Topic 3: Fixed target experiments
Proton and muon beams

Nhan Tran, Fermilab

+ input from many people (thanks!)

RF6 kick-off

August 13, 2020

Outline

- Preamble: Why proton and muon beams?

- **Visible dark sectors** with proton beams
  - DarkQuest/LongQuest
  - FerMini, SubMET

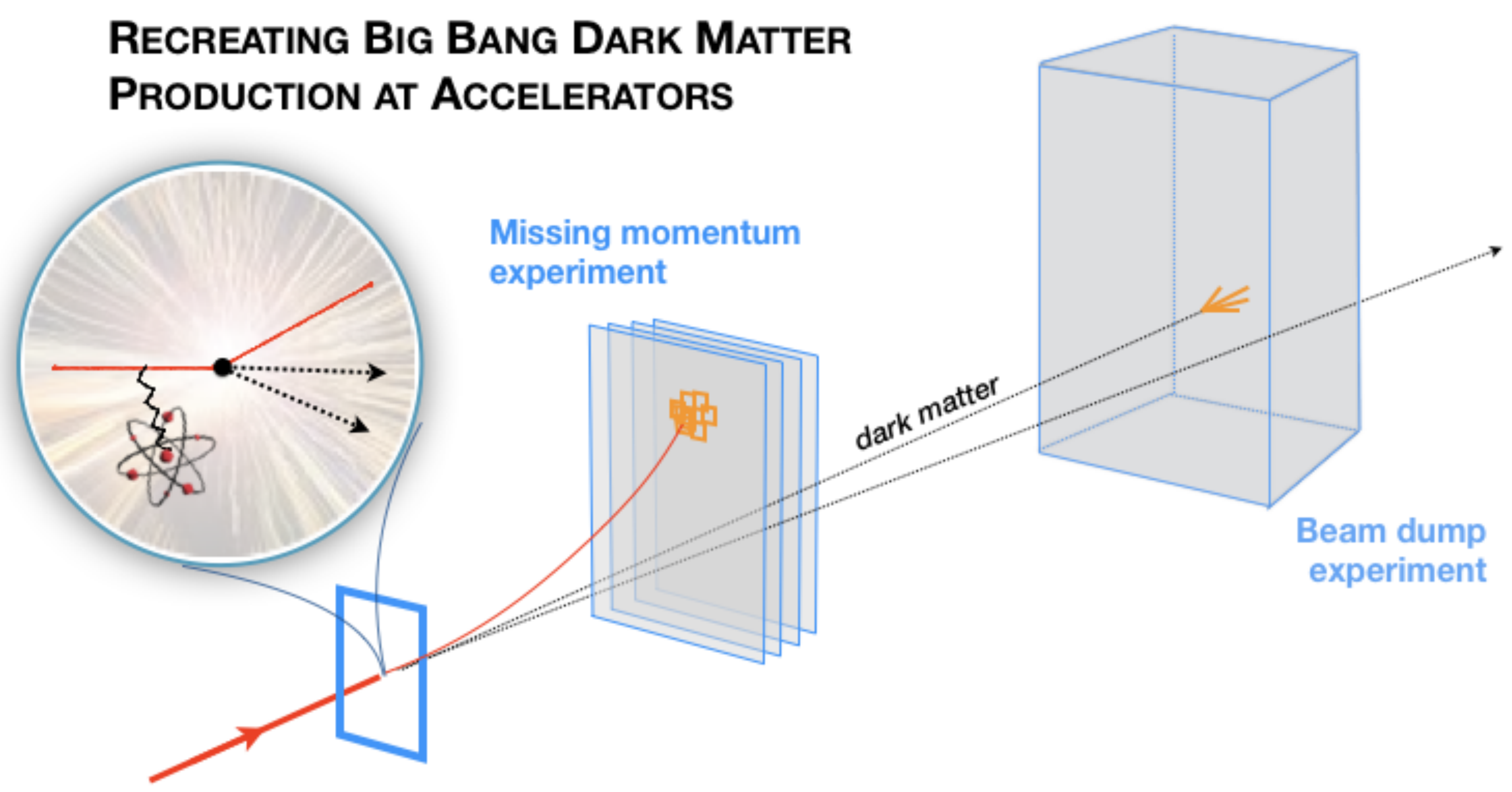
- **Muon beams**
  - mu3e
  - M^3 / NA64μ
  - Muon beam dumps

Motivation

- **Protons** make all kinds of stuff, **versatile** production mechanism
  - e.g. mesons, muons, taus, heavy quarks,…
  - Cons: protons make all kinds of stuff, including neutrinos
    - Need a lot of shielding

- **Muons** are **unique window** to 2nd generation
  - Heavy (at least than electrons), clean (minimum ionizing)
  - Cons: muon beams are harder to come by and control

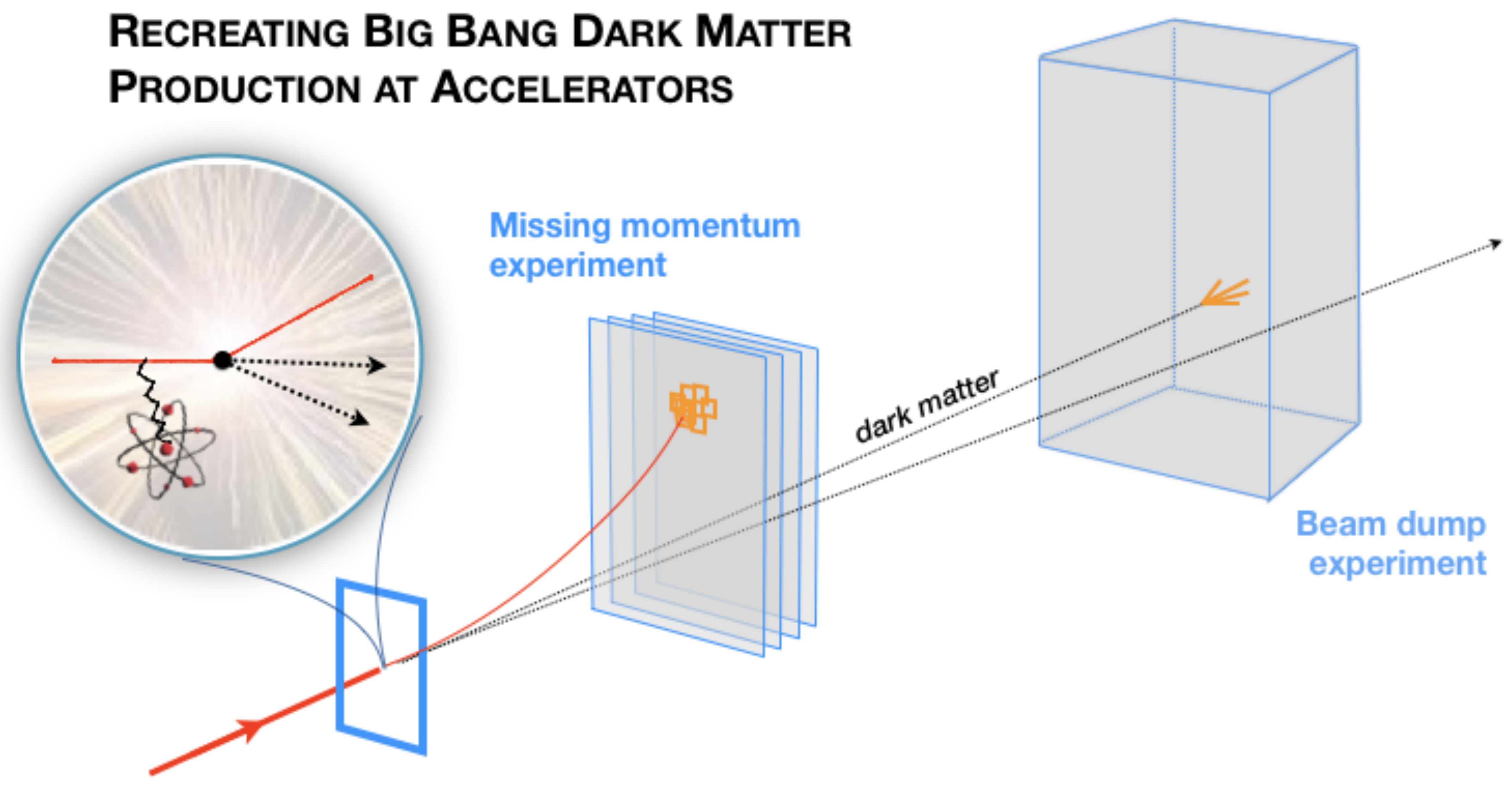
Types of experiments and related talks



Will not cover proton beams for dark matter production, but will address **muon beams**

Typical efforts here use existing neutrino experiments
See Brian Battell's talk [Topic 6, neutrino experiments]
MiniBooNE, SBND, COHERENT, CCM, DUNE, ...

Types of experiments and related talks



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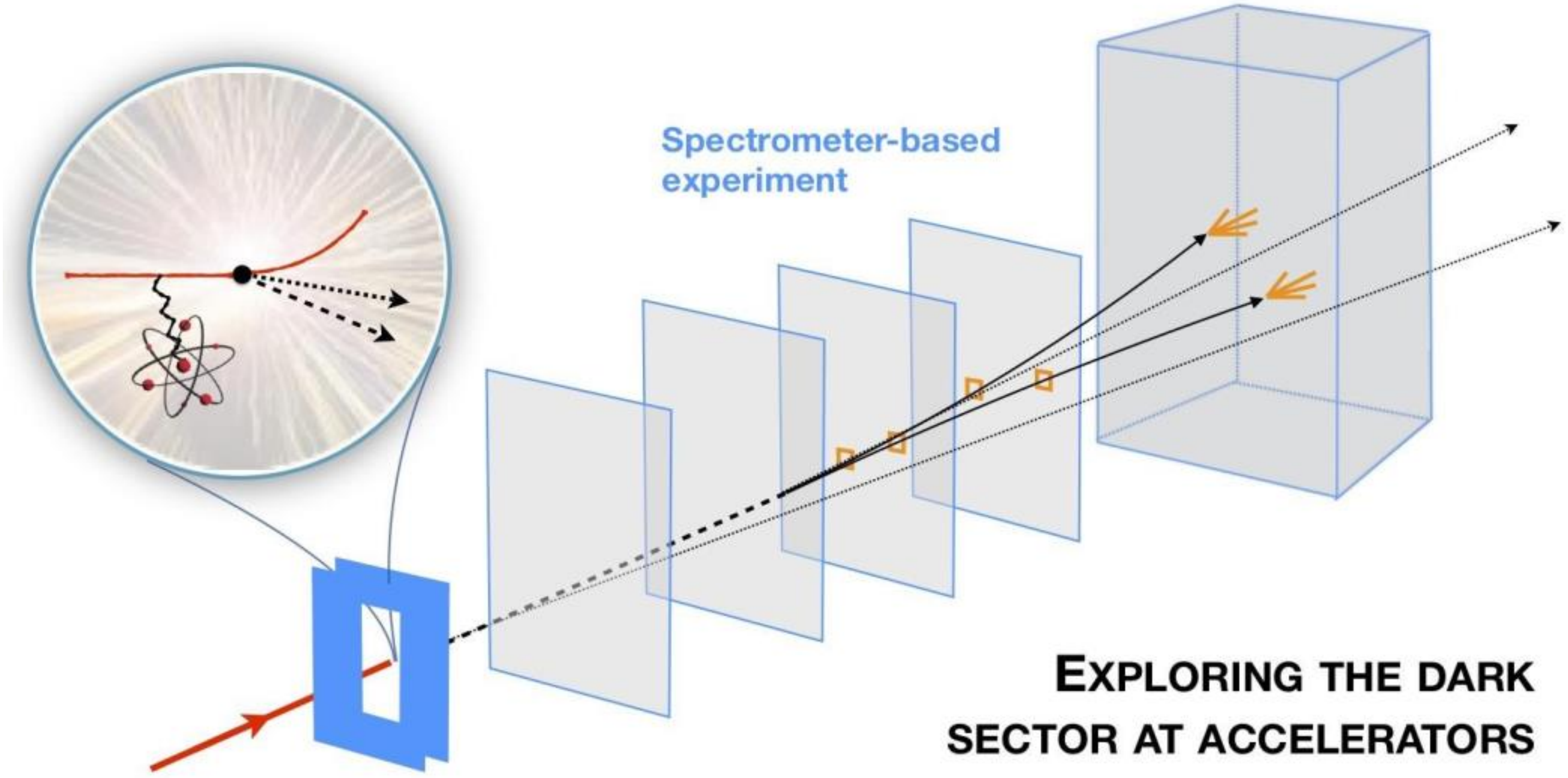
See Brian Battell's talk [Topic 6, neutrino experiments]
MiniBooNE, SBND, COHERENT, CCM, DUNE, ...

Proton beams for dark sector exploration have contributions from many topics!

Jakob Salfeld-Nebgen [Topic 2, energy frontier]
Dean Robinson [Topic 2, energy frontier]
Matthew Citron [Topic 2, energy frontier]
Diego Redigolo [Topic 4, kaon frontier]
Brian Battell [Topic 6, neutrino experiments]



Dark sector scenarios

Will cover all of these in this talk!

Invisible, non-SM

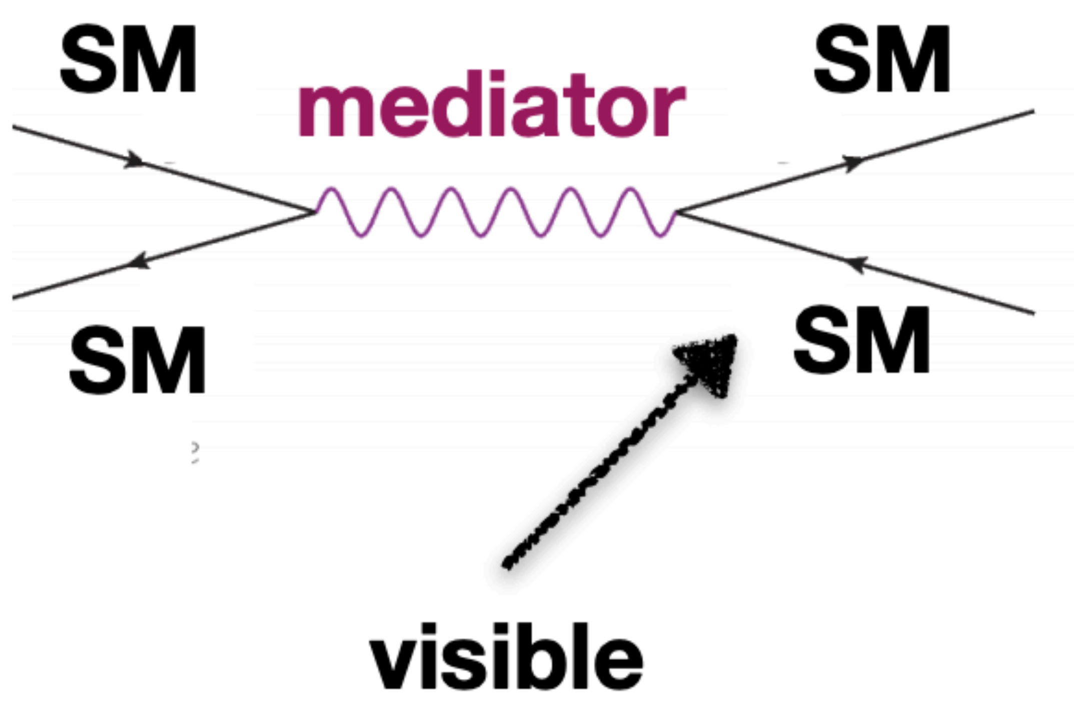
Dark Matter production

Producing stable particles that could be (all or part of) Dark Matter

Visible, SM

Production of portal-mediators that decay to SM particles

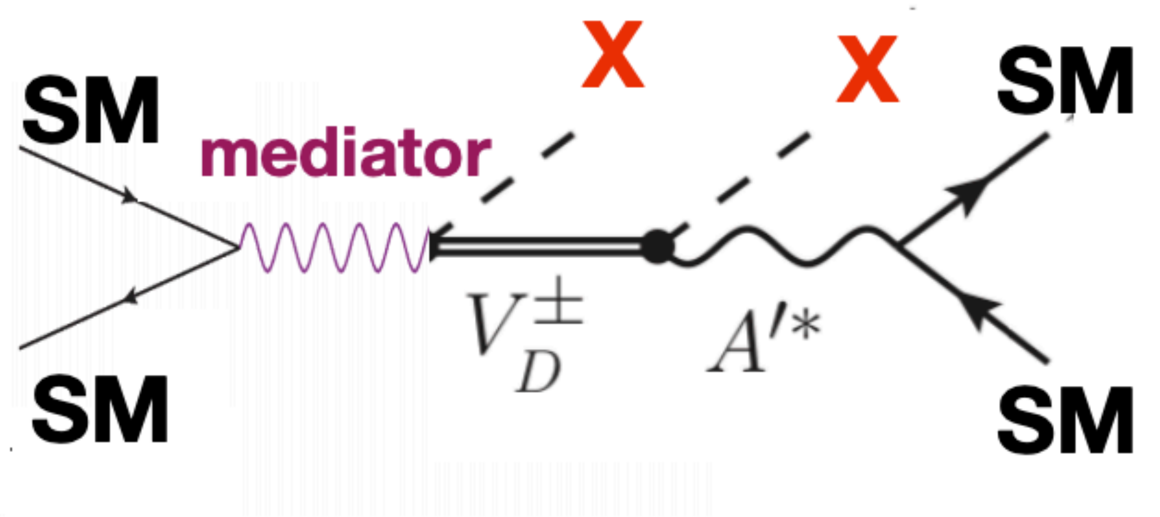
Systematically exploring the portal coupling to SM particles



Mixed visible-invisible

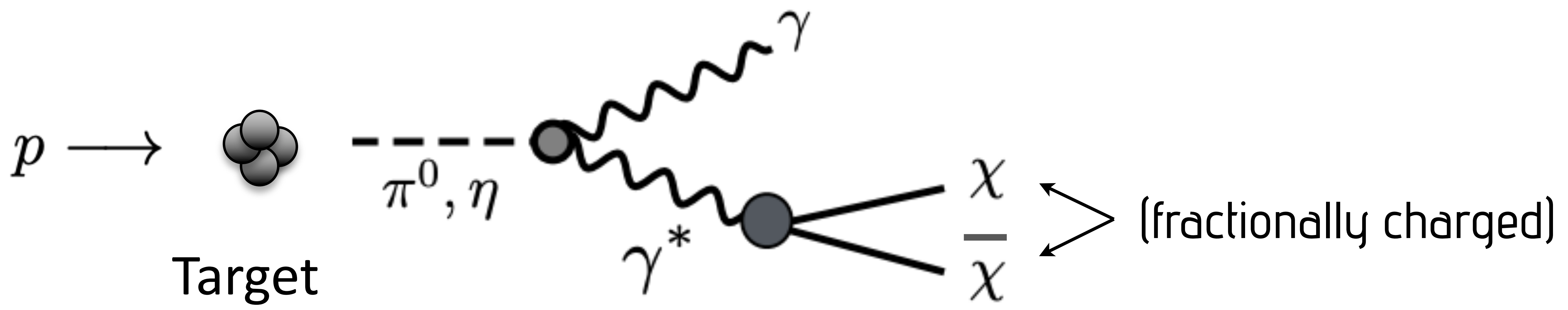
Production of "rich" dark sectors

Testing the structure of the dark sector



Millicharges

- In portal mediator scenario, fermions can appear with **fractional charge**



- This requires special searches and potentially dedicated detector technologies
  - A number of scintillator-based experiments for millicharged particle searches
  - To be discussed: FerMini, SubMET
- Complementary sensitivity comes from not detecting the millicharged particles at all

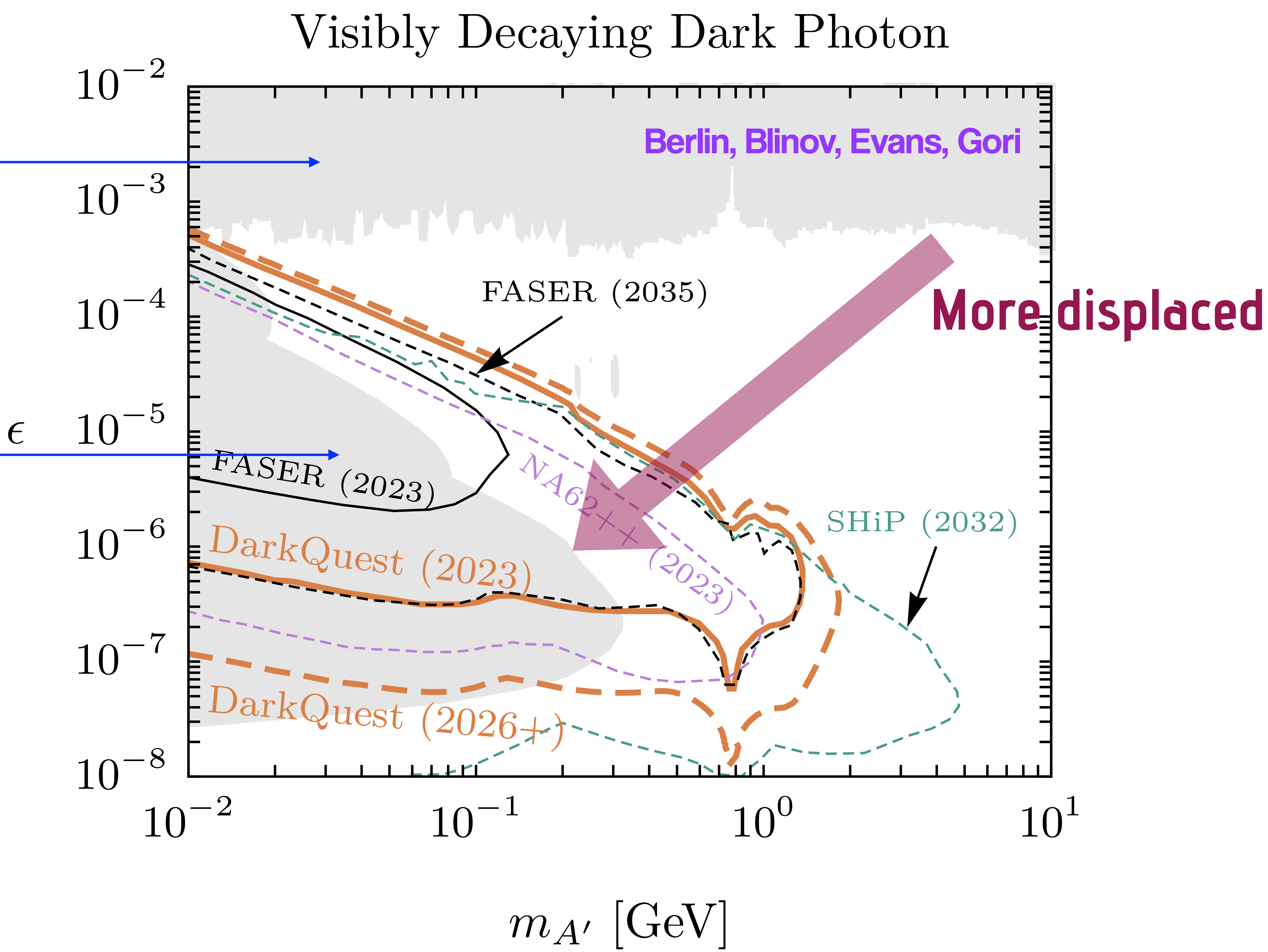
Proton fixed-target

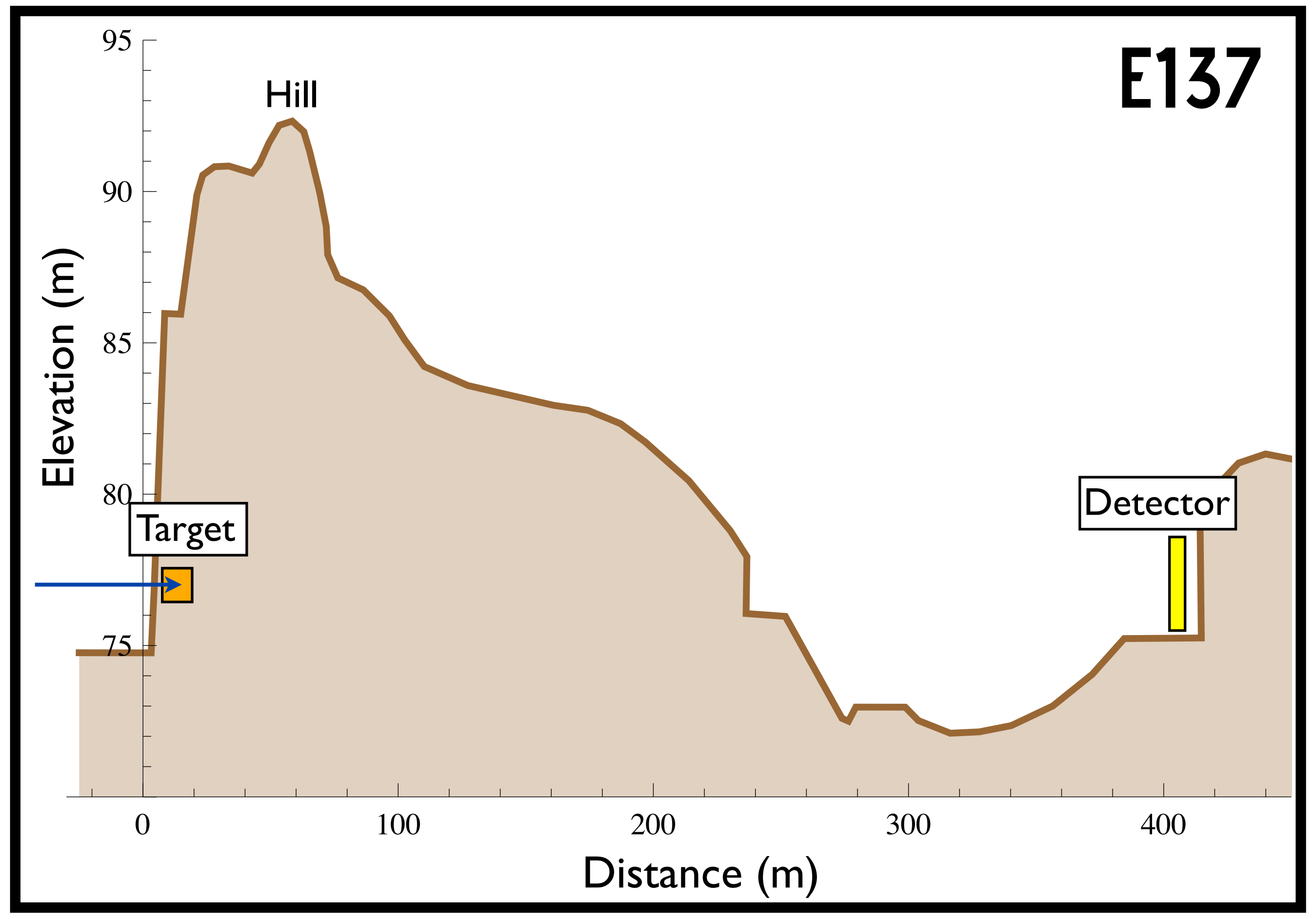
One example…

Important: a full program is needed to disentangle a dark sector zoo - only using the minimal picture as an example

Existing constraints from prompt searches

Existing constraints from beam dumps





Proton beam dark sector taxonomy

- Facility choices
  - Distance from target, position (on/off-axis)
  - Beam energy, beam power, beam structure

- Detector choices
  - Type of signature: Missing momentum, DM re-scatter, Visible dark sector, fractionally charged
  - Detector technology: expected background/signals

Proton beam dark sector taxonomy

Beam Energy
TeV (LHC)
100s GeV
10s GeV
1 GeV

More mass reach, production XS

Really close
(cm-m)

Kind of close
~few m to 10s m

Far away
100s of m

Protons

Proton missing mom.?
LHCb, REDTOP

DarkQuest, KOTO, SBND-DM
COHERENT, CCM, JSNS^2,
DM@PIP-II, Codex-b, MilliQan
[LSND, NuCal]

FASER, NA62,
FerMINI, SubMET
SHiP, SBND, MiniBooNE, T2K,
DUNE, [CHARM]

Target
width = 1e-6 to 1e3 m

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Beam Energy
TeV (LHC)
100s GeV
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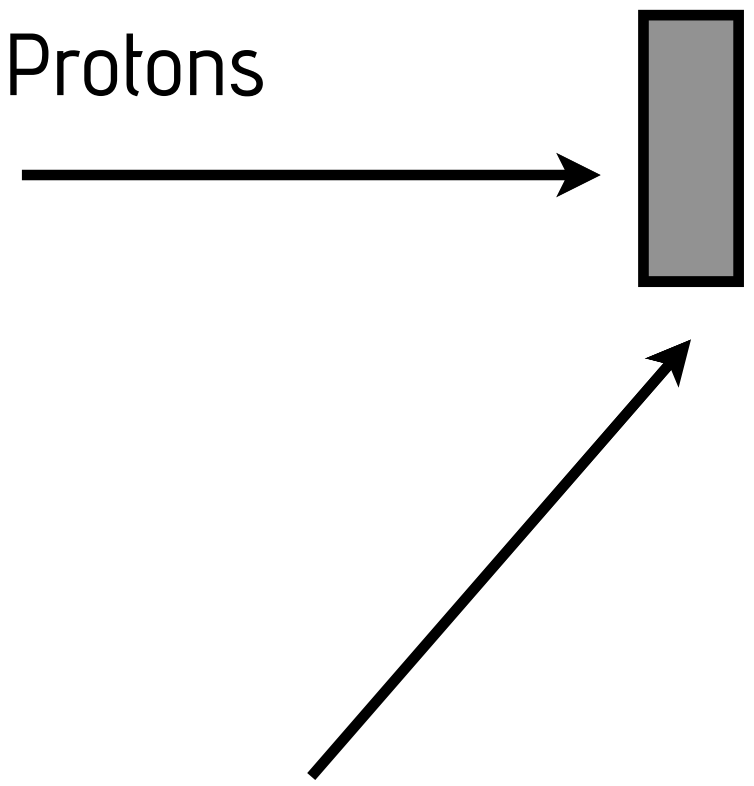


Target
width = 1e-6 to 1e3 m

Really close (cm-m)	Kind of close ~few m to 10s m	Far away 100s of m
Proton missing mom.? LHCb, REDTOP	DarkQuest, KOTO, SBND-DM COHERENT, CCM, JSNS^2, DM@PIP-II, Codex-b, MilliQan [LSND, NuCal]	FASER, NA62, FerMINI, SubMET SHiP, SBND, MiniBooNE, T2K, DUNE, [CHARM]

Detector signatures:

missing momentum: precise/versatile, possible (?!)

DM re-scatter - dense, not busy, preferably precise/versatile

visible dark sector - precise (not dense), versatile

fractional charge - low noise, not busy

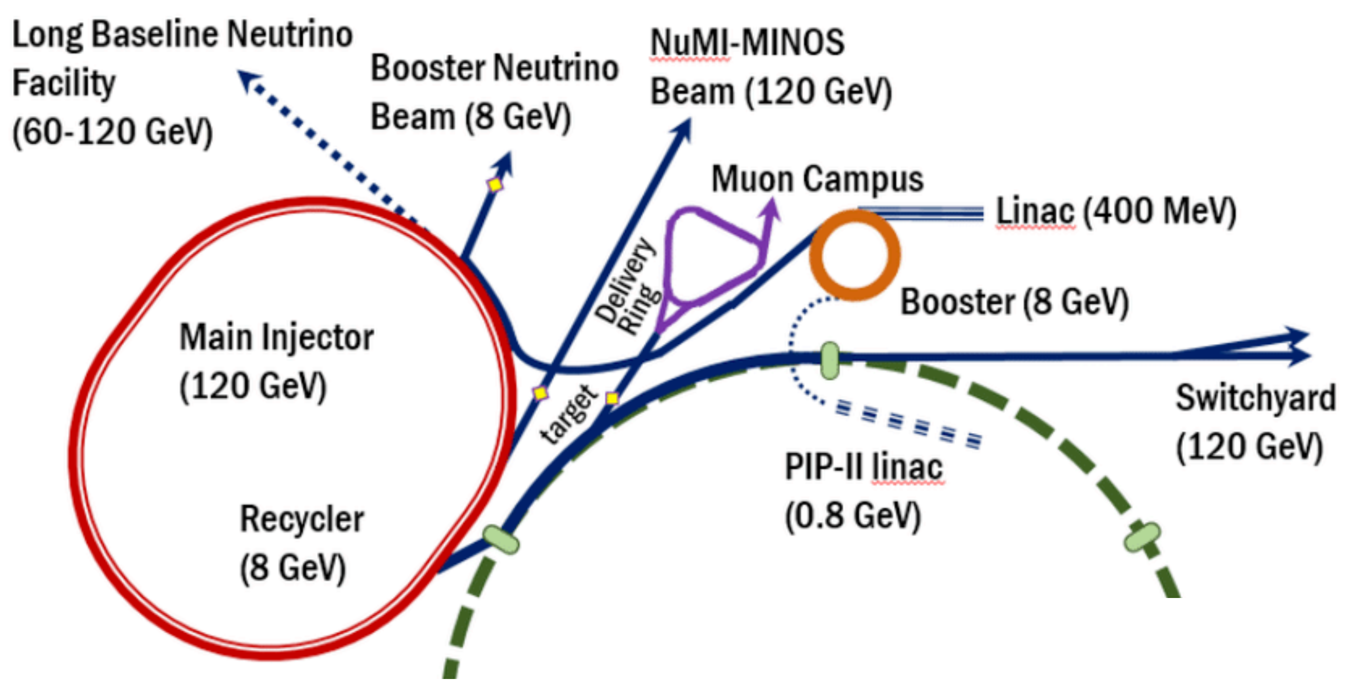
N.B. Need to combine beam energy and distance to get displacement sensitivity ($\gamma c\tau$)

More details
see Cristina's talk

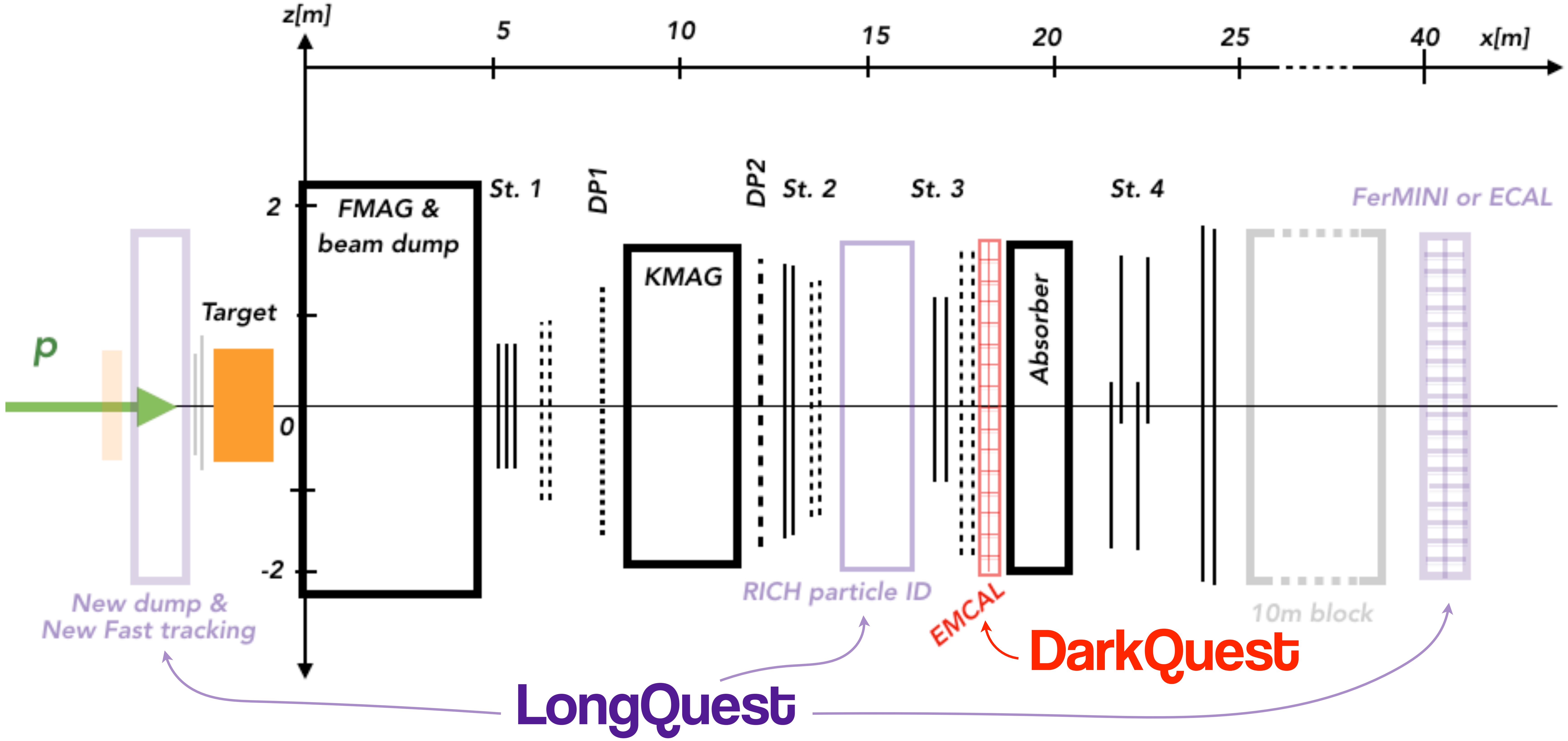
DarkQuest

Berlin, Gori, Toro, Schuster
http://arxiv.org/pdf/1804.00661.pdf

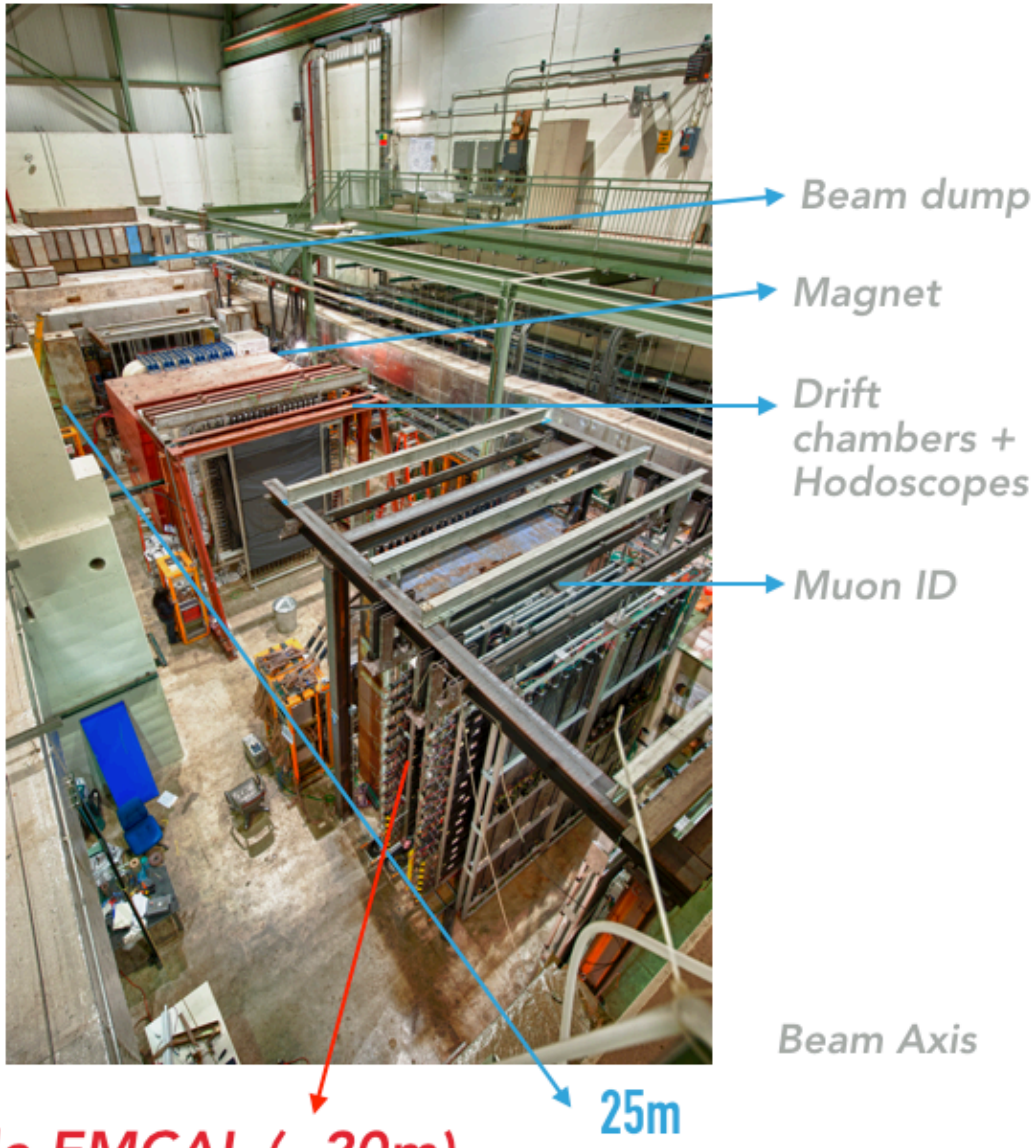
Y-D Tsai, deNiverville, M.X. Liu
https://arxiv.org/abs/1908.07525



SeaQuest: Original nuclear physics experiment
SpinQuest: Upgrade with polarized target (& DP triggers)

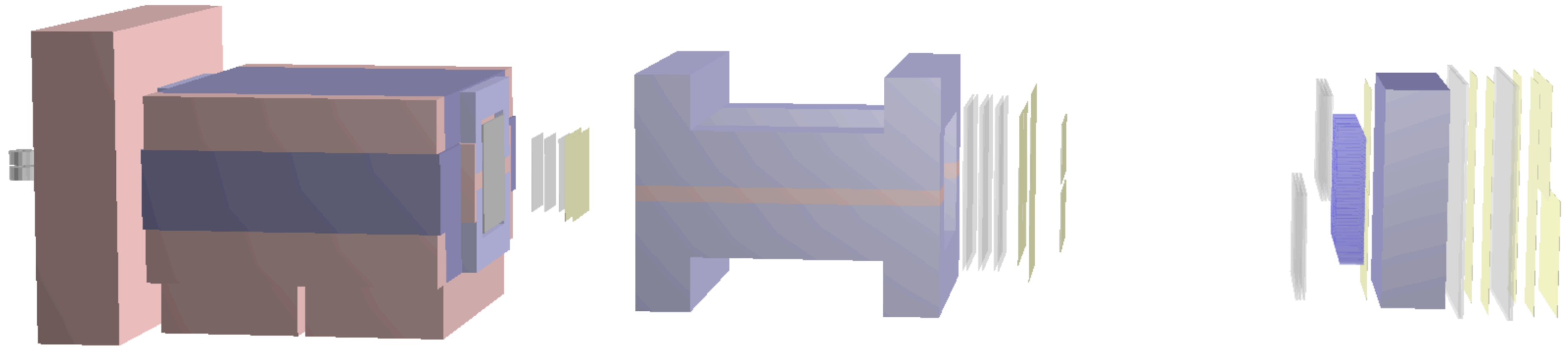


NM4 hall



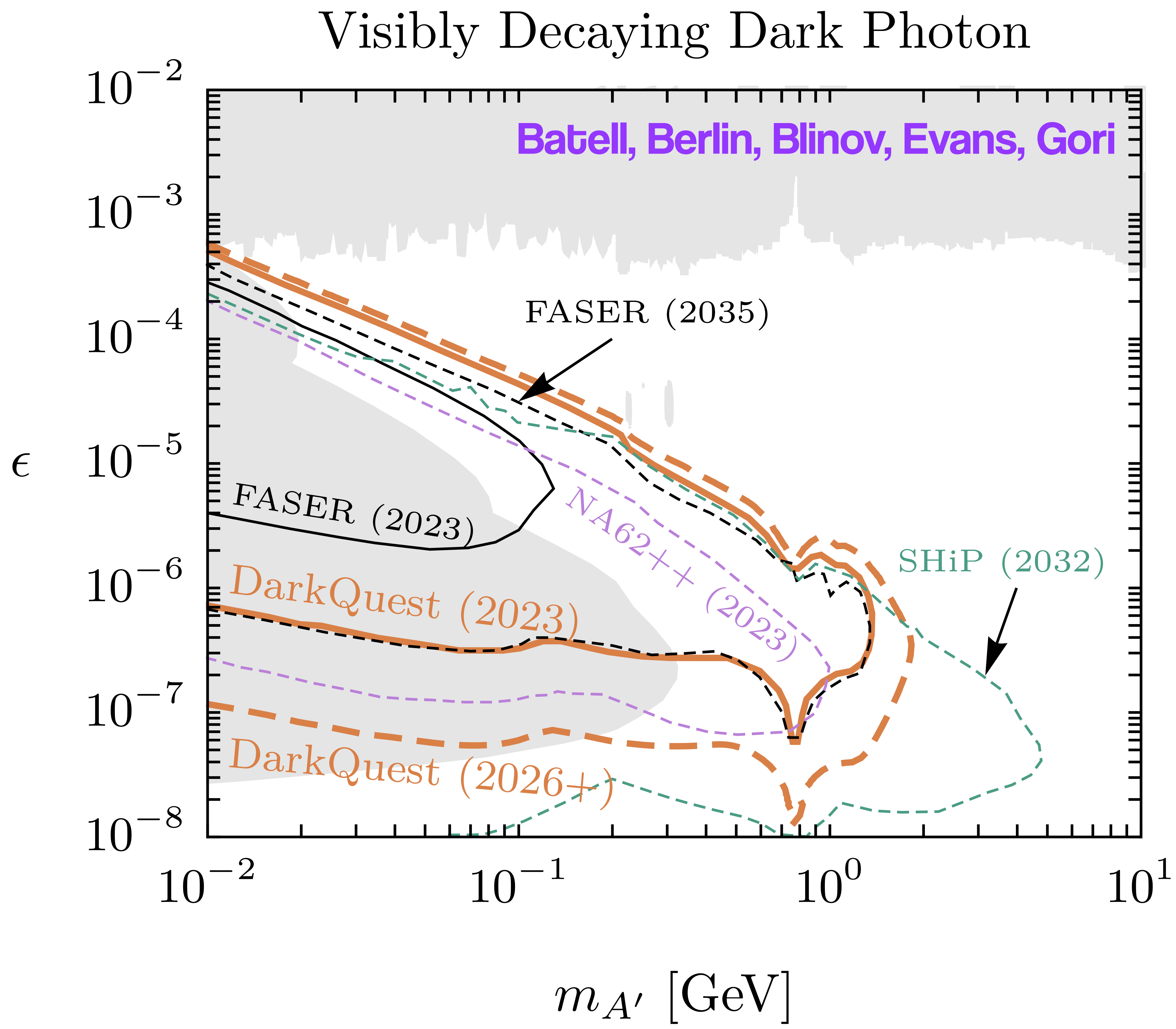
Possible EMCAL (~20m)

Recycled PHENIX EMCal modules in hand



DarkQuest status and reach

- DarkQuest with 2 projections
  - 1.4e18 PoT, 1e20 PoT
- DarkQuest similar to other efforts
  - shorter displacement baseline
  - timeline, 2023-24 and beyond
  - infrastructure mostly exists!
- **To do**: background and signal GEANT simulations including EMCal; study data from 2017 for occupancies; EMCal test stands and readout;
  - **Layout LongQuest concept**



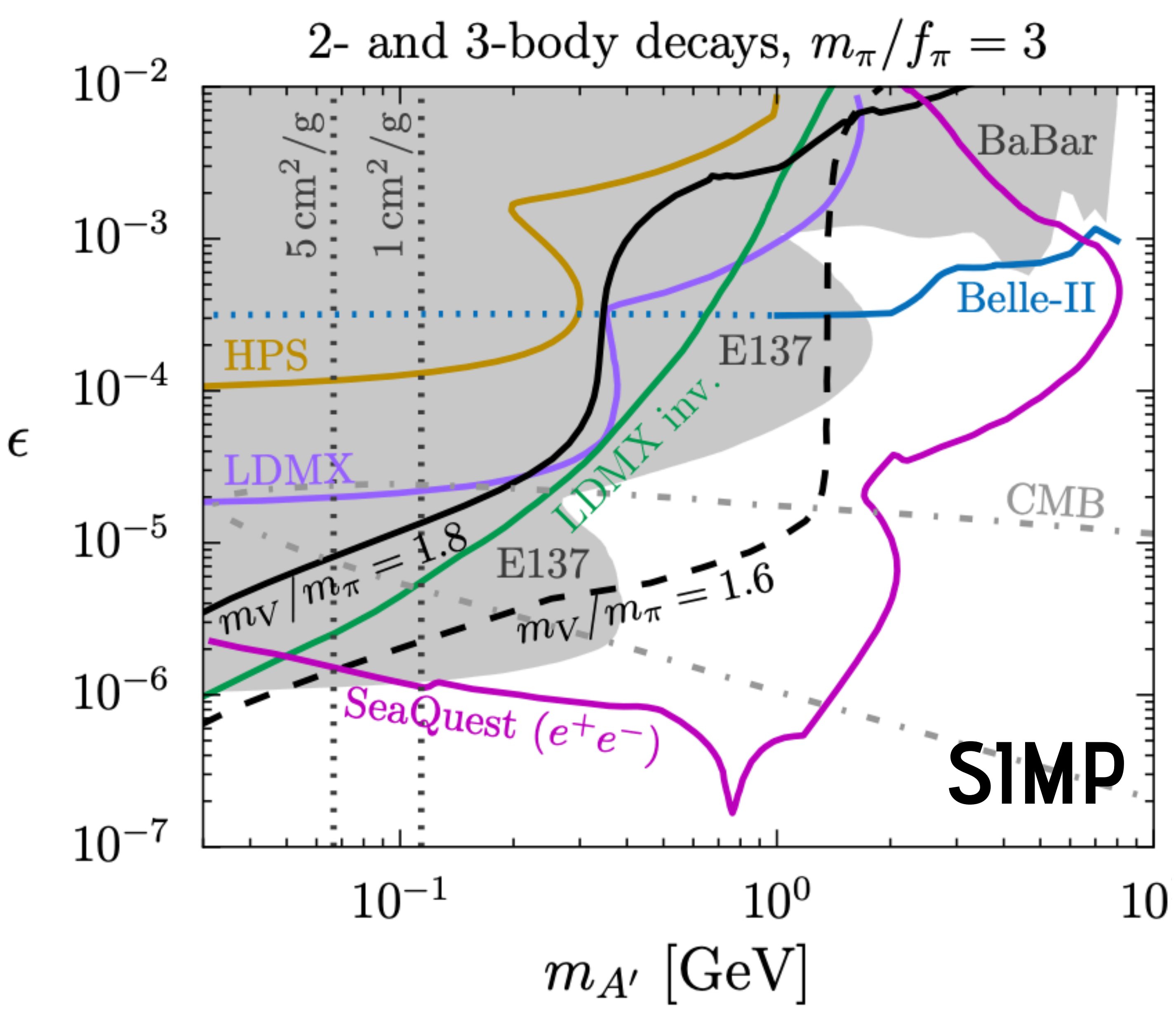
NM4	OPEN	SpinQ	SpinQ	SpinQ	SpinQ	OPEN	OPEN	
	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25

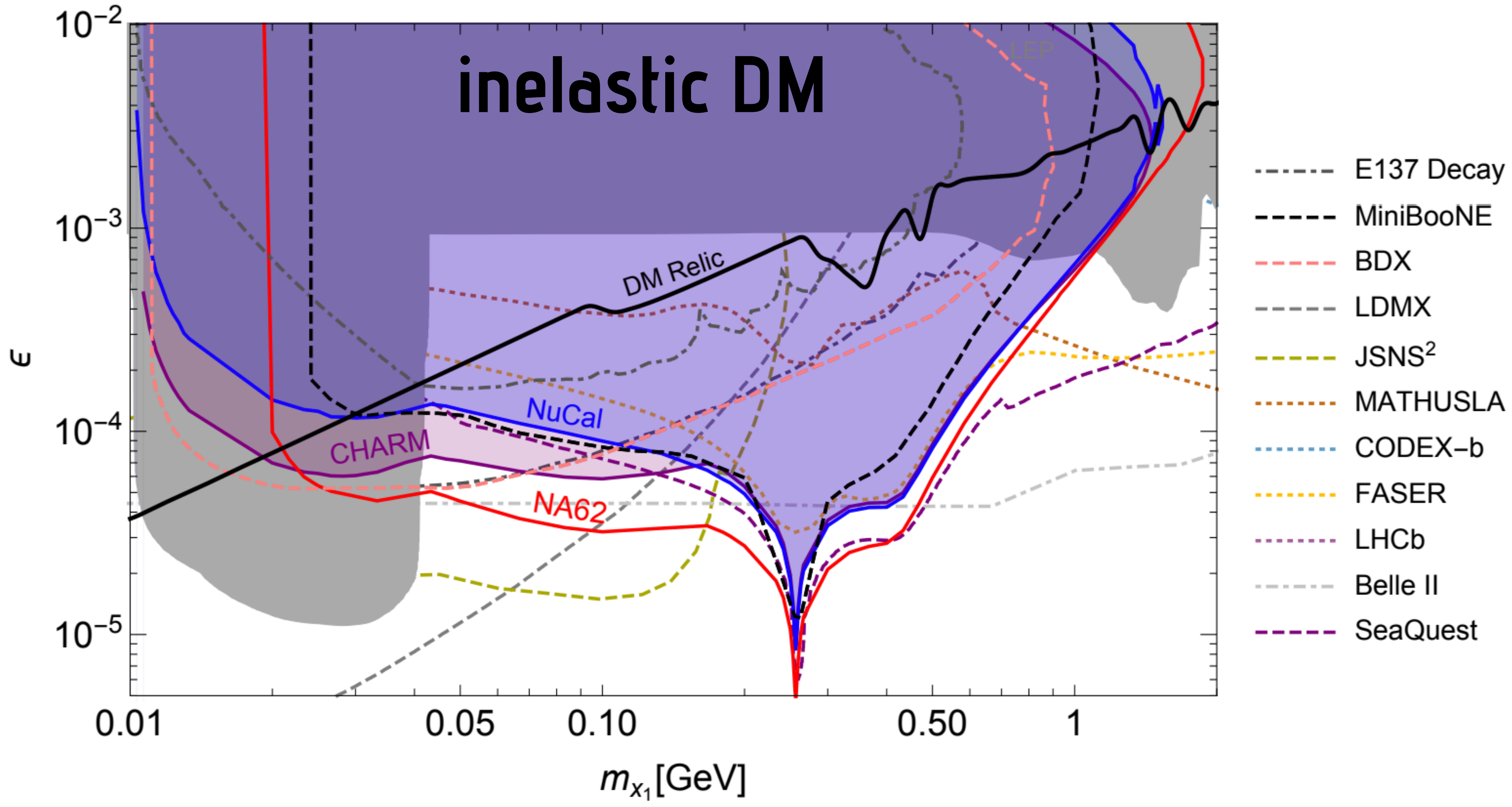
More dark sector signatures

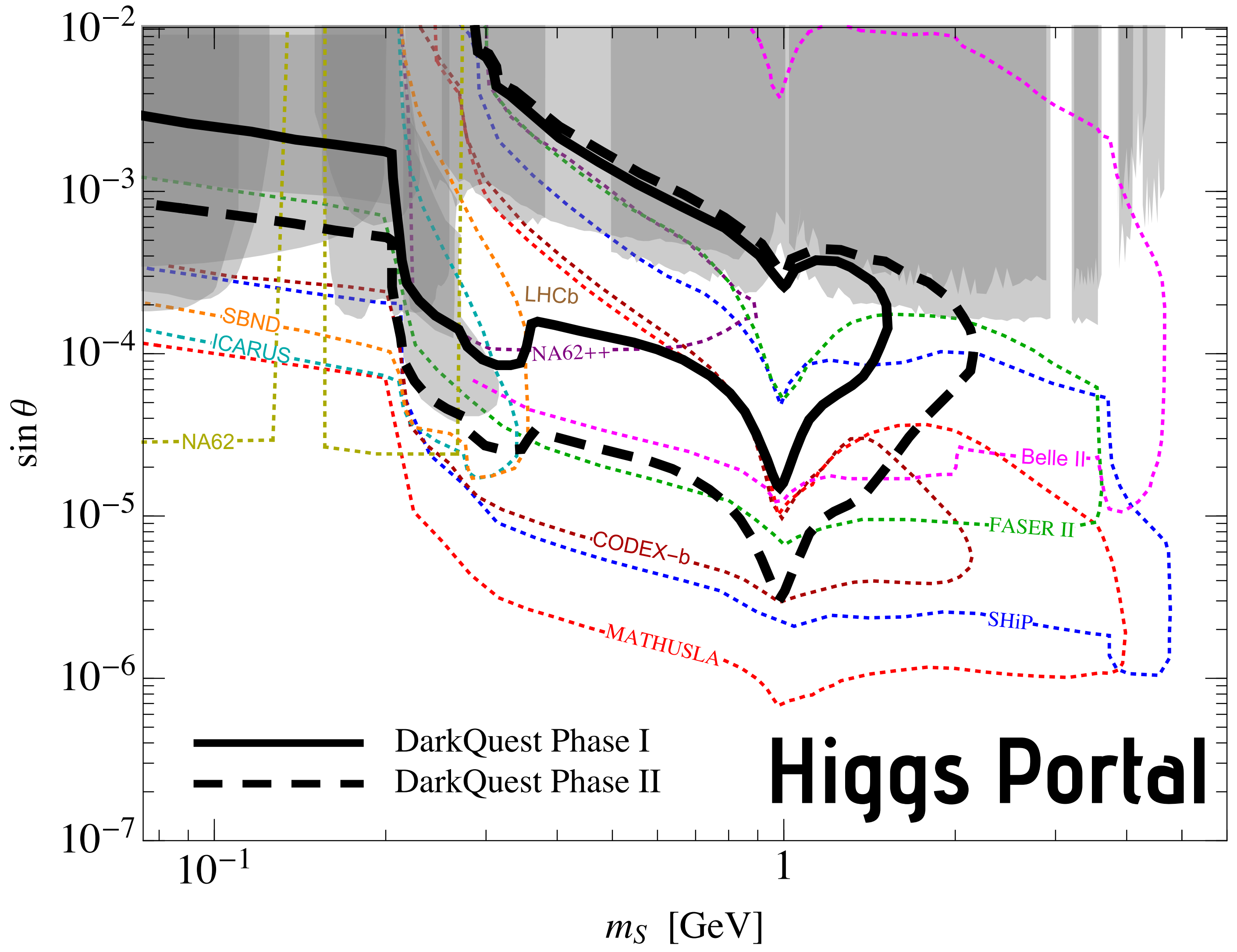
Signature	Model
e^+e^-	dark photon dark Higgs leptophilic scalar*
$e^+e^-e^+e^-$	Higgsed dark photon
$e^\pm\pi^\mp, e^\pm K^\mp, \cdots$	sterile neutrino
$e^+e^- +$ MET	inelastic dark matter strongly interacting dark matter hidden valleys
$\pi^+\pi^-, K^+K^-, \cdots$	dark Higgs*
$\gamma\gamma$	axion-like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

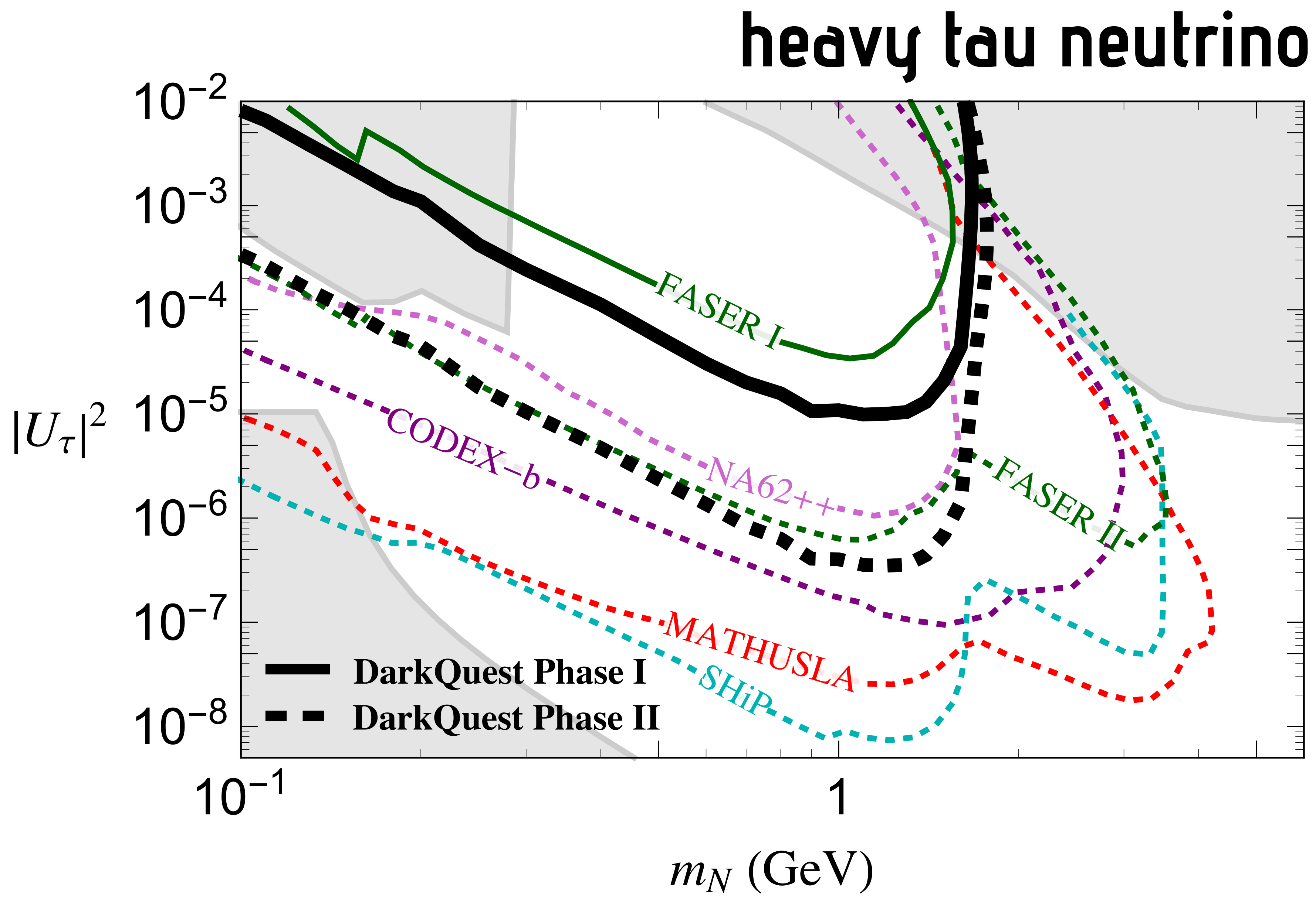
Plots from various sources:
Batell, Berlin, diNiverville, Blinov, Evans, Gori, Toro, Tsai, Shuster

Exploring several benchmark scenarios in full simulation for Snowmass

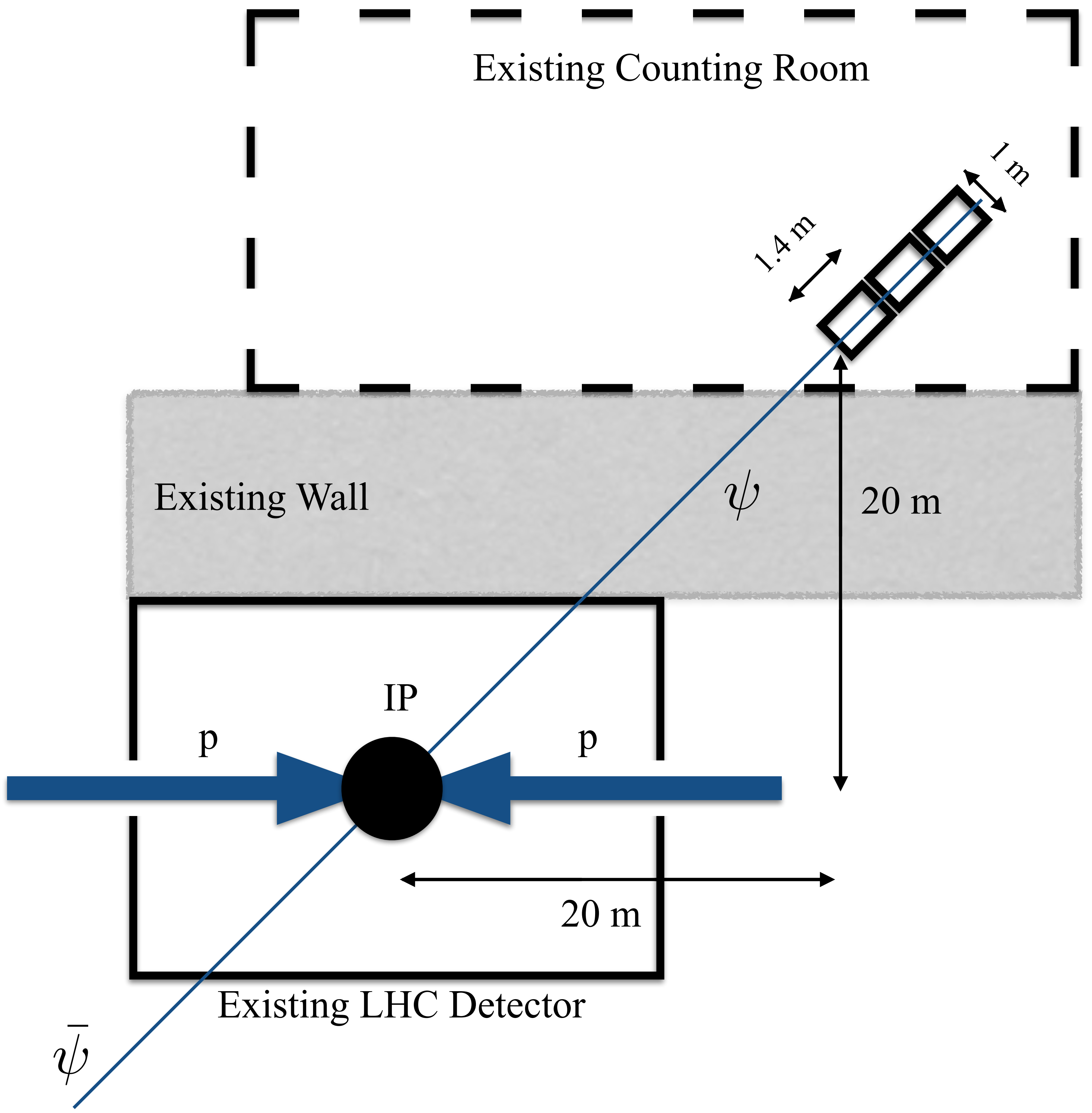






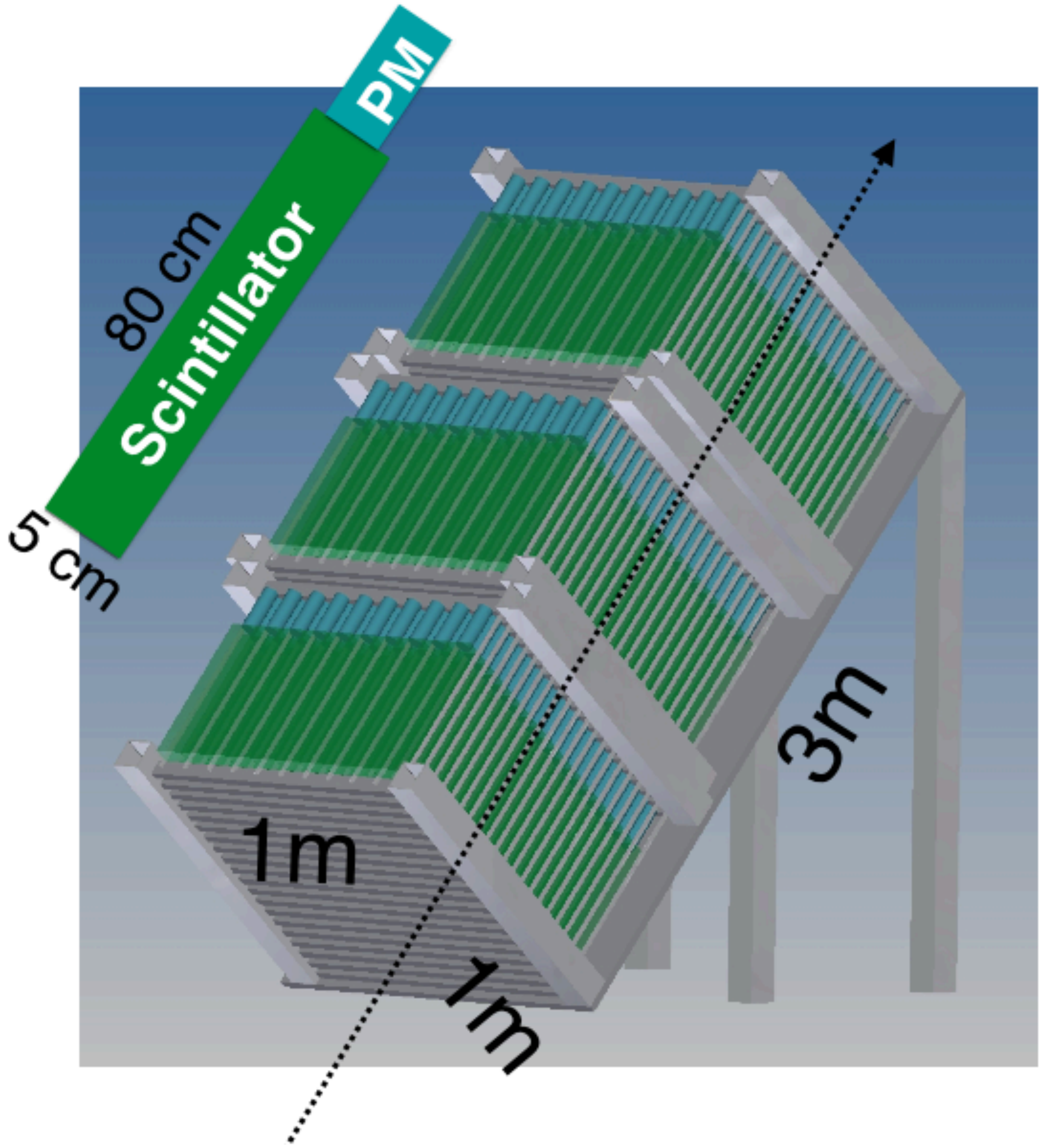


Scintillator arrays for millichargess



A portable setup of scintillator arrays

- inexpensive detector technology
- long, sensitive active material to detect Q ~ 10^{-3}e
- triple coincidence to reduce backgrounds



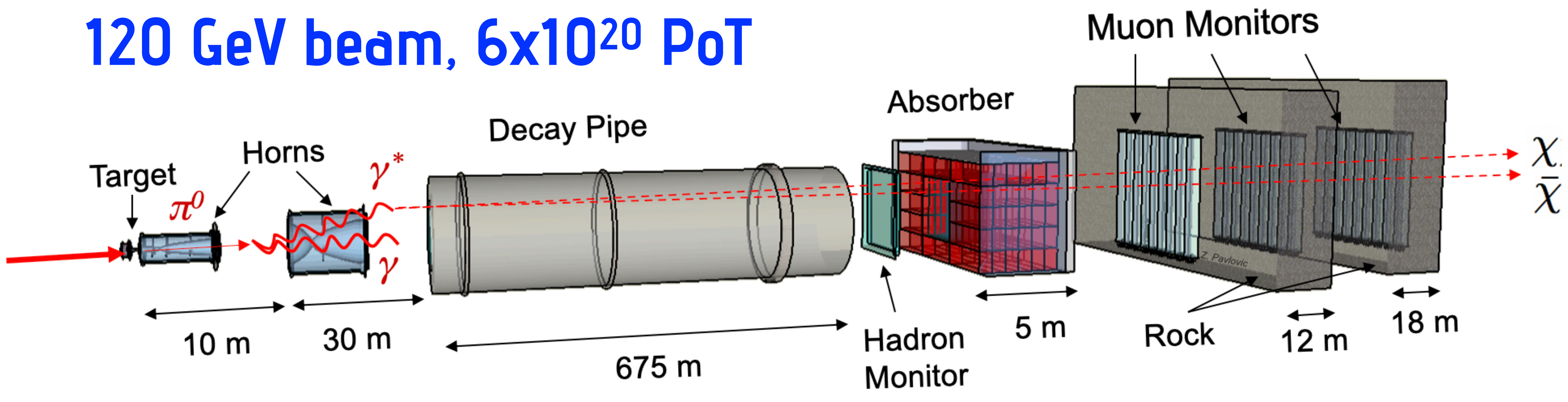
Phys.Lett.B 746 (2015) 117-120 (Haas, Hill, Izerguirre, Yavin)
Now running, MilliQan demonstrated near CMS
See Matthew Citron's talk for more details

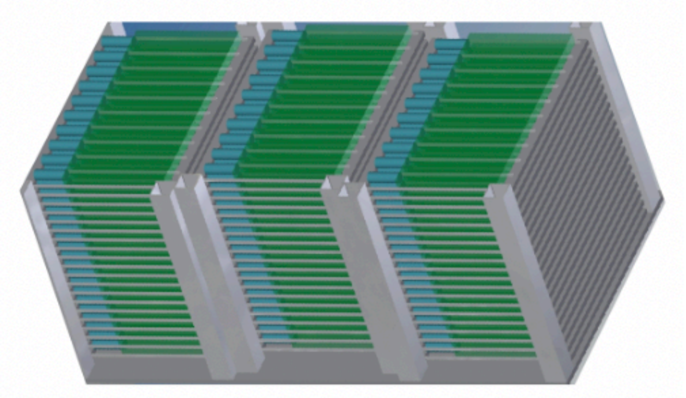
Magill, Plestid, Pospelov, Tsai
https://arxiv.org/abs/1806.03310
Kelly, Tsai
https://arxiv.org/abs/1812.03998

FerMINI & SUBMET

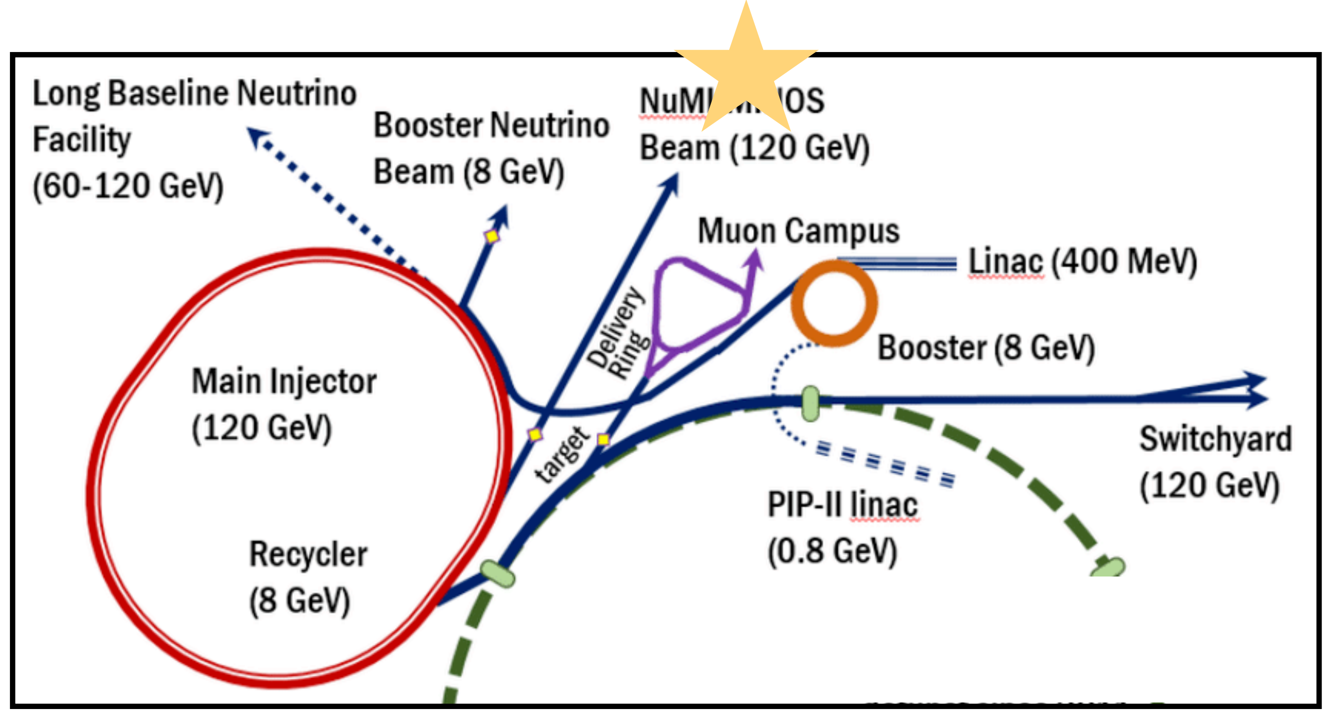
J. Yoo, et al
https://arxiv.org/abs/2007.06329

120 GeV beam, 6x10^{20} PoT





FerMINI Detector



Zarko Pavlovic & Yu-Dai Tsai, Fermilab

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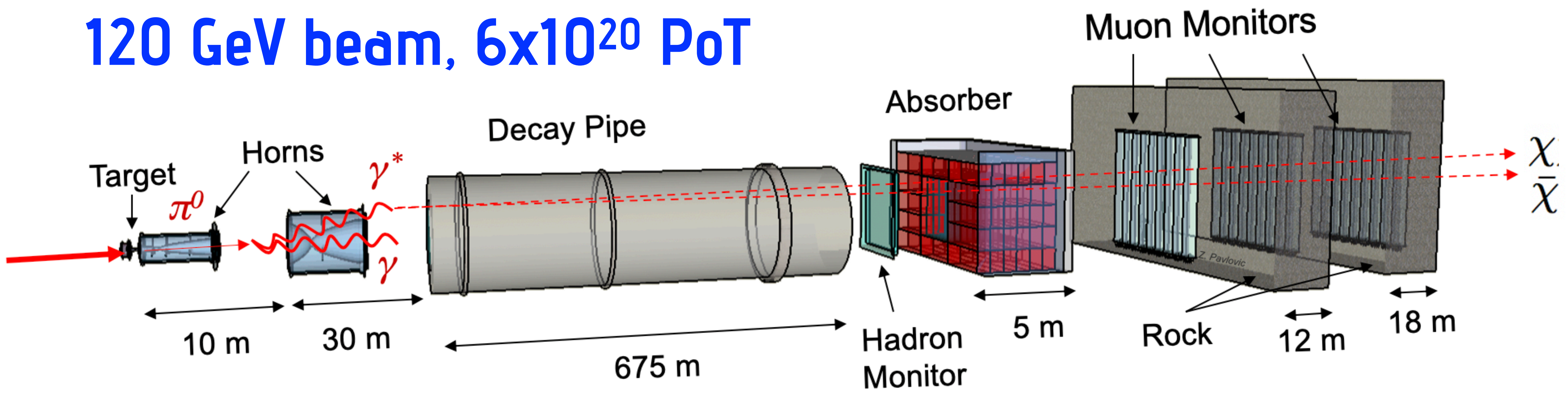
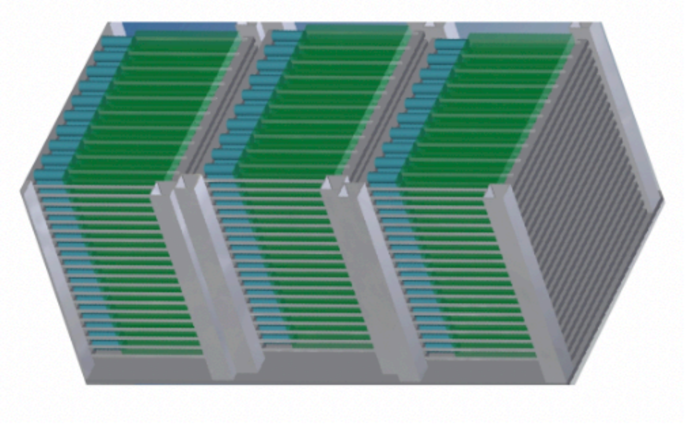
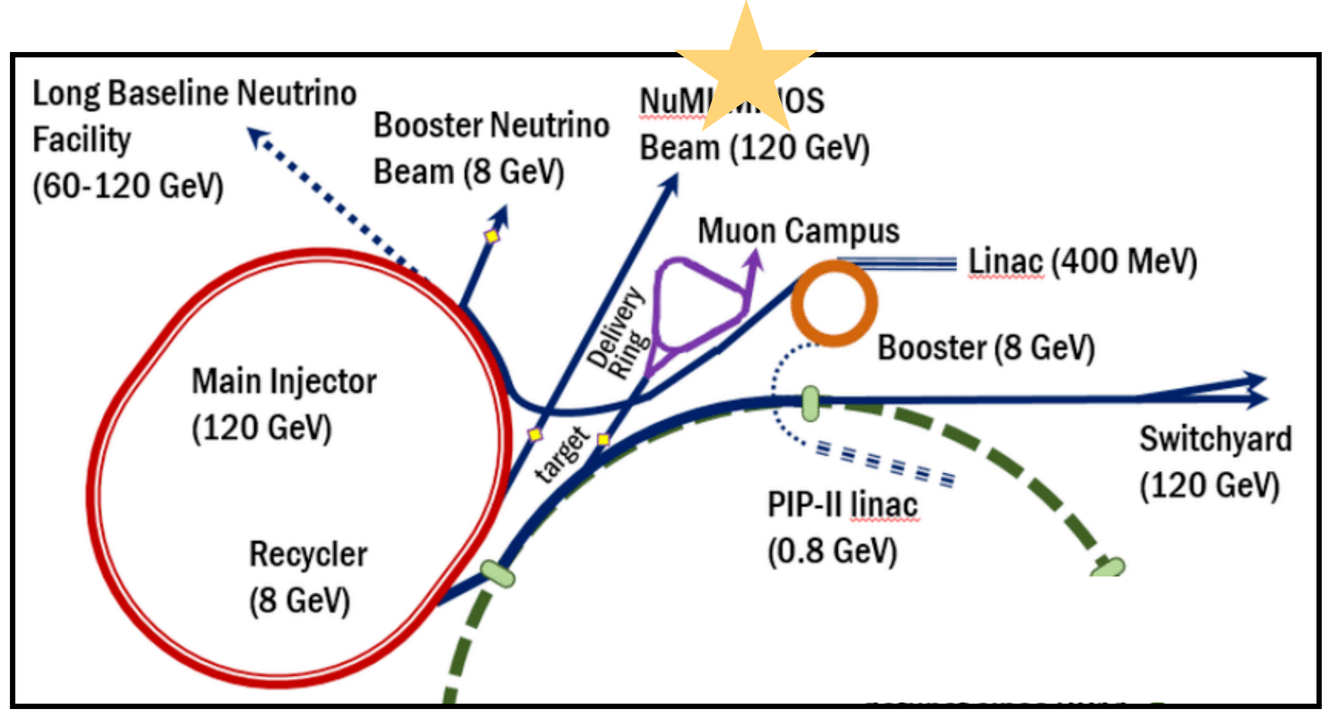
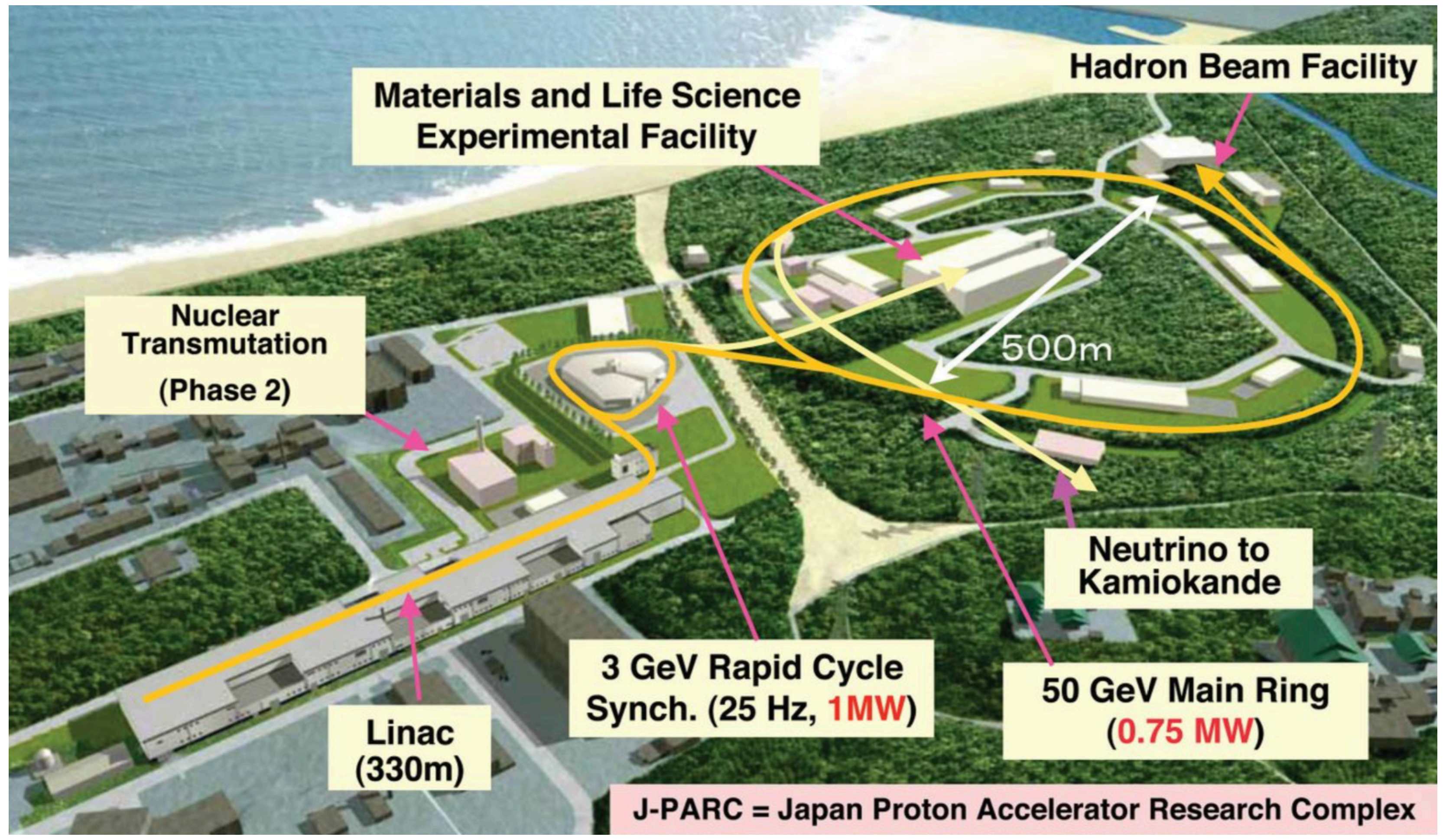


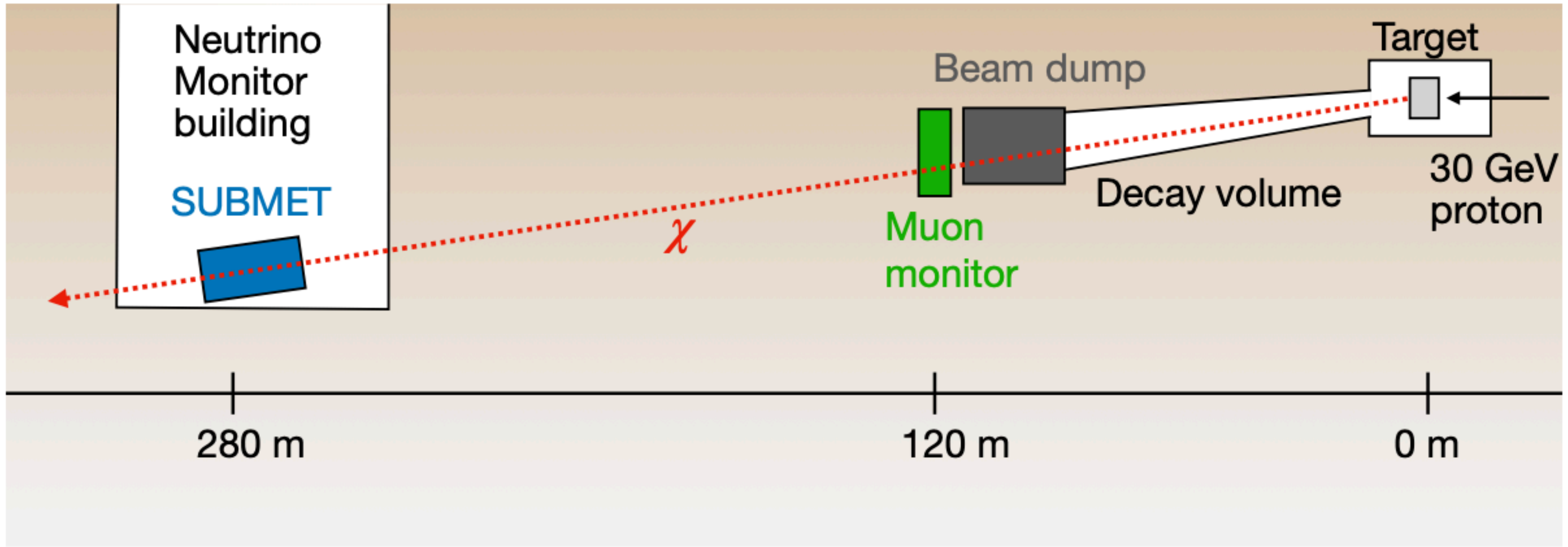


FerMINI Detector



Zarko Pavlovic & Yu-Dai Tsai, Fermilab



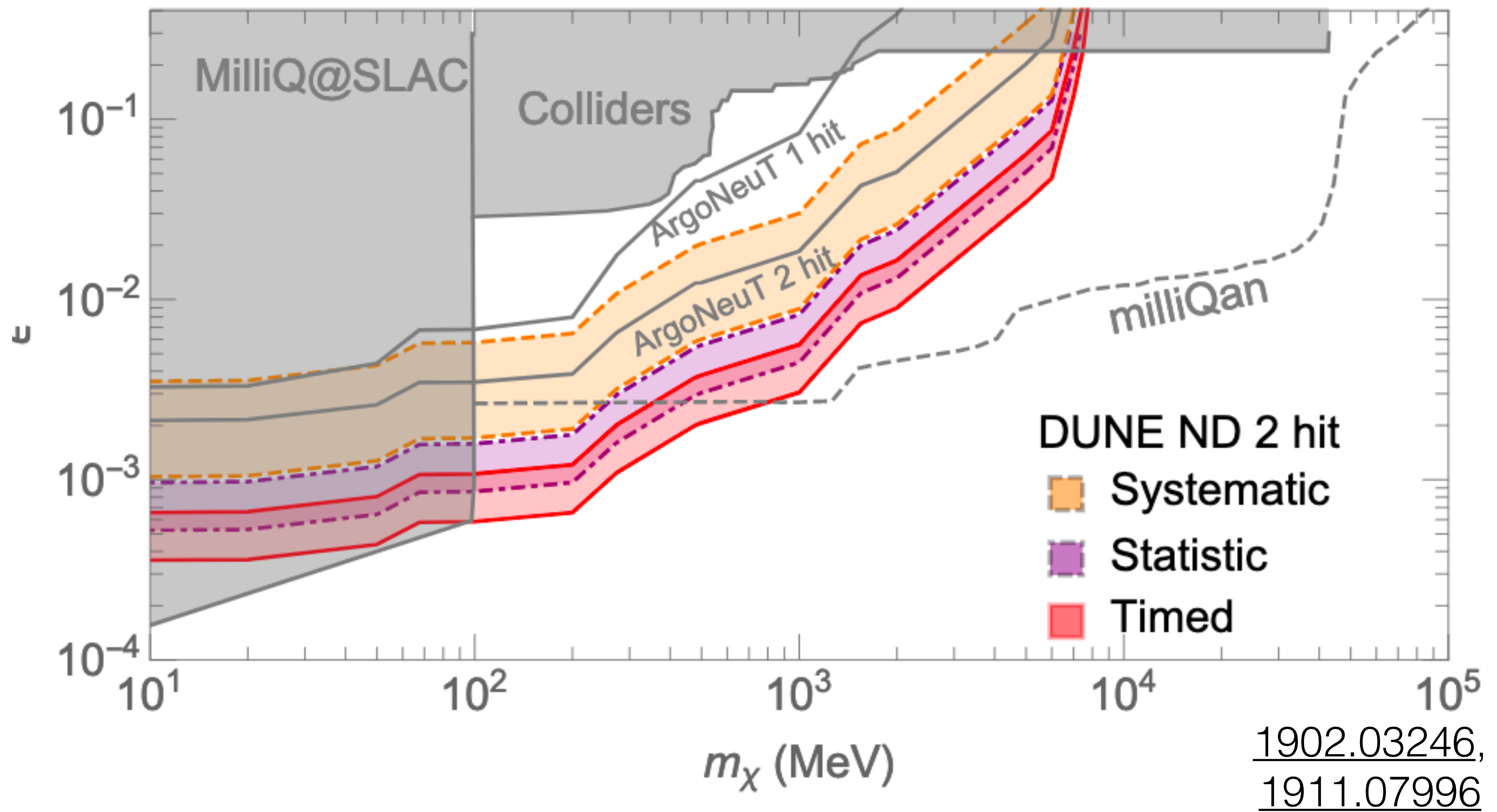


30 GeV beam, 10^{22} PoT

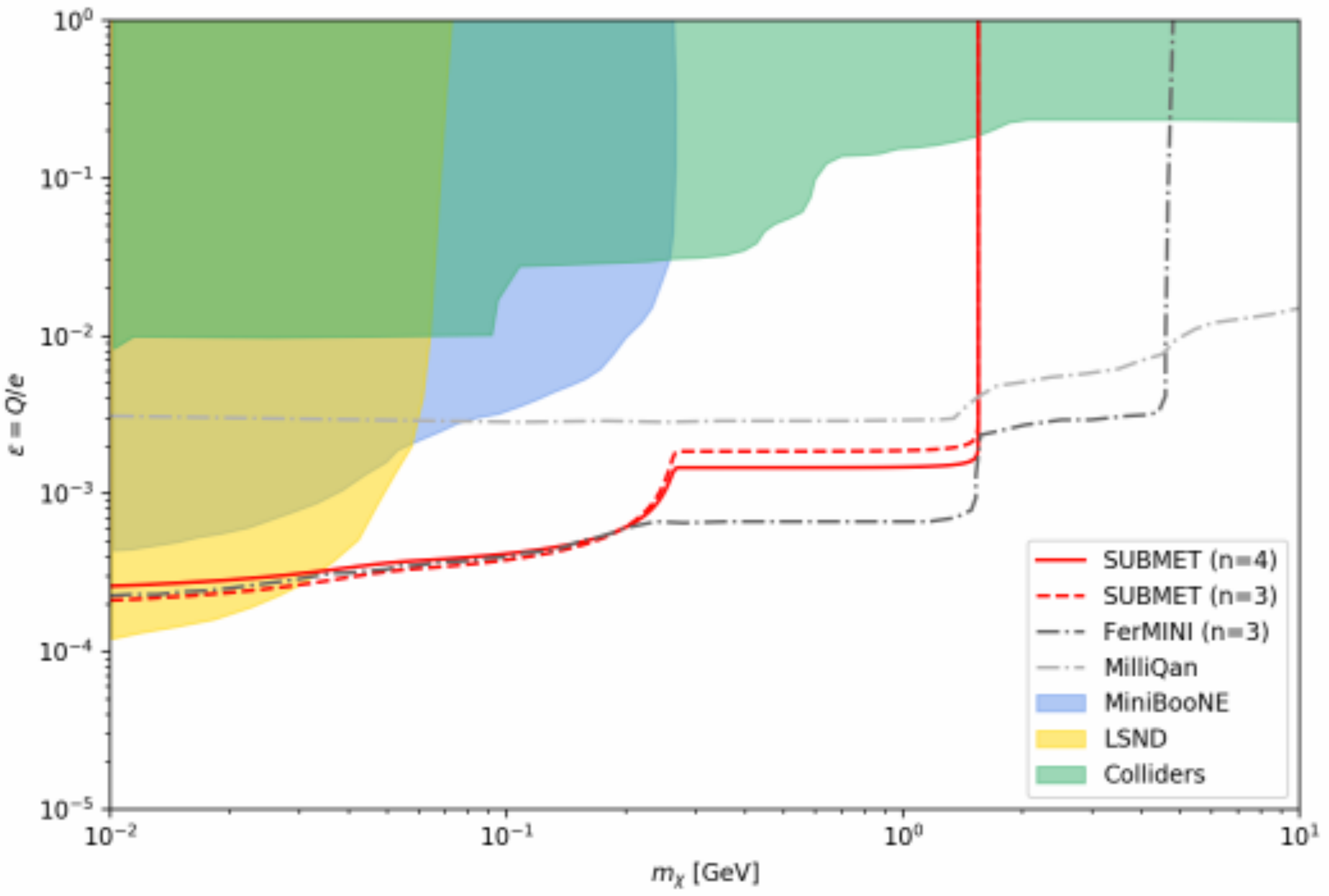
Millicharged sensitivity

The complementarity of different scintillator array configurations is shown here.

Different physics reaches as a function of beam energy and luminosity



1902.03246, 1911.07996



Comparing to sensitivities from neutrino experiments

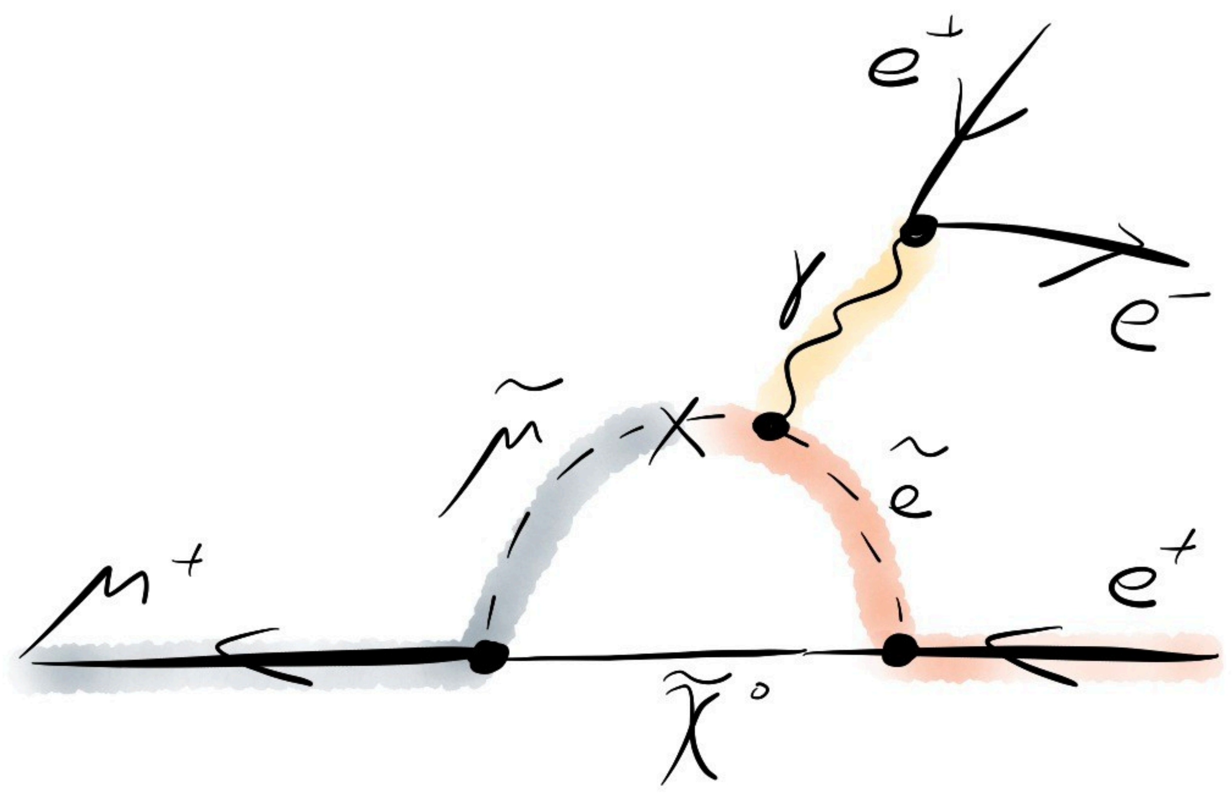
Muon fixed-target

Physics scenarios redux: muons

- **Muons** are **unique window** to 2nd generation
  - Heavy (at least than electrons), clean (minimum ionizing)
  - Cons: muon beams are harder to come by and control

- Covered here:
  - **mu3e**: clean environment to study high intensity muon beams
  - **M^3** & **NA64μ**: muon missing momentum for unique couplings and mass sensitivity
  - **"Muon" beam dumps:** dedicated muon beams and full circle with proton beams

Dark sectors at mu3e

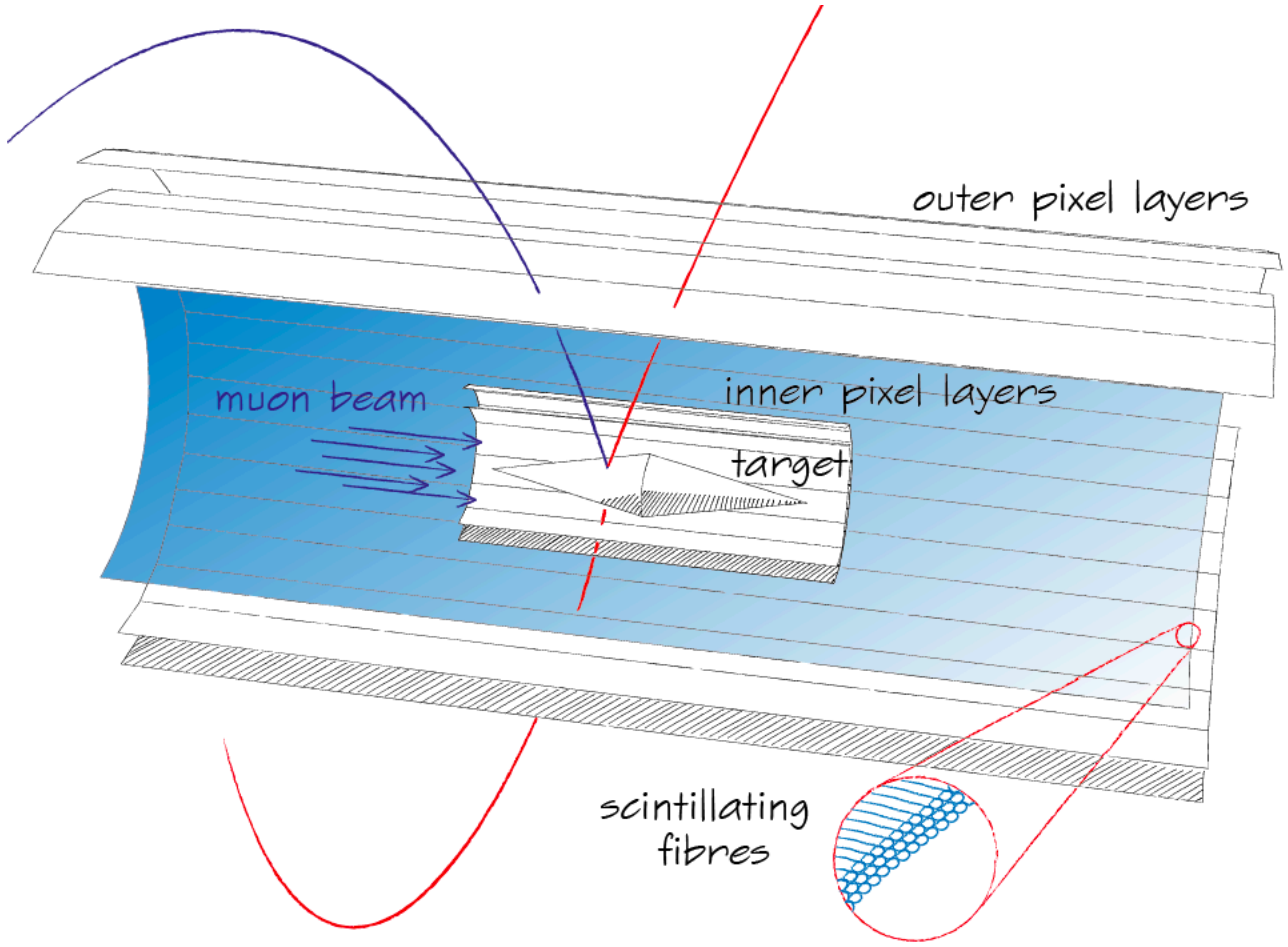


Primary physics program looking for

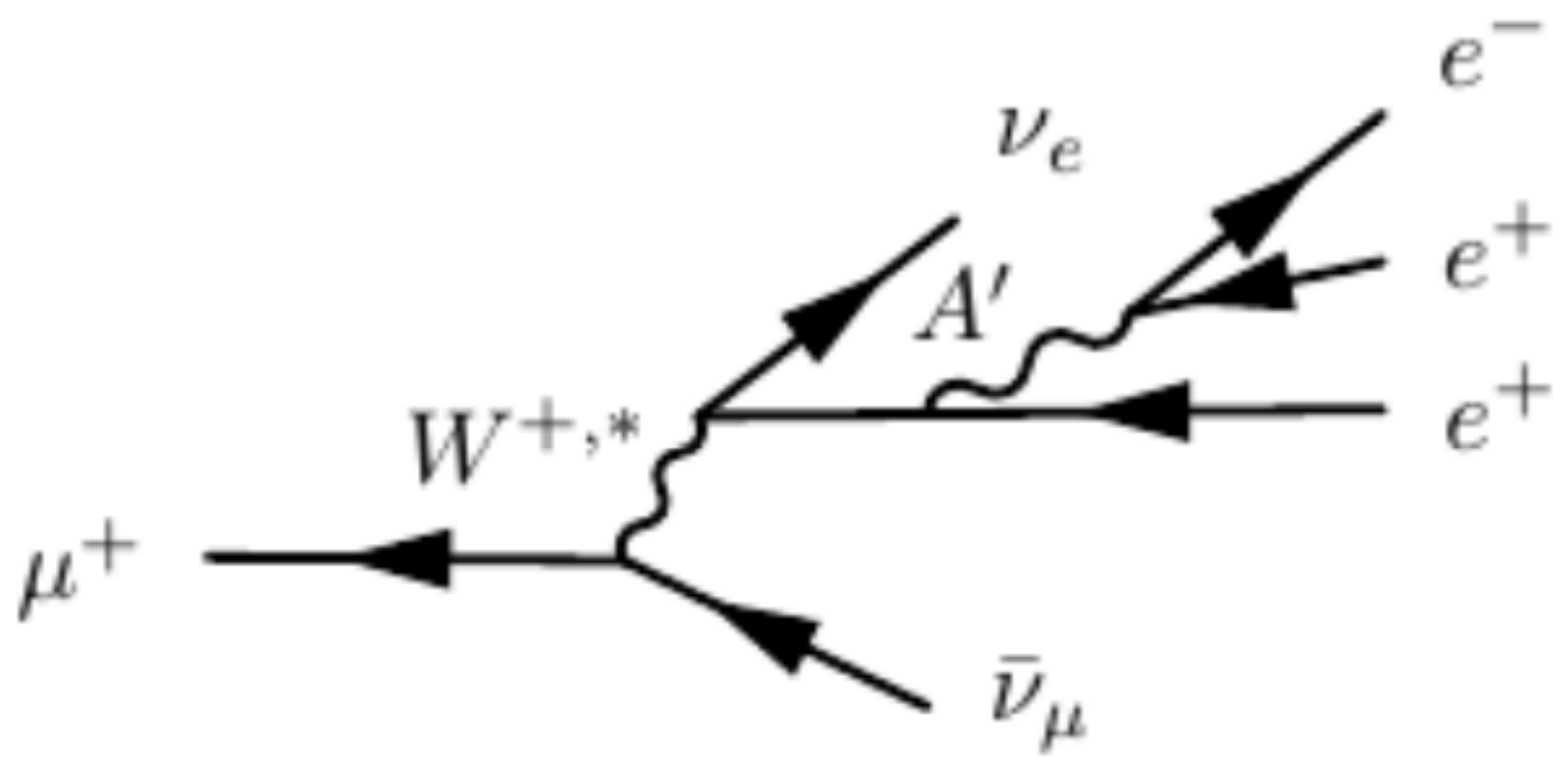
$\mu \to 3e$ where $m_{3e} = m_\mu$

Can use clean experimental environment and high muon beam intensity (10^9 μ/s) to explore dark sectors too!

Echenard, Essig, Zhong
arXiv:1411.1770v2



Dark sectors at mu3e



Final state:

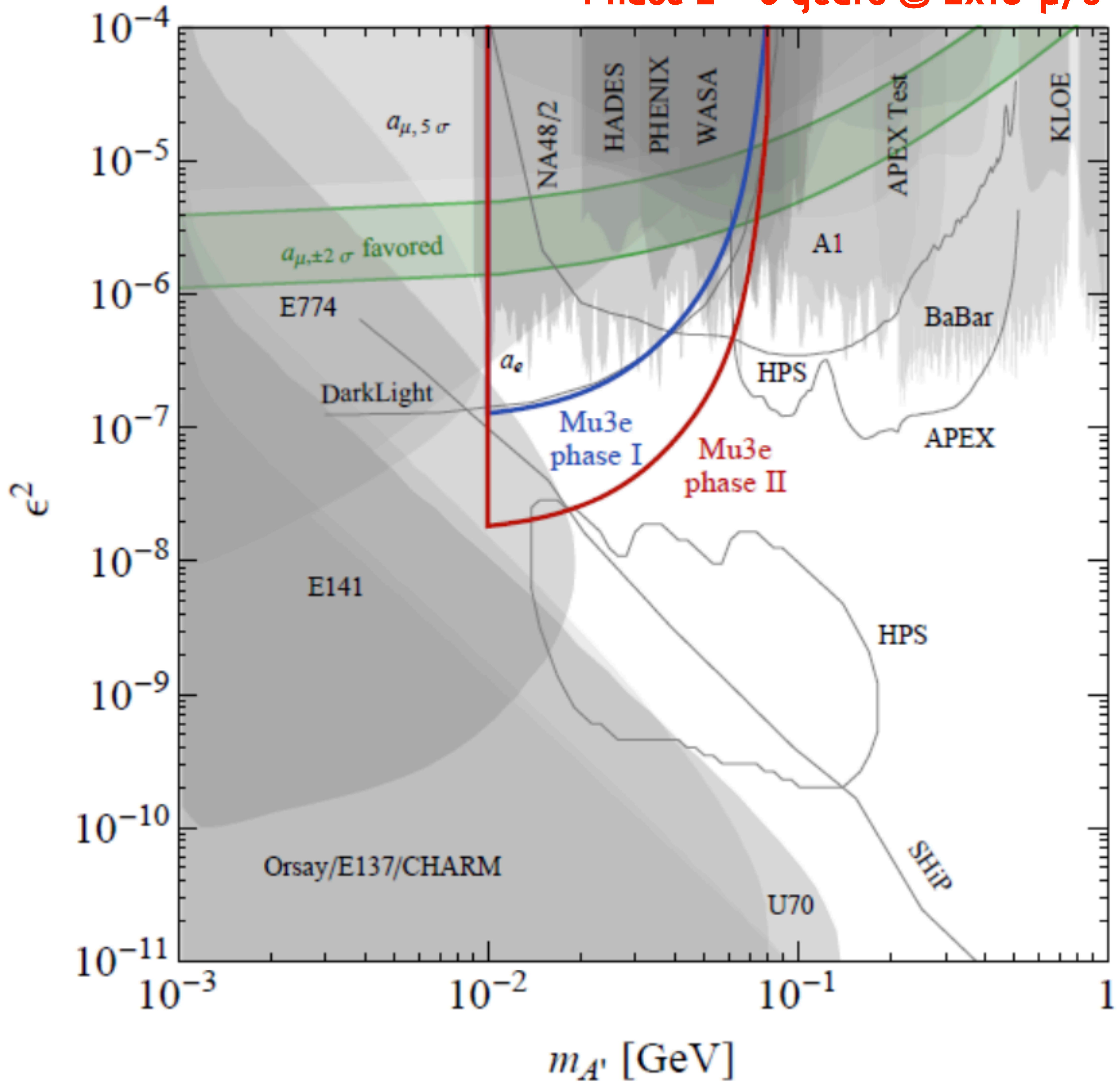
$\mu^+ \rightarrow e^+e^+e^-\nu_e\nu_\mu$

With resonance in the e+e- pair

Analysis needs to be done online; this final state exceeds experimental compute capabilities

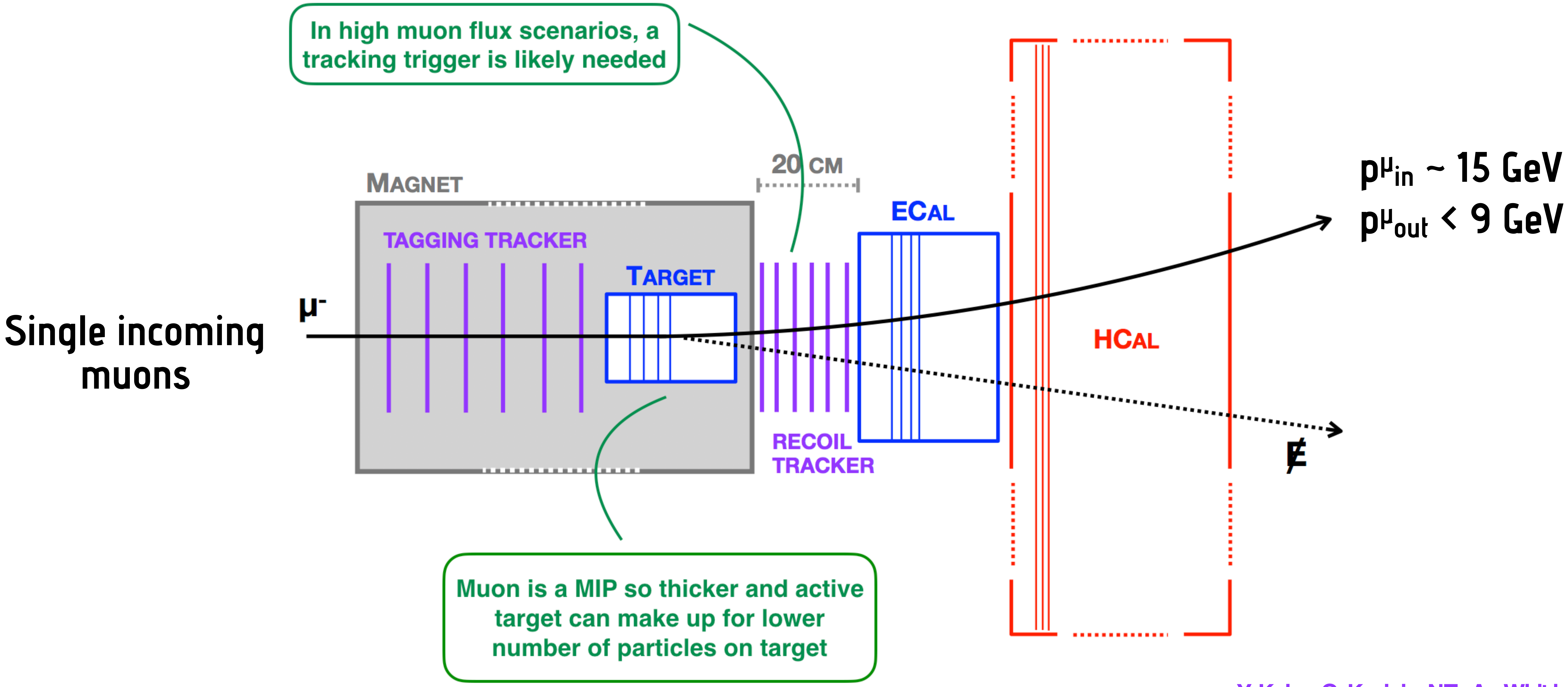
Phase 1 ~ 3 years @ $10^8\mu/s$

Phase 2 ~ 3 years @ $2\times10^9\mu/s$



Muon missing momentum, M³

Very similar concept to electron missing momentum (see Tim Nelson's talk)



Y. Kahn, G. Krnjaic, N.T., A . Whitbeck
https://arxiv.org/abs/1804.03144

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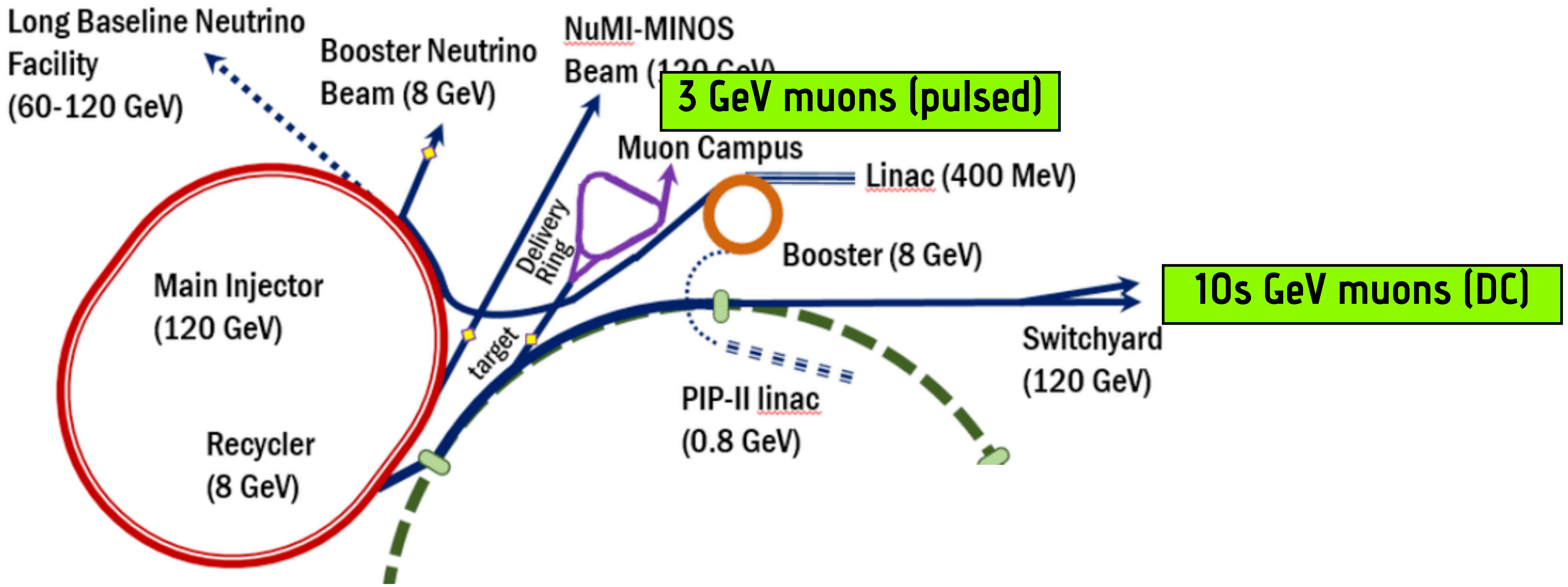


Unique challenges with producing and controlling muon beams, but with muon missing momentum exploits unique capabilities

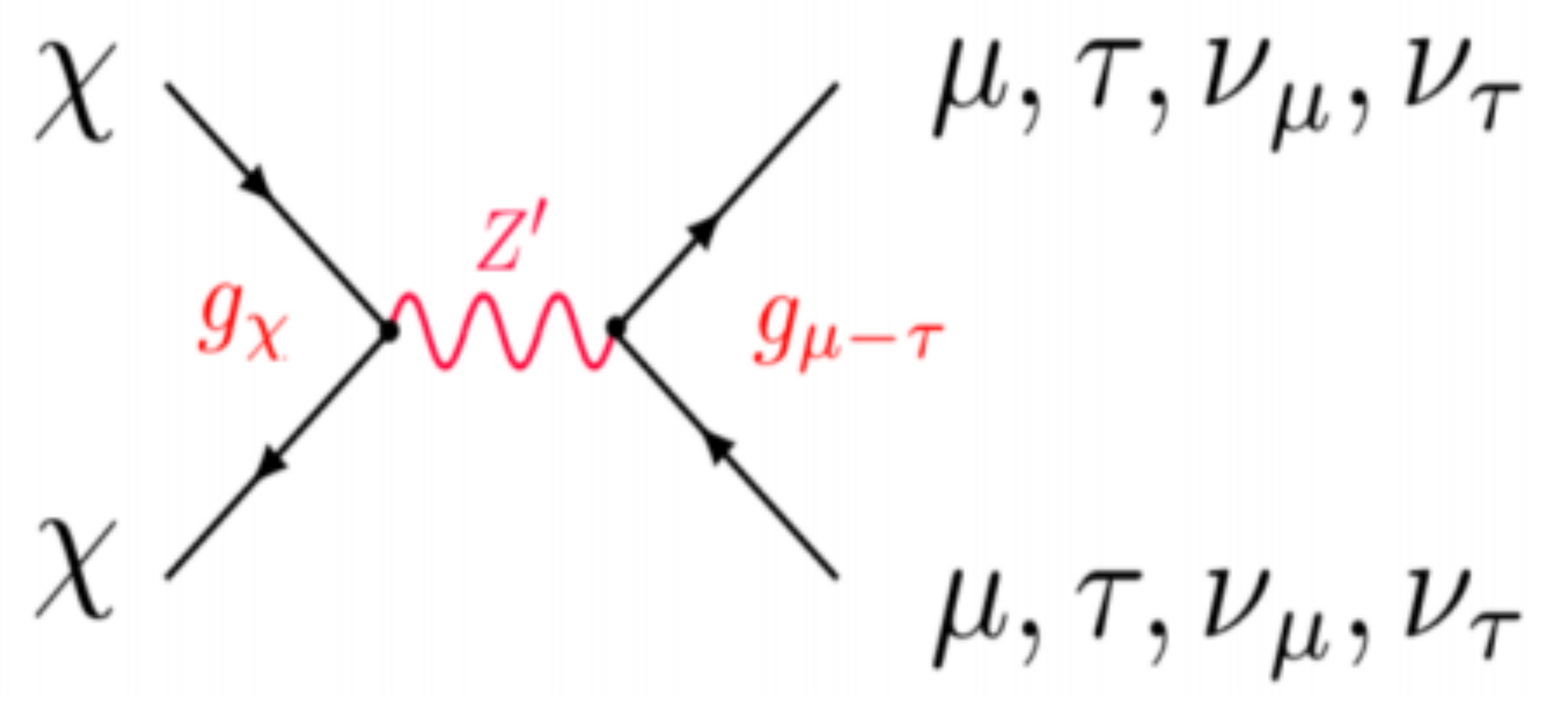
- If g-2 excess persists (or grows), muon beams become very relevant
  - A test of muon-philic couplings with minimal dependence on other model assumptions
- In addition heavier muon (than electron) provides different mass sensitivity

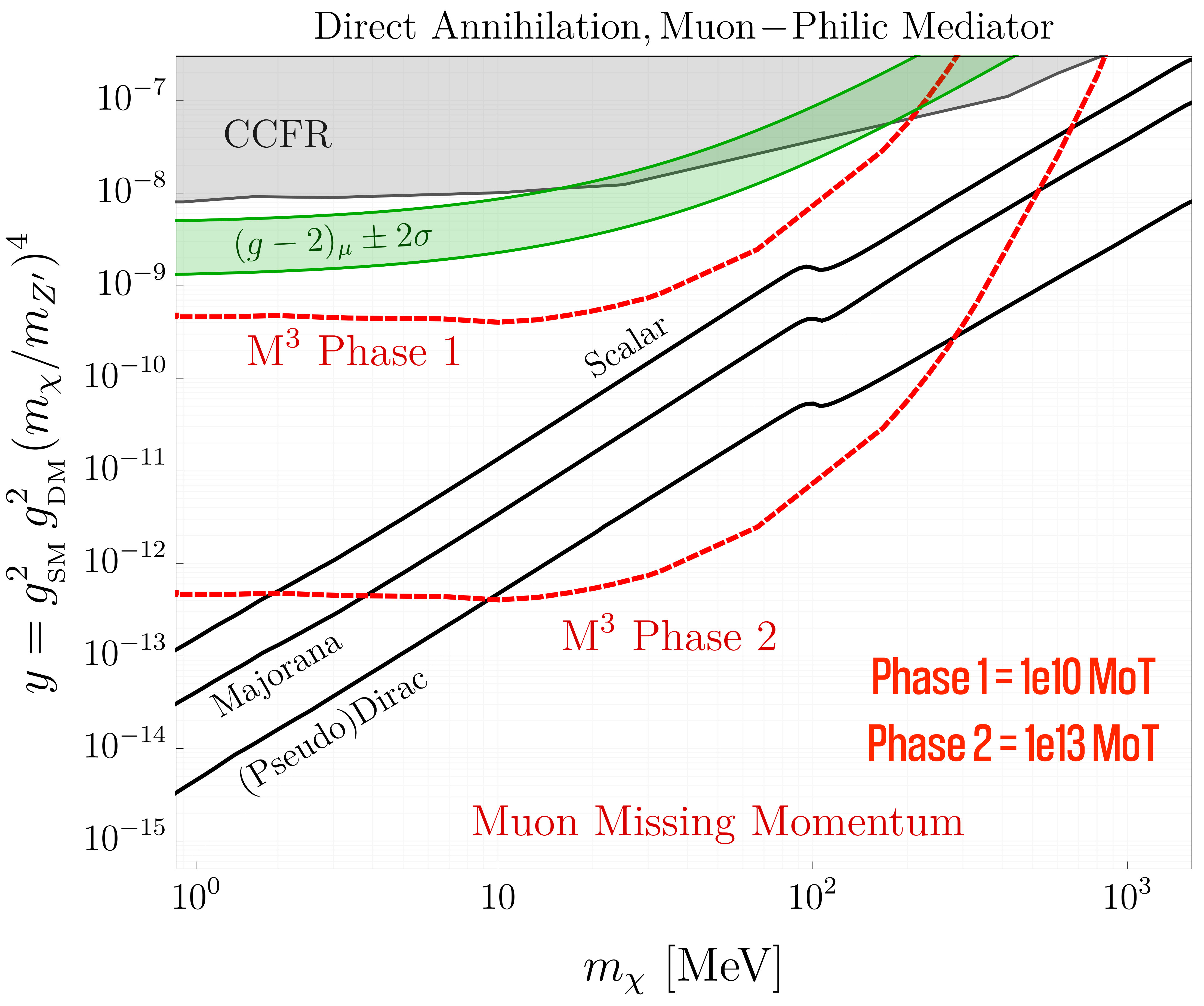
Y. Kahn, G. Krnjaic, N.T., A . Whitbeck
https://arxiv.org/abs/1804.03144

M³ sensitivity

Muon beams provide model-independent probe of light new physics contributing to $(g-2)_\mu$ anomaly

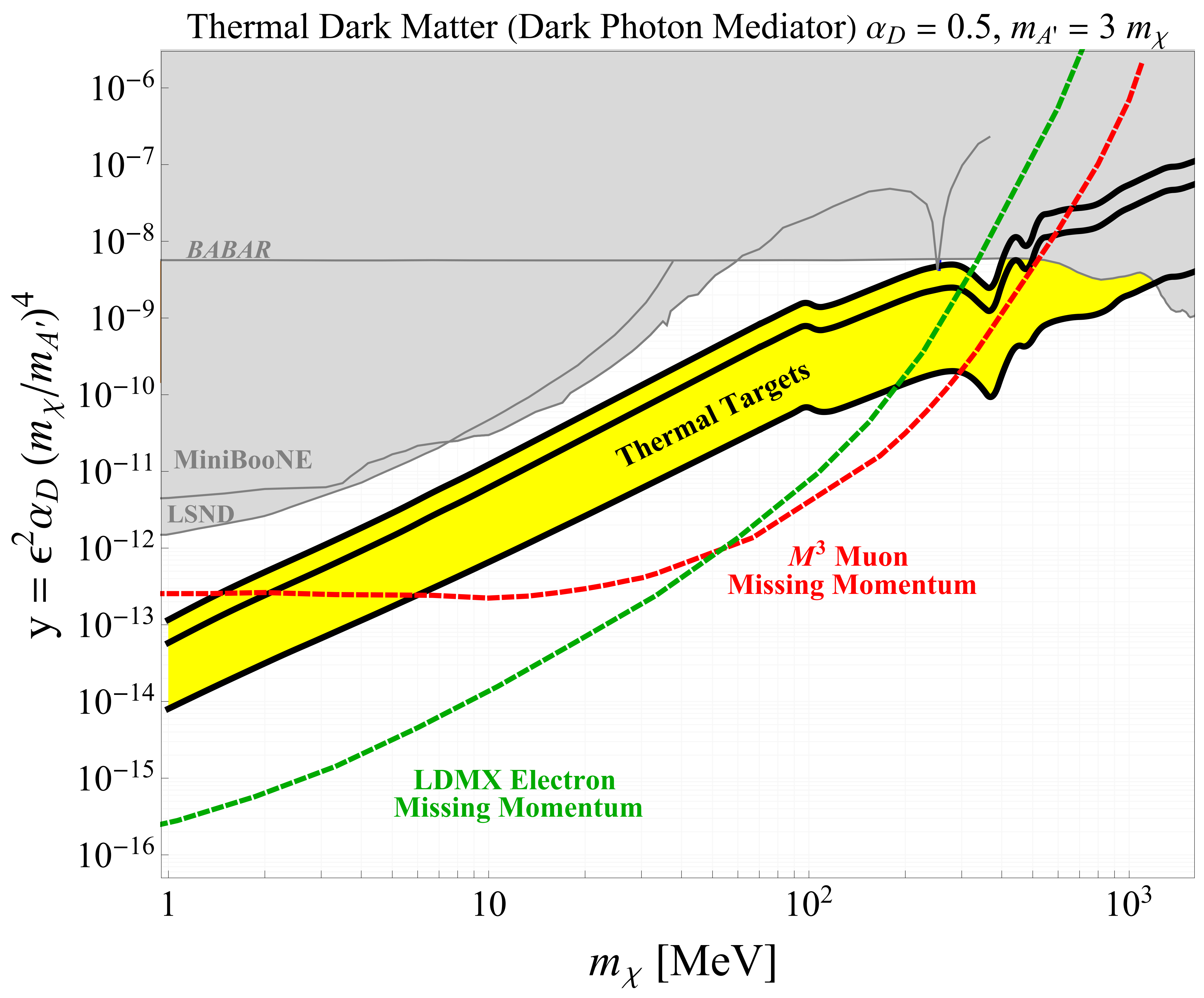
Muon-Philic Mediator, $L_{\mu-\tau}$



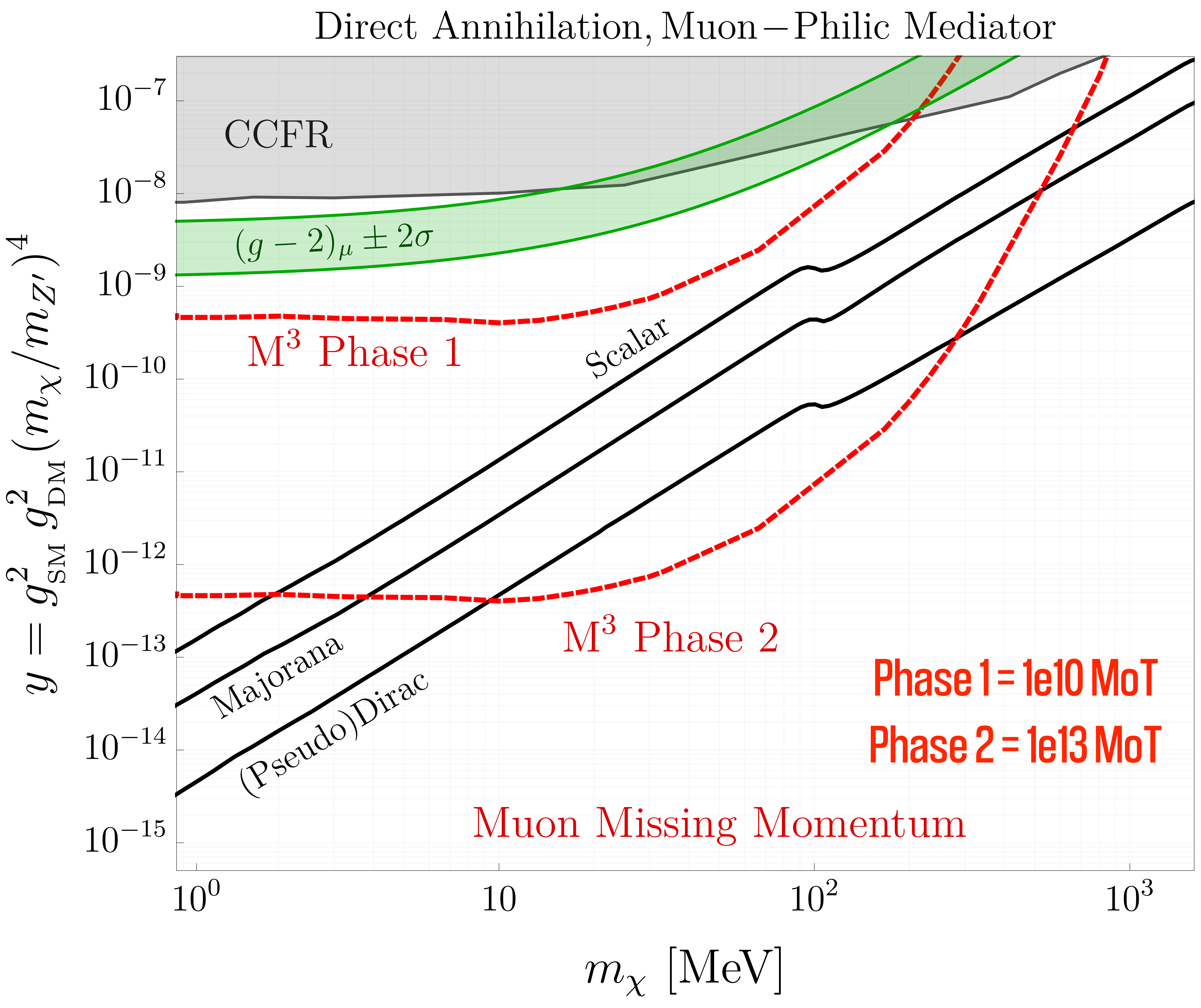


M^3 sensitivity

Muon missing momentum has good sensitivity to $m\chi$ > ~m_μ for flavor agnostics models too



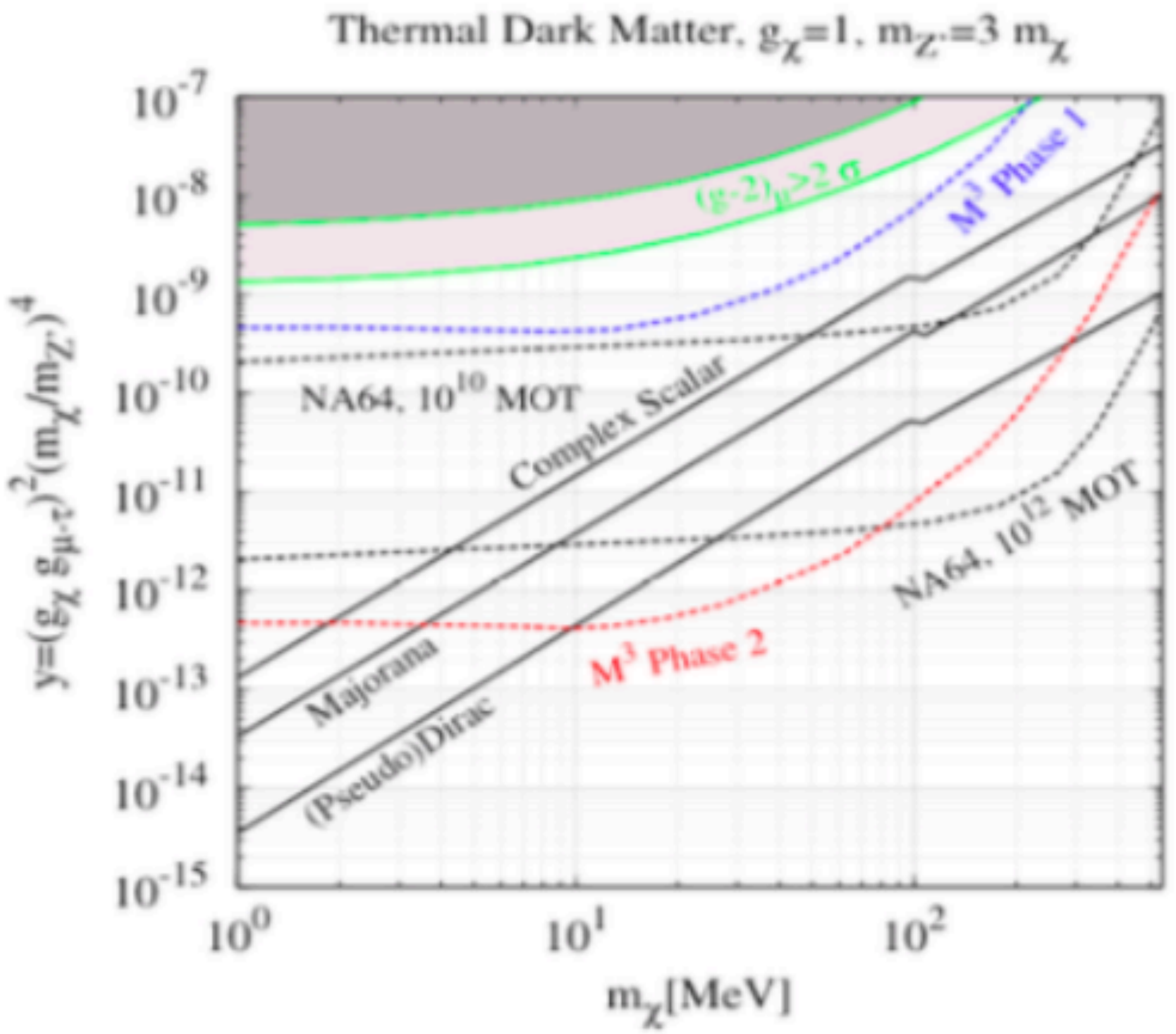
Muon beams provide model-independent probe of light new physics contributing to $(g-2)_\mu$ anomaly



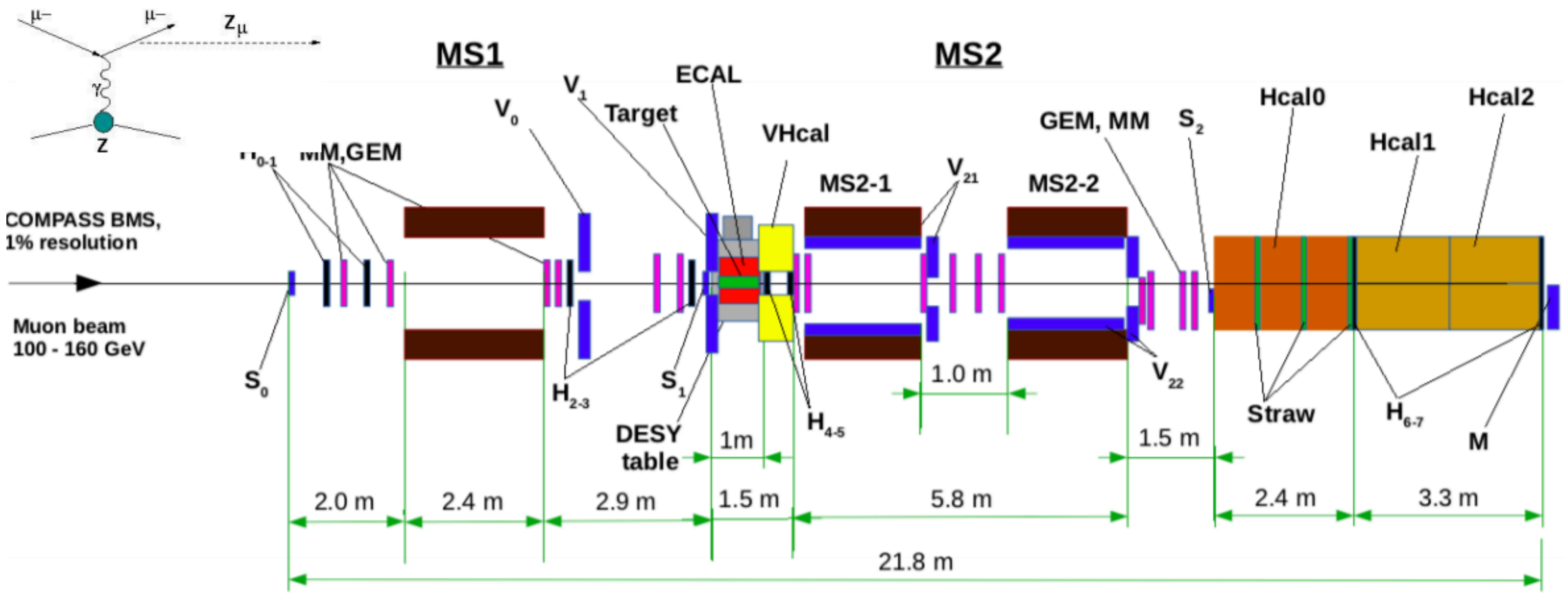
NA64-μ

S. Gninenko talk at PBC

- Proposed at the M2 beam line at CERN
- 100-160 GeV secondary muon beam
- Same missing momentum concept, but stretched out due to higher beam energy



With similar phasing to M^3, NA64μ shows comparable sensitivity

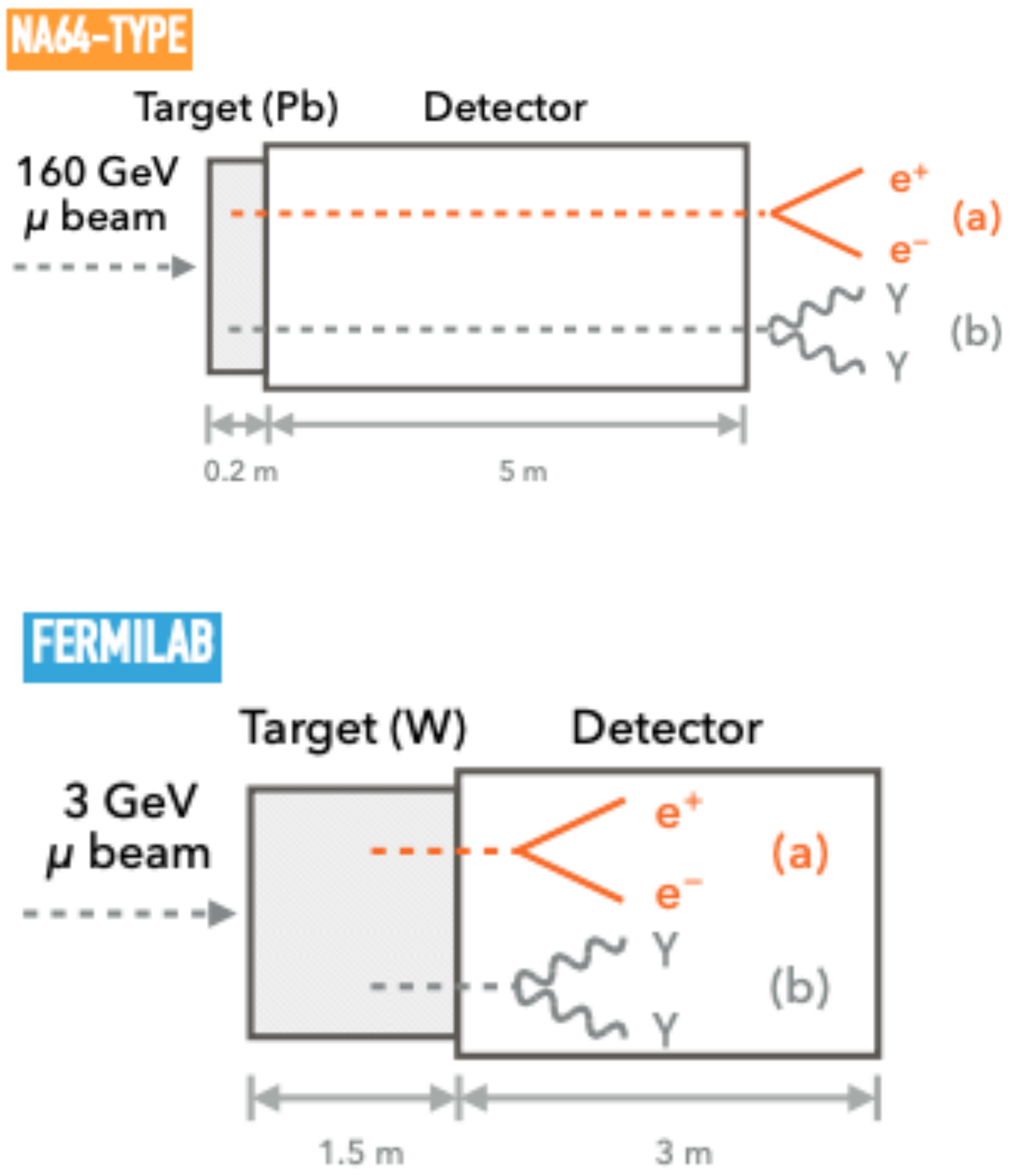


Muon beam dumps

Chen, Pospelov, Zhong
https://arxiv.org/pdf/1701.07437.pdf

- Consider a leptophilic scalar model
  - Model A: coupling proportional to mass
  - Model B: only couplings to muons

- NA64μ is a similar type of setup
- For Fermilab, now using the muon campus 3GeV muon beam



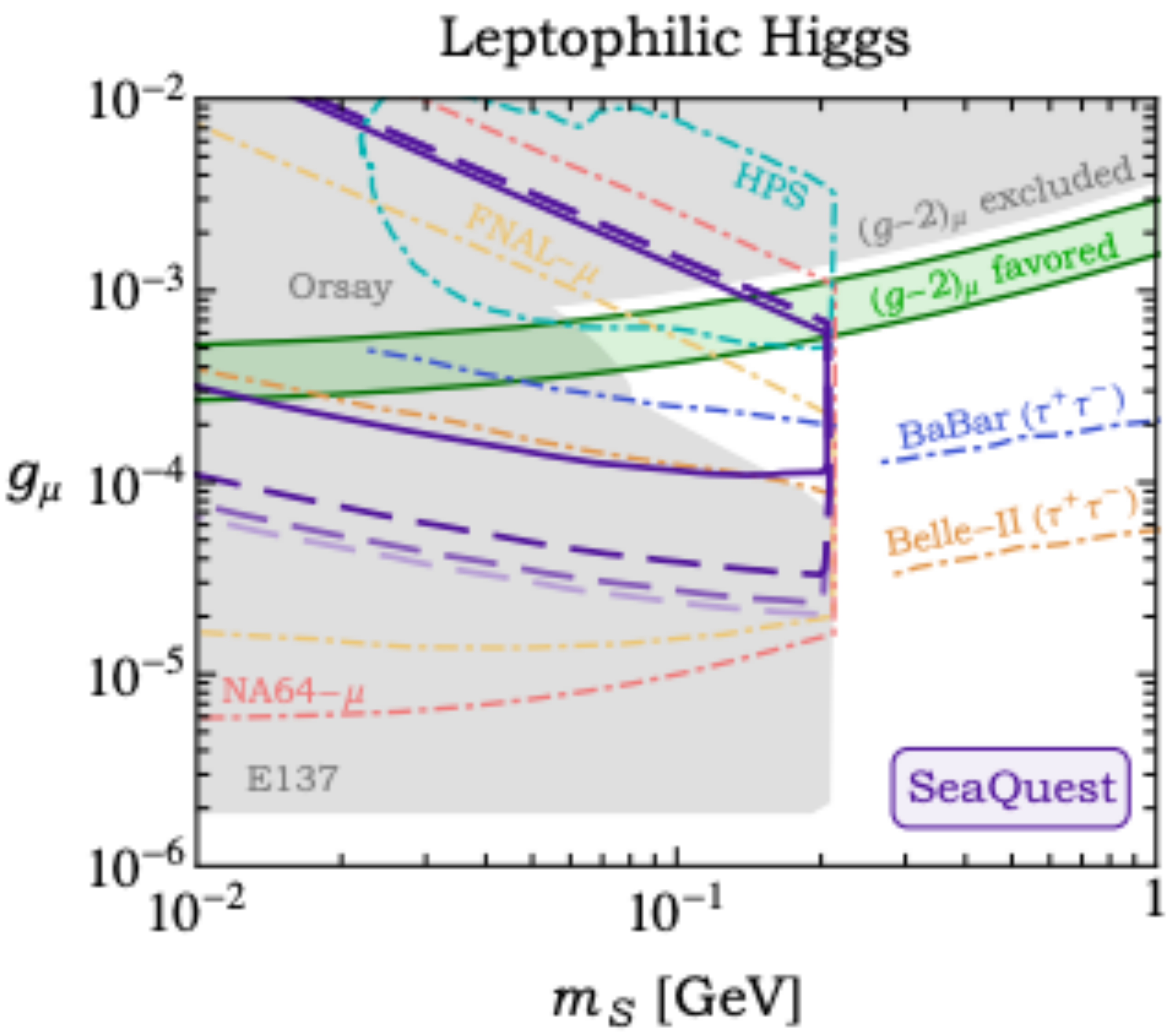
“Muon” beam dumps

Berlin, Gori, Toro, Schuster
http://arxiv.org/pdf/1804.00661.pdf

- Here the proton versatility shows
  - Proton beam dump contributes as well

- Muons are created in the dump via pion production and **effectively becomes another muon beam dump**

- Sensitivity shown here for the e+e− final state, similar sensitivity shape for γγ final state
  - Hard cutoff at $2m_\mu$



Summary

Summary

- **Proton and muon fixed target experiments provide a powerful probe of dark sectors**

- **Protons** are a Swiss-army knife, versatile production mechanism
  - A lot of options to explore for proton beams more widely

- **Muons** are a unique probe for particular models and phase space