MIP2025 @ HNU

PSI

Development of the muEDM Muon Trigger Detector

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on behalf of the ***muEDM*** collaboration

16th May 2025

李政道研究所
TSUNG-DAO LEE INSTITUTE

Why measure the (μ)EDM?

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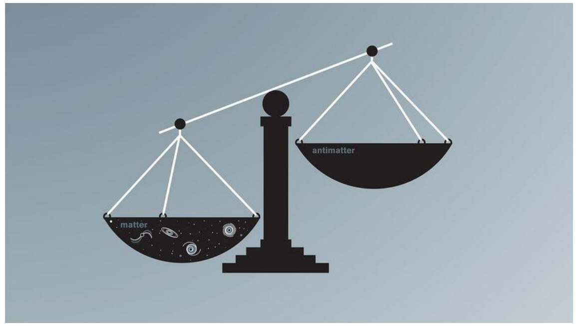
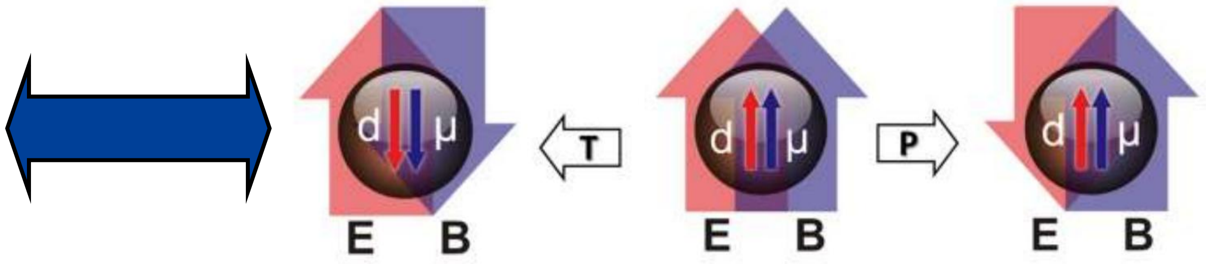
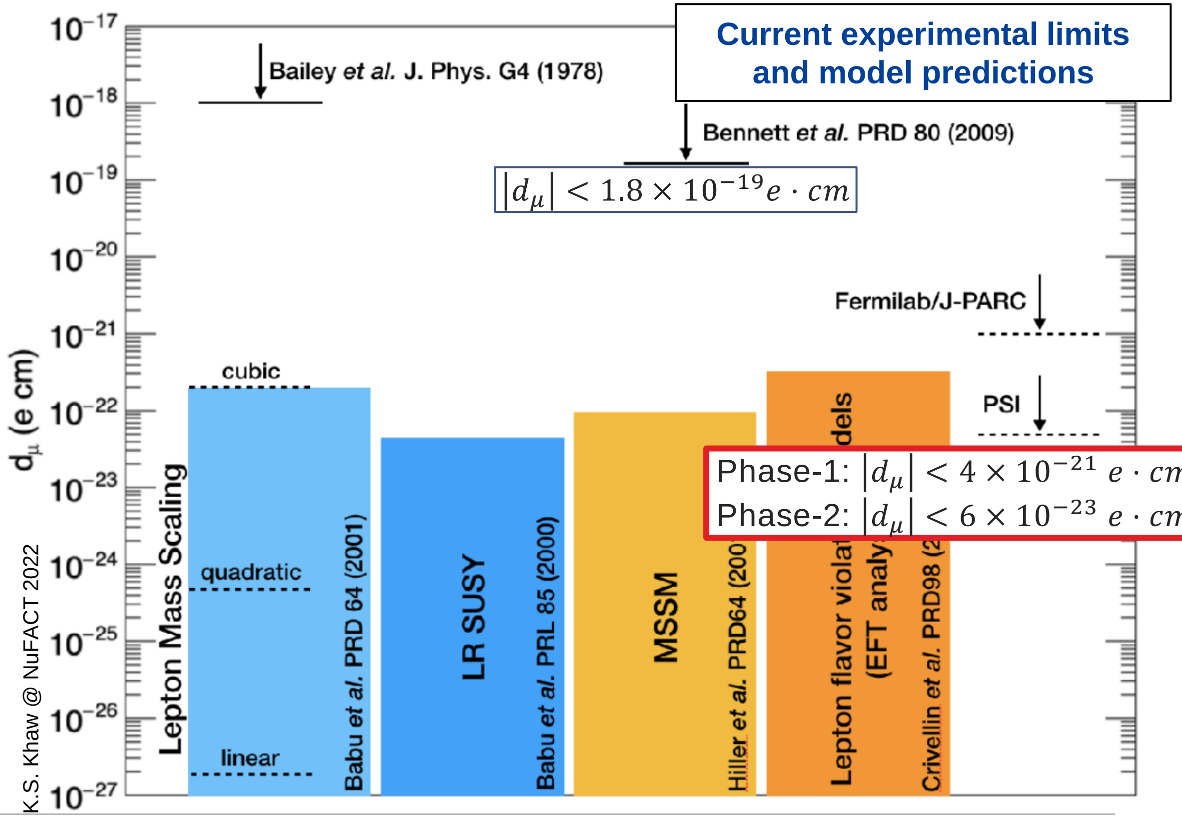
Credit: Symmetry Magazine / Sandbox Studio, Chicago



https://edm.ethz.ch/research/nedm.html

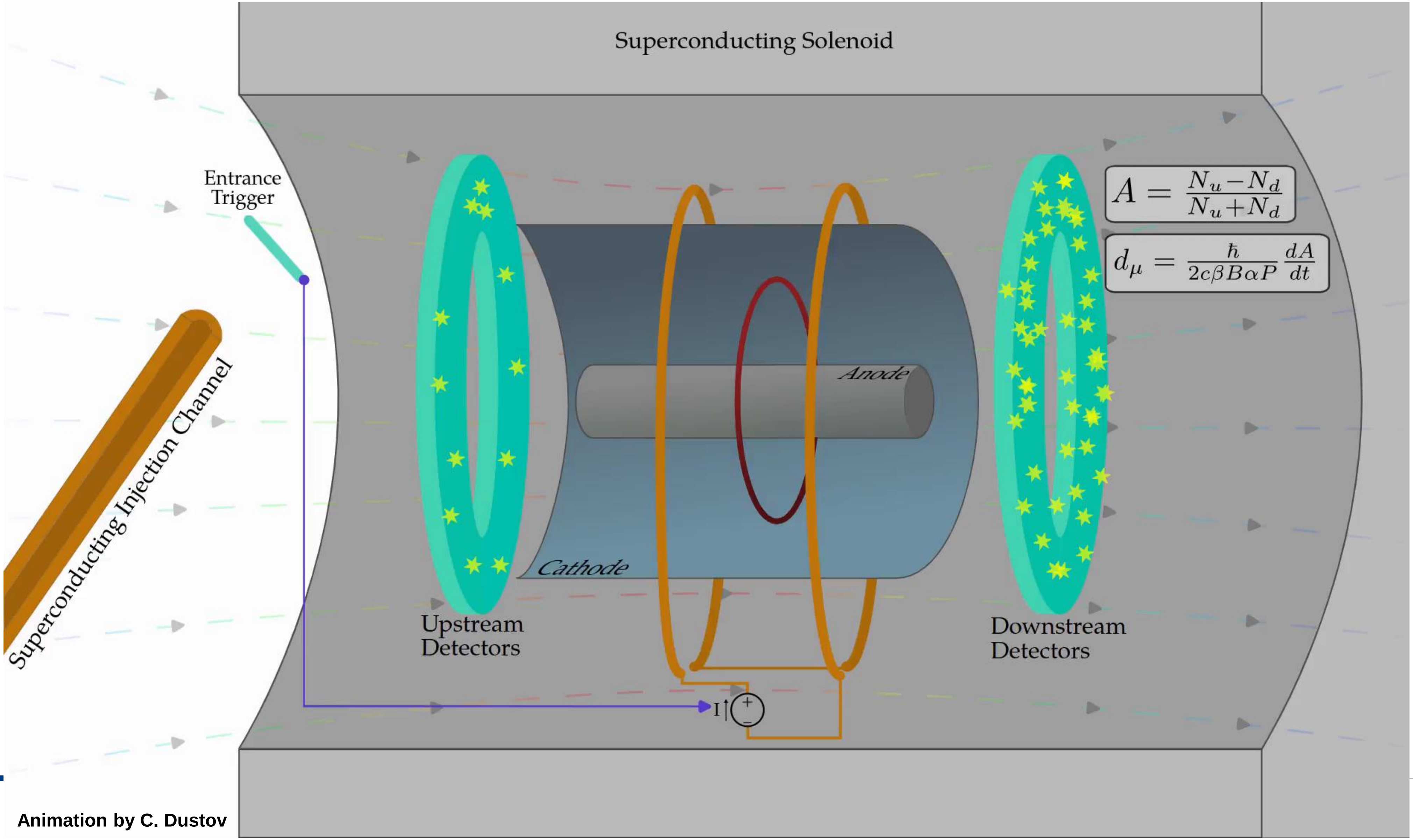


- **Free from SM backgrounds**
  - CKM phase contribution: $d_\mu \sim 10^{-42}\ e \cdot cm$
    PRD **89** (2014) 056006
  - Hadronic long-distance contribution: $d_\mu \sim 10^{-38}\ e \cdot cm$
    PRL **125** (2020) 241802
- **Various BSM models predicts enhanced EDM**
  - EDMs are good probes for BSM physics
  - μEDM of particular interest: muon g-2 anomaly, B-anomalies



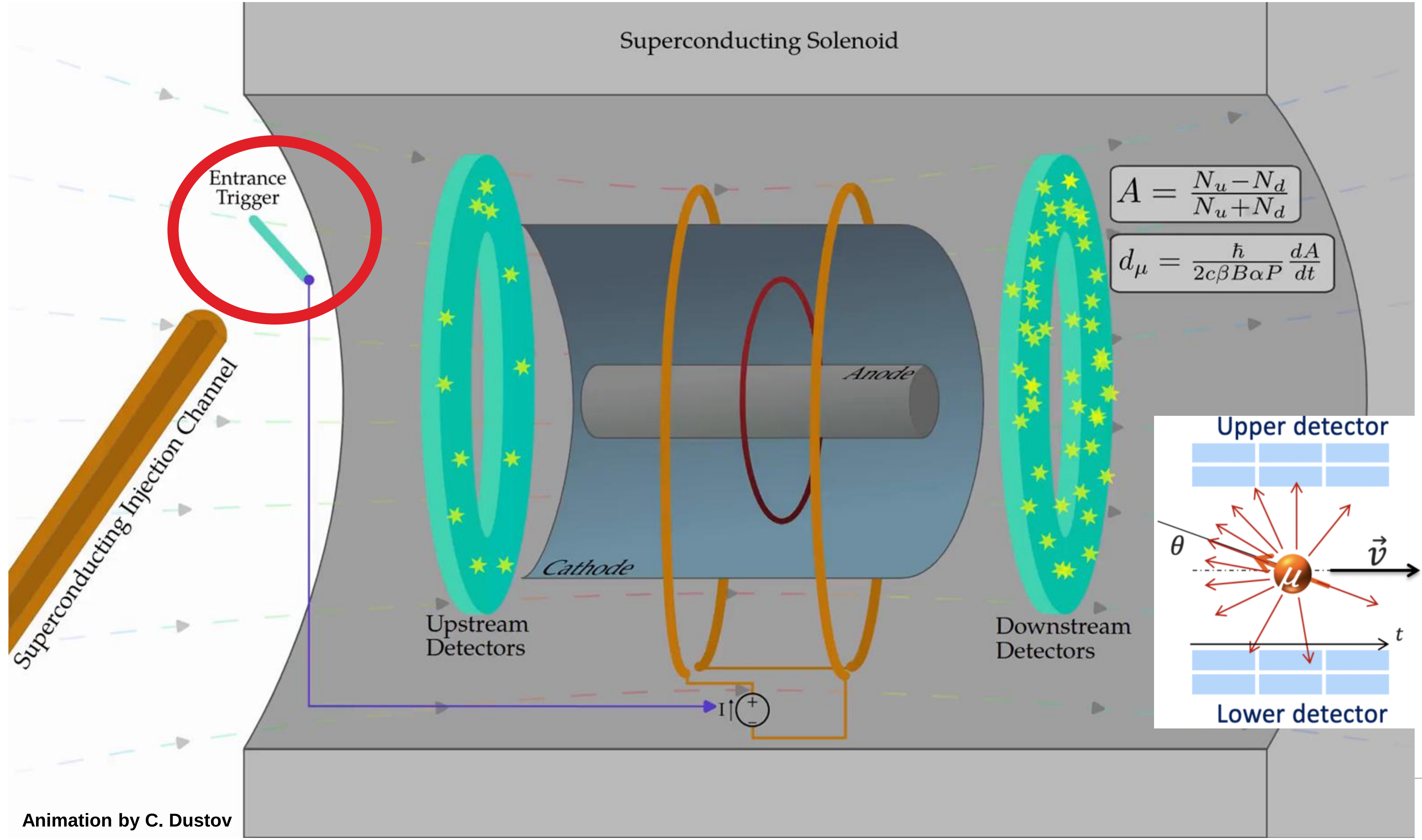
*also in these models:
Muon specific 2HDM *PLB 831 (2022) 137194*
Radiative muon mass model *JHEP02 (2023) 234 (4)*

muEDM experiment



Animation by C. Dustov

muEDM Signal



Animation by C. Dustov

Sensitivity from the asymmetry, "PENTA":

$$\sigma(d_\mu) = \frac{\hbar\gamma^2 a_\mu}{2PE_f\sqrt{N}\,\gamma\tau_\mu\,\alpha}$$

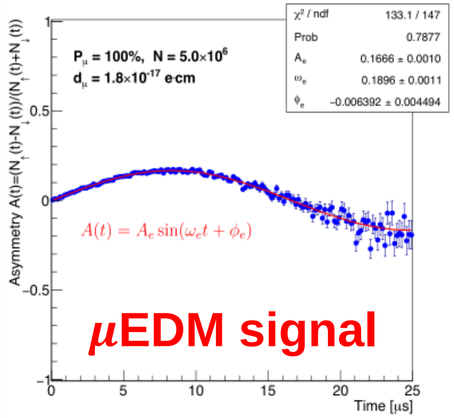
P := initial polarization

E_f := Electric field in lab

$\sqrt{N}$:= number of positrons

τ_μ := lifetime of muon

α := mean decay asymmetry



Muon trigger detector (TrigDet)

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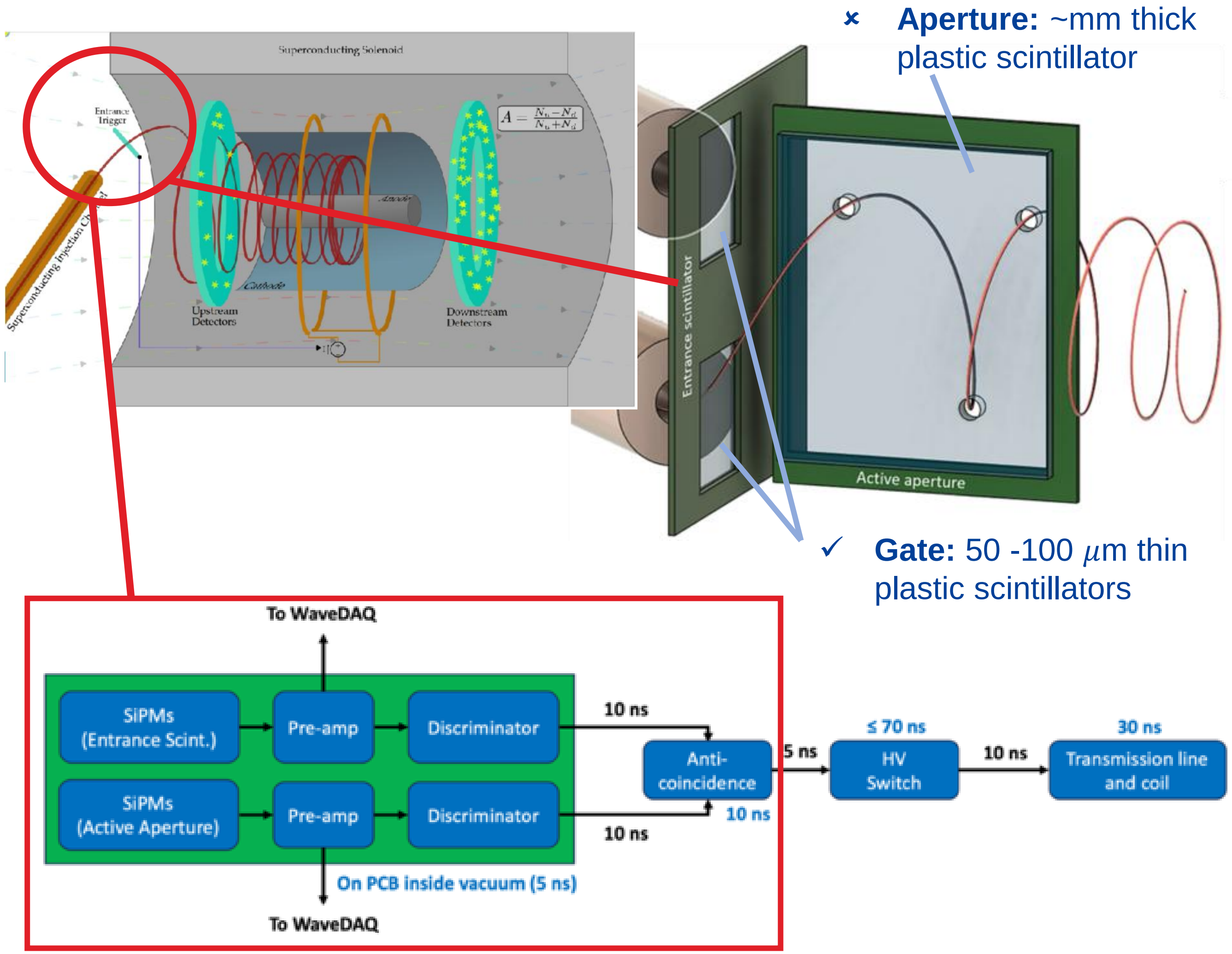


- ***Fast*** **and** ***precise*** **trigger system**
- **Responsible for triggering the pulse kicker to store muons**
- **Trigger: Gate in *anti-coincidence* with Aperture**
- **Detector requirements**
  - ***Fast***: time delay between trigger and pulse kick, t_{delay}< 105ns
  - ***Precise***: triggers selectively on storable muons, maximise acceptance and rejection rate
    - $\epsilon_a \geq 95\%$ (statistics)
    - $\epsilon_r \geq 98\%$ (pulse kicker max. load)
  - High detection efficiency for incoming muons
  - Non-invasive detection of incoming muons
  - Compact mechanical design to be accommodated within a < 150 mm space

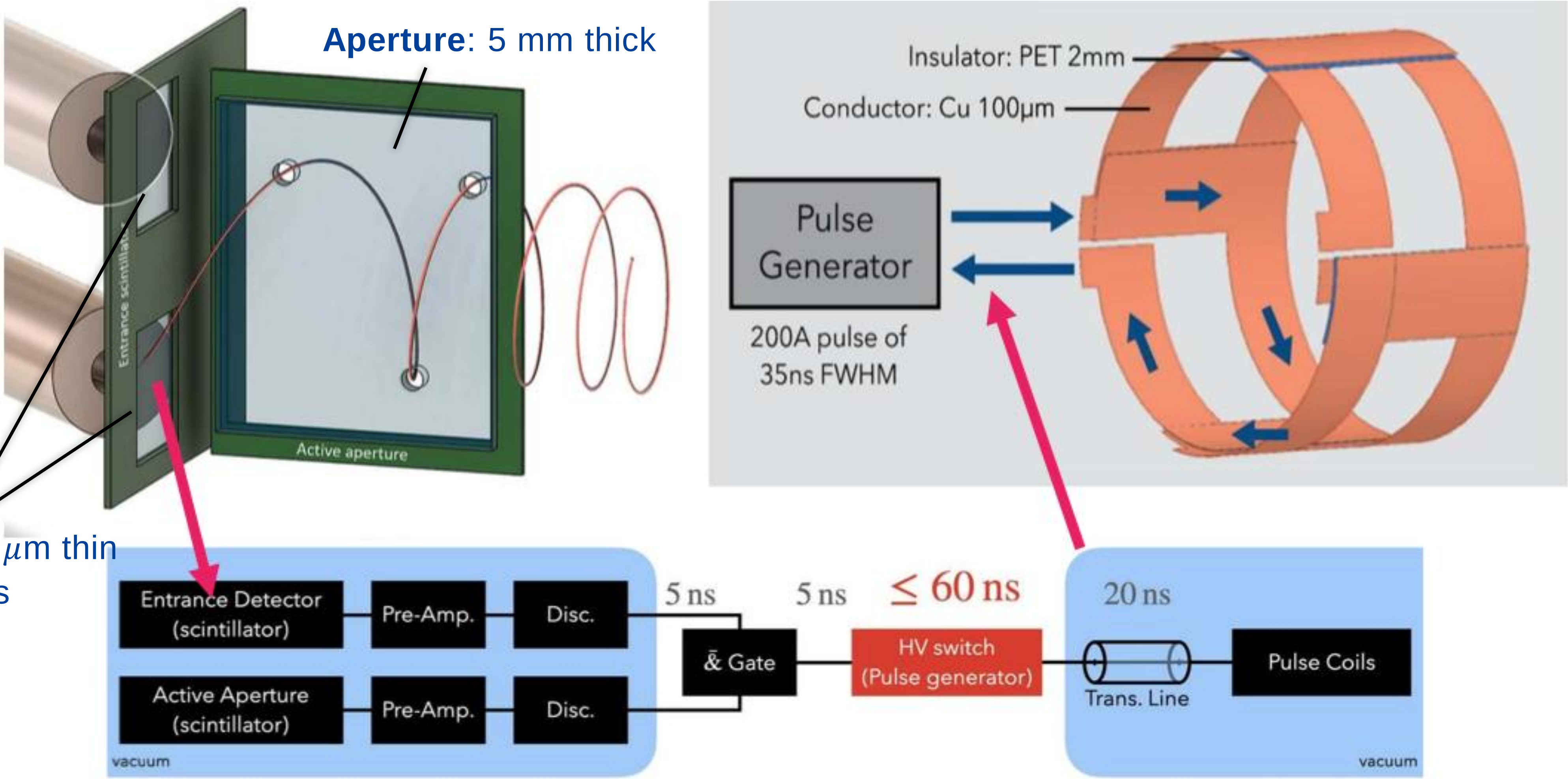
Muon trigger detector (TrigDet)

Conceptual sketch of the Phase-1 trigger detector

~28 MeV/c μ^+

TrigDet composed of plastic scintillators & SiPMs

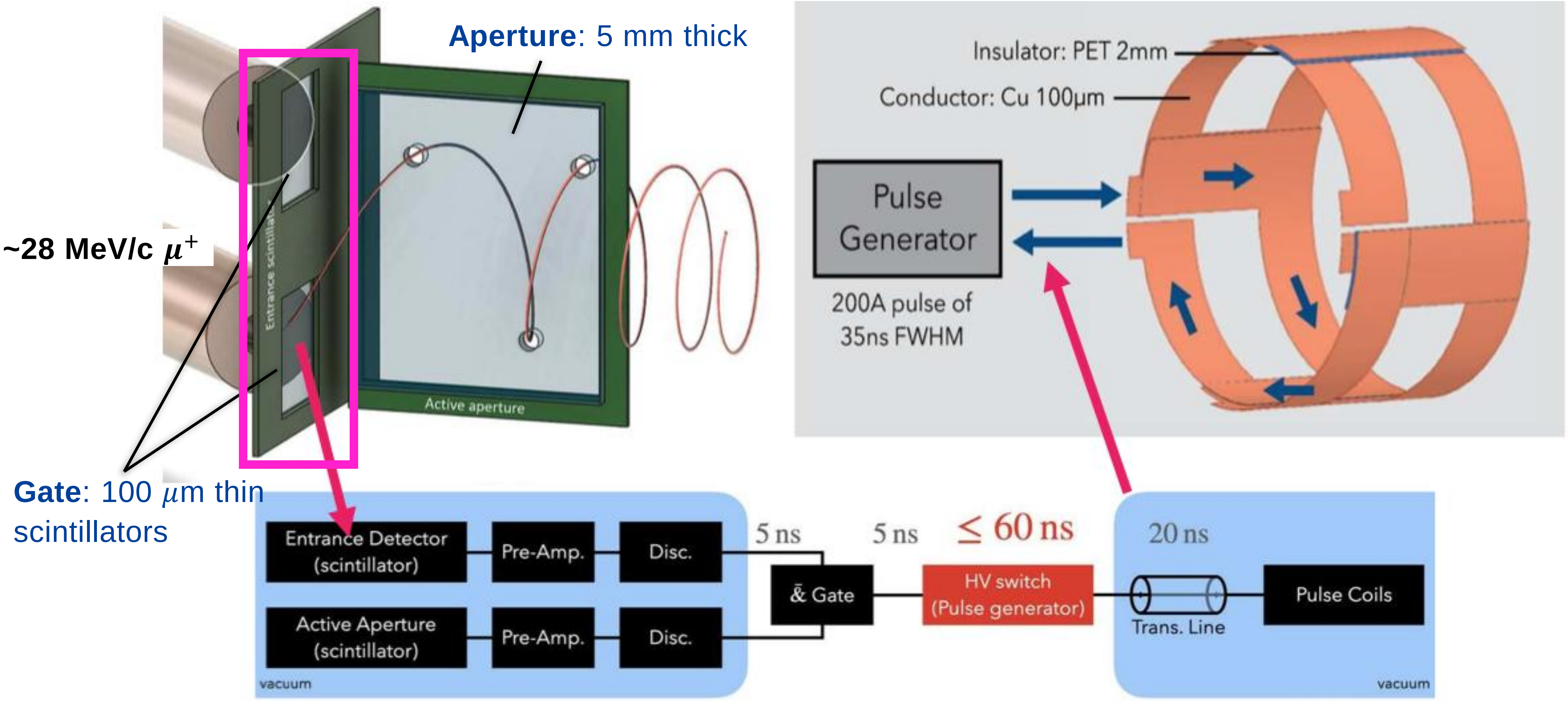
Aperture: 5 mm thick



Gate: 100 μm thin scintillators

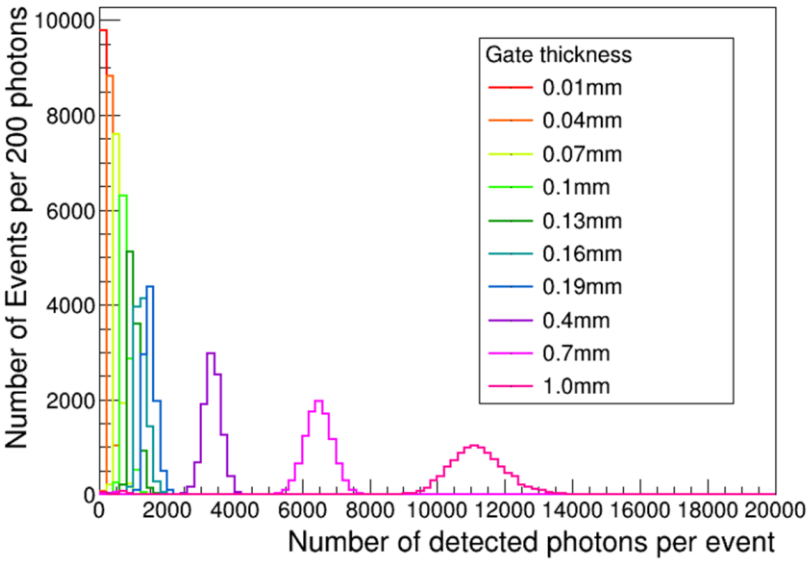
Gate design

Conceptual sketch of the Phase-1 trigger detector

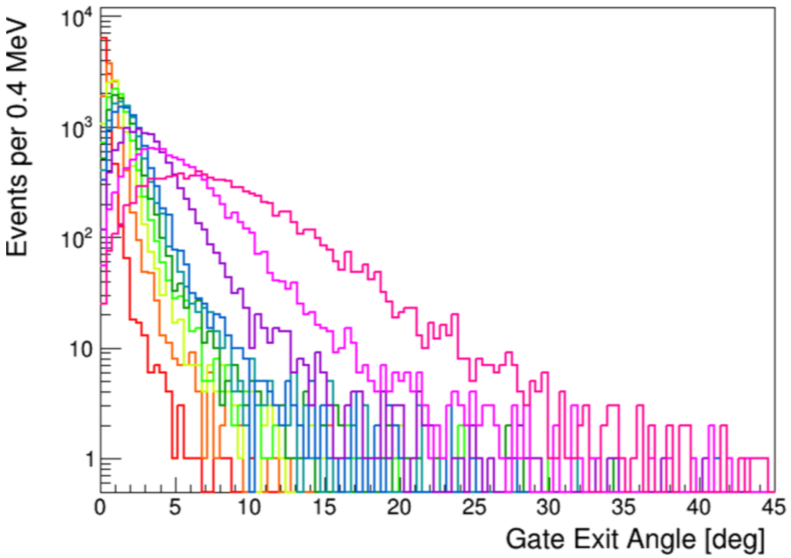


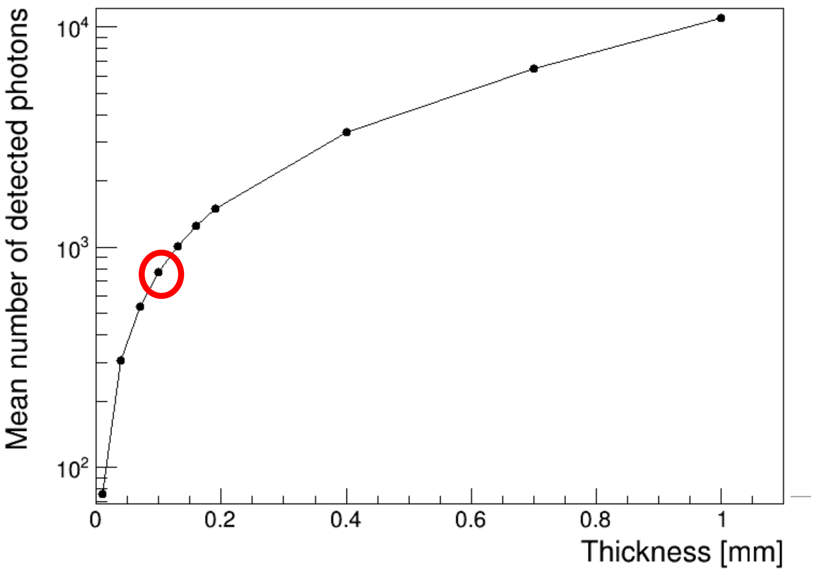
Gate design

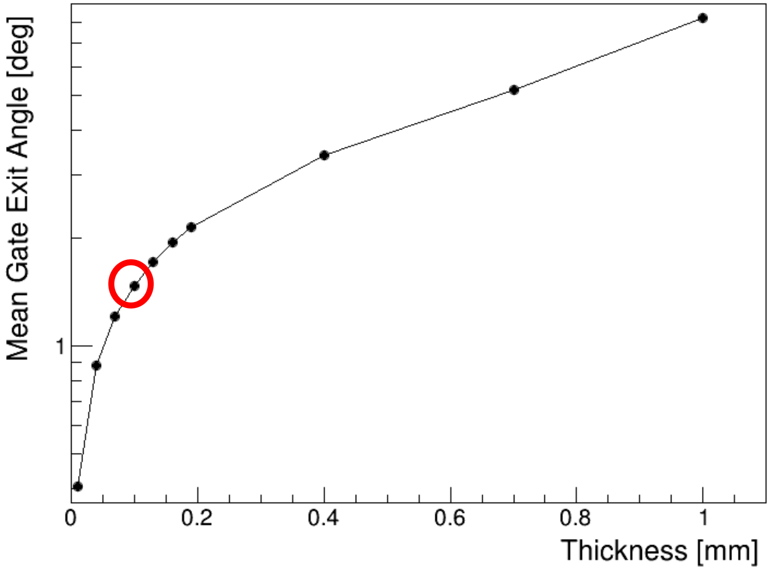
Optical photons produced



Scattering angle

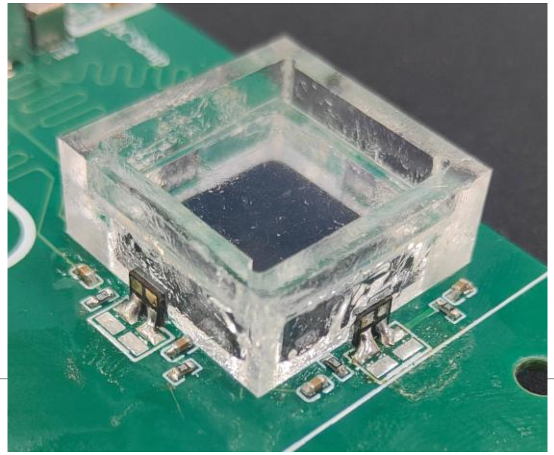




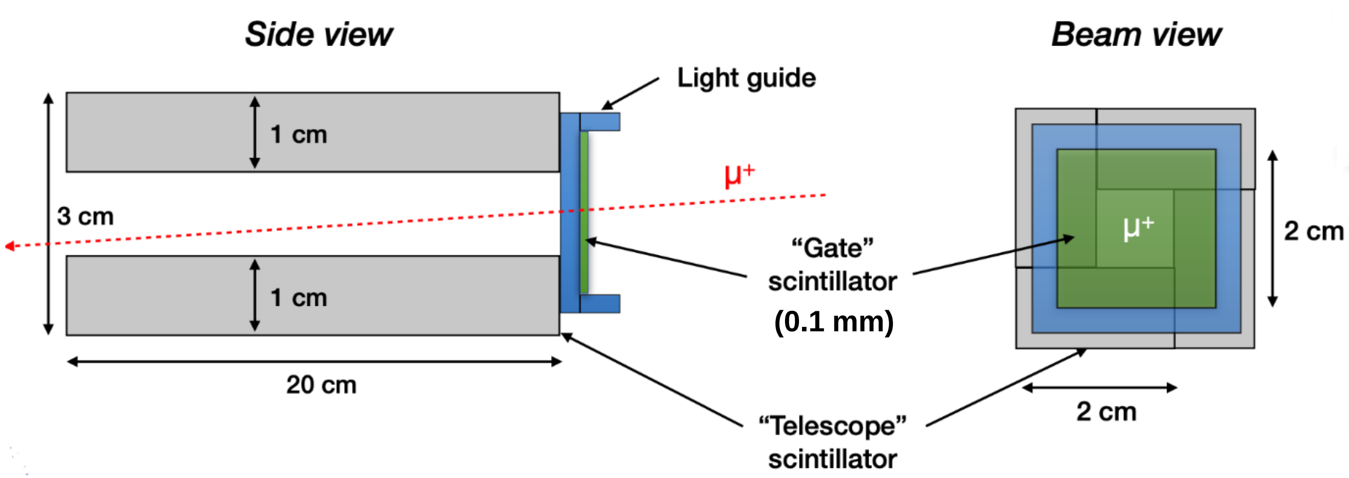


- **Gate design optimised for**
  - Number of optical photons collected
  - Scattering angle induced on μ^+ exiting the Gate
- **Optimisation by studying**
  - Gate thickness vs exit angle
  - Gate thickness vs optical photons collected

✓ **Simulation results indicates 0.1 mm Gate thickness to be optimal**

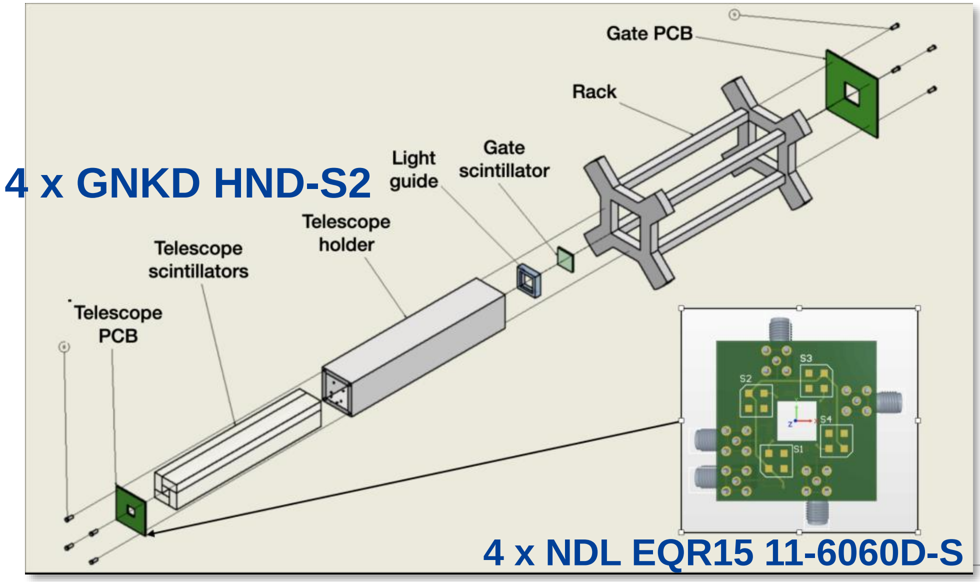


TrigDet proof-of-concept

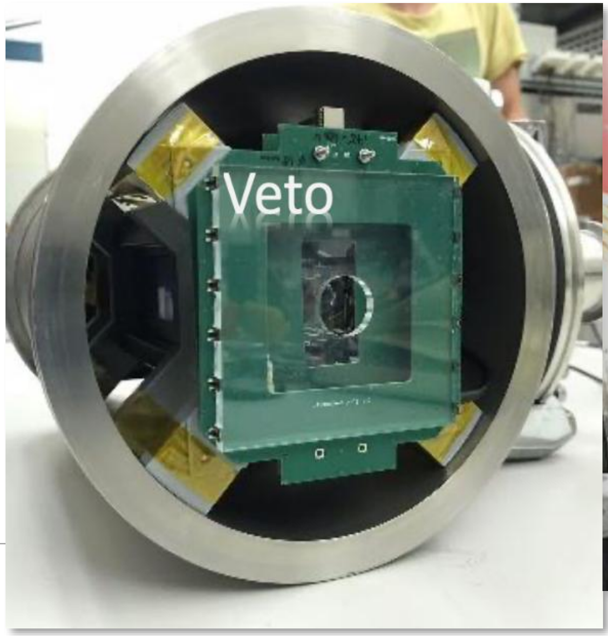


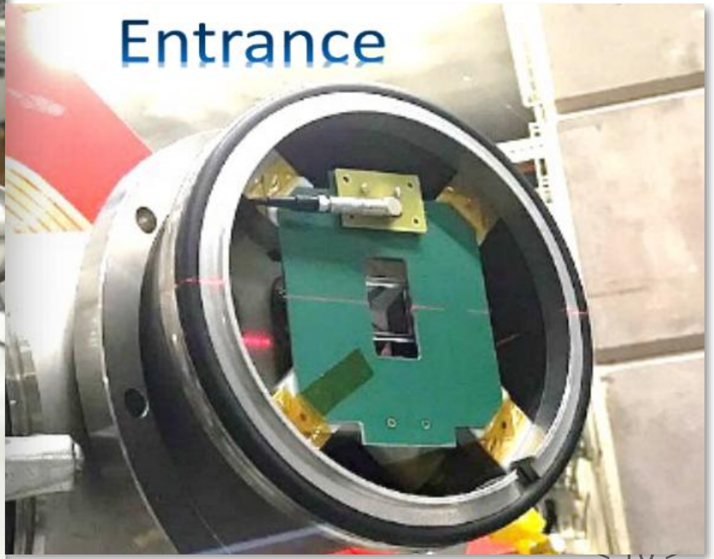
- **Demonstrate anti-coincidence logic**
  - Muons passing through **gate** but not hitting *telescopes*
- **Beam within acceptance selected with anti-coincidence logic**
- **Composed of plastic scintillators and light-readout by SiPMs (*fast*)**
- **Test beam 2022 at PSI πE1 beamline**

4 x GNKD HND-S2



4 x NDL EQR15 11-6060D-S





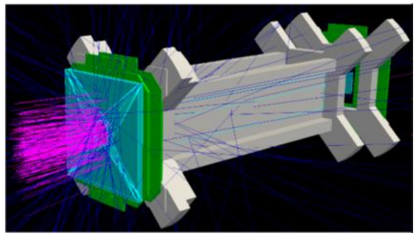
TrigDet proof-of-concept

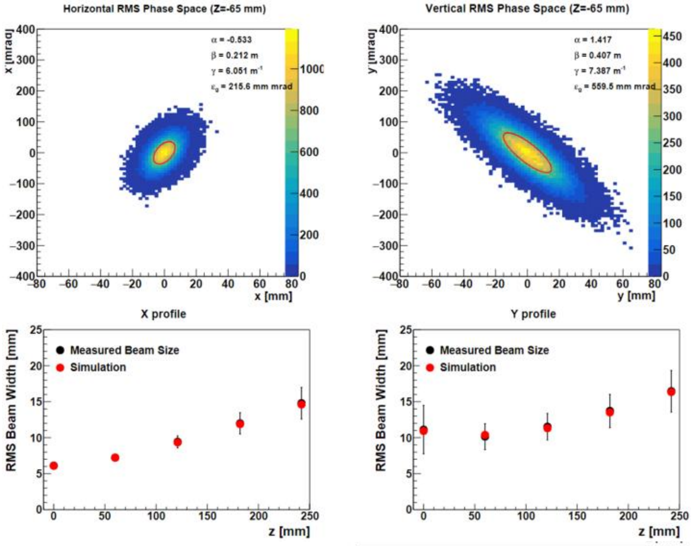
Simulation validation of TrigDet-TB22 detector response

Test beam model in simulation

Reproduction of optical response

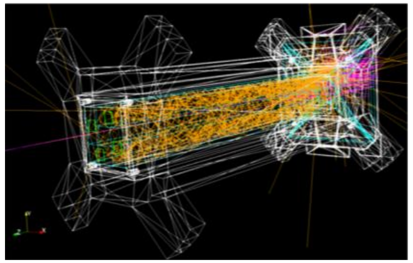
Reproduction of relative event rates

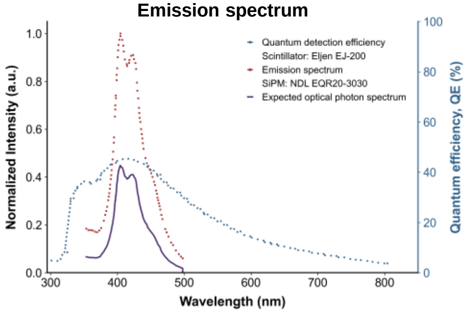


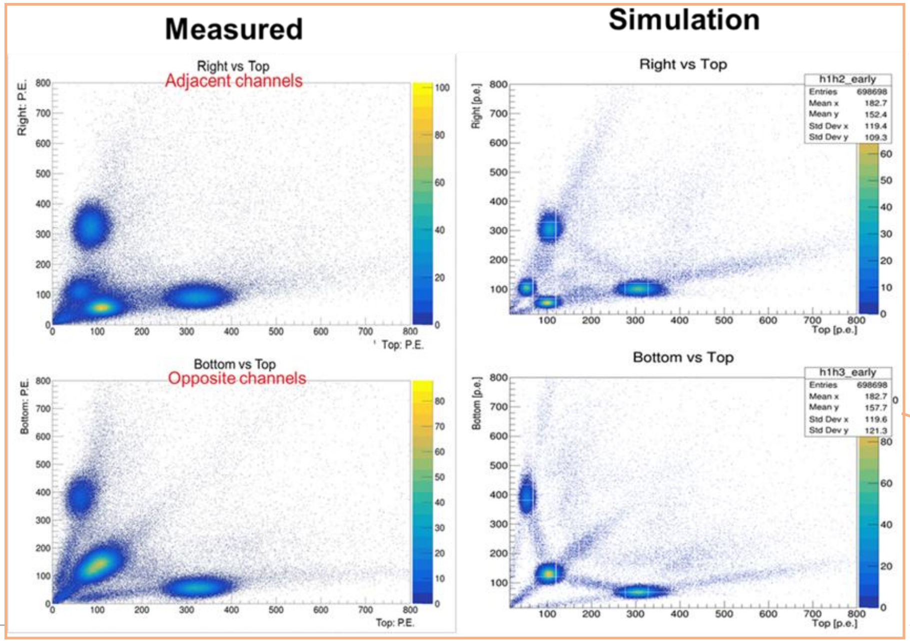


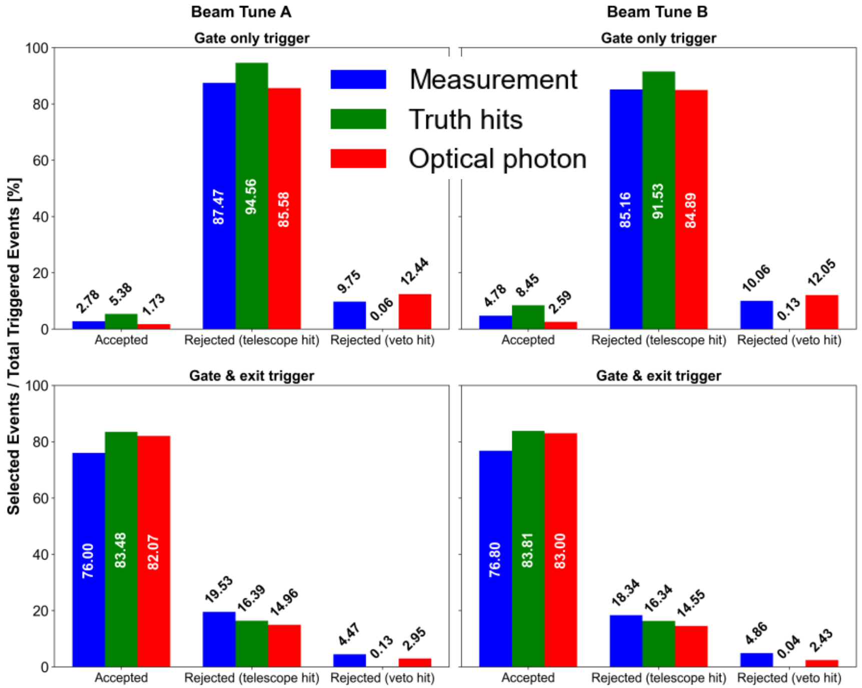
Measured beam profiles reproduced in simulation for input of detector performance studies

Optical photon propagation in prototype detector









Optical response of detector studied by reproducing measured optical photon distribution

Measured event rates studied at truth level simulation and replicated with optical photon

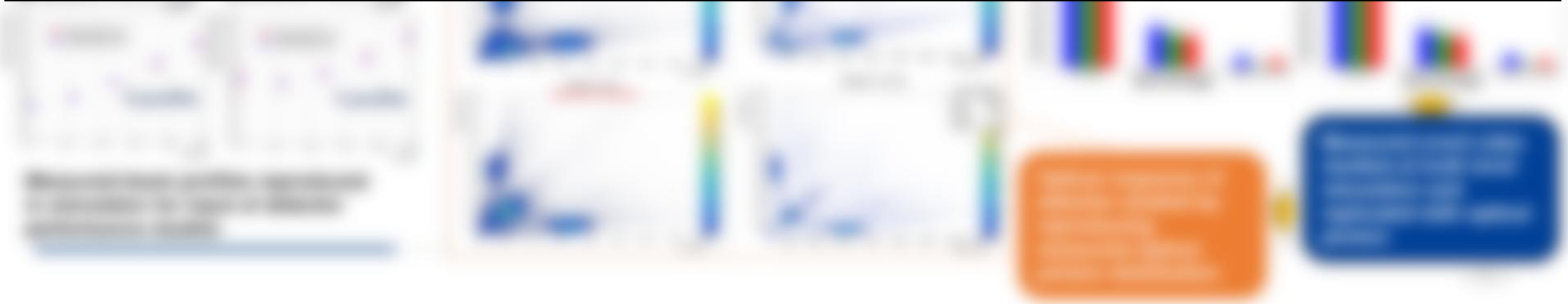
TrigDet proof-of-concept

Tsung-Dao Lee Institute

Simulation validation of TrigDet-TB22 detector response

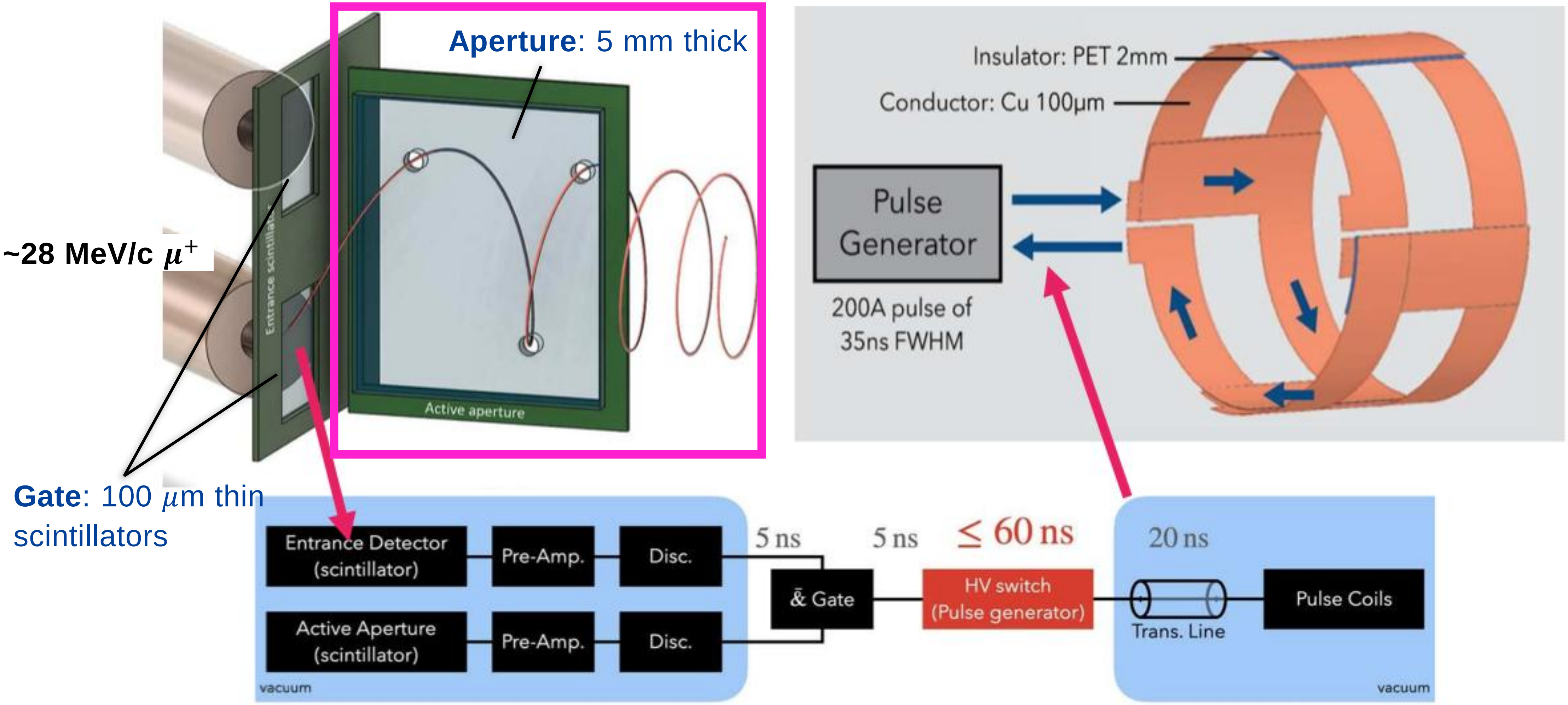
Summary of TrigDet-TB22 ([arXiv: 2501.01546](https://arxiv.org/abs/2501.01546))

- ✓ Demonstrates the anti-coincidence scheme and thin Gate design
- ✓ Establishes the design intuition for Phase-1 TrigDet



Aperture design

Conceptual sketch of the Phase-1 trigger detector



Simulation-based design

- **TrigDet designed with G4beamline and musrSim**
- **To determine Aperture geometry and dimensions**
  - Aperture openings should be optimised for maximum **acceptance** ϵ_a and **rejection rate** ϵ_r
- **Workflow overview:**

Beam related effects (G4BL)

Reproduce **storage efficiency,** ϵ_{sto}: nominal storage μ^+ trajectories

$$\epsilon_{sto} = \frac{N_{sto}}{N_{inj}}$$

Virtual plane implemented along storage events: **storage acceptance** informs Aperture dimensions

Detector response (musrSim)

CAD model of Aperture implemented in musrSim

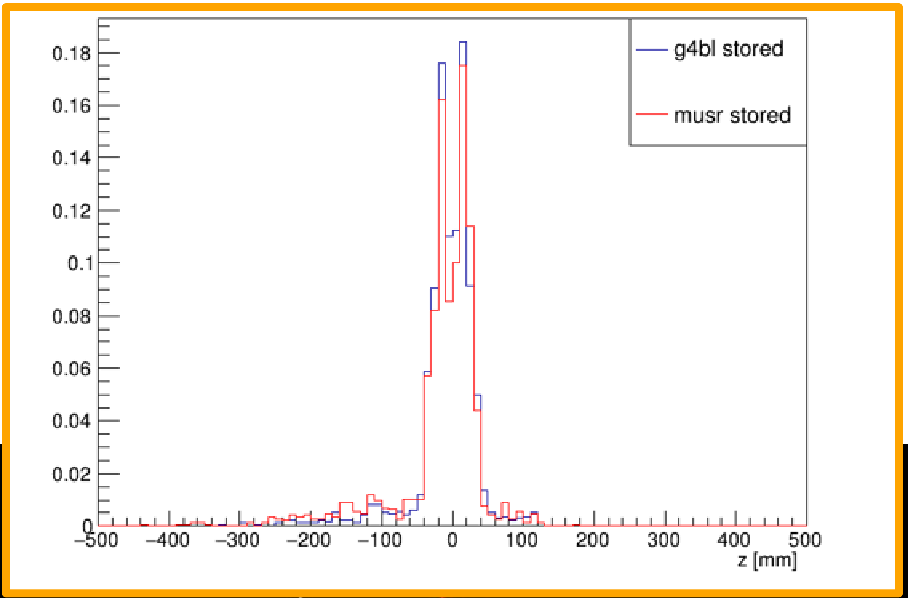
Event topology studied by analysing energy depositions in each detectors

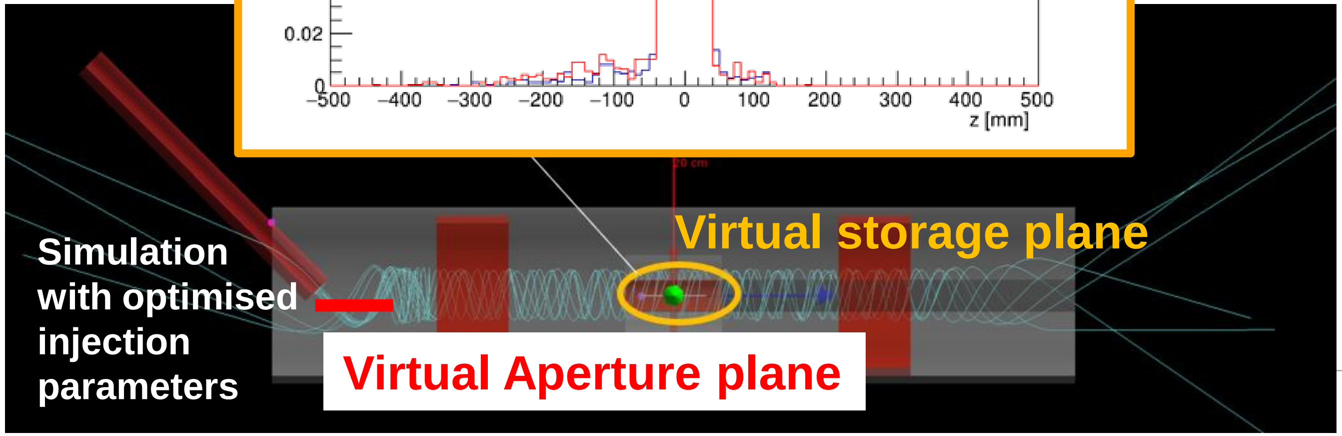
Simulation workflow

G4beamline: beam related effects

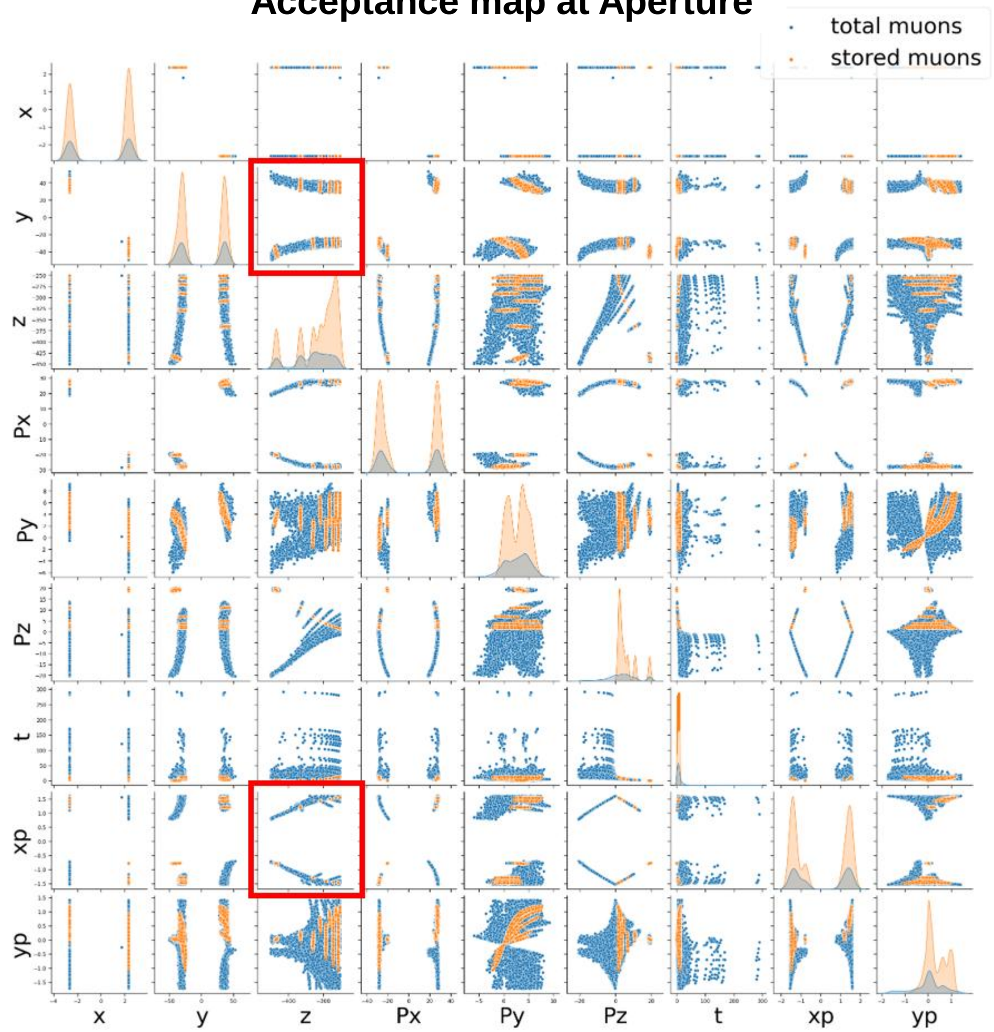
Reproduce storage efficiency → Storage acceptance map informs Aperture design geometry

μ^+ distribution on storage plane, N_{sto}





Acceptance map at Aperture



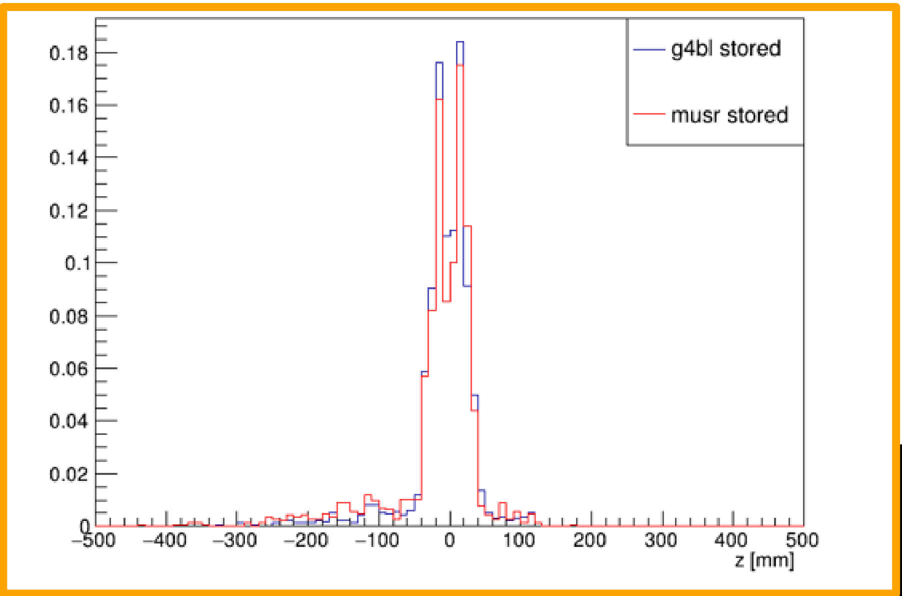
Simulation workflow

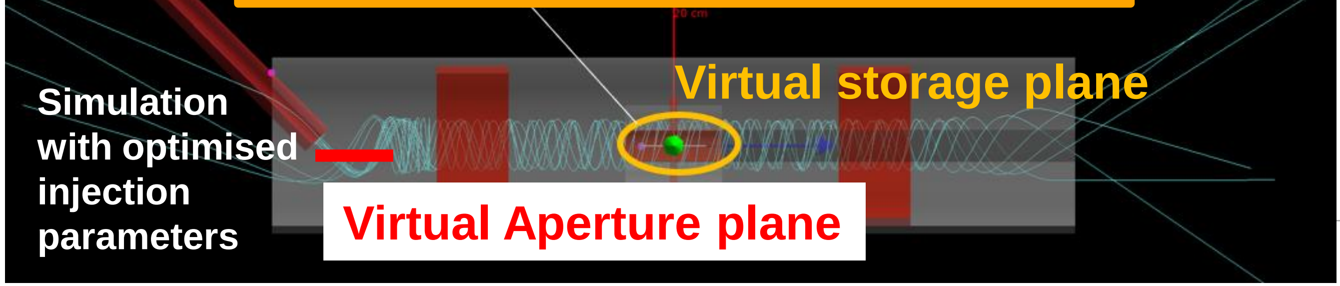
G4beamline: beam related effects

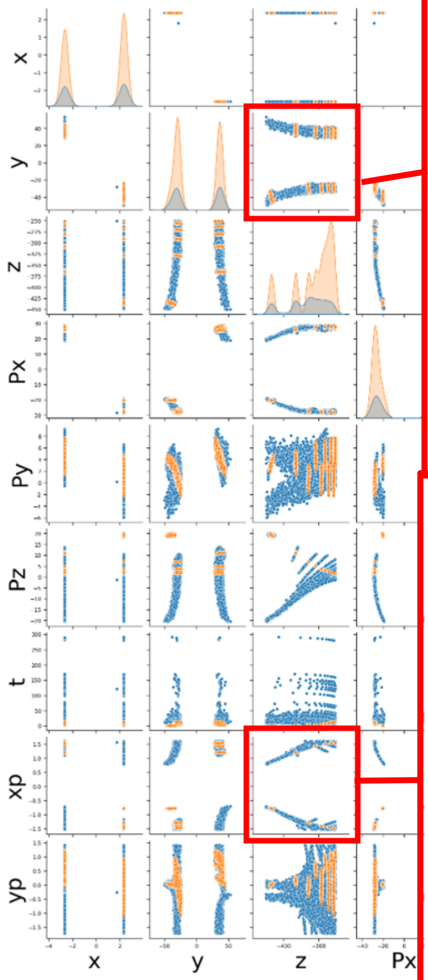
Reproduce storage efficiency

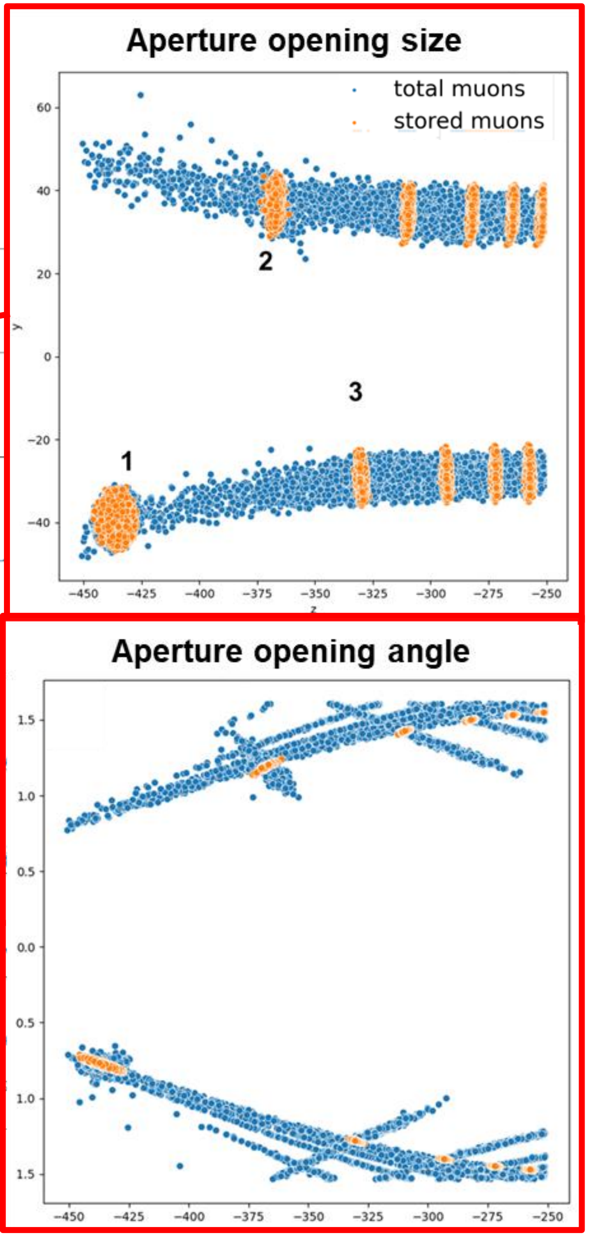
Storage acceptance map informs Aperture design geometry

μ^{+} distribution on storage plane, N_{sto}



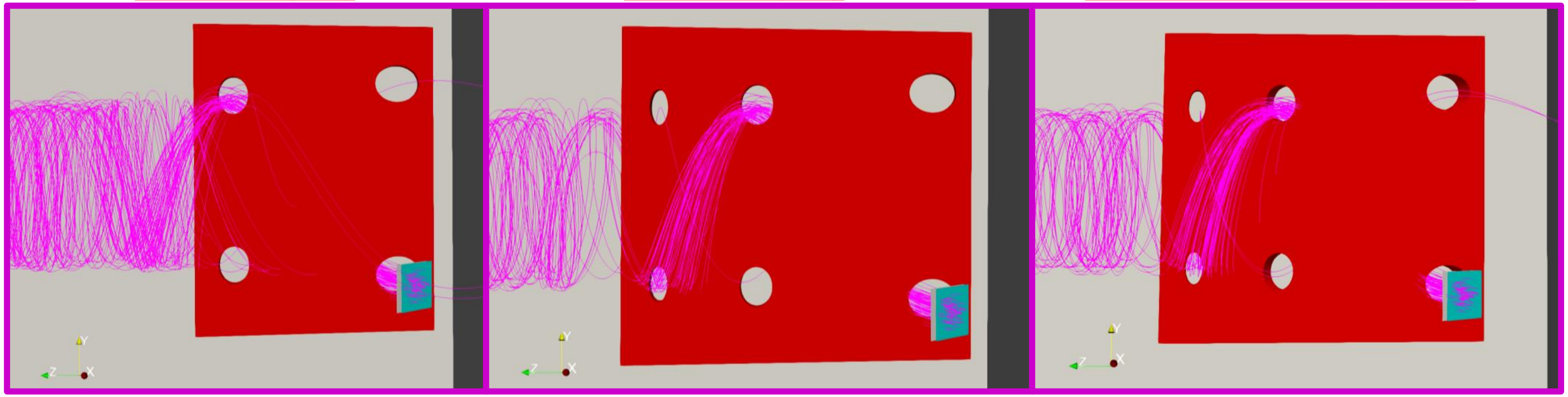






Design optimisation

2 holes (2H) | 3 holes (3H) | 3 holes slanted (3Hsl)



Caveat:
- *long μ lifetime (10^{12} s)*
- *kill all e^+*

musrSim: detector response

- **Event topology studied by obtaining relative event rates**
- **Event rates used to deduce:**

Acceptance rate,

$$\epsilon_a = \frac{\#\ storable\ \mu^+\ not\ hitting\ Aperture}{\#Actual\ storable\ \mu^+};$$

Rejection rate,

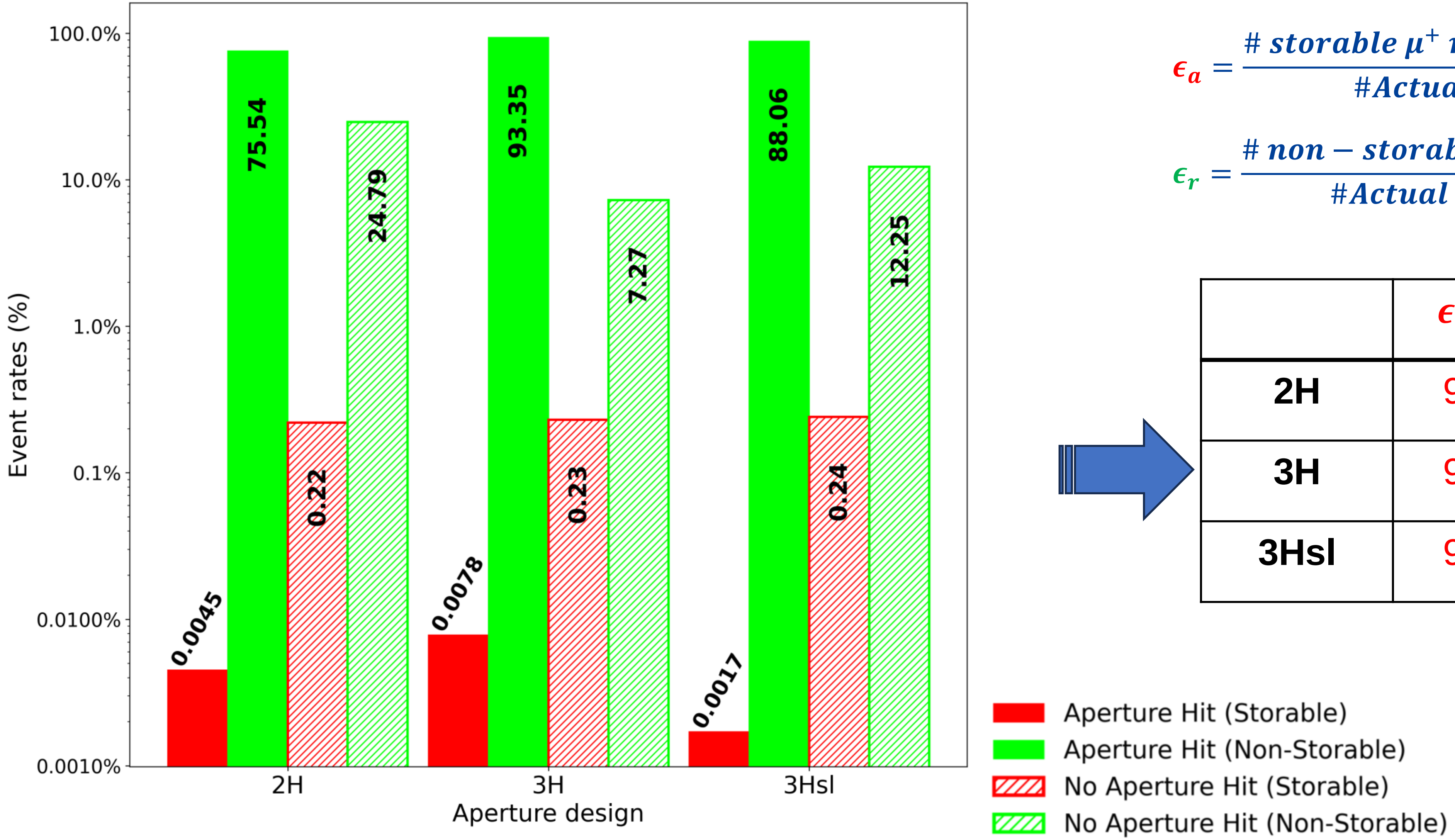
$$\epsilon_r = \frac{\#\ non\!-\!storable\ \mu^+\ hitting\ Aperture}{\#Actual\ non\!-\!storable\ \mu^+};$$

Designs are optimised for ϵ_a & ϵ_r

Truth level event rates

*with multiple scattering from Gate accounted

- **Actual storable μ^+*: 0.25%; non-storable μ^+: 99.75%**



$$\epsilon_a = \frac{\#\ storable\ \mu^+\ not\ hitting\ Aperture}{\#Actual\ storable\ \mu^+}$$

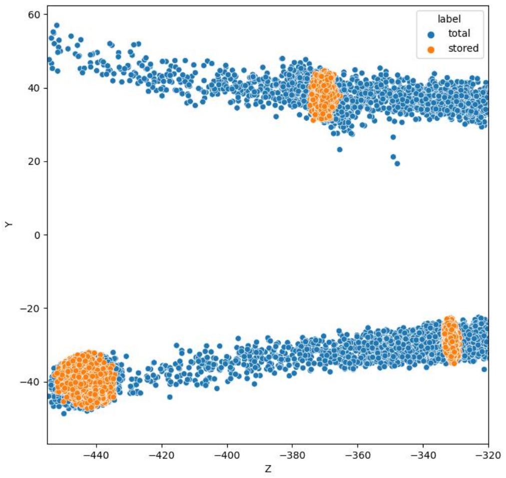
$$\epsilon_r = \frac{\#\ non-storable\ \mu^+\ hitting\ Aperture}{\#Actual\ non{-}storable\ \mu^+}$$

	ϵ_a (%)	ϵ_r (%)
2H	97.93	75.72
3H	96.81	94.18
3HsI	99.34	88.28

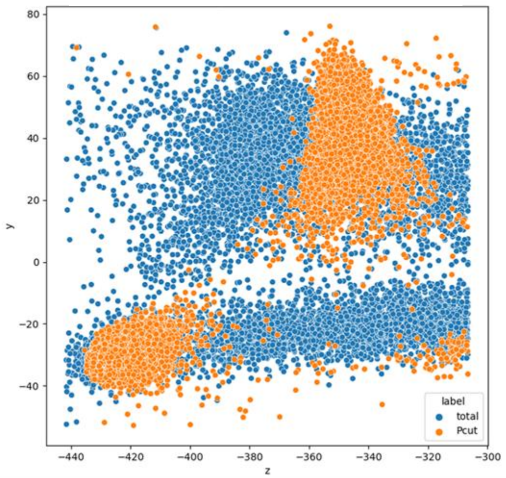
Test beam design

- **TrigDet-TB24: design variant to accommodate PSI October 2024 test beam condition**
  - Magnetic field: 3 T → 0.78 T (superconducting injection channels not ready, 3 T produces strong fringe field)
  - Beam momentum: 28 MeV/c → 14.6 MeV/c (retain same track orbit radius from the scaled down B-field)
- **Aperture geometry strongly dependent on B-field and beam momentum**
- **TB24 conditions inflict larger Aperture opening**

μ^+ 28 MeV/c @ 3T

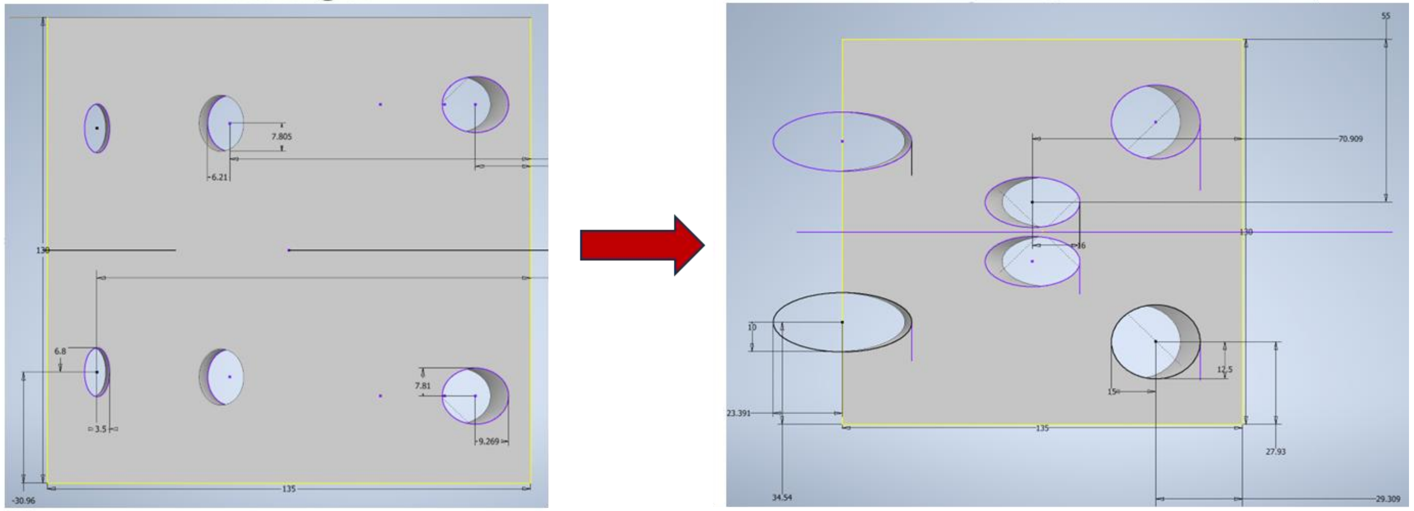


μ^+ 14.6 MeV/c @ 0.78 T



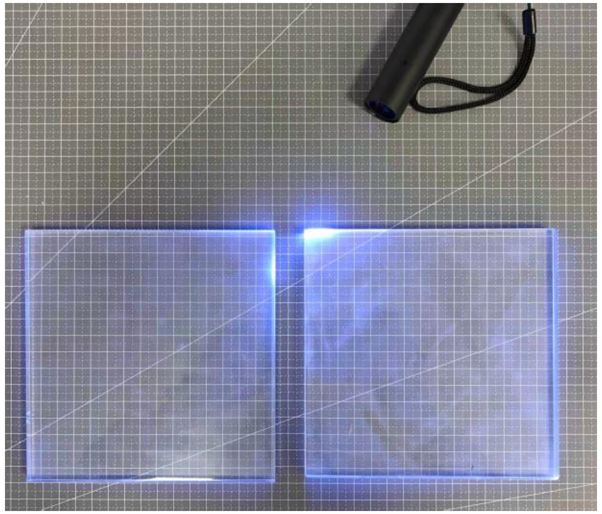
28 MeV/c @ 3T

14.6 MeV/c @ 0.7 T



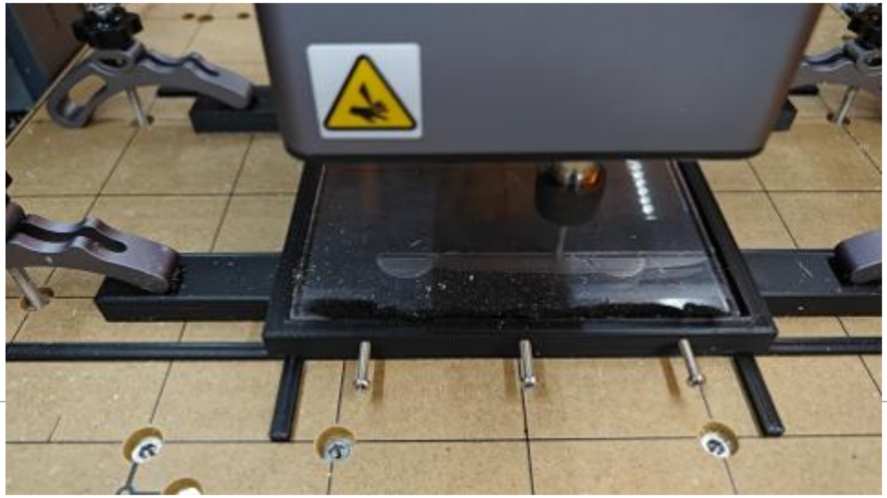
Detector construction

- **Aperture fabrication: high precision hole drilling with in-house CNC machine**



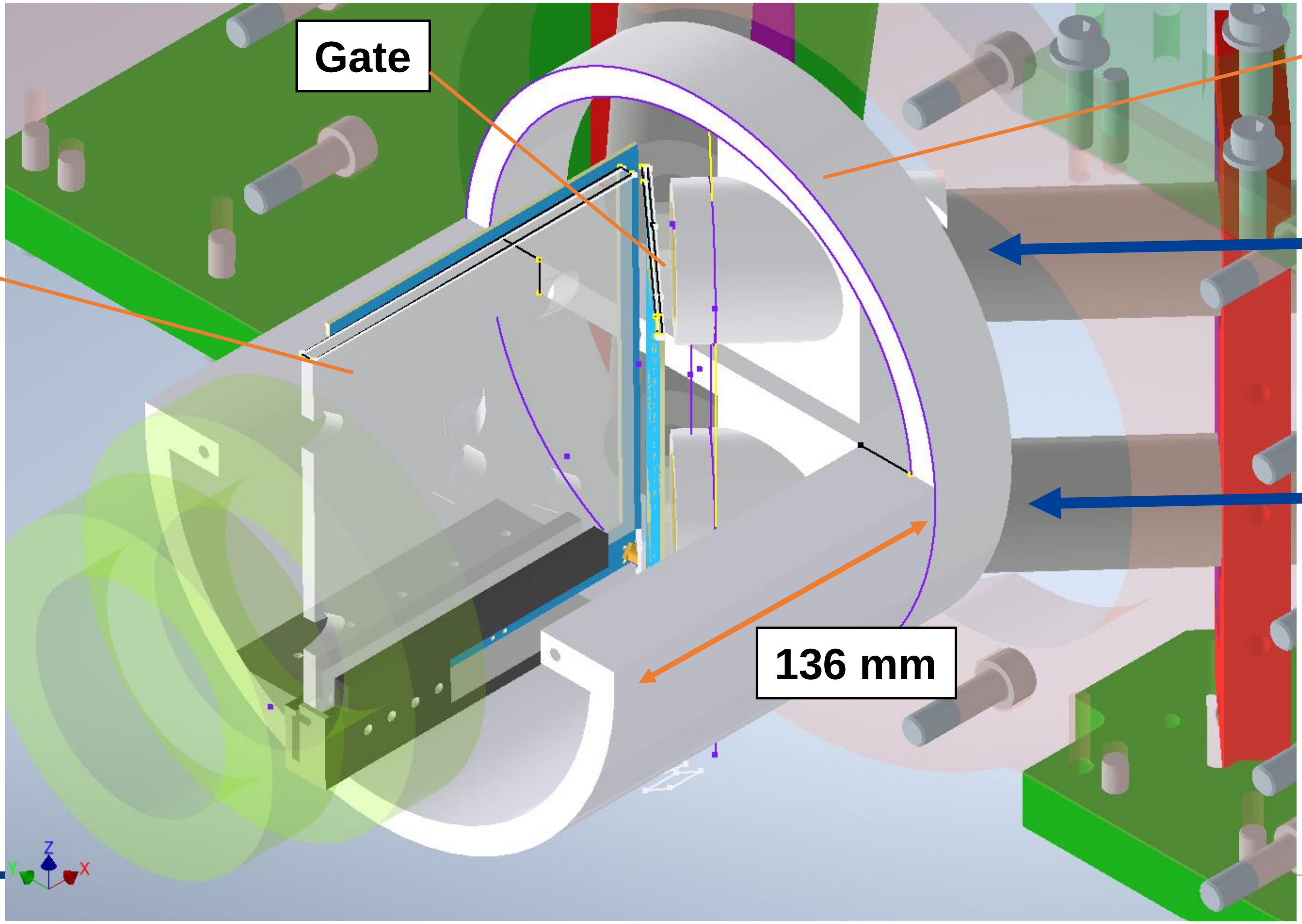
- Eljen EJ-200 plastic scintillator cube processed by USTC workshop
- Slabs of plastic scintillators processed in the dimensions 135 mm * 130 mm * 5 mm

- CAD model of Aperture imported to CNC cutter terminal
- 0.1 mm precision cutting achieved with CNC cutter and dedicated support platform



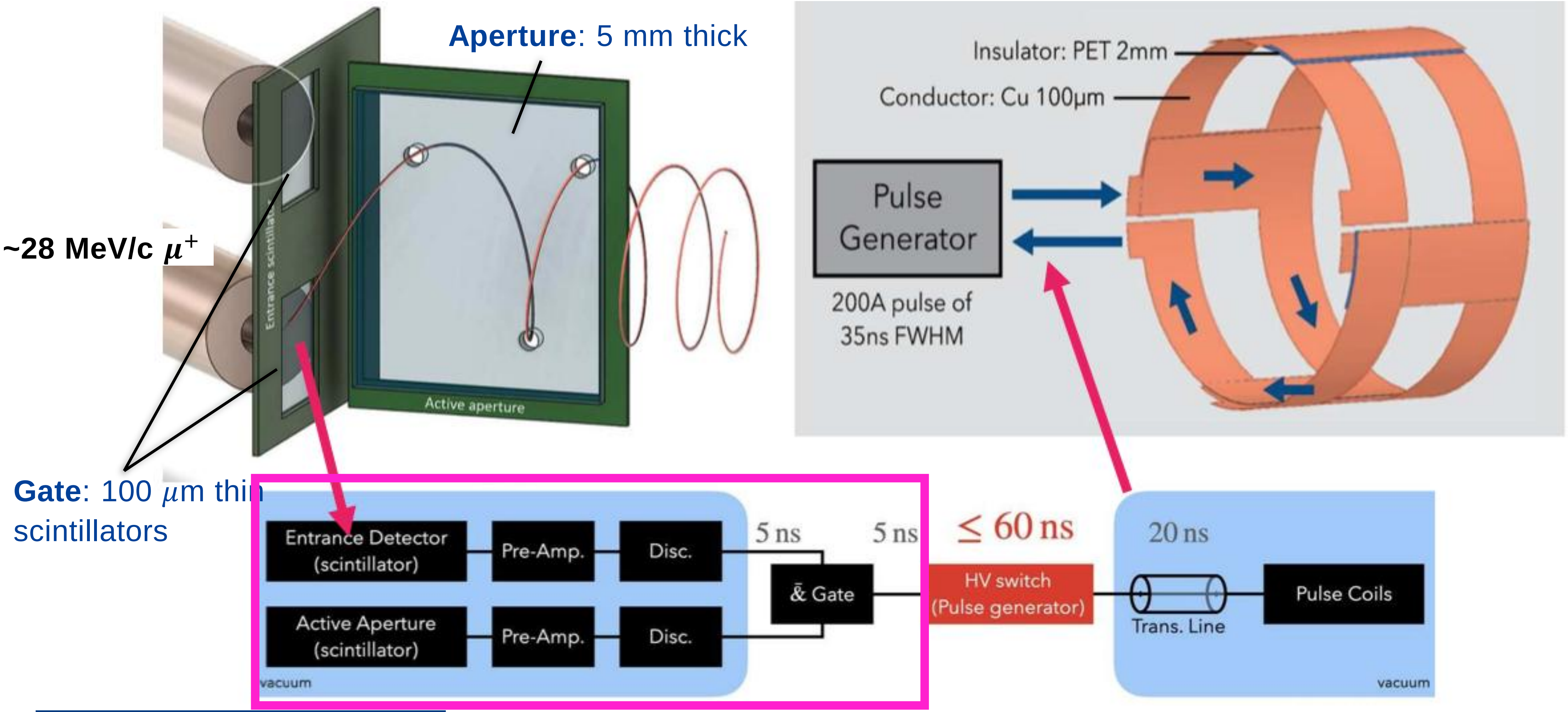
Detector construction

- **Dedicated mechanical support structure with 3D-printing**

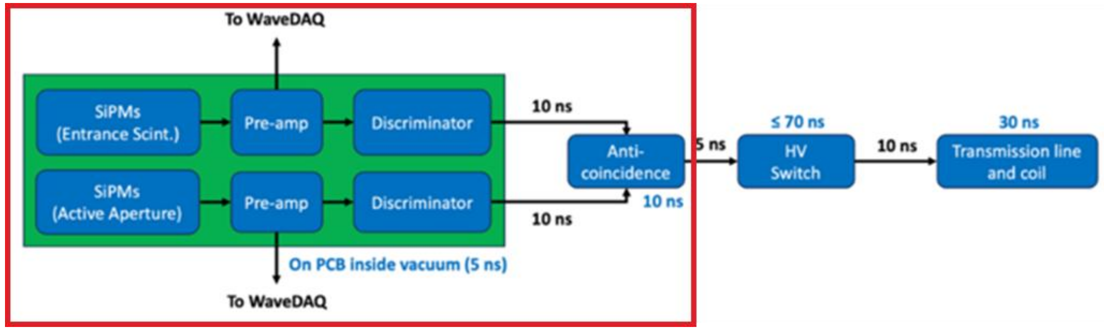


Fast electronics

Conceptual sketch of the Phase-1 trigger detector

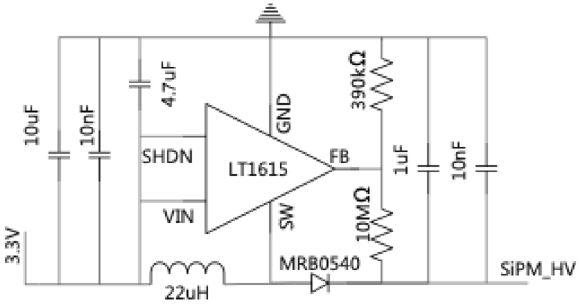


Fast circuit schematics

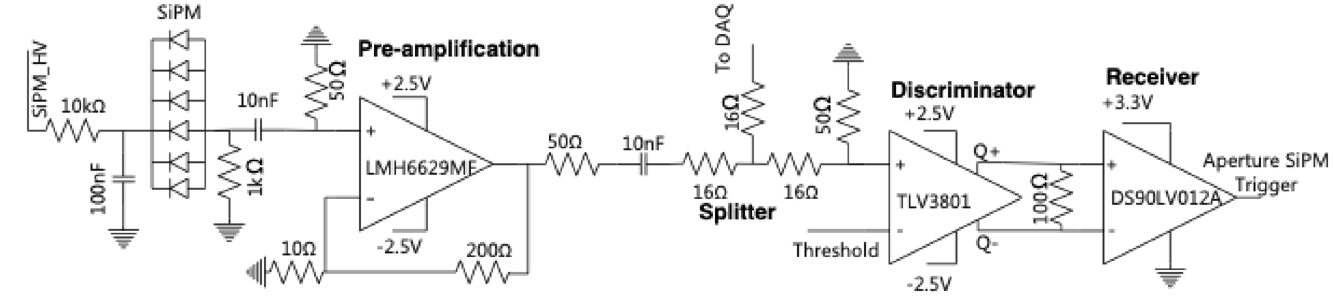


- **Fast circuitry design**
- **Produces signal at $t \leq 15$ ns**
- **Anti-coincidence LVTTL signal**
- **Integrates step-up converter, pre-amp, and discriminator**

Step-up DC-DC Converter

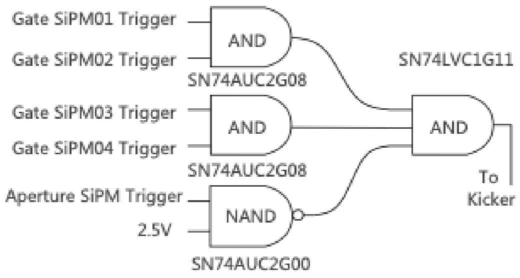


Aperture SiPM Electronics Readout

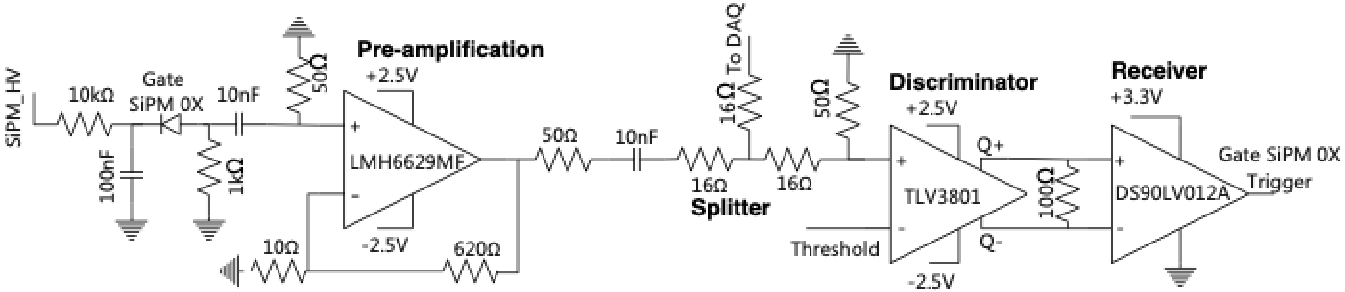


Courtesy of **HU** Tianqi

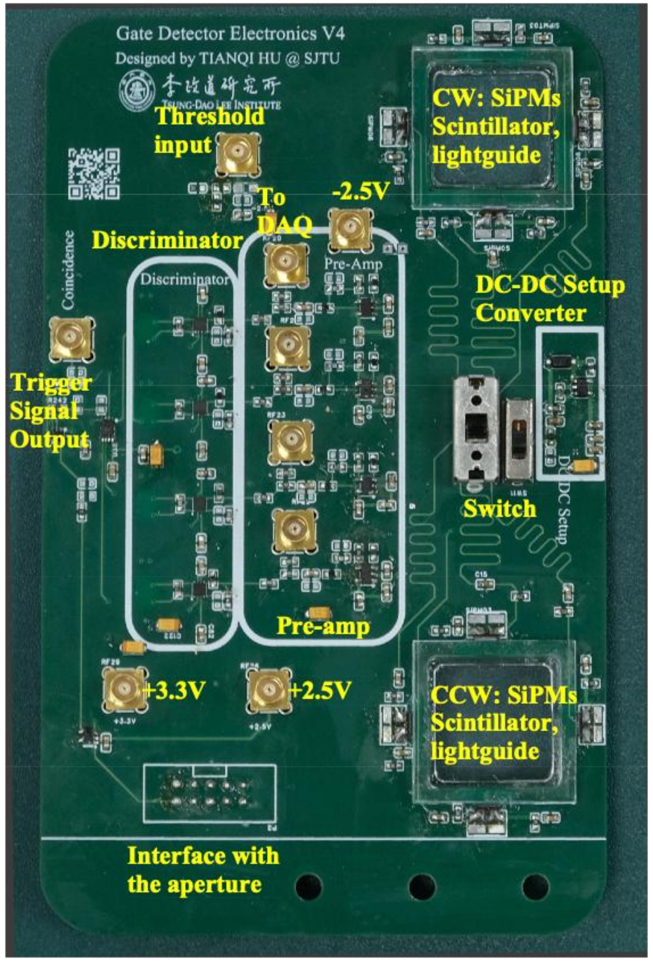
Anti-Coincidence Circuit



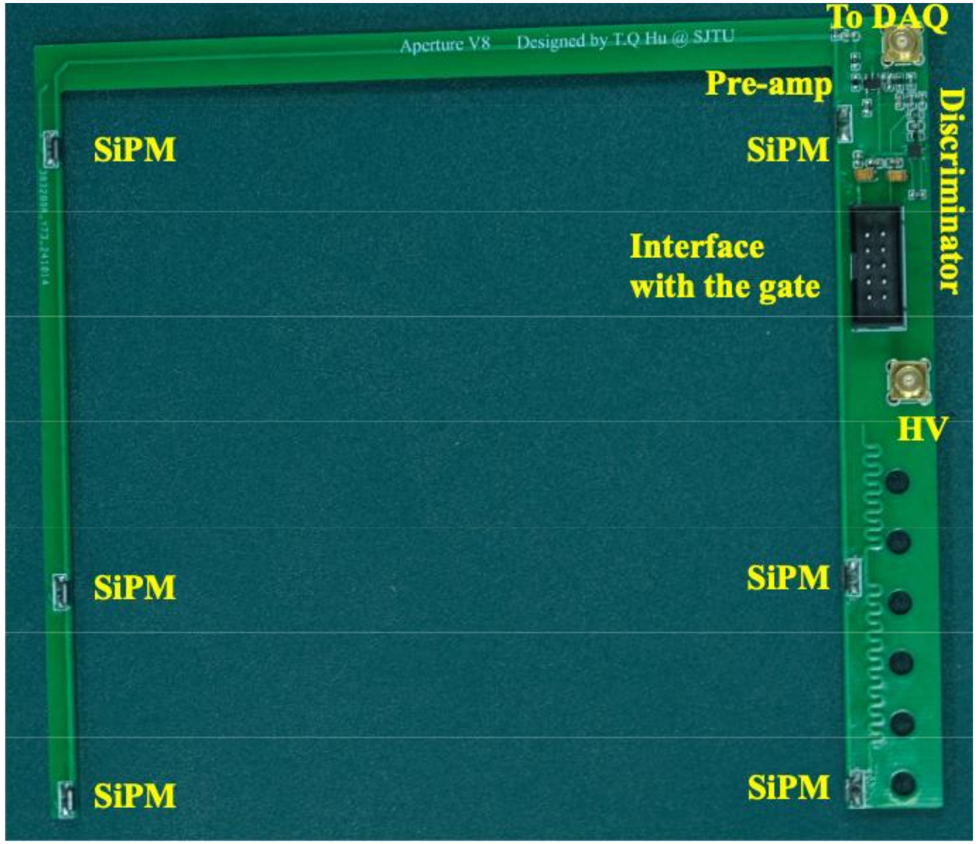
Gate SiPM Electronics Readout



Fast electronics prototype



Aperture signal transmitted to Gate PCB

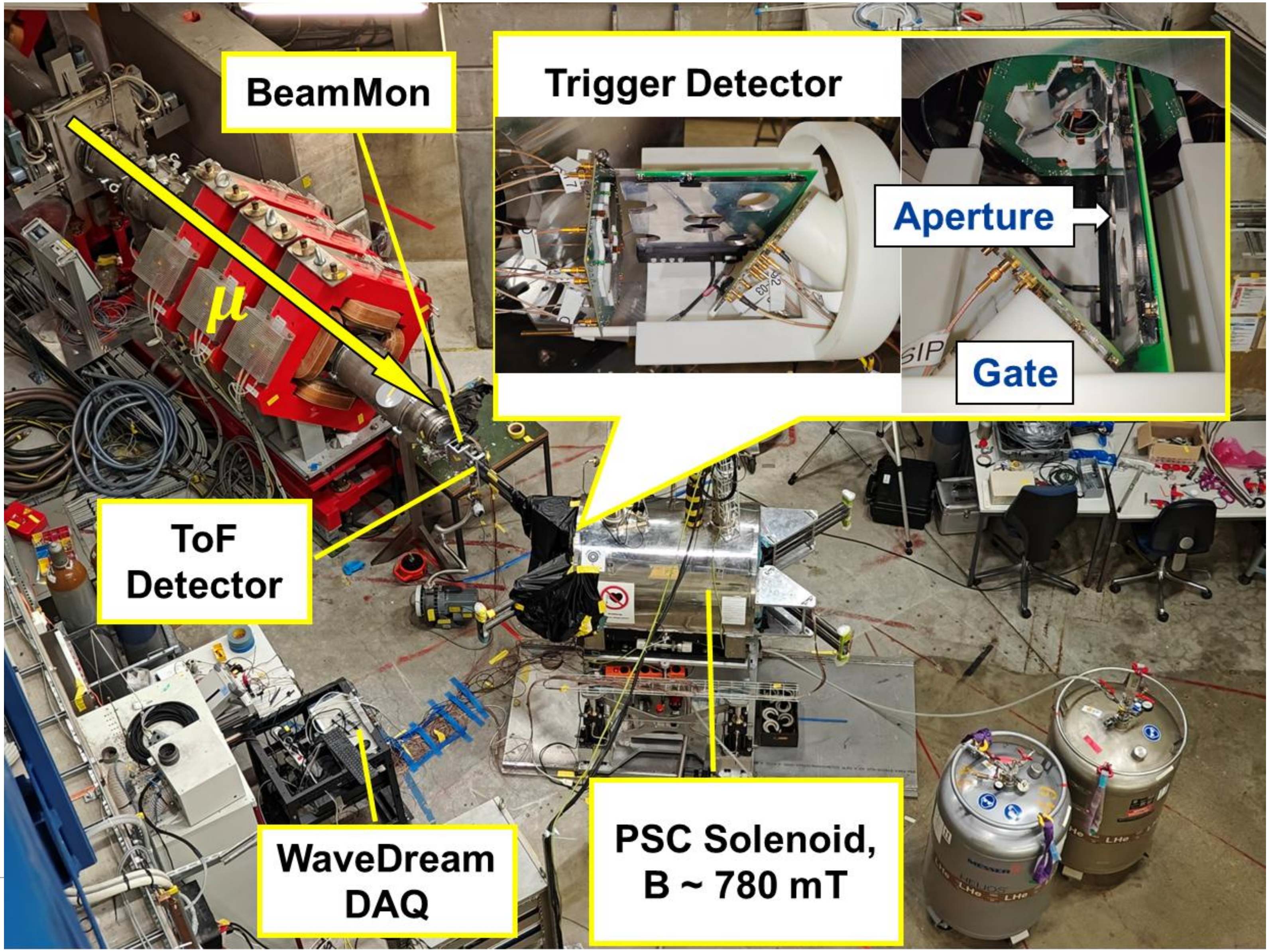


Gate PCB
- Four channel read-out of Gate SiPMs
- Produces LVTTL signal on anti-coincidence

Aperture PCB
- Six SiPMs in parallel
- Single channel read-out

Test beam 2024 (TB24)

- **Test spiral injection**
  - Clockwise (CW) and counter-clockwise (CCW) injection
  - Momentum control when switching between CW and CCW injection
- **Characterise Trigger Detector**
  - Performance of fast electronics readout
  - Acceptance rate and rejection rate
  - Induced background studies



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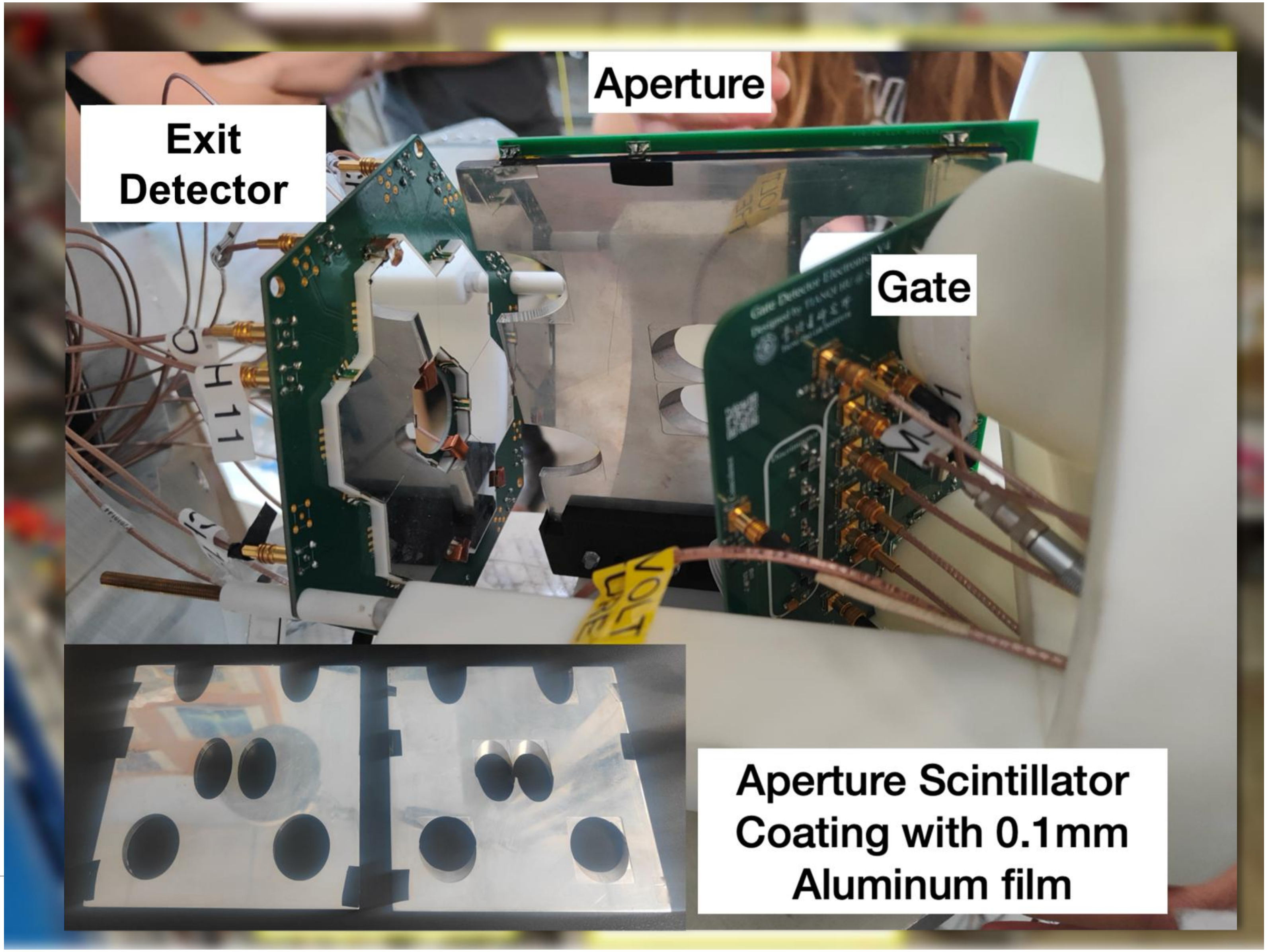
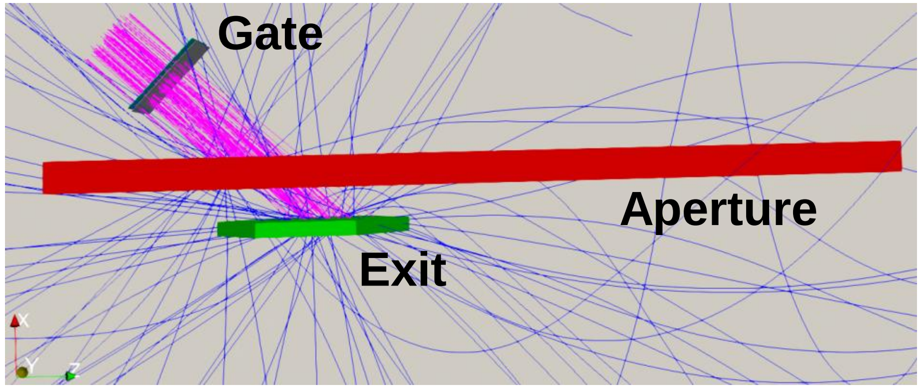


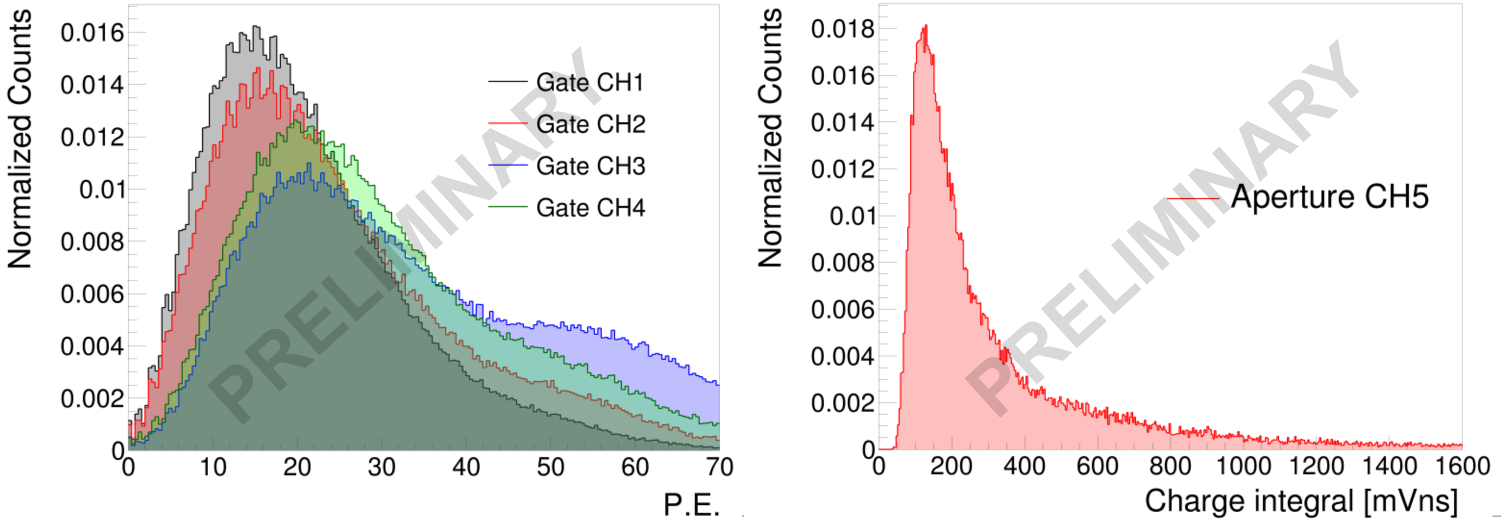
Test beam 2024 results

- **Analysis goals**
  - Obtain charge distribution to study detector response
  - Obtain event rates for event topology study
  - Measurement-simulation agreement of event topology fractions informs trigger detector performance (detector response) → **answers *precise* requirement of muEDM**
- **Prelim analysis focus on muon data set:**

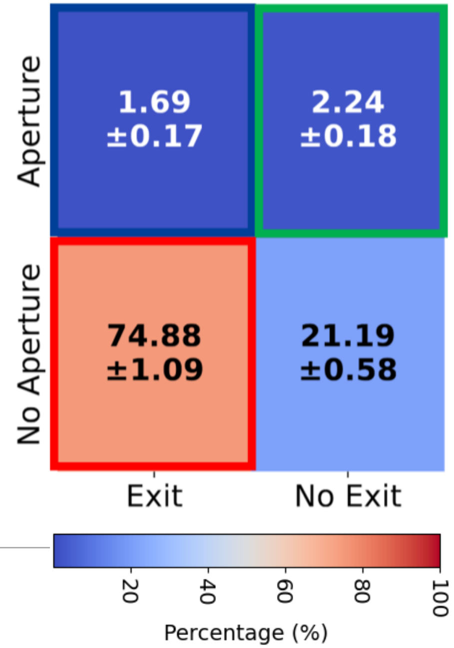
TB24 simulation setup

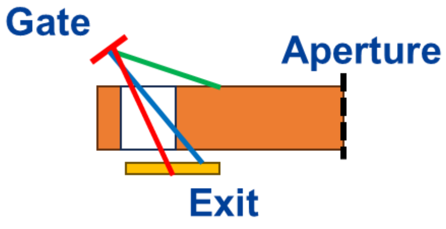


Detector charge distribution



Measured event rates

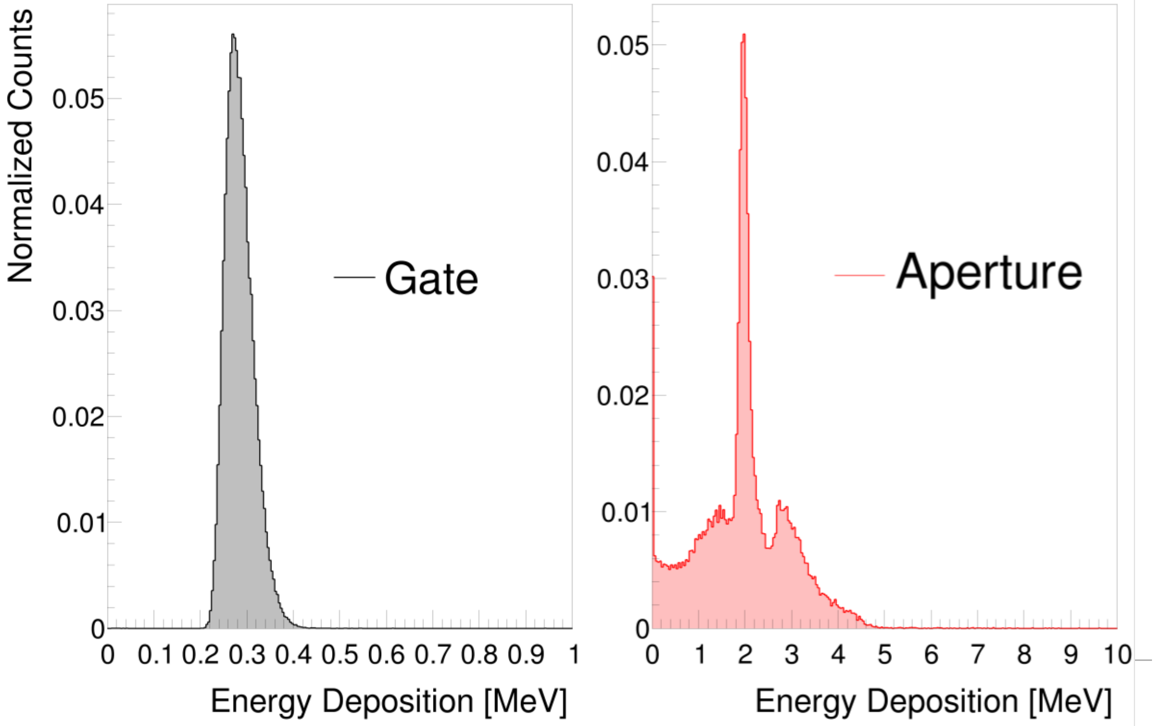




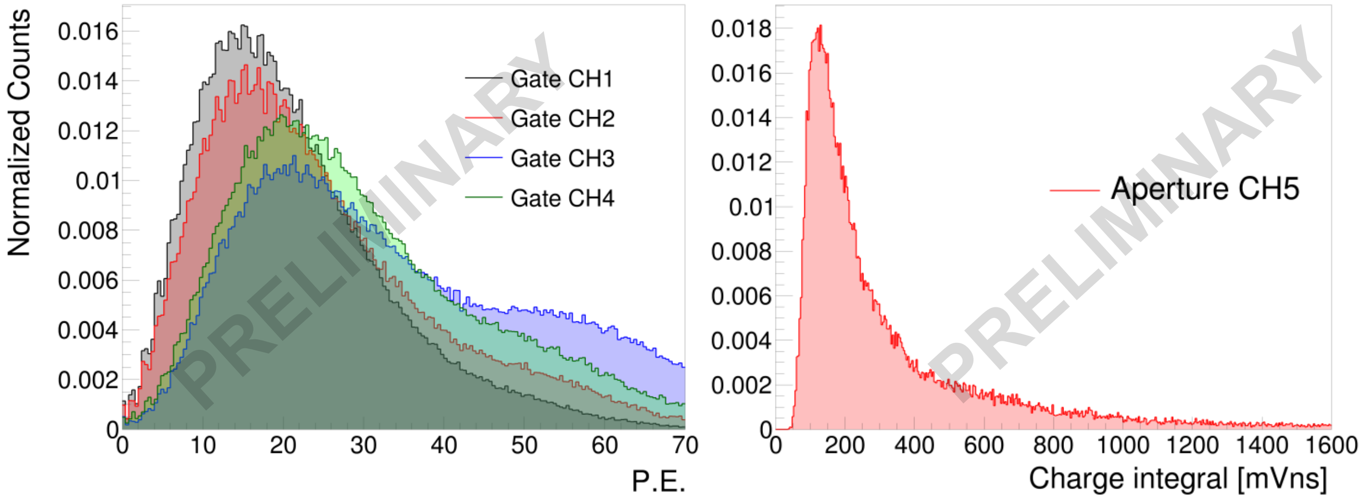
Validating measurement

- **Optical photon distribution compared between measurement and simulation**
- **Comparison informs optical photon number cut to be applied in analysis of simulation output**

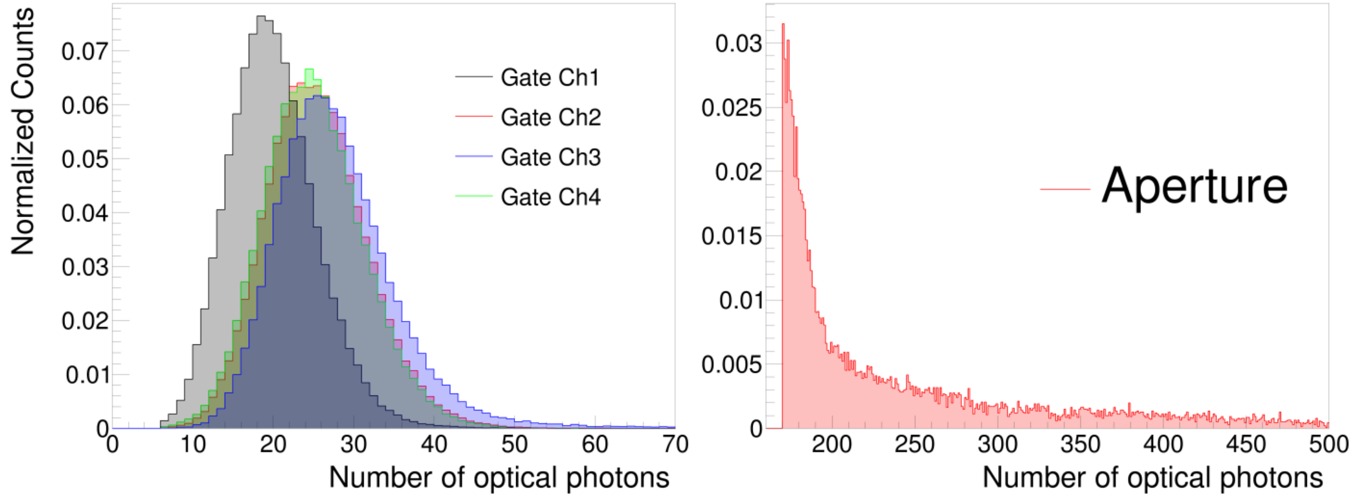
Truth level energy deposition



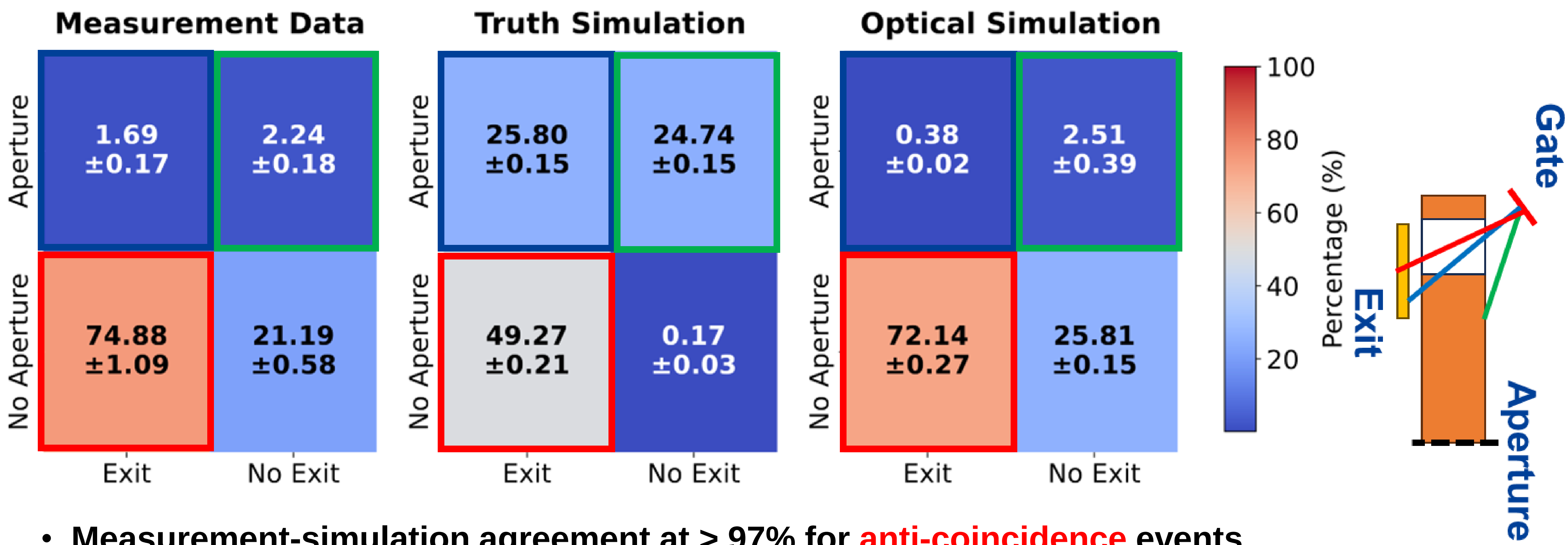
Measured charge distribution



Simulation optical photon



Validating measurement

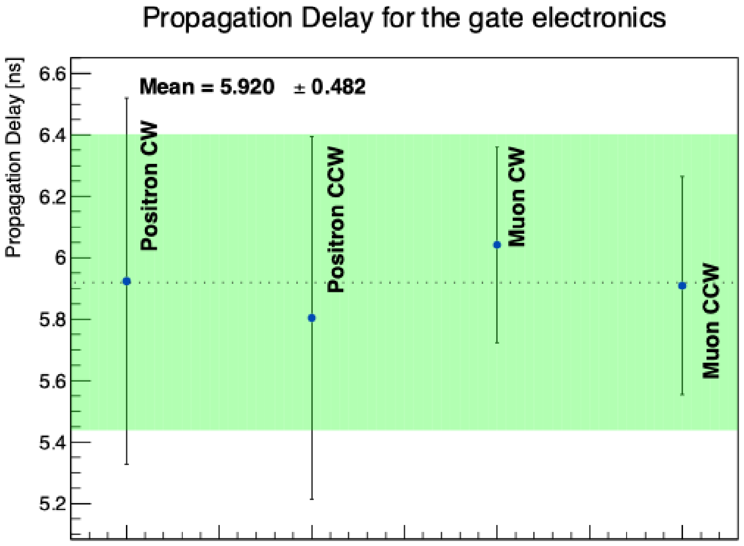


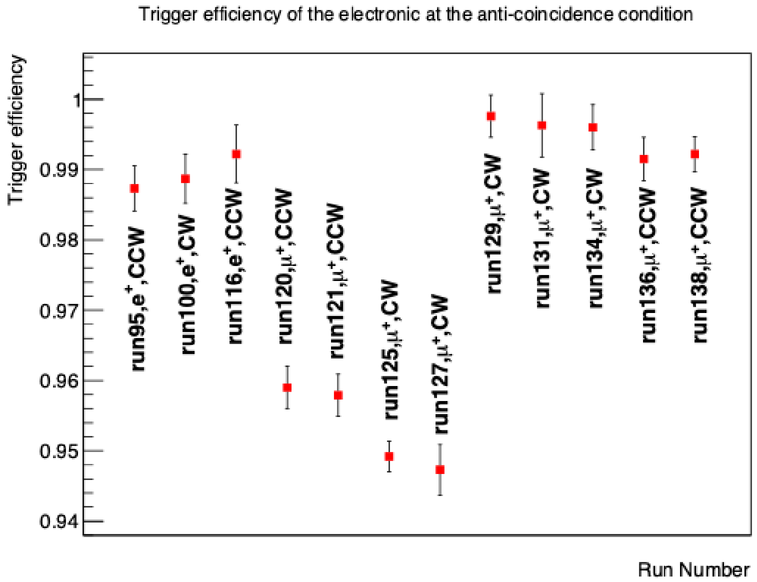
- Measurement-simulation agreement at > 97% for anti-coincidence events
- Confirms reproducibility of detector response in simulation
- Residual discrepancies due to simplified optical interfaces

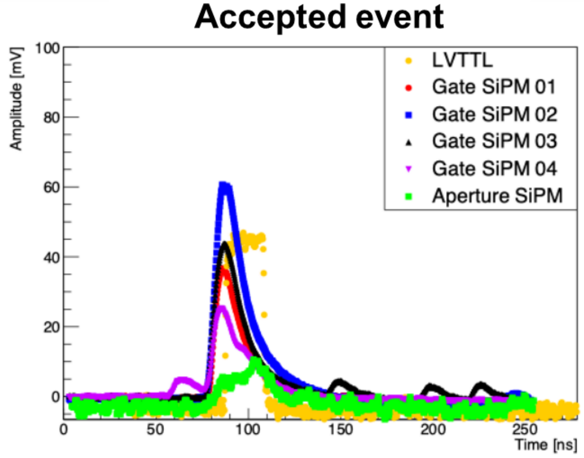
Fast electronics performance

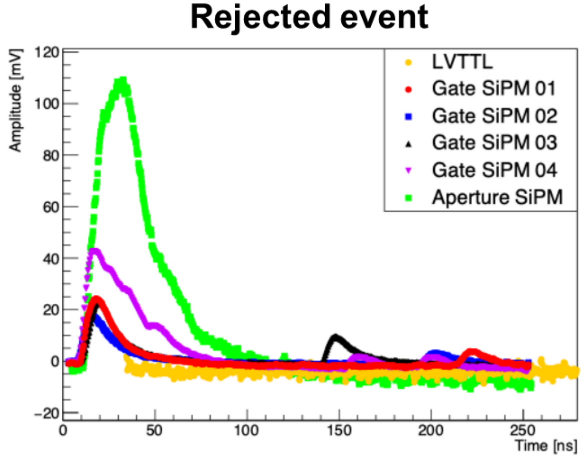
李政道研究所 Tsung-Dao Lee Institute

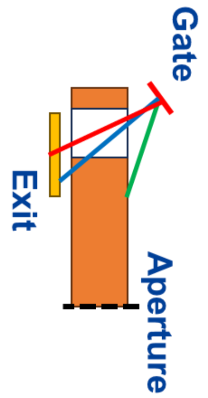
- **Propagation delay of trigger detector, t_{pd}**
  - Define t_{pd} as time interval of SiPM signals and LVTTL
  - ✓ $t_{pd} \sim 5.92 \pm 0.48$ ns, meets fast requirement of $t_{delay} \leq 15$ ns
- **Trigger efficiency**
  - Anti-coincidence efficiency ~ acceptance rate
  - Coincidence efficiency ~ rejection rate
  - ✓ Both rates at $\geq$ 99%











arXiv: 2502.11186
submitted to IEEE TNS

Summary

- **A muon trigger detector is developed for the muEDM experiment**
- **The muon trigger detector produces a signal to trigger the pulse kicker for muon storage**
- **Simulation design**
  - ✓ Aperture geometry obtained from acceptance map study
  - ✓ $\epsilon_{acc} \approx 99\%$, $\epsilon_{rej} \approx 90\%$
- **TrigDet prototype tested at test beam 2024 at PSI πE1 beamline**
  - ✓ **Measurement-simulation agreement at > 97%**
  - ✓ Fast electronics with $\boldsymbol{t_{pd} < 15\ \mathrm{ns}}$ and **trigger efficiencies $\geq$ 99%**
  - ✓ Demonstrates design scheme fulfilling muEDM requirements
- **Established a development scheme for future iterations**

***Beam test performance of a prototype muon trigger detector for the PSI muEDM experiment*, [arXiv.2501.01546](https://arxiv.org/abs/2501.01546) (accepted at RDTM)**

***Development of fast front-end electronics for the Muon Trigger Detector in the PSI muEDM Experiment*, [arXiv.2502.11186](https://arxiv.org/abs/2502.11186) (under review at IEEE TNS)**

Bayesian optimization of beam injection and storage in the PSI muEDM Experiment, arXiv.2503.01607 (in preparation)