



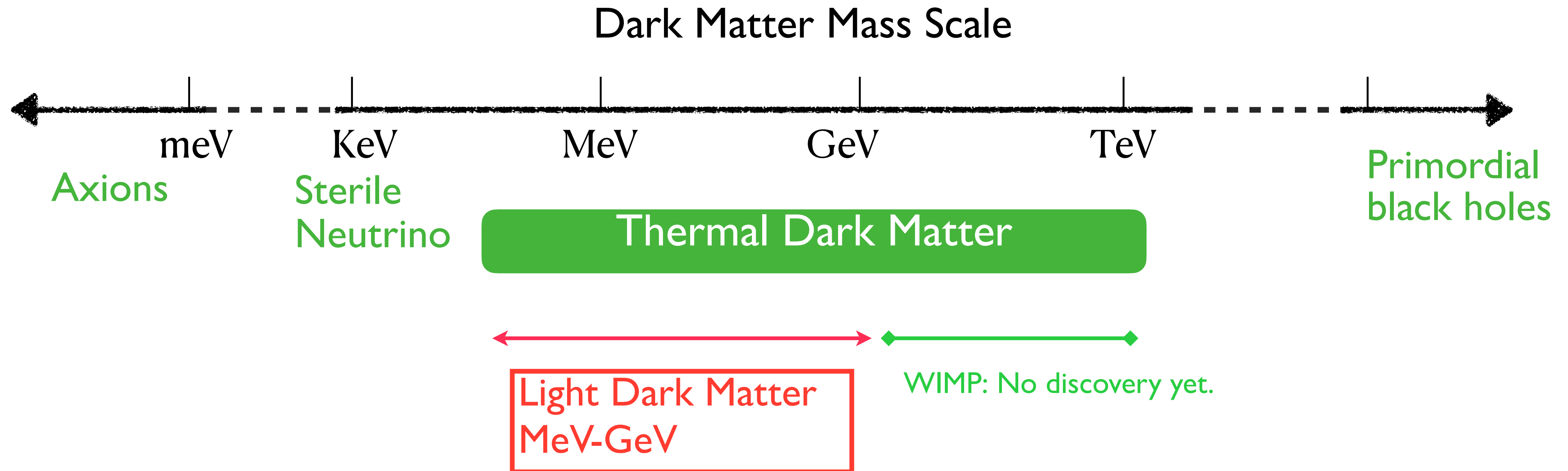
DarkQuest - Probing Dark Sector with a Proton Fixed-Target Experiment at Fermilab

Yongbin Feng (Fermilab)

MEPA 2023 Workshop, Hefei, Anhui

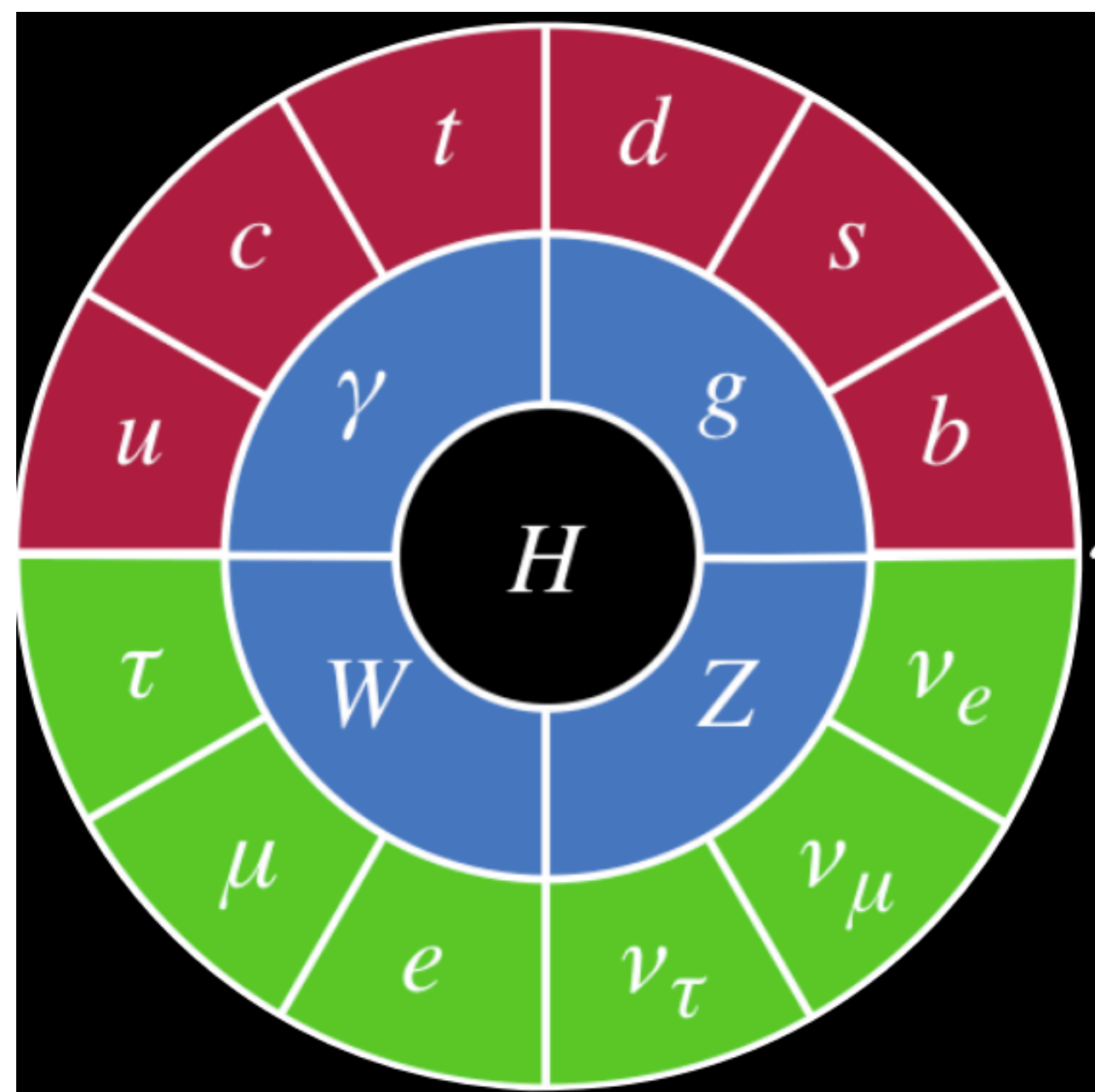
October 20th, 2023

Light Dark Matter



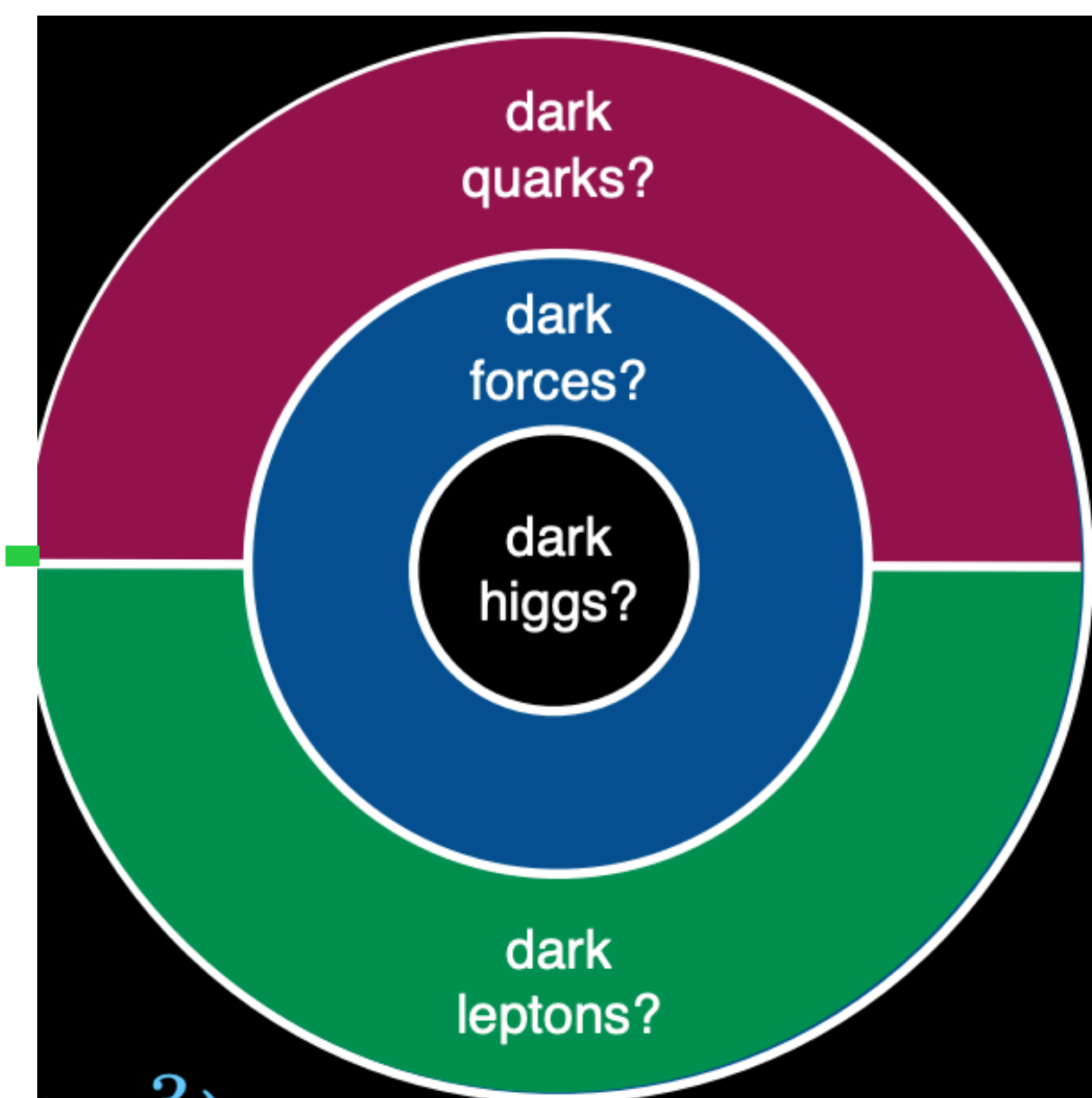
- Thermal dark matter is very promising and well motivated dark matter candidates:
 - ✦ Easily realizable, predictive, UV insensitive
- Light dark matter requires light mediators -> **Dark Sector**

Dark (Hidden) Sector



SM

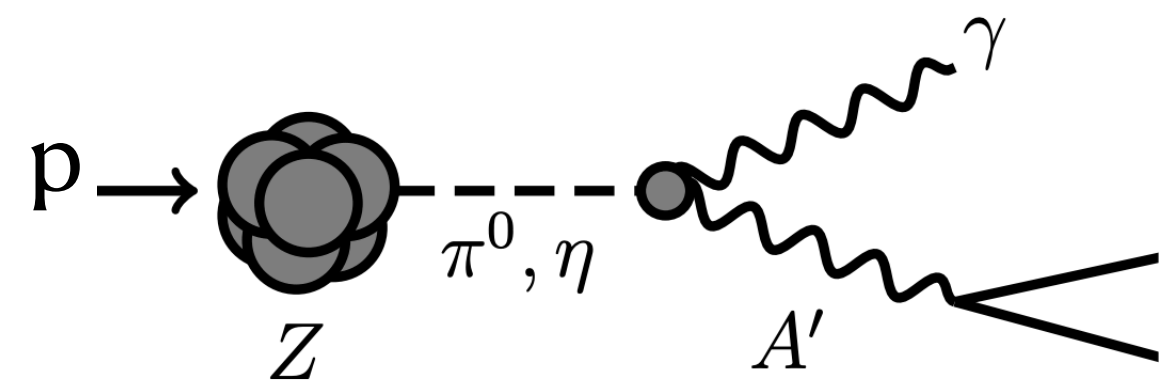
- Vector Portal: dark photons
- Higgs Portal: dark scalar
- Neutrino Portal: heavy neutral leptons
- Axion Portal: Axion-like particles



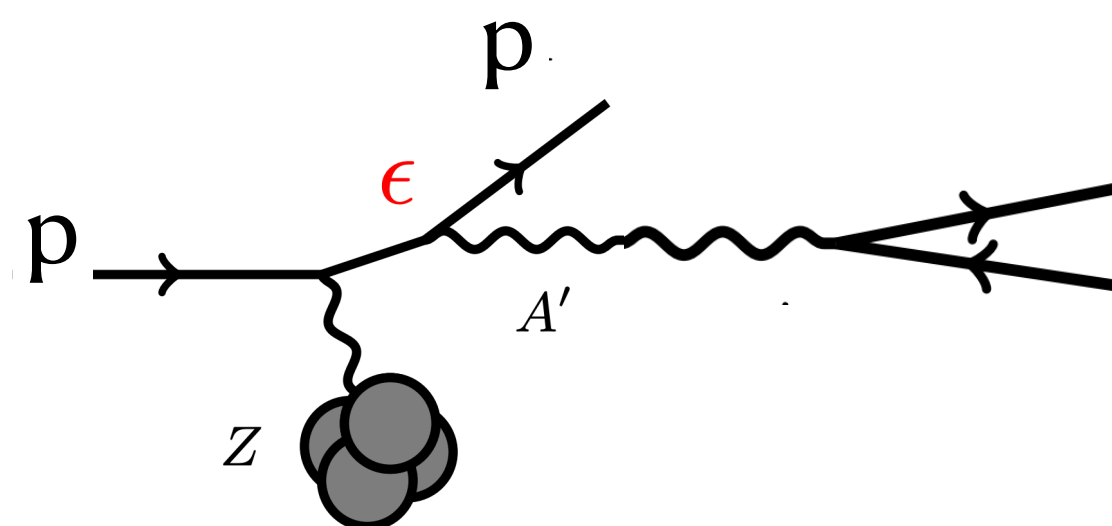
DM

- Dark Sectors can connect to SM sectors via some new couplings.
- Can probe the dark sector by looking at the dark mediators and their decay products: missing E/p/m, displaced lepton/hadrons, etc
- High-intensity accelerators and fixed-target experiments provide an ideal environment to probe dark sector physics in MeV-GeV range

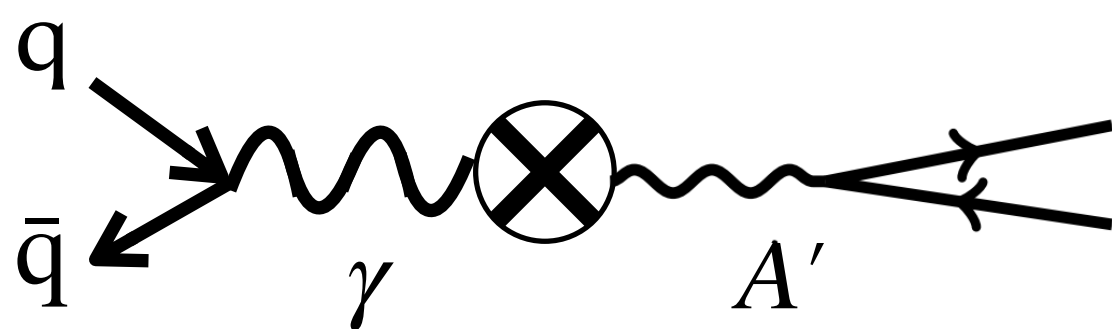
Example: Dark Photon Production with Proton Fixed-Target



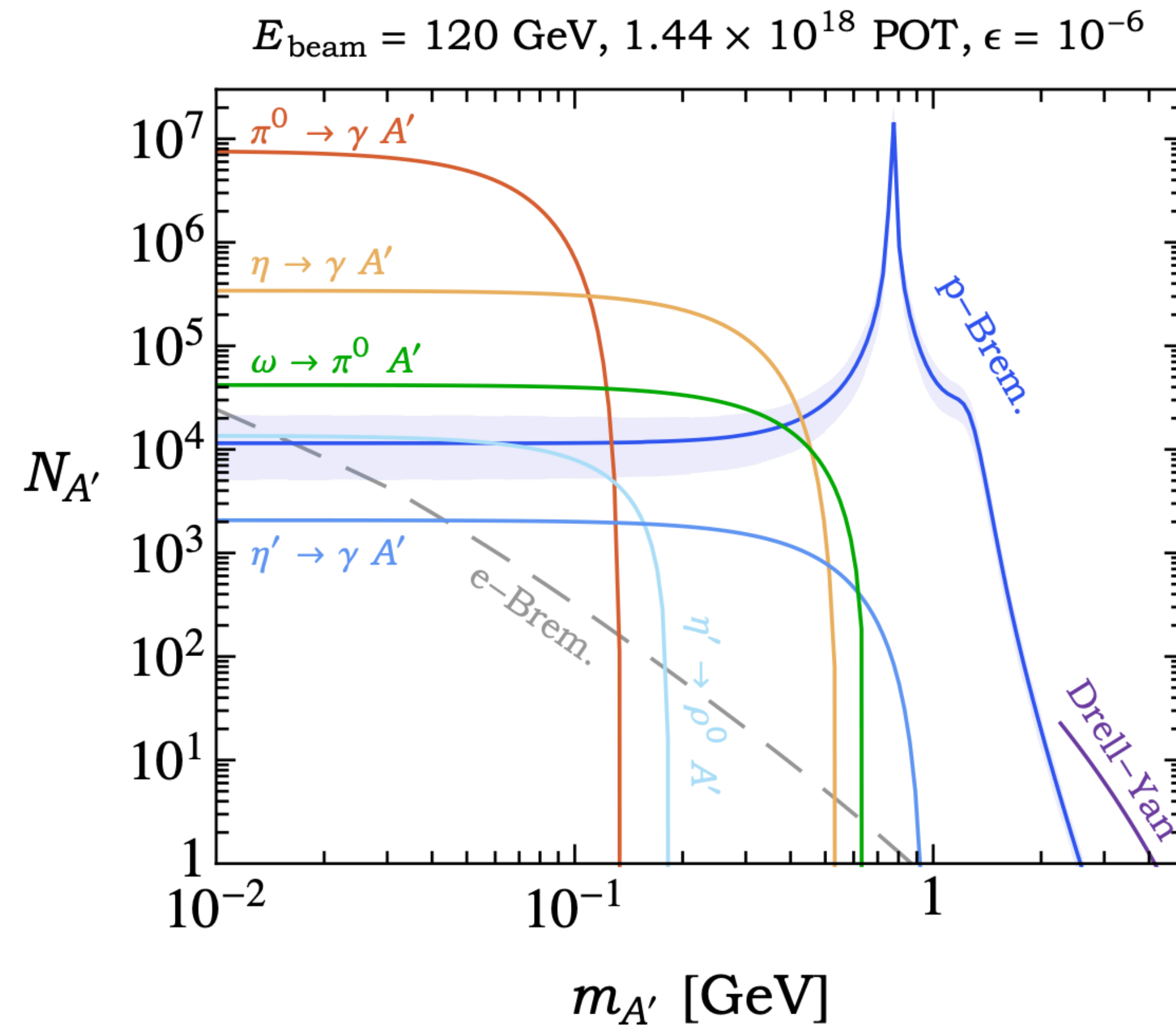
Meson decays



Proton bremsstrahlung



Drell-Yan process

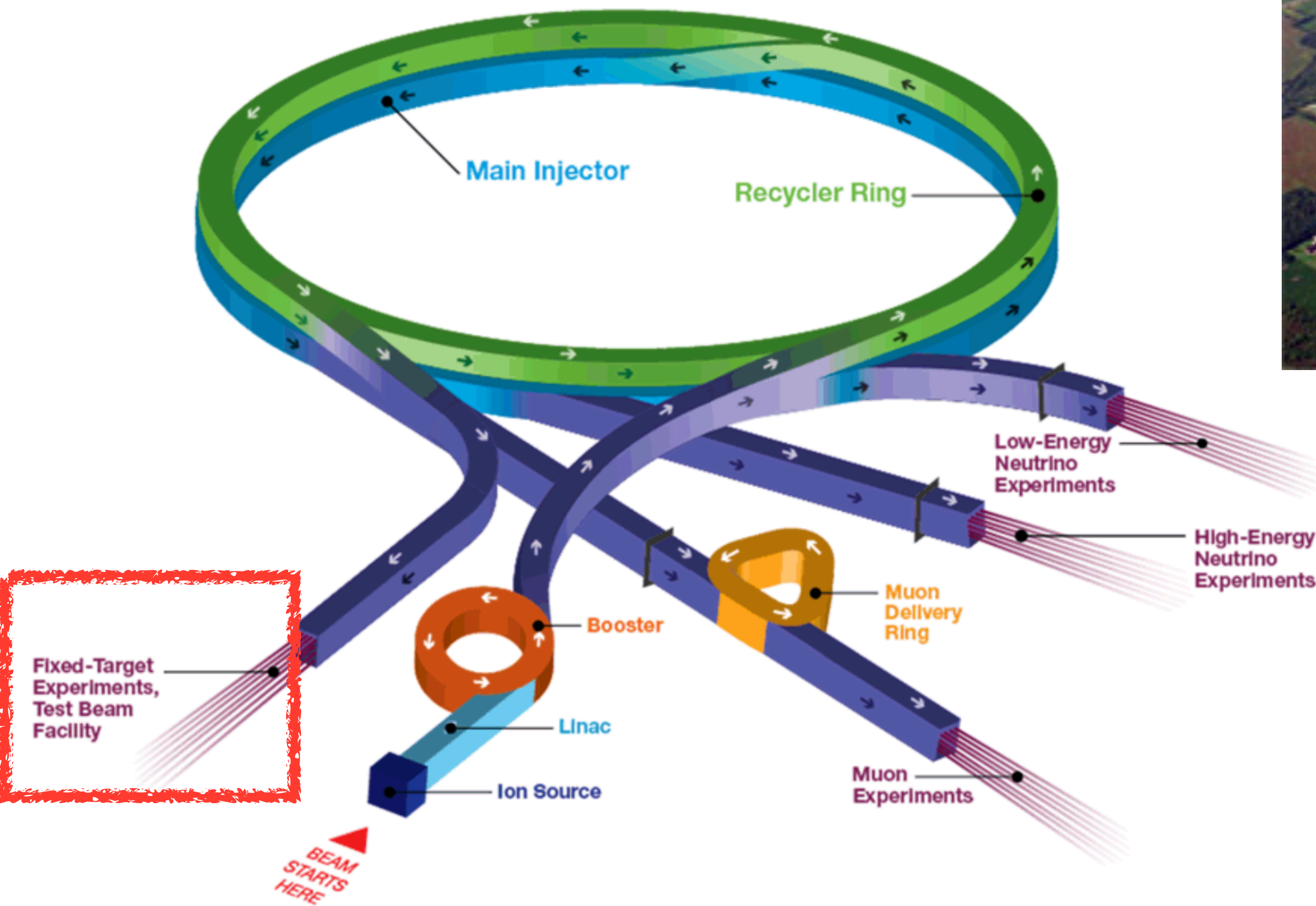


A.Berlin, S.Gori,
P.Schuster, N.Toro
Arxiv:1804.00661

- Large production rates with proton beams

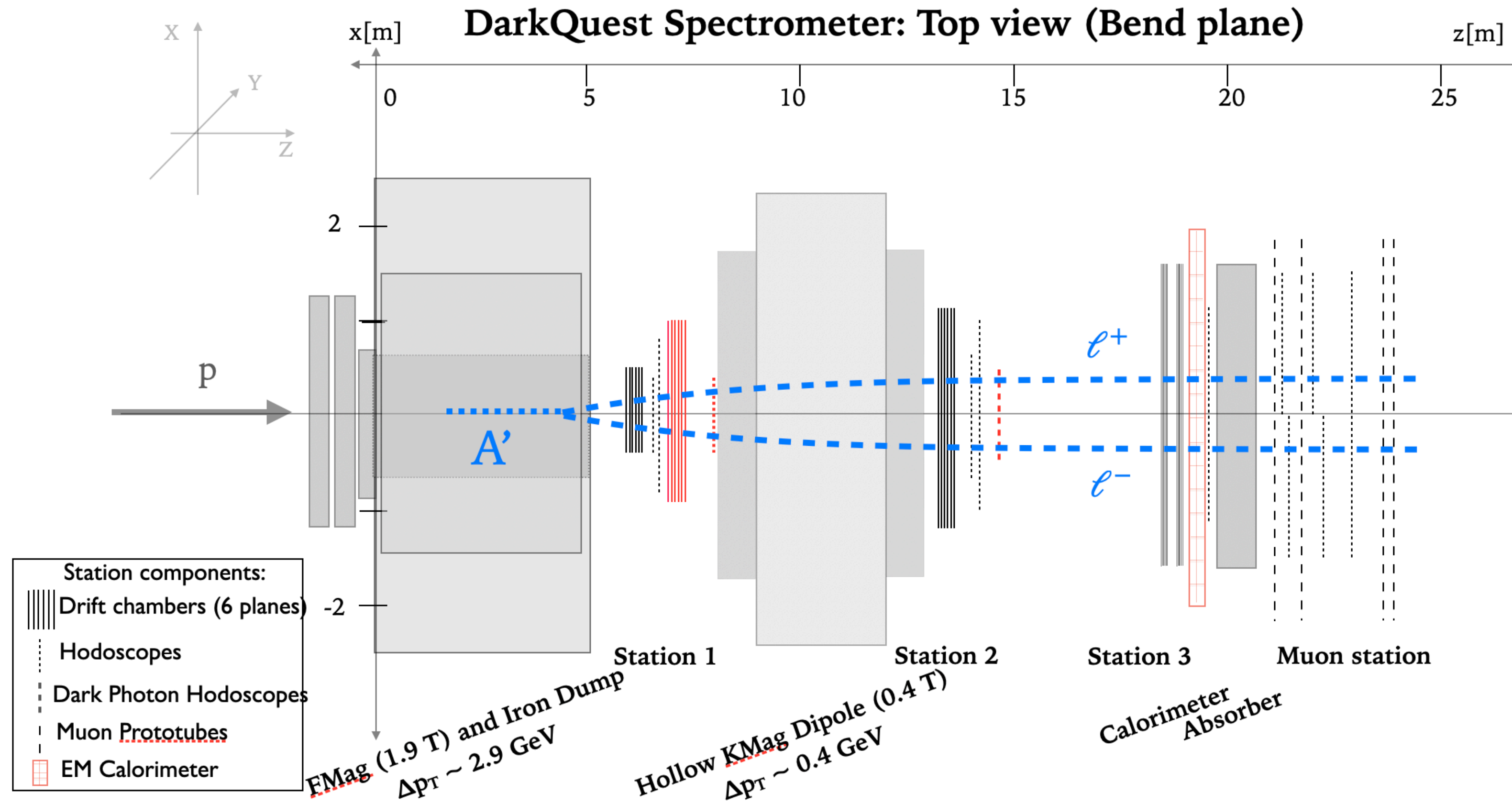
120GeV Proton Beam

Fermilab Accelerator Complex



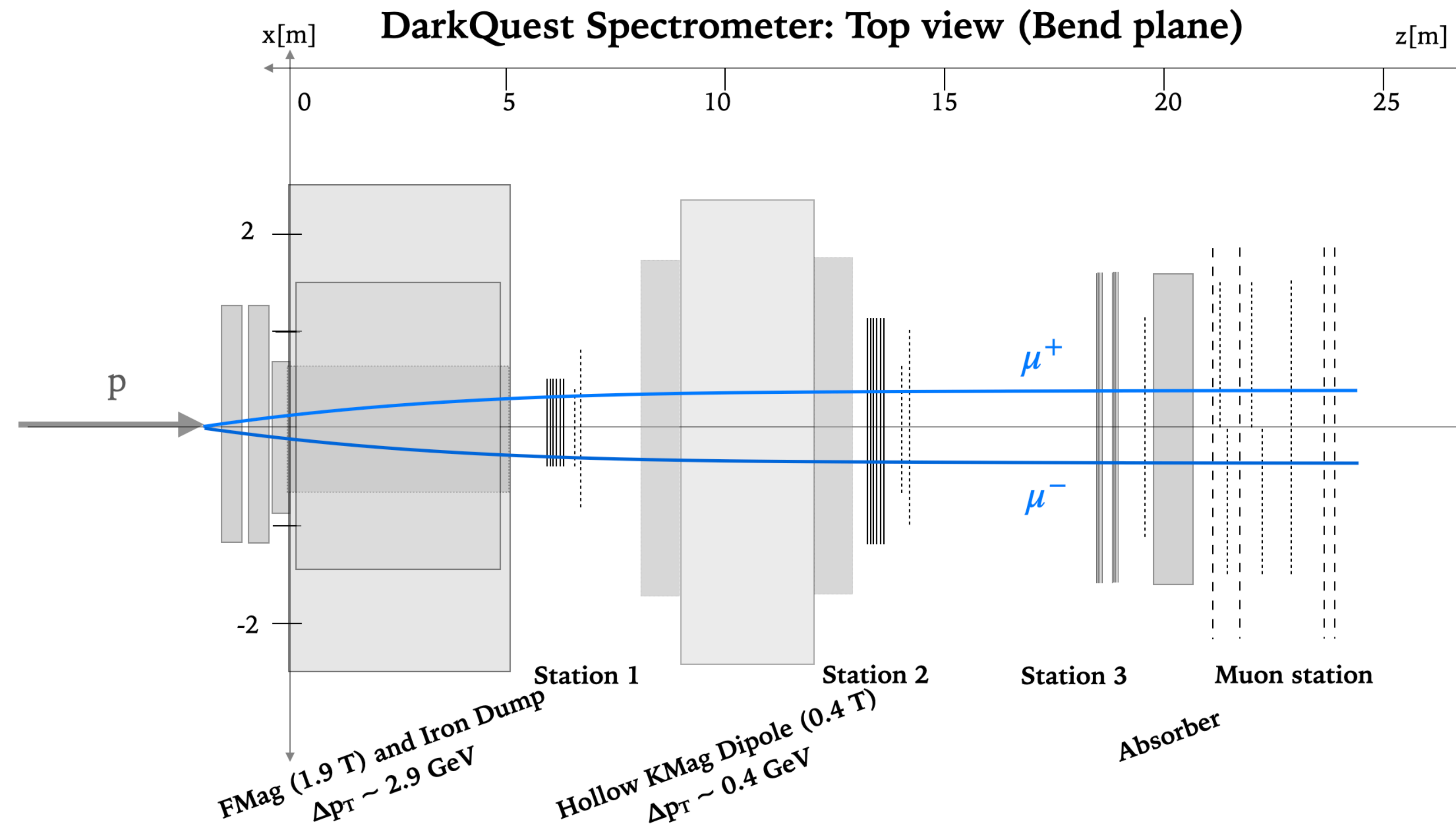
- 120 GeV high-intensity proton beam from the Fermilab Accelerator Complex
 - ❖ 4s beam every minute; 53.1MHz RF buckets, each bucket with 10^2 - 10^5 protons
 - ❖ Expect 10^{18} Protons on target (POT) in a 2-year parasitic run
 - ❖ 10^{20} POT for longer term runs

DarkQuest

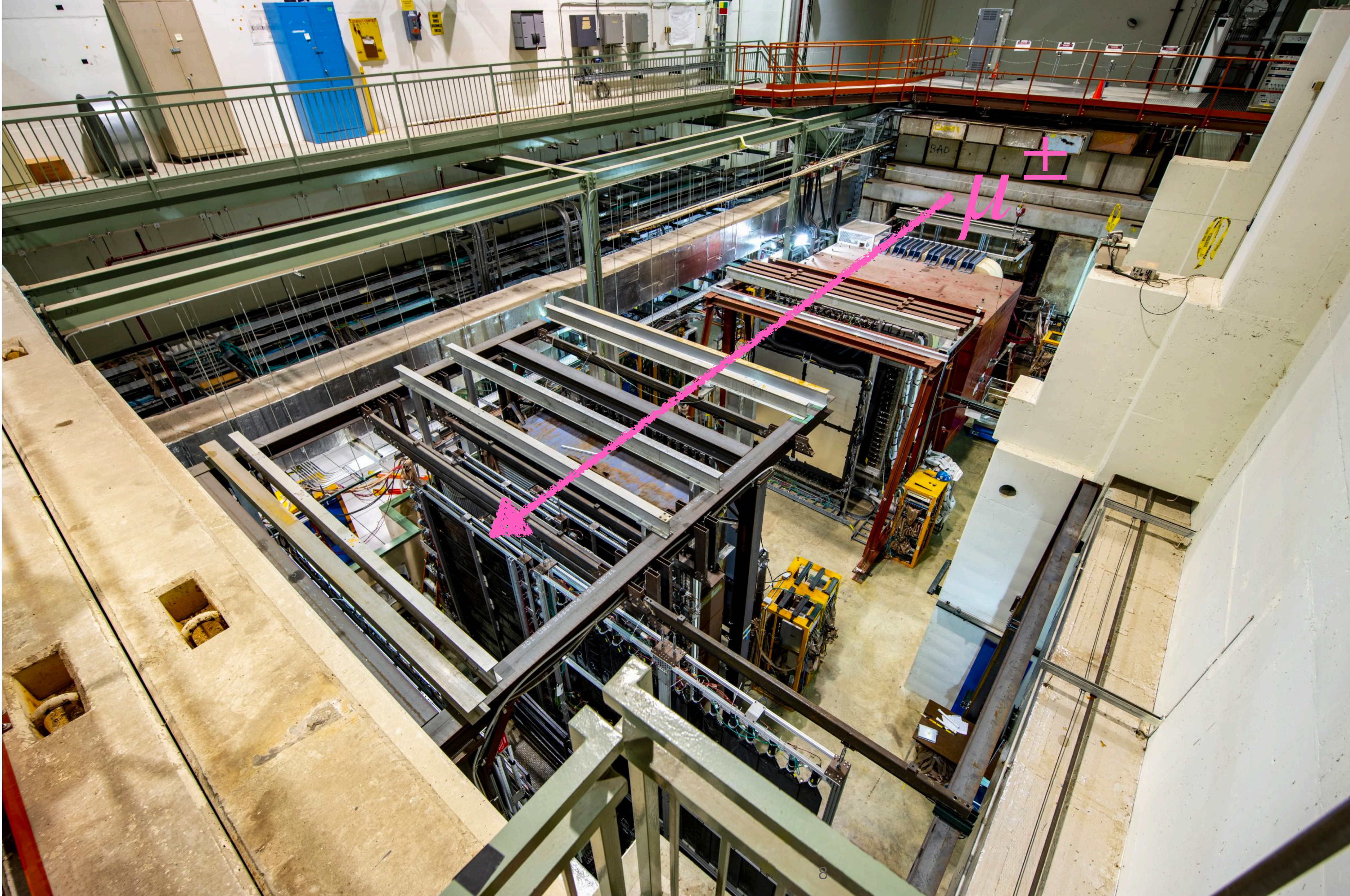


- DarkQuest: **proposed** proton fixed-target experiment at Fermilab:
 - ✿ Recently received NSF fundings to carry out the experiment!
- upgraded from the existing SpinQuest experiment

SpinQuest Spectrometer



- SpinQuest spectrometer:
 - ❖ FMag: beam dump and absorber;
 - ❖ Hollow KMag + 4 stations of drift chambers: tracking
 - ❖ Scintillator hodoscopes: triggering
 - ❖ Muon station: tagging muons
- Measuring the Drell-Yan process for studying the Transverse Momentum Dependent PDFs (TMDs) inside the proton



SpinQuest
spectrometer

SpinQuest Spectrometer

NM3: looking downstream



NM4: looking upstream



cryo platform

shielding

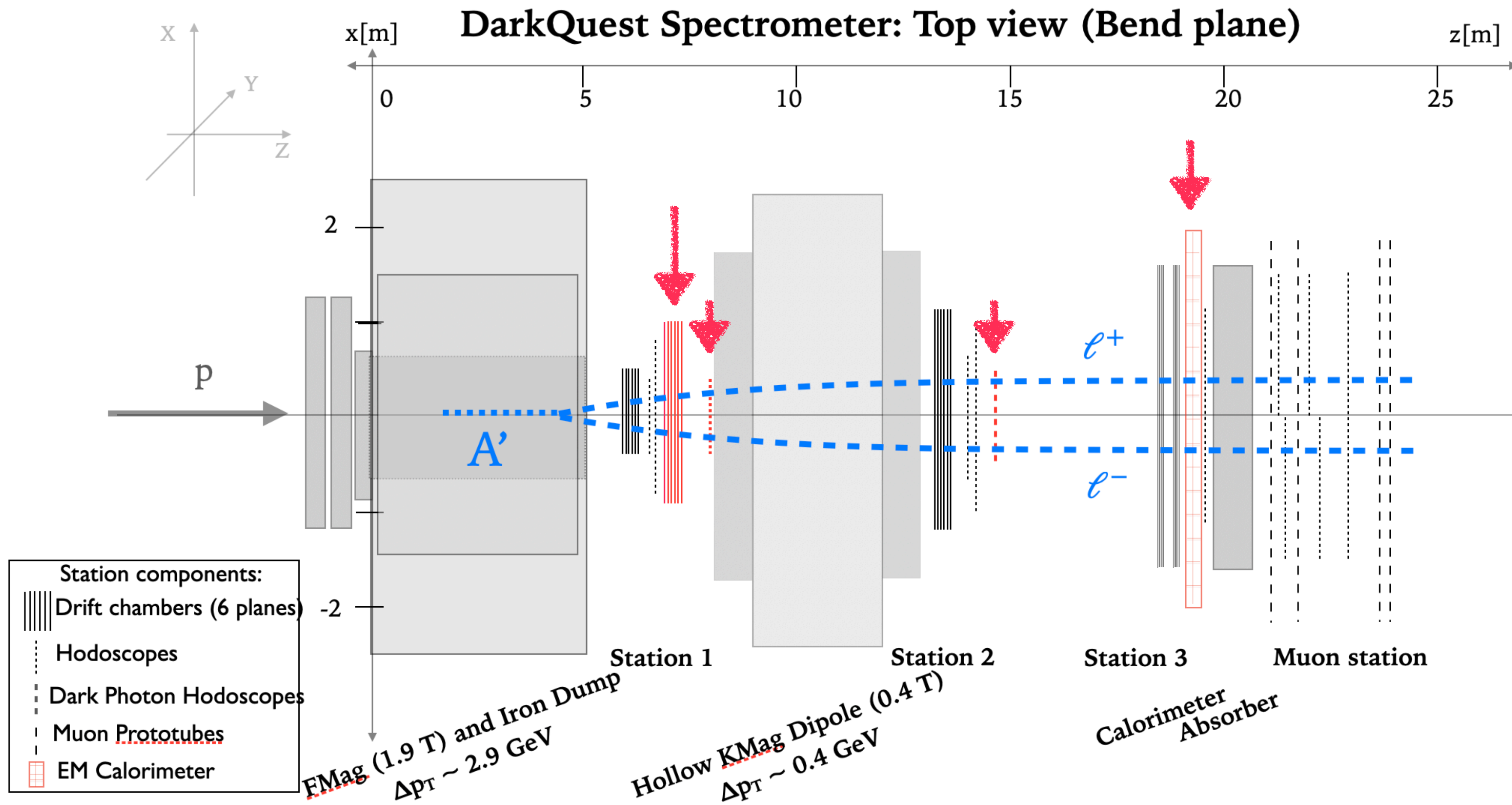
collimator

target cave

spectrometer

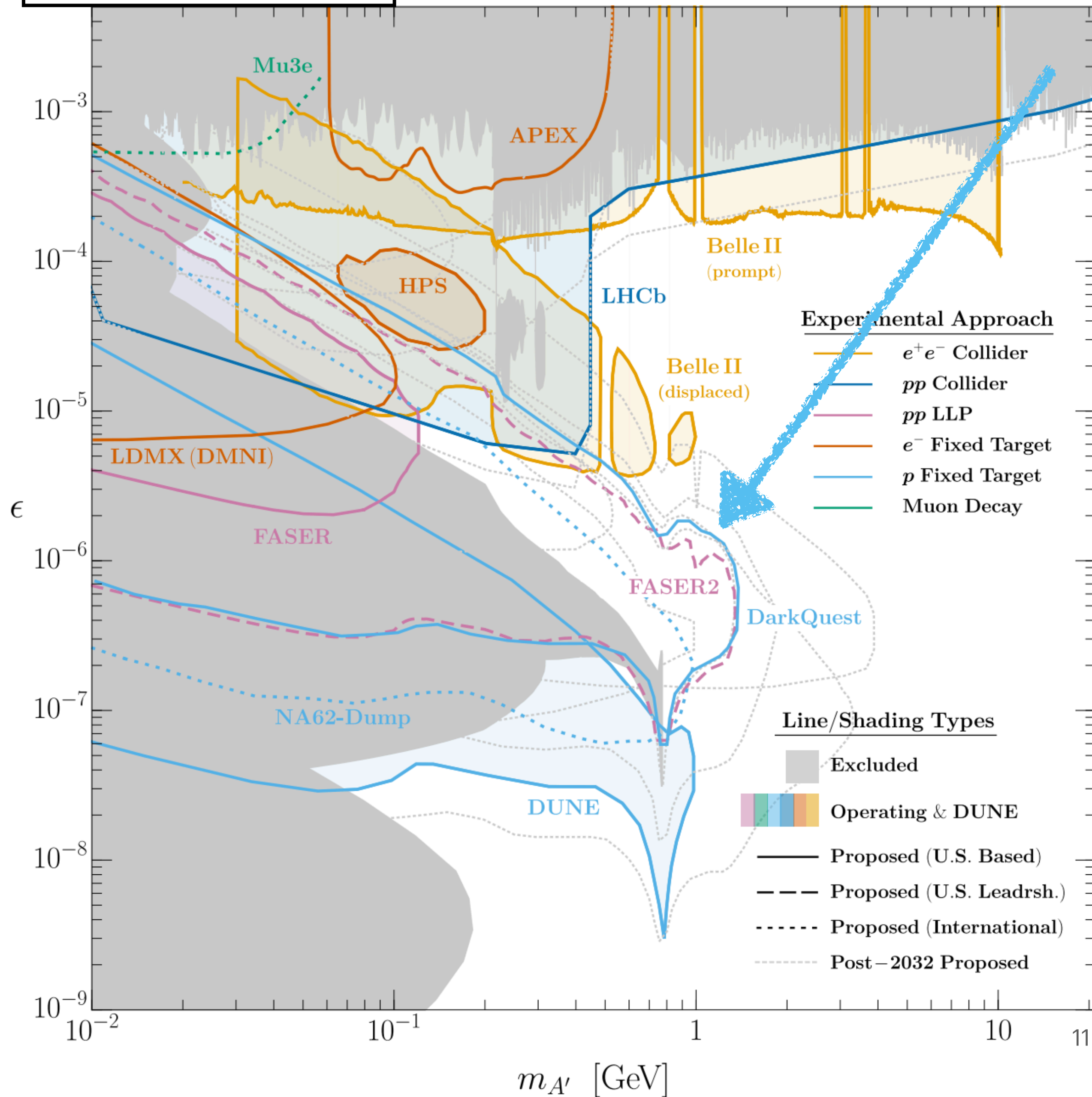
beam direction

DarkQuest Spectrometer



- DarkQuest spectrometer:
 - ✦ Probing dark sector by looking at displaced signals
- Upgrades on SpinQuest:
 - ✦ Additional tracking layers from HyperCP experiment
 - ✦ Hodoscopes to trigger on displaced signals
 - ✦ EMCal from PHENIX experiment: to trigger and reco electrons and photons, leading to more sensitivity to lower masses

Why DarkQuest

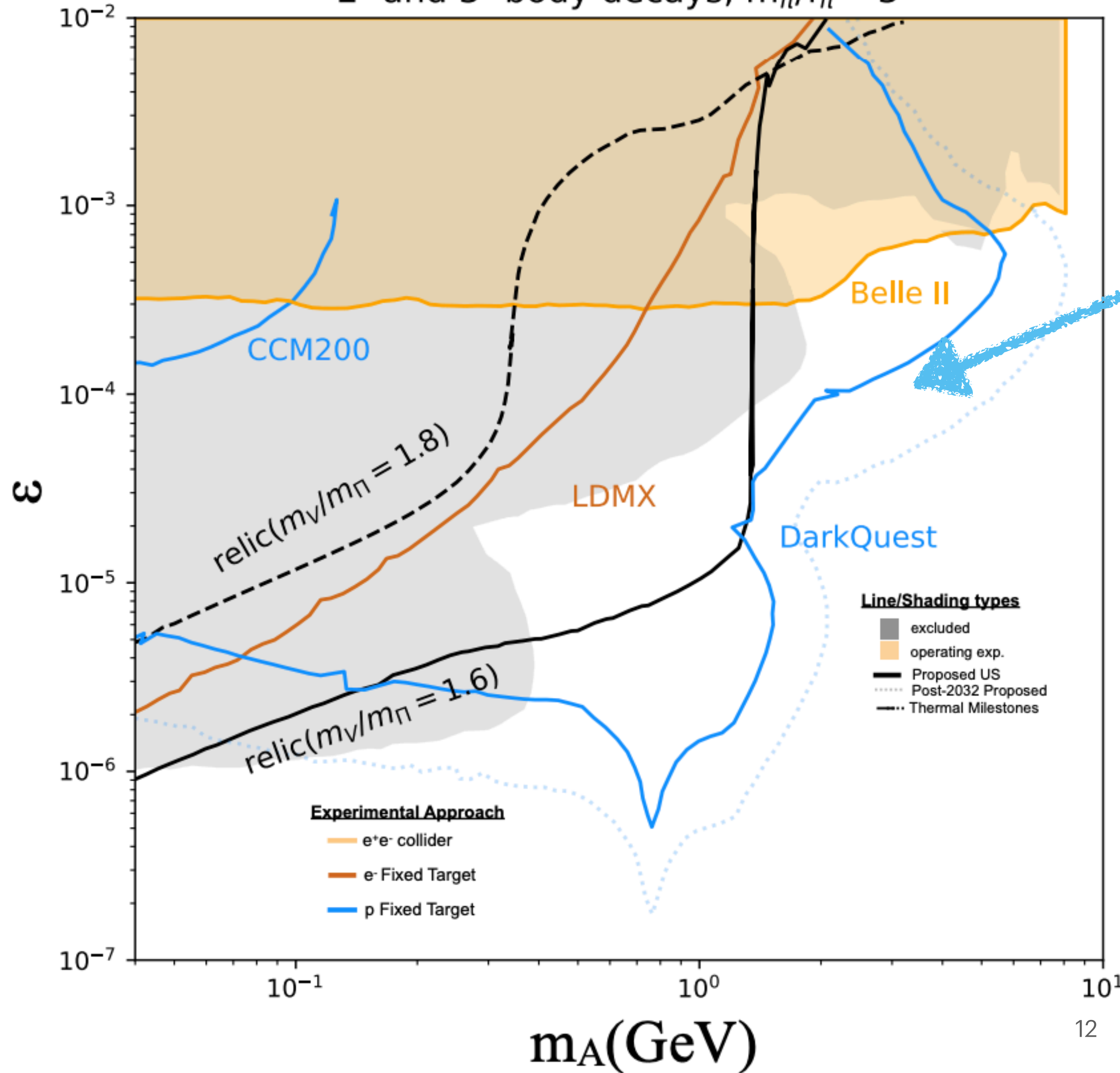


- Large dark sector production cross section with 120GeV high-intensity proton beam
- Compact geometry and relatively short displacement baseline (5m) to cover unique and broad phase spaces
- Most of the experimental components already exist, very low cost: ~1M

DarkQuest

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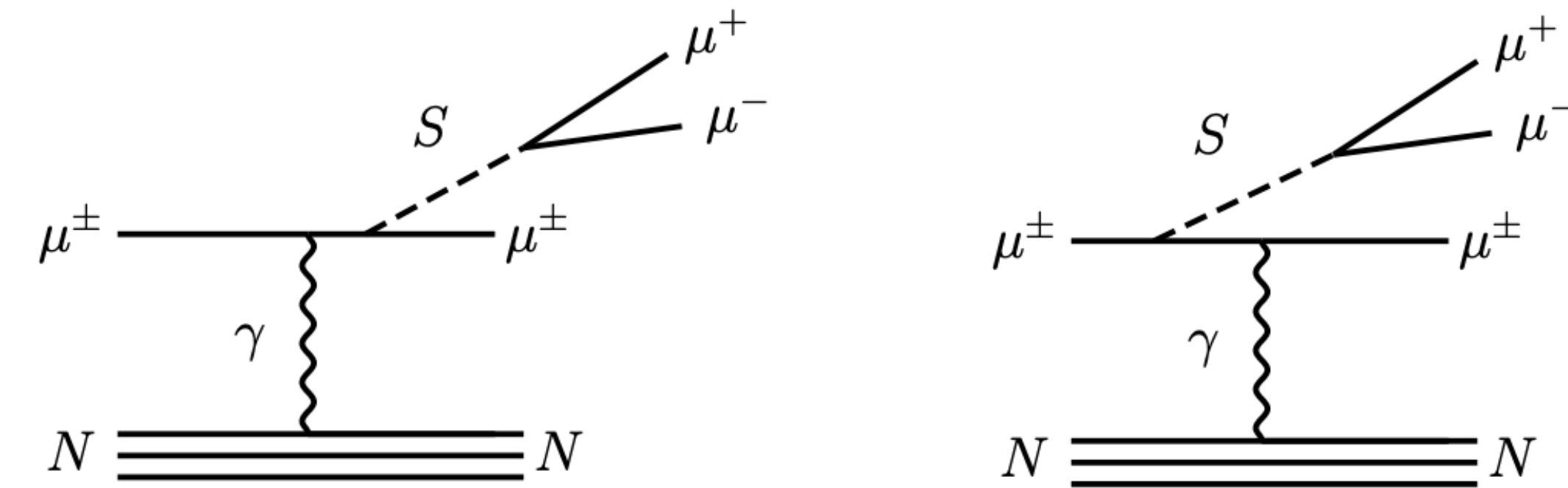
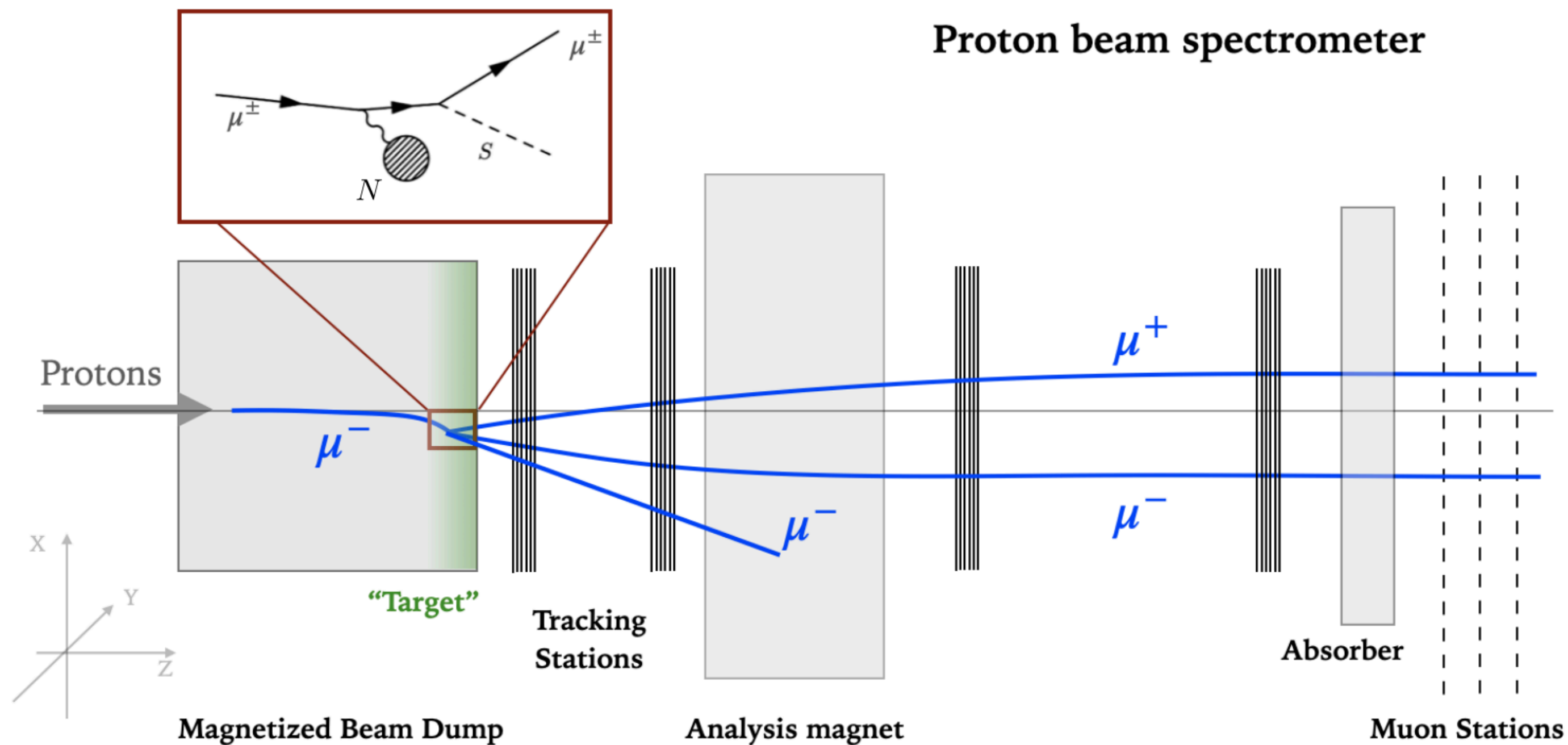
2- and 3- body decays, $m_\pi/f_\pi = 3$



• SIMP benchmark

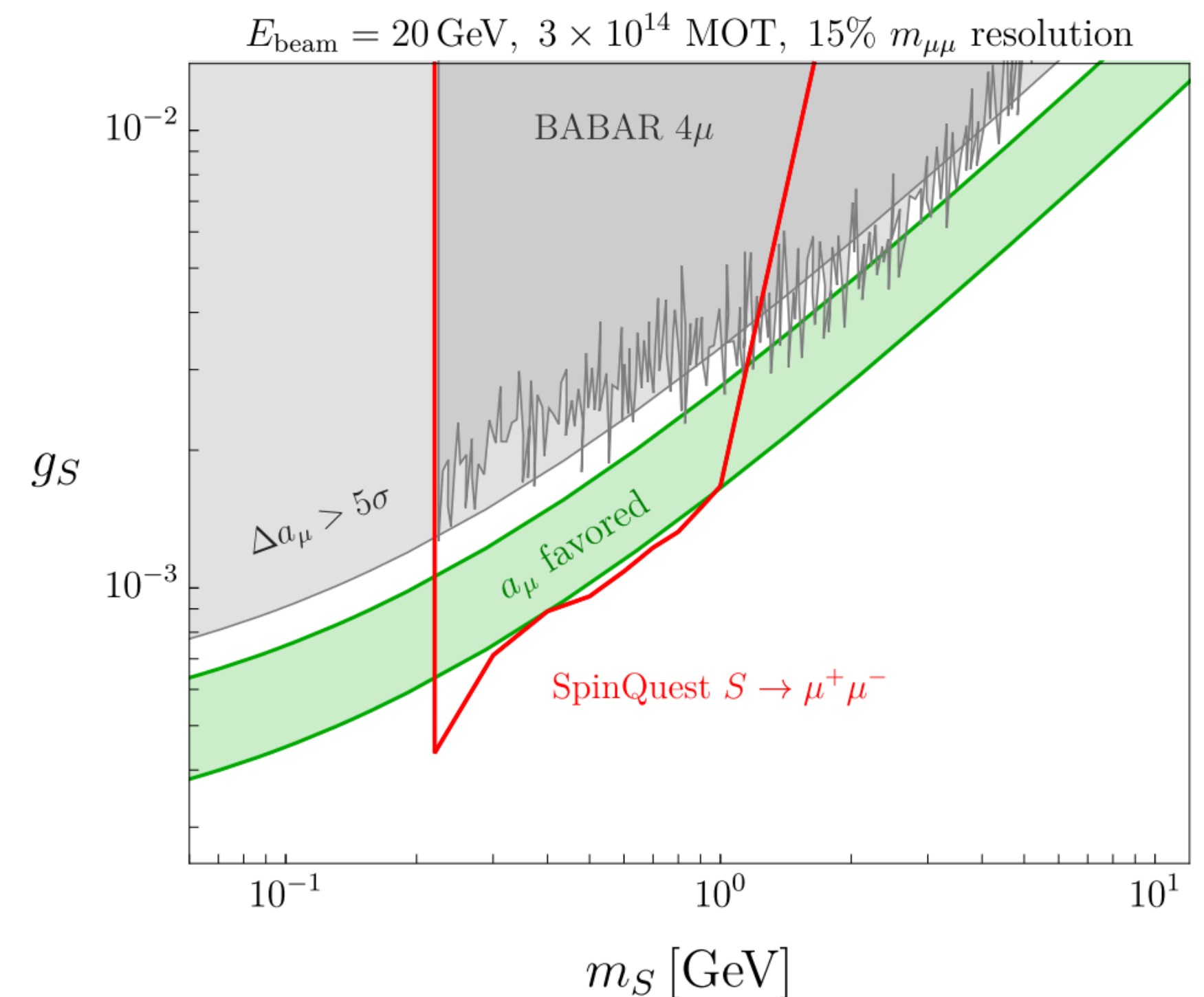
Secondary Muons As Muon Beam

Arxiv.2212.00033



- Use the secondary muons from the proton-target interactions as the **muon source**, and can treat it as a **"muon beam-dump"** experiment

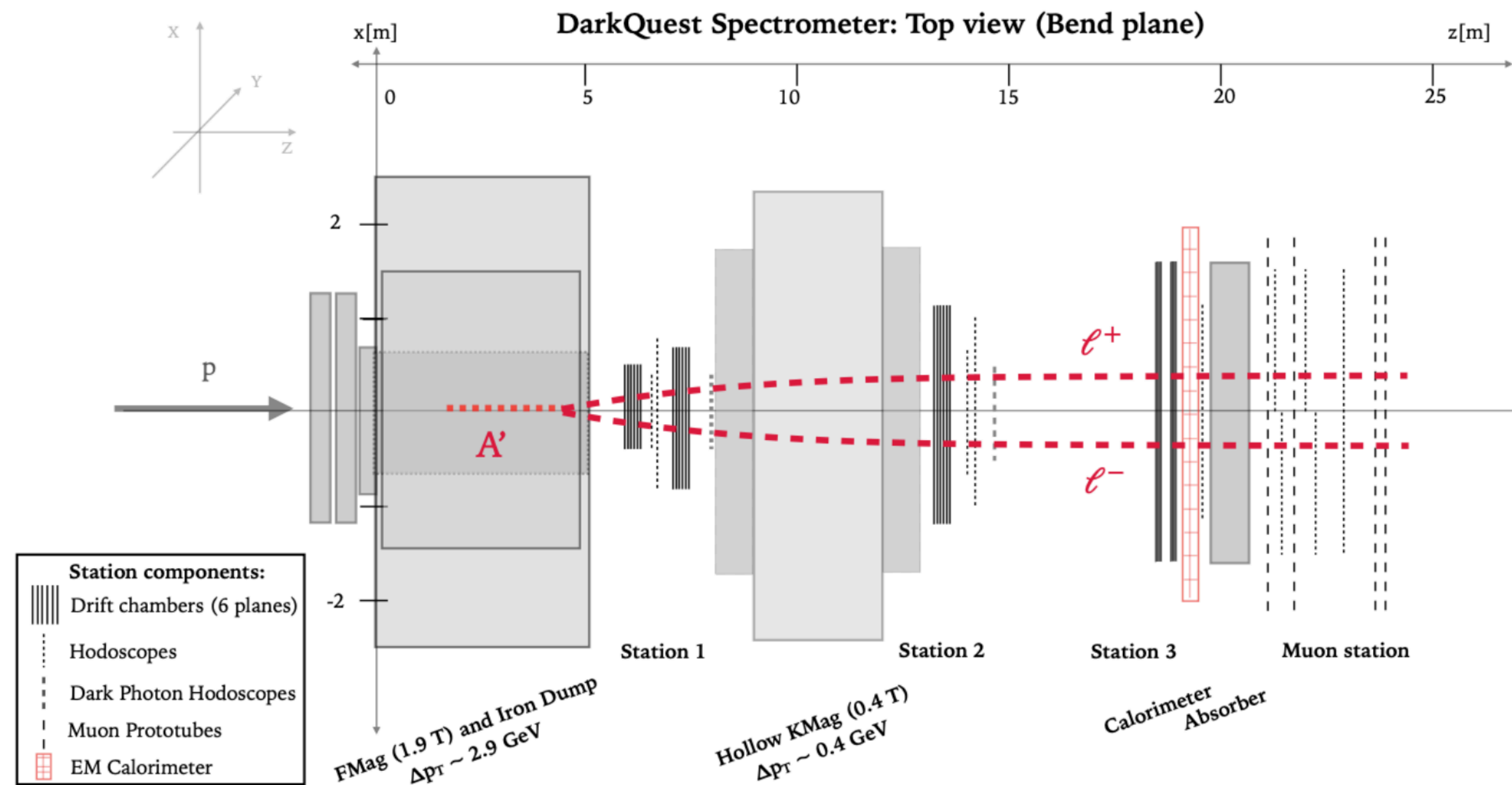
✿ Sensitivity to the muon sector, e.g., g-2 anomaly



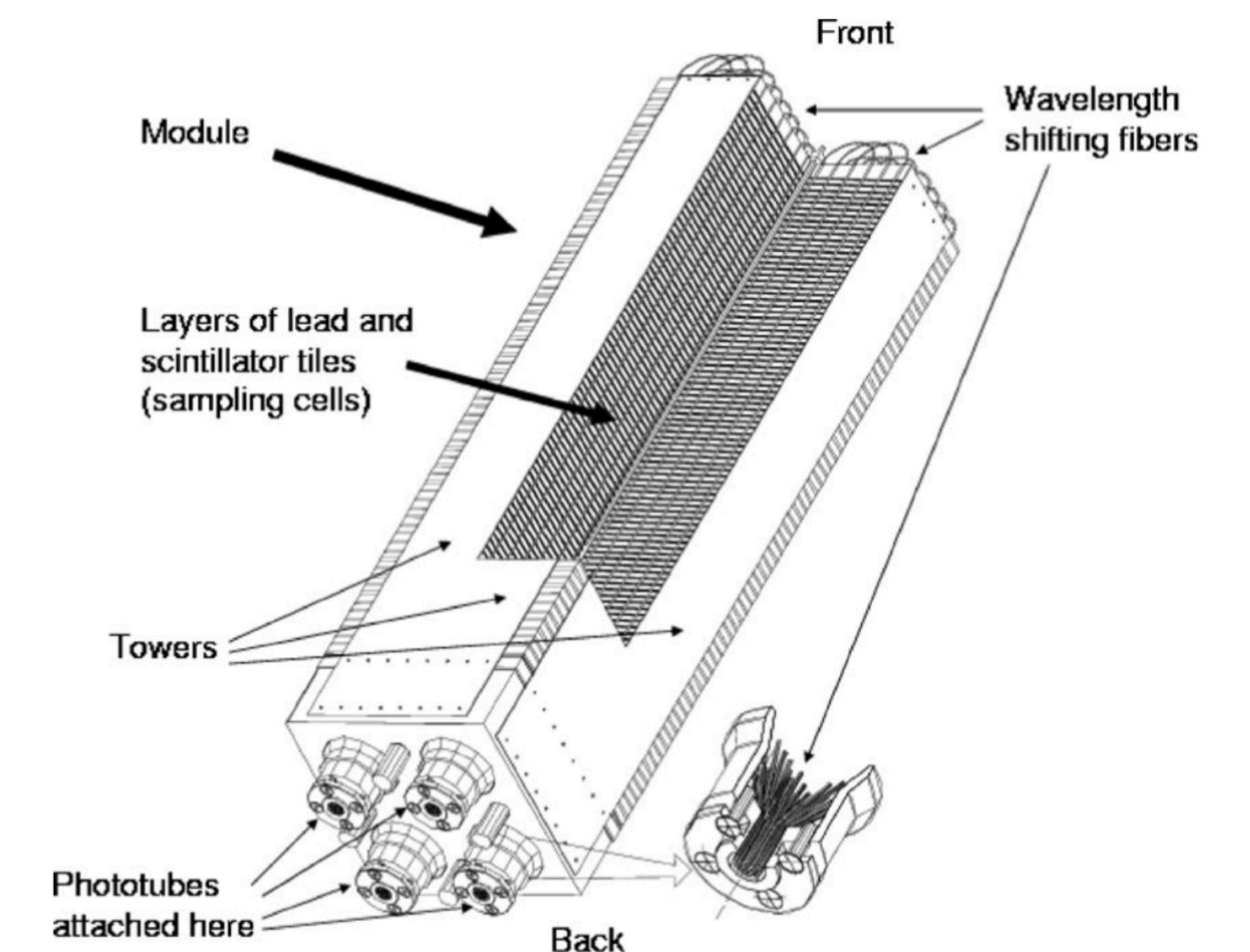
List of Experimental Studies

- Detector Upgrade:
 - ✦ EMCal integration into the spectrometer
 - ✦ Extra Tracking layer integration into the spectrometer
- Geant-based Simulation Studies:
 - ✦ EMCal simulations
 - ✦ Triggering
 - ✦ Tracking & vertexing
 - ✦ ParticleID: tracking + calorimeter information

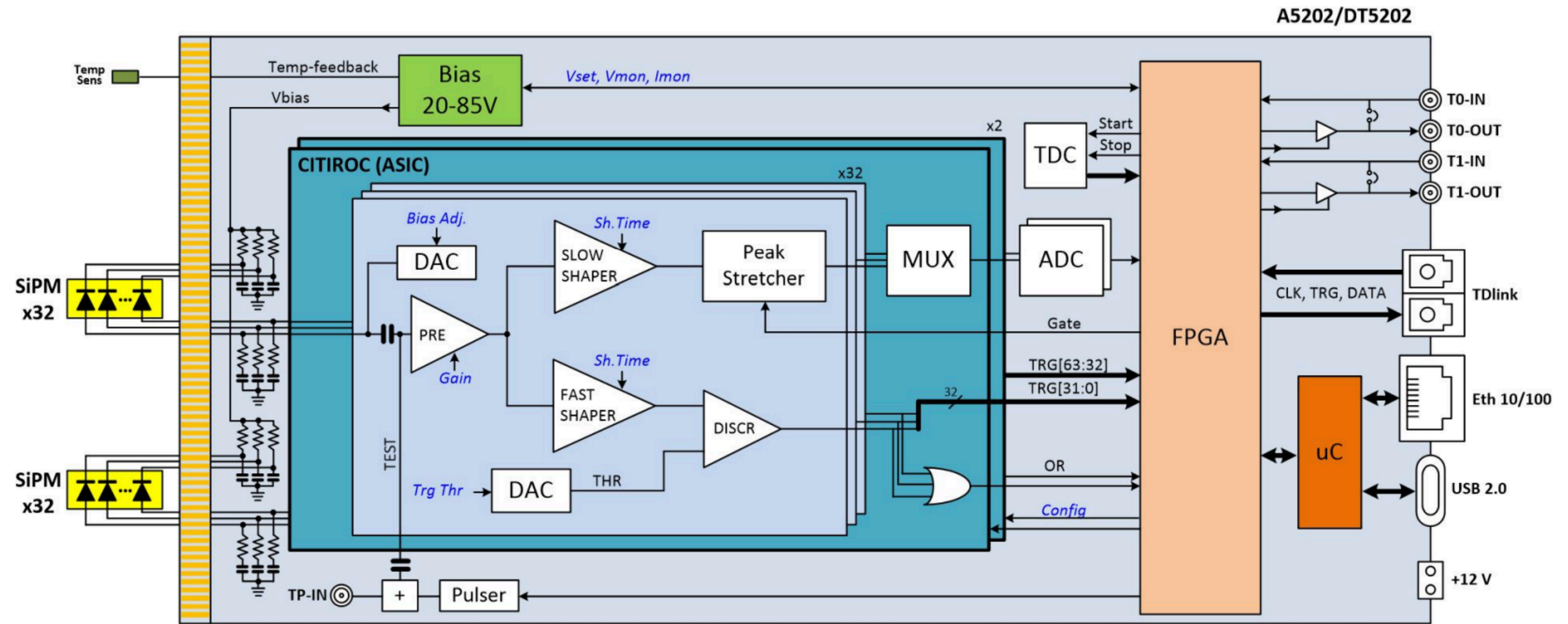
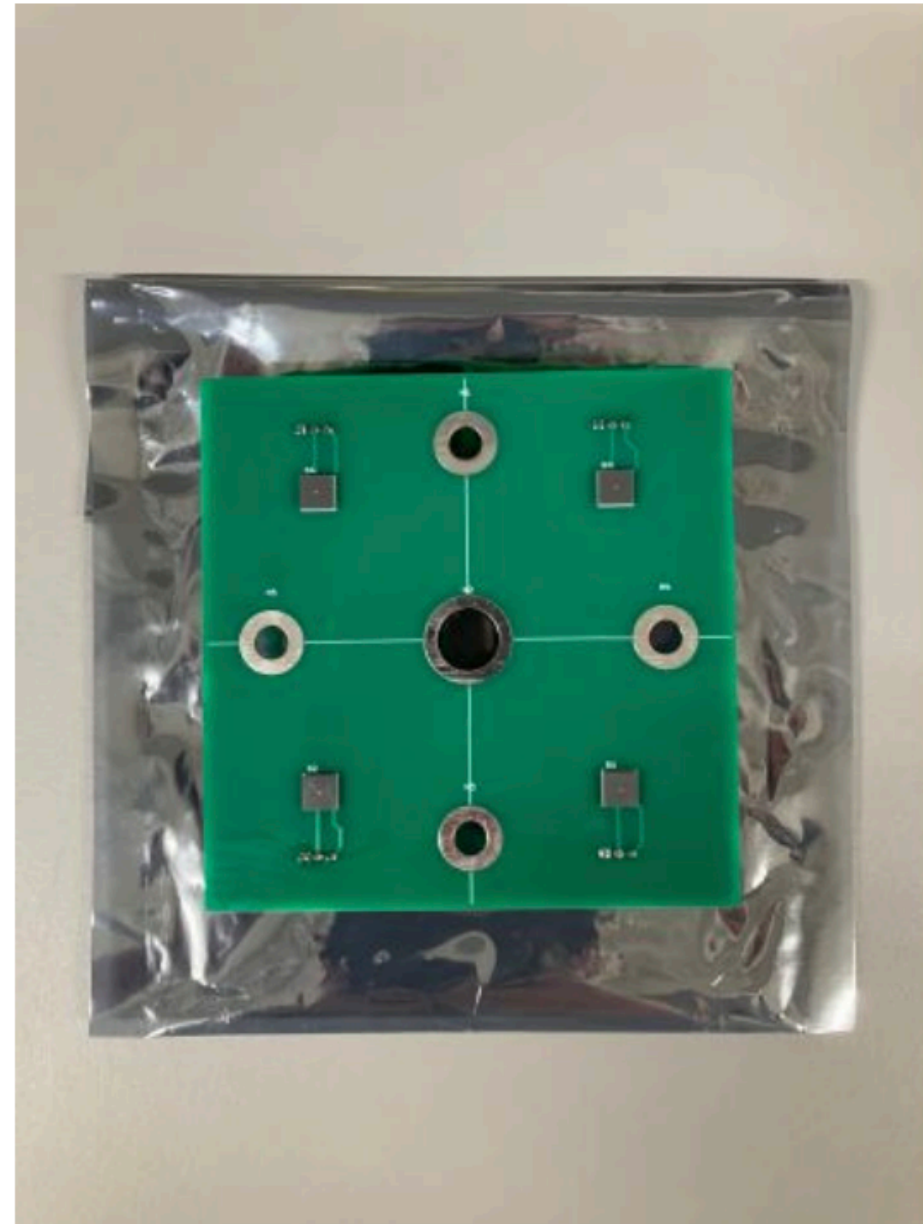
Detector Upgrade Studies



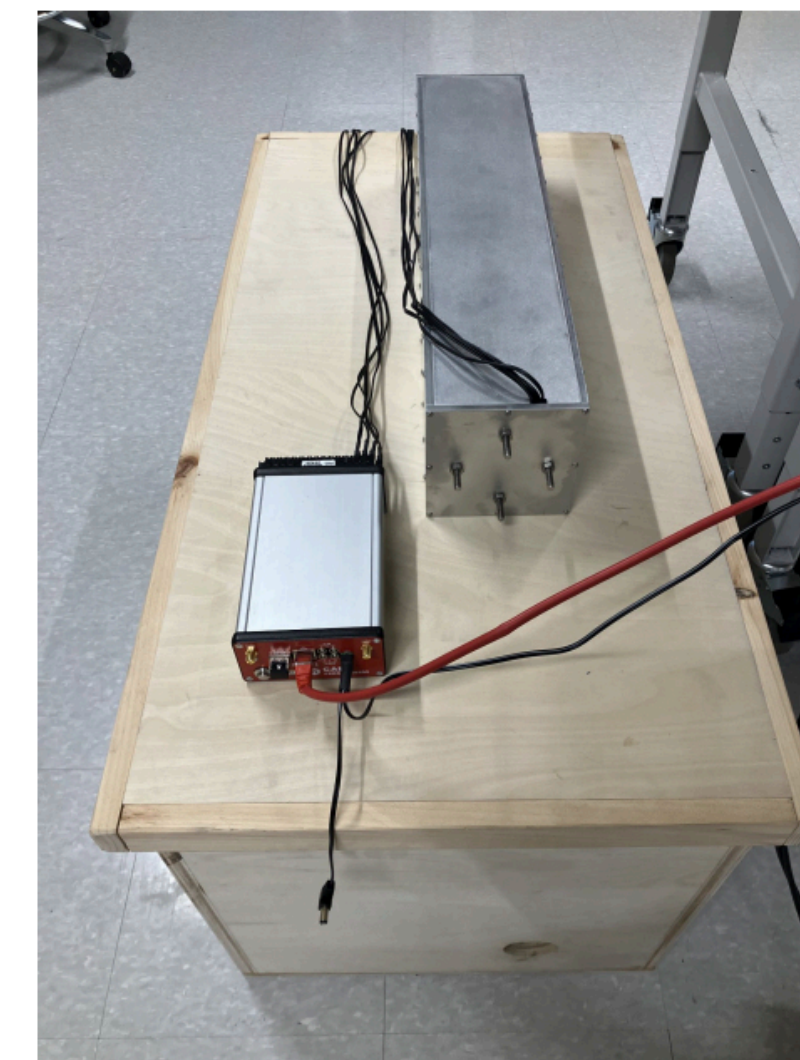
- EMCal: Lead + Plastic scintillator sampling calorimeter from PHENIX experiment
- EMCal integration into the spectrometer:
 - ❖ Developments of the readout and trigger system ongoing
 - ❖ Currently in possession of a few cells to explore SiPM readouts



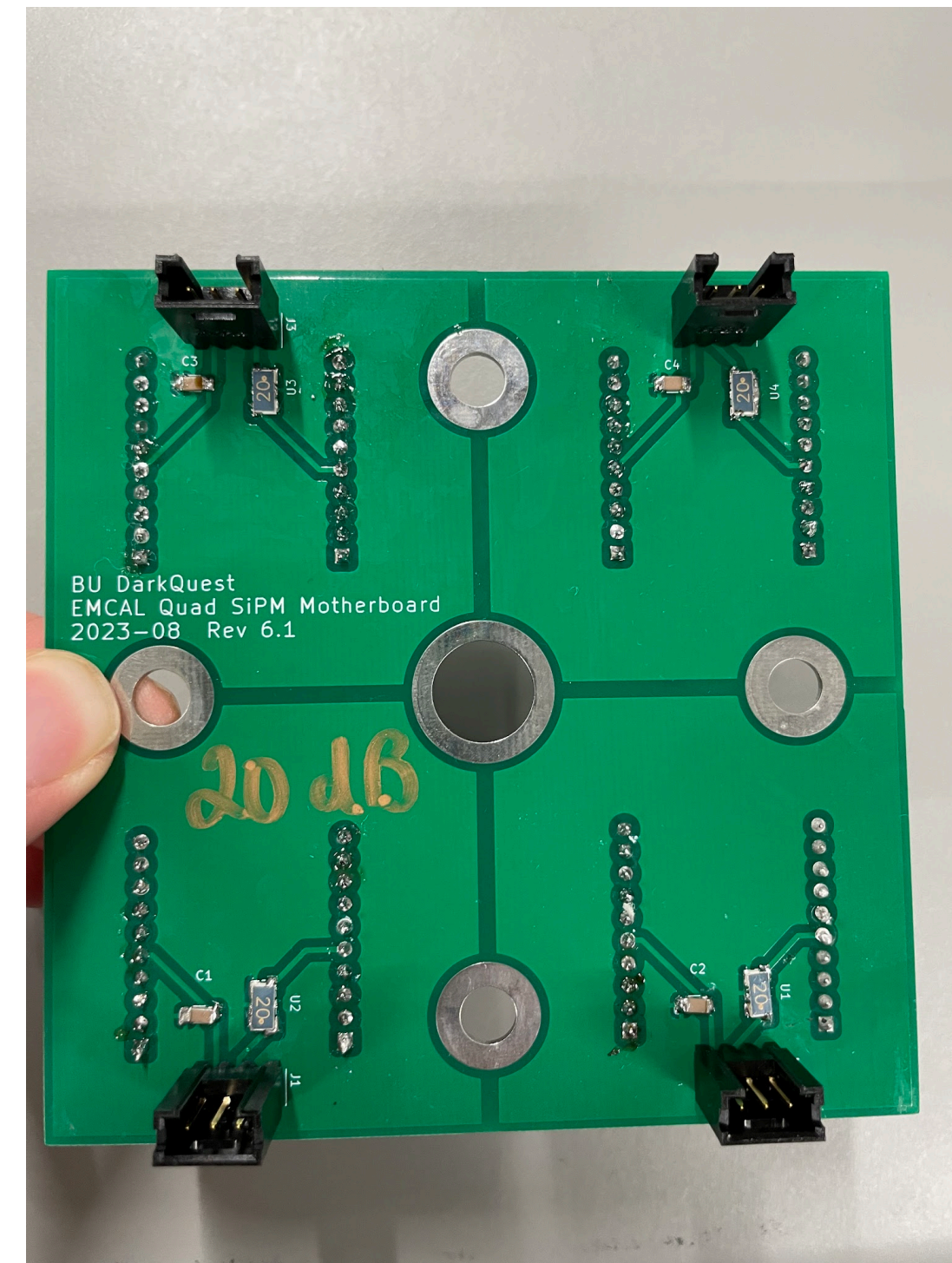
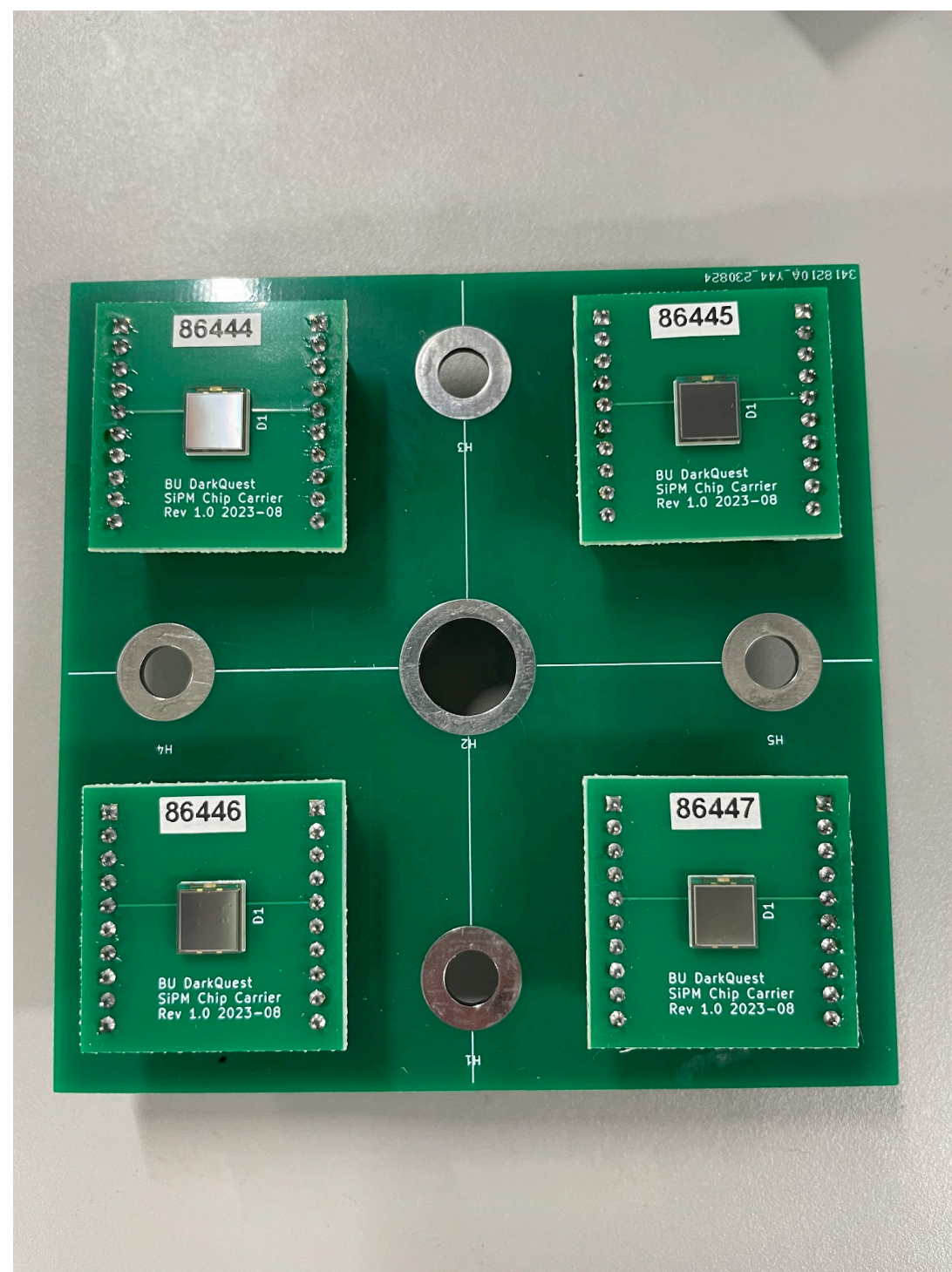
EMCal Readout Electronics



- EMCAL test stands have been developed to study new EMCAL readout electronics

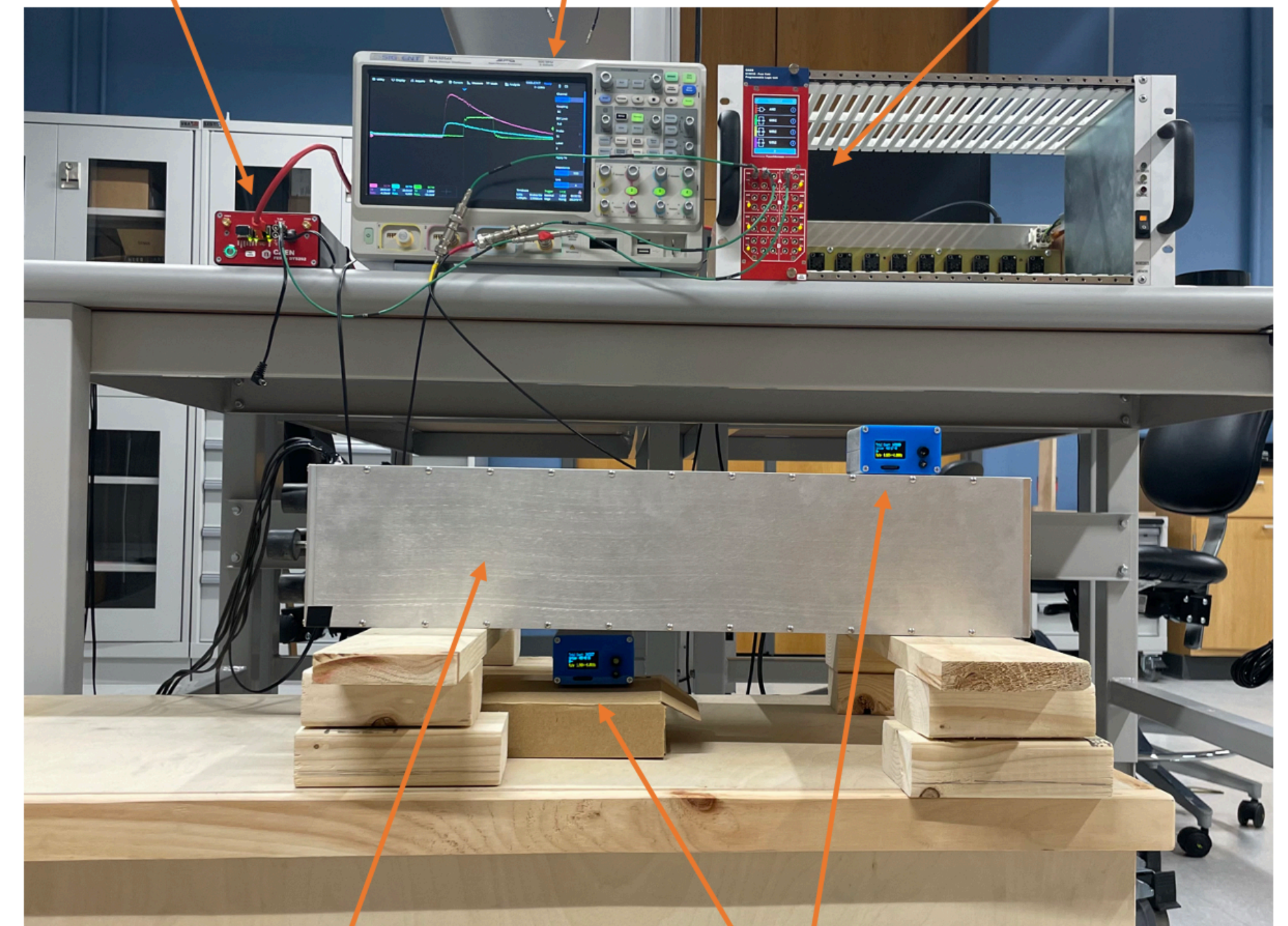


EMCal Readout Electronics



- EMCal test stands have been developed to study new EMCAl readout electronics
- Working on inter-calibrations of the four channels, temperature responses, and energy calibrations, etc

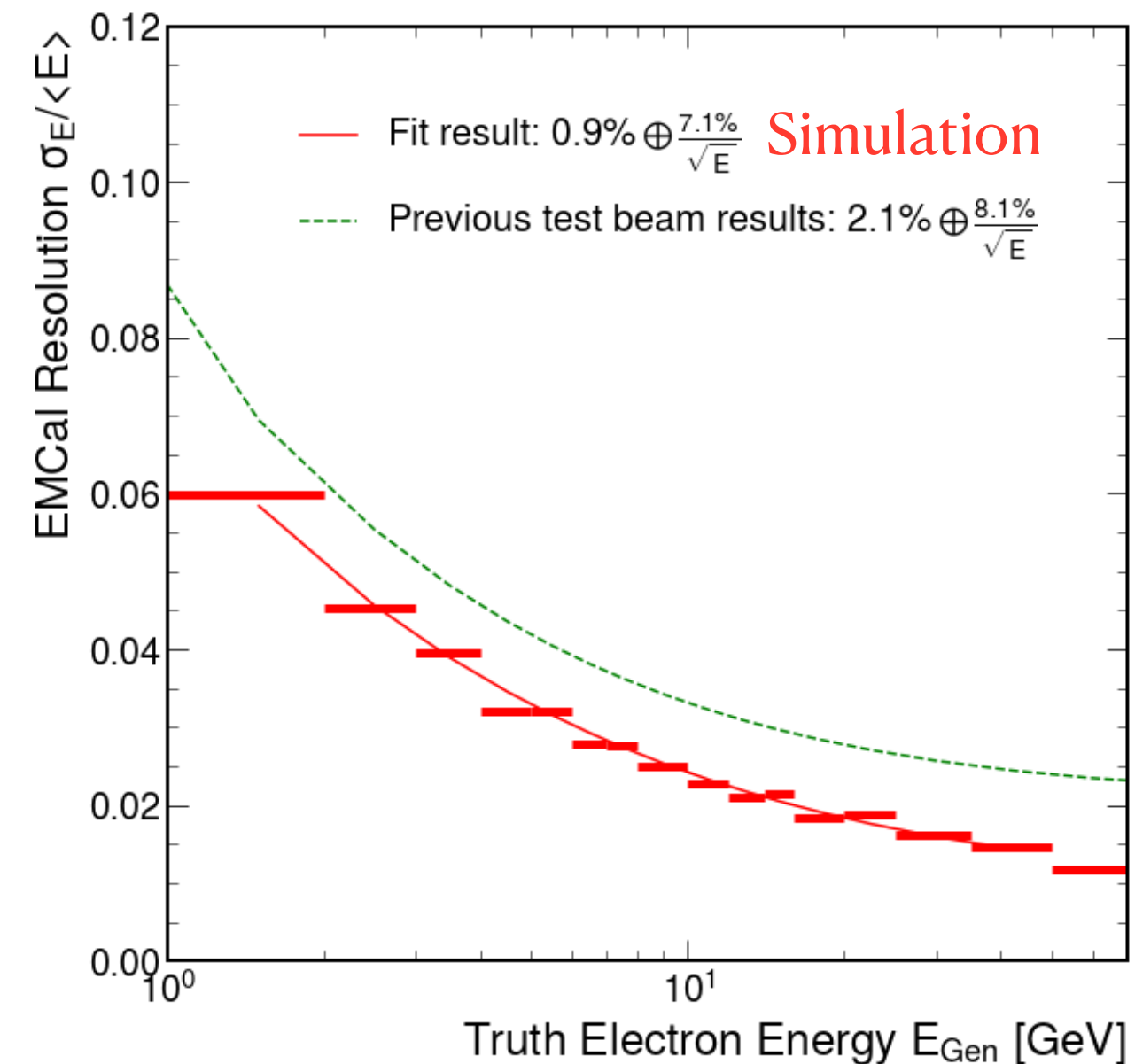
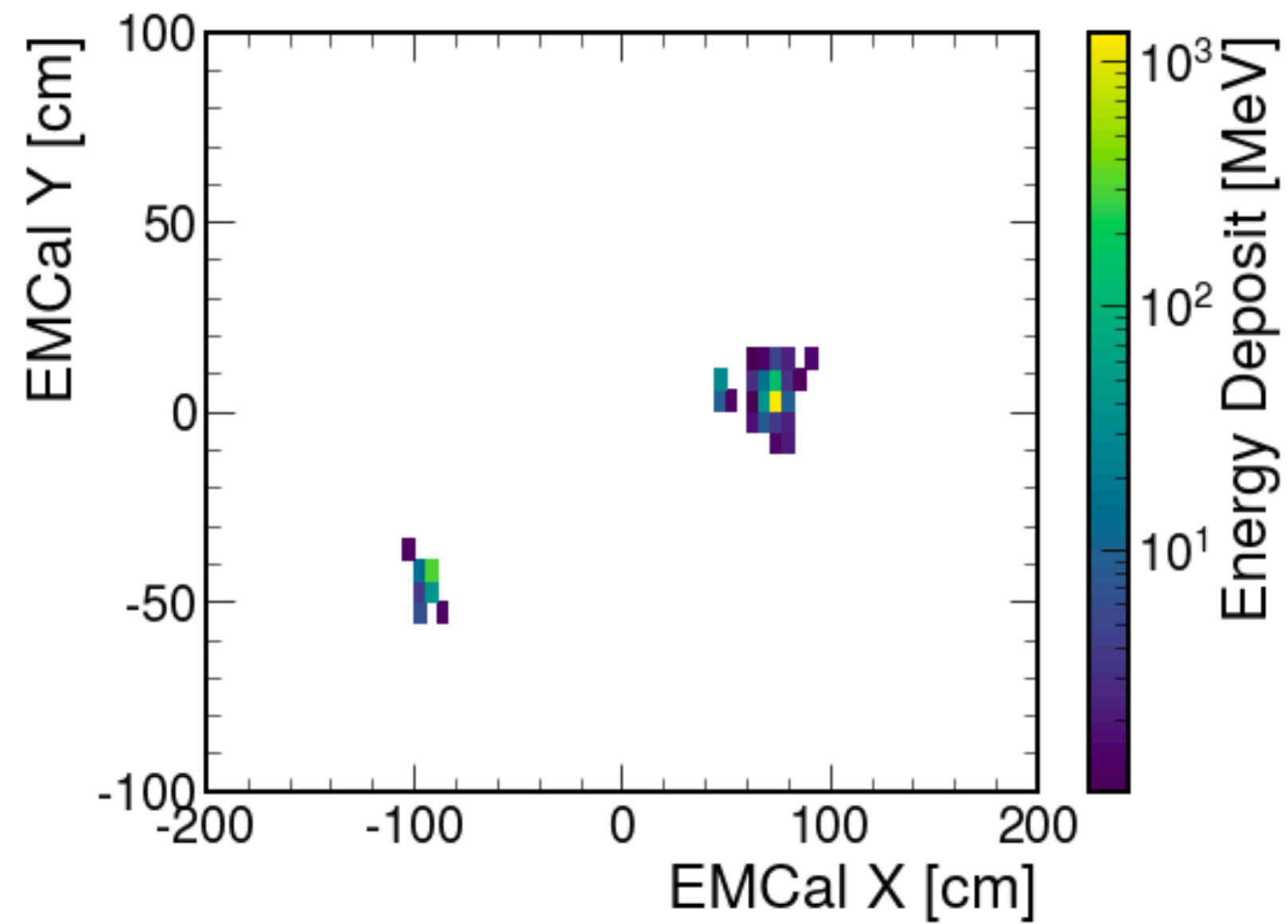
Oscilloscope
CAEN N1081B logic module (AND)
CAEN ASIC board (DT5202)



Dark box with EMCAl inside

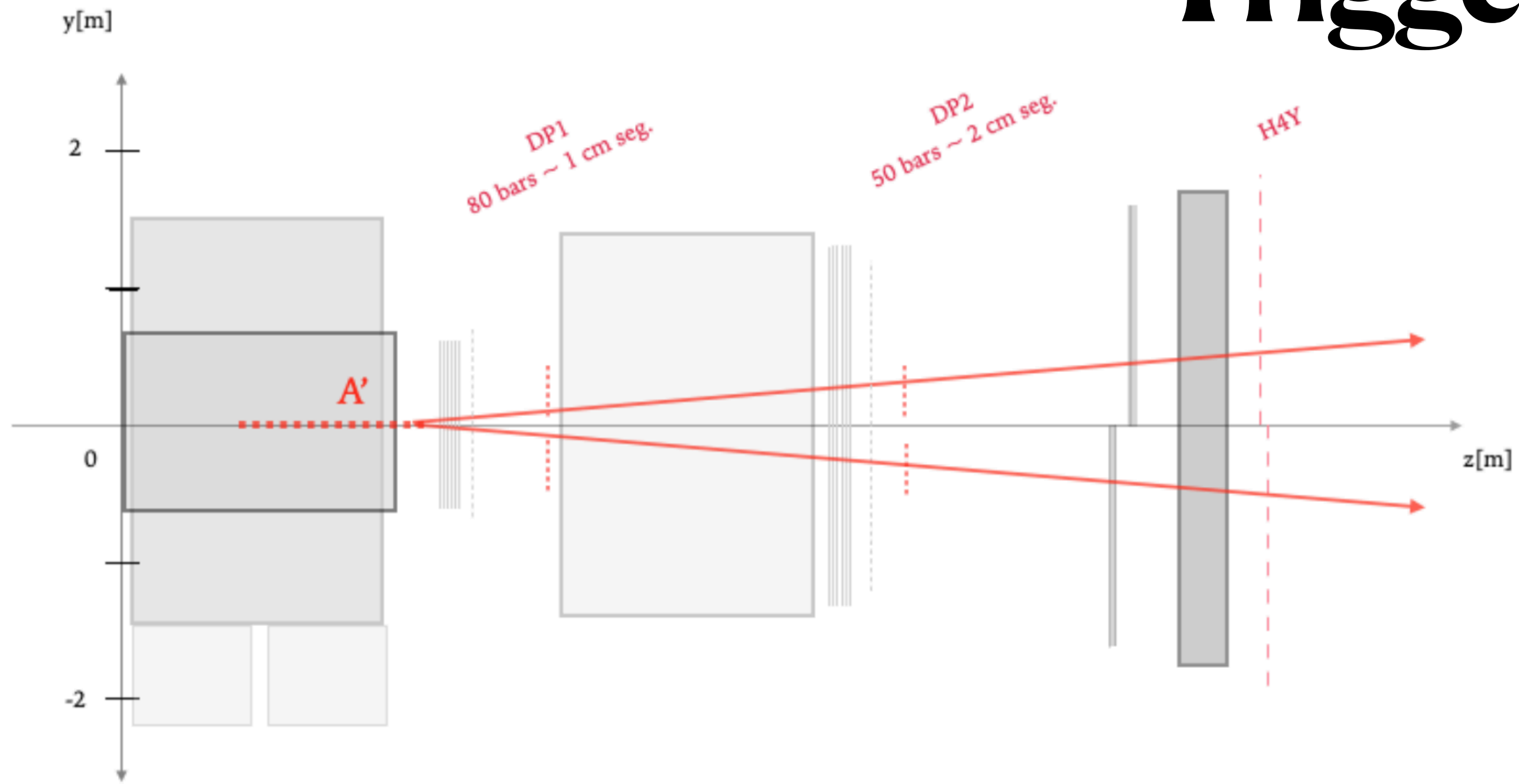
CosmicWatches

Ongoing Studies: EMCal Simulations

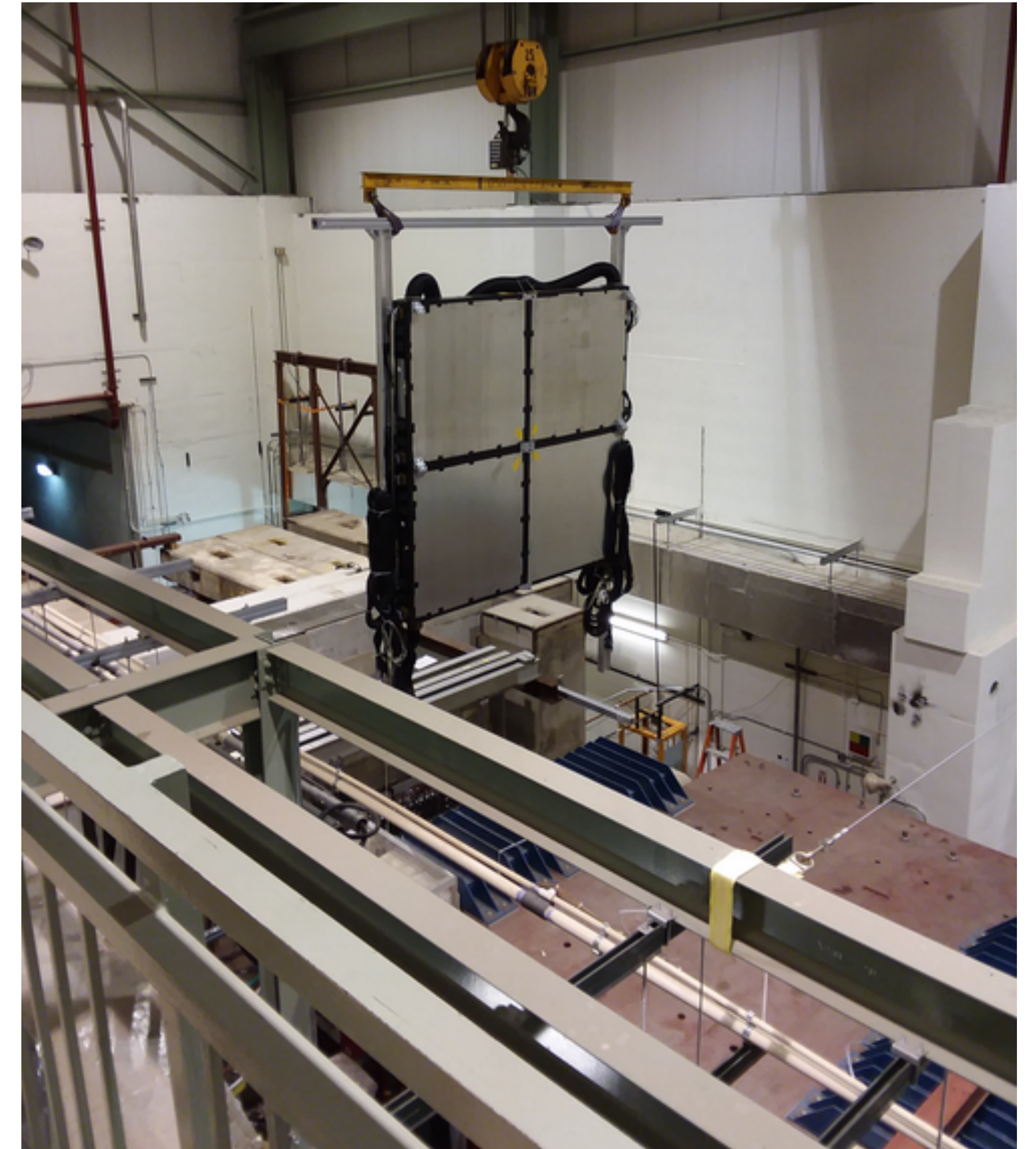


- EMCal: ~ 5 cm per cell (Molière radius of Pb-Scintillator is around 3cm): most energy deposit in one central cell
- Nice separation between two electron showers
- Agreement of the resolutions between the simulation (red) and the previous test beam results
- Test beam scheduled early next year to check the readout, performance, and also do calibrations

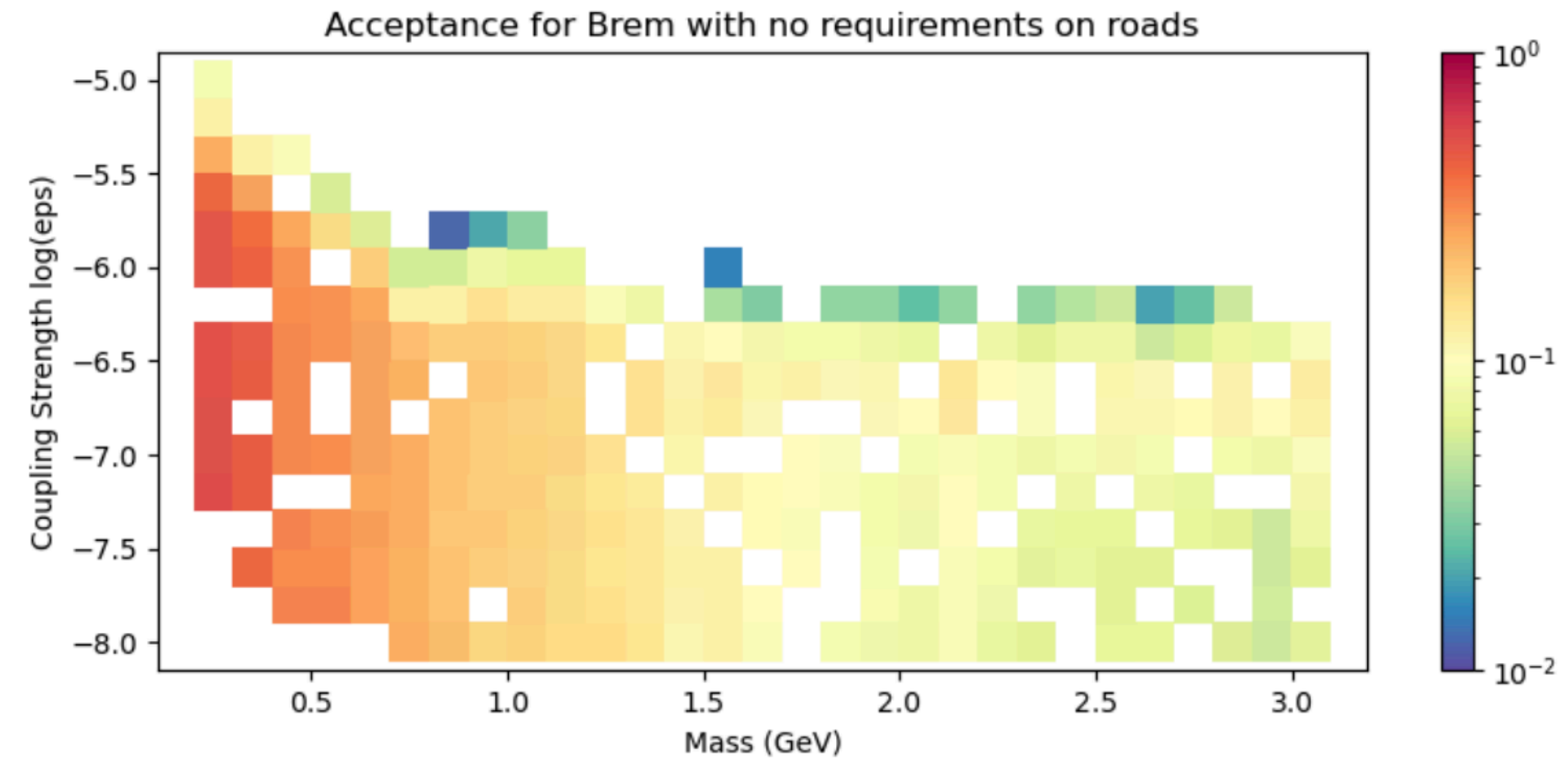
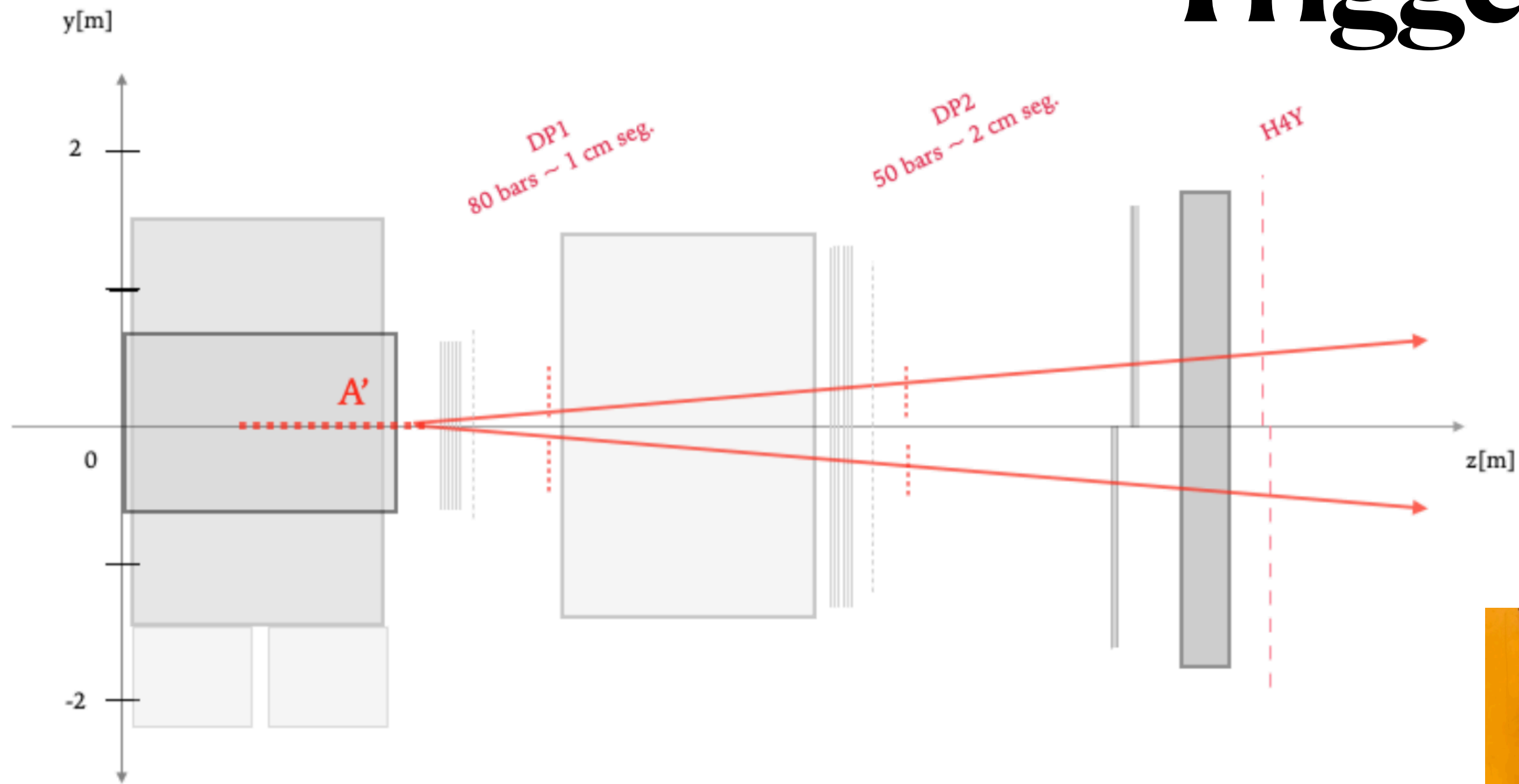
Trigger



- Exploring newly installed hodoscopes to trigger on displaced:
 - ✦ No bending in y direction: straight line matching



Trigger

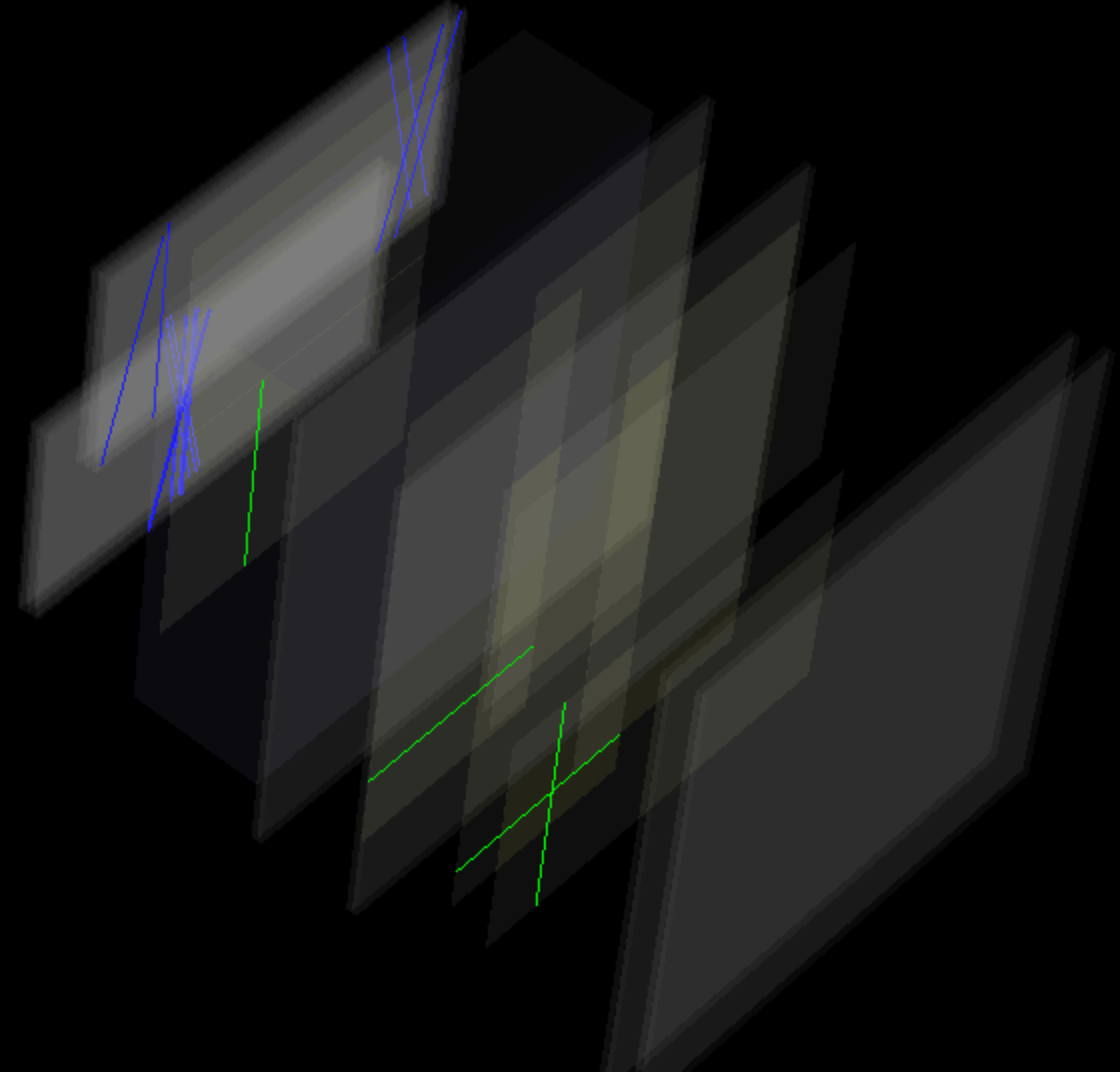
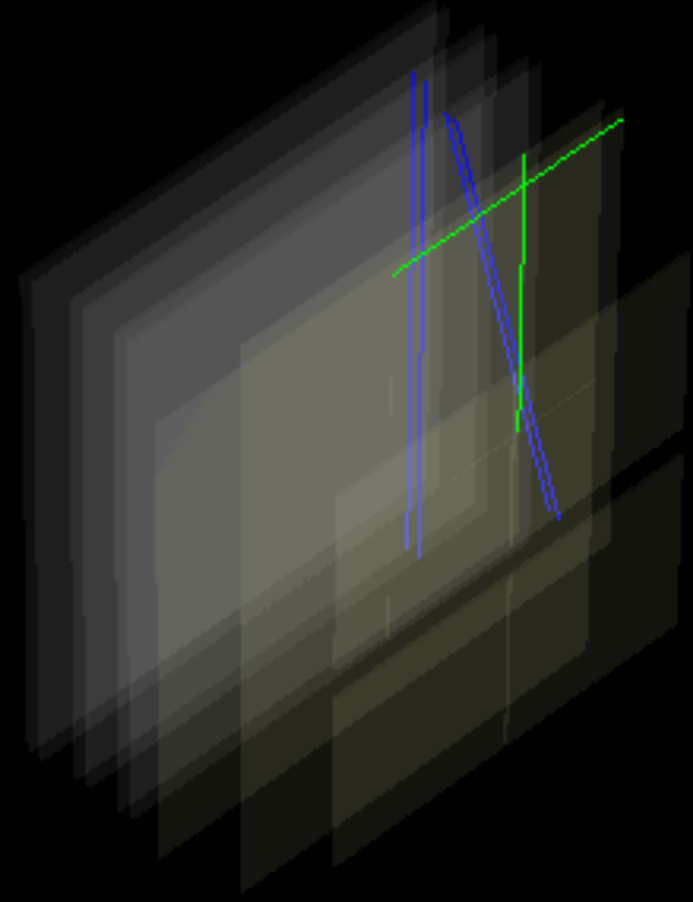


- Exploring newly installed hodoscopes to trigger on displaced:
 - No bending in y direction: straight line matching
 - Large improvements: $O(1\%) \rightarrow O(10-80\%)$
- Integrate these roads into the trigger system and test
- Plan to include EMCal information in the trigger system to trigger on Electron/Photons

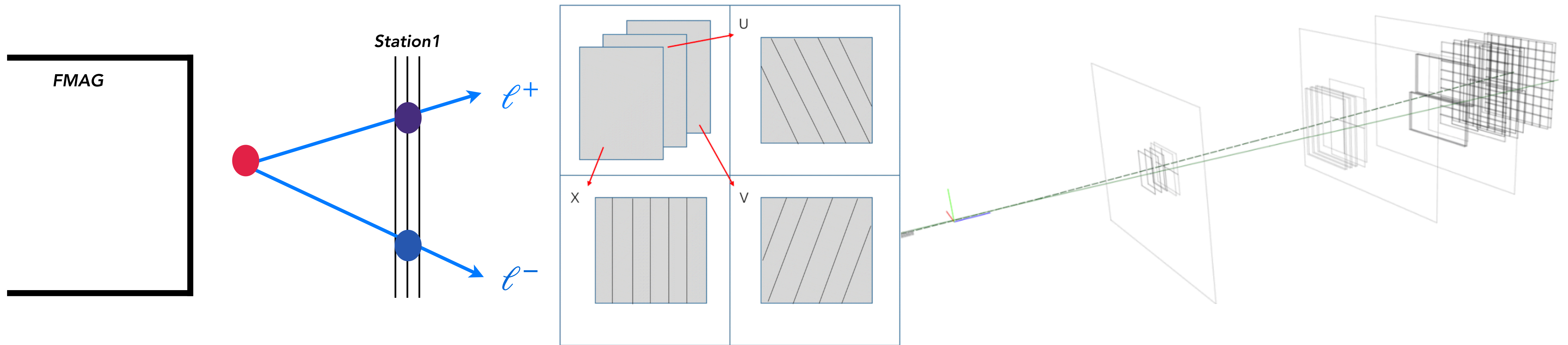


Run: 4510, Spill: 1, Event: 7978

NIM: {0, 0, 0, 0, 0} MATRIX: {1, 0, 1, 0, 0}

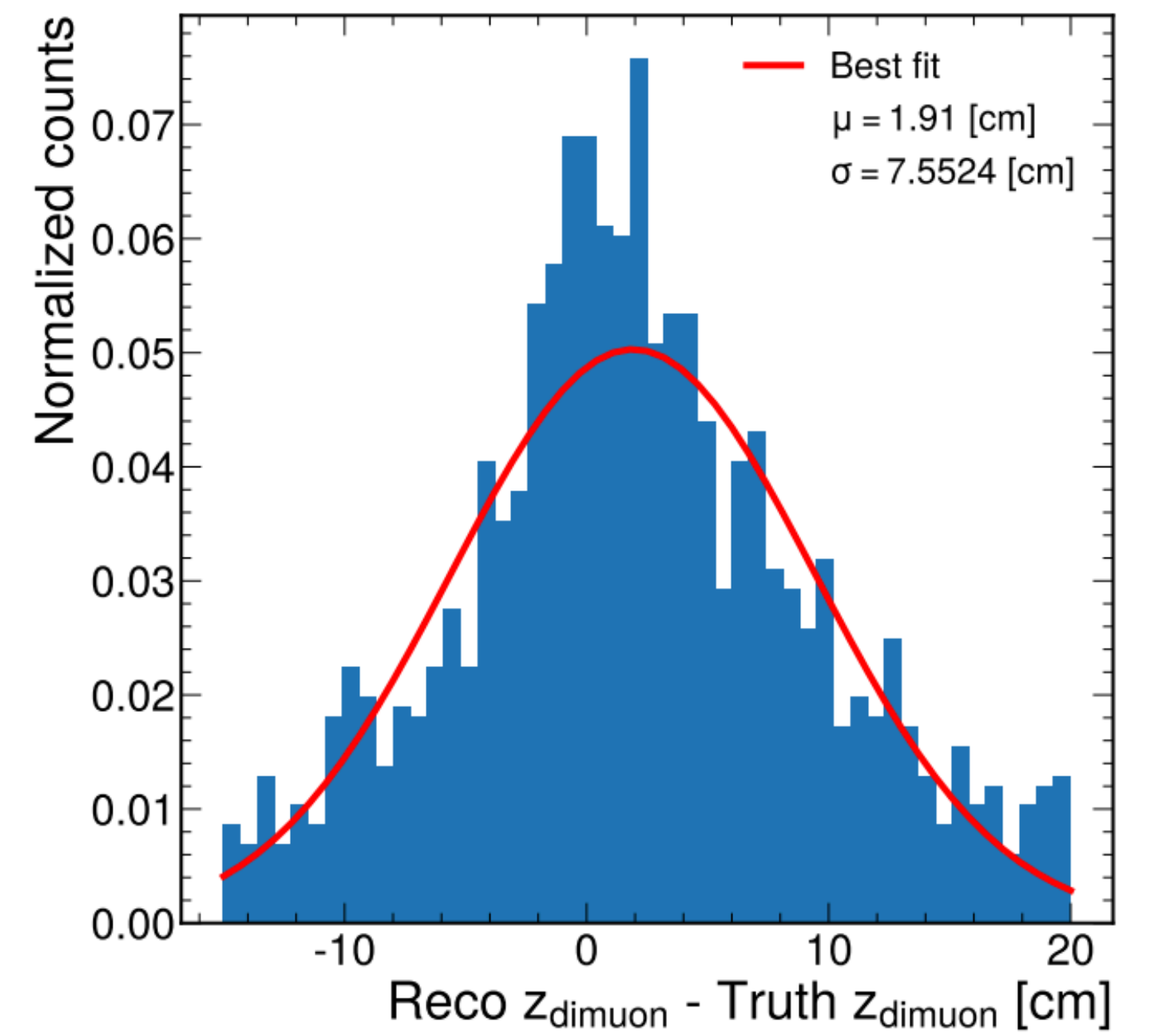
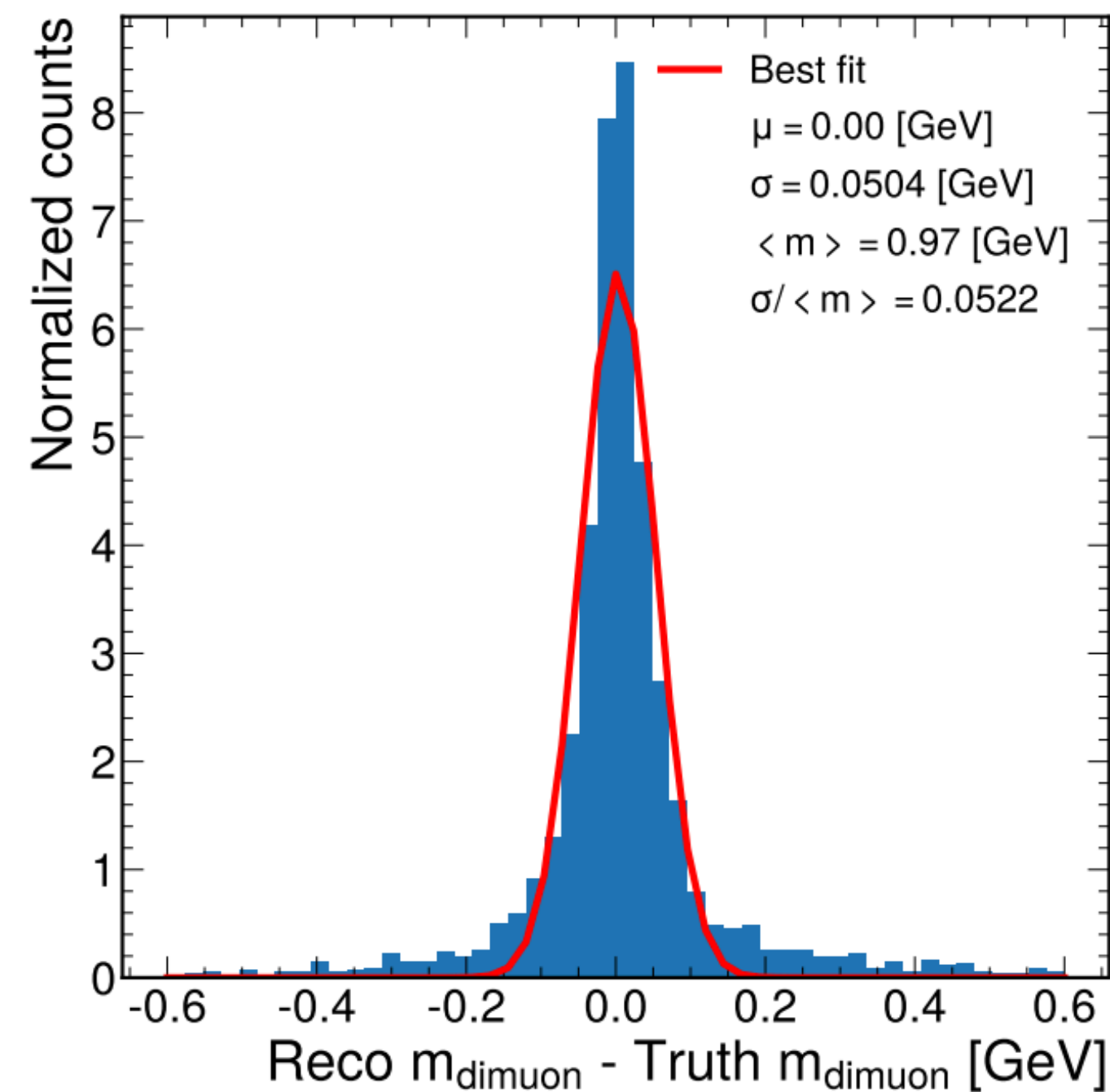
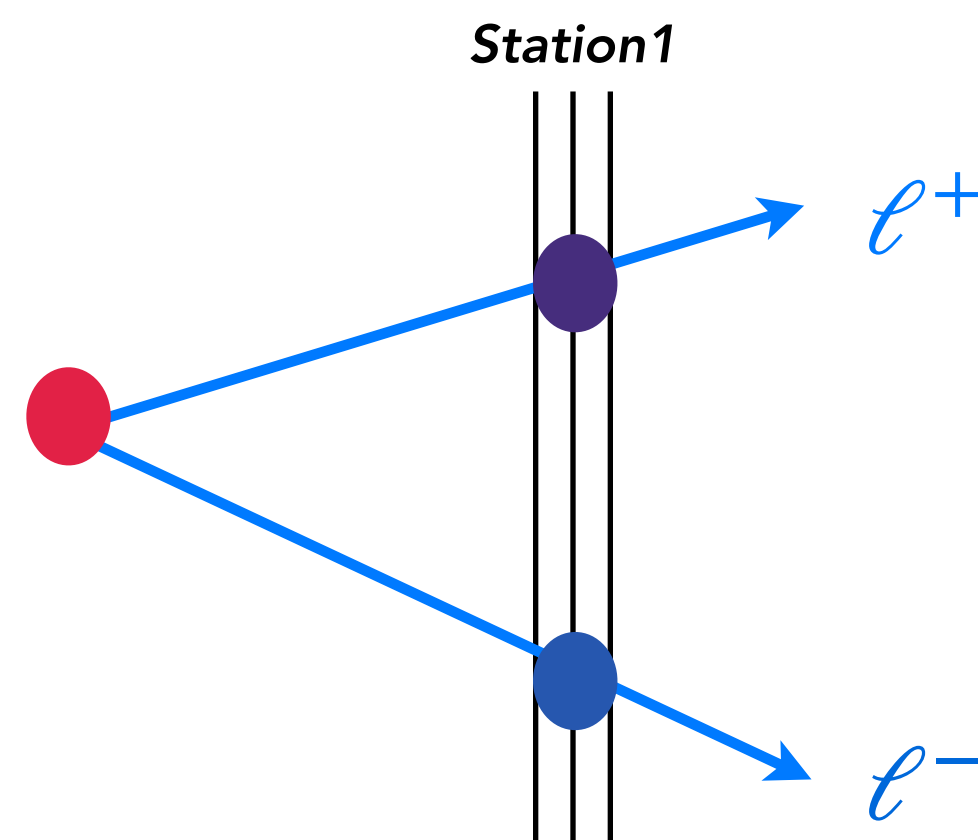


Tracking and Vertexing



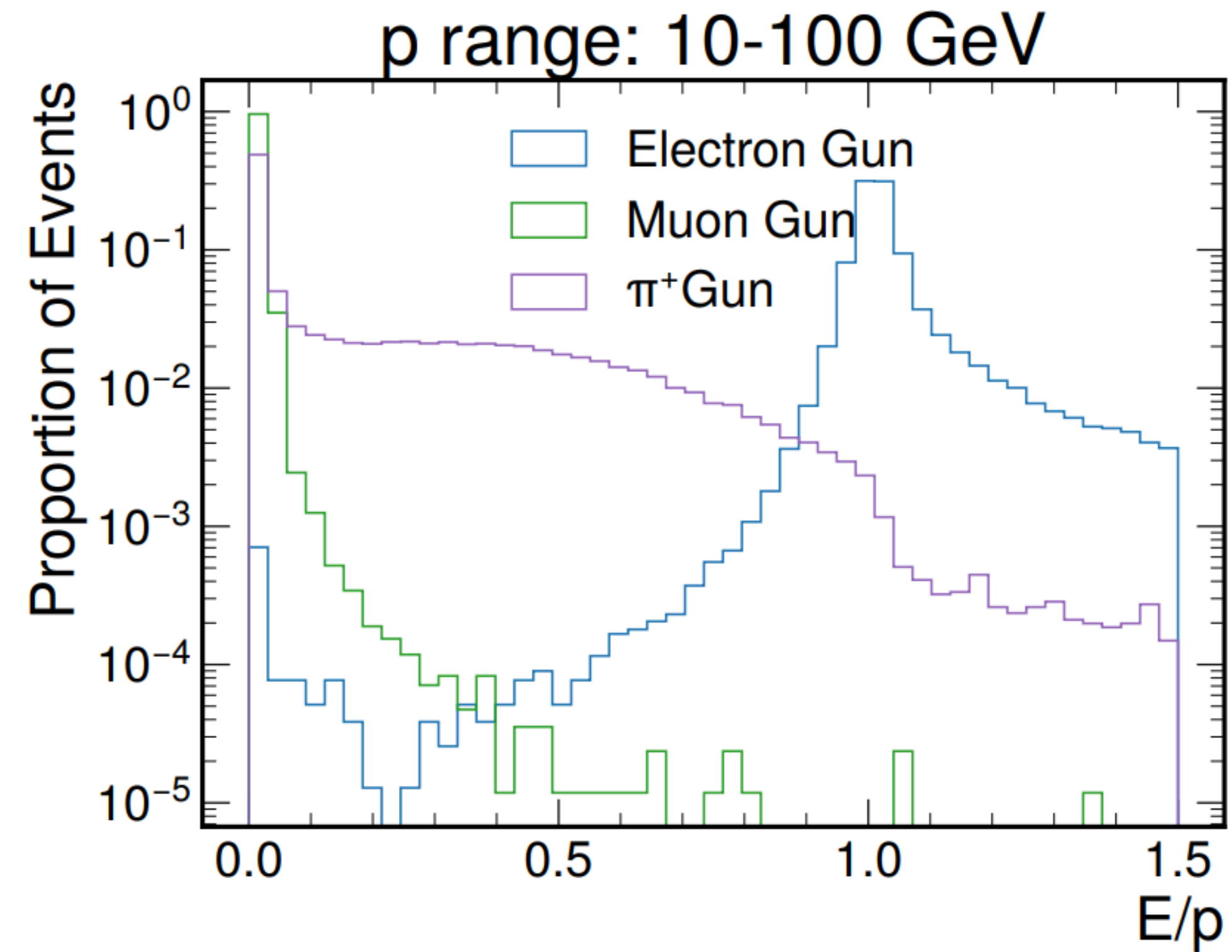
- For the dark photons decaying after the FMag, the leptons are less affected by the multiple scatterings in FMag. Better resolutions compared with prompt signals:

Tracking and Vertexing



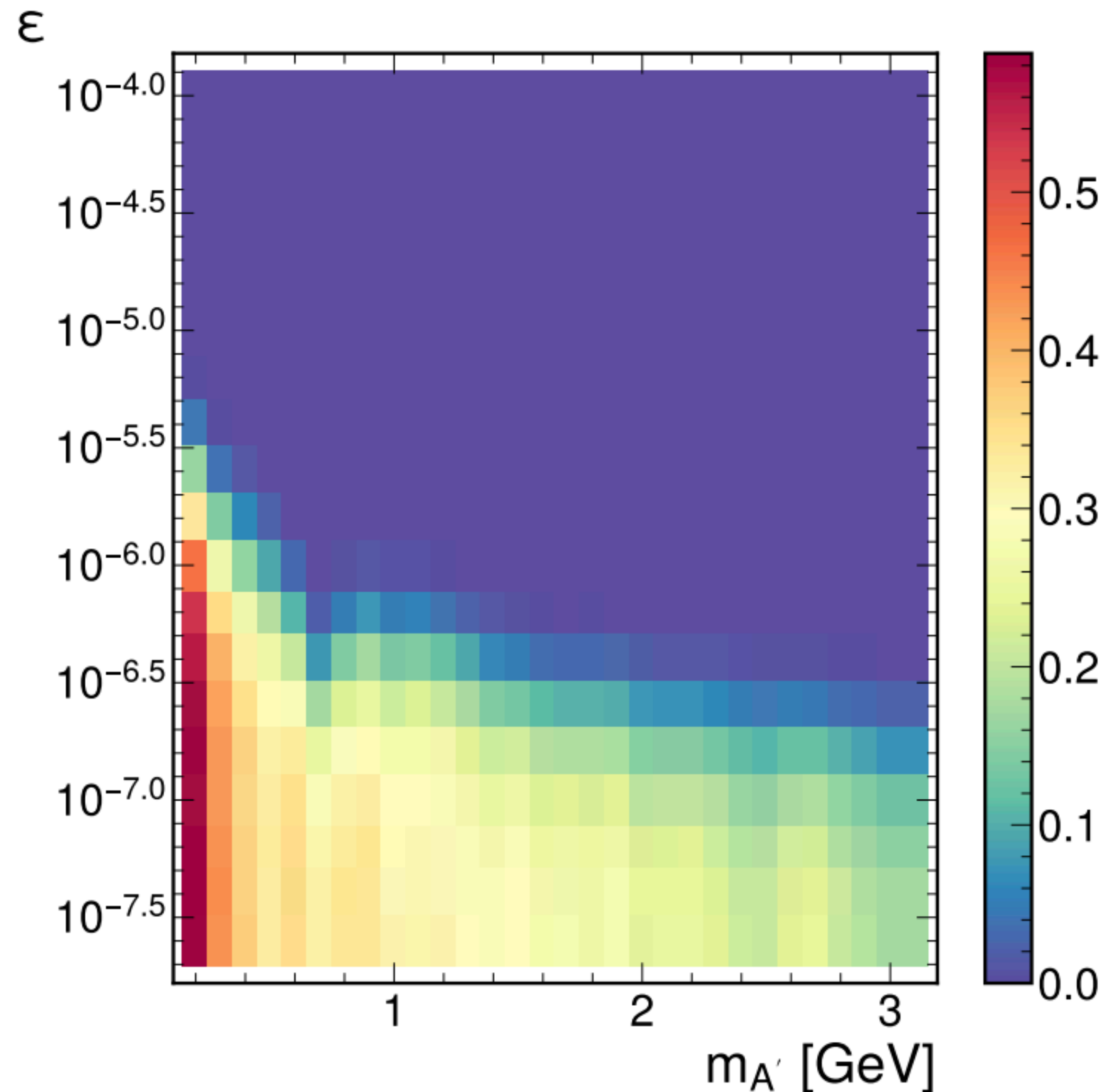
- Less affected by the multi scatterings in FMag. Better resolutions compared with prompt signals:
 - ✿ 75% track reconstruction efficiency for high momentum particles;
 - ✿ 5% mass resolution,
 - ✿ 5-10 cm Z resolution for dark photons decaying after FMag
- Working on improving the track and vertex reconstructions for dark photons decaying inside FMag

Particle Identification



- Working on Particle ID based on the combination of tracking and EMCal information

Signal & Background



- Dark photon signal acceptance as a function of coupling and masses
 - ✿ Only includes the muon channel; working on understanding the electron channel
- Simulation and study of the hadron and muon backgrounds ongoing. Finalizing soon.

Collaboration

- A strong team assembled of both experimentalists and theorists:



- One Snowmass paper: <https://arxiv.org/pdf/2203.08322.pdf>
- Working on finalizing the reconstruction studies and publish a technical paper on it
- Strong connections with the current SpinQuest collaboration
- Welcome to join the effort! Contact us if interested! (yfeng@fnal.gov ntran@fnal.gov)

DarkQuest: A dark sector upgrade to SpinQuest at the 120 GeV Fermilab Main Injector

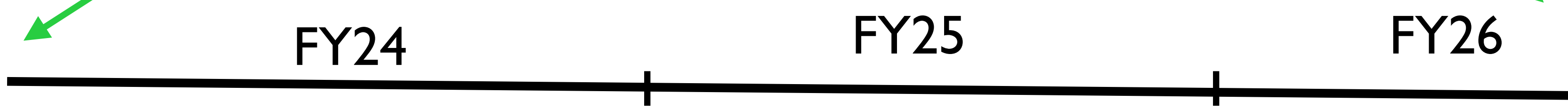
Aram Apyan¹, Brian Batell², Asher Berlin³, Nikita Blinov⁴, Caspian Chaharom⁵, Sergio Cuadra⁶, Zeynep Demiragli⁵, Adam Duran⁷, Yongbin Feng³, I.P. Fernando⁸, Stefania Gori⁹, Philip Harris⁶, Duc Hoang⁶, Dustin Keller⁸, Elizabeth Kowalczyk¹⁰, Monica Leys², Kun Liu¹¹, Ming Liu¹¹, Wolfgang Lorenzon¹², Petar Maksimovic¹³, Cristina Mantilla Suarez³, Hrachya Marukyan¹⁴, Amitav Mitra¹³, Yoshiyuki Miyachi¹⁵, Patrick McCormack⁶, Eric A. Moreno⁶, Yasser Corrales Morales¹¹, Noah Paladino⁶, Mudit Rai², Sebastian Rotella⁶, Luke Saunders⁵, Shinaya Sawada²¹, Carli Smith¹⁷, David Sperka⁵, Rick Tesarek³, Nhan Tran³, Yu-Dai Tsai¹⁸, Zijie Wan⁵, and Margaret Wynne¹²

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⁸University of Virginia, Charlottesville, VA 22904, USA
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¹⁴Yamagata University, Yamagata, 990-8560, Japan
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¹⁶Yerevan Physics Institute, Yerevan, 0036, Republic of Armenia
¹⁷Penn State University, State College, PA 16801, USA
¹⁸University of California Irvine, Irvine, CA 92697, USA

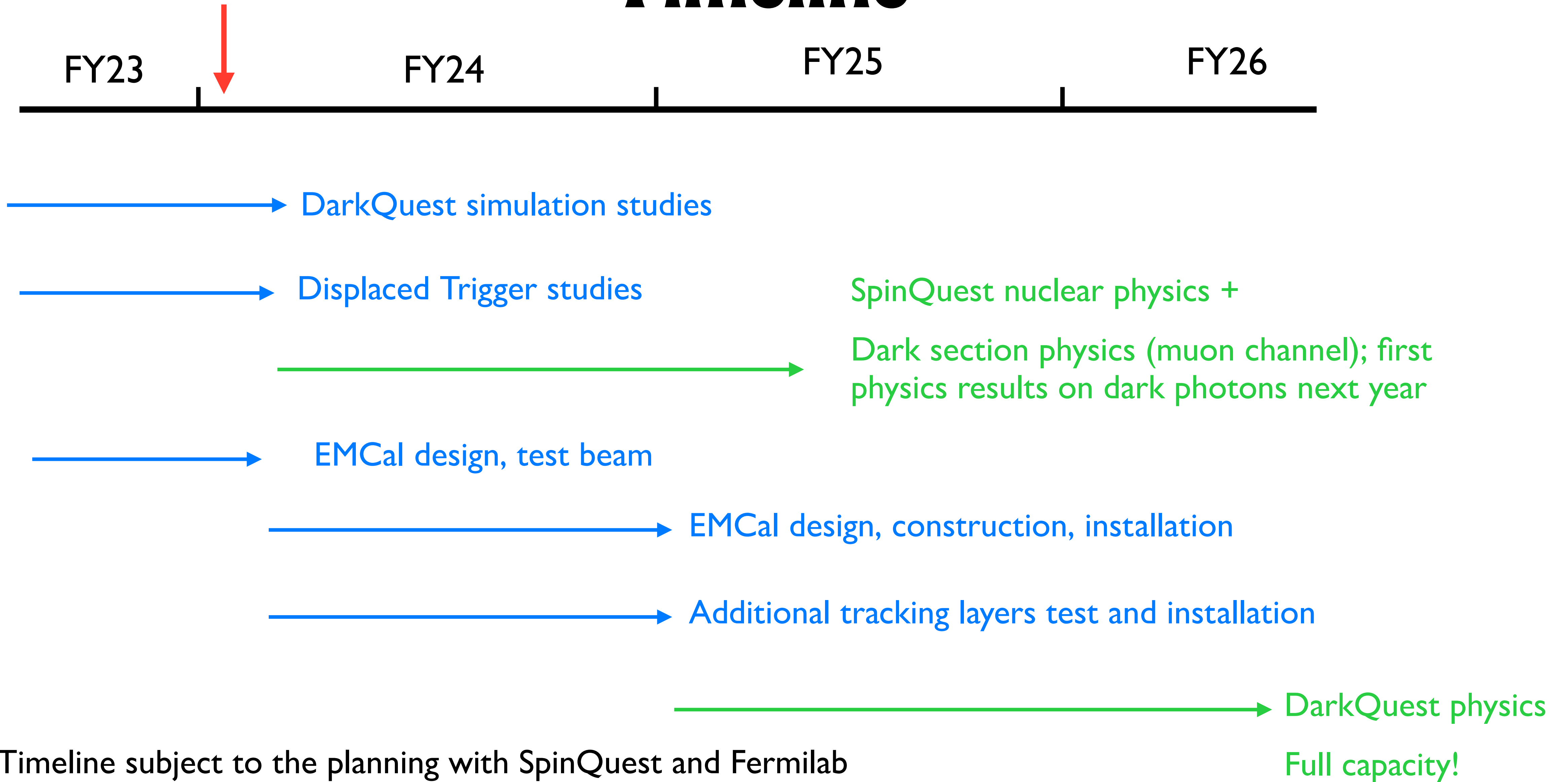
Fermilab Schedule



SY 120	MT	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF
	MC	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF
	NM4	OPEN	SpinQ	SpinQ	SpinQ	SpinQ	SpinQ	SpinQ	SpinQ	OPEN	OPEN					
LINAC	MTA				ITA	ITA	ITA	ITA	ITA	ITA	ITA					
		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30		



Timeline



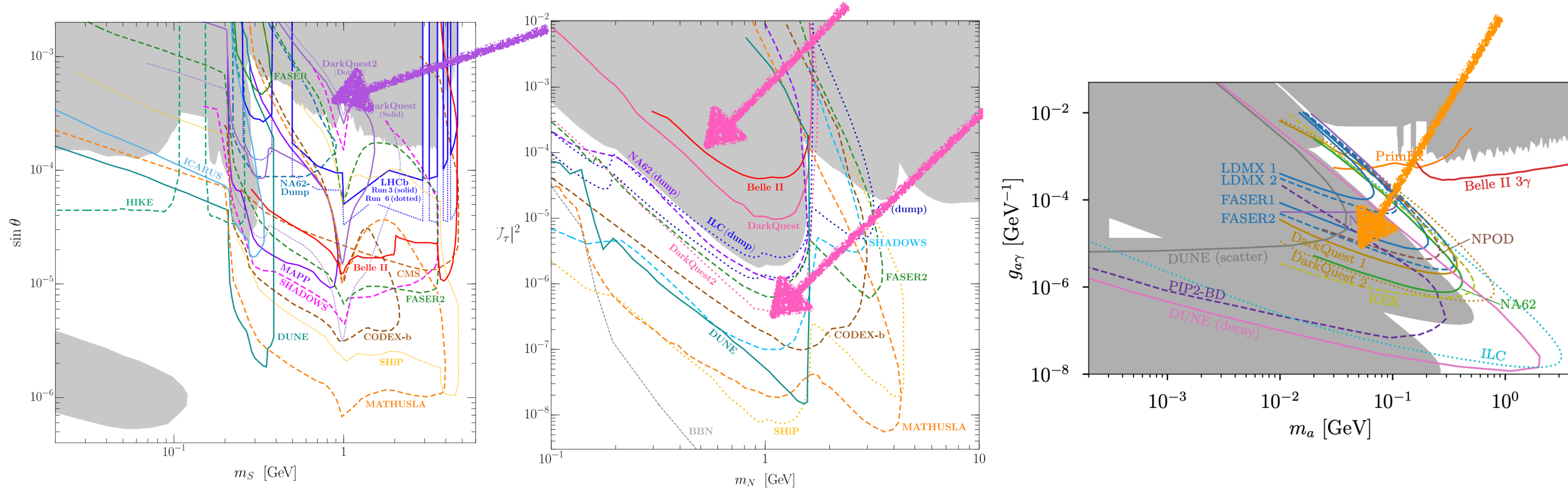
Summary

- Dark sector and light dark matter is an interesting yet not constrained region to explore
- DarkQuest offers a low-cost and near-term opportunity to uncover a broad range of MeV-GeV dark sectors
- Recently got funded! Plan to start dark sector exploration in April 2024!
- A lot of electronics design, simulation, and reconstruction studies ongoing; look forward to exciting detector and physics studies and results in the coming future!



Back Up

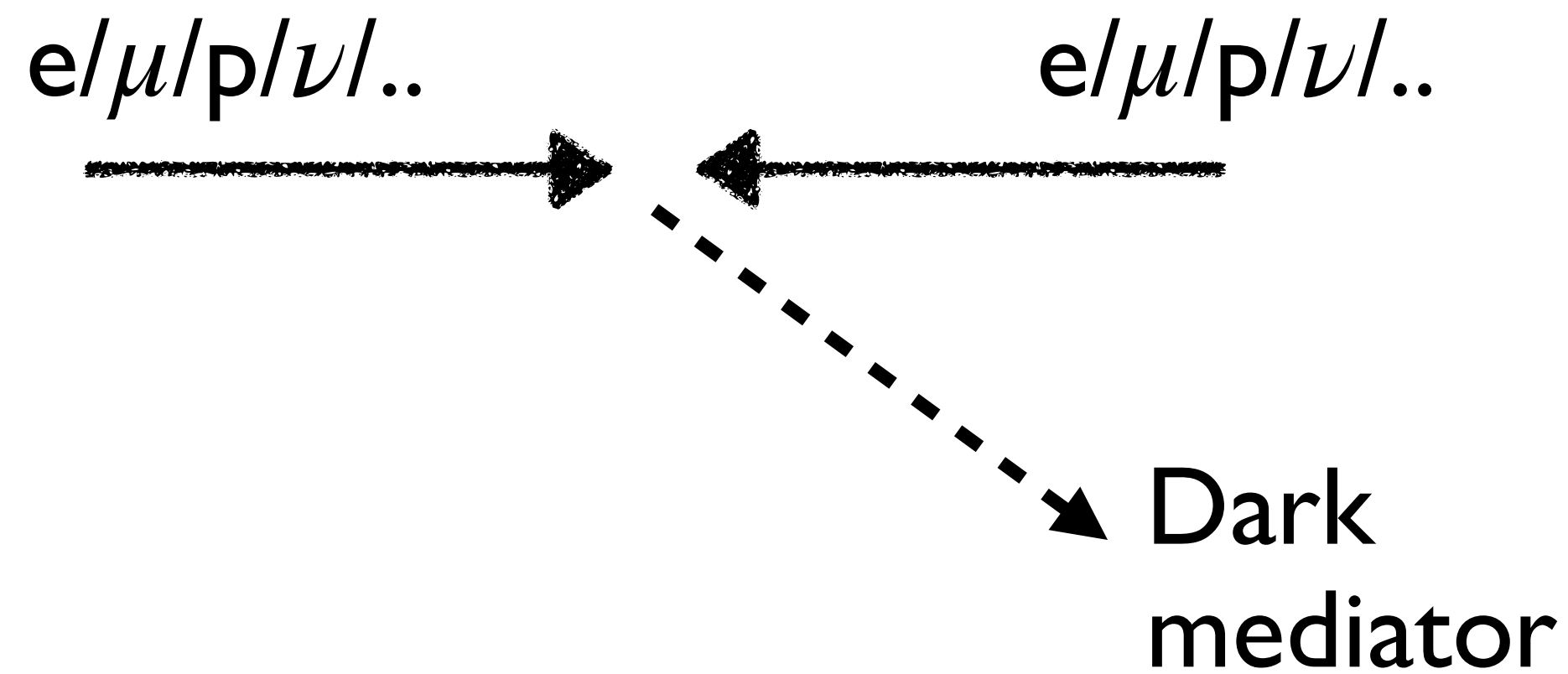
Broad Sensitivity Coverage



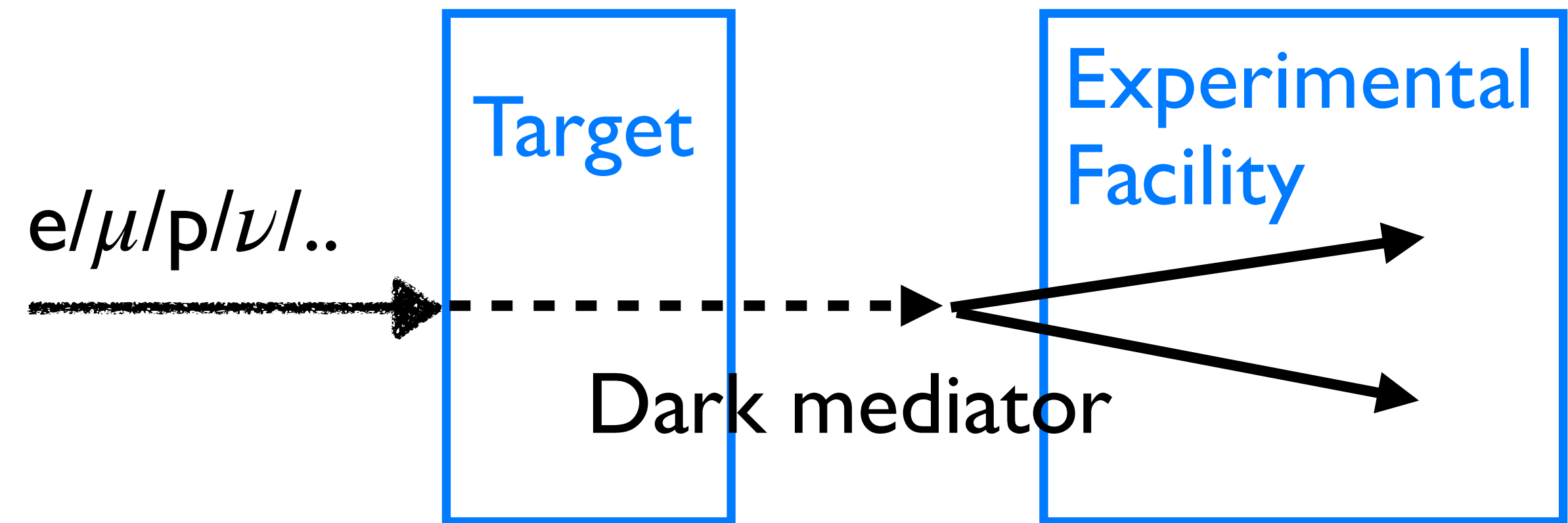
Arxiv.2207.06905

- Broad coverage to different theory models,
 - ✿ Different portals: scalar, vector, neutrino, axion-like, etc, by probing lepton/hadron/photon pairs

Probe Dark Sector with Accelerators

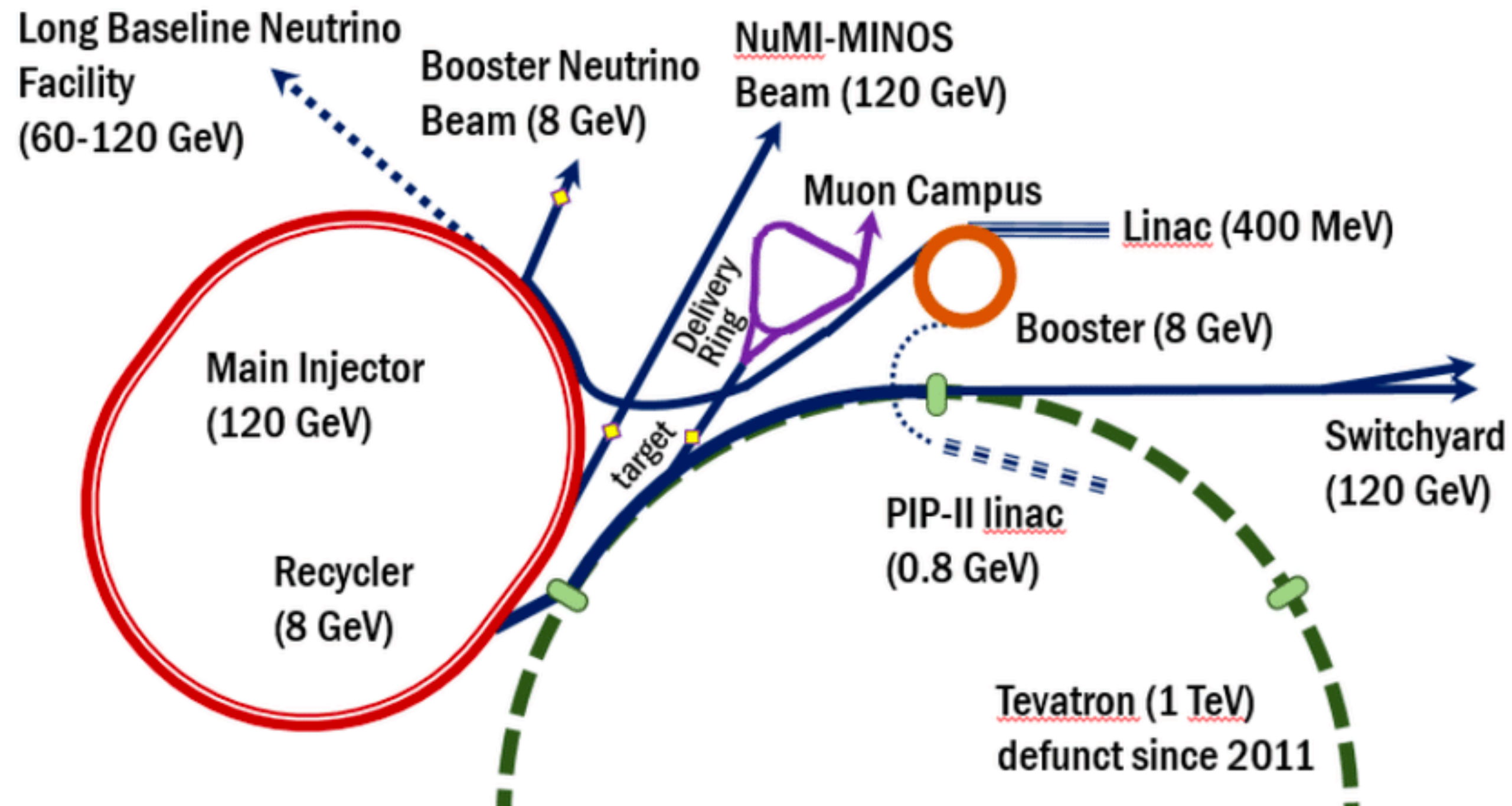


- Look for final states with bumps/displaced signals/missing E/p/m
 - ✦ ATLAS/CMS/LHCb, Belle, BES?



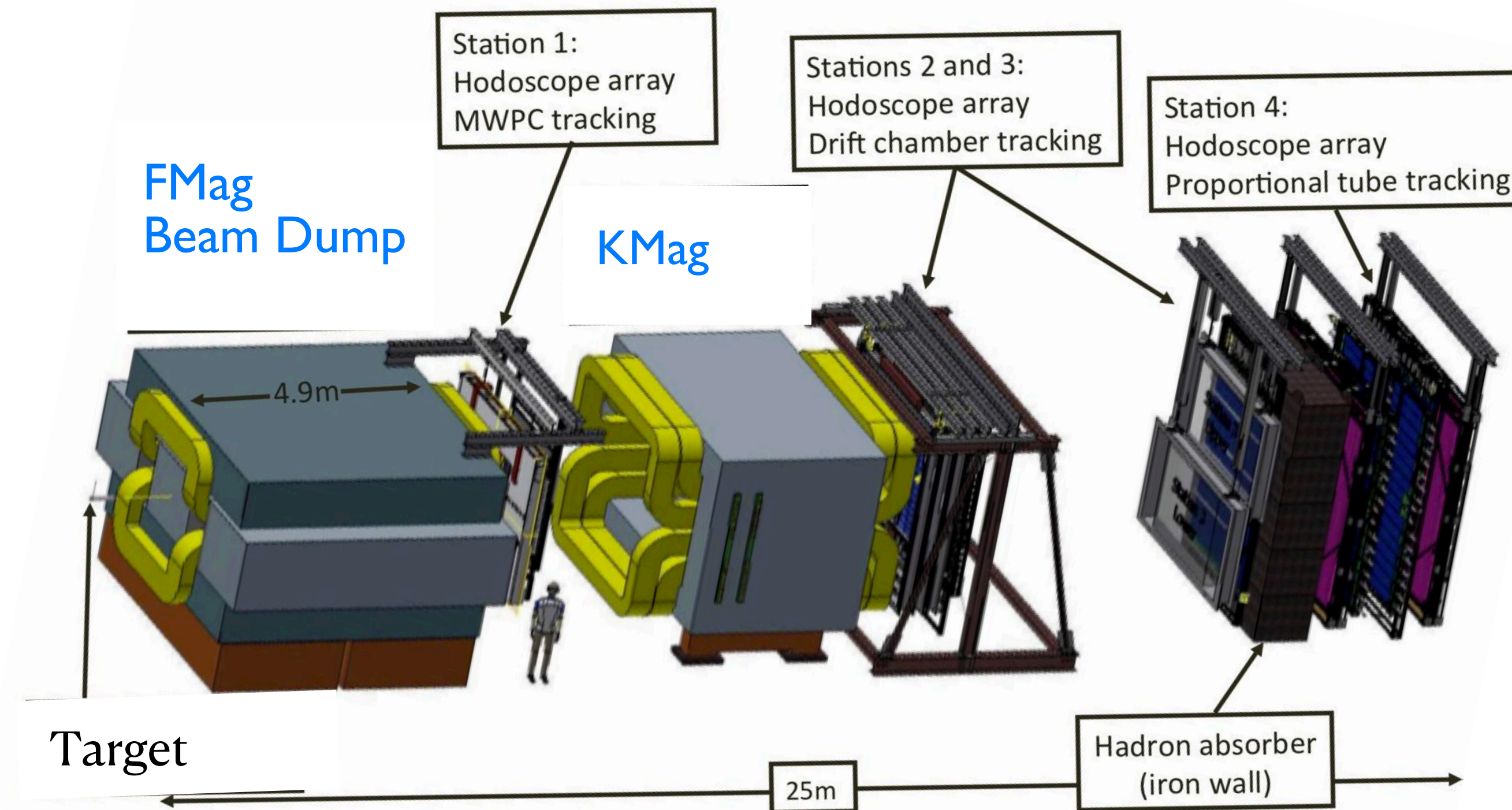
- Analyze the dark mediator decay products: bumps/displaced signals/missing E/p/m
 - ✦ NA64 @ CERN, LDMX @ SLAC, **DarkQuest @ Fermilab**
 - ✦ Usually low background, better sensitivity at low mass region

120 GeV Proton beam

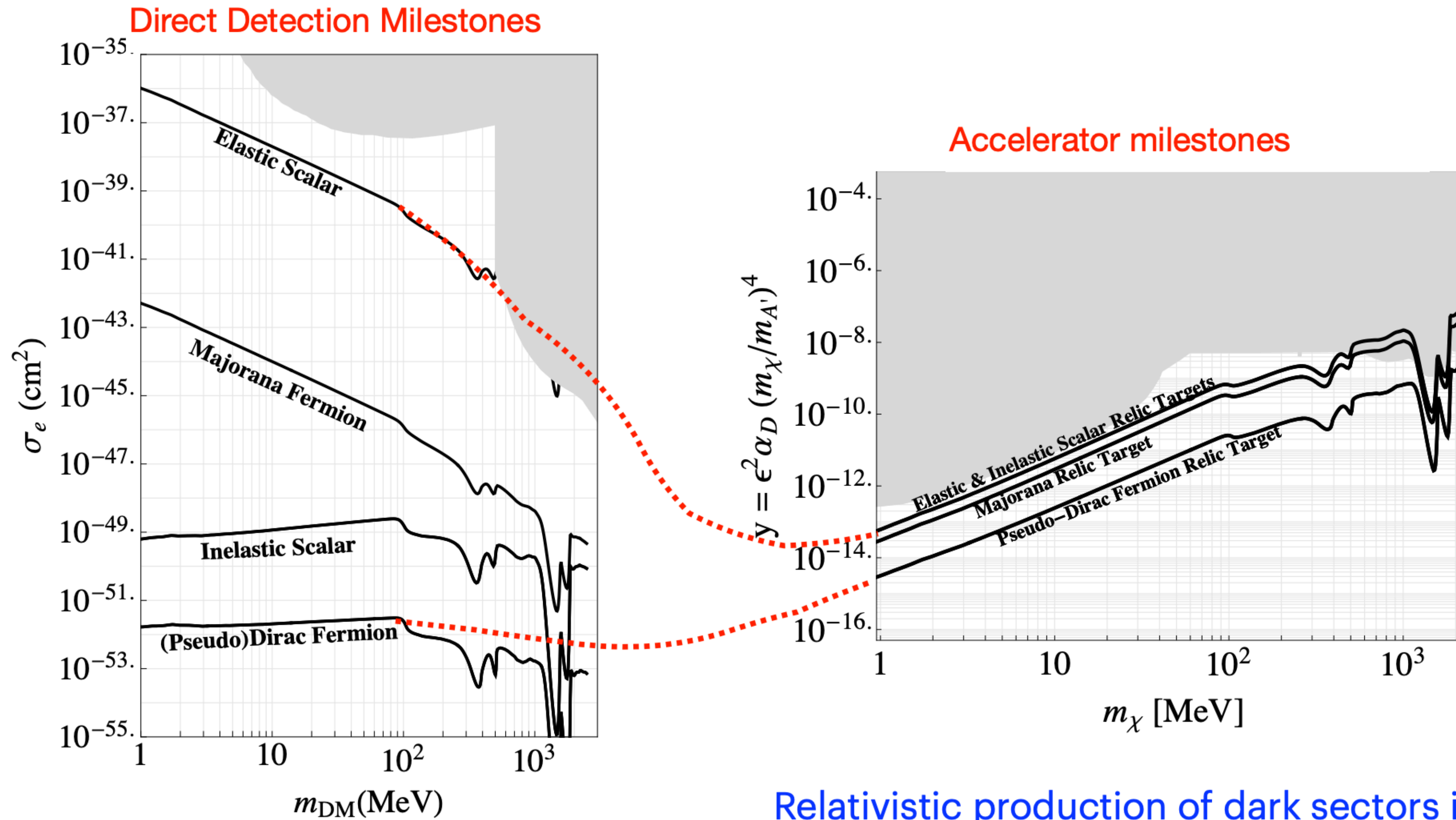


- 120 GeV high-intensity proton beam from the Fermilab Accelerator Complex
 - ✿ Expect 10^{18} Protons on target (POT) in a 2-year parasitic run, and 10^{20} POT after the PIP-II accelerator upgrade

SpinQuest spectrometer



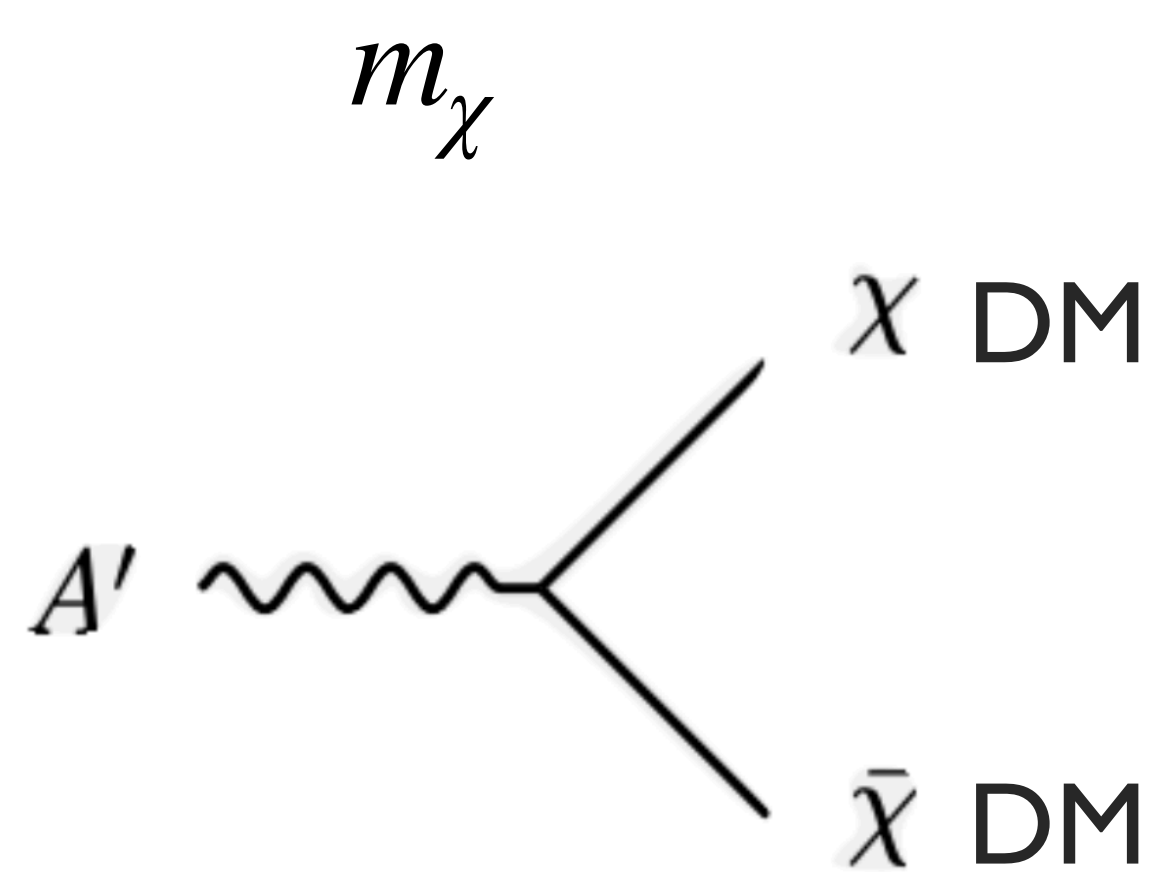
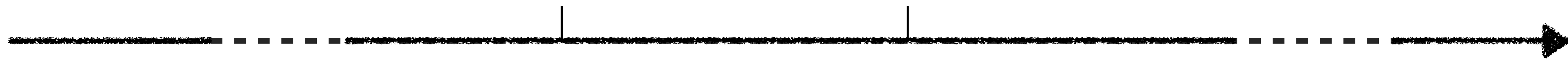
Accelerators



Relativistic production of dark sectors is less sensitive to loop- or velocity-suppression

Dark (Hidden) Sector

Dark Mediator Mass



- For mediator mass $> 2m_\chi$, can probe dark mediator decaying to dark matter
- Look for missing momentum/energy/mass



- Can probe the channel of dark mediator decaying to SM particles for the whole phase space

• Vector Portal: $F^{\mu\nu} A'_{\mu\nu}$:

$A' \rightarrow$ lepton pairs...

• Scalar Portal: $\phi h h^\dagger + \phi^2 h h^\dagger$:

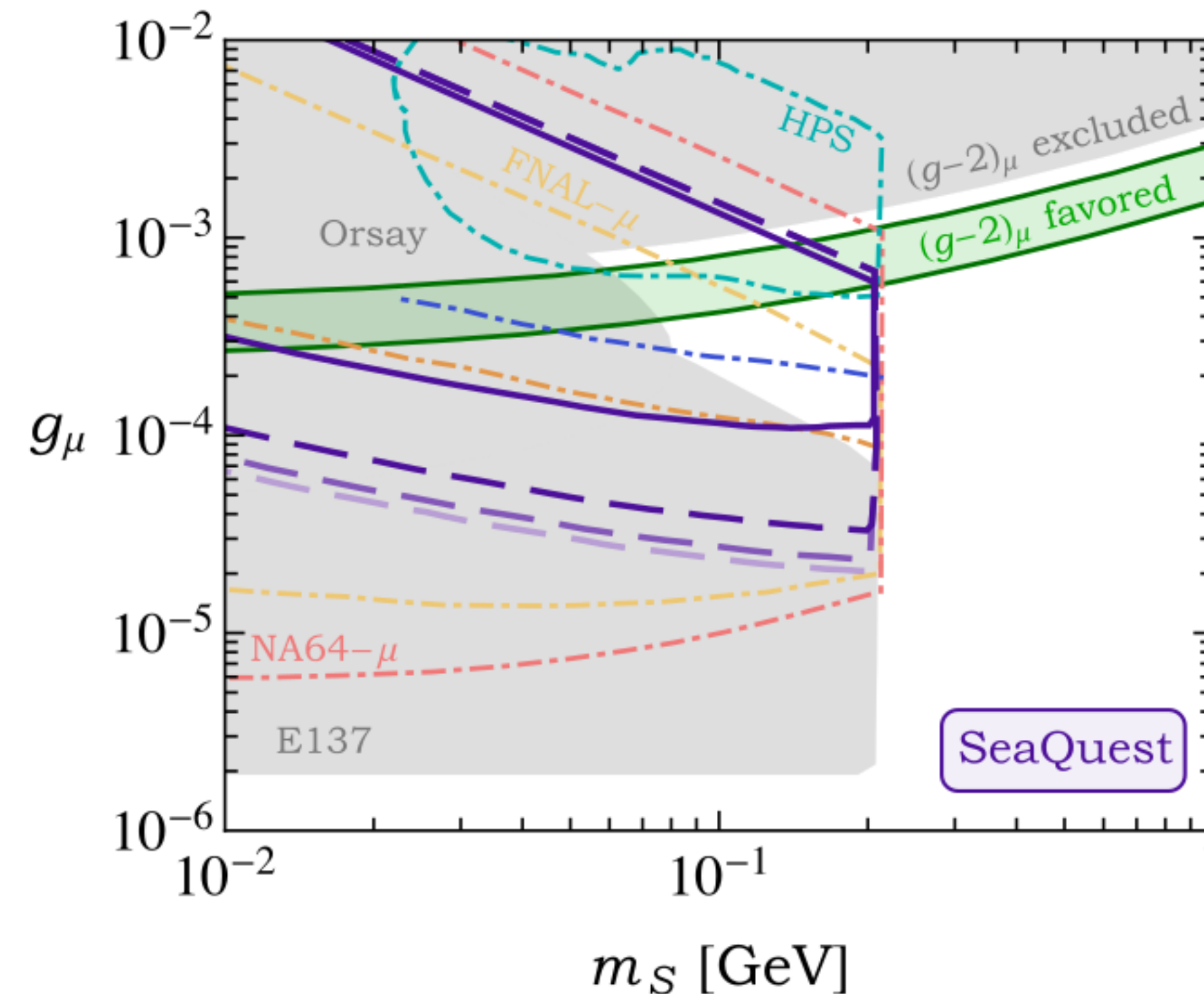
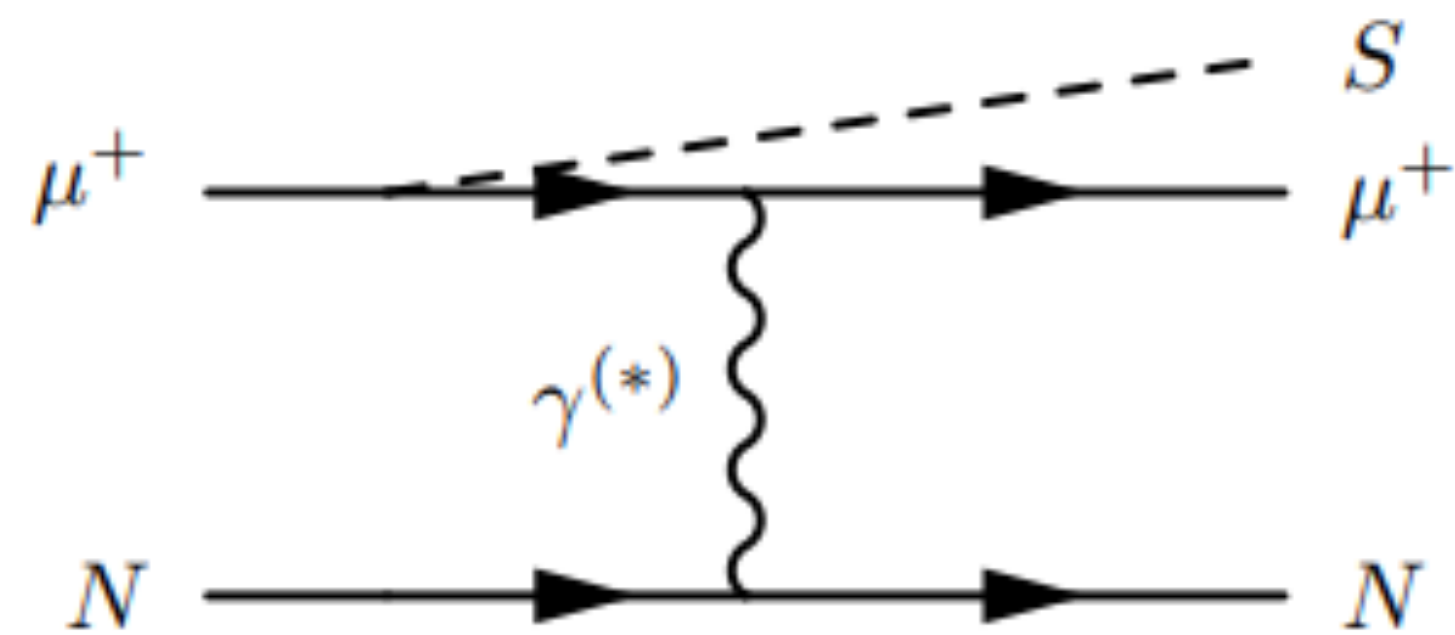
$\phi \rightarrow$ lepton/hadron pairs..

• Neutrino Portal: hLN :

$N \rightarrow$ lepton + hadrons..

• Axion Portal: $a(\vec{G}_{\mu\nu} \vec{G}^{\mu\nu} + F_{\mu\nu} F^{\mu\nu})$: $a \rightarrow$ photon/hadron pairs

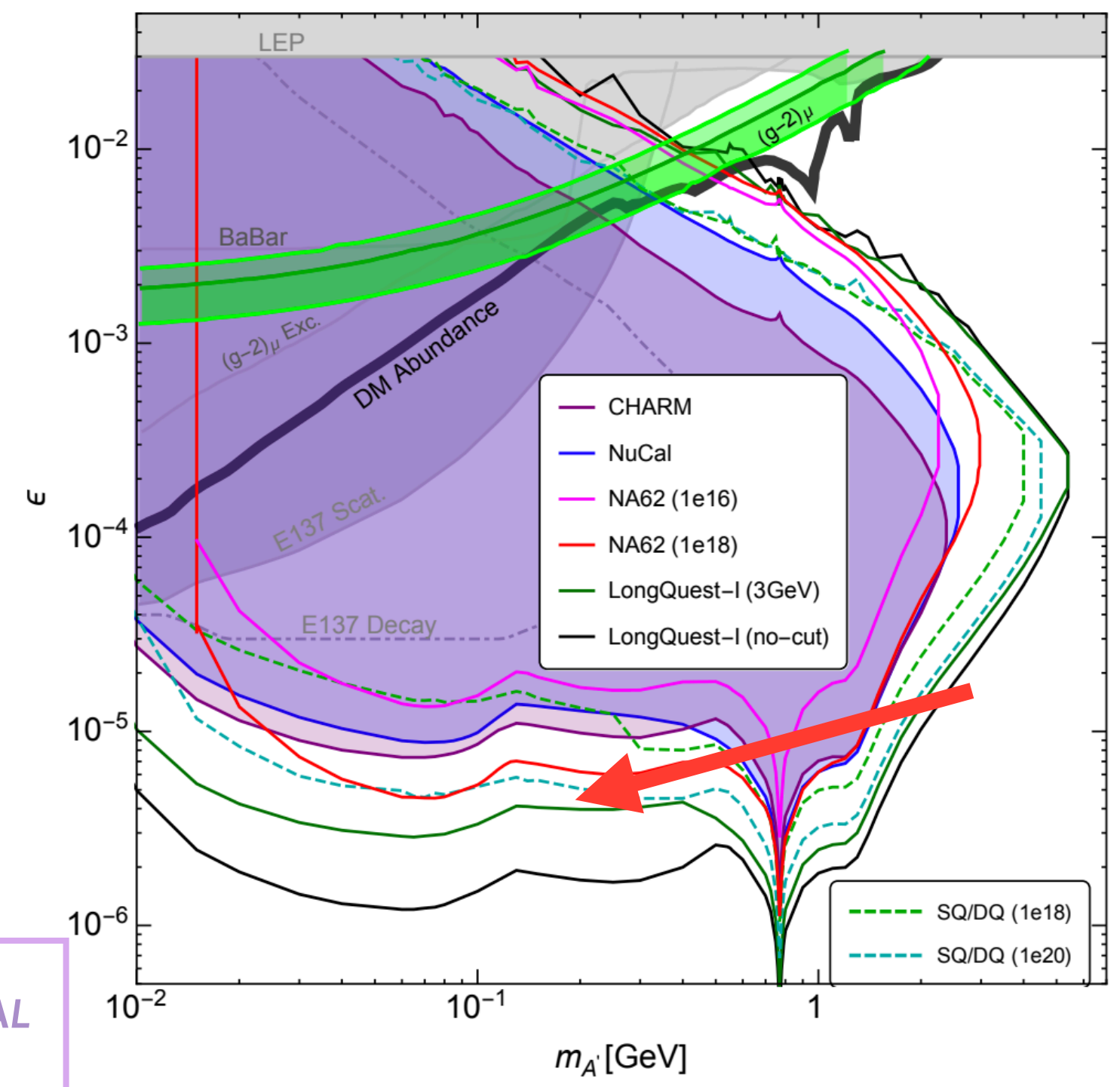
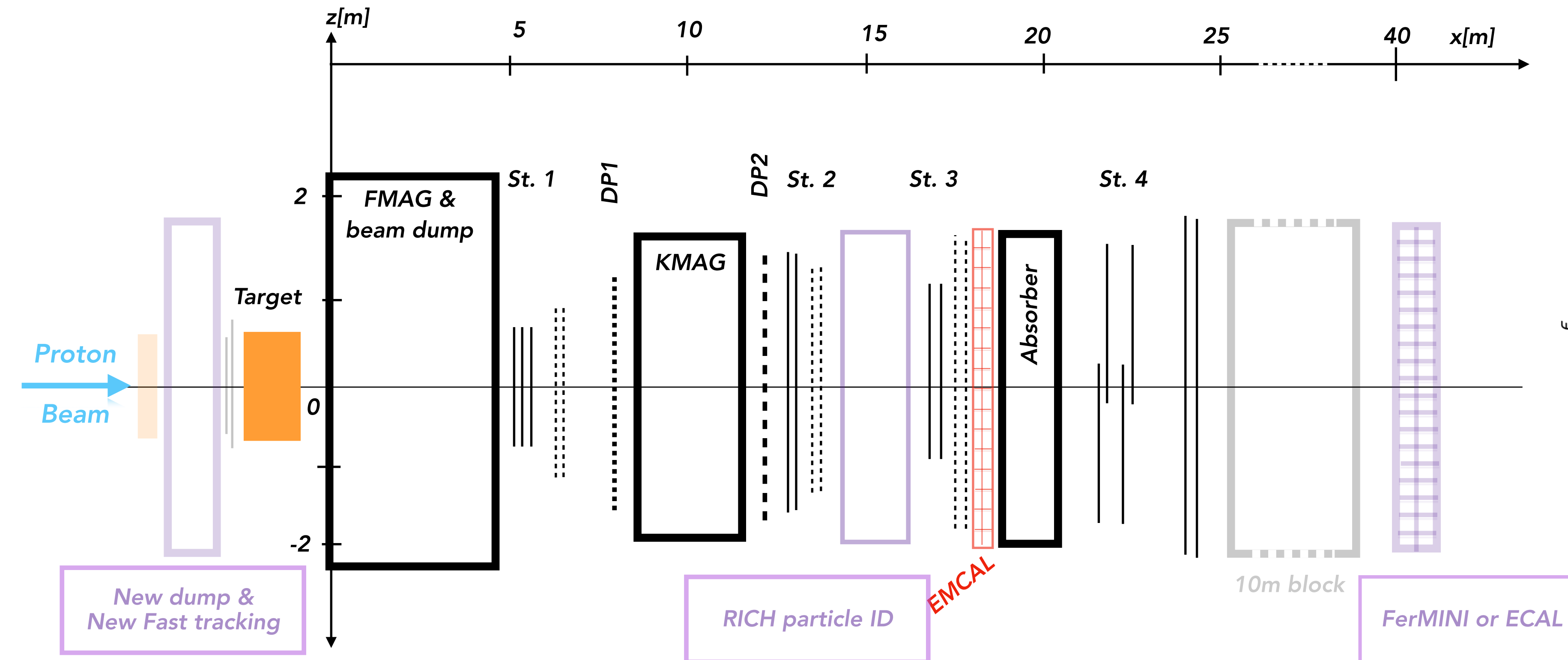
Why DarkQuest: Connection with (g-2) Anomaly



A.Berlin, S.Gori,
P.Schuster, N.Toro
Arxiv:1804.00661

- Large flux of secondary muons from pion decays traversing a thick target, which makes DarkQuest a muon beam dump experiment
- Search for displaced decays of light muon-coupled mediators

Future Upgrade: DarkQuest -> LongQuest



Y. Tsai, P. deNiverville, M. Liu
 Arxiv:1908.07525

- Future upgrades of DarkQuest - LongQuest: adding particle ID detector, new dump and new fast tracking, and ECAL, to further extend the coverage and sensitivity; explore this for Snowmass