Software Framework of the DarkSHINE Experiment

Yulei Zhang

Shanghai Jiao Tong University

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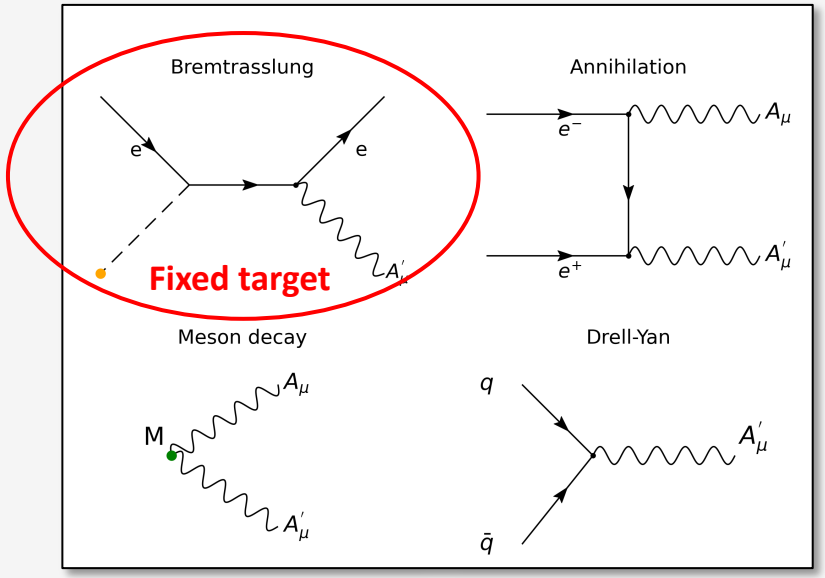
What is DarkSHINE?

A proposed fixed-target experiment

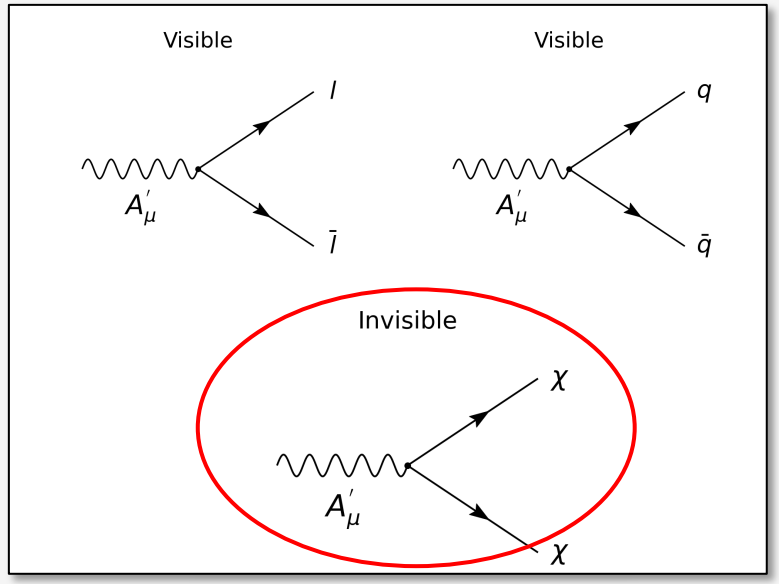
Dr. Jing CHEN's talk [link]

Prof. Shu LI's talk [link]

Physics process and anticipated signatures



- **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



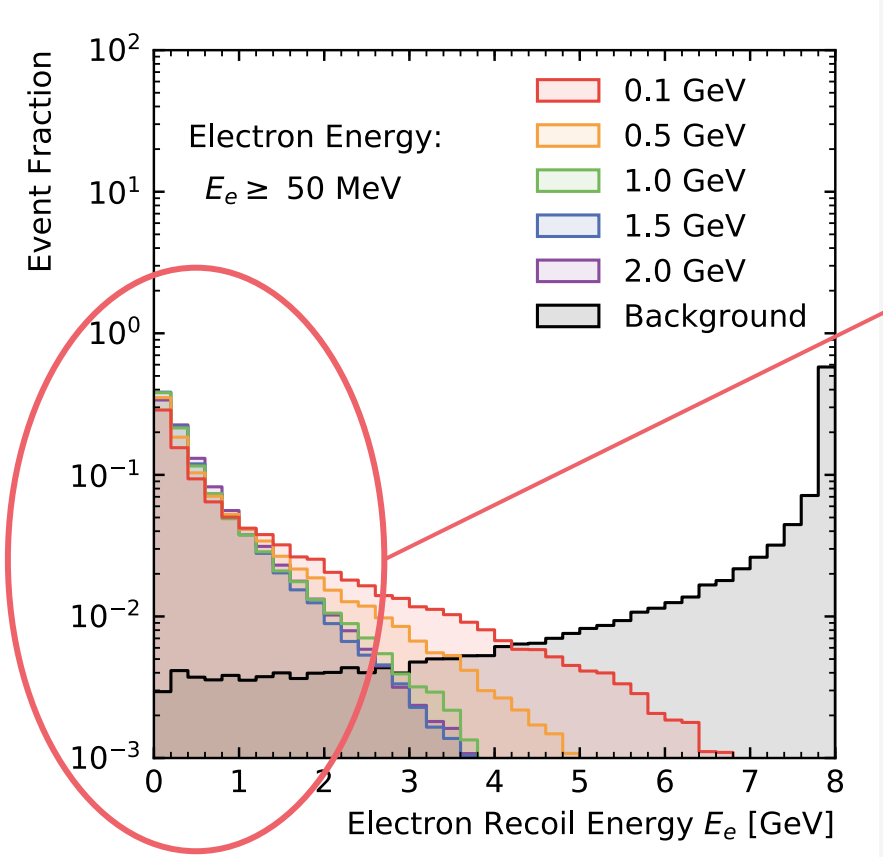
- **Visible decay**

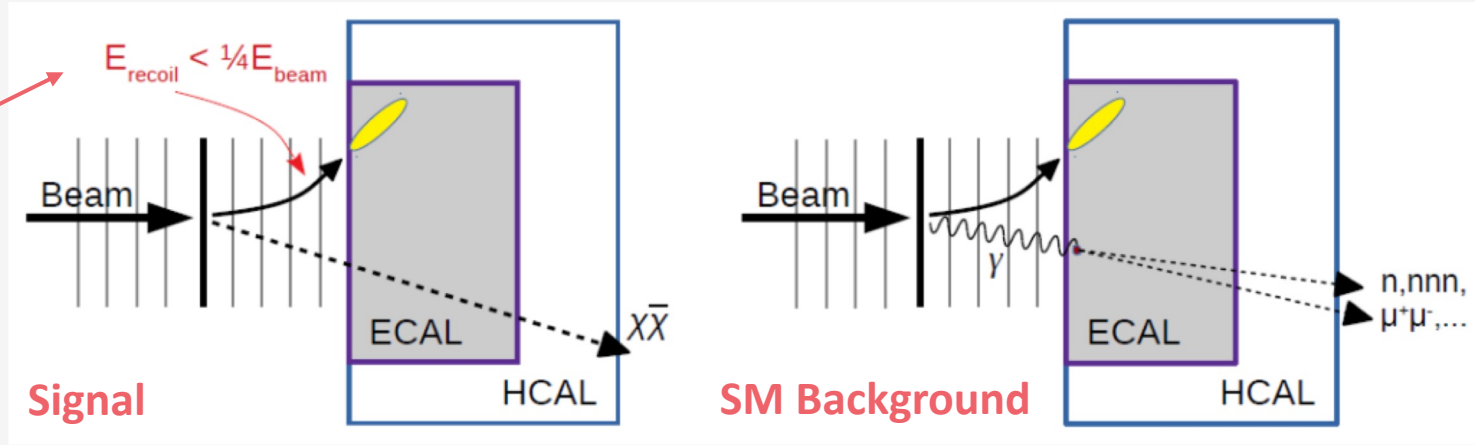
Two interaction vertices → production rate highly suppressed

- **Invisible decay**

One interaction vertex → interaction probability enhanced → **Better sensitivity!**

Signal & Background Signatures

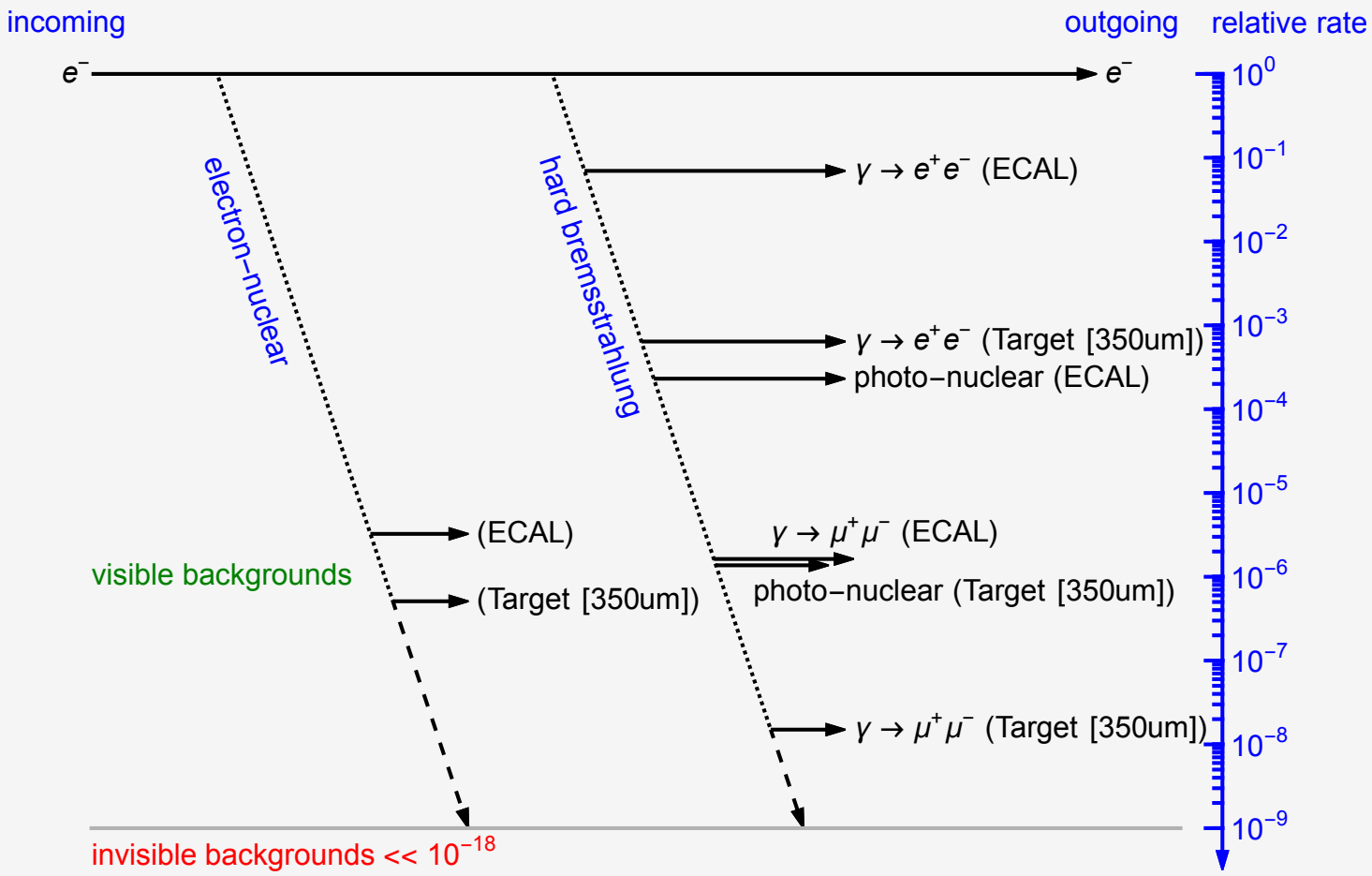




- Electron energy: 8 GeV, $\mathbf{3\times10^{14}}$ EOT per year (expected)
- Most of the incident momentum is transferred to A'.
- **Key signatures:** soft recoil electron, large missing energy & p_T.

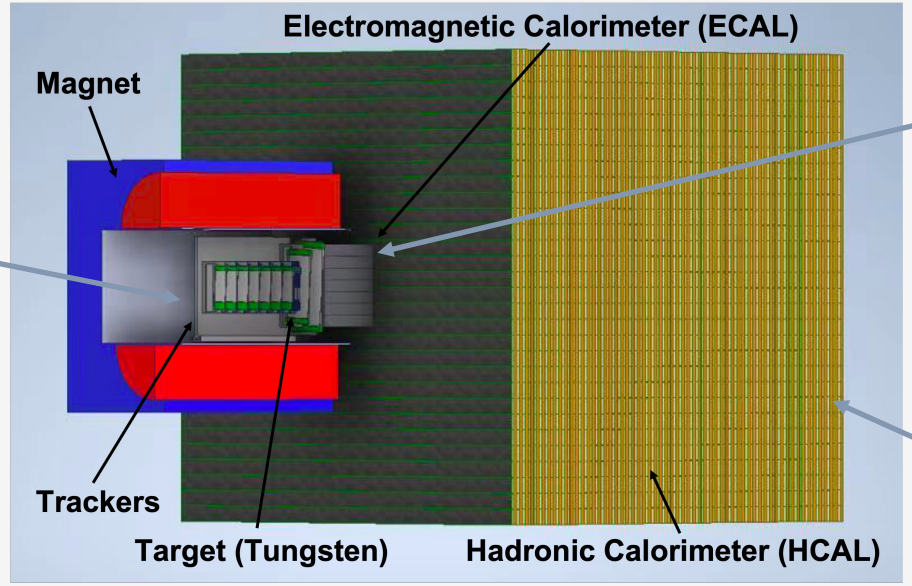
Standard Model Backgrounds

- **Leading Background:**
  - Hard Bremsstrahlung
- **Rare SM processes:**
  - Photonuclear *(w. hard-brem γ)*
  - Electronuclear
  - $\gamma \rightarrow \mu\mu$ *(w. hard-brem γ)*
- **Invisible Background:**
  - $eN \rightarrow e\nu\bar{\nu}N$ (trident process)
  - Moller/Brem + CCQE



Detector Conceptual Design

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



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.

DarkSHINE Event Display

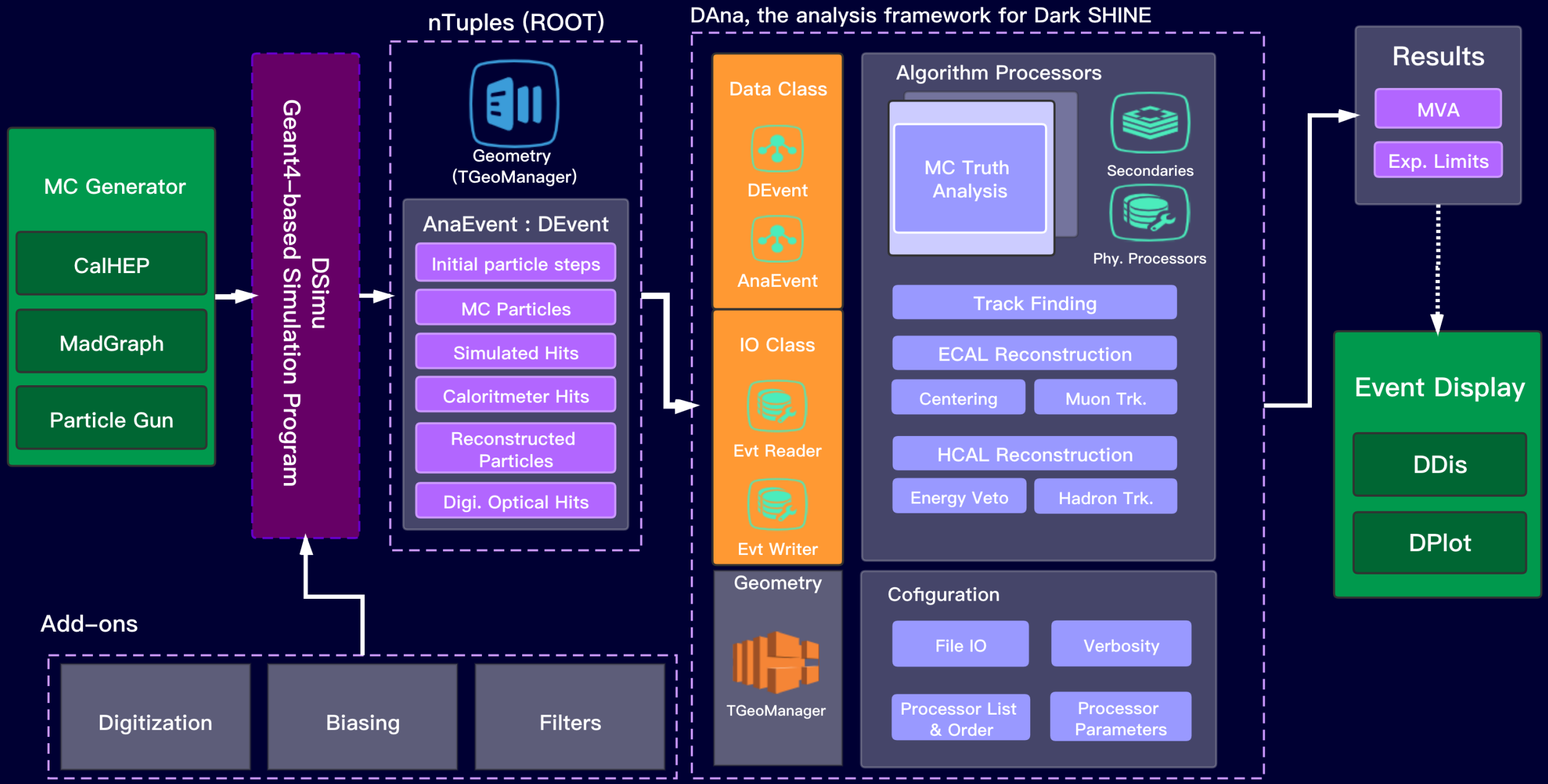
Software Framework

DSS: DarkSHINE Software

What is DarkSHINE Software

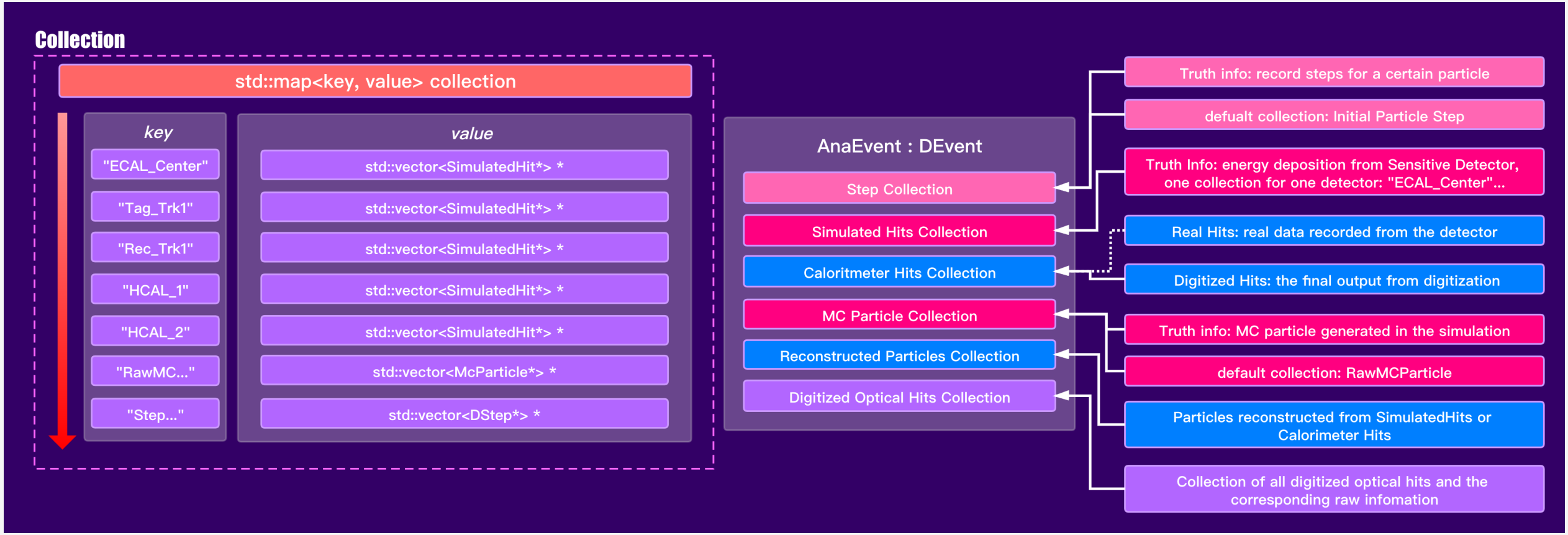
DarkSHINE Software is a software package, including five parts: **DSimu**, **DAna**, **DDis,** and **DPlot**.

- **DSimu** is the simulation program based on Geant4, characterized by Dark SHINE detector, controlled by yaml configuration.
- **DAna** is a *framework for the analysis and reconstruction tools*. It requires the output ROOT file (involving Geometry, DMagnet and DEvent) from **DSimu**.
- **DDis** is the event display for DSS. (requires Geometry and DEvent)
- **DPlot** is a quick plotting program for newbies and lazy man.
- **DEvent** is the *generic data structure* in DSS.


nTuples (ROOT)
DAna, the analysis framework for Dark SHINE
MC Generator
CalHEP
MadGraph
Particle Gun
DSimu
Geant4-based Simulation Program
Geometry
(TGeoManager)
AnaEvent : DEvent
Initial particle steps
MC Particles
Simulated Hits
Caloritmeter Hits
Reconstructed Particles
Digi. Optical Hits
Data Class
DEvent
AnaEvent
IO Class
Evt Reader
Evt Writer
Geometry
TGeoManager
Algorithm Processors
MC Truth Analysis
Secondaries
Phy. Processors
Track Finding
ECAL Reconstruction
Centering
Muon Trk.
HCAL Reconstruction
Energy Veto
Hadron Trk.
Cofiguration
File IO
Verbosity
Processor List & Order
Processor Parameters
Results
MVA
Exp. Limits
Event Display
DDis
DPlot
Add-ons
Digitization
Biasing
Filters

DEvent

- Customized event data structure based on ROOT
- Optimized data structure & memory (*Memory alignment technique*: 60.1 KB/event → 13.7 KB/event)

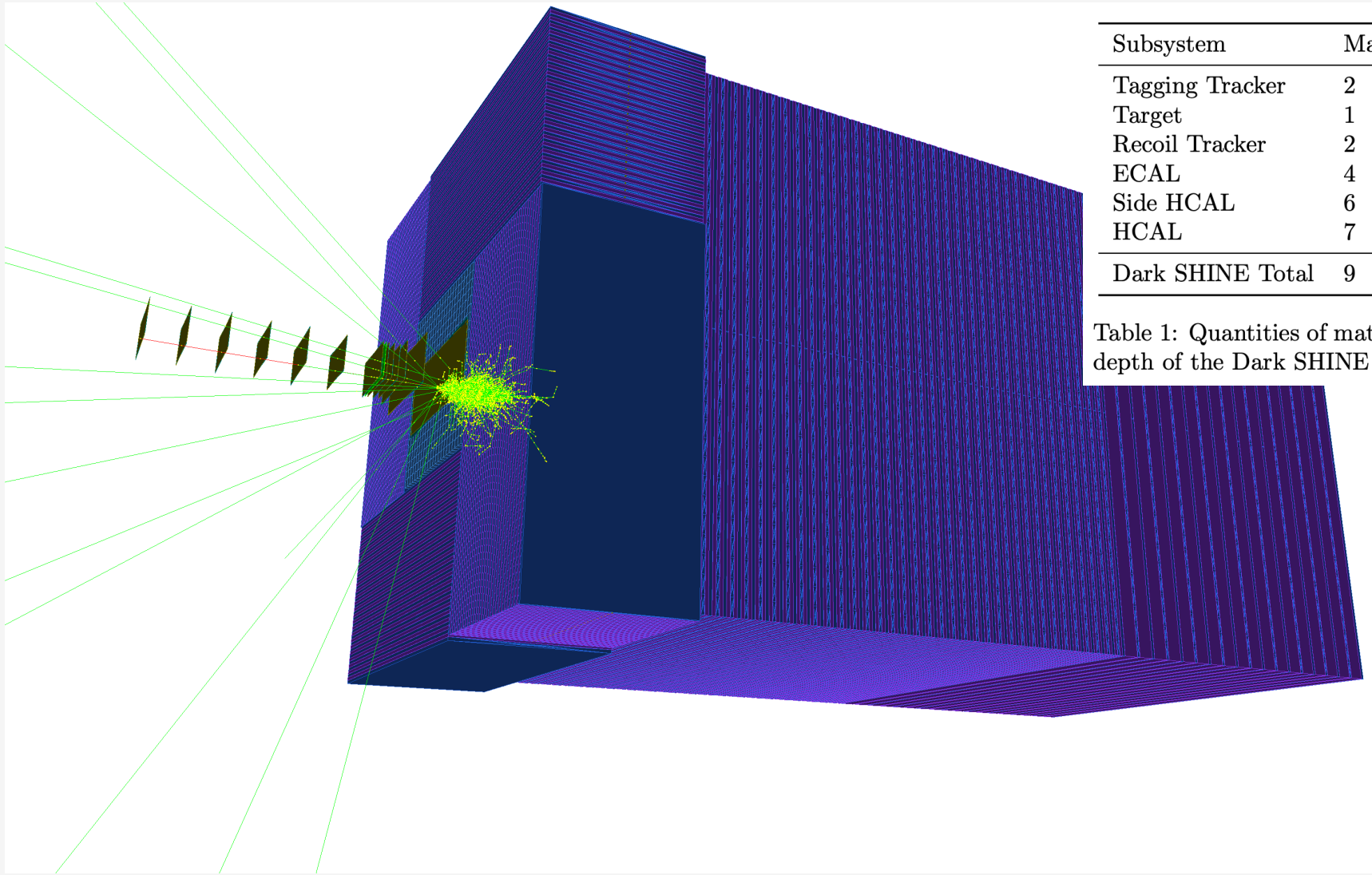


DSimu

- Independently developed based on Geant4 with C++17 standard.
- Key Features:
  - **Multi-Threading supported**
  - **BSM signal process simulation**: integrated with MadGraph/CalHEP (Look-up table)
  - **Rare SM processes simulation**: Biasing technique for certain particle in certain logical volume
  - **Truth Filter**: filtering events of interest based on truth information on-the-fly
  - **Flexible Detector Construction**:
    - Parameterized placement
    - Imported from GDML
    - Build from configuration file
  - **Bounding Volume Hierarchy**
  - **DMagnet**: Non-uniform magnetic field (*imported from Mathematica*)
  - **Full Optical Physics Simulation**

Credit: Xvliang ZHU

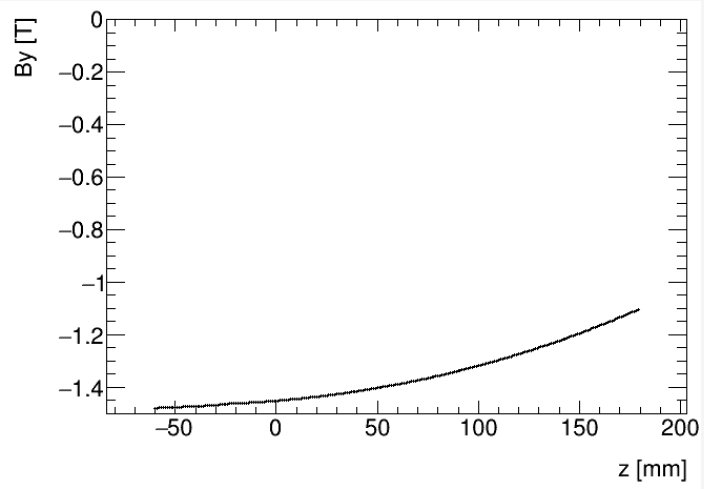
Detector Construction Overview

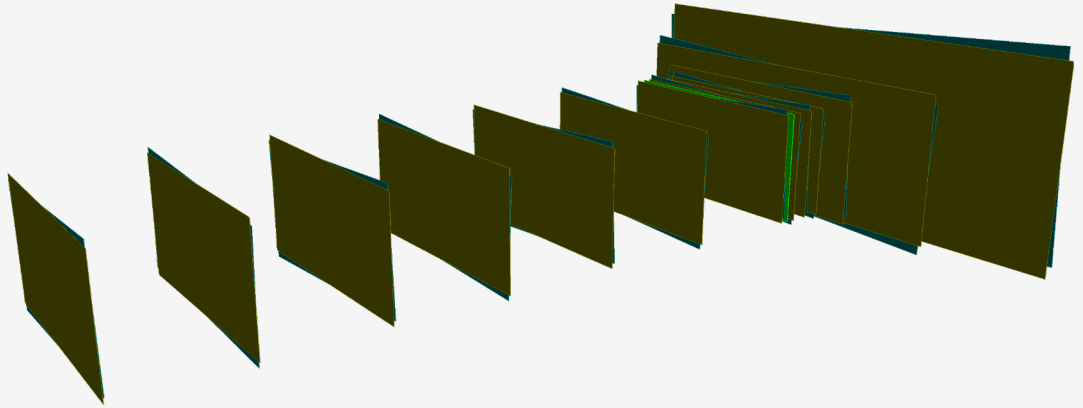


Subsystem	Materials	Logical Vol.	Physical Vol.	Vol. Depth
Tagging Tracker	2	43	94753	3
Target	1	1	1	0
Recoil Tracker	2	37	114749	3
ECAL	4	5	14653	3
Side HCAL	6	31	624	2
HCAL	7	96	27234	4
Dark SHINE Total	9	214	252015	5

Table 1: Quantities of materials, logical volumes, physical volumes, and volume depth of the Dark SHINE detector in simulation.

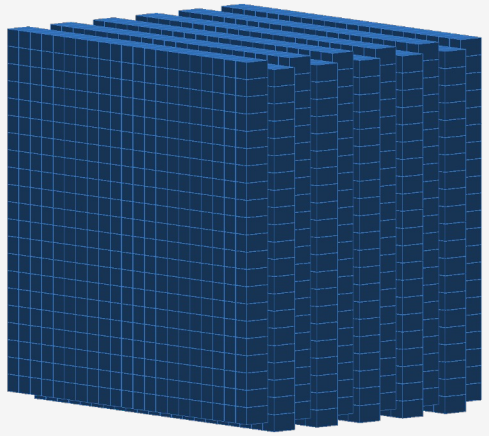
Tracker Region



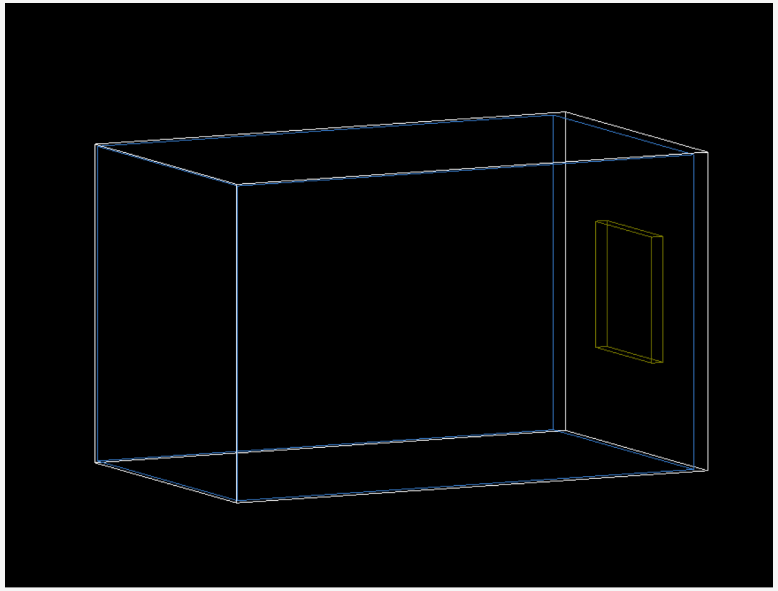


	Material	Region Material	Center z	Size	Layer Number	Strip distance	Strip Number	Angle
Target	W	Vacuum	0	20cm x 10 cm x 350 µm	1	-	-	-
Tagging Tracker	Si	Vacuum	-607.83 mm ~ -7.83 mm	20.1 cm x 10 cm x **150 µm**	7x2	30 µm	6700	±0.05 radian
Recoil Tracker	Si	Vacuum	7.73 mm ~ 180.23 mm	20.1 ~ 50.1 cm x 10 ~ 20 cm x **150 µm**	6x2	30 µm	6700 ~ 16700	±0.05 radian

Staggered ECAL Region

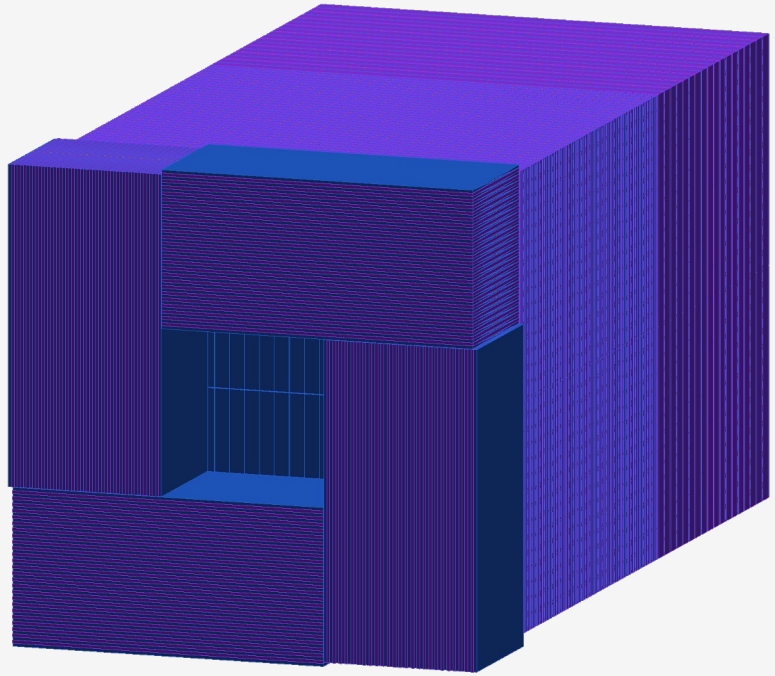


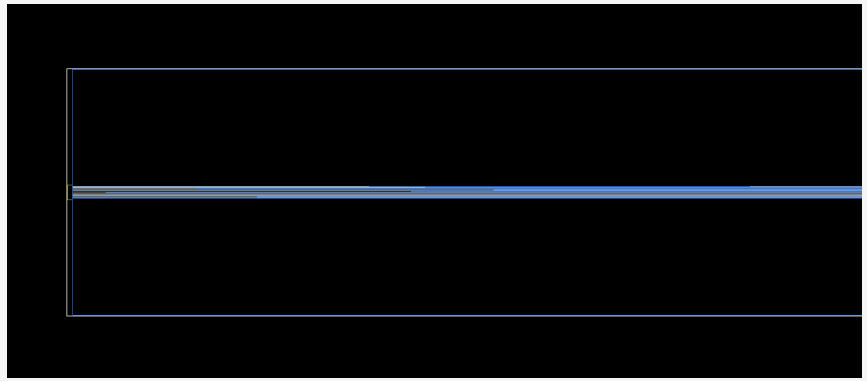
	Material	Region Material	Center z	Cell Size	Cell Number	Cell Gap
Wrapper	C	Carbon-Fiber	409.09 mm	2.53 cm x 2.53 cm x 4.13 cm	21 x 21 x 11	0.1 mm
APD	Si			1 cm x 1 cm x 0.1 cm		
ECAL Crystal	LYSO			2.5 cm x 2.5 cm X 4.0 cm		



HCAL Region

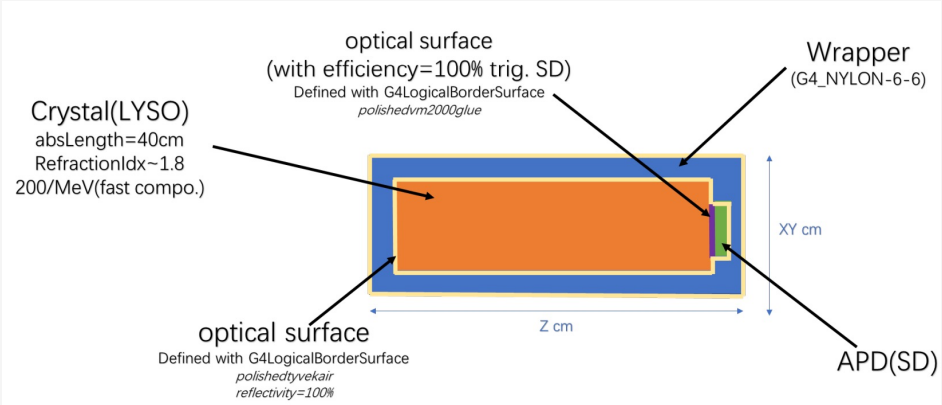
	Material	Region Material	Center z	Cell Size	Region Size	Module Gap
Wrapper	C	Carbon-Fiber	2703.1 mm	1.03 cm x 5.03 cm x 75.55 cm	~1.5 m x 1.5 m x 2.5 m	0.5 mm
APD	Si			3mm x 3mm x 1 mm		
HCAL Crystal	Polystyrene			1 cm x 5 cm x 75.42 cm		
SideHCAL Wrapper	C		409.085 mm	1.03 cm x 45.531 cm x 105.03 cm	~1.5 m x 1.5 m x 0.45 m	
SideHCAL Crystal	Polystyrene			1 cm x 45.511 cm x 105 cm		

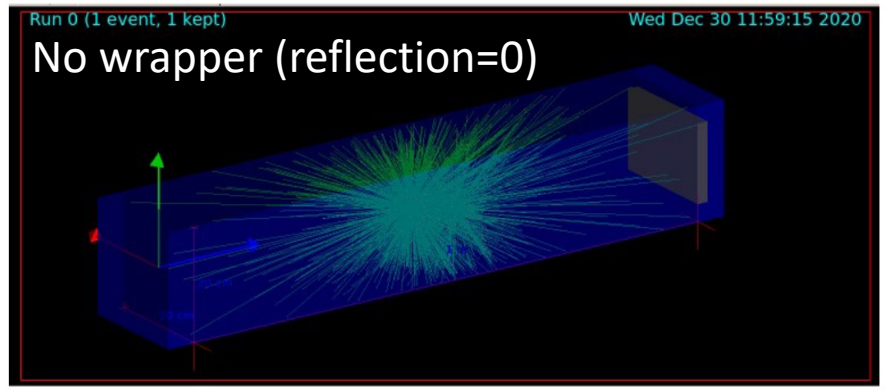




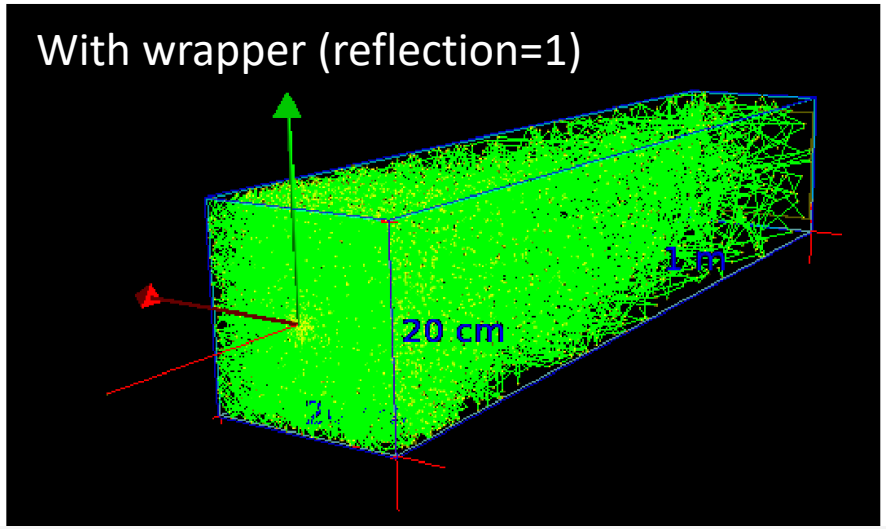
Optical Physics Simulation

- Optical simulation implemented in each single unit of ECAL
  - ✓ Realistic parameters set-up and cross-check with measurement and datasets, including:
  - ➢ Crystal optical property (light yield, decay length, decay time)
  - ➢ SiPM digitization (dynamic range, noise)
  - ➢ Wrapper (reflection)
  - ➢ Optical grease (transparency)
- Parametrization method applied in full simulation
  - Smearing & Calibration effect implemented with parameters extracted from optical simulation
  - Generally compatible with full optical simulation → **much faster**!





- Demonstration only.
- Actual reflection set in simulation according to manufacturer (~0.98)



Credit: Qibin LIU

Bounding Volume Hierarchy

- Detector Volumes are manually grouped as small sets and enclosed within larger bounding Volumes.
- Resulting in more efficient G4 Step Transportation.

General simulation speed ×6

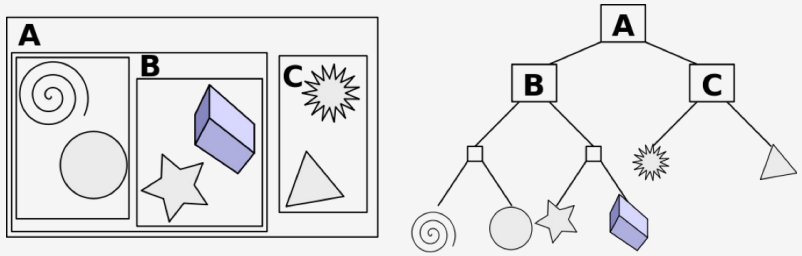
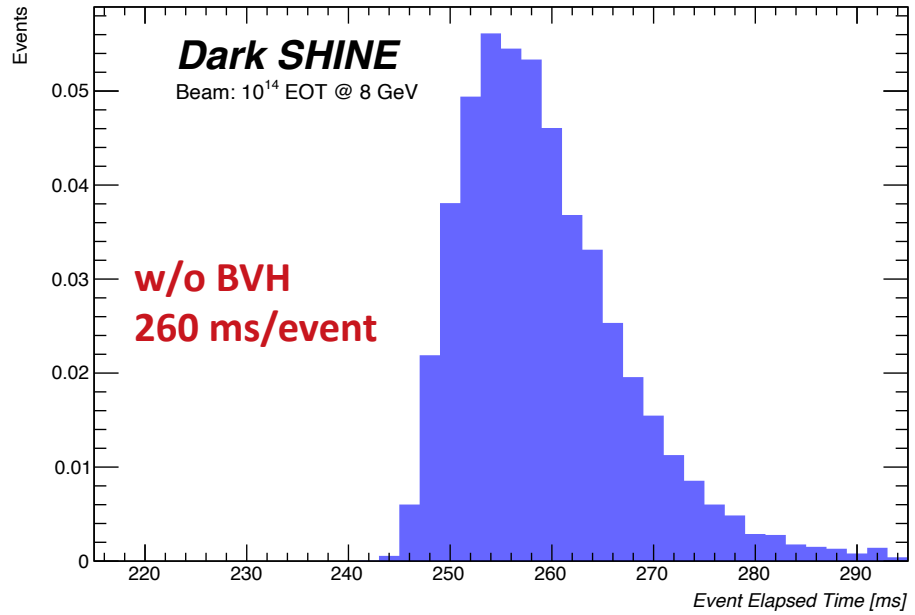
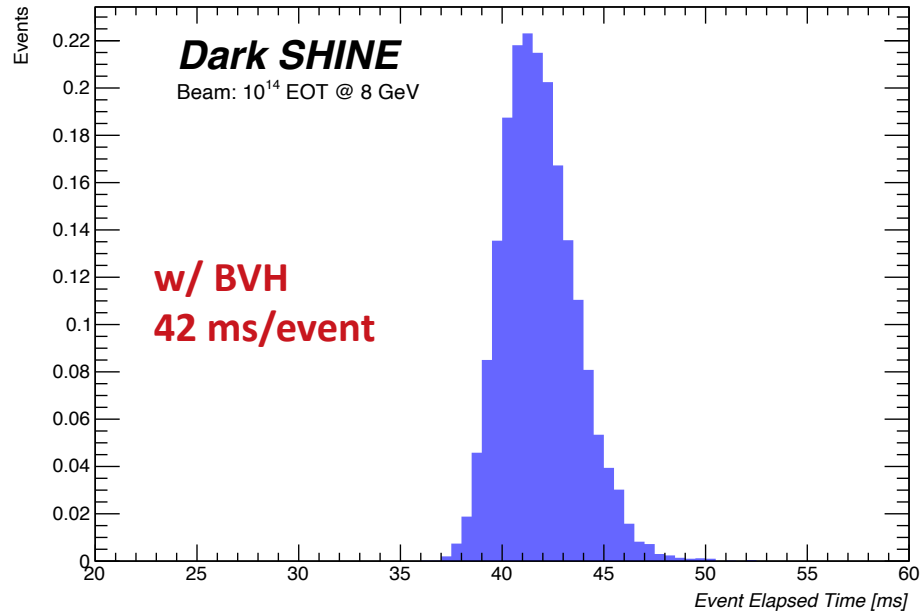
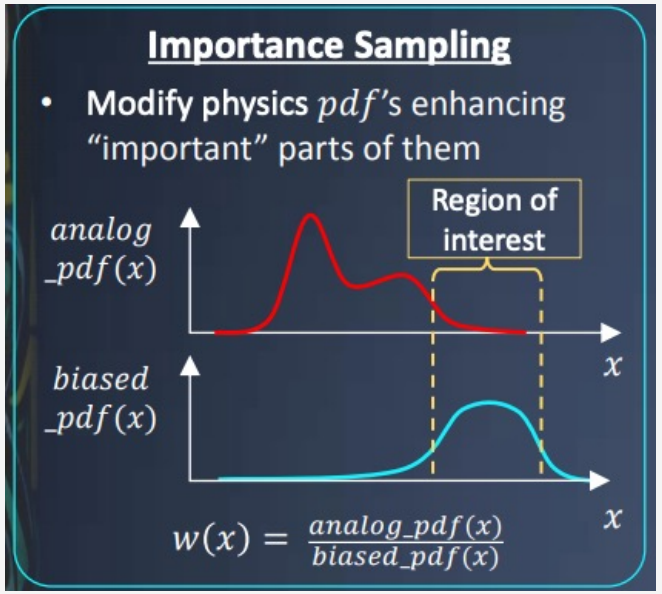


Figure: An Illustration of the tree structure of bounding volume hierarchy (cite: wiki)

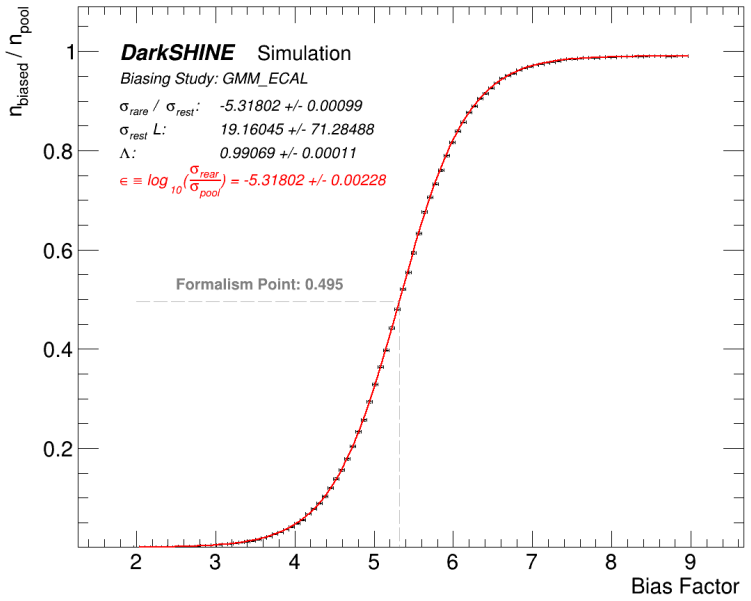


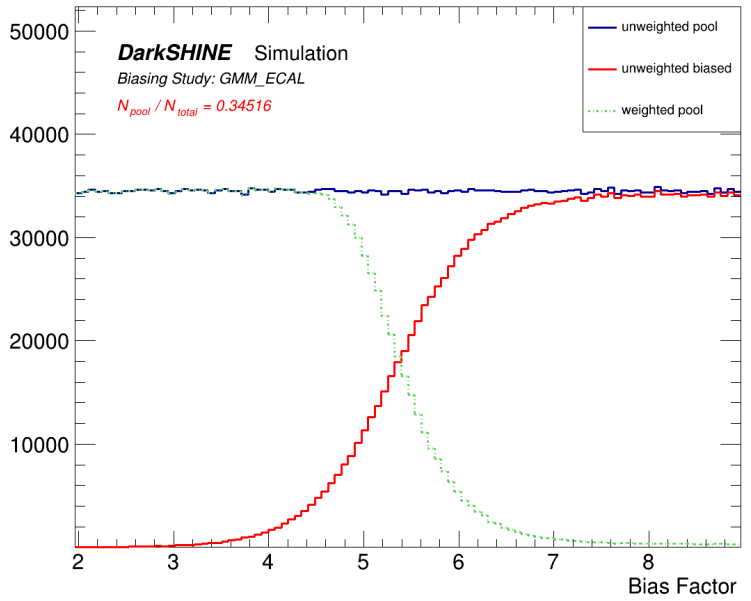


Event Biasing



- Rare SM processes Biasing:
  - Through importance sampling to increase cross-section for a given process in the region of interest.
  - Apply a bias factor to certain process to reduce the interaction length.





- σ_{biased} : cross-section of biased events
- σ_{pool} : cross-section of interested events
- ϵ : analog ratio between biased and interested events
- Formalism point : ratio corresponded to the ϵ

rel. to inclusive: 2.35×10^{-8}

Truth Filter

General Event Filter → General simulation speed $\times 15$

- Using Stepping Action and Stacking Action
- **Veto_ECAL**: **Abort** event immediately when truth ECAL deposit energy > 4 GeV
- **Veto_missP**: **Abort** event immediately when incident particle reach ECAL surface with truth $\Delta E < 4\ \mathrm{GeV}$

Customized Event Filter

- Abort event if no particle/ process of interests is generated within certain energy interval or detector volume
- Filter on primary particle (for hard-brem γ)
- Filter on secondary particle (for rare processes from hard-brem γ)
- Together with event biasing → rare process simulation

Sample Production

🏆 **Target EOT: 10^{14}**

Name	Process Branching Ratio	Biasing Factor	Filter Efficiency	Equivalent Event Number	Beam On Number	Estimate Time [16000 core hour]	Time per Event [ms]
Inclusive	1.00E+00	1E+00	100%	-	-	-	79.19
Inclusive w/ ECAL trigger	1.00E+00	1E+00	100%	**1E+11**	1.00E+11	**66.620**	38.37
Inclusive w/ ECAL+missP trigger	1.00E+00	1E+00	100%	**1E+12**	1.00E+12	**90.592**	5.22
GMM Target (with hardbrem) w/ ECAL+missP trigger	1.50E-08	1E+08	6.557%	🏆 **1E+14**	1.53E+07	**0.001**	3.17
GMM ECAL (with hardbrem) w/ ECAL+missP trigger	1.63E-06	1E+07	16.333%	🏆 **1E+14**	6.12E+07	**0.005**	4.47
PN Target (with hardbrem) w/ ECAL+missP trigger	1.37E-06	1E+06	6.466%	🏆 **1E+14**	1.55E+09	**0.128**	4.75
PN ECAL (with hardbrem) w/ ECAL+missP trigger	2.31E-04	1E+05	16.446%	🏆 **1E+14**	6.08E+09	**0.737**	6.98
EN Target (E > 4GeV) w/ ECAL+missP trigger	5.10E-07	1E+05	1.47%	🏆 **1E+14**	6.08E+10	**1.646**	1.39
EN ECAL (E > 4GeV) w/ ECAL+missP trigger	3.25E-06	1E+05	0.56%	🏆 **1E+14**	1.79E+11	**1.025**	0.33

Multi-Threading for DSimu (MTDSimu)

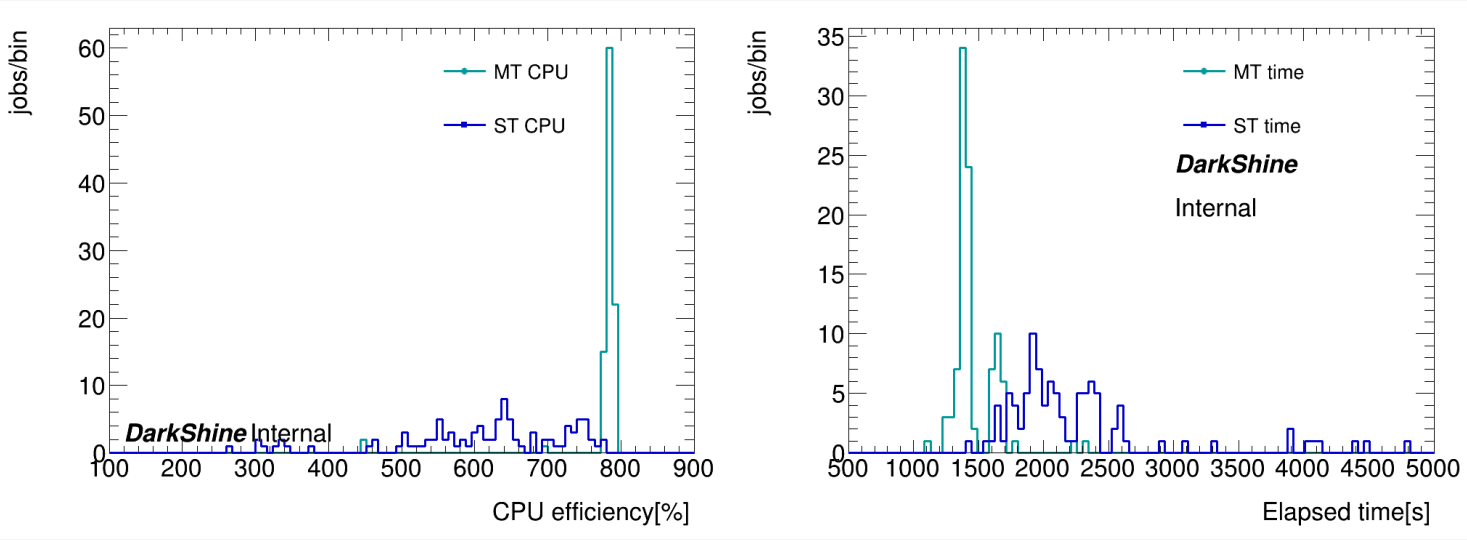
- Based on Geant4 Multi-Thread functionality (G4RunManager → G4MTRunManager)
  - Allocator/Singleton → ThreadLocal
  - Physics List, Random Number, Primary Generation Action
- Test 10^6 events based on single-thread and multi-thread

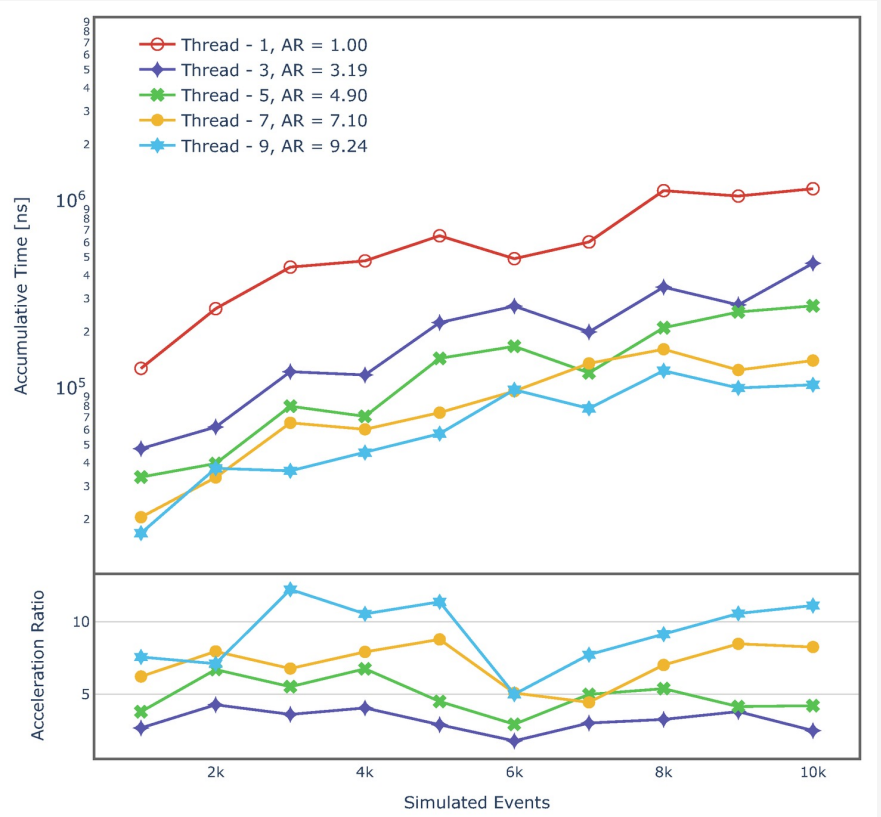
Time/Memory Validation

✅ Inclusive Process Validation

❑ Rare Process Validation

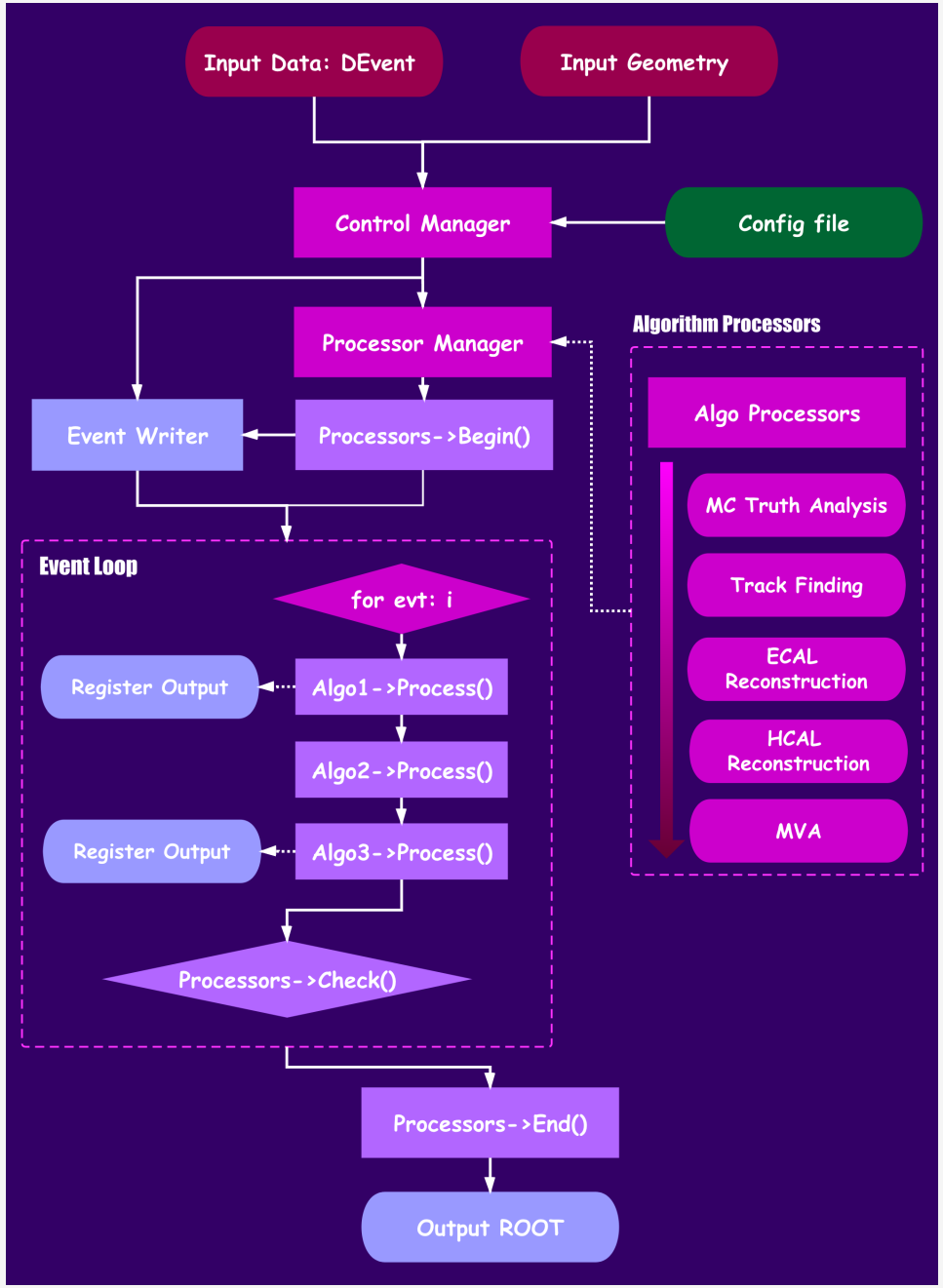
Type	Total elapsed time [s]	CPU Usage	Money [¥]
8 threads, 1 job	15328	785%	1.7
1 thread, 8 jobs	16648	646%	1.85





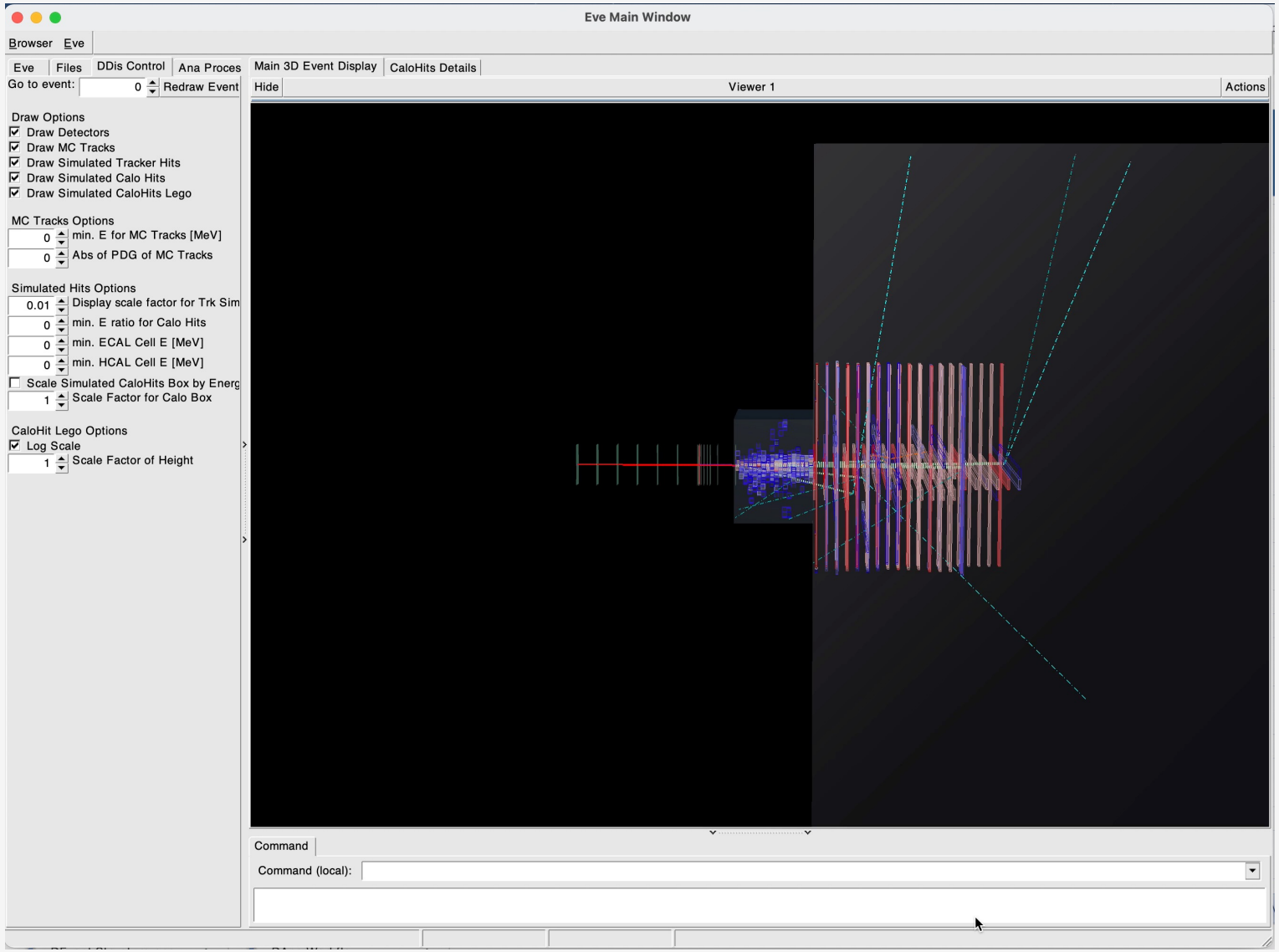
DAna

- Reconstruction and Analysis Framework for DarkSHINE Software
- Algorithm Processors:
  - Called subsequently
  - Analyzed data can be shared within the event
- Featured processors:
  - MC Truth Analysis
  - Digitizer
  - Track Reconstruction
  - ECAL Reconstruction
  - HCAL Reconstruction
  - Data Exporter for Machine Learning
  - *Neural network integration (work in progress)*
    - *"Application of Graph Neural Networks in Dark Photon Search with Visible Decays at Future Beam Dump Experiment". Springer Nature (CCIS, EI), 2023*
  - *ACTS integration (work in progress)*



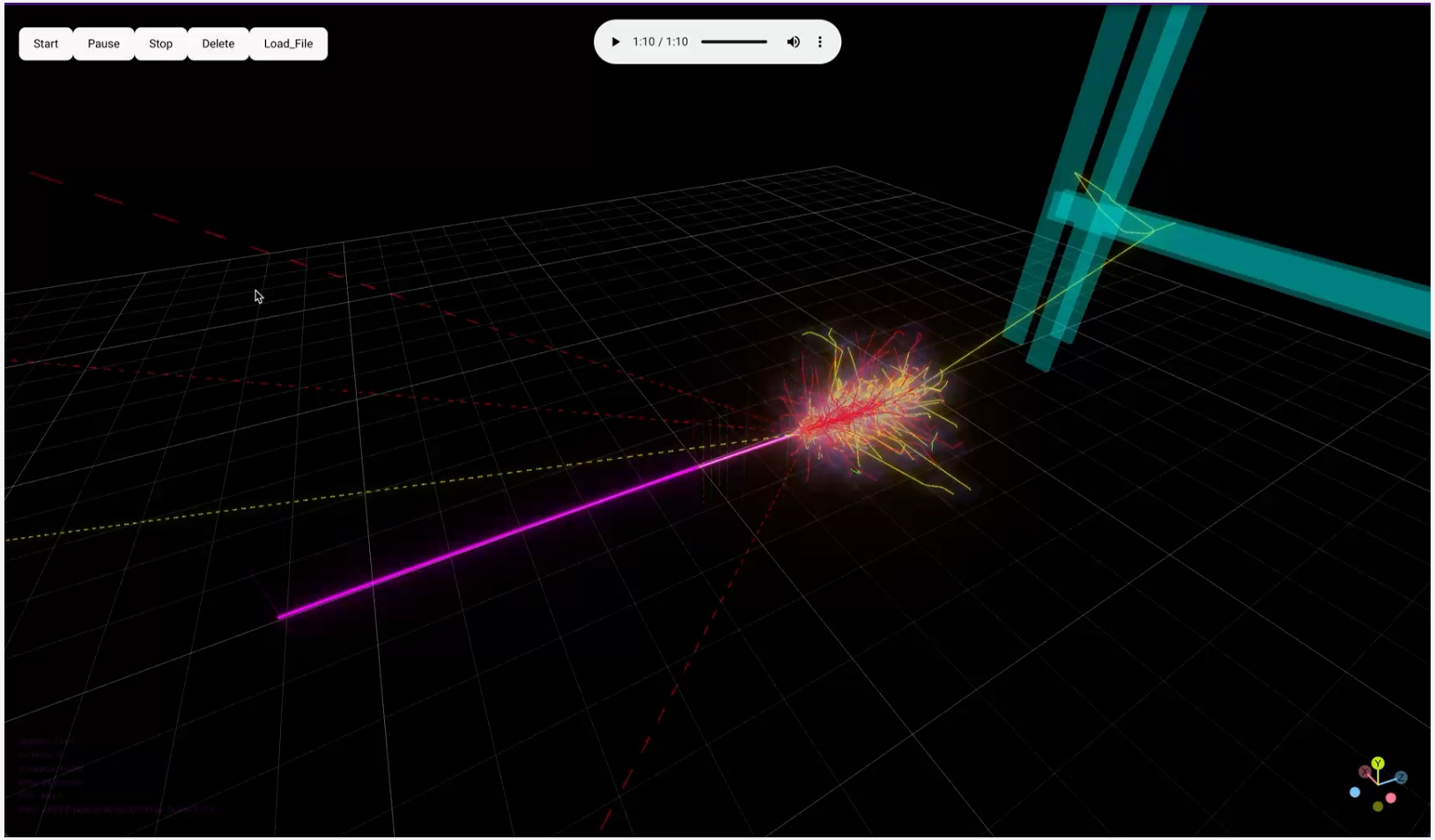
Event Display

- Event Display for DarkSHINE Software based on QT and ROOT
- Read Geometry and Event Collection from output of **DSimu**
- Draw event one by one
- Customized draw options
- Support online algorithm processors



Web-based Event Display

- New Event Display based on WEB
- Don’t need C++ & ROOT any more 😆
- Using three.js to render detector hits and MC particles



Summary

- DarkSHINE: a fixed-target experiment to search for light dark matter. First round of **preliminary study** has been finished:
  - Production: bremsstrahlung, $eZ \rightarrow eZA'$, with Invisible decay: $A' \rightarrow \chi\chi$.
  - Good signal efficiency, background well suppressed.
  - Expecting competitive sensitivity.
  - ➢ *"Prospective study of light dark matter search with a newly proposed DarkSHINE experiment". In: Sci. China Phys. Mech. Astron. 1 (2023), p. 211062. doi: 10.1007/s11433-022- 1983-8.*
- The DarkSHINE Software Framework integrates simulation, reconstruction, analysis, and event display functionalities.
- Fast Simulation in progress (both CPU-based and Machine-Learning based).

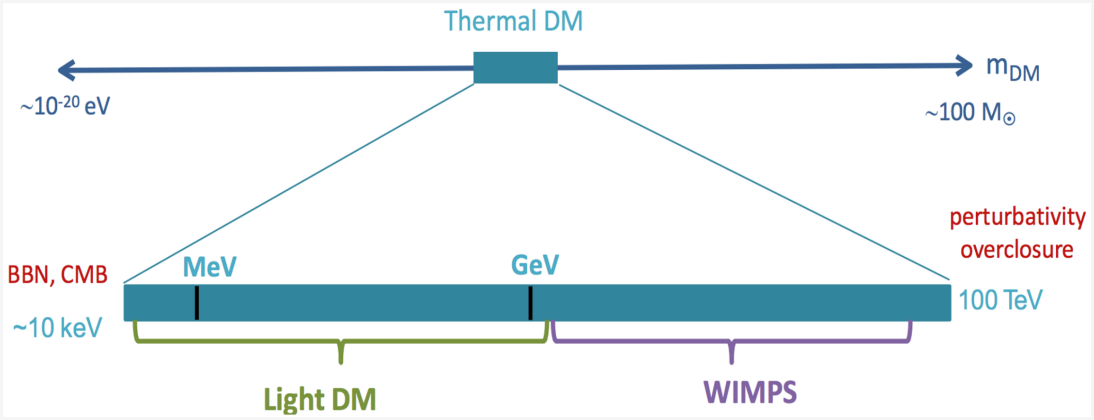
Thank you!

Backup

Dark Matter

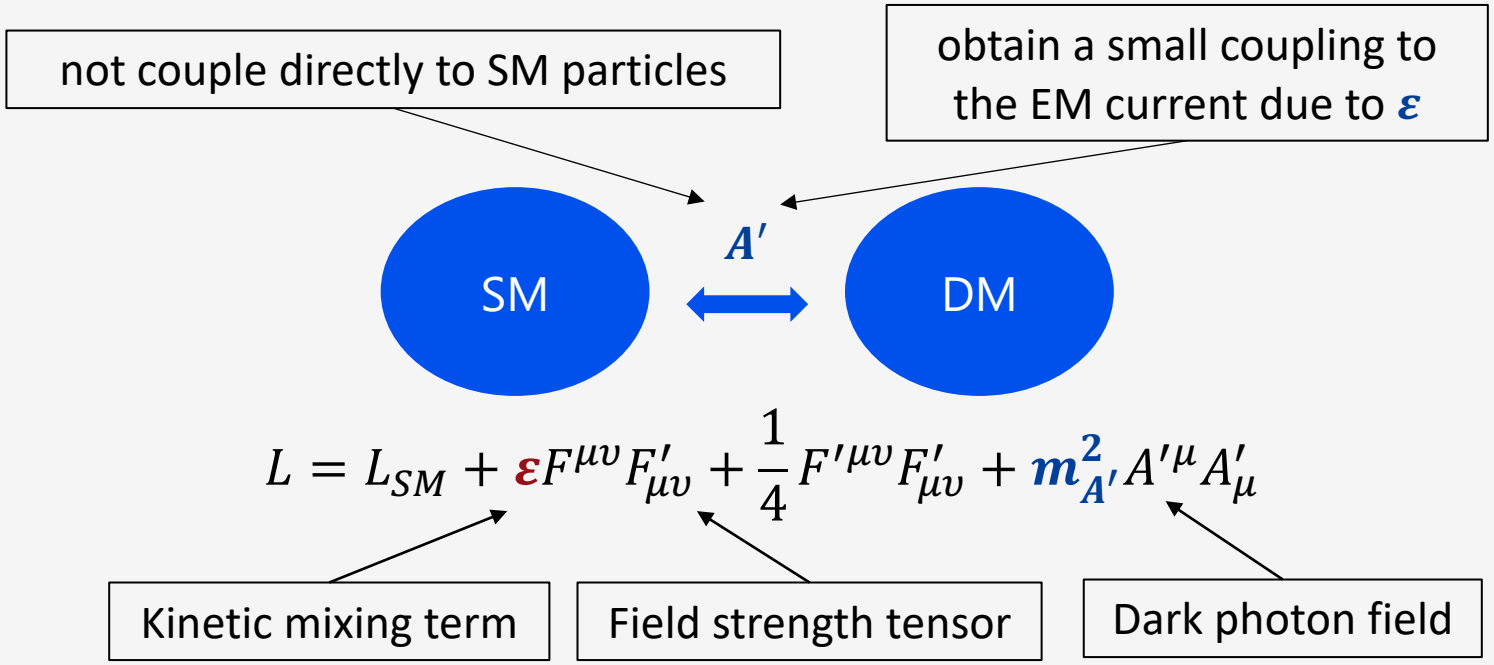
- Evidence from cosmology and astronomy showing that Dark Matter (DM) exists in the universe.
- Possible candidates of Dark Matter:
  - **Weakly Interacting Massive Particles (WIMP):** No evidence yet. A large parameter space ruled out in GeV~TeV mass range.
  - **Light DM (χ):** Sub-GeV mass range not fully explored yet.

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



Dark Photon Search

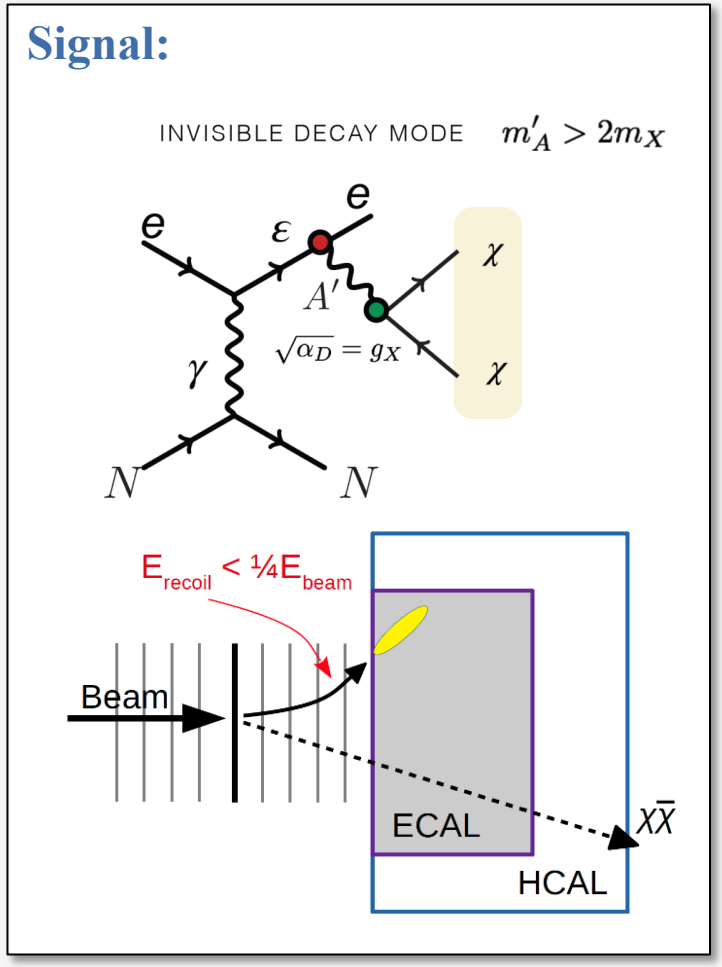
- Dark photon is an important portal between the standard model (SM) particles and the dark matter.

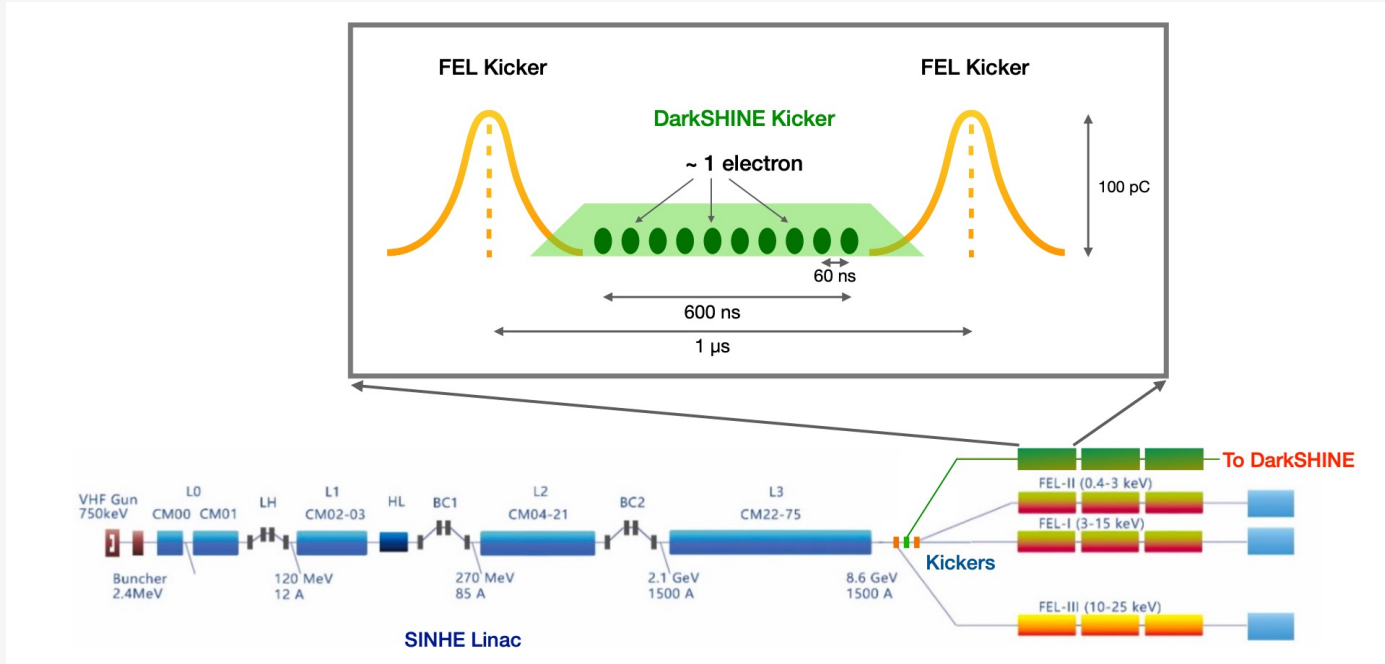


- DarkSHINE is an experiment based on the minimal dark-photon model with 3 unknown parameters:
- ε: kinetic mixing between the SM hypercharge and A' field strength tensors.
- $m_{A'}$: dark photon mass.
- Decay branching ratio of $A' \to \chi\chi$ (assumed to be 1 or 0)

arXiv:2104.10280

Dark Photon Search @ SHINE

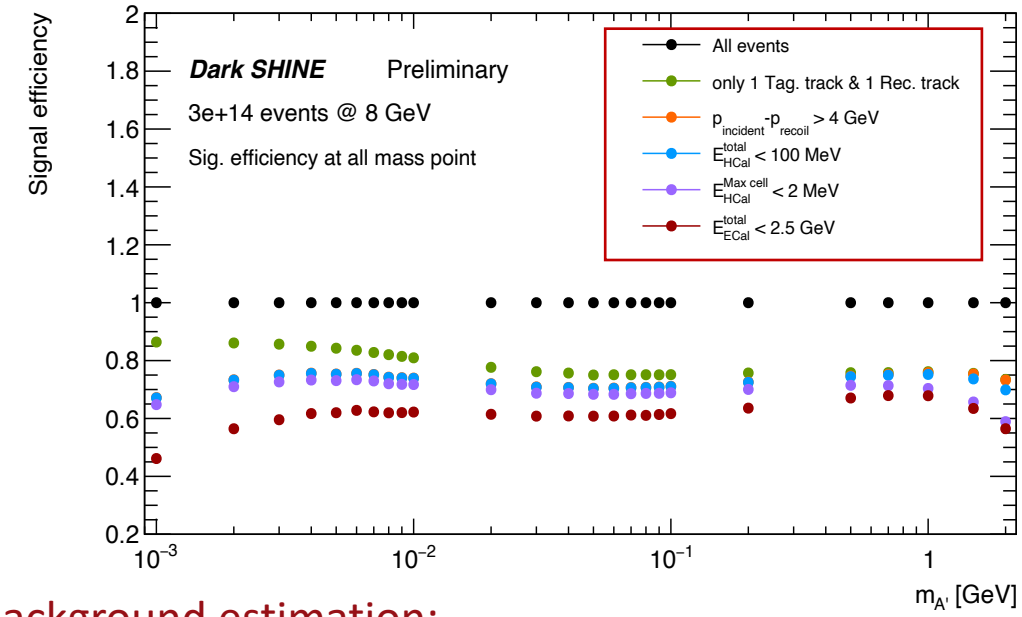




- A proposed fixed-target experiment, using electron beam hitting on target to produce dark photon.
- The high frequency electron beam is provided by SHINE *(Shanghai High Repetition-Rate XFEL and Extreme Light Facility).*
- Electron energy: 8 GeV, $\mathbf{3\times10^{14}}$ EOT per year
- **Missing particle signature:** soft recoil electron, large missing energy & p_T.

Signal Efficiency & Background Estimation

Signal region selections



Efficiency drops:

- **Low-mass region** of a few MeV: tight missing P cuts.
- **High-mass region** above 1 GeV: particles with large incident/recoil angle go into the HCAL directly.
- Around 60% signal events survive the cut-flow.

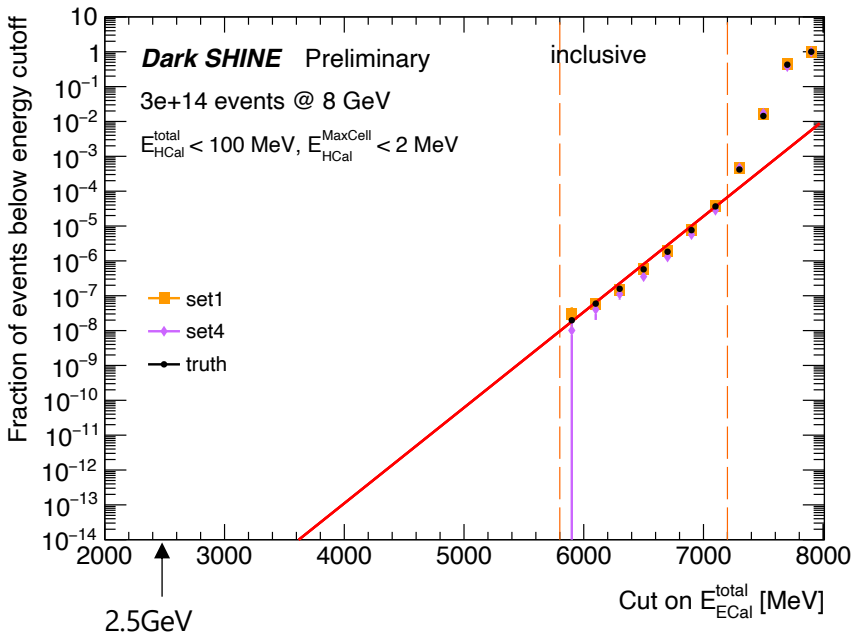
Background estimation:

Method	Cut flow	Rare. extra.	Incl.- extra.	Incl. vali.
Yield	0	1.5×10^{-2}	2.53×10^{-3}	9.23×10^{-3}

Extrapolate from rare processes simulation.

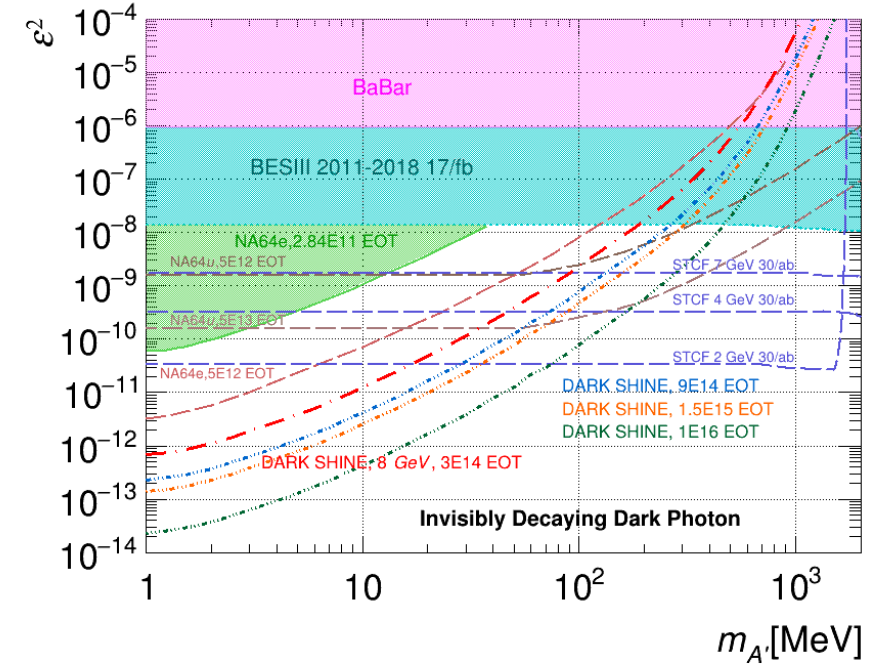
Extrapolate from inclusive background simulation.

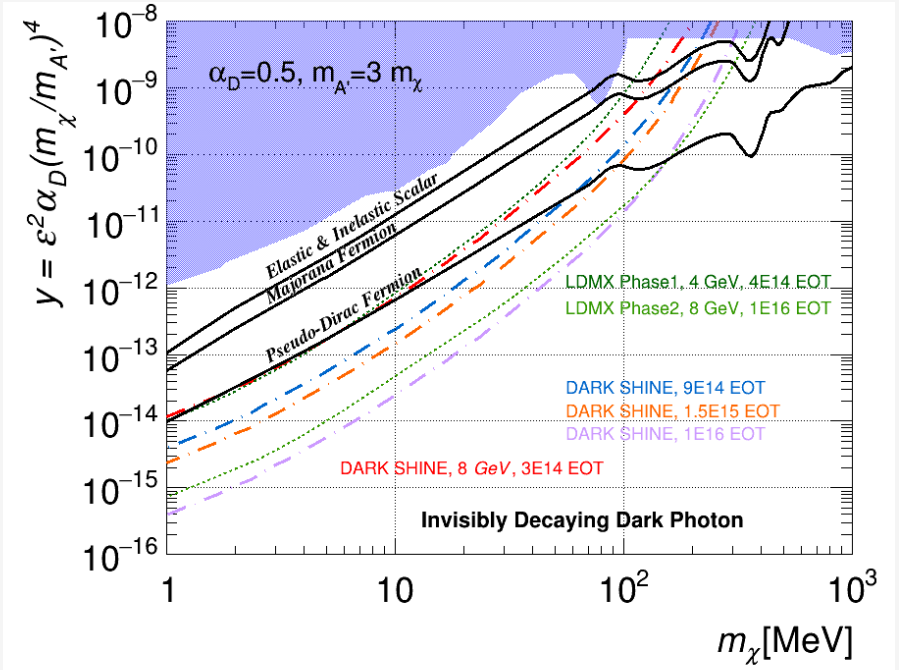
Validate Inclu.-extra: Scale low E_{beam} events to match the shoulder with $E_{beam} = 8$ GeV events.



Expected Sensitivity

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





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).

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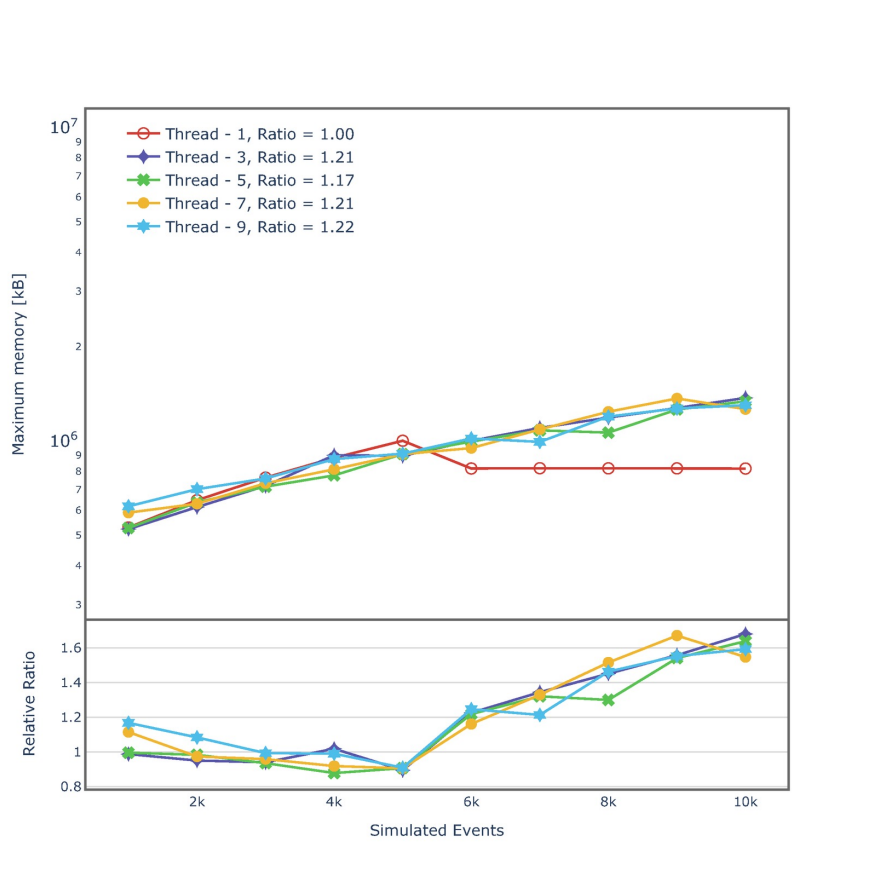
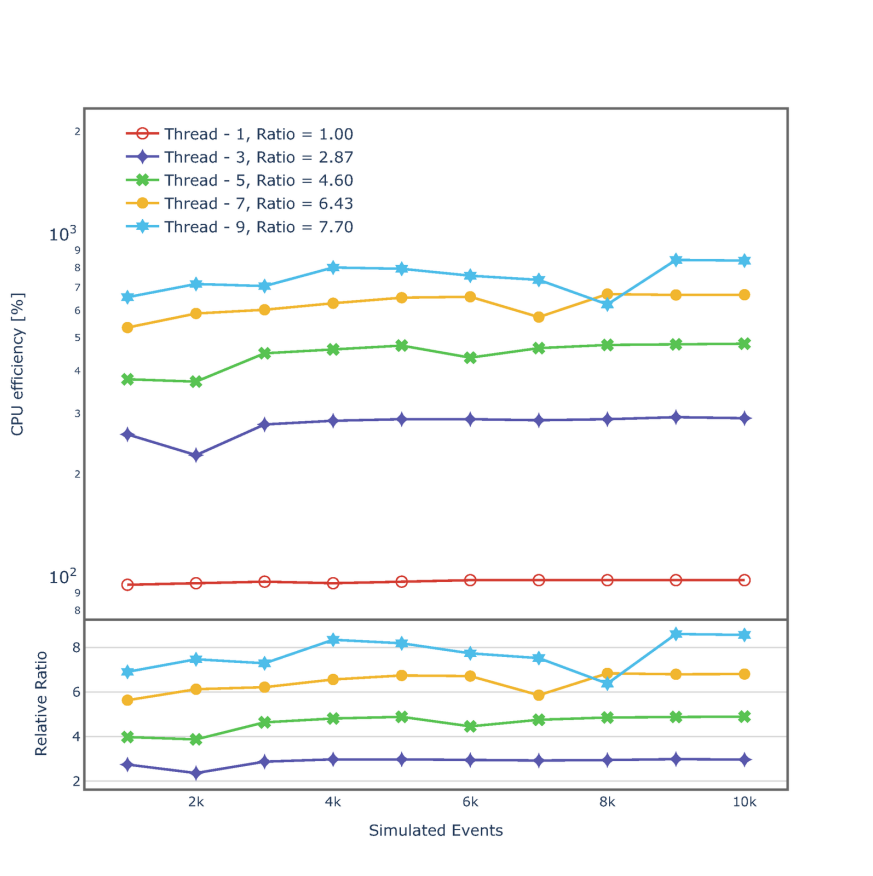

Thread - 1, Ratio = 1.00
Thread - 3, Ratio = 1.21
Thread - 5, Ratio = 1.17
Thread - 7, Ratio = 1.21
Thread - 9, Ratio = 1.22
Maximum memory [kB]
Relative Ratio
Simulated Events


Thread - 1, Ratio = 1.00
Thread - 3, Ratio = 2.87
Thread - 5, Ratio = 4.60
Thread - 7, Ratio = 6.43
Thread - 9, Ratio = 7.70
CPU efficiency [%]
Relative Ratio
Simulated Events