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

Yongbin Feng (Fermilab)

For SpinQuest DarkSector Working Group

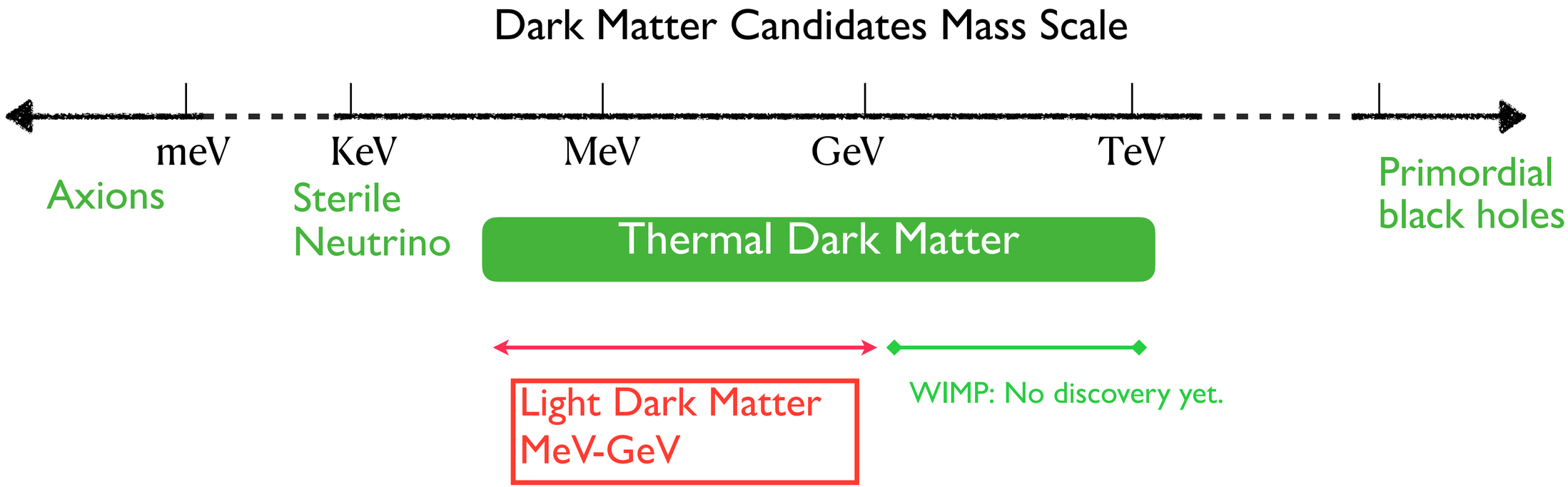
Aspen Center for Physics

March 28th, 2023

Outline

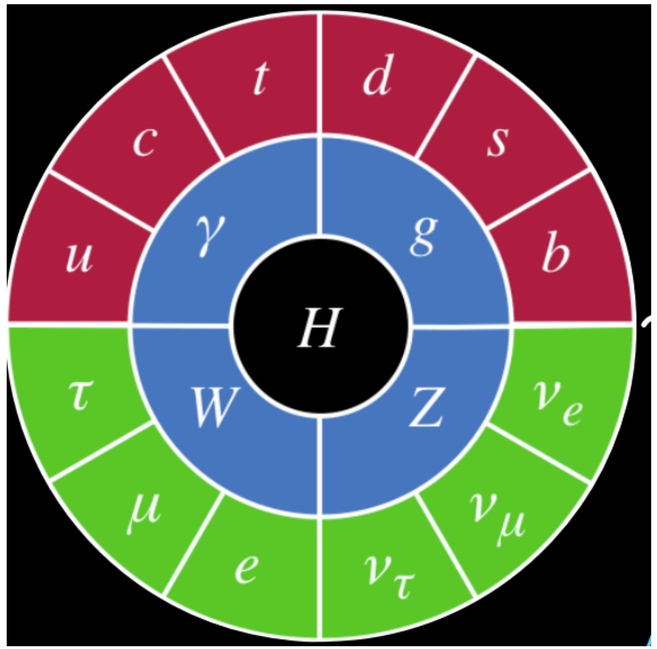
- Introduction: Dark Sector Physics
- SpinQuest, its Upgrades to DarkQuest, and Expected Sensitivities
- Upgrade Studies and Proposed Timeline
- Summary

Light Dark Matter



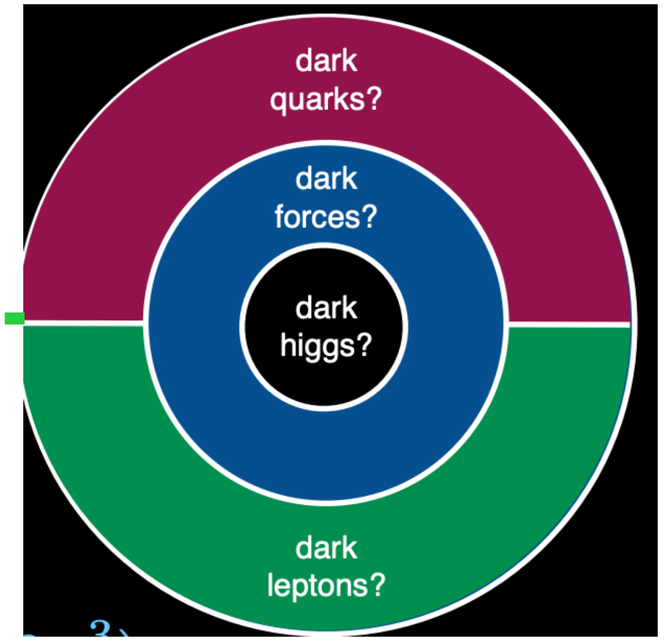
- Thermal dark matter's mass range is MeV - TeV, and WIMP has not been discovered yet.
- Light dark matter requires light mediators -> Dark Sector

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

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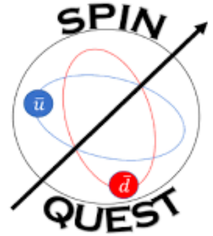
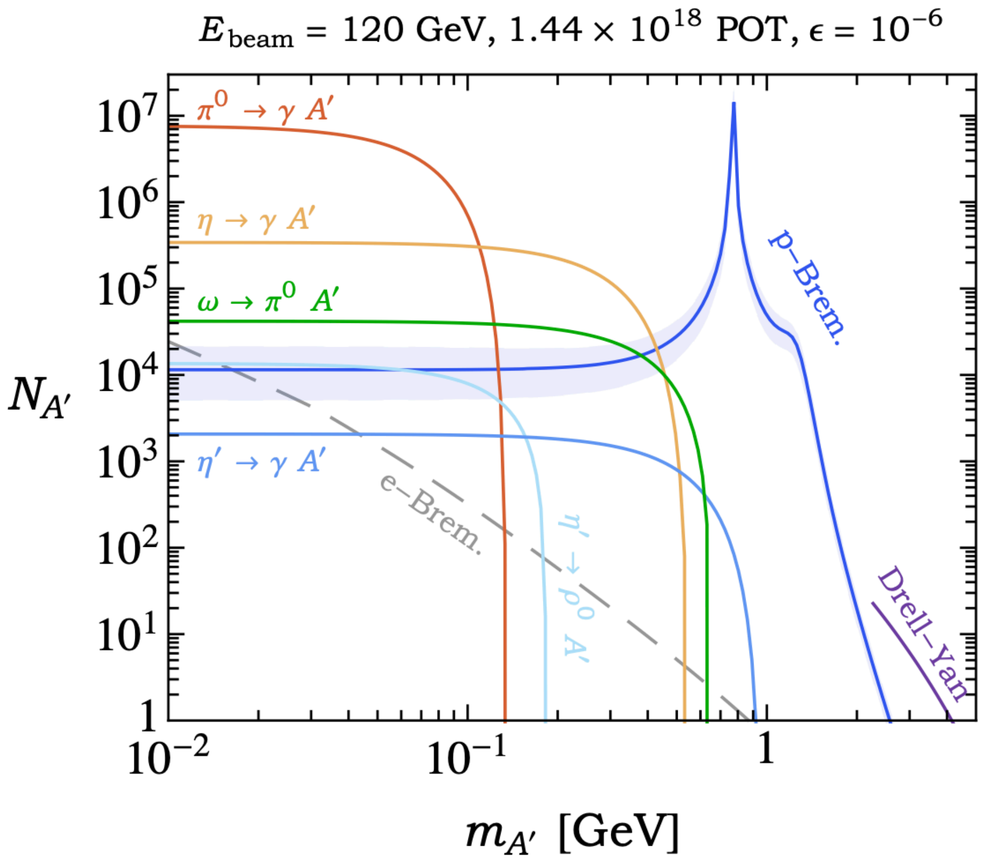


Fermilab

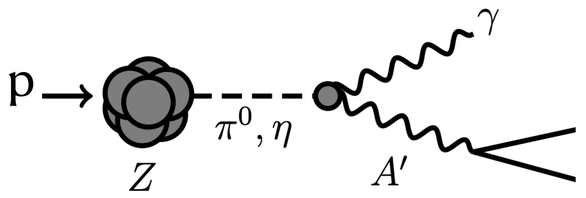
- Yes SpinQuest @ Fermilab and its DarkQuest upgrade have all these features!

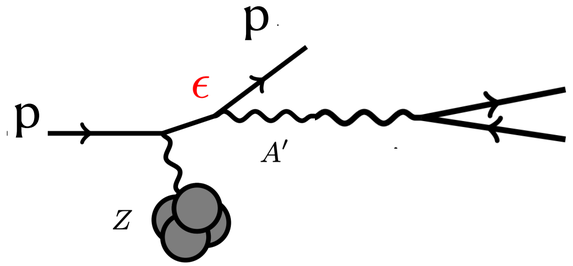
dark quest

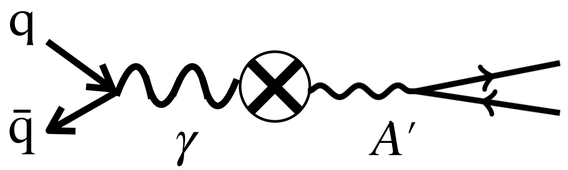
Dark Photon Production with Proton Fixed-Target



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

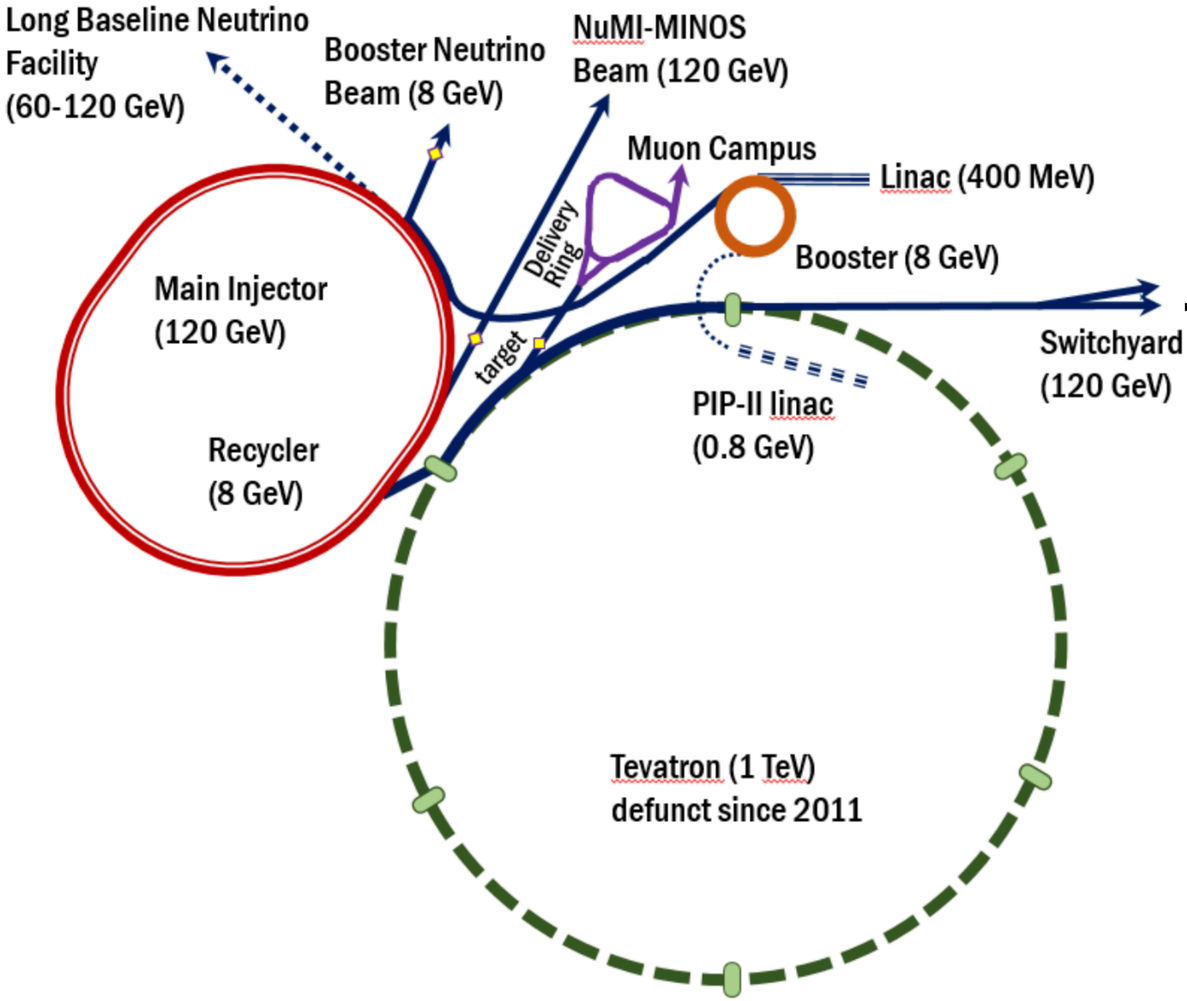


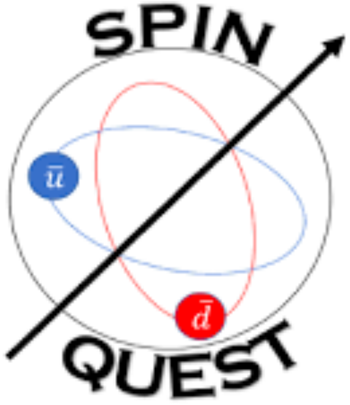




- Larger production rates with proton beams compared with electron beams

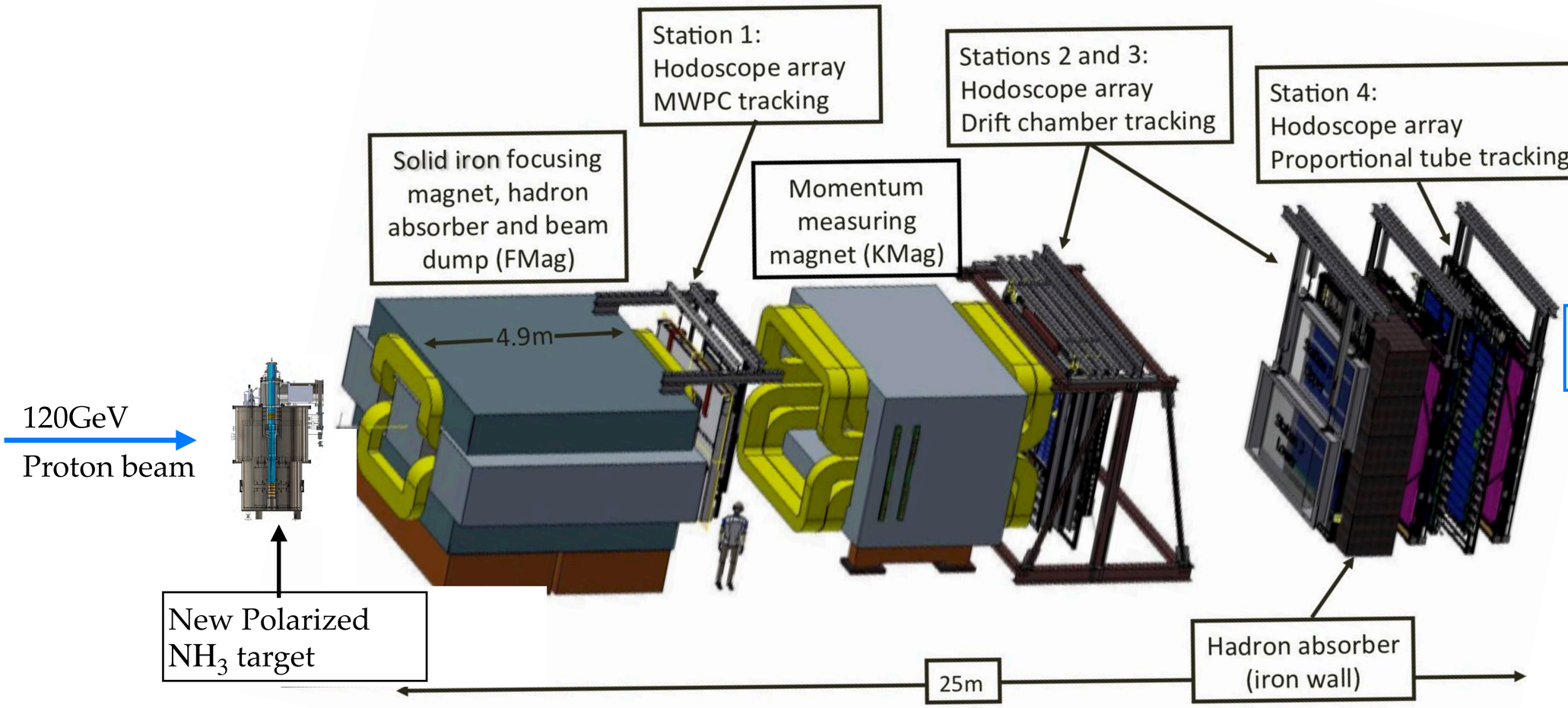
SpinQuest @ Fermilab





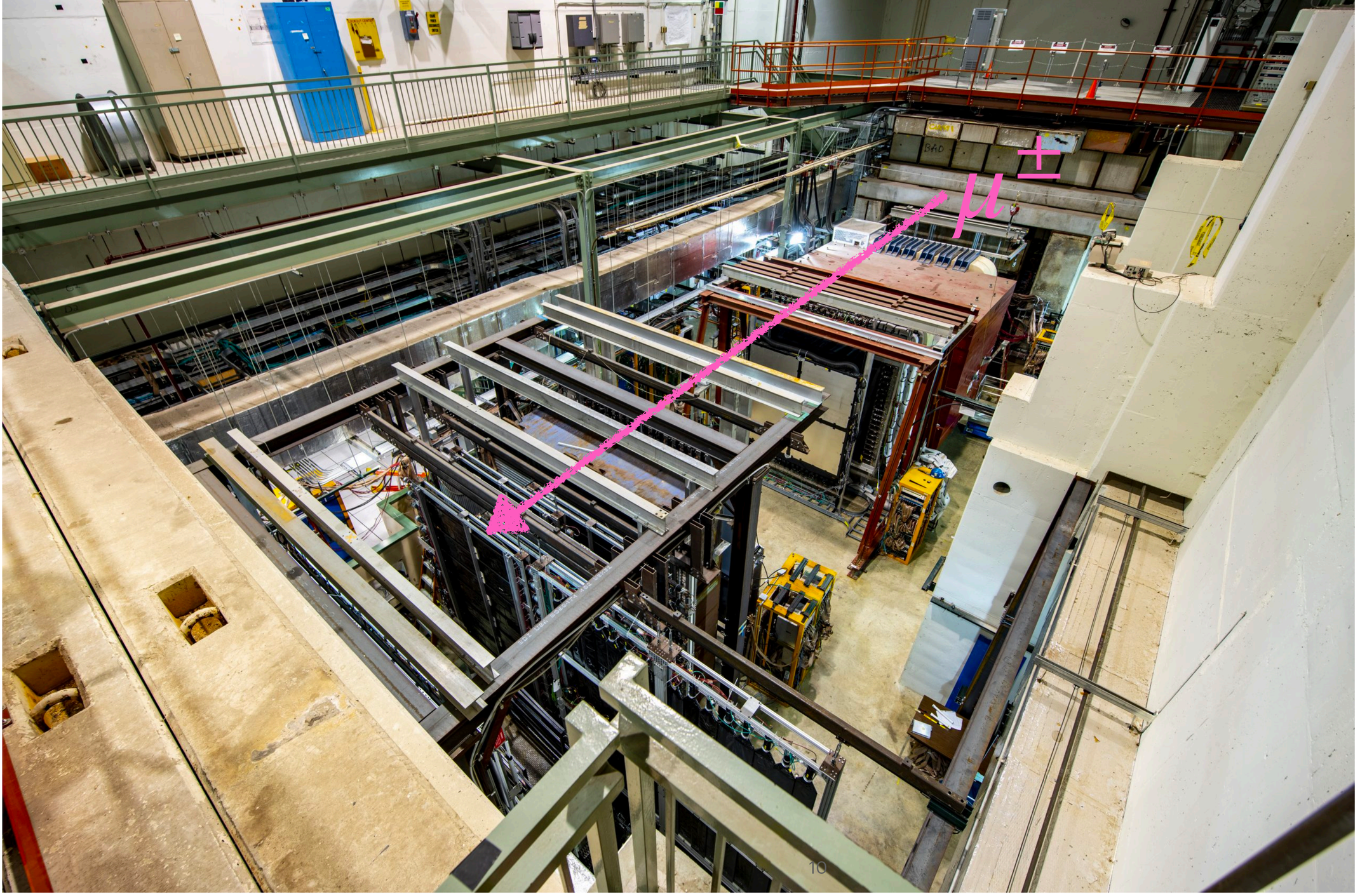
Fermilab

SpinQuest Spectrometer



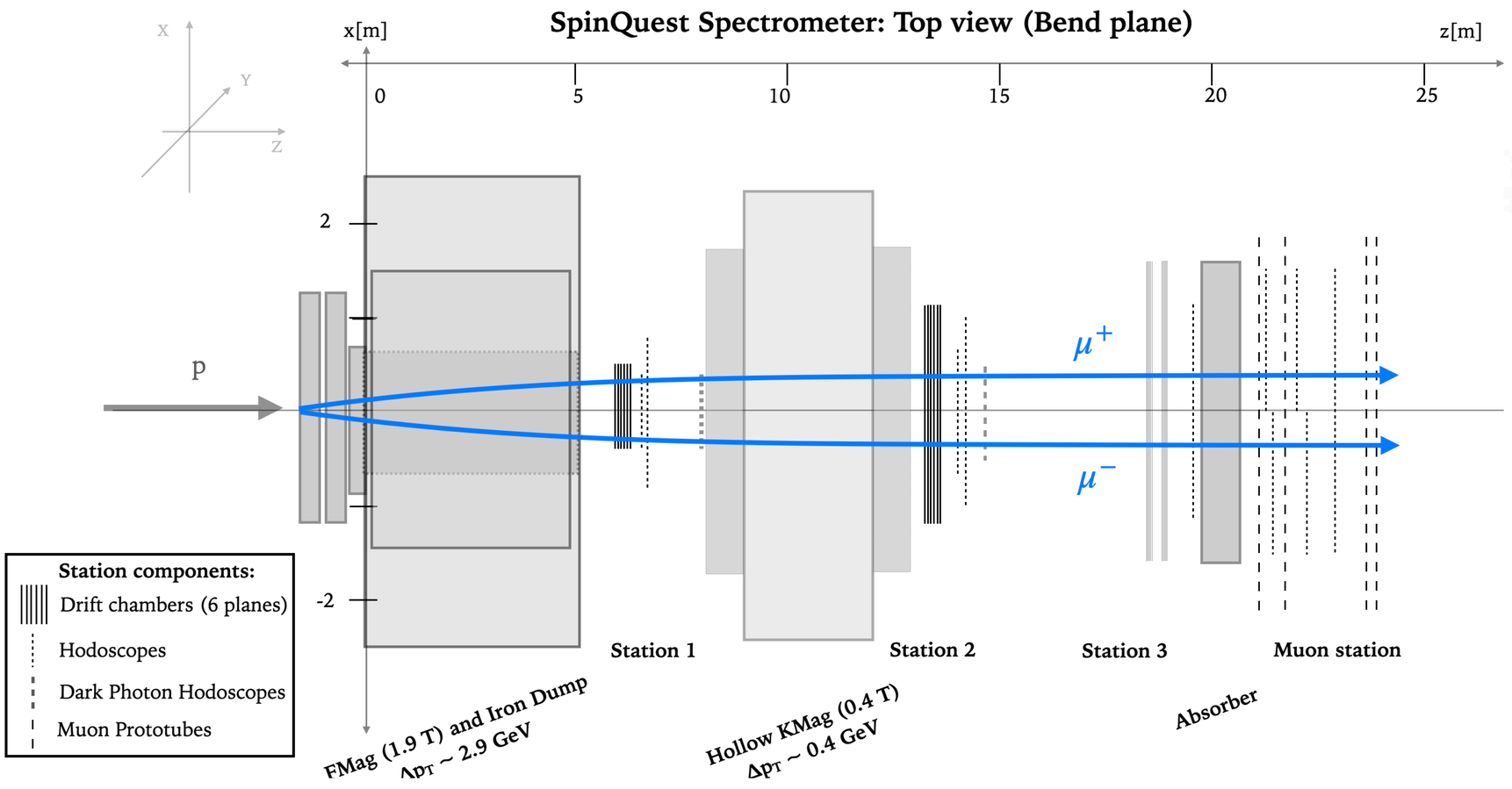
SeaQuest Collaboration
Arxiv:1706.09990

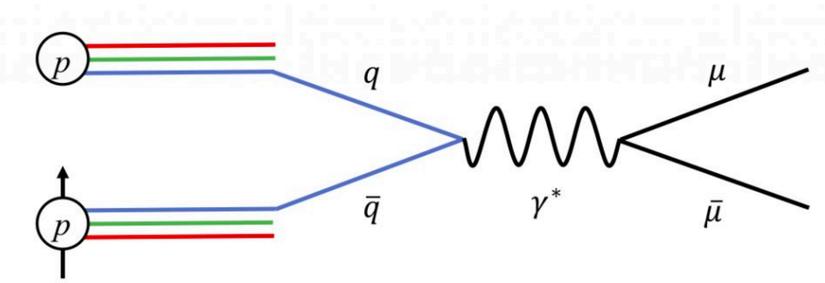
- Measuring the Drell-Yan process for studying the Transverse Momentum Dependent PDFs (TMDs) inside the proton



SpinQuest spectrometer

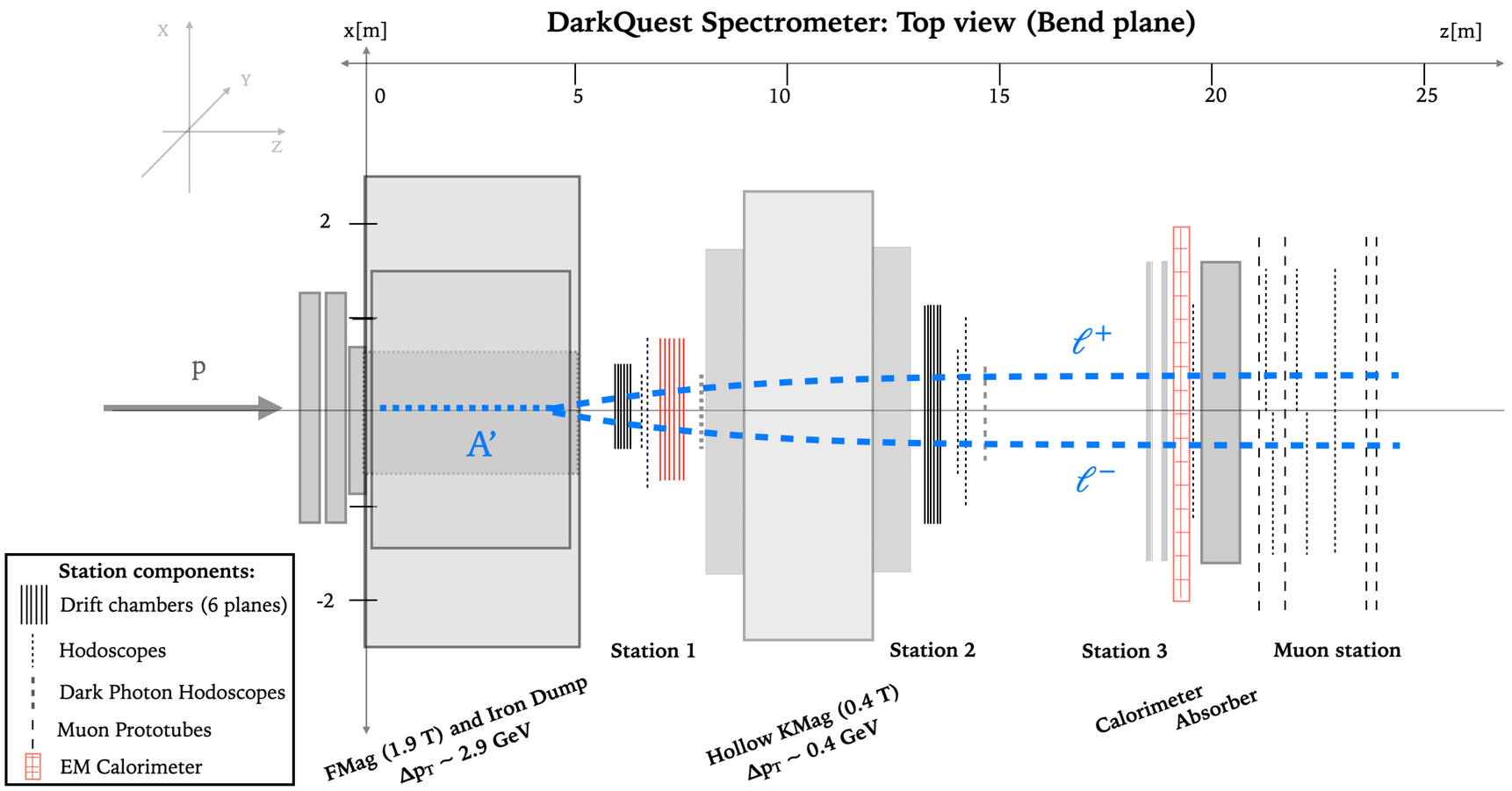
SpinQuest Spectrometer

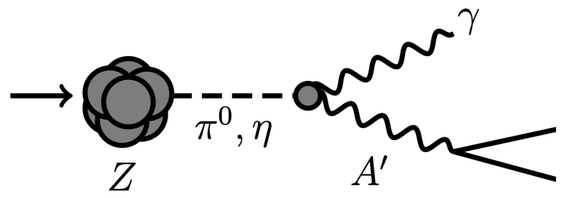




- Measuring the Drell-Yan process for studying the Transverse Momentum Dependent PDFs (TMDs) inside the proton

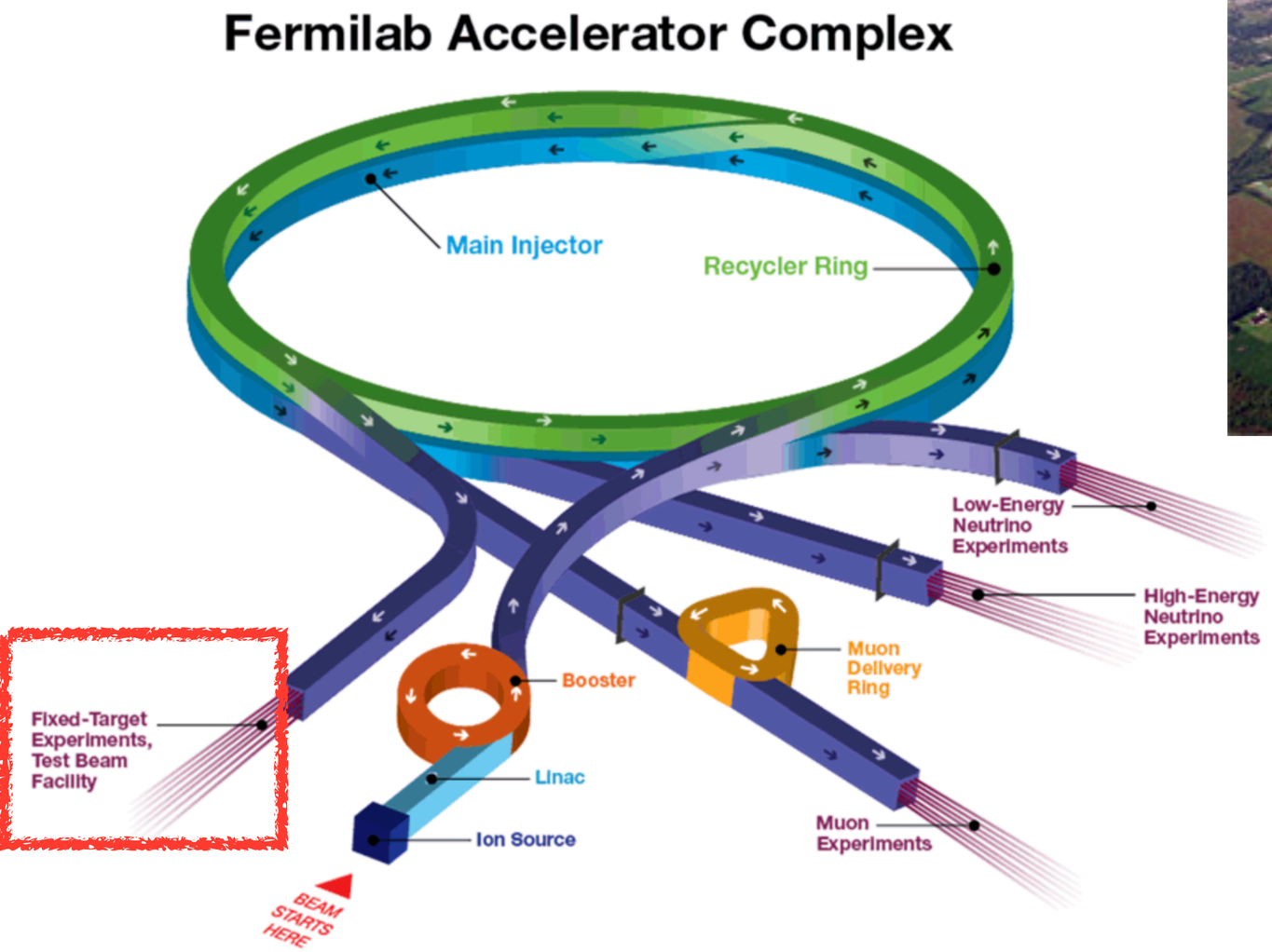
Exploring Dark Sector





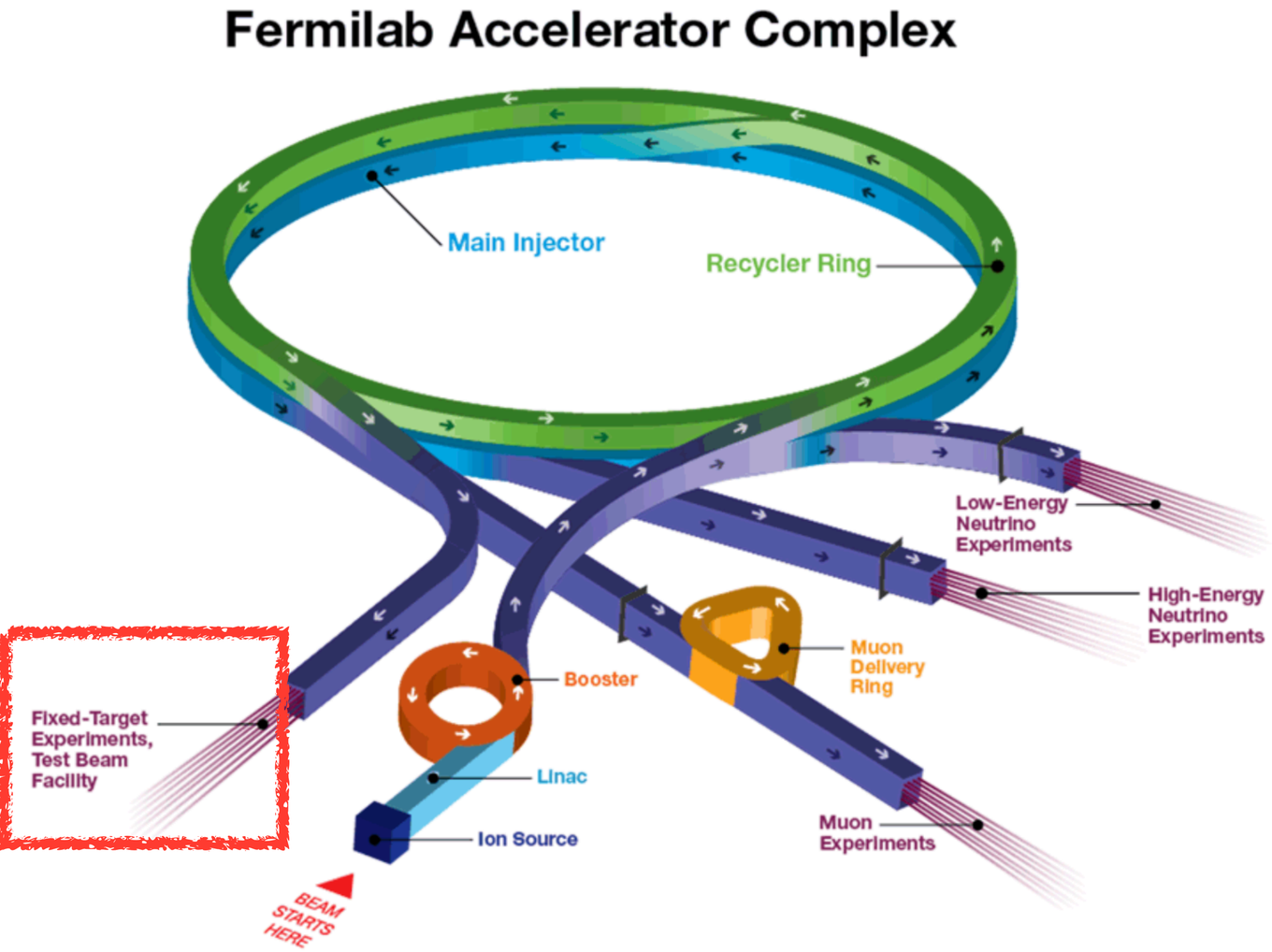
- DarkQuest: a proposed proton fixed-target experiment at Fermilab
- upgraded from the existing SpinQuest experiment

120GeV Proton Beam



- 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



- LHC 13TeV run: ~200 fb^{-1} of data, inelastic scattering σ ~ 80 mb. This brings to about 10^{16} "protons on target"

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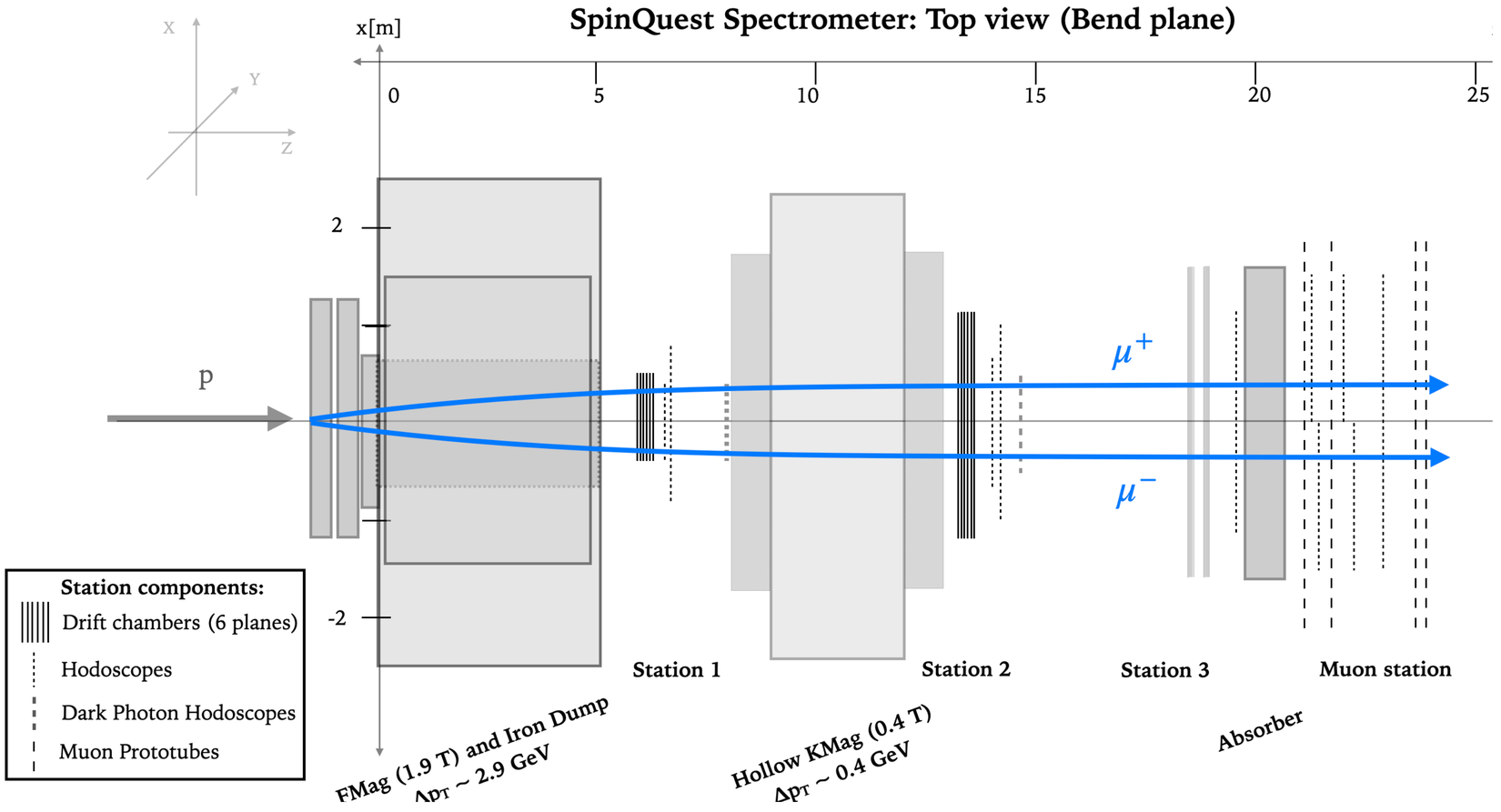
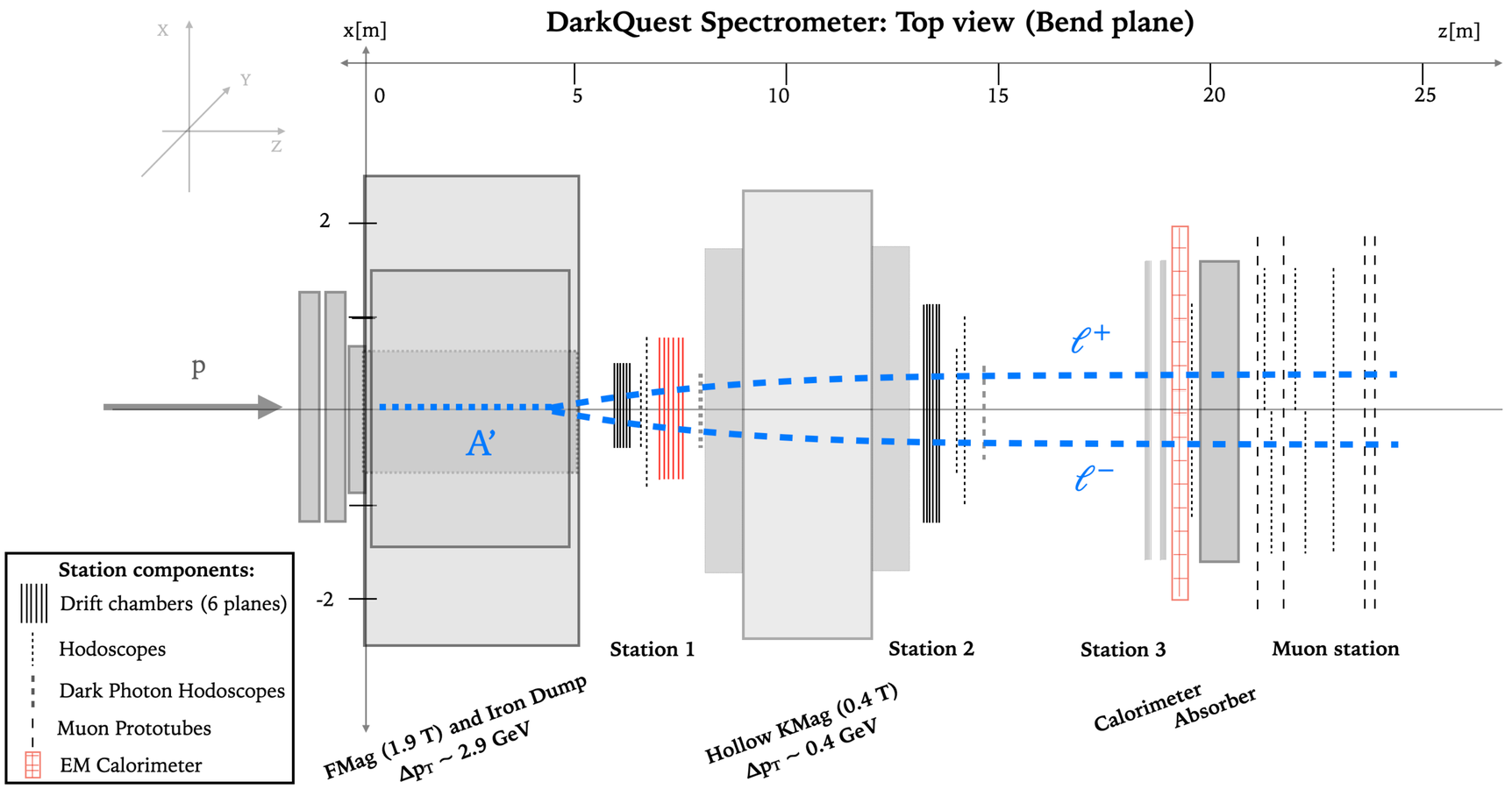
SpinQuest Spectrometer



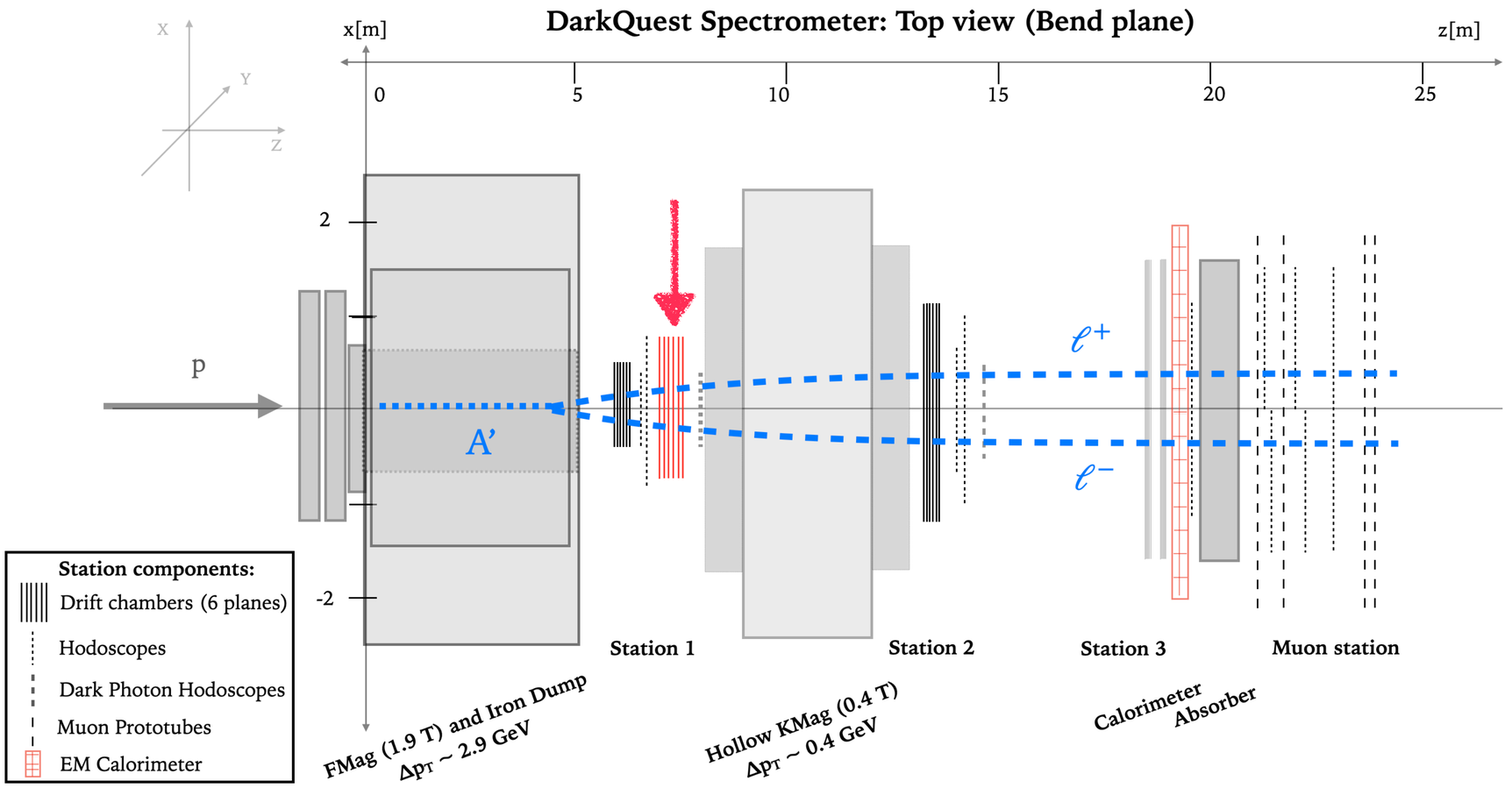
- SpinQuest spectrometer:
  - FMag: beam dump and absorber;
  - Tracking: Hollow KMag + 4 stations of drift chambers
  - Triggering: Scintillator hodoscopes
  - Muon ID: Muon stations after the iron absorber

DarkQuest Spectrometer



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

DarkQuest Spectrometer



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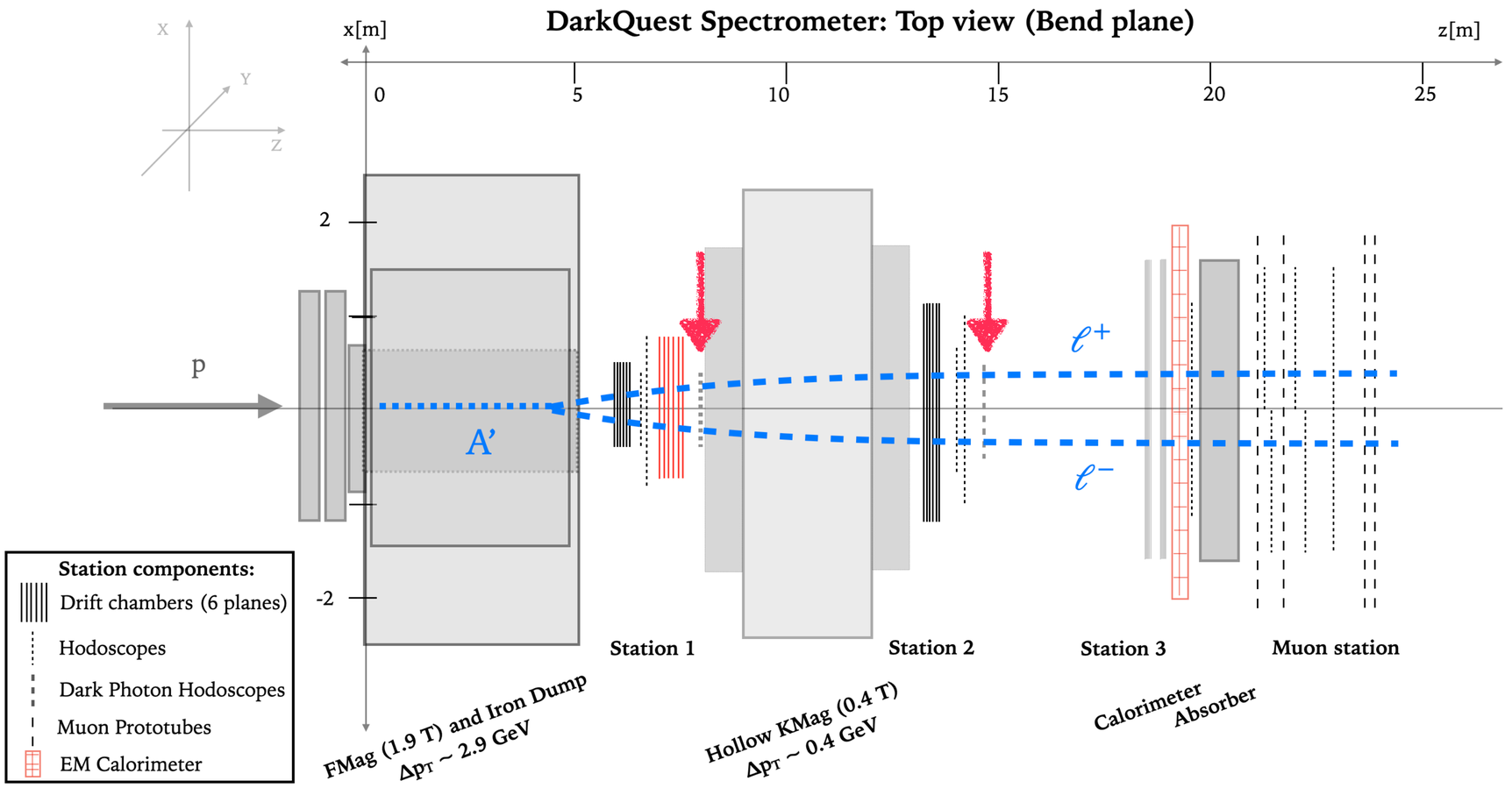
DarkQuest Spectrometer



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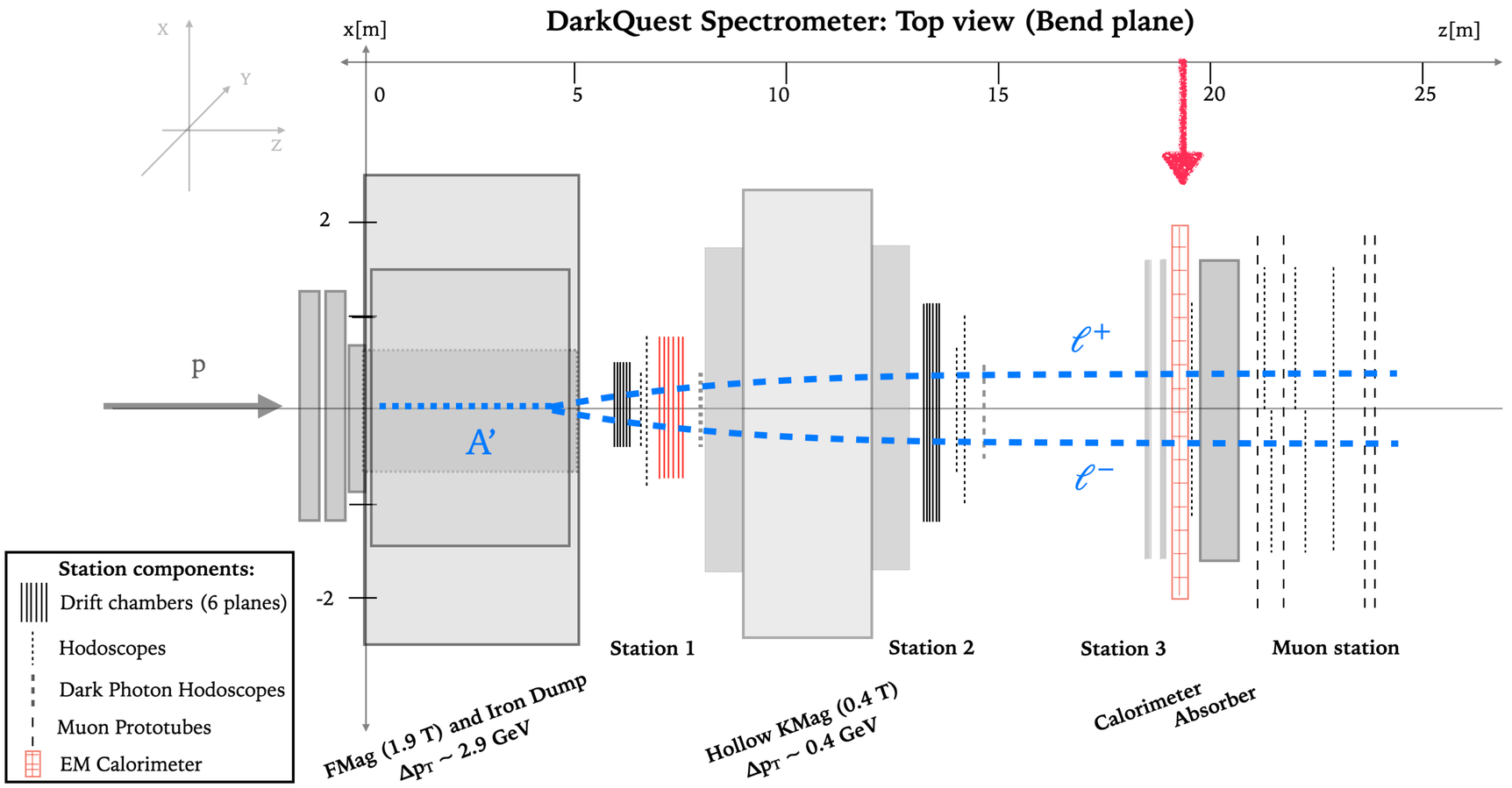


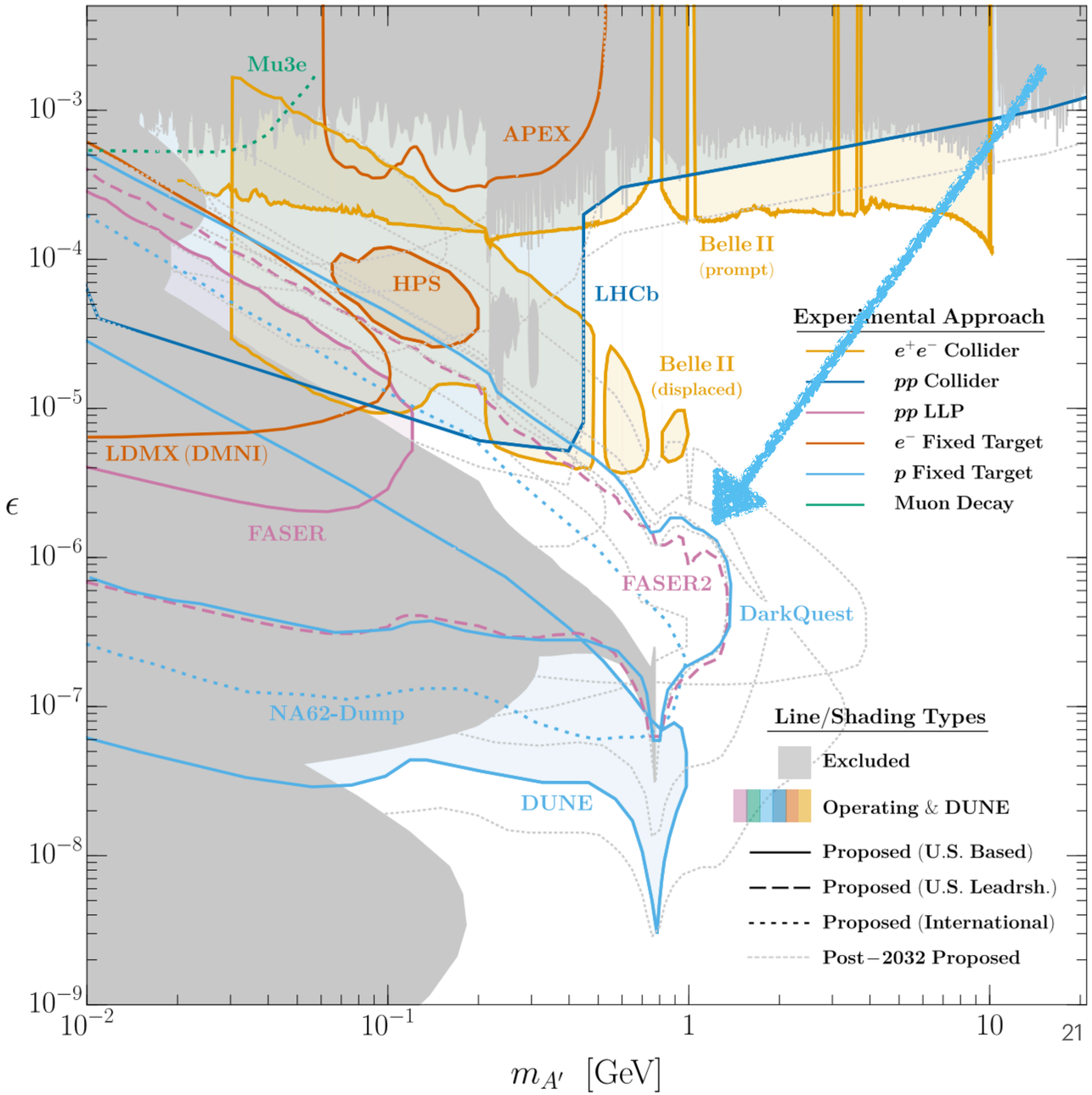
- DarkQuest spectrometer:
  - Probing dark sector by looking at displaced signals
- Upgrades on SpinQuest:
  - Additional tracking layers from HyperCP experiment
  - Hodoscopes to trigger on displaced signals
  - EMCal from PHENIX experiment: to trigger and reco electrons and photons. Allowing particle 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

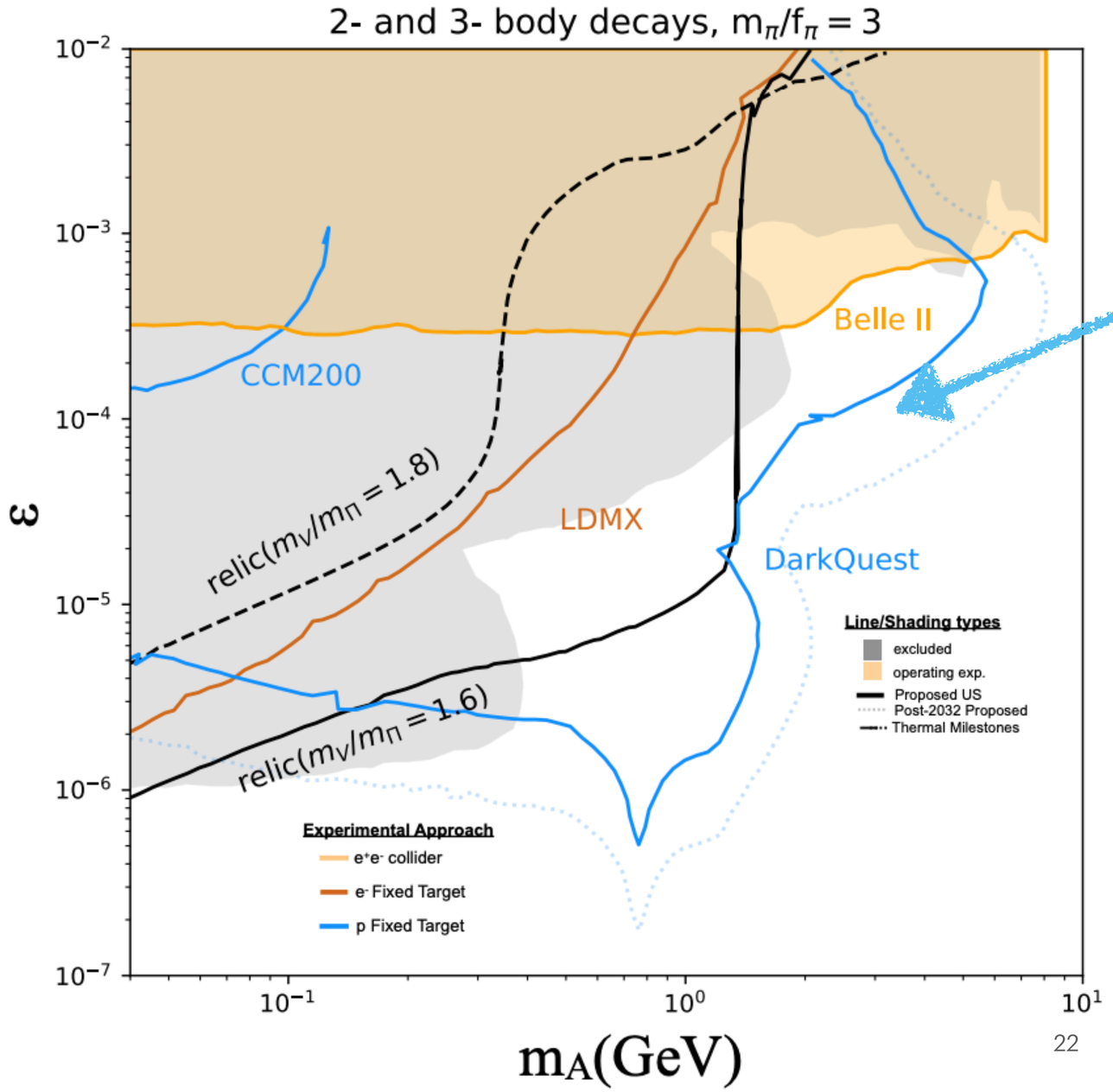
DarkQuest



Arxiv.2207.06905

- Visible dark photon portal benchmark

DarkQuest



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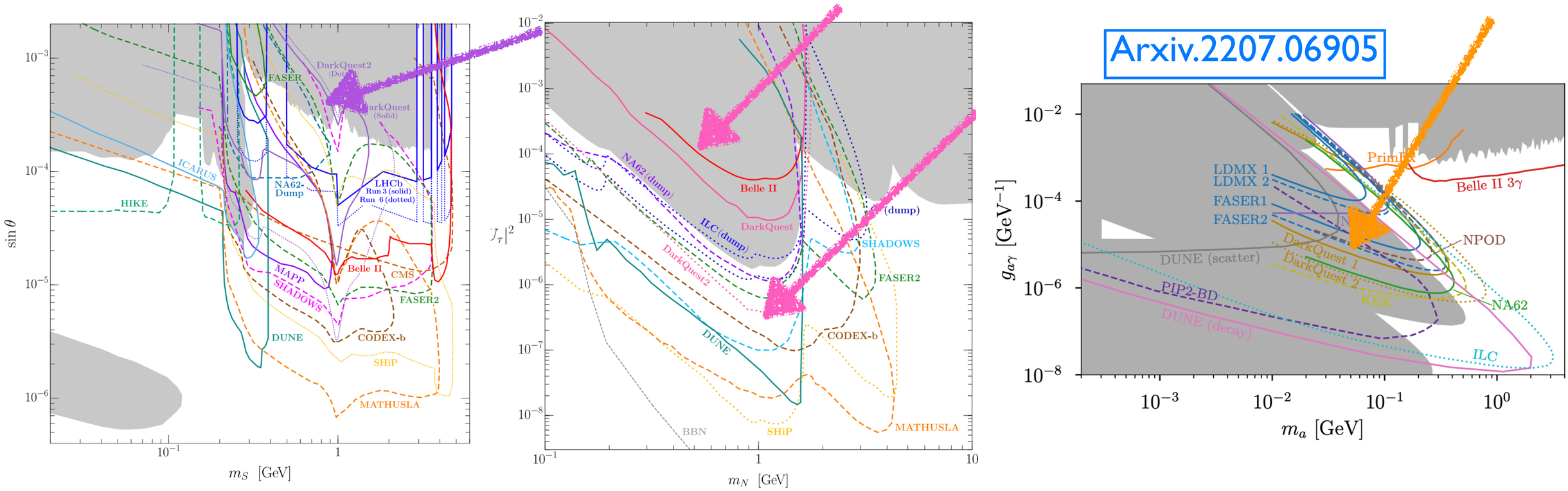
- SIMP benchmark

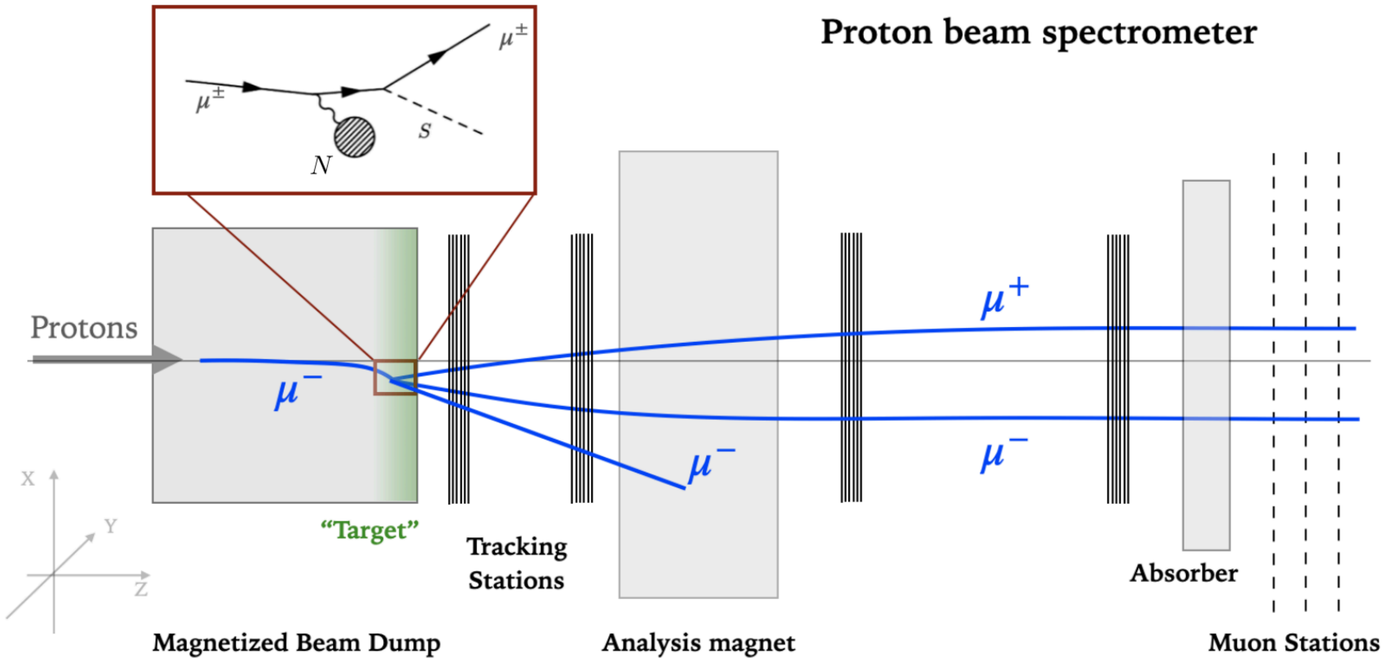
Broad Sensitivity Coverage

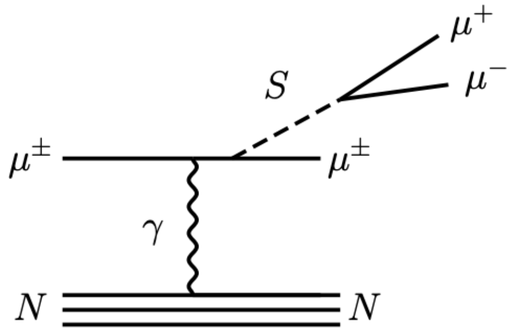


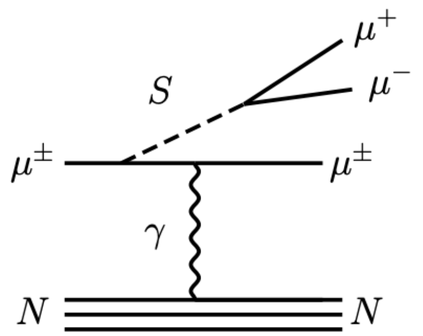
- Broad coverage to different theory models,
  - ✤ Different portals: scalar, vector, neutrino, axion-like, etc, by probing lepton/hadron/photon pairs

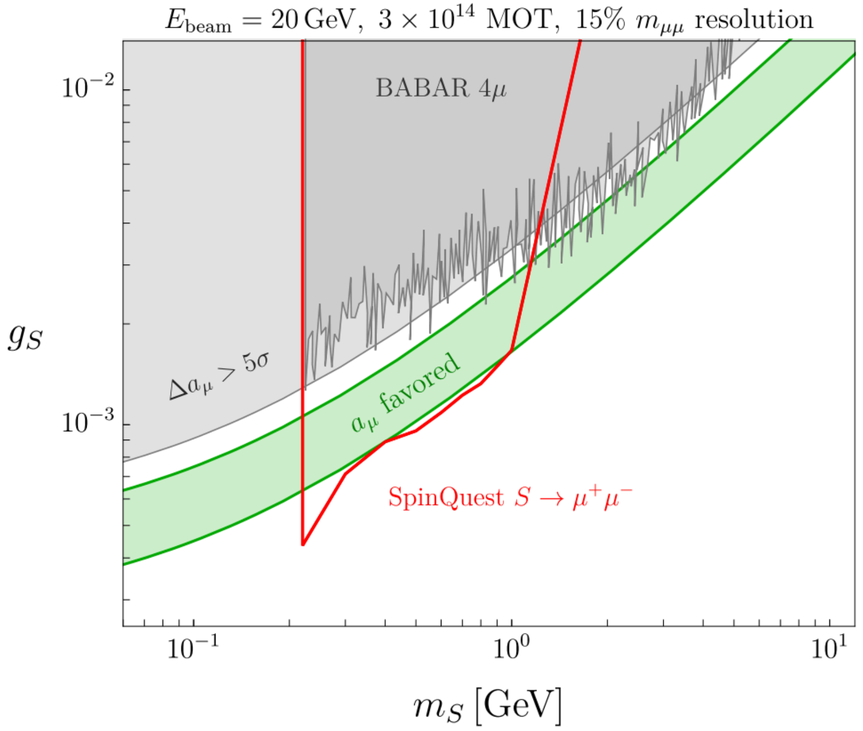
Second Muons As Muon Beam

Arxiv.2212.00033









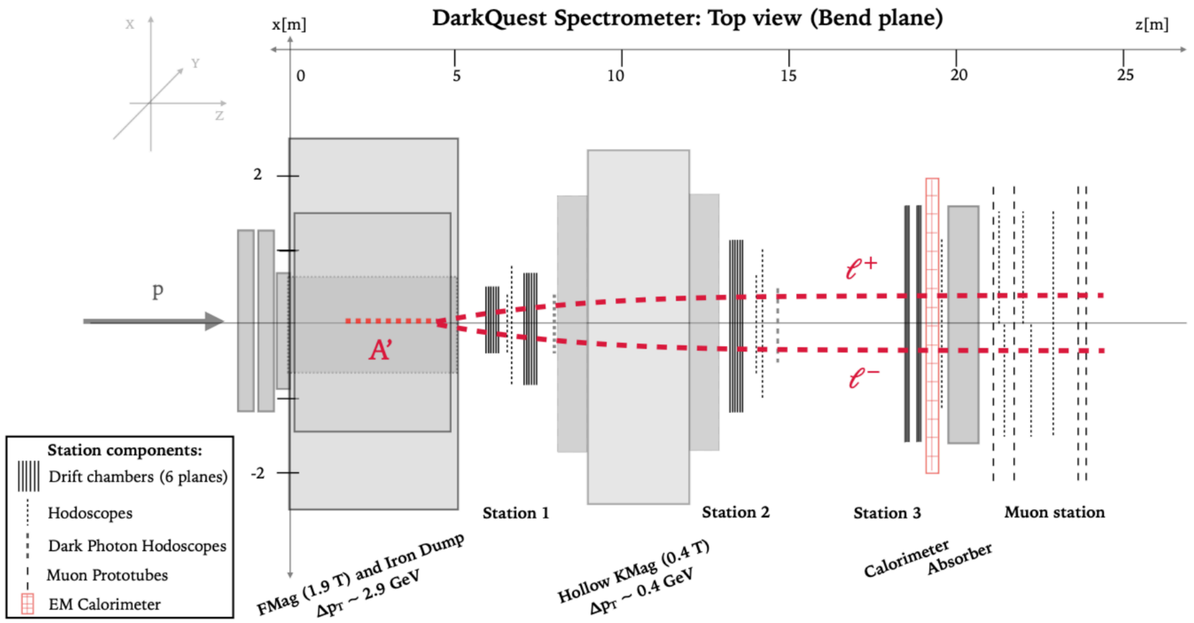
- Use the secondary muons from the proton-target interactions as the muon source, and can treat it as a "muon beam-dump" experiment
  - Sensitivity to the muon sector, e.g., g-2 anomaly

List of Experimental Studies

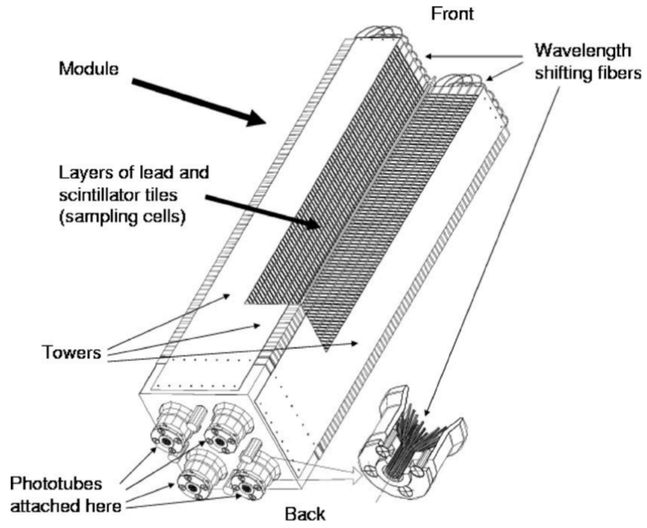
- Detector:
  - EMCal integration into the spectrometer
  - Extra Tracking layer integration into the spectrometer

- Geant-based Simulations:
  - EMCal simulations
  - Triggering
  - Tracking & vertexing
  - ParticleID: tracking + calorimeter information

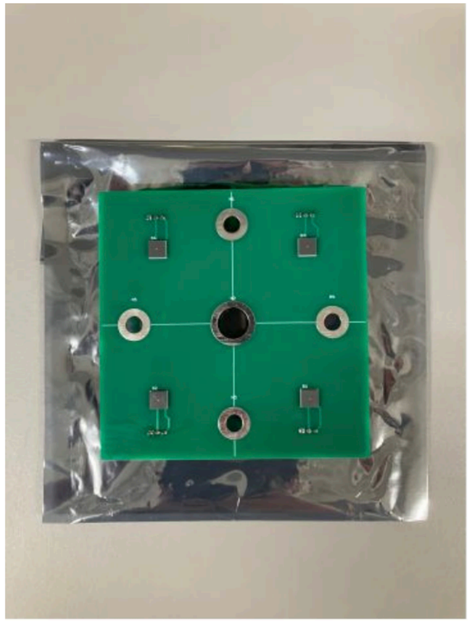
EMCal Integration

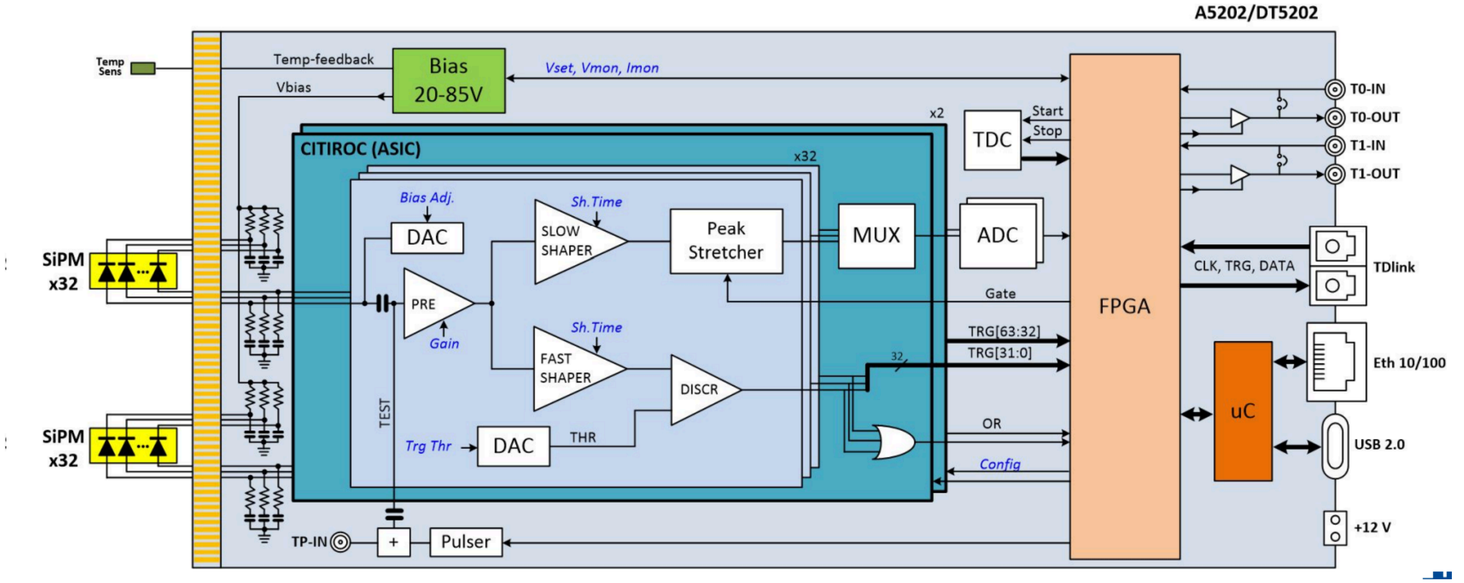


- EMCal: $PbWO_4$ + iron sampling calorimeter from PHENIX experiment
- EMCal integration into the spectrometer:
  - Developments of the readout and trigger system ongoing
  - Currently in possession of a few cells to explore SiPM readouts

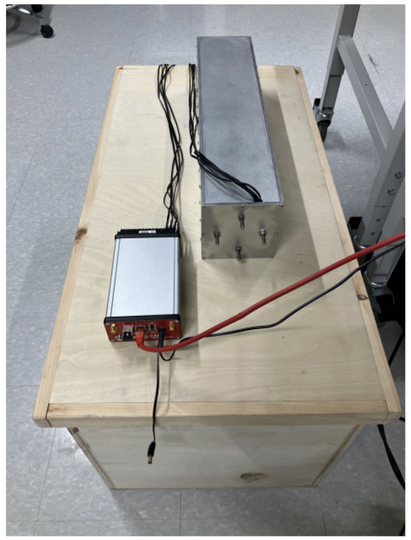


EMCal Readout Electronics

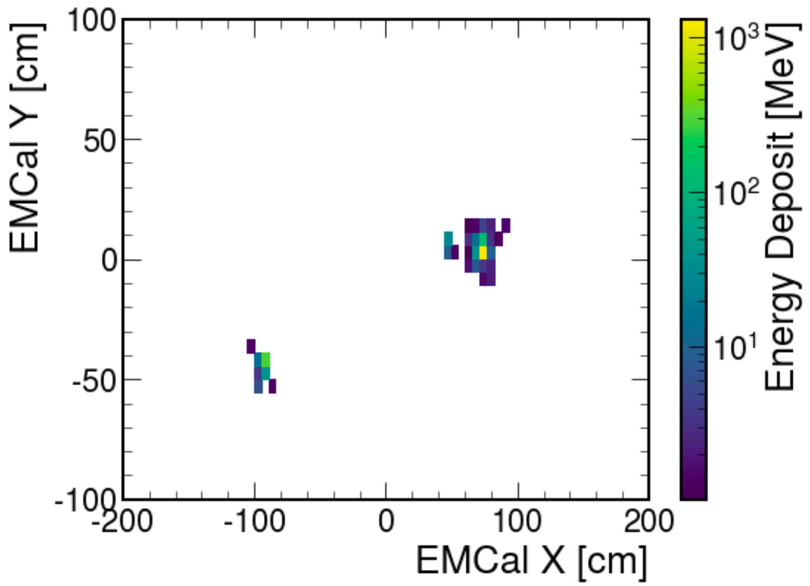


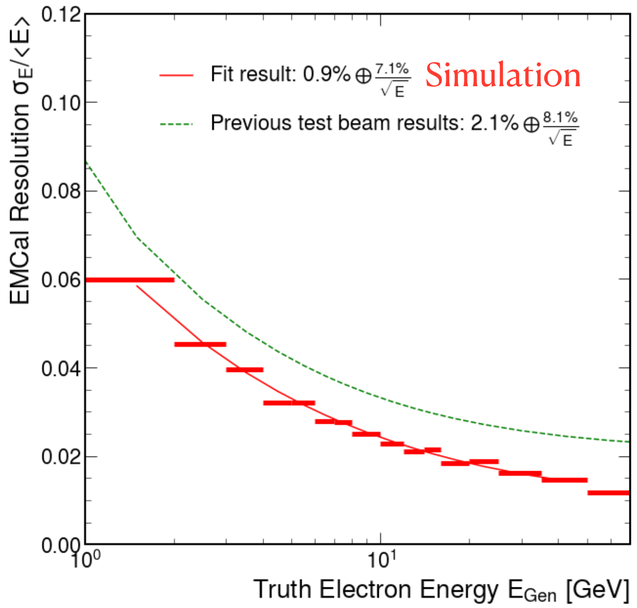


- EMCal test stands has been developed to study new EMCal readout electronics
- Available for test beam and background rate measurements in NM4 in 2023



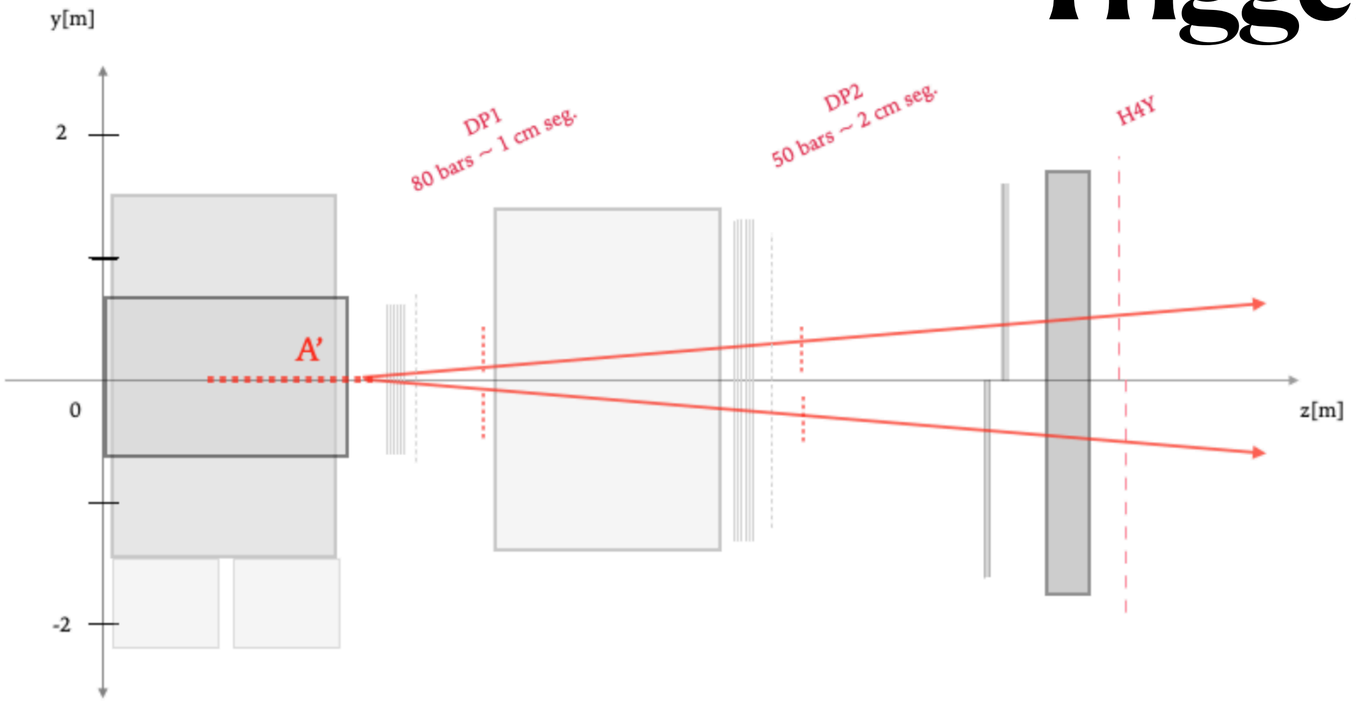
Ongoing Studies: EMCal Simulations

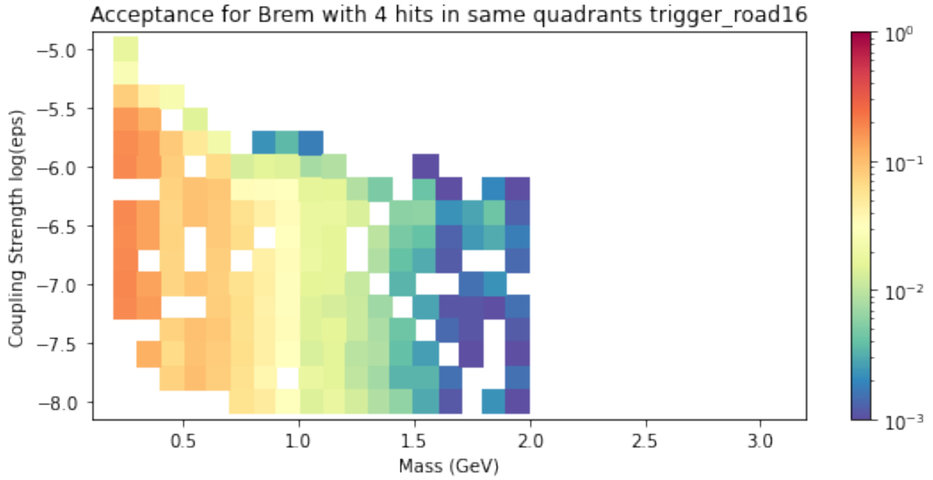


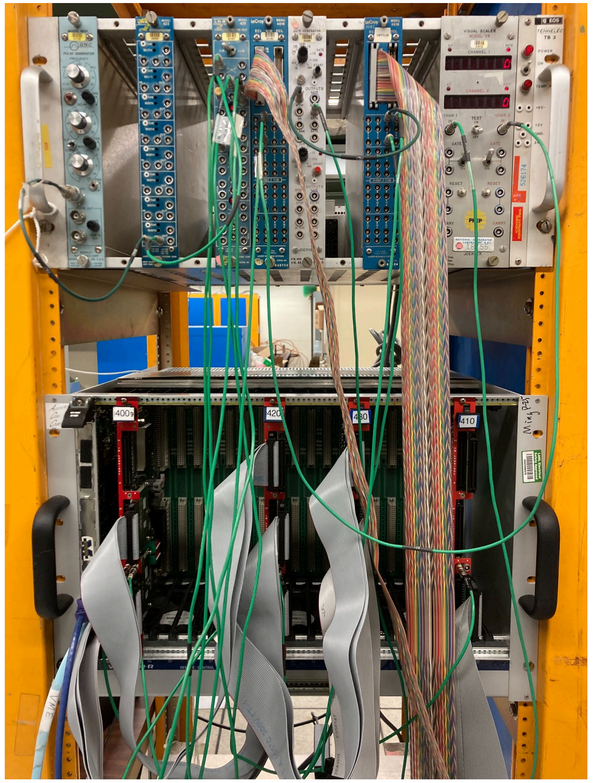


- EMCal: ~5cm per cell (2-3 Molière radius of $PbWO_4$): most energy deposit in one central cell
- Nice separation between two electron showers
- Agreement of the resolutions between the simulation (red) and the previous test beam results

Trigger

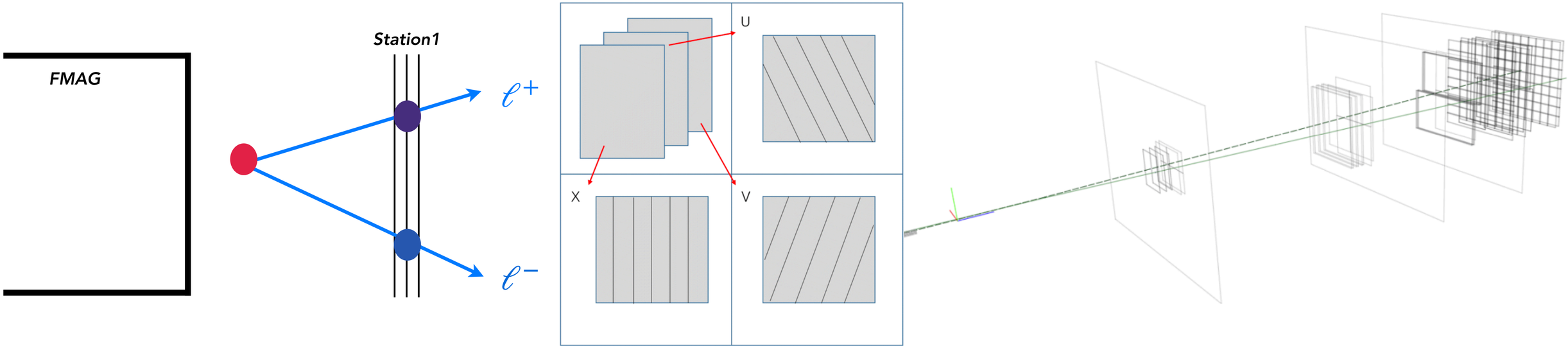






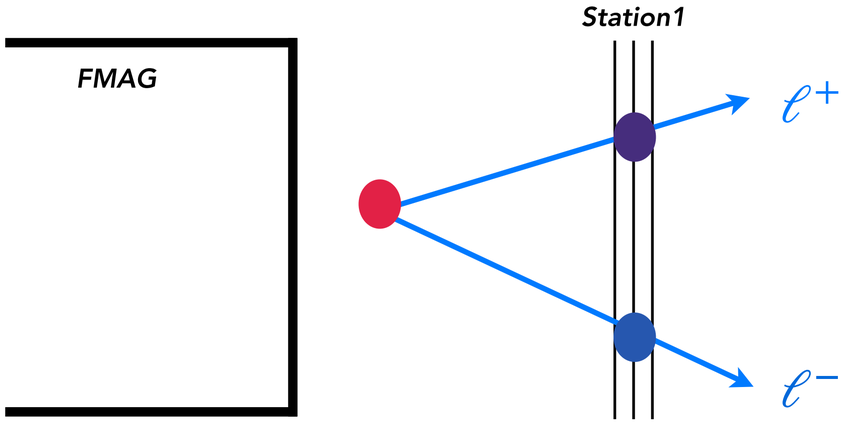
- Test the new trigger roads for displaced signals using the fiber hodoscope detectors installed in 2017
  - ✤ Trigger efficiency ~20% for decays in acceptance
- Ongoing work on integration into the trigger system and commissioning
- In the future plan to include EMCal information in the trigger system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

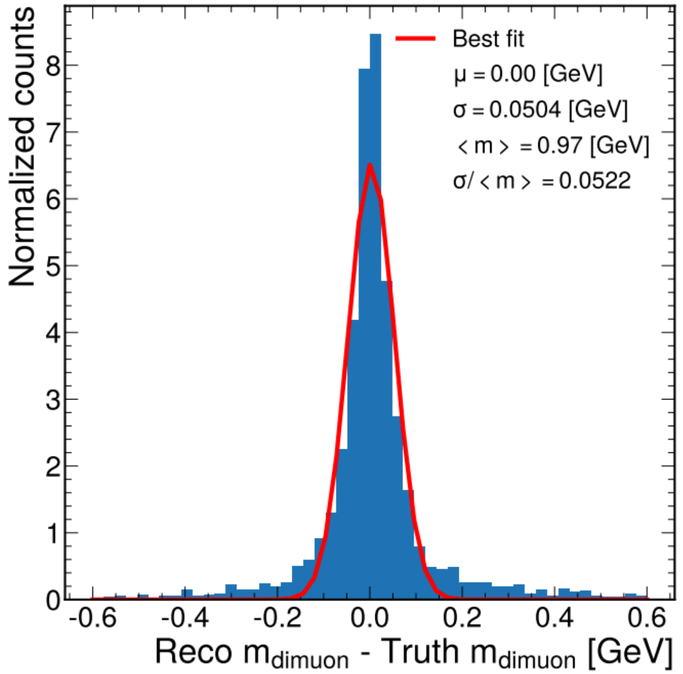
Tracking and Vertexing

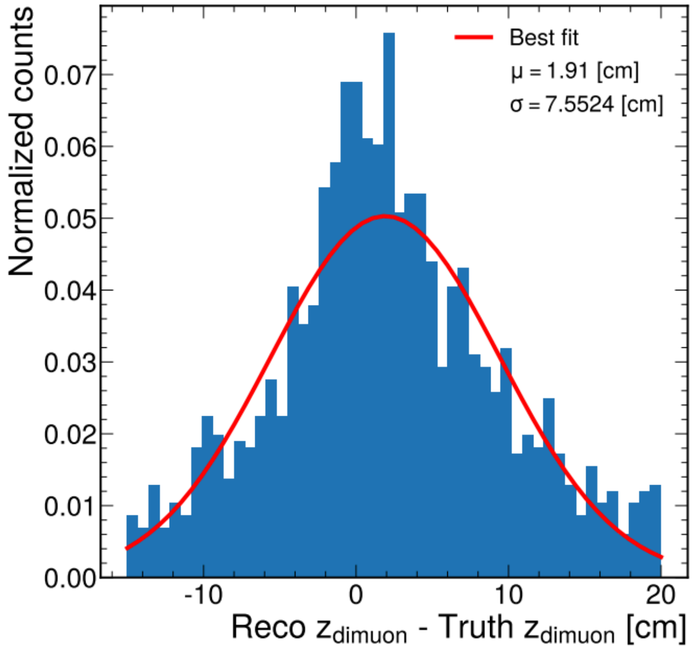


- For the dark photons decaying after the FMag, the leptons are less affected by the multiple scatterings in FMag. Better resolutions compared with prompt signals:

Tracking and Vertexing

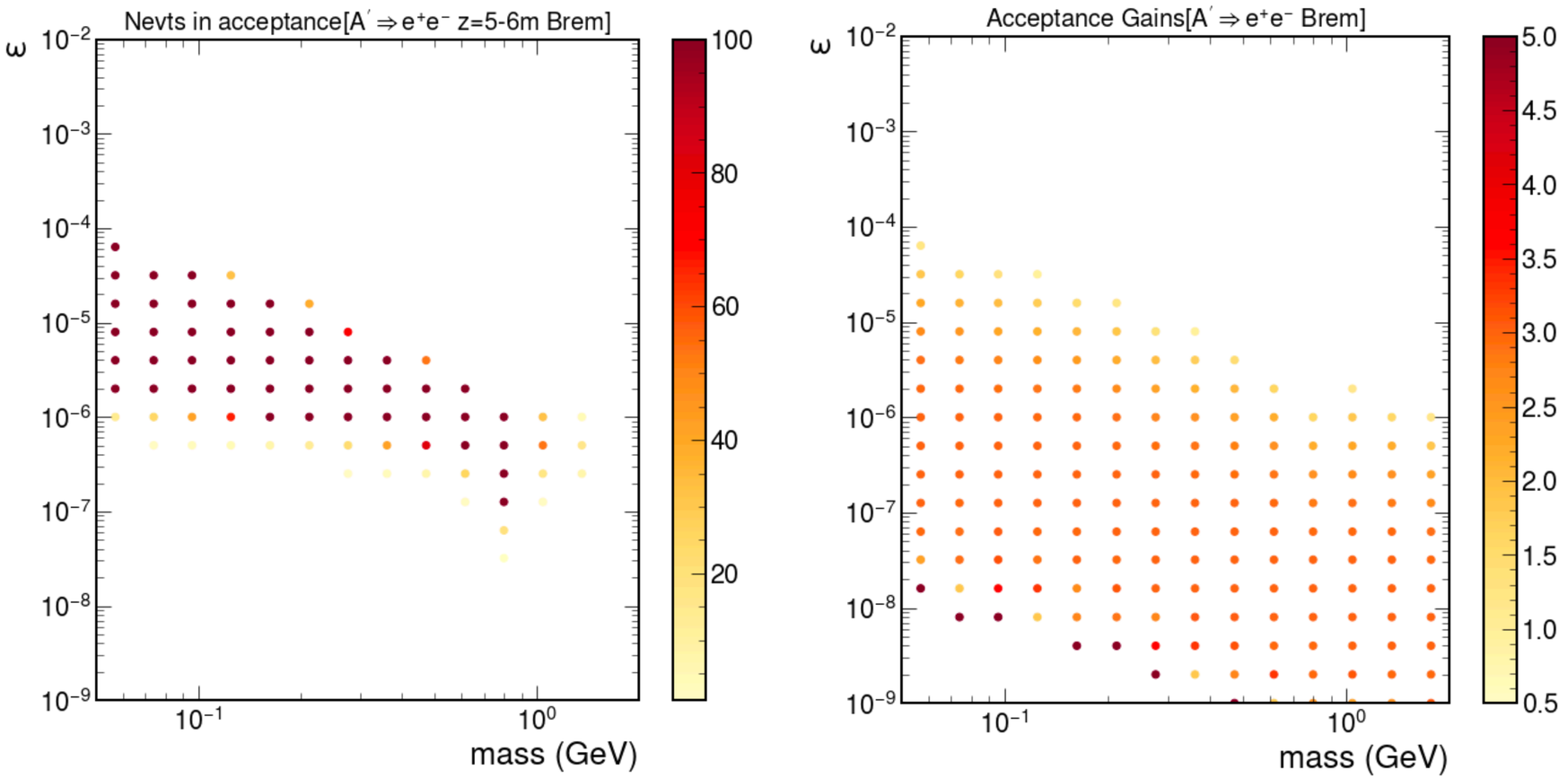






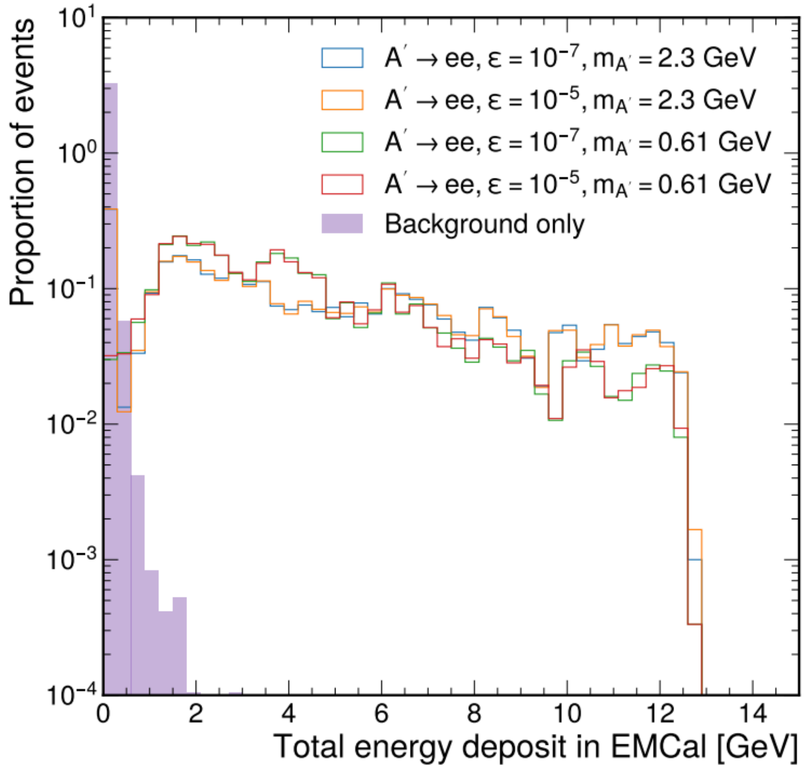
- Less affected by the multi scatterings in FMag. Better resolutions compared with prompt signals:
  - 75% track reconstruction efficiency for high momentum particles;
  - 5% mass resolution,
  - 5-10 cm Z resolution for dark photons decaying after FMag
- Working on improving the track and vertex reconstructions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

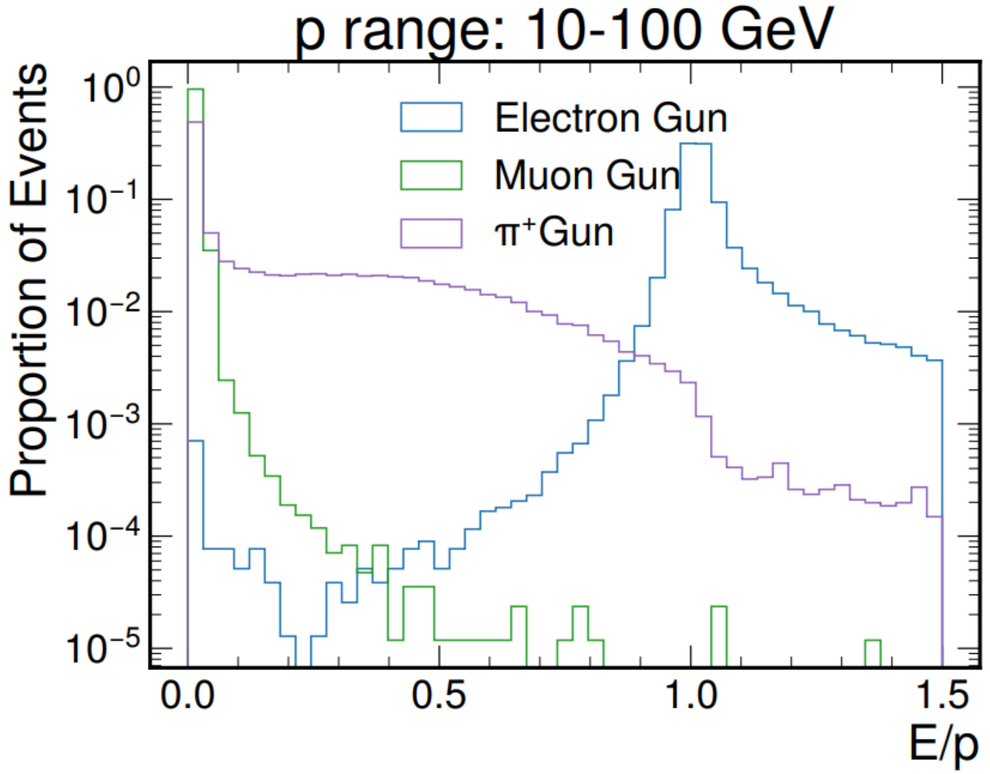
Tracking and Vertexing



- Additional tracking layers can increase the acceptance dramatically in certain phase spaces
- Improvements on the tracking and vertexing resolutions 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:

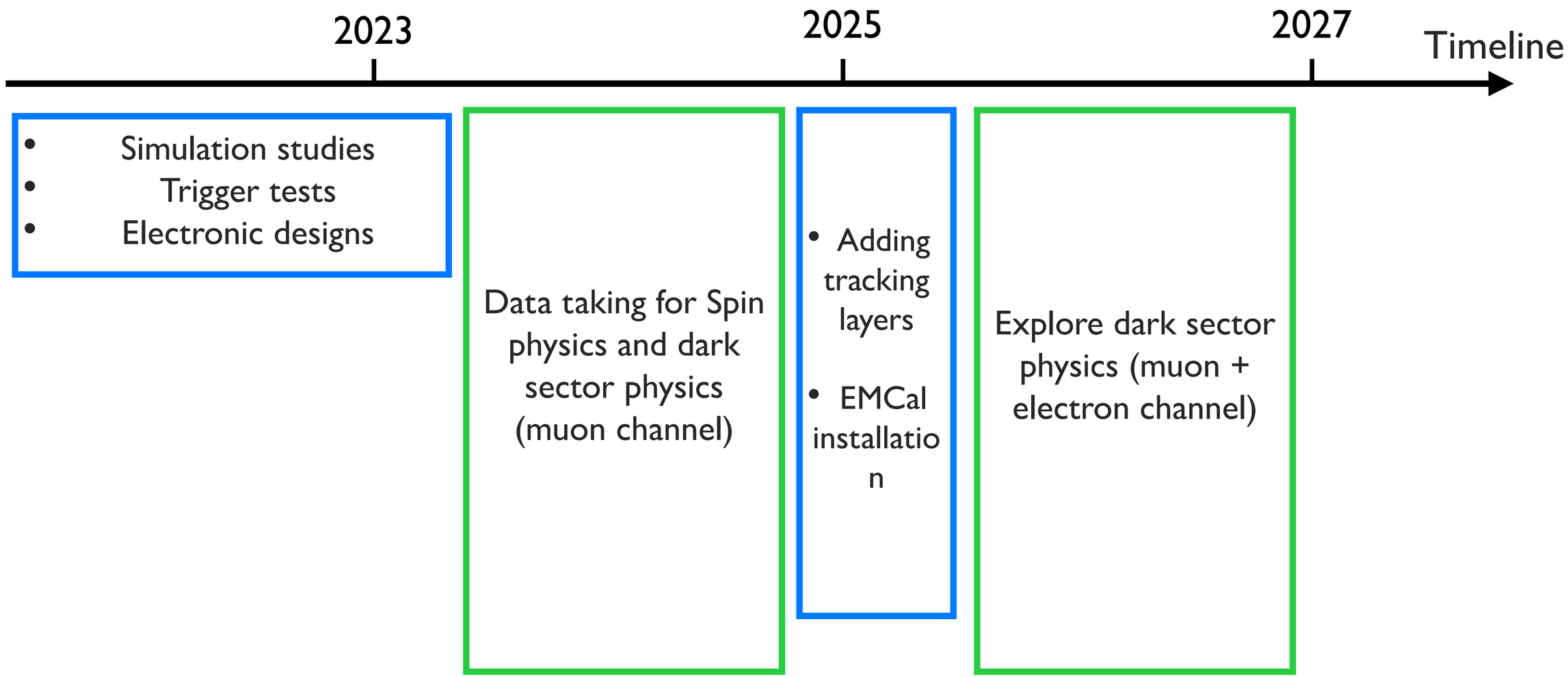
- One Snowmass paper: https://arxiv.org/pdf/2203.08322.pdf
- Strong connections with the current SpinQuest collaboration
- Ready to analyze the muon channel once the proton beam comes in!
- Welcome to join the effort! Contact us if interested! (yfeng@fnal.gov ntran@fnal.gov)

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

Aram Apyan[1], Brian Batell[2], Asher Berlin[3], Nikita Blinov[4], Caspian Chaharom[5], Sergio Cuadra[6], Zeynep Demiragli[5], Adam Duran[7], Yongbin Feng[3], I.P. Fernando[8], Stefania Gori[9], Philip Harris[6], Duc Hoang[6], Dustin Keller[8], Elizabeth Kowalczyk[10], Monica Leys[2], Kun Liu[11], Ming Liu[11], Wolfgang Lorenzon[12], Petar Maksimovic[13], Cristina Mantilla Suarez[3], Hrachya Marukyan[14], Amitav Mitra[13], Yoshiyuki Miyachi[15], Patrick McCormack[6], Eric A. Moreno[6], Yasser Corrales Morales[11], Noah Paladino[6], Mudit Rai[2], Sebastian Rotella[6], Luke Saunders[5], Shinaya Sawada[21], Carli Smith[17], David Sperka[5], Rick Tesarek[3], Nhan Tran[3], Yu-Dai Tsai[18], Zijie Wan[5], and Margaret Wynne[12]

[1]Brandeis University, Waltham, MA 02453, USA
[2]University of Pittsburgh, Pittsburgh, PA 15260, USA
[3]Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[4]University of Victoria, Victoria, BC V8P 5C2, Canada
[5]Boston University, Boston, MA 02215, USA
[6]Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[7]San Francisco State University, San Francisco, CA 94132, USA
[8]University of Virginia, Charlottesville, VA 22904, USA
[9]University of California Santa Cruz, Santa Cruz, CA 95064, USA
[10]Michigan State University, East Lansing, Michigan 48824, USA
[11]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[12]University of Michigan, Ann Arbor, MI 48109, USA
[13]Johns Hopkins University, Baltimore, MD 21218, USA
[14]Yamagata University, Yamagata, 990-8560, Japan
[15]KEK Tsukuba, Tsukuba, Ibaraki 305-0801 Japan
[16]Yerevan Physics Institute, Yerevan, 0036, Republic of Armenia
[17]Penn State University, State College, PA 16801, USA
[18]University of California Irvine, Irvine, CA 92697, USA

Proposed Timeline

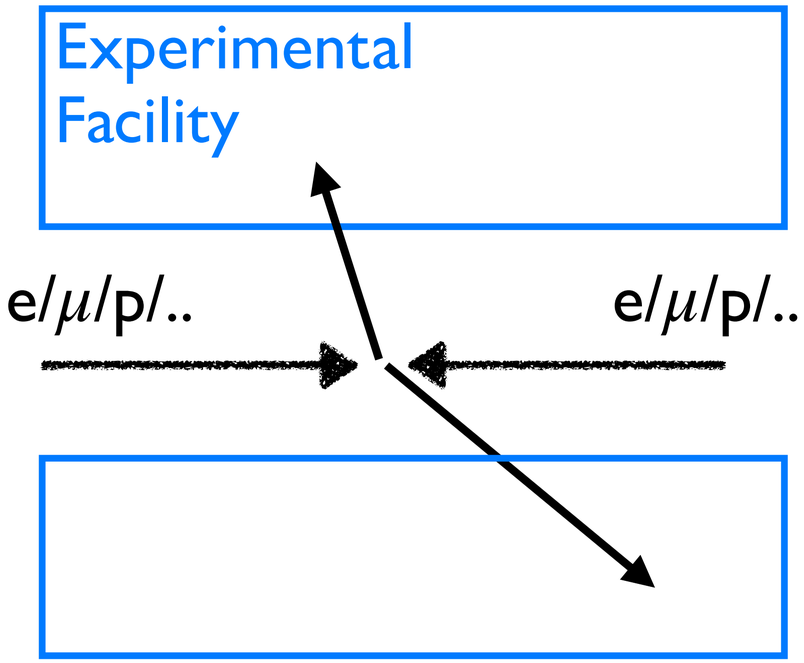


Summary

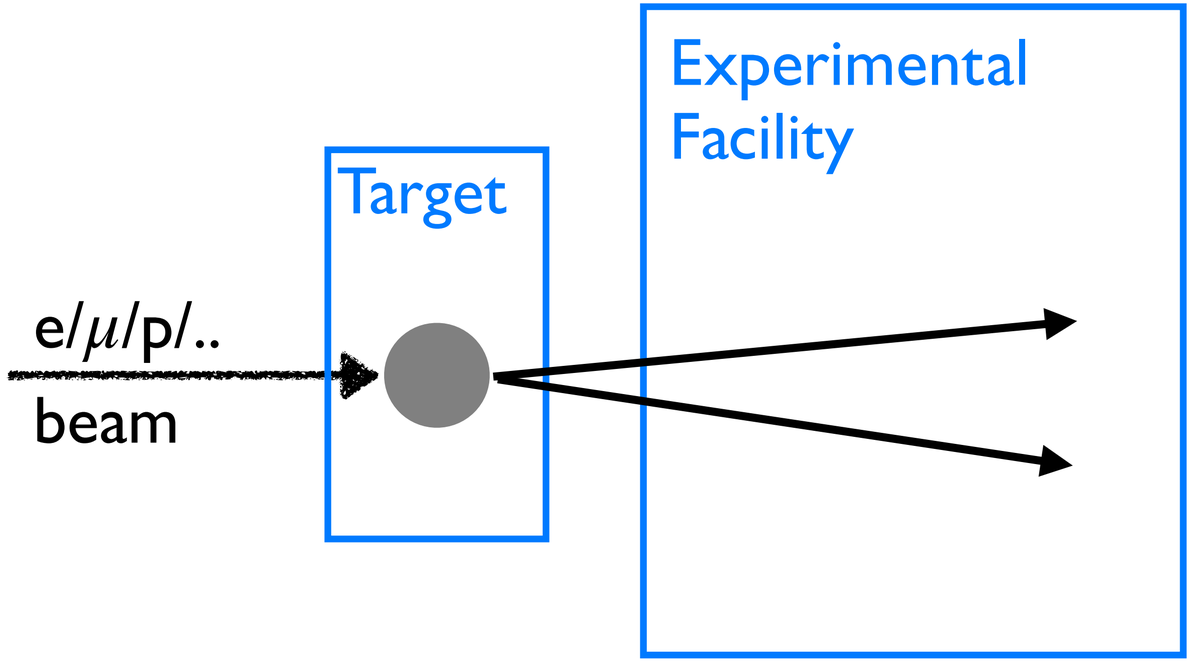
- Dark sector and light dark matter is an important yet not constrained region to explore
- DarkQuest offers a low-cost and near-term opportunity to uncover a broad range of MeV-GeV dark sectors
- Proposed timeline: dark sector exploration starting from this year, together with the Spin physics runs
- A lot of electronics design, simulation, and reconstruction studies ongoing

Back Up

Collider vs Fixed-target Experiments

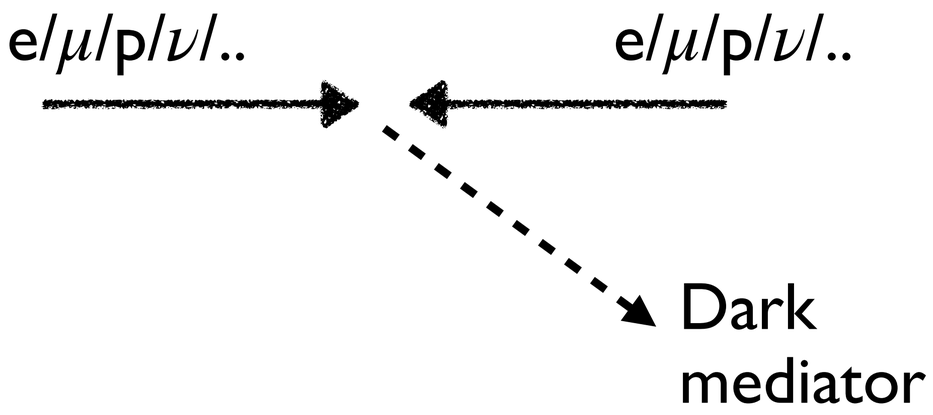


- Higher energy

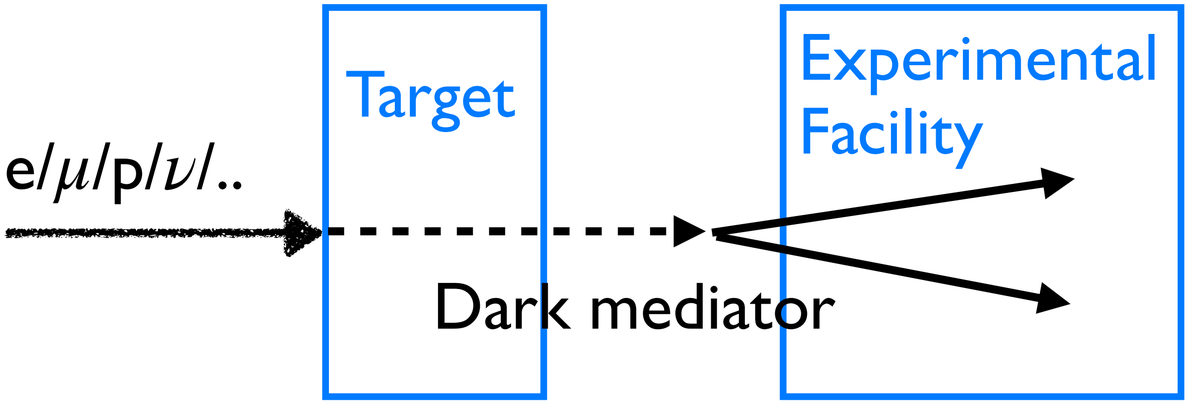


- Higher intensity

Probe Dark Sector with Accelerators

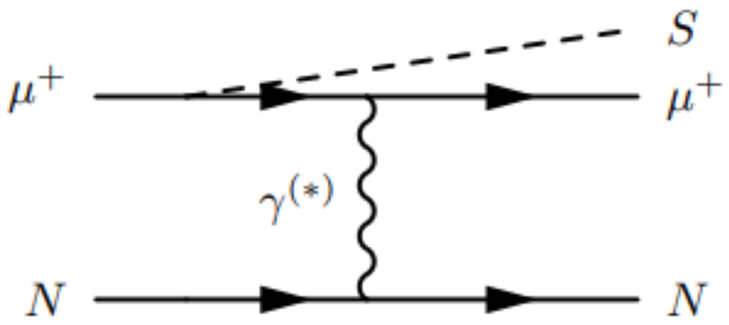


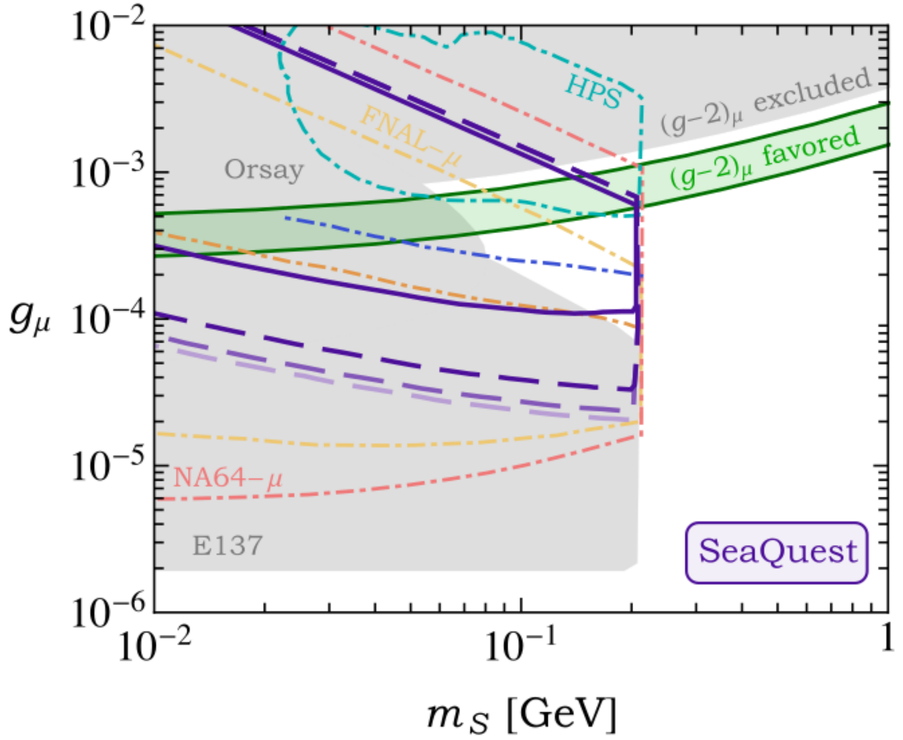
- Look for final states with bumps/ displaced signals/missing E/p/m
  - ATLAS/CMS/LHCb, Belle, BES?



- 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

Why DarkQuest: Connection with (g-2) Anomaly

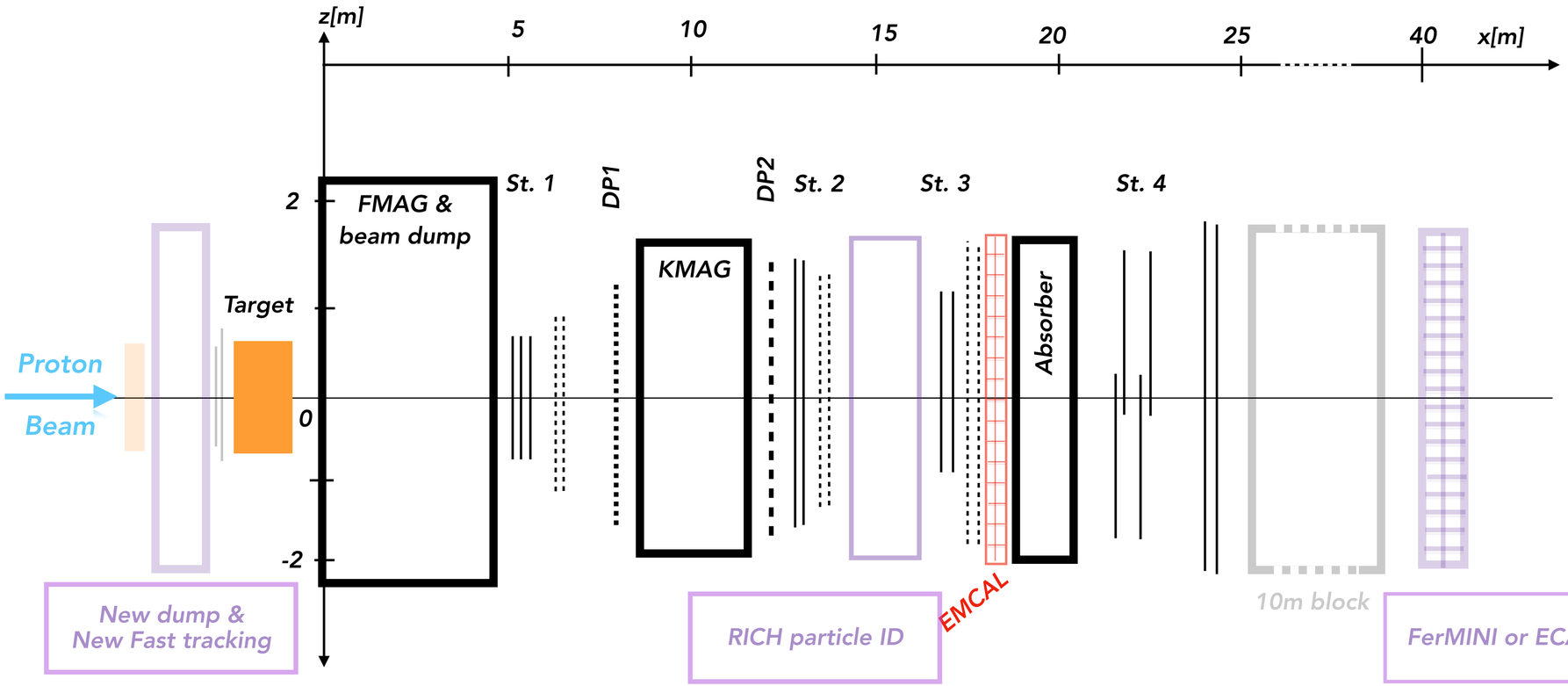


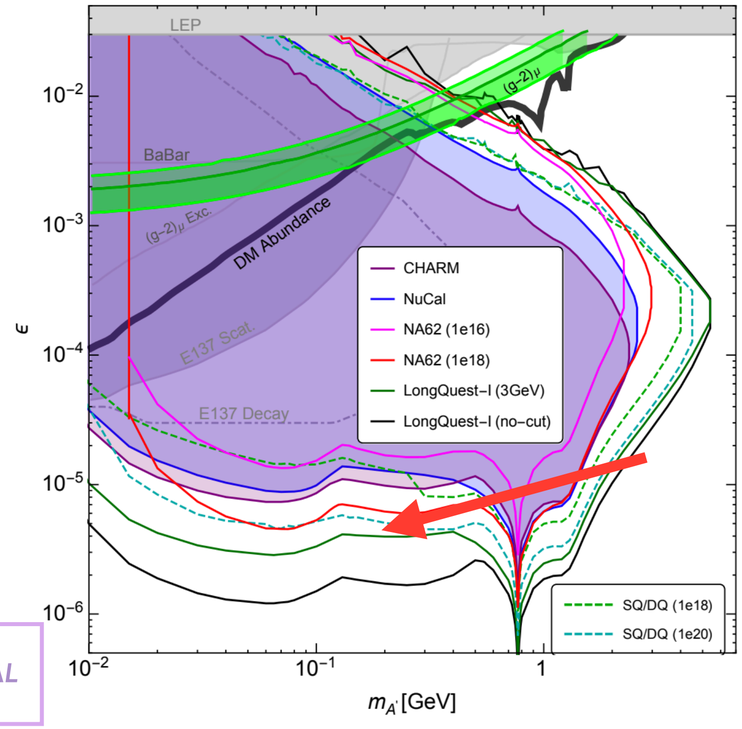


A.Berlin, S.Gori, P.Schuster, N.Toro Arxiv:1804.00661

- 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