Tracking for Dark SHINE experiment

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On behalf of Dark SHINE R&D Team

Workshop of Tracking in Particle Physics Experiments

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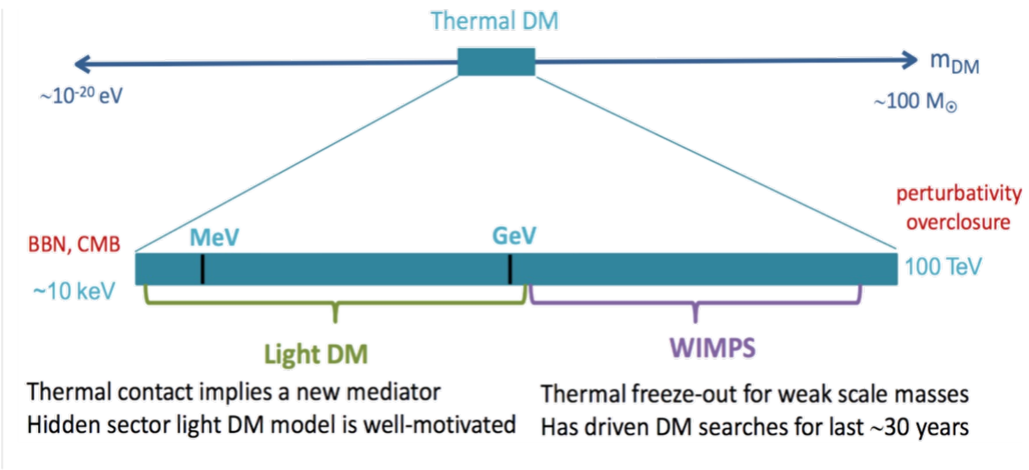
李政道研究所
Tsung-Dao Lee Institute

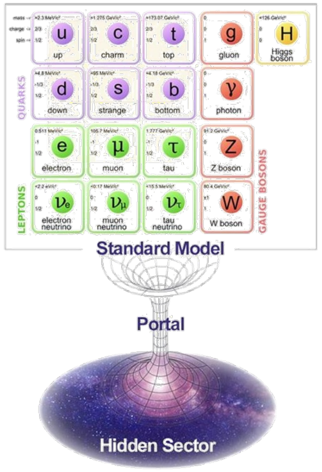
Outline

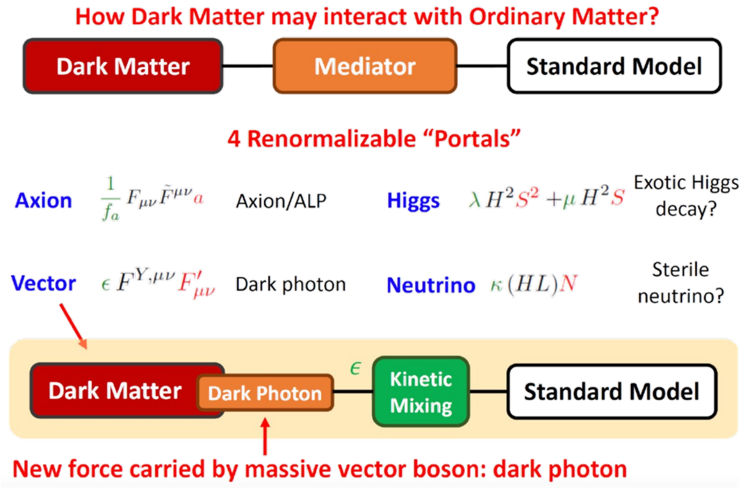
1. Overview & motivation for Dark SHINE experiment
2. Detector layout & design of Dark SHINE
3. Hardware design & performance for Dark SHINE trackers
4. Dark SHINE software & its track reconstruction
5. Track reconstruction in Dark SHINE using ACTS
6. Summary

Overview & motivation for Dark SHINE experiment

- Thermal Dark Matter (DM) originating as a relic of the hot early universe is one of the most compelling paradigms.
  - Temperature drops due to the over-expansion of the universe -> DM density becomes stable (“freeze-out” mechanism).
- Dark photons is a good candidate of vector massive boson.





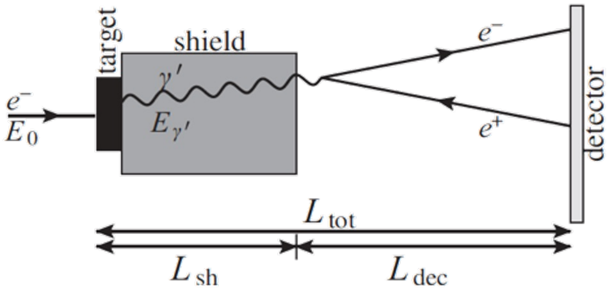


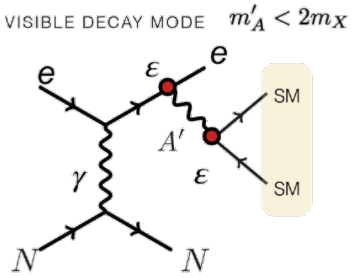
Overview & motivation for Dark SHINE experiment

- Dark photon can be produced in eN interaction (electron-on-target)
- Two ways of detection, via its:
  - Visible decay:

    2 interaction vertices -> production rate is suppressed.

    $N \sim \varepsilon^4$

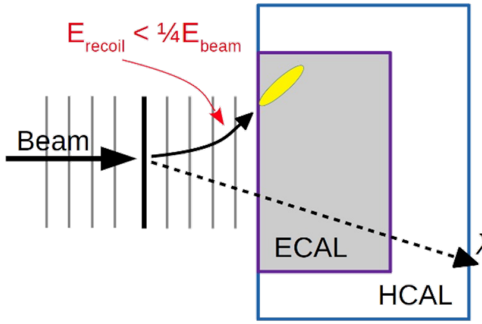


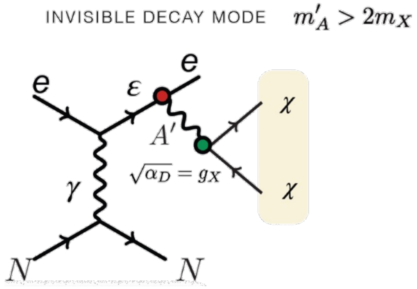


  - Invisible decay:

    Better sensitivity due to higher production rate.

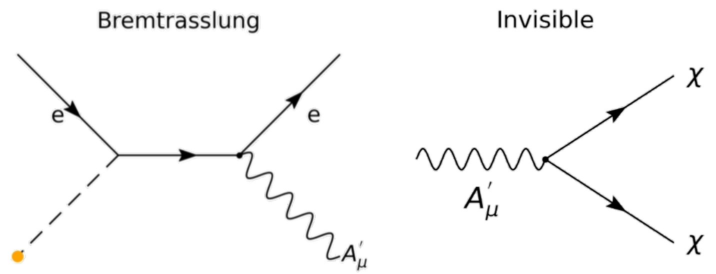
    $N \sim \varepsilon^2 (1- \varepsilon^2)$

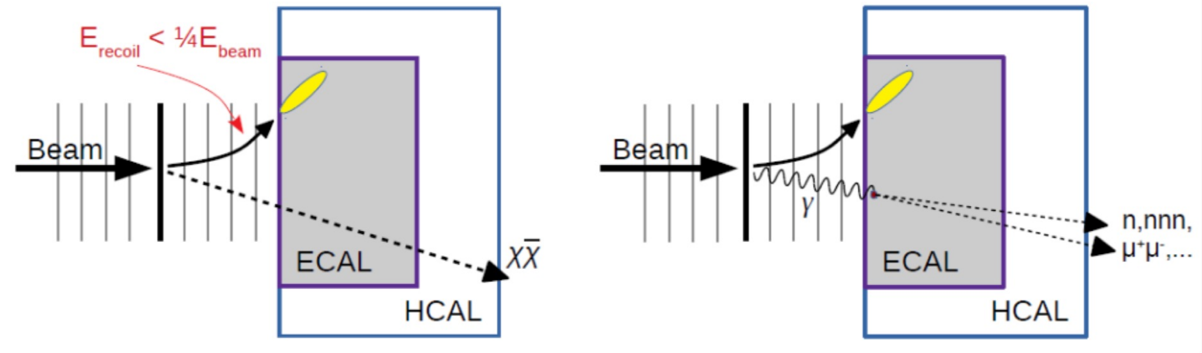


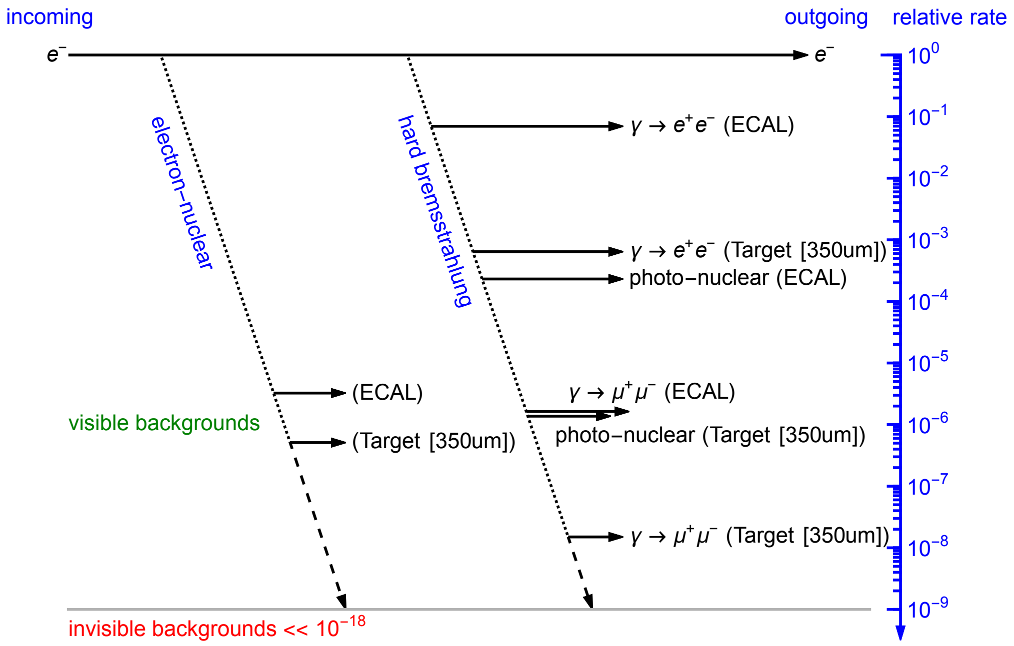


Overview & motivation for Dark SHINE experiment

- Invisible decay's signal signature:
  - soft recoil electron,
  - large missing energy & p_T
- Leading background: bremsstrahlung photons

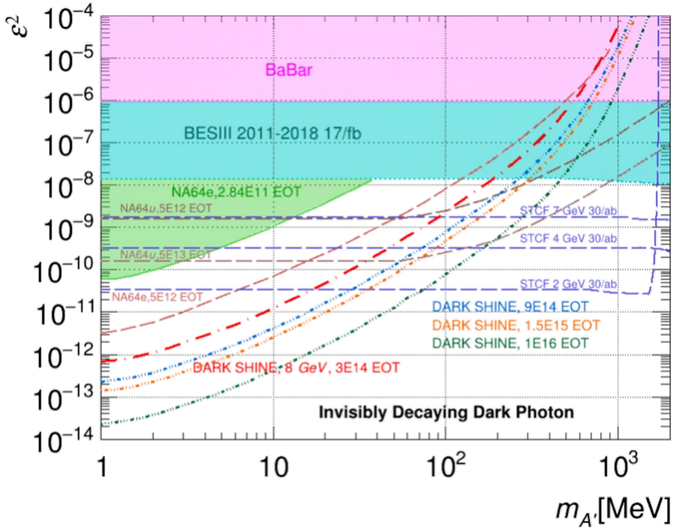


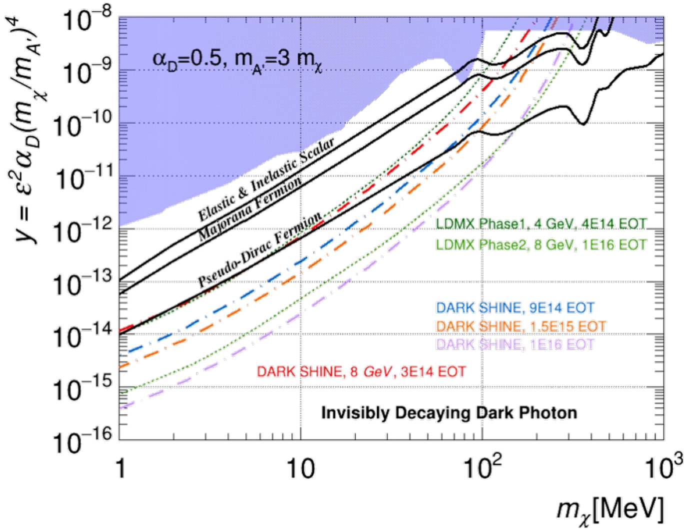




Overview & motivation for Dark SHINE experiment

- Expect a competitive projected sensitivity:
  - 90% C.L. limits are extracted on the ε^2 (kinetic mixing parameter) as a function of dark photon mass.
  - Expected to exclude the most sensitive regions from some popular LDM models with >1 yr run.



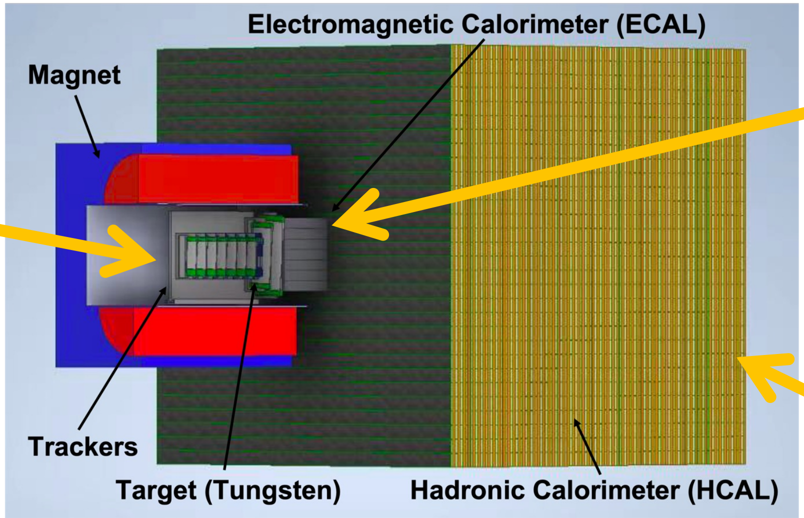


Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)

Detector layout & design of Dark SHINE

- 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.
Designed resolution:
horizontal $\sigma_{exp} < 10$ μm
vertical $\sigma_{exp} < 60$ μm
momenta $\sigma_{exp} < 1\%$



DarkSHINE detector sketch

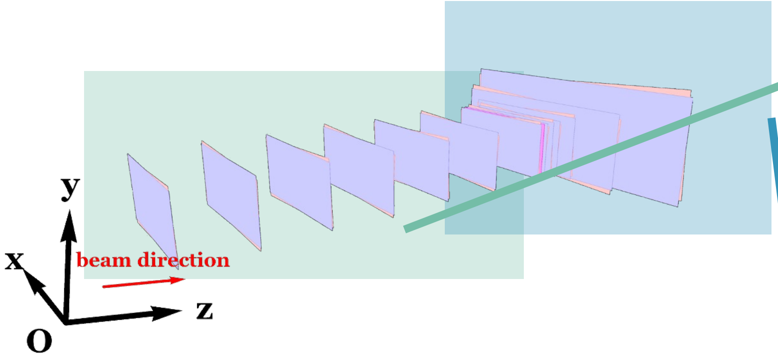
Electromagnetic calorimeter:
Measure the deposited energy: electron and photon.

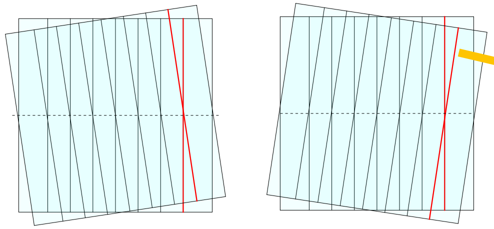
Hadronic calorimeter:
Measure the deposited energy: muon and hadron backgrounds.

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

Detector layout & design of Dark SHINE

- Designed tracking system layout:

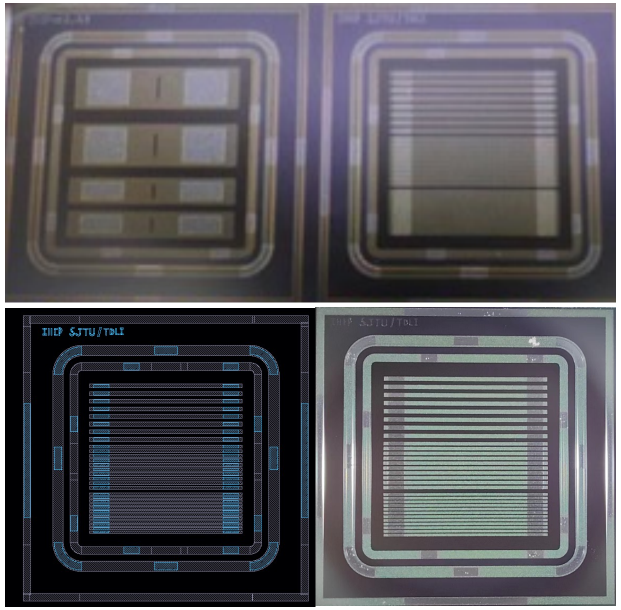


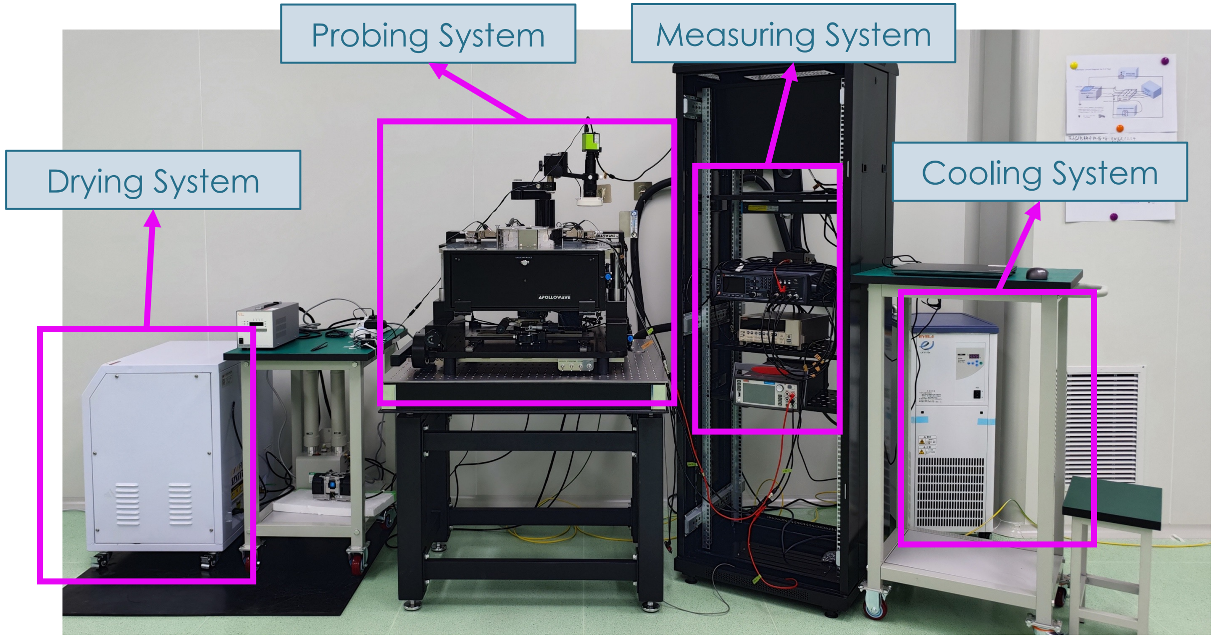


Tagging Tracker							
Z location [mm]	-607.755	-507.755	-407.755	-307.755	-207.755	-107.755	-7.755
X width [mm]	201 mm						
Y width [mm]	100 mm						
# of strips	6700 (width 30um)						
rot angle [rad]	0.05	-0.05	0.05	-0.05	0.05	-0.05	0.05
thickness	150 um						

Recoil Tracker						
Z location [mm]	7.905	22.905	38.905	53.905	89.905	180.405
X width [mm]	201	201	201	240	360	501
Y width [mm]	100	100	100	115	140	200
# of strips	6700	6700	6700	8000	12000	16700
rot angle [rad]	-0.05	0.05	-0.05	0.05	-0.05	0.05
thickness	150 um					

Hardware design & performance for Dark SHINE trackers





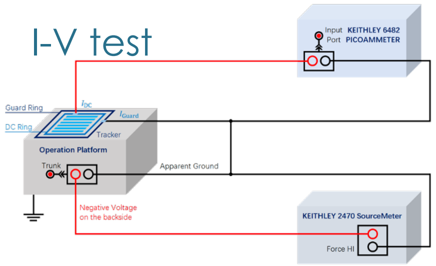
- **AC-LGAD** silicon strip sensor 1x1 mm^2 designed with different strip-pad periods.
- The design of AC-LGAD sensor was completed in collaboration with Prof. Zhijun LIANG and Prof. Mei ZHAO from IHEP. (arXiv: 2310.13926)

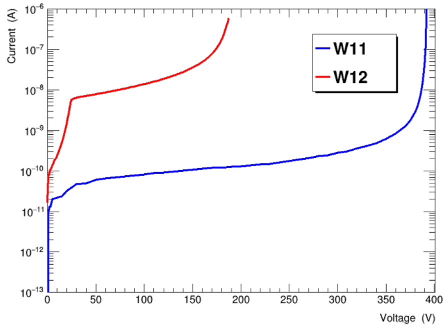
- High Precision Tracking Detector Experimental Platform @ TDLI.
- Probing system: connect the silicon sensor to test circuits (including the measuring system).
- Drying system and cooling system: a stable temperature and humidity environment for sensor testing.

Hardware design & performance for Dark SHINE trackers

- I-V test: To identify its **conductivity** and **leakage properties**.
- C-V test: focus on sensors' **junctions**, **doping concentration** and the **depletion width**.
- W11 & w12 refer to two different sensor wafers with different n+ doping levels (0.01P vs. 10P).

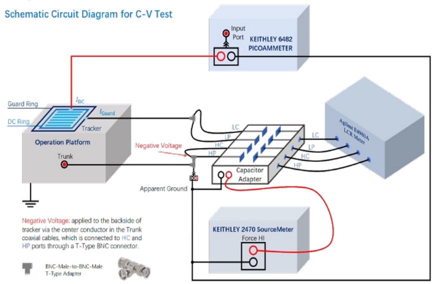
I-V test

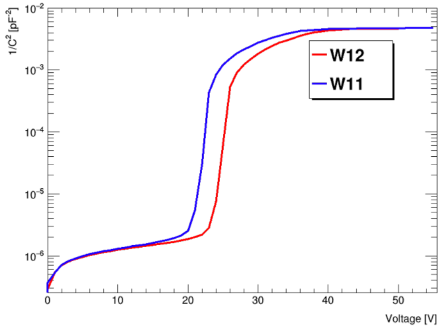




C-V test

Schematic Circuit Diagram for C-V Test

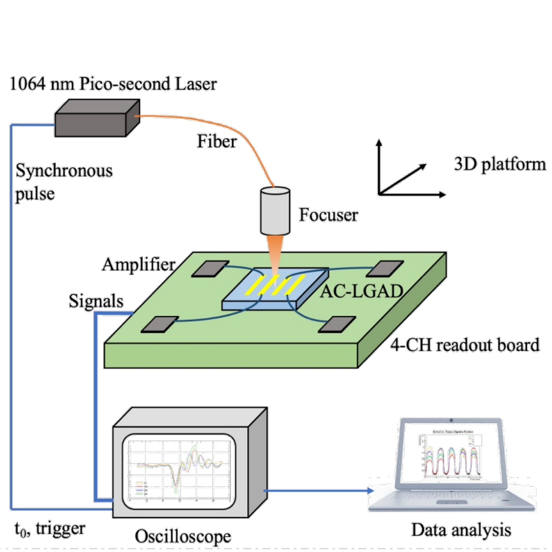


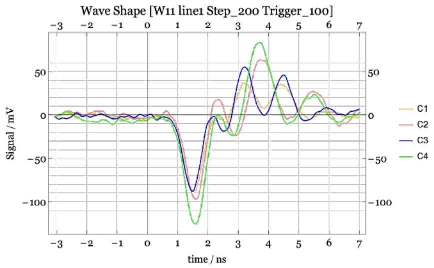


Type	W11	W12
Break down voltage [V]	390	190
Gain layer depletion voltage [V]	20	24
Full-depletion voltage [V]	40	40

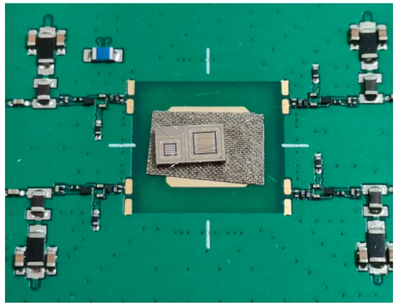
Hardware design & performance for Dark SHINE trackers

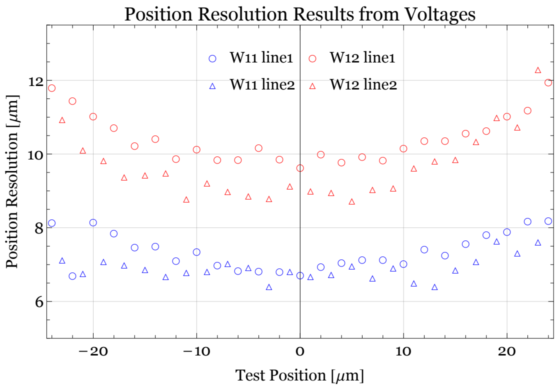
- For spatial and time resolution tests:
  - A focused laser beam (1064nm) serves as signal source.
  - Sensor is wire-bounded to a 4-channel readout board.
  - The waveforms are collected by an oscilloscope.

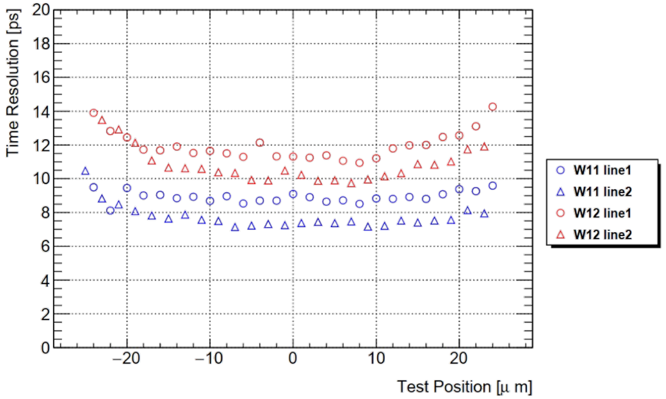




(b) Signal waveforms.



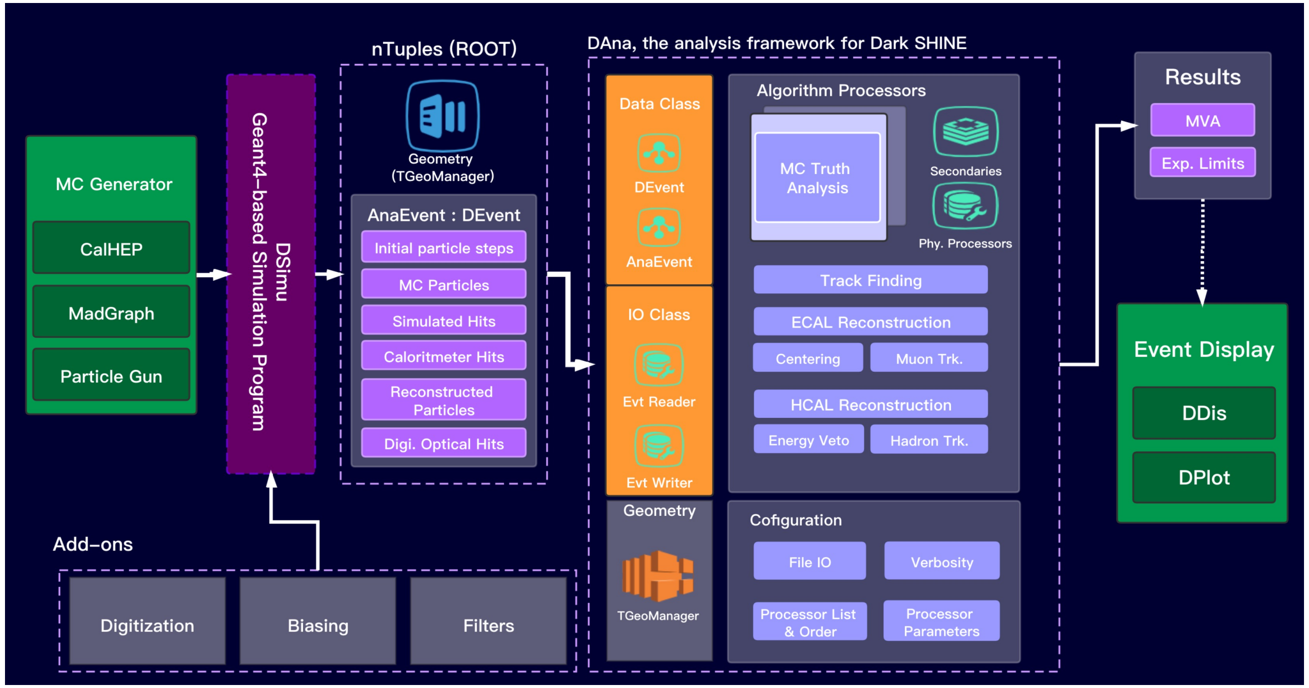


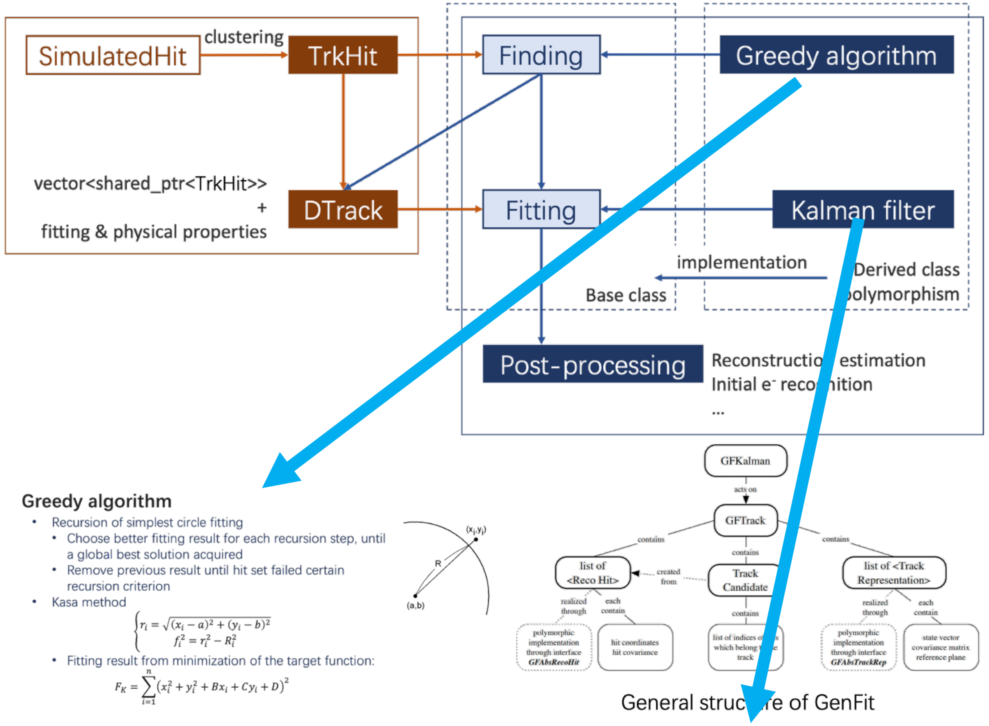


Distribution of spatial/time resolution with respect to x coordinates.

Type	W11	W12
Spatial resolution [μm]	6.5~8.2	8.8~12.3
Mean value of time resolution [ps]	8.3	11.4

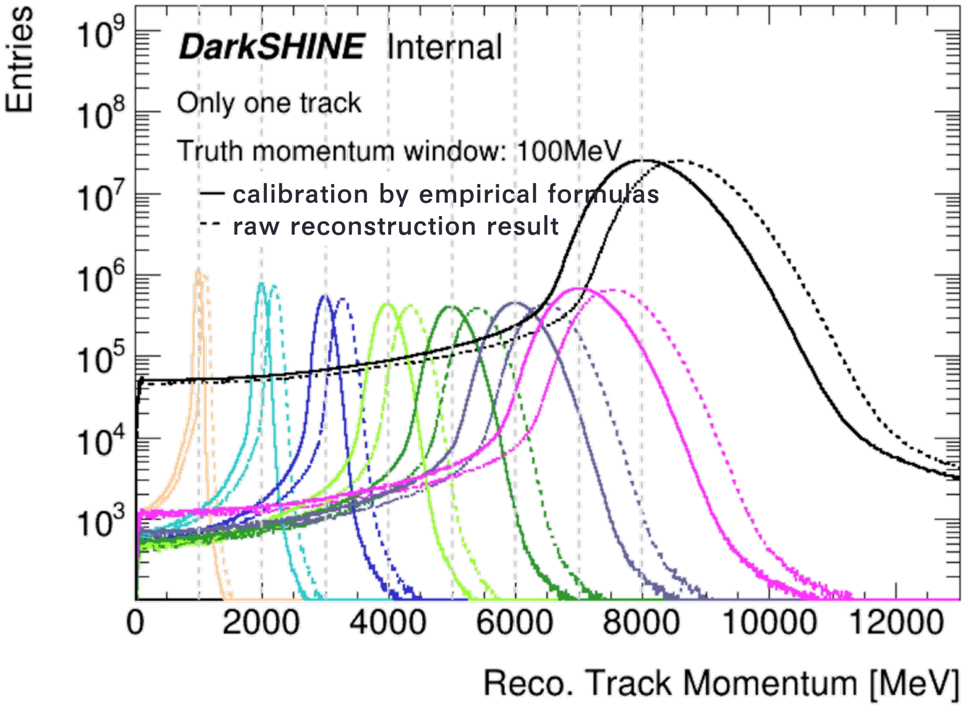
Dark SHINE software & its track reconstruction



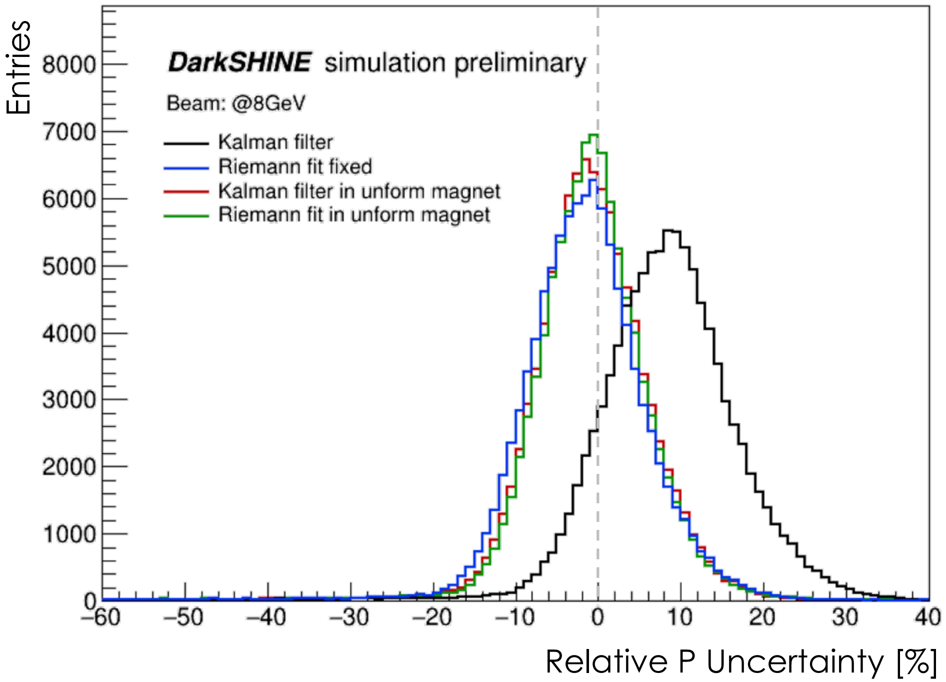


- Based on GEANT4 v10.6.0: simulation, analysis, and the event visualization.
- In earlier baseline, tracking algo based on Greedy-Kasa method and KF from Genfit.

Dark SHINE software & its track reconstruction



Momentum reconstruction results from various energy regions were obtained using the earlier DS baseline

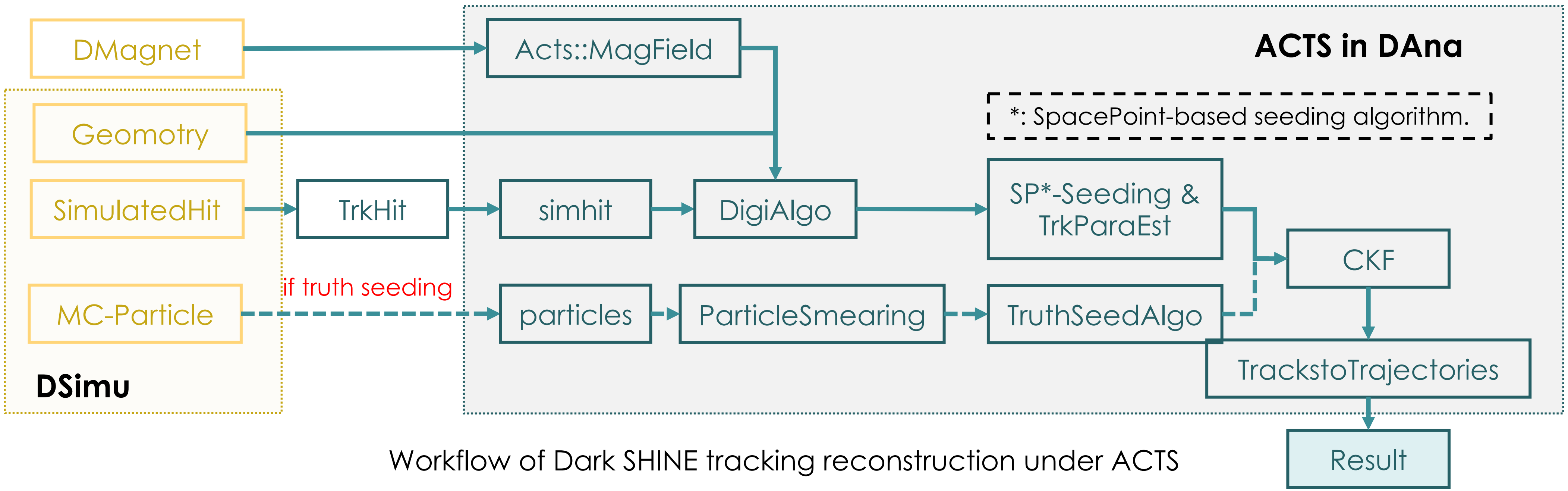


The relative uncertainty in reconstructed momentum obtained from **earlier DS baseline**

Using different magnetic fields and mathematical methods (Kalman Filter @ Genfit vs. Riemann Fitter).

Track reconstruction in Dark SHINE using ACTS

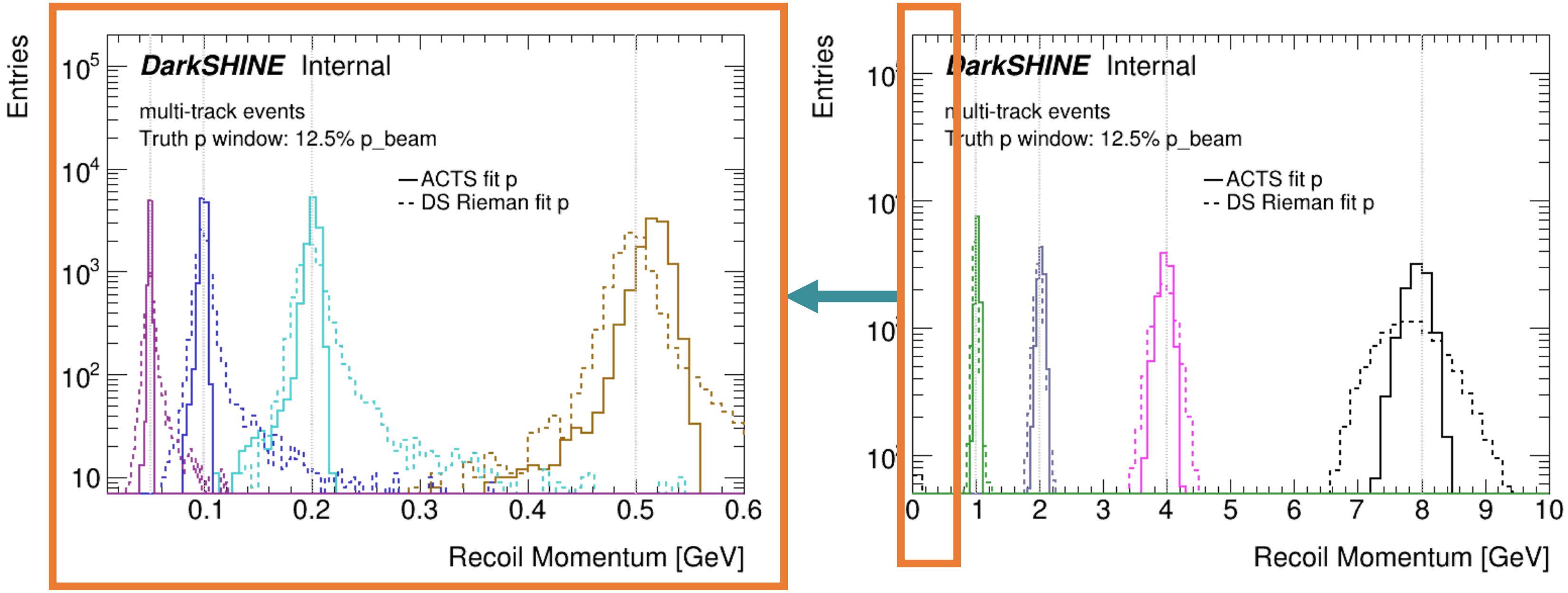
- It is hard for Dark SHINE to achieve under earlier framework:
  - non-uniform magnetic field,
  - accurate reconstruction of multi-particle events …



Workflow of Dark SHINE tracking reconstruction under ACTS

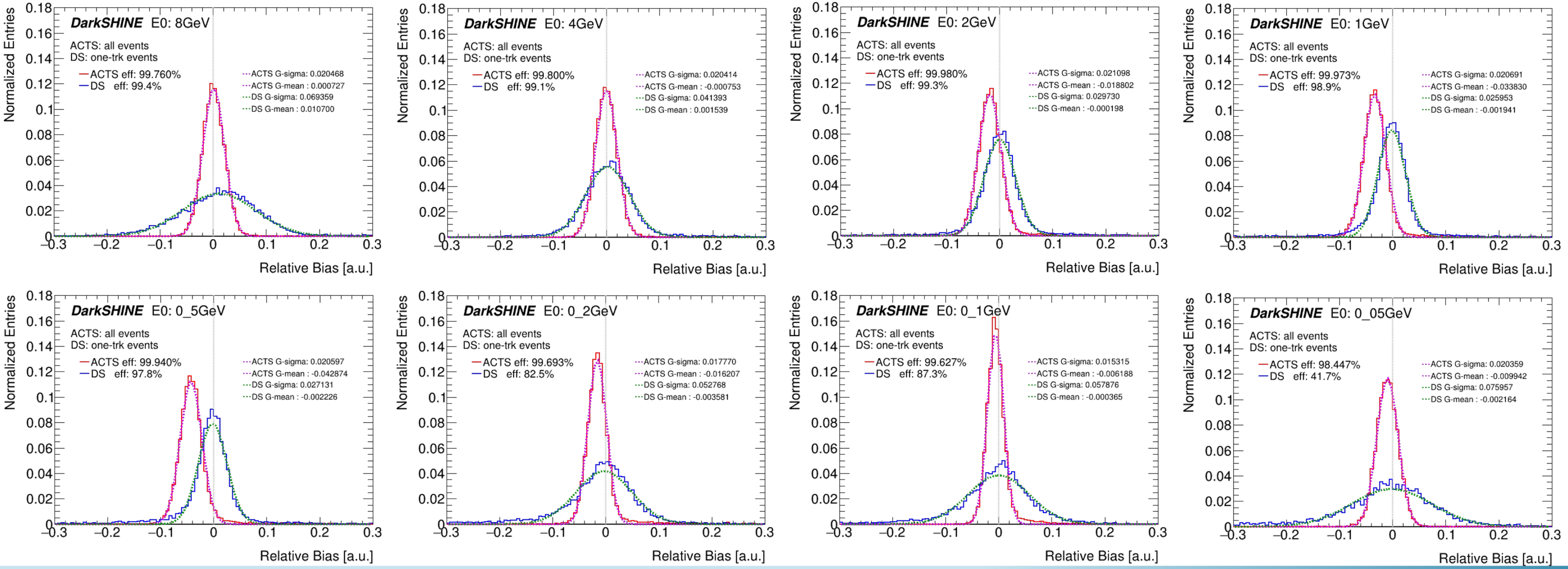
Track reconstruction in Dark SHINE using ACTS

- The integration of `TruthSeeding` and `KalmanFilter` within the ACTS framework yields significant enhancements.
- Evident in both the reconstructed momentum centroid and width (~7.5% -> ~2.0%).



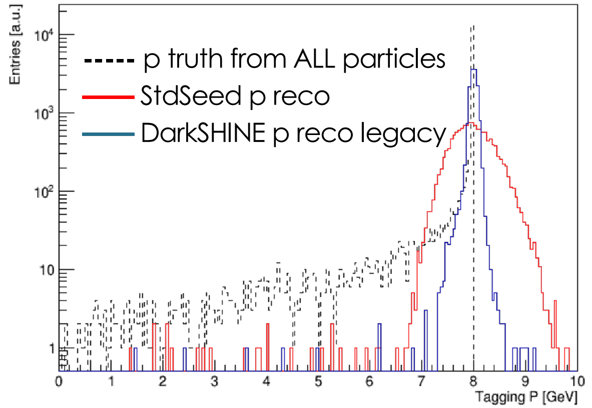
Track reconstruction in Dark SHINE using ACTS

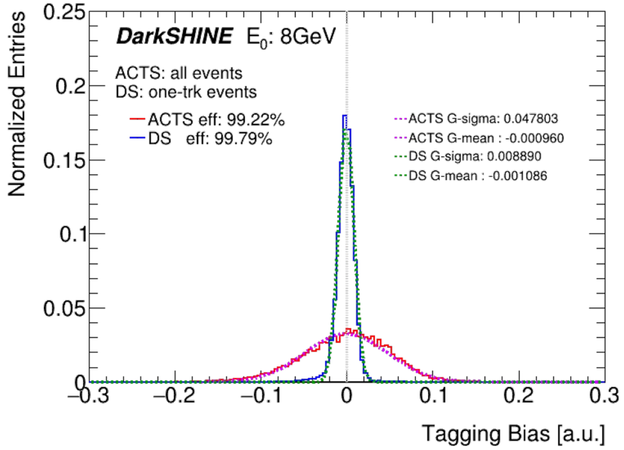
- Comparison of momentum uncertainty between earlier DS tracking Algo & ACTS TruthSeed+KF fitting



Track reconstruction in Dark SHINE using ACTS

- Momentum reconstruction performance after the application of `ActsExamples::SeedingAlgorithm` and CKF.
  - tagging single-electron events manifests as follows:
  - The truthP window for reconstructed momentum is 8 ± 0.625GeV
  - efficiency: 99.22% Gauss fit sigma = 0.0478
- Some problems arises…
  ① SeedFilter and functionality of KF.
  ② The circular region beam (source) spot affects our use of SP-based-Seeding algorithm.





Summary

- DarkSHINE: a fixed-target experiment searching for dark photon to light dark matter, demonstrating competitive sensitivity. (Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)).
- The tracking structure of DS is divided into a 7-layer tagging tracking region and a 6-layer Recoil tracking region. Each layer contains two strip sensors that rotate alternately.
- W11 and W12 sensors, from different doping concentrations, exhibit varied electrical performance:

Type	W11	W12
Spatial resolution [μm]	6.5~8.2	8.8~12.3
Mean value of time resolution [ps]	8.3	11.4
Break down voltage [V]	390	190
Gain layer depletion voltage [V]	20	24
Full-depletion voltage [V]	40	40

- ACTS has greatly improved the tracking reconstruction performance of Dark SHINE. However, some issues arise when using the ActsExamples::SeedingAlgorithm & CKF.

Dark SHINE R&D Team

Dark SHINE R&D Team

"Dark Photon Signals", may be :-D

Thank you!

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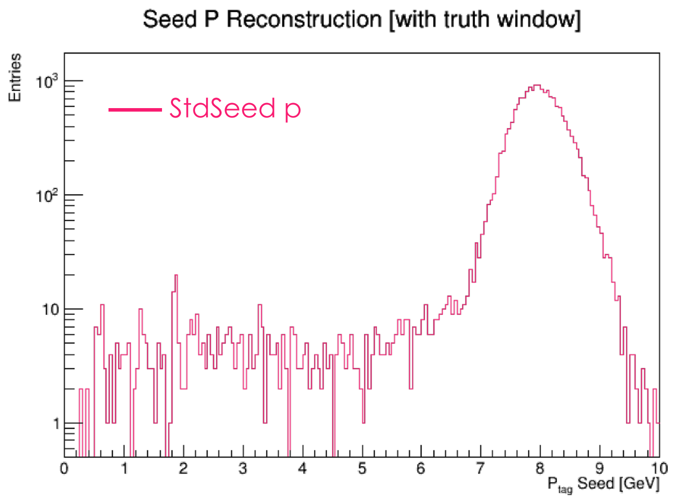
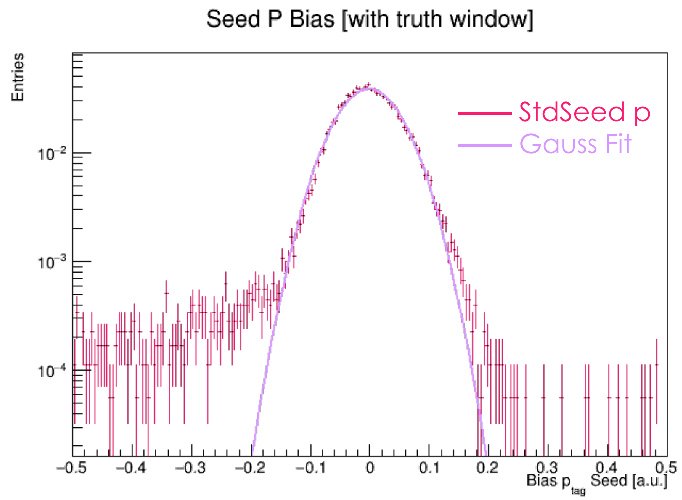
Backup

1. Problem from Filter:
   - Because seeding induces a 5% p deviation,
   - After using CKF, decreases to 4.8%.
   - May be focusing on the functionalities of KF and SeedFilter.

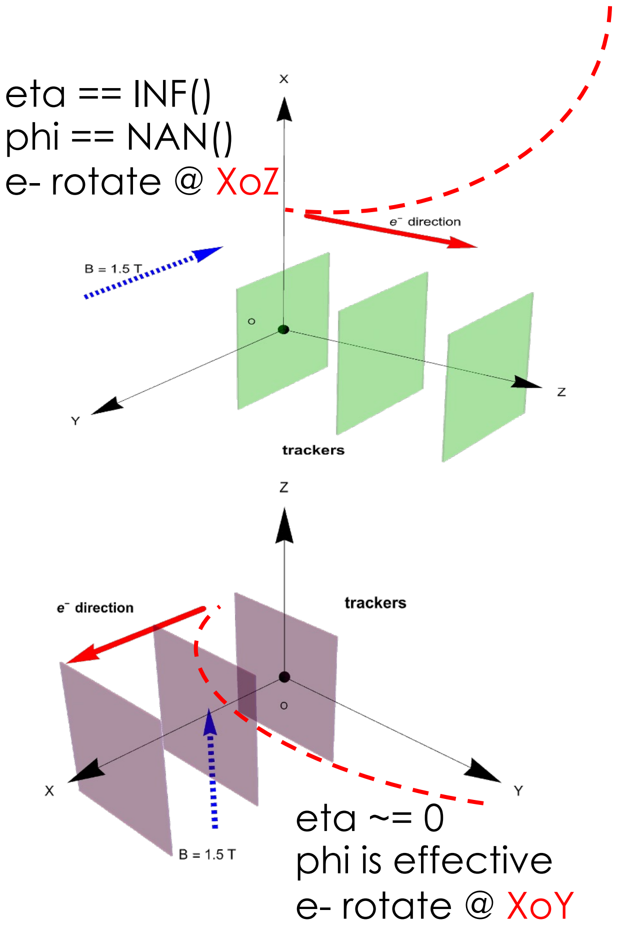




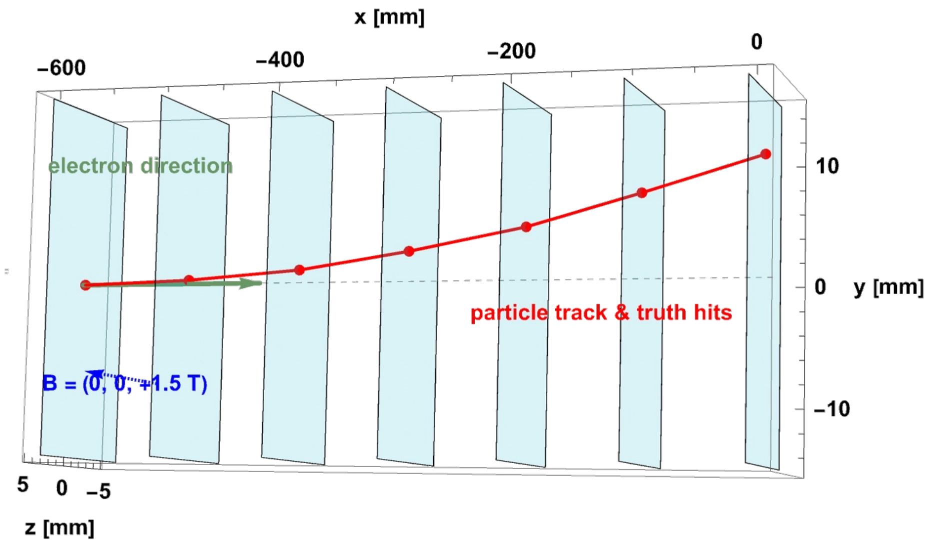
Backup

2. Problem from coordinate system:

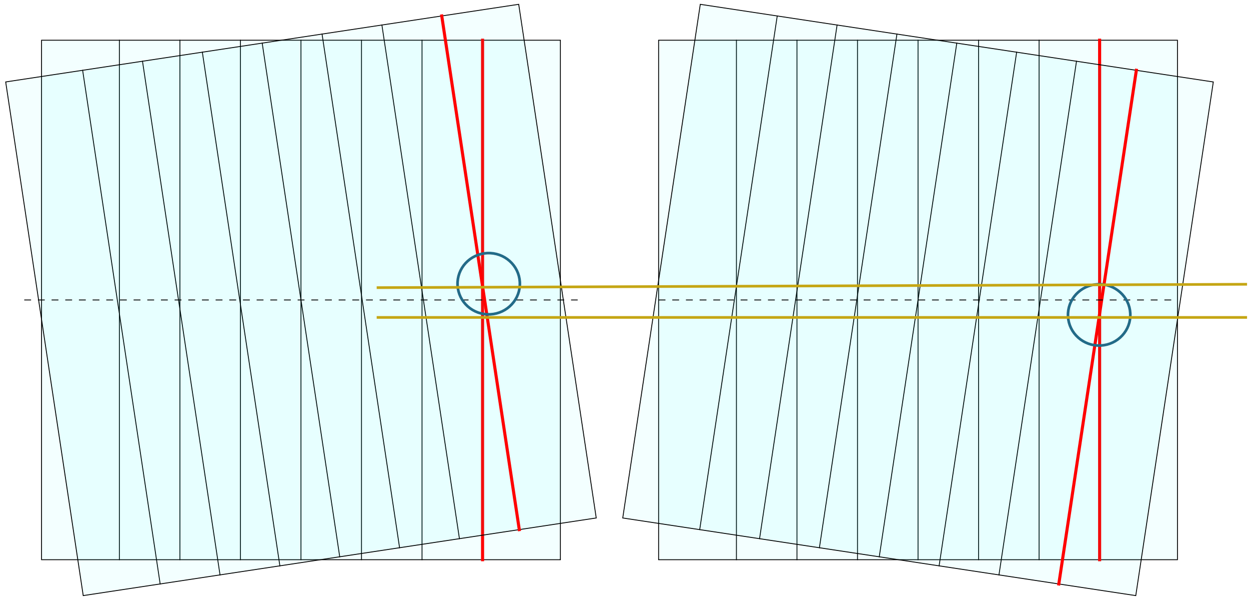
- The old coordinate system -> eta=INF() and phi=NULL().
- After rotation -> eta=0 and phi~=0.
- ∅ = 60mm circular region beam spot on the sensor plane presents a challenge for calculating the primary vertex using `StandardSeeding` algorithm.
- Despite attempts at solutions like vertex shifting, (which risks losing physical information,) no viable alternatives have been identified to address this issue.



Backup



Sketch for tagging tracking volume



The DS trackers are characterized by the alternating rotation of every two modules, resulting in a more pronounced vertical deviation than the horizontal deviation.

Backup

- Results from IHEP

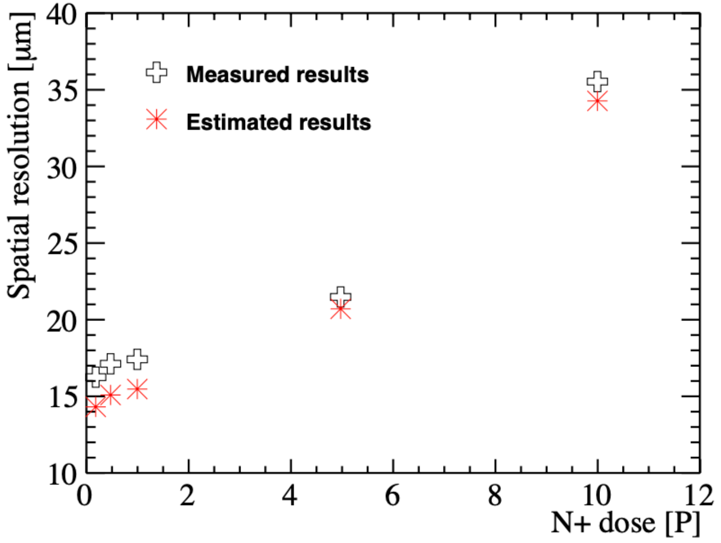


Fig. 8. The directly-measured spatial resolution (black marks) and estimated spatial resolution (red marks) at different N+ doses.

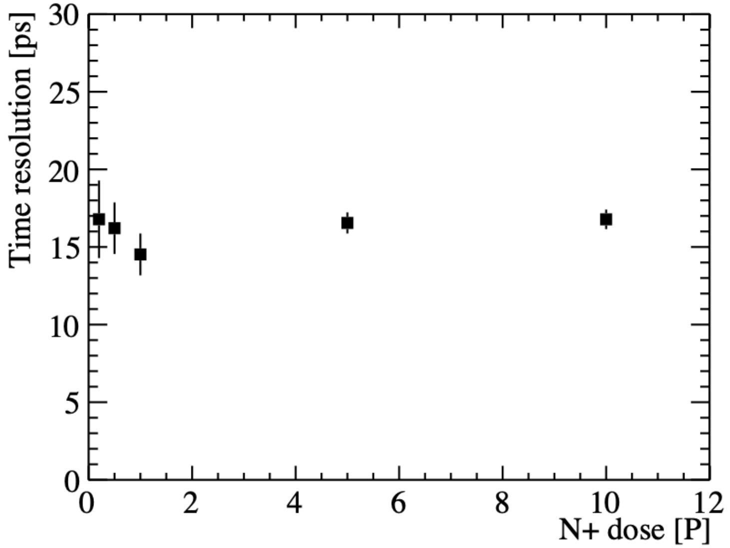
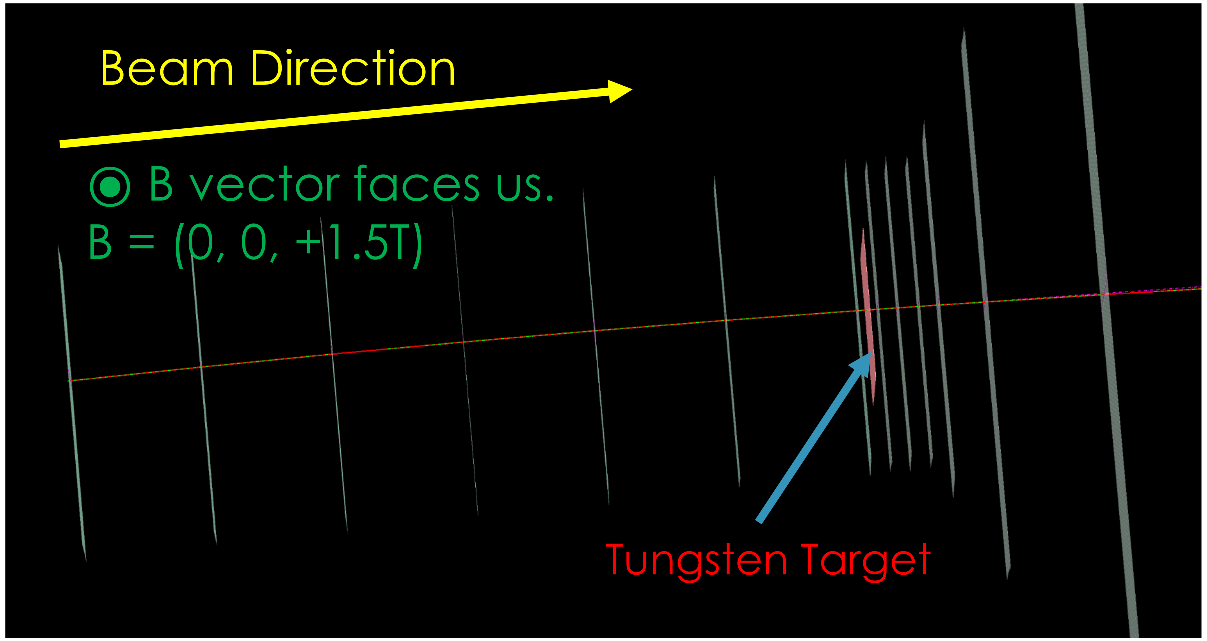


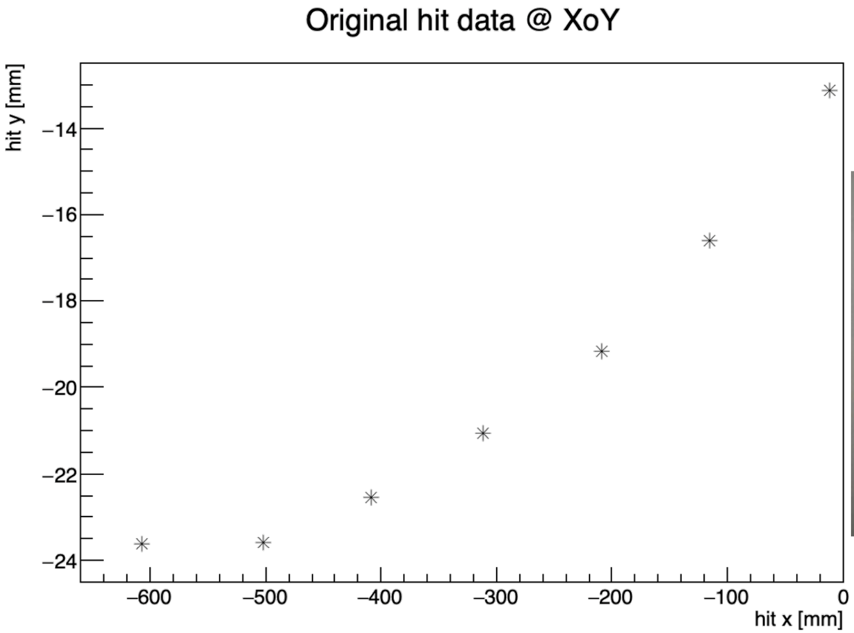
Fig. 11. The jitter component of the time resolution with different N+ doses.

arXiv: 2212.03754

Backup



Beam Direction
◉ B vector faces us.
B = (0, 0, +1.5T)
Tungsten Target



Original hit data @ XoY
hit y [mm]
−14
−16
−18
−20
−22
−24
−600
−500
−400
−300
−200
−100
0
hit x [mm]