



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

Yongbin Feng (Fermilab)

For DarkQuest Working Group

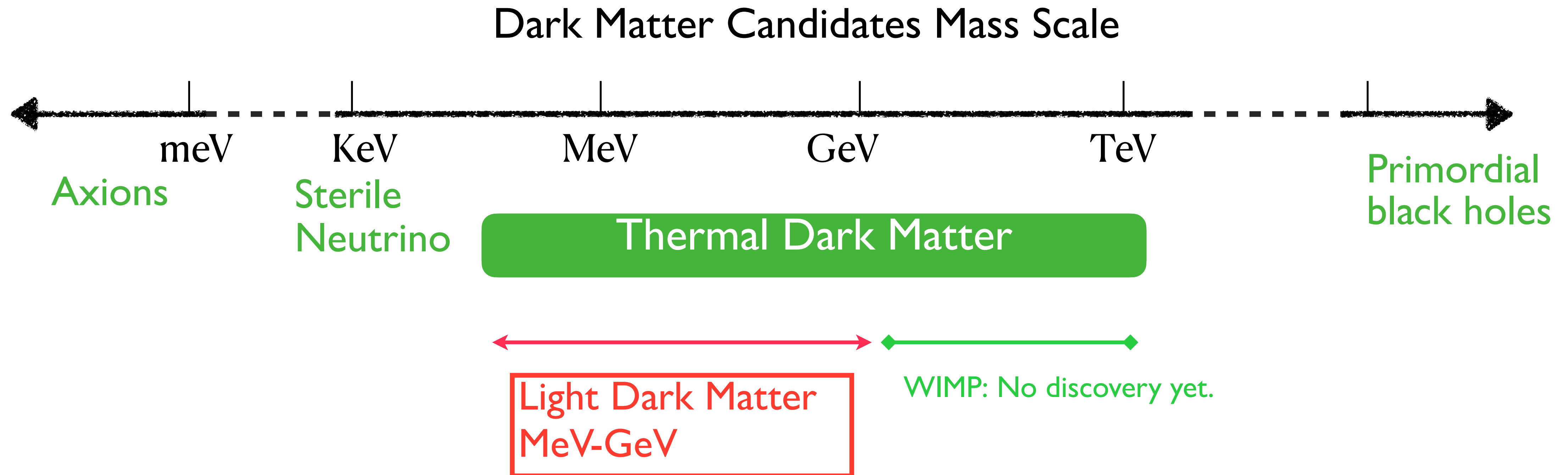
Aspen Center for Physics

March 28th, 2023

Outline

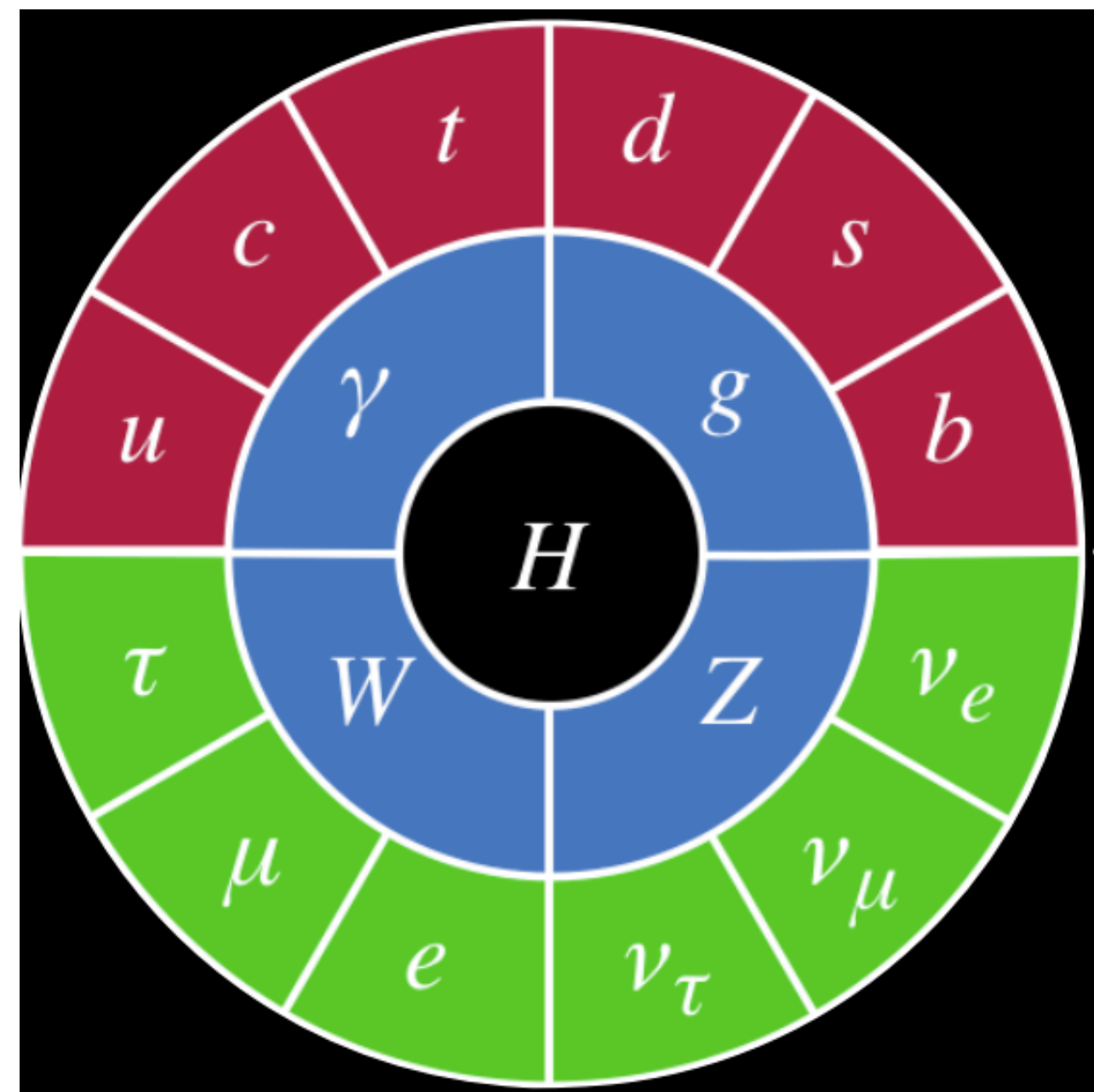
- Introduction: Dark Sector Physics
- SpinQuest, its Upgrades to DarkQuest, and Expected Sensitivities
- Upgrade Studies and Proposed Timeline
- Summary

Light Dark Matter



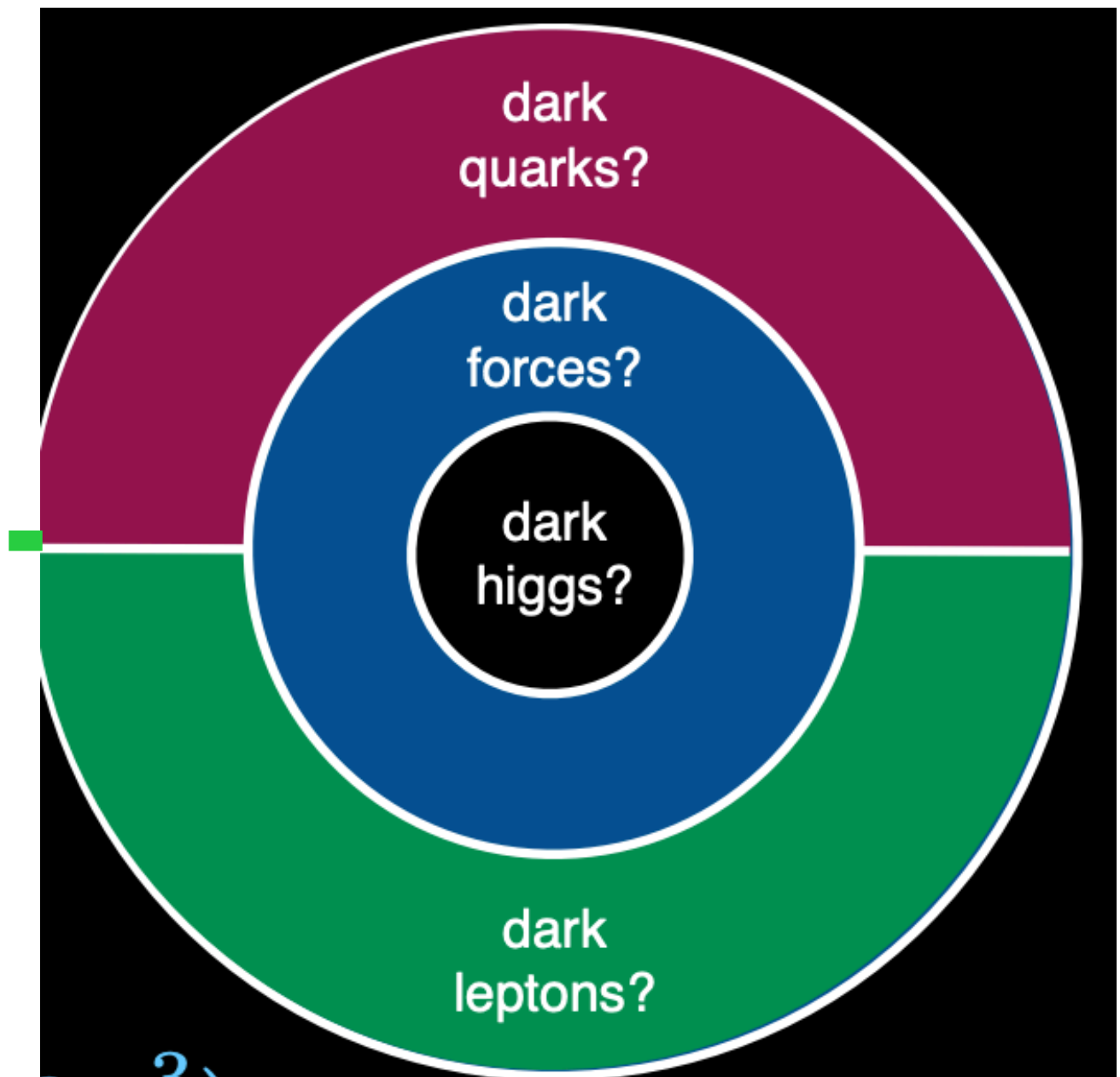
- Thermal dark matter's mass range is MeV - TeV, and WIMP has not been discovered yet.
- Light dark matter requires light mediators -> **Dark Sector**

Dark (Hidden) Sector



SM

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



DM

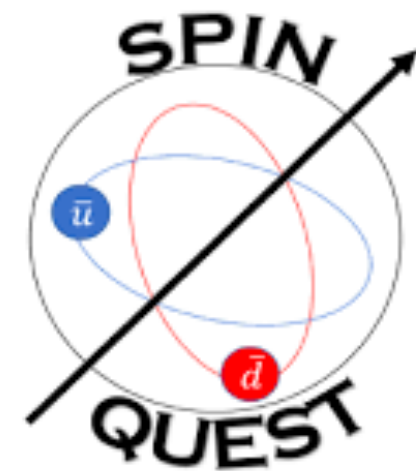
- Dark Sectors can connect to SM sectors via some new couplings.
- Can probe the dark sector by looking at the dark mediators and their decay products: missing E/p/m, displaced lepton/hadrons, etc
- High-intensity accelerators and fixed-target experiments provide an ideal environment to probe dark sector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

Goals

- Large dark sector production cross section
- Proper geometry for large acceptance
- Sensitivity to different final states
- Good reconstruction performance: efficiency and resolution
- Small background
- Cost and timescale

Goals

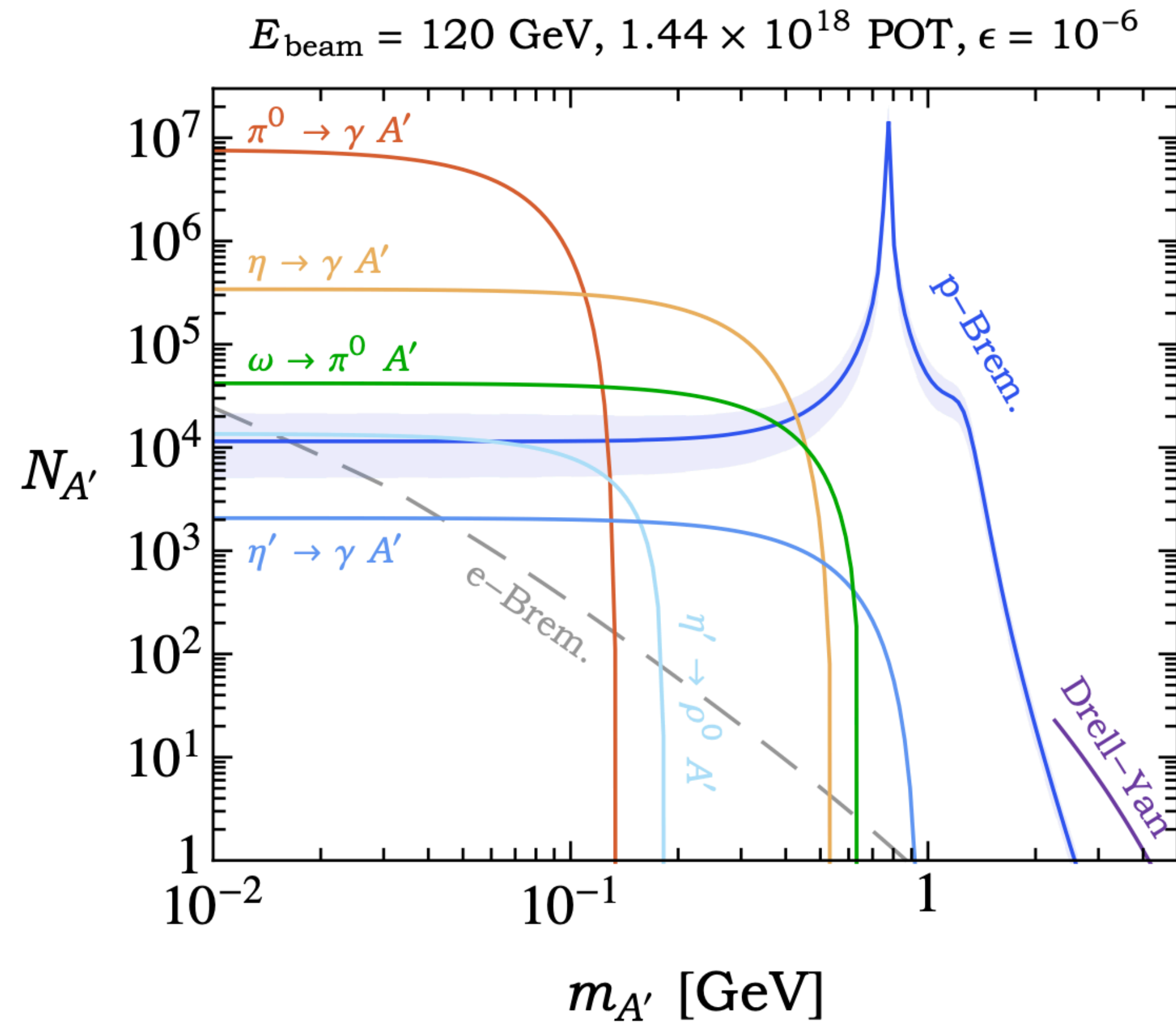
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-
- Yes SpinQuest @ Fermilab and its DarkQuest upgrade have all these features!



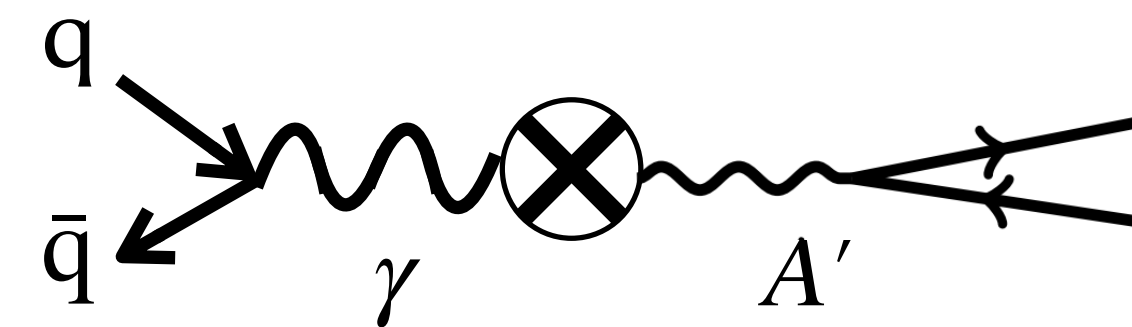
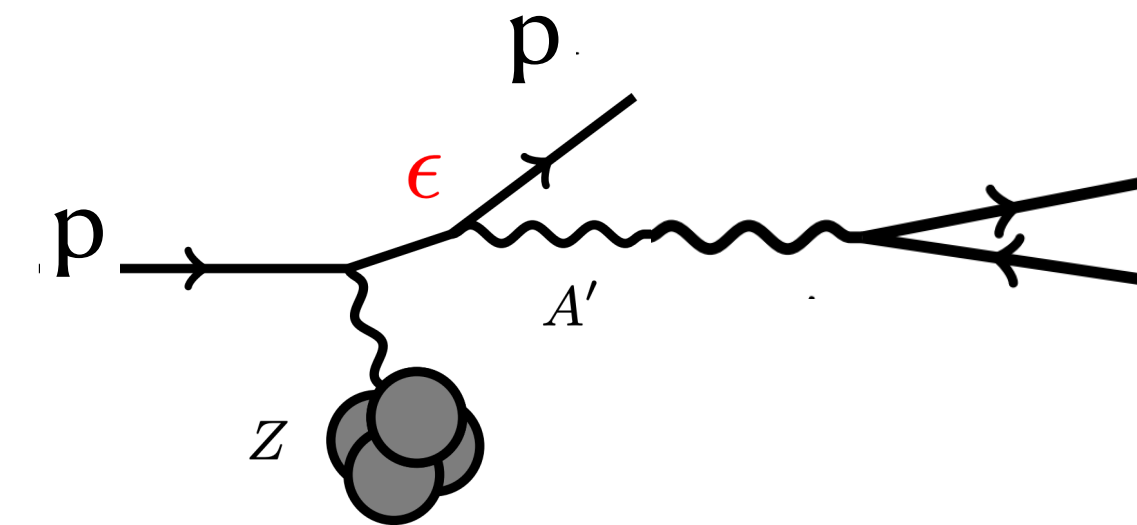
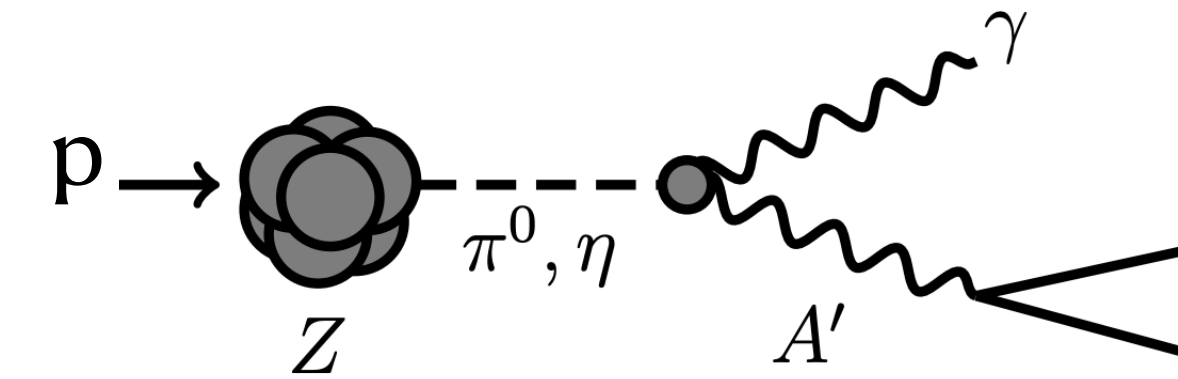
 **Fermilab**

**dark
quest**

Dark Photon Production with Proton Fixed-Target

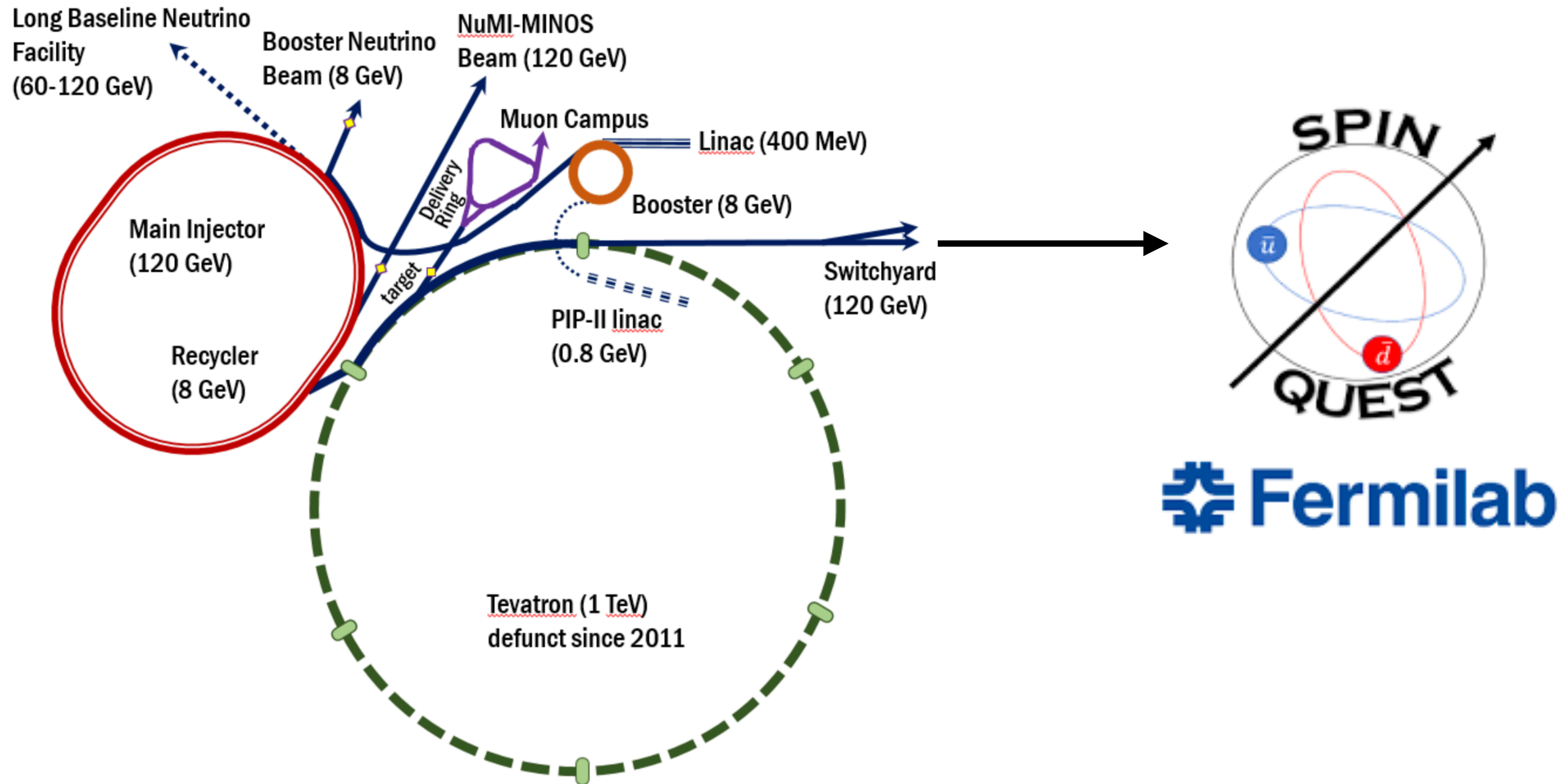


A.Berlin, S.Gori,
P.Schuster, N.Toro
Arxiv:1804.00661

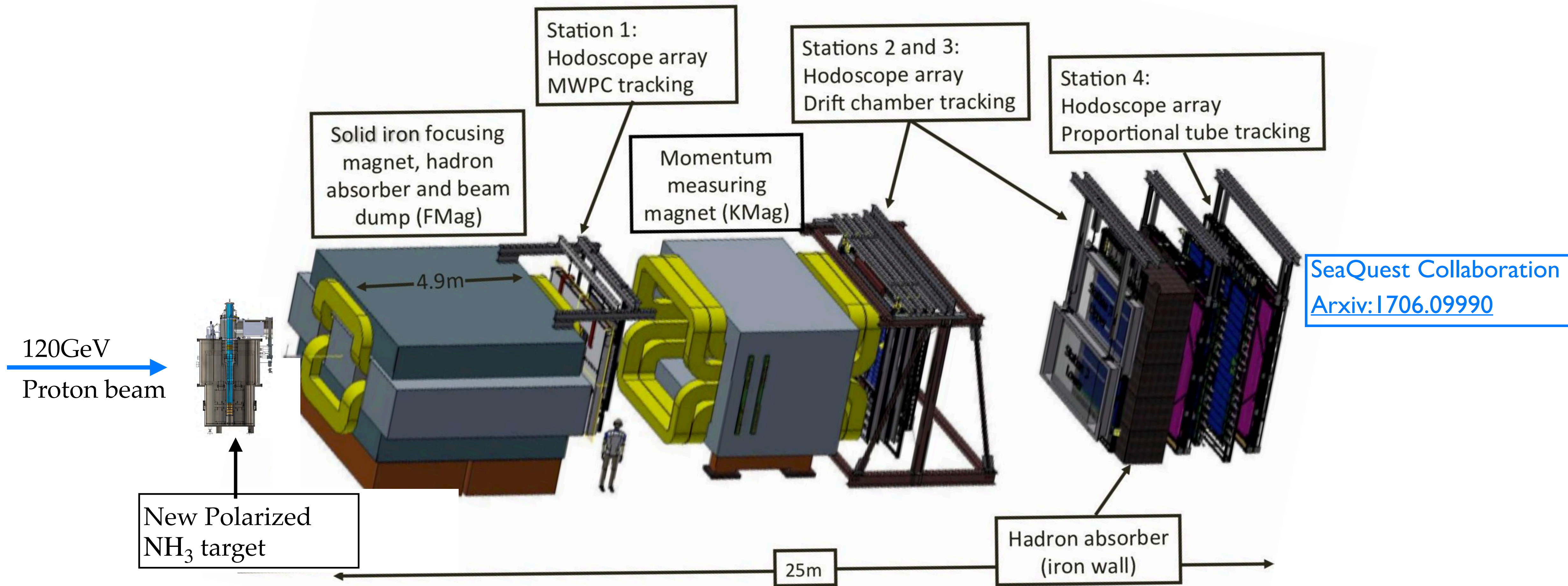


- Larger production rates with proton beams compared with electron beams

SpinQuest @ Fermilab



SpinQuest Spectrometer

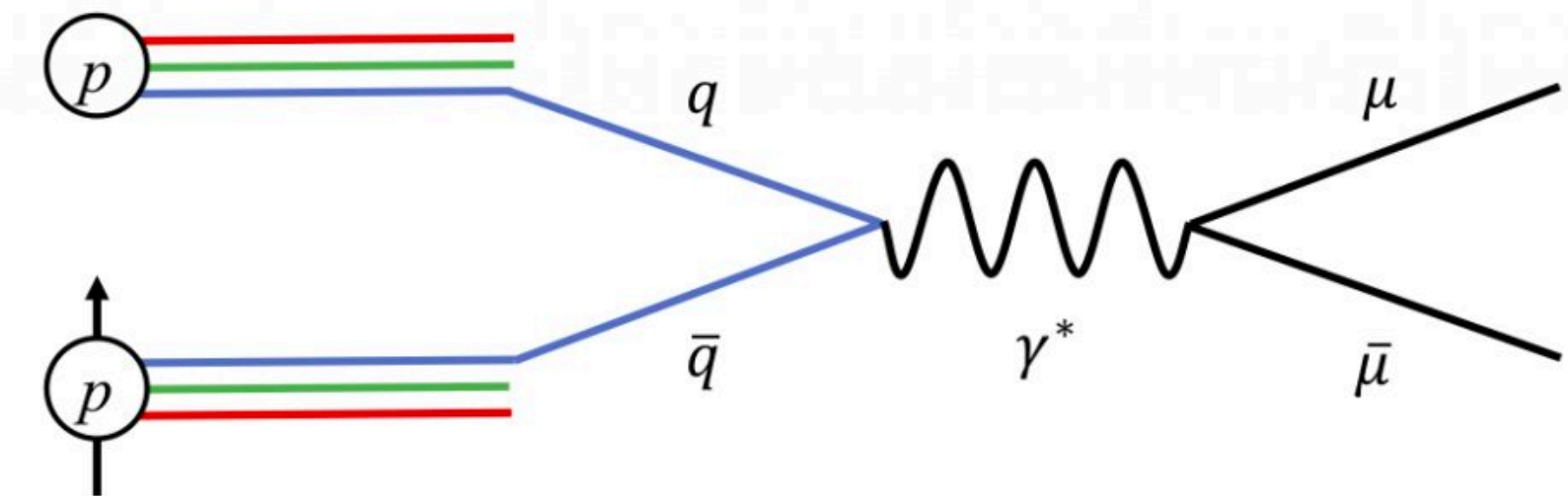
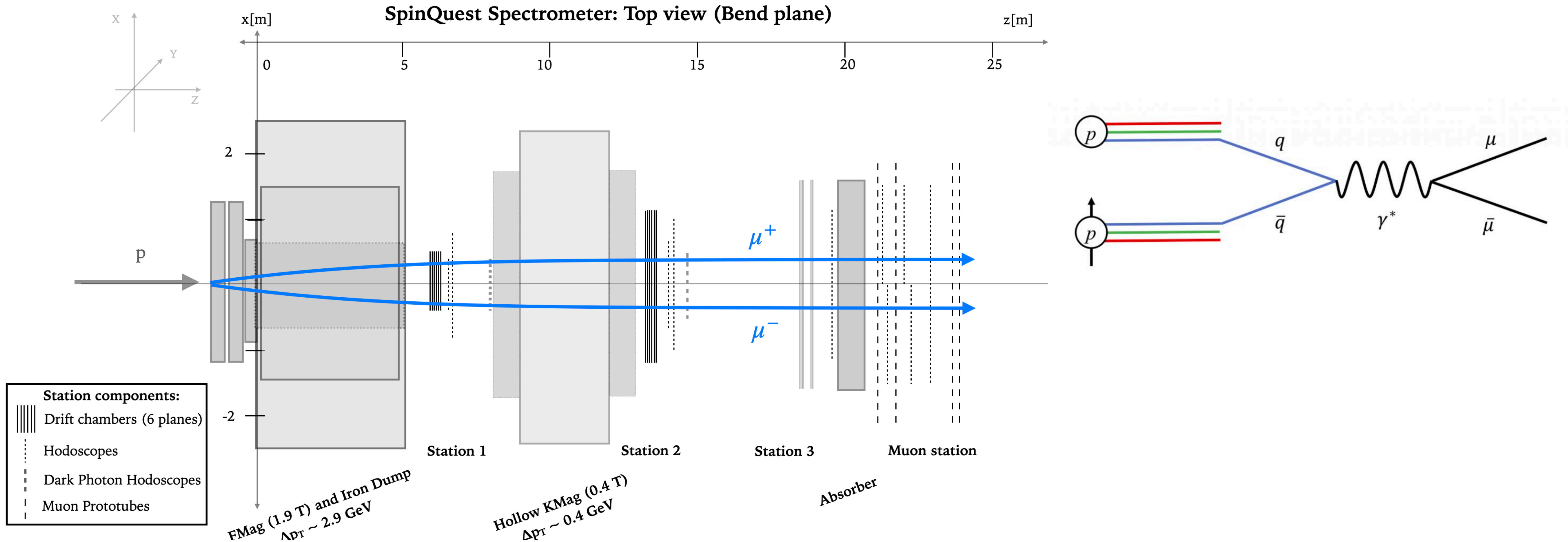


- Measuring the Drell-Yan process for studying the Transverse Momentum Dependent PDFs (TMDs) inside the proton



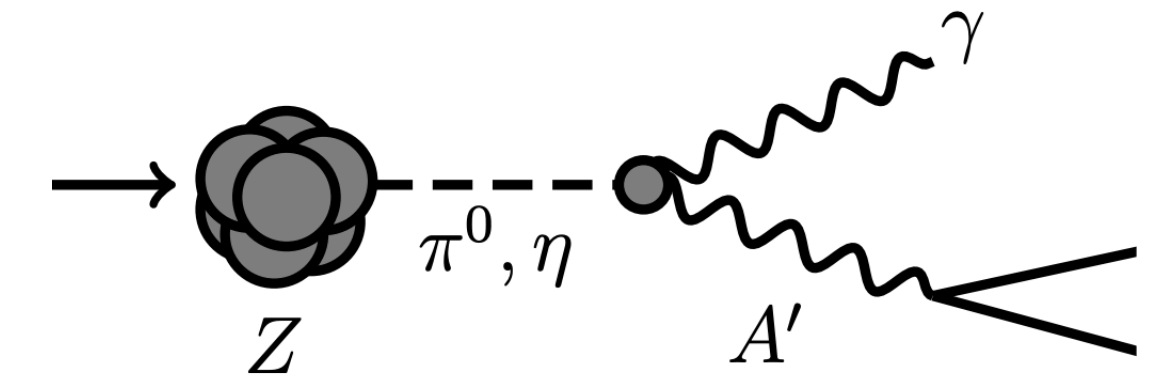
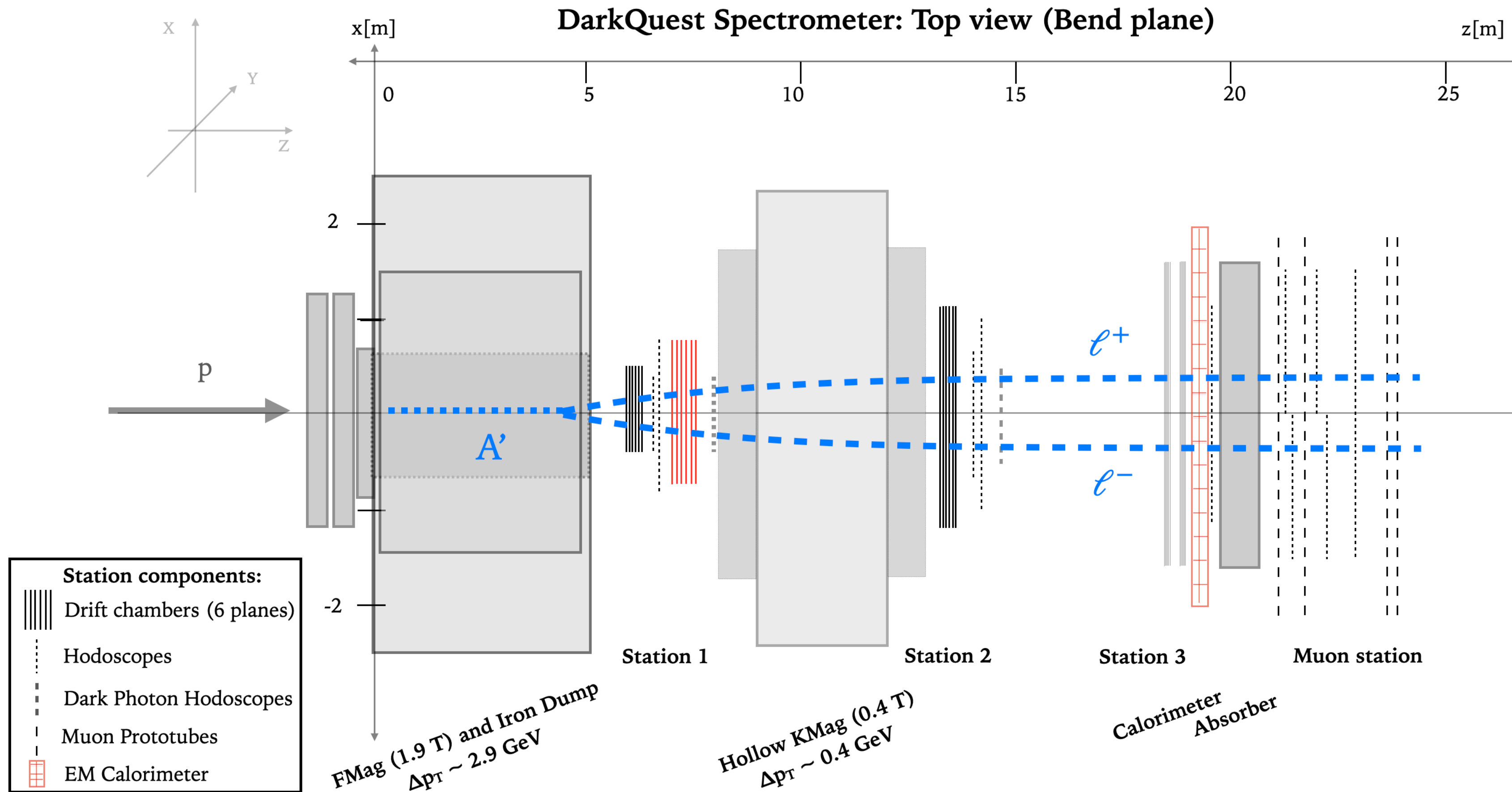
SpinQuest
spectrometer

SpinQuest Spectrometer



- Measuring the Drell-Yan process for studying the Transverse Momentum Dependent PDFs (TMDs) inside the proton

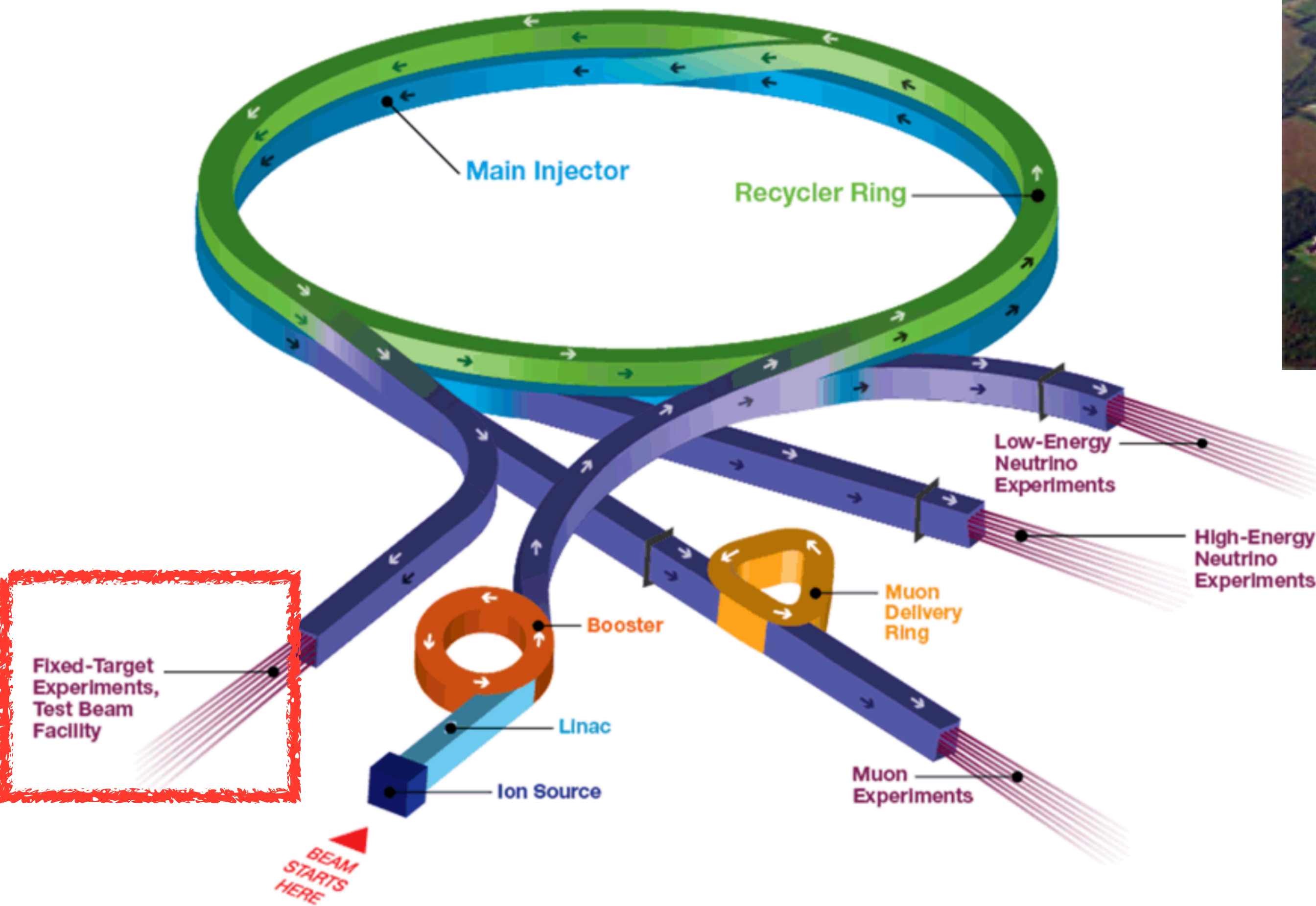
Exploring Dark Sector



- DarkQuest: a proposed proton fixed-target experiment at Fermilab
- upgraded from the existing SpinQuest experiment

120GeV Proton Beam

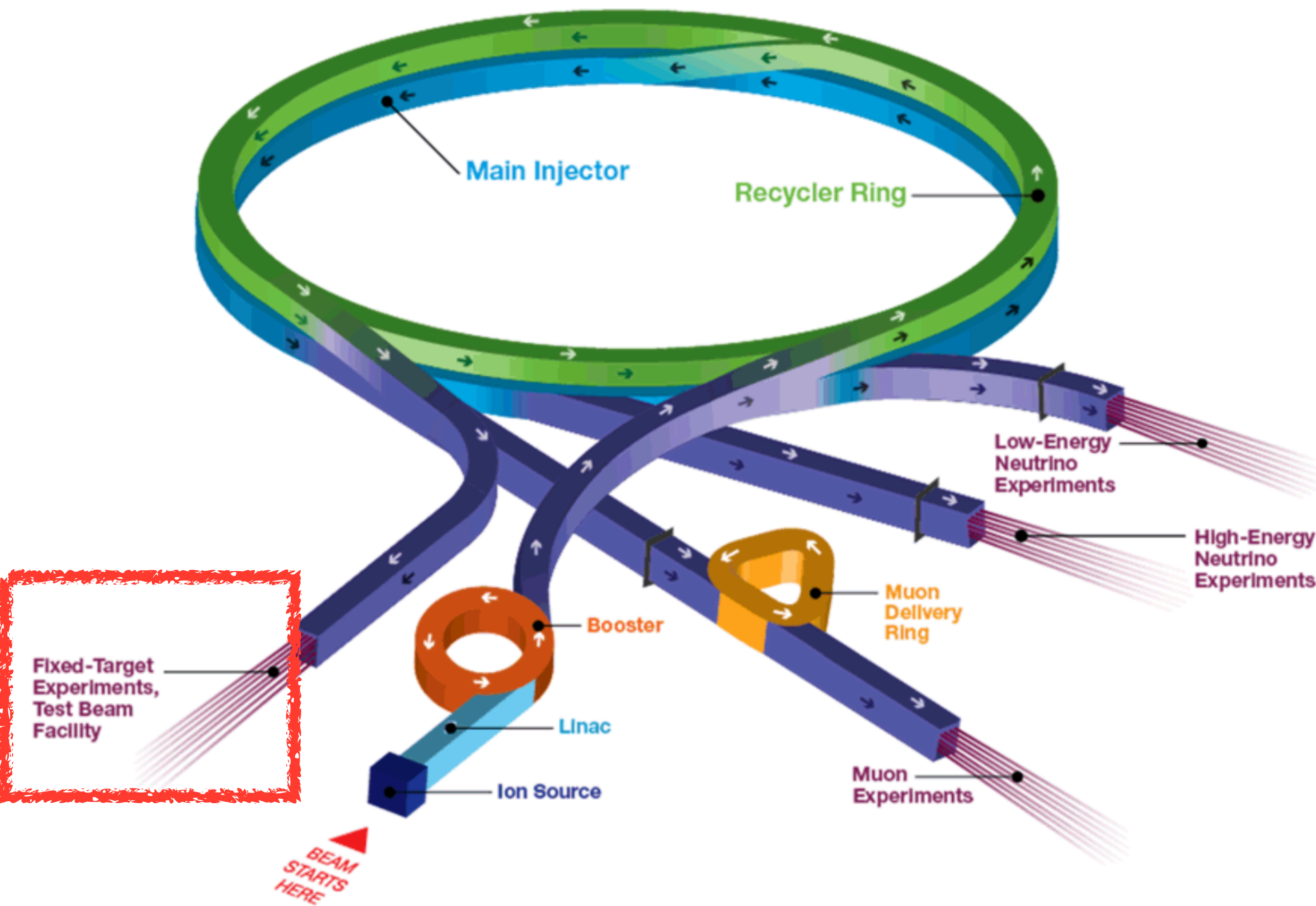
Fermilab Accelerator Complex



- 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
 - ❖ Can have 10^{20} POT for longer term runs

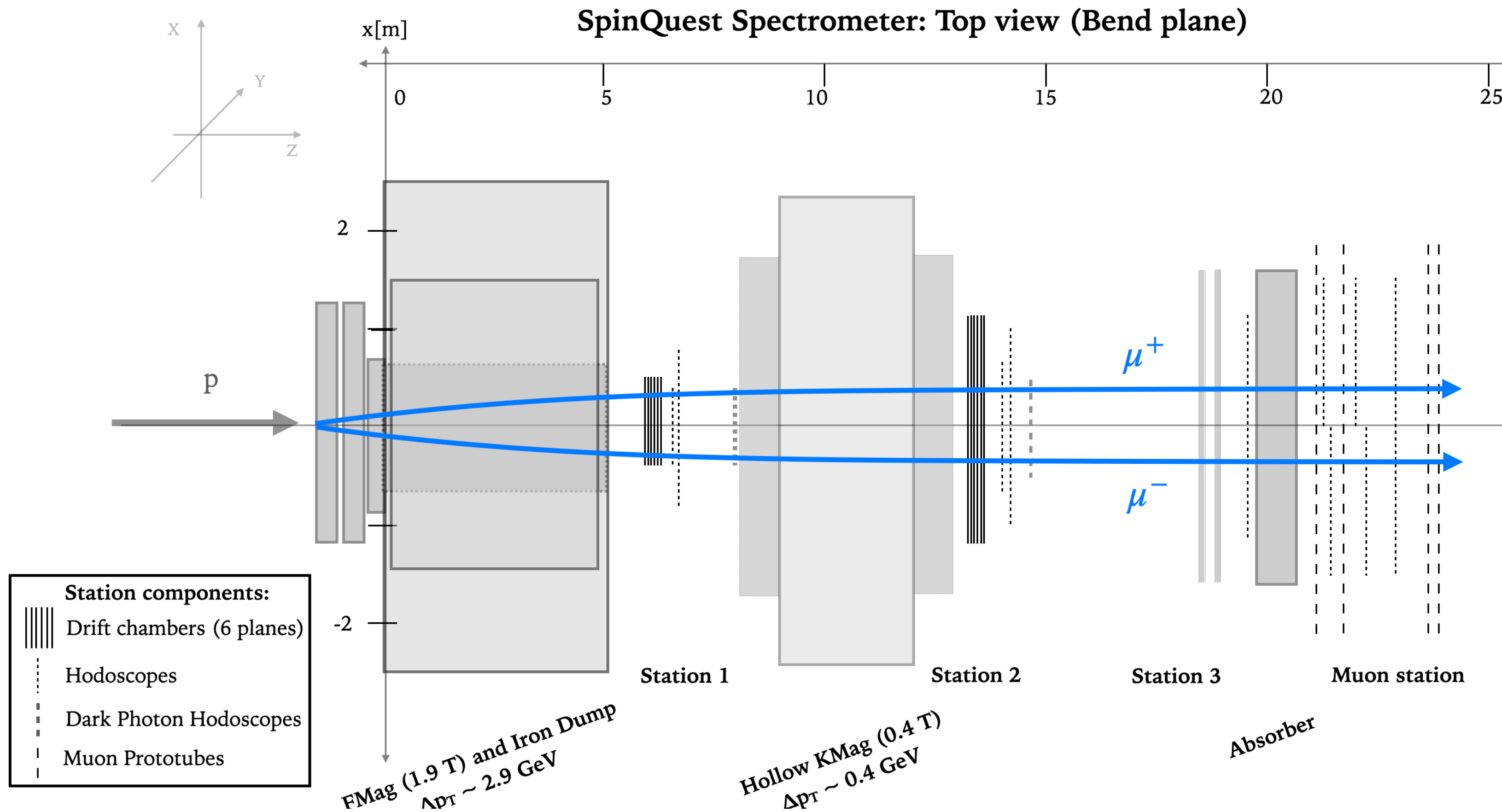
120GeV Proton Beam

Fermilab Accelerator Complex



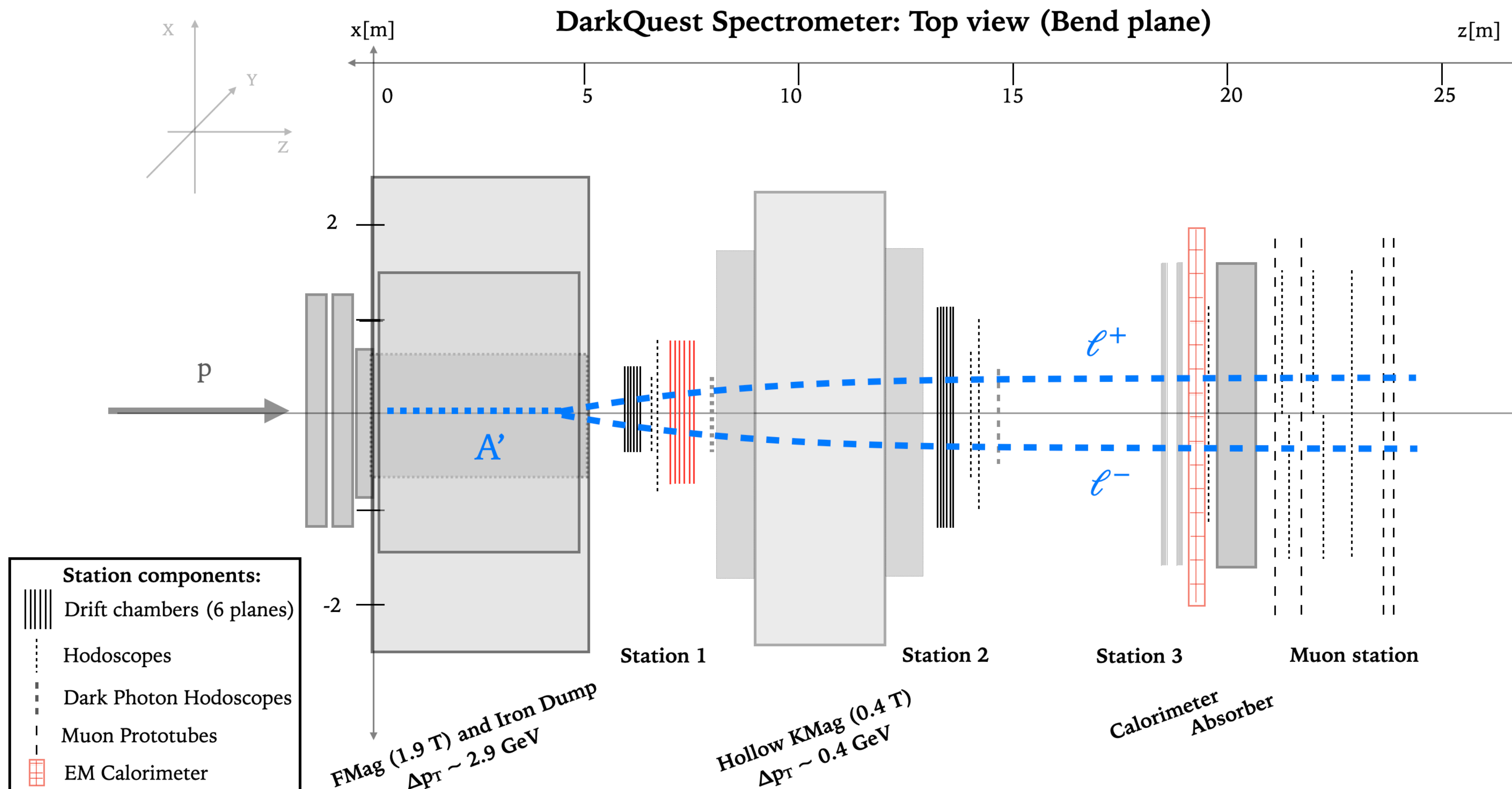
- LHC 13TeV run: $\sim 200 \text{ fb}^{-1}$ of data, inelastic scattering $\sigma \sim 80 \text{ mb}$. This brings to about 10^{16} “protons on target”
- 120 GeV high-intensity proton beam from the Fermilab Accelerator Complex
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SpinQuest Spectrometer



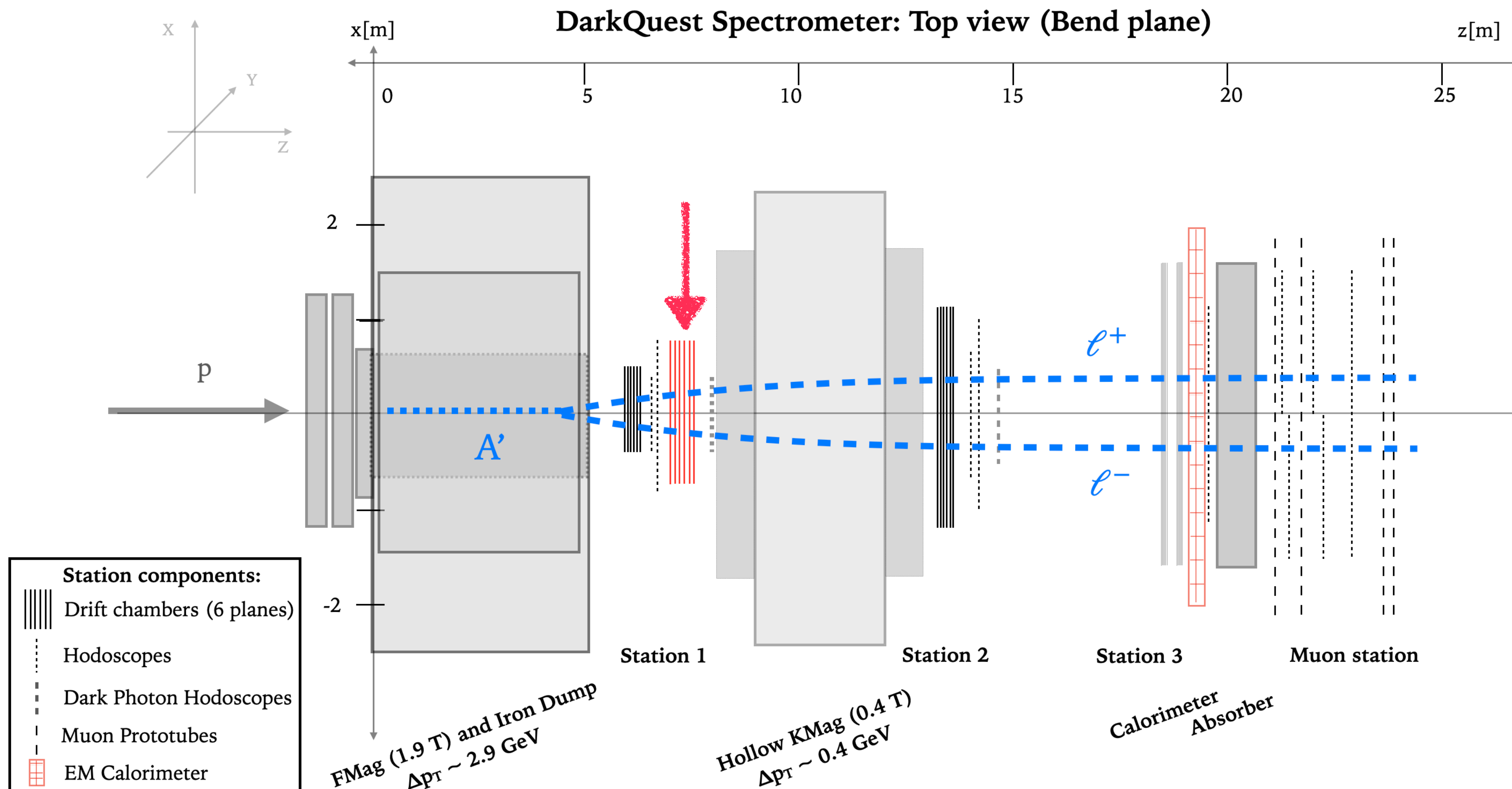
- SpinQuest spectrometer:
 - ❖ FMag: beam dump and absorber;
 - ❖ Tracking: Hollow KMag + 4 stations of drift chambers
 - ❖ Triggering: Scintillator hodoscopes
 - ❖ Muon ID: Muon stations after the iron absorber

DarkQuest Spectrometer



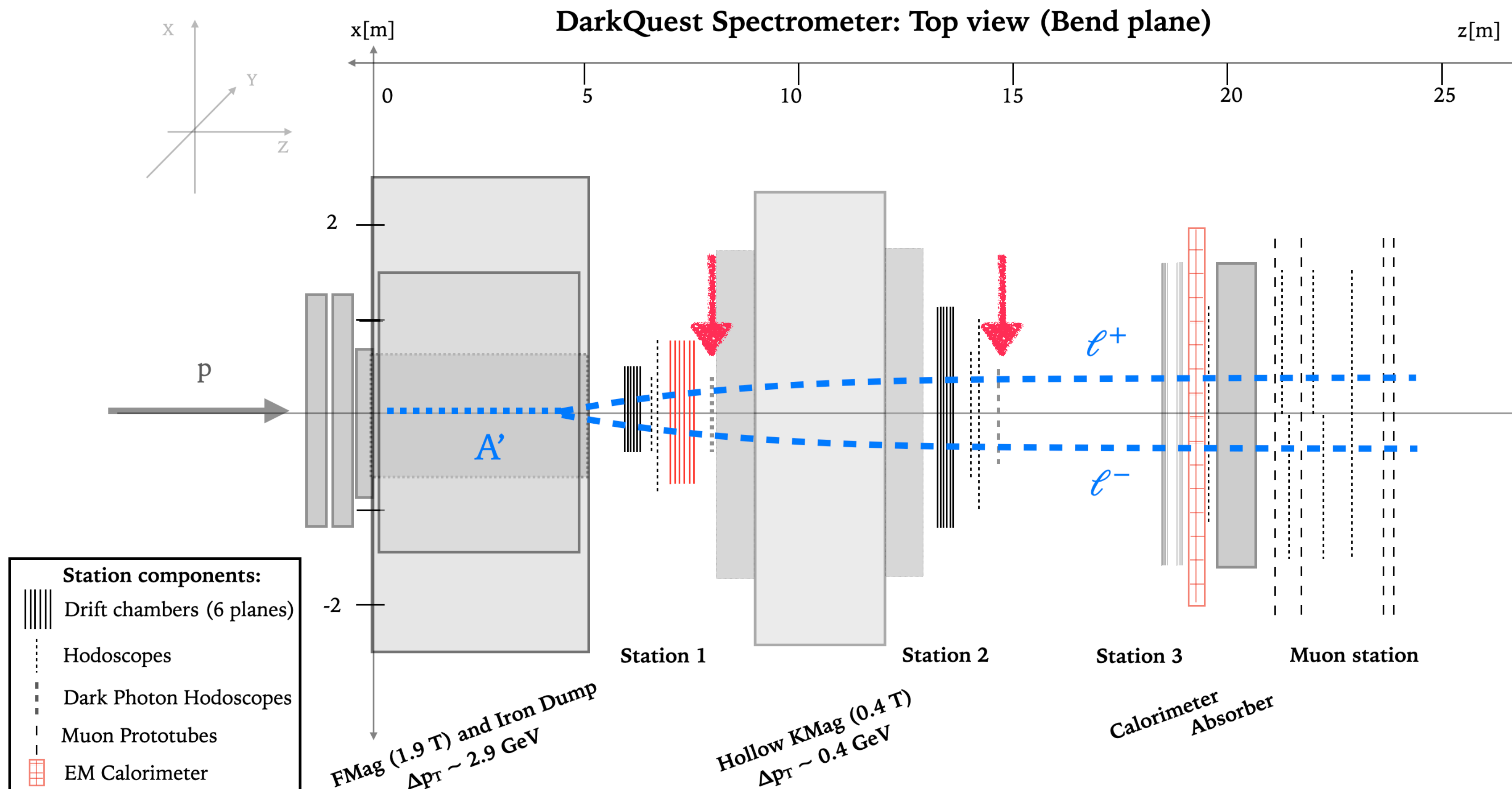
- DarkQuest spectrometer:
 - ✦ Probing dark sector by looking at displaced signals
- Upgrades on SpinQuest:

DarkQuest Spectrometer



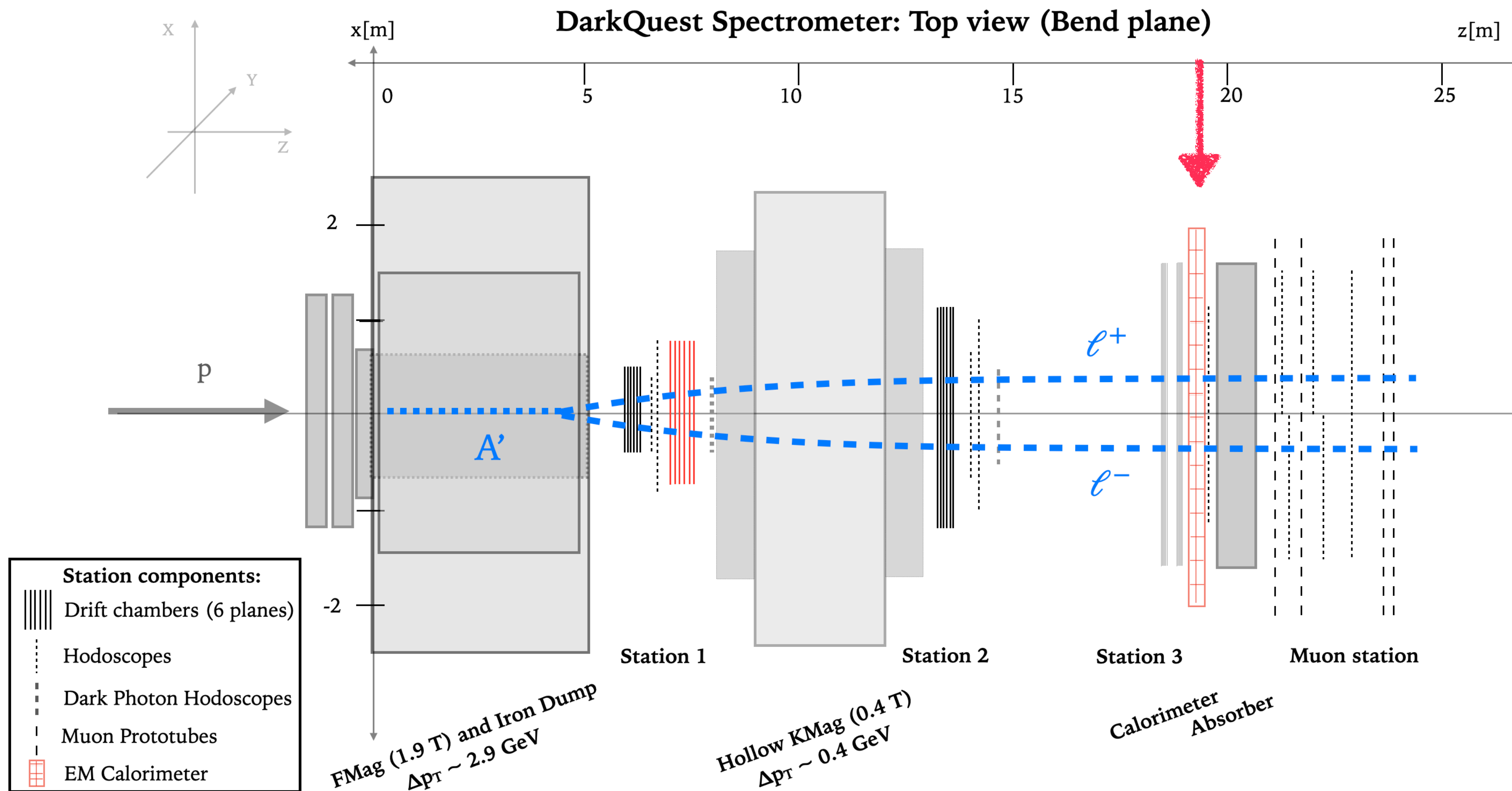
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DarkQuest Spectrometer



- DarkQuest spectrometer:
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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. Allowing particle IDs, **leading to more sensitivity to lower masses**

Goals -> What we have

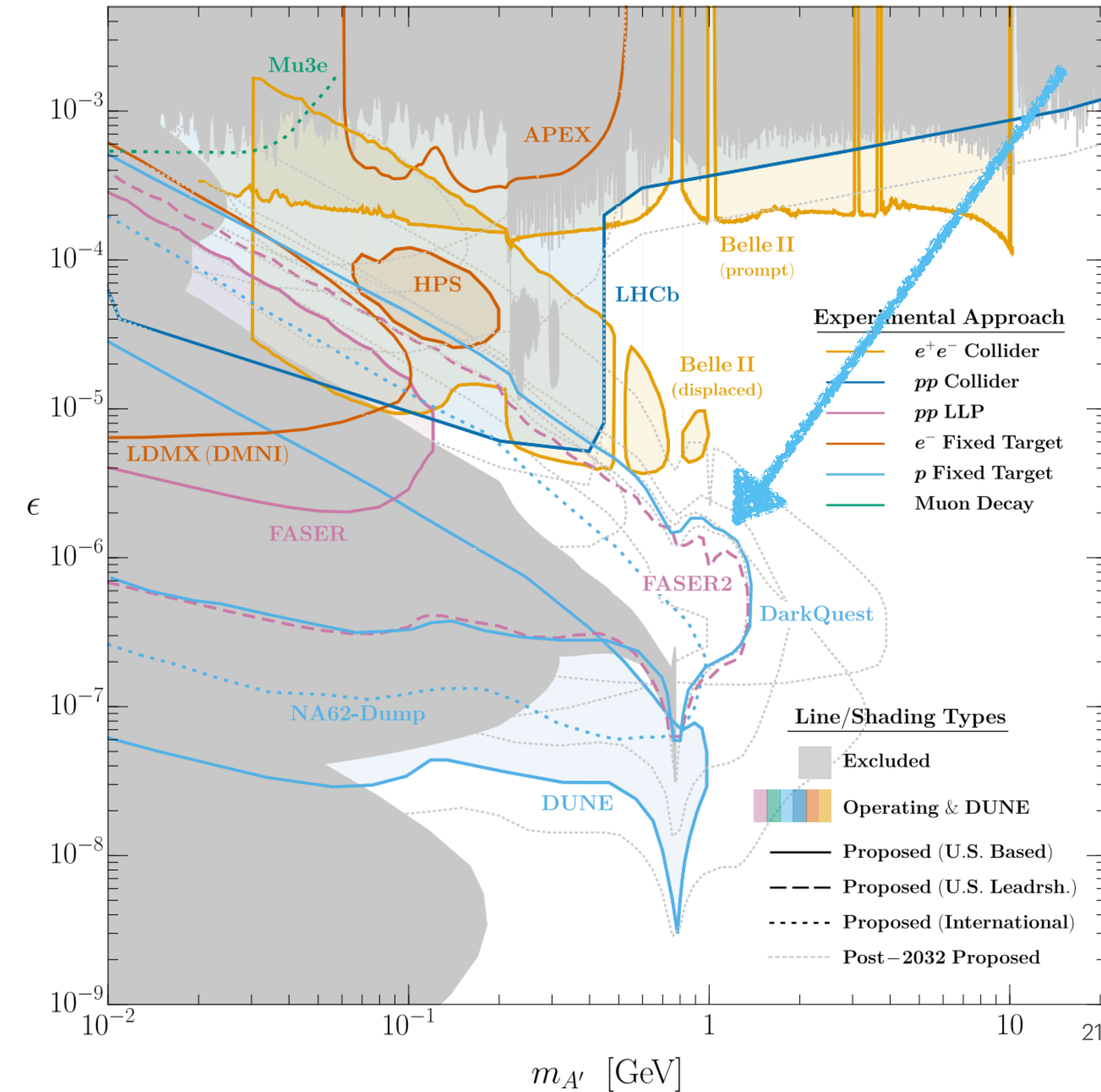
- ⦿ Large dark sector production cross section:
- ⦿ Proper geometry for large acceptance
- ⦿ Sensitivity to different final states
- ⦿ Good reconstruction performance: efficiency and resolution
- ⦿ Small background
- ⦿ Cost and timescale

- 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
- EMCal provides sensitivity to different final states
- Excellent tracking and vertexing performances
- FMag absorbs large fractions of backgrounds
- Most of the experimental components already exist, very low cost: ~1M; muon-channel exploration is ready

DarkQuest

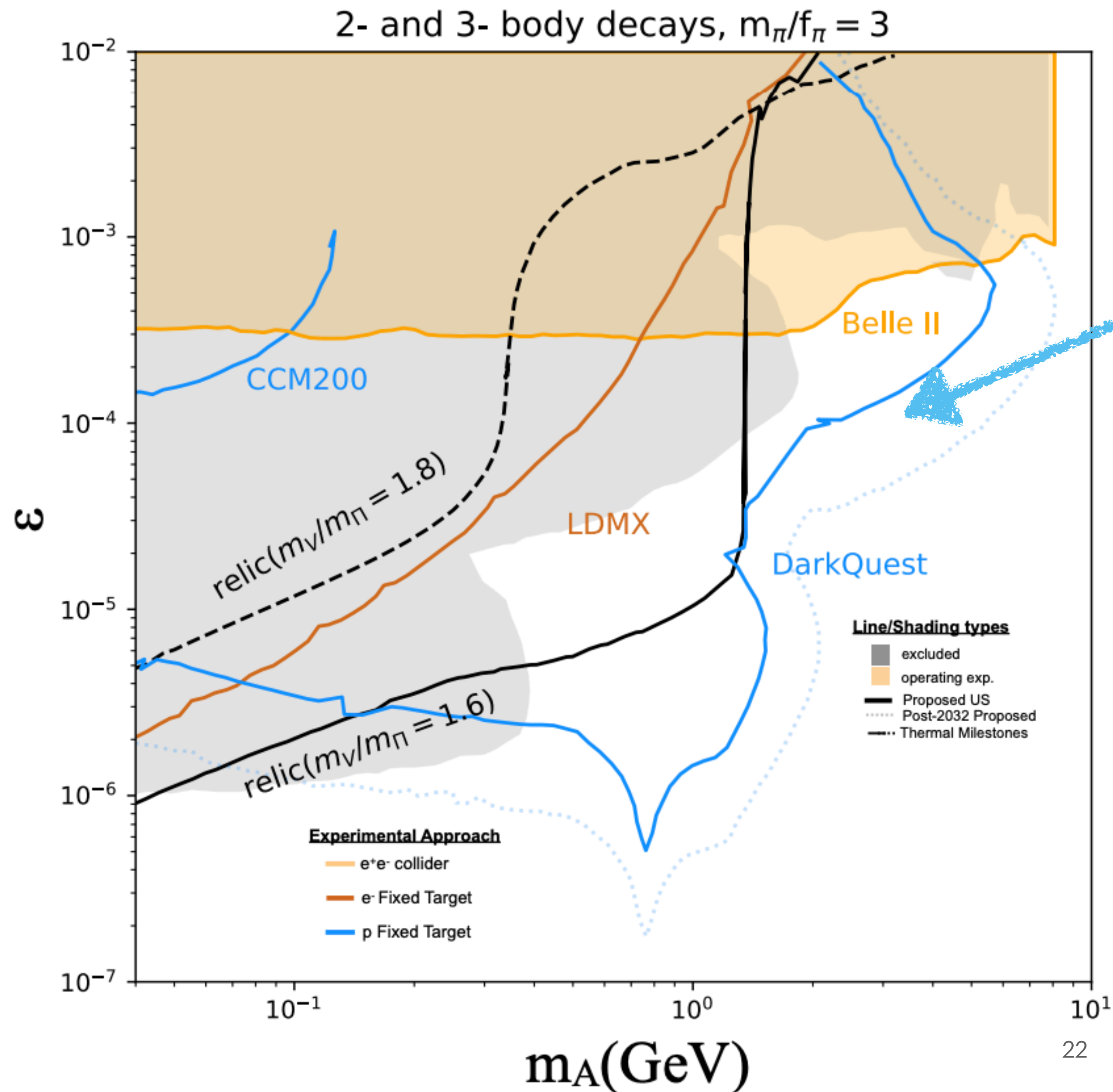
Arxiv.2207.06905

- Visible dark photon portal benchmark



DarkQuest

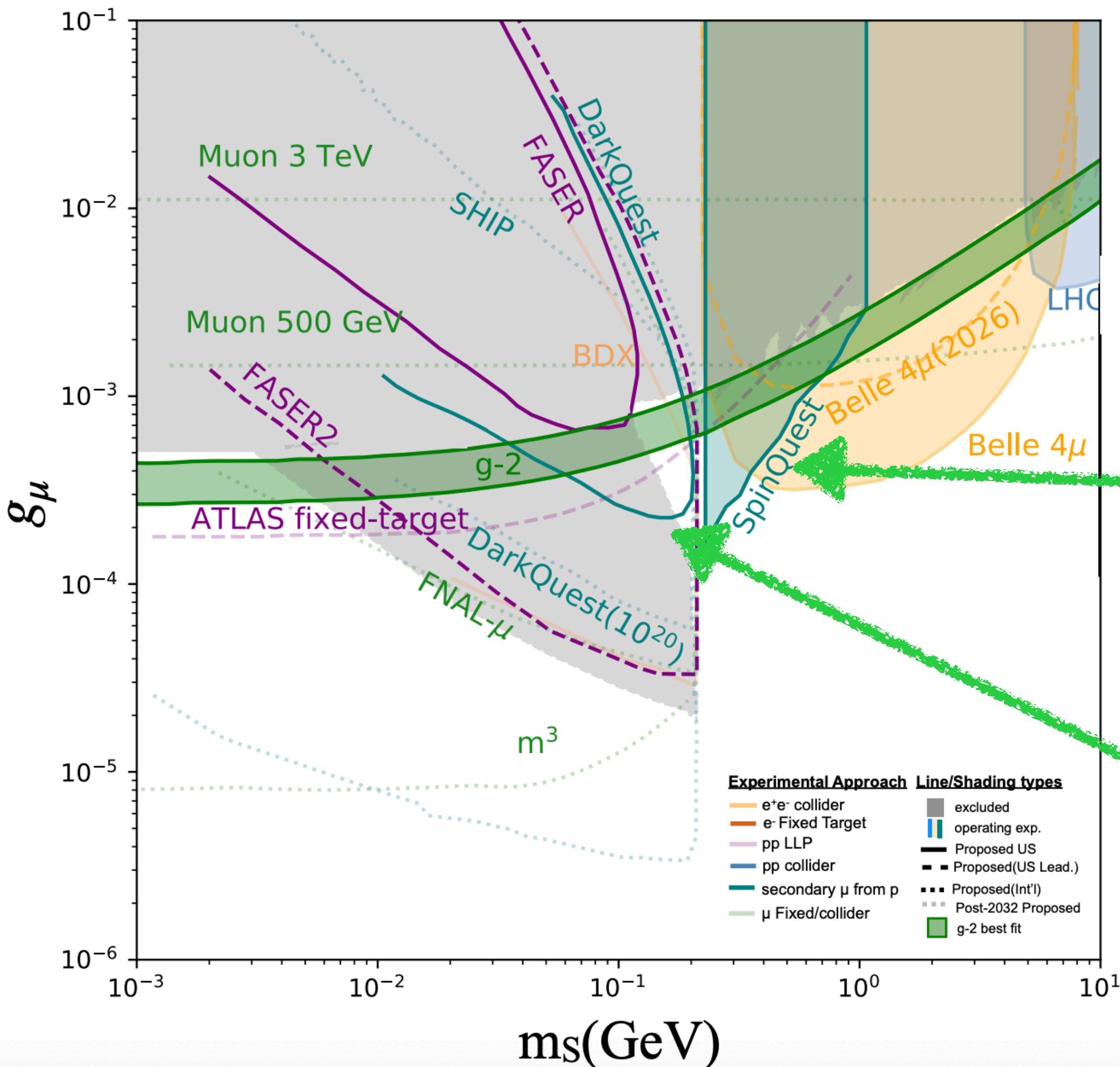
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- SIMP benchmark

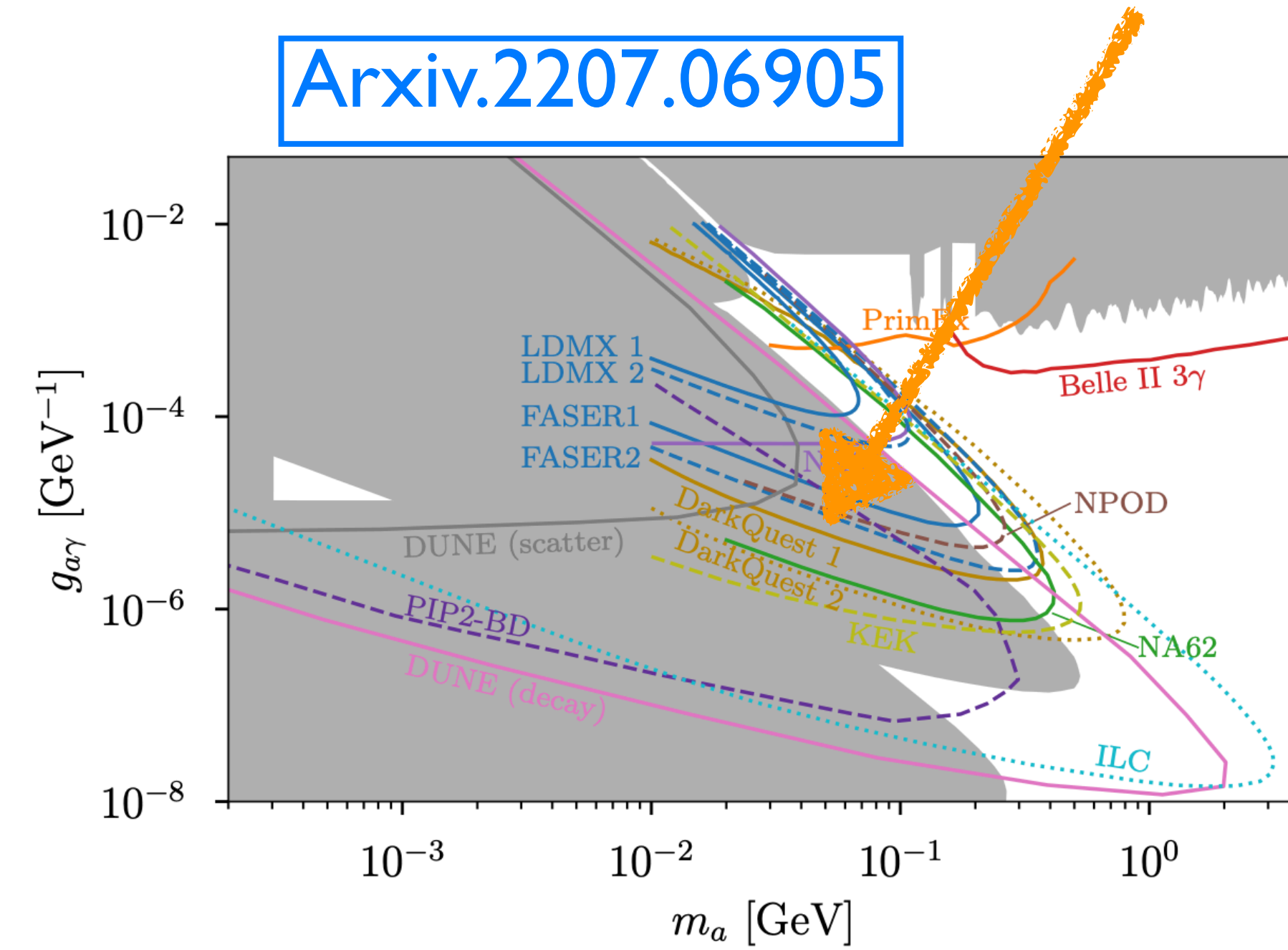
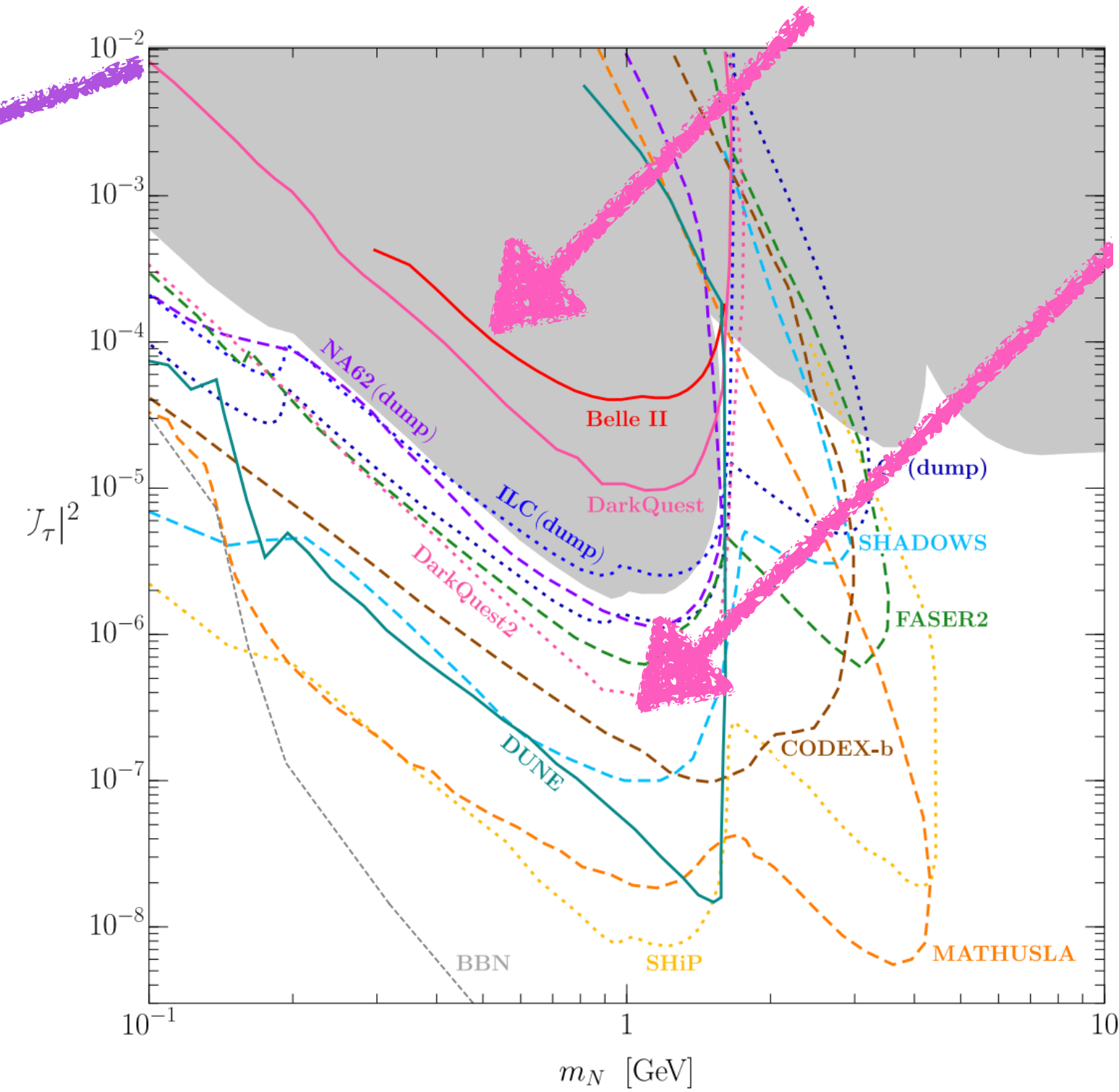
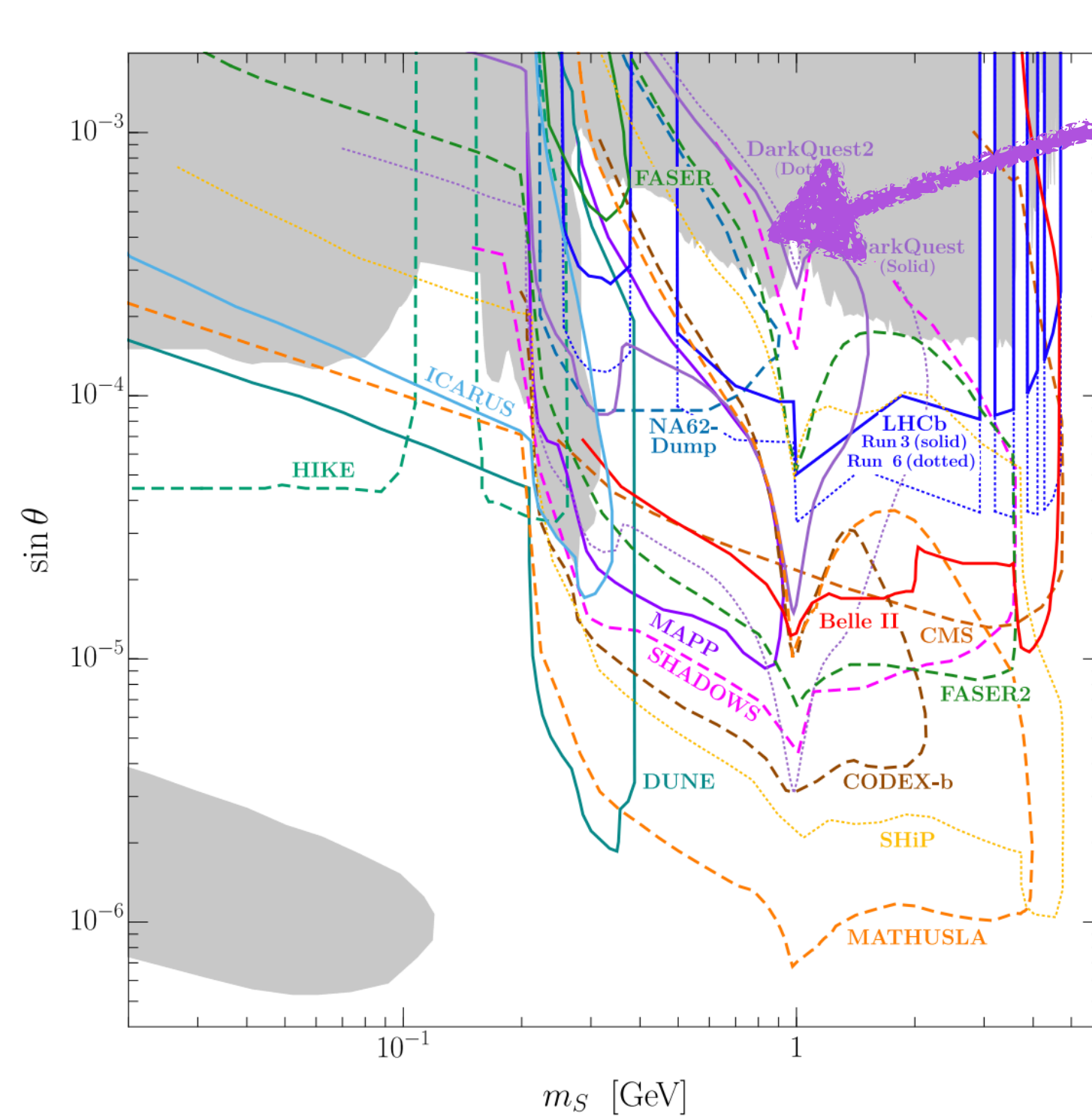
DarkQuest

Arxiv.2207.08990



- Muon-philic scalar g-2 benchmark
- Use “secondary” muons from proton-dump interactions as the muon source
 - ✿ Arxiv: 2212.00033
- Use displaced electrons from DarkQuest

Broad Sensitivity Coverage

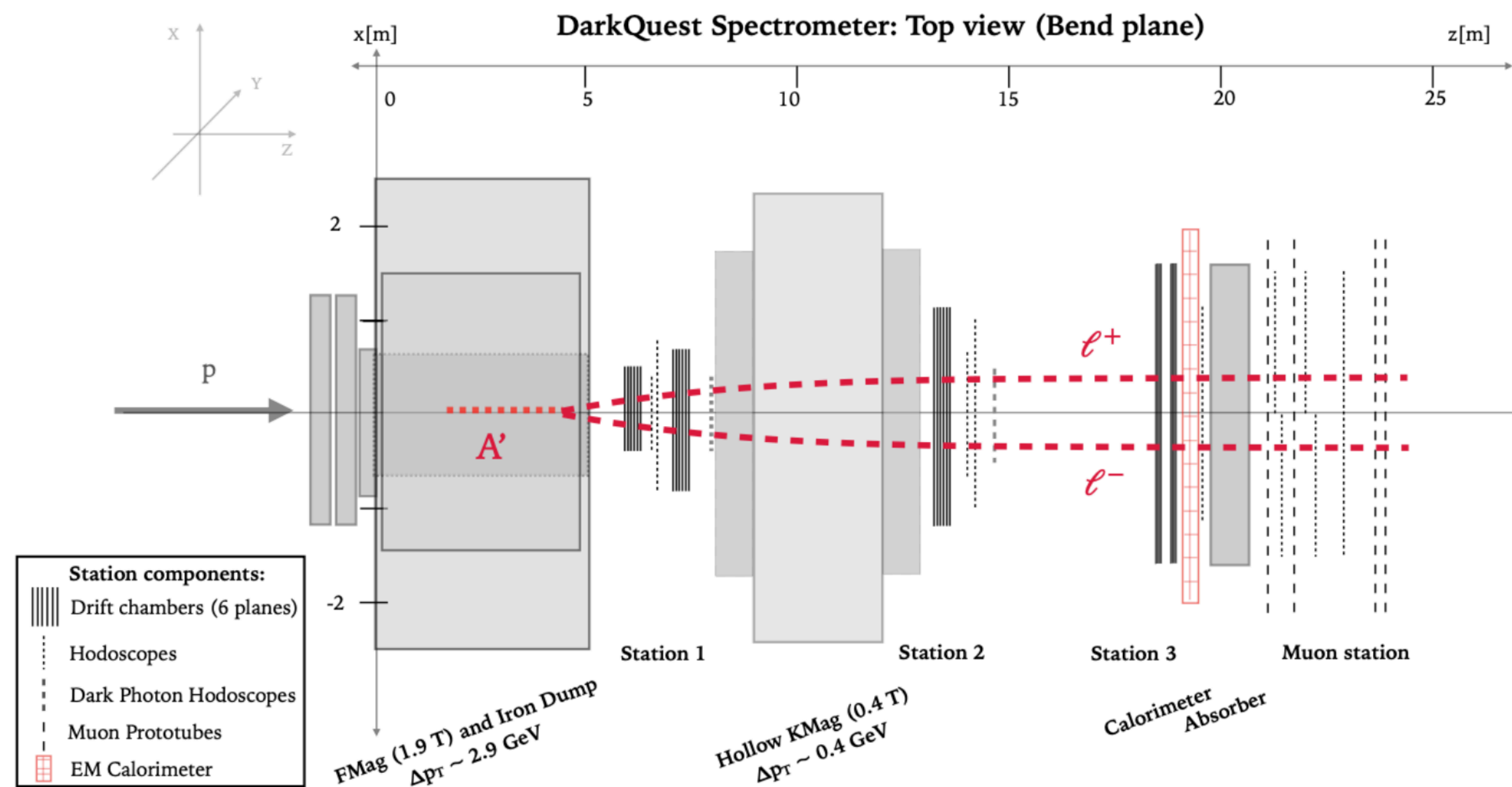


- Broad coverage to different theory models,
 - ✿ Different portals: scalar, vector, neutrino, axion-like, etc, by probing lepton/hadron/photon pairs

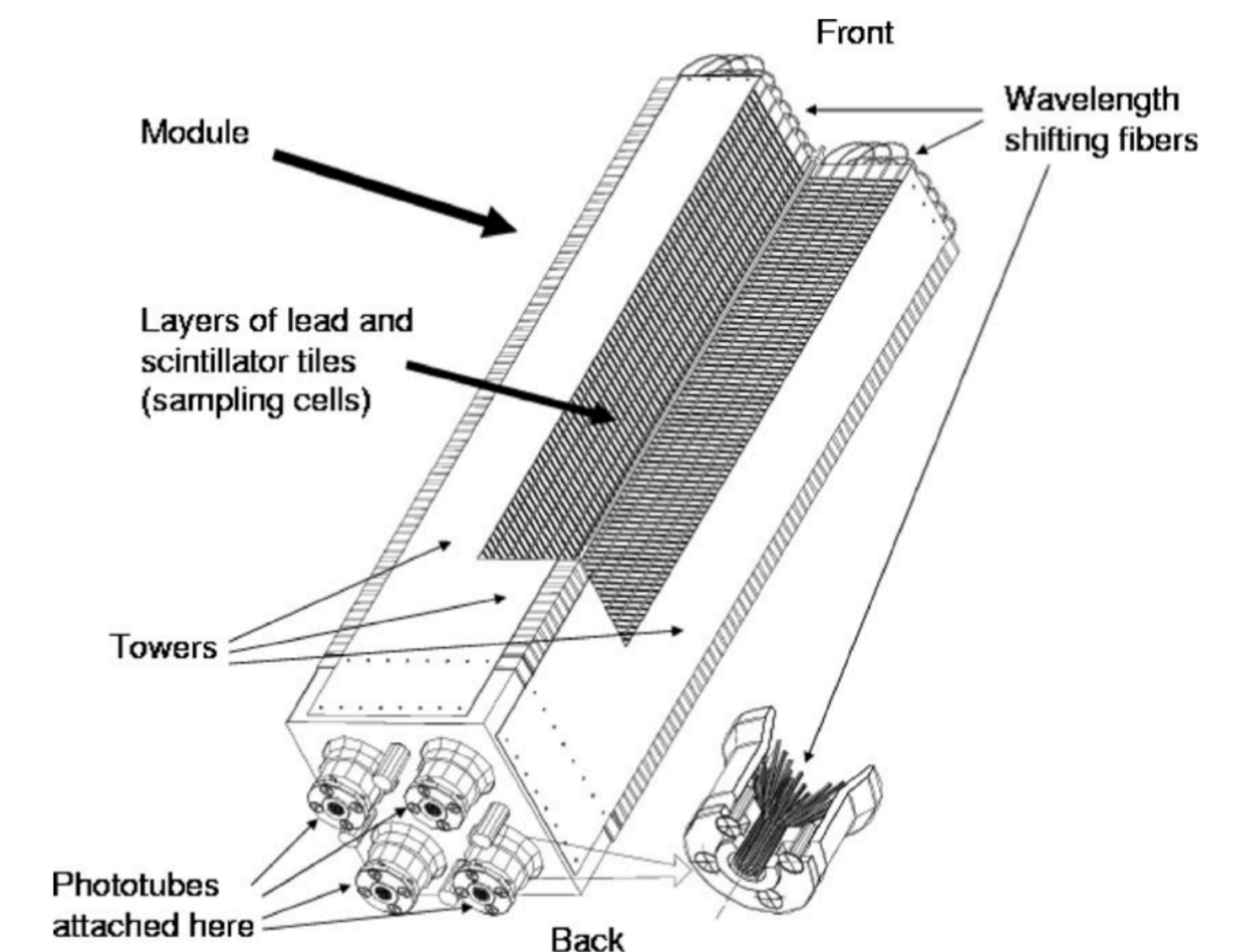
List of Experimental Studies

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

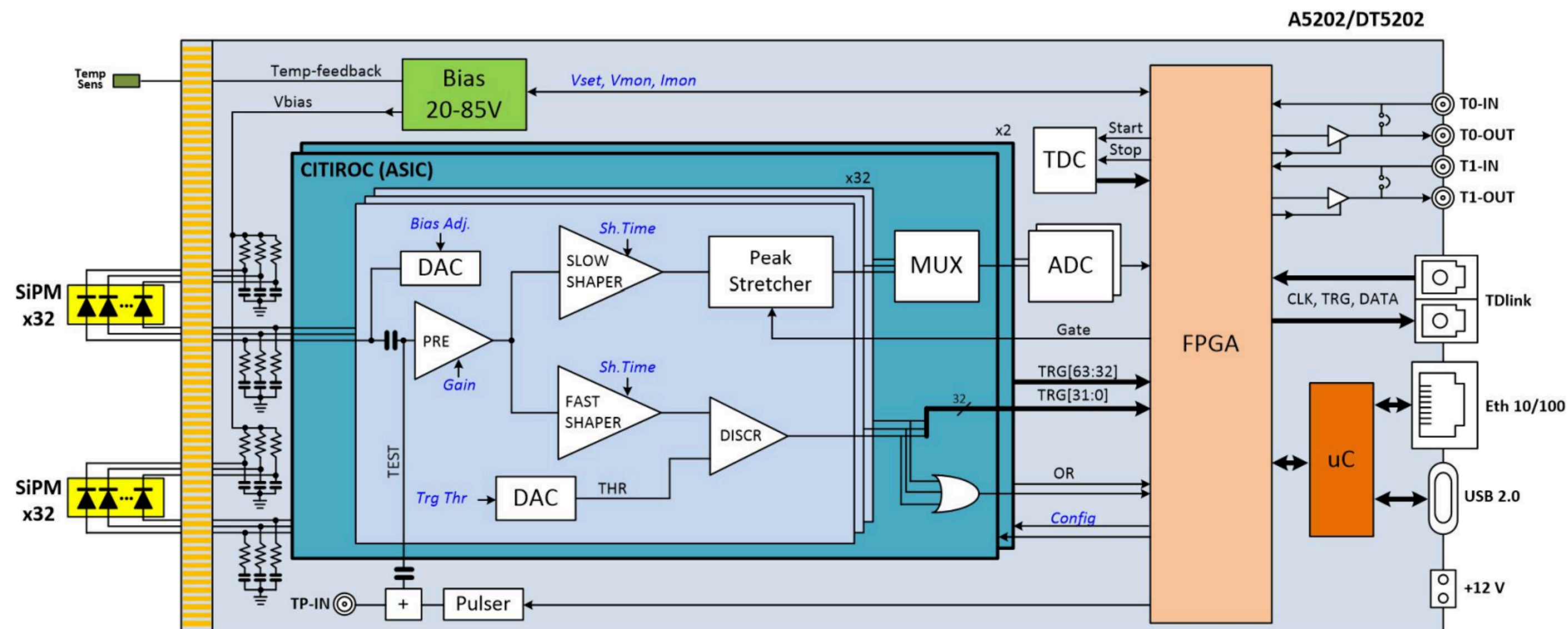
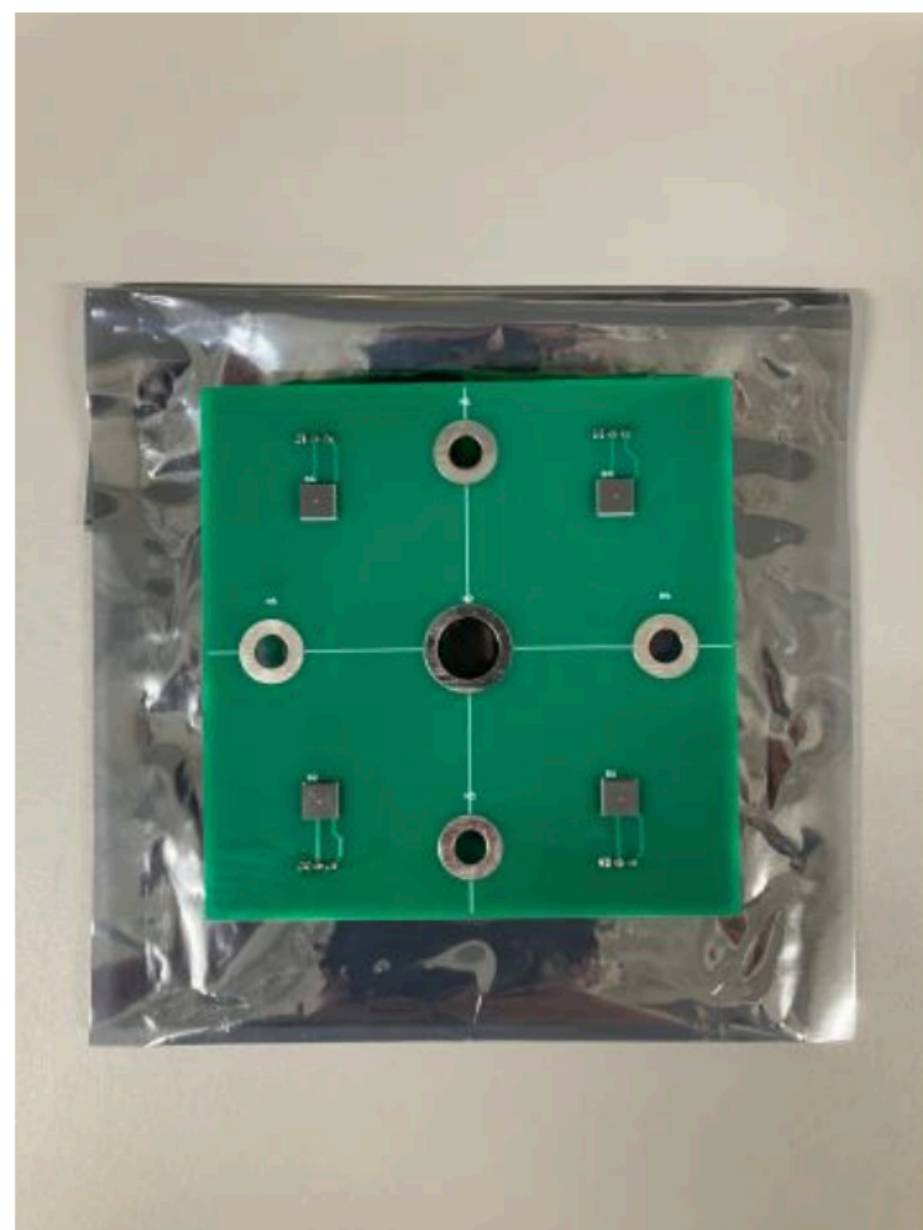
EMCal Integration



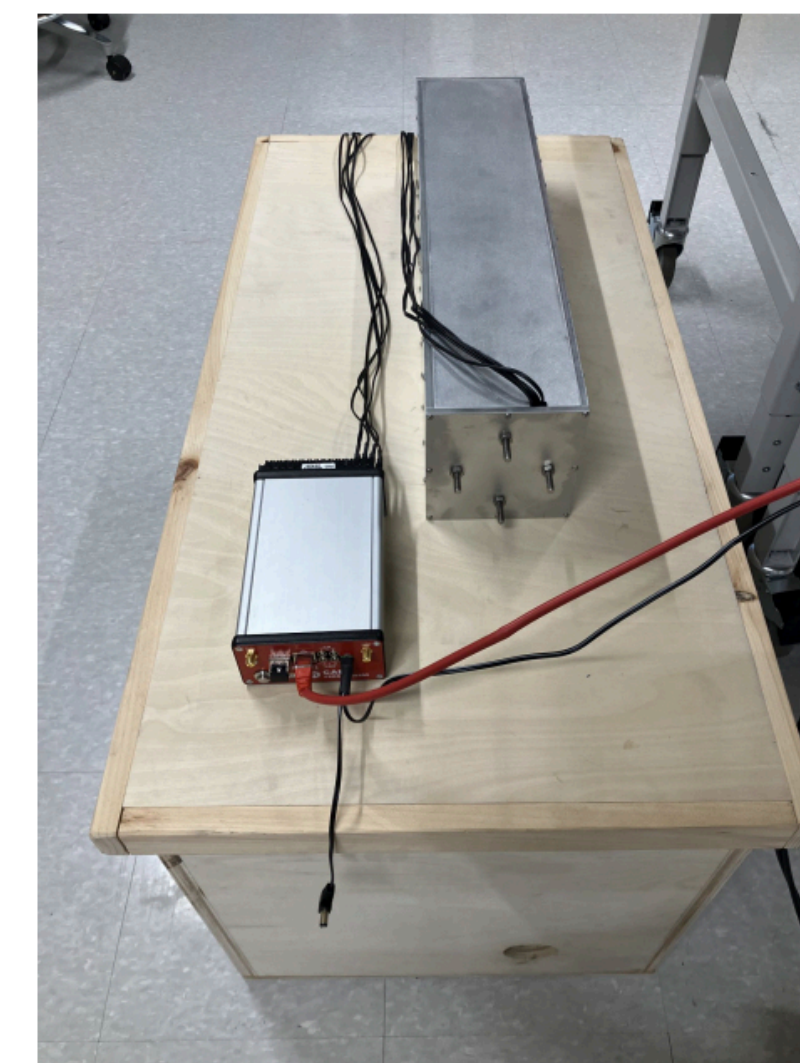
- EMCal: PbWO_4 + iron sampling calorimeter from PHENIX experiment
- EMCal integration into the spectrometer:
 - ✿ Developments of the readout and trigger system ongoing
 - ✿ Currently in possession of a few cells to explore SiPM readouts



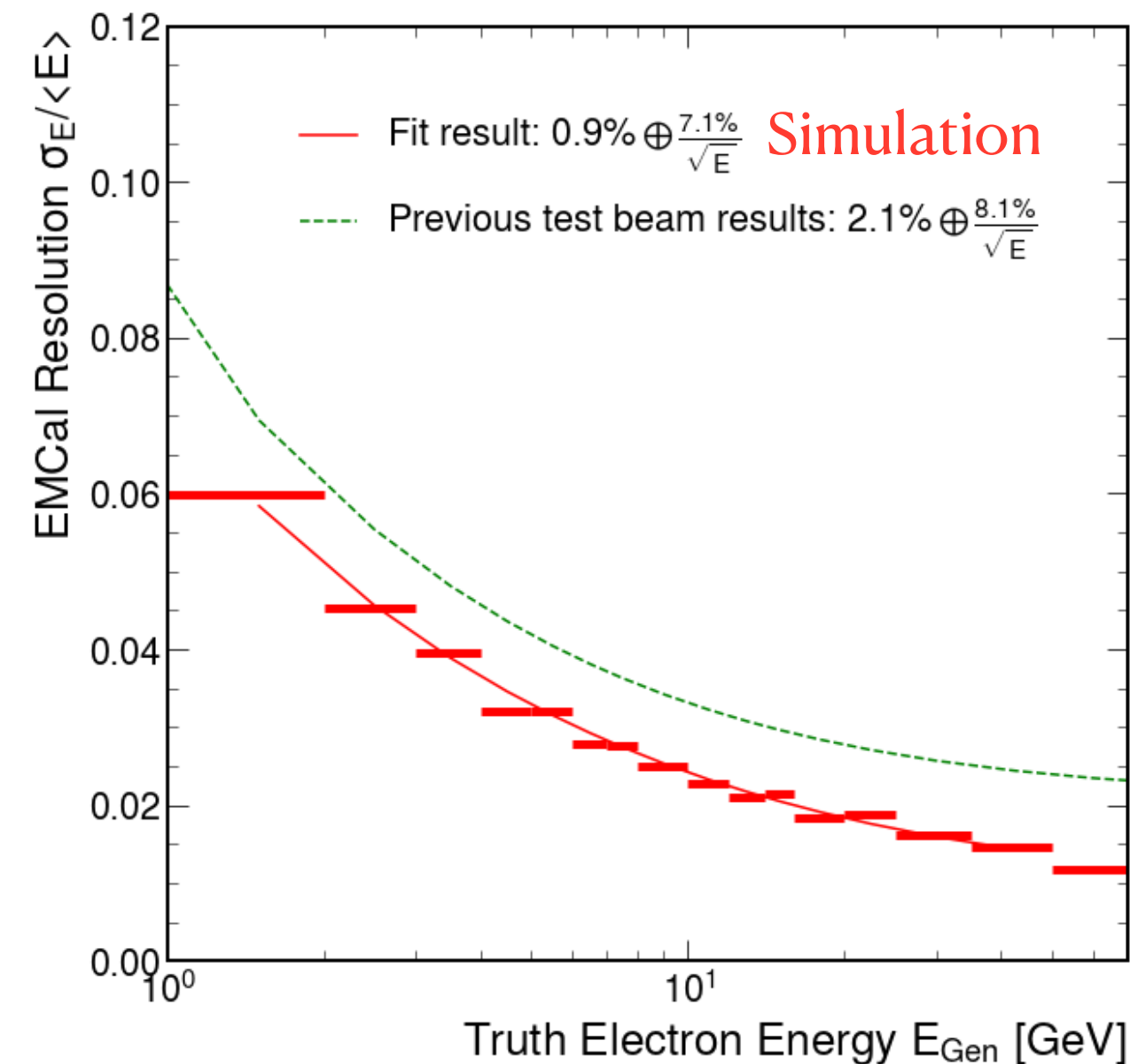
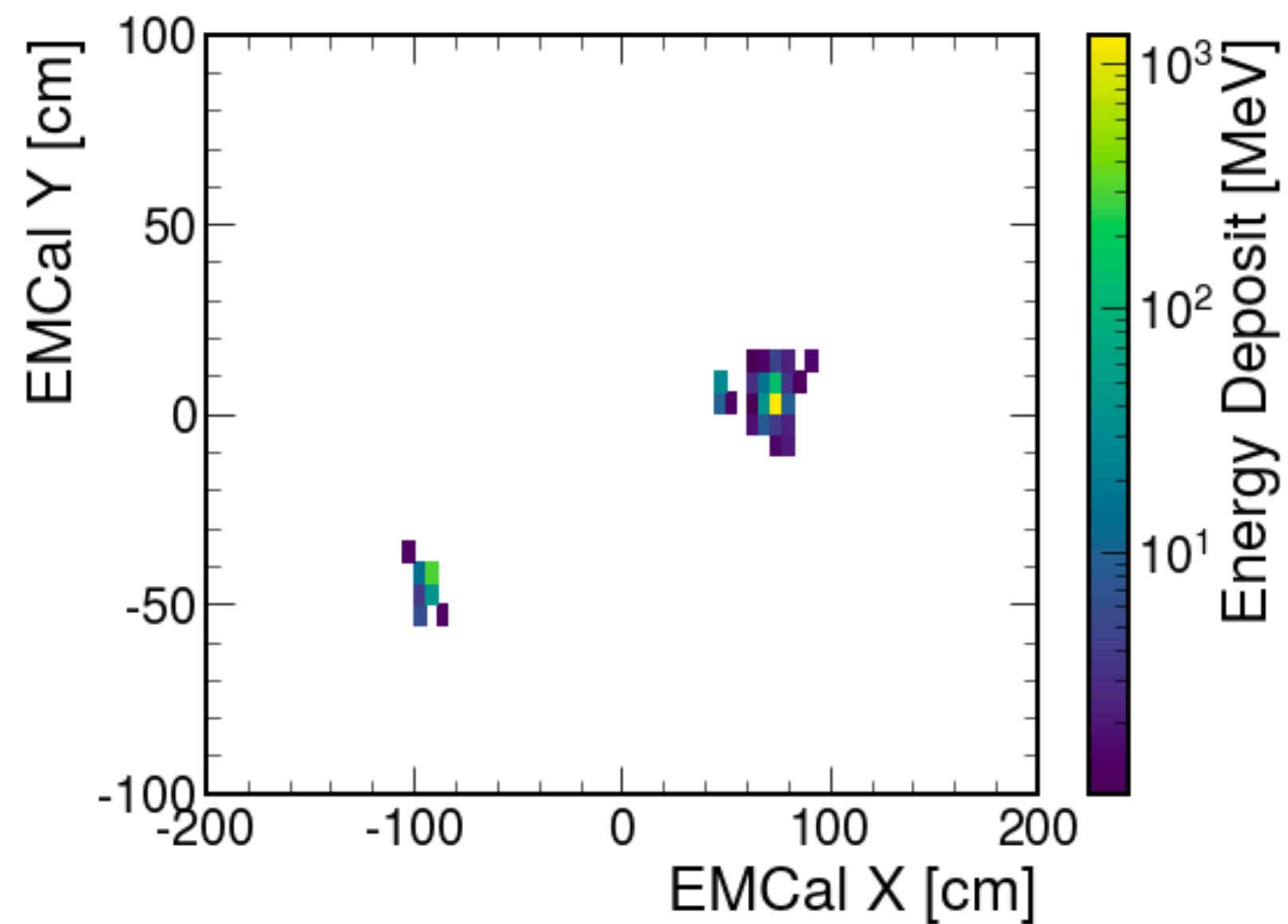
EMCal Readout Electronics



- EMCAL test stands has been developed to study new EMCAL readout electronics
- Available for test beam and background rate measurements in NM4 in 2023

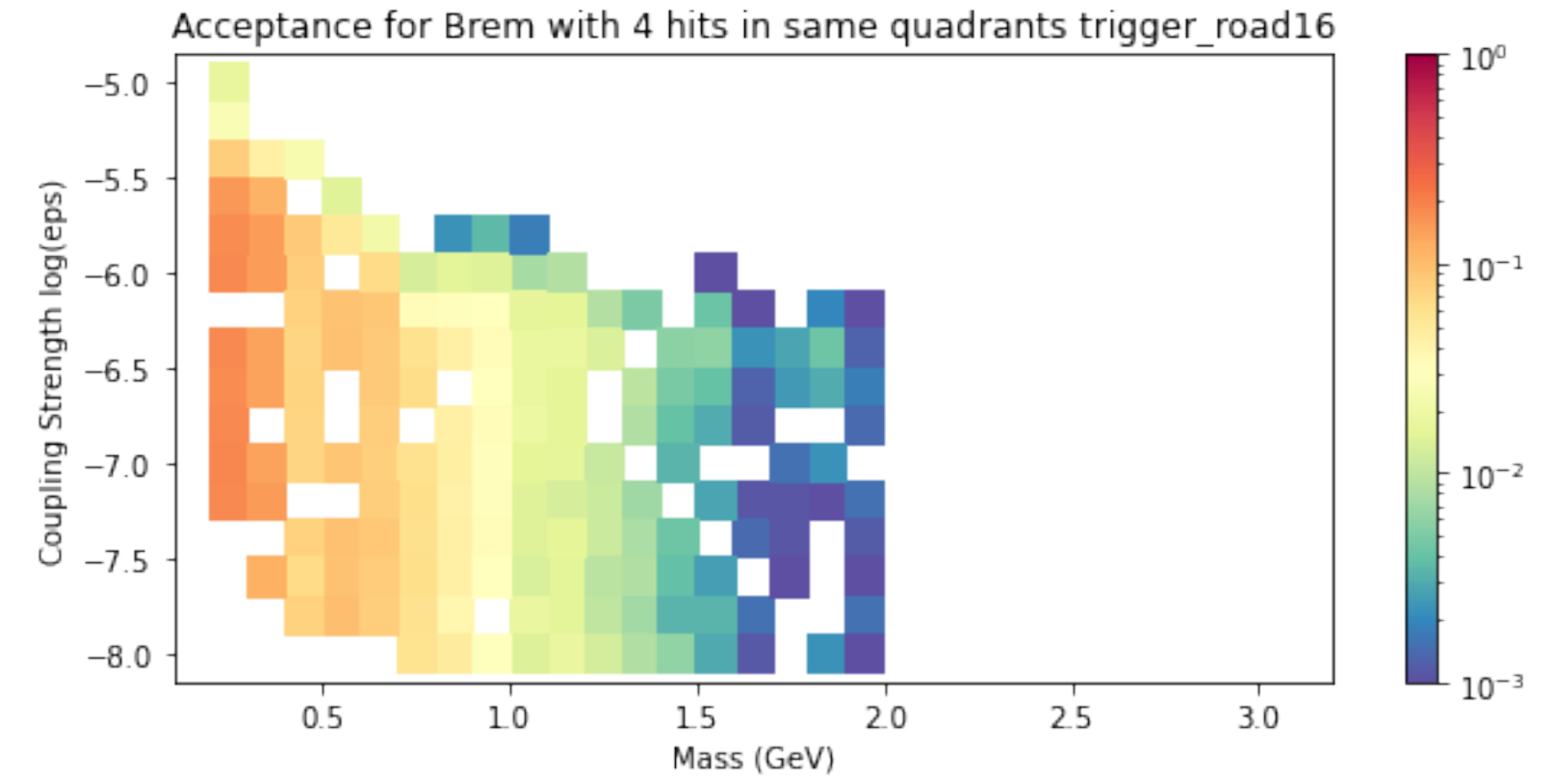
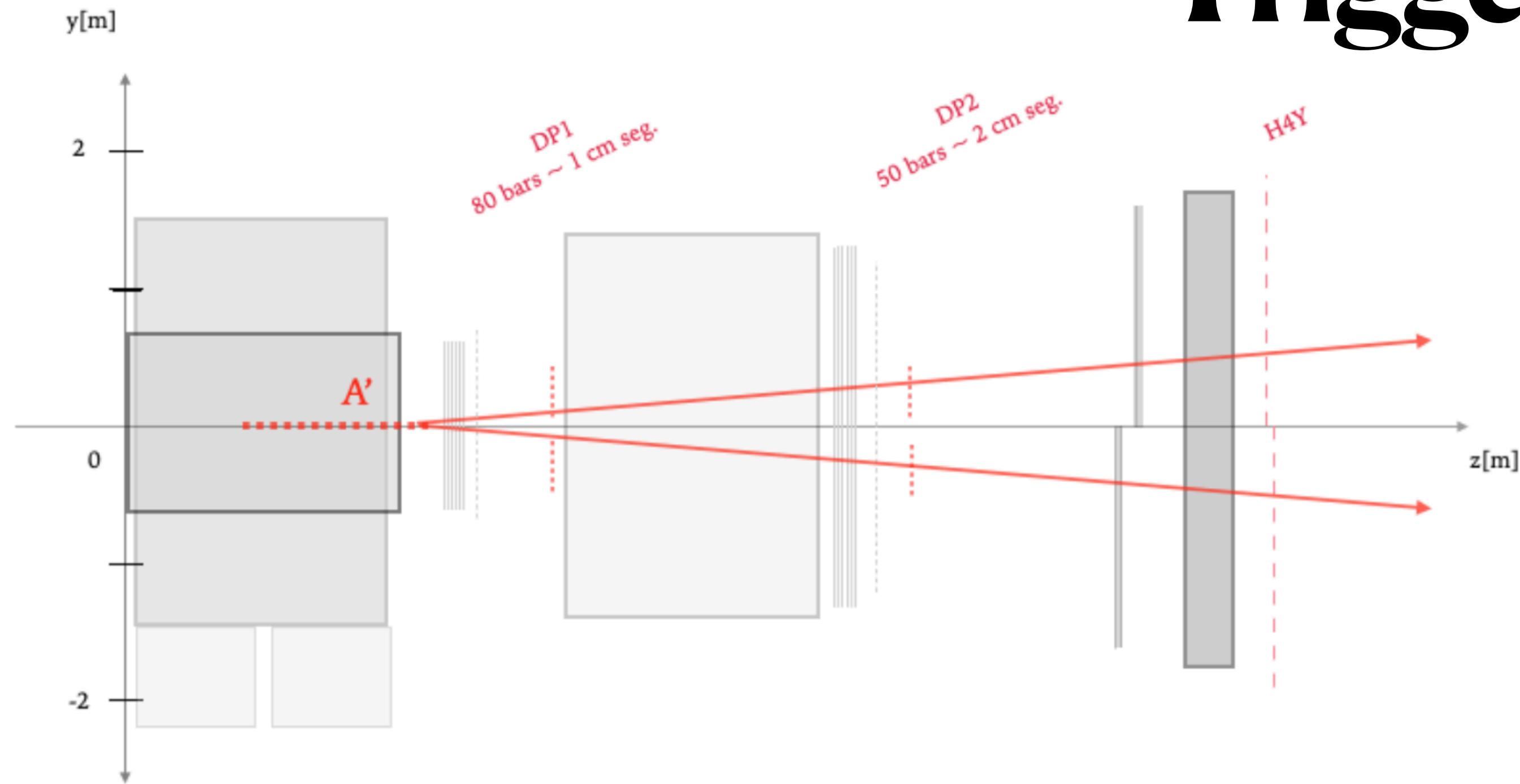


Ongoing Studies: EMCal Simulations

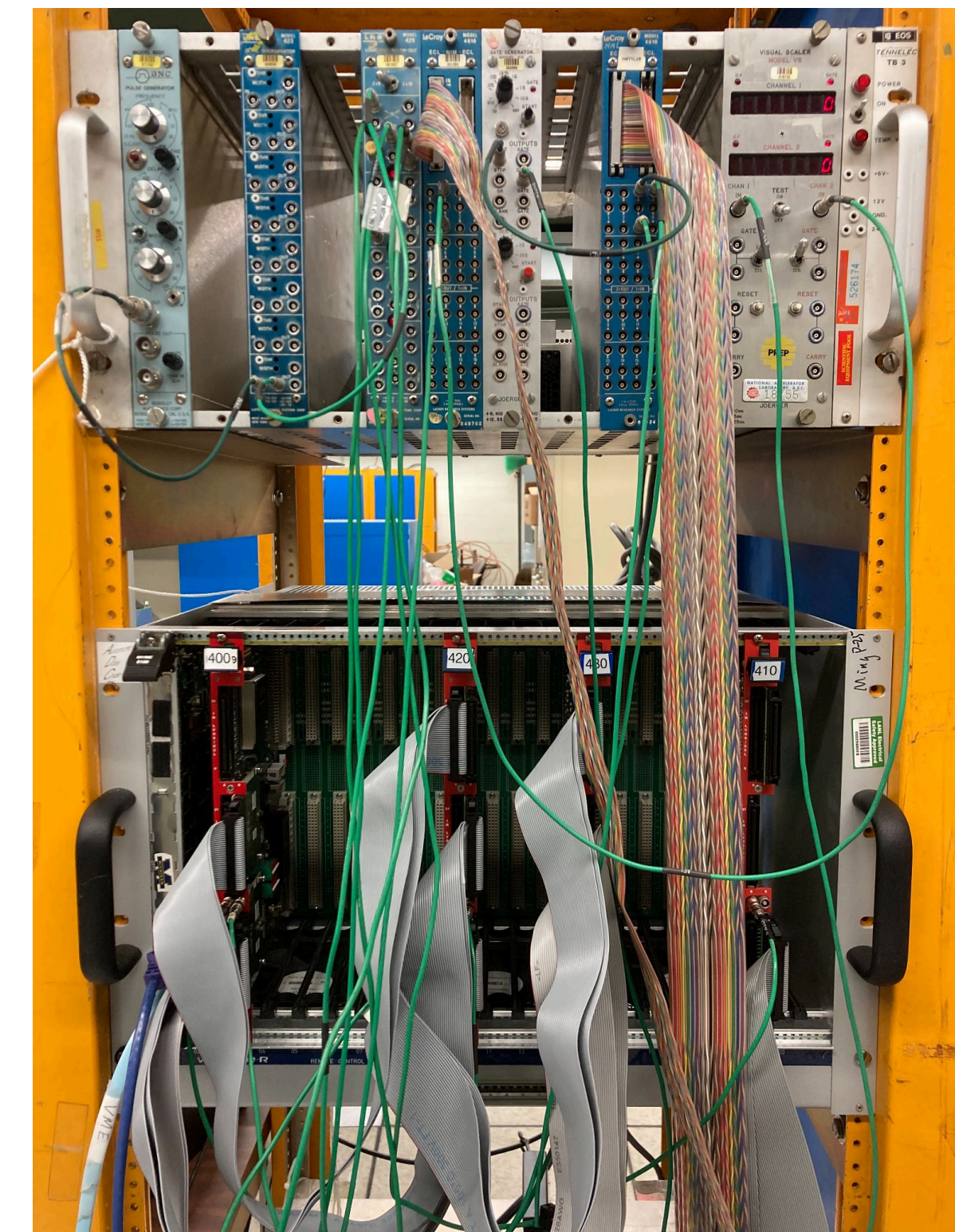


- EMCal: $\sim 5\text{cm}$ per cell (2-3 Molière radius of PbWO_4): most energy deposit in one central cell
- Nice separation between two electron showers
- Agreement of the resolutions between the simulation (red) and the previous test beam results

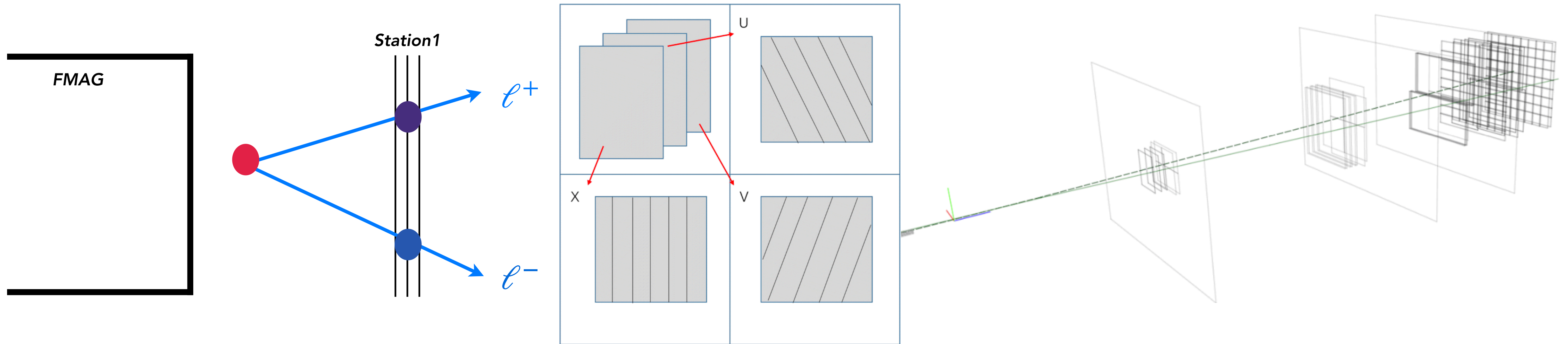
Trigger



- Test the new trigger roads for displaced signals using the fiber hodoscope detectors installed in 2017
 - ✧ Trigger efficiency ~20% for decays in acceptance
- Ongoing work on integration into the trigger system and commissioning
- In the future plan to include EMCal information in the trigger system to trigger on Electron/Photons

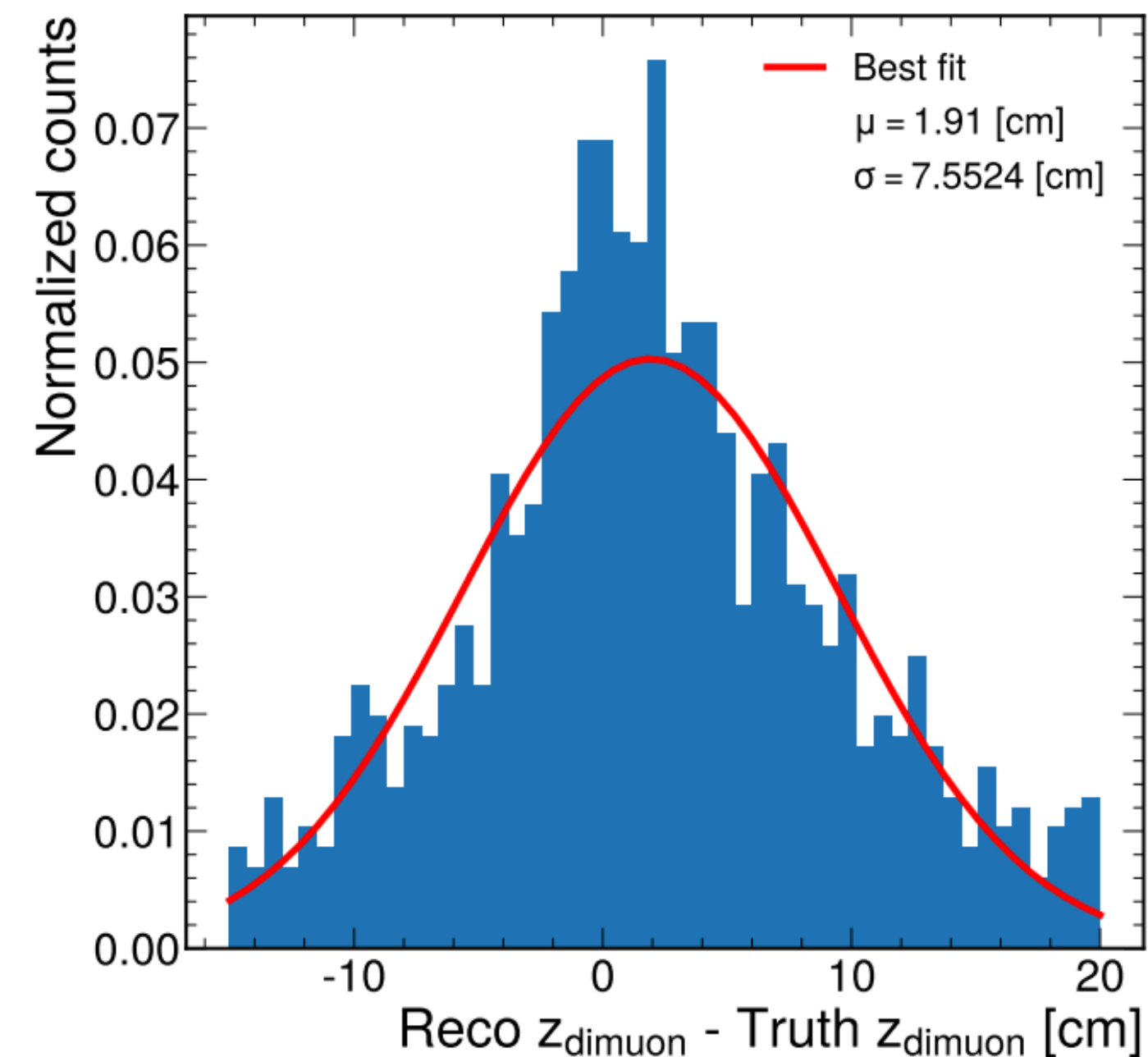
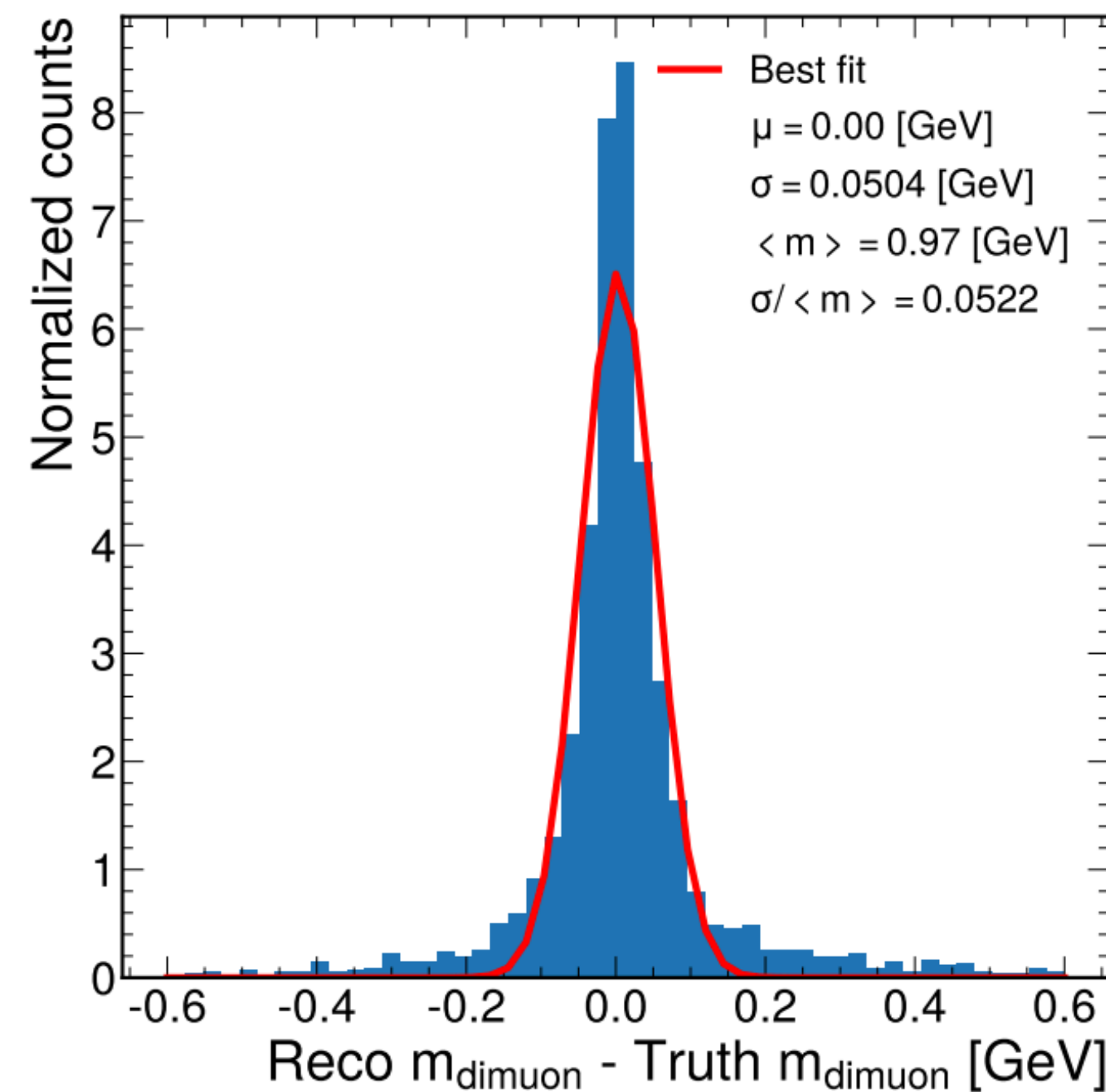
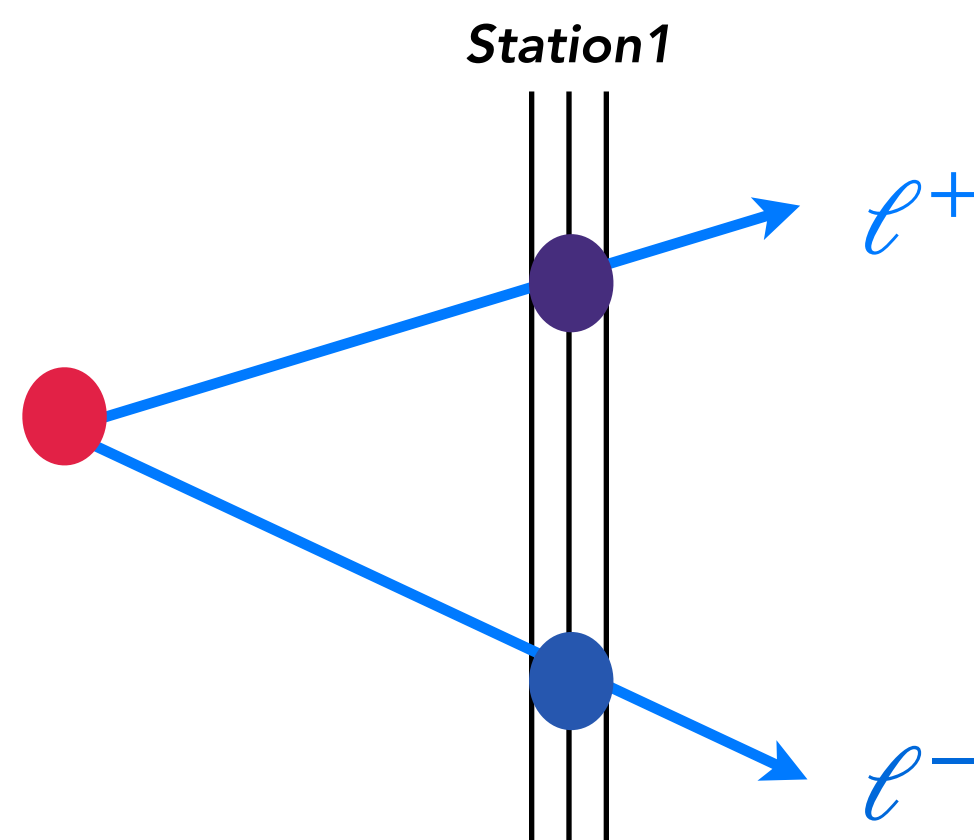


Tracking and Vertexing



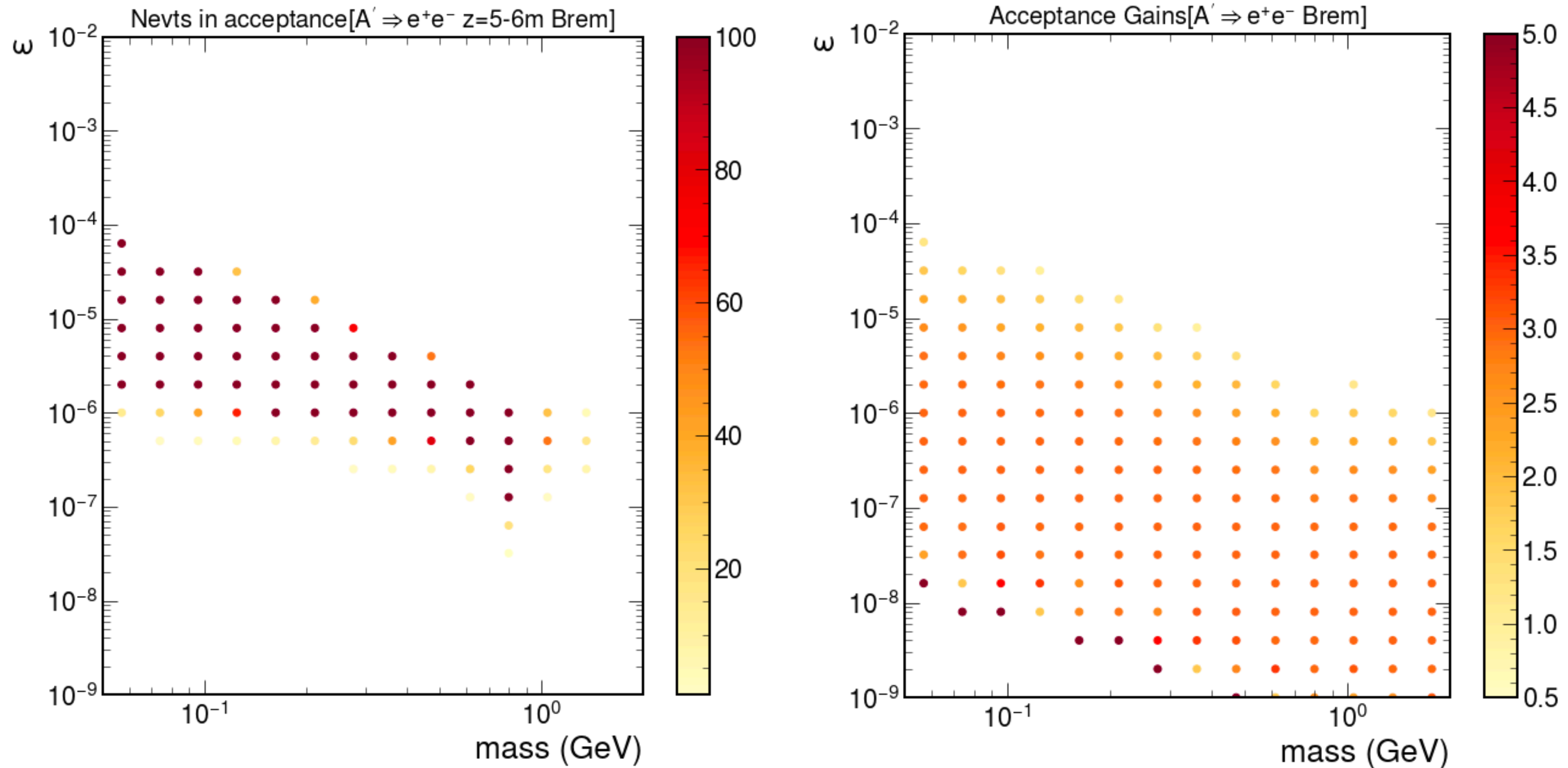
- For the dark photons decaying after the FMag, the leptons are less affected by the multiple scatterings in FMag. Better resolutions compared with prompt signals:

Tracking and Vertexing



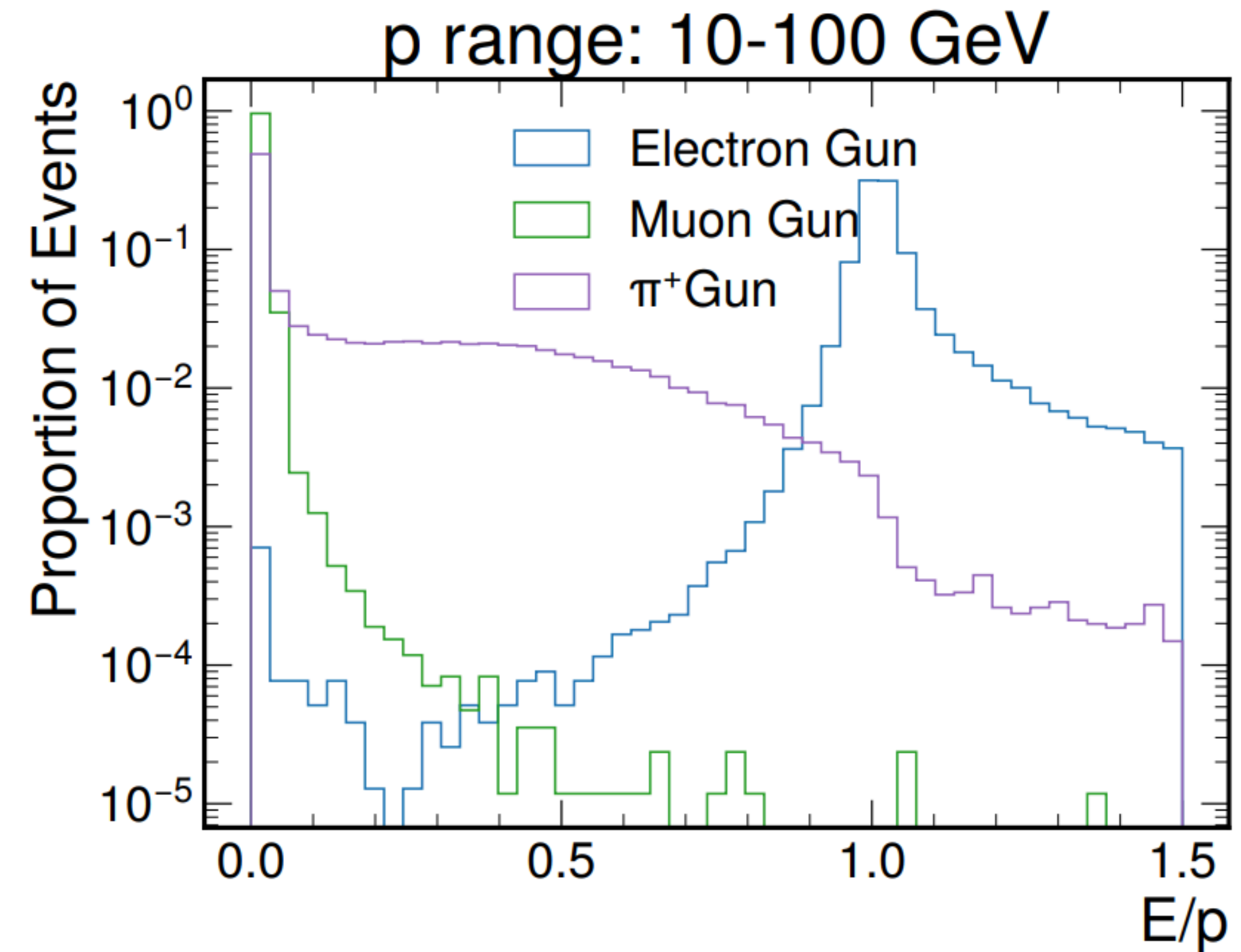
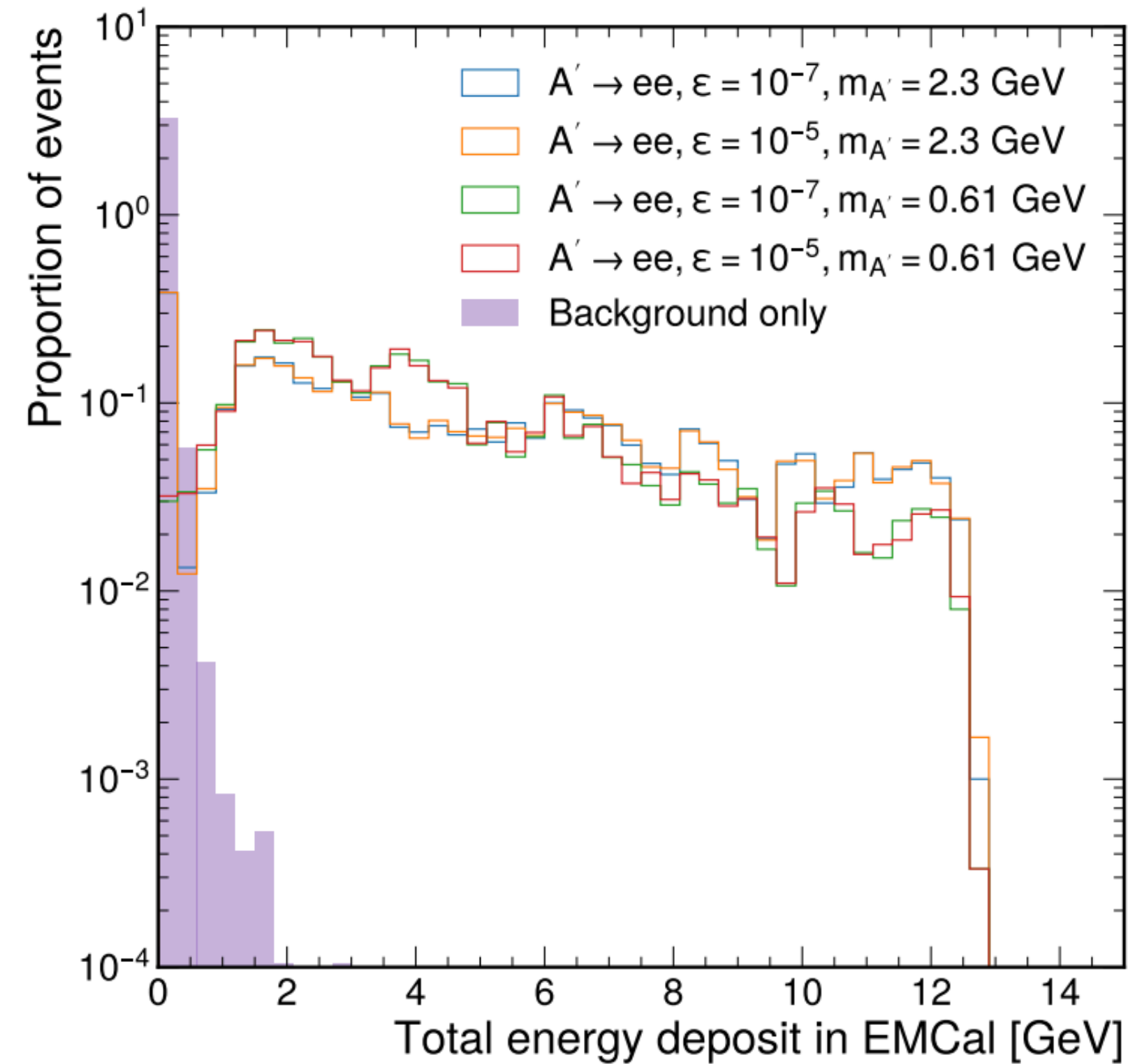
- Less affected by the multi scatterings in FMag. Better resolutions compared with prompt signals:
 - ✧ 75% track reconstruction efficiency for high momentum particles;
 - ✧ 5% mass resolution,
 - ✧ 5-10 cm Z resolution for dark photons decaying after FMag
- Working on improving the track and vertex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

Tracking and Vertexing



- Additional tracking layers can increase the acceptance dramatically in certain phase spaces
- Improvements on the tracking and vertexing resolution currently ongoing

Particle Identification



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

Collaboration

- A strong team assembled of both experimentalists and theorists:



- One DarkQuest Snowmass paper: <https://arxiv.org/pdf/2203.08322.pdf>
- Strong connections with the current SpinQuest collaboration
- Ready to analyze the muon channel once the proton beam comes in!
- 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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¹²University of Michigan, Ann Arbor, MI 48109, USA

¹³Johns Hopkins University, Baltimore, MD 21218, USA

¹⁴Yamagata University, Yamagata, 990-8560, Japan

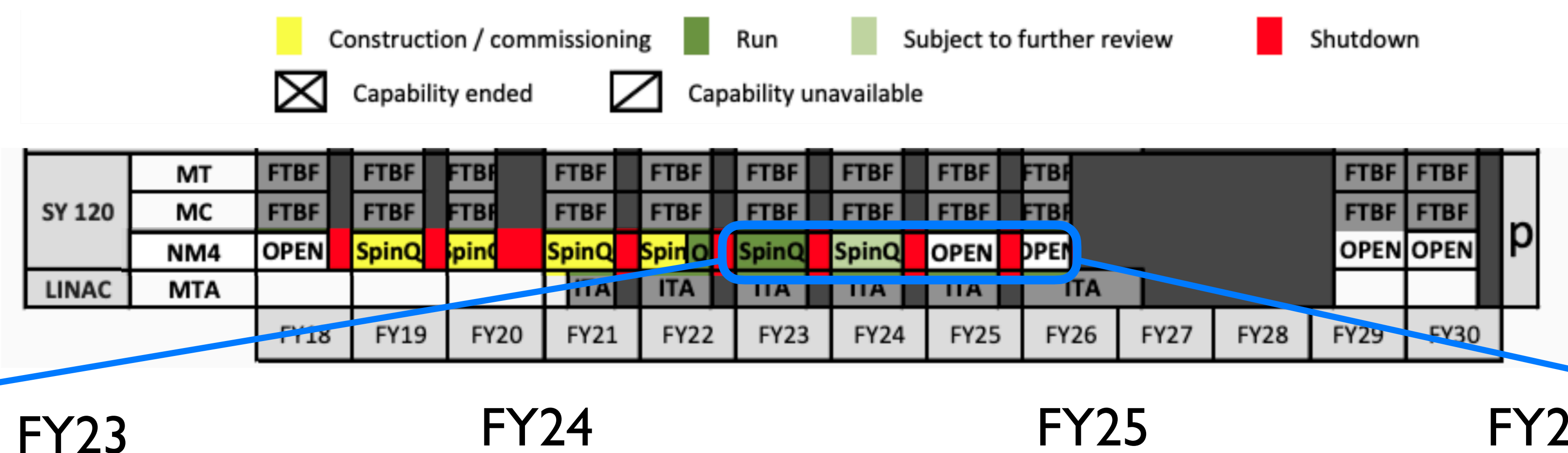
¹⁵KEK Tsukuba, Tsukuba, Ibaraki 305-0801 Japan

¹⁶Yerevan Physics Institute, Yerevan, 0036, Republic of Armenia

¹⁷Penn State University, State College, PA 16801, USA

¹⁸University of California Irvine, Irvine, CA 92697, USA

Proposed Timeline



- Simulation studies
- Trigger tests
- Electronic designs

Data taking for Spin physics and dark sector physics (muon channel)

- Adding tracking layers
- EMCal installation

Explore dark sector physics (muon + electron channel)

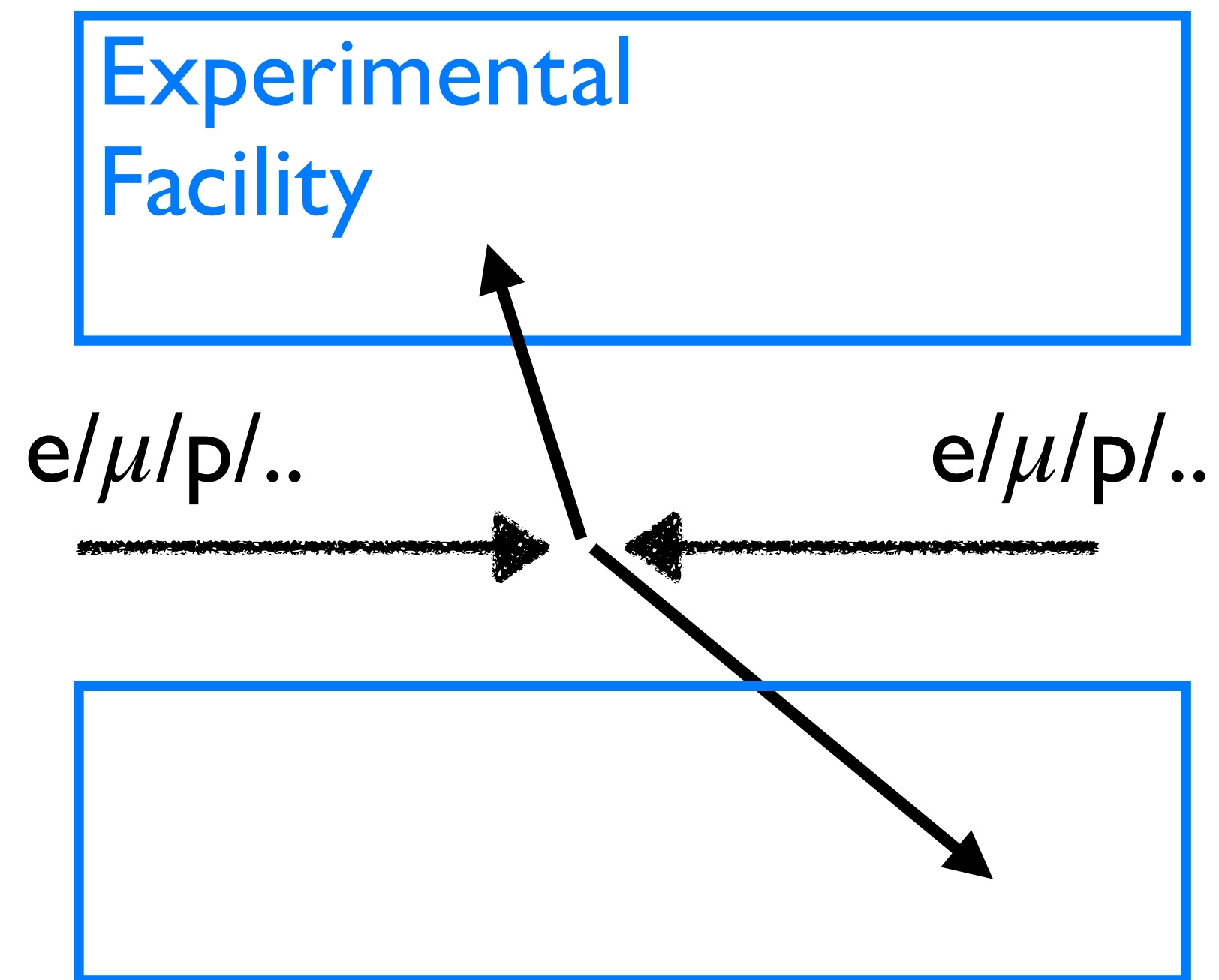
Summary

- Dark sector and light dark matter is an important 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: visible portable, scenarios related to g-2, and many others
- Proposed timeline: dark sector exploration starting from this year, together with the Spin physics runs
- A lot of electronics design, simulation, and reconstruction studies ongoing

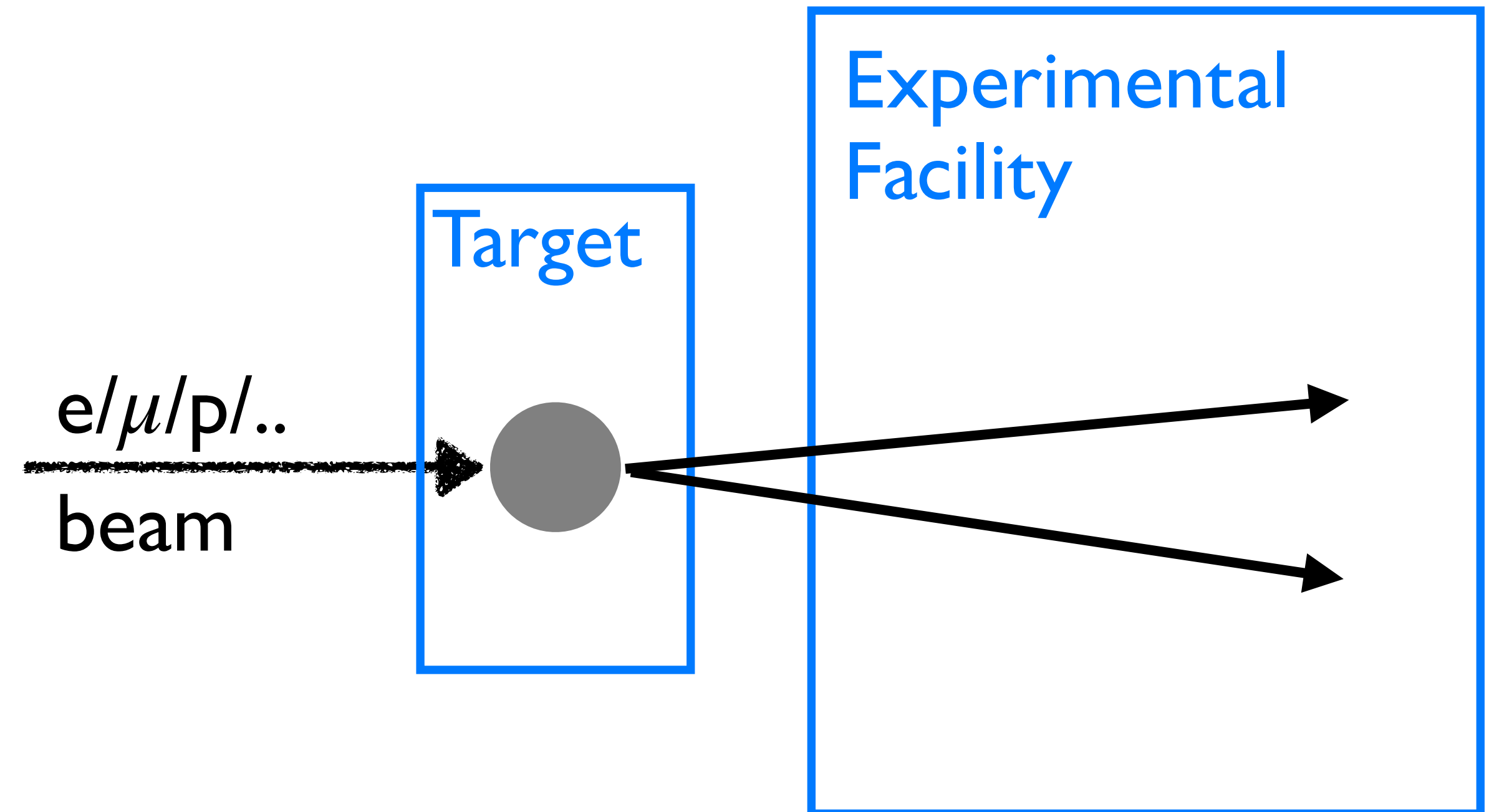


Back Up

Collider vs Fixed-target Experiments

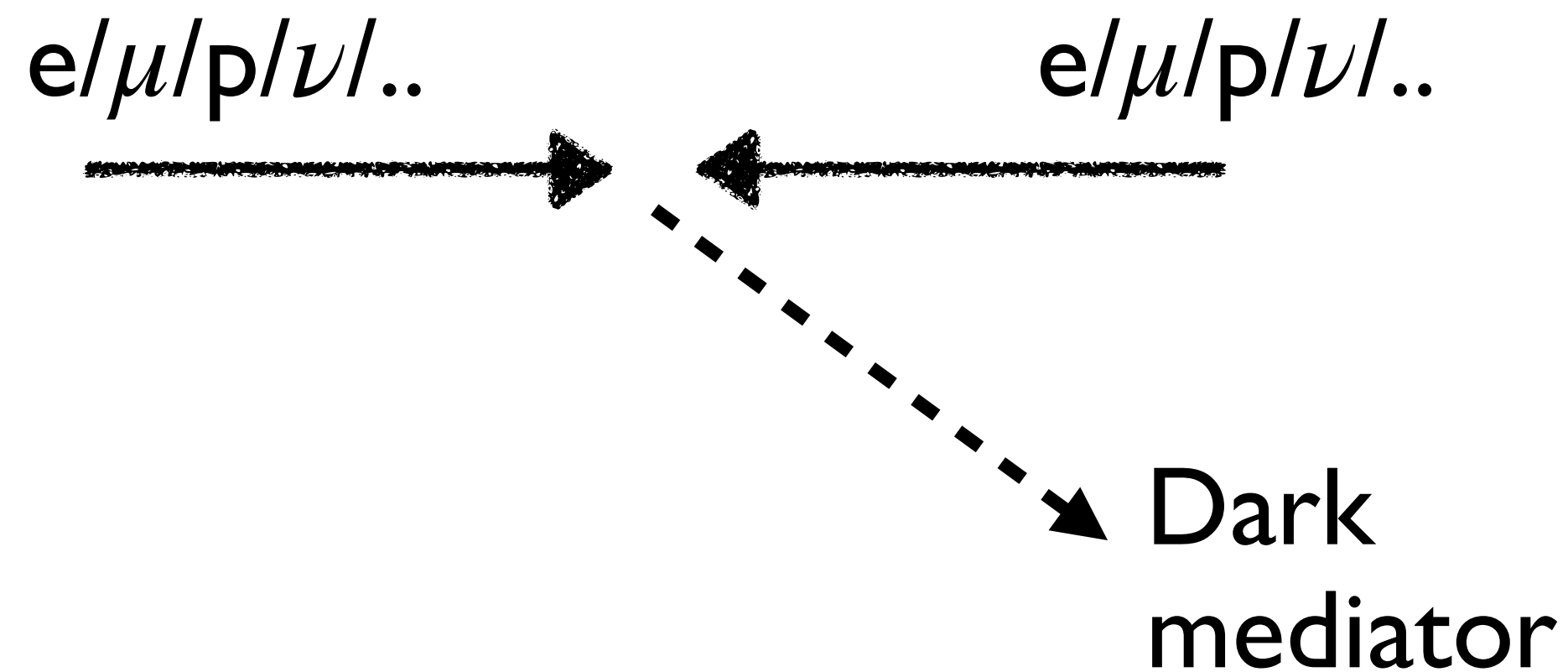


- Higher energy

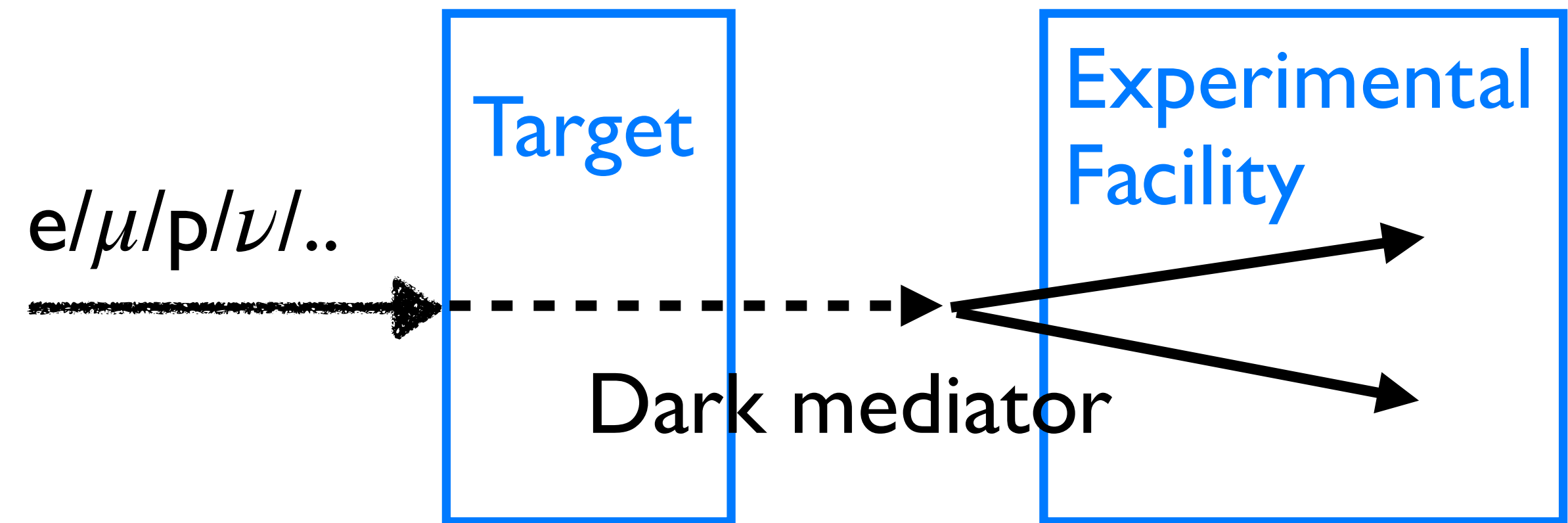


- Higher intensity

Probe Dark Sector with Accelerators

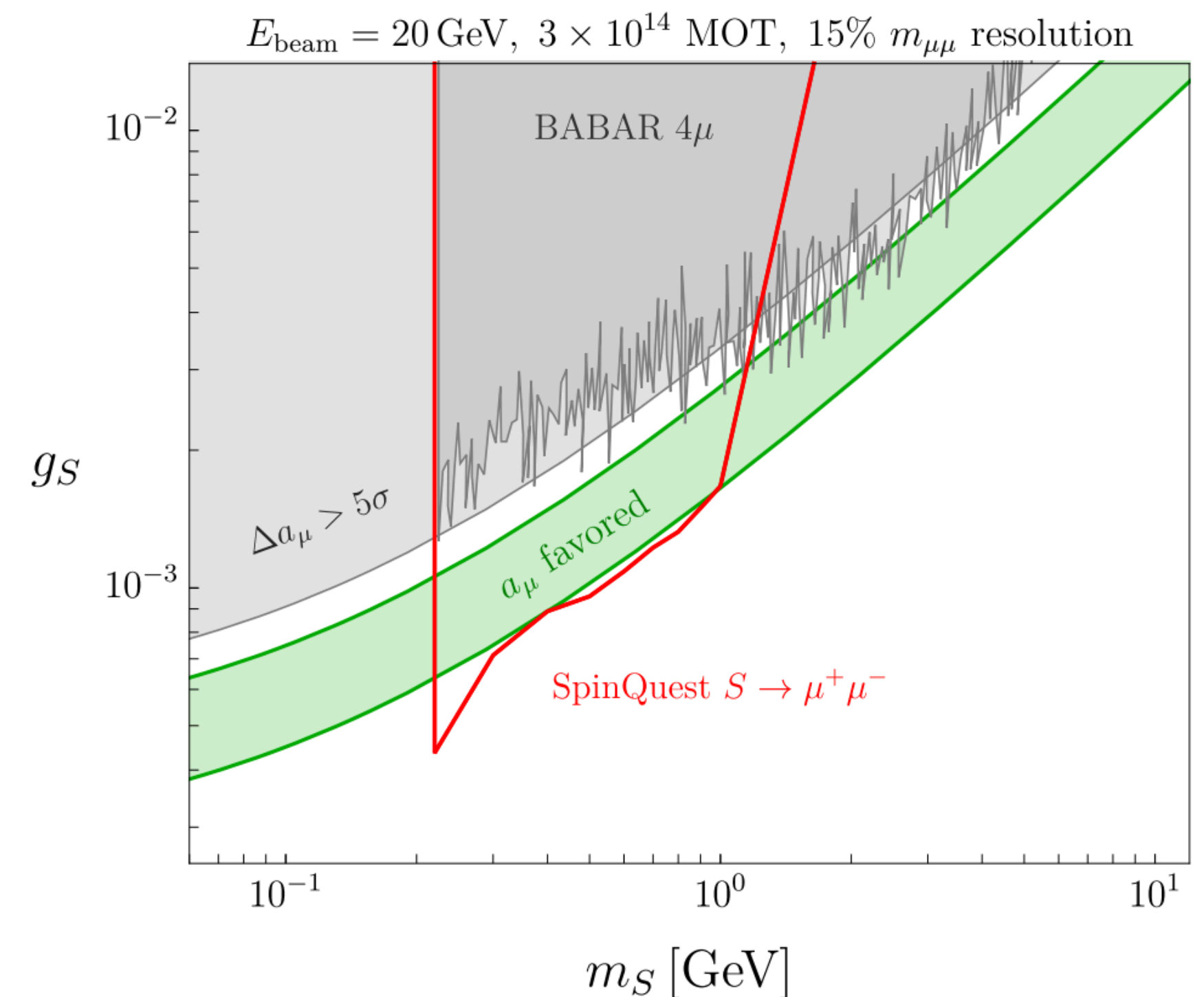
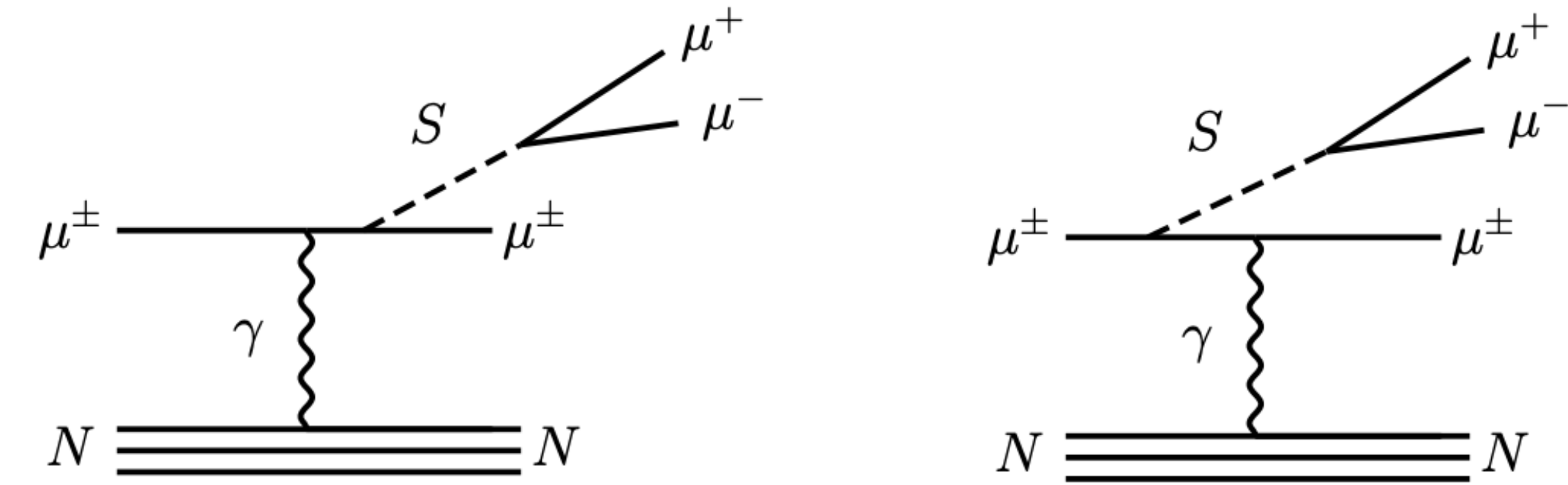


- Look for final states with bumps/displaced signals/missing E/p/m
 - ✦ ATLAS/CMS/LHCb, Belle, BES?



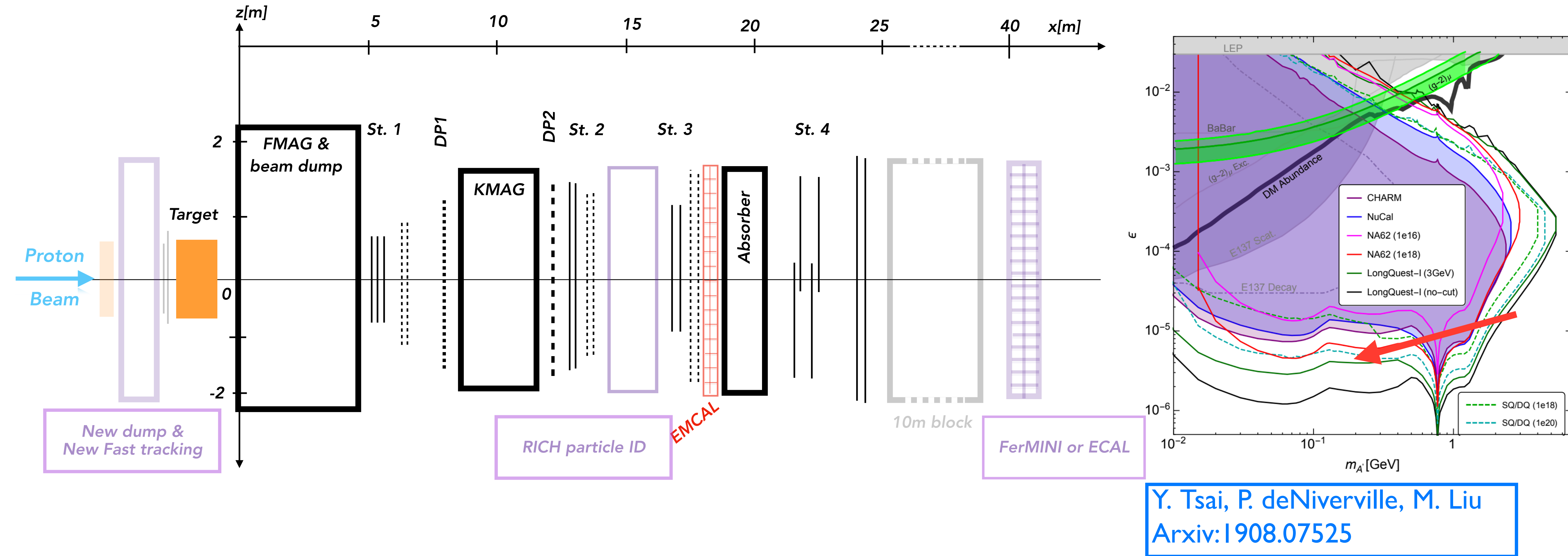
- Analyze the dark mediator decay products: bumps/displaced signals/missing E/p/m
 - ✦ NA64 @ CERN, LDMX @ SLAC, **DarkQuest @ Fermilab**
 - ✦ Usually low background, better sensitivity at low mass region

Arxiv.2212.00033



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Future Upgrade: DarkQuest -> LongQuest



- 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