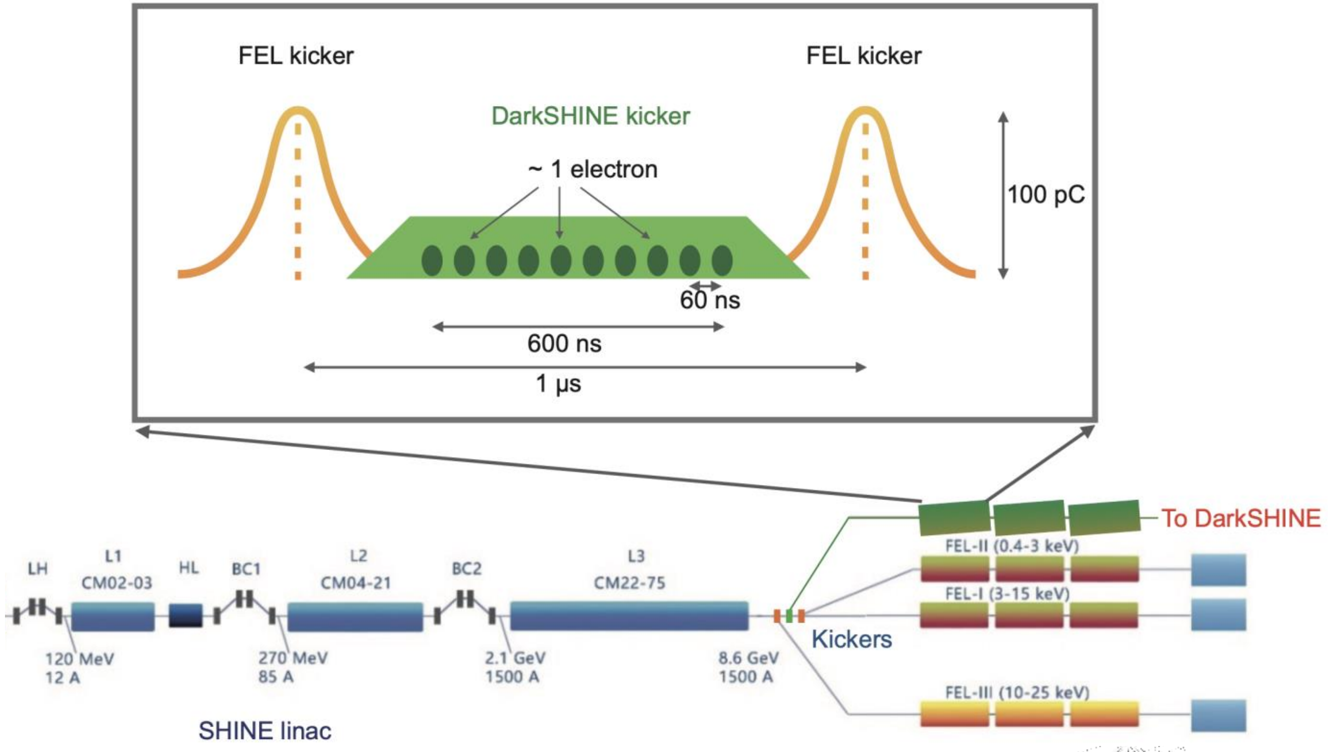


The SHINE Facility

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: 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.**





Dark Photon Theory Progresses at TDLI/SJTU

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY | 李政道研究所 Tsung-Dao Lee Institute

PHYSICAL REVIEW D **101,** 075016 (2020)

CP-violating dark photon interaction

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Constraining photon portal Dark Matter with TEXONO and COHERENT data

Shao-Feng Ge[a,b] and Ian M. Shoemaker[c]

Regular Article -Theoretical Physics

Probing the dark axion portal with muon anomalous magnetic moment

Shao-Feng Ge[1,2,a], Xiao-Dong Ma[1,2,b], Pedro Pasquini[1,2,c]

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Search for a heavy dark photon at future e^+e^- colliders

Min He,[a] Xiao-Gang He,[a,b,c] Cheng-Kai Huang[b] and Gang Li[b]

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Dark photon dark matter in the minimal $B - L$ model

Gongjun Choi,[a] Tsutomu T. Yanagida[a,b] and Norimi Yokozaki[c]

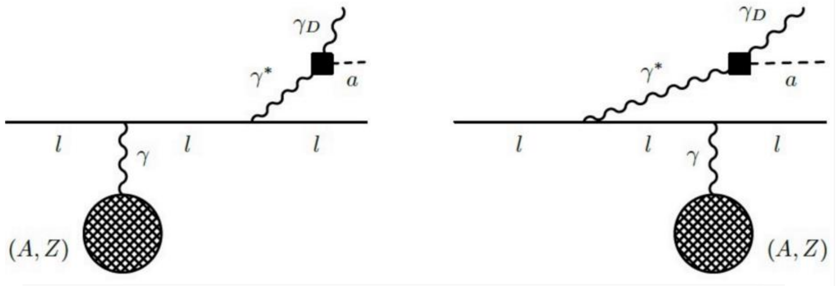
PHYSICAL REVIEW D **102,** 075001 (2020)

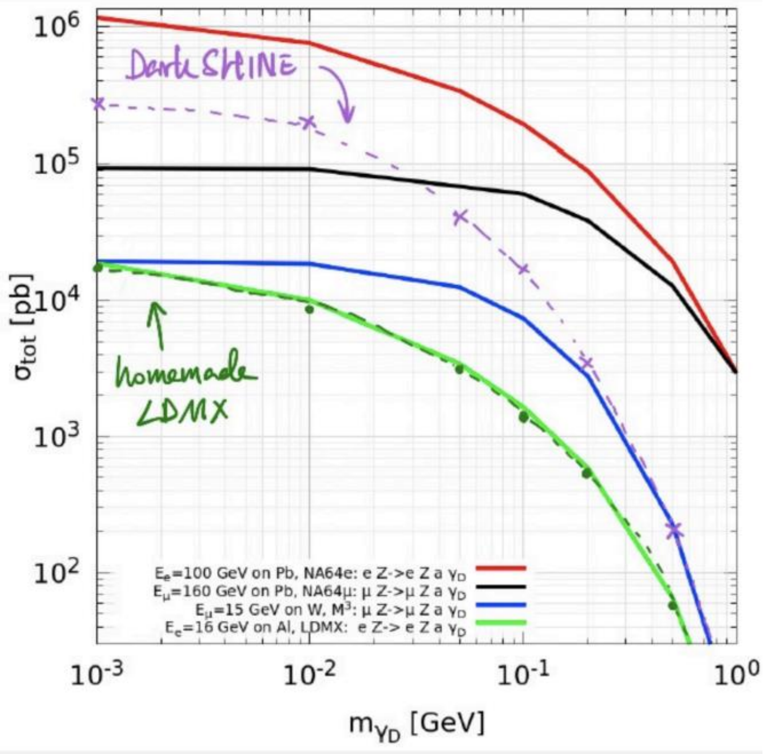
Strongly-interacting massive particle and dark photon in the era of the intensity frontier

Ayuki Kamada,[1] Masaki Yamada,[2,3,4] and Tsutomu T. Yanagida[5,6]

More Physics Opportunities…

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





- Dramatically different sensitivity curve of Dark Photon search when changing from **electron beam to positron beam**
- Extra s/t-chan annihilation diagrams come into play for Dark Photon production
- SHINE can also deliver positron beam with low current…

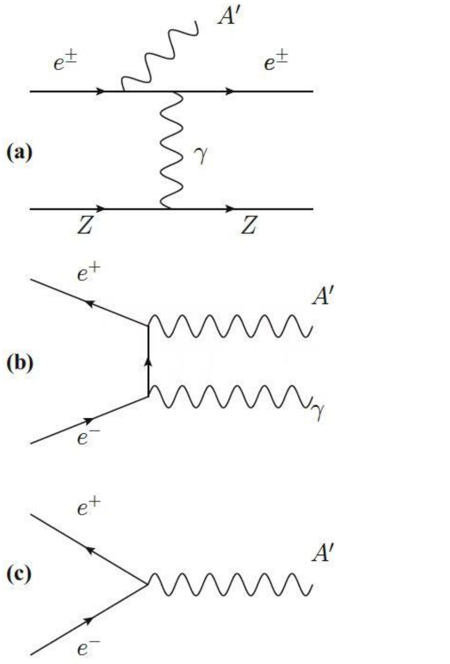
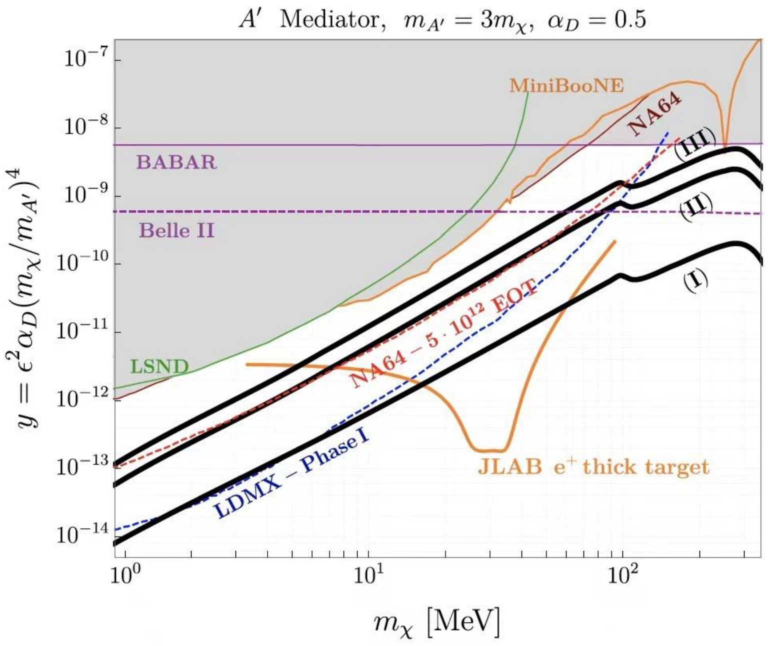


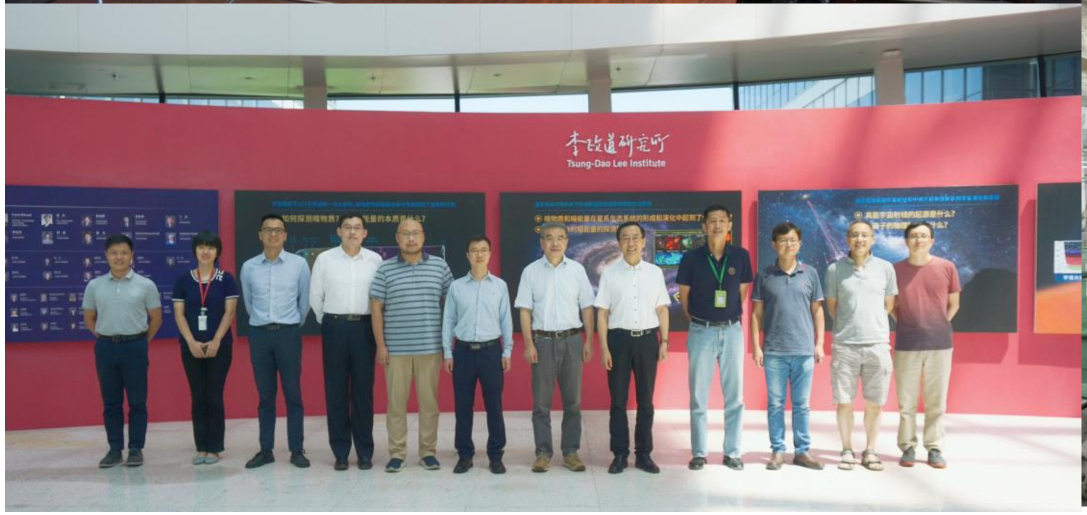
Fig. 1 Three different A' production modes in fixed target lepton beam experiments: (*a*) A'-strahlung in e^-/e^+-nucleon scattering; (*b*) A'-strahlung in e^+e^- annihilation; (*c*) resonant A' production in e^+e^- annihilation



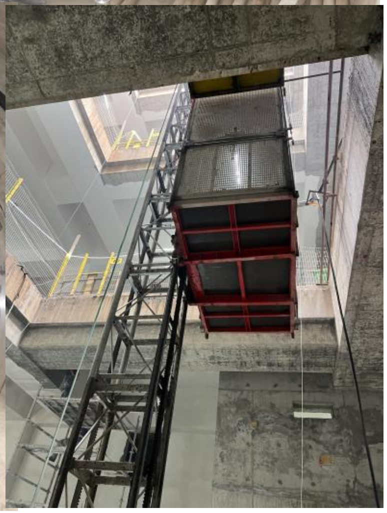
Eur. Phys. J. A (2021) 57:253

Collaboration with SHINE









DARK SHINE

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