DarkQuest - Uncovering the Dark Sector with a Proton Beam Dump Spectrometer

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for the DarkQuest Collaboration

PPC 2021, Norman, Oklahoma, USA

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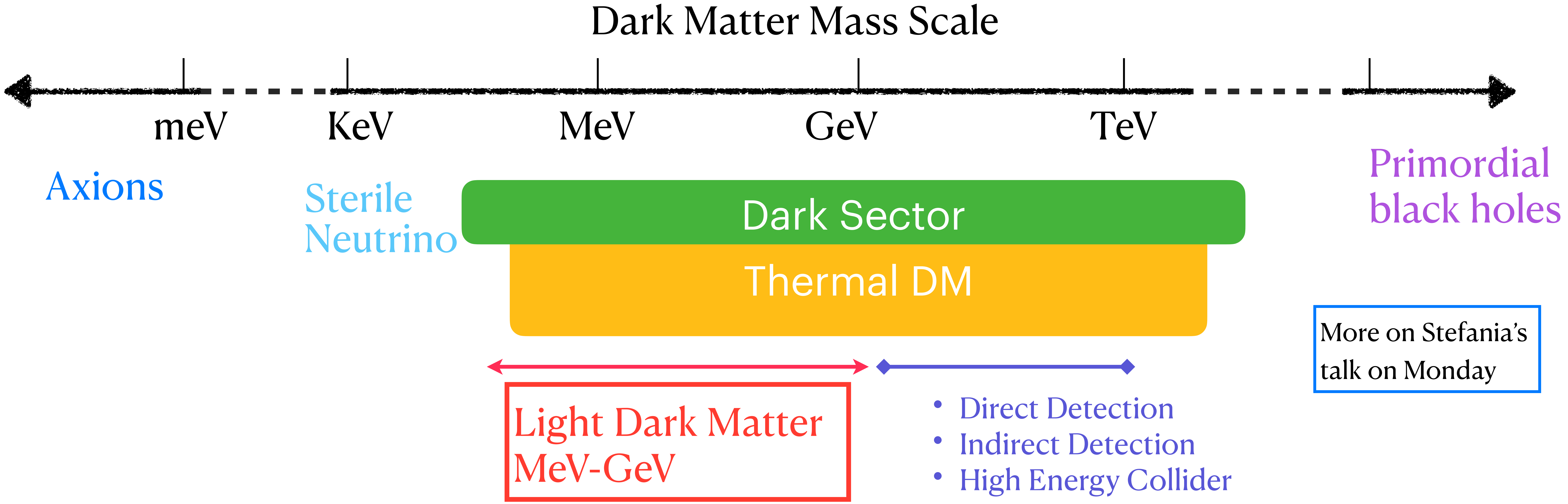
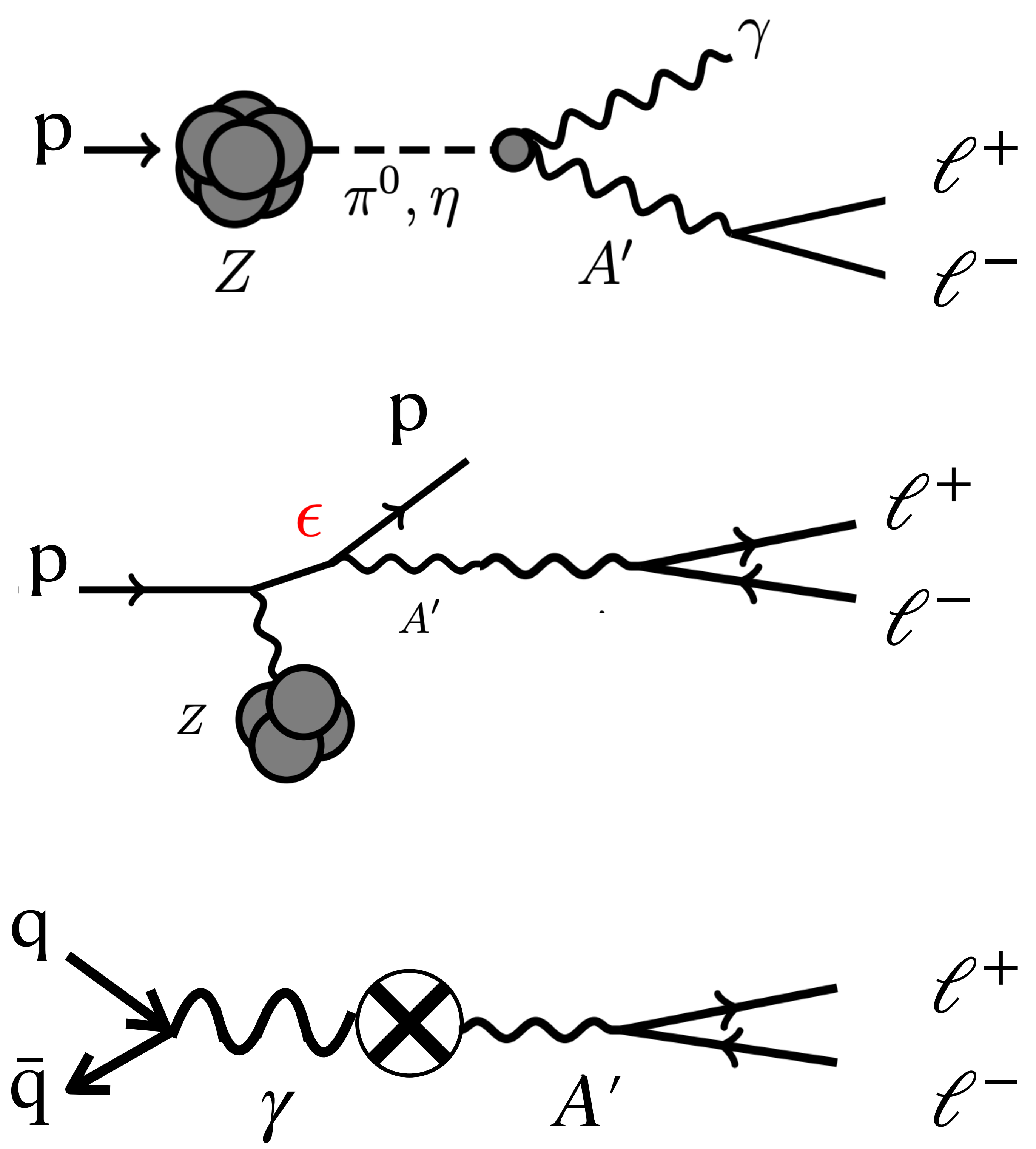
Physics Motivation

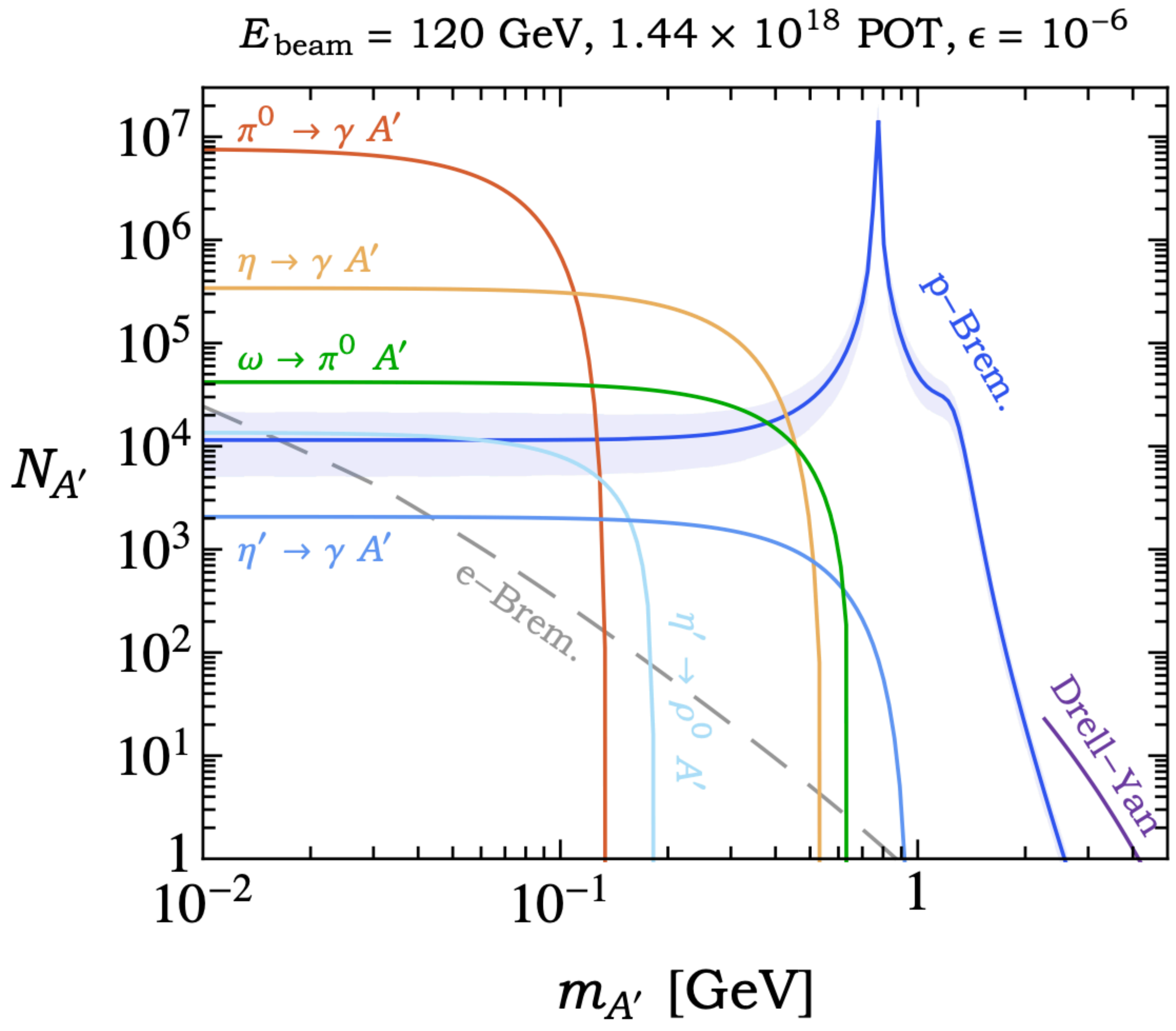


More on Stefania's talk on Monday

- Dark Sectors provide the DM candidates, and can also address many other open problems in particle physics (baryogenesis, strong CP problem, neutrino masses, hierarchy problem, etc)
- High-intensity accelerators and fixed-target experiments provide an ideal environment to probe dark sector physics in MeV-GeV range

Signal Processes: Dark Photon Example

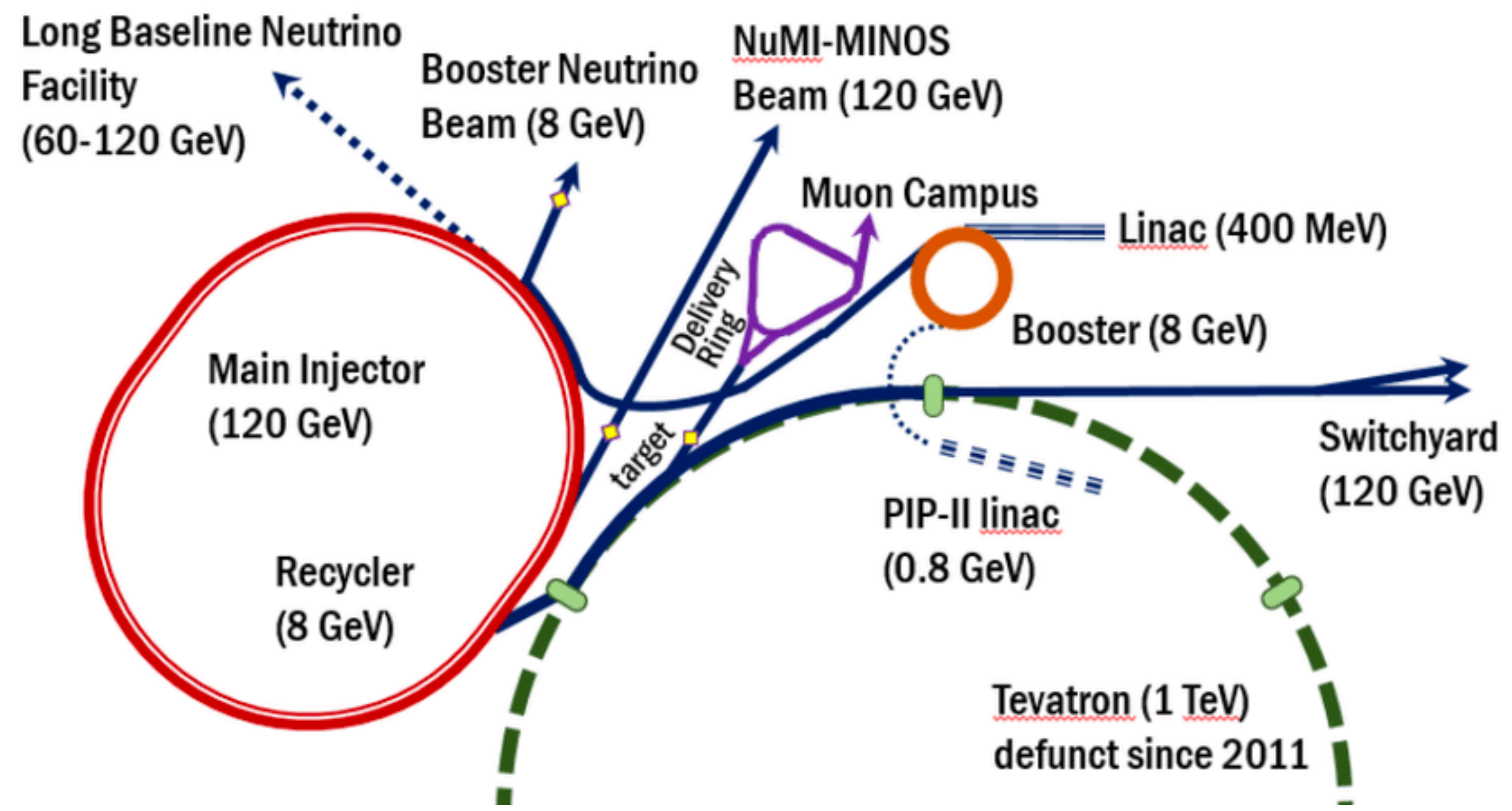




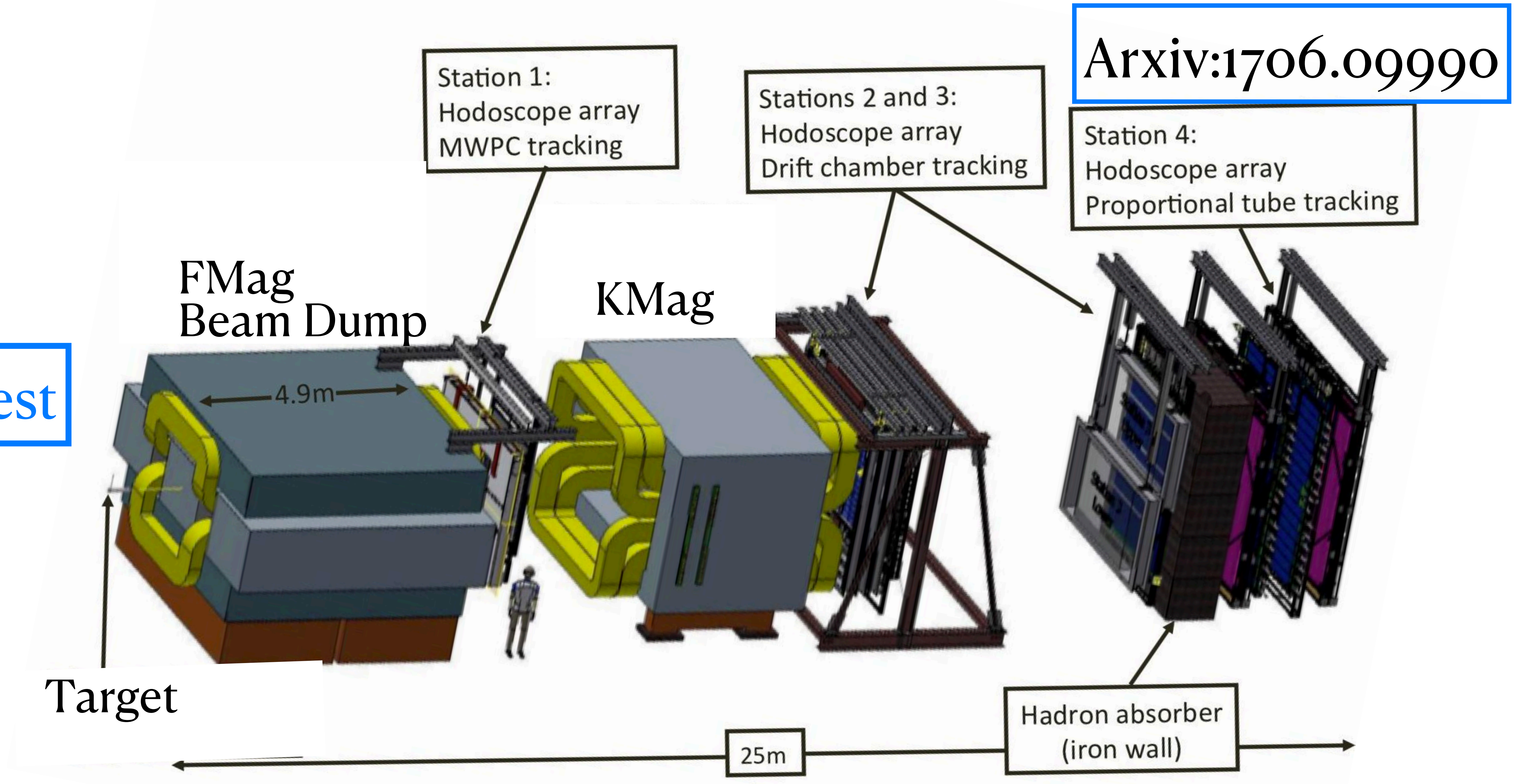
A.Berlin, S.Gori, P.Schuster, N.Toro Arxiv:1804.00661

- Three dominant signal production mechanisms for proton fixed-target beam dump experiment: meson decay, proton bremsstrahlung, and Drell-Yan process
- Larger production rates with proton beams compared with electron beams

Experimental Setup: SpinQuest

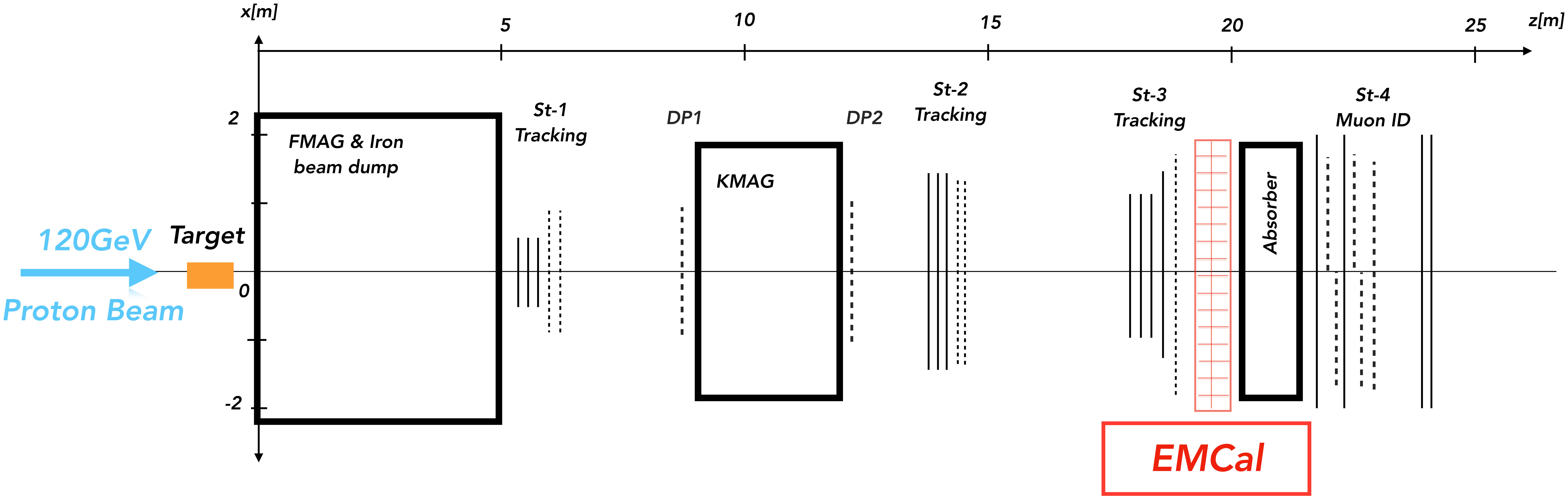


SpinQuest



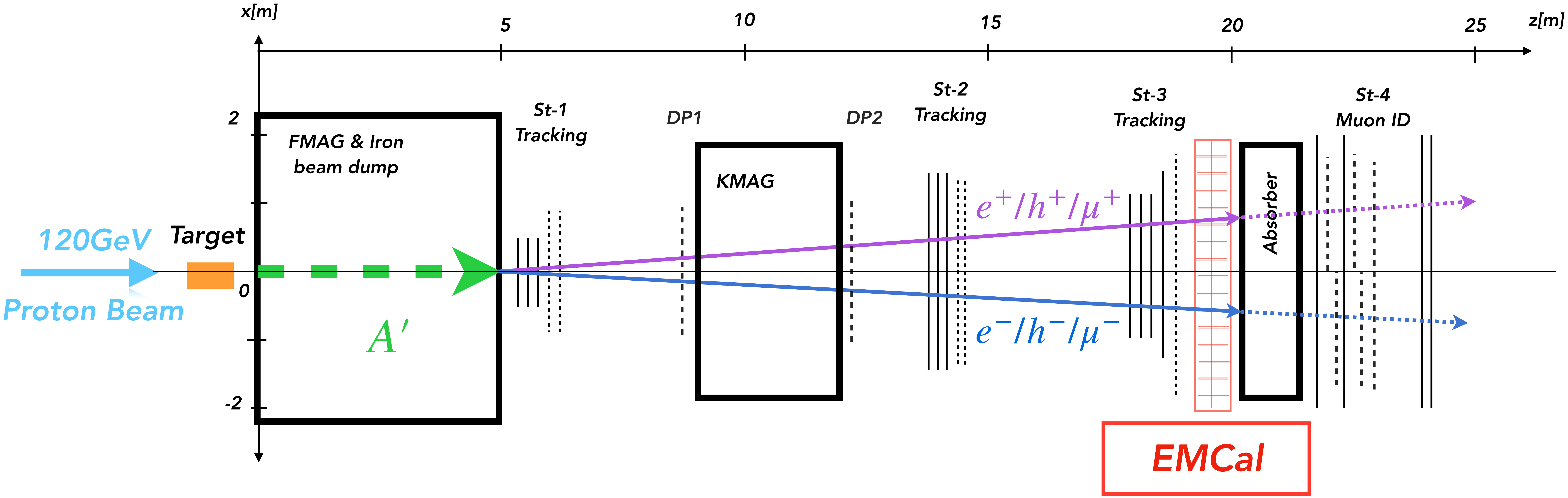
- 120 GeV high-intensity proton beam from the Fermilab Accelerator Complex
  - Expect 1e18 Protons on target (POT) in a 2-year parasitic run, and 1e20 POT after the upgrade
- SpinQuest spectrometer has 5m thick FMag as the beam dump and absorber, hollow KMag for tracking, and 4 stations of drift chambers (tracking) and scintillator hodoscopes (triggering)
  - Measuring the Drell-Yan process for studying the Transverse Momentum Dependent PDFs (TMDs) inside the proton

Experimental Setup: DarkQuest



- Make full use of the existing SpinQuest spectrometer
- Upgrade the spectrometer with one Electromagnetic calorimeter (EMCal) sector (from PHENIX Experiment, 2mx4m, to be installed to DarkQuest), which enables us access to electron and photon final states
  - Broaden the coverage to lower masses below $2m_\mu$
  - Provide more sensitivity by rejecting muon backgrounds

Experimental Setup: DarkQuest



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Why DarkQuest

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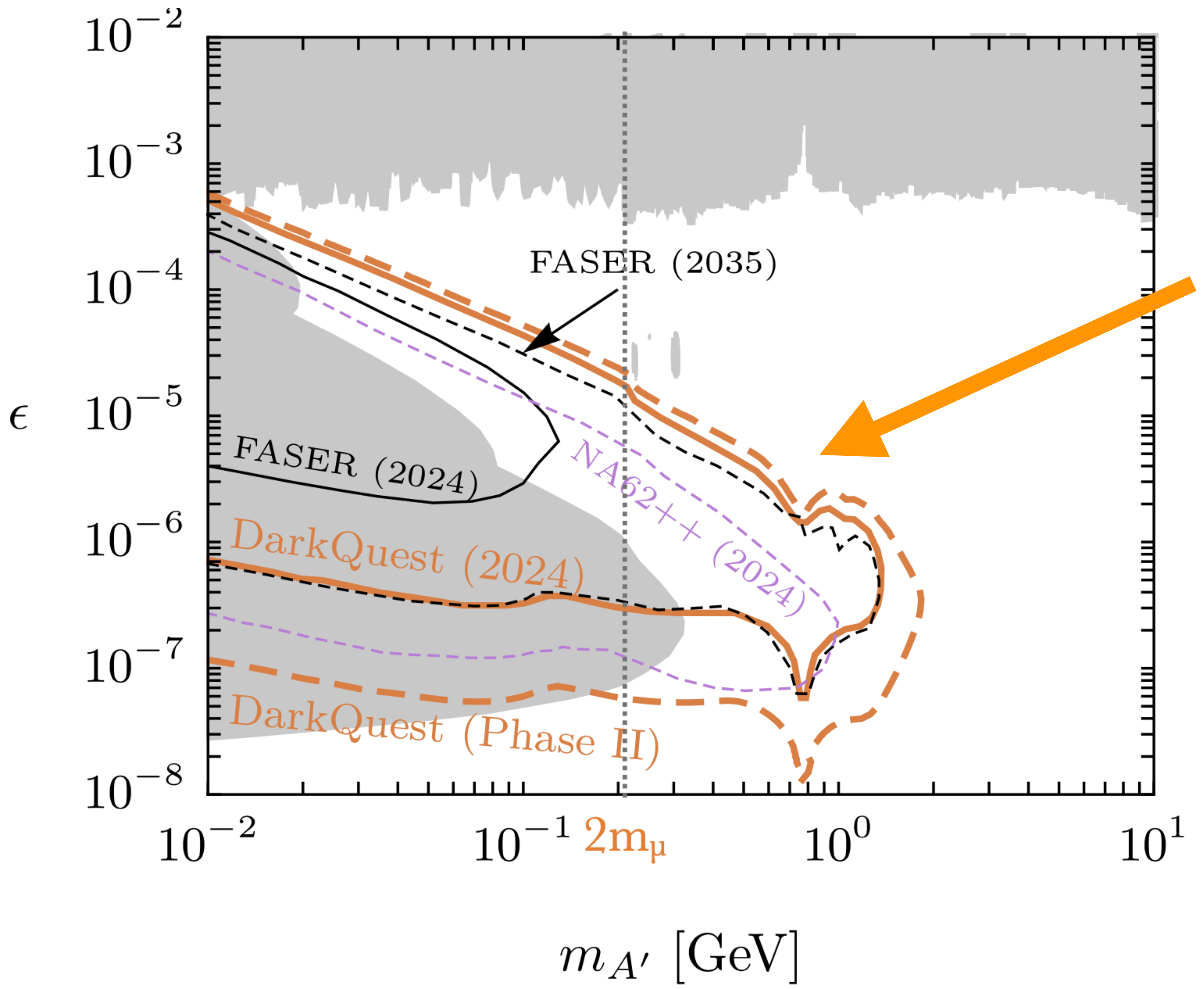
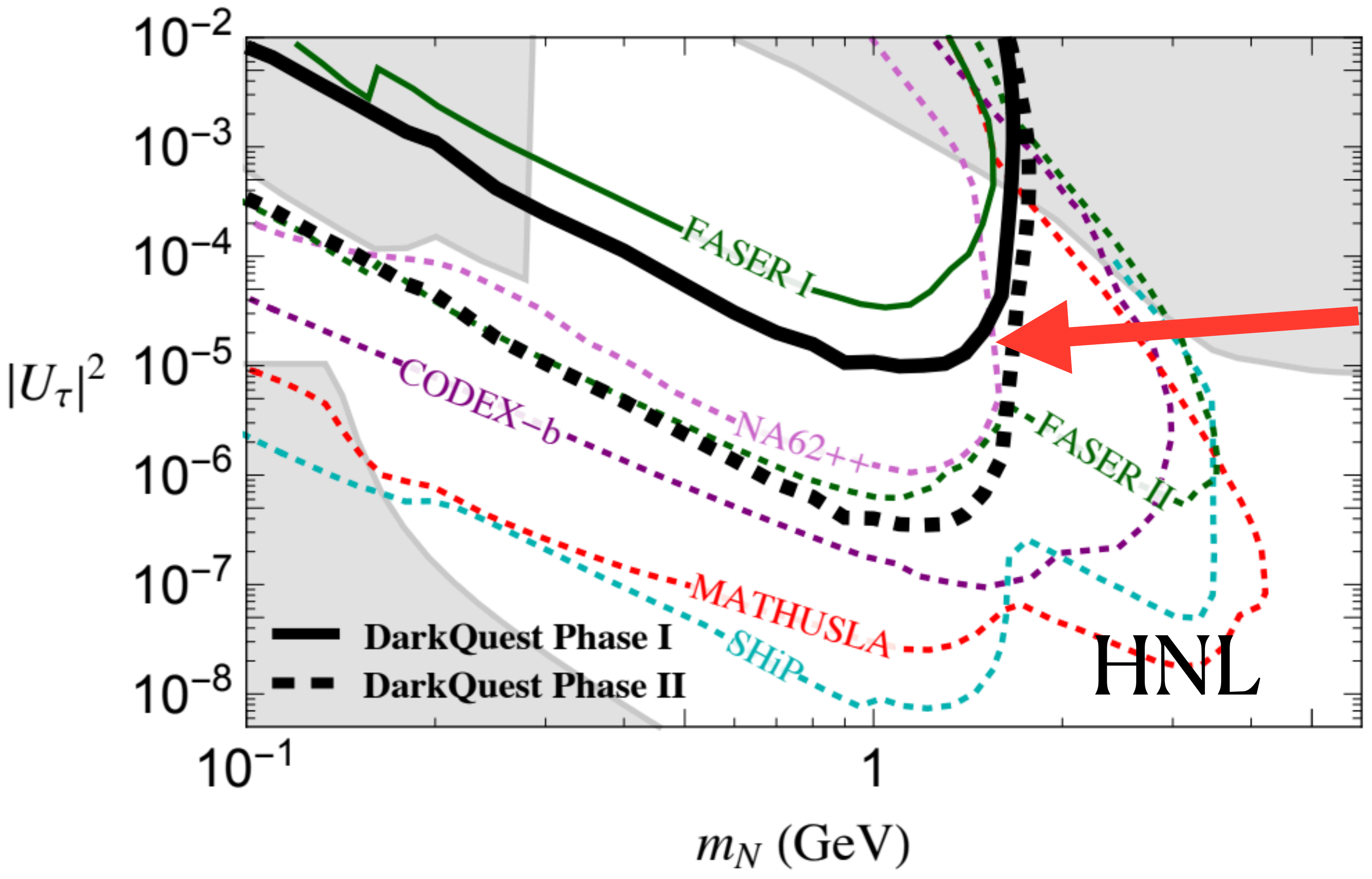
	E_{beam}	p_{min}	POT	z_{min}	z_{max}
DarkQuest	120 GeV	10 GeV	$10^{18} - 10^{20}$	5 m	10 m
NA62	400 GeV	-	10^{18}	100 m	250 m
SHiP	400 GeV	100 GeV	10^{20}	65 m	125 m
FASER	6500 GeV	1 TeV	$10^{16} - 10^{17}$	390 m	400 m

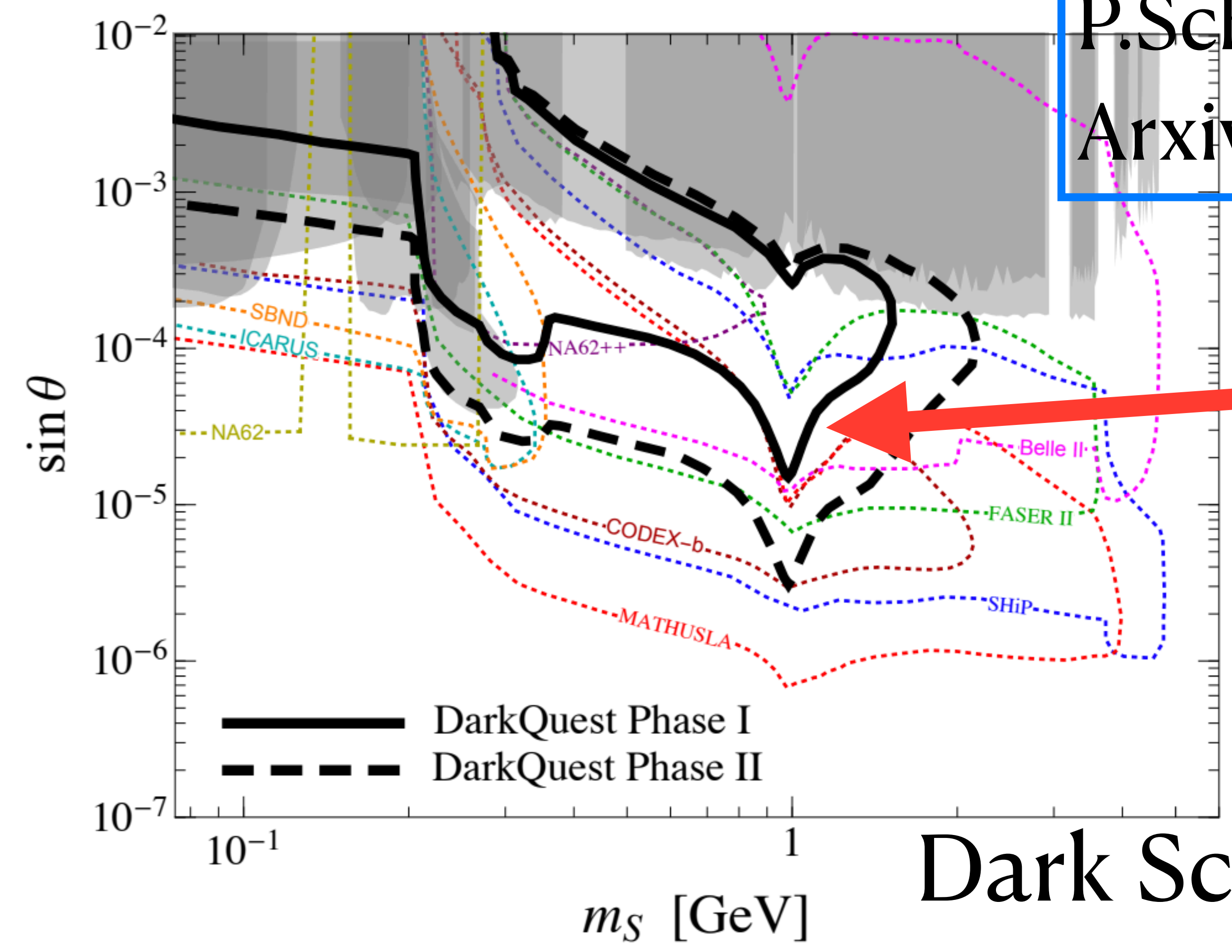


- Large dark sector production cross section with 120GeV high-intensity proton beam
- Compact geometry and relatively short displacement baseline (5-10m) to cover unique and broad phase space:
  - KMag and 3-4 tracking layers provide good momentum measurement
  - EMCal opens up new final states distinct from large muon backgrounds
- Most of the experimental components already exist, very low cost

Why DarkQuest: Broad Coverage

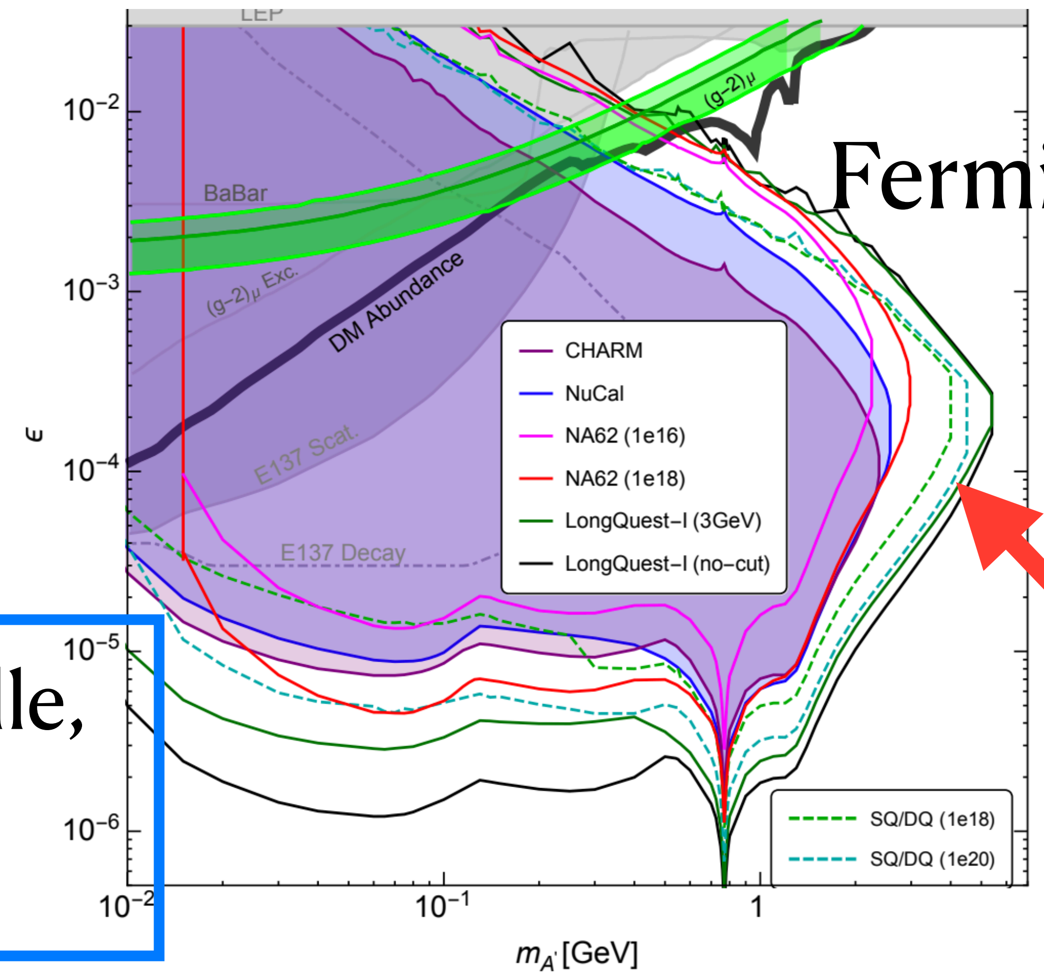
Signature	Model
e^+e^-	dark photon dark Higgs leptophilic scalar*
$e^+e^-e^+e^-$	Higgsed dark photon
$e^\pm\pi^\mp, e^\pm K^\mp, \cdots$	sterile neutrino
e^+e^- + MET	inelastic dark matter strongly interacting dark matter hidden valleys
$\pi^+\pi^-, K^+K^-, \cdots$	dark Higgs*
$\gamma\gamma$	axion-like particle*





Dark Scalar

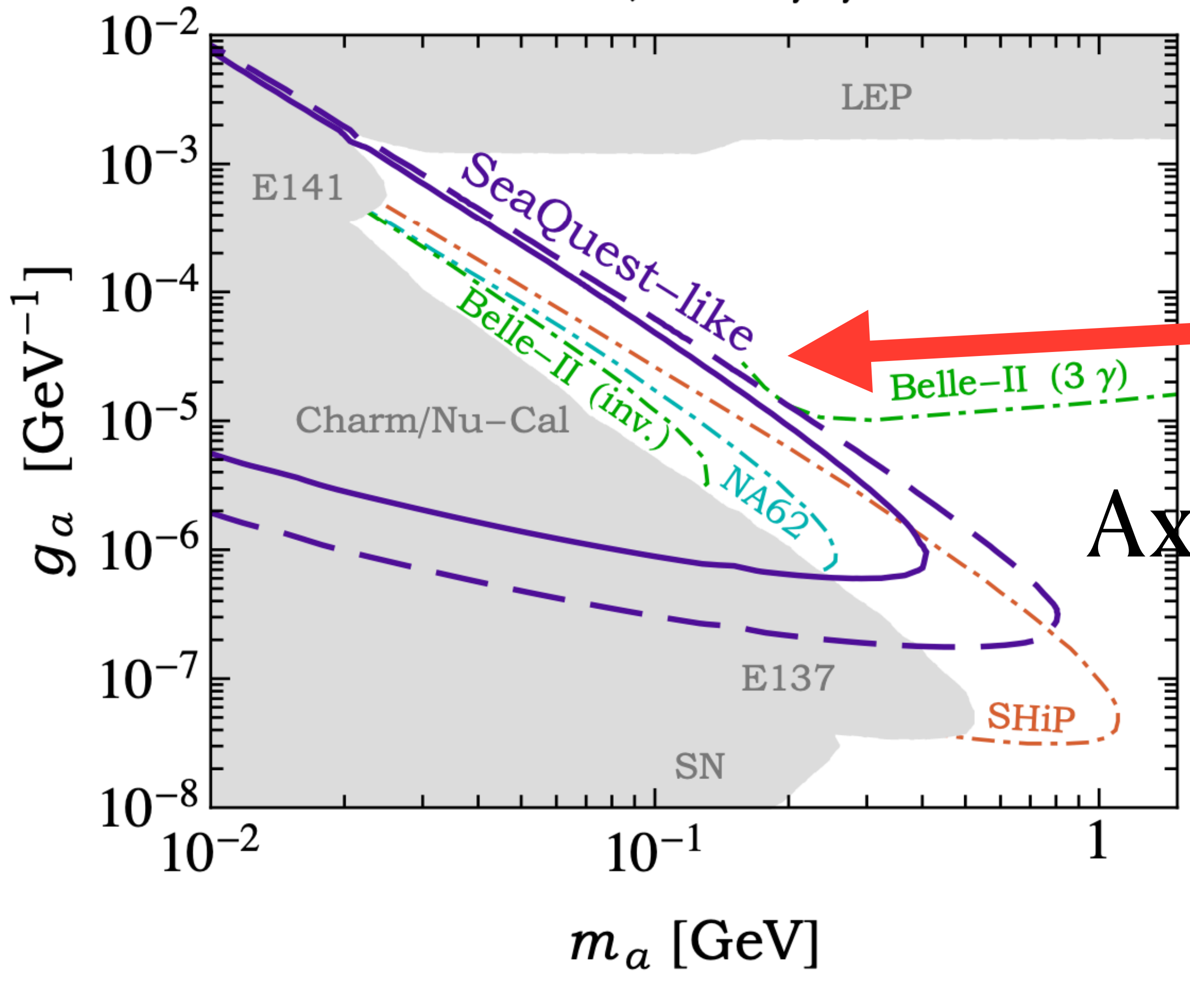
B. Batell, J. Evans, P.Schuster, M. Rai
Arxiv:2008.08108



Fermionic iDM

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

ALP, $a \to \gamma\,\gamma$



Axion-like particles

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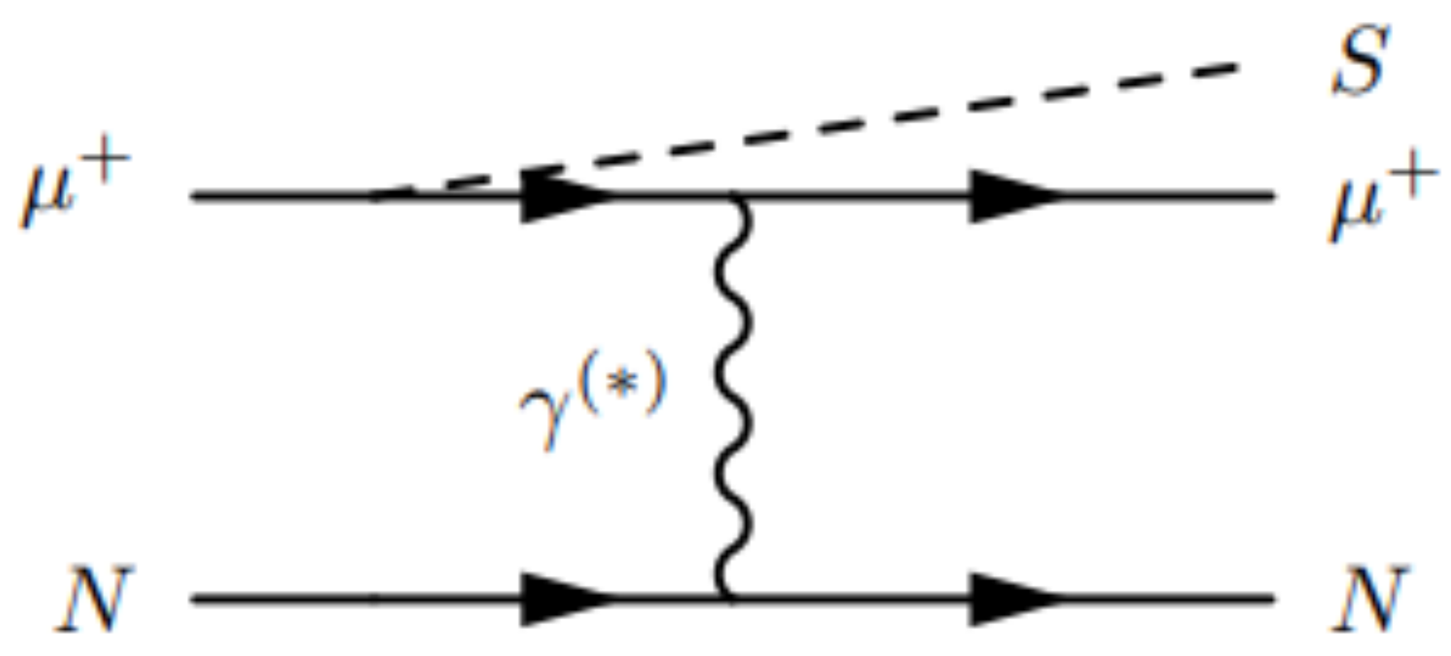
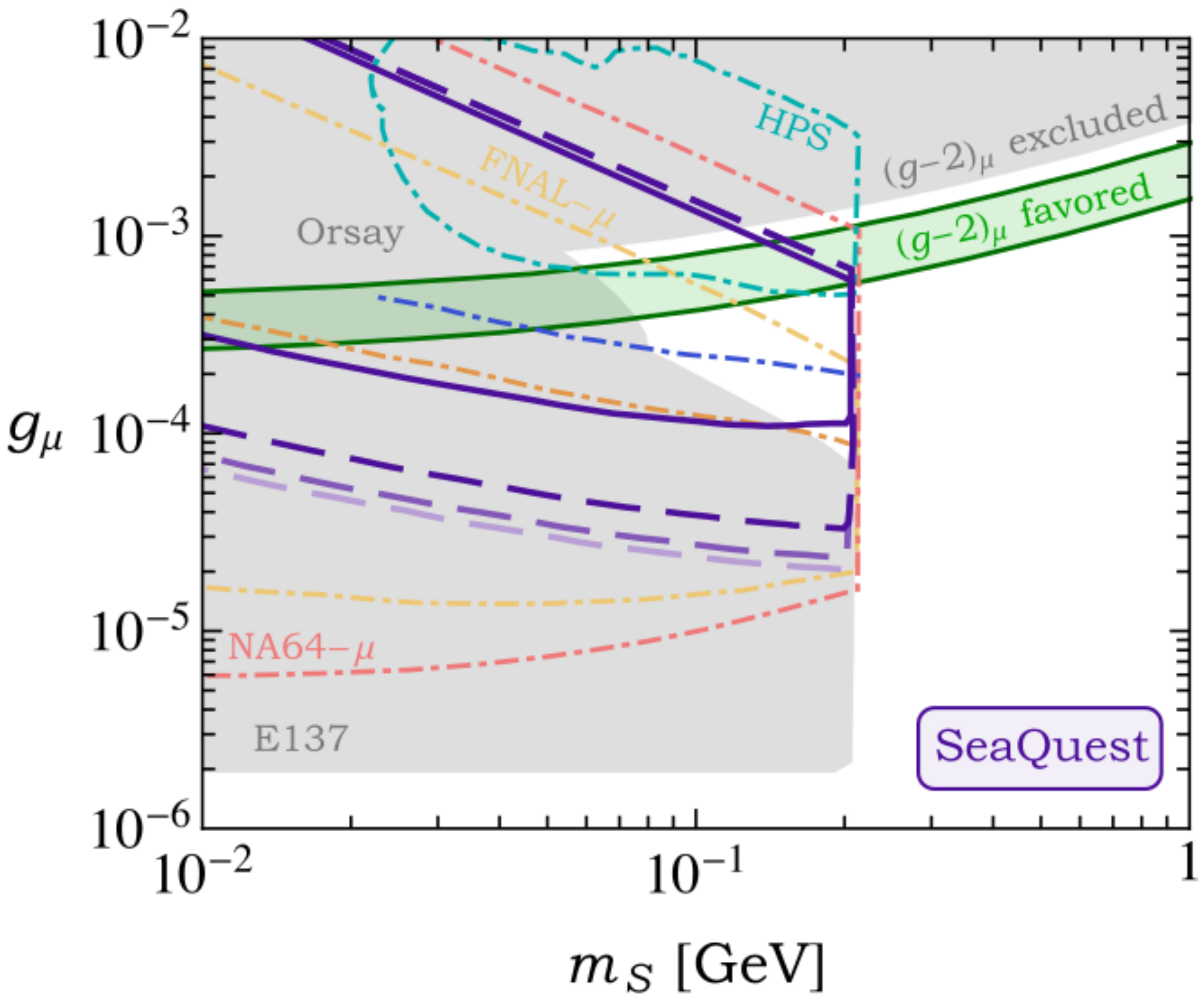
- 120 GeV High-intensity proton beam, compact geometry, and relatively short displacement baseline (5-10m) to cover unique and broad phase space

Why DarkQuest: Connection with (g-2) Anomaly



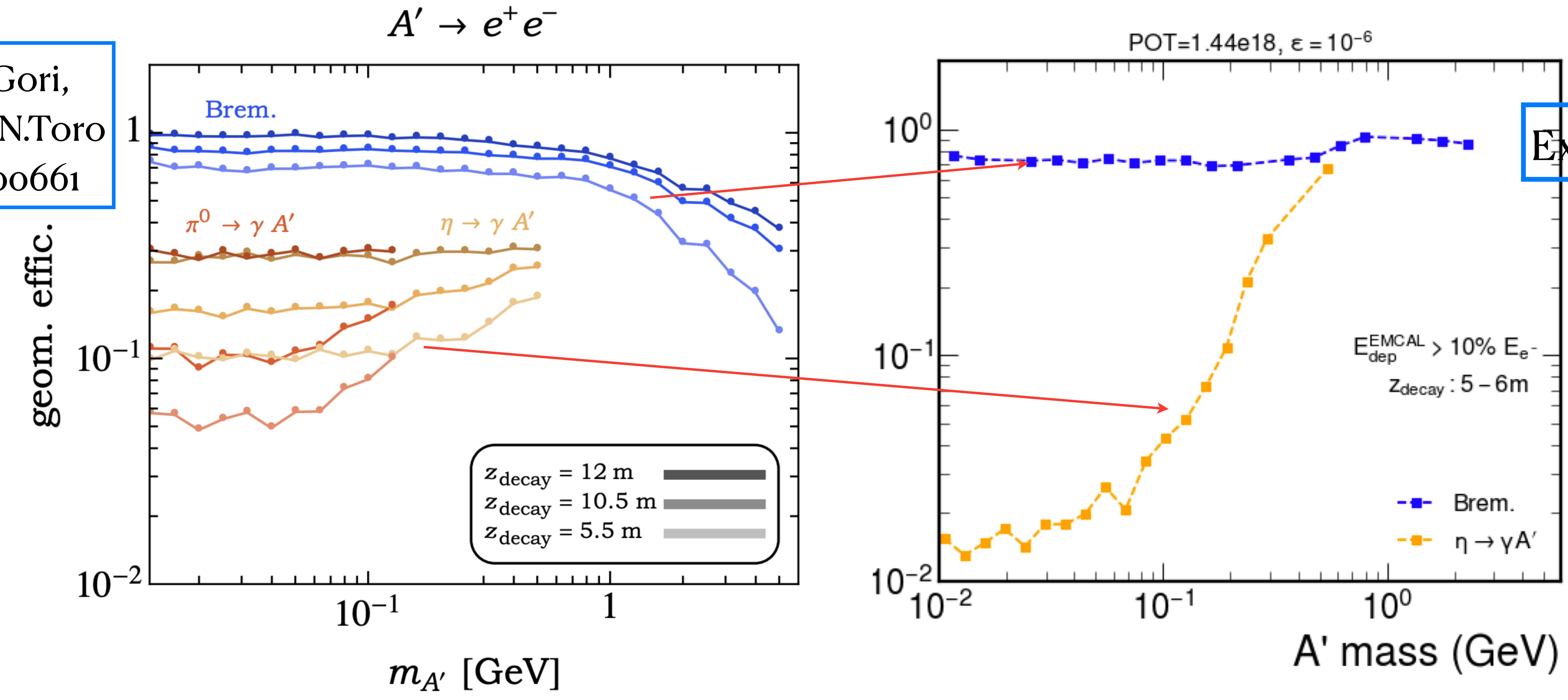


A.Berlin, S.Gori, P.Schuster, N.Toro Arxiv:1804.00661

- 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

Ongoing Studies: Signal Acceptance

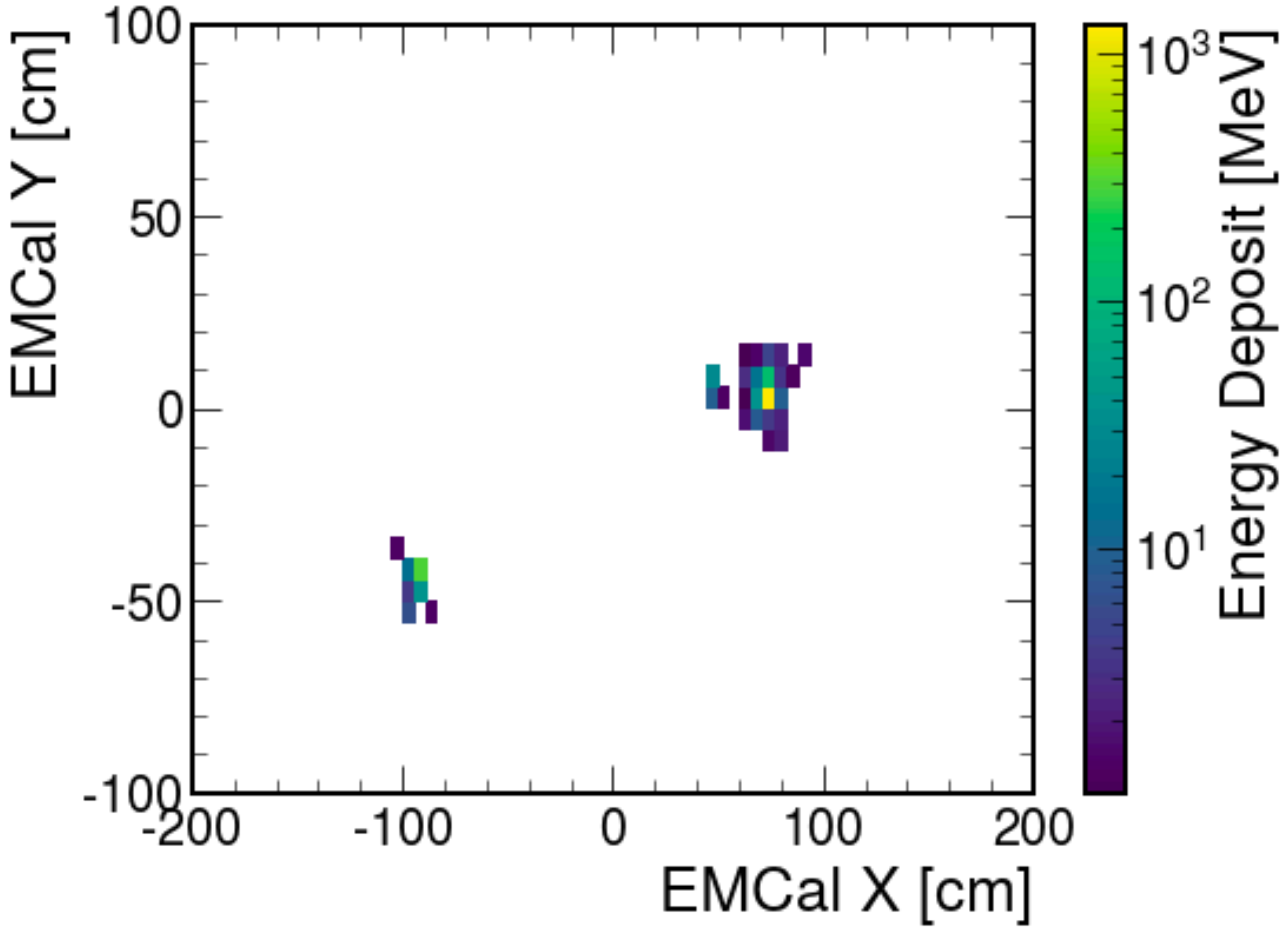
A.Berlin, S.Gori,
P.Schuster, N.Toro
Arxiv:1804.00661

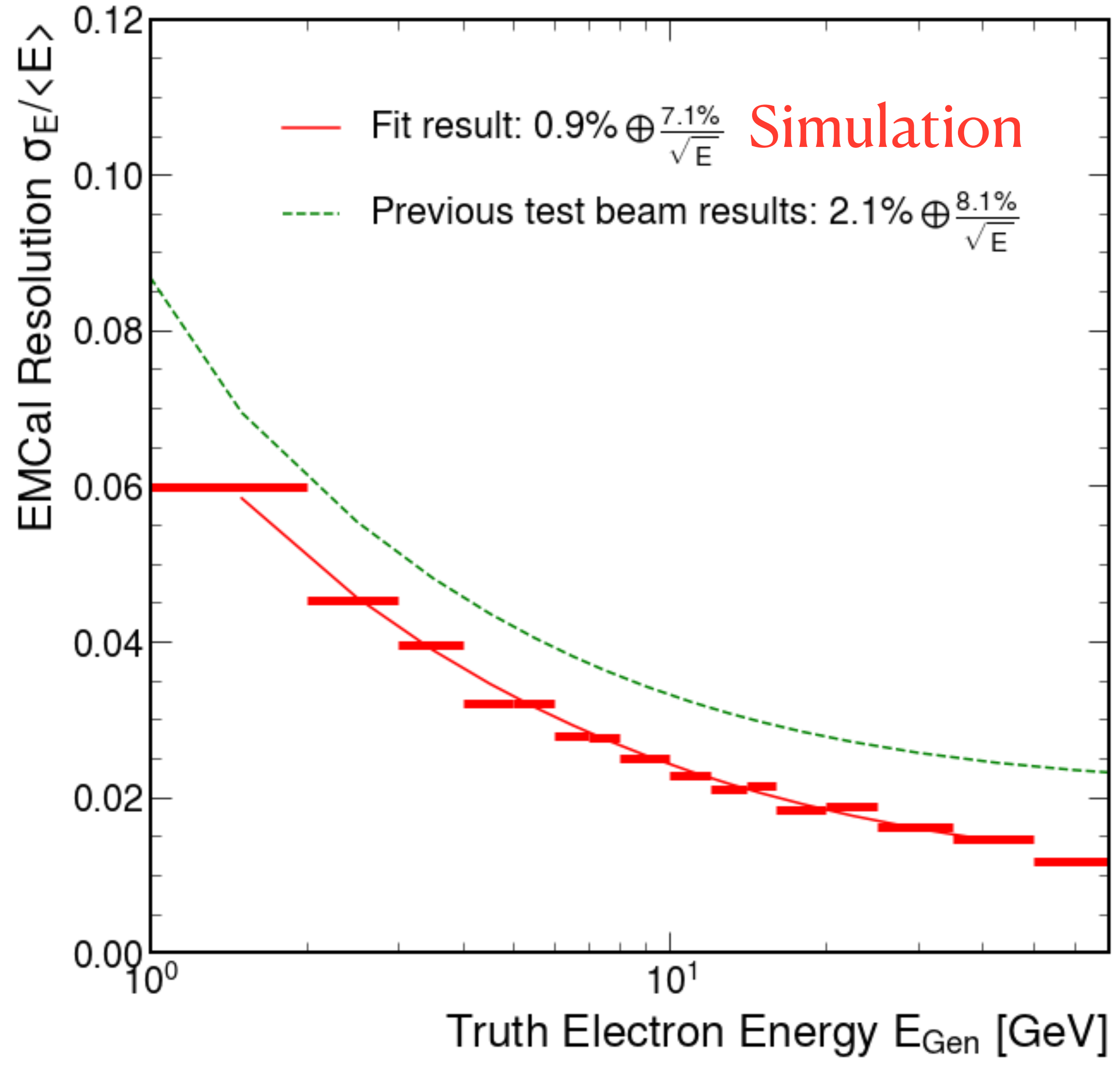


Experimental Simulation

- Adapt SpinQuest simulation framework to simulate the signal processes, and validate the acceptance with the phenomenological paper
- Work in progress to understand the acceptance differences

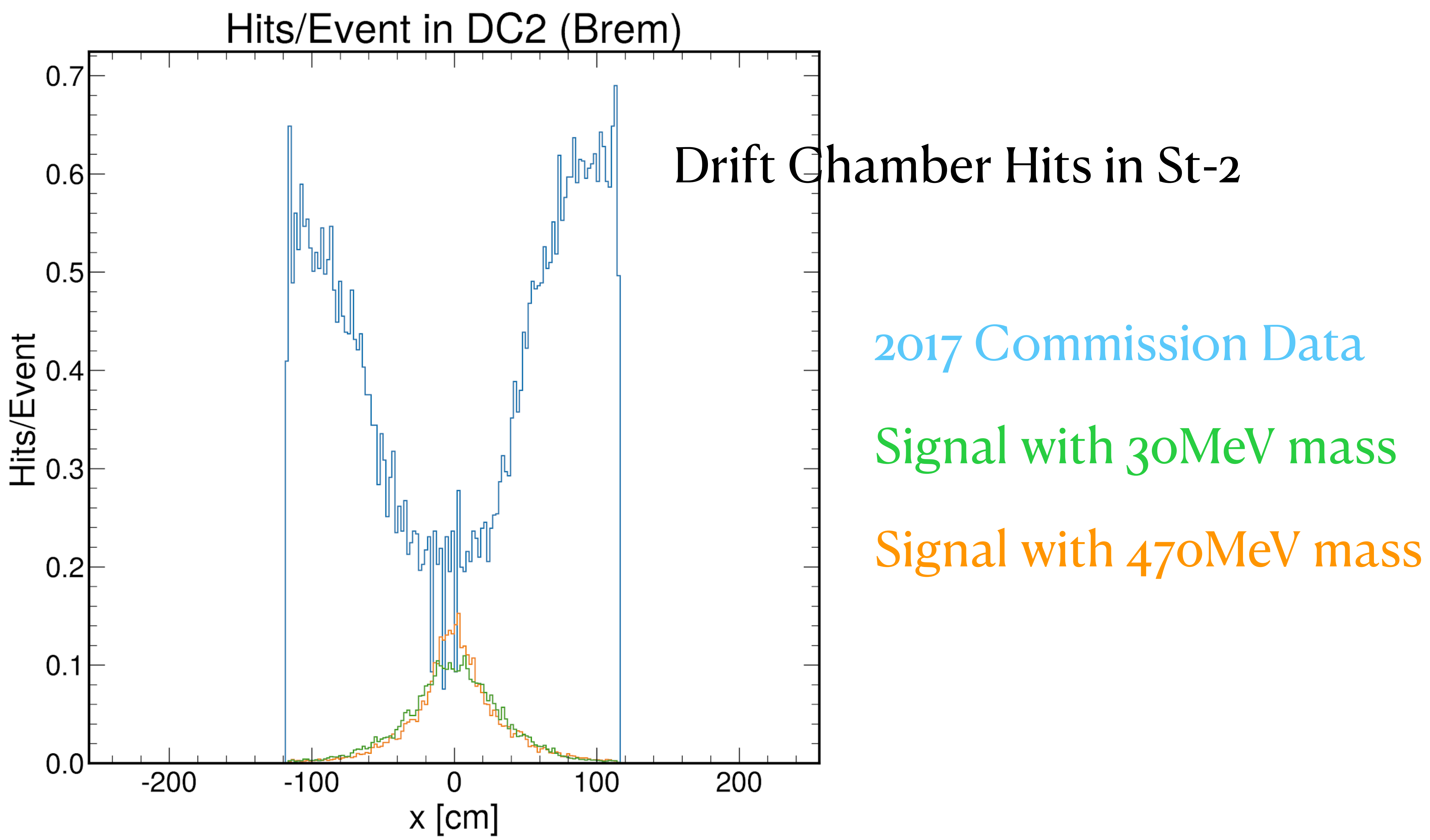
Ongoing Studies: EMCal Simulations





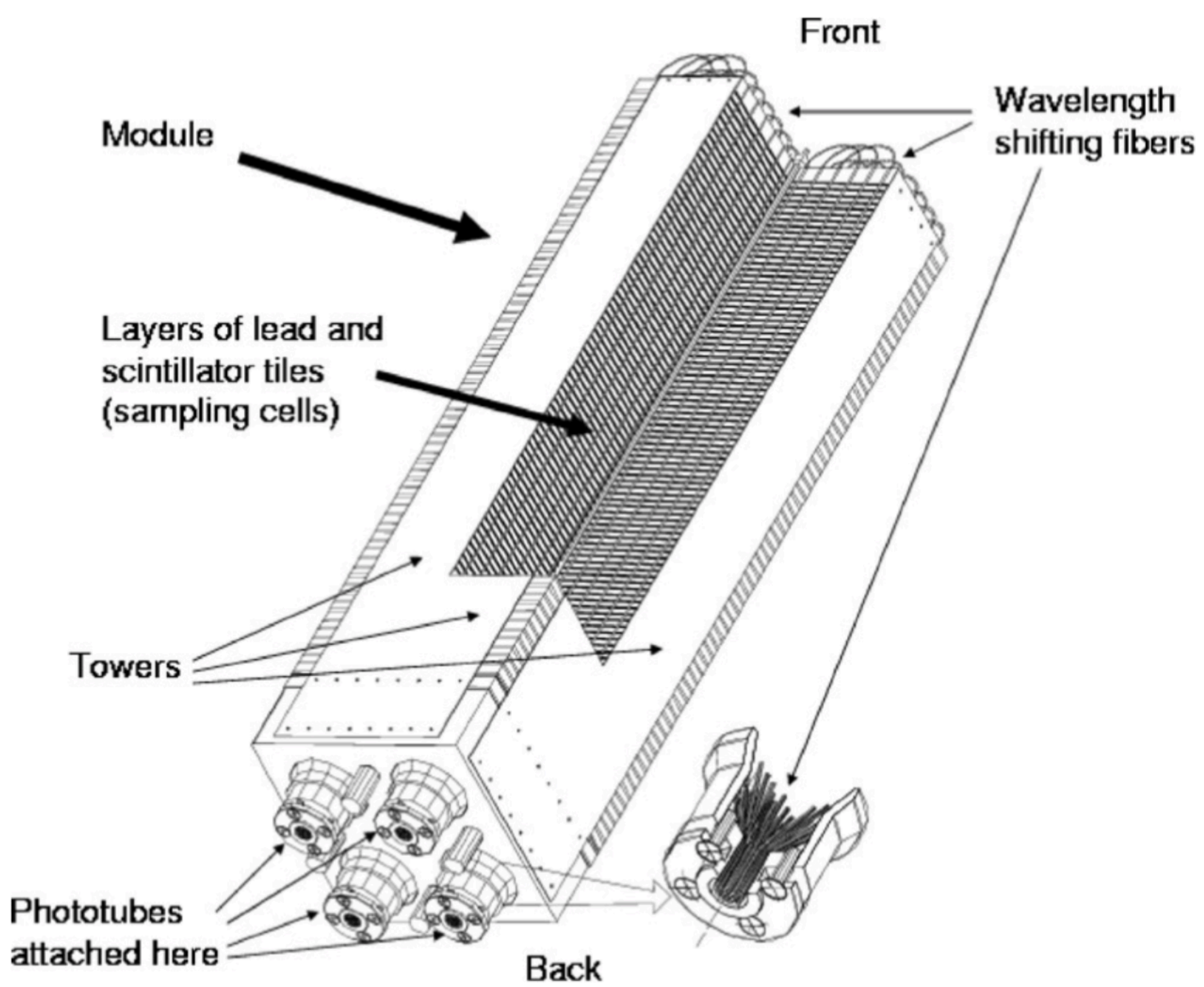
- Integrate the EMCal into the SpinQuest simulation framework; validate the performance and study the reconstructions
- Left plot is one example event display of two electron showers in the EMCal
- Right plot shows the agreement of the resolutions between the simulation (red) and the previous test beam results

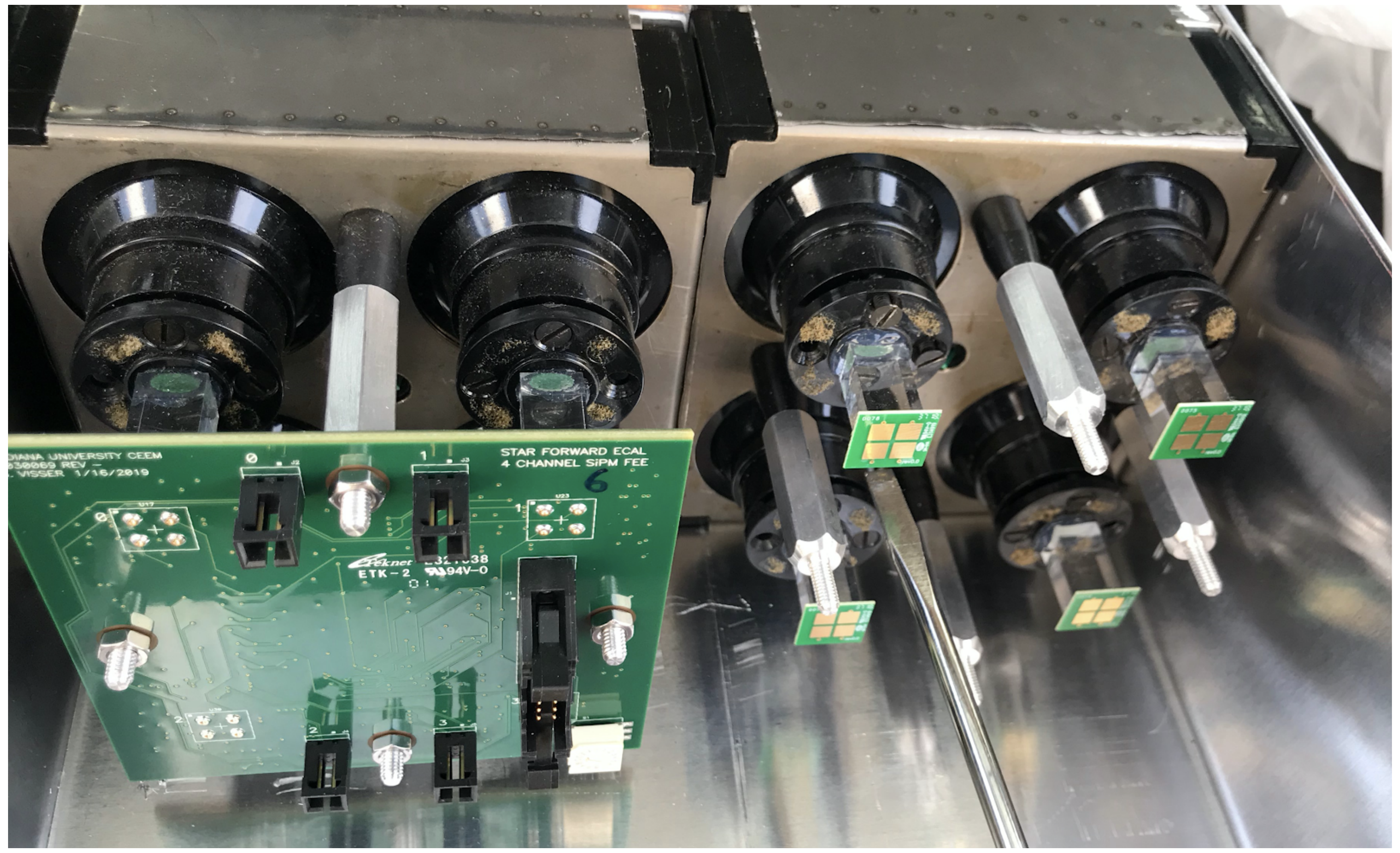
Ongoing Studies: Signal vs Background



- Compare the signal simulation with the 2017 data from SpinQuest regular runs (background for Dark Sector signals), to understand backgrounds in data and simulation
- Combining with other information (tracking, EMCal, etc) to define signal selection criteria

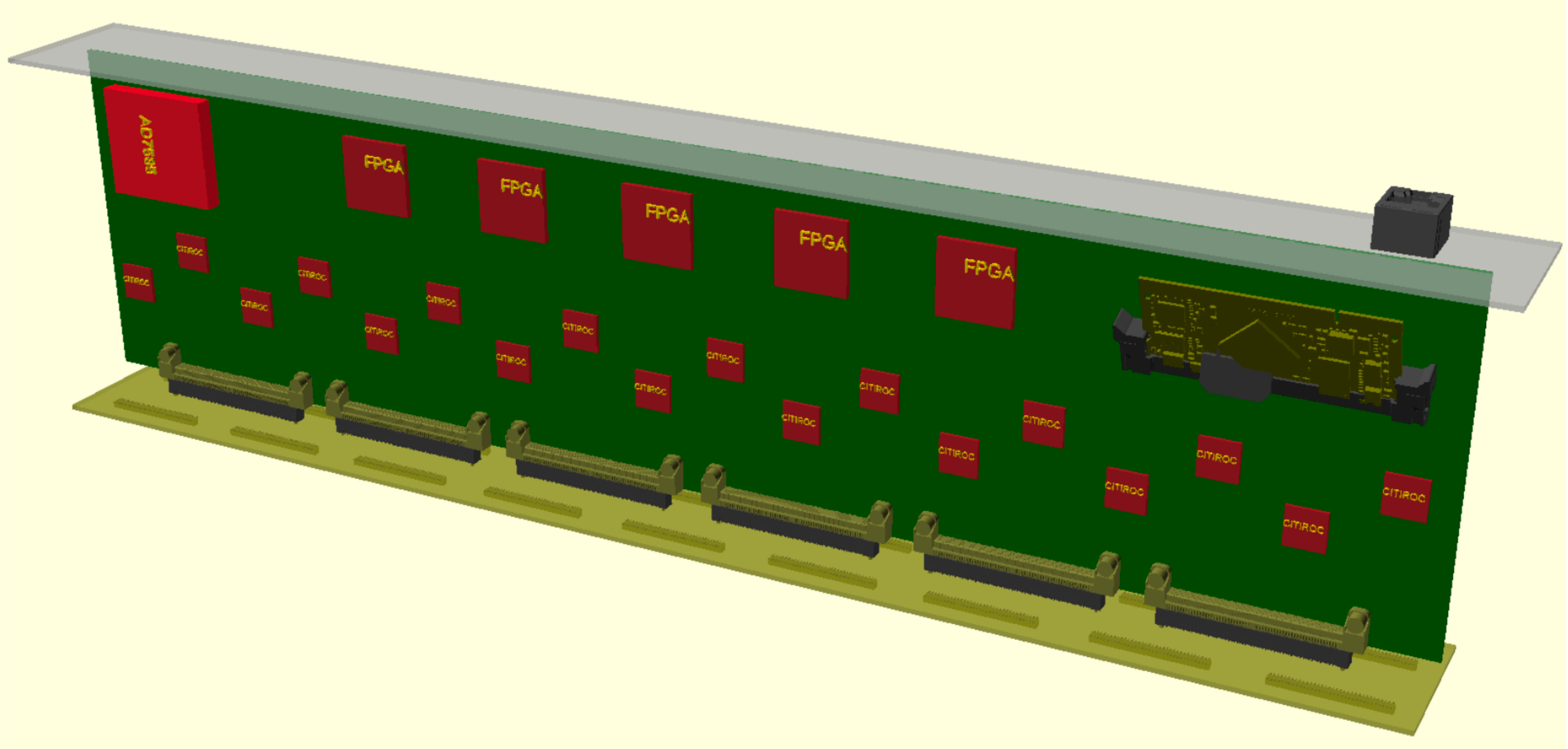
Ongoing Work: EMCal Electronics Design

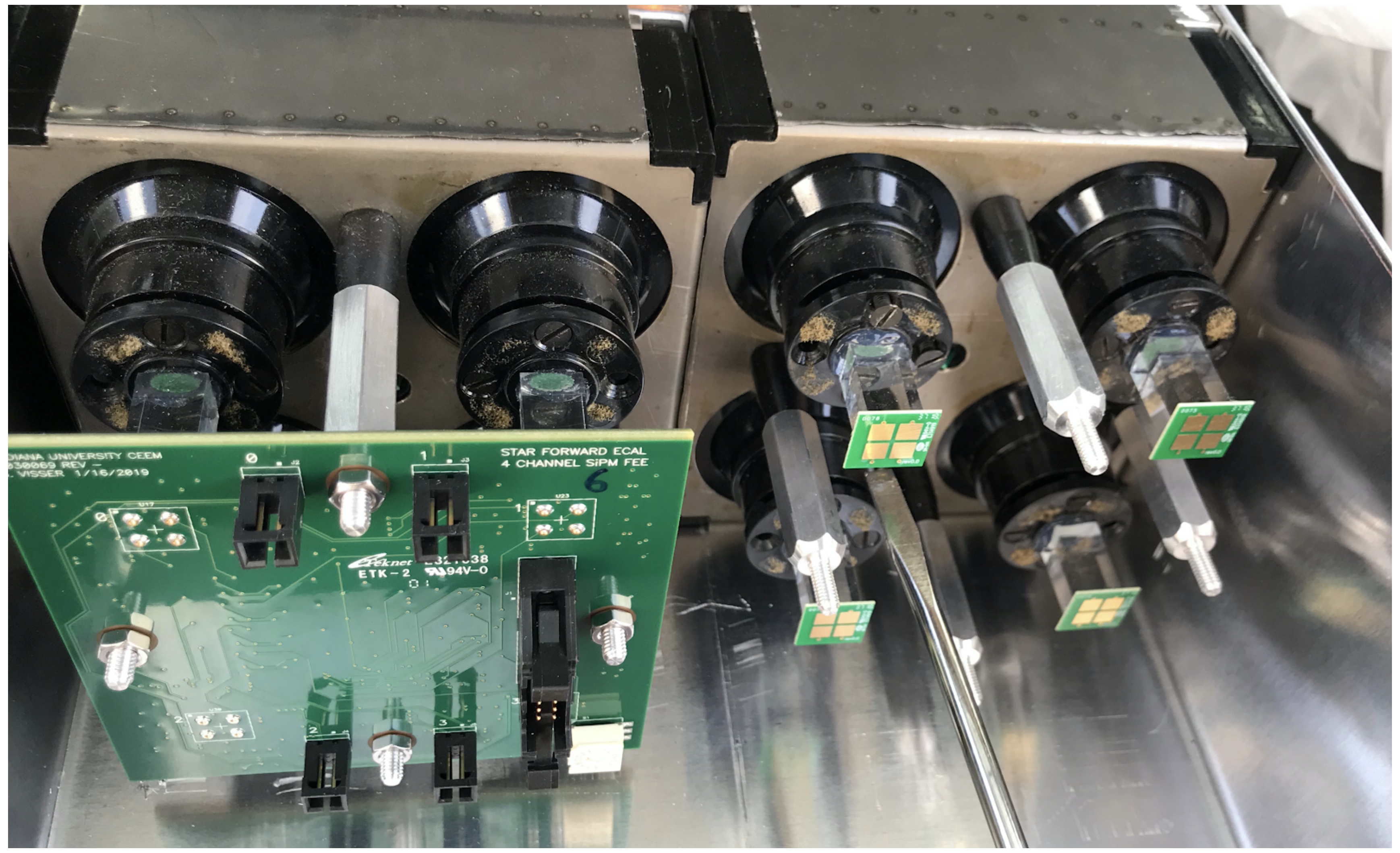




- EMCal from the PHENIX Experiment available at BNL (a 2m x 4m Pb-scintillator calorimeter)
- Replace the PMTs with SiPMs, and design the readout electronics. Integrate with the SpinQuest DAQ.

Ongoing Work: EMCal Electronics Design





- Exploring existing technologies for EMCal SiPM readout, for example from the design in the EMPHATIC experiment (left)

Collaboration

- A strong team assembled of both experimentalists and theorists; having regular meetings for more than a year

Experimentalists:

- BU: Zeynep Demiragli, David Sperka, Amitav Mitra
- FNAL: Nhan Tran, Cristina Mantilla Suarez, Yongbin Feng
- JHU: Petar Maksimovic
- LANL: Ming Liu, Kun Liu
- MIT: Phil Harris, Duc Hoang, Noah Paladino, Sergio Cuadra
- SLAC: Omar Moreno, Tim Nelson

Theorists:

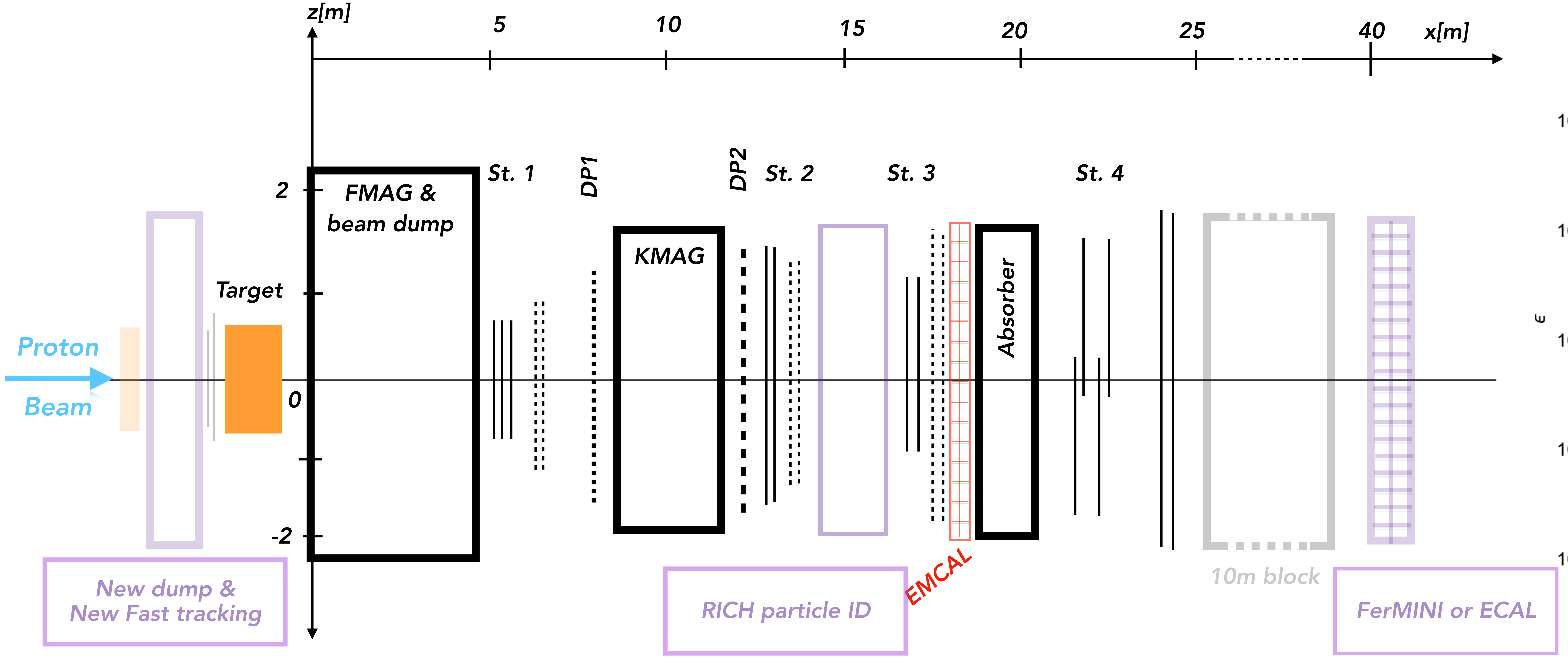
- FNAL: Nikita Blinov, Yu-Dai Tsai
- NYU: Asher Berlin
- Pitt: Brian Batell, Mudit Rai
- UCSC: Stefania Gori

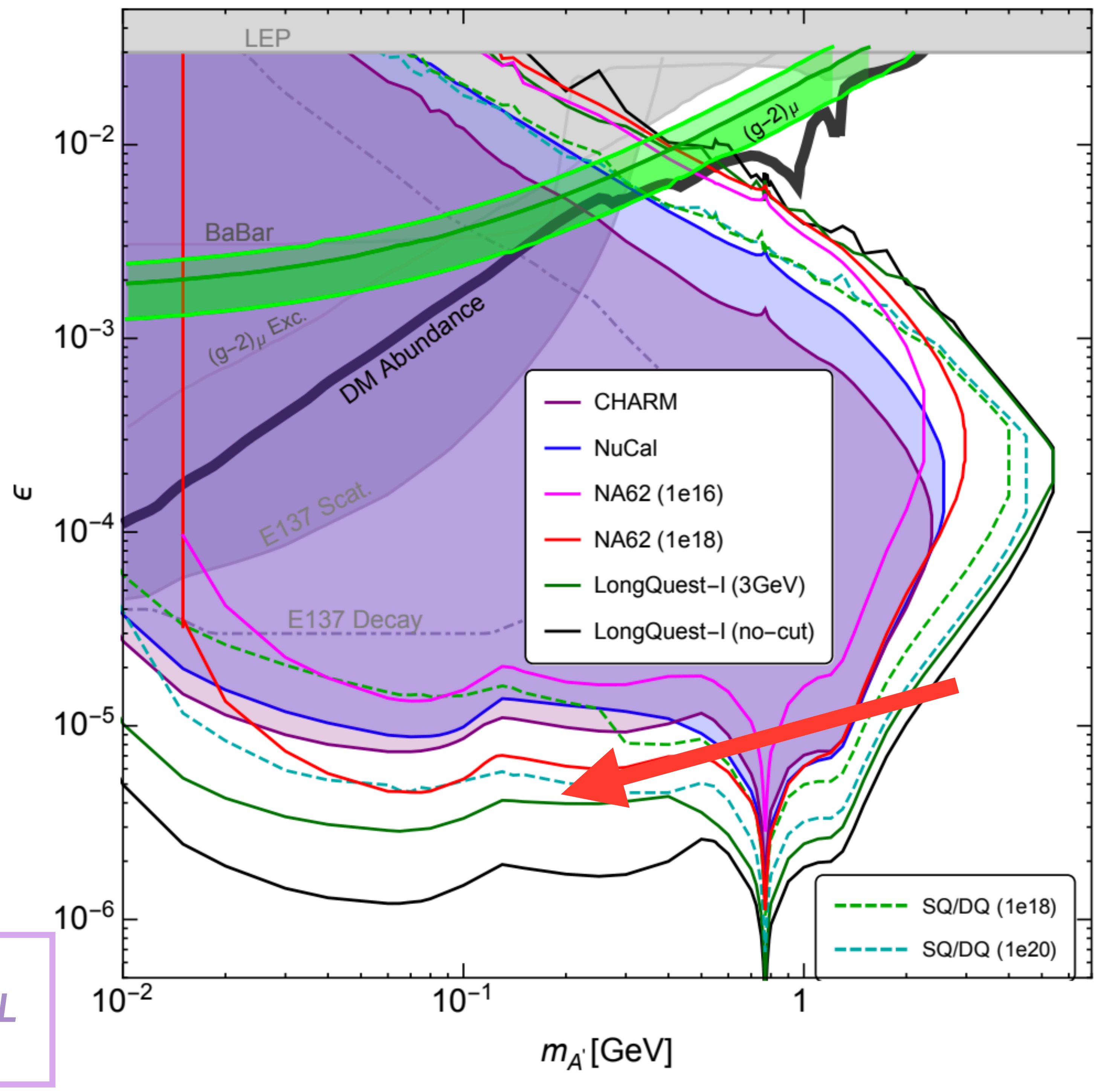
- We are establishing strong connections with the current SpinQuest collaboration
- **Welcome to join the effort!** Contact us if interested! (yfeng@fnal.gov ntran@fnal.gov)

Timeline & Plans

- Current SpinQuest runs planned for Fall 2021 and Fall 2022; DarkQuest aims to start on Fall 2023
- Integrate Dark Sector studies into SpinQuest collaboration
- Develop simulation studies:
  - Experimental: Signal Acceptance, EMCal, displaced tracking and vertexing, background studies
  - Theory: More models beyond the minimal dark photon, e.g., ALPs and SIMPs
- Develop project plans for the EMCal upgrade
  - Exploring existing technologies for EMCal SiPM readout, for example EMPHATIC experiment
  - Rough estimate of total cost of the EMCal upgrade: ~500K

Future Upgrade: DarkQuest -> LongQuest





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- 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

Summary

- DarkQuest is a proton beam dump experiment, which makes use of current SpinQuest experiment, with the upgraded EMCal from PHENIX experiment
- DarkQuest offers a low-cost and near-term opportunity to uncover a broad range of MeV-GeV dark sectors
- Planned timeline: SpinQuest run (-2022) and DarkQuest aiming to start from Fall 2023!
- A lot of electronics design, simulation, and reconstruction studies ongoing; **welcome to join the efforts!** (yfeng@fnal.gov, ntran@fnal.gov)

Back Up

Trigger logic

- Two levels: identify displaced tracks, trigger on pairs
- L1: three-way coincidence within each quadrant
  - Identify displaced tracks ($z_0 \in [400, 650]$ cm) in each quadrant using hit patterns ("roads")
- L2: two-out-of-four coincidence between quadrants
  - Require pairs of displaced tracks, opposite sign