Dark Sectors Landscape Update

Tim Nelson - SLAC

HPS Collaboration Meeting @ JLab - June 3, 2024

U.S. DEPARTMENT OF ENERGY
Office of Science

What's New?

An explosion of dark sector physics, both theoretically and experimentally

Cameron will discuss how some of this intersects with HPS.

I will focus on things that are closer to home:

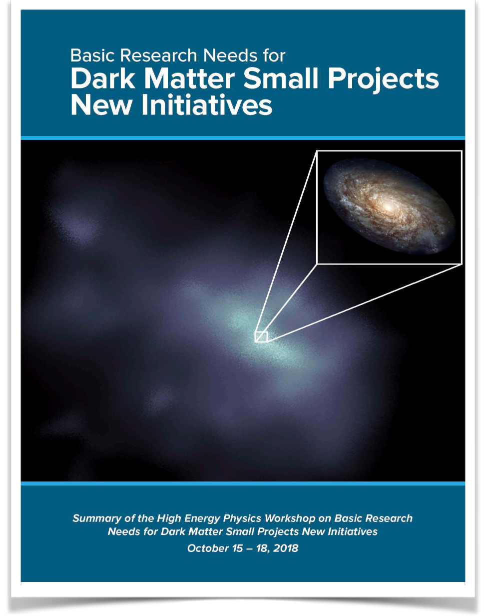
- visible dark photon searches
- invisible dark photon searches
- dark matter searches
- P5 and the HEP funding landscape for future experiments

Visible Search Outlook at PAC48

- NA64: working to exclude X17*

  *currently running
- LHCb?
- FASER

The Dark Matter New Initiatives (DMNI) program did not select any searches for visibly decaying dark sectors (PRD1, Thrust 2)

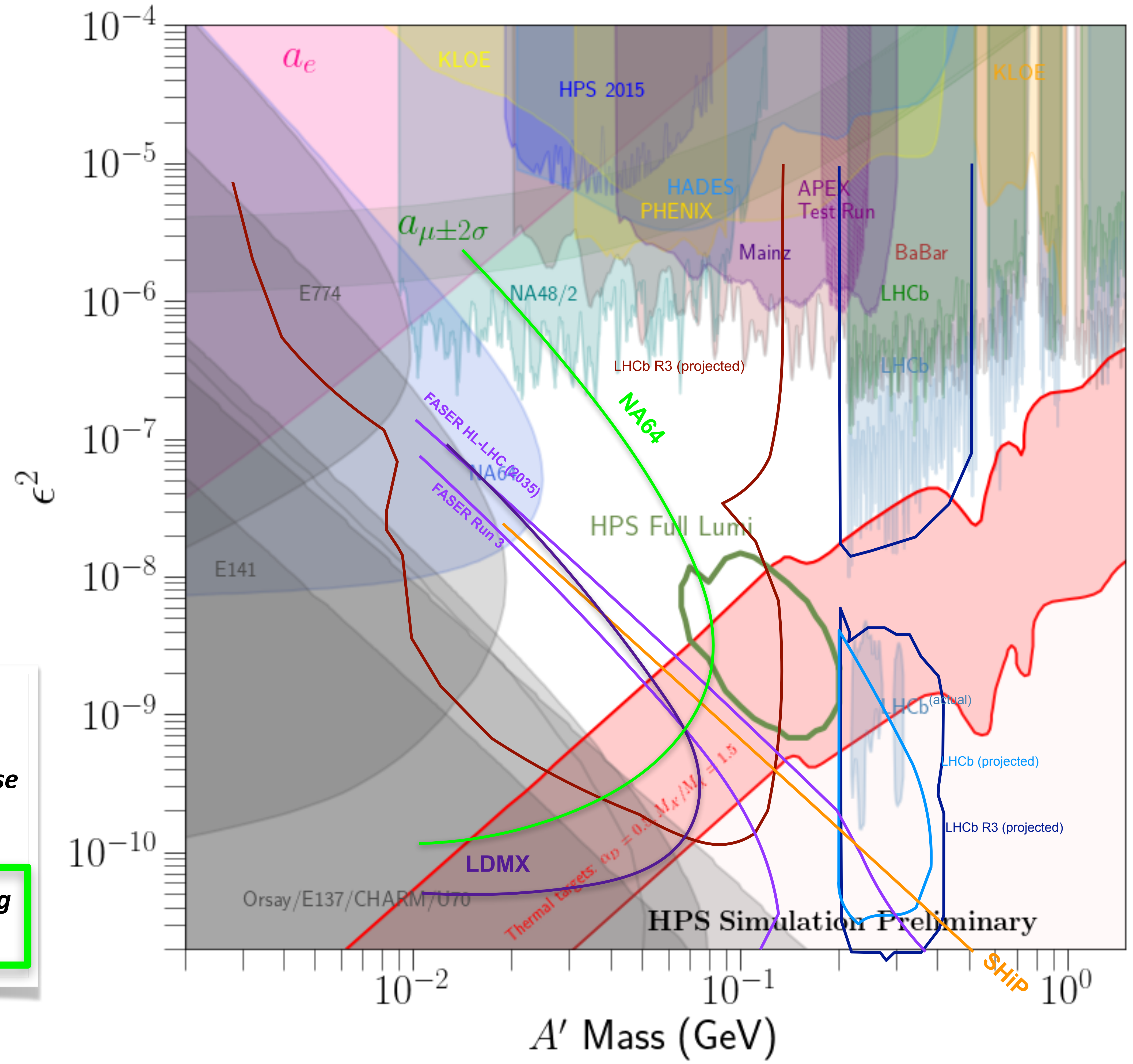


PRD 1: Create and detect dark matter particles below the proton mass and associated forces, leveraging DOE accelerators that produce beams of energetic particles.

Thrust 1 (near term): Through 10- to 1000-fold improvements in sensitivity over current searches, use particle beams to explore interaction strengths singled out by thermal dark matter across the electron-to-proton mass range.

Thrust 2 (near and long term): Explore the structure of the dark sector by producing and detecting unstable dark particles.

From European Strategy Update – arXiv:1910.11775



LHCb – Run 2 (2015-2018) and Run 3 (2022-2026)

Potential for reach in two mass ranges.

arXiv:1603.08926 [hep-ph]

Run 2 and Run 3 above dimuon threshold

$$A' \to \mu^+\mu^-$$

Unexpected long-lived backgrounds impacted reach.

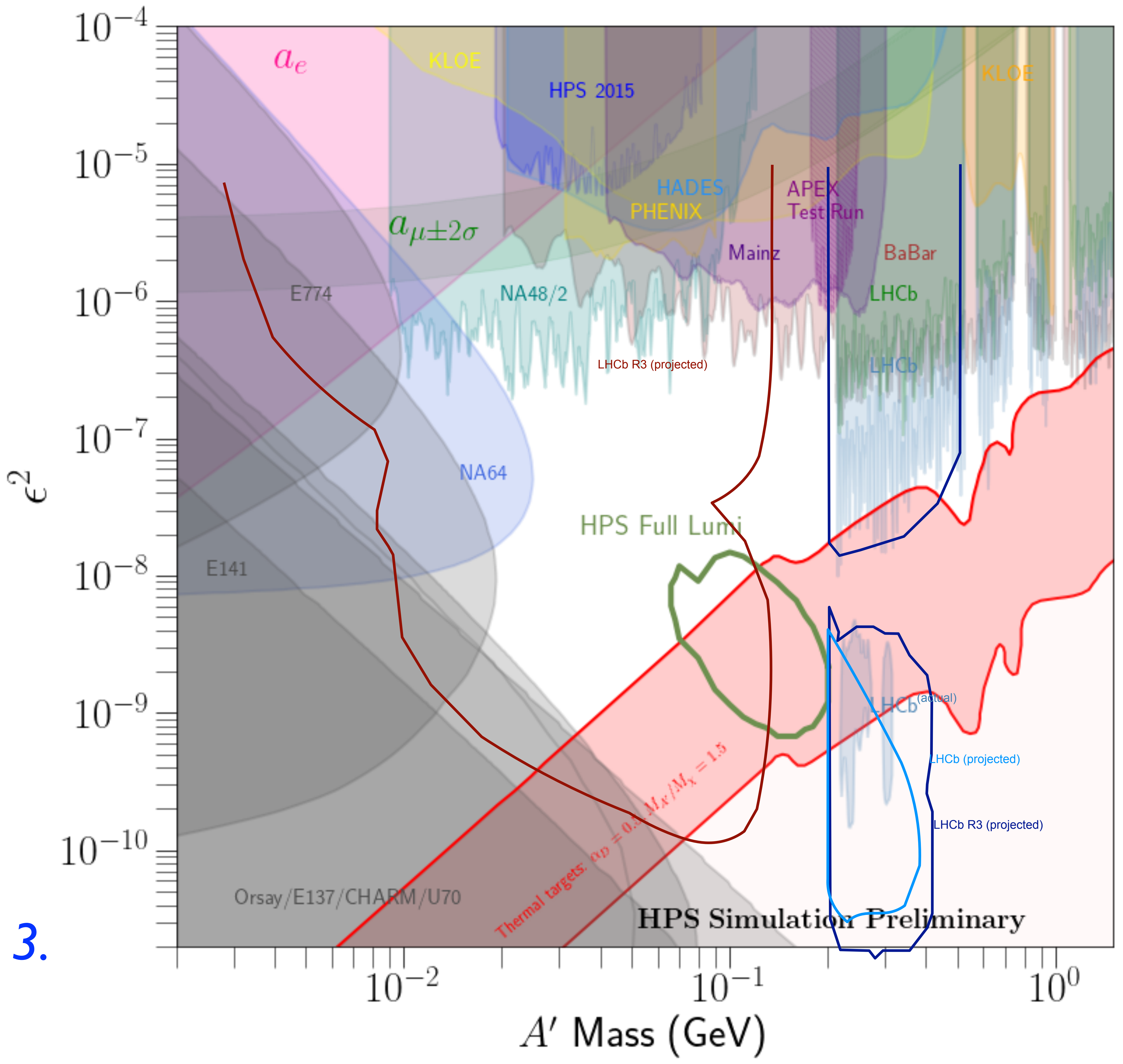
Run 3 below the $D^{\star 0}$-D^0 mass difference

$$D^{\star 0} \to D^0 A'$$

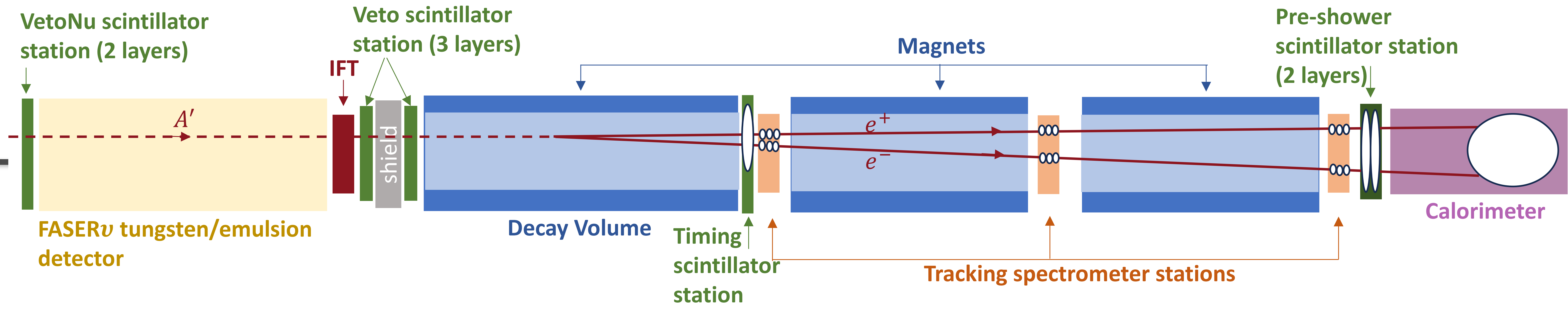
$$A' \to e^+e^-$$

Requires upgraded vertex detector (VELO) and triggerless readout = full recon in real time. Backgrounds still unknown.

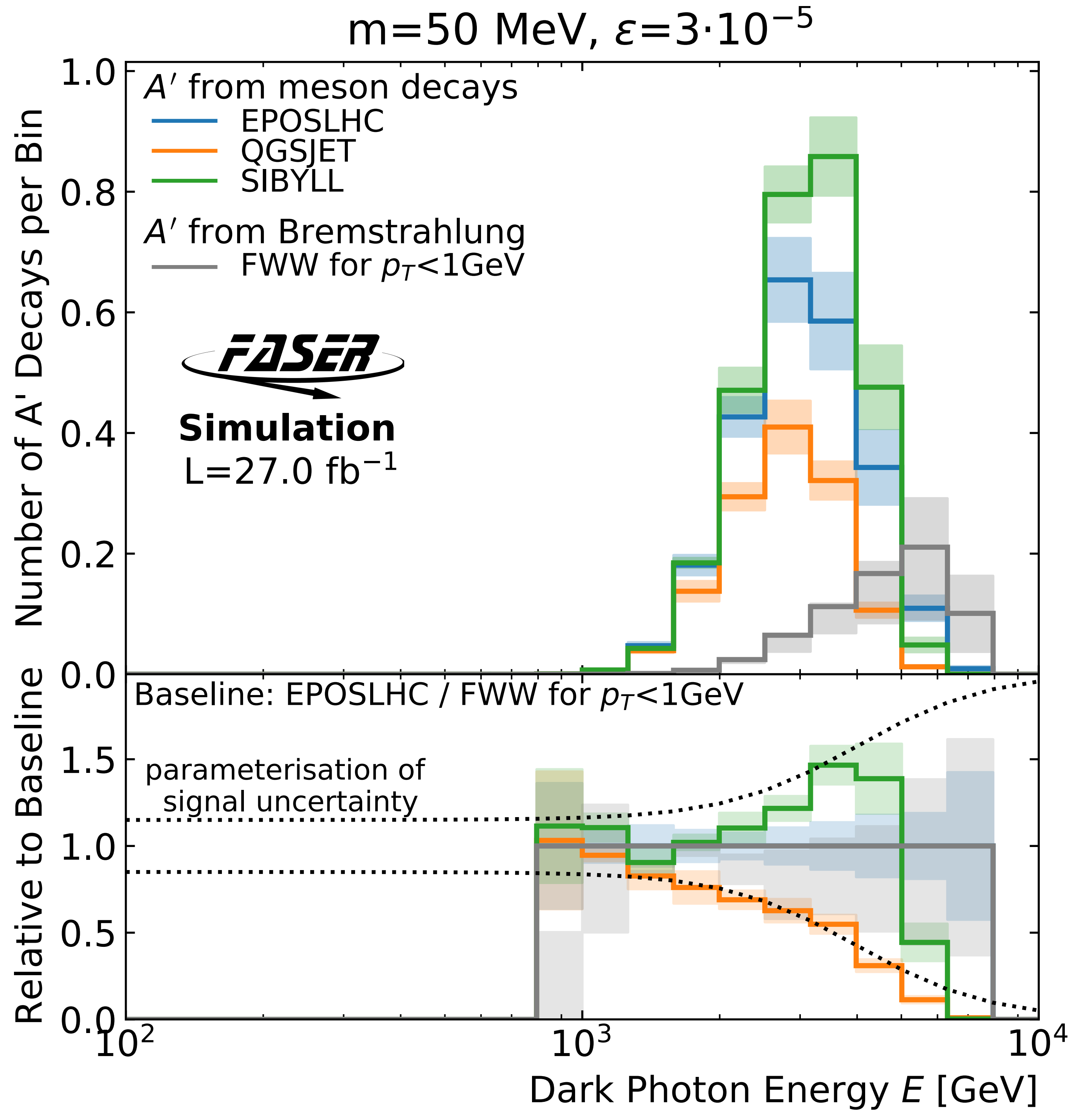
A pressure failure rendered VELO inoperable early in Run 3. Replacement and restart occurred this April.

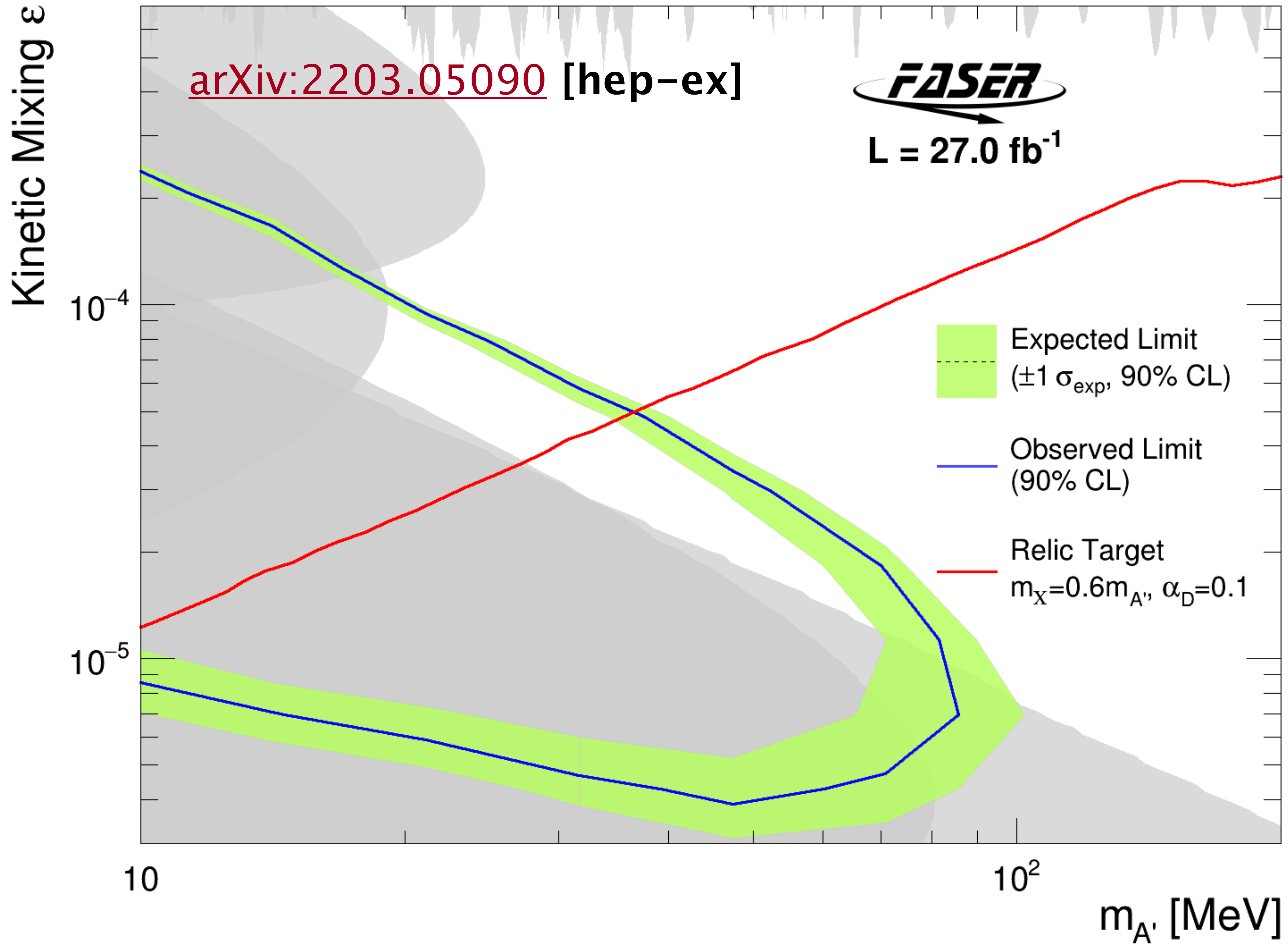


FASER



$$L = c\beta\tau\gamma \approx (80\ \text{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\text{TeV}}\right] \left[\frac{100\ \text{MeV}}{m_{A'}}\right]^2$$

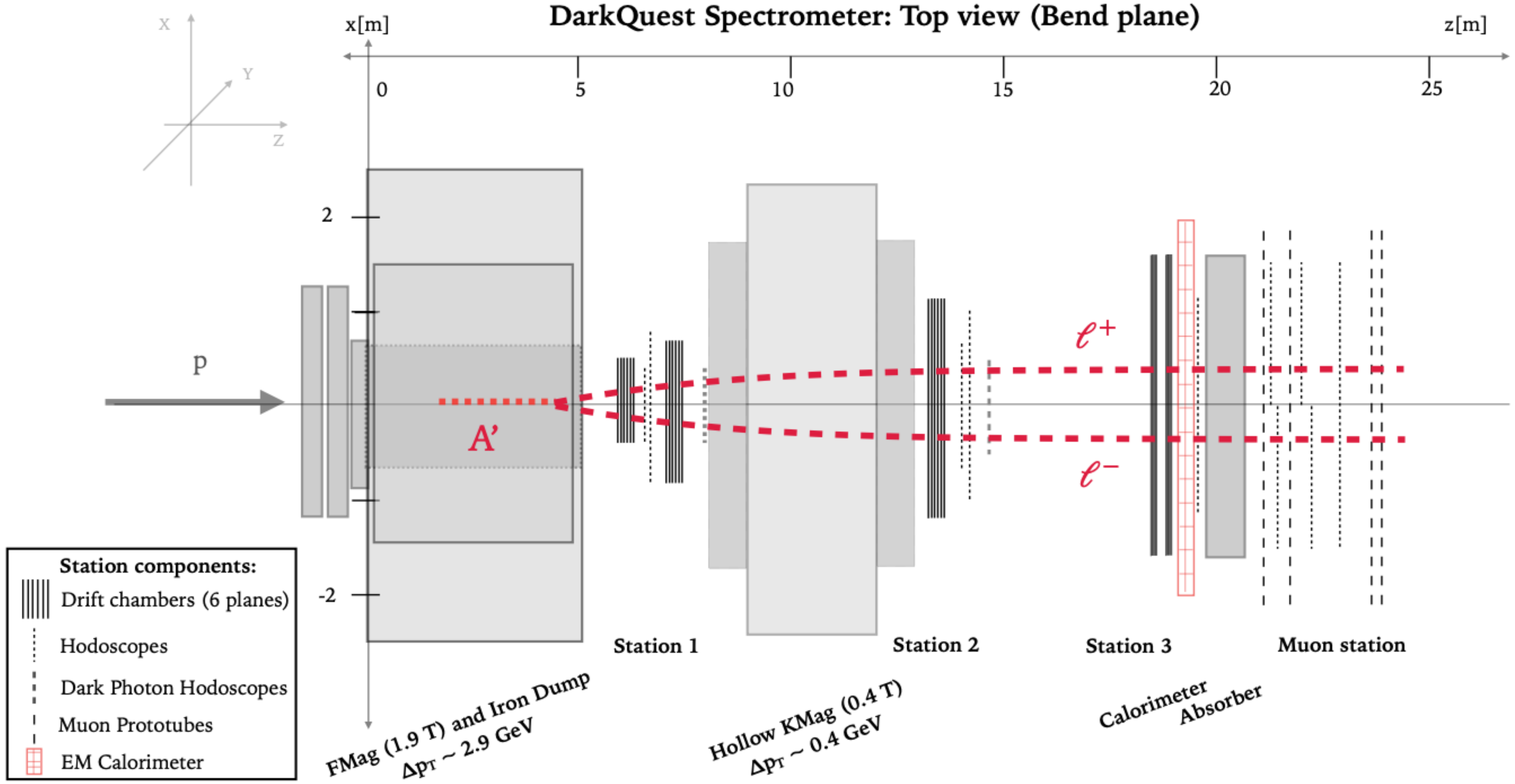


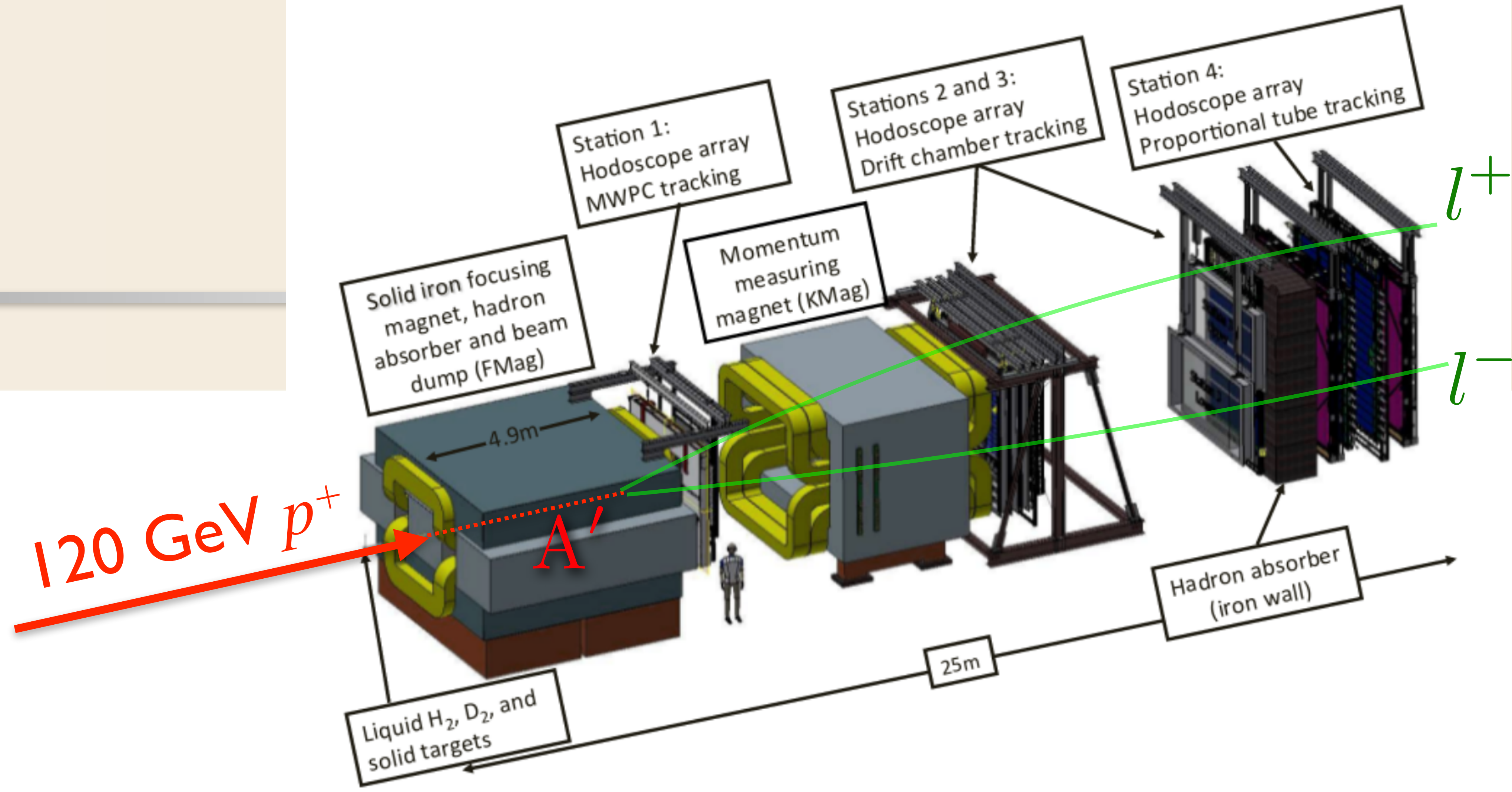


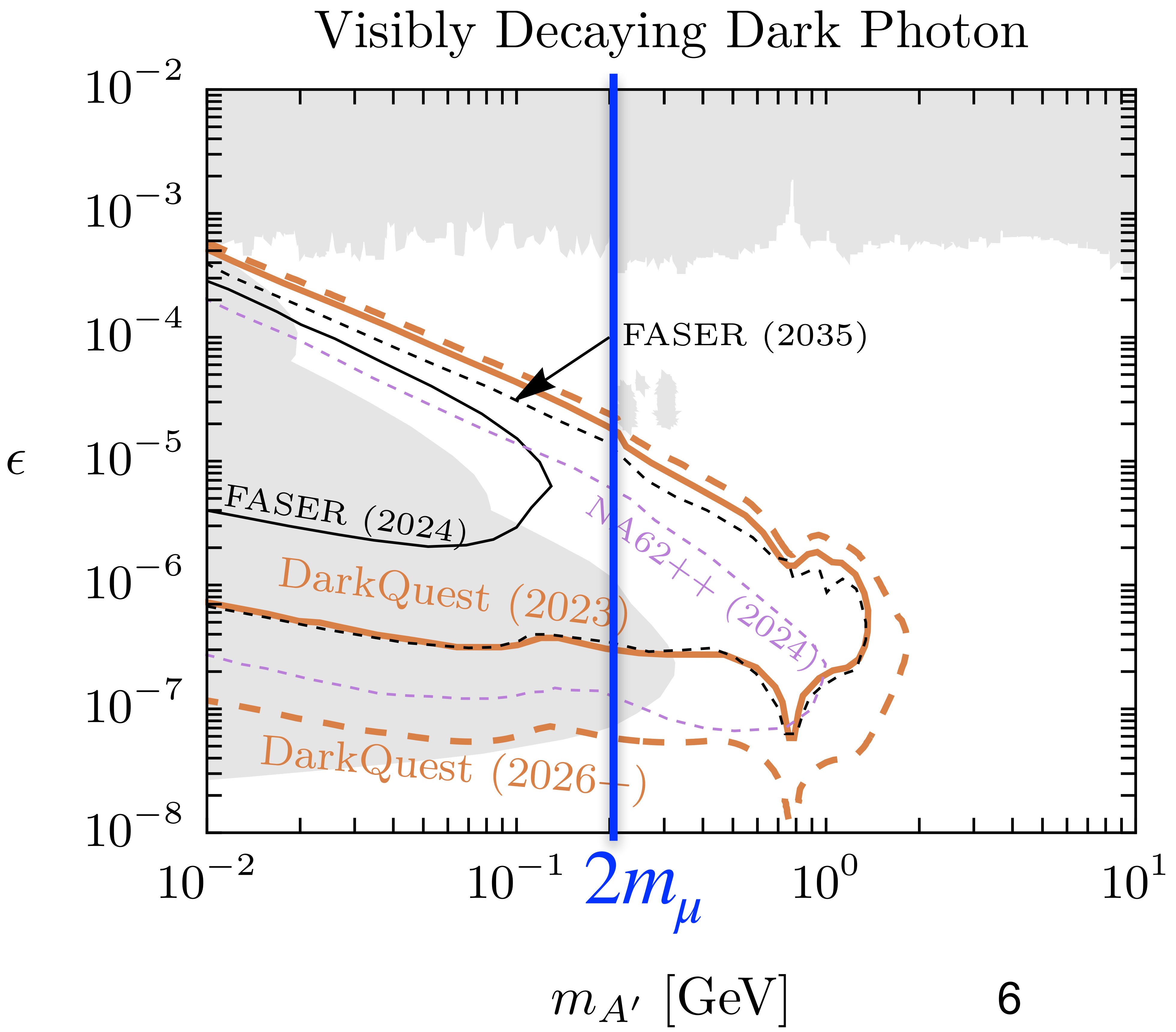
With help of private funding, FASER got an earlier start!

DarkQuest

Evolution of SeaQuest/SpinQuest experiment:







DarkQuest has been awarded NSF MRI funding ($877K) to install ECal!

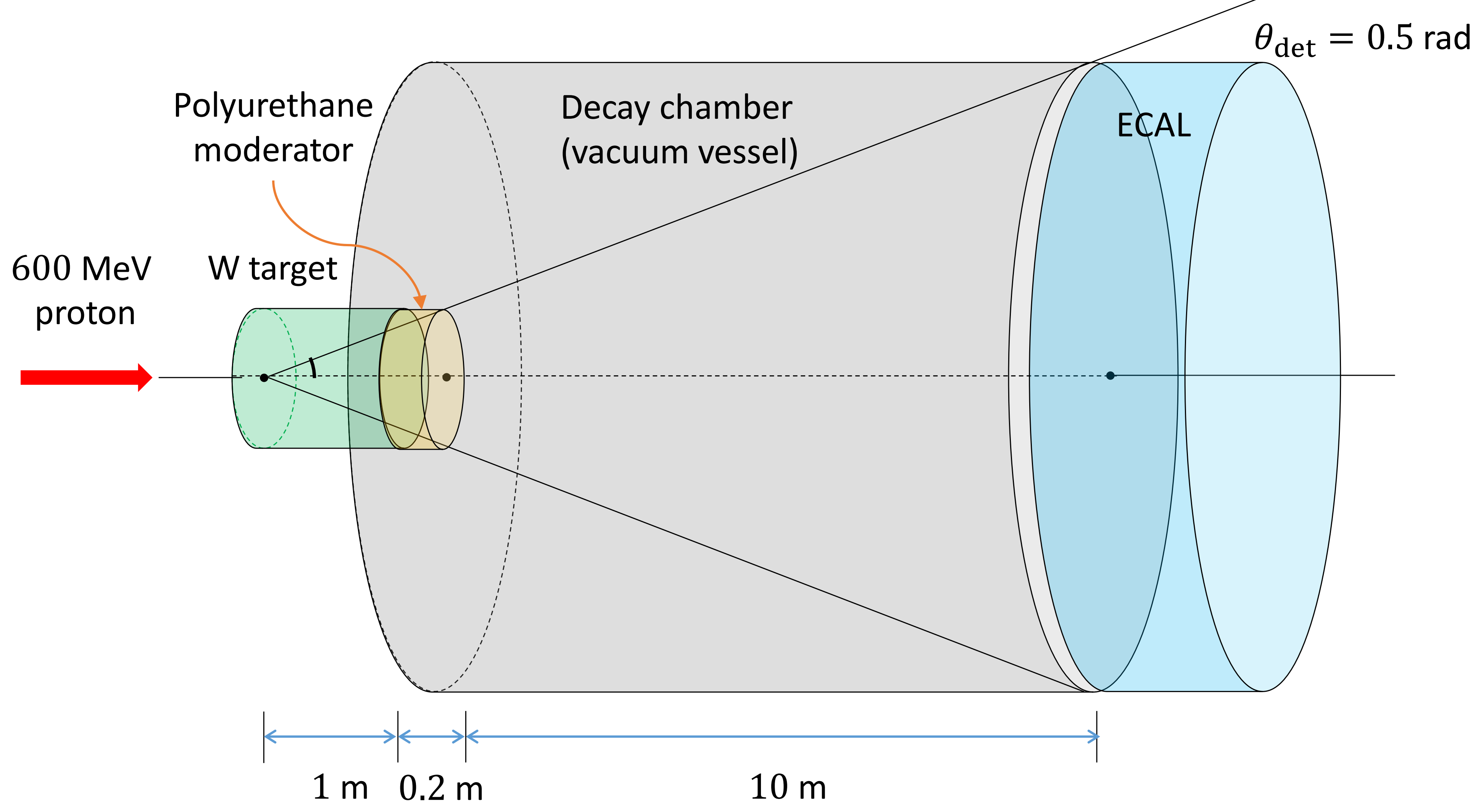
DAMSA (Jae Yu, Juan Estrada)

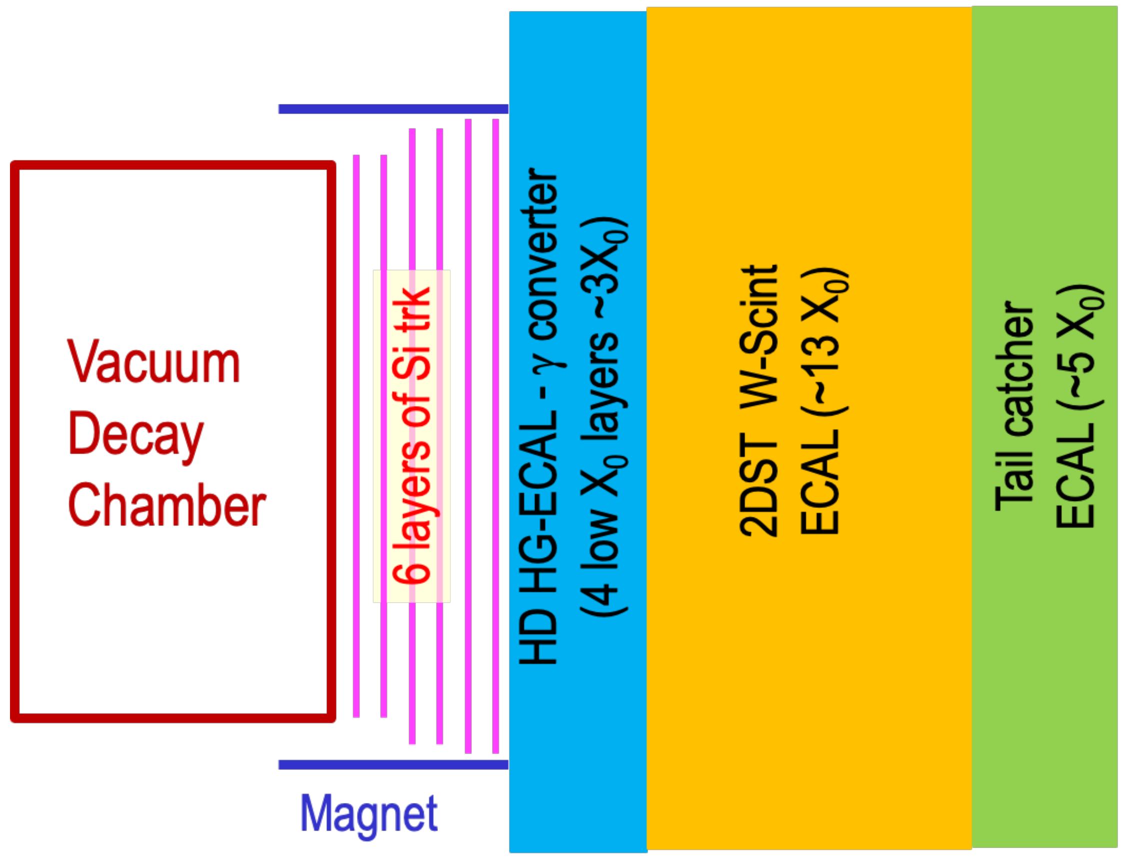
Large detector to search for ALPs with 600 MeV proton beam

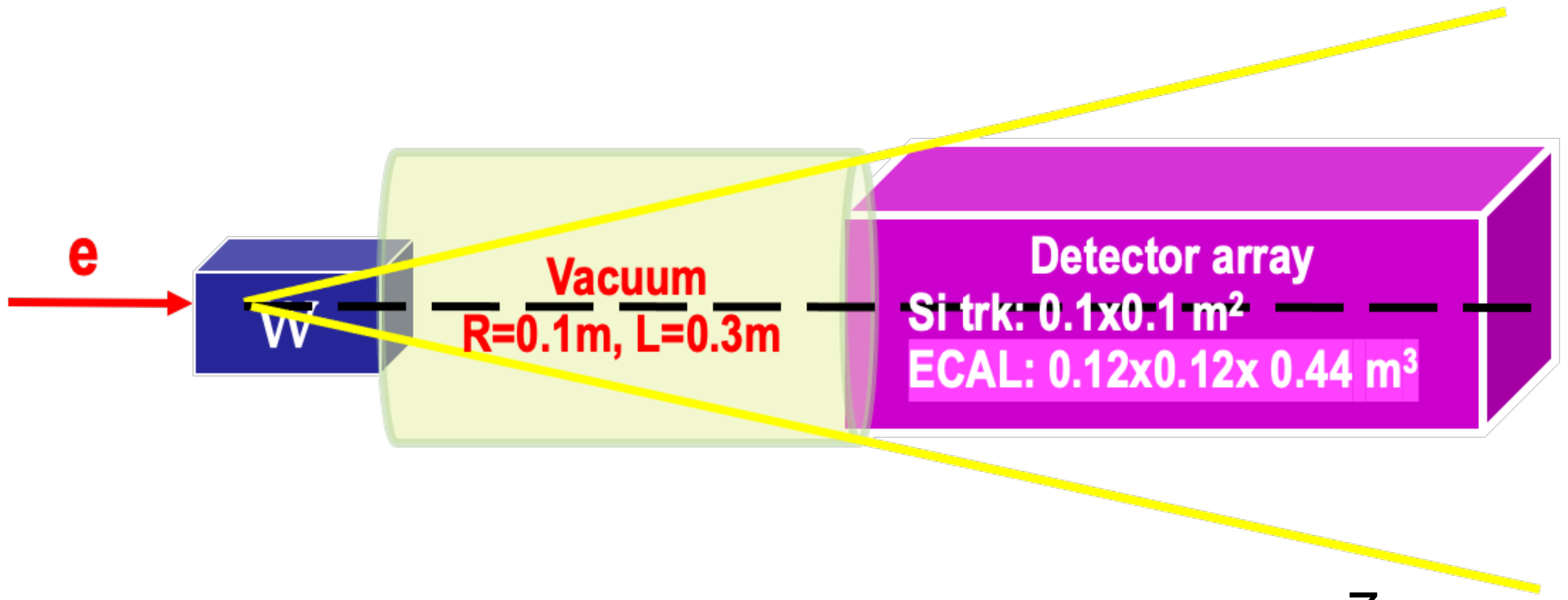
- tungsten target/dump
- soft neutron shield
- very large vacuum chamber decay volume
- large area ECal

Sensibly, this concept evolved…

- Beam: 300MeV e^- @ FAST (Fermilab), greatly reduces neutron backgrounds relative to proton beams
- Target: 5cm x 5cm x 10cm W block (~28.5X_0)
- Vacuum decay chamber: 10cm (r) x 30cm (L)
- Detector:
  - 6 x10cm x 10cm Si tracker
  - 12cmx12cmx44cm (24.5X_0) CsI ECal w/ SiPM readout







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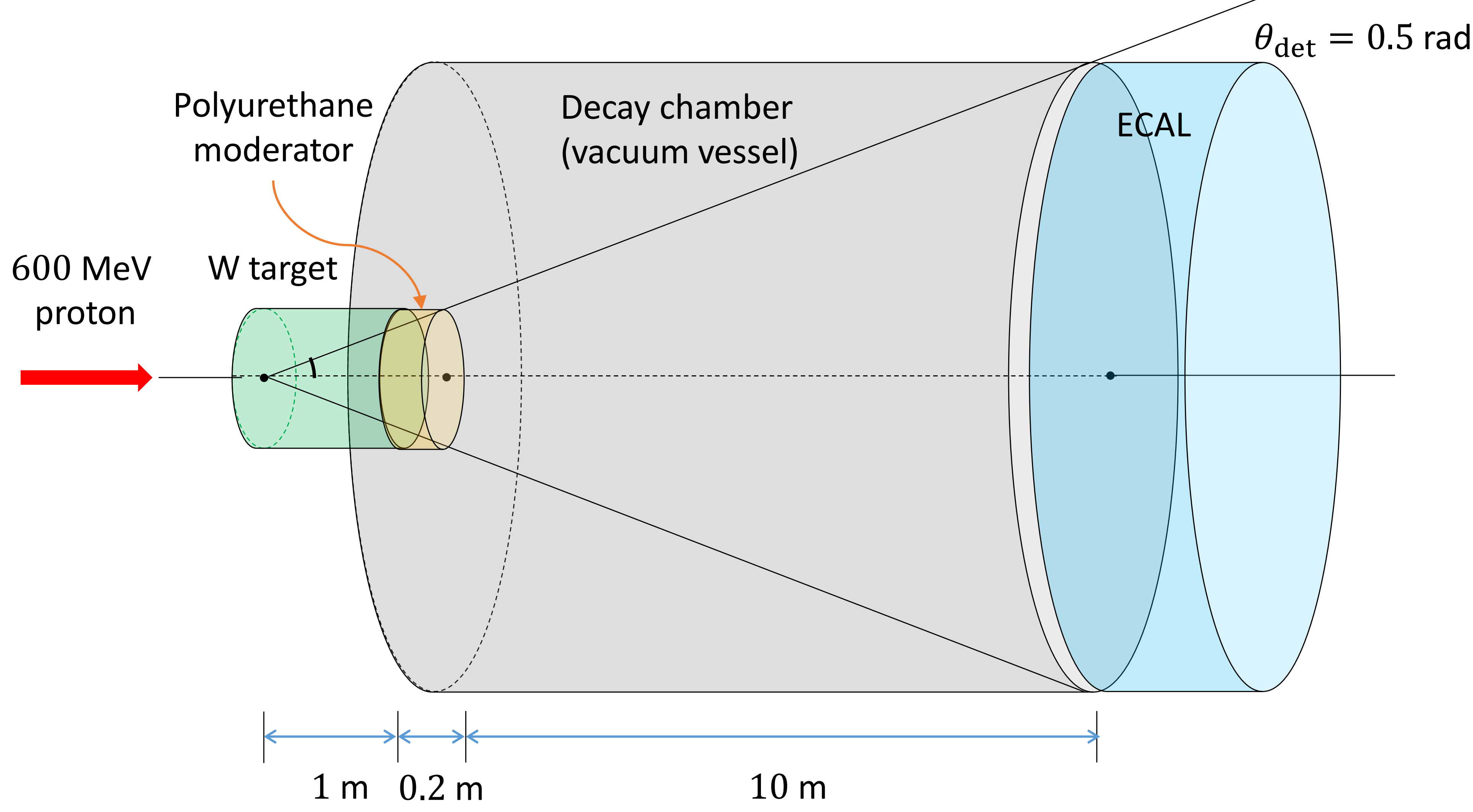
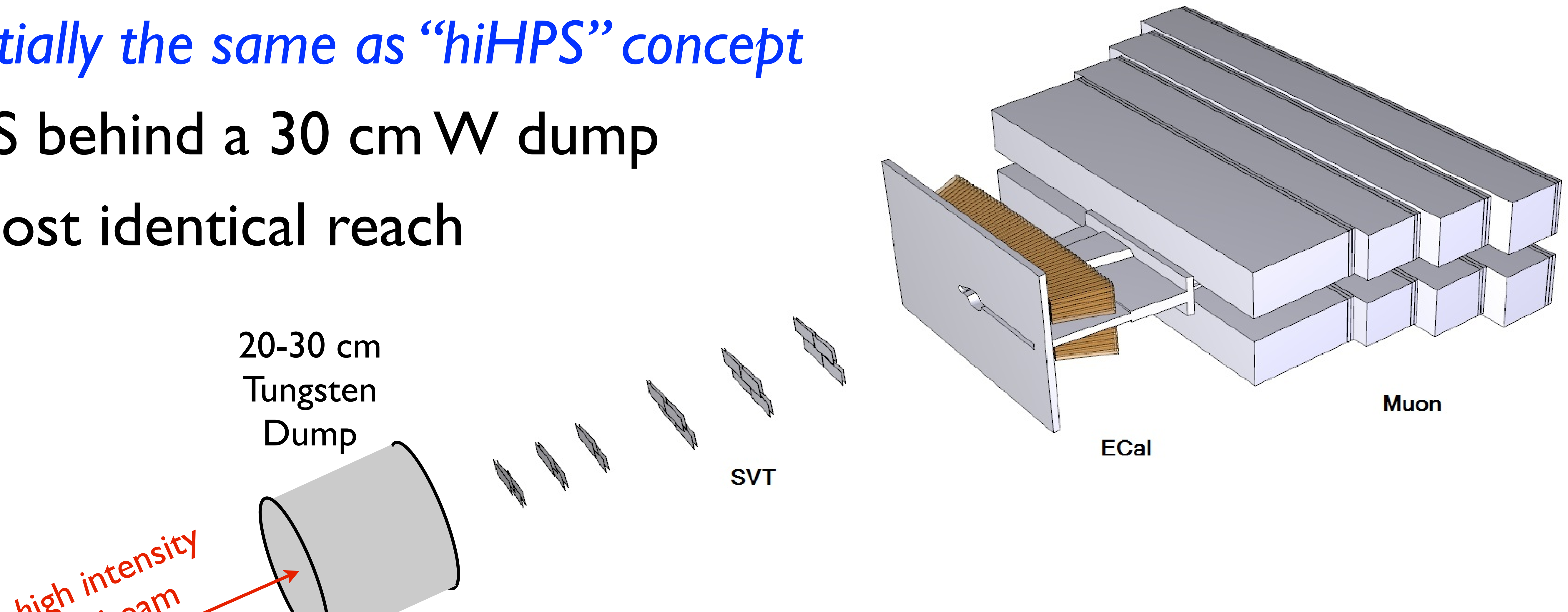
- tungsten target/dump
- soft neutron shield
- very large vacuum chamber decay volume
- large area ECal

Sensibly, this concept evolved…

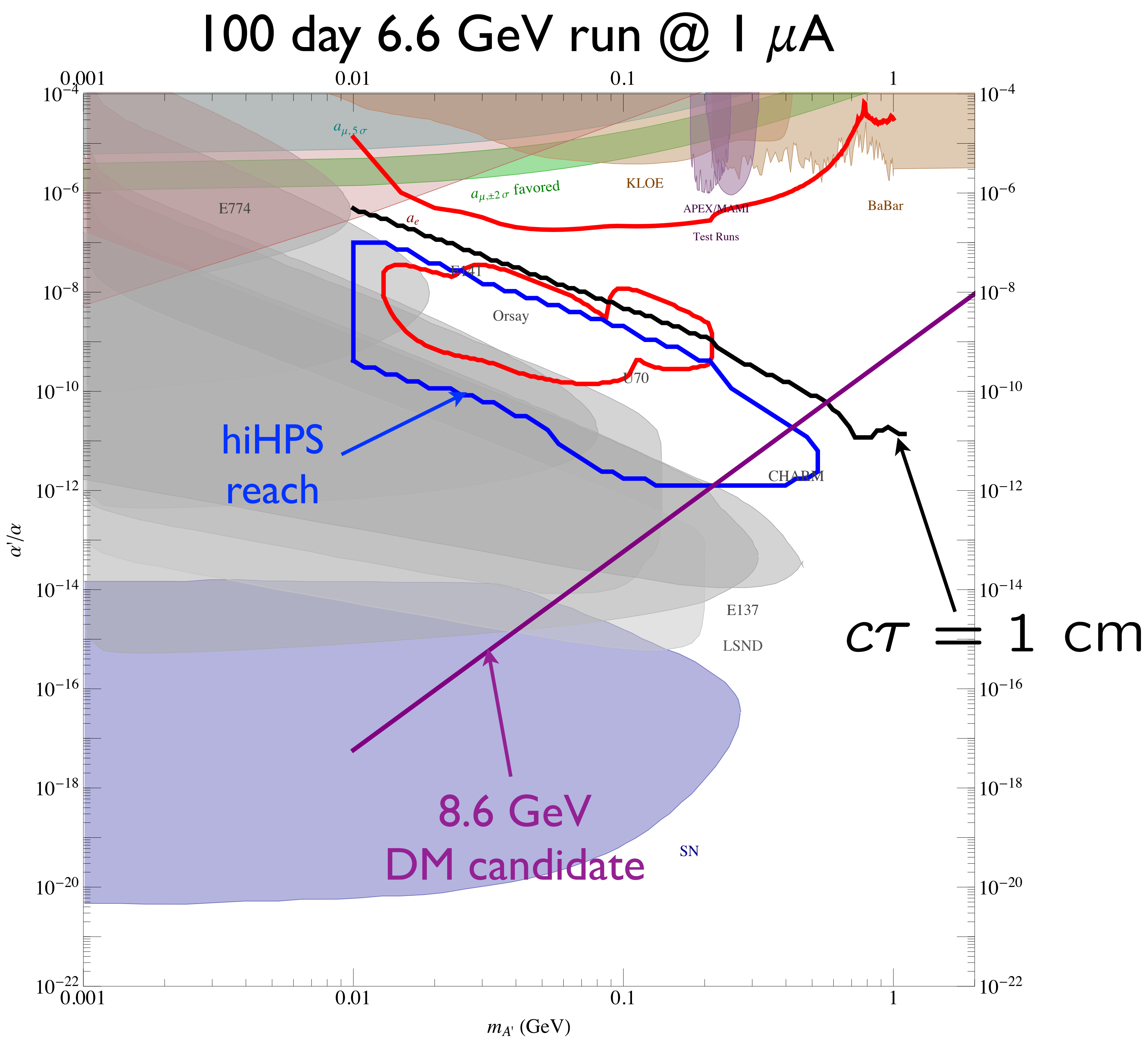
Essentially the same as "hiHPS" concept

- HPS behind a 30 cm W dump
- almost identical reach



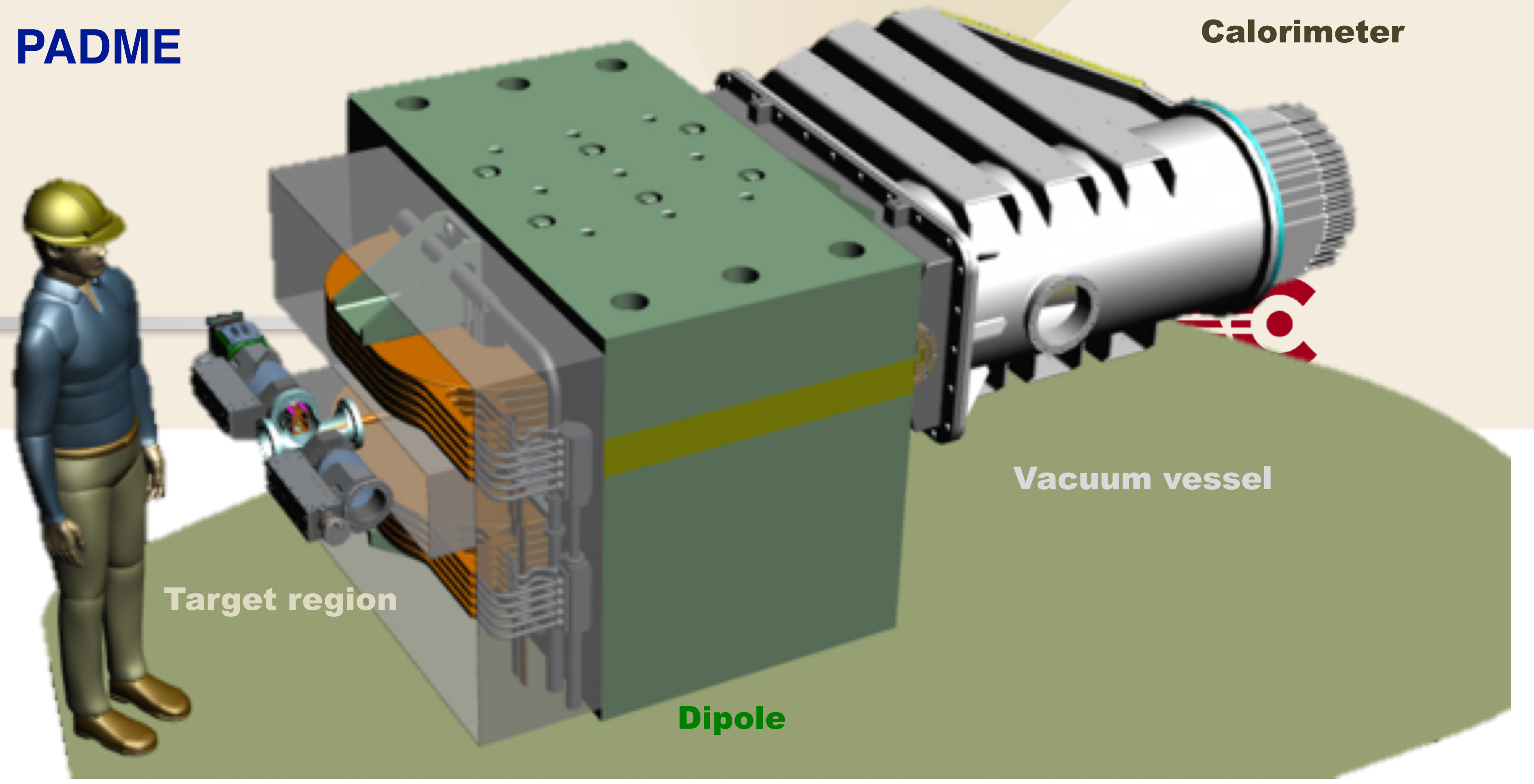


Could also be done with LESA beam

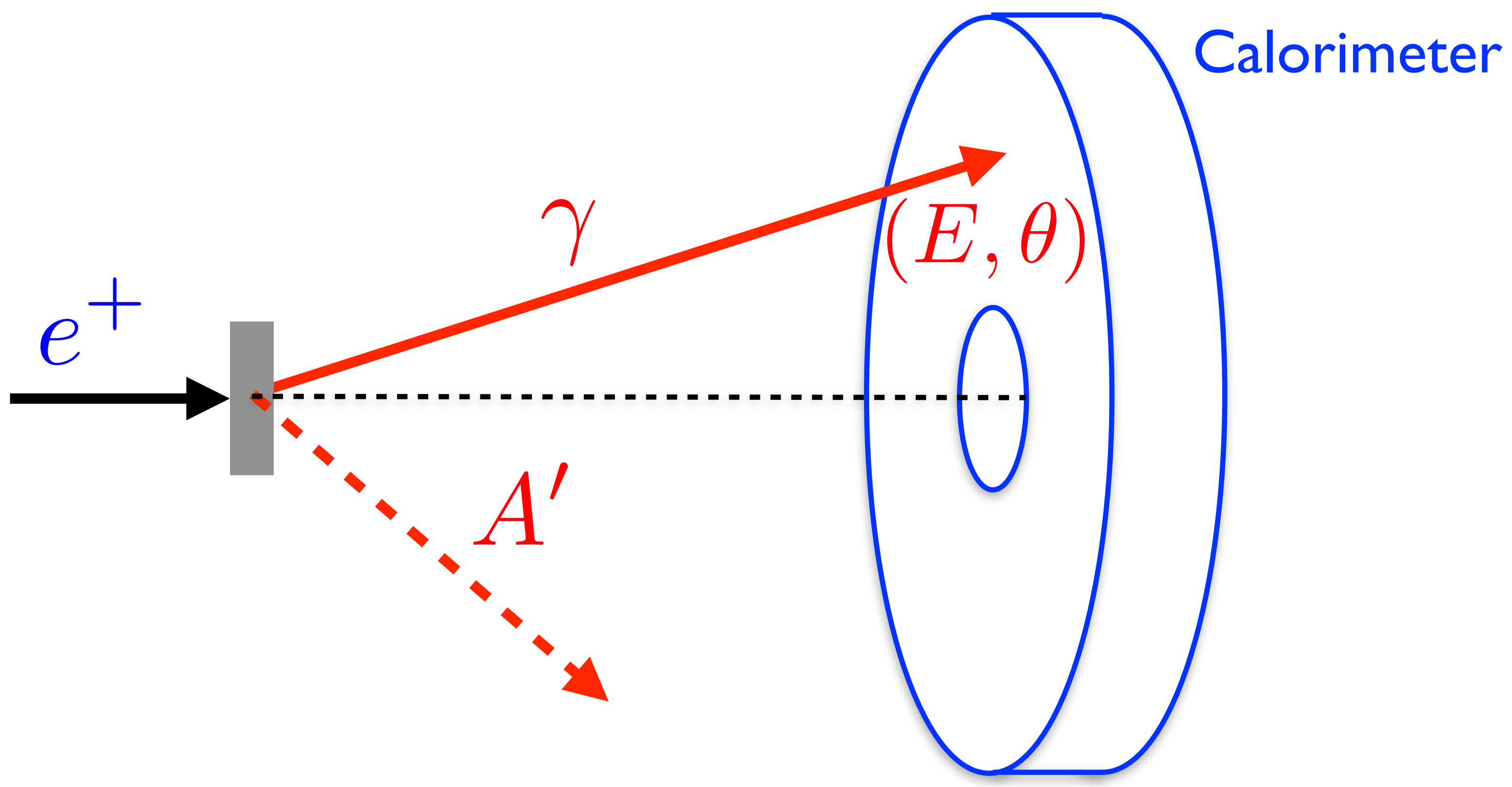


Invisible Dark Photon Searches

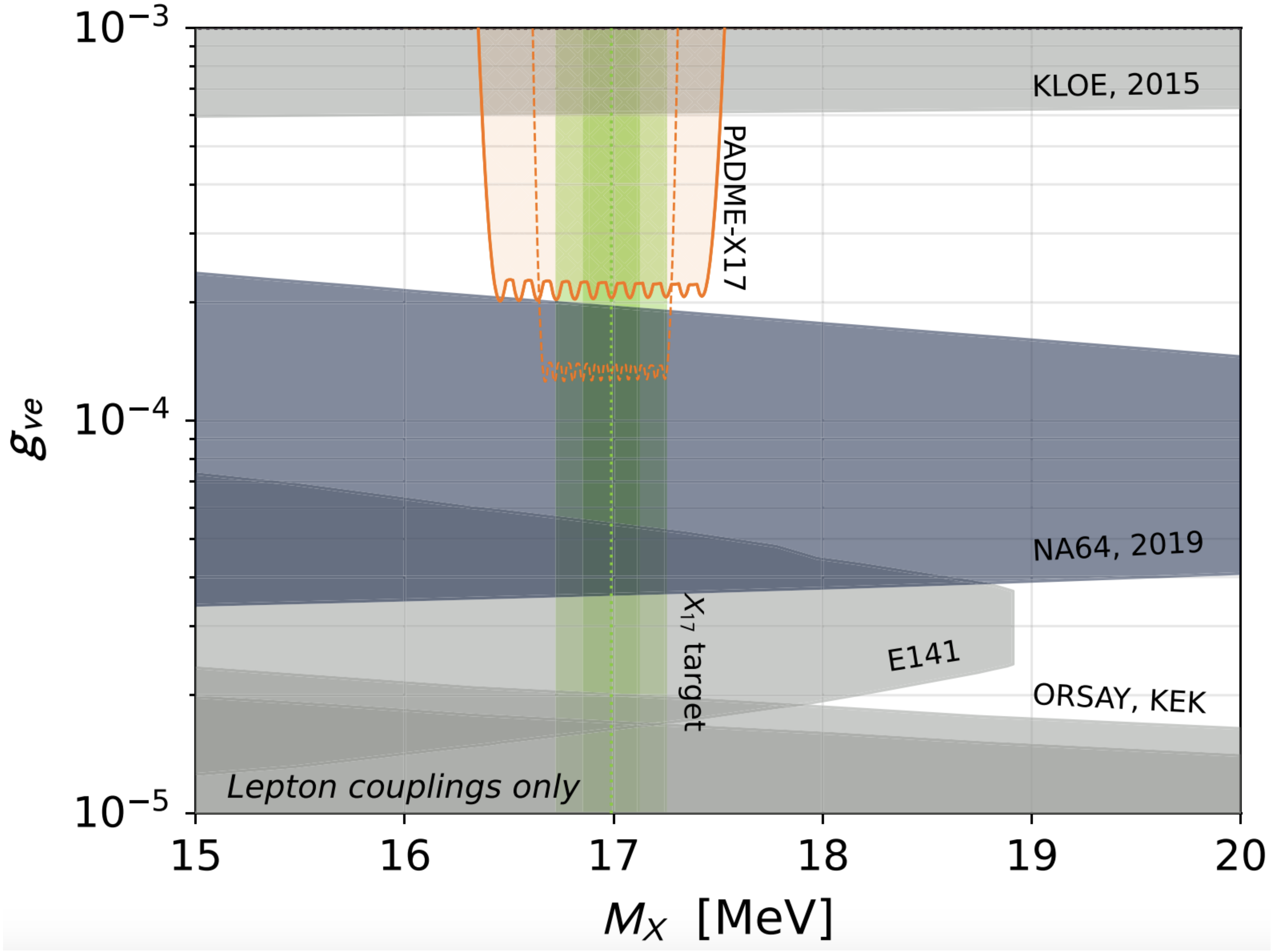
Missing mass: Reconstruction of A′ mass without measurement of decay products yields ensitivity to both visible and invisible mediator decays.



$$e^+e^- \to \gamma + X$$



$$M^2_{\rm rec} = 2m_e\left(E_+ - E_\gamma(1+\frac{E_+}{2m_e}\theta^2_\gamma)\right)$$

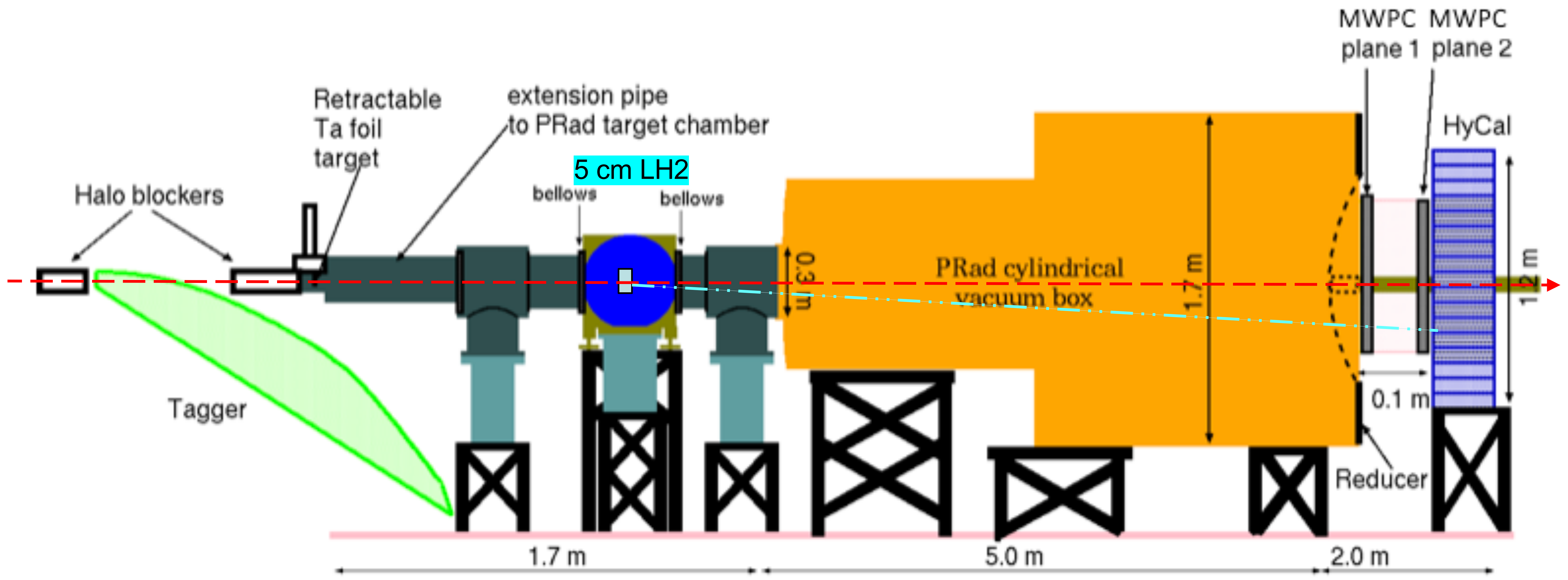


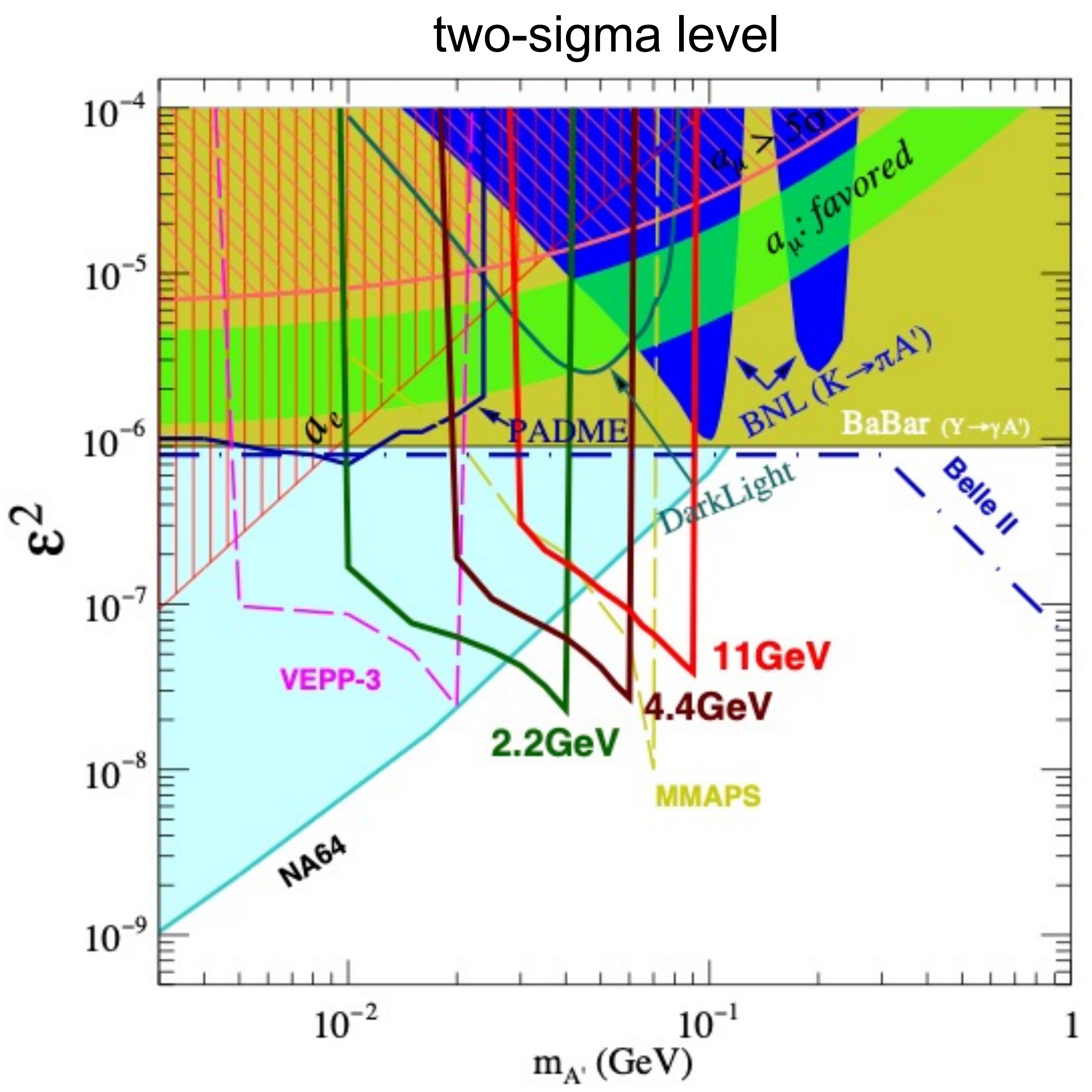
N.B. not a generic dark matter search since signal process is explicitly mediator dependent.

Missing Mass at JLab

Proposal for missing mass at multiple energies using PRAD with positron beam.

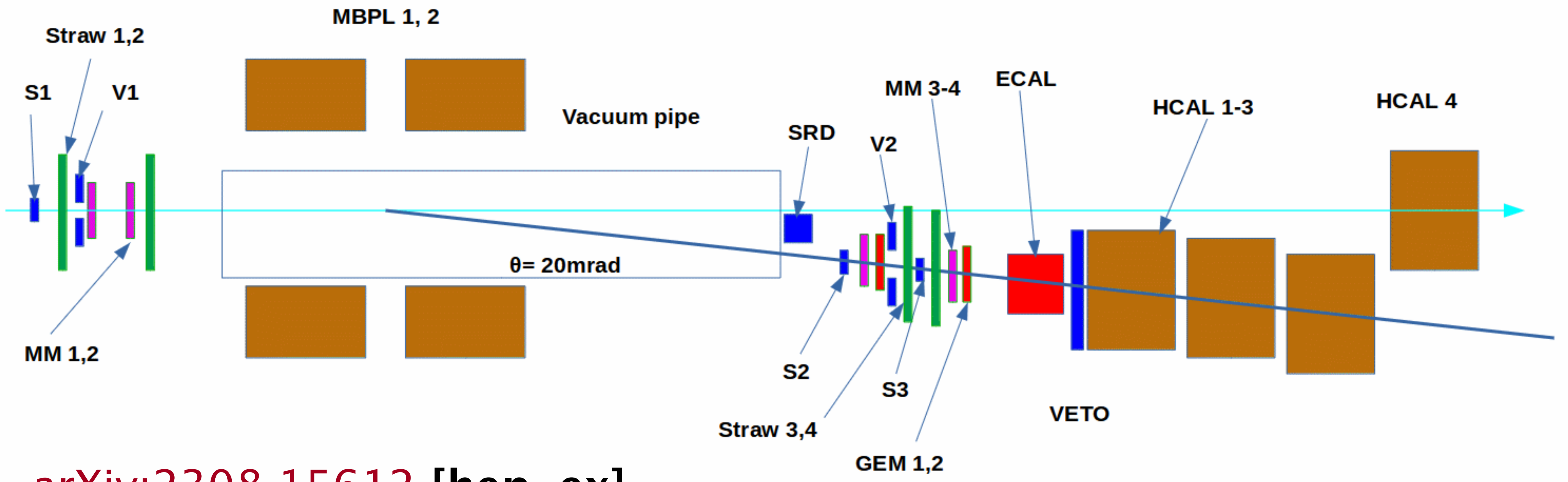
See Bogdan's Talk!!



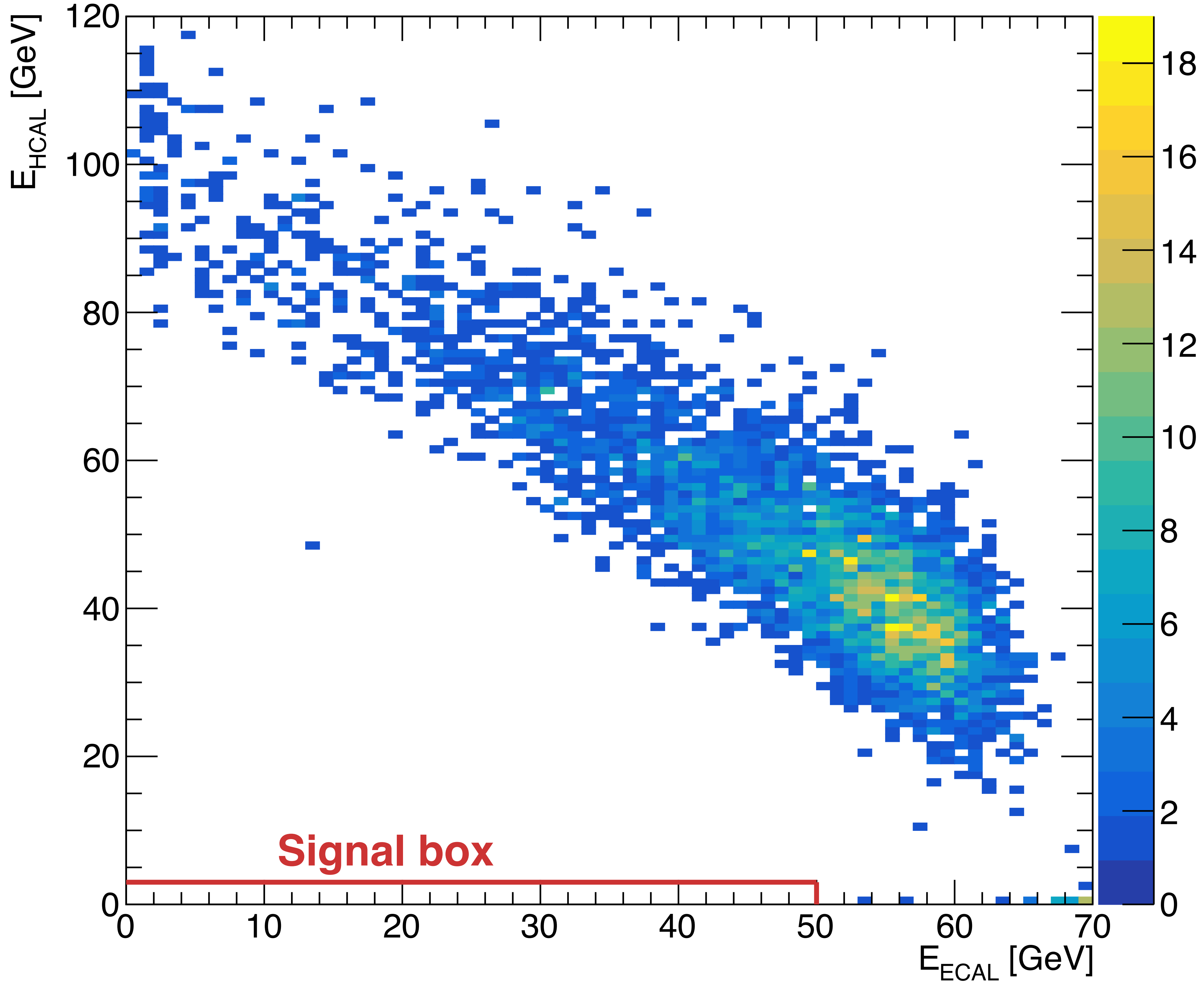


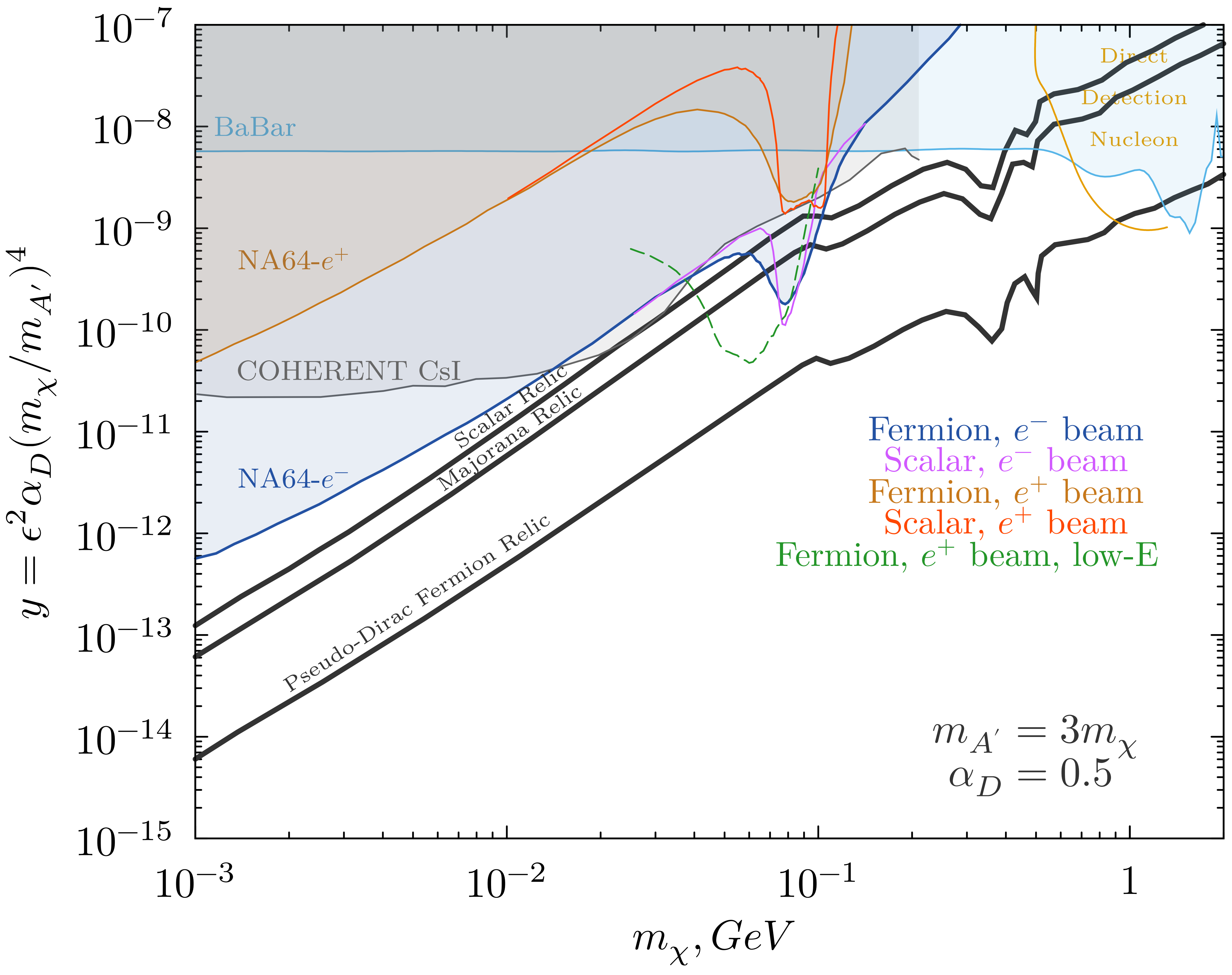
https://www.jlab.org/exp_prog/proposals/23/PR12+23-005.pdf

NA64 with positrons



arXiv:2308.15612 [hep-ex]

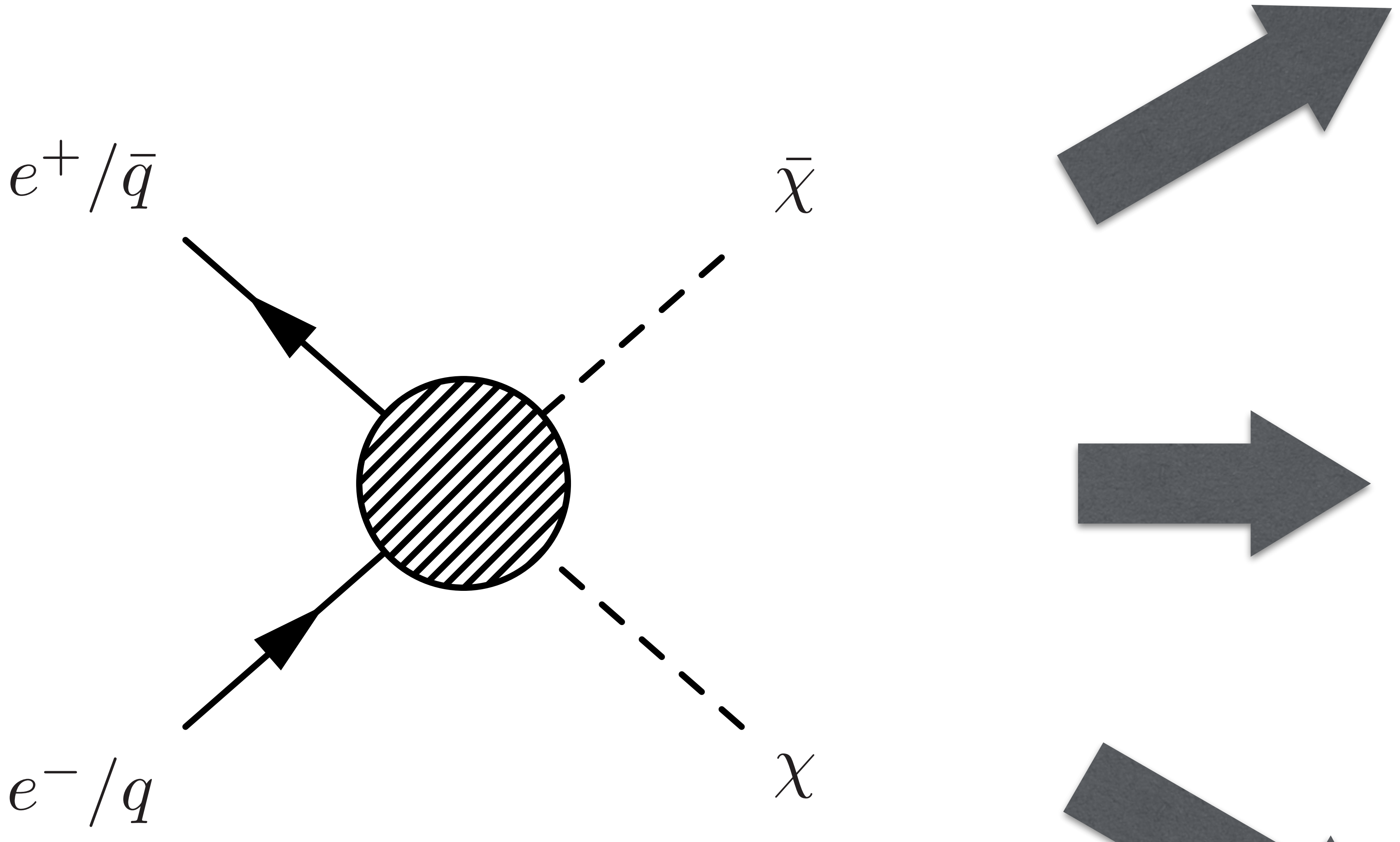




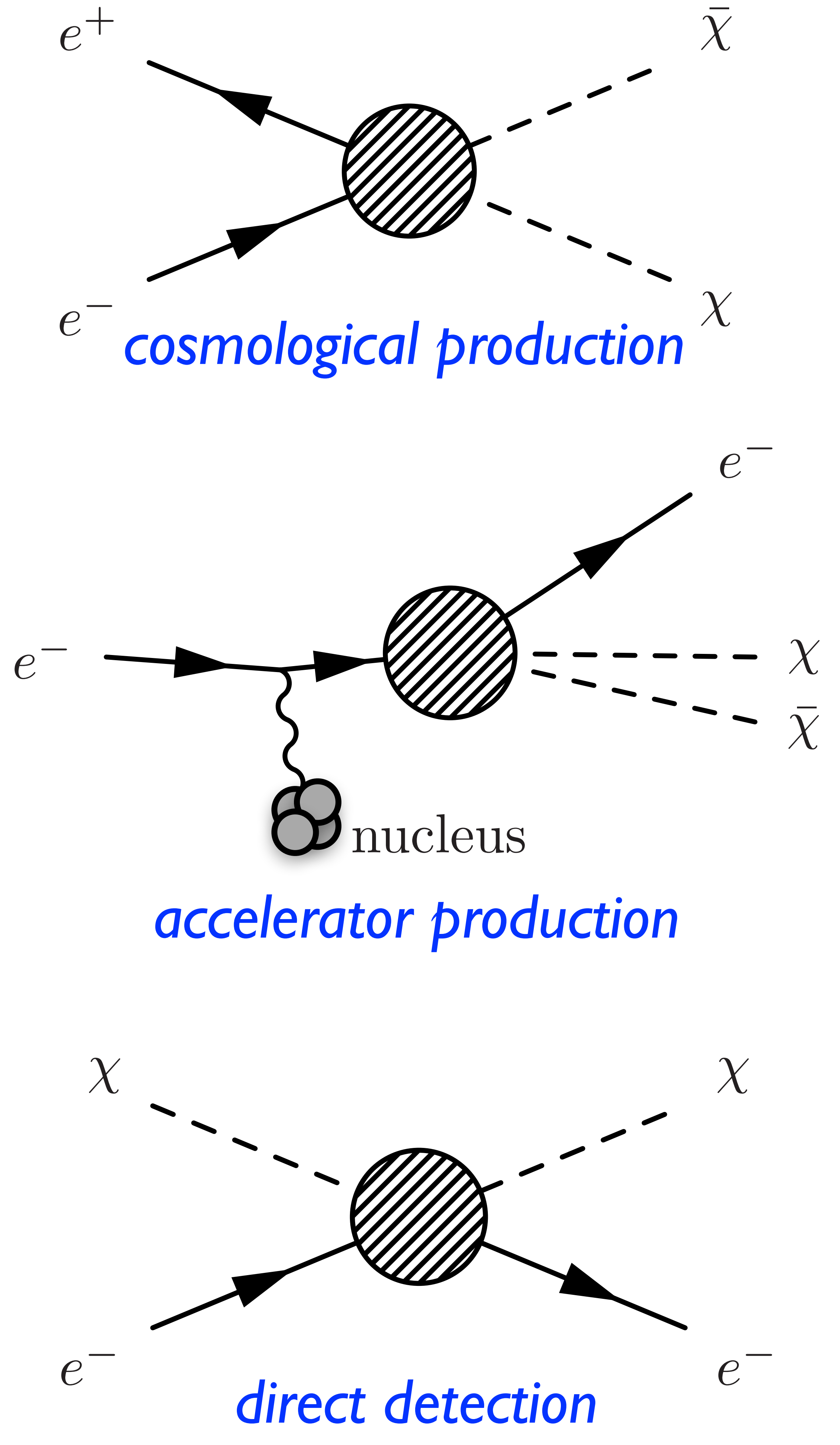
This is a missing energy, not missing mass search, but is still mediator dependent!

Freeze-out Thermal Relics

Start with a simple ansatz for DM-SM interactions:



related by crossing symmetry



scale probed

$q \sim m_\chi$

↕ *origin of predictiveness*

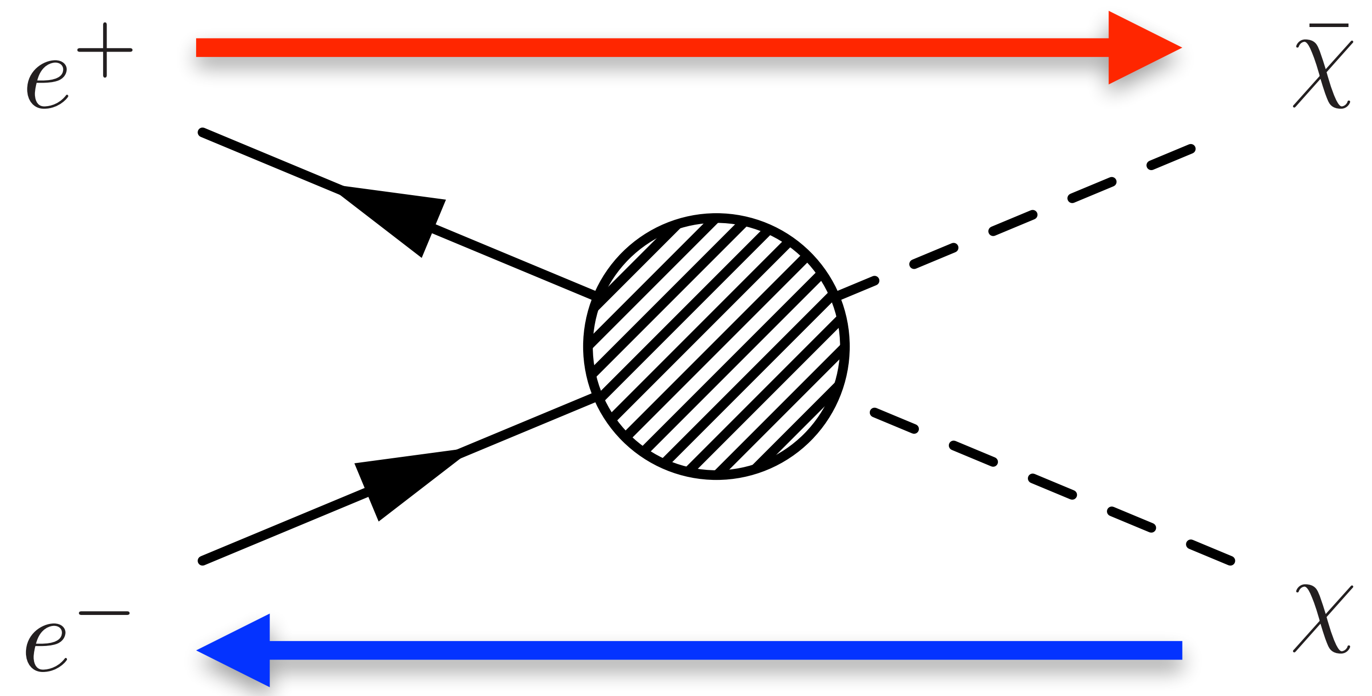
$q \gtrsim m_\chi$

↕ *origin of complementarity*

$q \ll m_\chi$

Accelerator Experiments and Freeze-out Thermal Relics

cosmological production

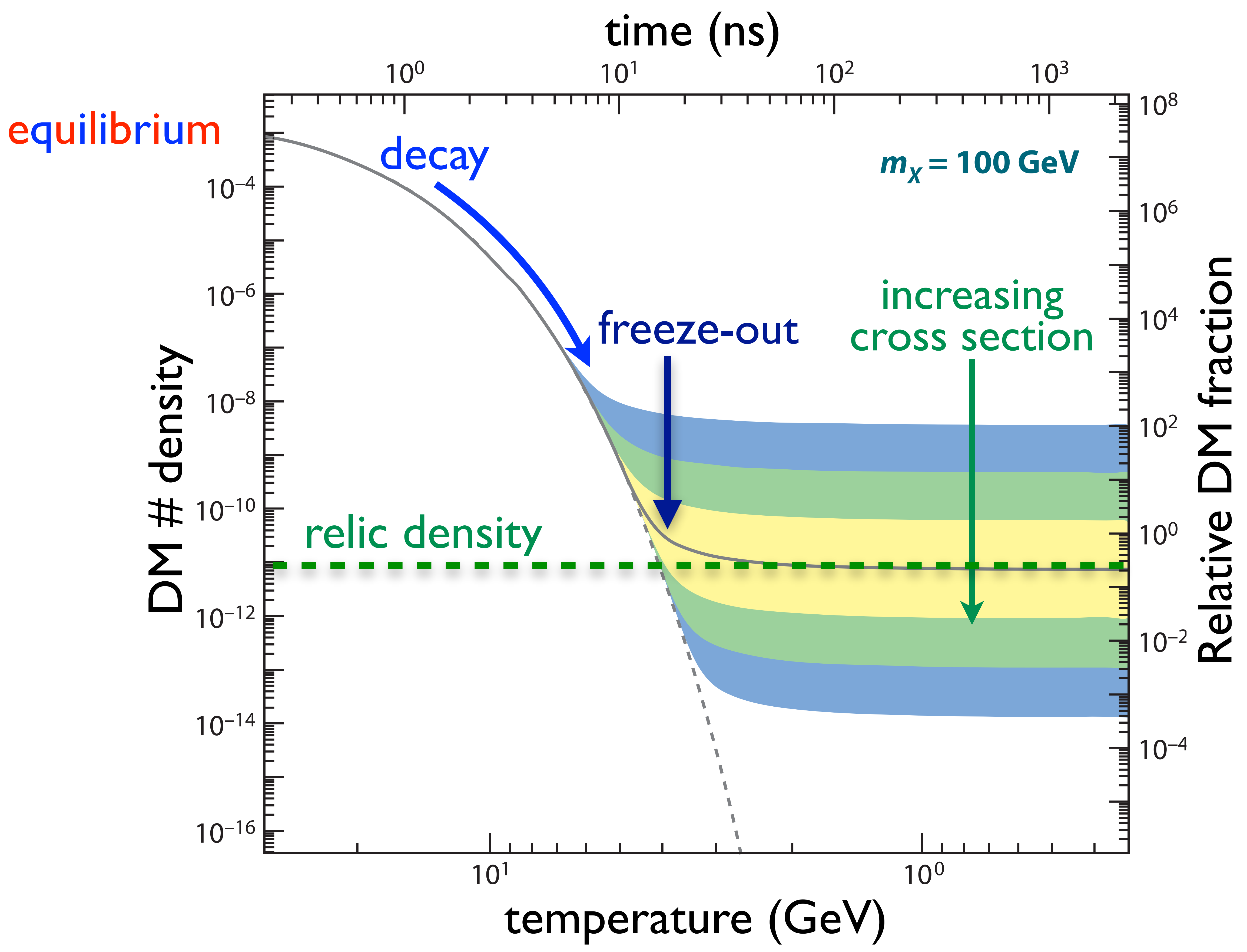


$$\sigma v = \frac{1}{16\pi^2}\frac{\bar{\mathcal{M}}(s)}{s}$$

at freeze-out:

$$s_{\rm fo} \approx (2m_\chi)^2$$
$$\sigma v = 3\cdot 10^{-26}{\rm cm}^3/s$$

$$\Rightarrow |\bar{\mathcal{M}}(s_{\rm fo})|^2 = 10^{-6} m_\chi^2/{\rm GeV}^2$$



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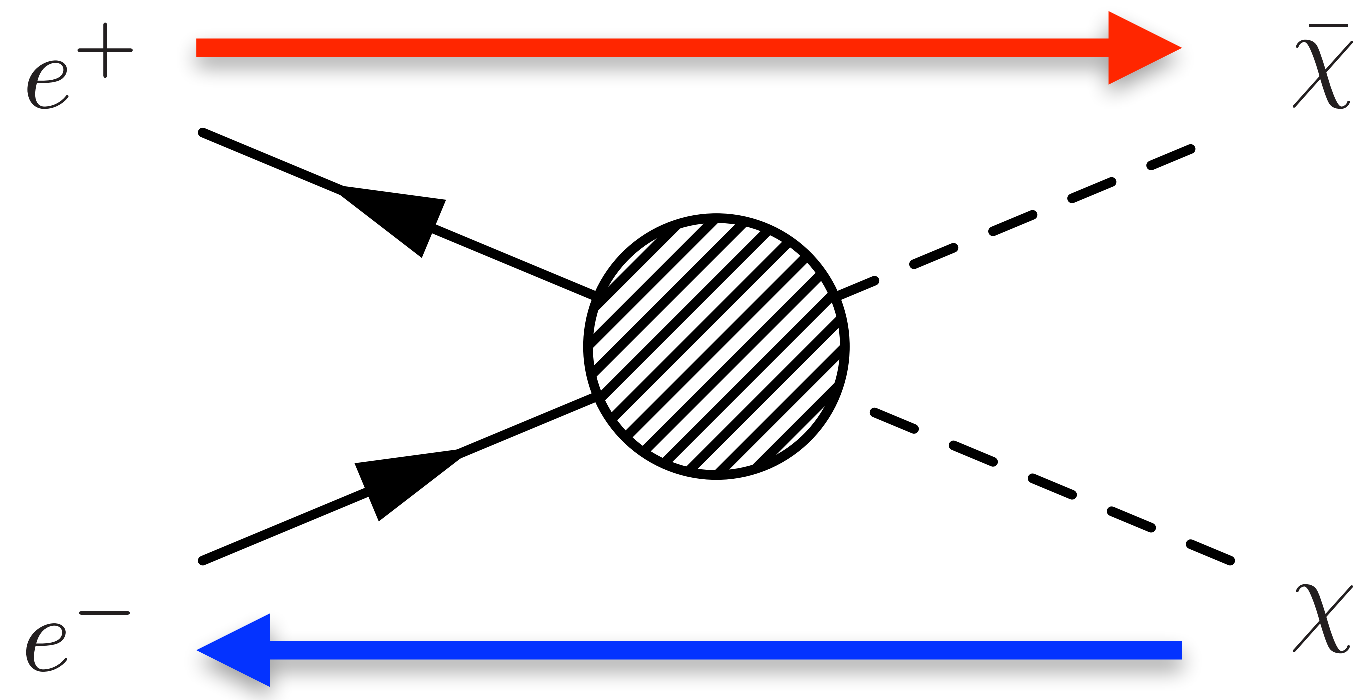
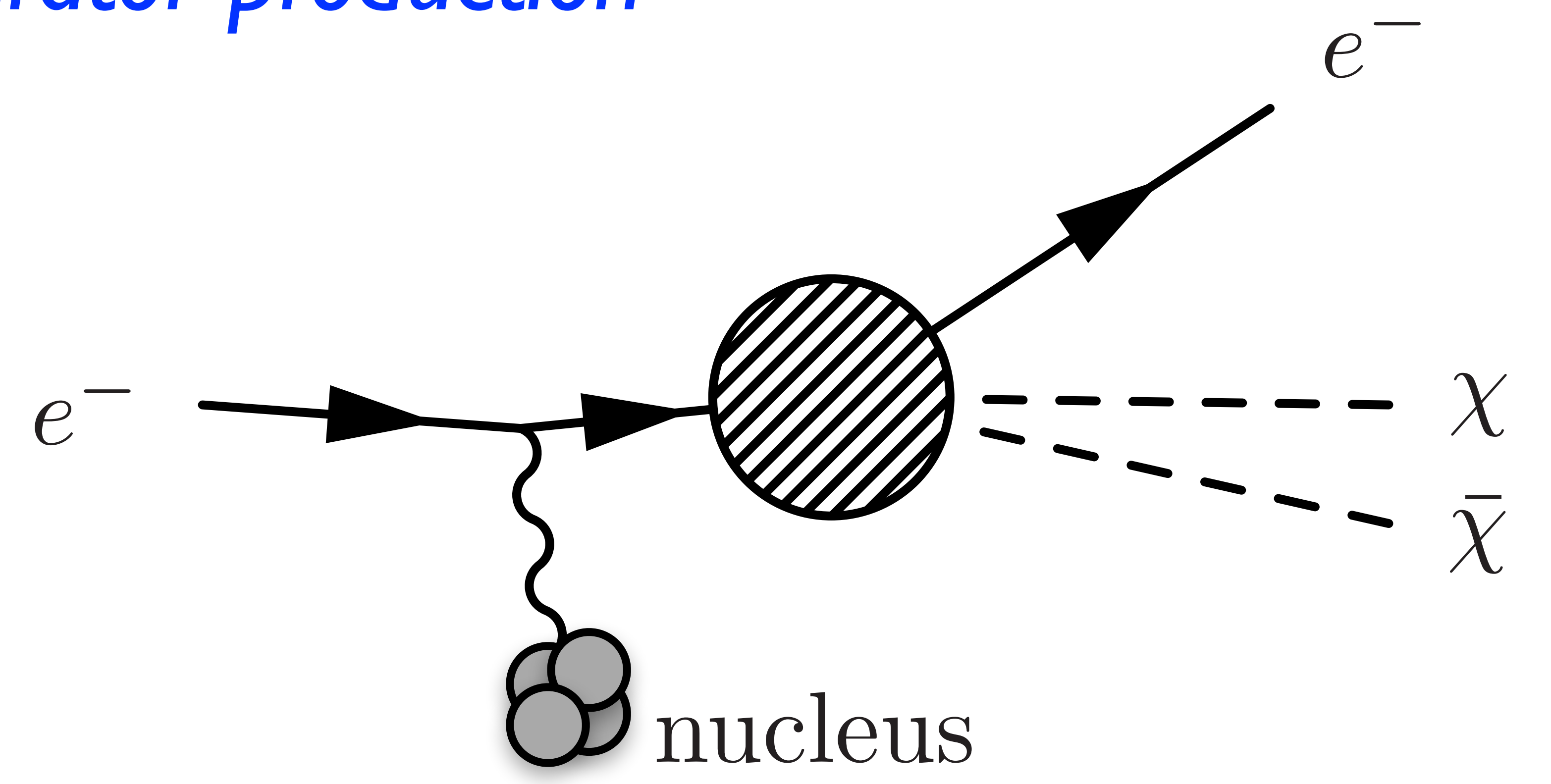


accelerator production



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for production at $s \approx s_{\rm fo}$:

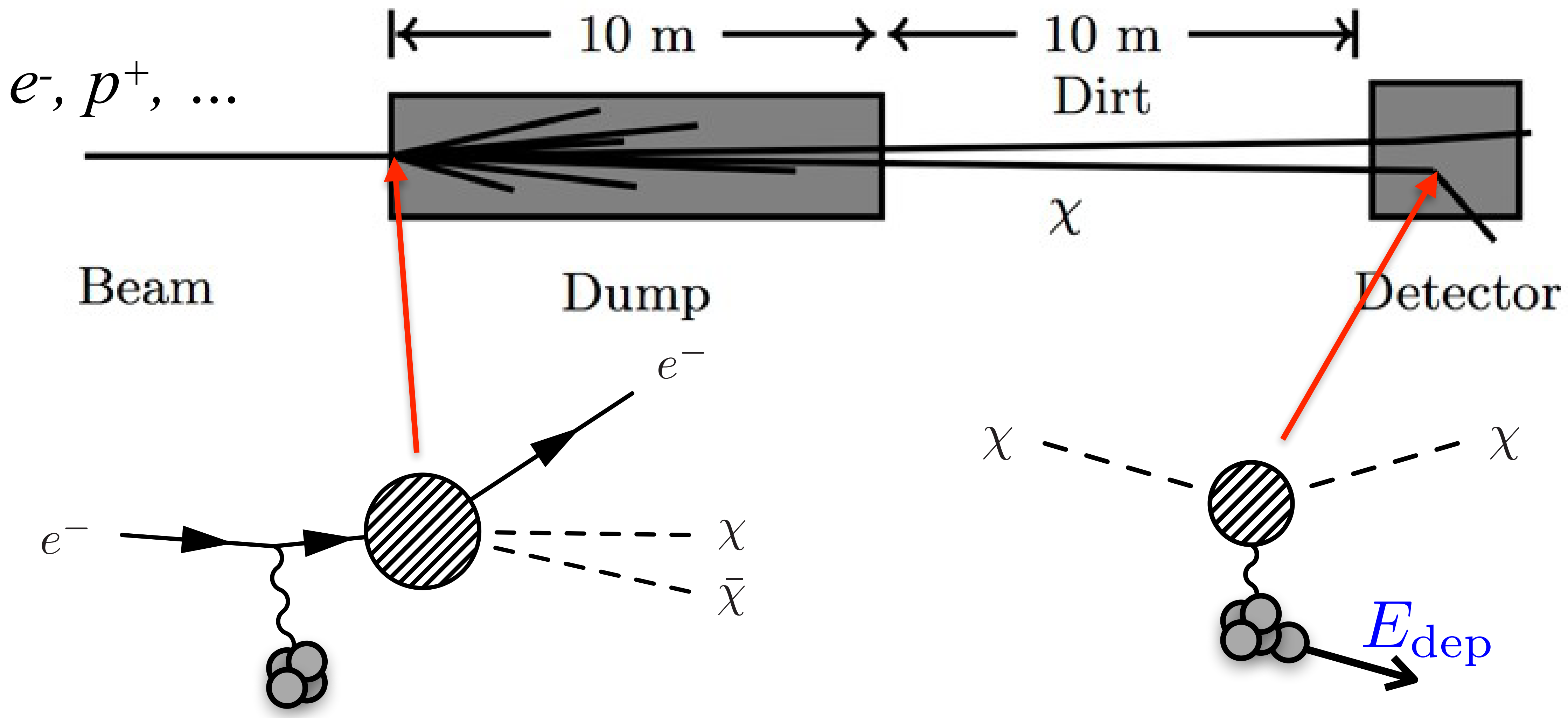
$$\frac{\sigma_{\chi\bar{\chi}}}{\sigma_{\rm brem}} \approx \frac{|\mathcal{M}|^2}{e^2}\frac{1}{48\pi^2}\frac{(2m_\chi)^{-2}}{m_e^{-2}} f_{\rm coh} \approx 2\cdot 10^{-15} f_{\rm coh}$$

where $f_{\rm coh}$ is $\mathcal{O}(1)$ for $m_\chi \lesssim 100$ MeV

Since smaller cross sections result in DM overabundance, an accelerator experiment with ~10^{16} electrons has generic ability to produce sub-GeV freeze-out thermal relics.

Fixed Target Dark Matter Search Approaches

Beam Dumps: Produce and re-scatter DM

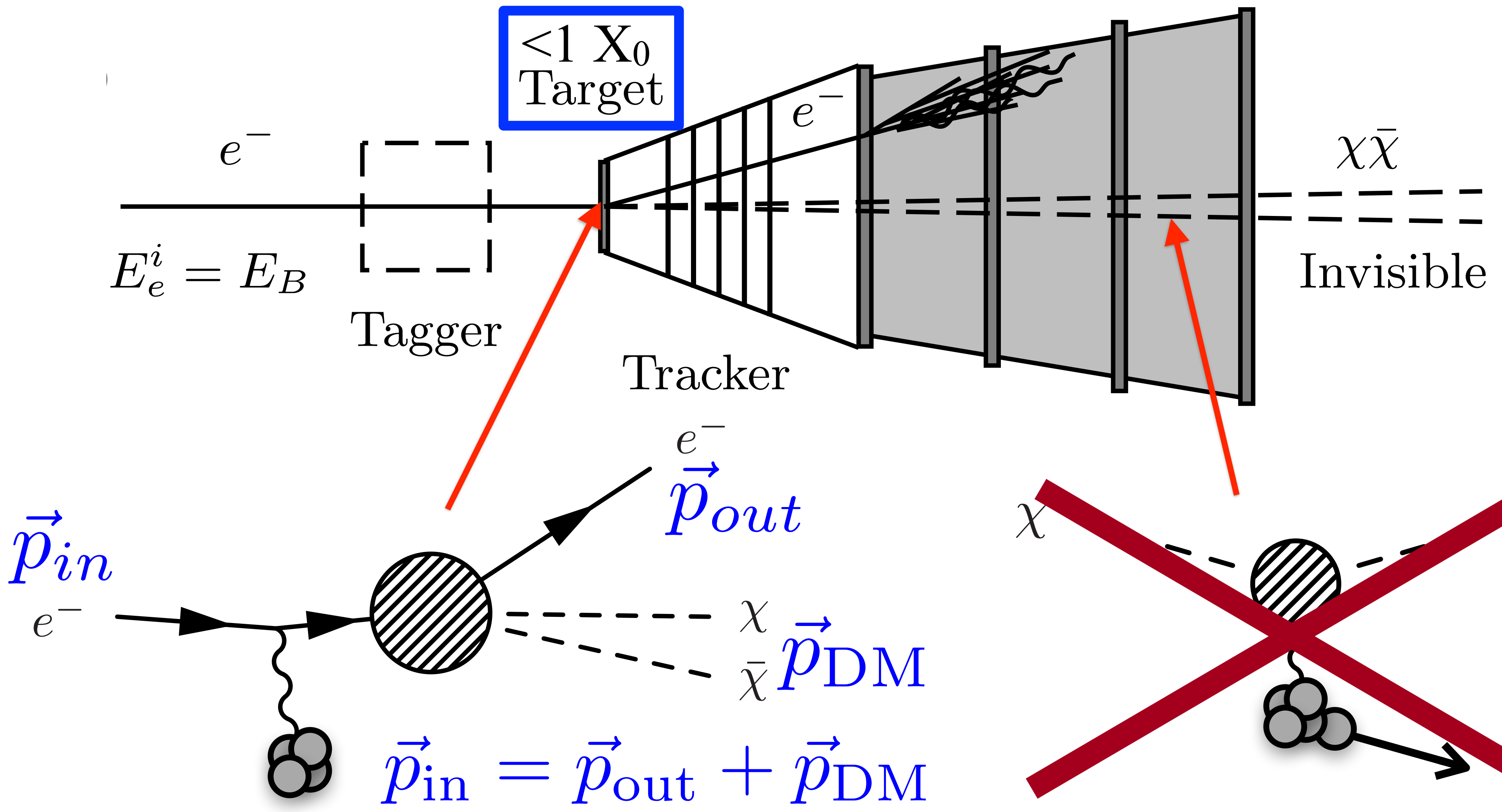


- new sensitivity with ~10[21] particles
- covers thermal targets with ~10[28] particles
- re-scattering adds model dependence

Requirements:

- most powerful and energetic beam available
- most massive detector available
- key backgrounds: neutrinos, cosmics

Missing Momentum: Detect DM production



- new sensitivity for ~10[12] electrons
- covers thermal targets for ~10[16] electrons
- electron production is extremely generic

Requirements:

- high rate beam at ~1 e^-/bunch (1 year = 3×10[16] ns)
- fast, sensitive, detector systems
- key backgrounds: $e^- \rightarrow e^- + \gamma$, $\gamma N \rightarrow$ hadrons

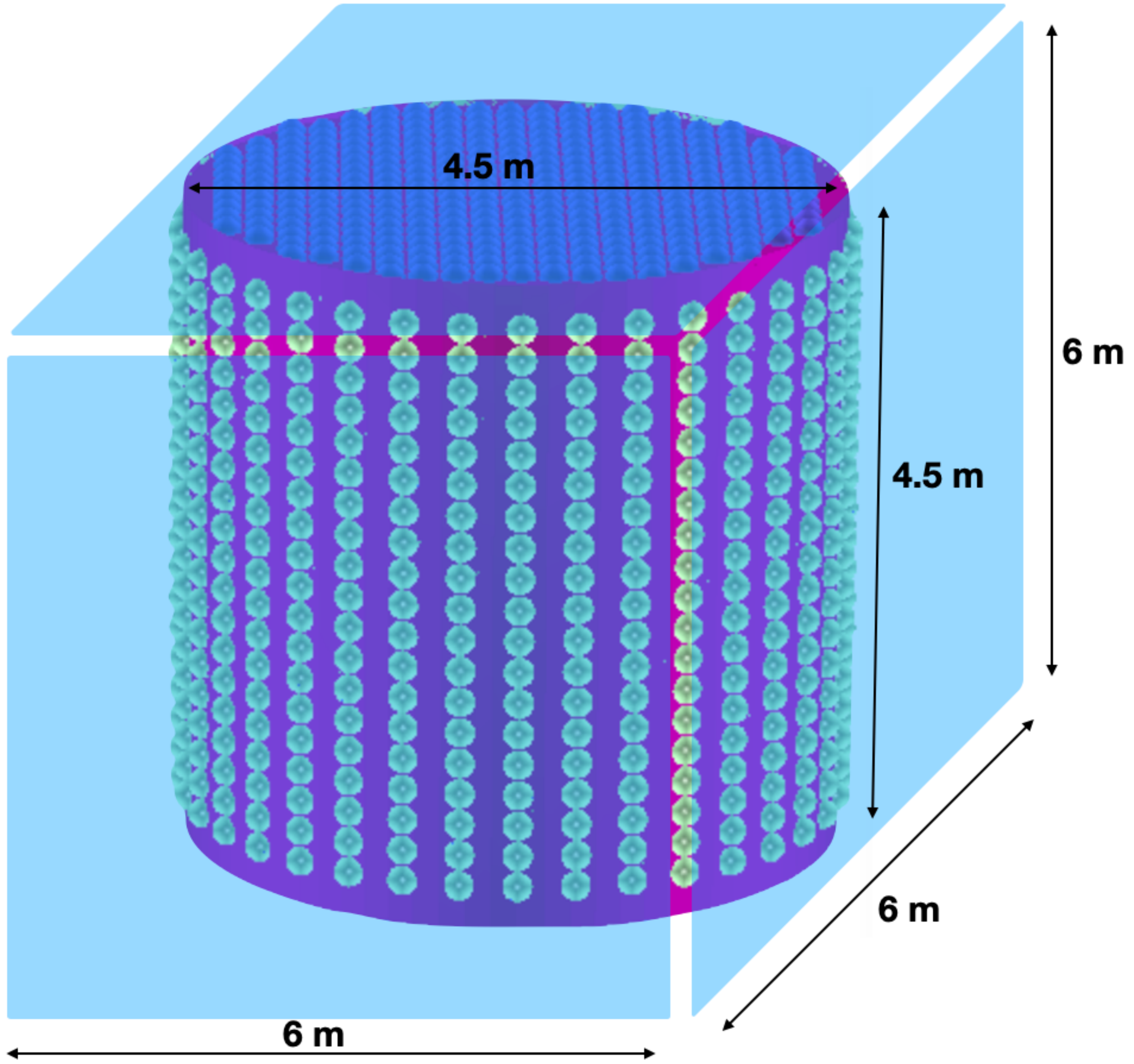
BDX at JLab

I am the wrong person for this slide.

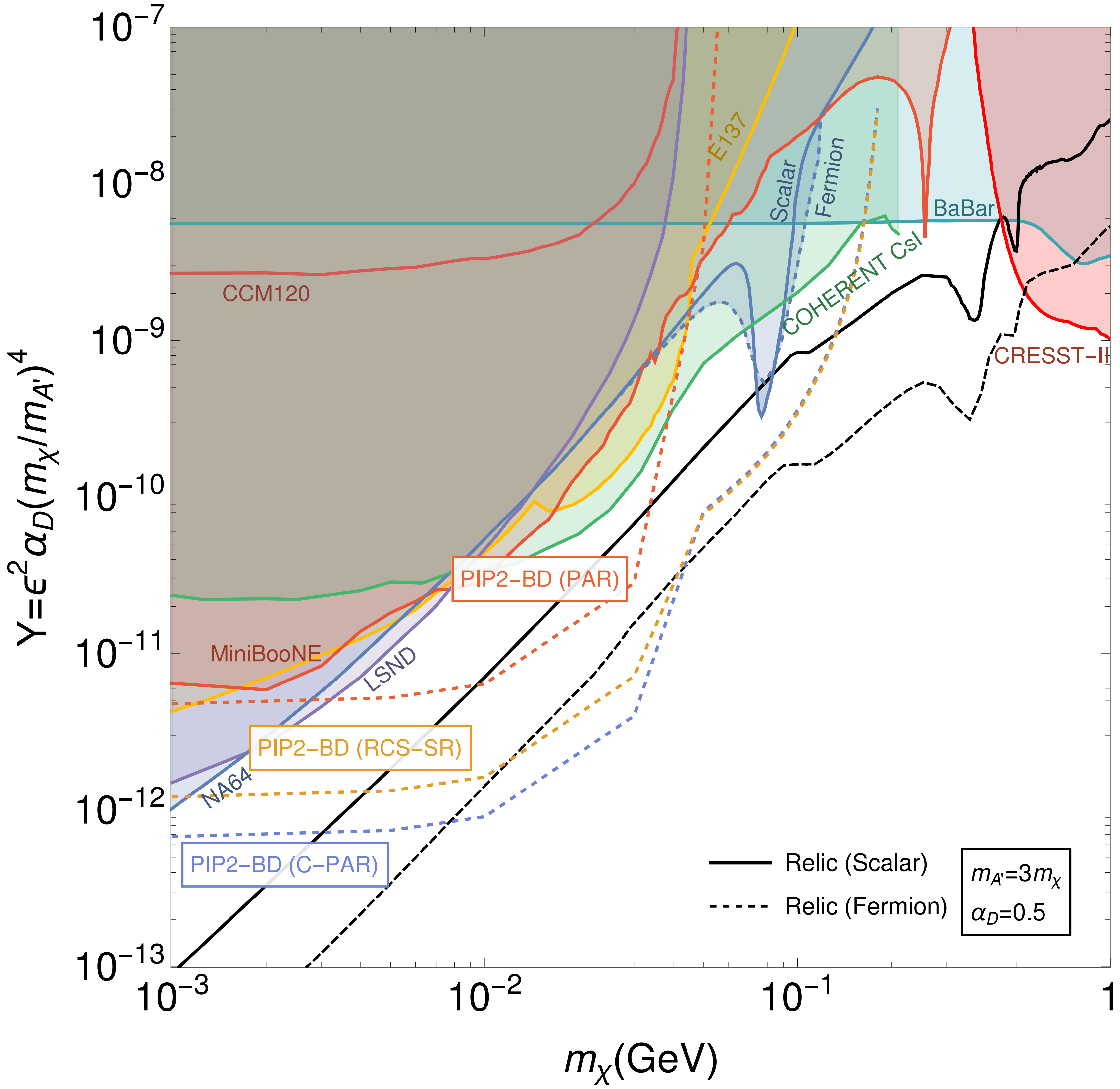
PIP-2 BD

Leverage major investments at FNAL

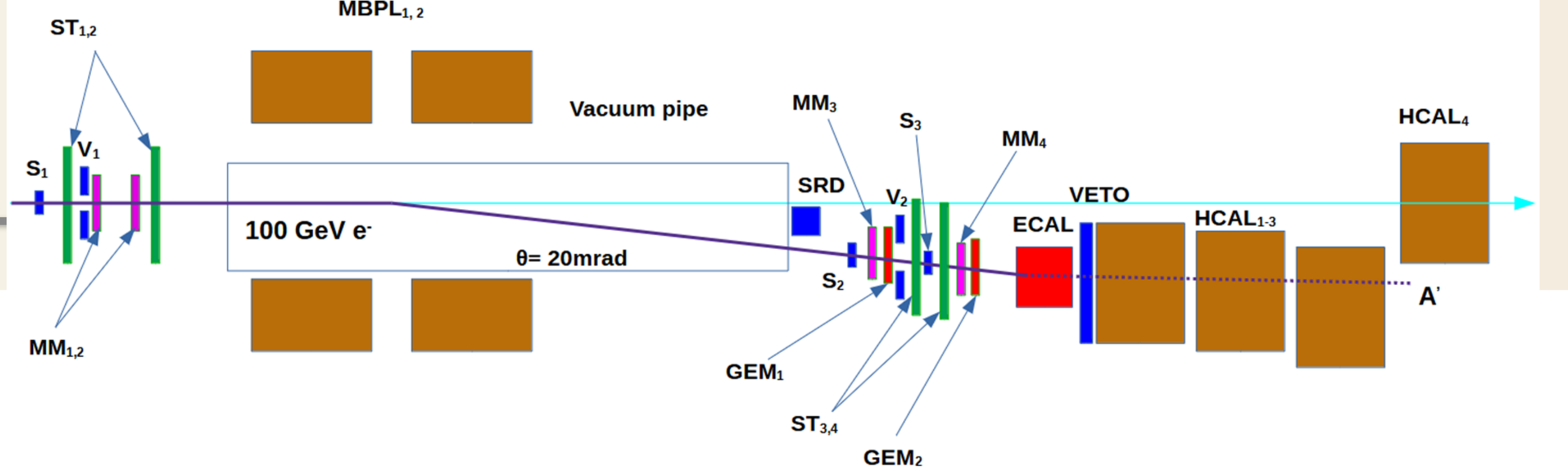
- 1 MW 800 MeV p+ beam
- 100 ton LAr detector



arXiv:2203.08079 **[hep-ex]**

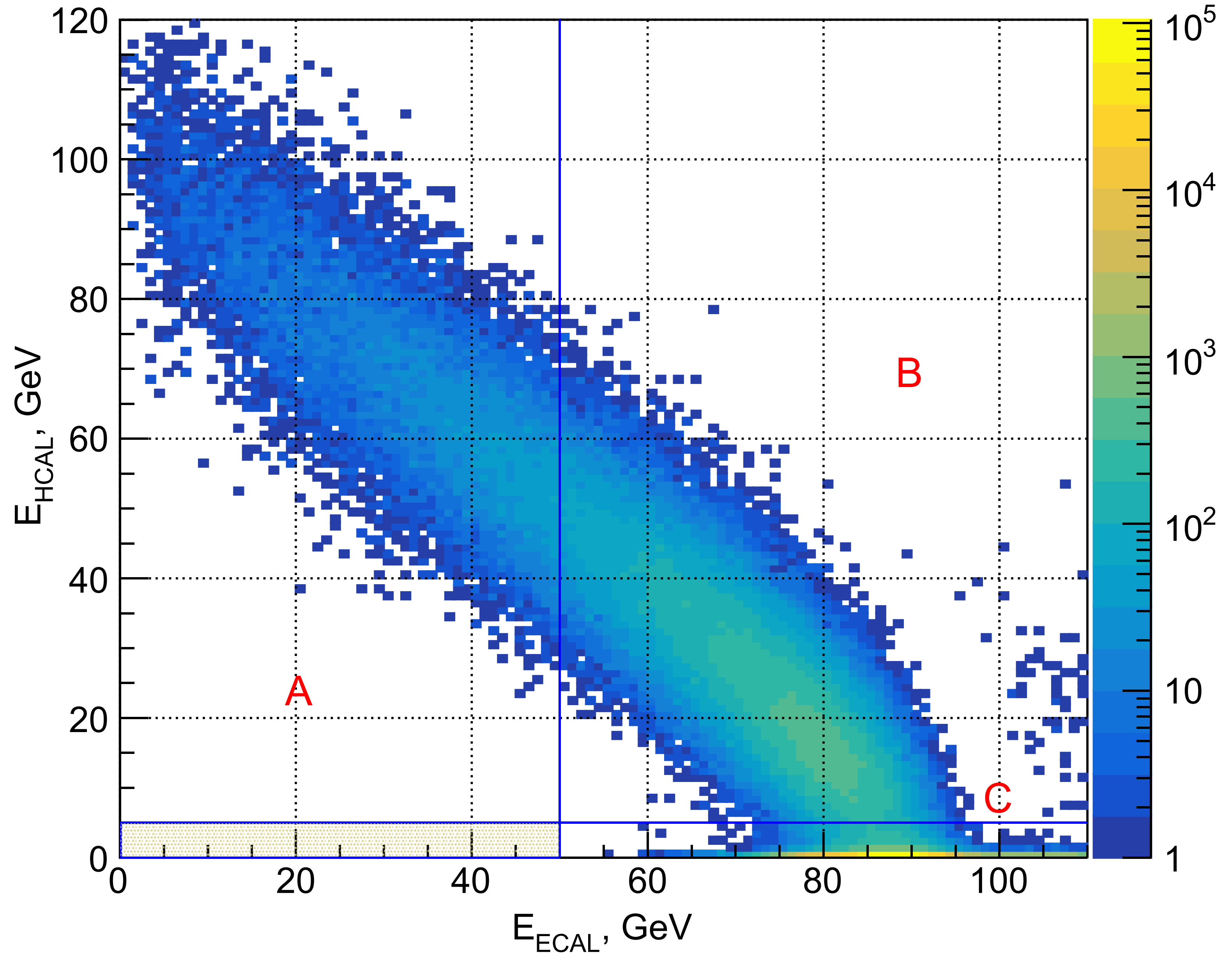


NA64e "invisible"

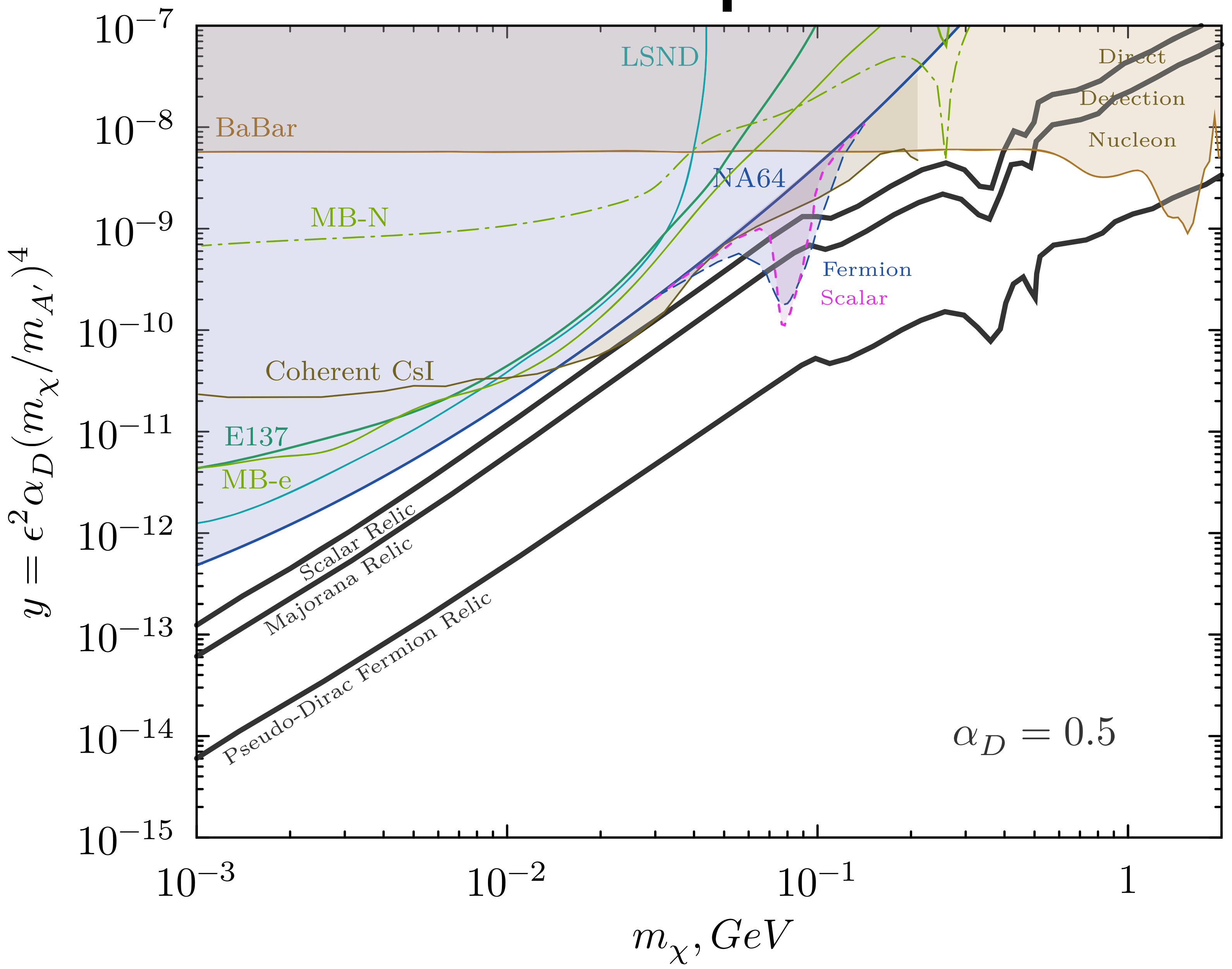


Update last summer includes newest data and resonant enhancement in showers.

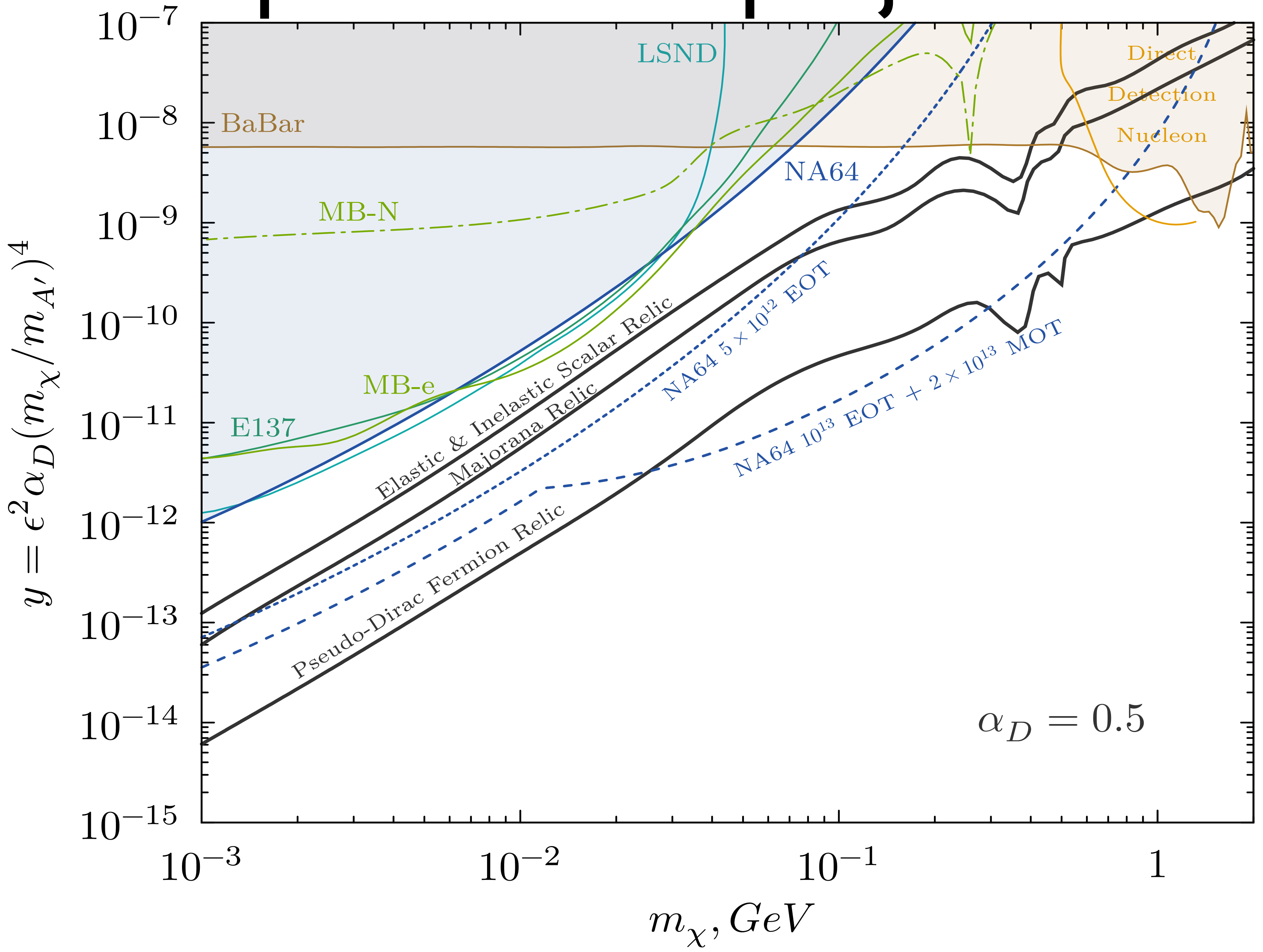
arXiv:2307.02404 [hep-ex]



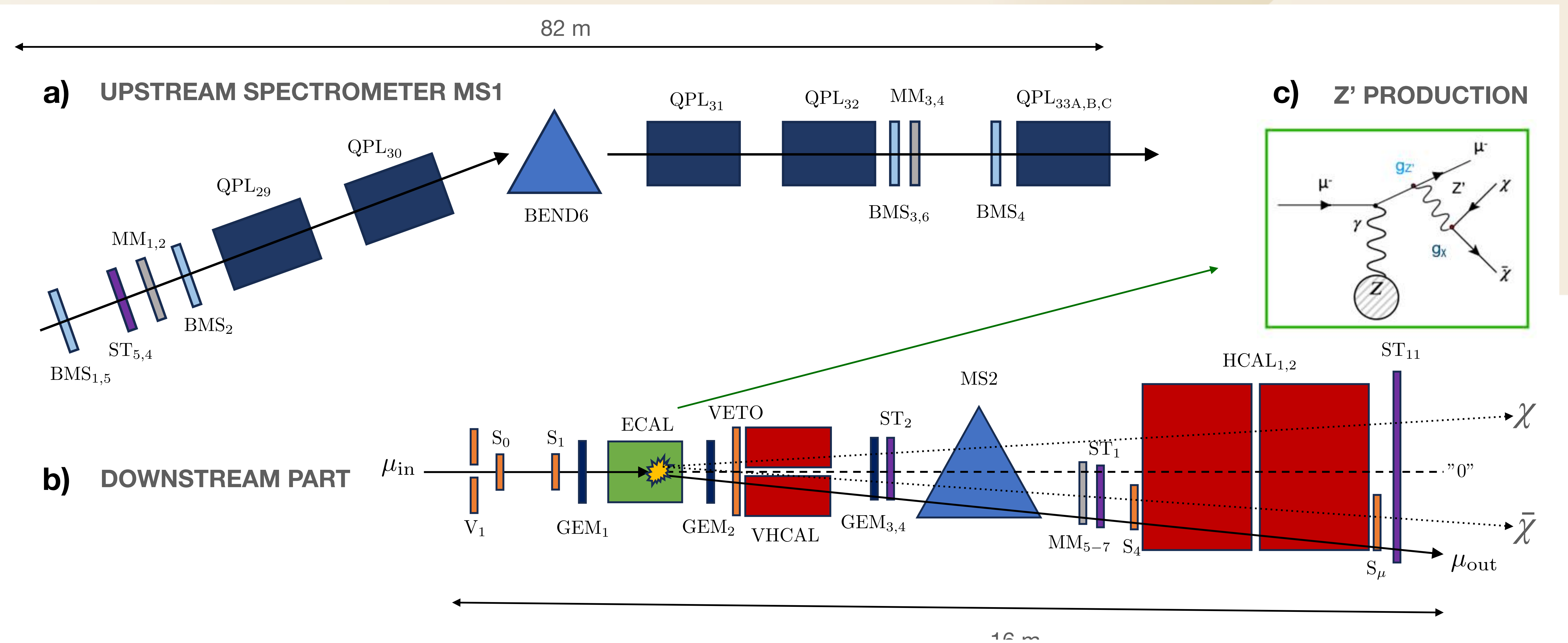
latest update



previous w/ projections



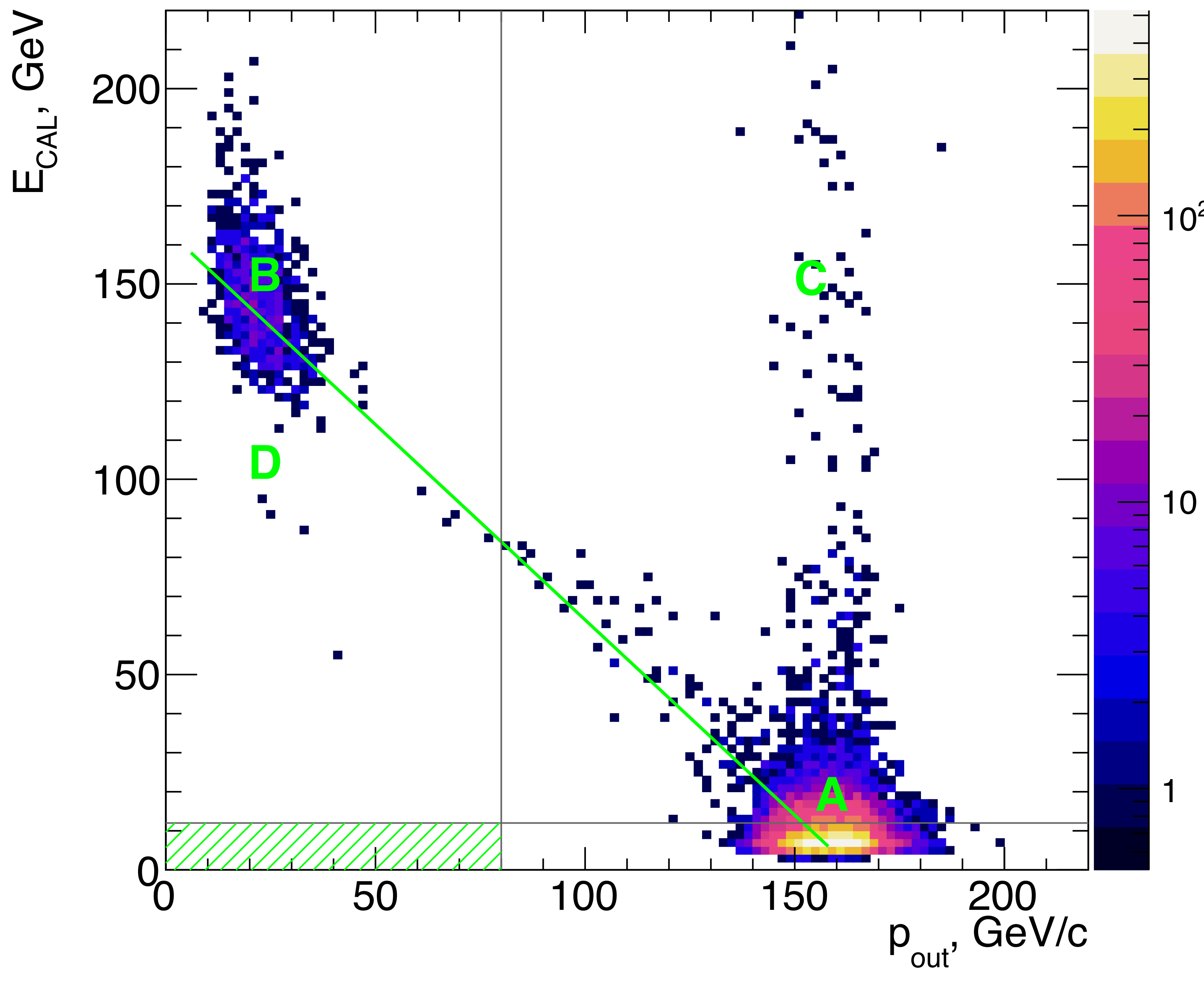
NA64μ

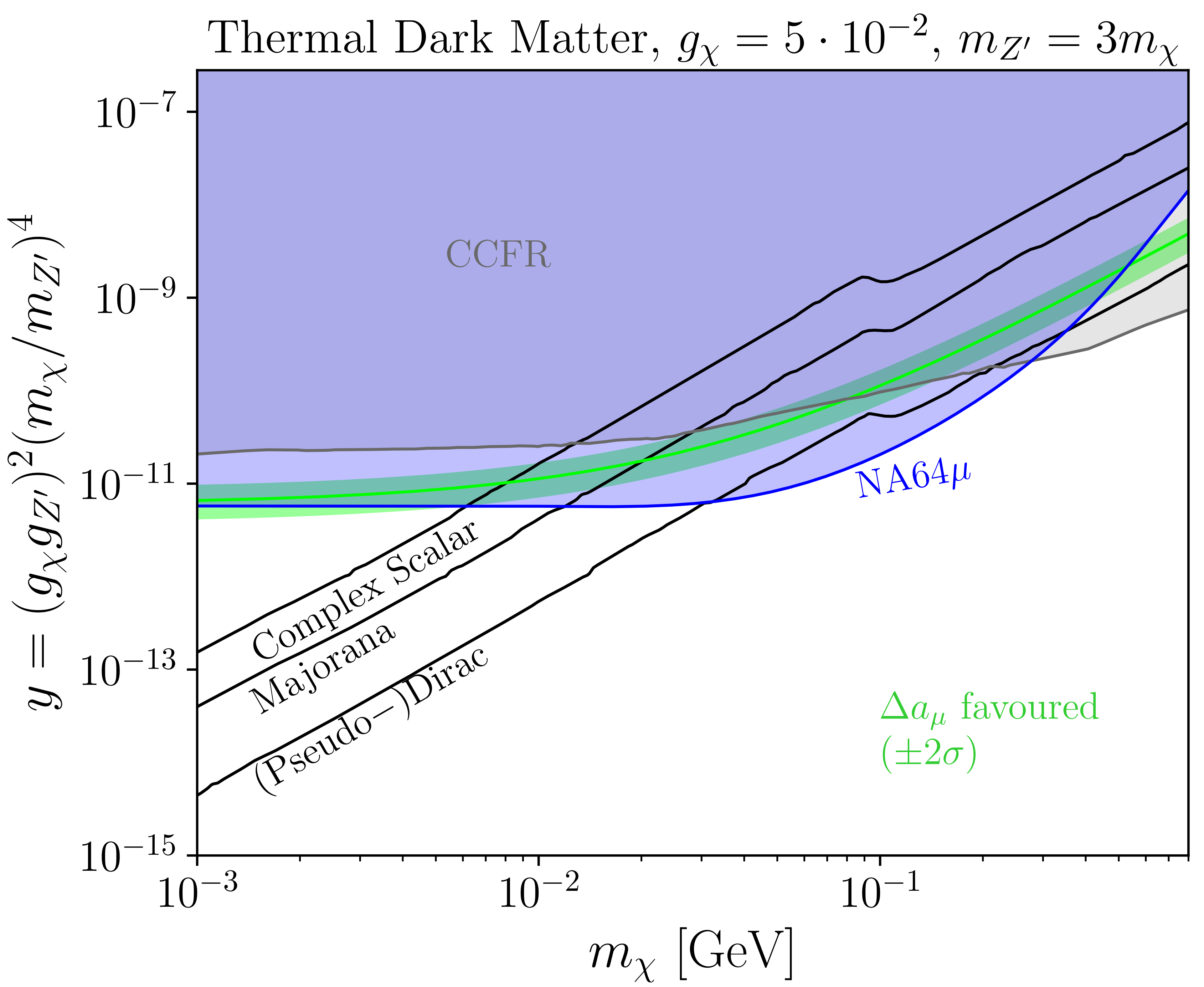


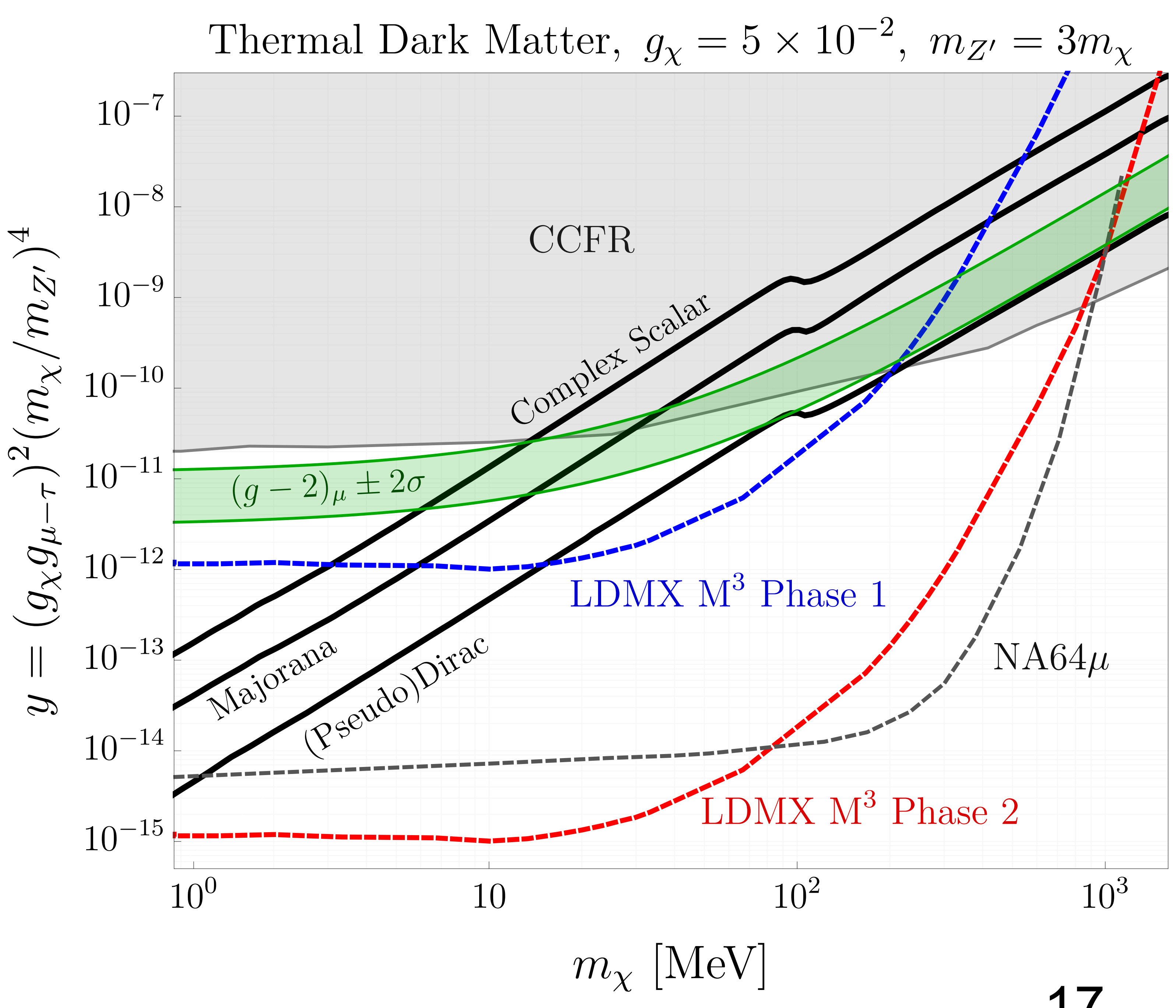
First run of NA64 with muons!

over 3 orders of magnitude from predicted ultimate sensitivity.

arXiv:2401.01708 **[hep-ex]**

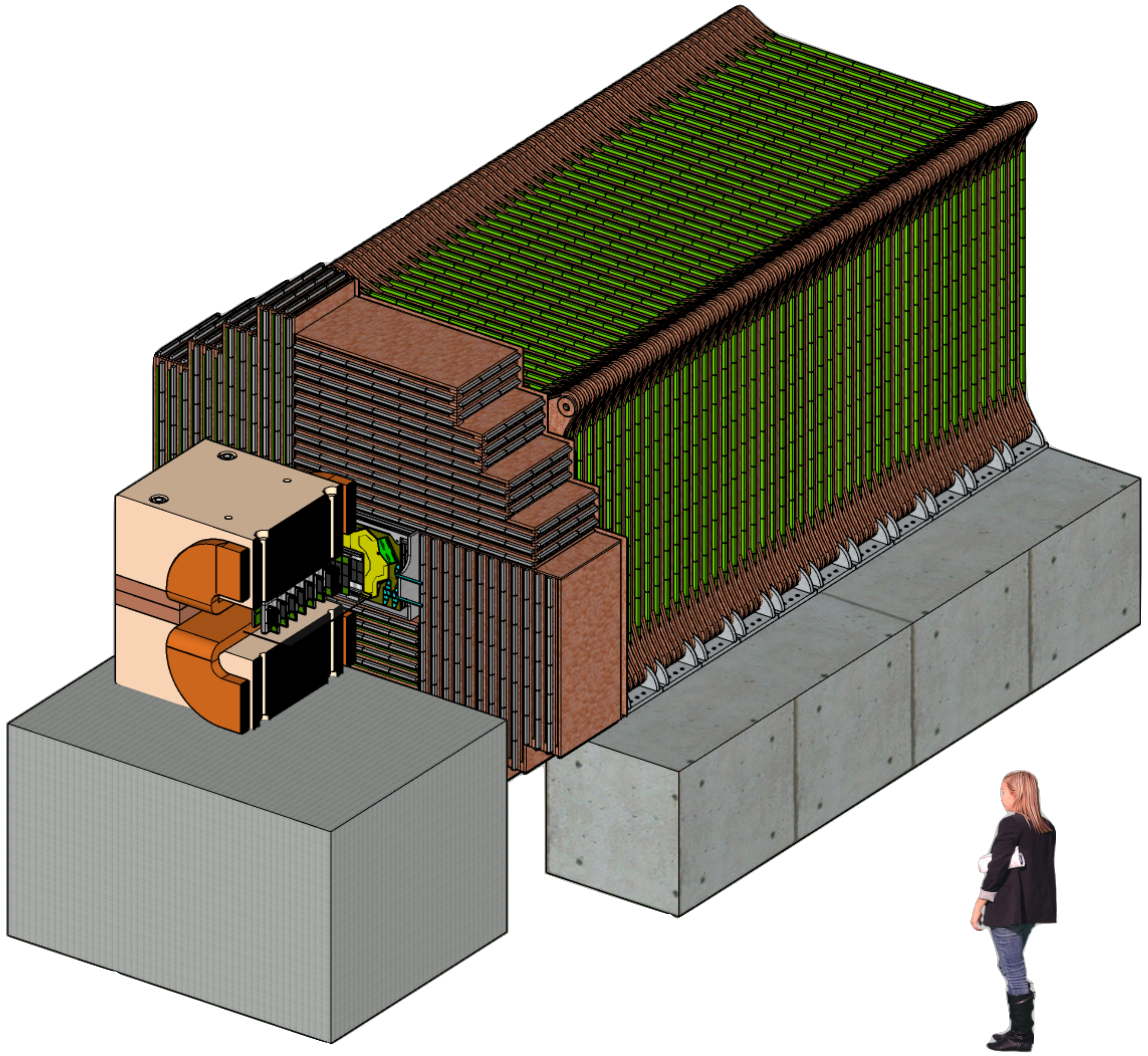


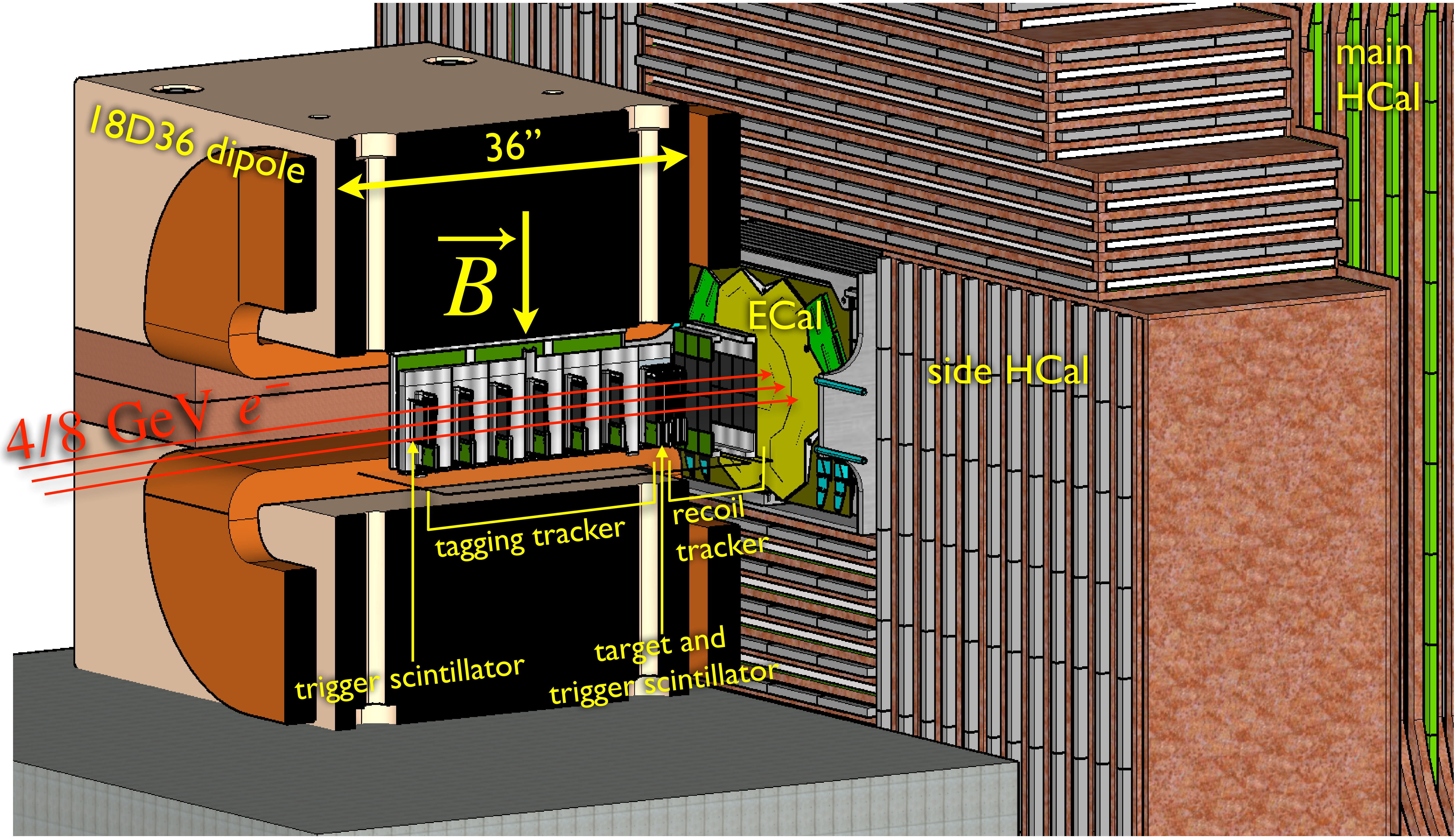




Light Dark Matter eXperiment at SLAC

LDMX Whitepaper arXiv:1808.05219





LDMX is an electron missing momentum experiment designed for up to 10^{16} electrons

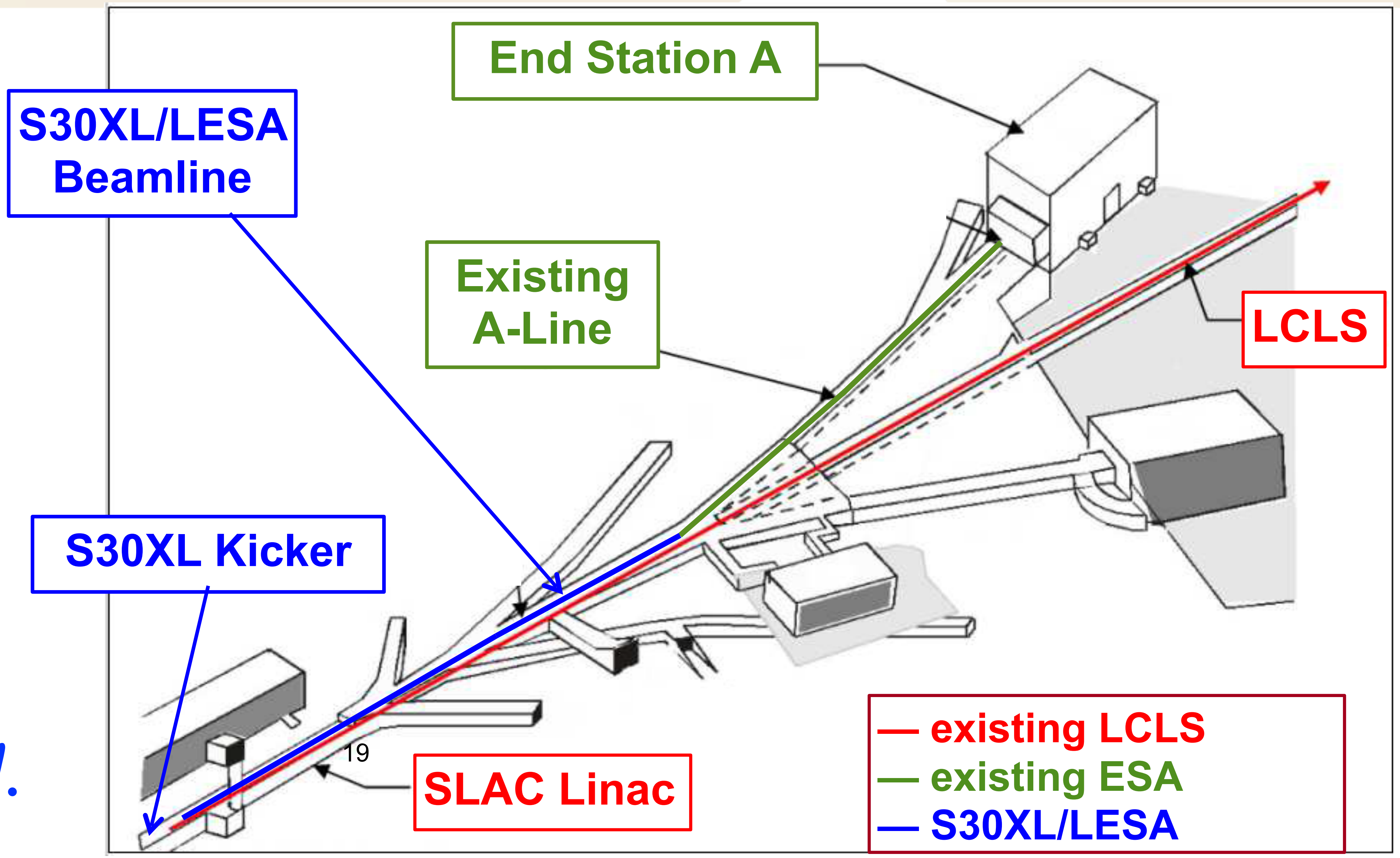
Linac to End Station A (LESA) at SLAC

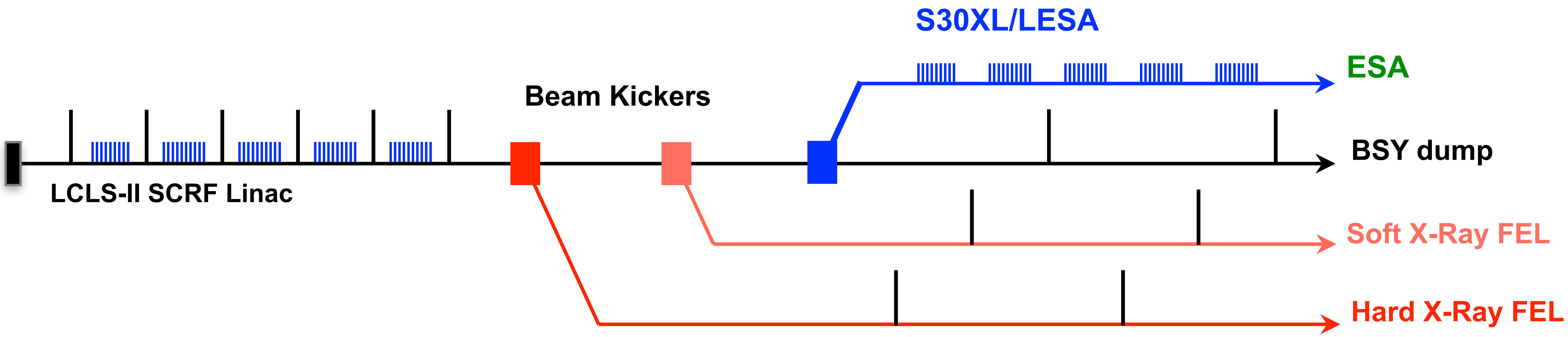
LCLS-II 4/8 GeV drive beam accelerates 186 MHz bunches

- ~5000 hours/year operation for photon science
- LCLS-II uses 929 kHz: >99% of bunches go to dump
- Sector 30 Transfer Line (S30XL) diverts ~60% of unused, low-charge bunches to LESA with LDMX as a primary user.

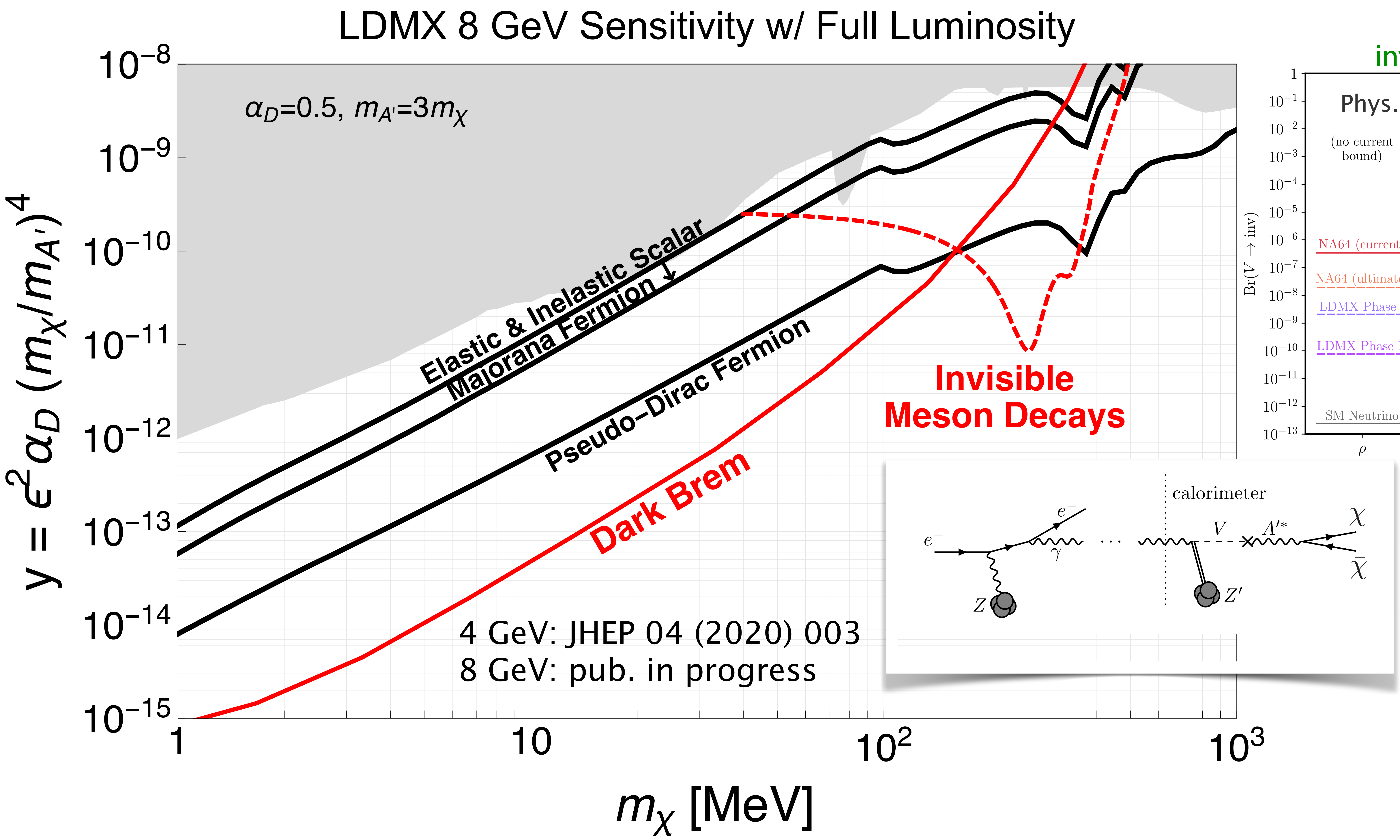
S30XL AIP is currently under construction alongside LCLS-II.

LESA is expected to deliver beam to End Station A later this year!.

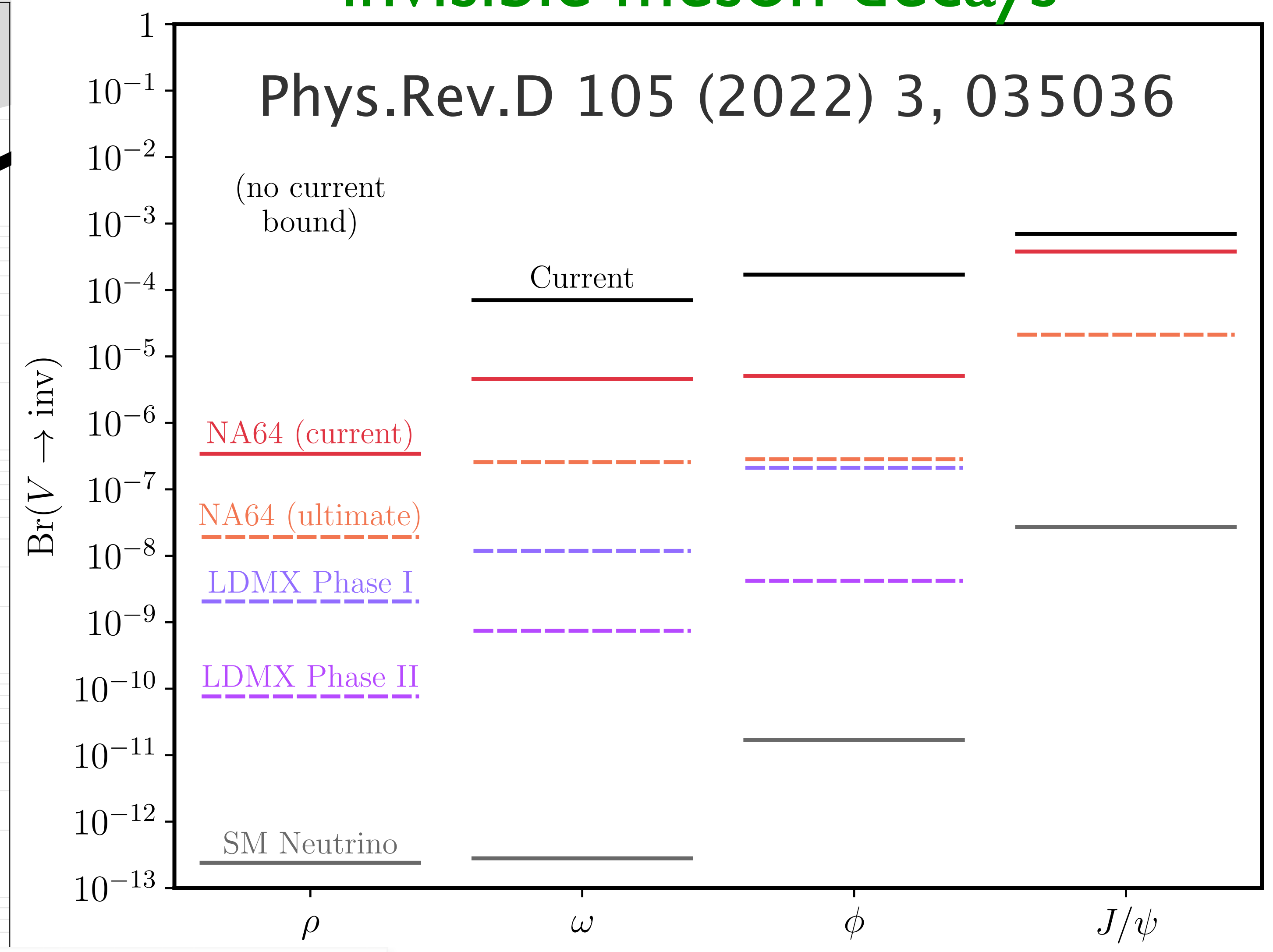




LDMX Sensitivity

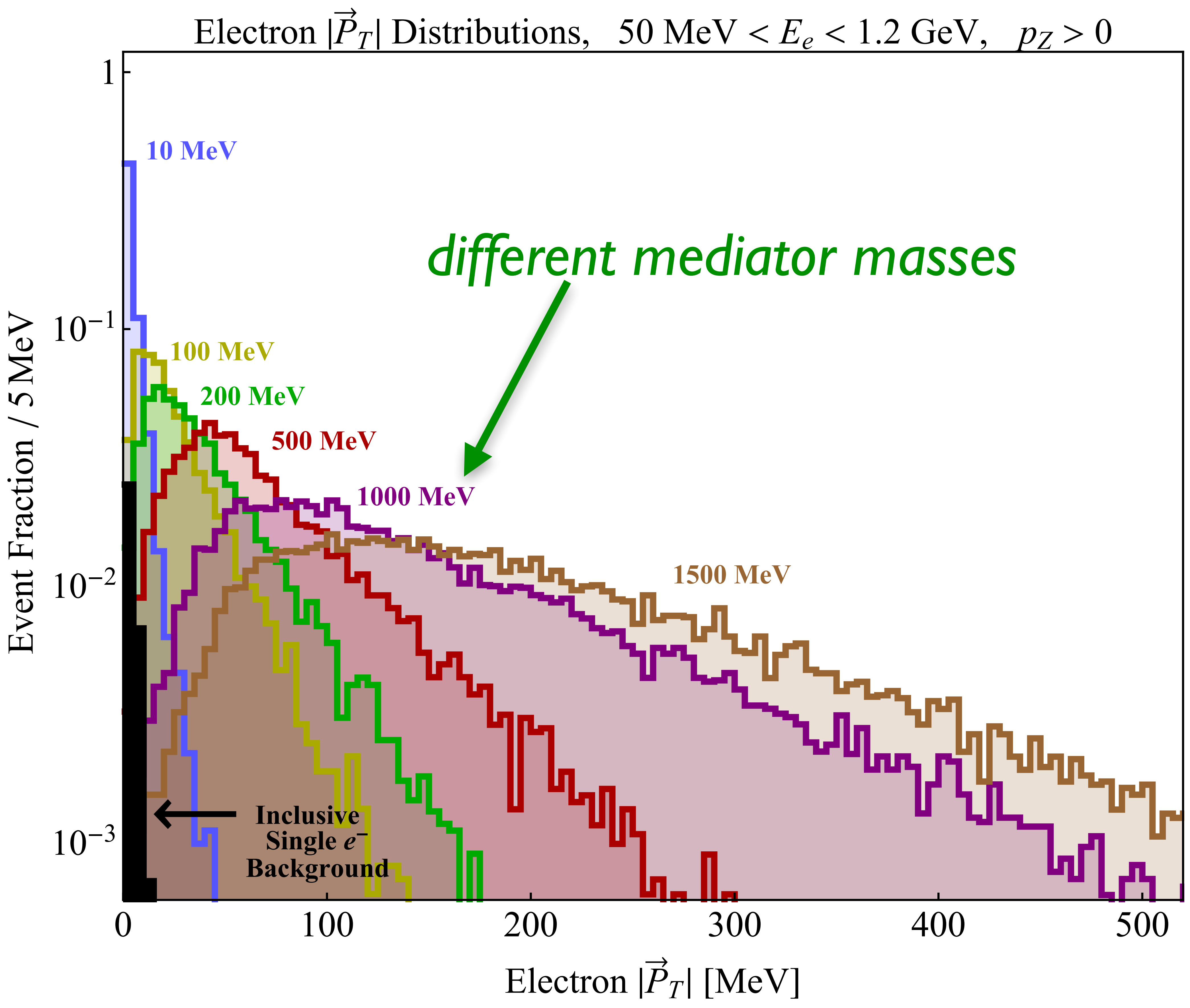


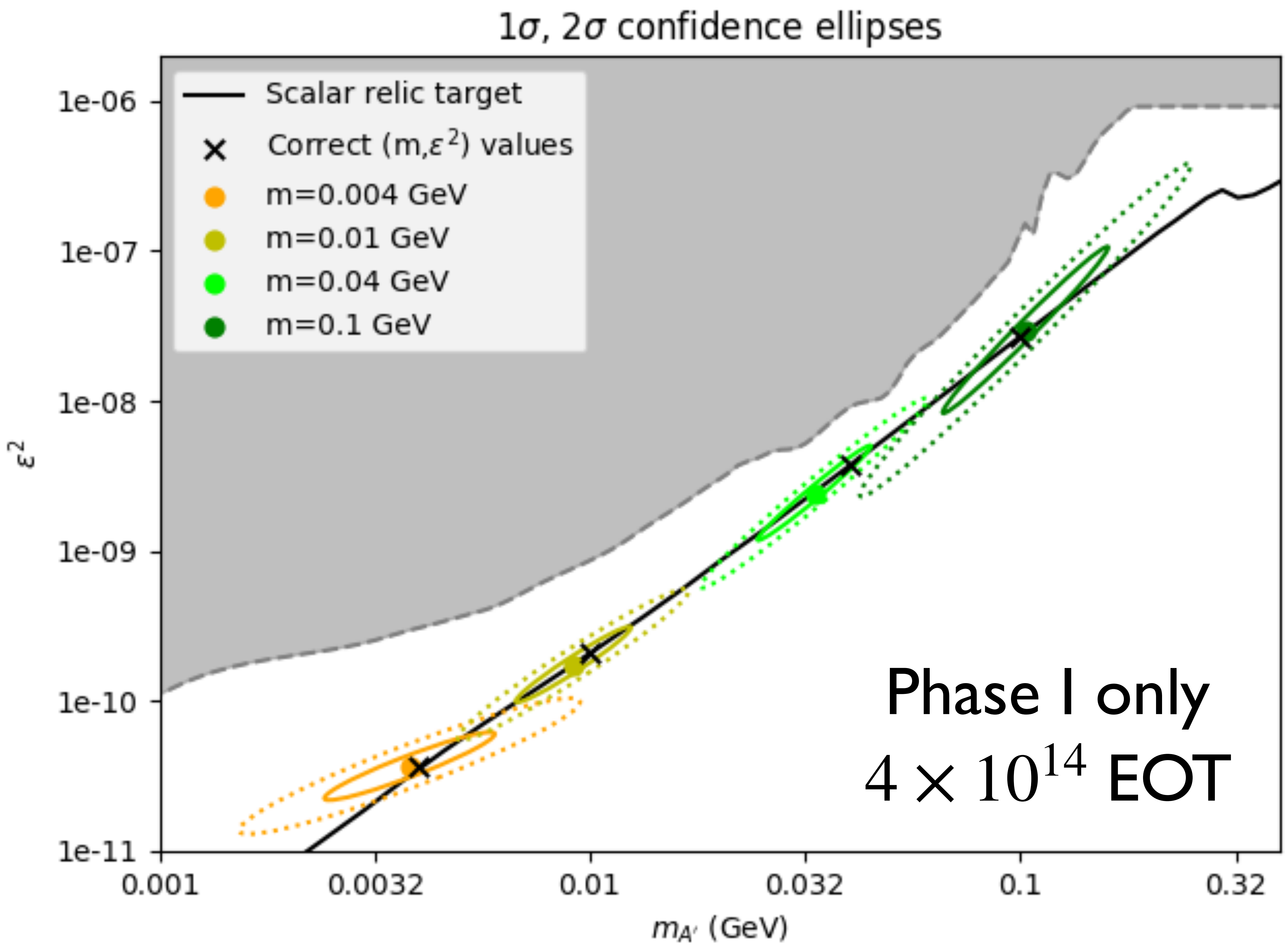
invisible meson decays



probes hadronic couplings in mass range relevant to freeze-out

LDMX Sensitivity





Fit to Δp_T spectrum of recoiling electron allows measurement of mediator mass

HEP Landscape

Previous P5 recognized the importance of small projects but the mandate was vague:

However, small-scale experiments can also address many of the questions related to the Drivers. These experiments combine timely physics with opportunities for a broad exposure to new experimental techniques, provide leadership roles for young scientists, and allow for partnerships among universities and national laboratories. In our budget exercises, we maintained a small projects portfolio to preserve budgetary space for a number of these important small projects, whose costs are typically less than $20M. These projects individually are not large enough to come under direct P5 review. Small invest-

2014 P5

	Scenarios			Science Drivers					
Project/Activity	Scenario A	Scenario B	Scenario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
		some reductions with							

Lack of a clear mandate for HPS, and smaller projects in general, has created ongoing challenges in arguing for support for smaller projects under heavy budget pressure on the HEP program.

During recent P5 process, issues were discussed with panelists, related to the timeliness (cadence) and effectiveness of the small projects portfolio as demonstrated by the LDMX(DMNI) experience.

Enter ASTAE

SLAC

Advancing Science and Technology through Agile Experiments

ASTAE §		P	P	P	P	P	P

Recommendation 3a. Implement a new small-project portfolio at DOE, **Advancing Science and Technology through Agile Experiments (ASTAE)**, across science themes in particle physics with a competitive program and recurring funding opportunity announcements. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP (section 6.2).

ASTAE

2. For the ASTAE program to be agile, we recommend a **broad, predictable, and recurring (preferably annual) call for proposals**. This ensures the flexibility to target emerging opportunities and fields. A program on the scale of **$35 million per year in 2023 dollars** is needed to ensure a healthy pipeline of projects.
3. To preserve the agility of the ASTAE program, **project management** requirements should be outlined for the portfolio and should be adjusted to be commensurate with the scale of the experiment.
4. A successful ASTAE experiment involves 3 phases: **design, construction, and operations**. A design phase proposal should precede a construction proposal, and construction proposals are considered from projects within the group that have successfully completed their design phase.
5. **The DMNI projects** that have successfully completed their design phase and are ready to be reviewed for construction, **should form the first set of construction proposals for ASTAE.** The corresponding design phase call would be **open to proposals from all areas of particle physics.**

From LDMX perspective, this is the strongest statement we could have expected from P5.

While ASTAE is clearly patterned after the DMNI example, some details are still unclear or TBD by OHEP; budgets in less favorable scenario (said to be ~$20M), details of and process for ongoing calls, project management scenarios.

What Didn't Fare Well

Figure 2 – Construction in Various Budget Scenarios

Index: Y: Yes N: No R&D: Recommend R&D only C: Conditional yes based on review P: Primary S: Secondary

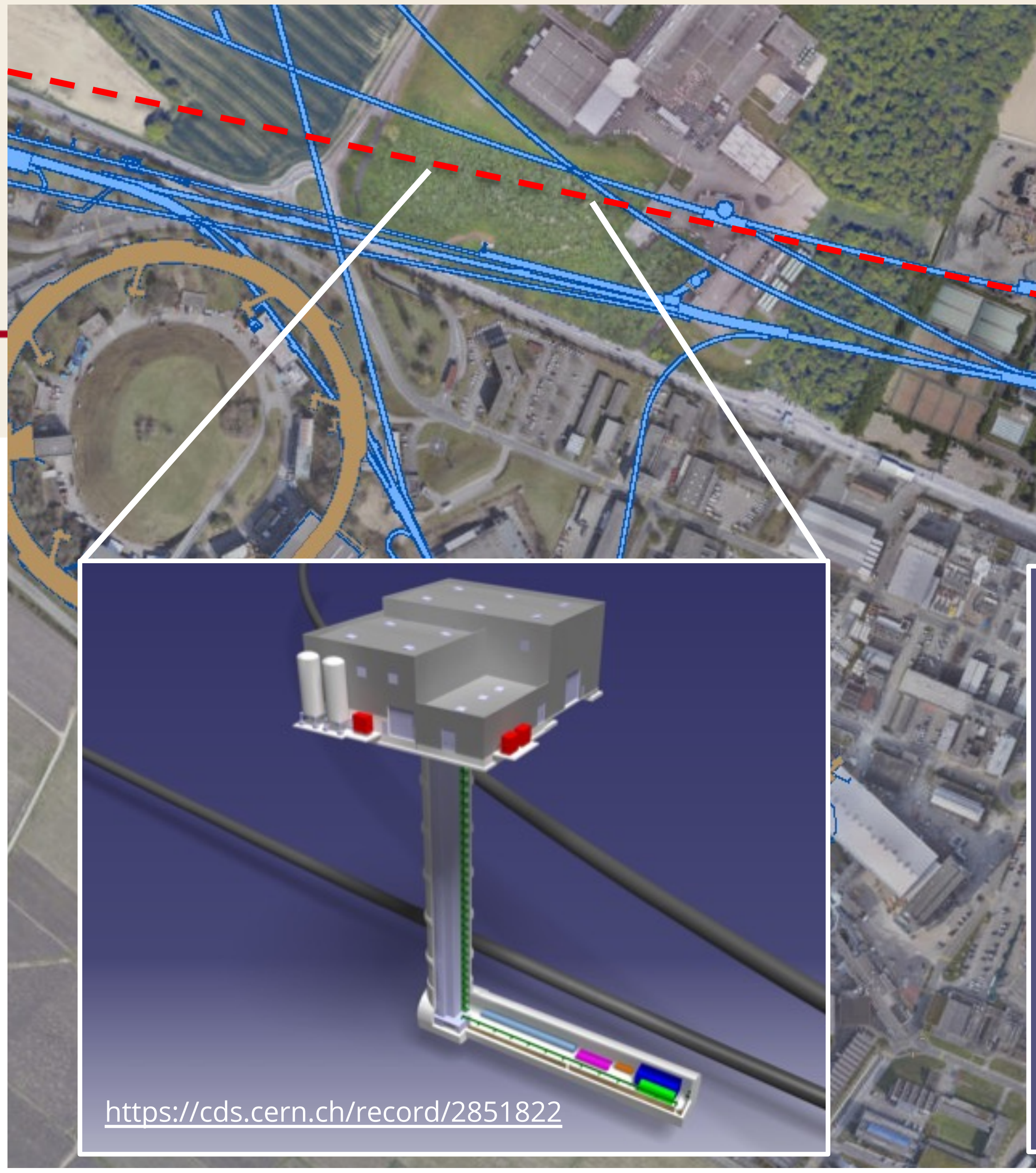
Delayed: Recommend construction but delayed to the next decade

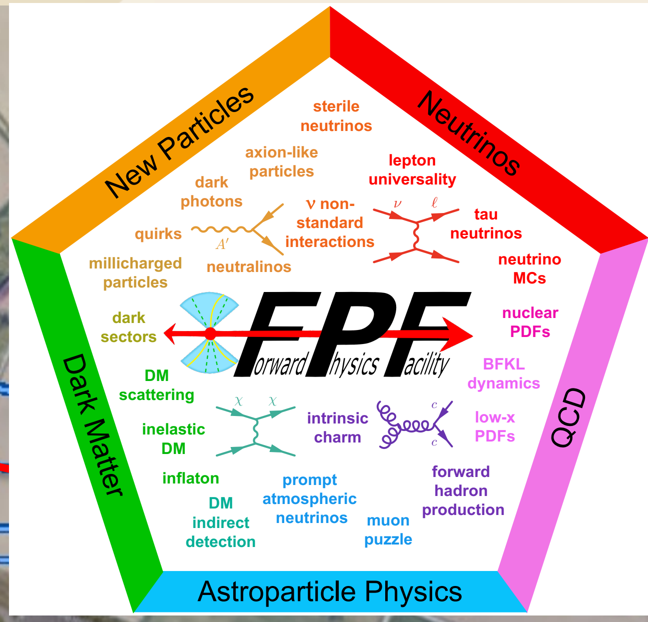
† Recommend infrastructure support to enable international contributions

Can be considered as part of ASTAE with reduced scope

US Construction Cost **$60–100M**

	Scenarios			Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints
SURF Expansion	N	Y	Y	P		P			
DUNE MCND	N†	Y	Y	P				S	S
MATHUSLA	N#	N#	N#			P		P	
FPF Trio	N#	N#	N#	P		P		P	

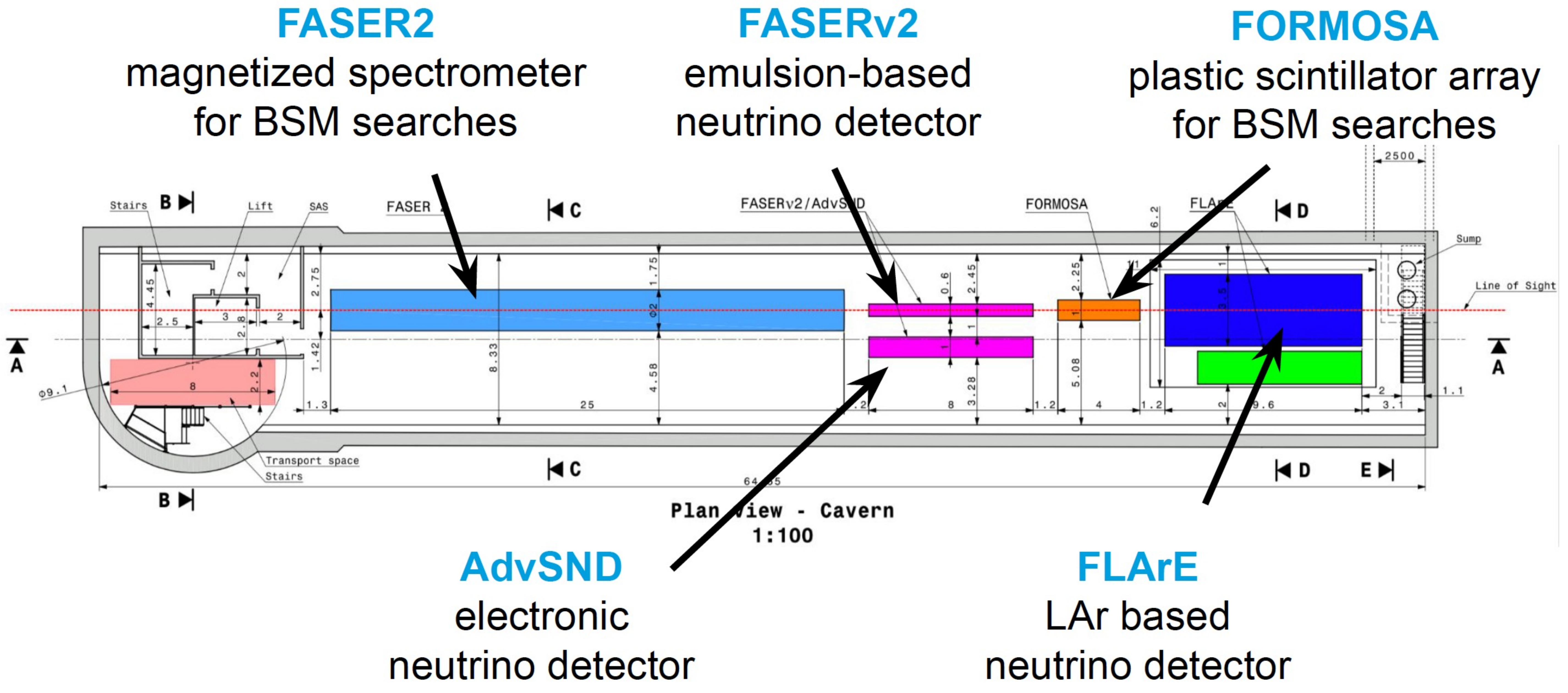




- The site is on CERN land in France
- The cavern is 65 m-long, 9 m-wide/high
- Shielded from ATLAS by 200m of rock
- Disconnected from LHC tunnel
- Vibration, safety studies: can construct FPF without disrupting LHC operations
- Radiation studies: can work in FPF while LHC is running (HL-LHC starts 2029)

Forward Physics Facility (FPF)

Builds on FASER concept to create a multipupose facility



What Didn’t Fare Well

Figure 2 – Construction in Various Budget Scenarios

Index: Y: Yes N: No R&D: Recommend R&D only C: Conditional yes based on review P: Primary S: Secondary

Delayed: Recommend construction but delayed to the next decade

† Recommend infrastructure support to enable international contributions

Can be considered as part of ASTAE with reduced scope

US Construction Cost **$60–100M**

Scenarios				Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints
SURF Expansion	N	Y	Y	P		P			
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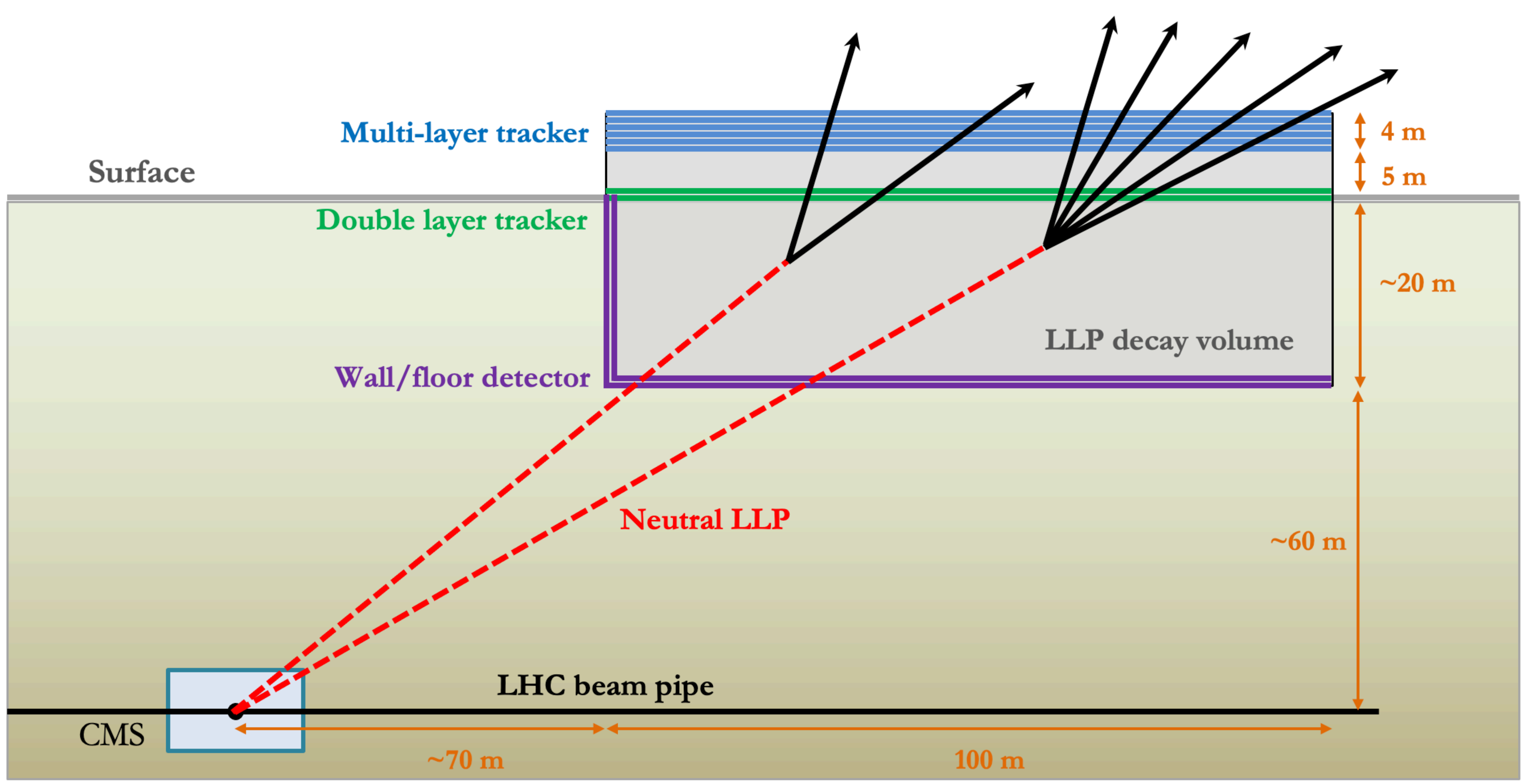
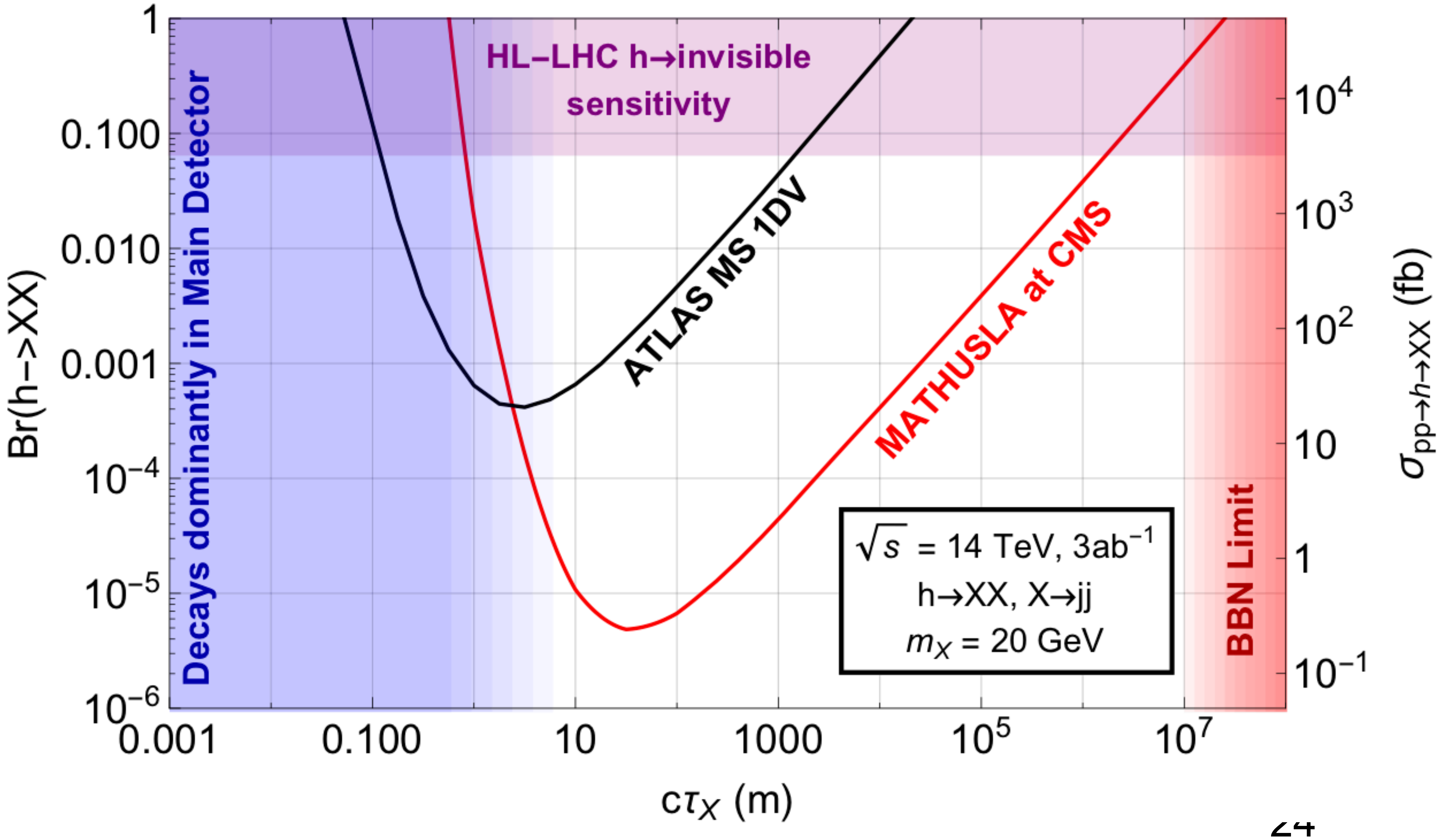
Forward Physics Facility (FPF)

Builds on FASER concept to create a multipupose facility

MATHUSLA

Large apparatus on surface above CMS to look for long-lived particles





DOE Response to P5

R. Rameika @HEPAP / M. Procario @DPF/Pheno

SLAC

ASTAE

- From P5 Report recommendation #3 : *Implement a new small-project portfolio at DOE,* ***Advancing Science and Technology through Agile Experiments (ASTAE)****, across science themes in particle physics with a competitive program and recurring funding opportunity announcements. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP.*
- DOE response and actions:
  - DOE will initiate fabrication of 1-3 DMNI projects
    - 5 projects remain under consideration
  - The key word for new projects is AGILE.
- P5's call for agile implies that we should complete these experiments quickly, and shift course when it comes time to start new ones.
  - 2 years for R&D, 2-3 for fabrication, 2-3 to operate, and then decommission.
    - This is still 6-8 years.
  - Start a new projects fabrication every year.

AGILE

HEP is developing a plan on how implement ASTAE. Using lessons learned from DMNI. What we have concluded so far.

This requires actions from DOE:

- Limit the number of reviews. Select a just few concepts at a time to develop into projects.
- Tailor the oversight to the size of the project.
- Provide adequate funding to complete the work on a technically limited schedule.
- Protect the budget envelope for the program.

And the community:

- Concentrate R&D on the critical enabling technology.
- Do the necessary up-front planning
- Arrange for adequate resources be available when needed: engineering, procurement, etc.

DMNI Status

Concept	DM type	Mass range	Lead lab	Orig R&D request ($K)	R&D $K thru FY24	Est. Fab. cost ($M)
ADMX-EFR	Axions	9-17 μeV	FNAL	1,976	3,140	$20
DM-Radio	Axions	<μeV	SLAC	993	1,560	$24
LDMX	Hidden sector	10-300 MeV	SLAC	1,960	1,950	$21
OSCURA	WIMPs	1MeV-1GeV	FNAL	3,943	3,544	$15
TESSERACT	WIMPs	>10 MeV	LBNL	3,975	1,815	<$10
Total				12,847	12,309	$90

- These are the remaining DMNI proposals.
  - CCM at LANL was funded, fabricated and is operating.
- The French have funded a proposal to host TESSERACT.
- DOE has decided to fund TESSERACT starting in FY25 based on its cost effectiveness and the French offer to host.
  - These considerations made it the ideal concept to go next.
- We are still working on the process to select other DMNI proposals.
  - Most likely start will be in FY 26
- HEP will try to select 2 additional DMNI's to move to fabrication, with the rest folded into the ASTAE program competition. This will also allow new dark matter proposals to be considered.

DMNI Status

Concept	DM type	Mass range	Est. Fab. cost ($M)
ADMX-EFR	Axions	9-17 μeV	$20
DM-Radio	Axions	<μeV	$24
LDMX	Accelerator-produced DM particles	< 1 GeV	$21
OSCURA	particles	1MeV-1GeV	$15
TESSERACT	particles	>10 MeV	$10
SUM			**90**

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Parting Thoughts

We have reached a point where there is too much going on to discuss in a single talk! Even hitting only highlights, this became very long, very fast.

Small experiments, especially those aimed at dark sectors are overall doing well. The ASTAE recommendation will help.

Things to be mindful of:

- Visibles: LHCb may finally be coming
- Dark Matter: NA64 is chipping away, other efforts are still on the horizon

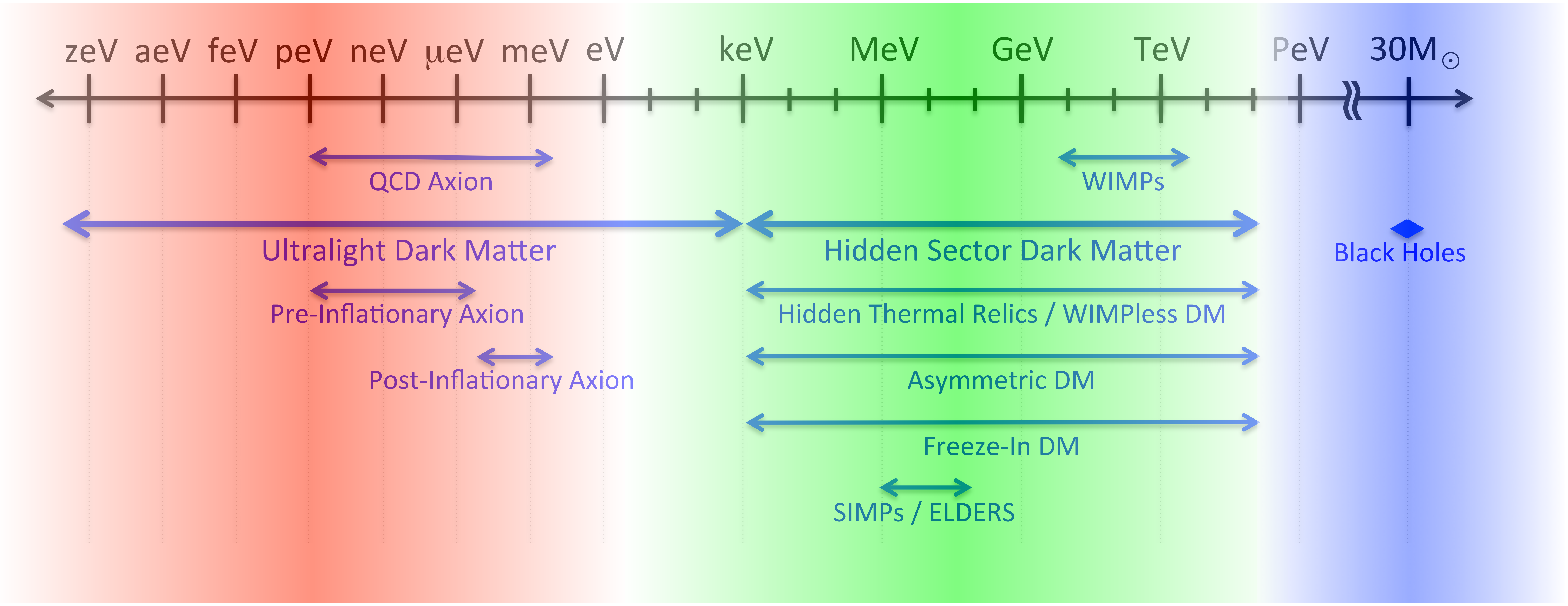
Extras

Dark Matter Landscape

SLAC

Everything we know about the mass of Dark Matter arXiv:1707.04591 **[hep-ph]**

too diffuse



too lumpy

wave-like

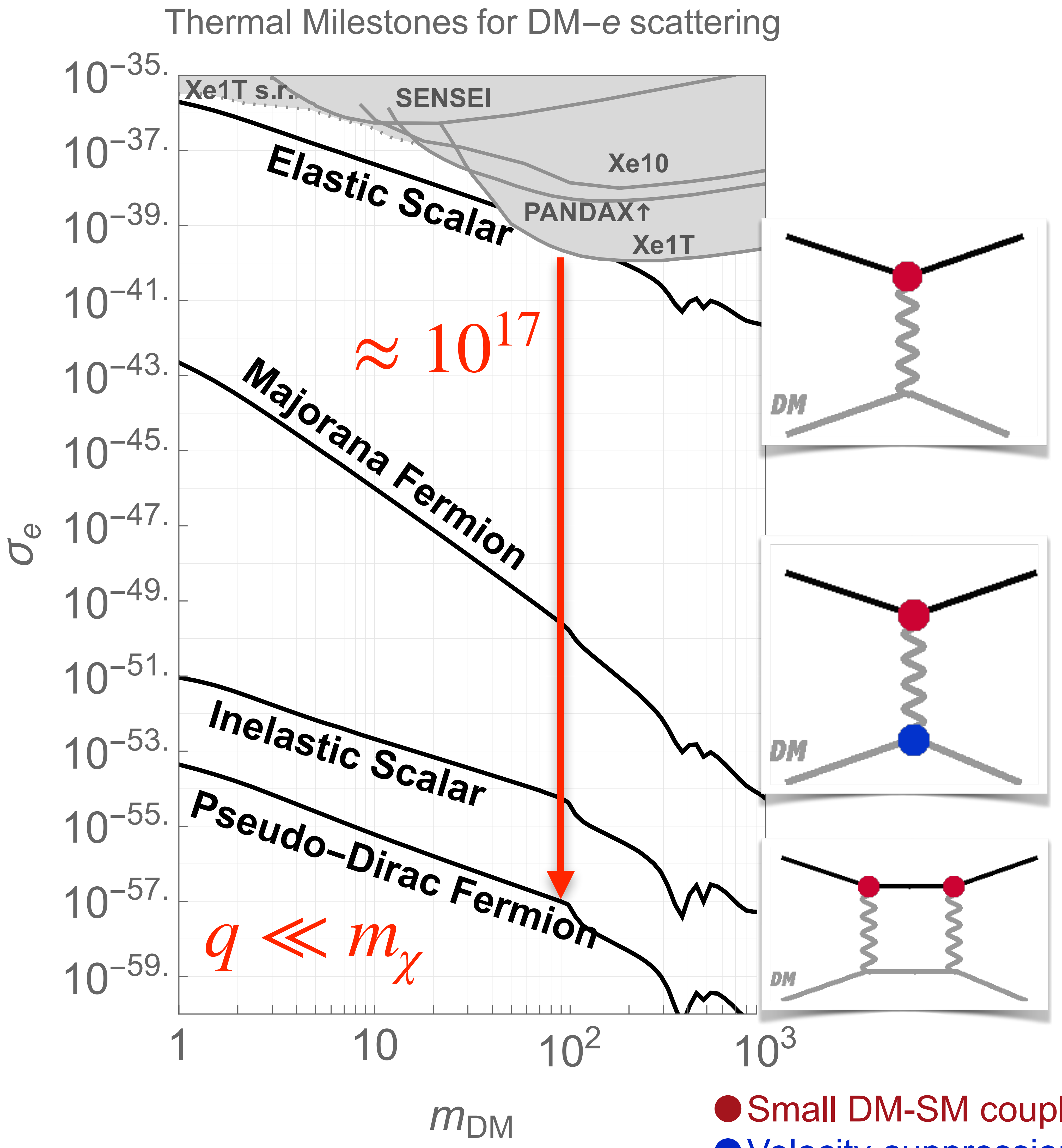
particle-like

star-like

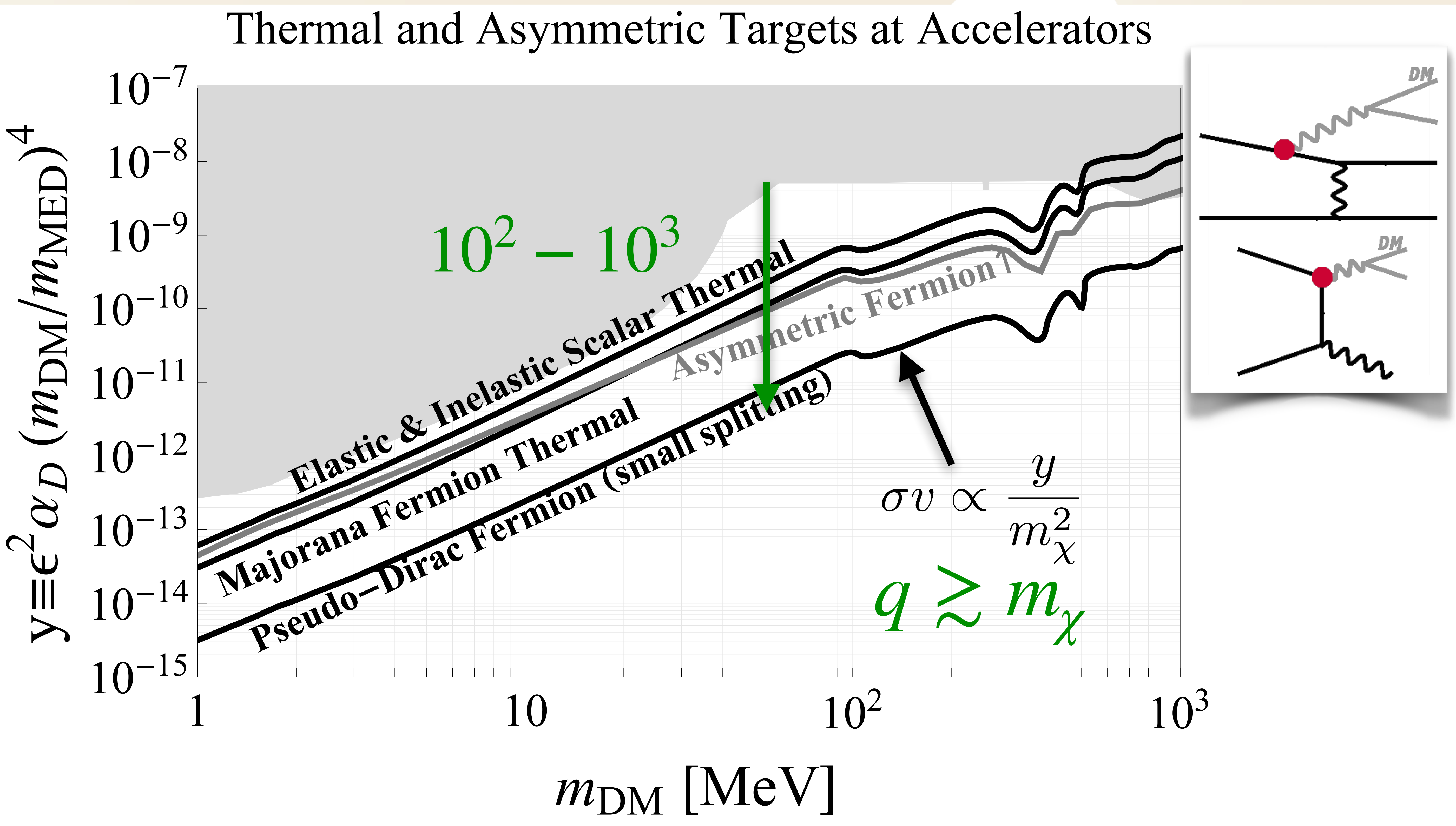
Thermal relics are an important class of dark matter where sub-GeV region is still relatively unexplored.

Concrete Example:
Dark Photon Mediator

SLAC



● Small DM-SM coupling
● Velocity-suppression



relativistic production ⇒ no suppression

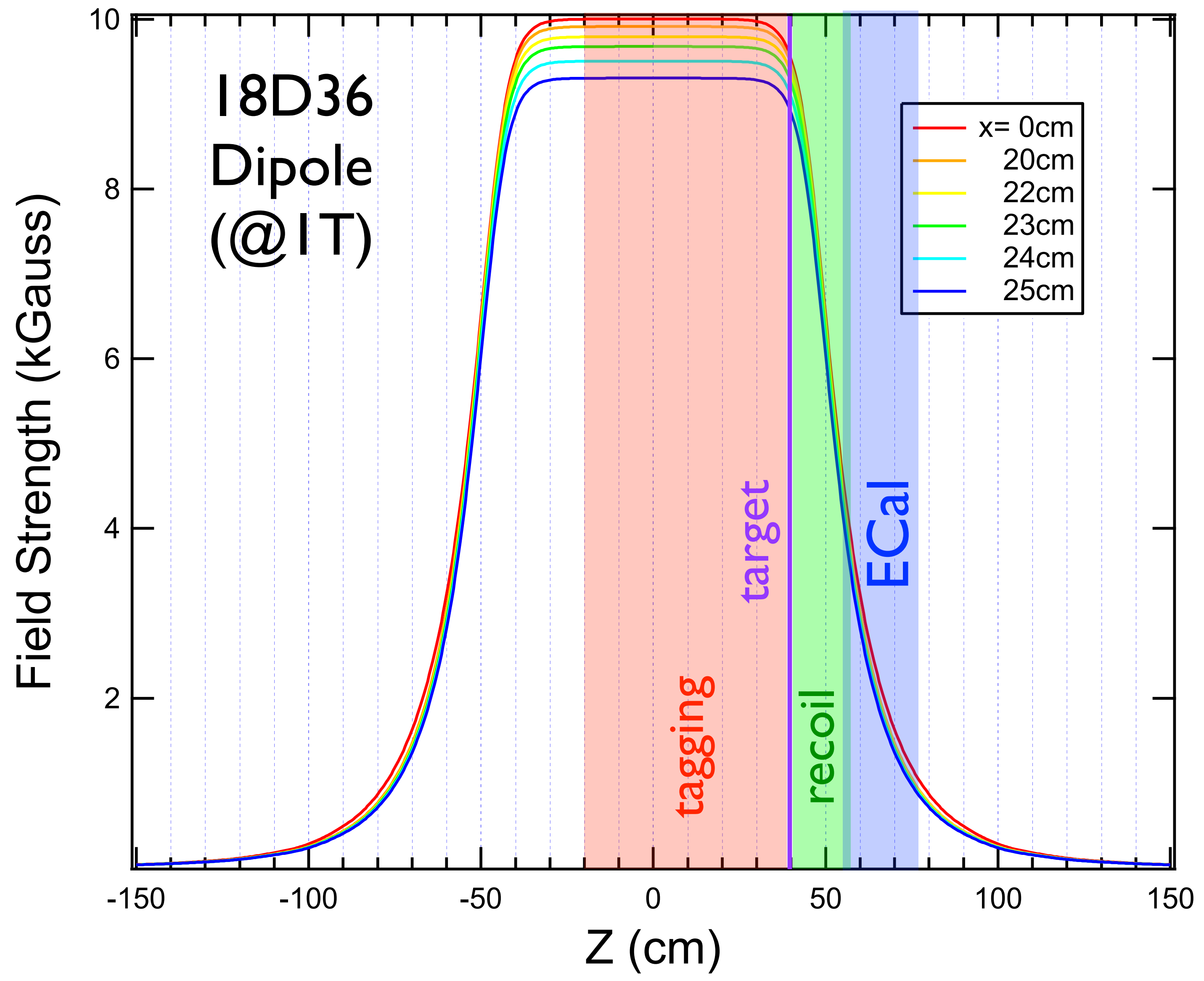
MeV-GeV freeze-out thermal relics are the "killer application" for accelerator searches.

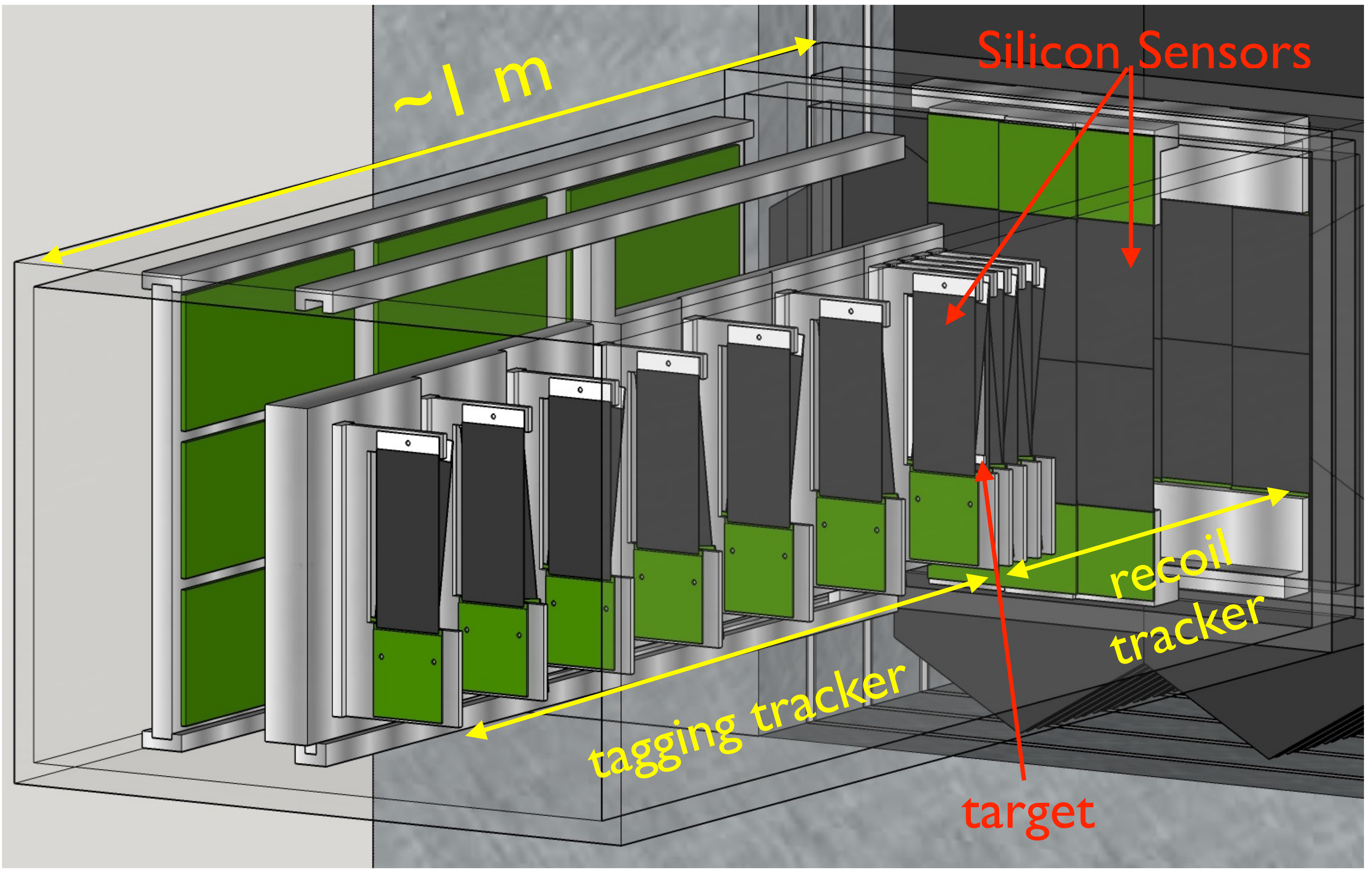
"Big Idea 1" of Snowmass RF6

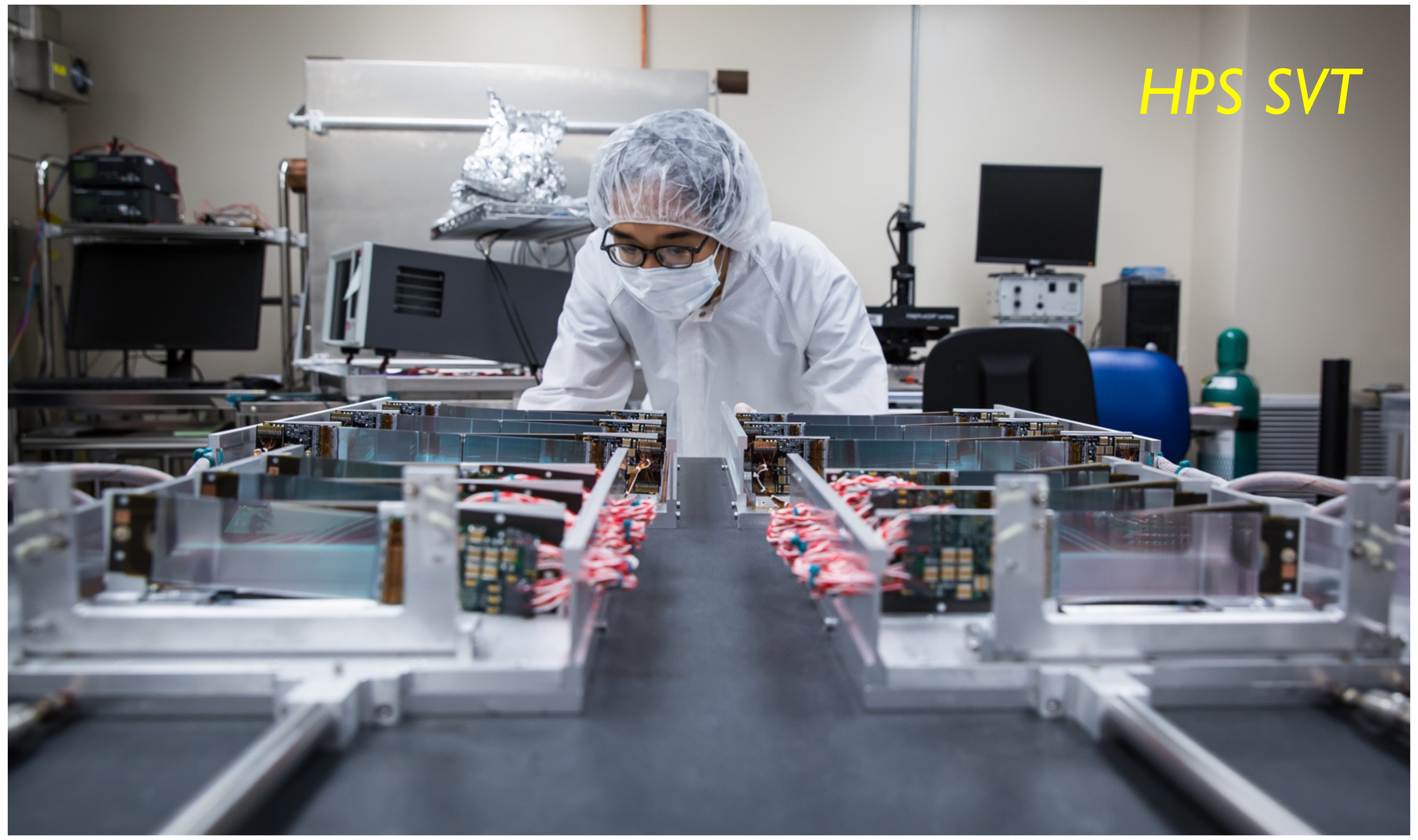
LDMX Detector Subsystems

Tracking based on HPS (orig. CMS)

- refurbish existing dipole
- reuse HPS designs for detector modules and readout







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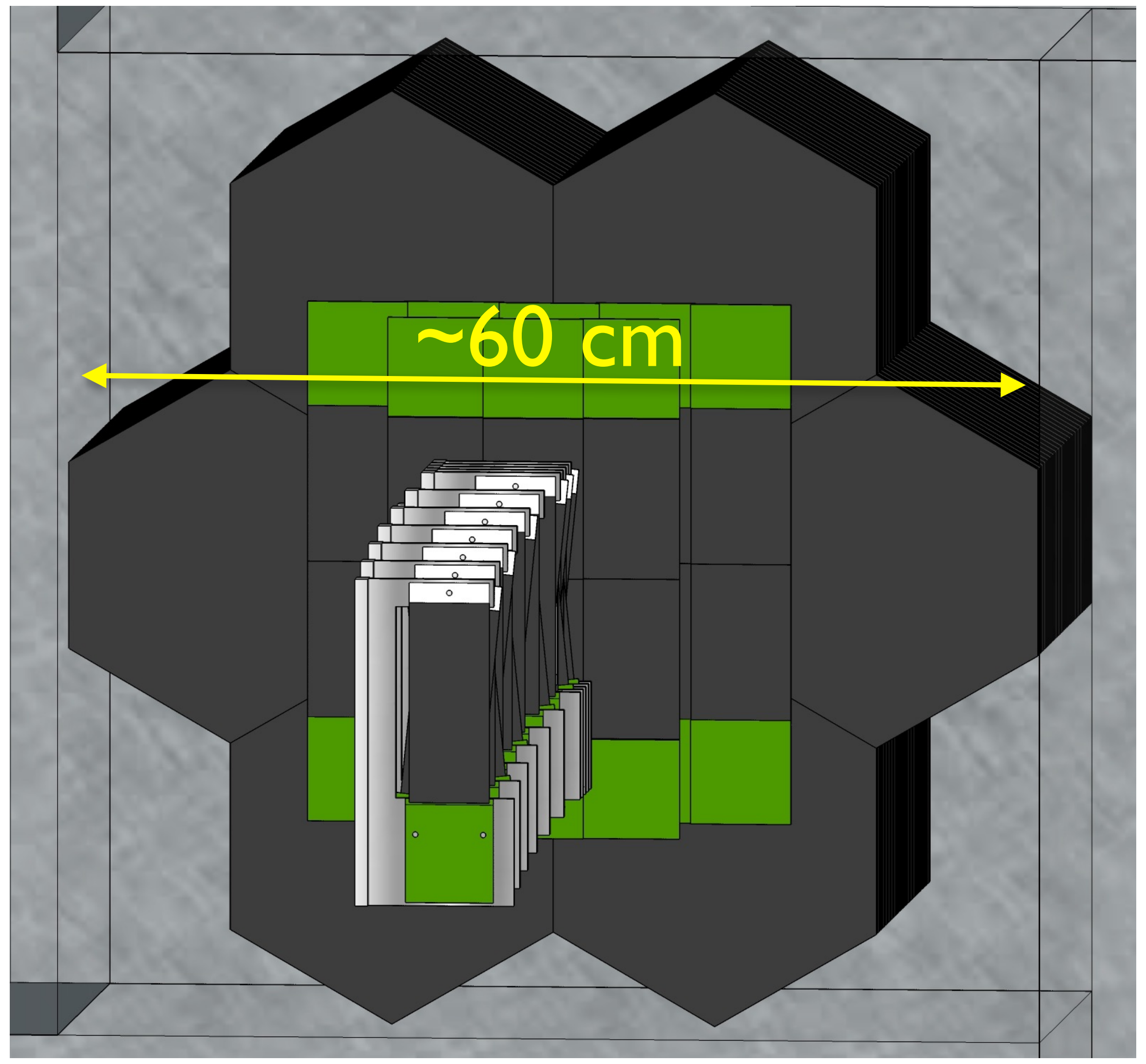
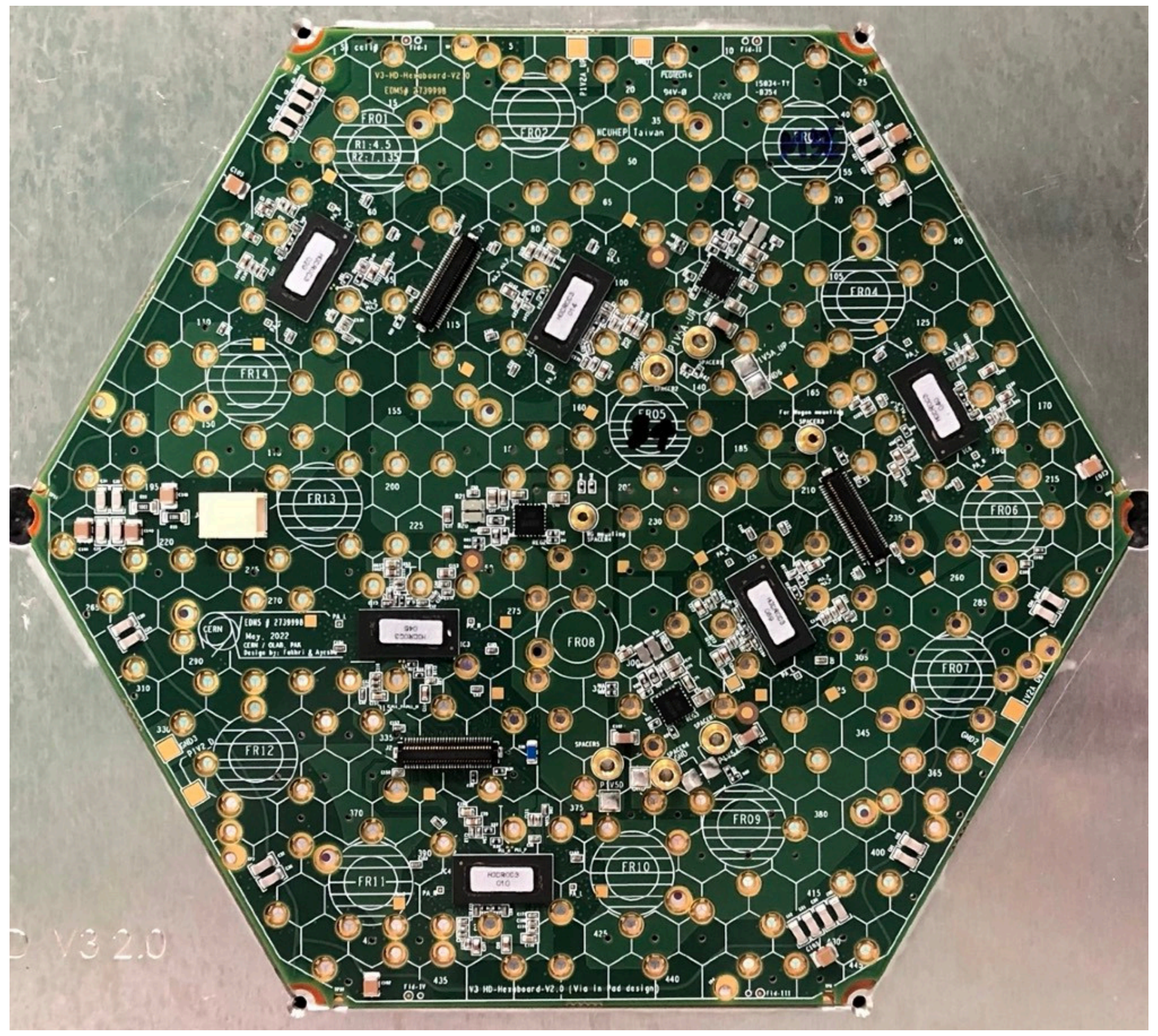
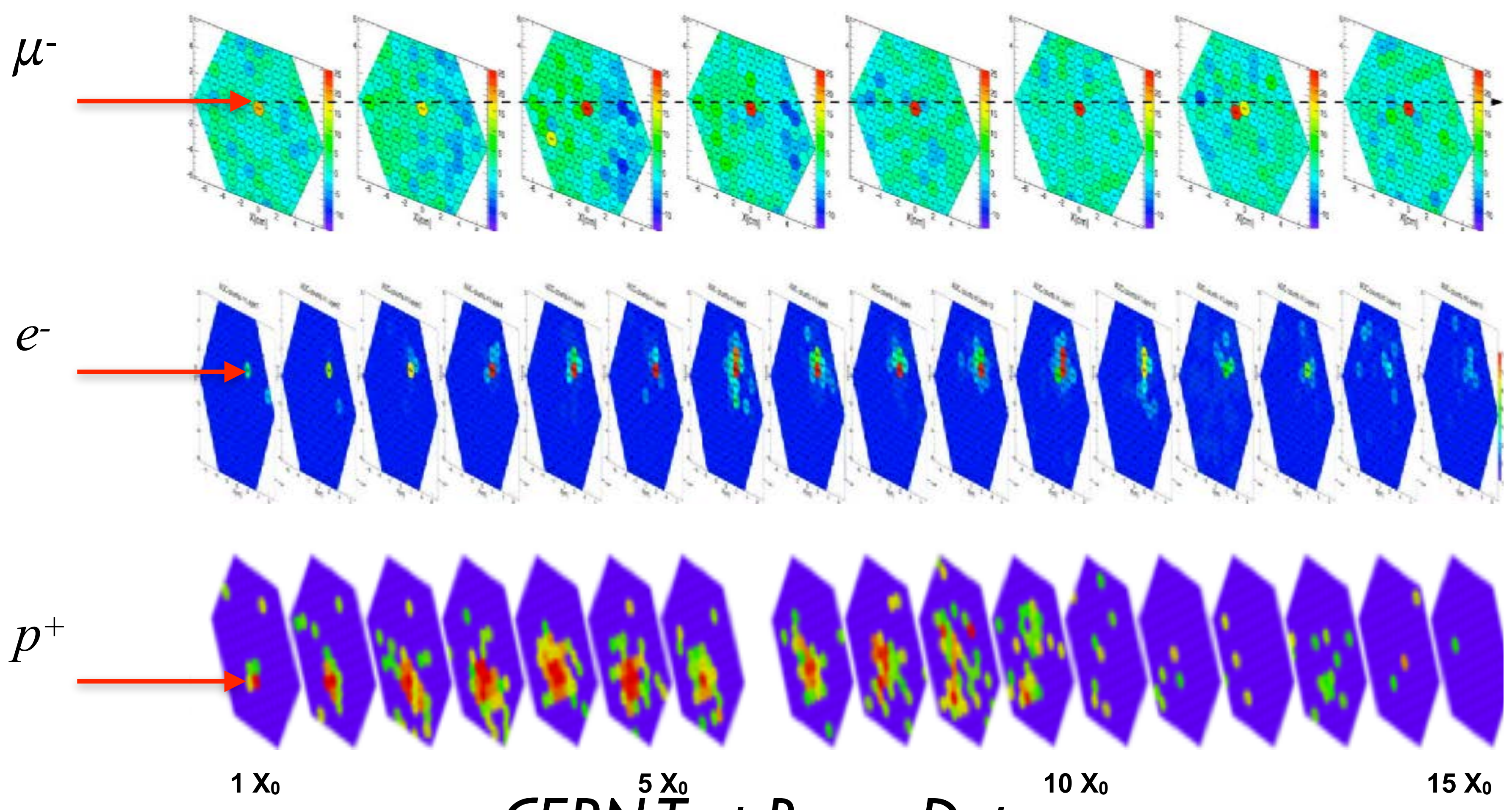
- silicon/tungsten High Granularity Calorimeter for Phase 2 upgrade
- powerful for rejection of rare backgrounds

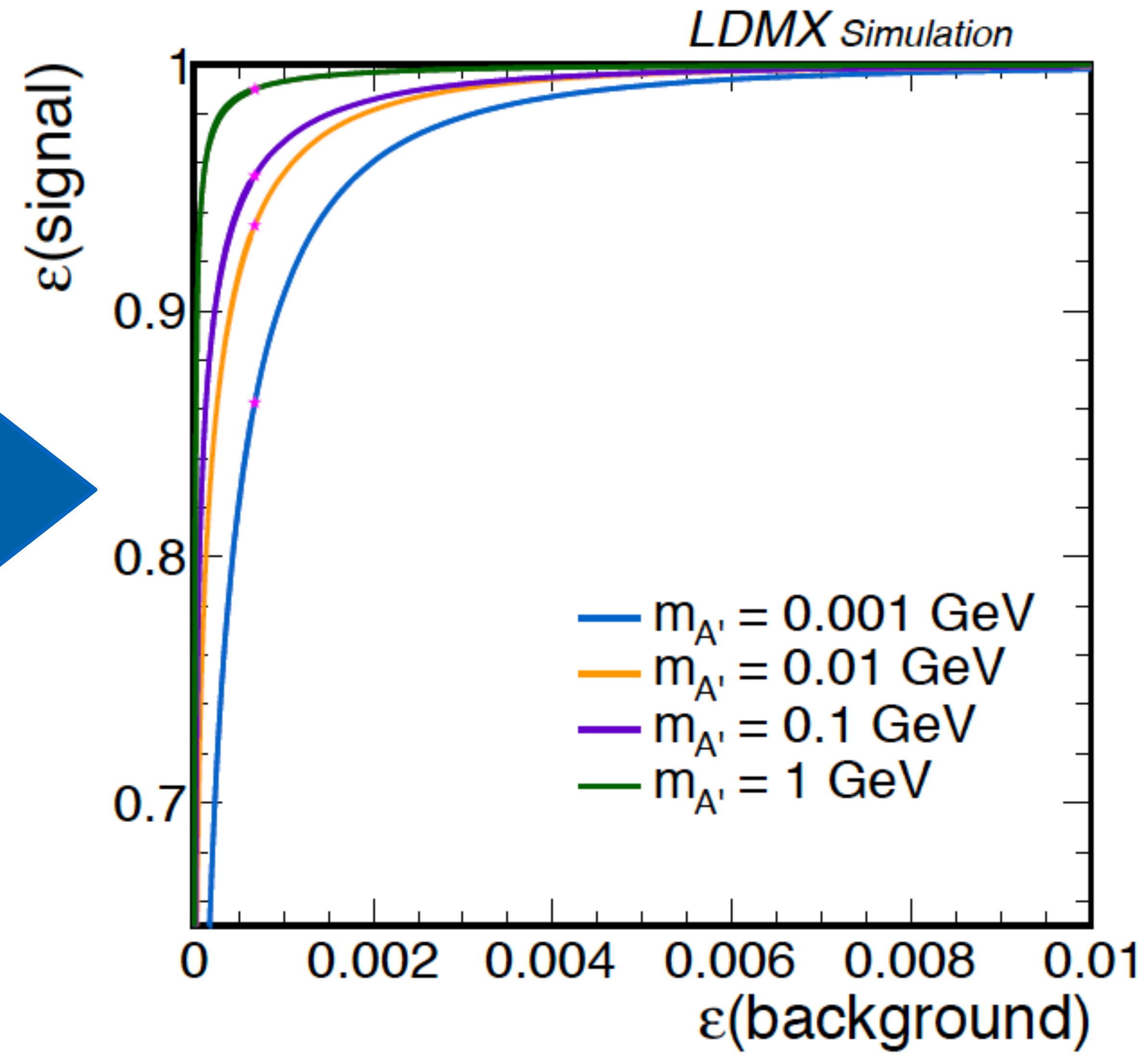






CERN Test Beam Data

Boosted Decision Tree



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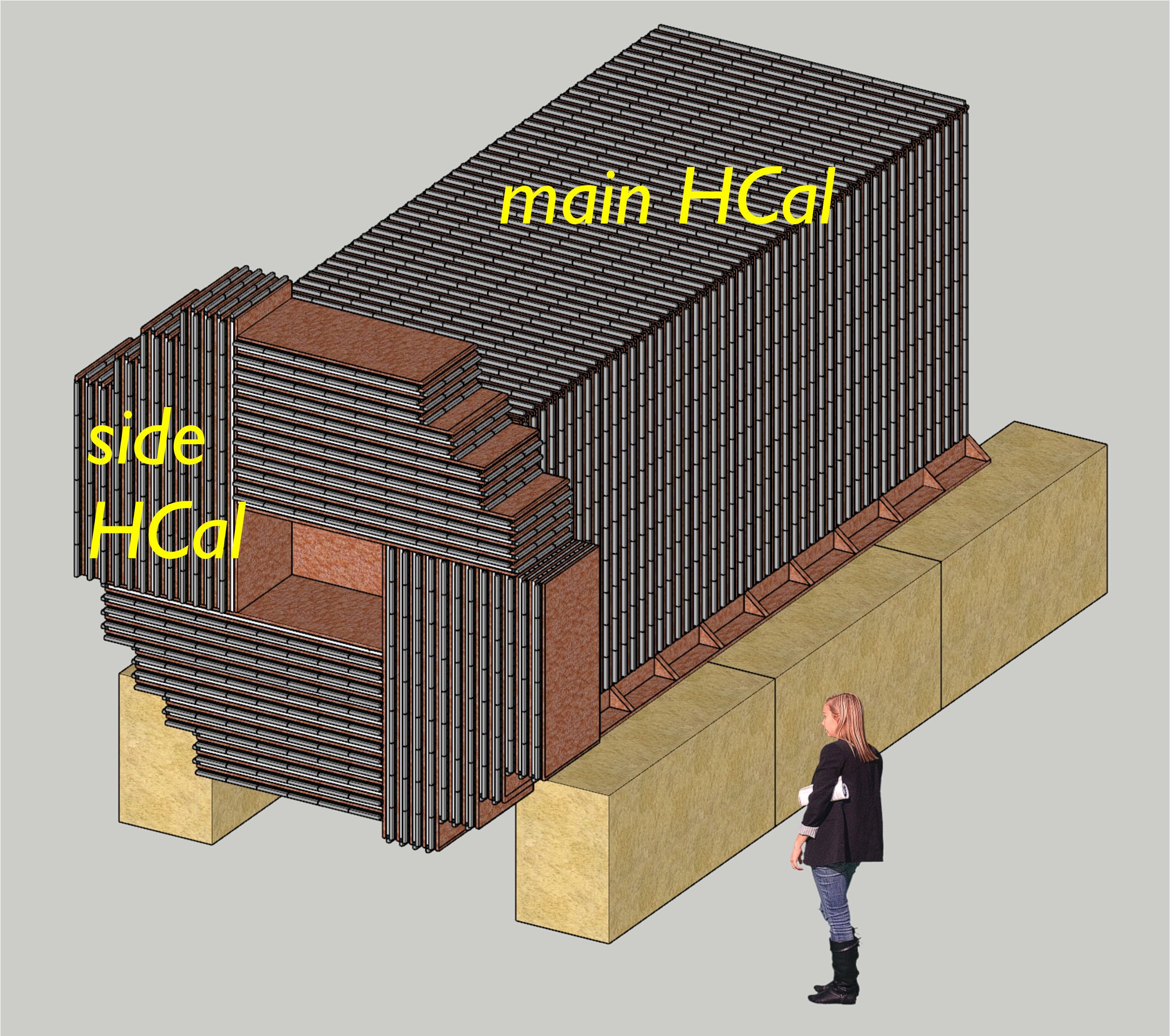
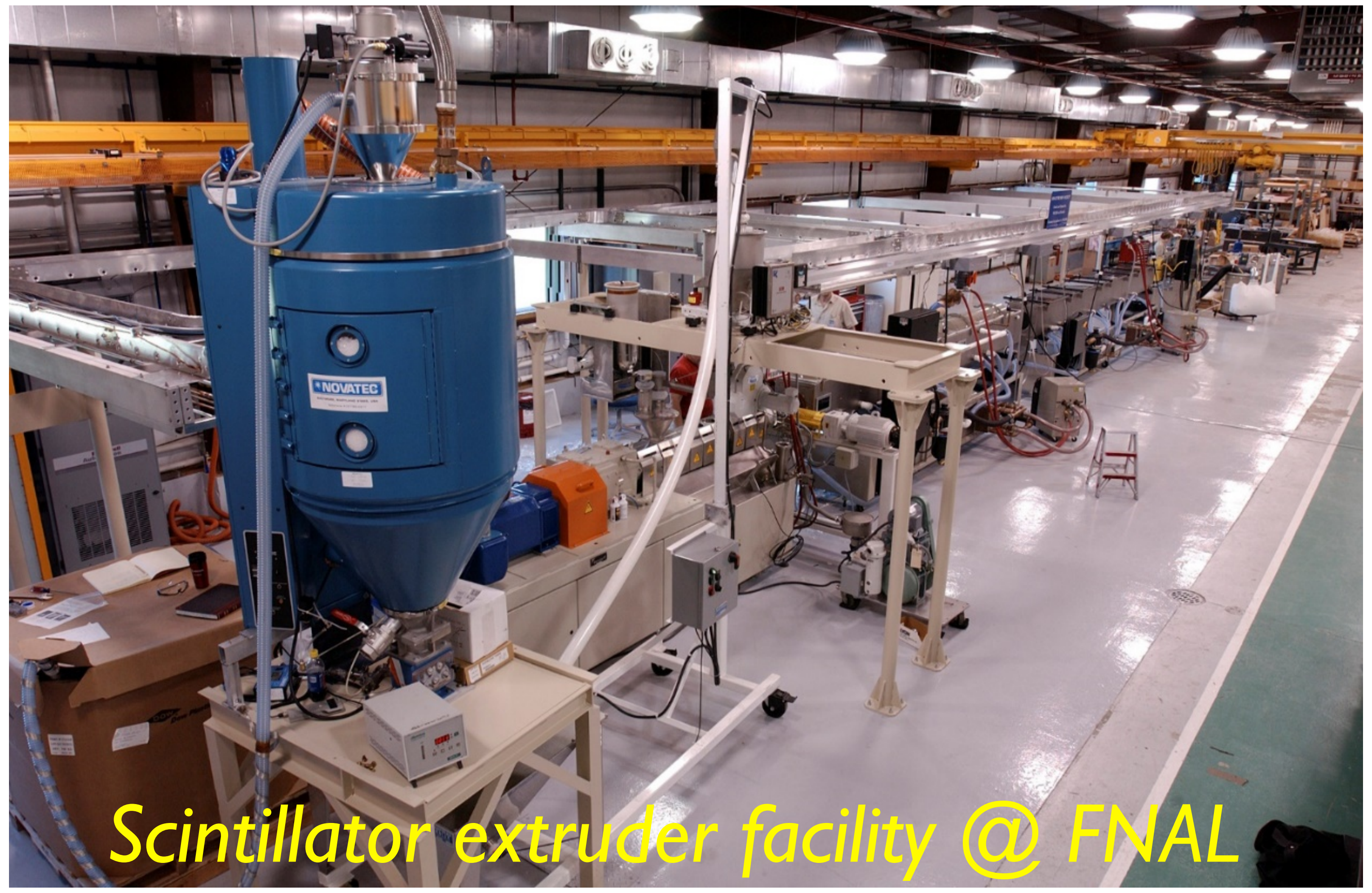
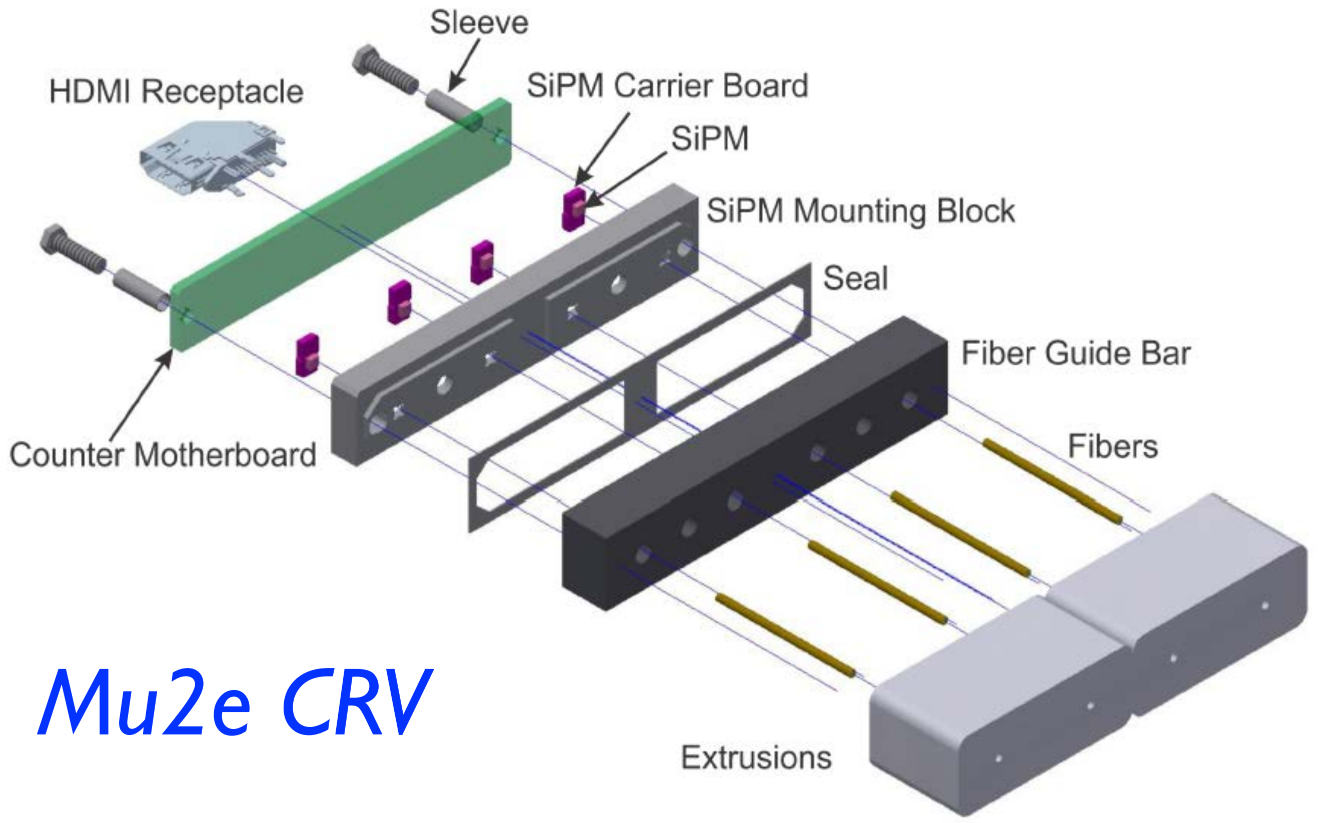
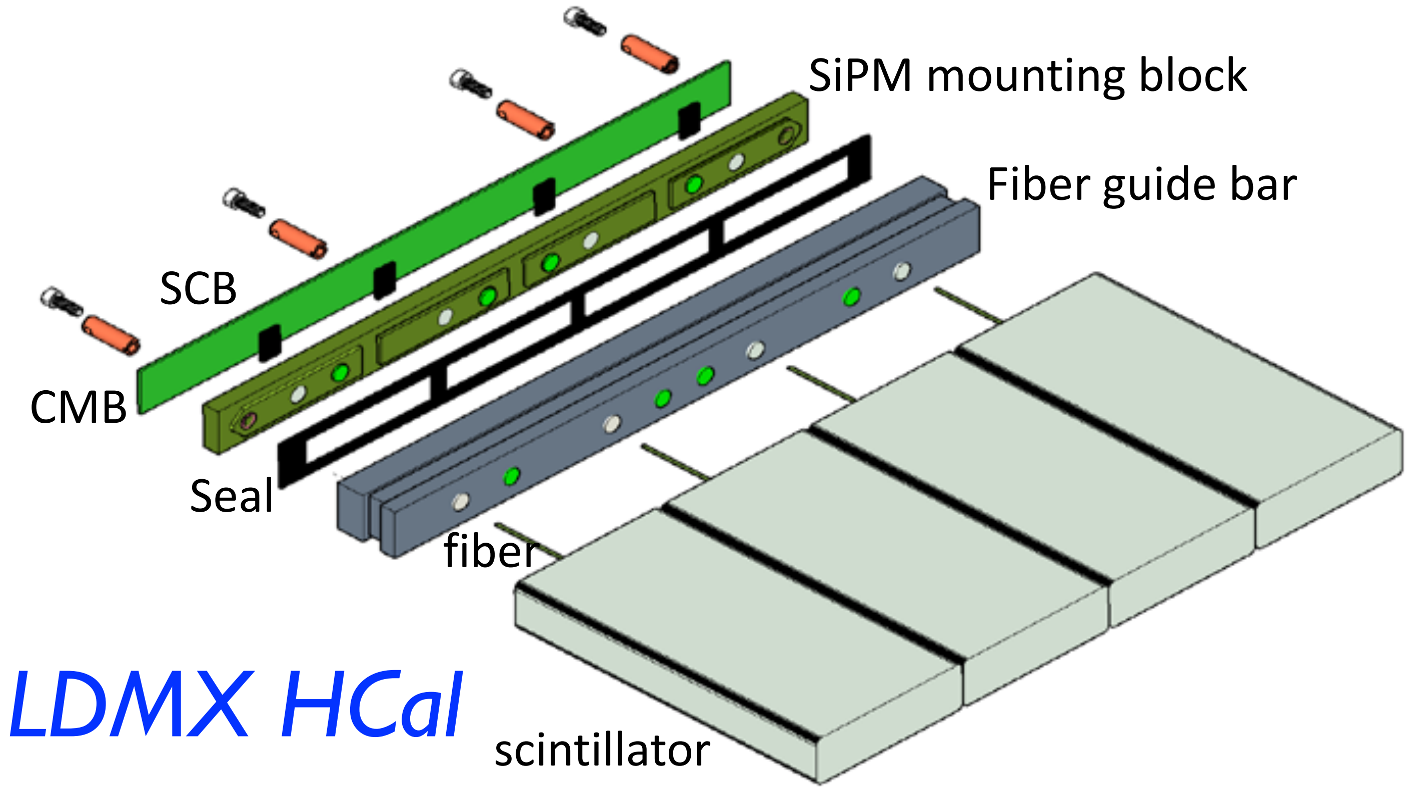
- extruded plastic scintillator/iron
- low veto threshold for neutrons







Mu2e CRV



LDMX HCal

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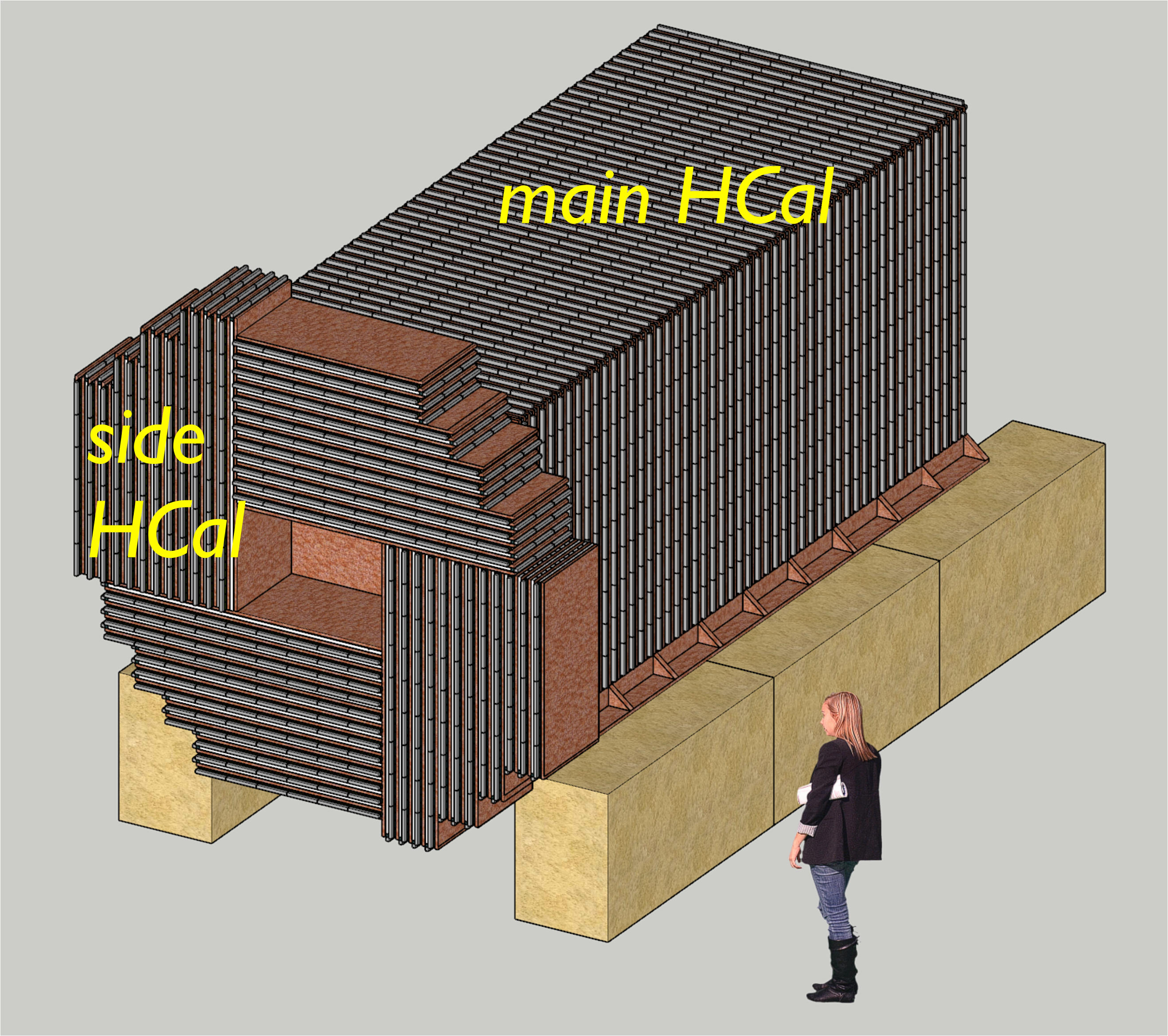
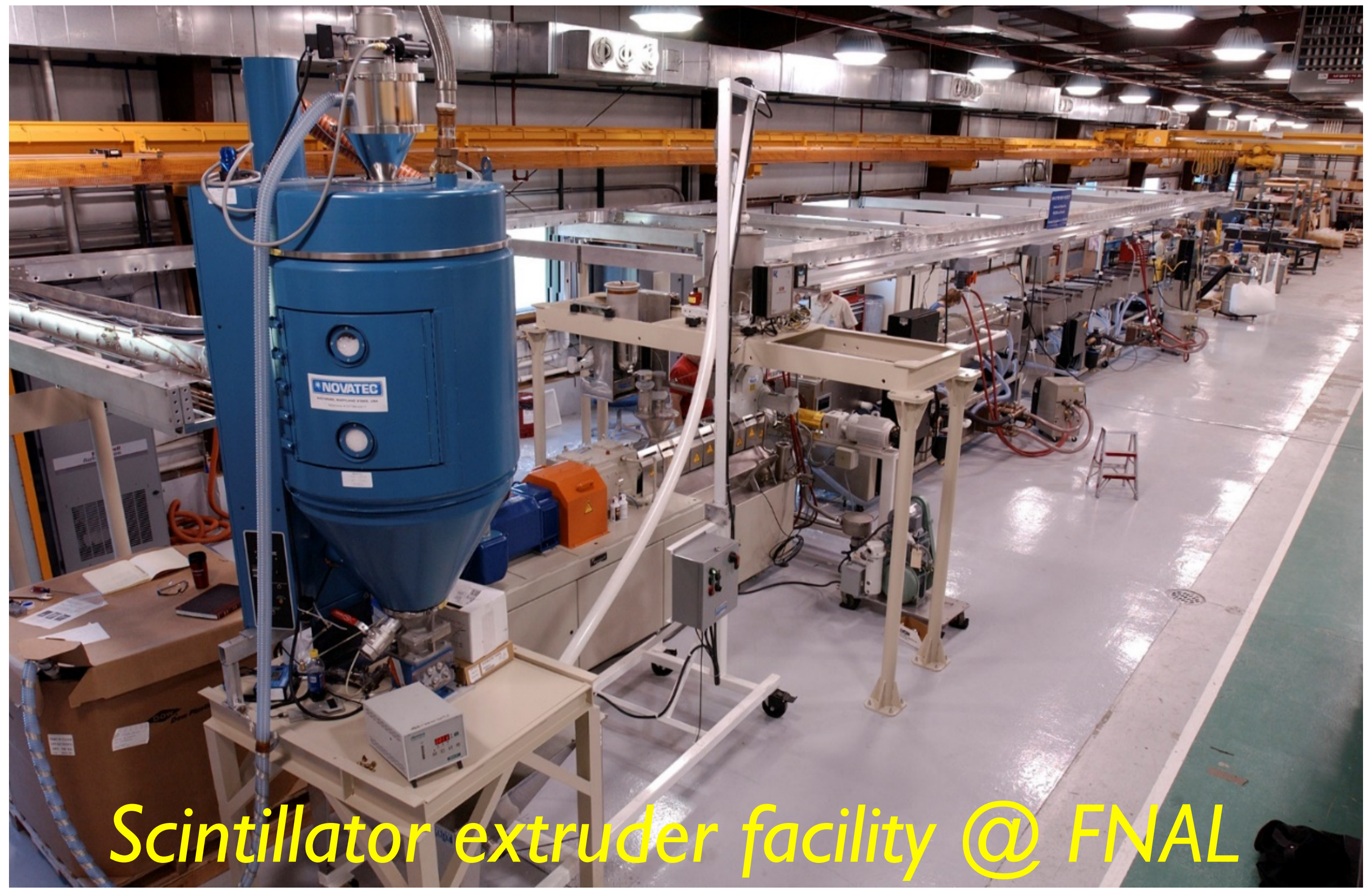
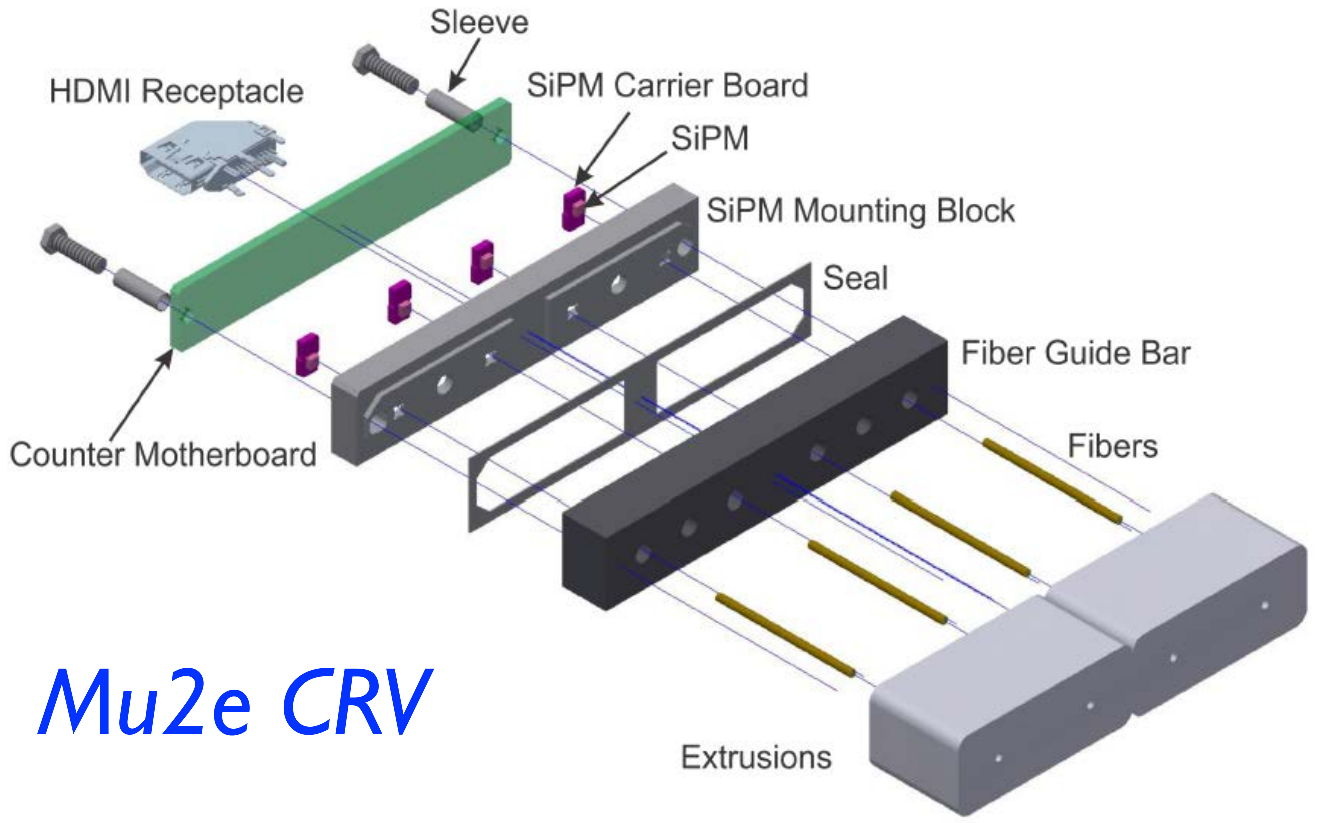
re-using existing technologies, LDMX is inexpensive, shovel ready







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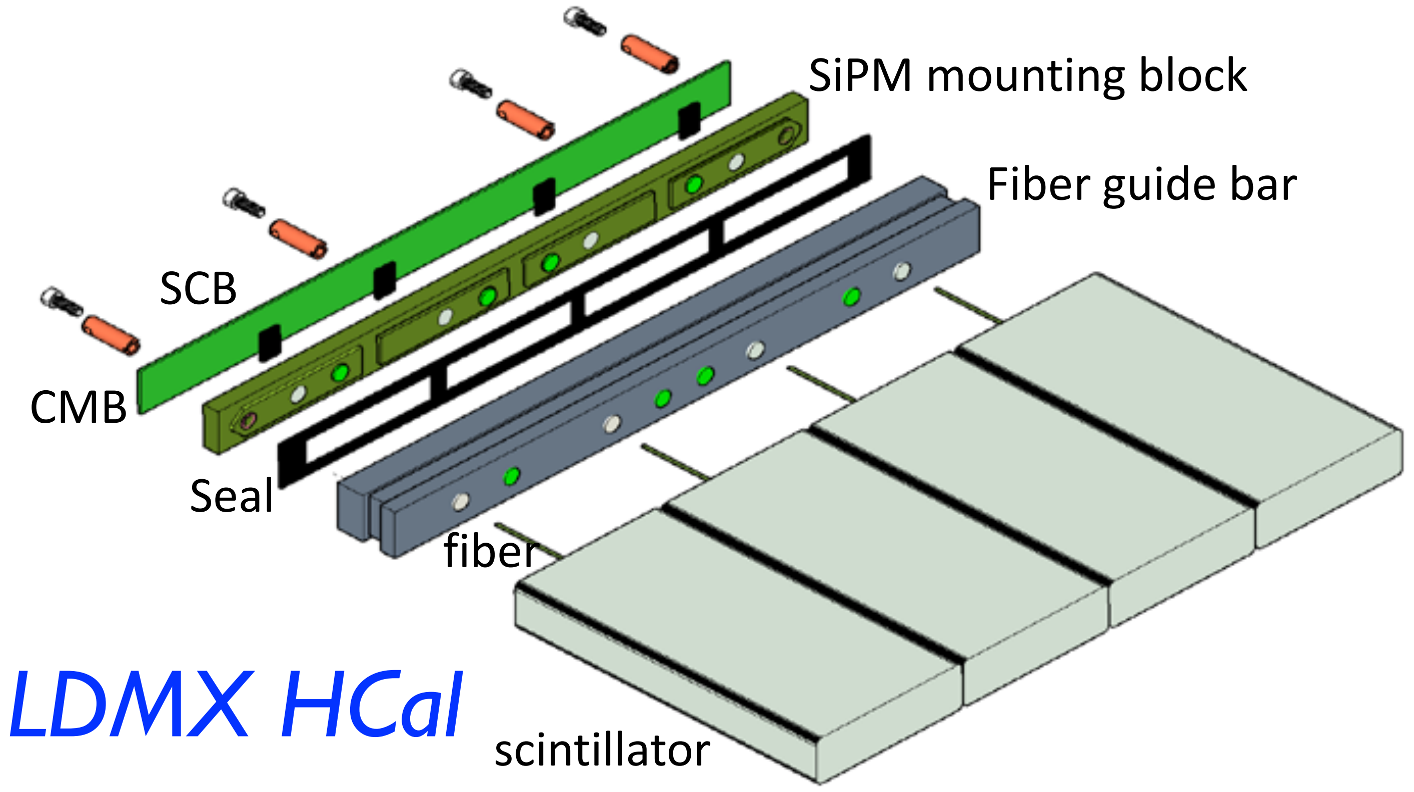


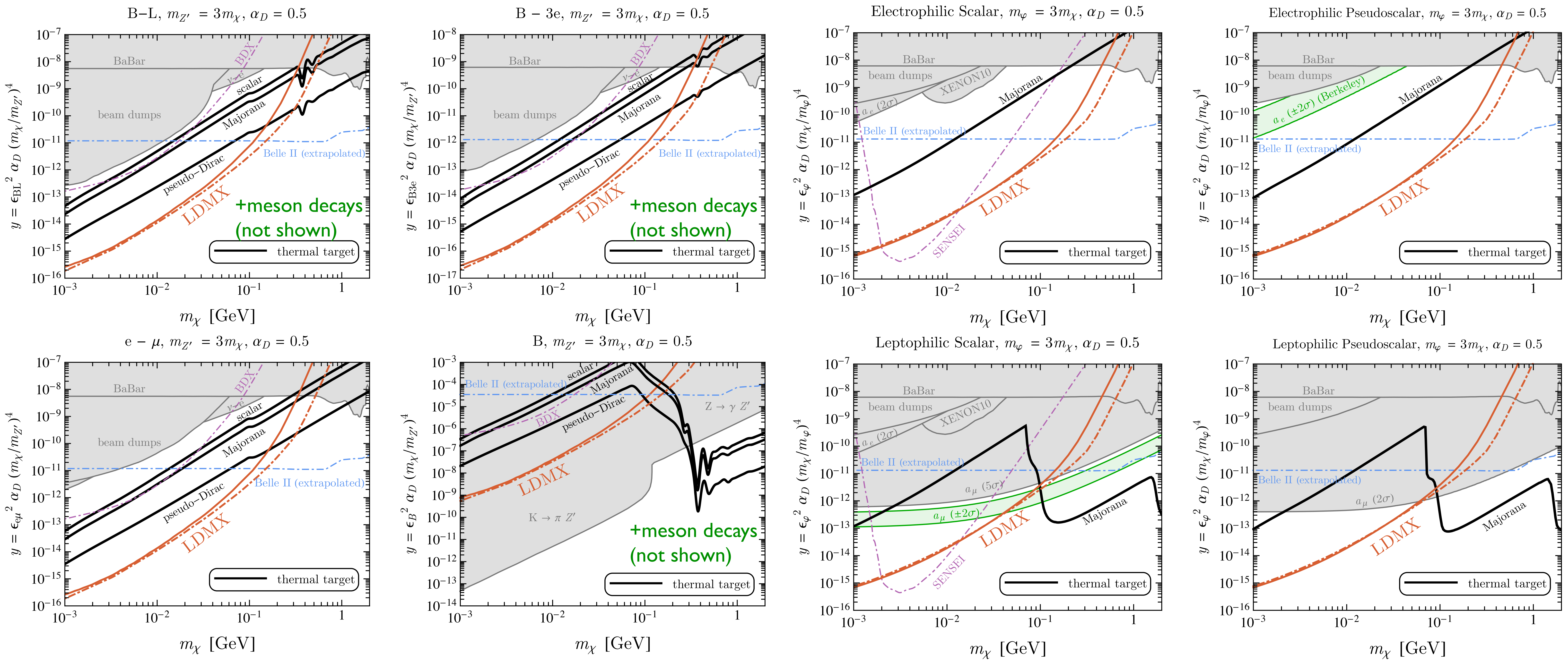
LDMX HCal

LDMX: Broader Physics Case

(other examples in backup)

Invisible Signatures

- different mediators →



- milicharged particles: arise from ~massless dark photons and thrust into spotlight by EDGES anomaly
- inelastic Dark Matter (iDM): large mass-splittings in dark states
- Strongly Interacting Massive Particles (SIMPs): a confining interaction in the dark sector (both visible and invisible signatures)
- freeze-in DM

Visible Signatures

- Dark Photons
- Axion-like particles (ALPs)

arXiv:1807.01730 [hep-ph]
Phys. Rev. D 99, 075001 (2019)

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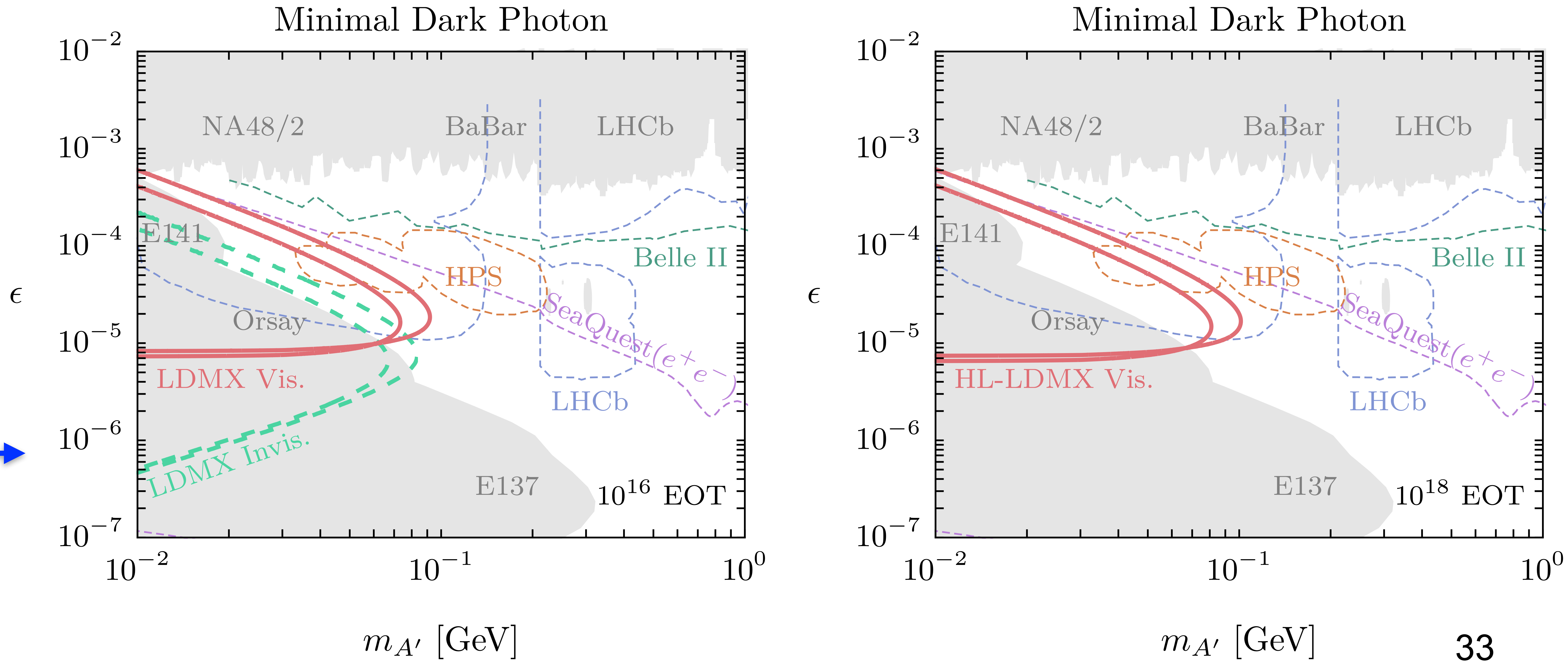

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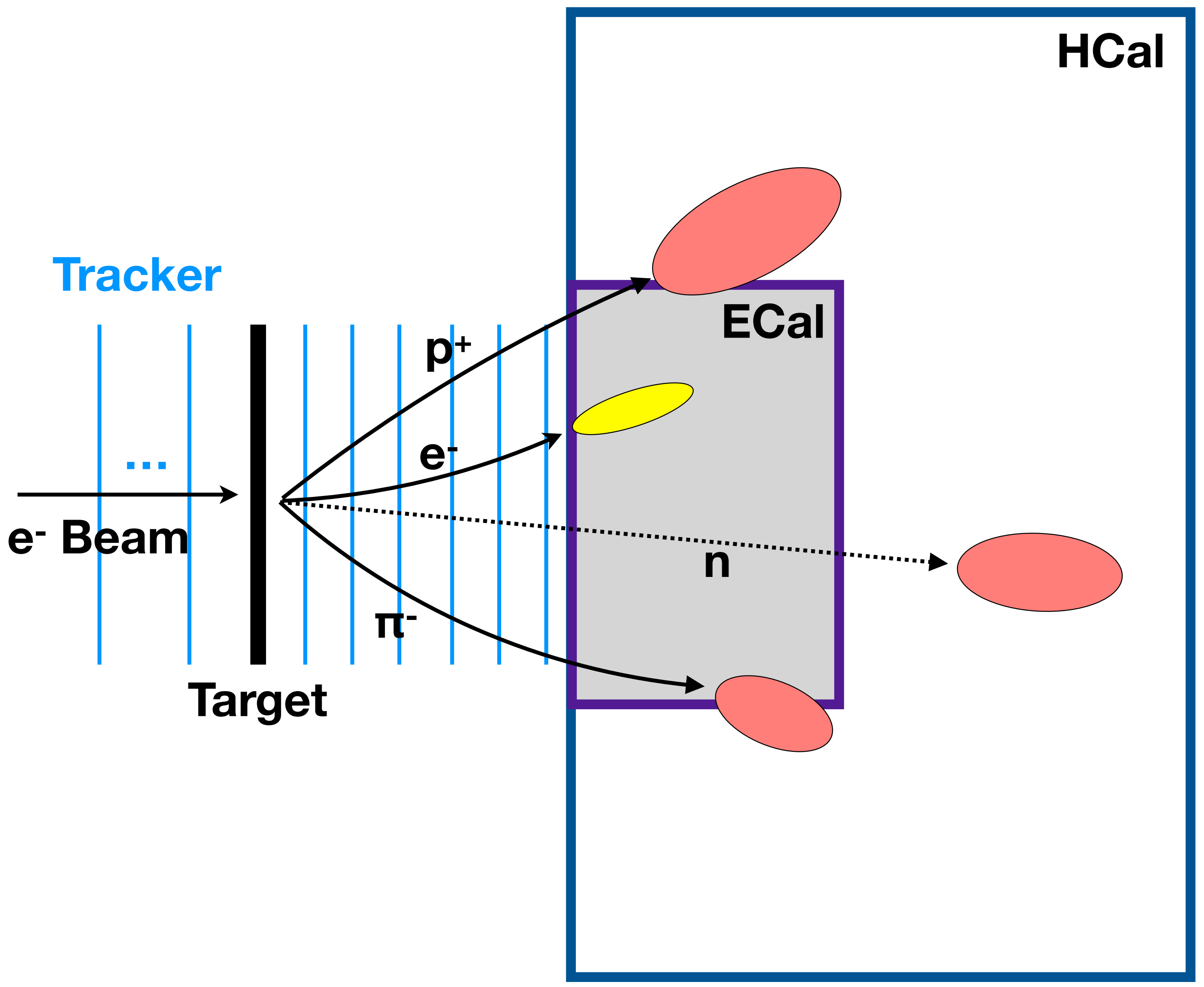
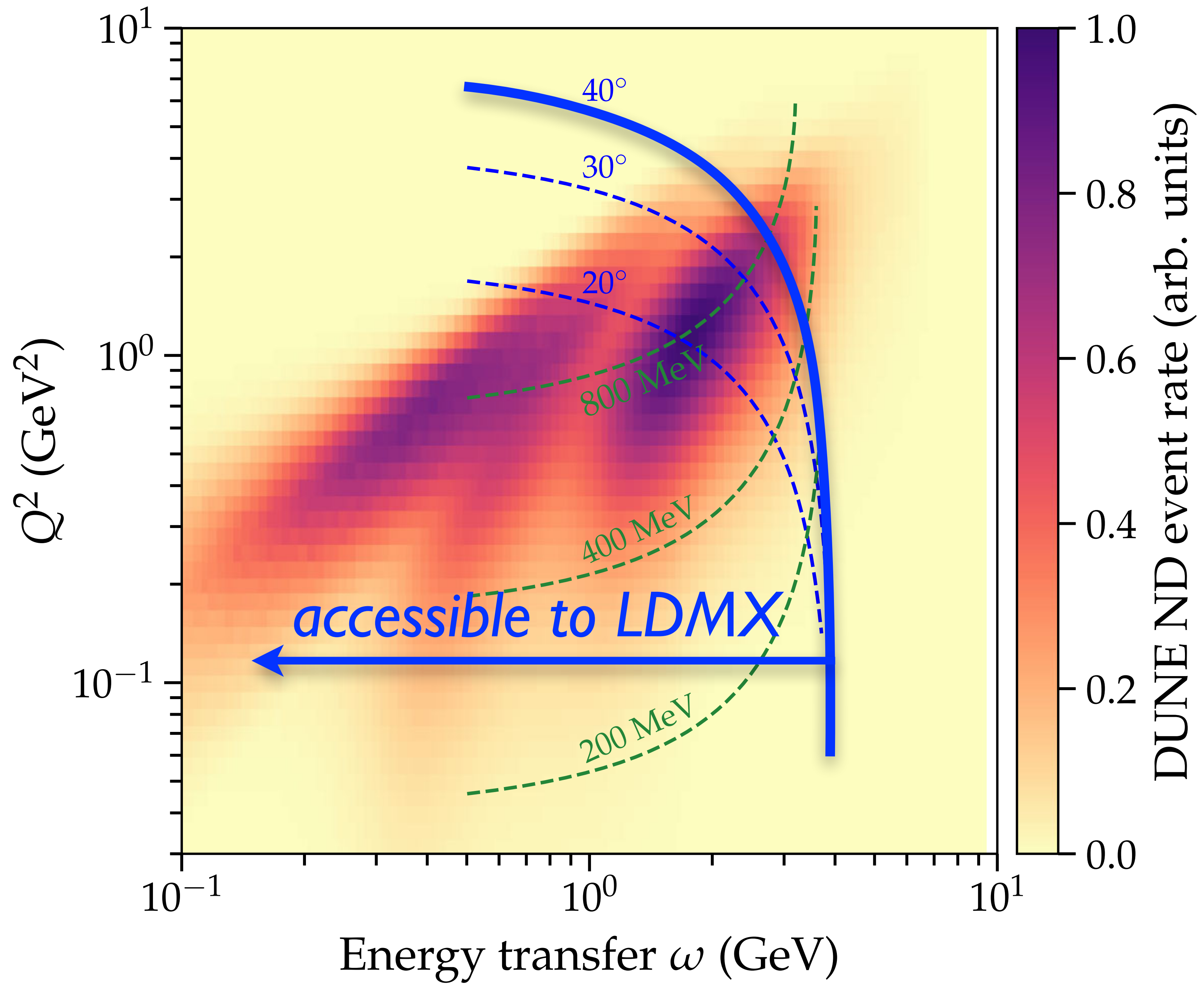
LDMX also enables measurements of electron-nucleon cross-sections that would be critical to the neutrino program





PHYSICAL REVIEW D 101, 053004 (2020)

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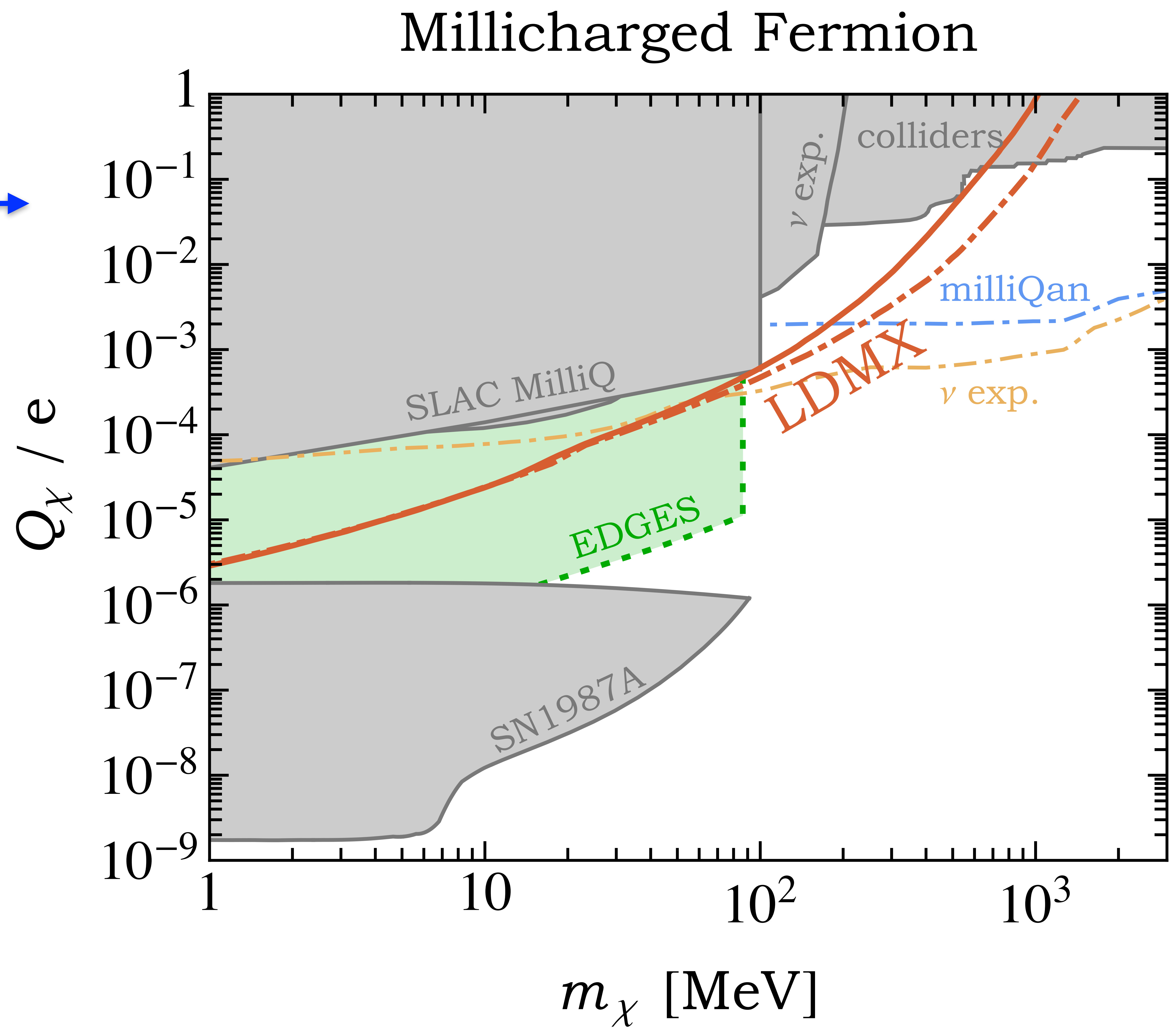

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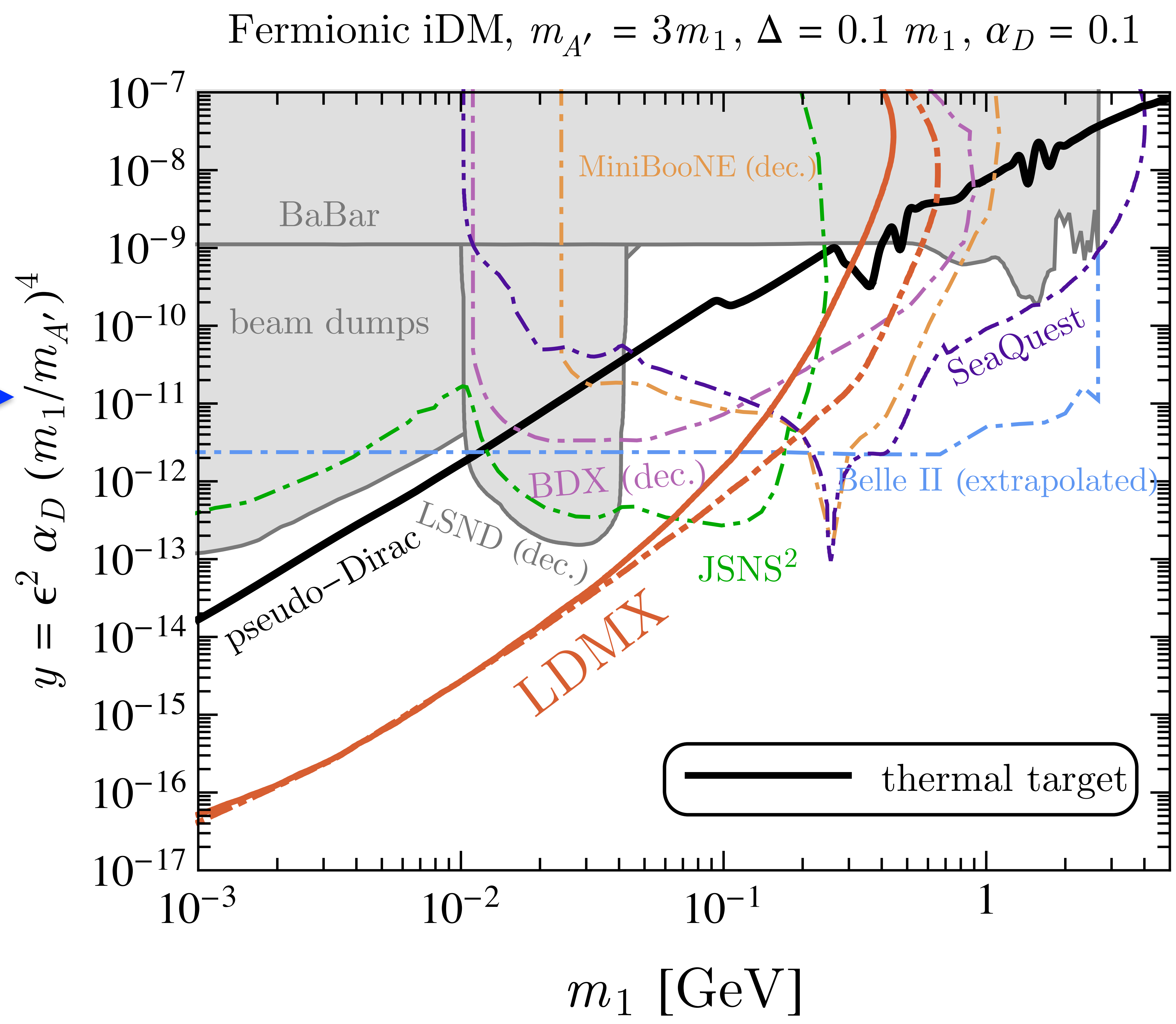

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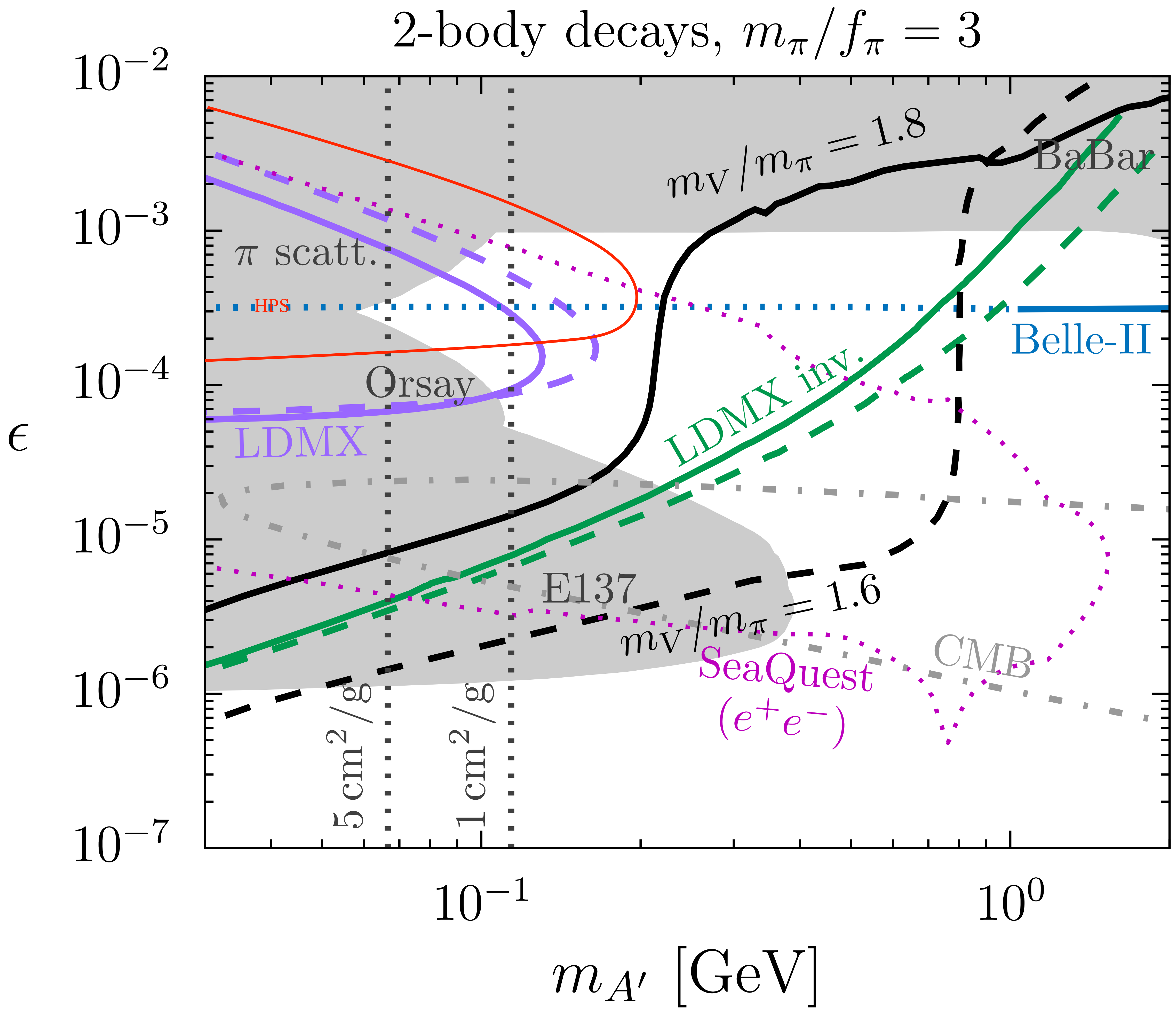

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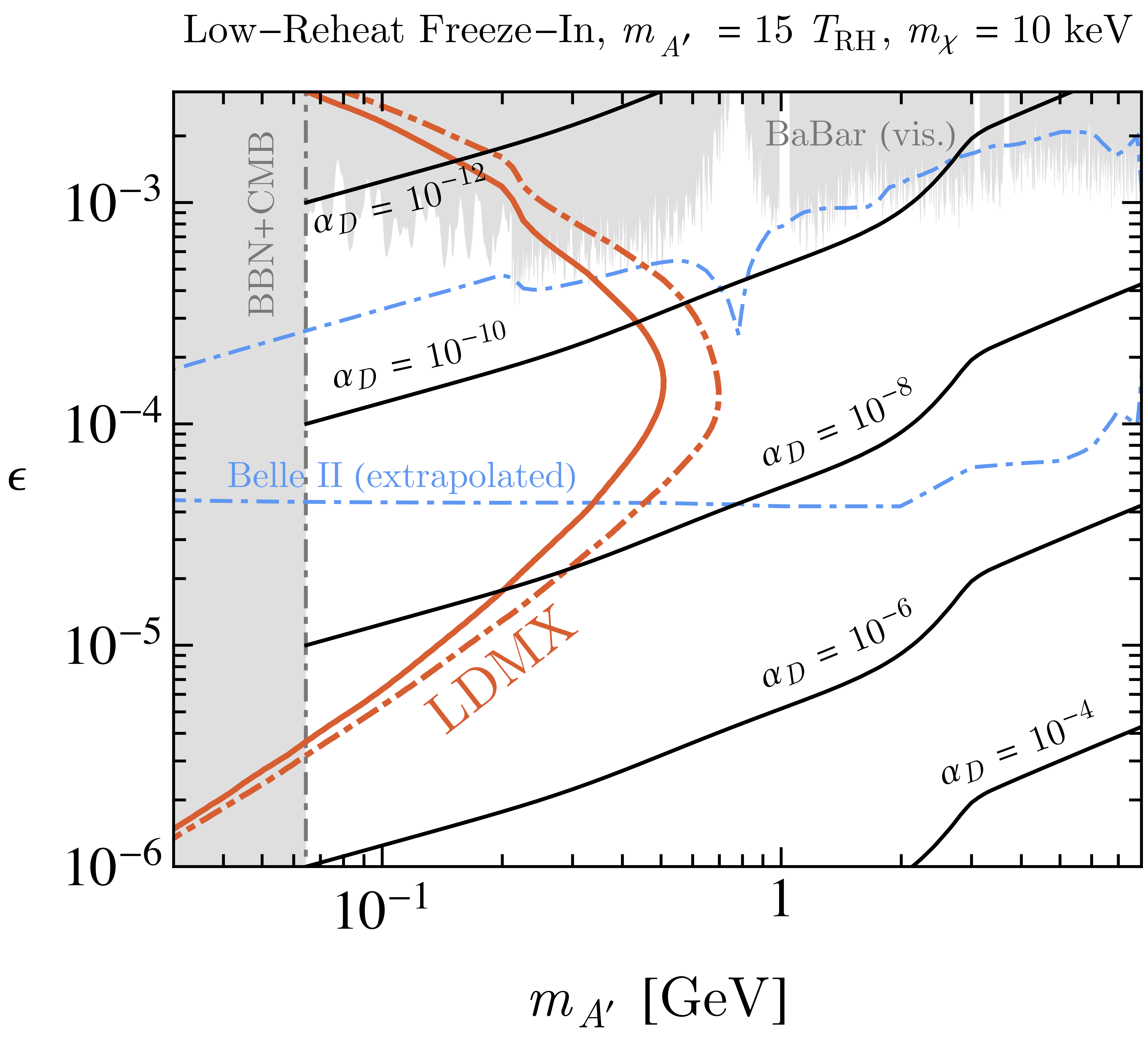

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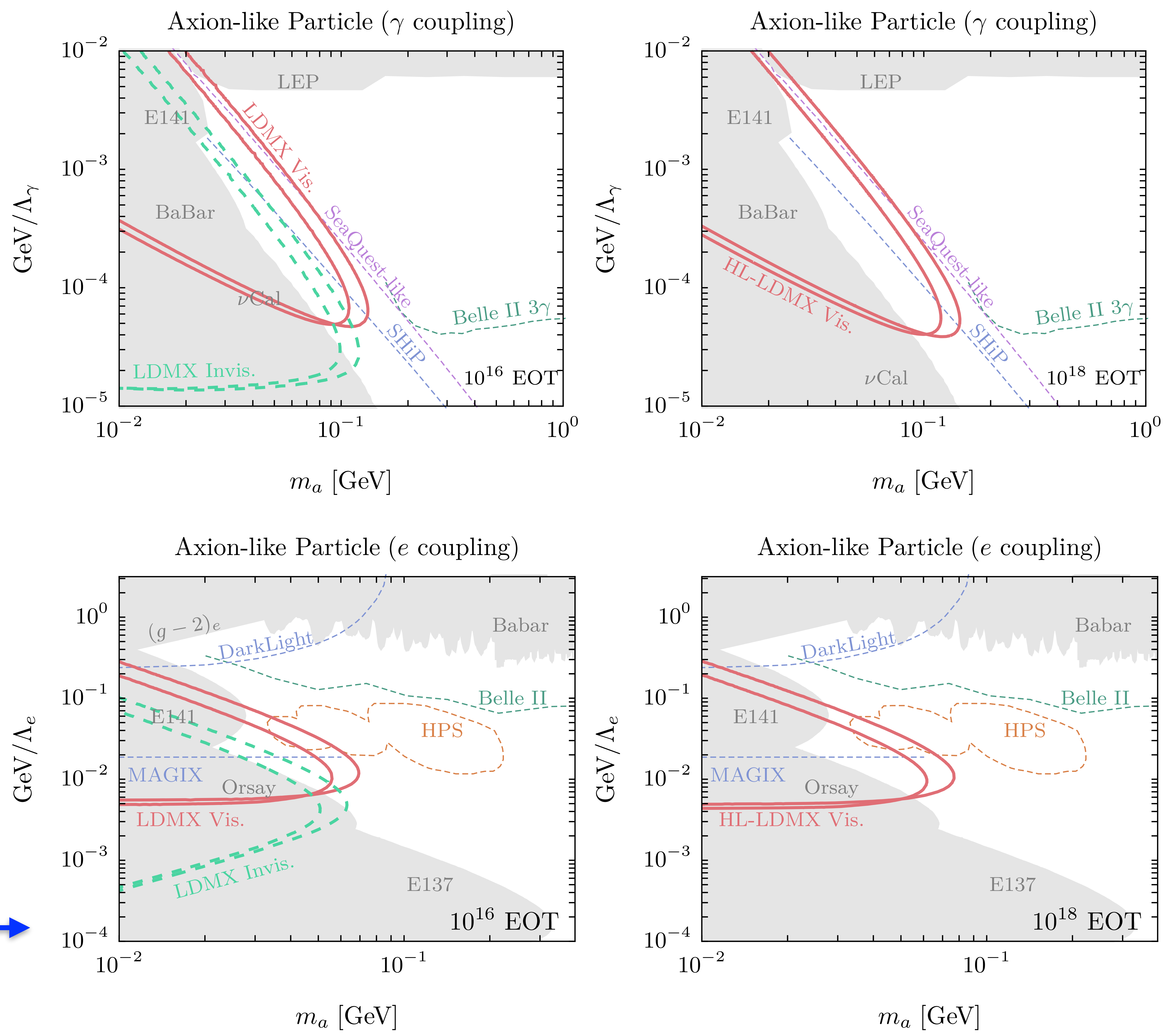

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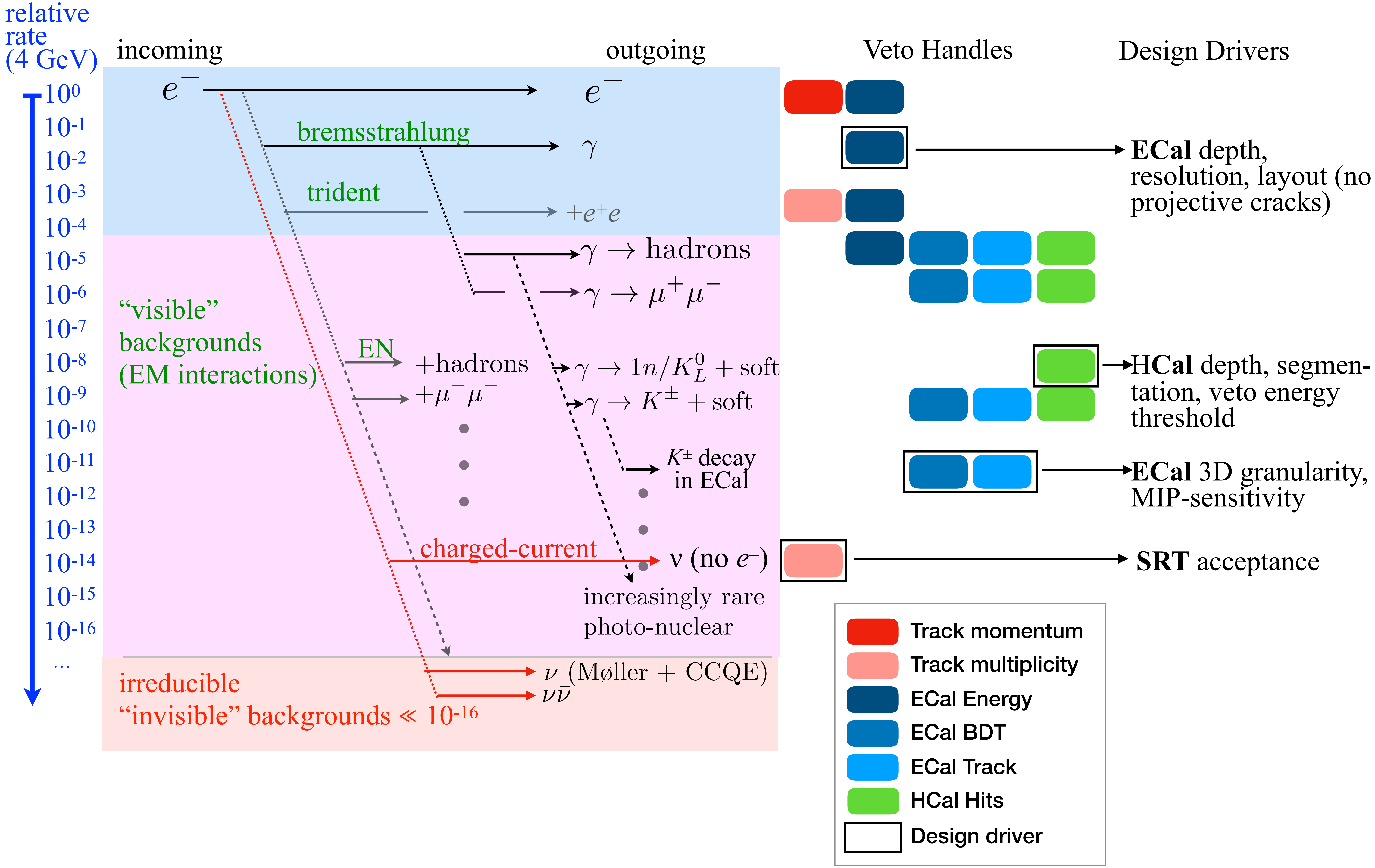
Missing Momentum Design Drivers: Backgrounds

Gaussian energy fluctuations

Rare reactions → products escape ECal and/or anomalous energy deposition

Irreducible prompt $\not{E}$

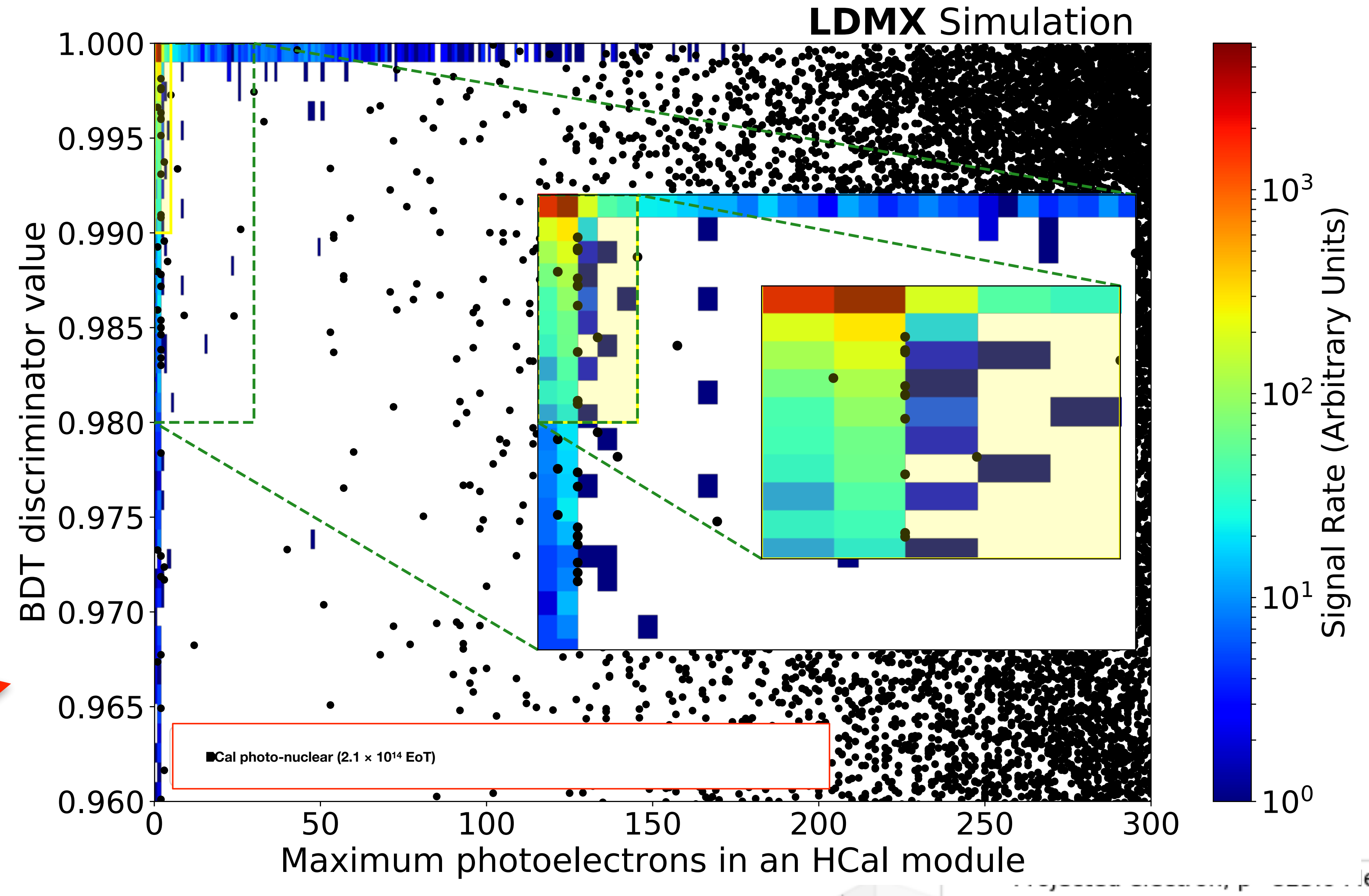


LDMX Phase I Sensitivity (4 GeV)

Initial LCLS-II operation provides 4 GeV beam,
1 year ≈ 4000 hours operation $\Longrightarrow$ 4×10^{14} e$^-$

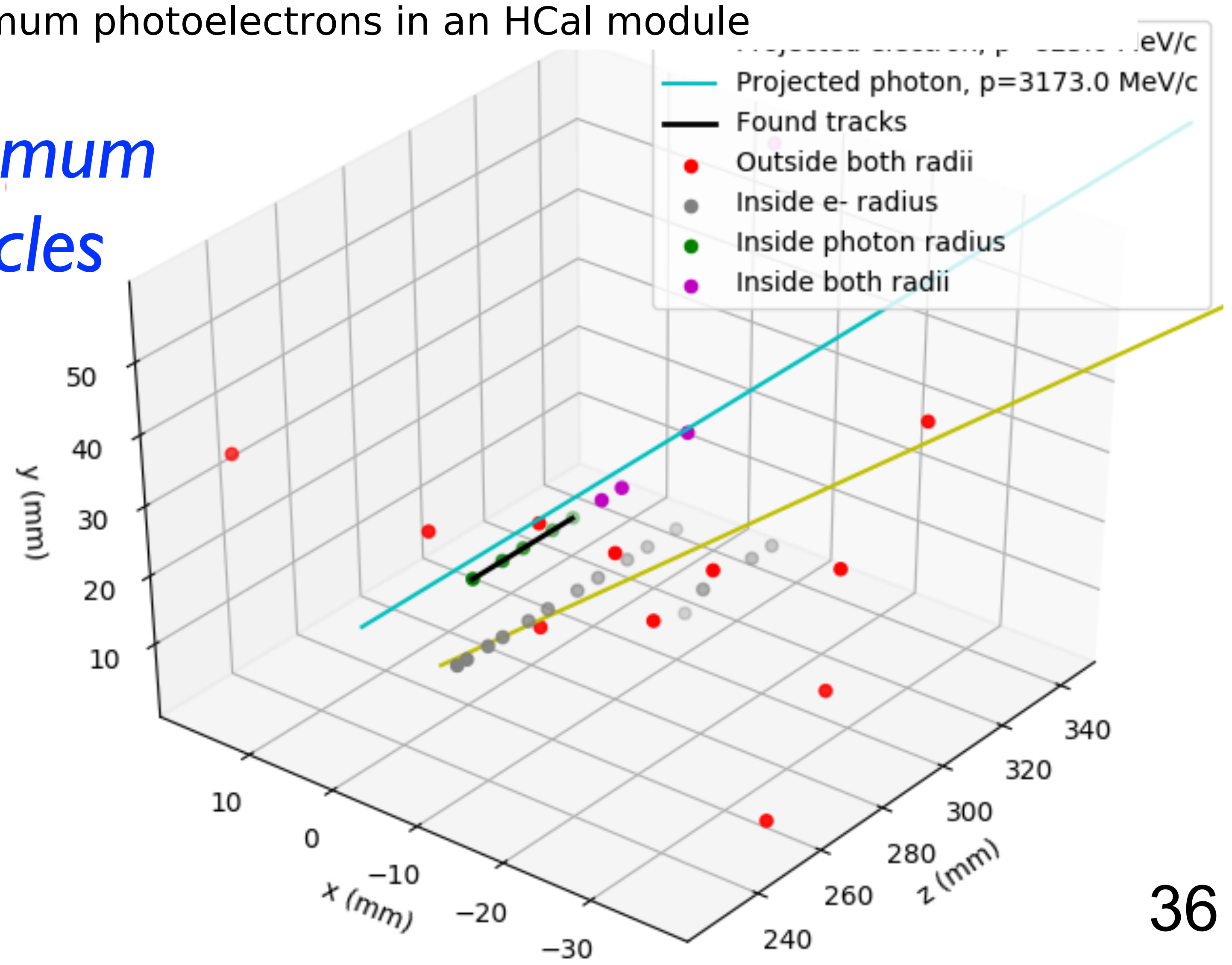
Analysis strategy developed on full simulation JHEP 04 (2020) 003

	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.7×10^{11}	6.3×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.6×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.3×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.3×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks $= 0$	< 1	< 1	< 1	< 1



- have put major development work into GEANT 4 photonuclear modeling: also studying variation among simulation tools (FLUKA, PHITS, MCNP)
- p_T can always be used to eliminate remaining backgrounds but also allows reconstruction of mediator mass
- Most difficult backgrounds strongly suppressed with 8 GeV beam

Tracking minimum ionizing particles in ECal



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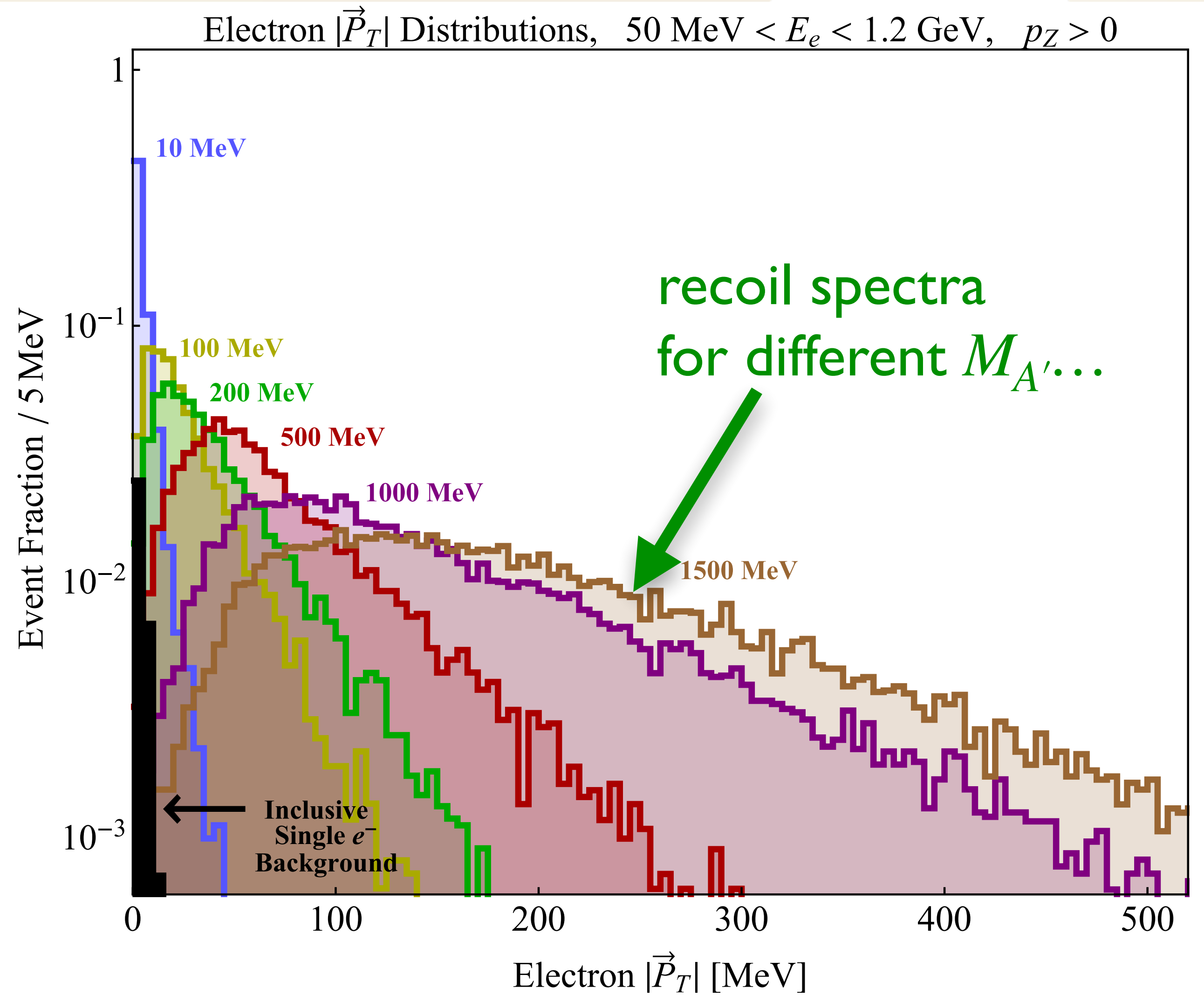
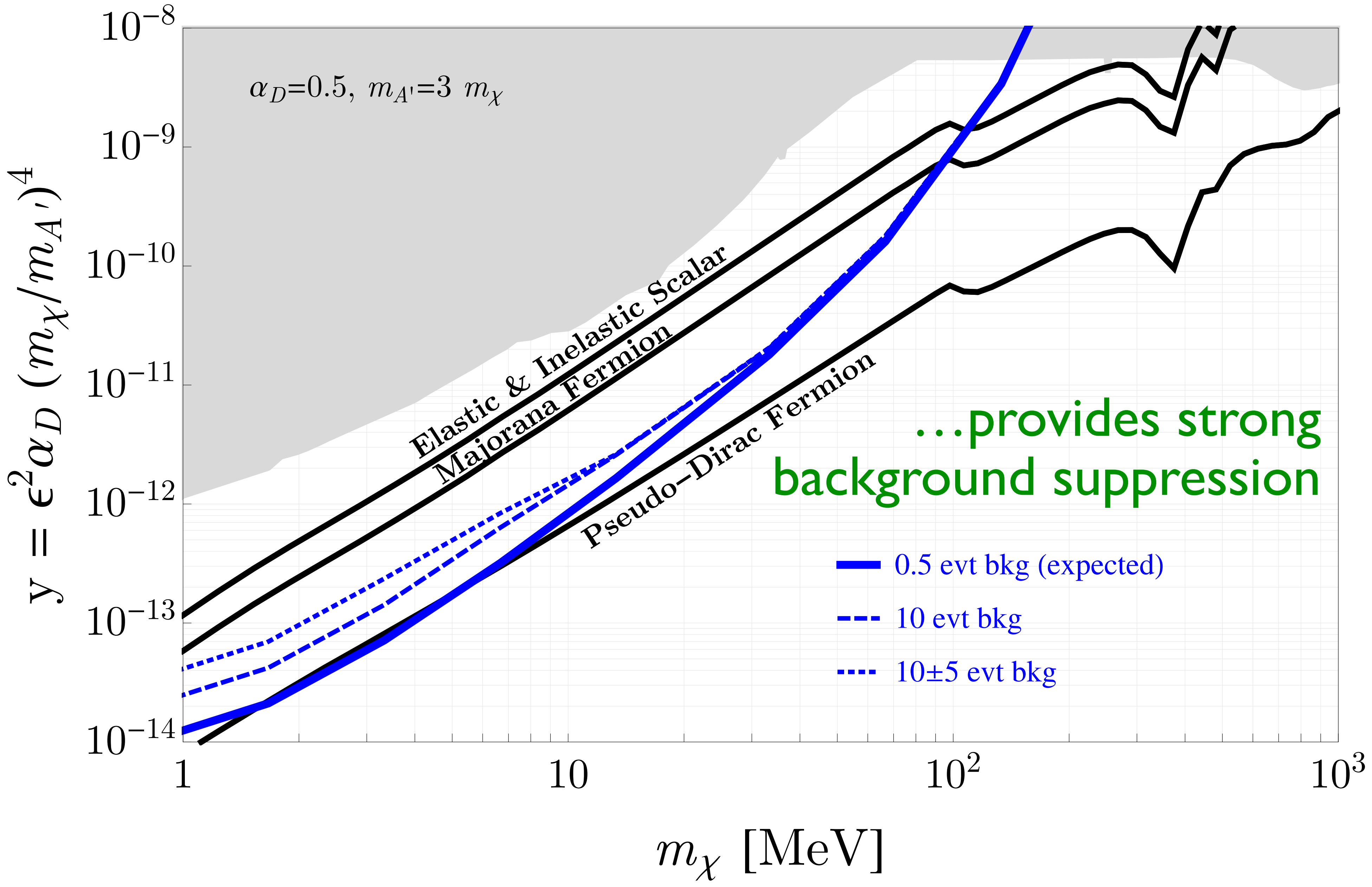




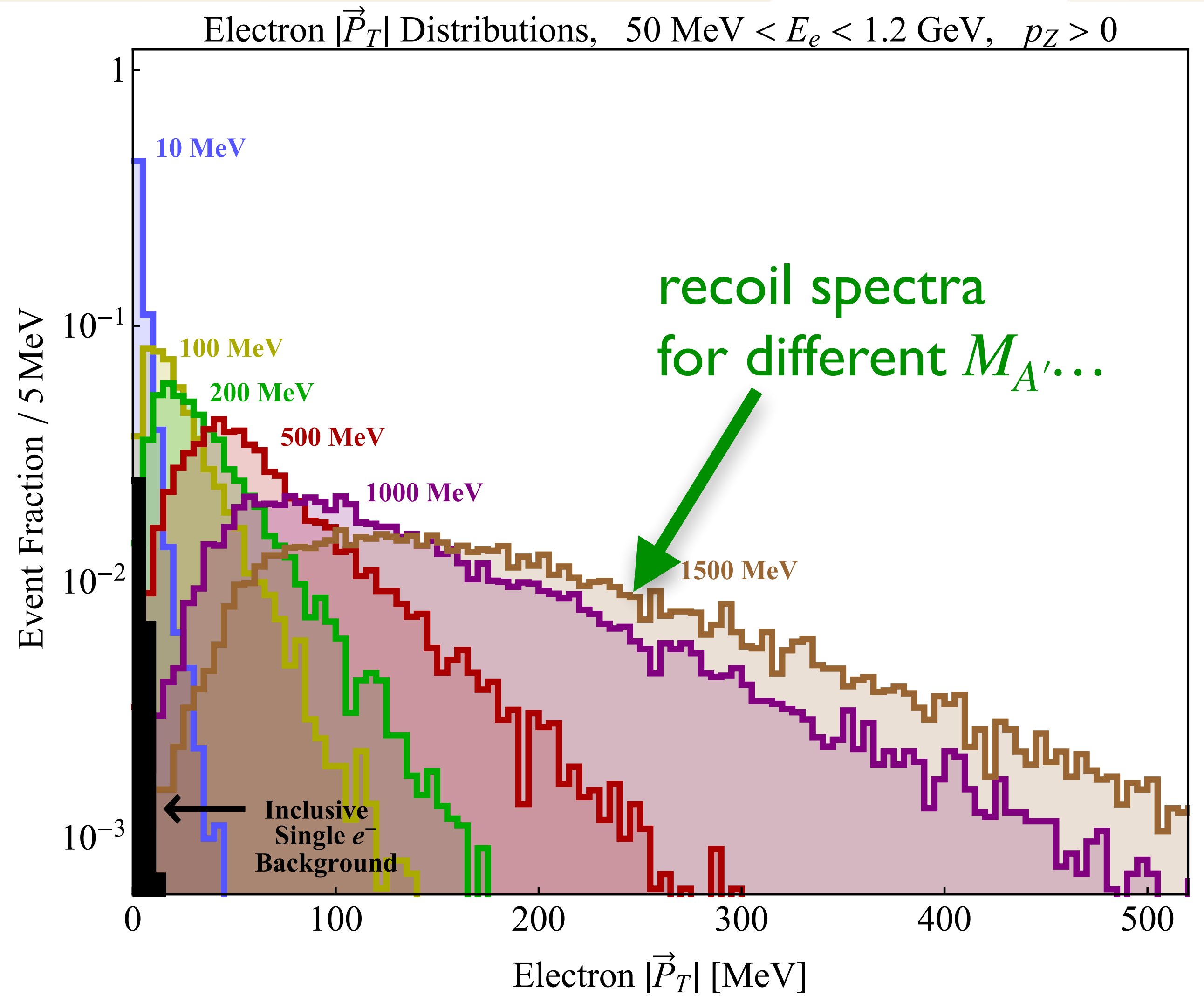
LDMX Phase I Sensitivity (4 GeV)

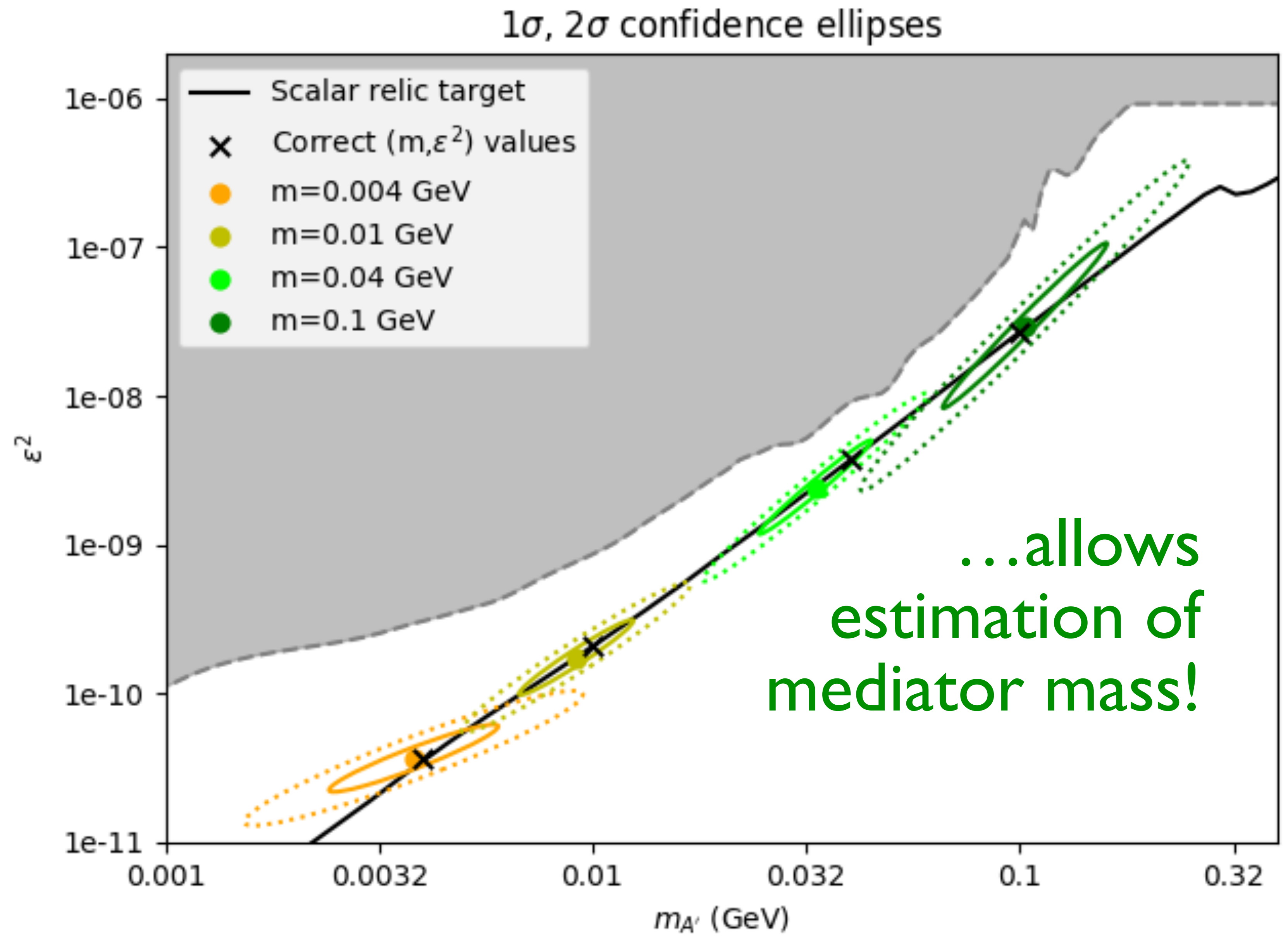
Initial LCLS-II operation provides 4 GeV beam,
1 year ≈ 4000 hours operation ⟹ 4×10¹⁴ e⁻

Analysis strategy developed on full simulation JHEP 04 (2020) 003

	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.7×10^{11}	6.3×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.6×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.3×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.3×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks $= 0$	< 1	< 1	< 1	< 1

- have put major development work into GEANT 4 photonuclear modeling: also studying variation among simulation tools (FLUKA, PHITS, MCNP)
- p_T can always be used to eliminate remaining backgrounds but also allows reconstruction of mediator mass
- Most difficult backgrounds strongly suppressed with 8 GeV beam

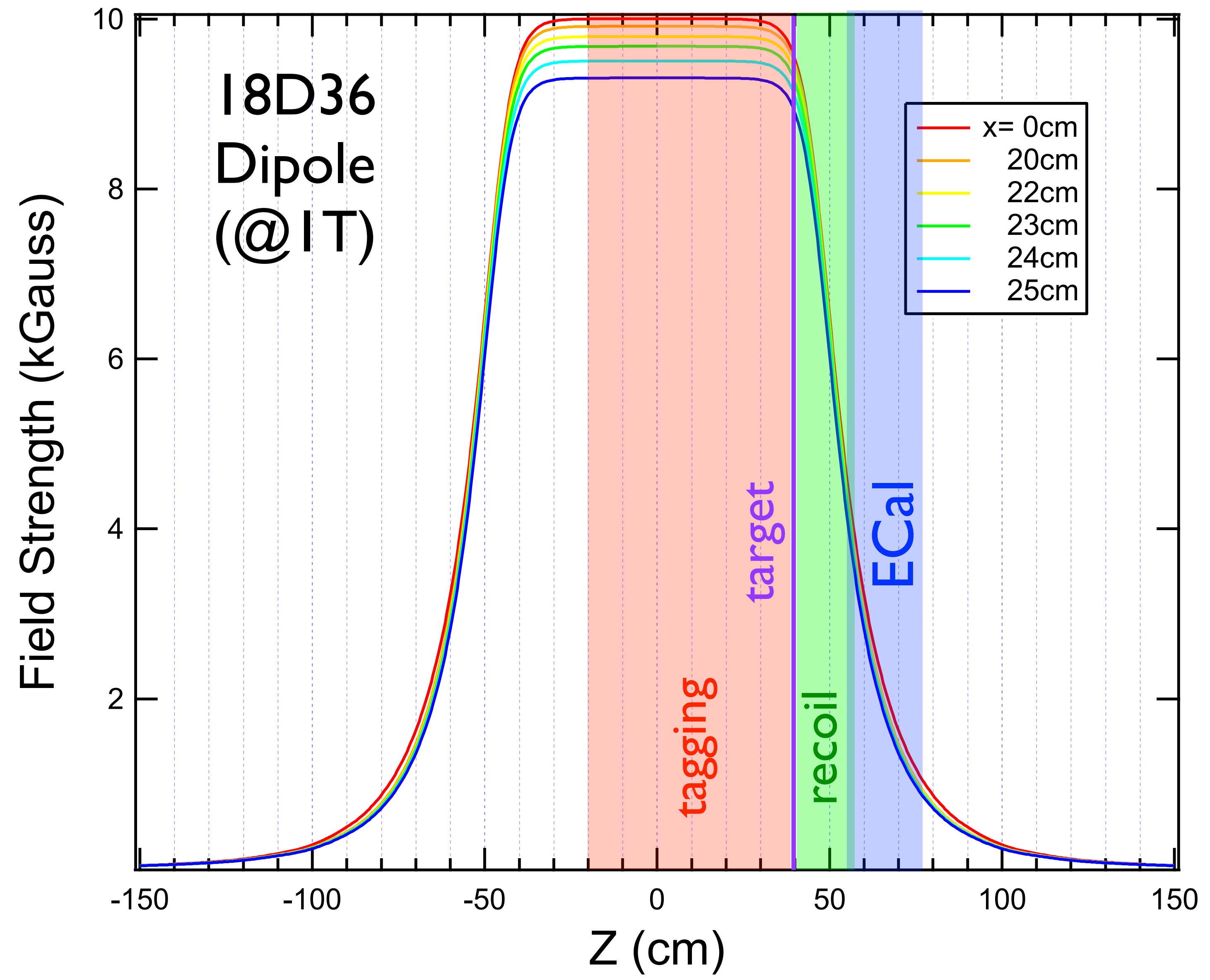




LDMX Subsystems and Technology Choices

WBS 1.1 – Beamline and Magnet: (SLAC core competency)

- final section of beam pipe with vacuum window
- common dipole magnet provides high(low) field for incoming(recoiling) e^-



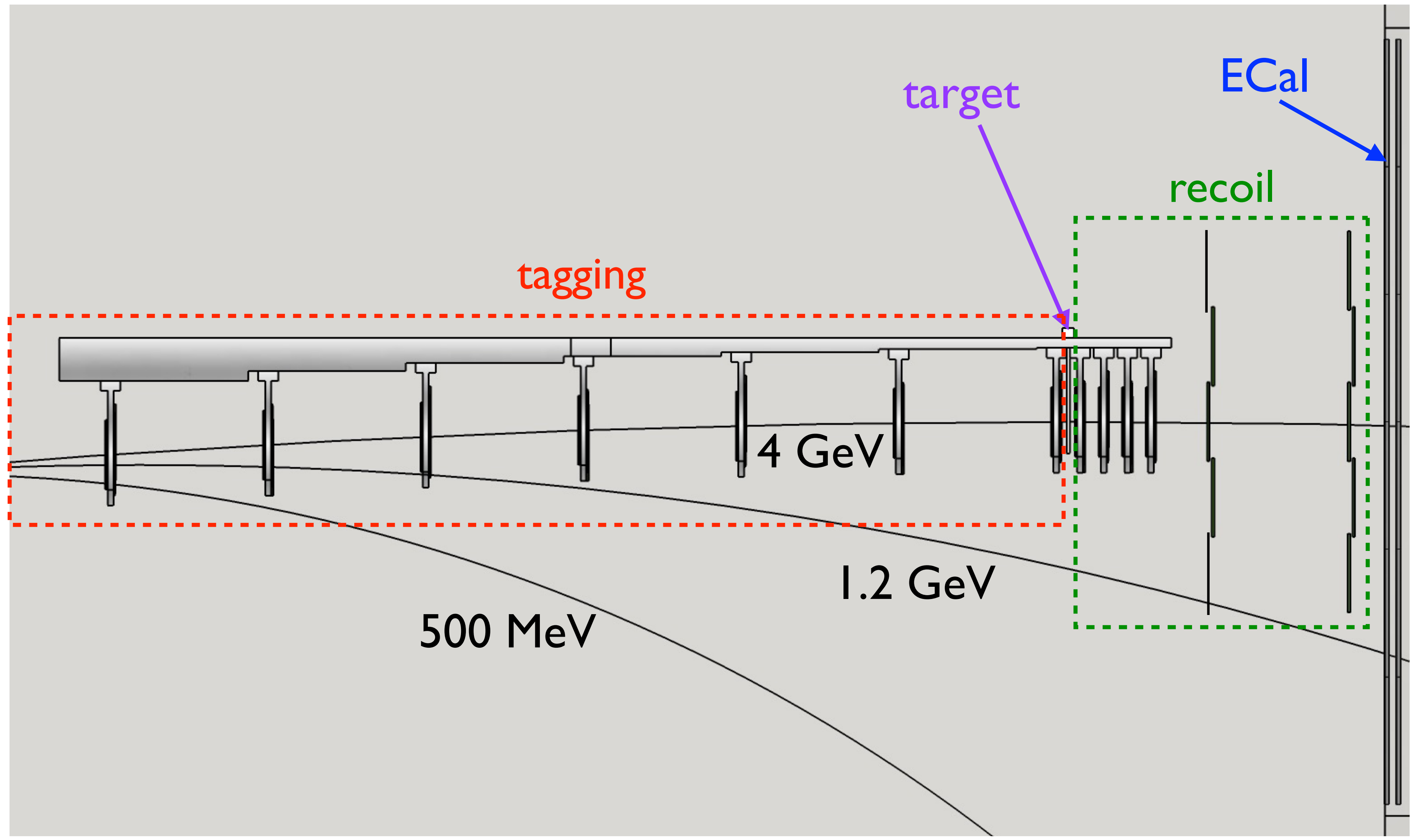
WBS 1.3 – Trackers: (from HPS Silicon Vertex Tracker built at SLAC)

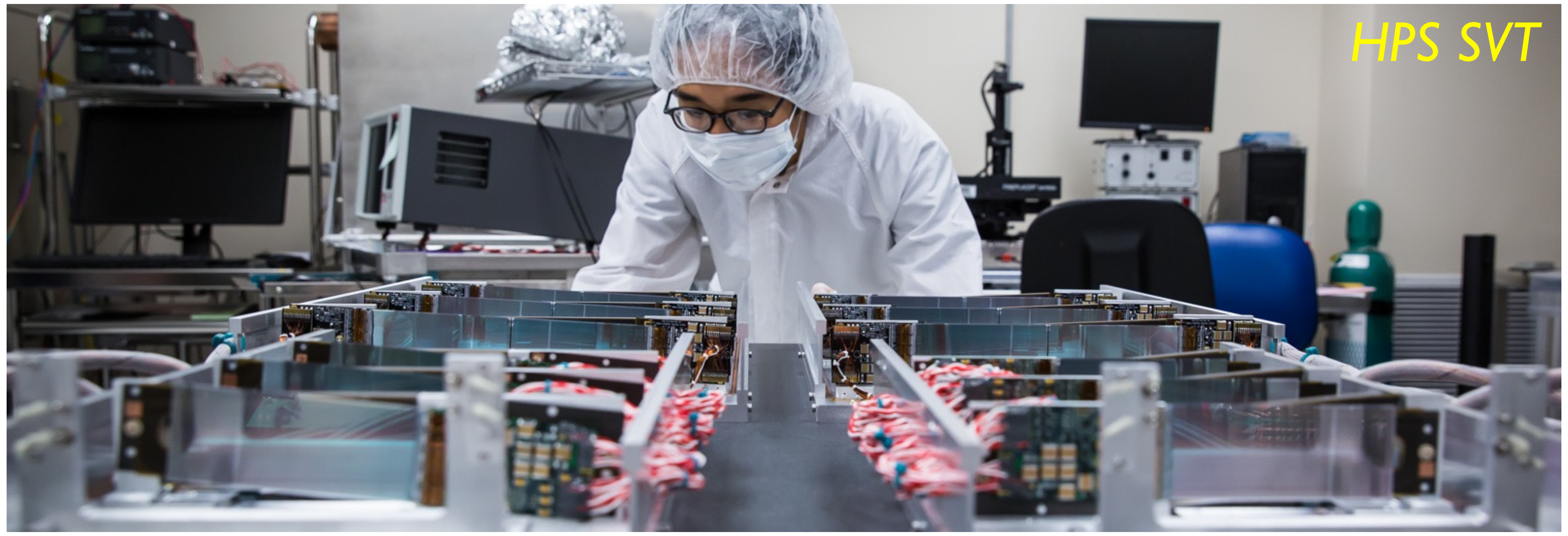
Tagging Tracker: long, narrow, in uniform 1.5 T field for p_e = 4 GeV

- 7 double-layers provide robust tag of incoming electrons

Recoil Tracker: short, wide, in fringe field for p_e = 0.05 - 1.2 GeV

- 4 double-layers + 2 axial-only layers provide good acceptance, Δp_T resolution limited by multiple scattering in target

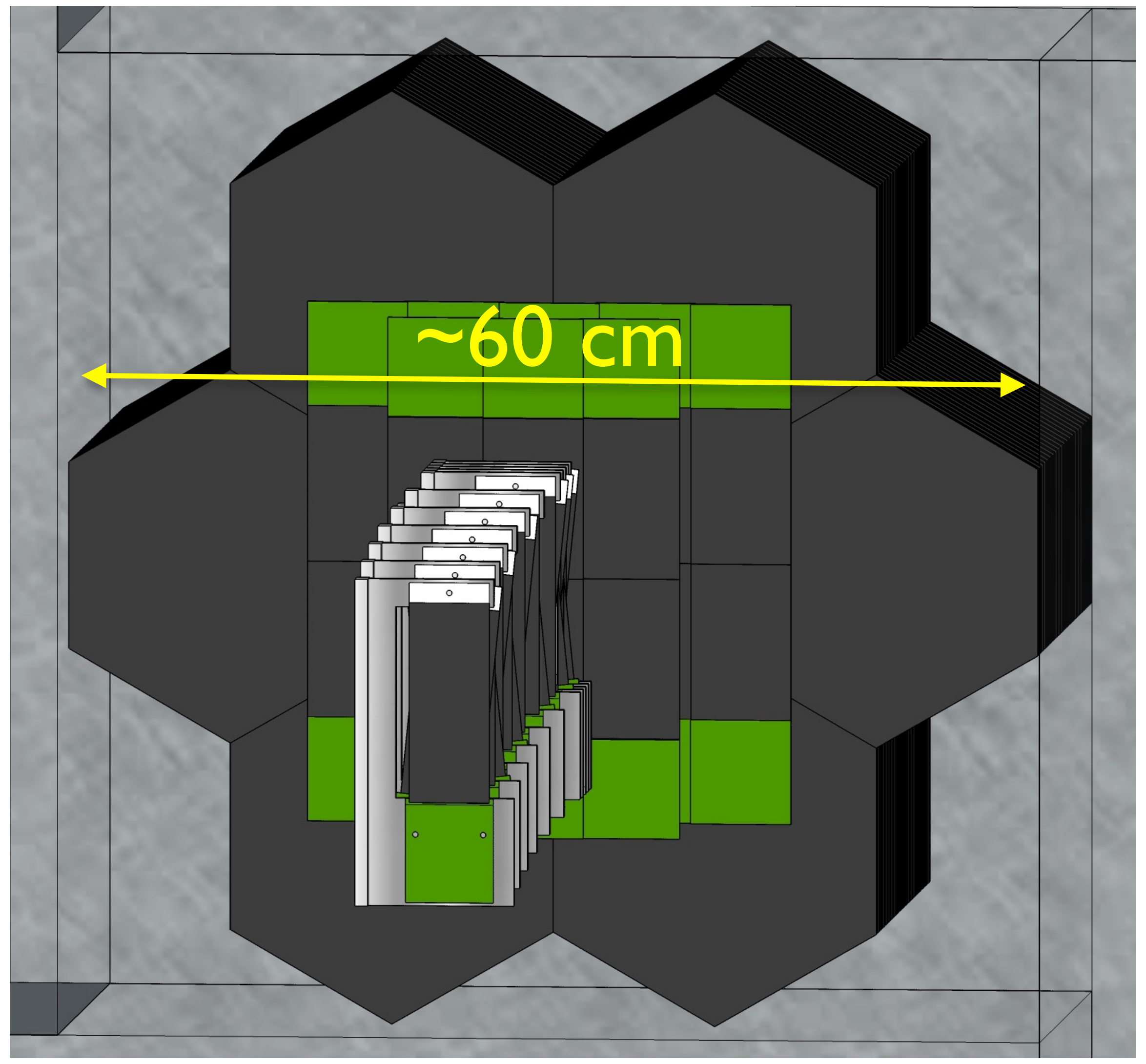


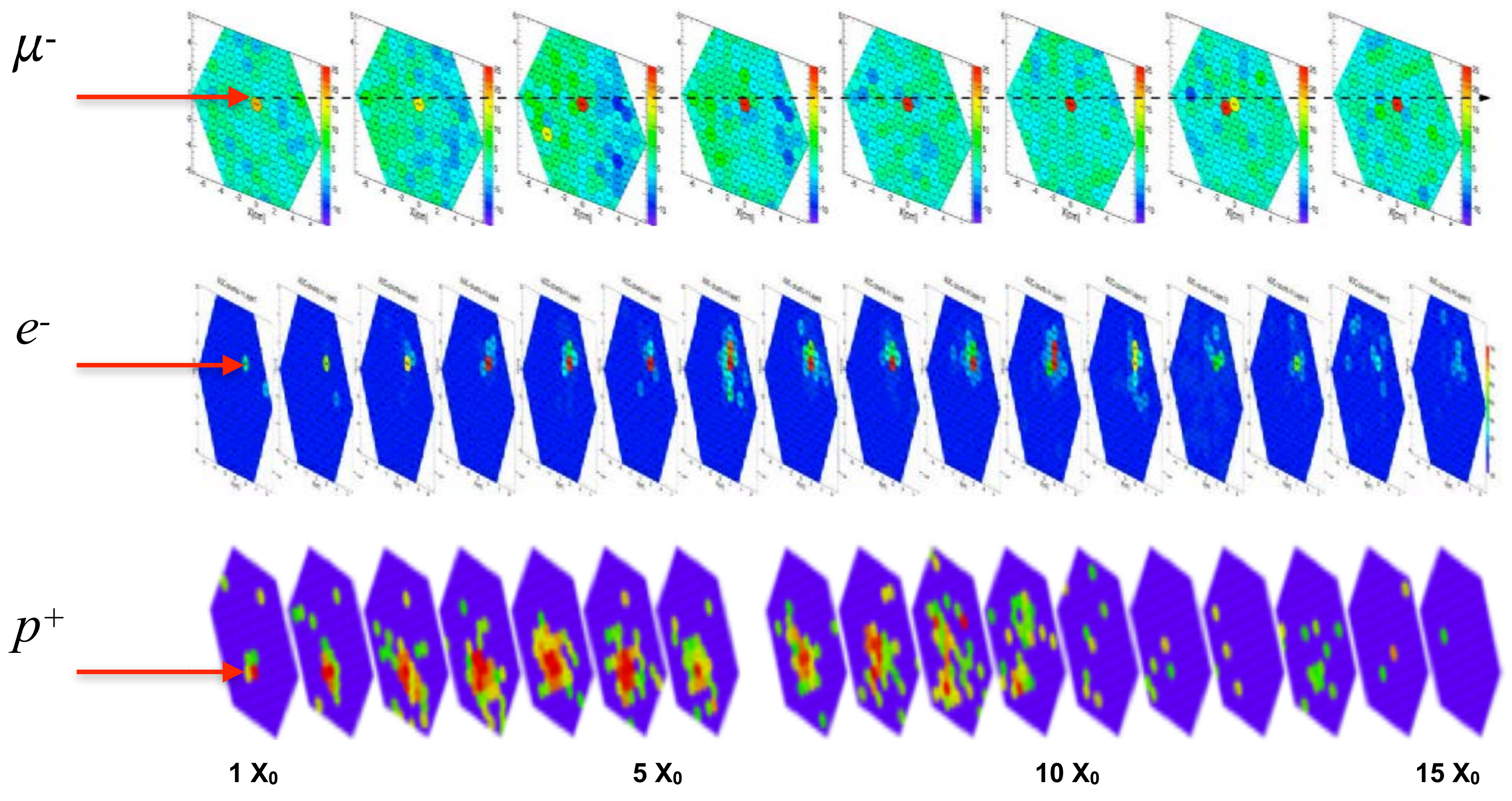


LDMX Subsystems and Technology Choices

WBS 1.4 – ECal: from CMS HGCal (UCSB – Incandela, U. Minn. – Mans)

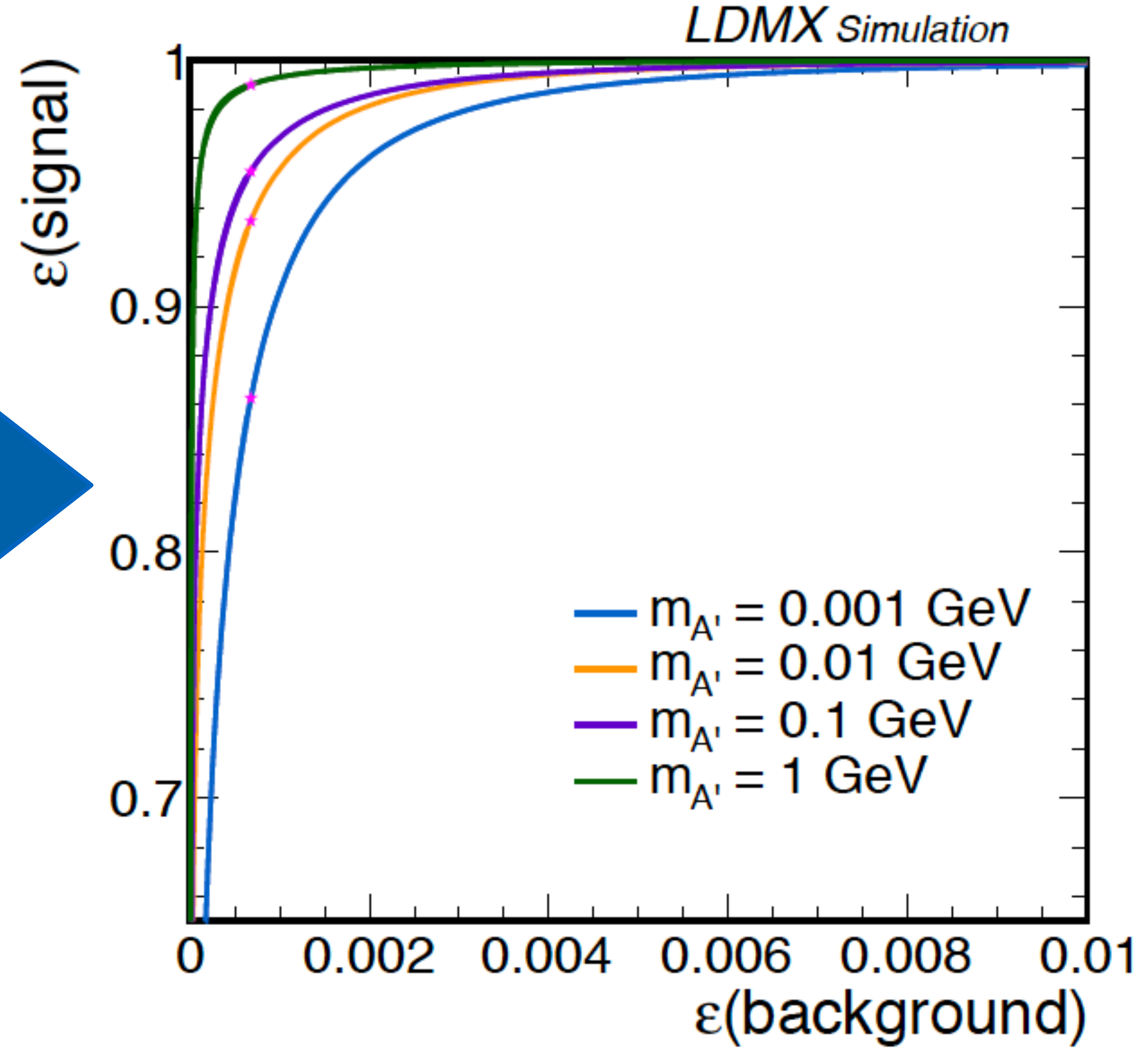
- Si-W sampling calorimeter: fast, dense, high radiation tolerance
- 40 X_0 deep: excellent containment of EM showers
- Granularity and MIP sensitivity: imaging and MIP tracking are powerful for rejecting rare backgrounds (e.g. photonuclear reactions and $\gamma \rightarrow \mu\mu$)
- designed to provide fast trigger (here using ECal energy < 0.3 E_{beam})

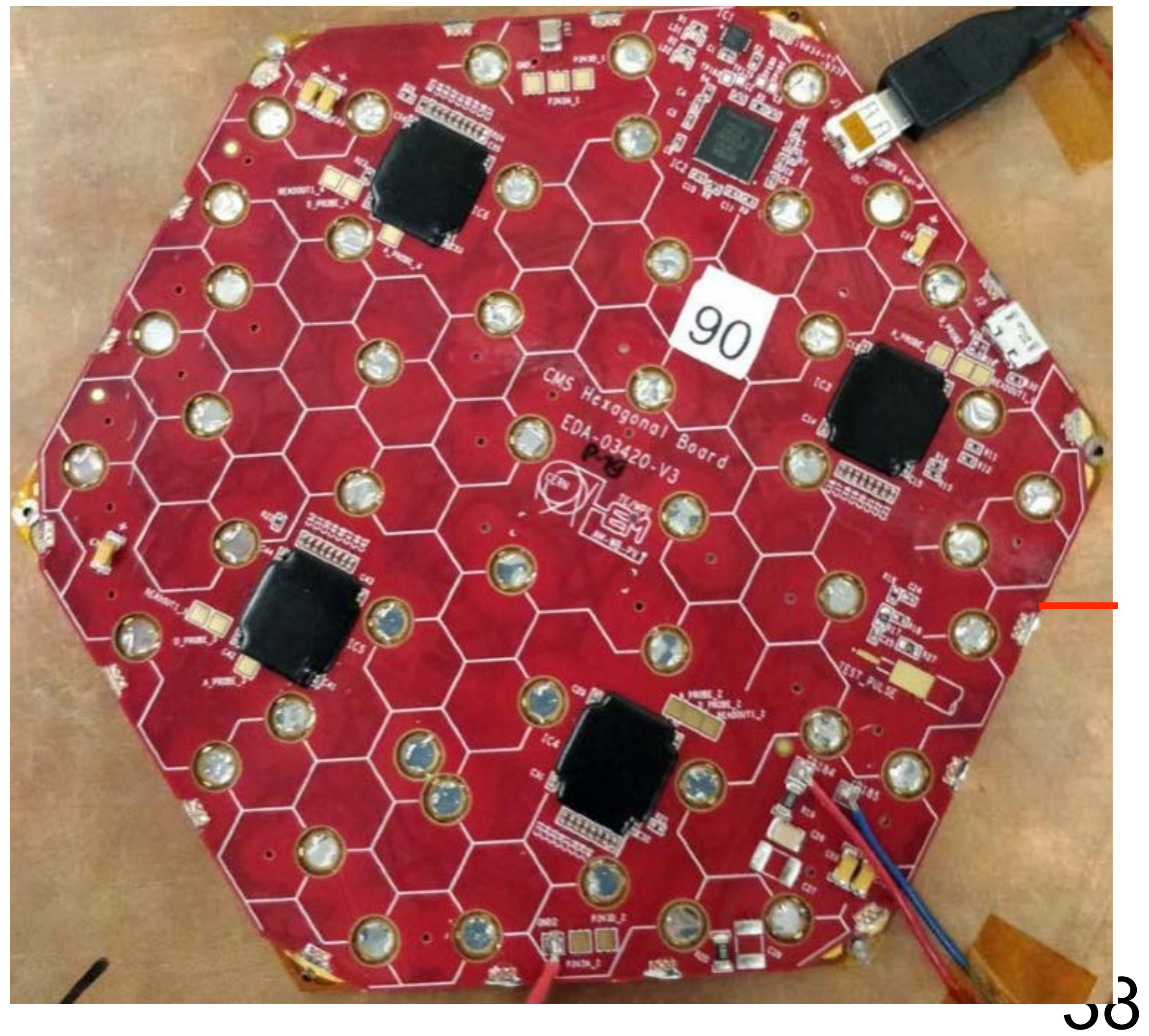




CERN Test Beam Data

Boosted
Decision
Tree

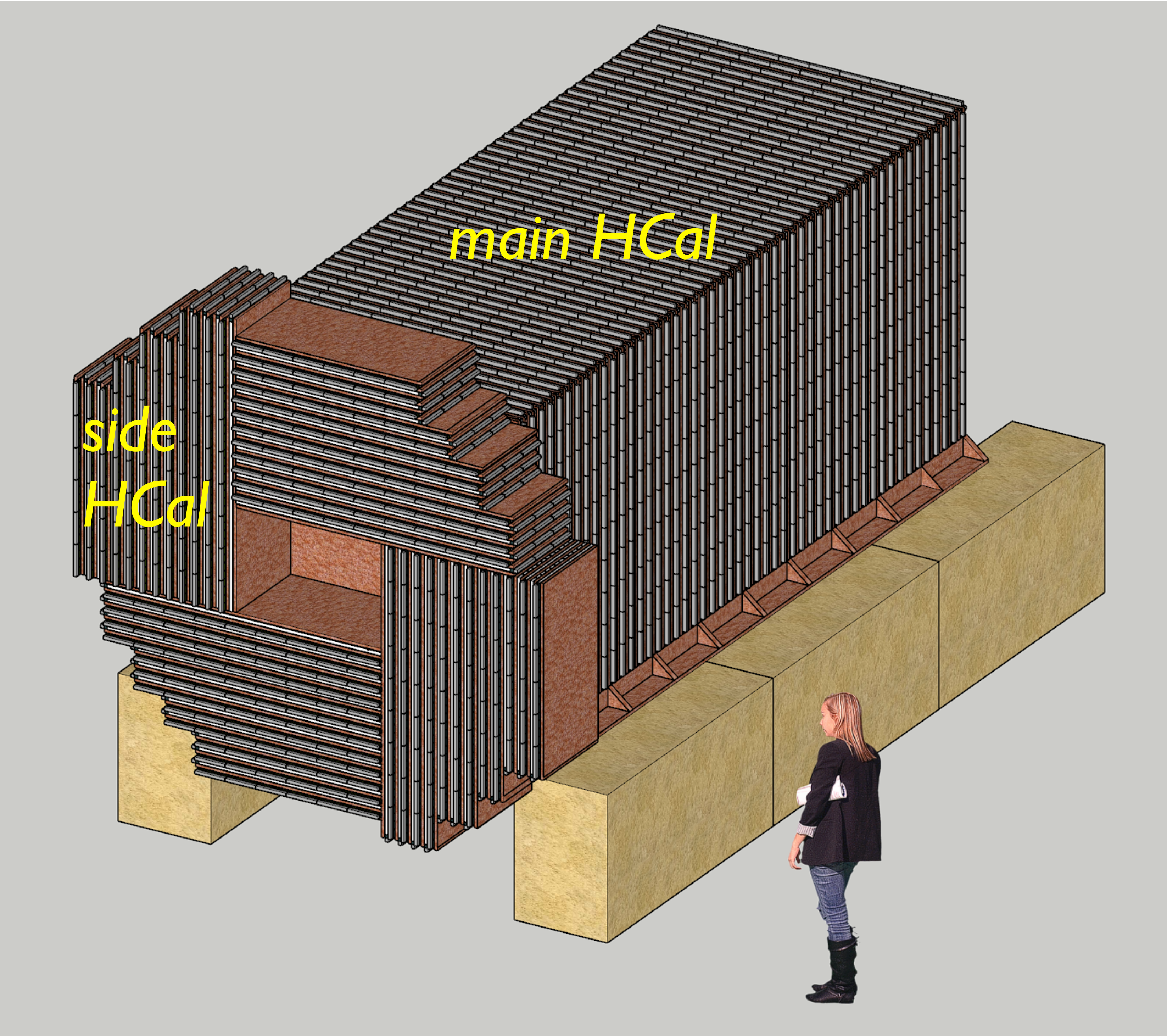


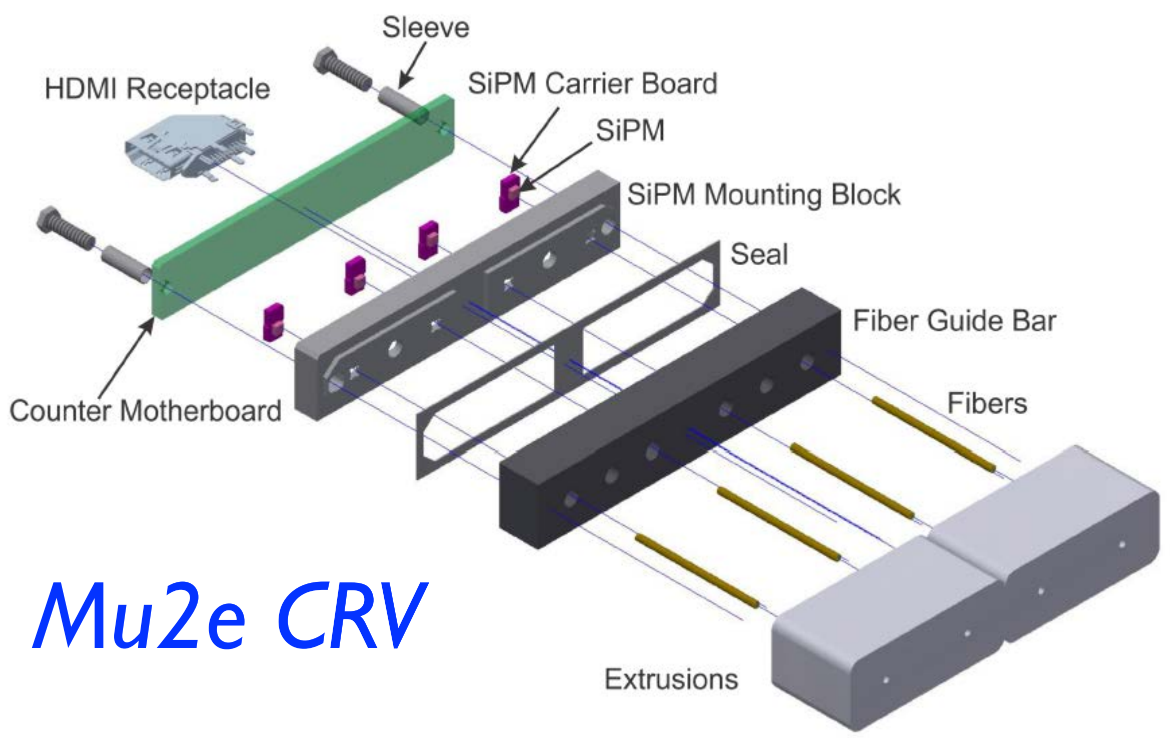


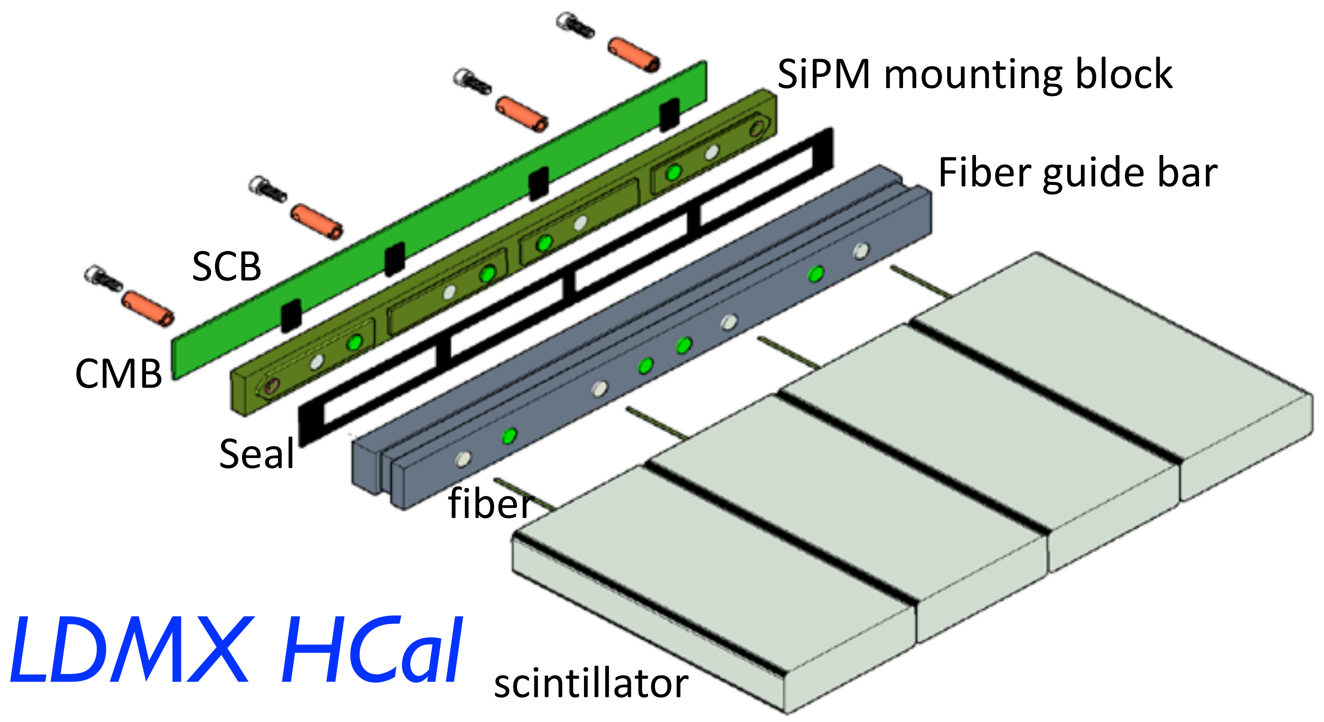
LDMX Subsystems and Technology Choices

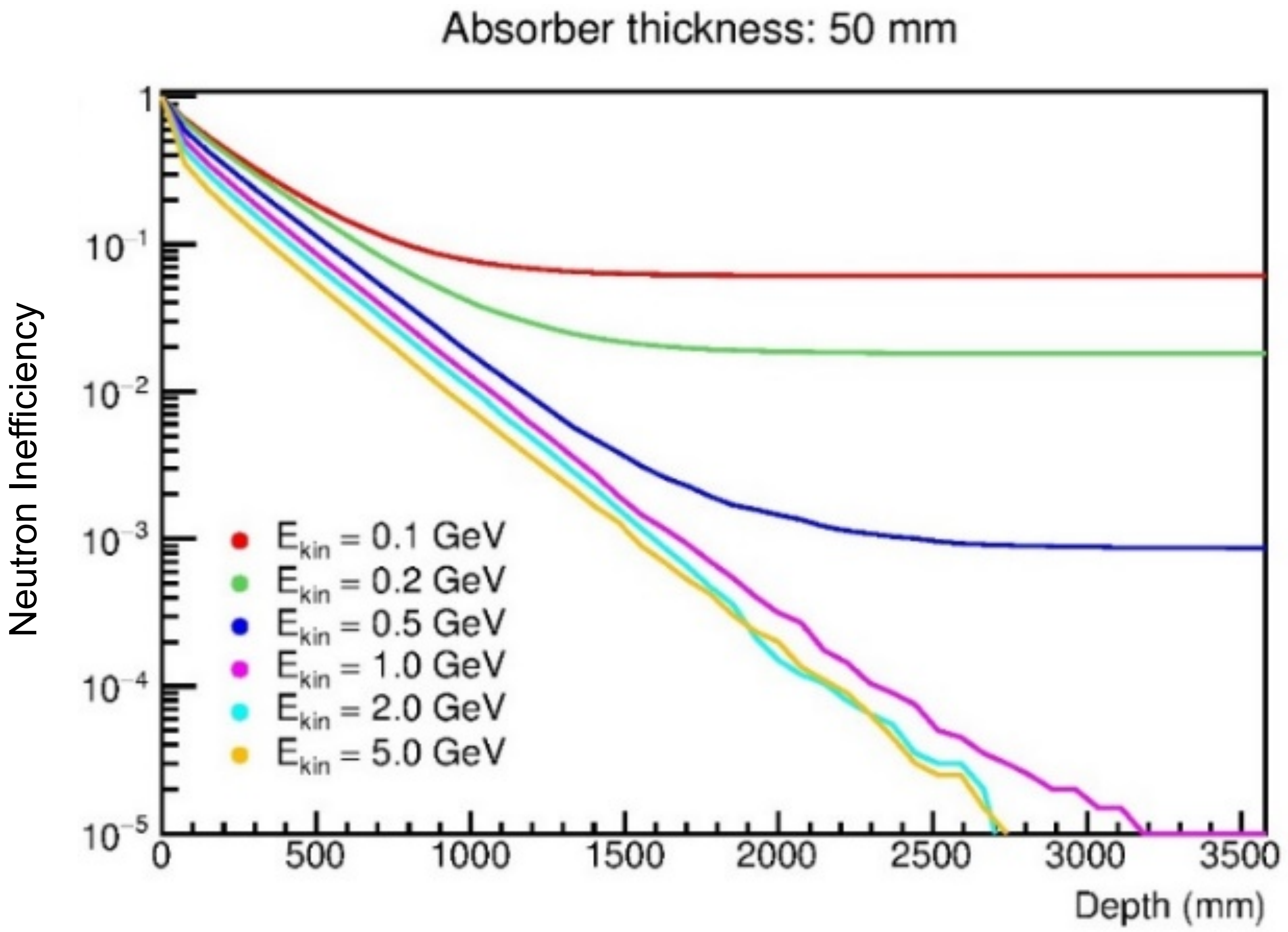
WBS 1.5 – HCal: from Mu2e Cosmic Ray Veto (UVA – Group)

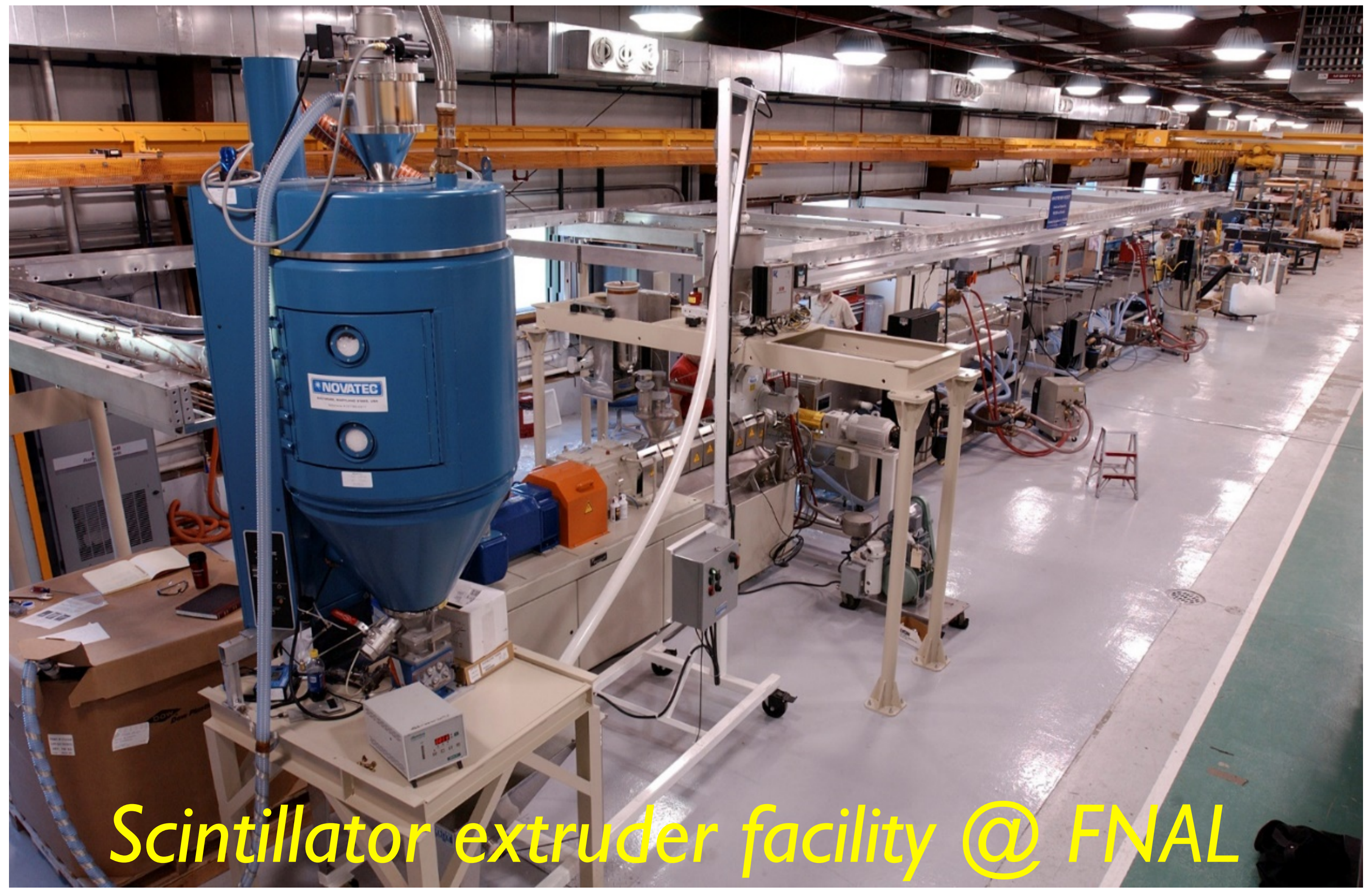
- extruded polystyrene scintillator with WLS fibers and SiPM readout
- main HCal: sufficient depth for rare events with very hard neutrons ($E_n \sim E_\gamma$)
- side HCal: important for high-multiplicity final states and wide-angle brems







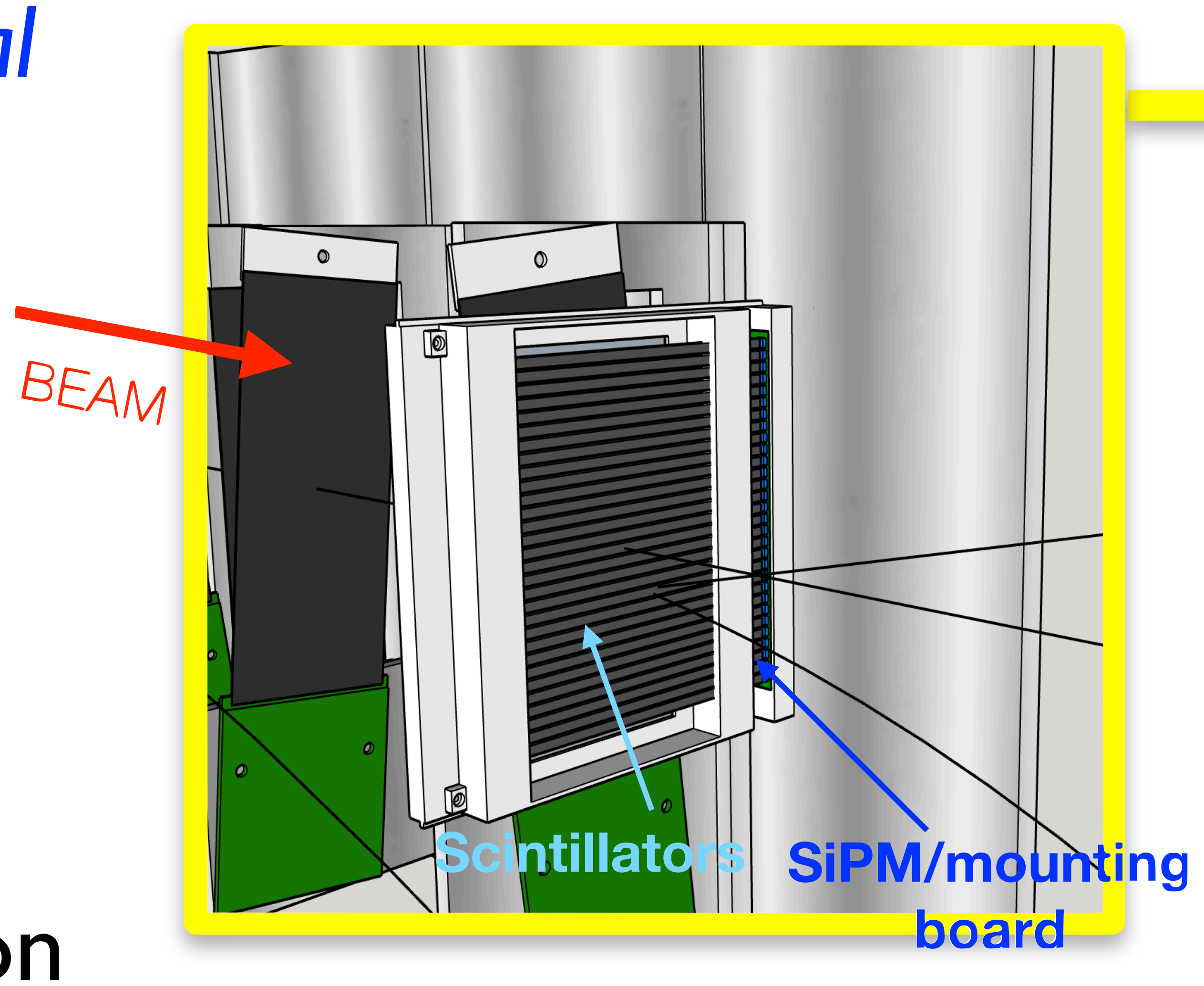


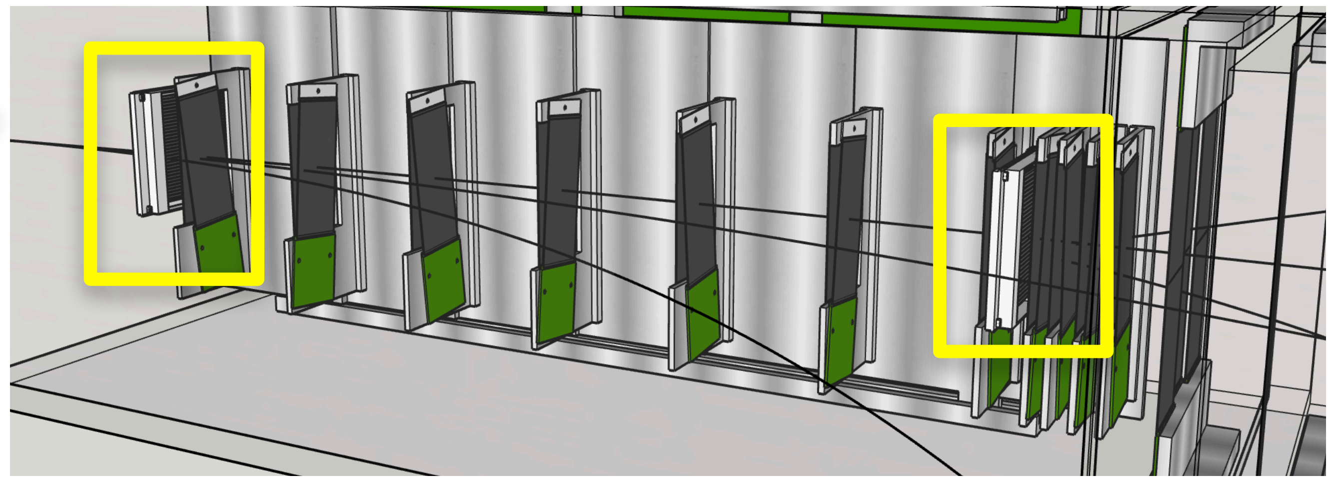


LDMX Subsystems and Technology Choices

WBS 1.2 – Trigger Scintillator: from CMS HCal

- Low-energy ECal trigger requires knowledge of n_e/pulse
- layers of segmented scintillators provides fast estimate of n_e
- also considering segmented LYSO active target: provides additional information about hard interactions in the target



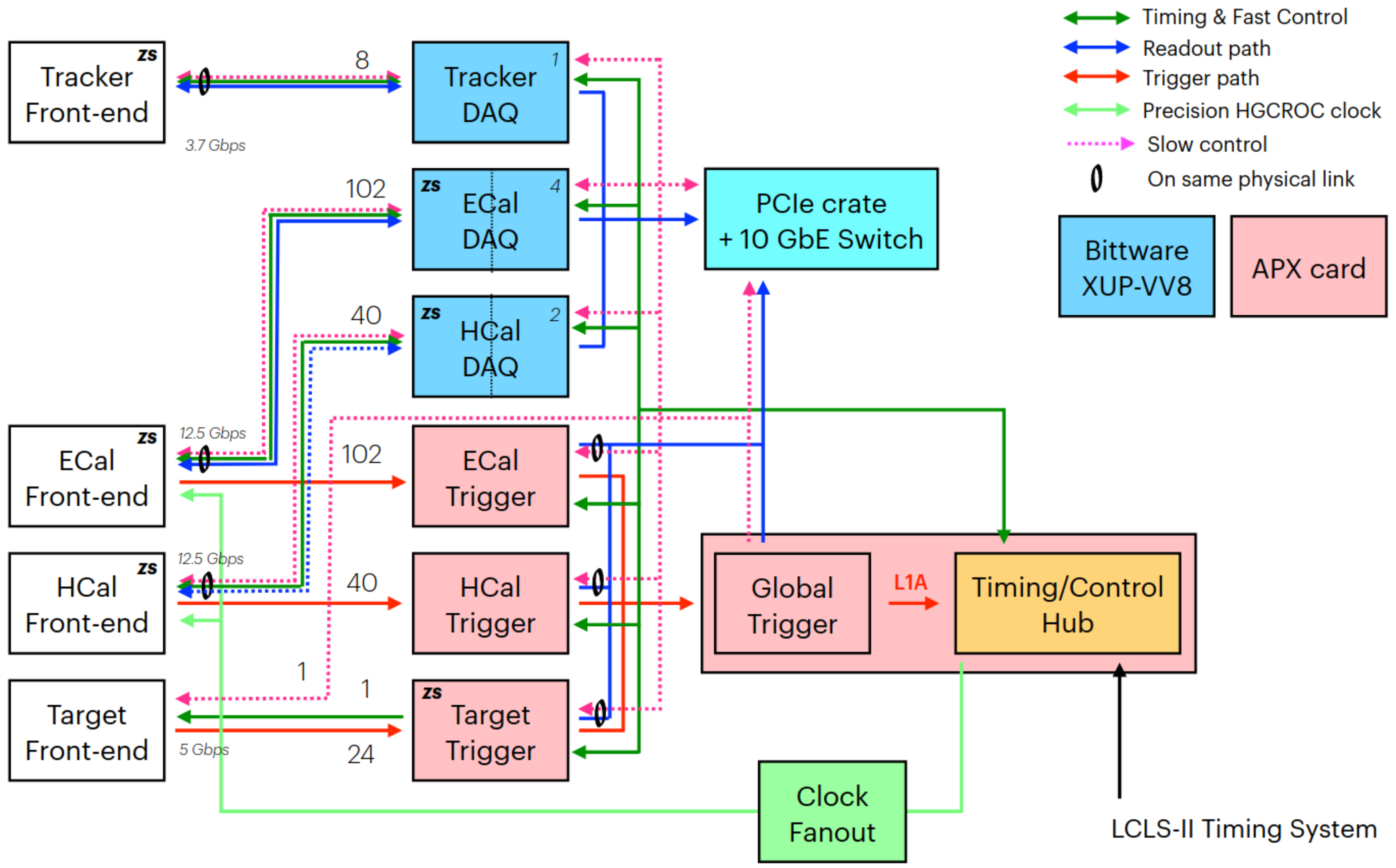


4 GeV trigger summary

n_{beam}	Fraction of Bunches (Signal)	Trigger Scintillator Efficiency	Missing Energy Threshold [GeV]	Calorimeter Trigger Efficiency	Rate [Hz]	Signal Inefficiency
1	36.8% (36.8%)	100%	2.50	99.2%	588	0.3%
2	18.4% (36.8%)	97.4%	2.35	98.0%	1937	1.7%
3	6.1% (18.4%)	92.4%	2.70	91.6%	1238	2.8%
4	1.5% (6.1%)	84.3%	3.20	77.2%	268	1.6%
Total					4000	8.8%

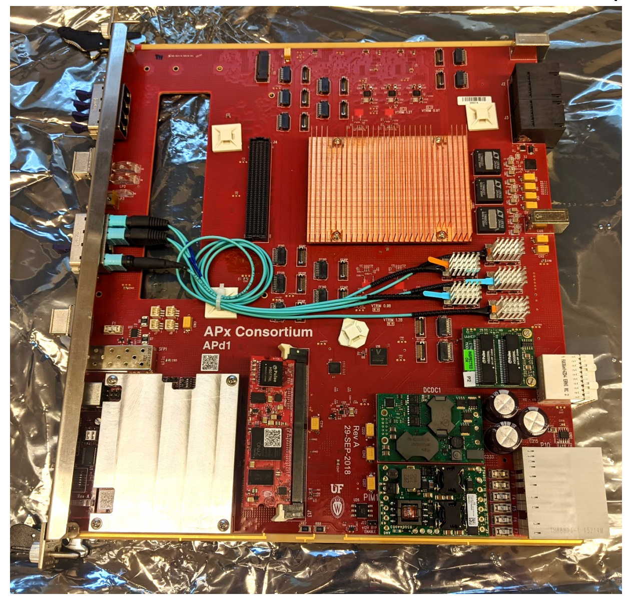
WBS 1.6 – Trigger and DAQ: from SLAC/FNAL tech

- back end DAQ based on PCIe FPGA platform developed at SLAC
- trigger DAQ based on APx DAQ developed for CMS



Bittware XUP-VV8

Advanced Processor demonstrator (APd)



LDMX Subsystems and Technology Choices

WBS 1.7 – Computing and Software

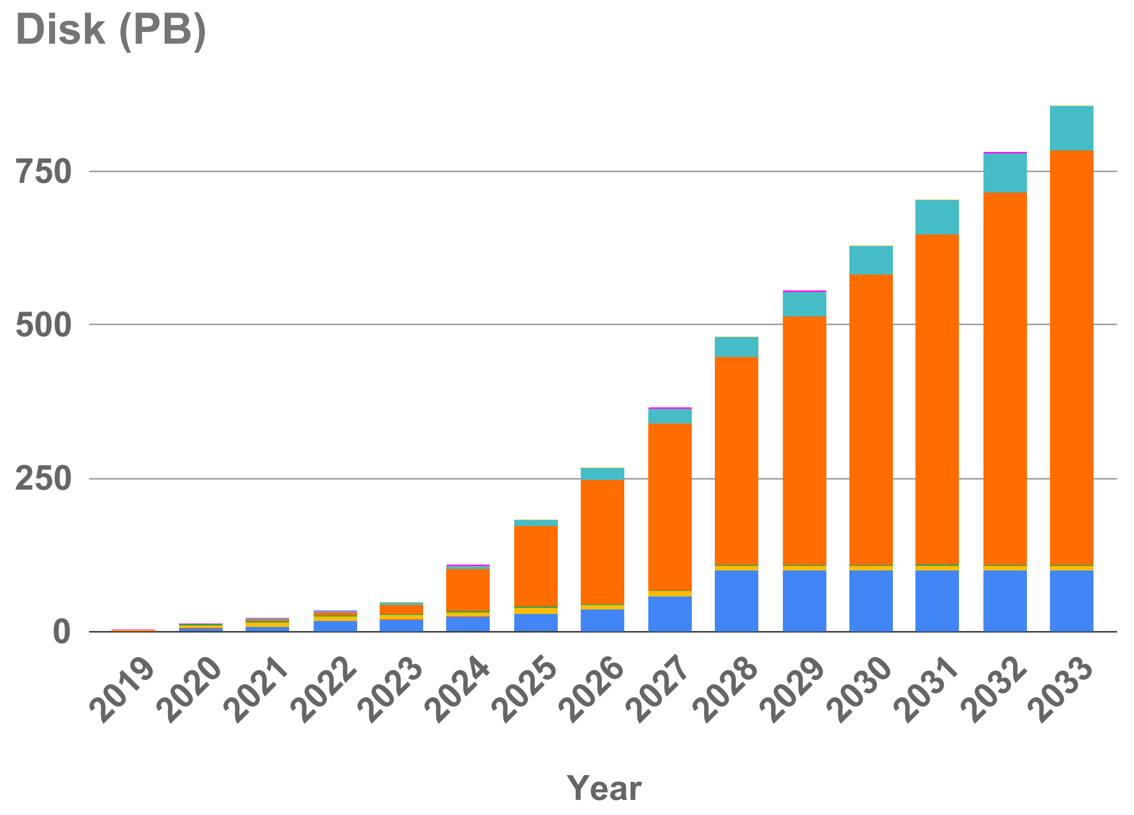
LDMX requires significant computing resources: Datasets and MC will total ~8 PB (disk+tape) after filtering and require ~15M CPU hours to process.

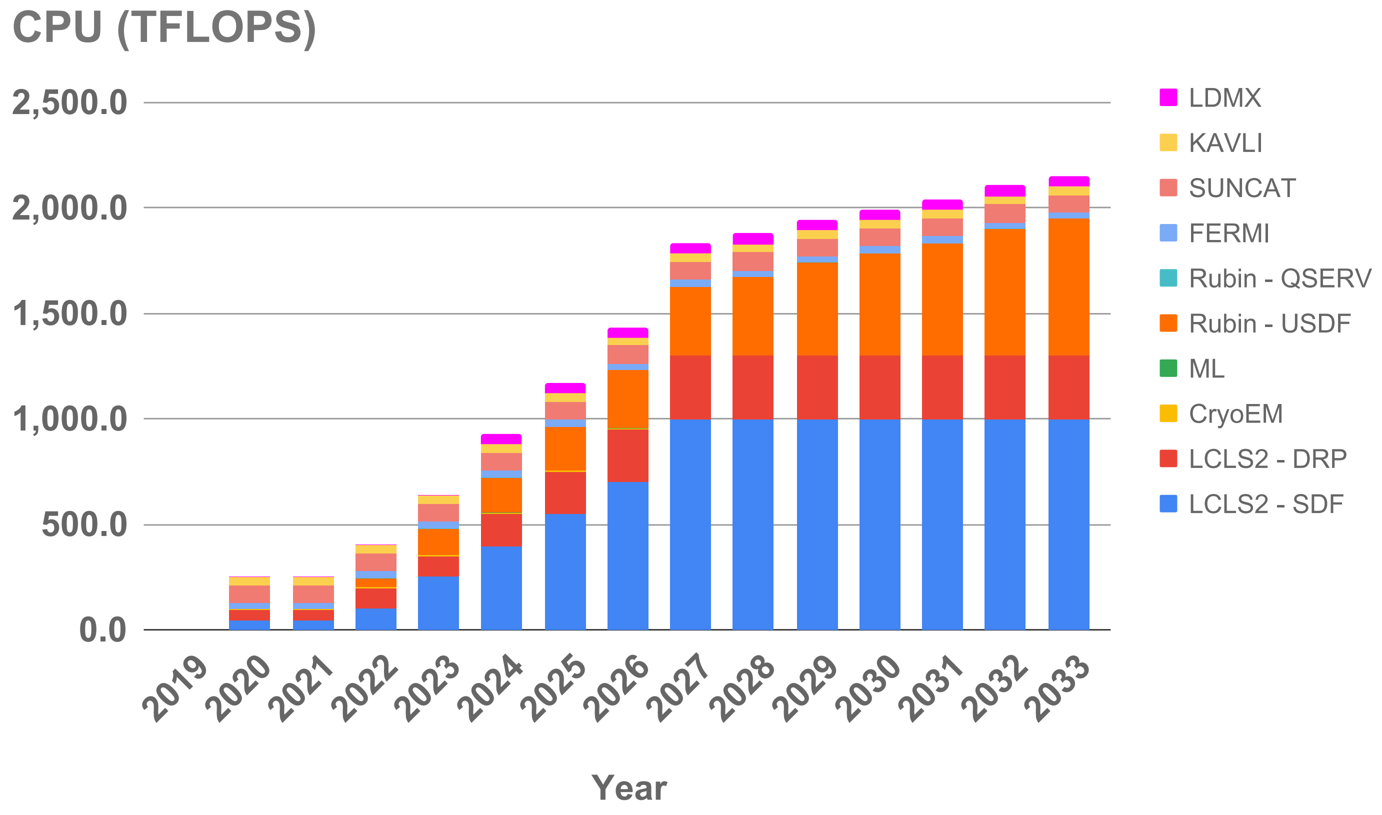
- SLAC Shared Scientific Data Facility (SDF)
- LDMX distributed computing pilot project:
  Lightweight Distributed Computing System (LDCS)
  arXiv:2105.02977 **[hep-ex]**

ldmx-sw: C++ software framework for event generation and reconstruction

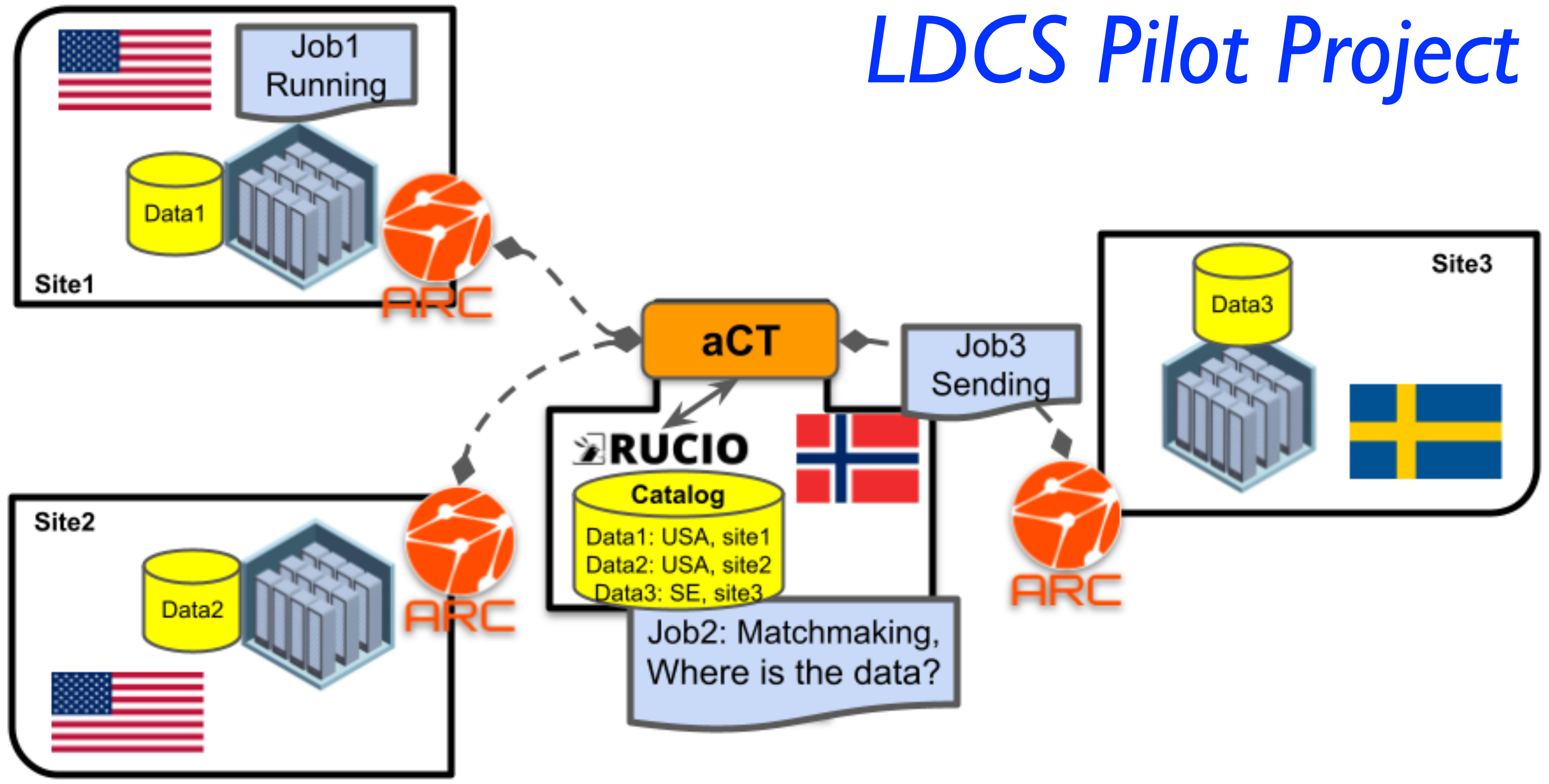
https://github.com/LDMX-Software/ldmx-sw/

SLAC Shared Scientific Data Facility (SDF)





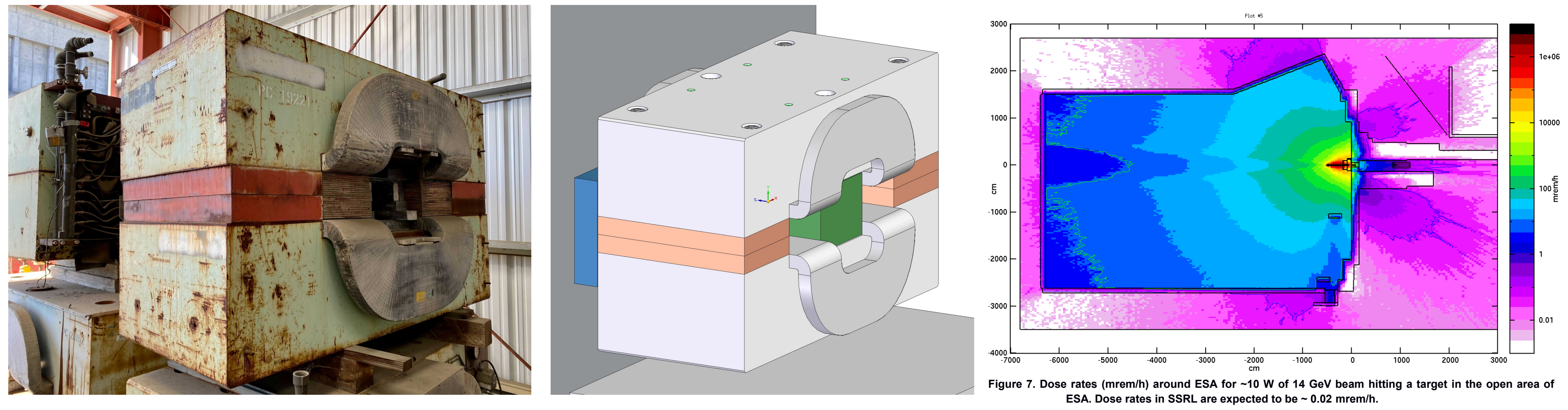
LDCS Pilot Project



LDMX DMNI Project Plan: technical development

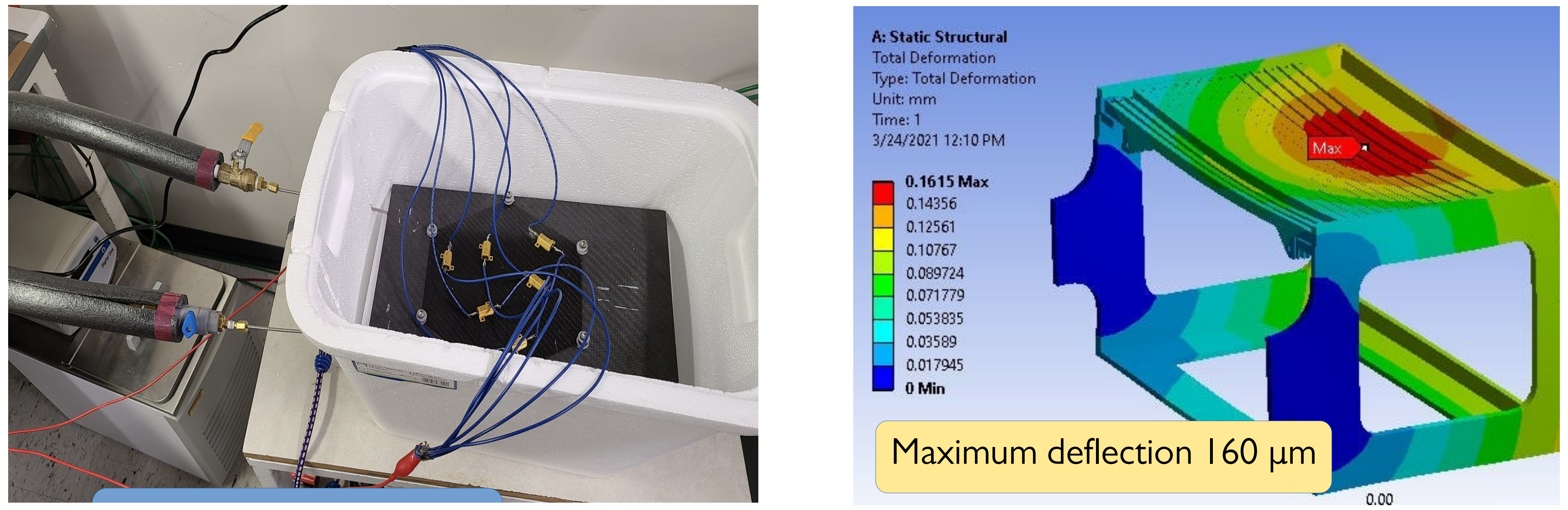
LDMX DMNI project consists of development work required to adapt existing technologies and prepare a design report and execution plan ready to be reviewed and baselined for a small project fabrication, as well as final engineering work that enables the immediate start of construction.

Beamline: magnet design and radiation studies



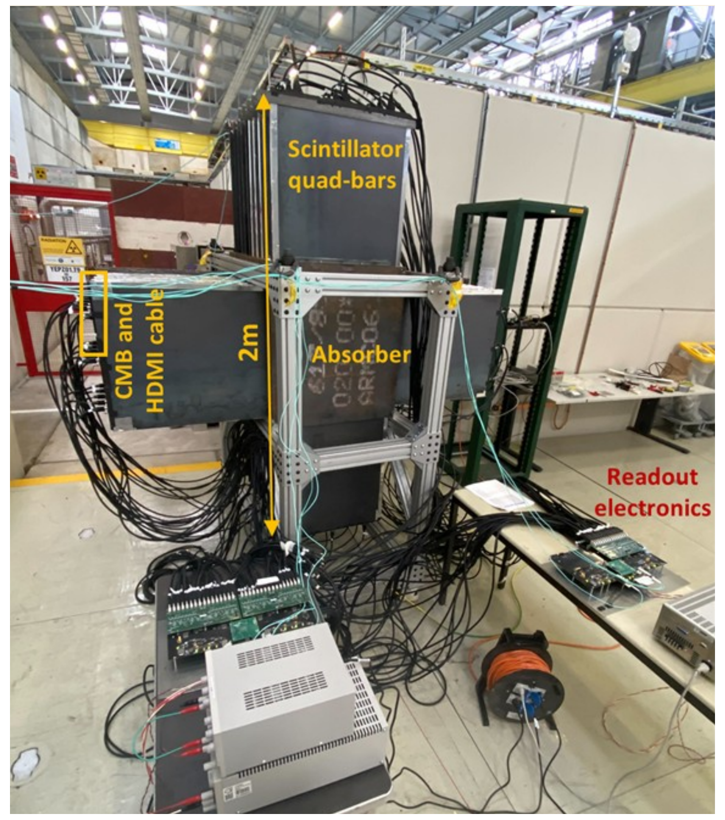
ECal/HCal/Trigger Scintillator: readout prototypes

ECal cooling tests and mechanical studies

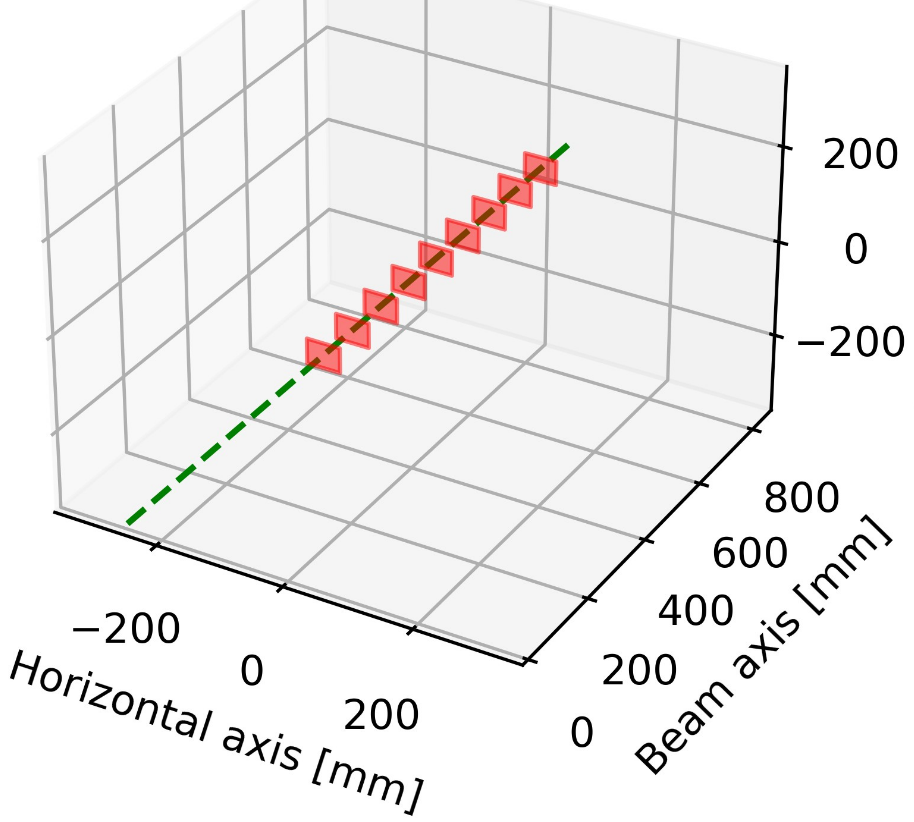


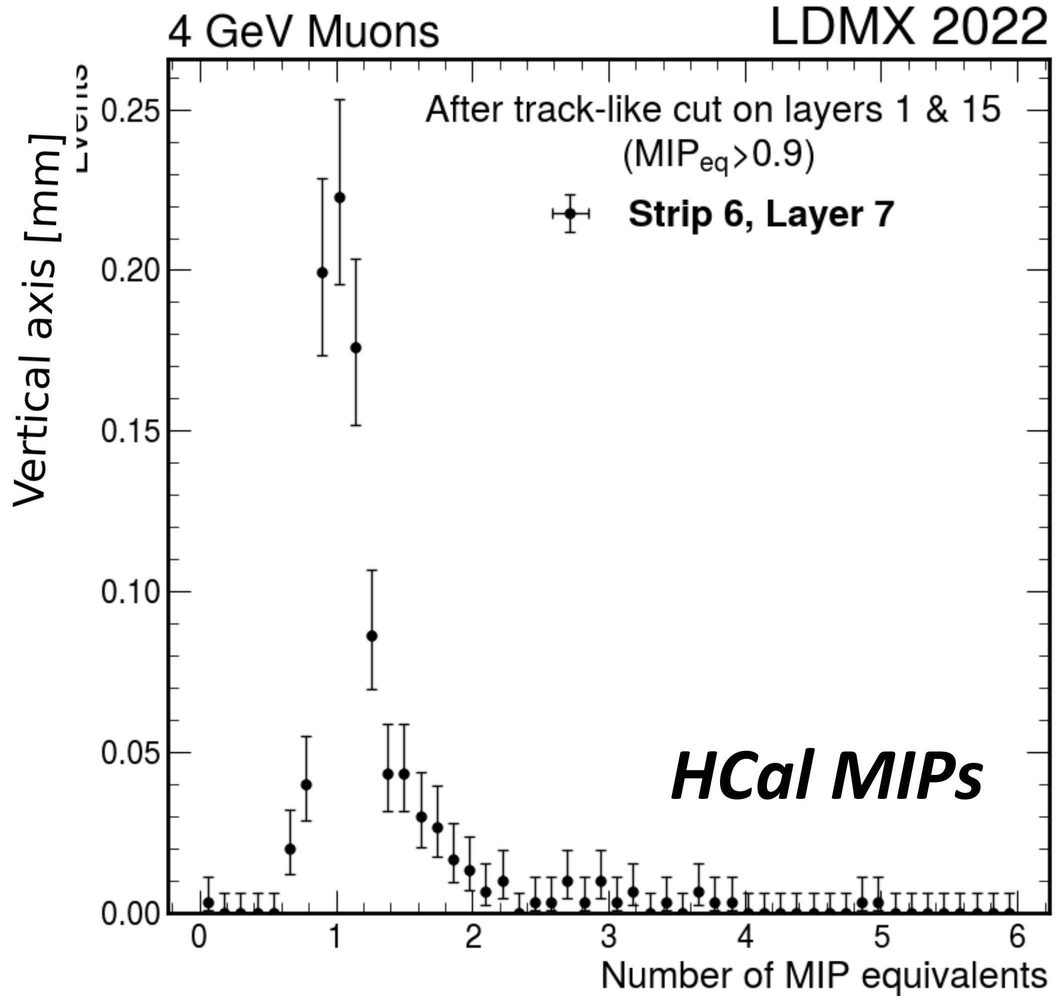
LDMX Test Beam at CERN

HCal prototype



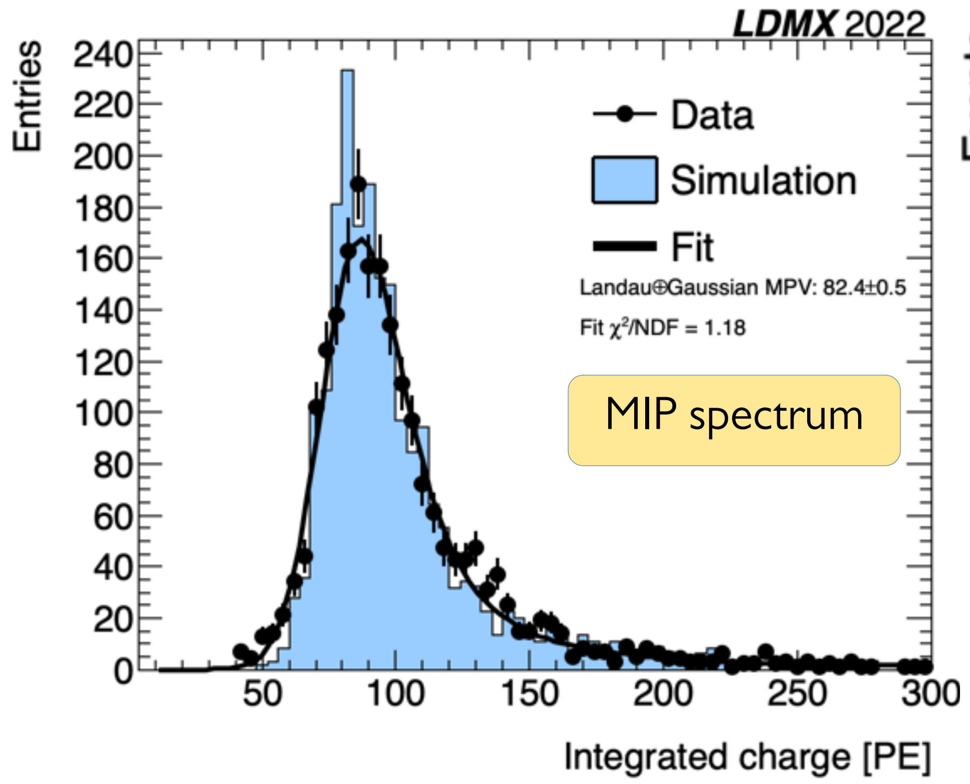
HCal MIPs



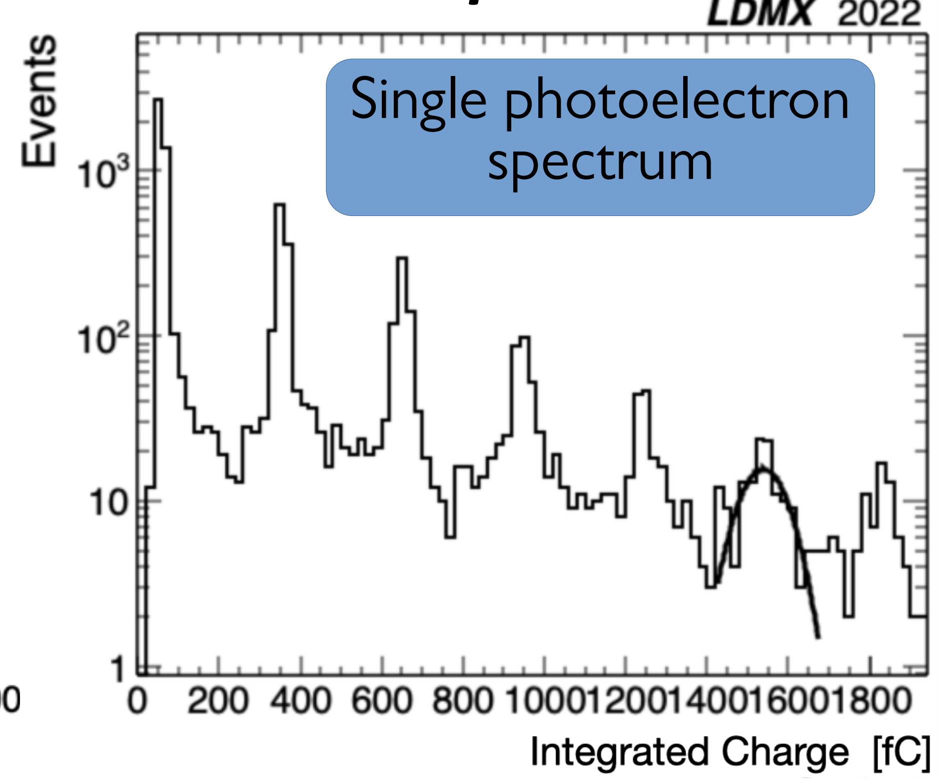


Trigger Scintillator (TS) prototype

TS MIPs



TS PE spectrum



CERN Status and Timelines

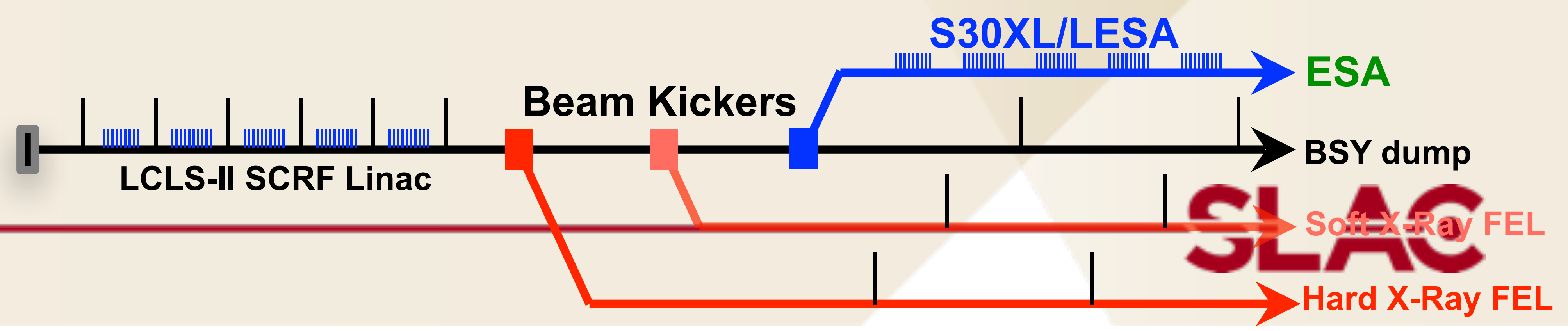
SLAC

A very nice talk by Mike Lamont for Snowmass outlines the planned and potential facilities at CERN for these experiments:

			2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
		SPS	LS2						LS3					
		LHC	LS2		Run 3				LS3			Run 4		
North Area	NA64-electron	Operational	LS2		Data Taking									
	NA64-mu	< 1 MCHF	Studies		Test	Pilot	Phase 1							
	NA61/Shine	< 2 MCHF	Detector upgrade		Data Taking					Data Taking				
	MUonE	< 2 MCHF	Preparation		Pilot	Run 1	Data Taking							
	NA62-beamdump	< 1 MCHF	Studies		1e18 PoT in Run 3									
	KLEVER	~40 MCHF	EoI/proposal		R&D/Construction				Installation	Data Taking				
	COMPASS++	~10 MCHF	Studies/proposal		Phase1 Data Taking/Studies/R&D				Installation	Data Taking				
LHC	ALICE fixed target	<5 MCHF			Design/tests				Preparation/Construction			Data Taking		
	LHCb fixed target	<5 MCHF		Design	Construction and testing			Data	LS3			Data Taking		
	LHC Spin	~5 MCHF	Study		R&D				Production/Installation			Data Taking		
	FASER	~5 MCHF	Installation		Data Taking				Upgrade - phase 2			Data Taking		
	MATHUSLA	<100 MCHF		Funding to test design			Construction					Data Taking		
	CODEX-b	<5 MCHF	EoI		Beta		Beta data taking		Production/Installation			Data Taking		
	MilliQan	<5 MCHF	Demonstrator		Funding/Construction				Upgrade			Data Taking		
SPS	LDMX/eSPS	<10 MCHF			Studies		Production/Installation			Data Taking				
	SHiP	~70 MCHF	CDR		TDR/Prototypes			Production/construction			Installation		Data Taking	
	TauFV	tbc	Design		CDR	TDR/Prototypes		Production/construction			Installation		Data Taking	
TECH	BabyIAXO (DE)	<5 MCHF		Production/construction			Commission	Data Taking						
	IAXO	~60 MCHF					Design, prototyping, construction, integration and commissioning (start tbc)							
	VMB	<5 MCHF	LoI	Studies										
	AION-100	tbc			Studies									
FACILITY	AWAKE	~15 MCHF	Prep/construction		AWAKE Run 2				LS3	AWAKE++?				
	eSPS	~80 MCHF	CDR		TDR		Preparation/Construction			Data Taking				
	Beam Dump Facility	~160 MCHF	CDR	TDR			Construction/Installation						Operation	
	Gamma Factory	~2 MCHF		CDR	SPS Proof of Principle/TDR				Preparation			LHC demo		
	nuSTORM	>160 MCHF	Study	CDR		TDR/Prototyping						Approval		
	CPEDM prototype (DE)	~20 MCHF	Study	CDR		TDR		Construction		Data Taking				

https://indico.fnal.gov/event/44819/contributions/193721/attachments/132920/163635/DS-facilities-RF6-kickoff.pdf

LDMX: Origins



Light Dark Matter eXperiment searches for sub-GeV thermal relics, with sufficient sensitivity to fully explore couplings implied by the observed relic abundance across the MeV-GeV mass range.

LDMX was proposed in 2016 using technologies developed for other experiments and unused bunches from LCLS-II drive beam to minimize cost, risks, and time to completion.

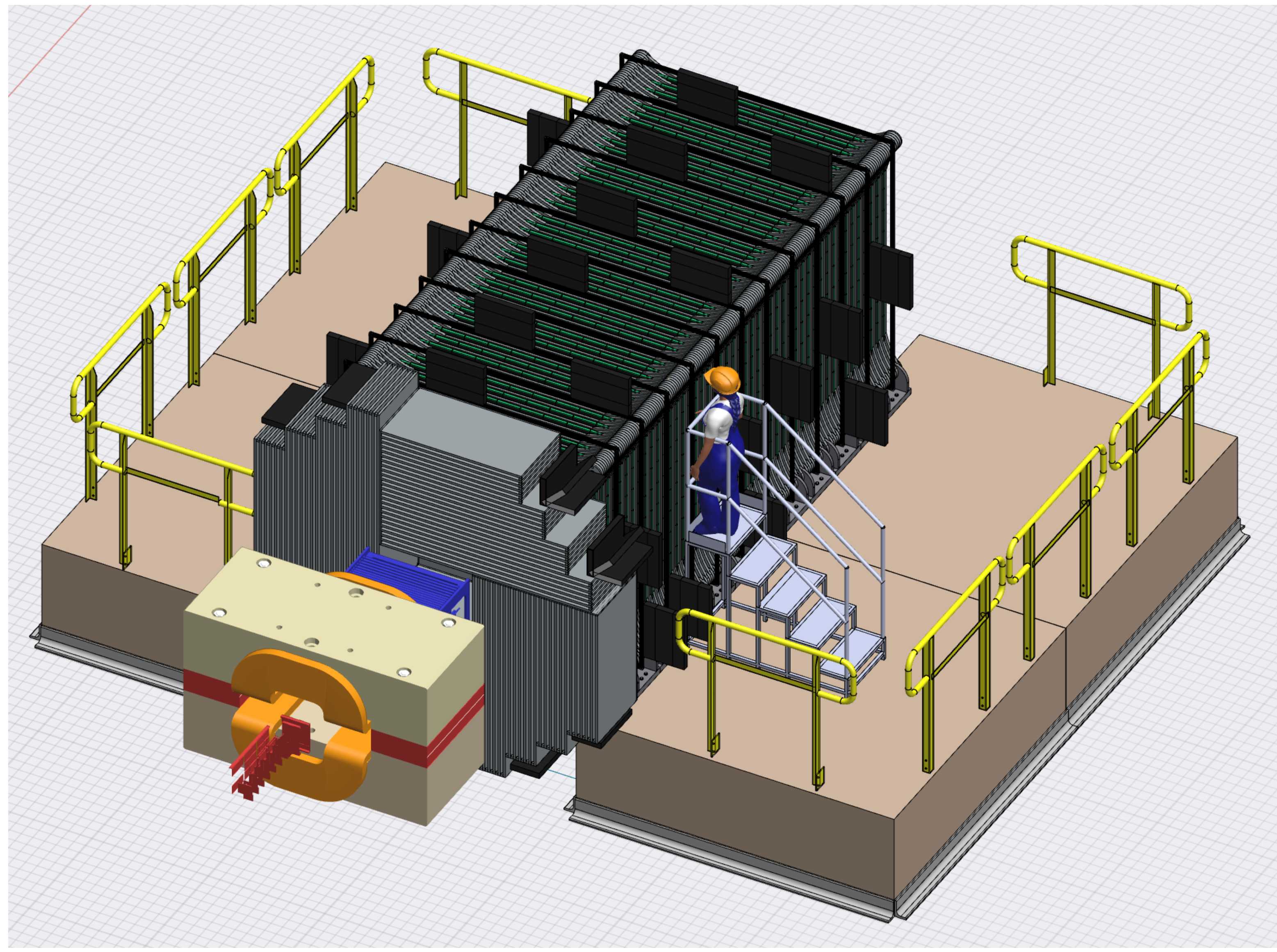
Partly in response to LDMX, DOE decided to develop a clear mandate for new small projects in DM using the Basic Research Needs process:

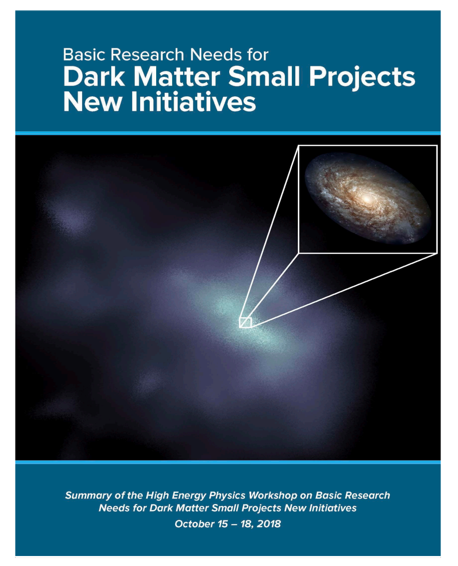
1. A community workshop (US Cosmic Visions: New Ideas in Dark Matter 2017)
2. A DOE Commissioned Panel Report (Basic Research Needs for Dark Matter Small Projects New Initiatives)

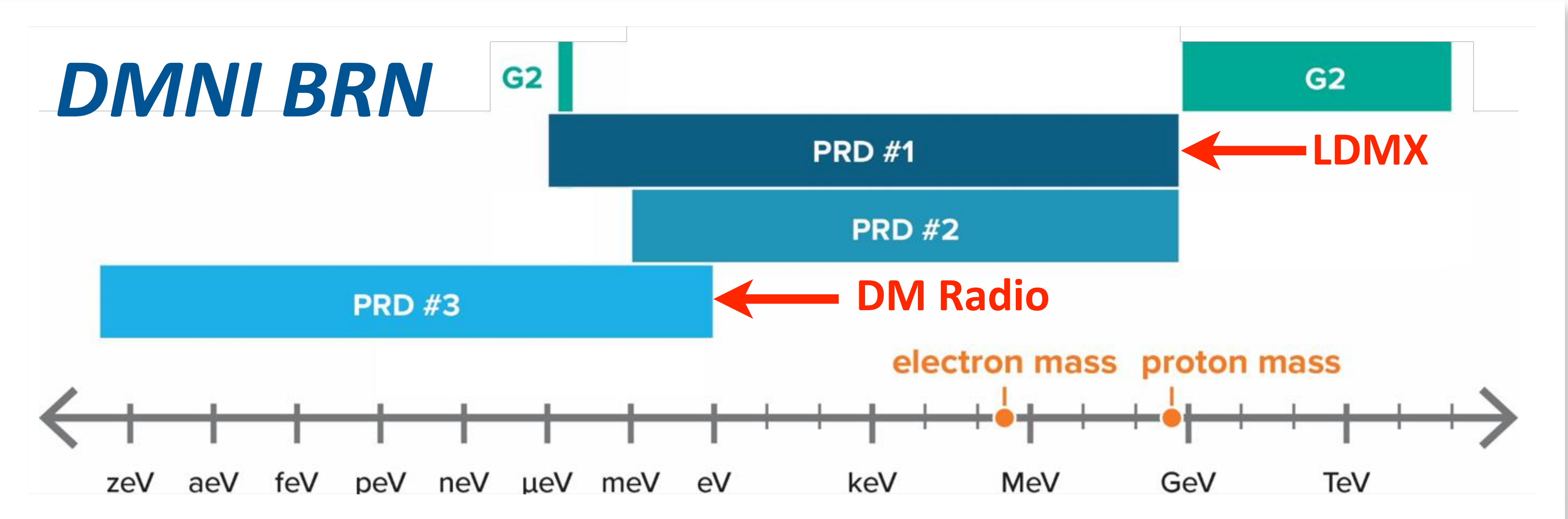
DOE then created a program to develop a set of Small Projects to address the Priority Research Directions (PRD) identified by the BRN with a FOA in 2019: the "DMNI Program"

SLAC-led LDMX proposal was one of six proposals chosen - two from each PRD. (DMRadio was another)

FOA defines a two year design/development phase culminating in a design report to be reviewed for construction.







PRD 1: Create and detect dark matter particles below the proton mass and associated forces, leveraging DOE accelerators that produce beams of energetic particles.

Thrust 1 (near term): Through 10- to 1000-fold improvements in sensitivity over current searches, use particle beams to explore interaction strengths singled out by thermal dark matter across the electron-to-proton mass range.

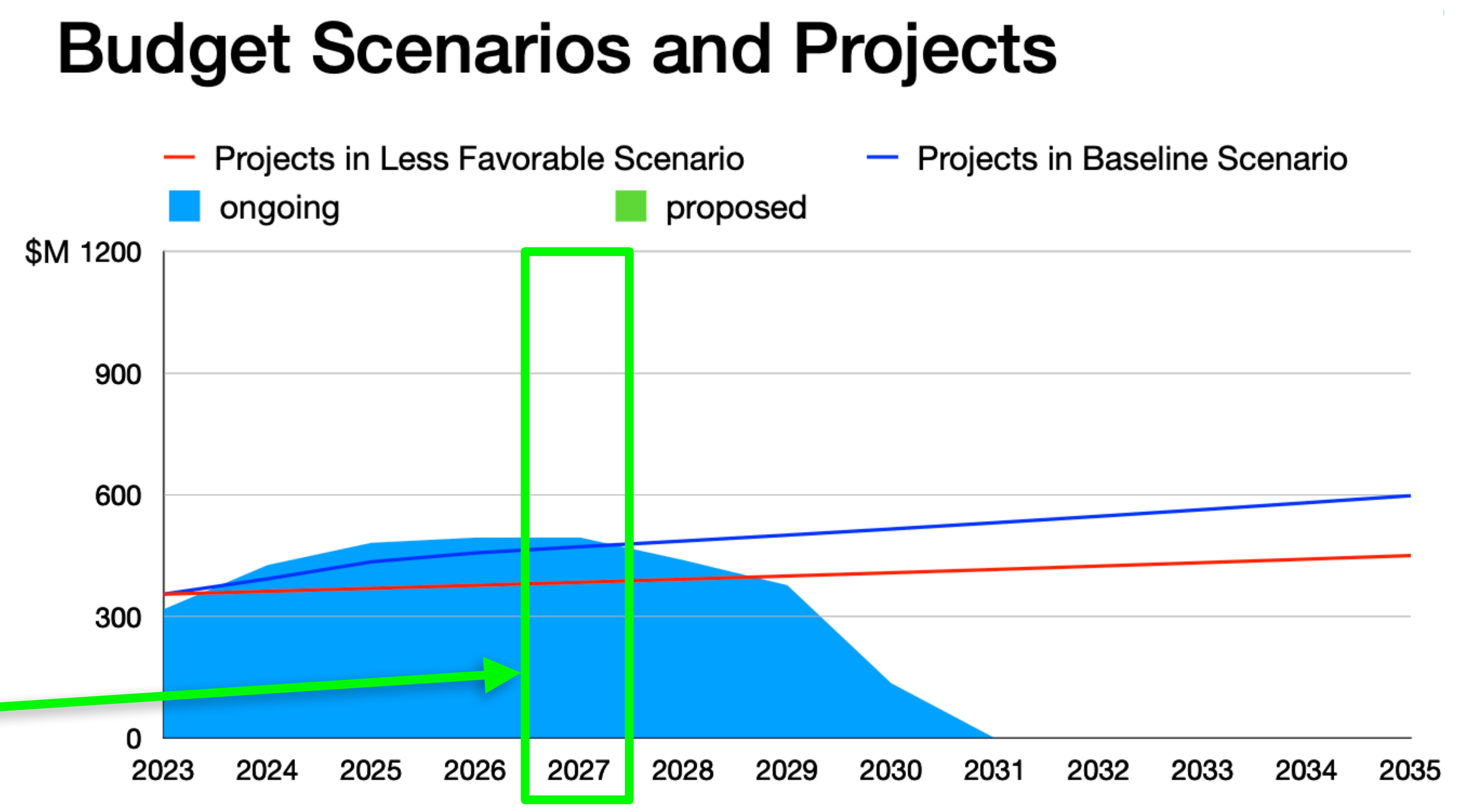
LDMX: pre-P5 Progress/Status

Due to tight budget, planned profile for LDMX DMNI design phase was stretched from two years to three (FY20-F22).

Subsequent shortfalls have stretched out the design phase through at least FY24. Silver lining: this has allowed for more thorough design, prototyping, and performance studies for the design report than initially planned.

Starting in Summer 2023, we began receiving the following guidance:

- CD0 in FY25 (probably of entire DMNI based on statements of BRN)
- Other Project Costs (OPC) funding (design and development) in FY26
- Constructing funding available in FY27 at earliest



This guidance applies to all of the DMNI projects, which have similar scale (~$20M TPC w/ contingency).

During P5 process, some important issues were covered at Town Halls and in discussions with panelists, related to the timeliness (cadence) and effectiveness of the small projects portfolio as demonstrated by the DMNI experience.

- Lack of clear mandate/process for pursuing smaller projects.
- Unclear budget outline for small projects portfolio.
- Difficulty in defining appropriate project oversight for smaller projects (413.3b is the only tool DOE knows).

The 2024 P5 report makes a serious attempt to address these!