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

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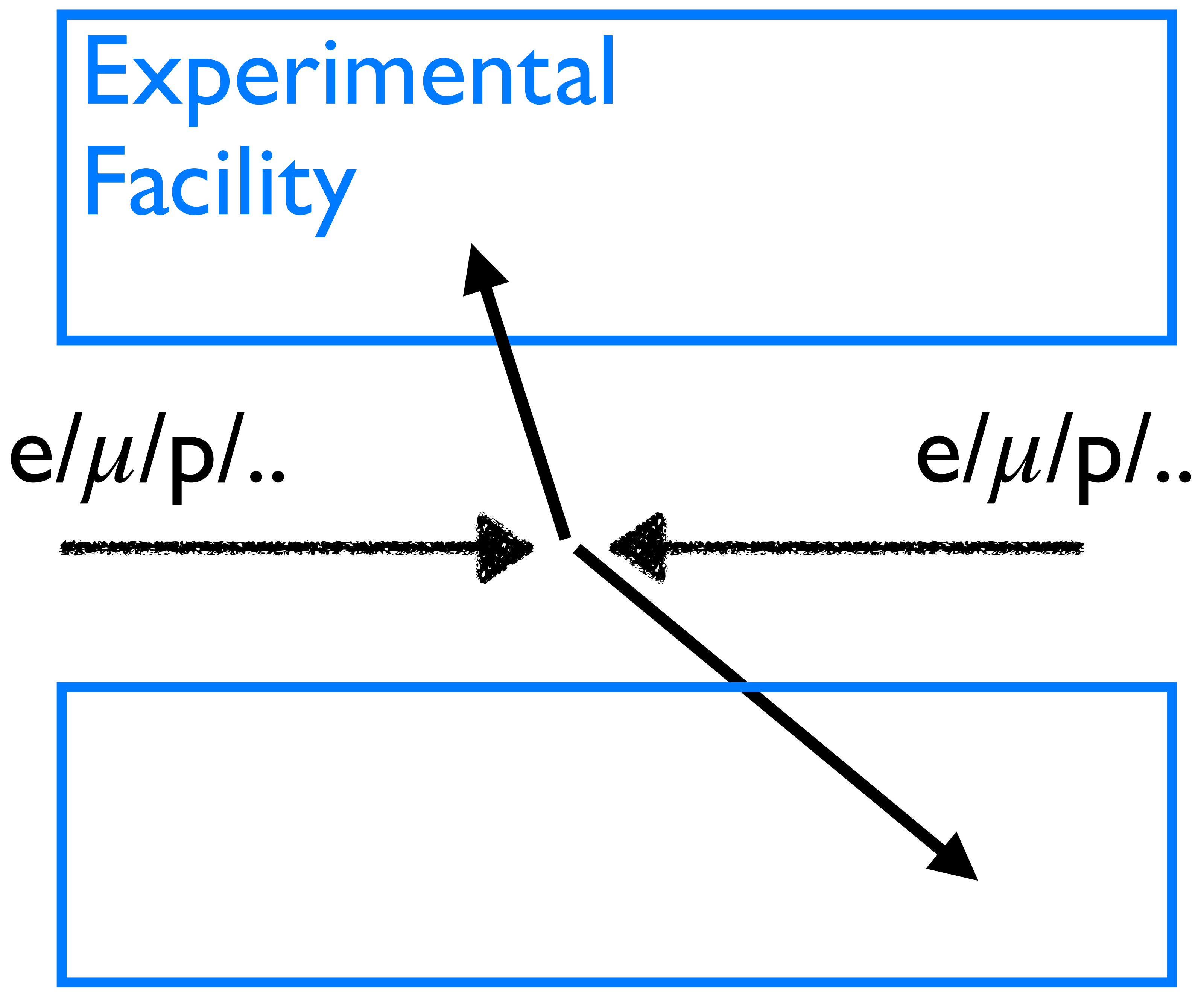
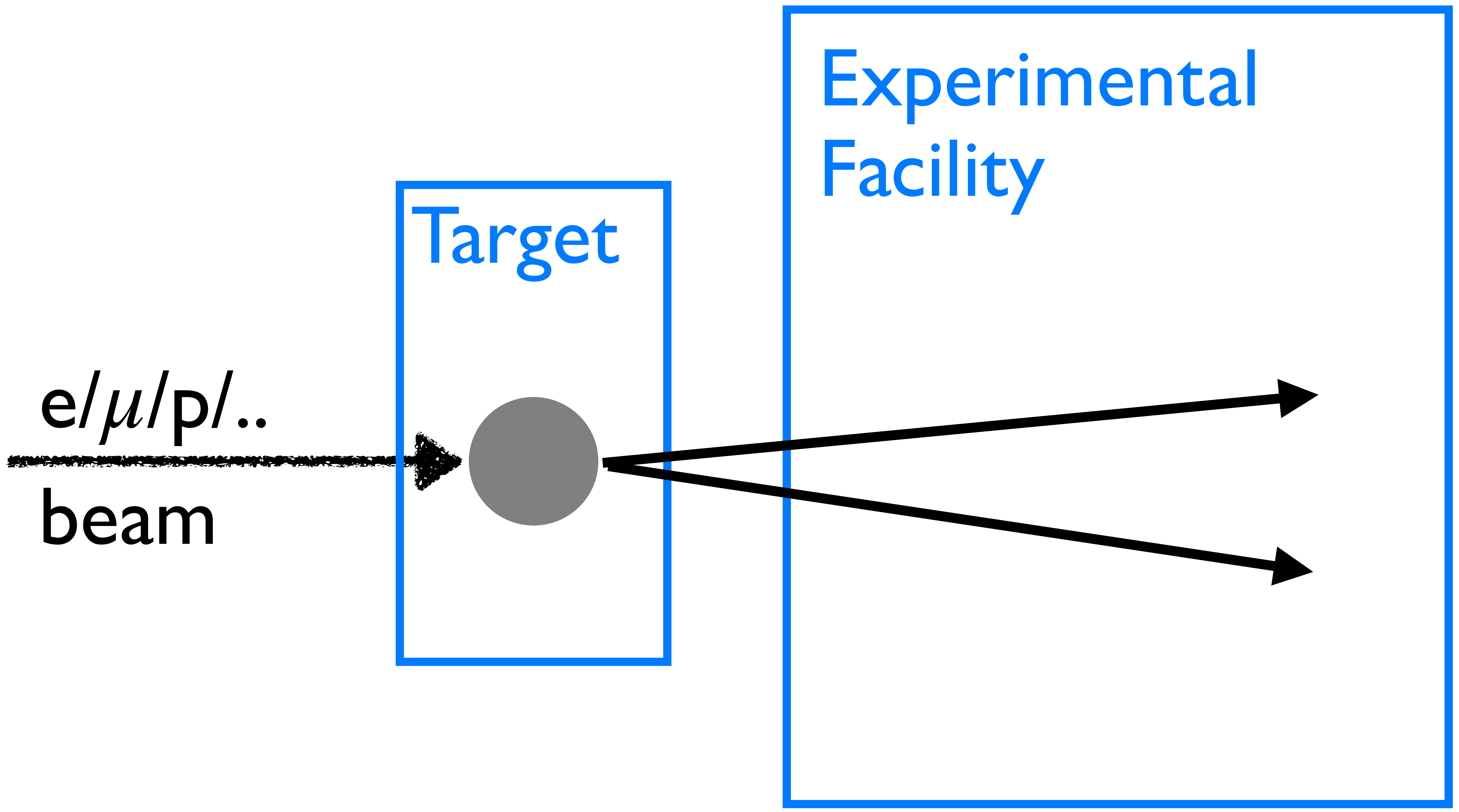
SYSU-PKU Particle Physics Forum

May 25th, 2022

Collider vs Fixed-target Experiments



- Higher energy



- Higher intensity

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

Outline

- Dark Sector:
  - ✤ What? Why? How?

- DarkQuest:
  - ✤ Proton fixed-target experiment based on SpinQuest
  - ✤ How to use DarkQuest to probe dark sectors:
    - ➡ Spectrometer upgrades
    - ➡ Simulation studies on calorimeter, tracking, triggering, ParticleID
    - ➡ Acceptance & Sensitivity

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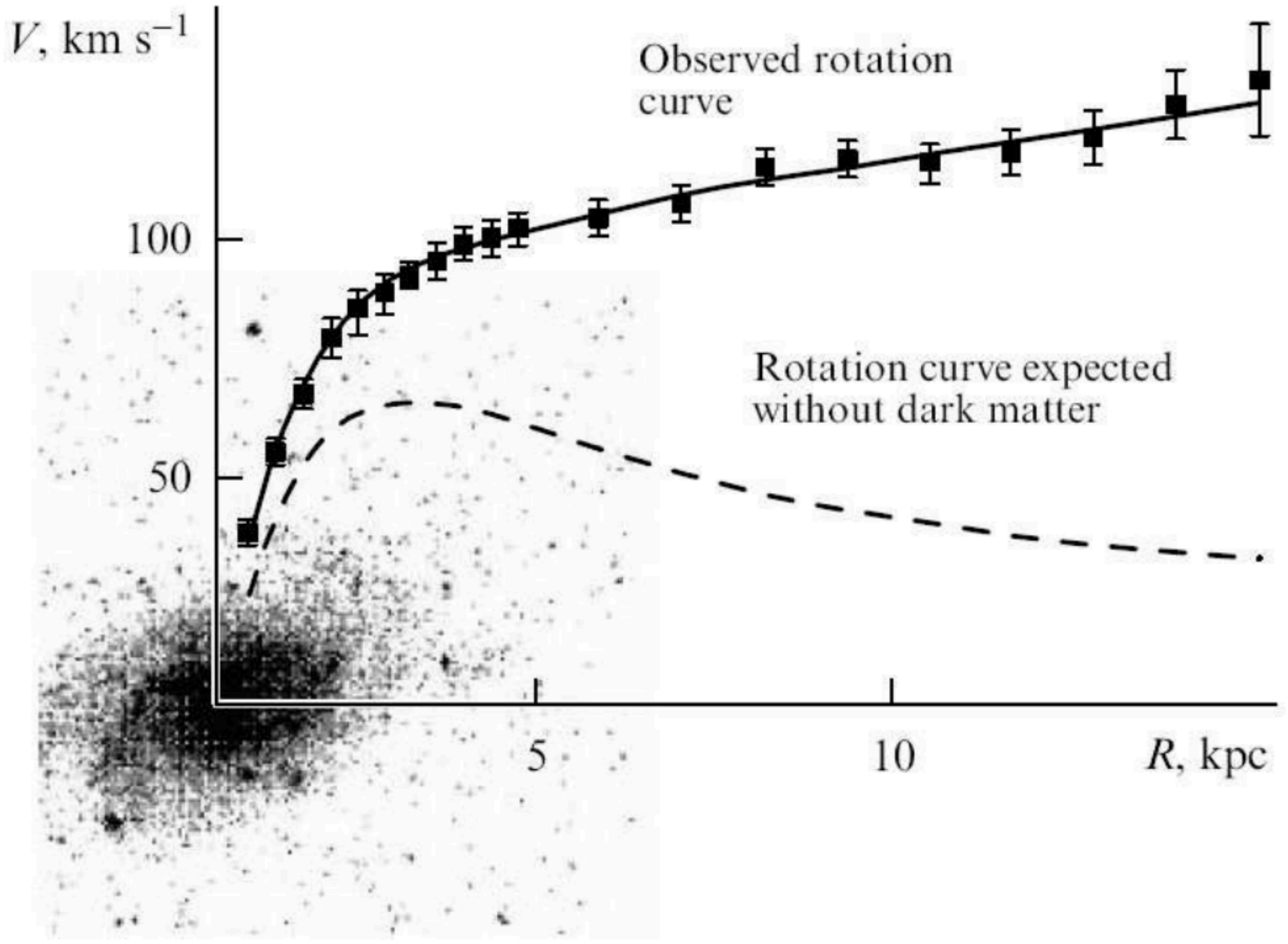
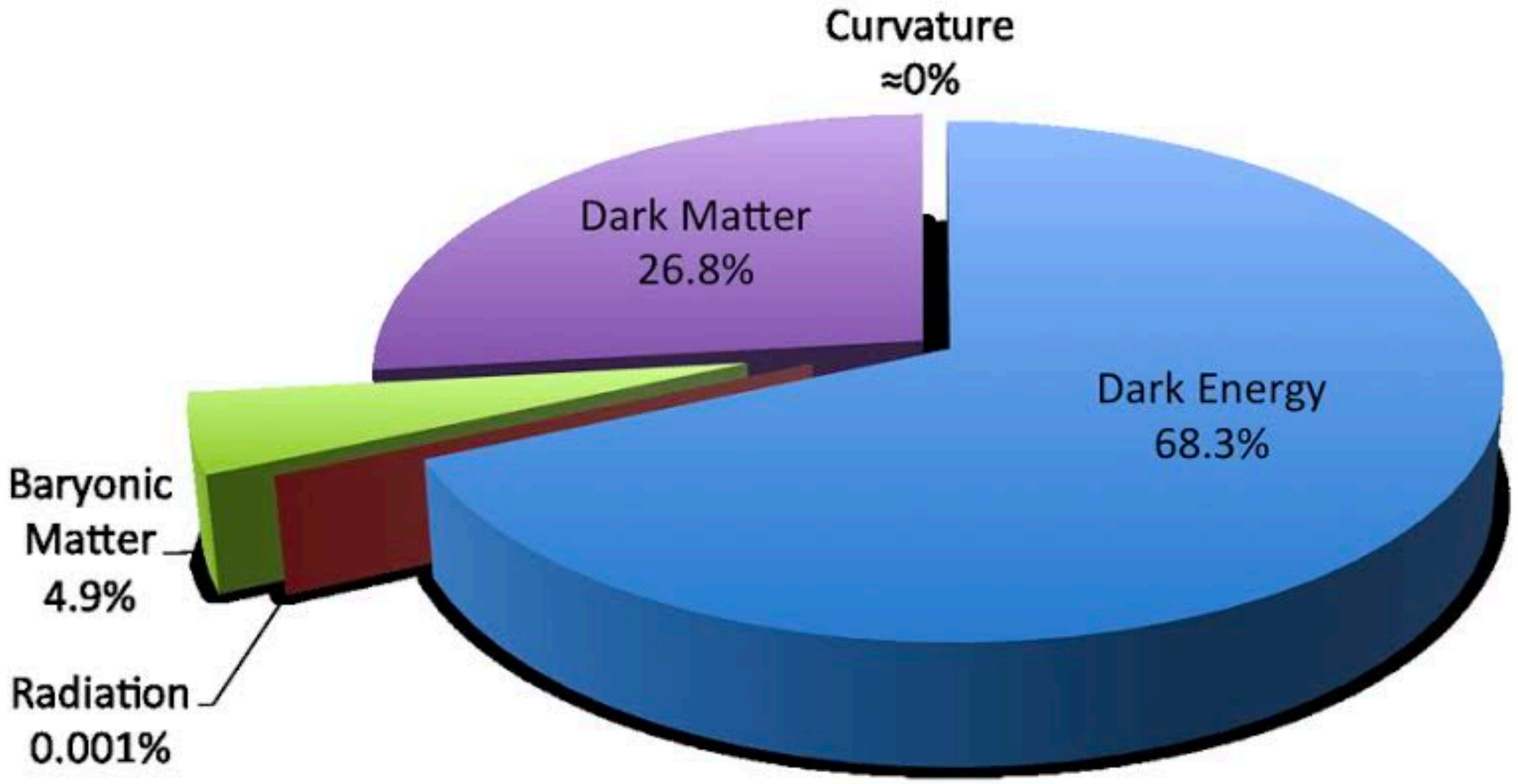
Dark Matter

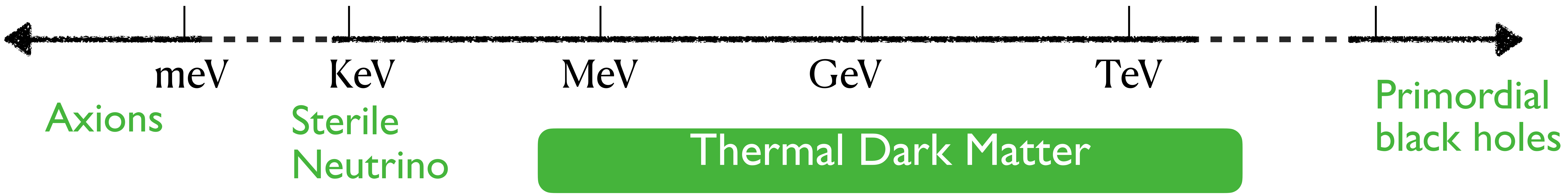




- From experimental observations we know dark matter exist, and they participate in gravitational interactions. Where are they?

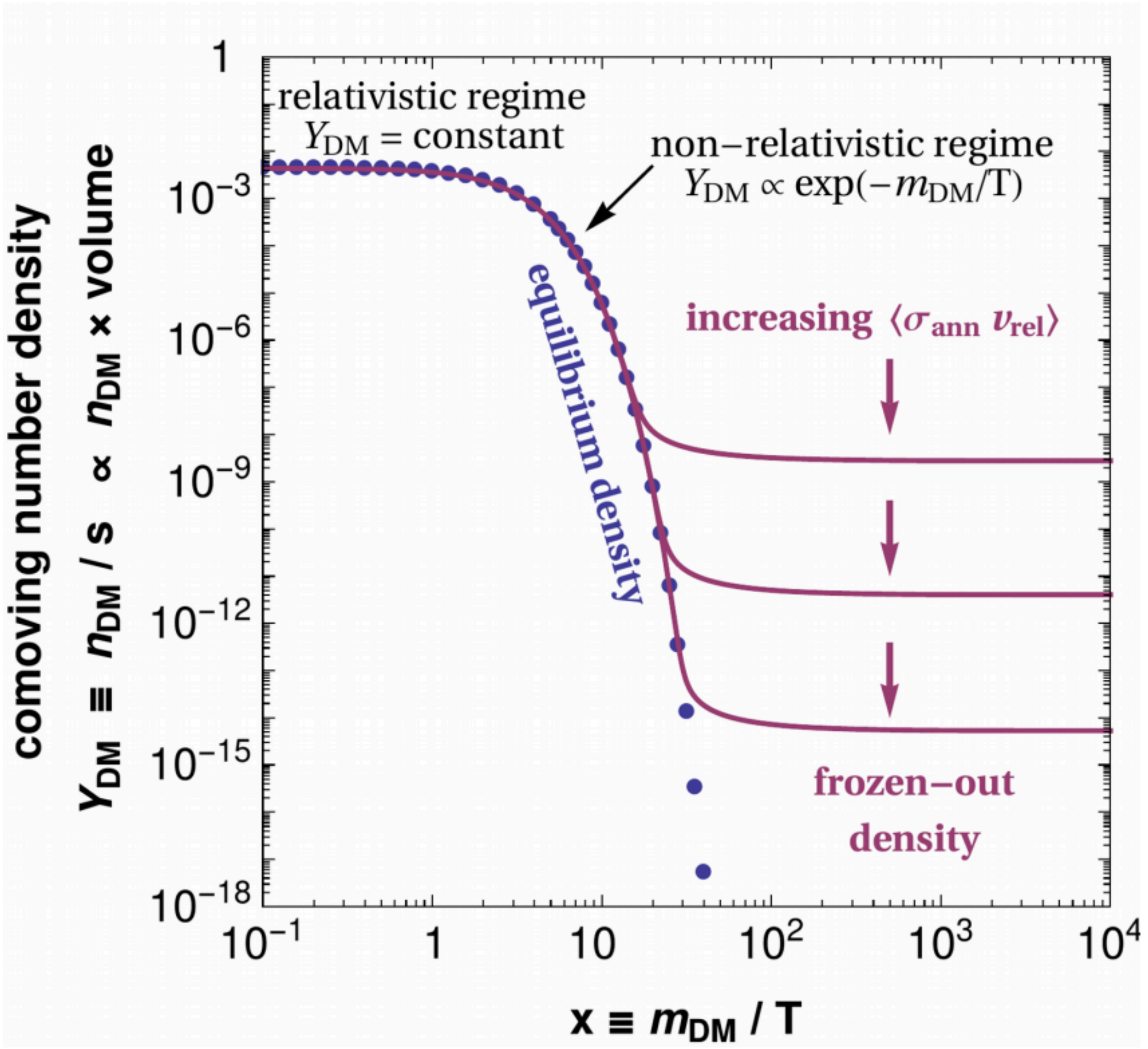
Dark Matter Mass Scale

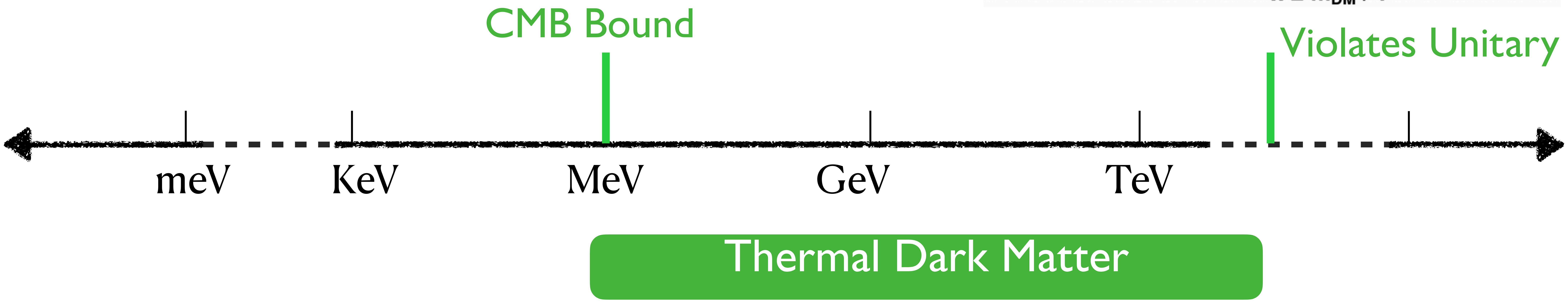
Dark Matter Mass Scale



Thermal Dark Matter

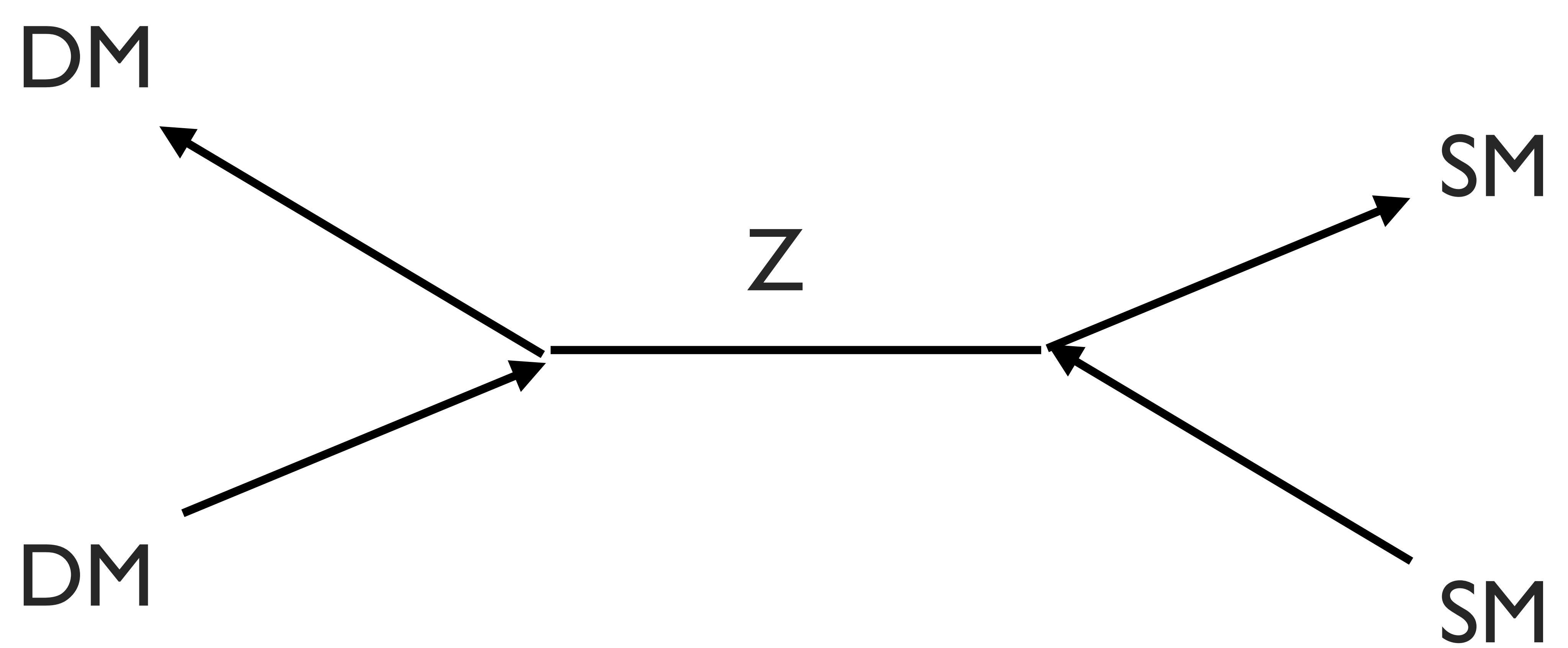
- Thermal freeze-out is a nice story for dark matter:
  - Easily realizable, predictive, UV insensitive
- Prefers the DM mass to be around MeV to TeV scale

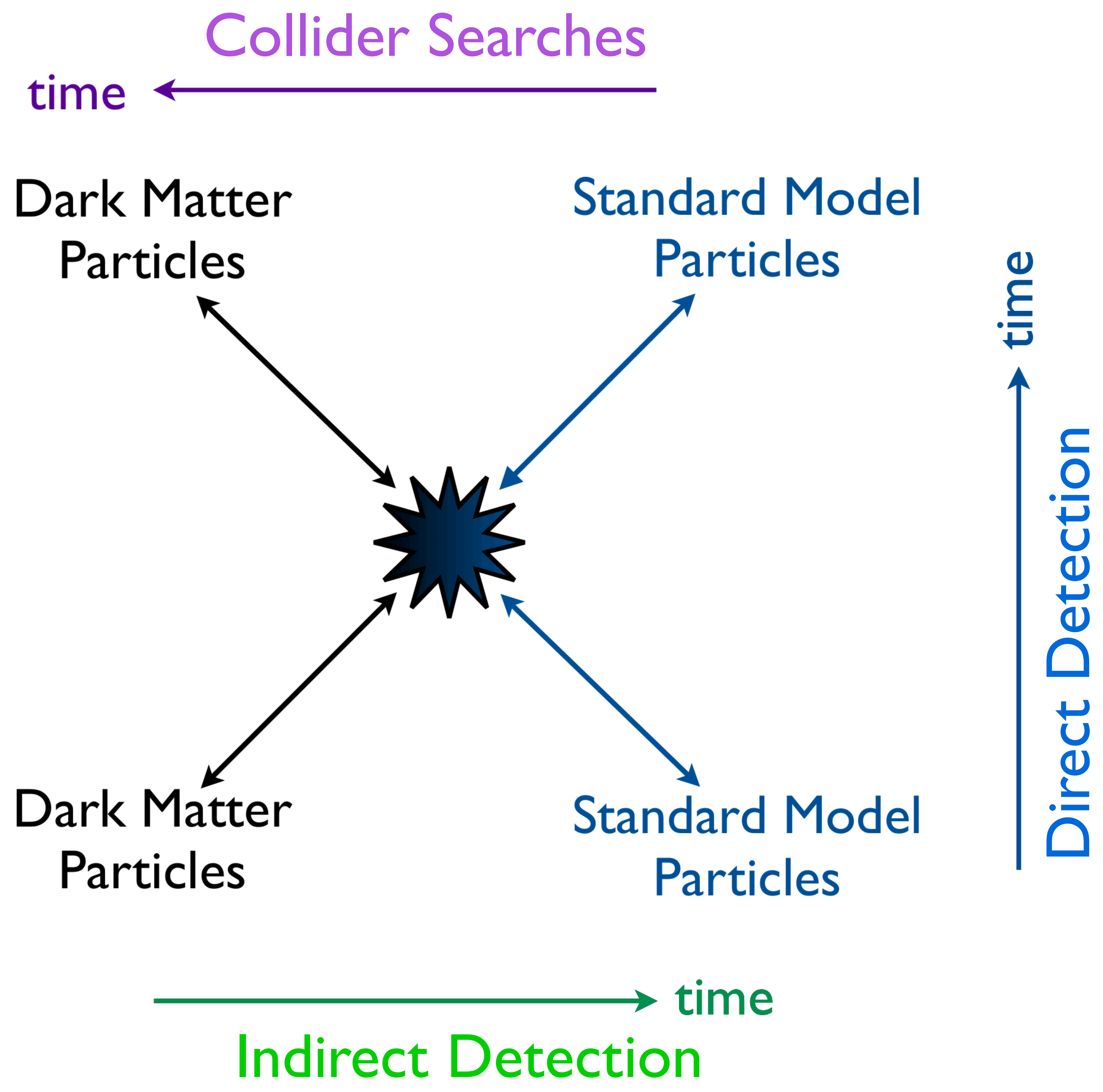




WIMP

- Popular candidates: Weakly Interacting Massive Particles (WIMP)
- Typically have masses around GeV to TeV (“WIMP miracle”)

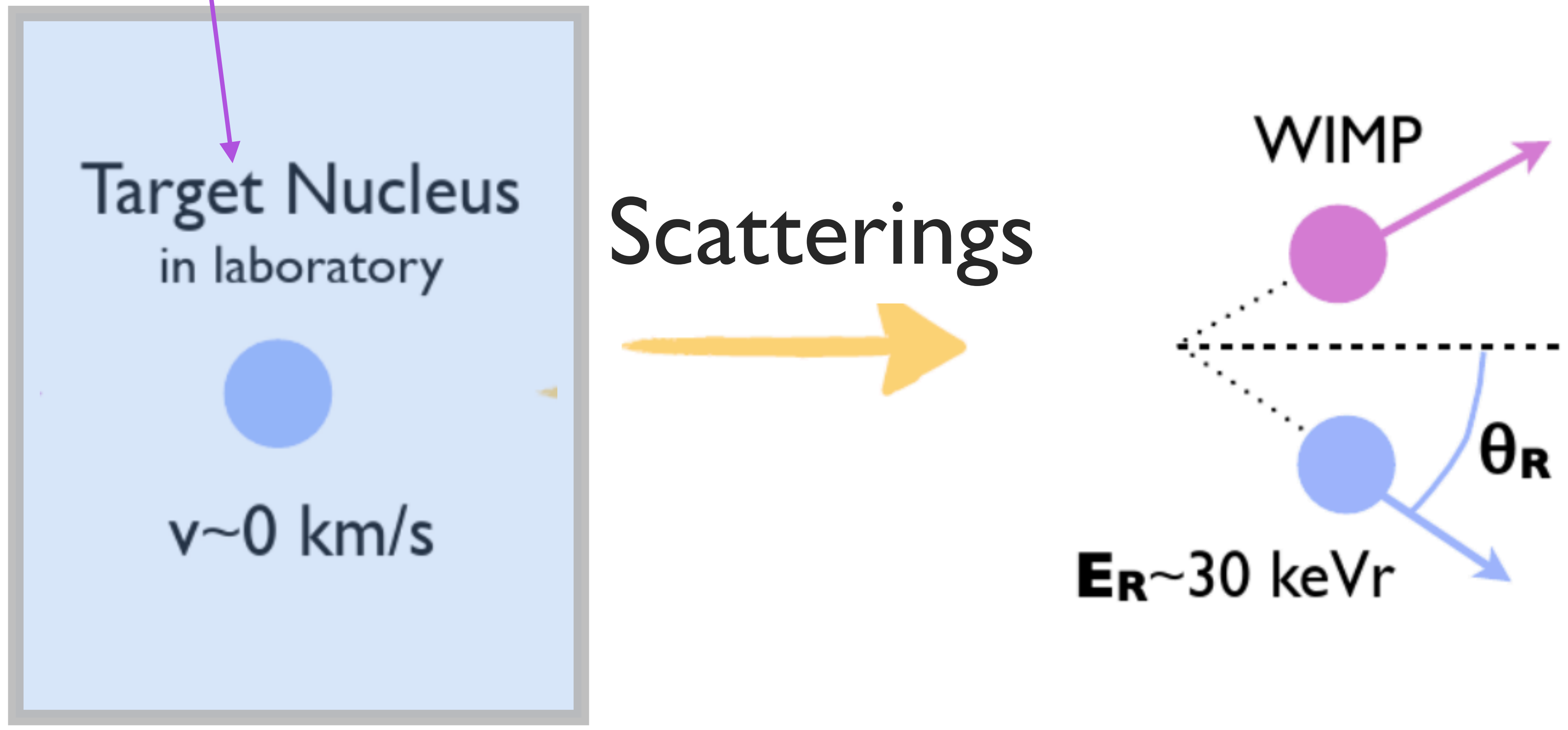


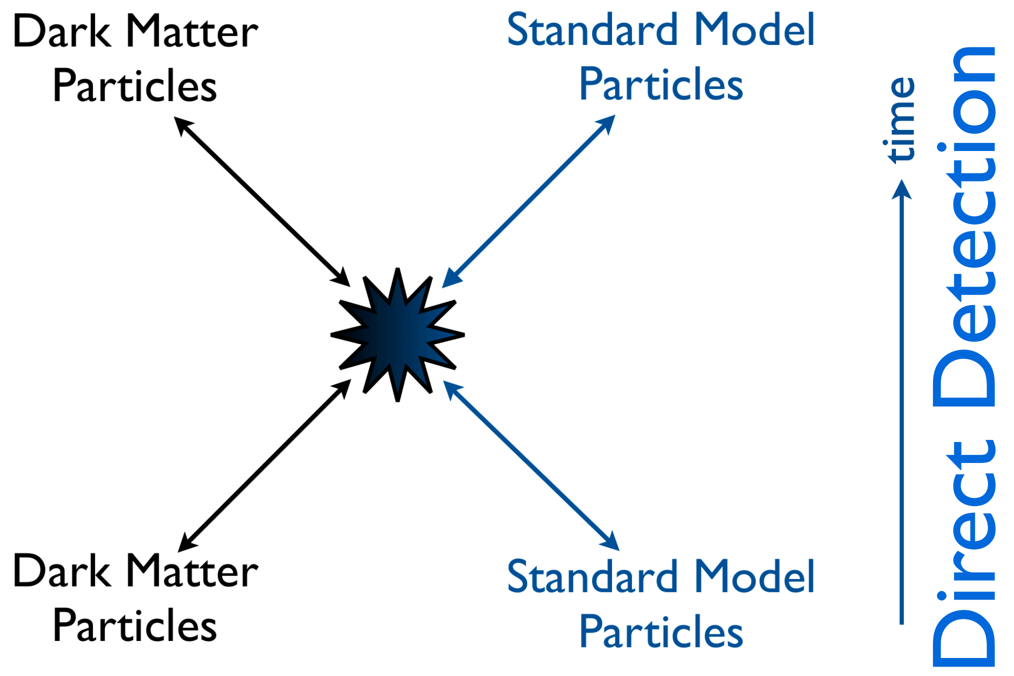


WIMP

- **Direct detection:**
- typically underground, e.g., PANDA-X, LUX/LZ, SuperCDMS,

WIMP, from galactic halo, $10^{-3} * c$ speed





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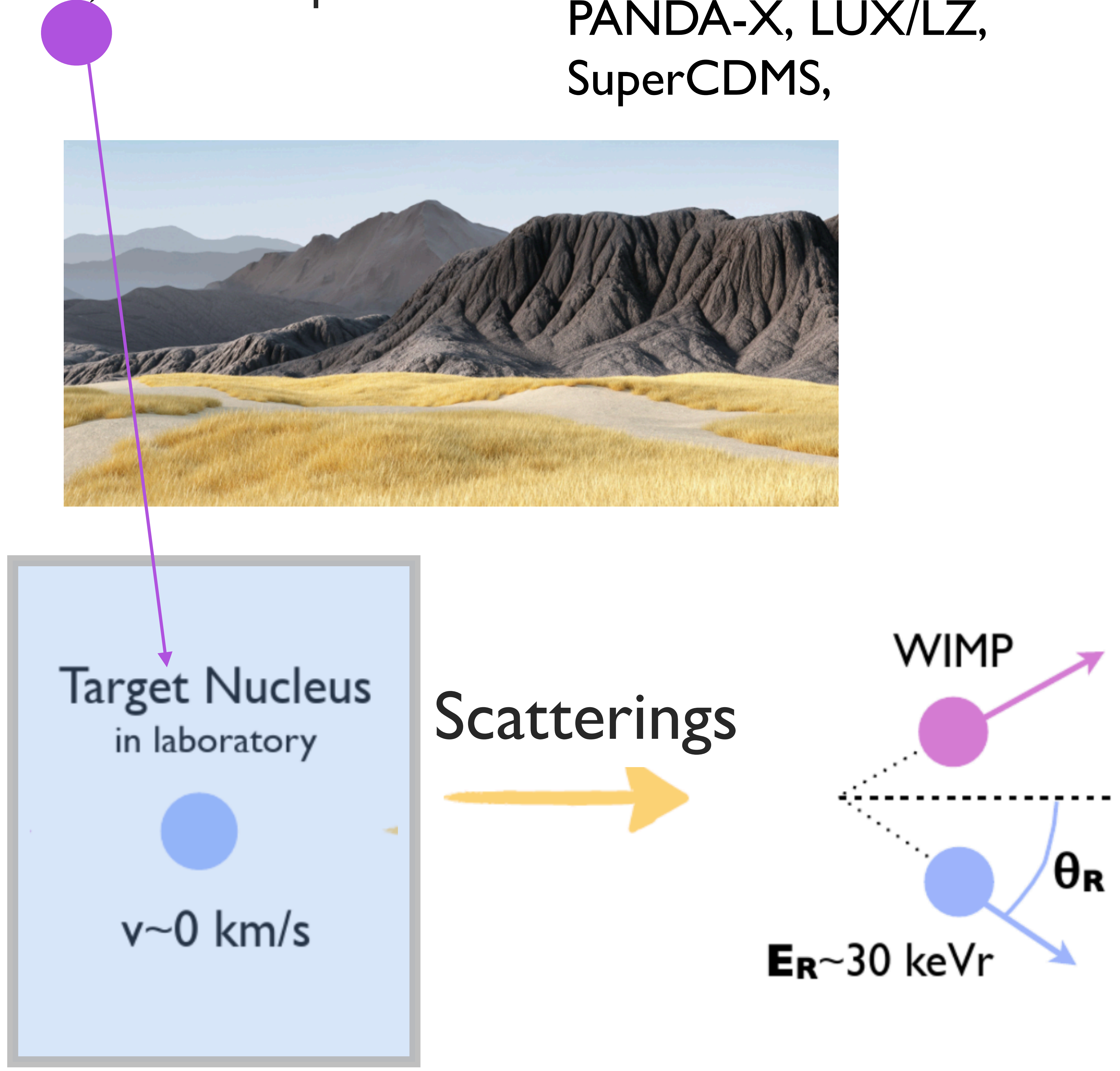
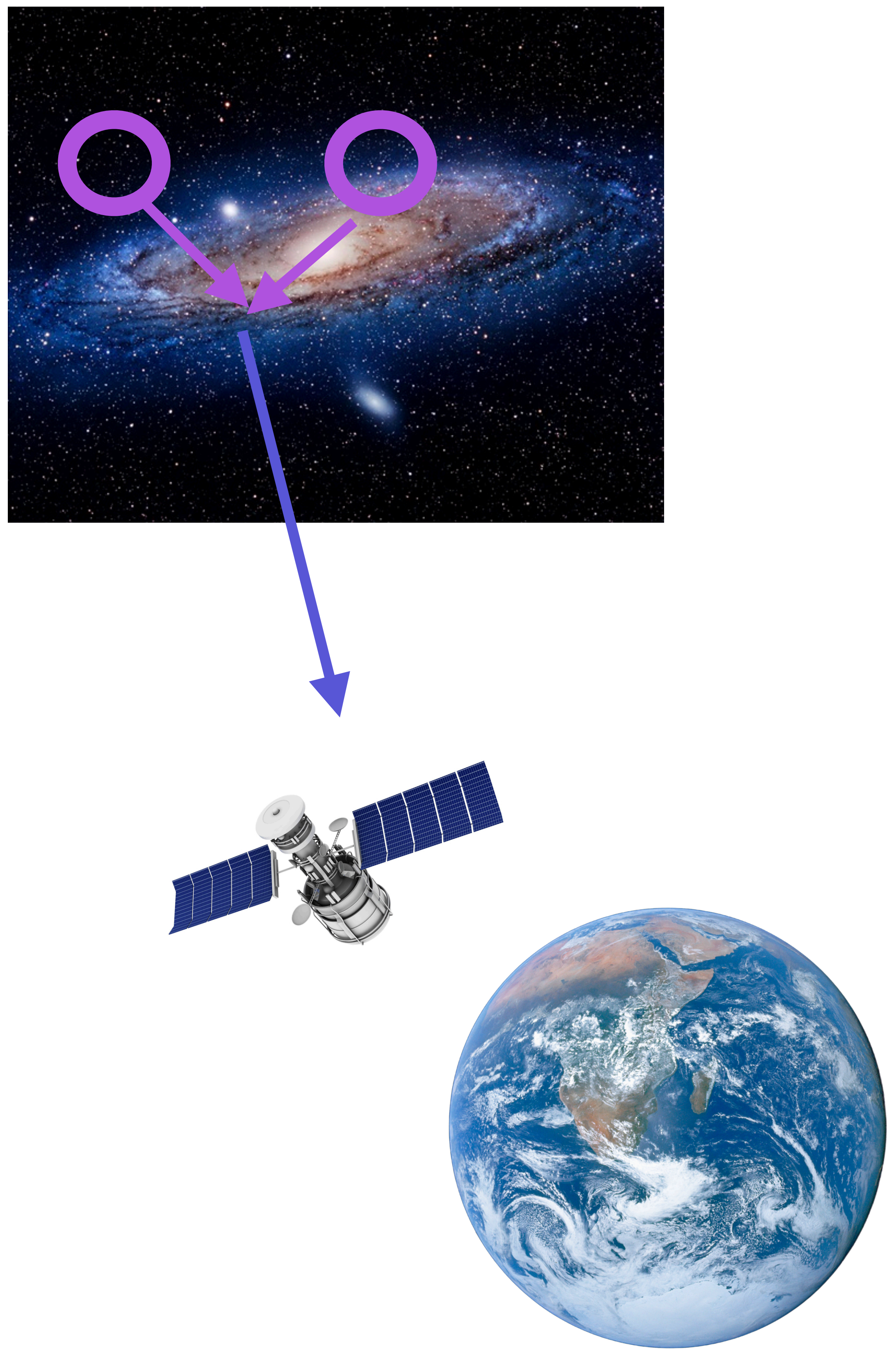
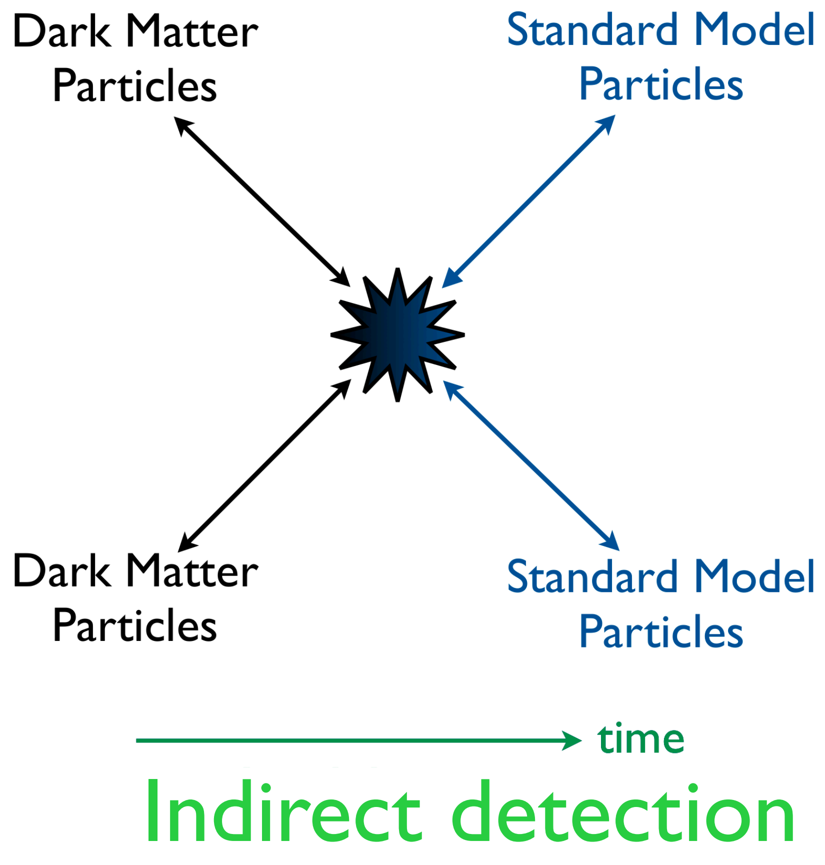


- **Indirect detection:**
- typically in the sky: DAMPE, AMS, FermiLAT





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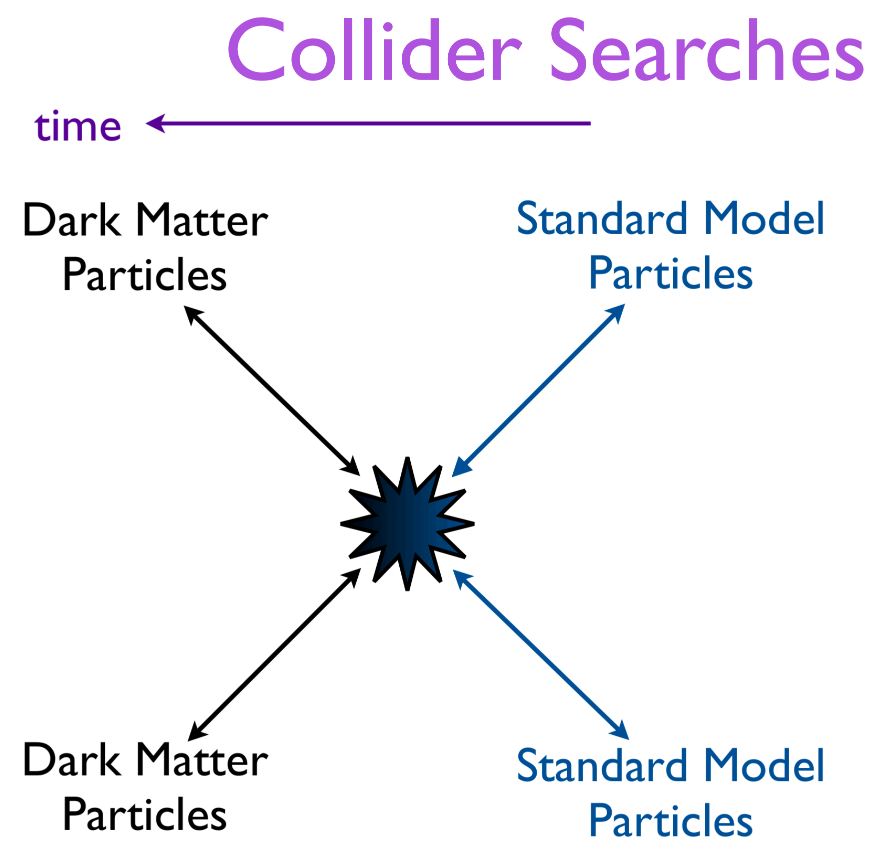

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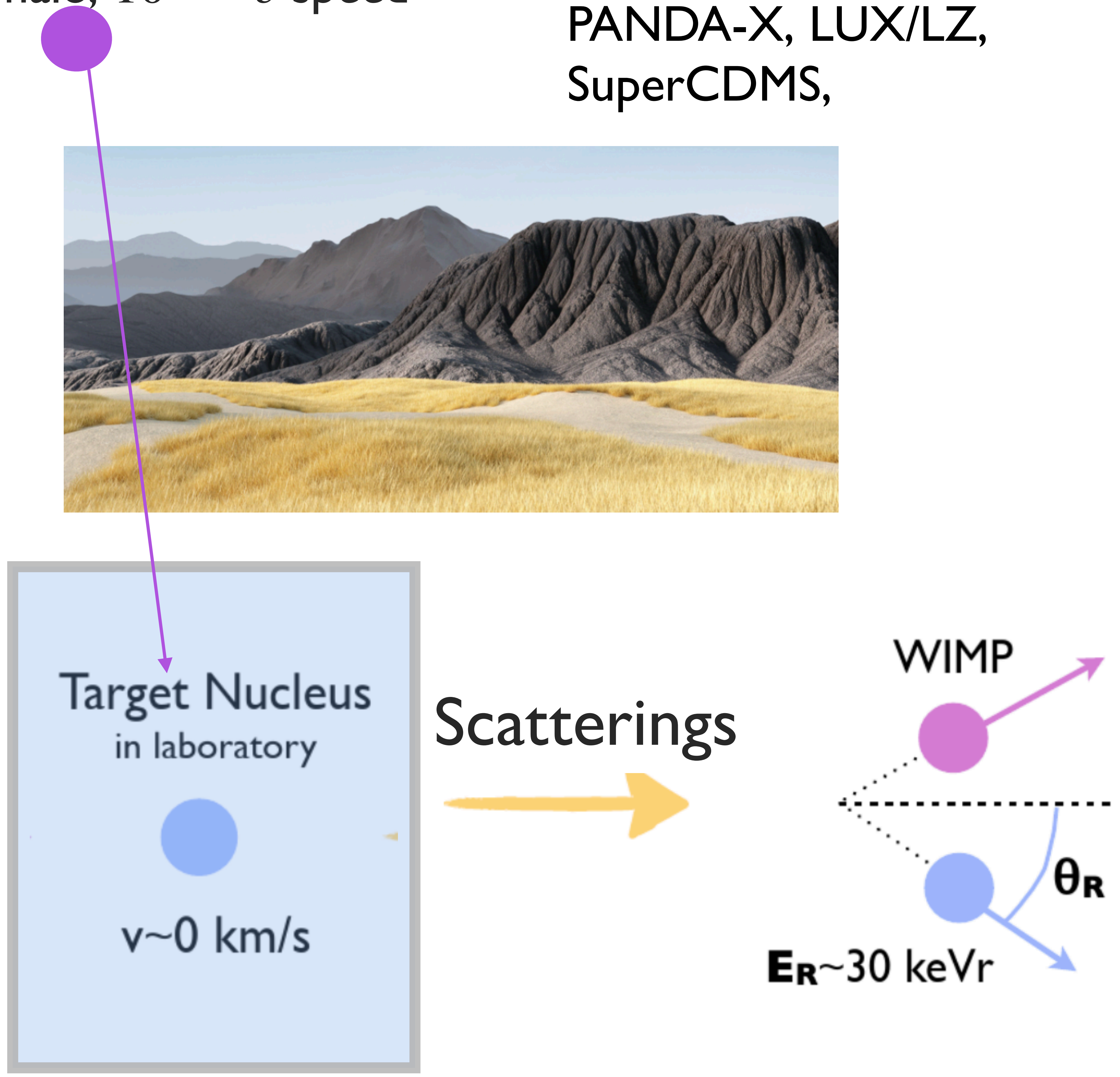

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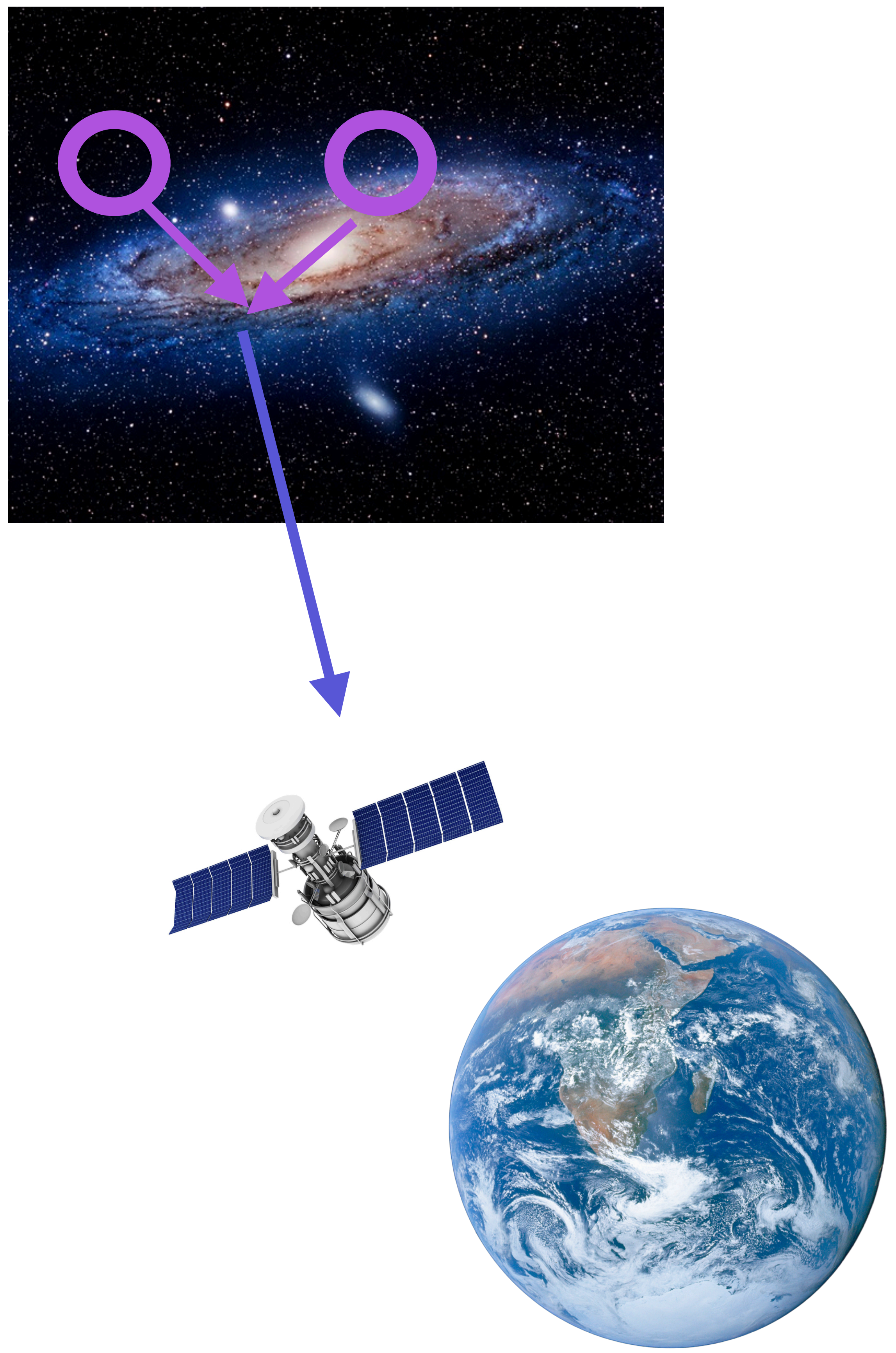
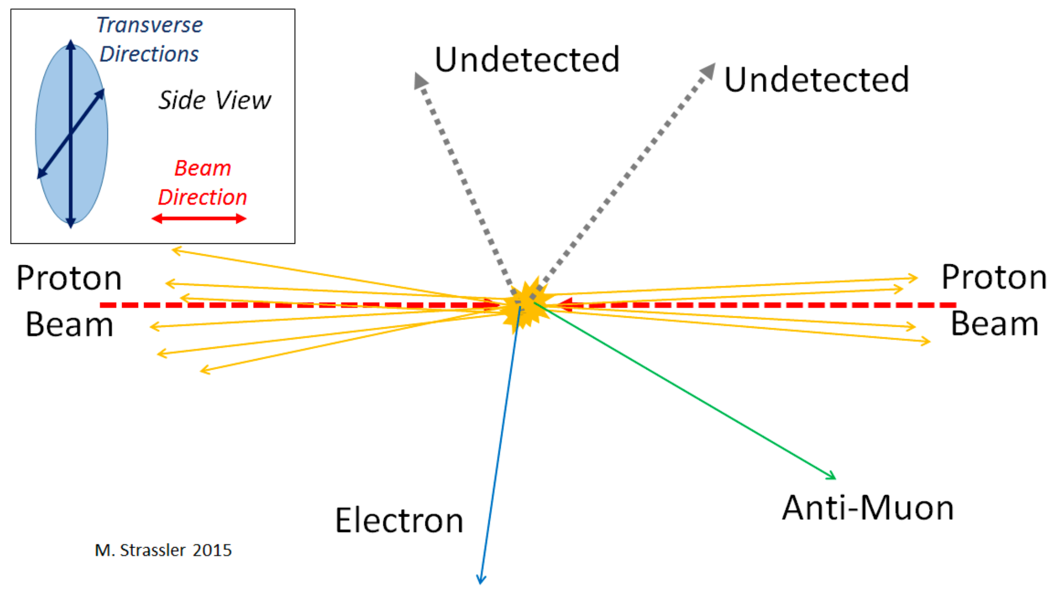


- **Collider searches**
- e.g., look for mono-Jet/ photon/lepton etc



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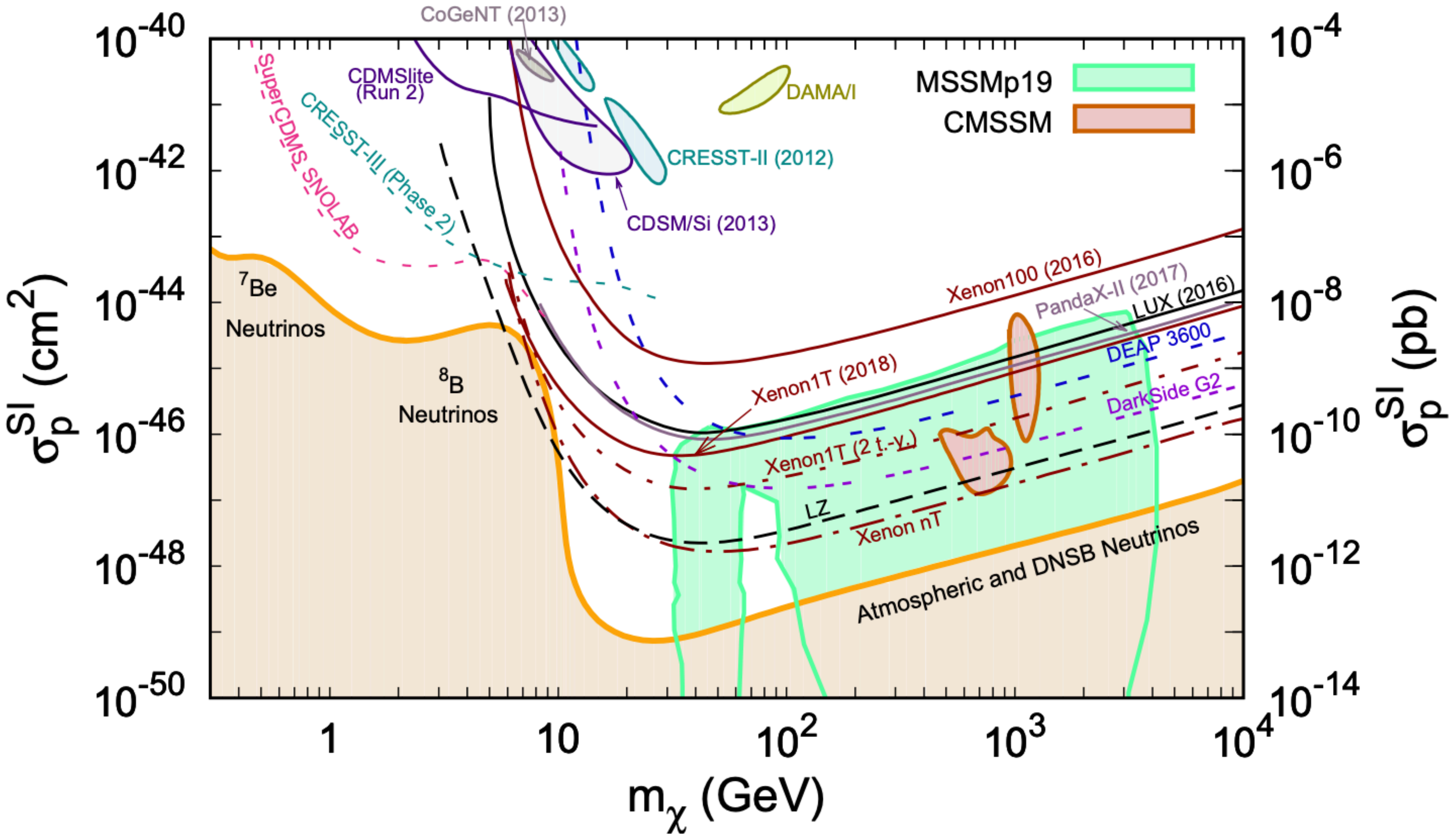
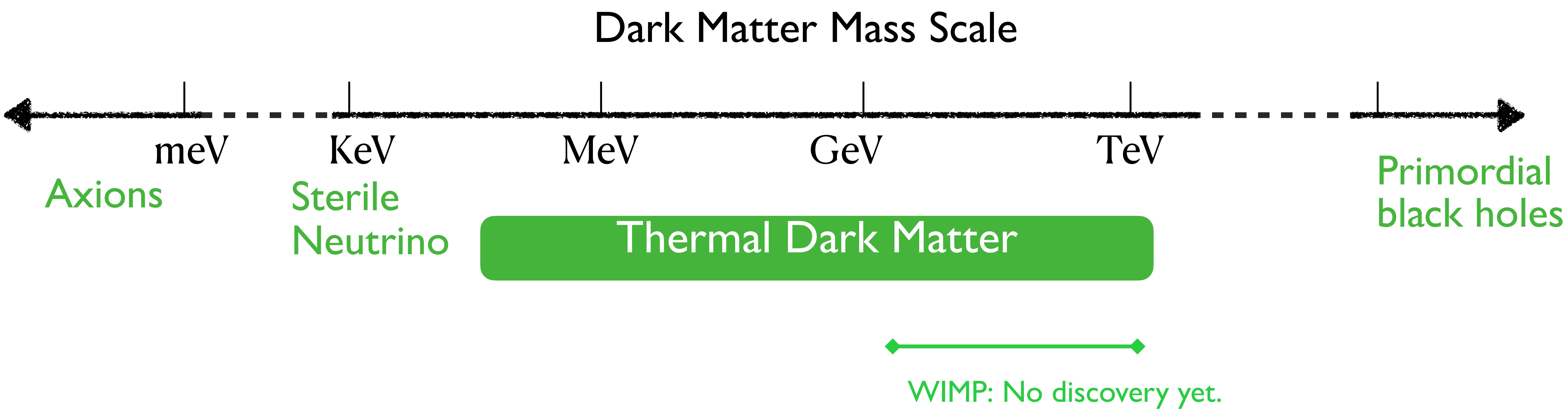


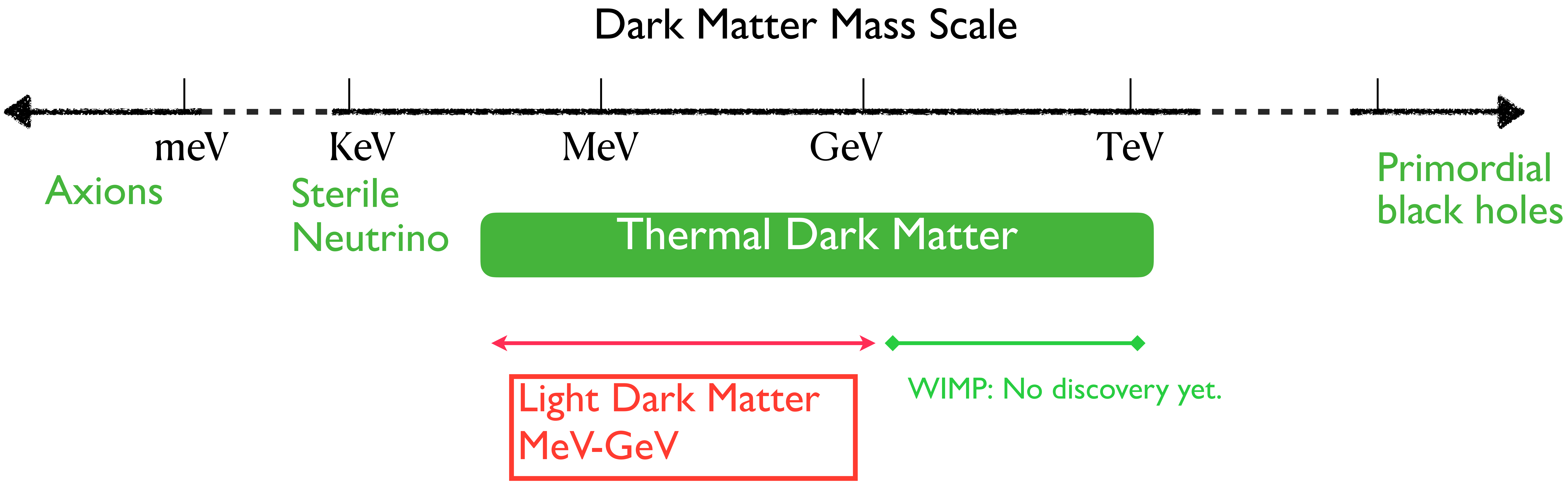
- Sensitivity is close to the neutrino boundaries
- but no discovery yet.

Light Dark Matter



- What next?

Light Dark Matter



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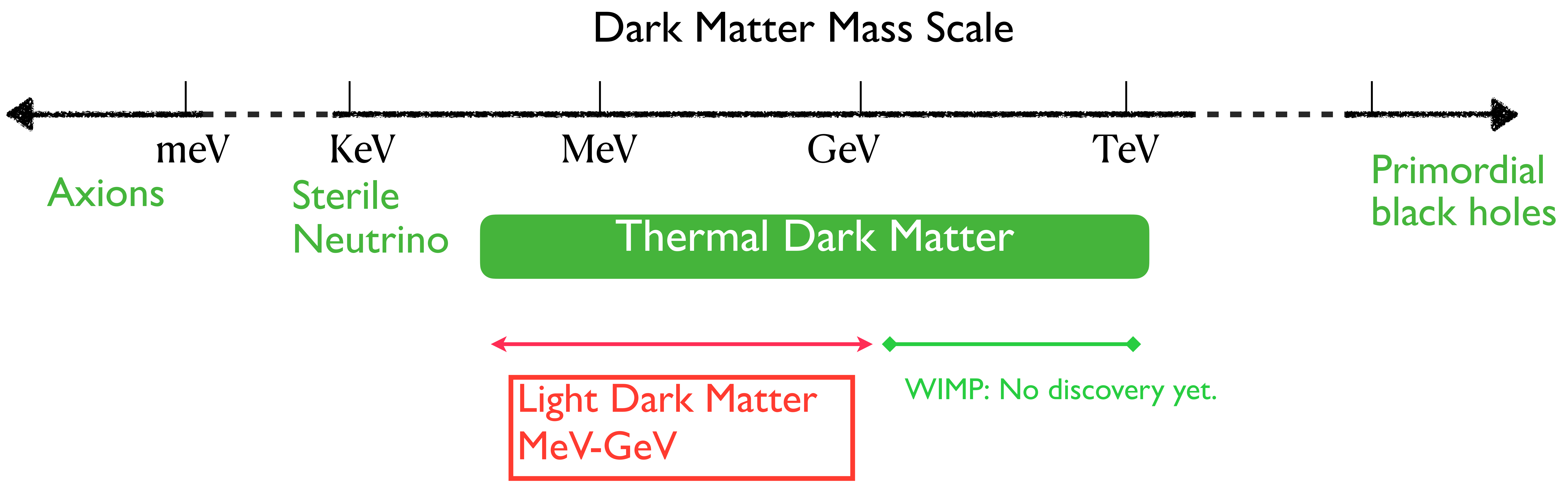
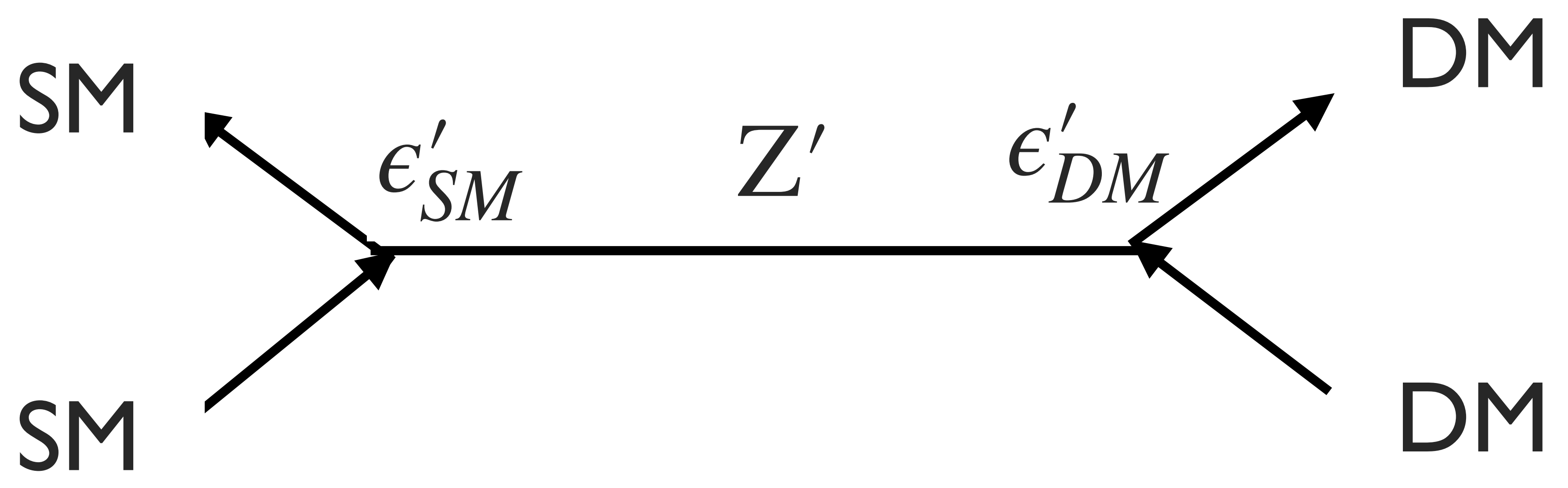
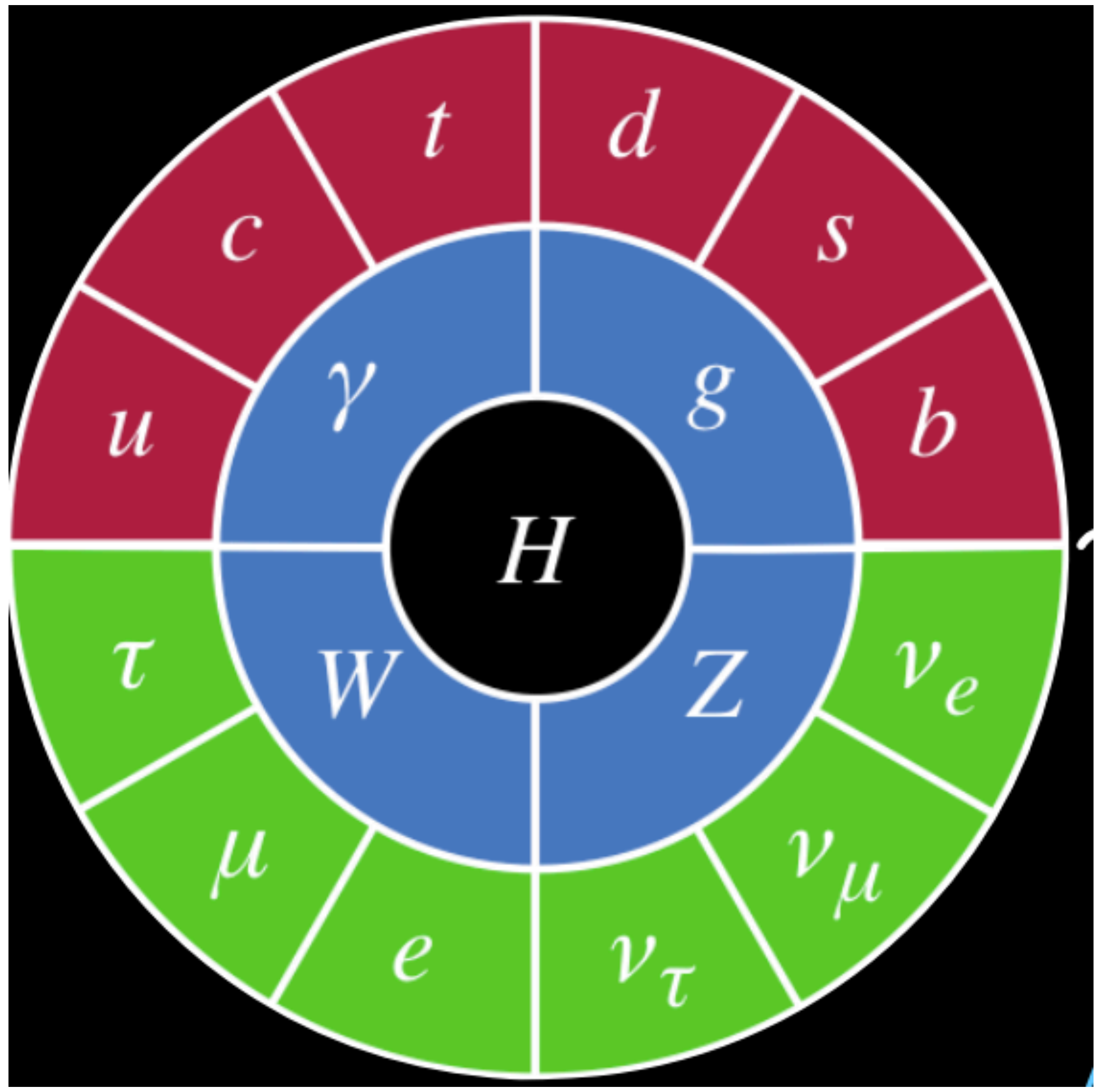


- Light dark matter requires light mediators -> Dark Sector

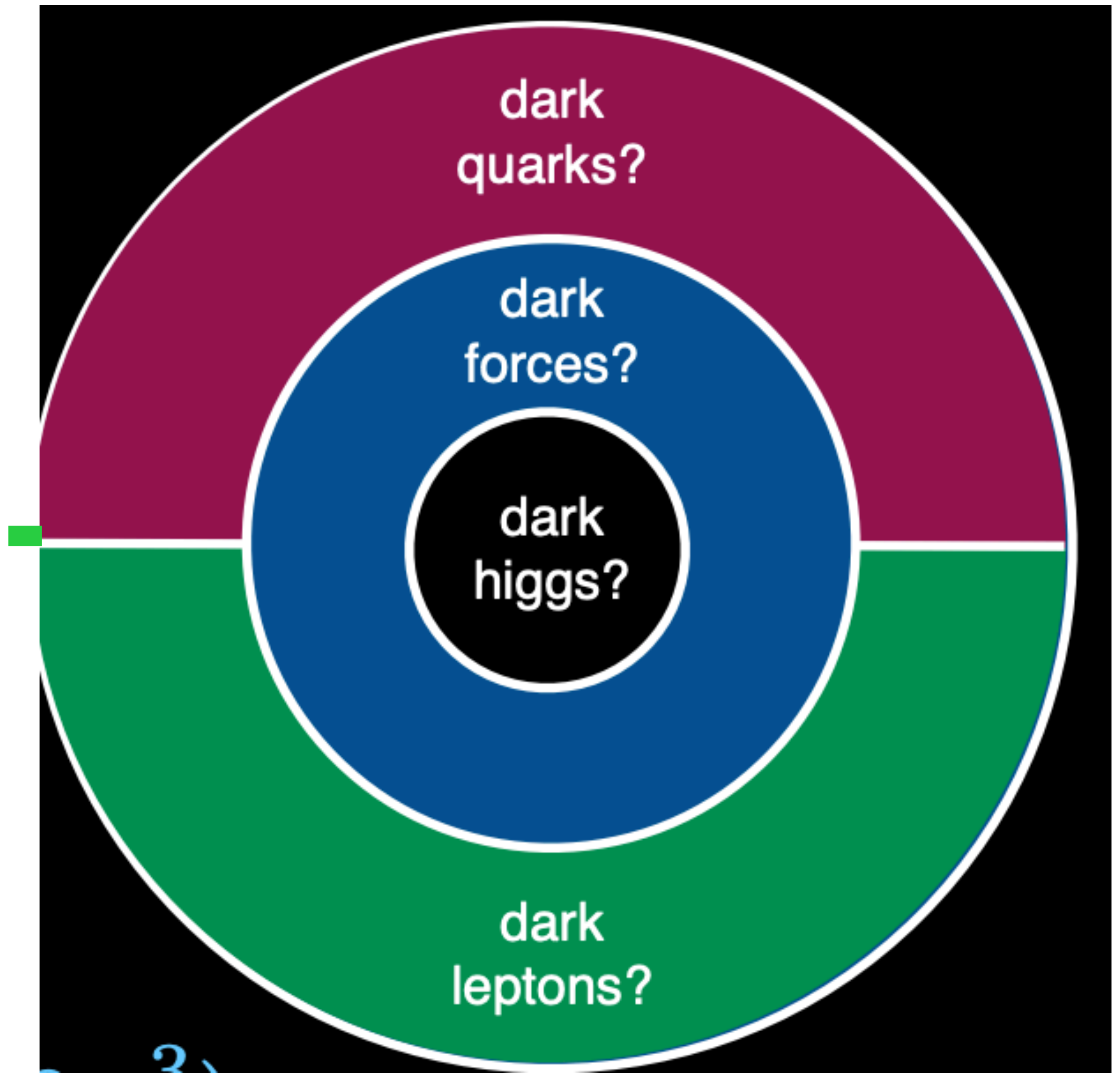


Dark (Hidden) Sector



SM

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

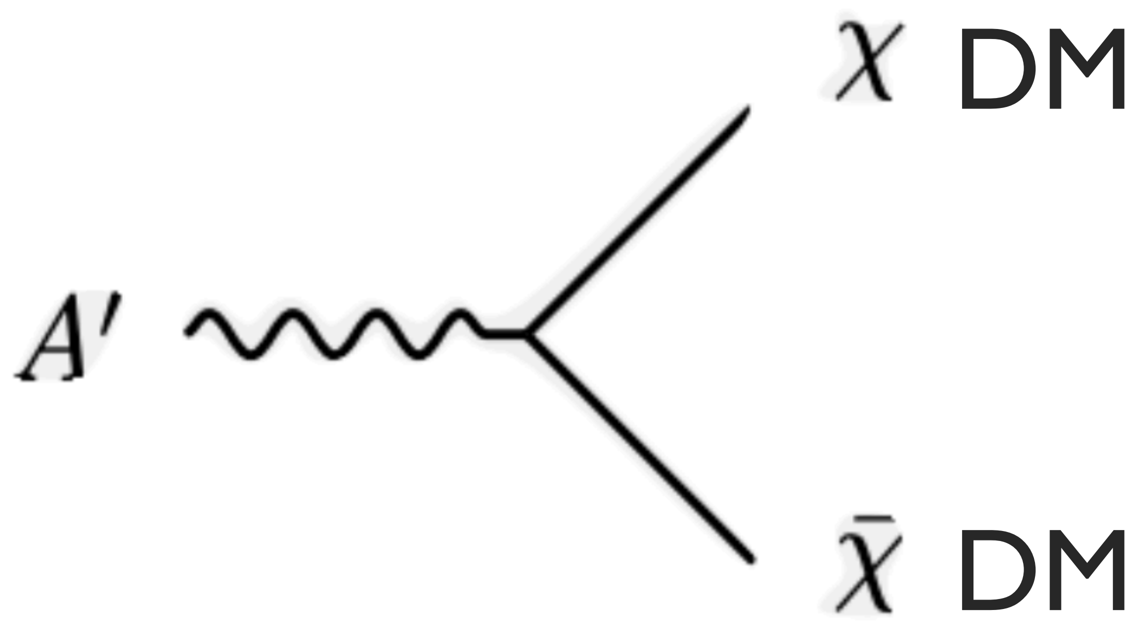


DM

- 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

How to Probe Dark Sector

How to Probe Dark Sector



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

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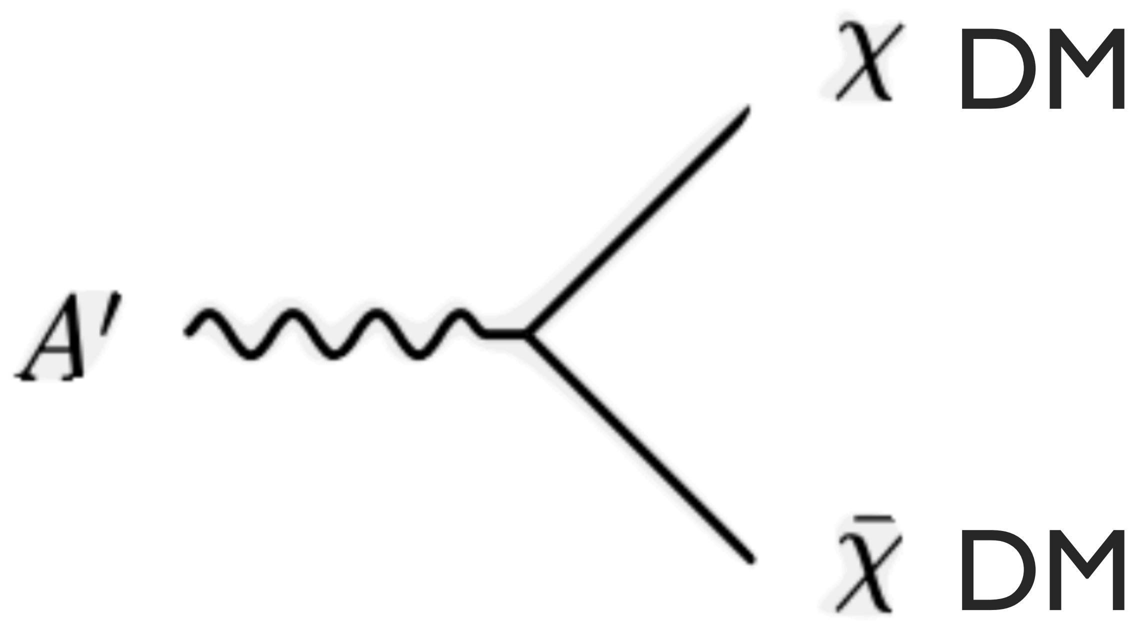

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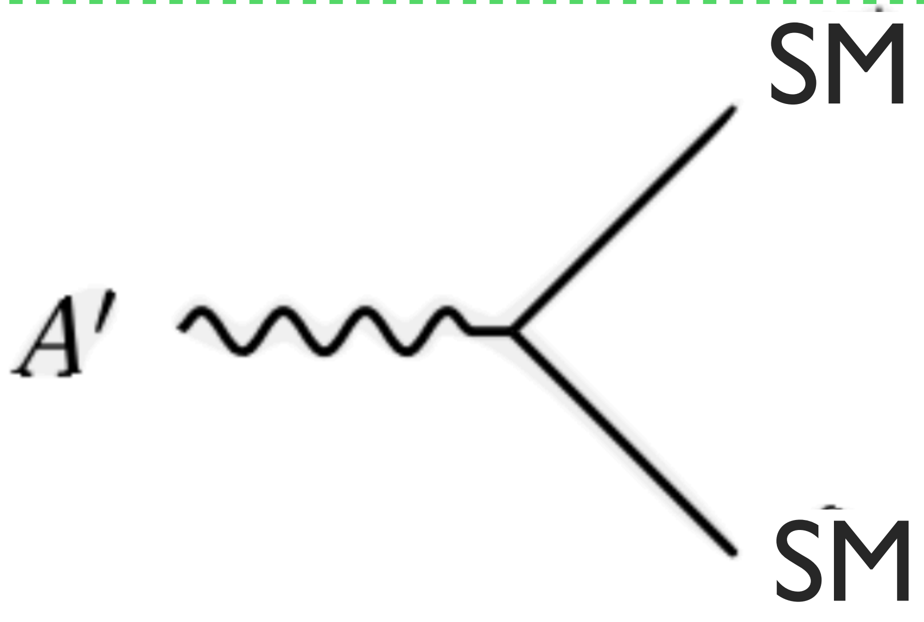
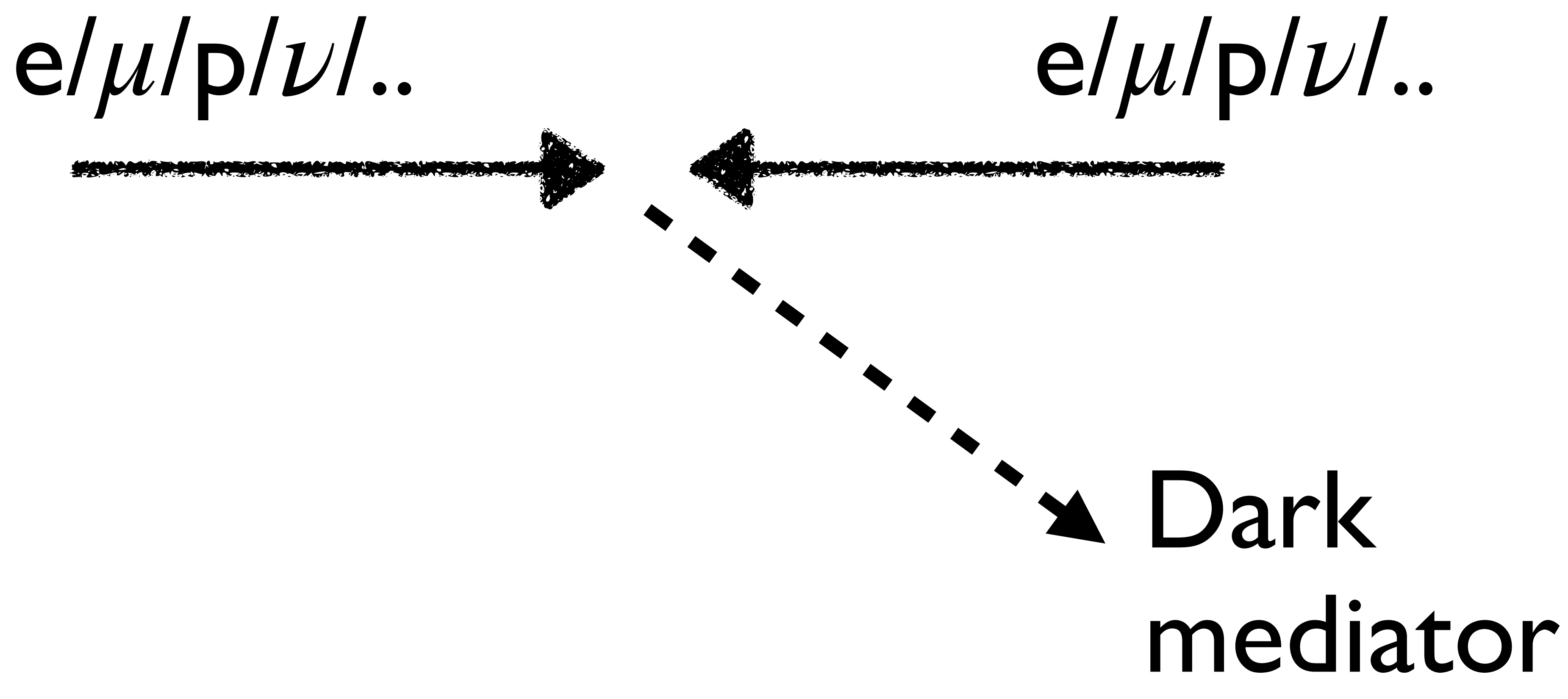


- Can probe the channel of dark mediator decaying to SM particles for the whole phase space

Probe Dark Sector with Accelerators

- Beam from accelerator: electron/muon/proton/neutrino beam

Probe Dark Sector with Accelerators



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

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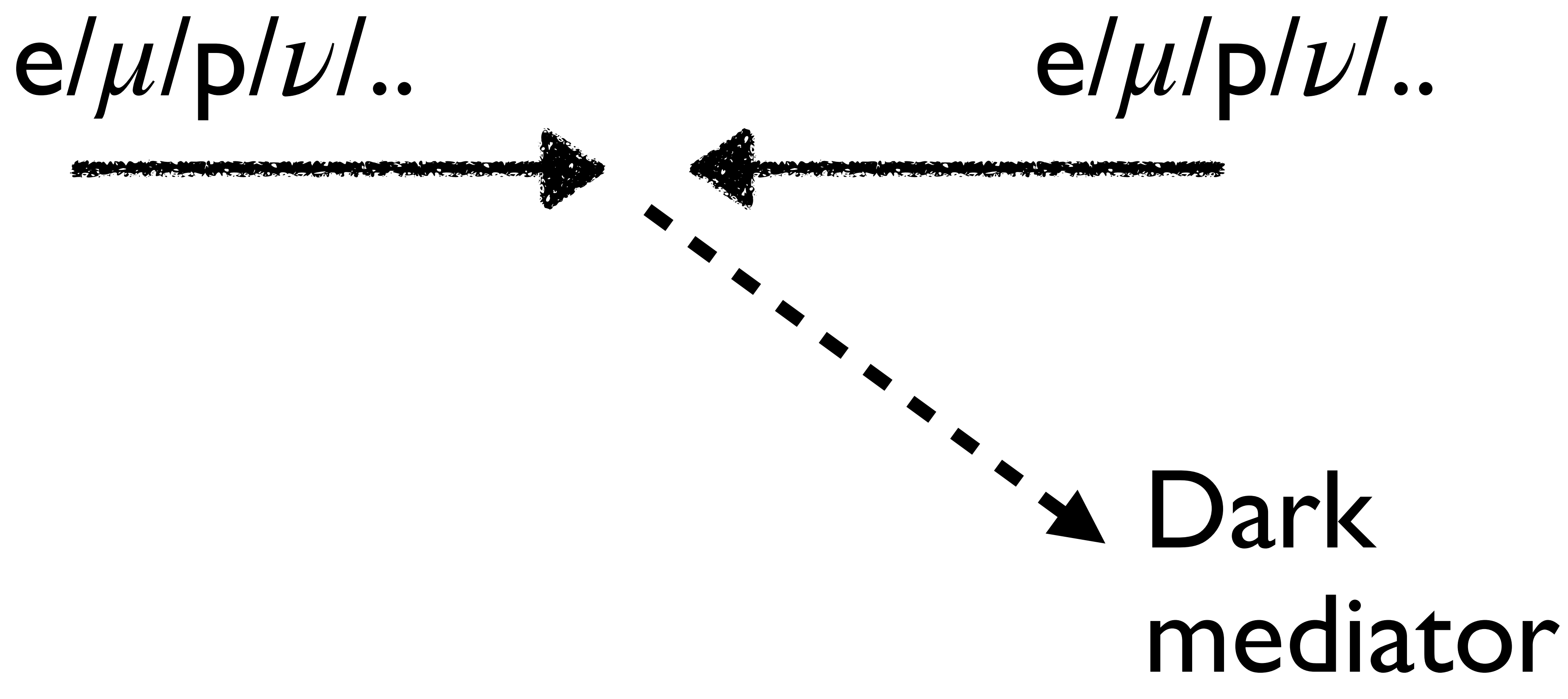

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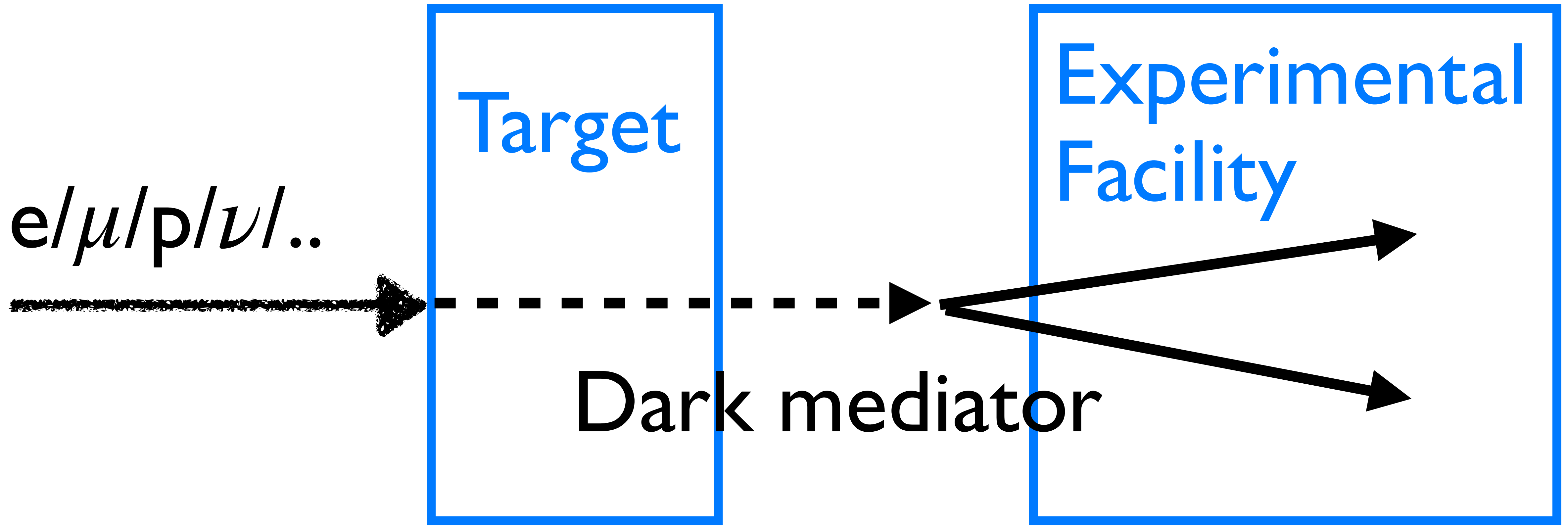
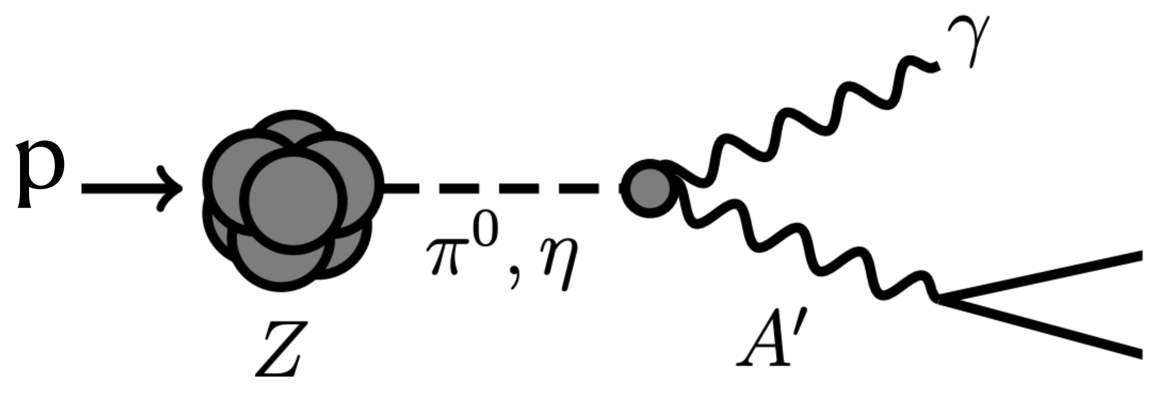
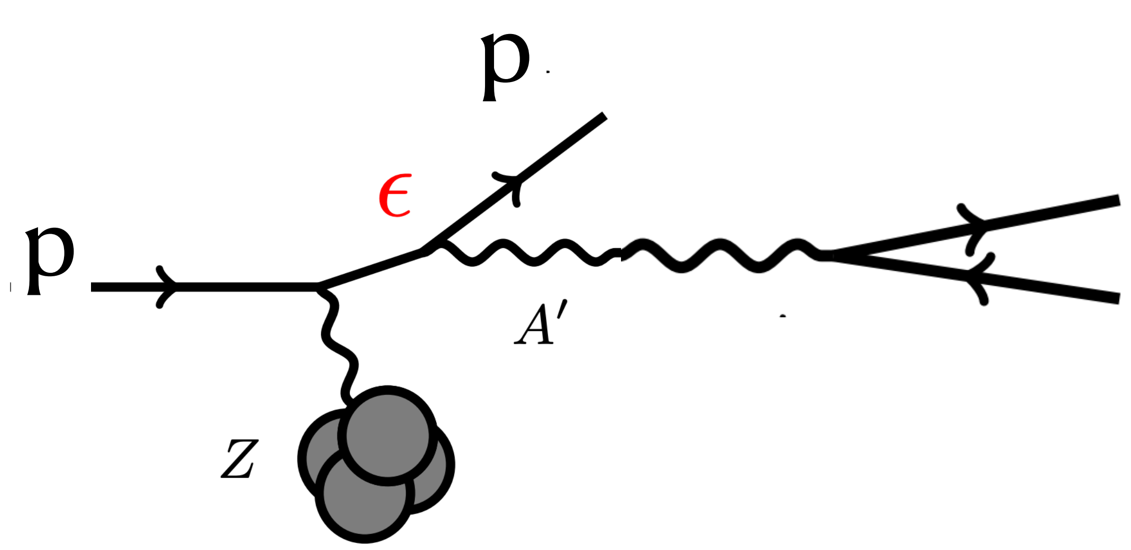


- Analyze the dark mediator decay products: bumps/displaced signals/missing E/p/m
  - NA64 @ CERN, LDMX @ SLAC, DarkQuest @ Fermilab
  - Usually low background, better sensitivity at low mass region

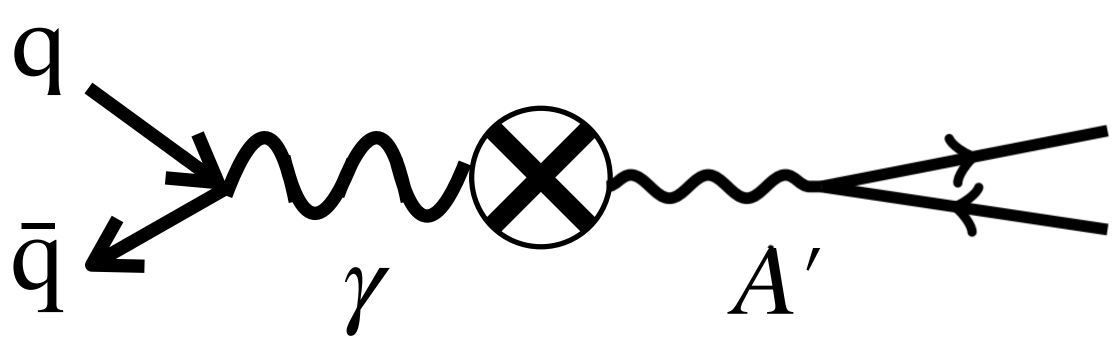
Example: Dark Photon Production with Proton fixed-target



Meson decays to A'



Proton bremsstrahlung to A'



Drell-Yan process

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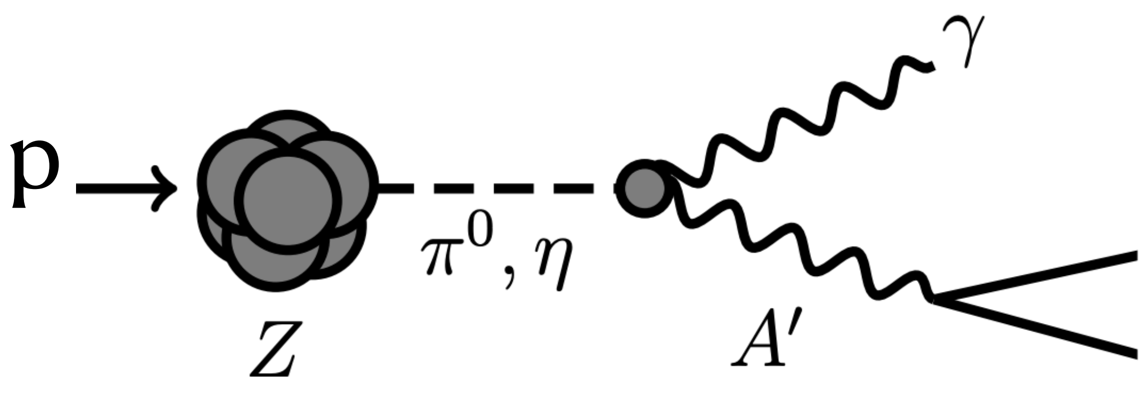
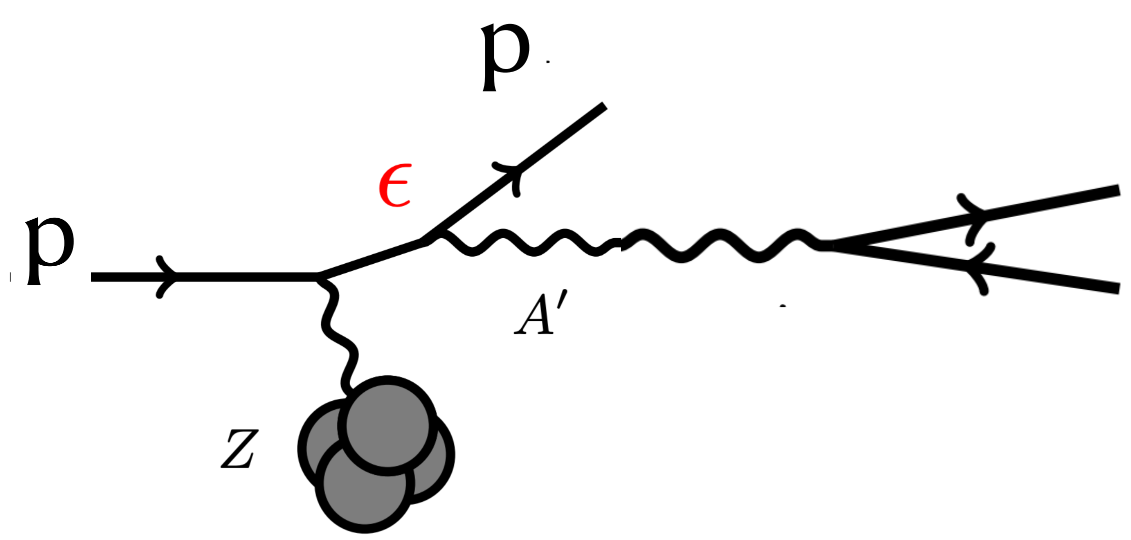
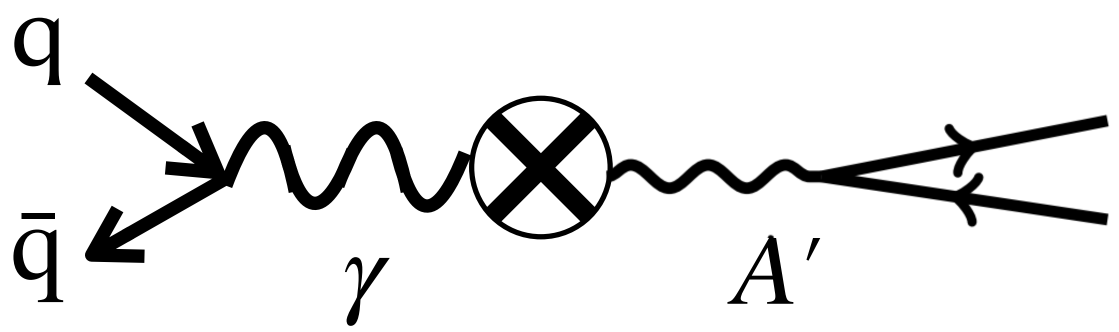
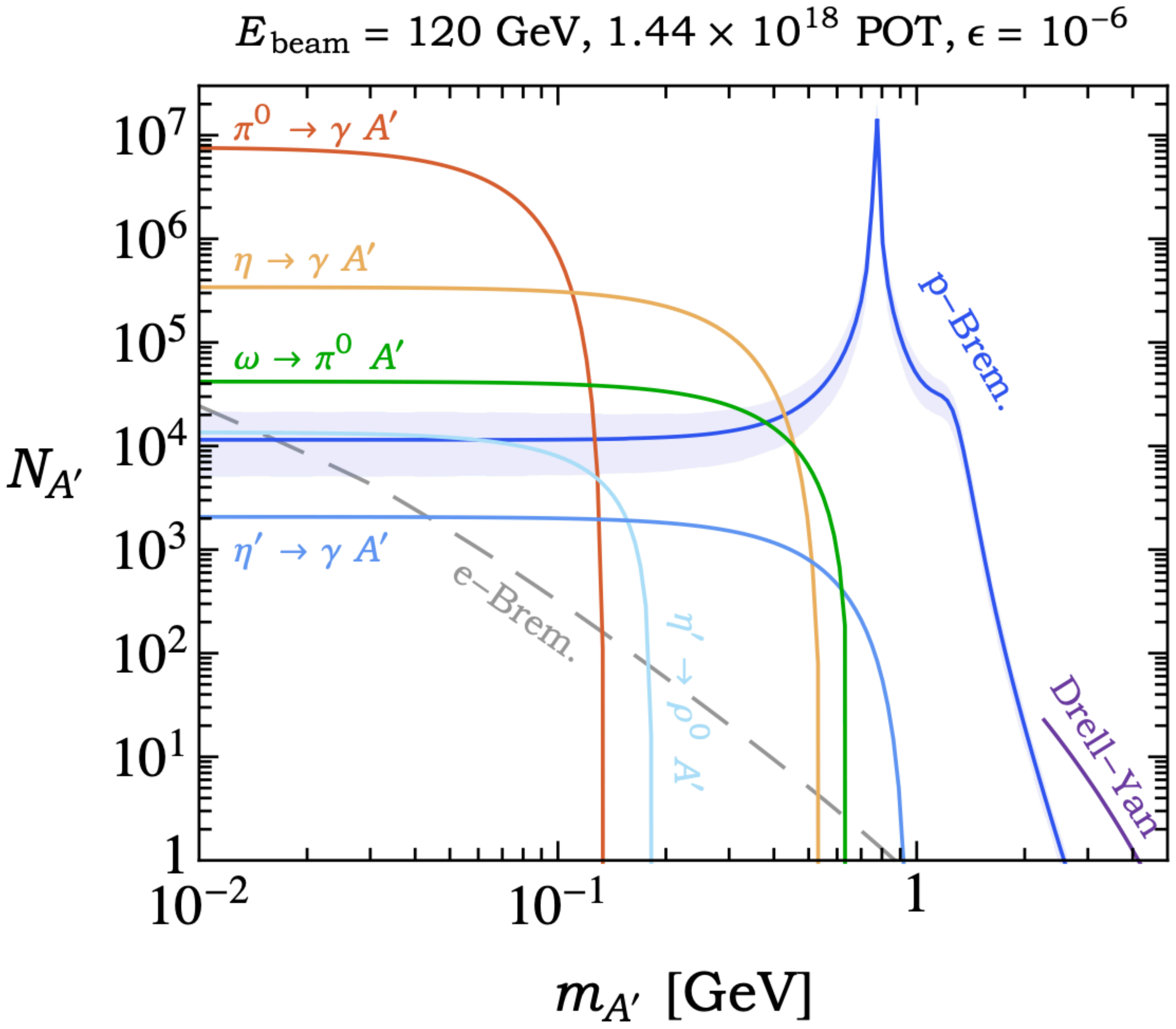




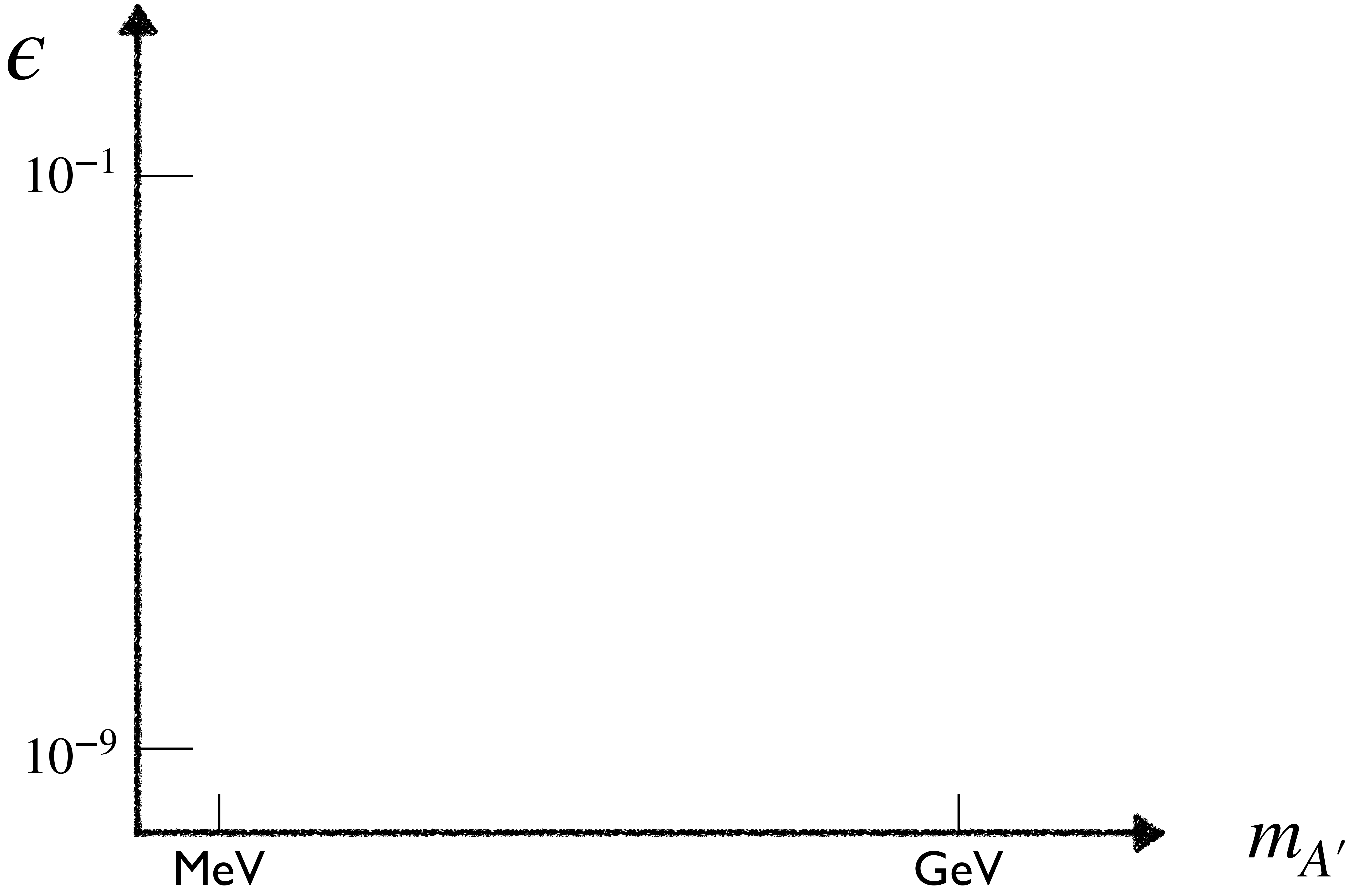




A.Berlin, S.Gori, P.Schuster, N.Toro Arxiv:1804.00661

- Larger production rates with proton beams compared with electron beams

Dark Photon Phase Space



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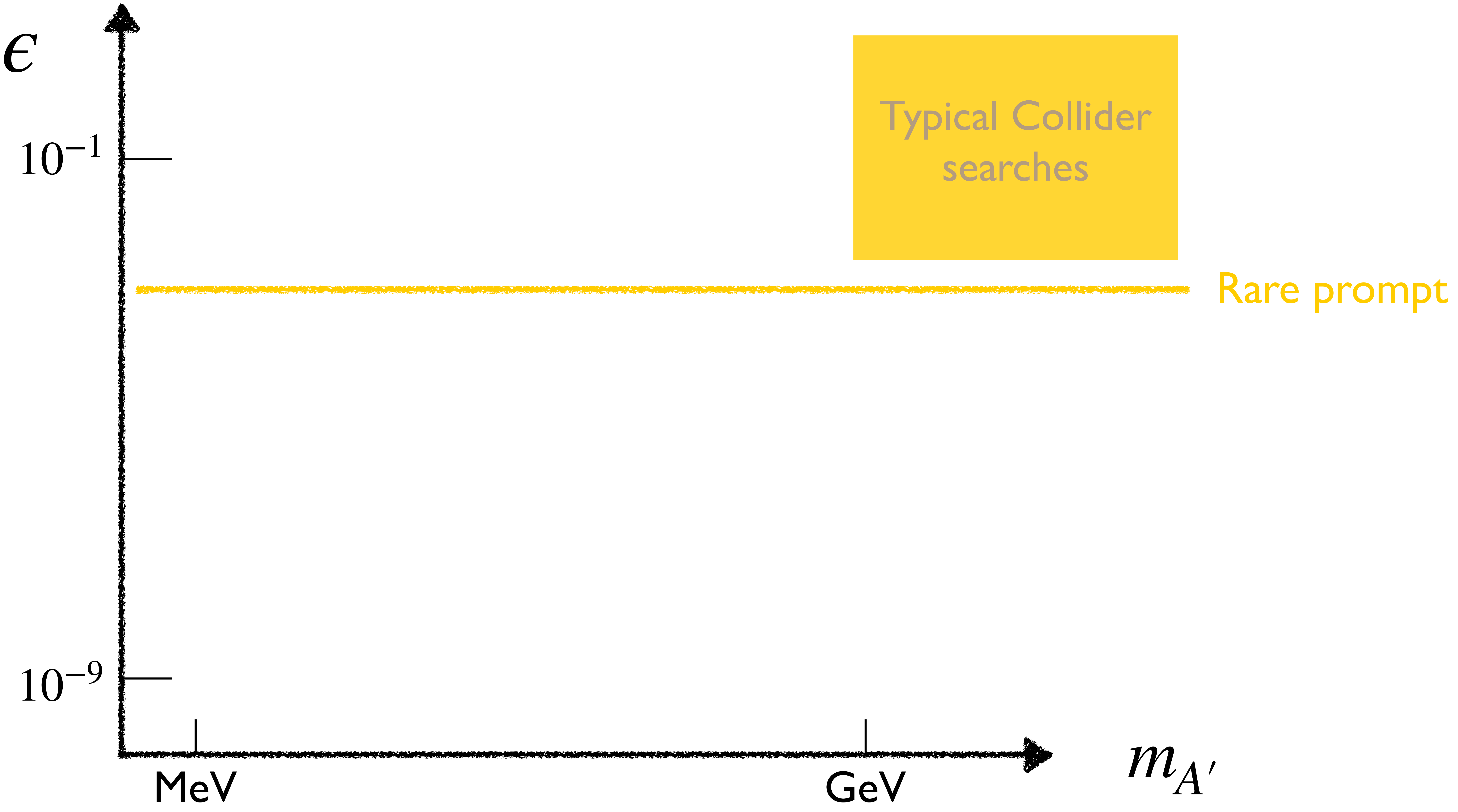

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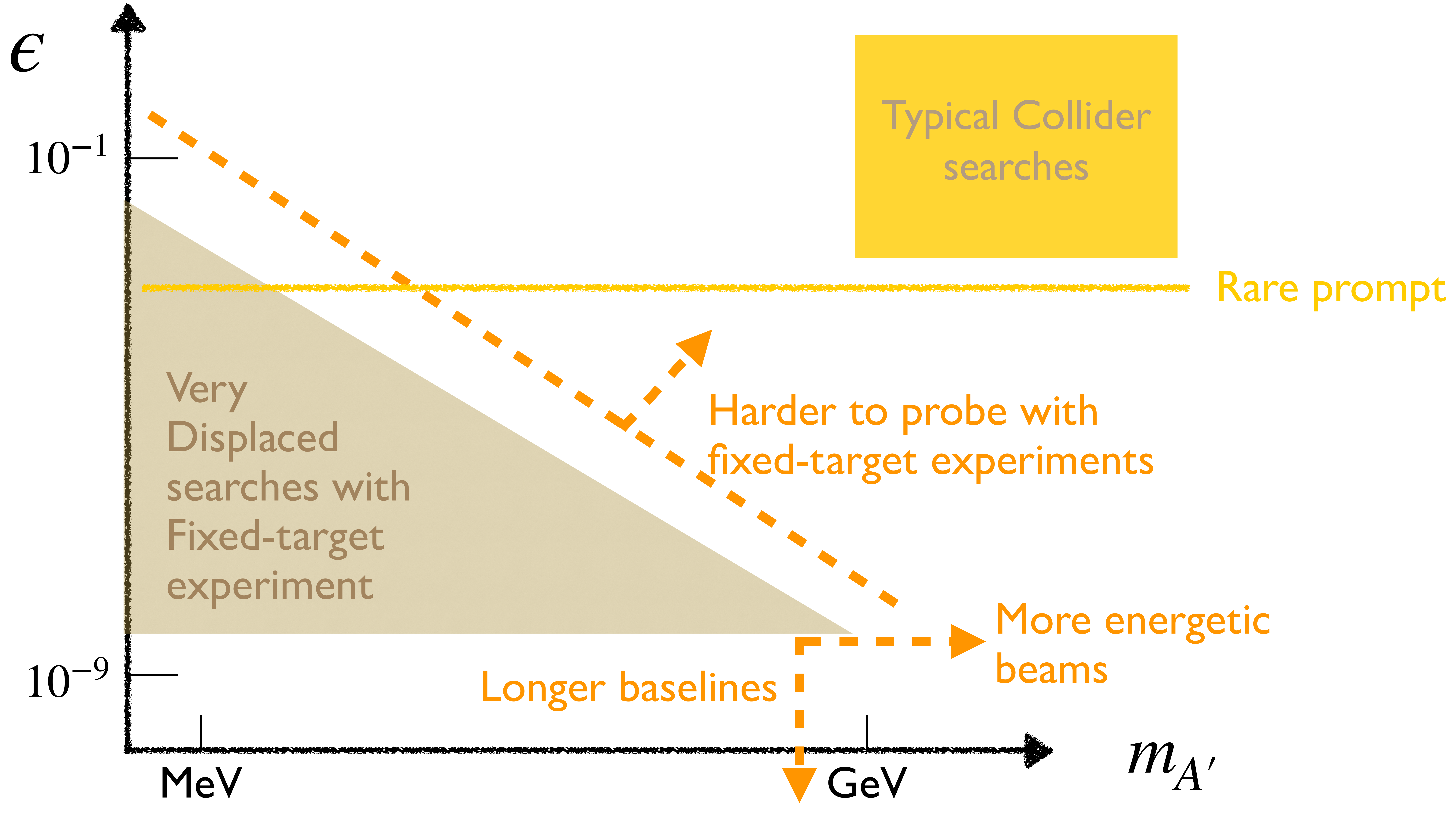

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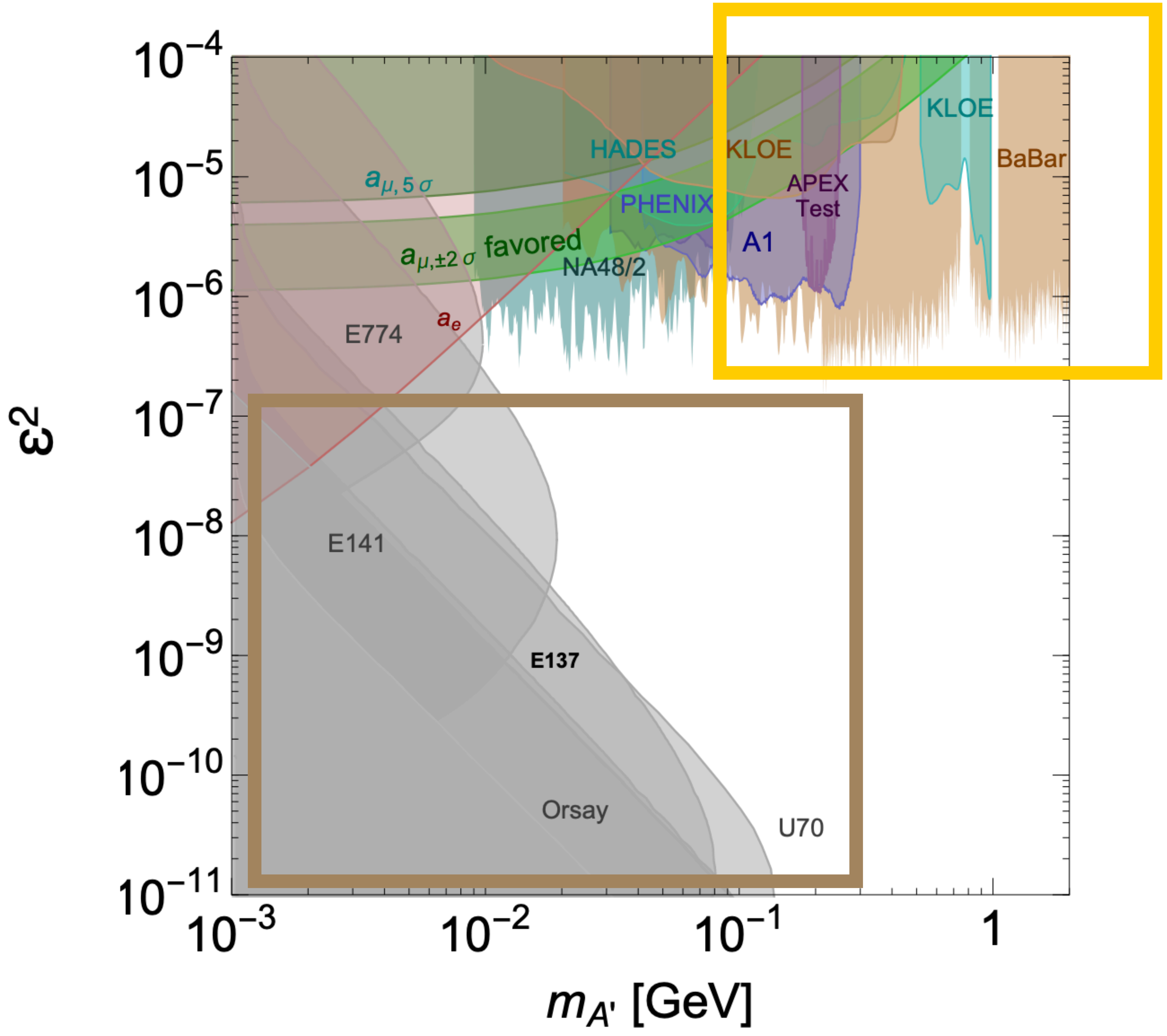

Short Summary

- Thermal dark matter is a “natural” dark matter candidate

- MeV-GeV scale light dark matter and dark sectors are promising and mostly unconstrained yet

- Fixed-target experiments provide an unique and very sensitive way to probe this light dark matter and dark sector region

- Dark Sector:
    - What? Why? How?

- DarkQuest:
    - Proton fixed-target experiment based on SpinQuest
    - How to use DarkQuest to probe dark sectors:
        - ➡ Spectrometer upgrades
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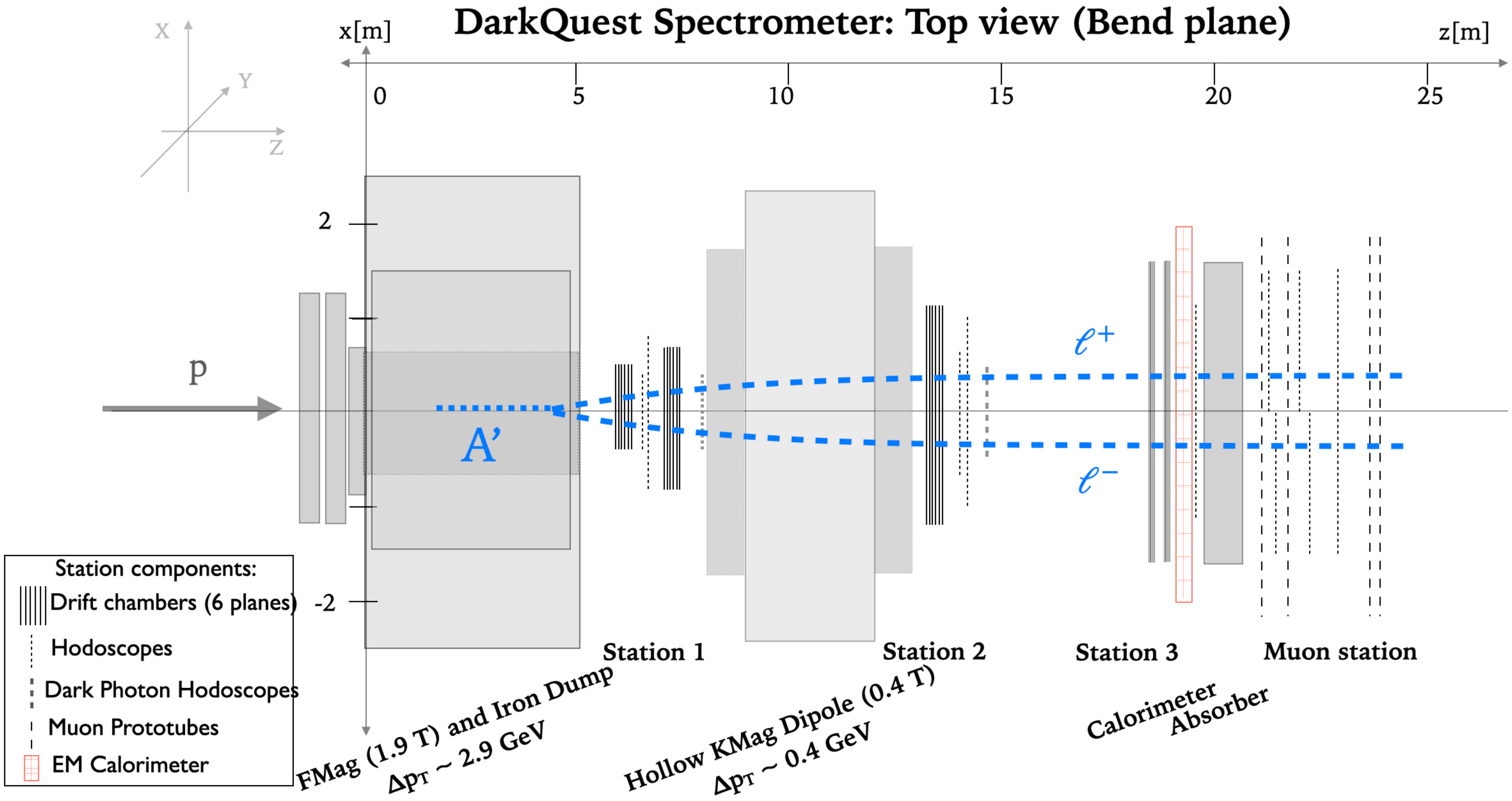
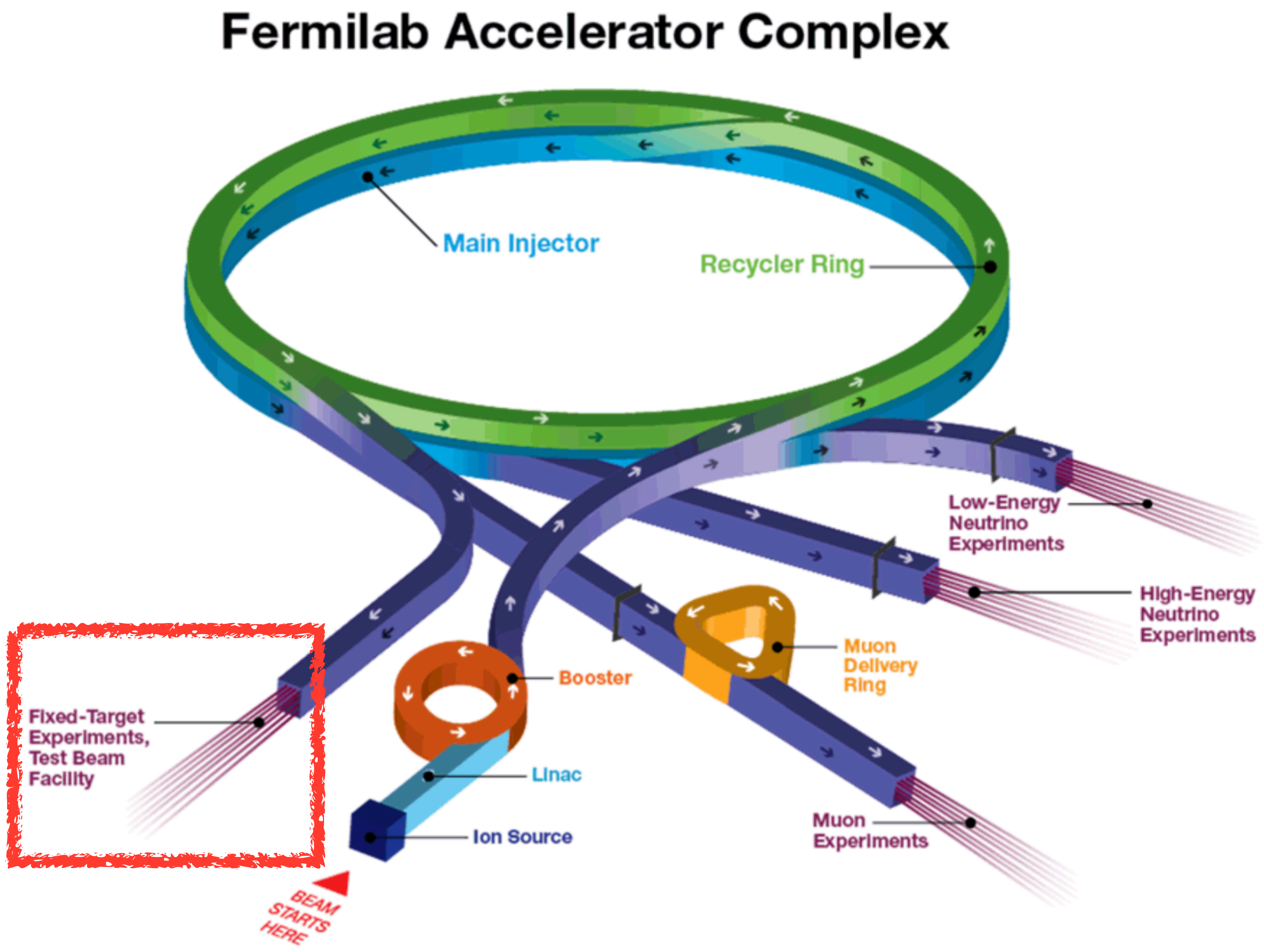
DarkQuest



- 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
  - Expect 10^{18} Protons on target (POT) in a 2-year parasitic run
  - 10^{20} POT for longer term runs

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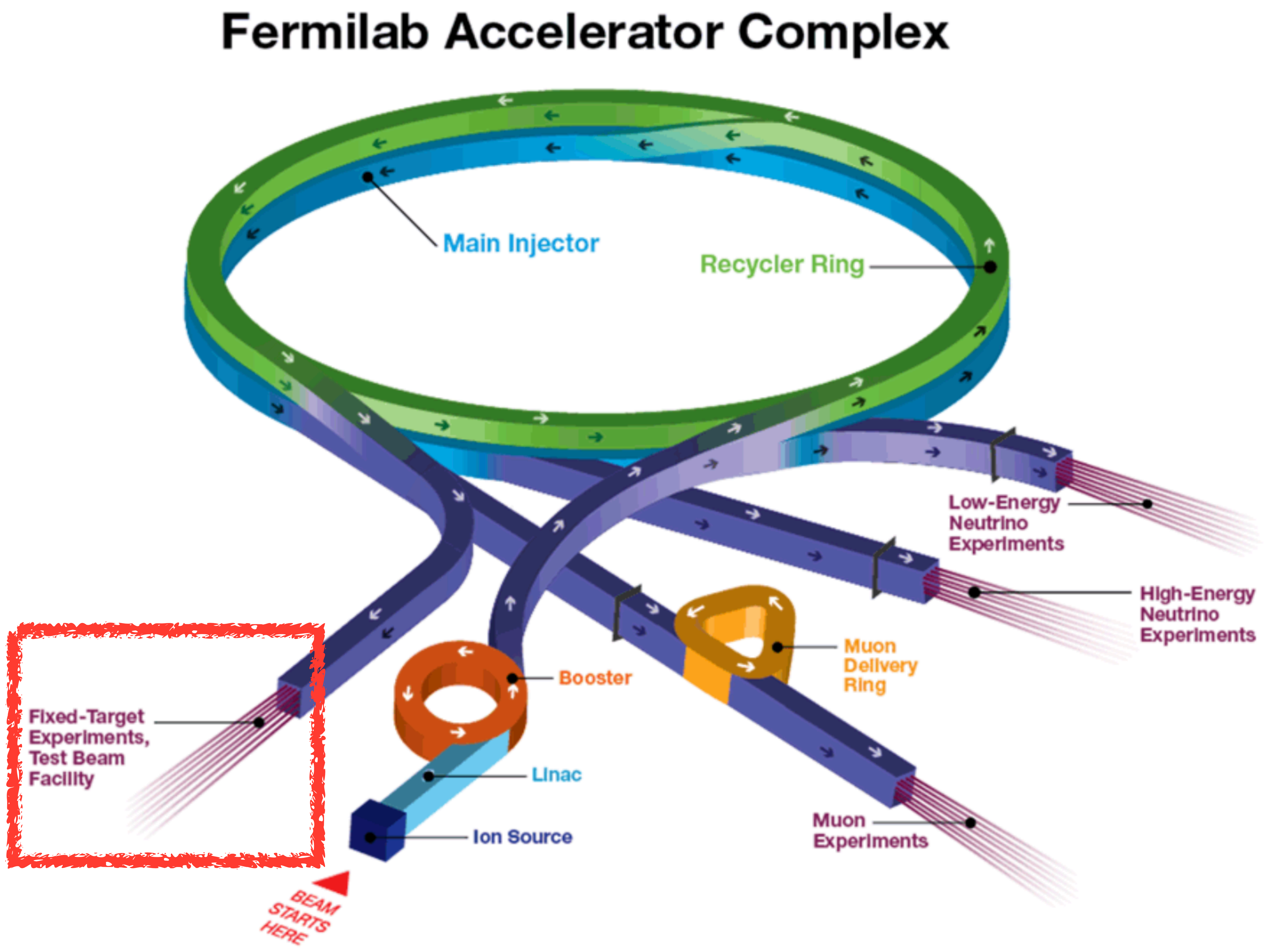

- LHC 13TeV run: ~150 fb^{-1} of data, inelastic scattering σ ~ 80 mb. This brings to about 10^{16} "protons on target"

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SpinQuest Spectrometer

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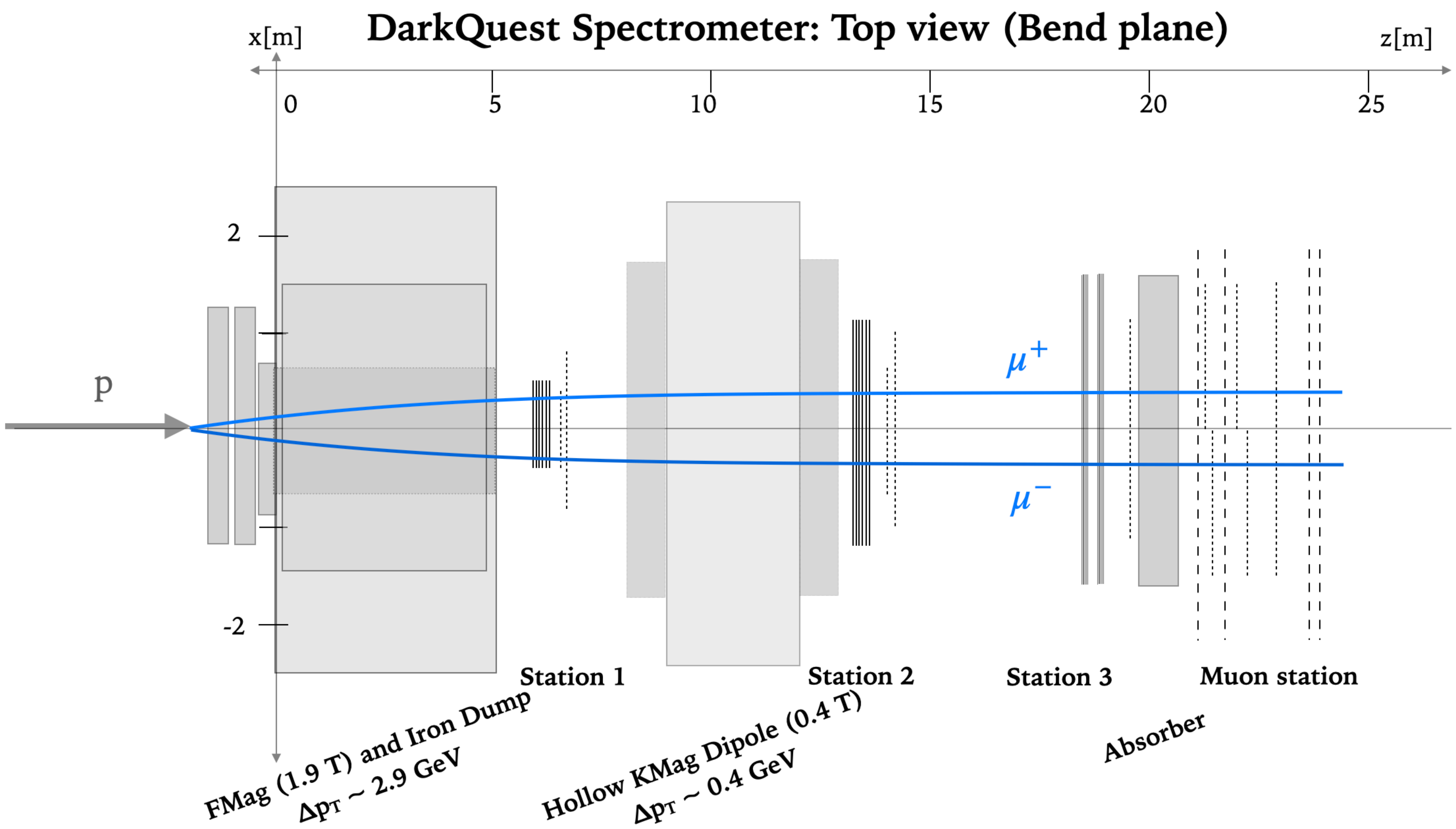
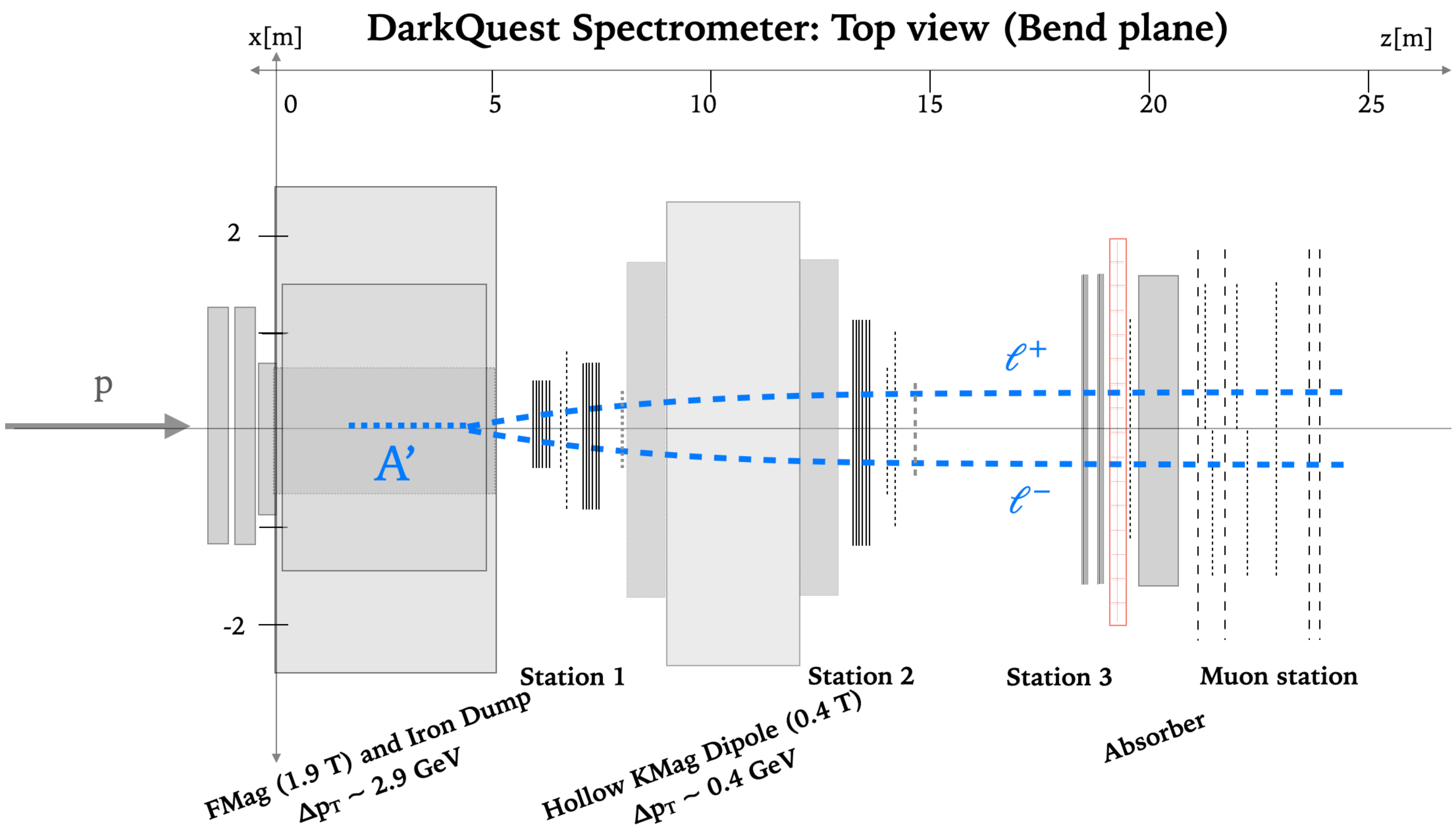


- SpinQuest spectrometer:
  - FMag: beam dump and absorber;
  - Hollow KMag + 4 stations of drift chambers: tracking
  - Scintillator hodoscopes: triggering
  - Muon station: tagging muons

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

DarkQuest Spectrometer



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- Upgrades on SpinQuest:

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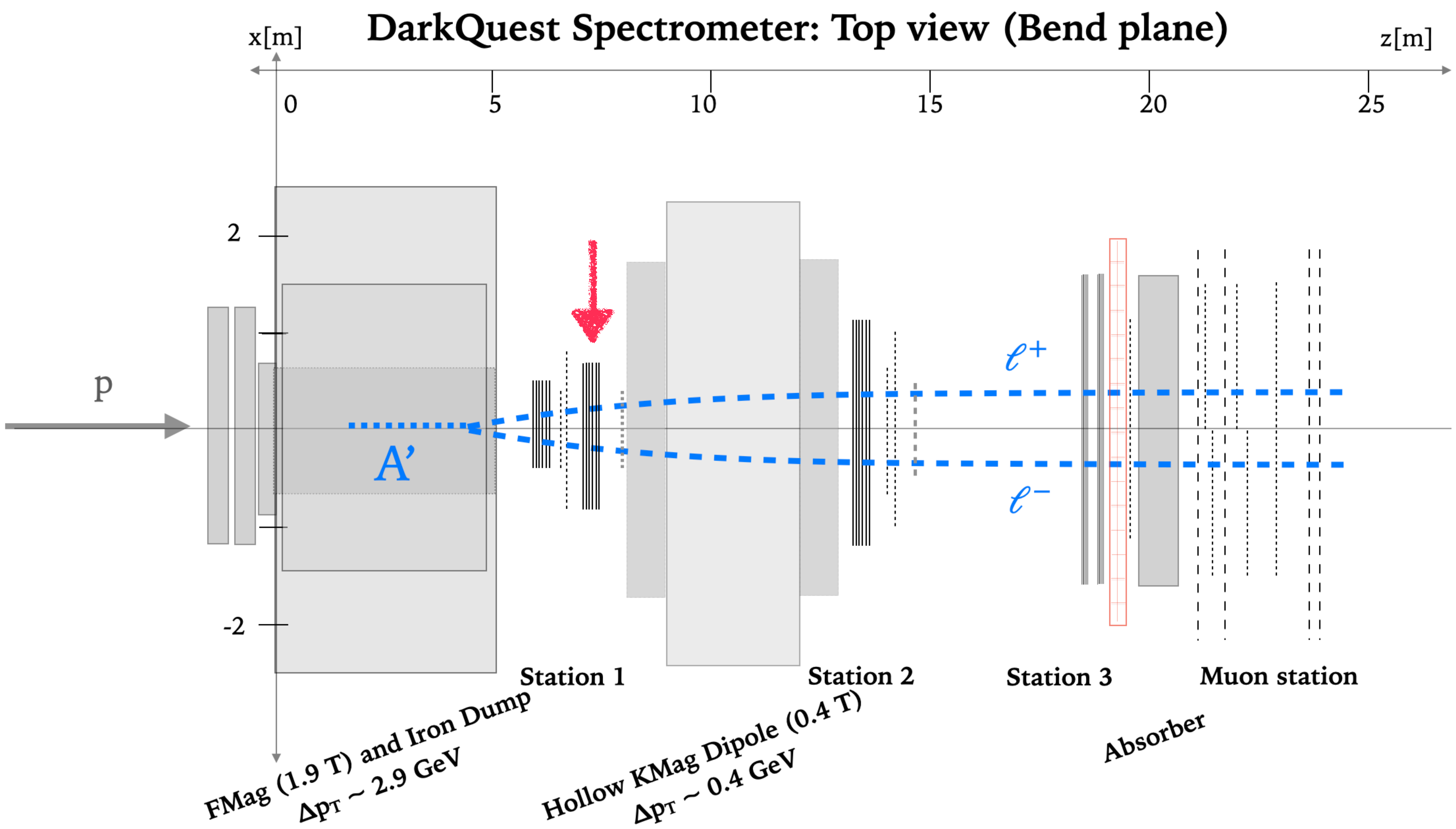

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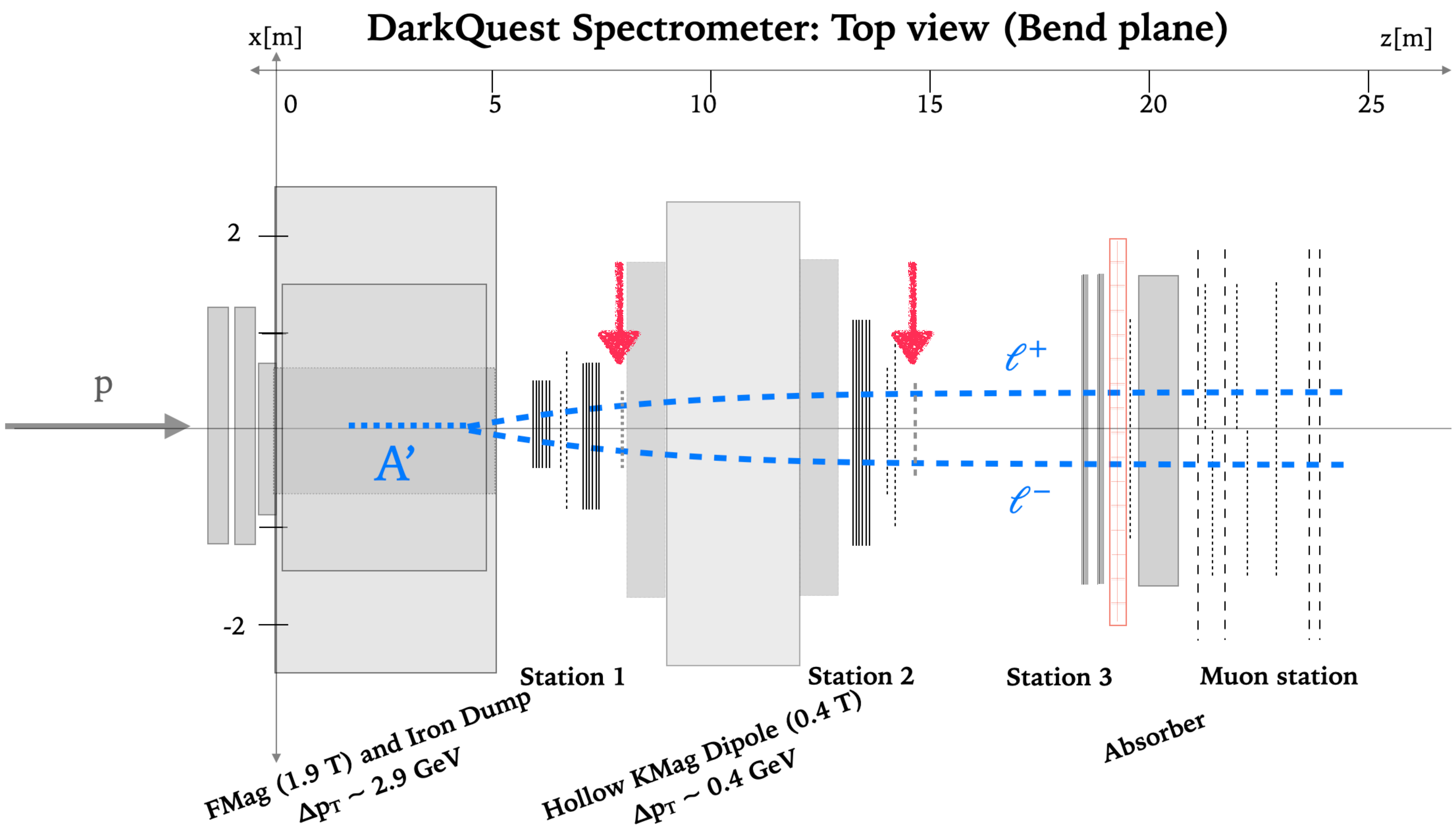

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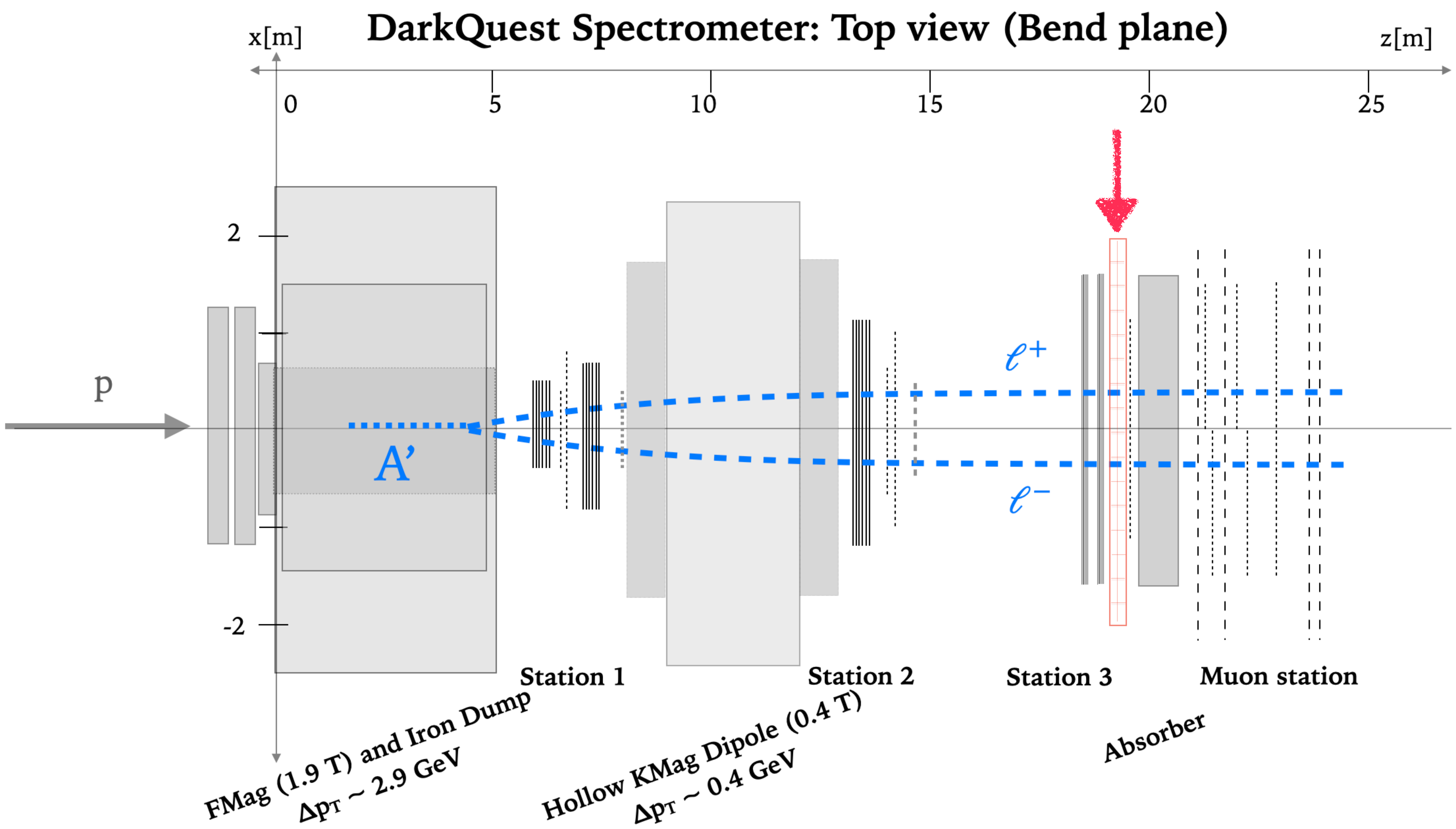
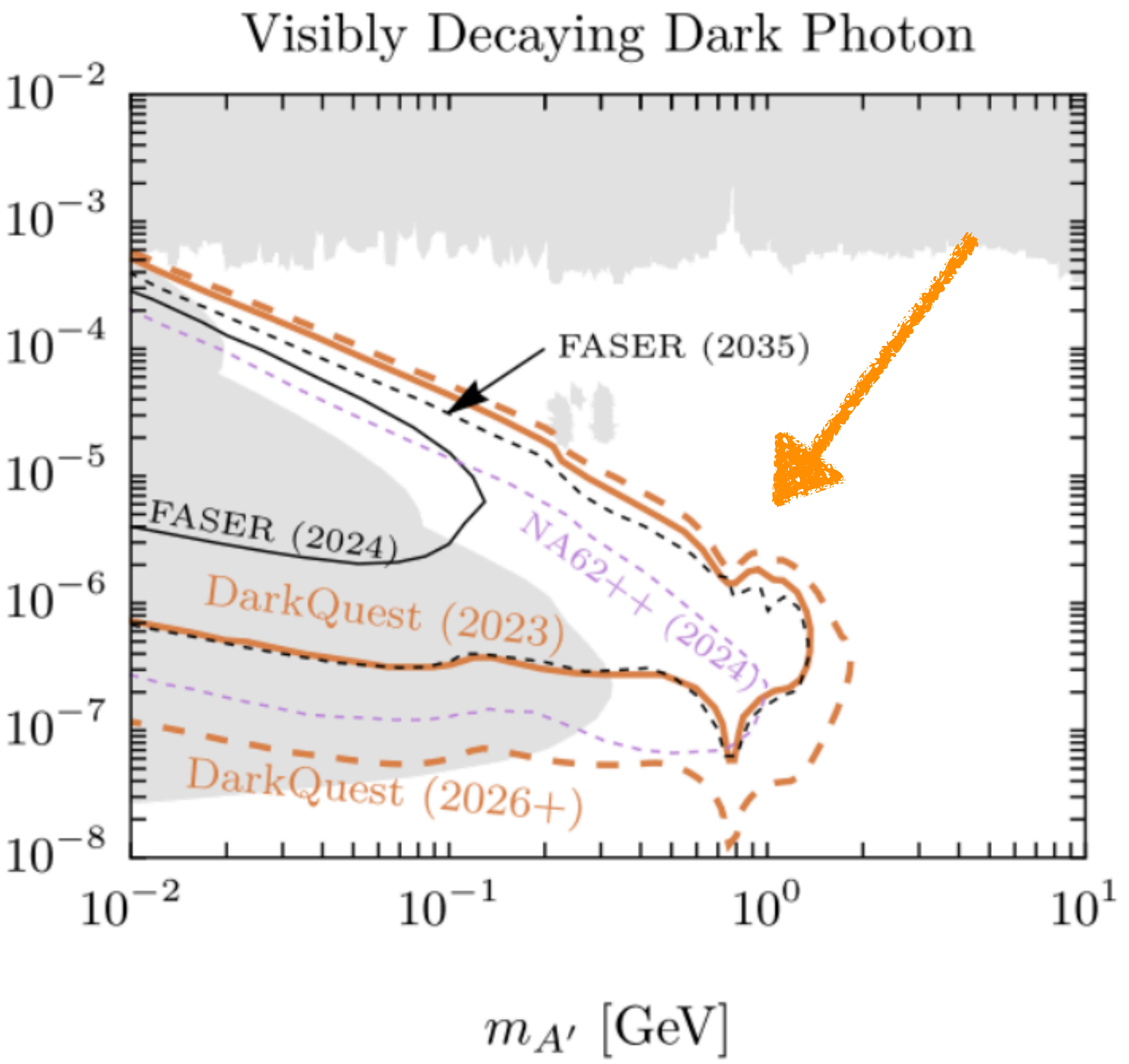


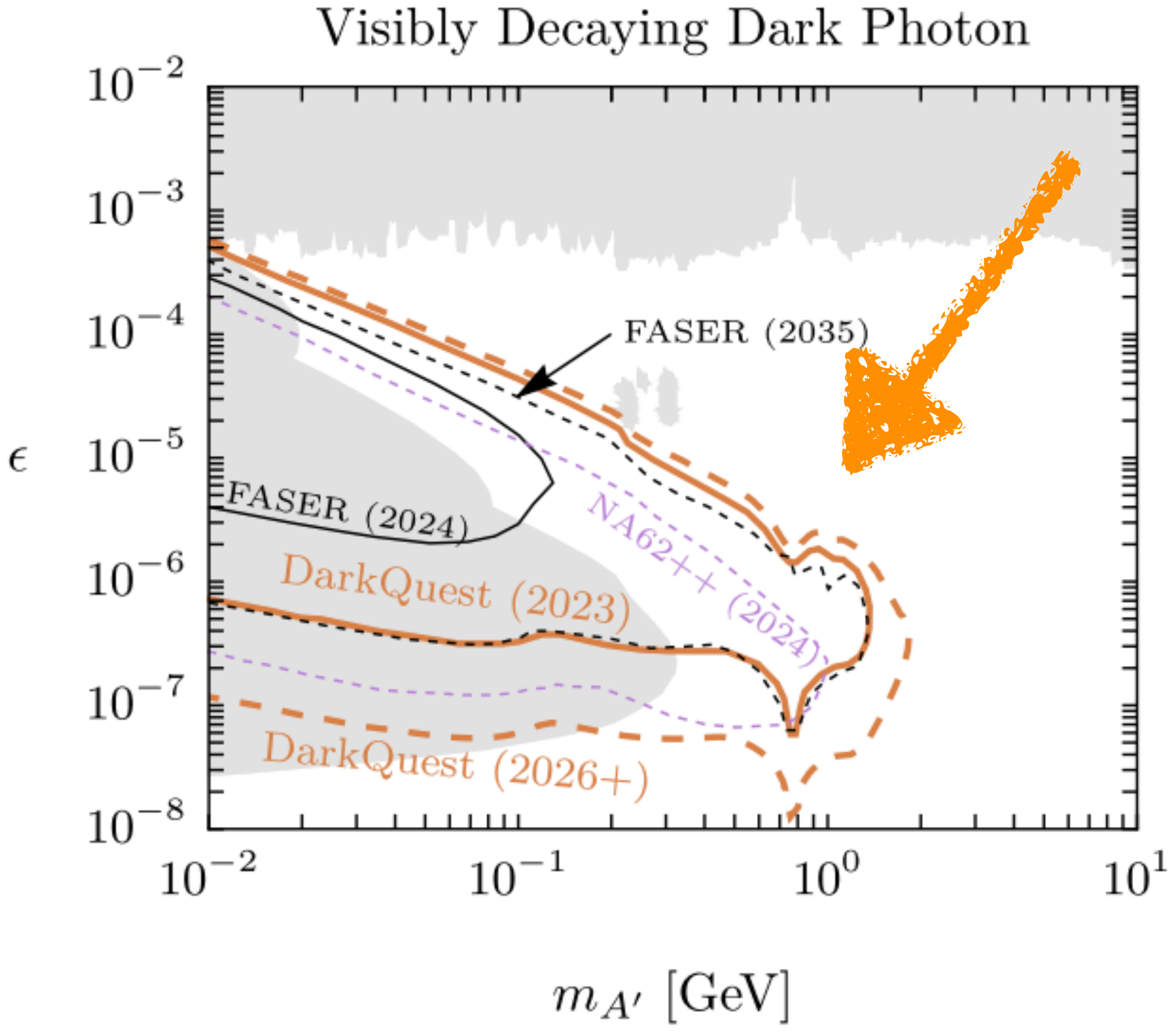
- DarkQuest spectrometer:
  - Probing dark sector by looking at displaced signals
- Upgrades on SpinQuest:
  - Additional tracking layers from HyperCP experiment
  - Hodoscopes to trigger on displaced signals
  - EMCal from PHENIX experiment: to trigger and reco electrons and photons, leading to more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

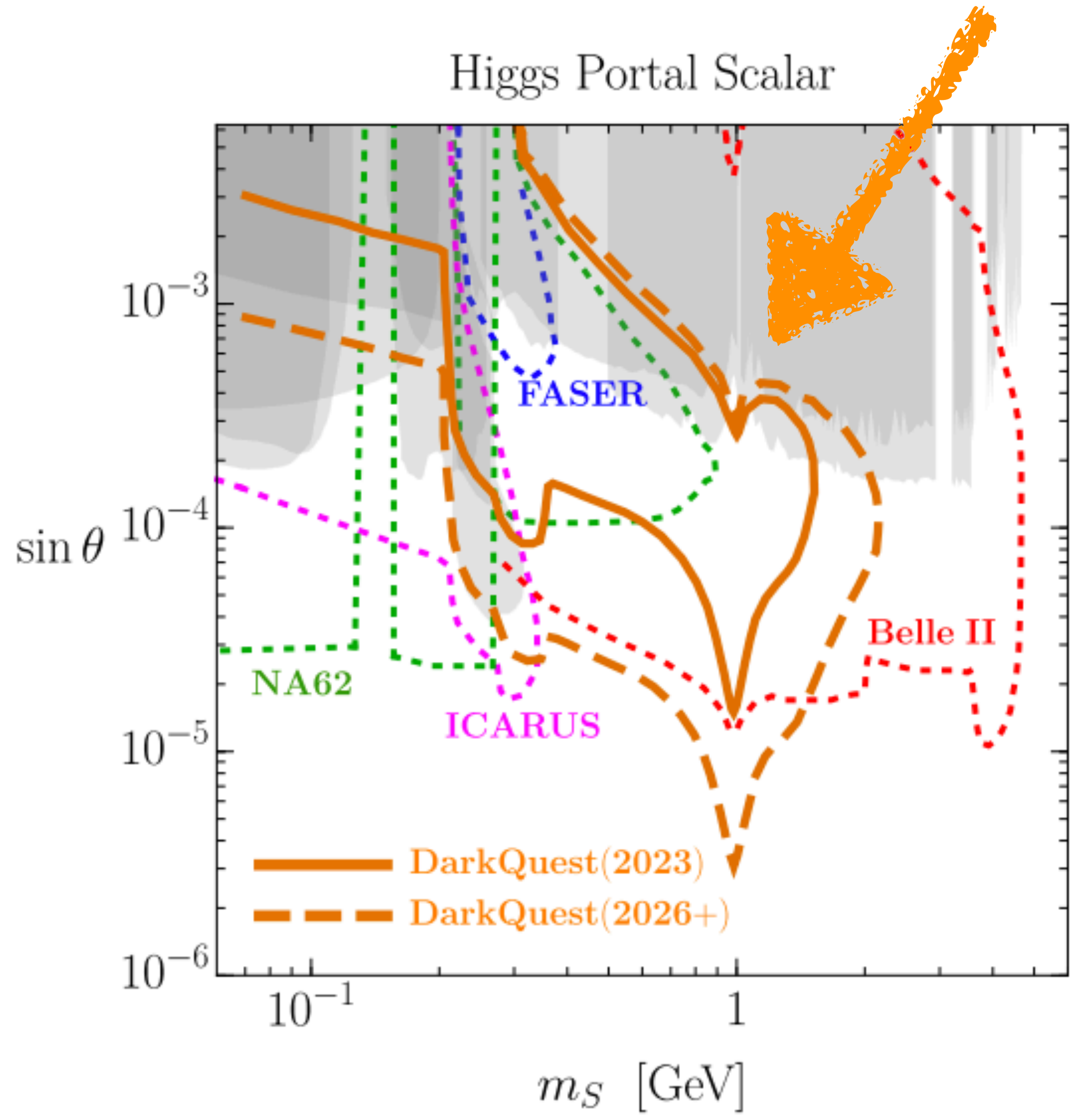
Why DarkQuest

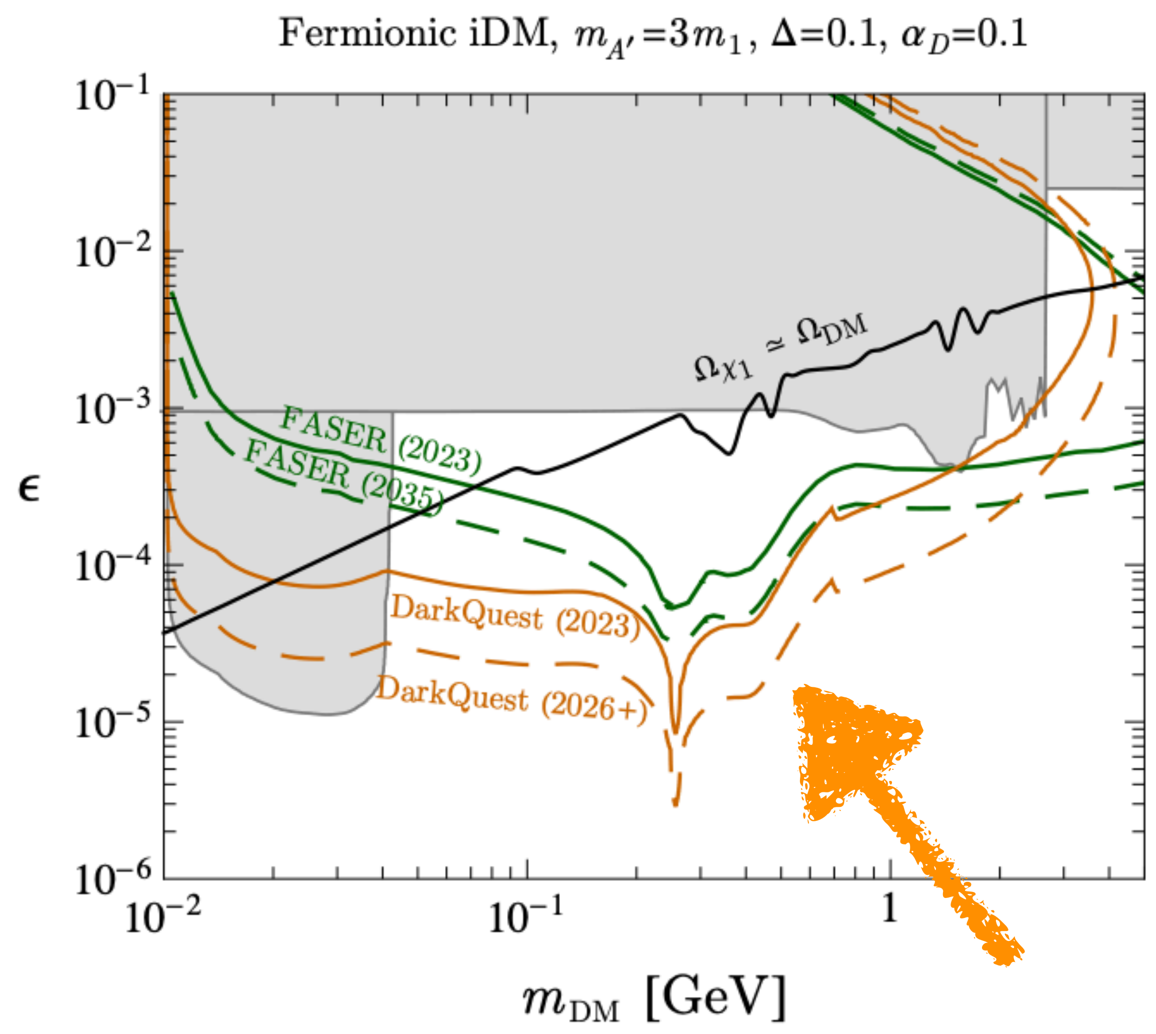


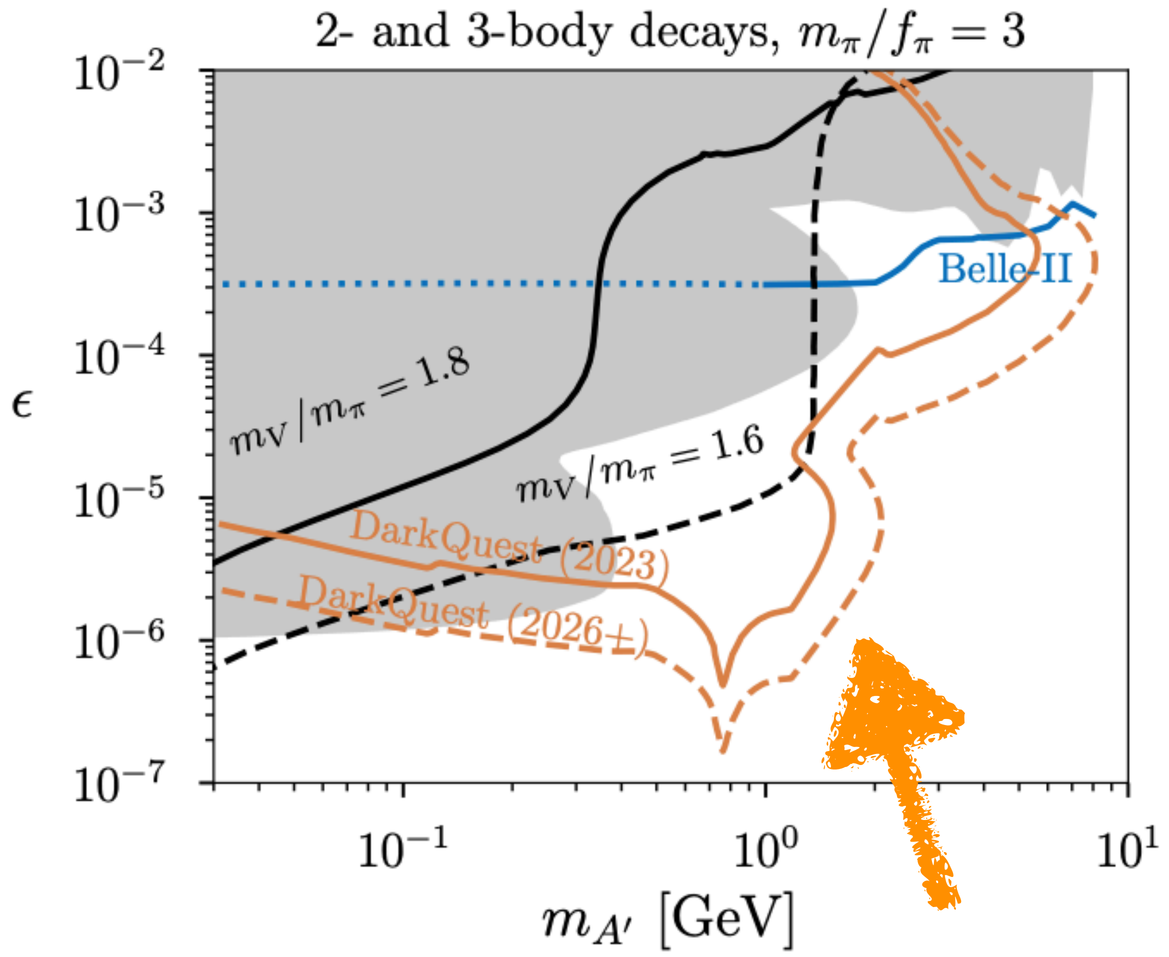
- Large dark sector production cross section with 120GeV high-intensity proton beam
- Compact geometry and relatively short displacement baseline (5m) to cover unique and broad phase spaces
- Most of the experimental components already exist, very low cost: ~1M

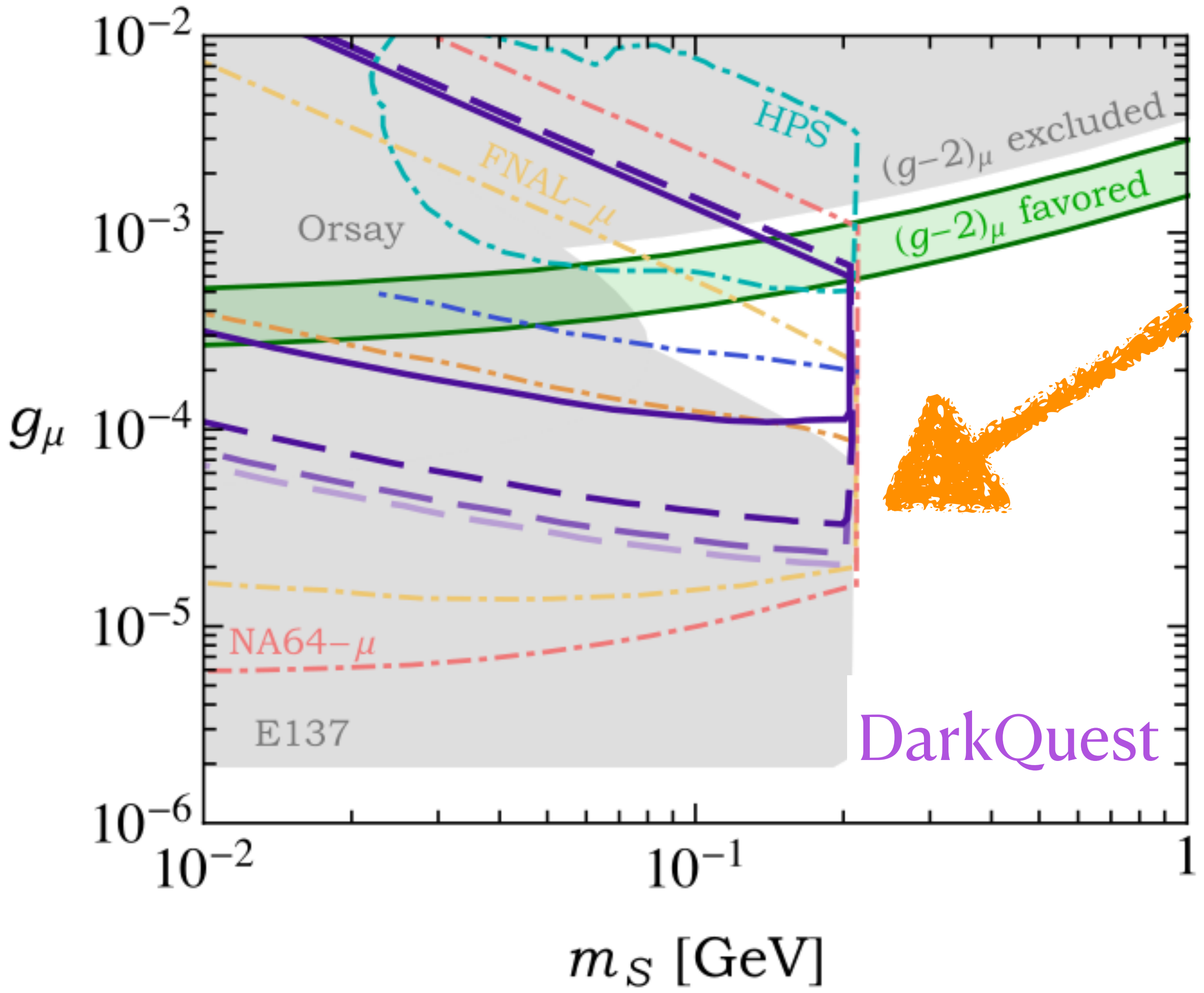
Broad Sensitivity Coverage

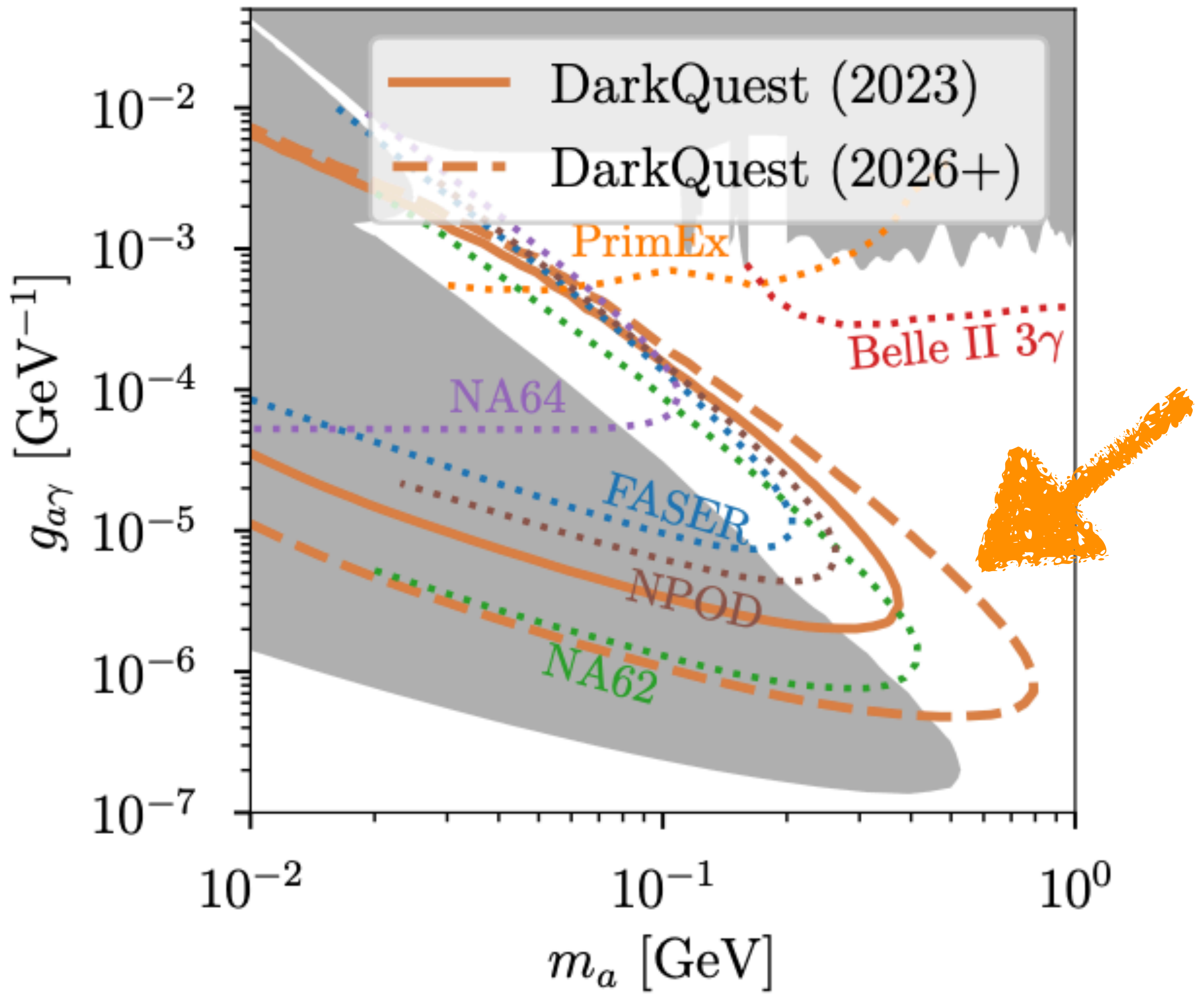












- Broad coverage to different theory models,
  - Different portals: scalar, vector, neutrino, axion-like, etc, by probing lepton/hadrons
  - Arxiv.1804.00661, Arxiv.2008.08108, Arxiv.1801.05805

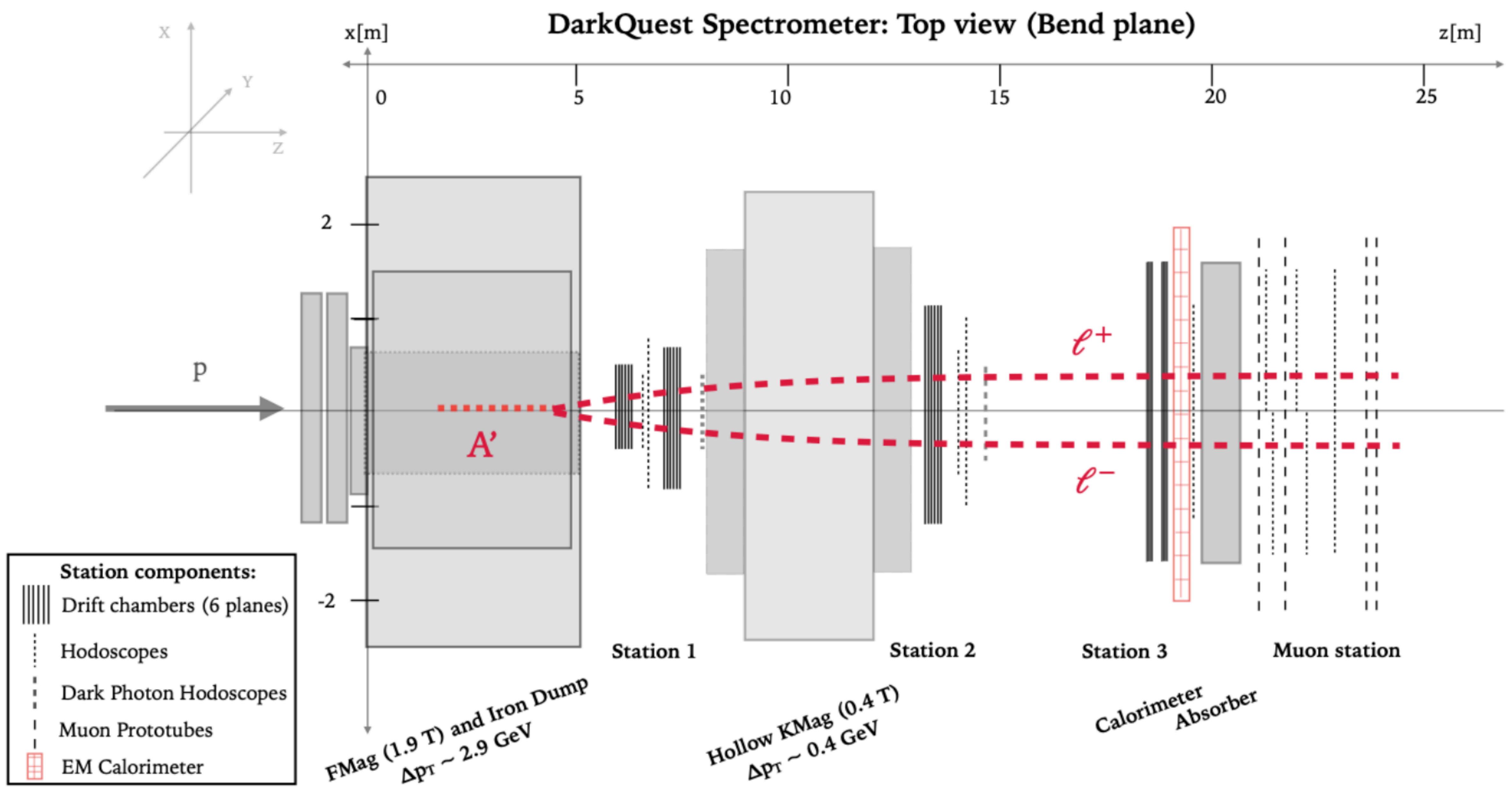
List of Studies

- Detector: EMCal integration into the spectrometer

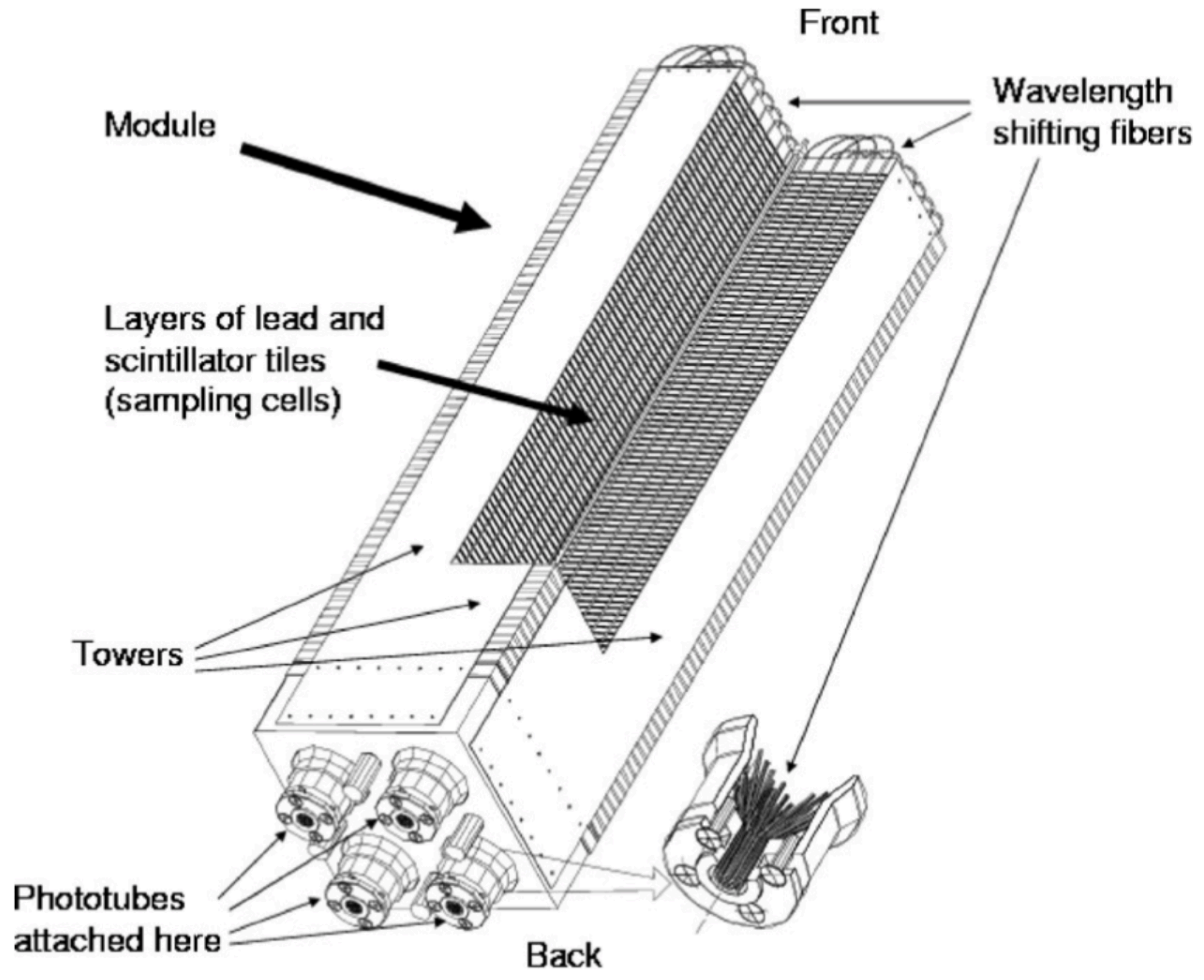
- Geant-based Simulations:
  - EMCal simulations
  - Triggering
  - Tracking & vertexing
  - ParticleID: tracking + calorimeter information

- Acceptances & Sensitivity

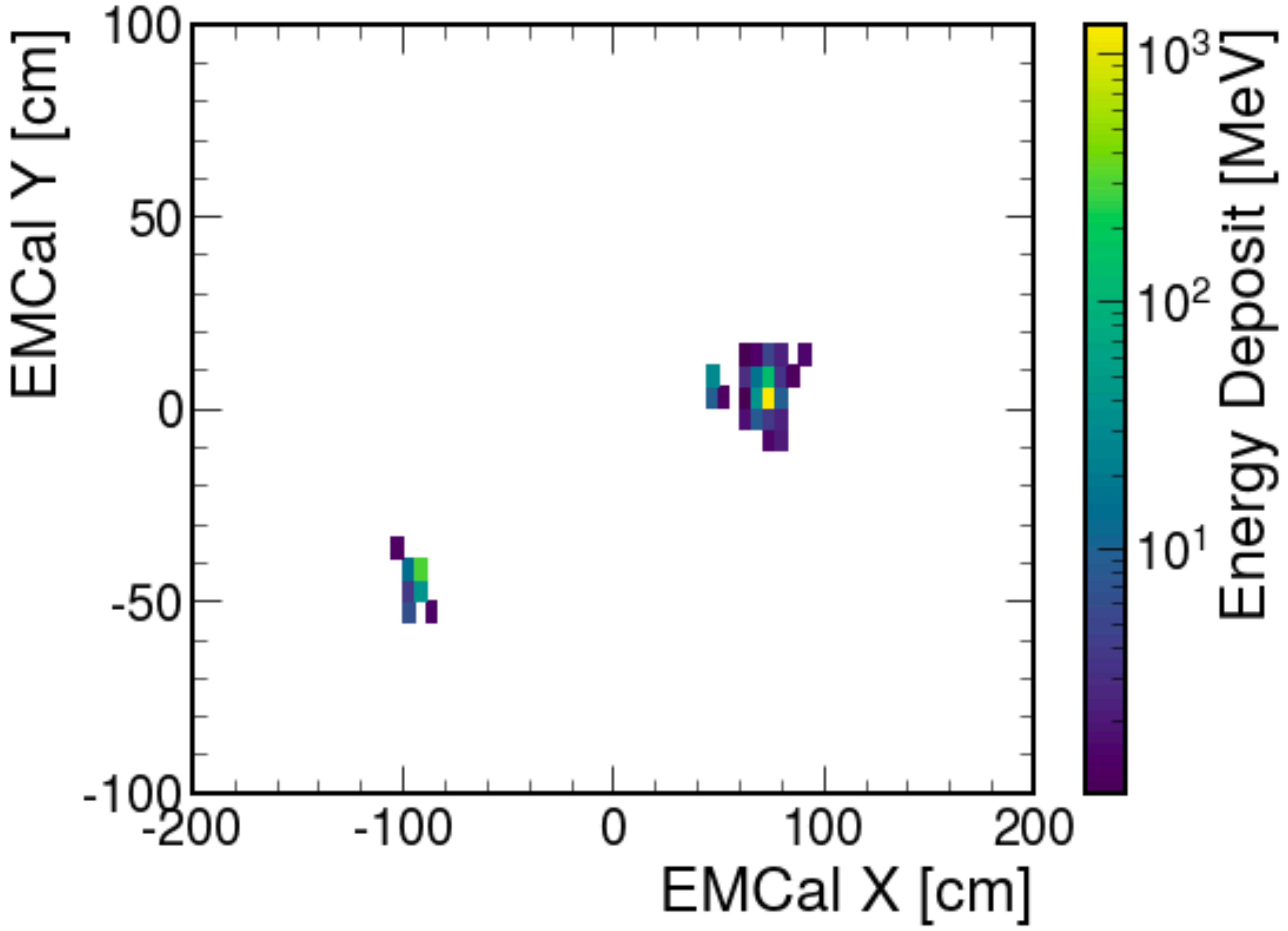
Detector Upgrade Studies

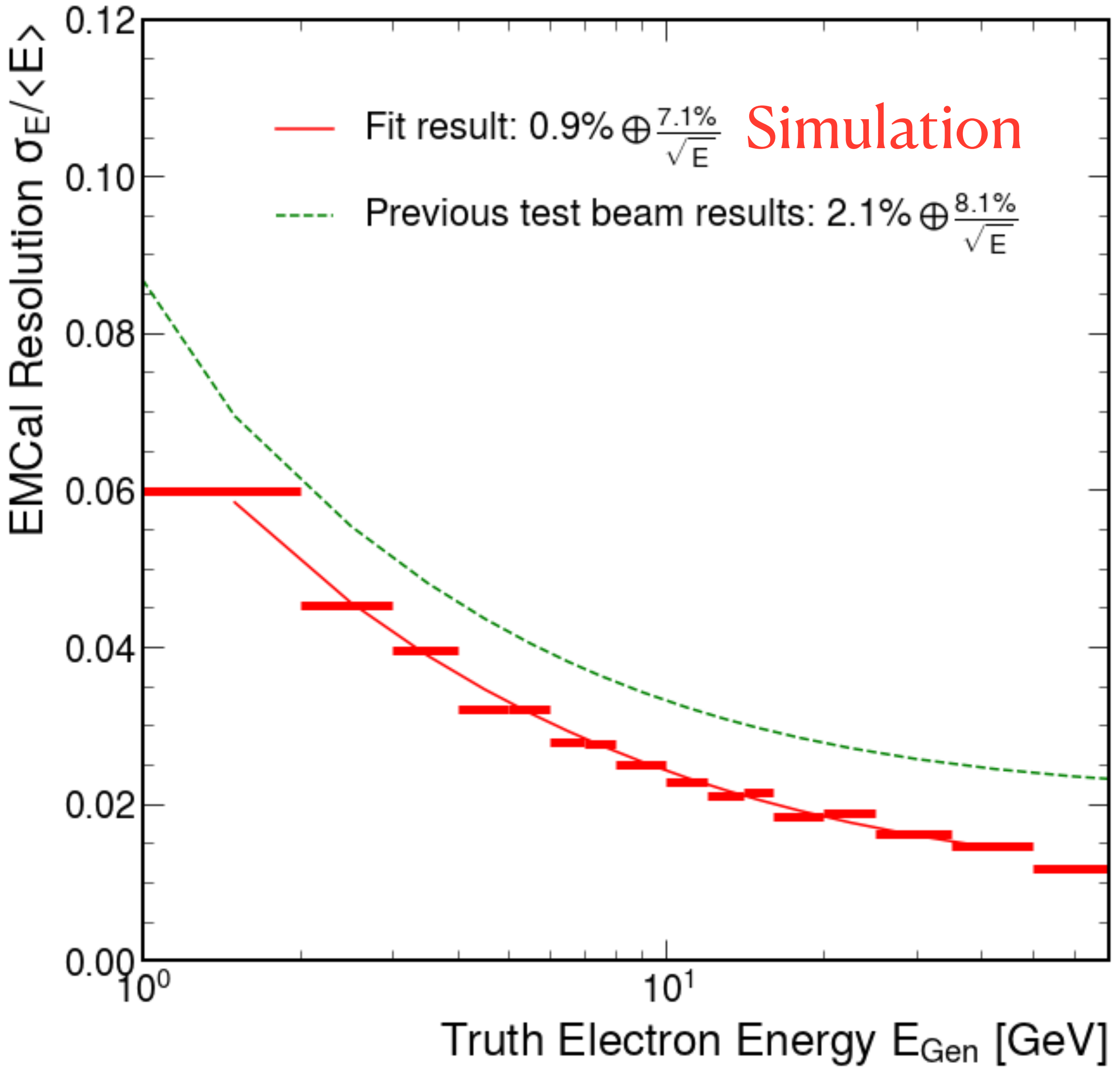


- EMCal: $PbWO_4$ + iron sampling calorimeter from PHENIX experiment
- EMCal integration into the spectrometer:
  - Developments of the readout and trigger system ongoing
  - Currently in possession of a few cells to explore SiPM readouts



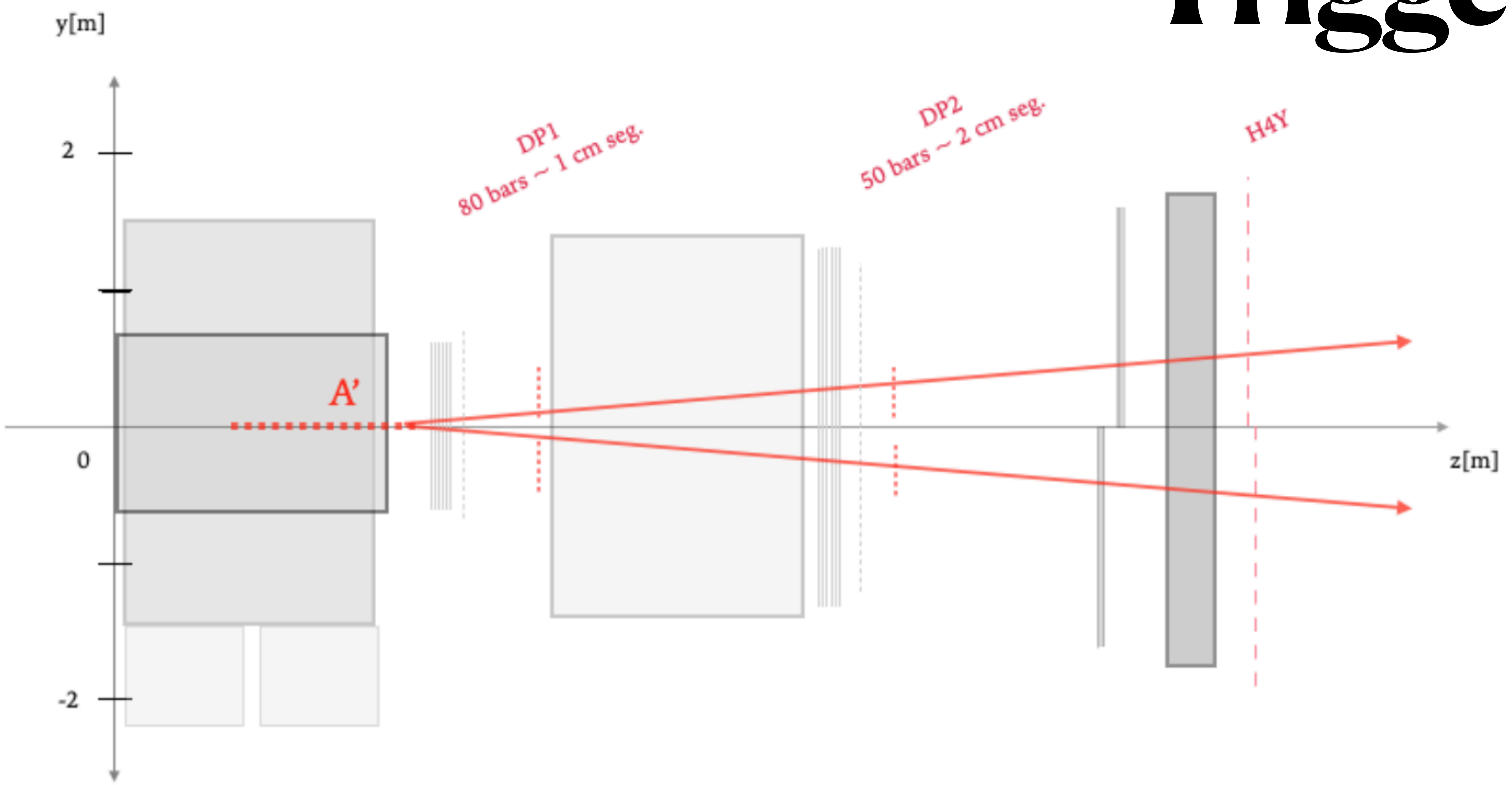
Ongoing Studies: EMCal Simulations

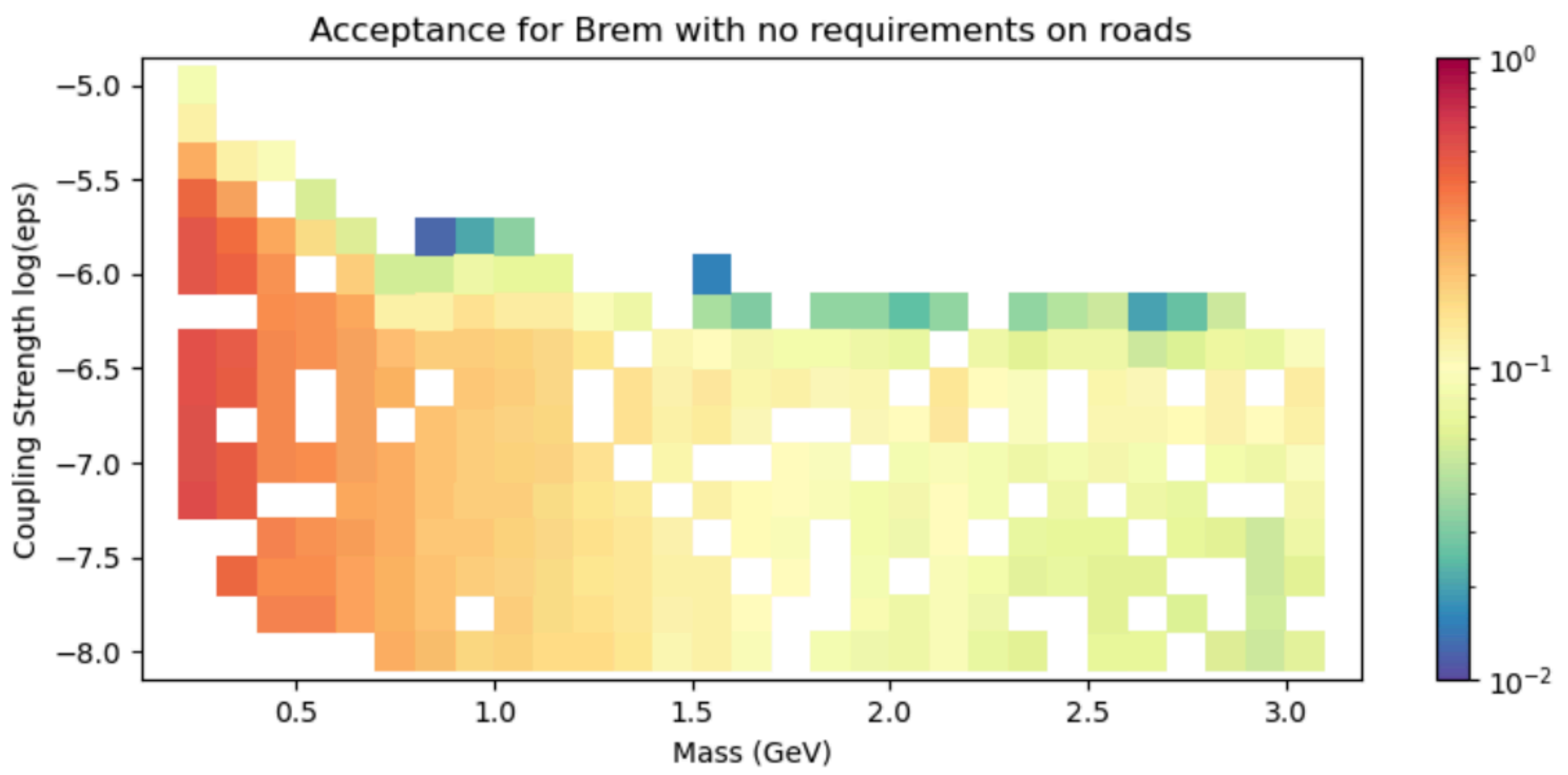


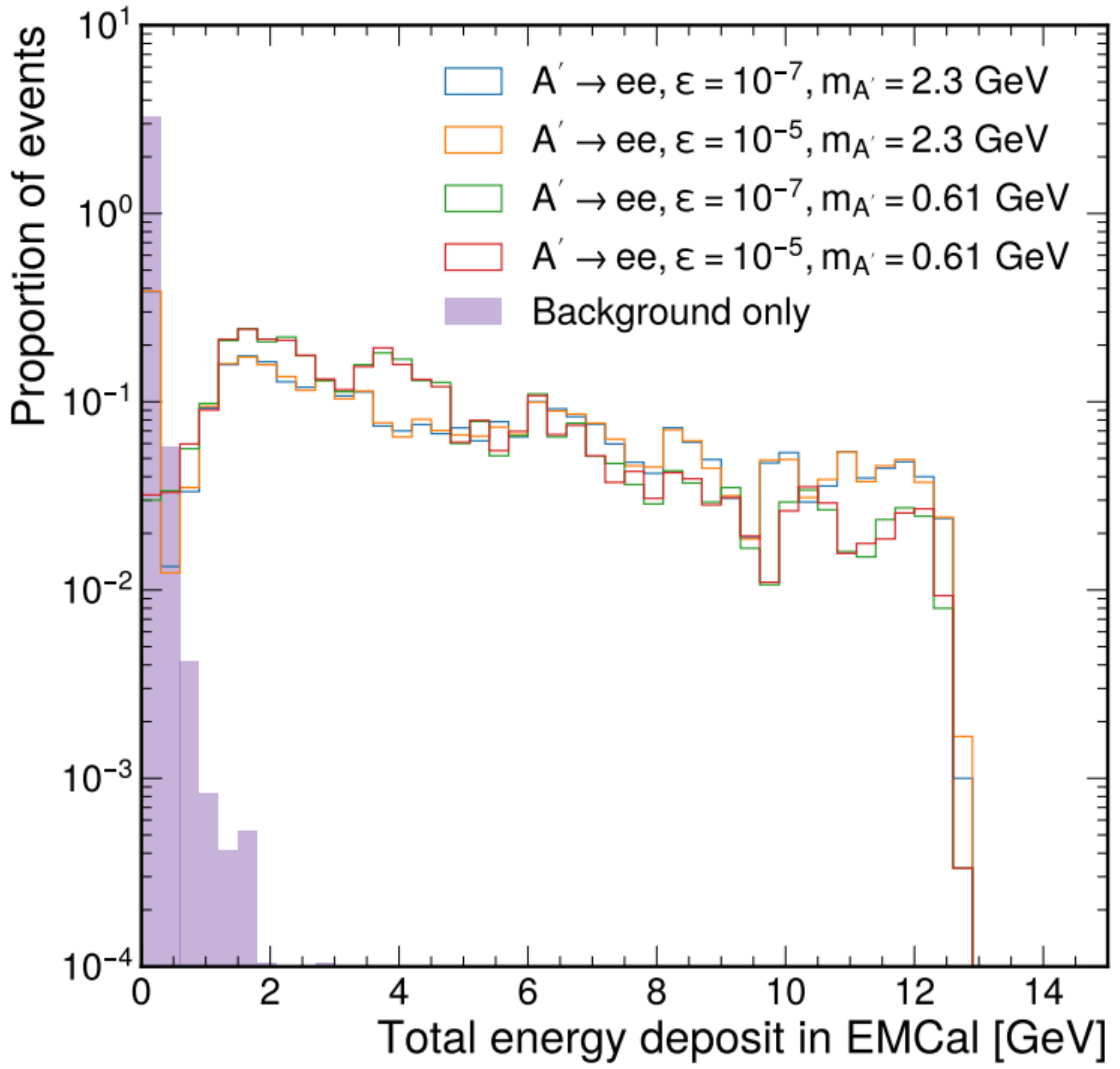


- EMCal: ~5cm per cell (2-3 Molière radius of $PbWO_4$): most energy deposit in one central cell
- Nice separation between two electron showers
- Agreement of the resolutions between the simulation (red) and the previous test beam results

Trigger

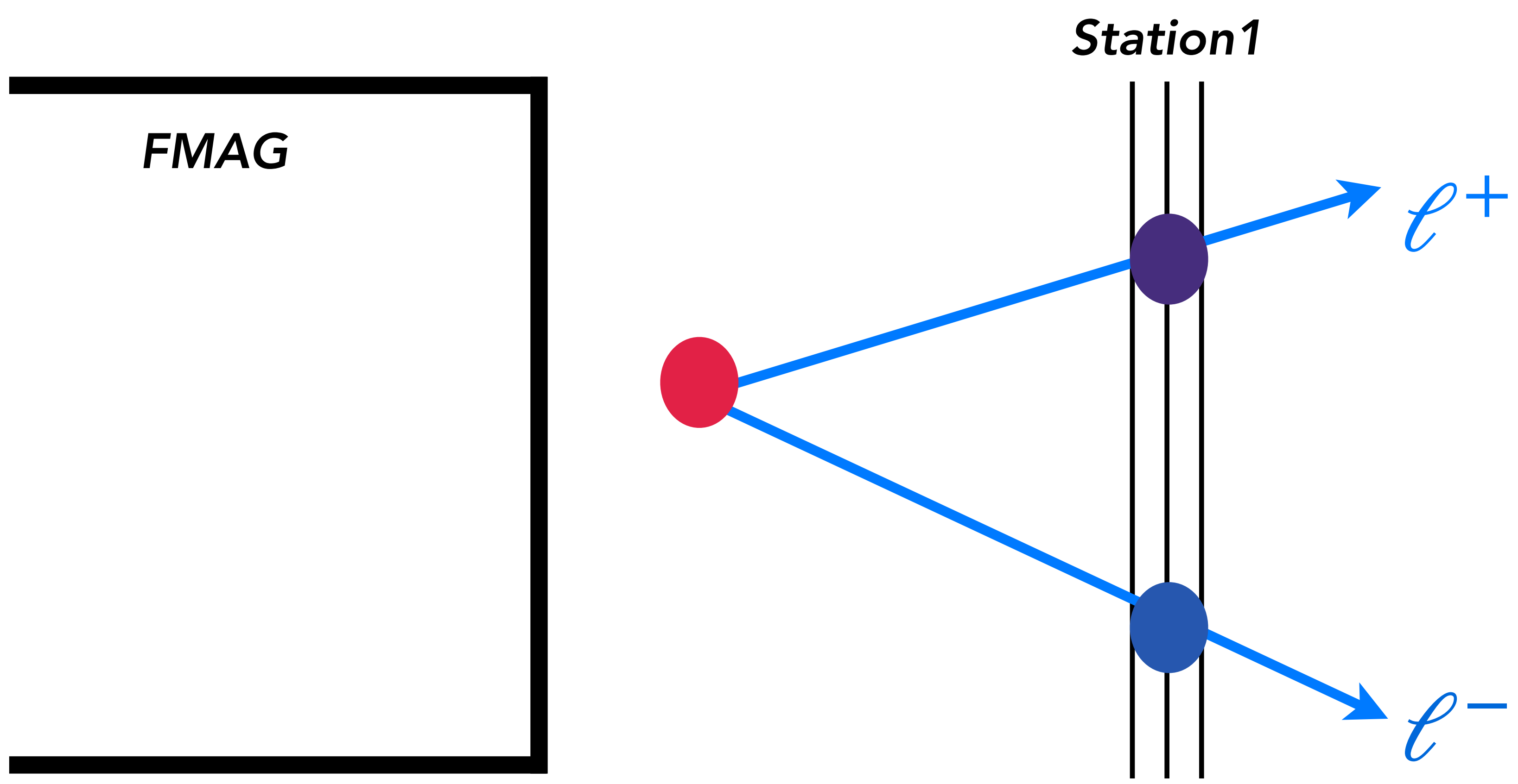


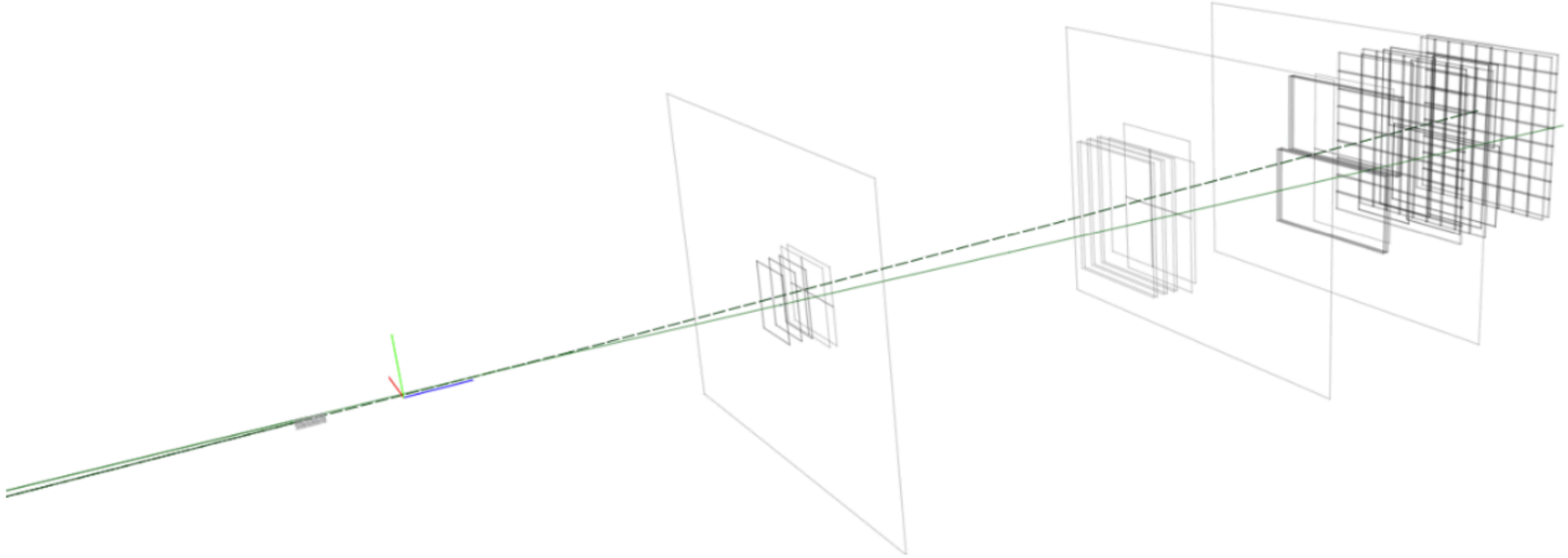




- Exploring newly installed hodoscopes to trigger on displaced:
  - No bending in y direction: straight line matching
  - Large improvements: O(1%) -> O(10-80%)
- Include EMCal information in the trigger system to trigger on Electron/Photons

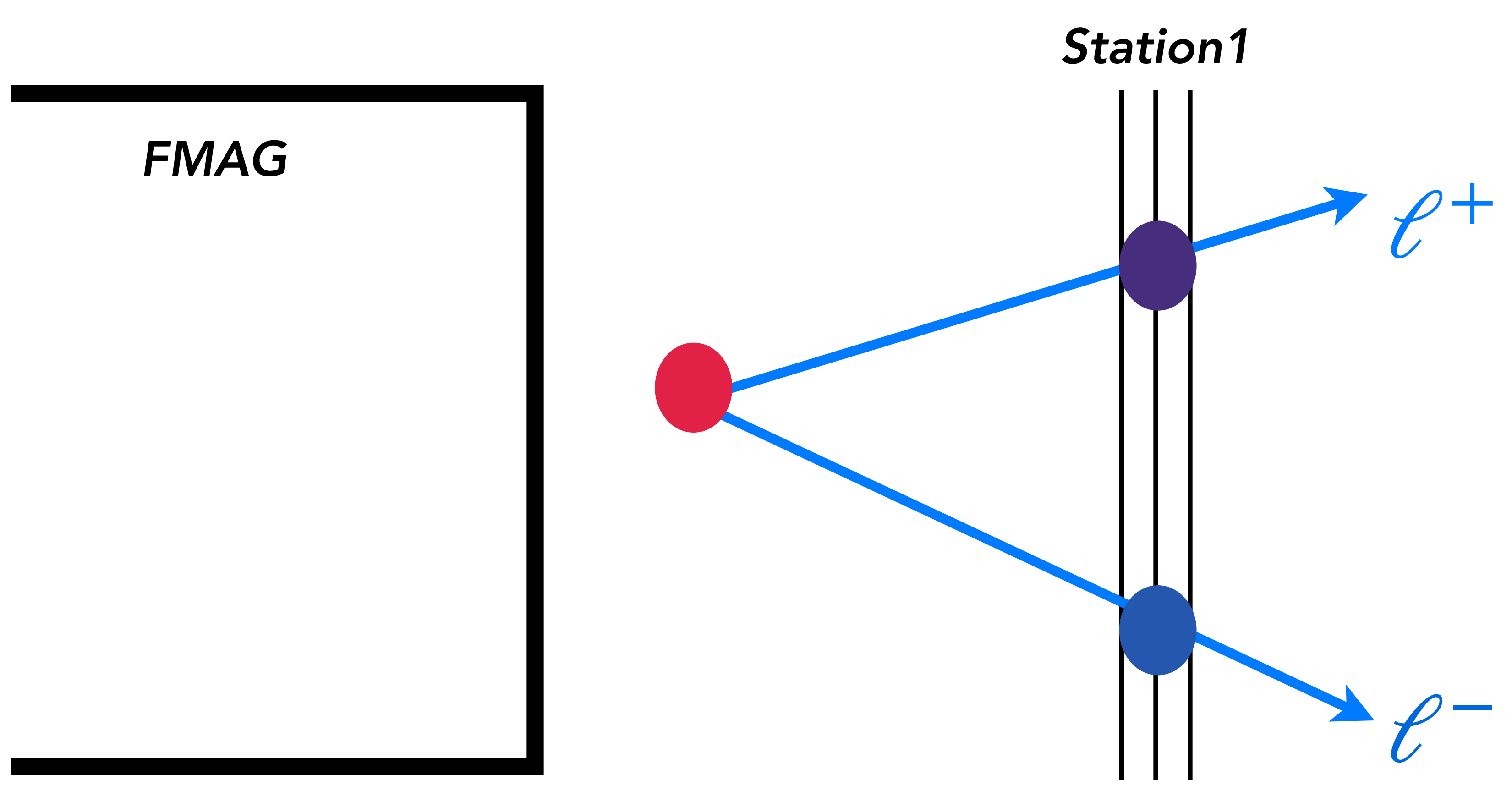
Tracking and Vertexing

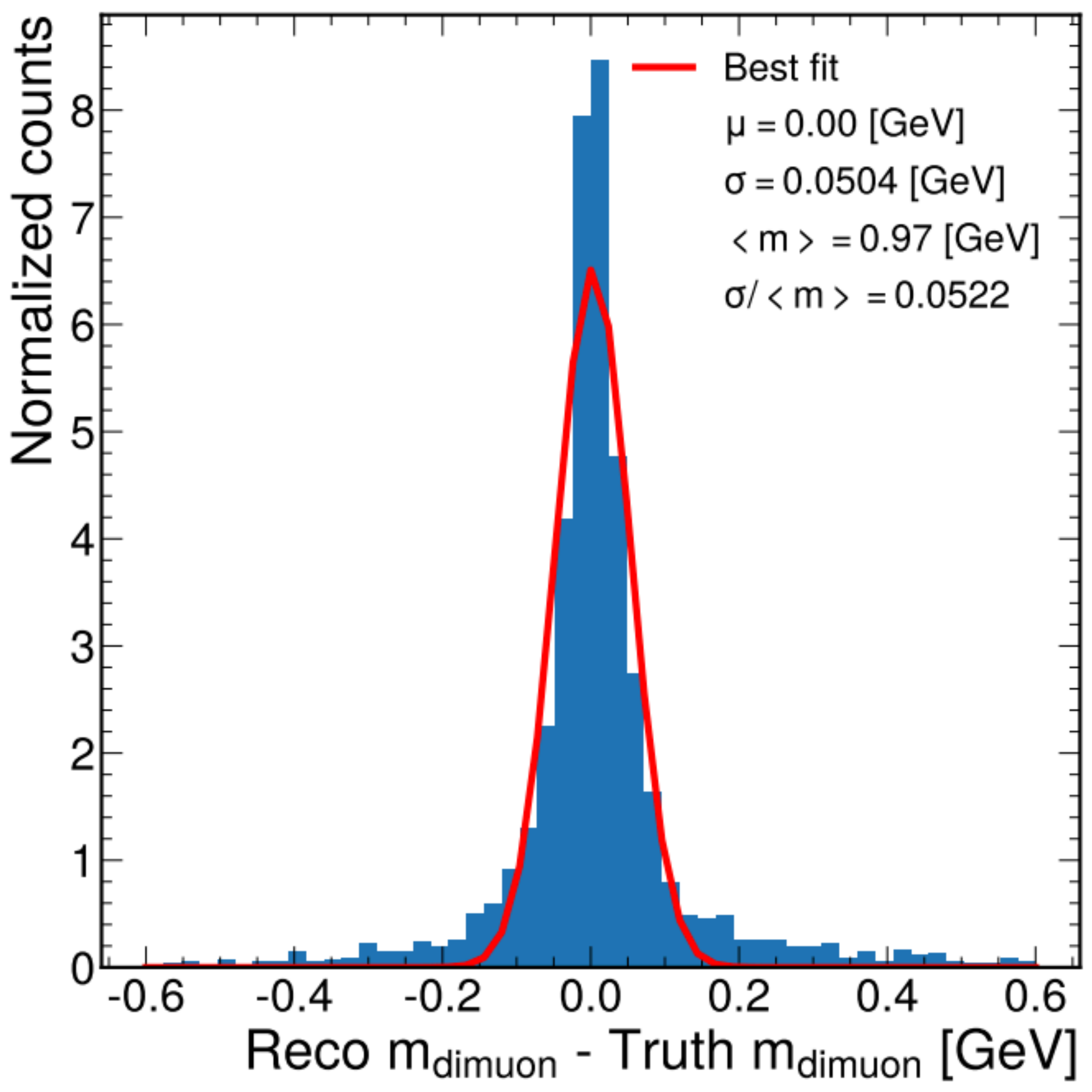


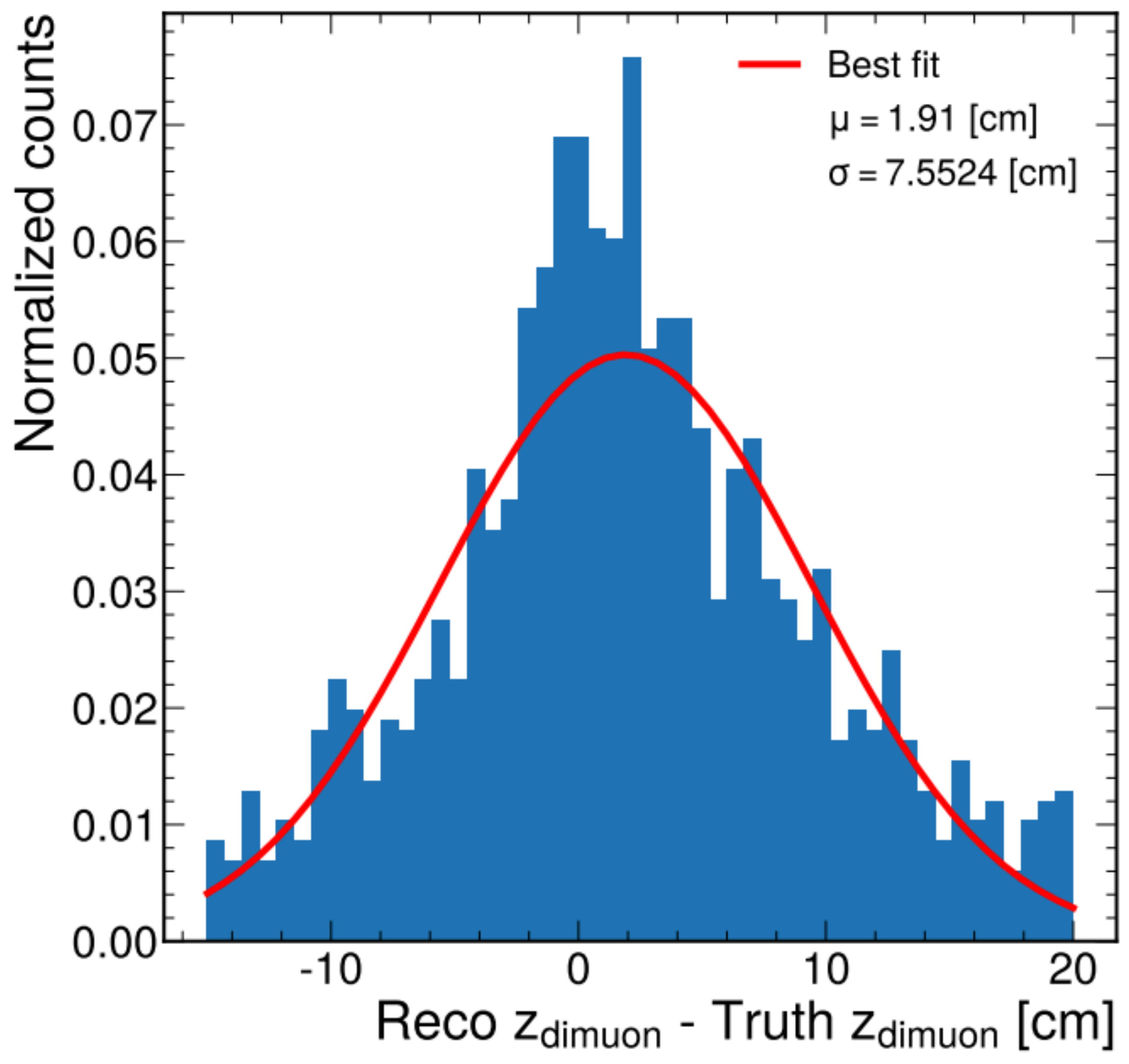


- Less affected by the multiple scatterings in FMag. Better resolutions compared with prompt signals:

Tracking and Vertexing

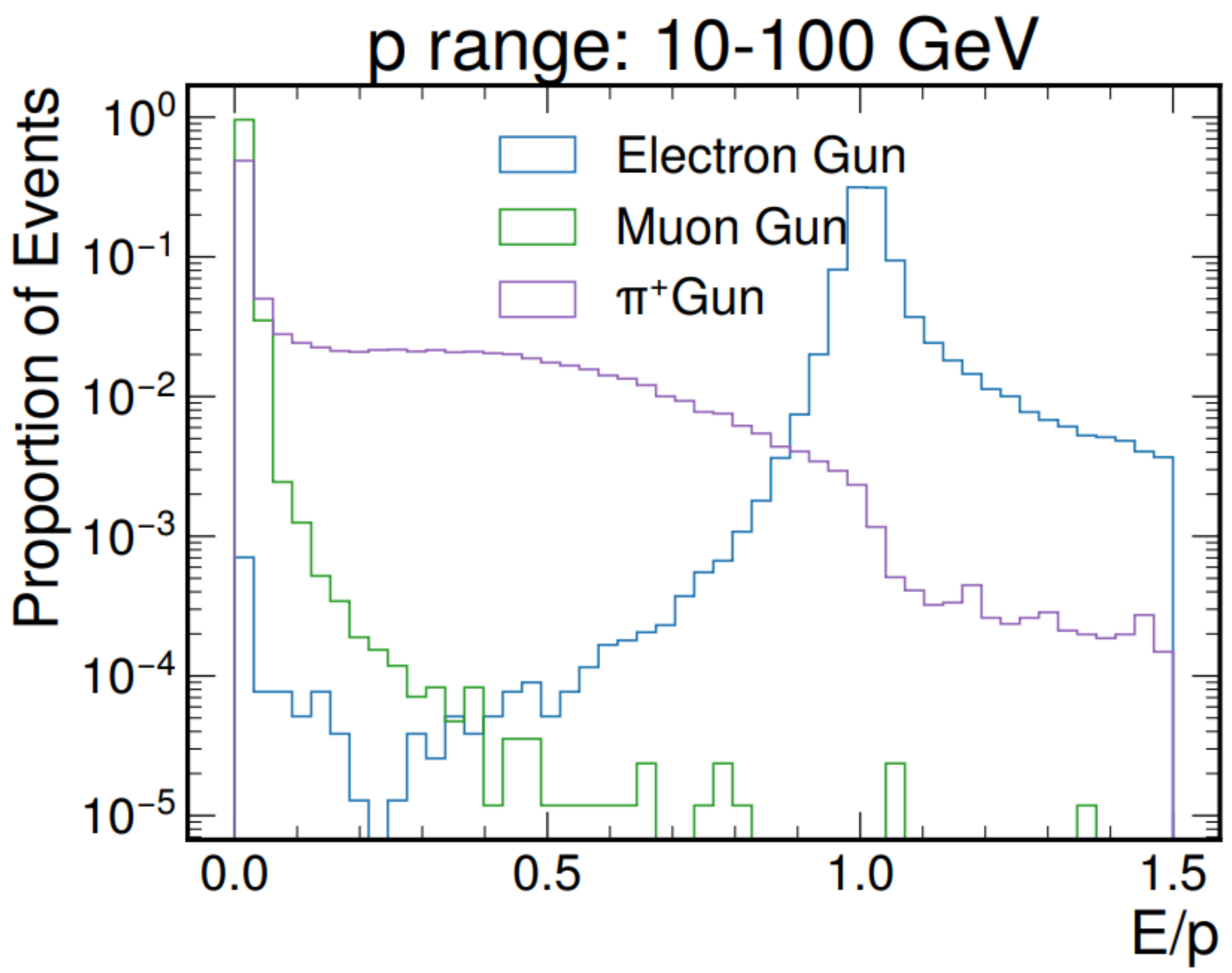






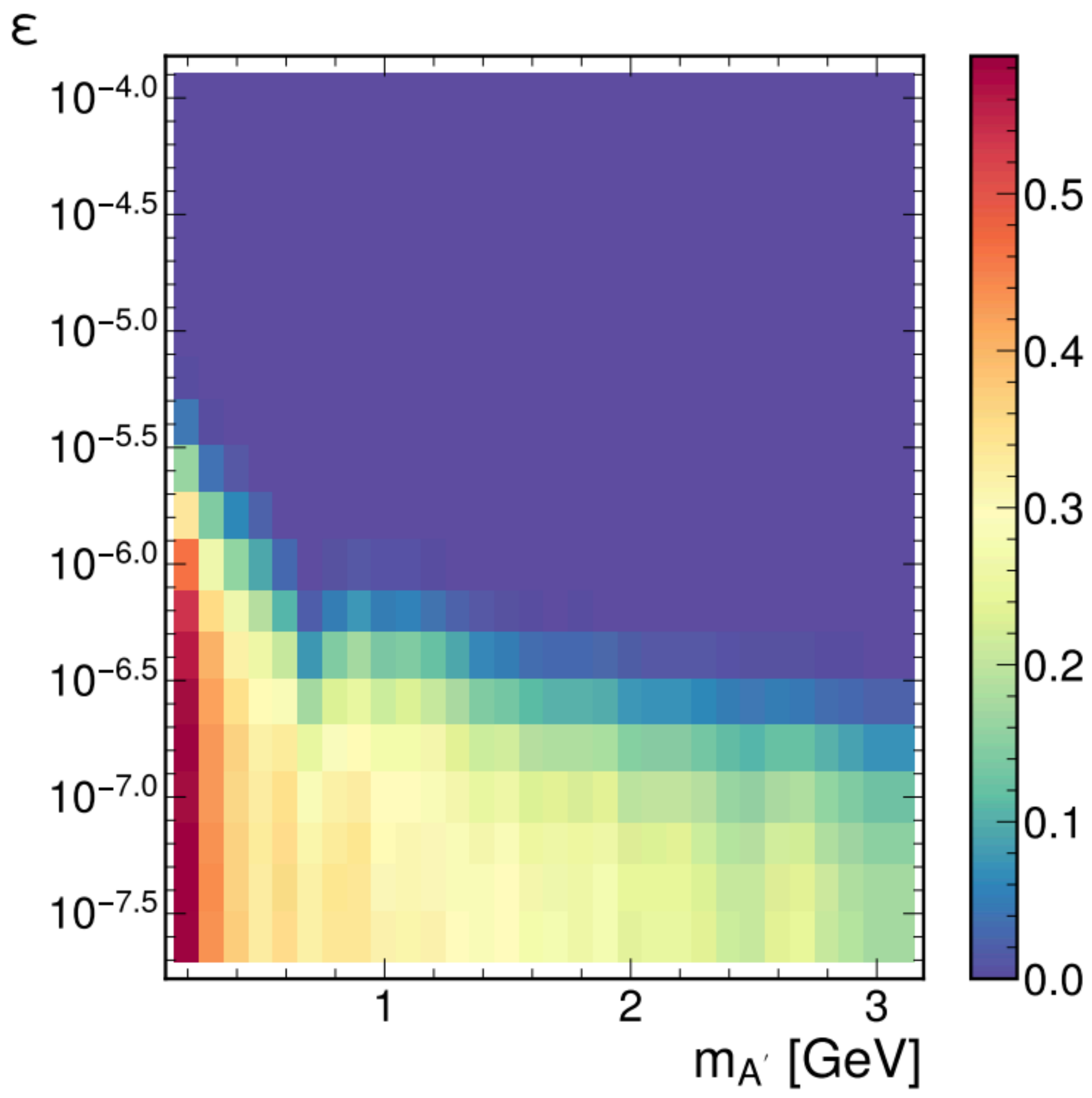
- Less affected by the multi scatterings in FMag. Better resolutions compared with prompt signals:
  - 75% track reconstruction efficiency for high momentum particles;
  - 5% mass resolution,
  - 5-10 cm Z resolution for dark photons decaying after FMag

Particle Identification



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

Signal Acceptance



- 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:

Collaboration

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- One Snowmass paper: https://arxiv.org/pdf/2203.08322.pdf

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]

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[2]University of Pittsburgh, Pittsburgh, PA 15260, USA
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[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

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
- Welcome to join the effort! Contact us if interested! (yfeng@fnal.gov ntran@fnal.gov)

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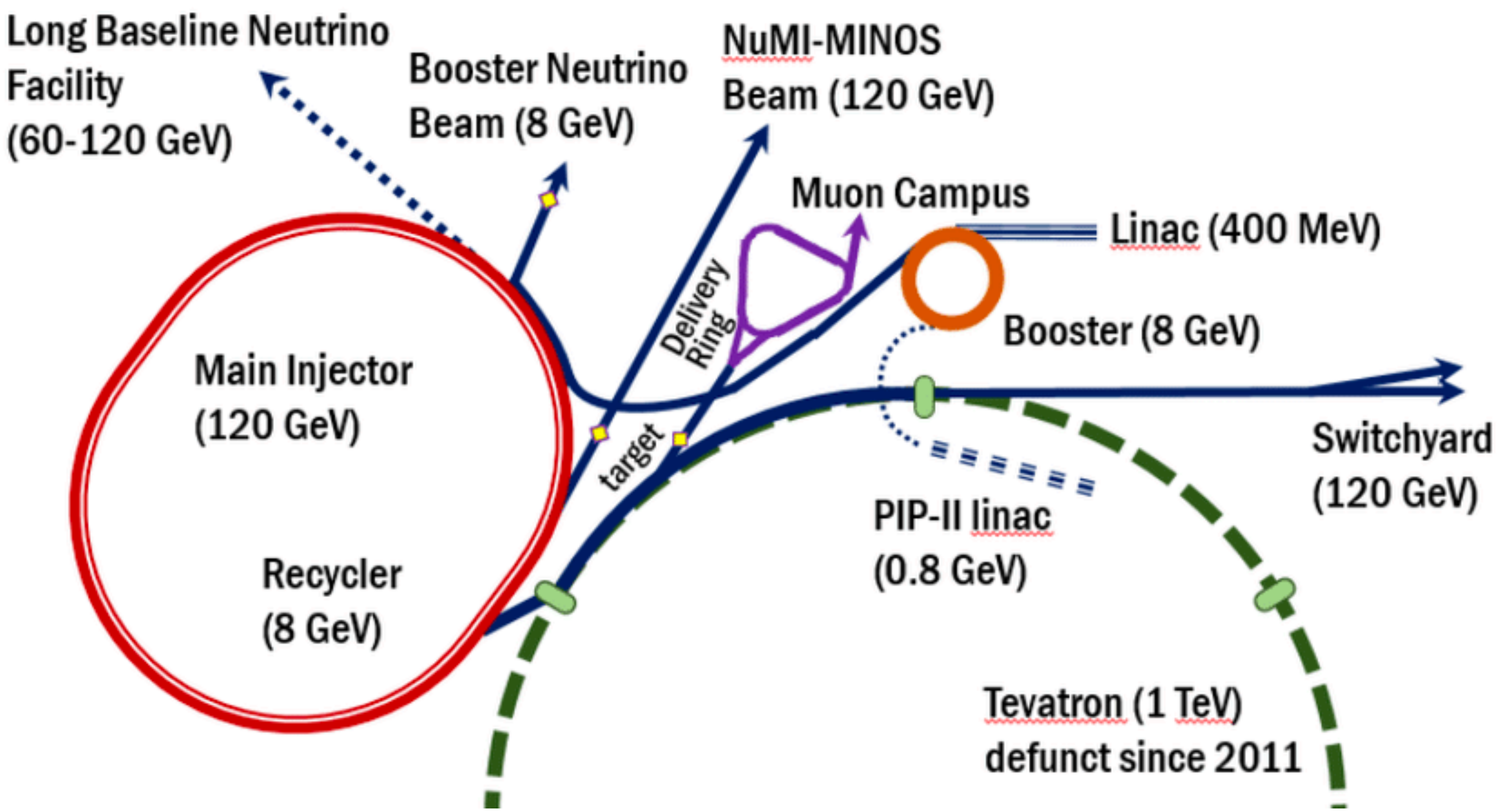
Summary

- 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
- Planned timeline: SpinQuest run (~2022) and aim to start dark sector exploration in 2023-2024!
- A lot of electronics design, simulation, and reconstruction studies ongoing

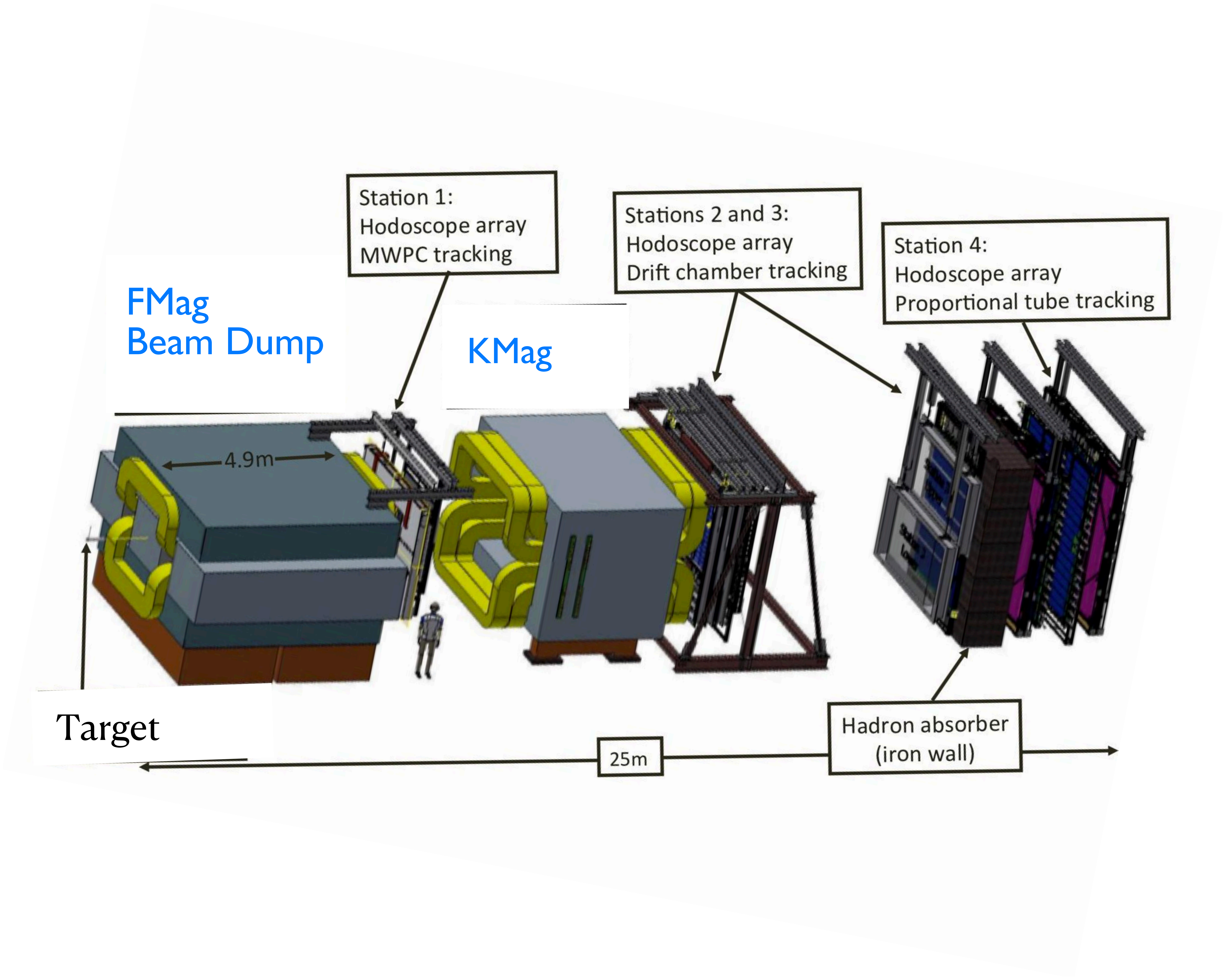
Back Up

120GeV Proton beam

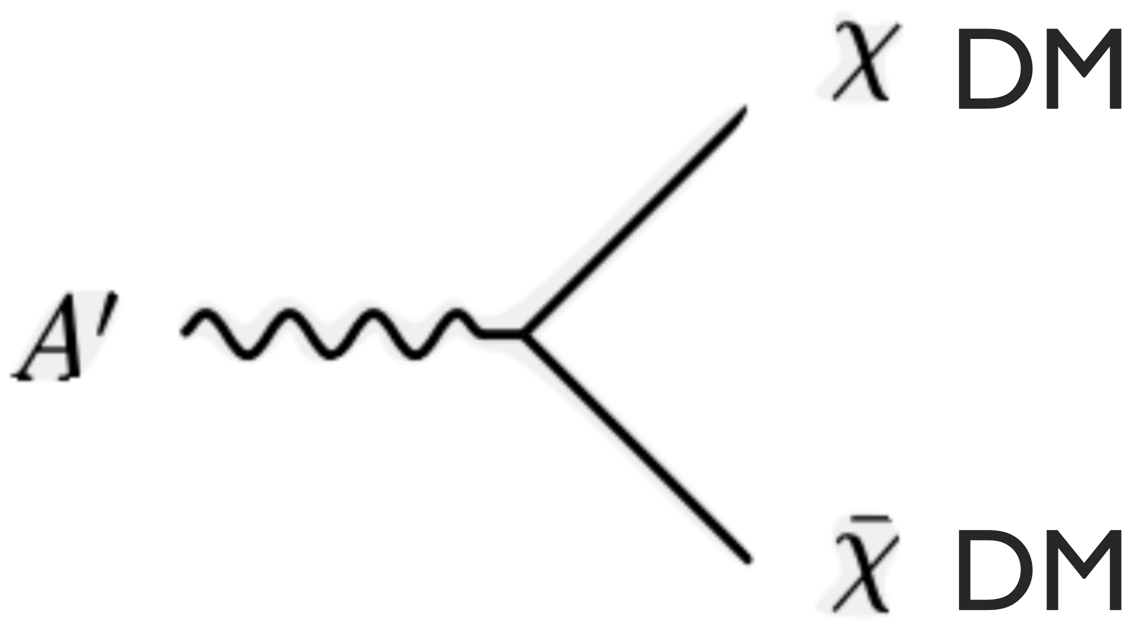


- 120 GeV high-intensity proton beam from the Fermilab Accelerator Complex
  - Expect 10^{18} Protons on target (POT) in a 2-year parasitic run, and 10^{20} POT after the PIP-II accelerator upgrade

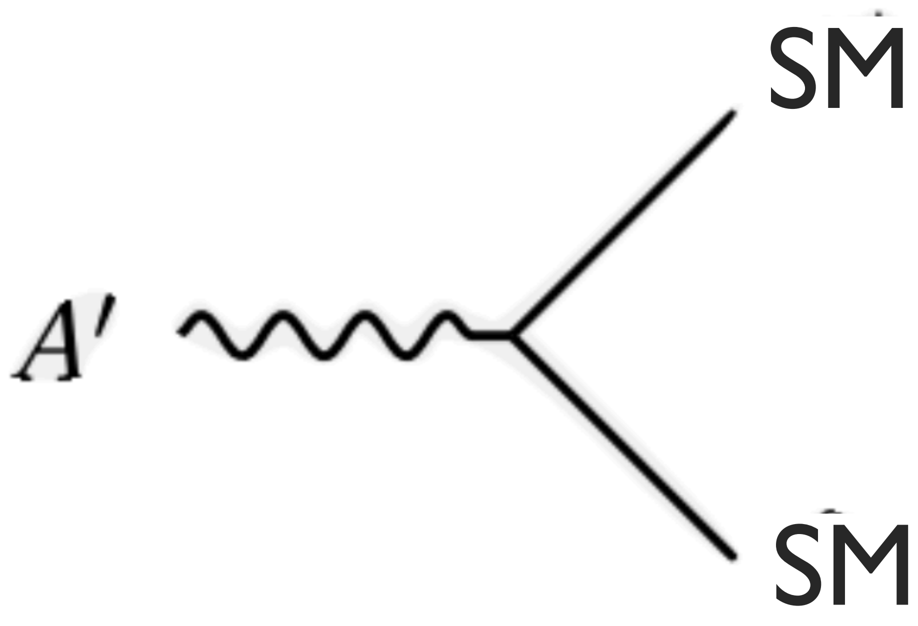
SpinQuest spectrometer



Dark (Hidden) Sector

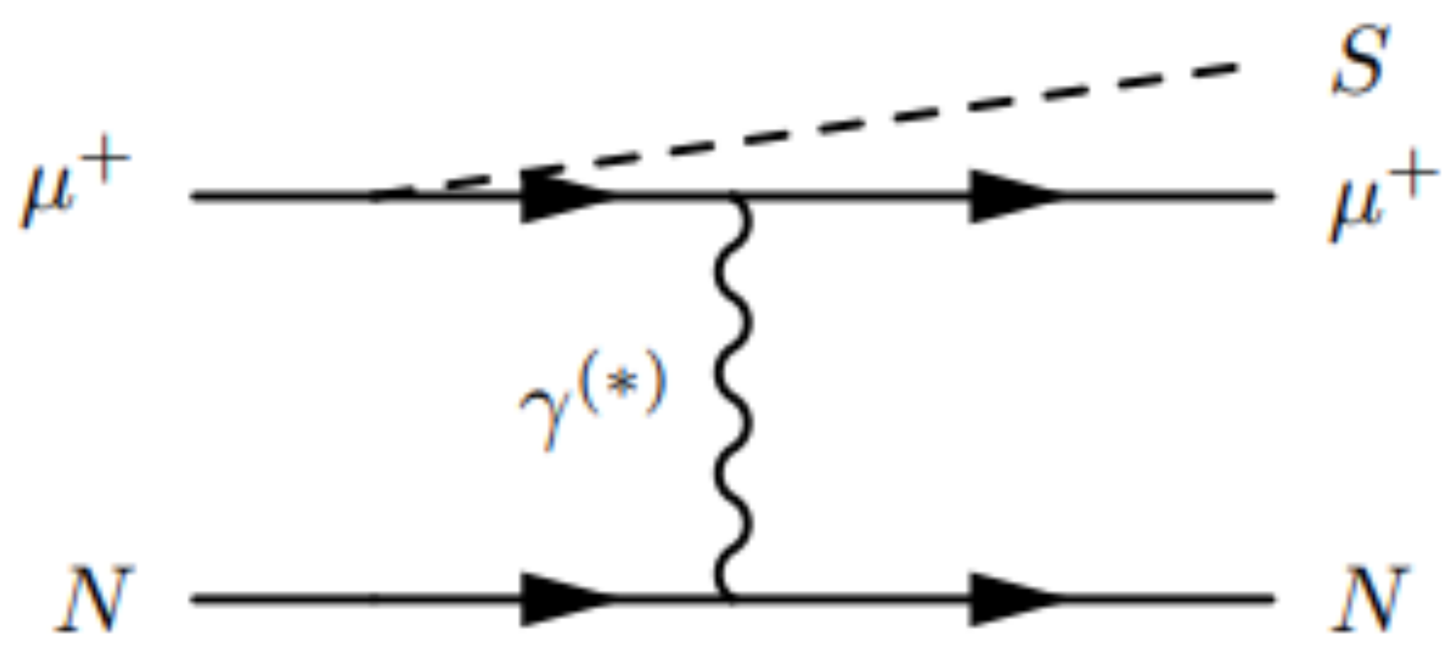


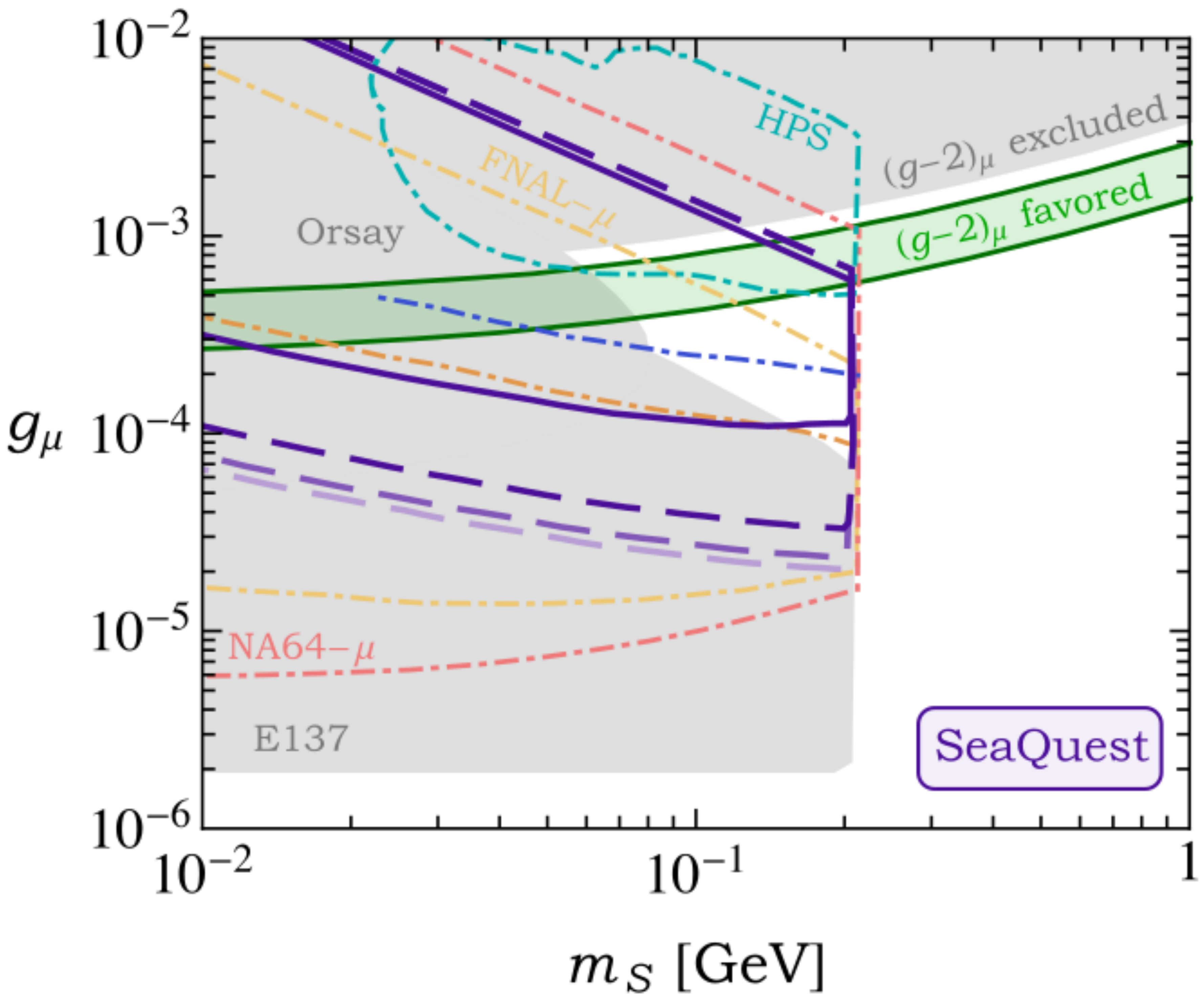
- For mediator mass > $2m_\chi$, can probe dark mediator decaying to dark matter
- Look for missing momentum/energy/mass



- Can probe the channel of dark mediator decaying to SM particles for the whole phase space
  - Vector Portal: $F^{\mu\nu}A'_{\mu\nu}$: $A' \to$ lepton pairs…
  - Scalar Portal: $\phi \mathrm{hh}^\dagger + \phi^2 \mathrm{hh}^\dagger$: $\phi \to$ lepton/hadron pairs..
  - Neutrino Portal: hLN: $N \to$ lepton + hadrons..
  - Axion Portal: $a(\overrightarrow{G}_{\mu\nu}\overrightarrow{G}^{\mu\nu} + F_{\mu\nu}F^{\mu\nu})$: $a \to$ photon/hadron pairs

Why DarkQuest: Connection with (g-2) Anomaly

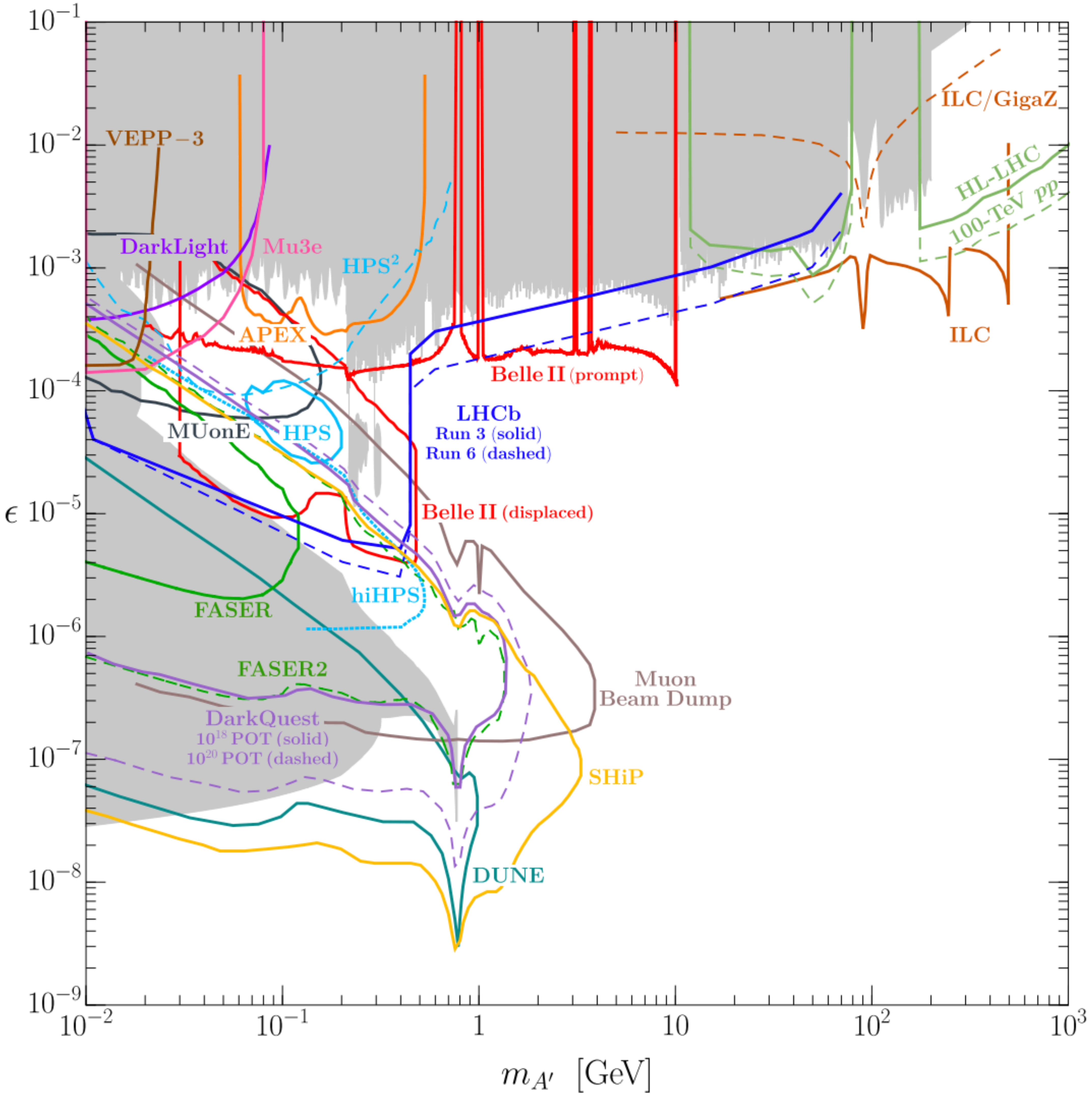




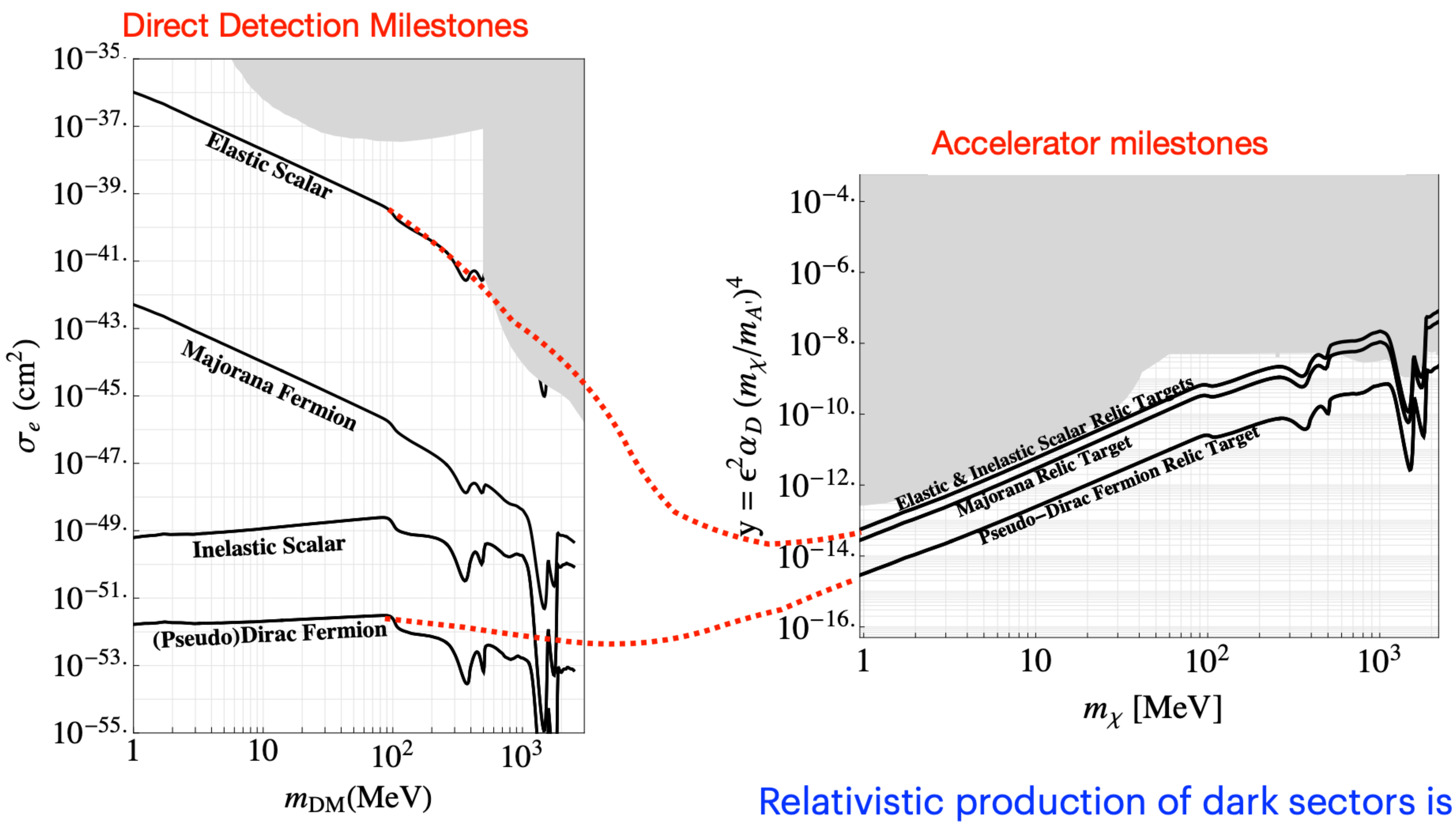
A.Berlin, S.Gori, P.Schuster, N.Toro Arxiv:1804.00661

- 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

Sensitivity

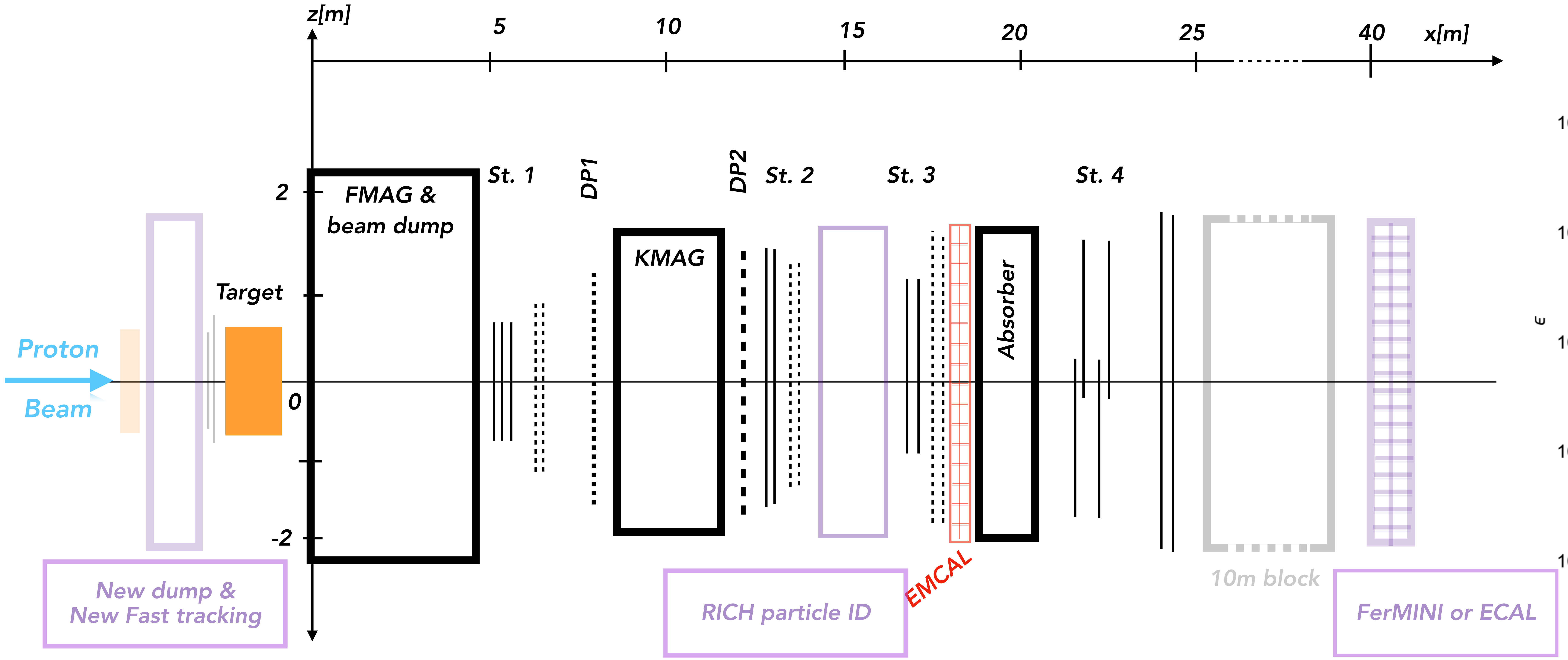


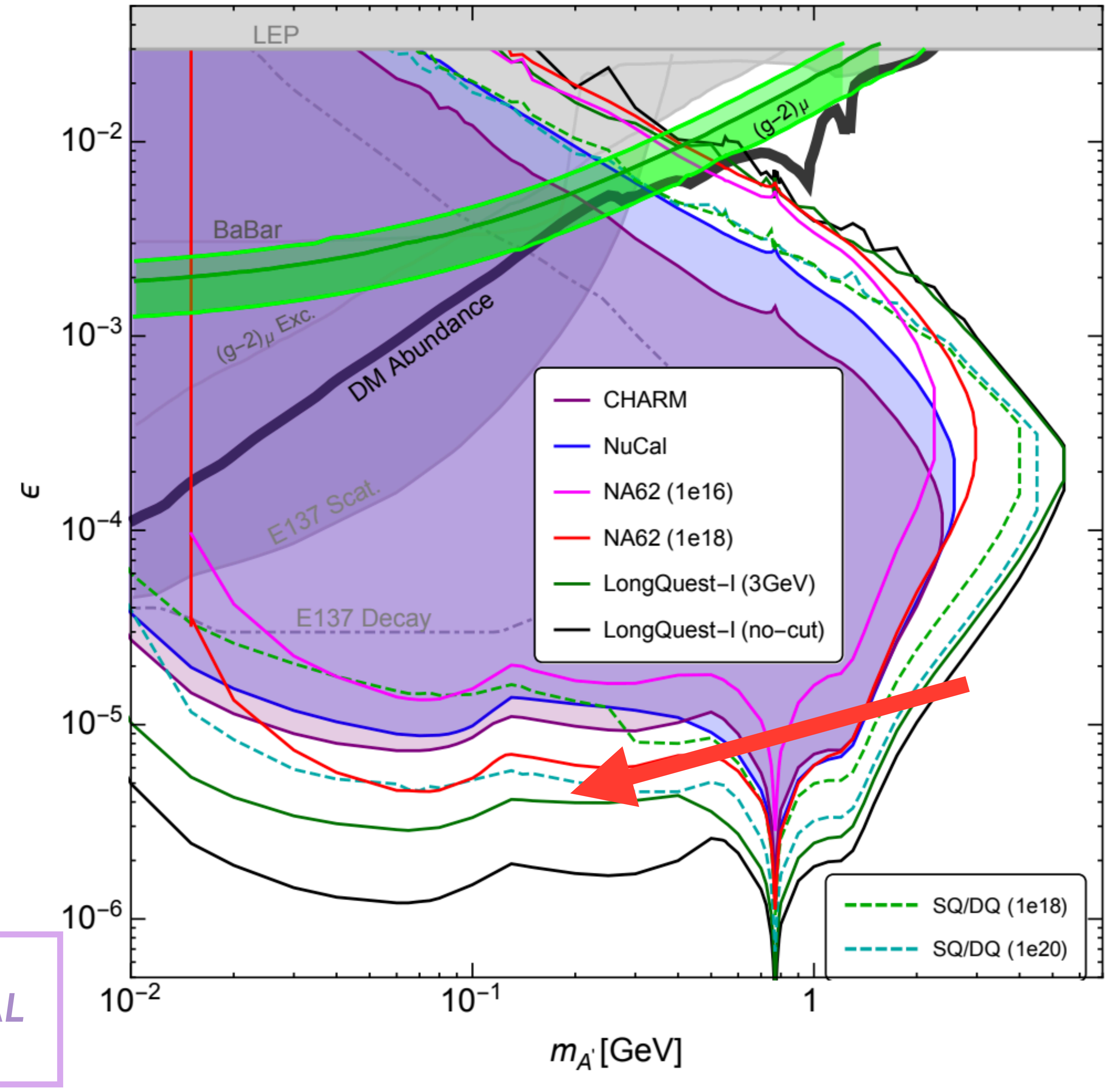
Accelerators



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

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