

Dark Matter Searches at LDMX

With a little commentary on HPS

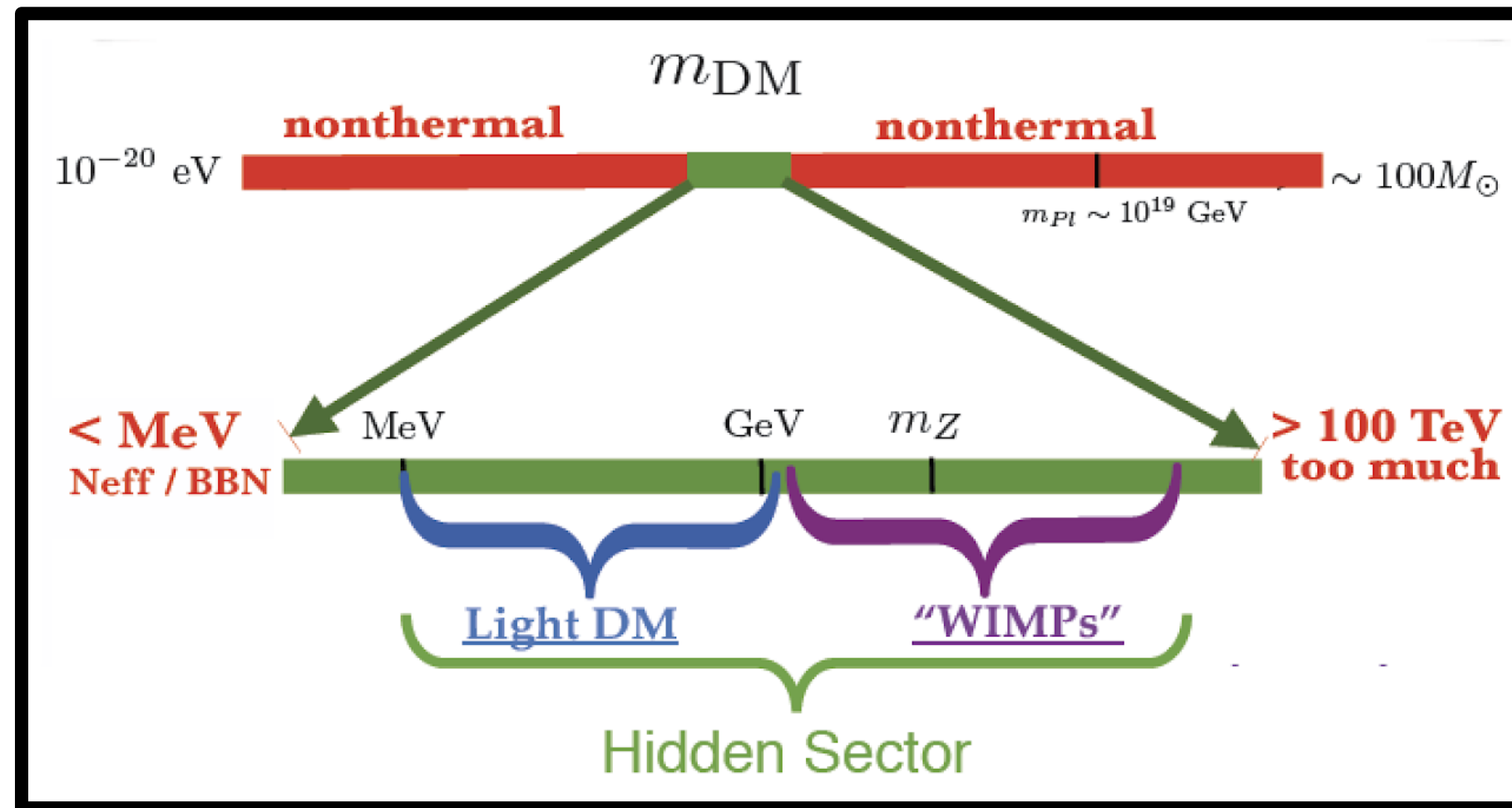
Lauren Tompkins, Stanford University

Accelerating the Search for Light Dark Matter Community Workshop

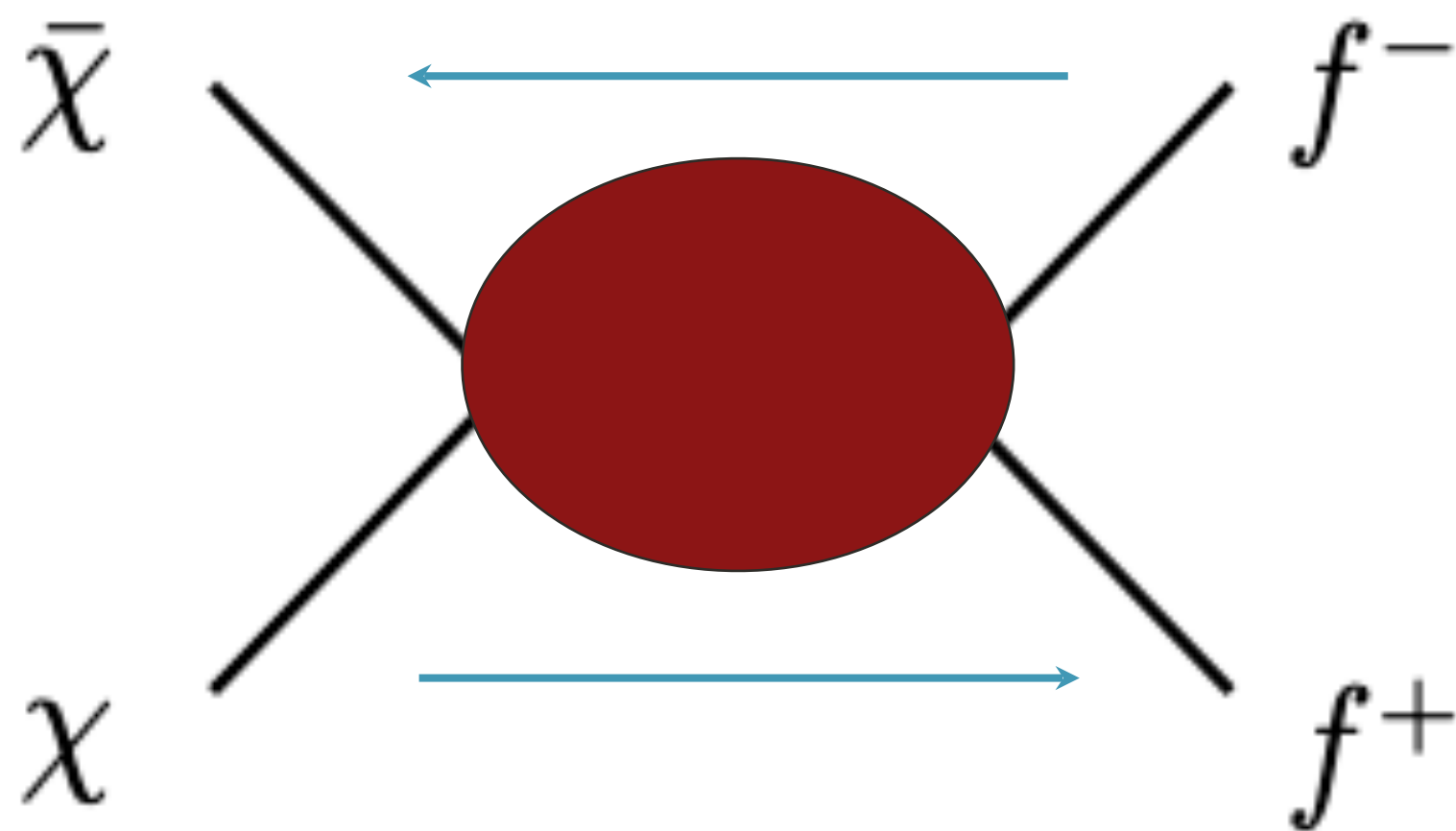


Thermal Relic Dark Matter Beyond WIMPs

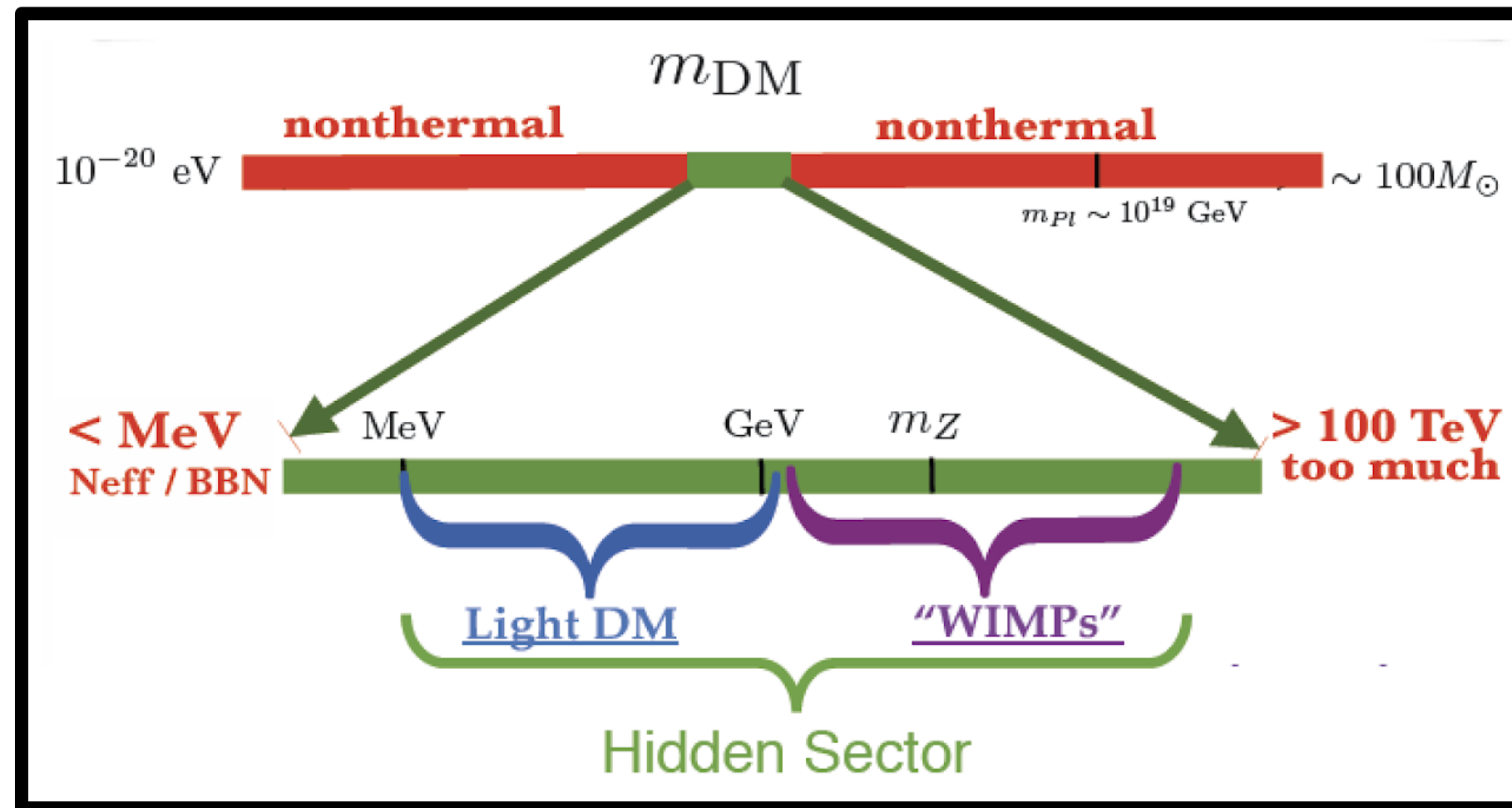
Thermal Relic Dark Matter Beyond WIMPs



Thermal relic dark matter is a compelling explanation for the DM abundance

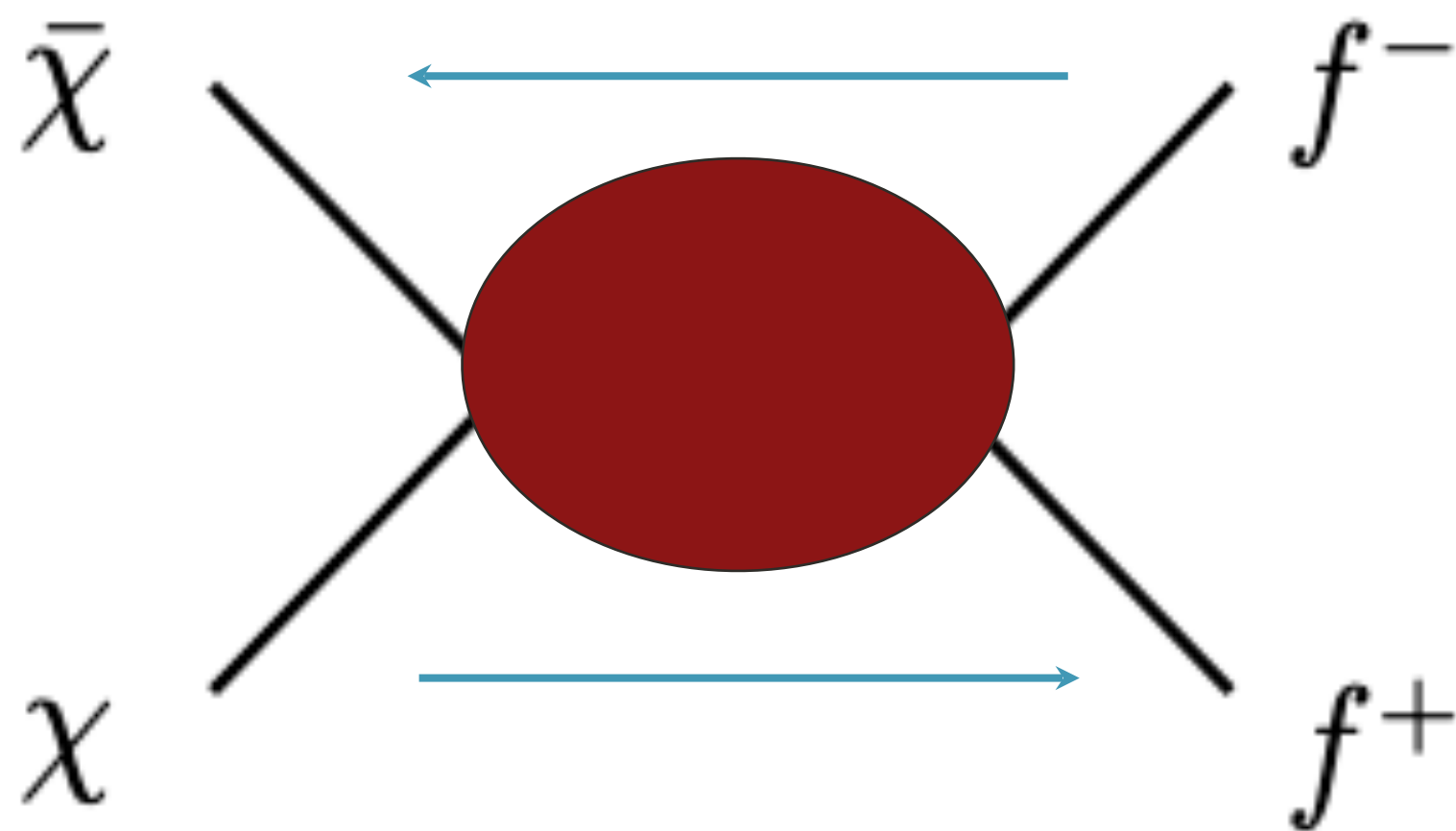


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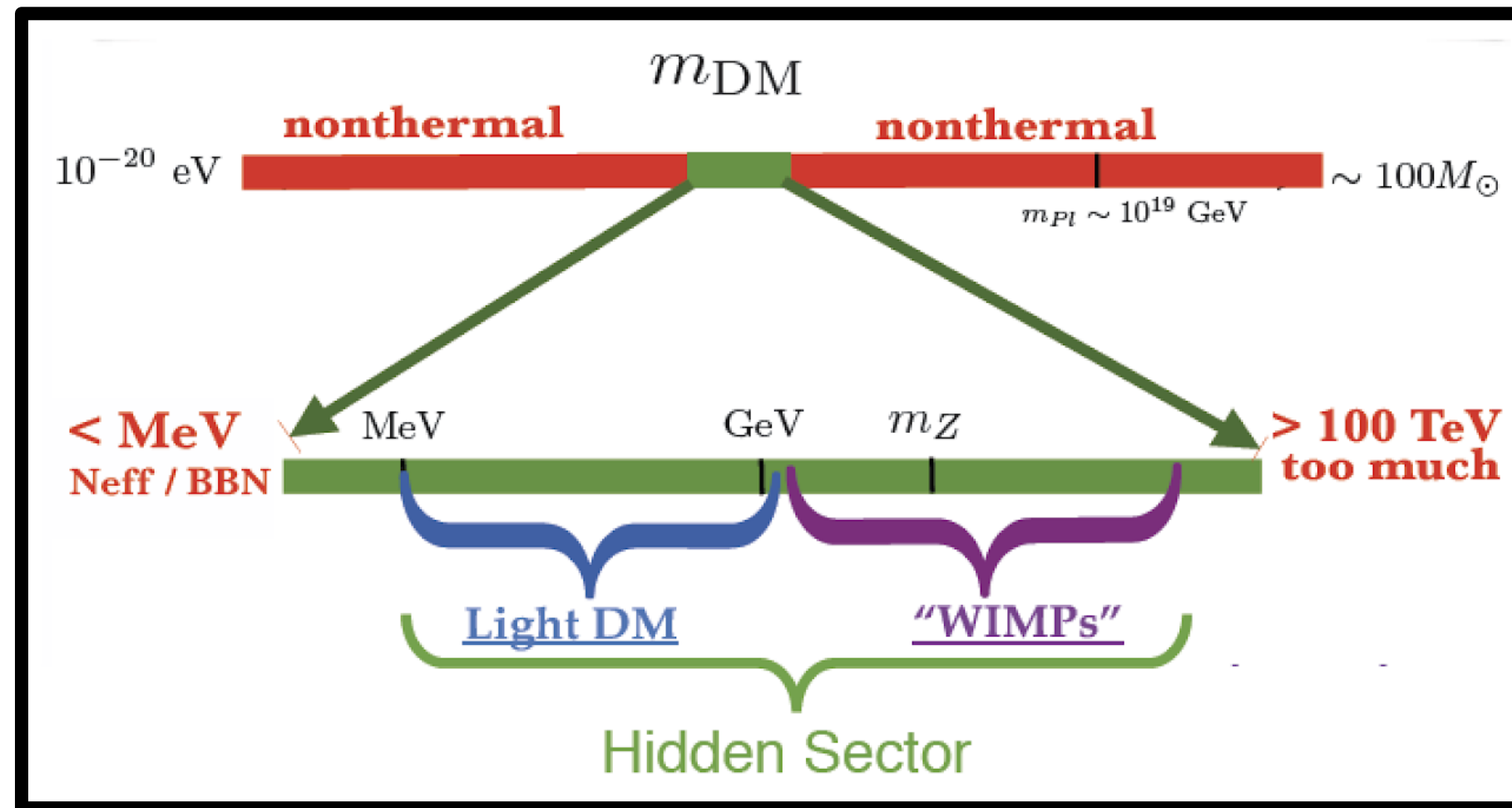


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★ Simple

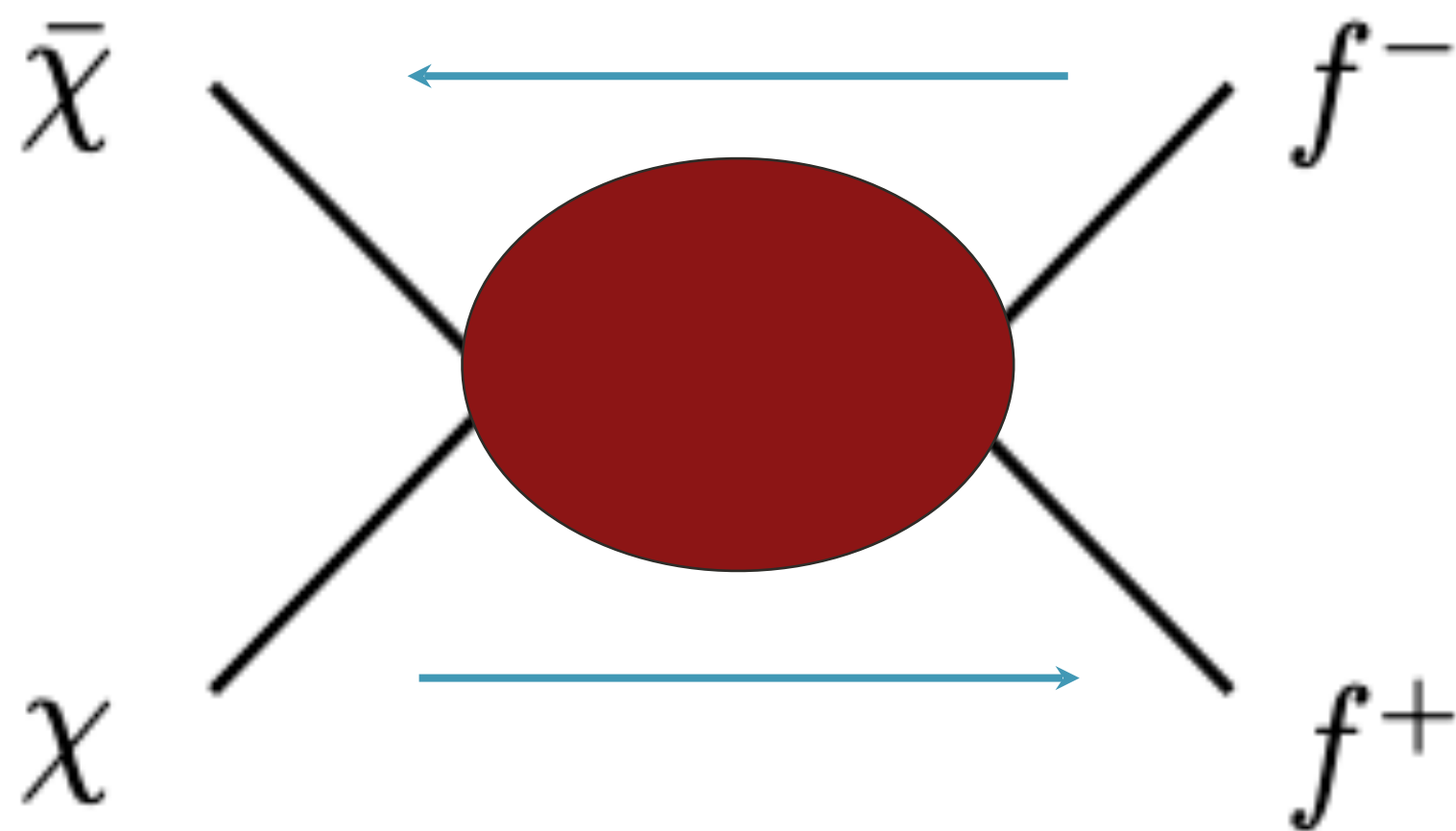


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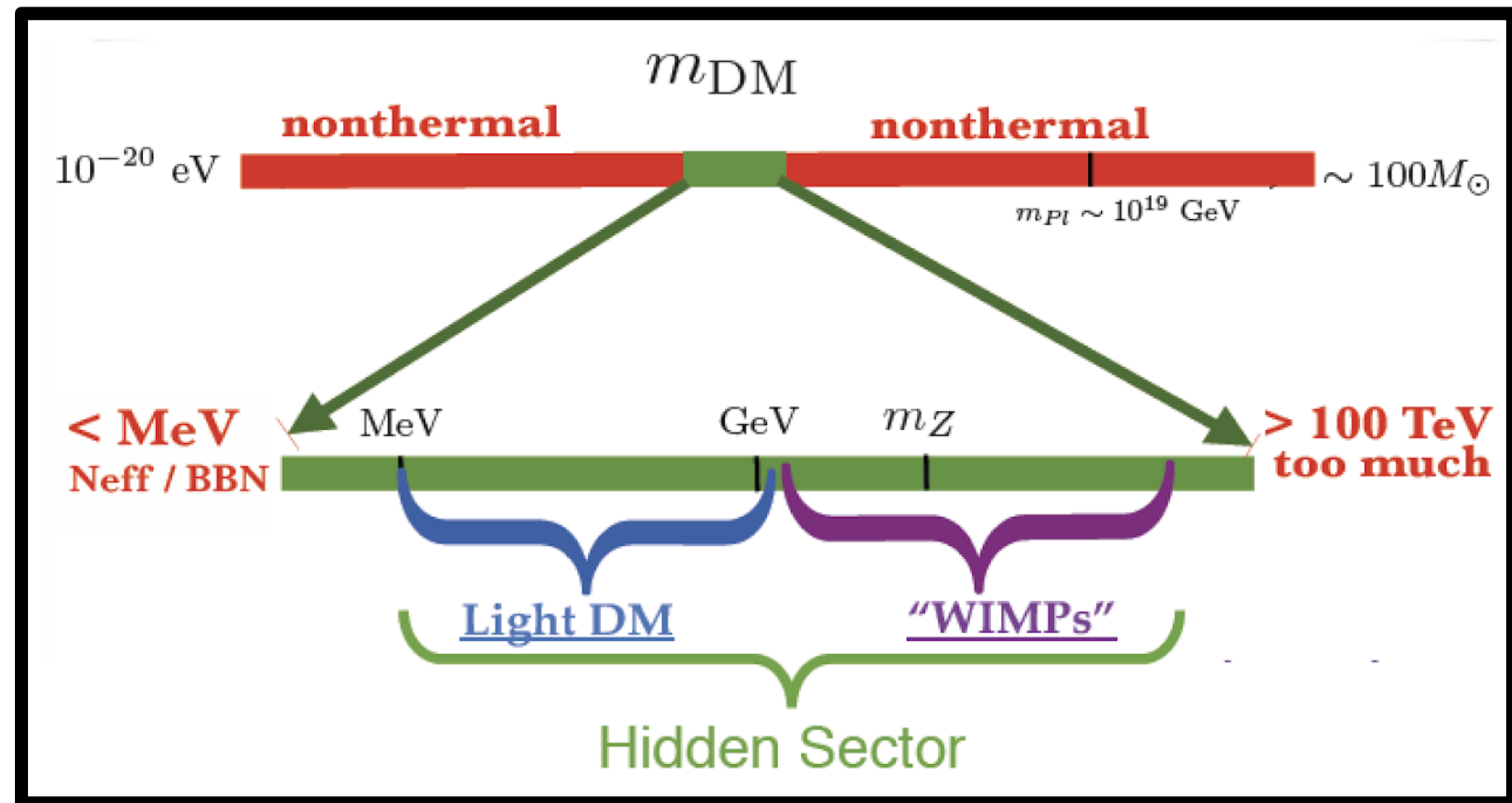


Thermal relic dark matter is a compelling explanation for the DM abundance

- ★ Simple
- ★ Generic

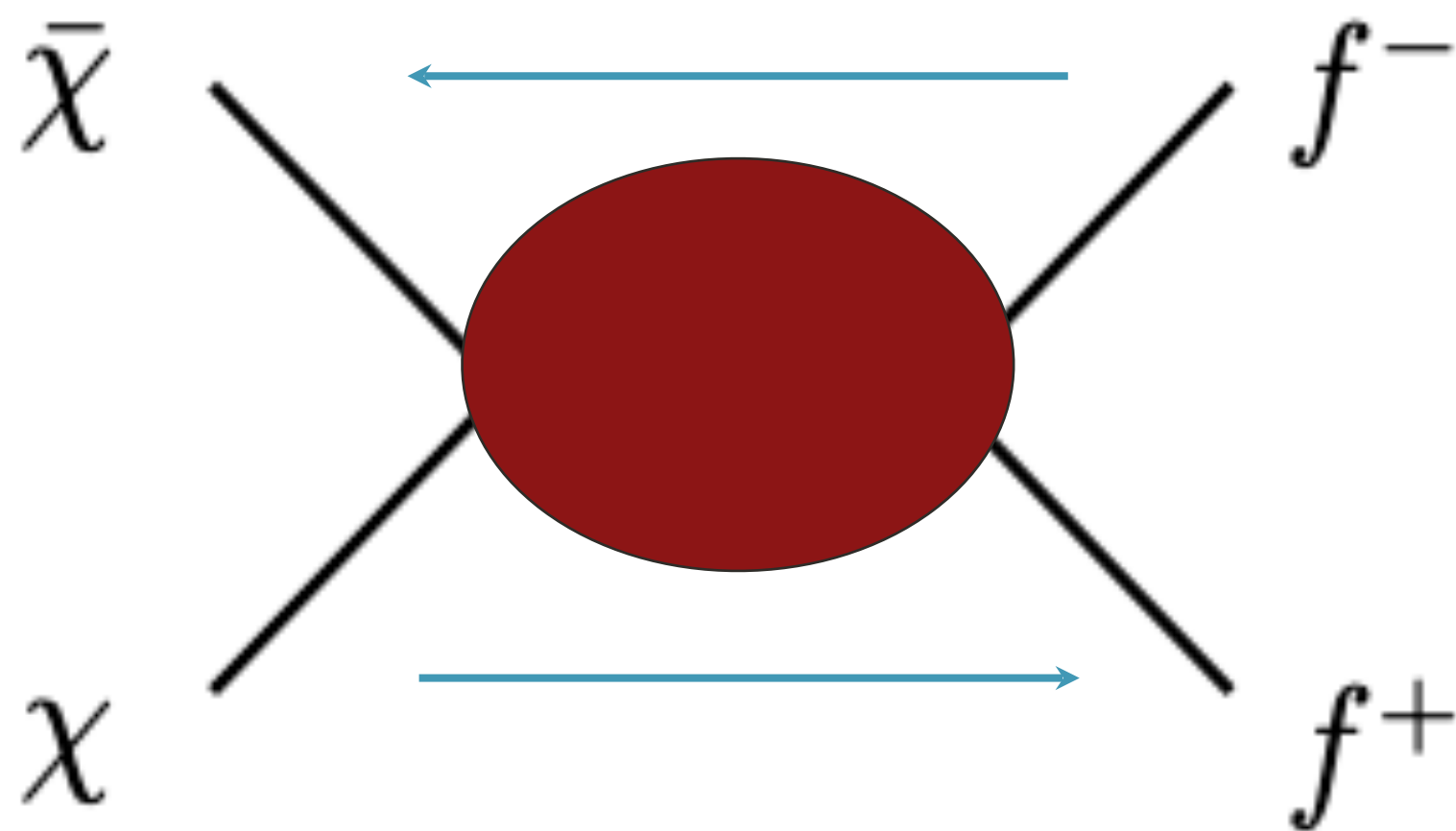


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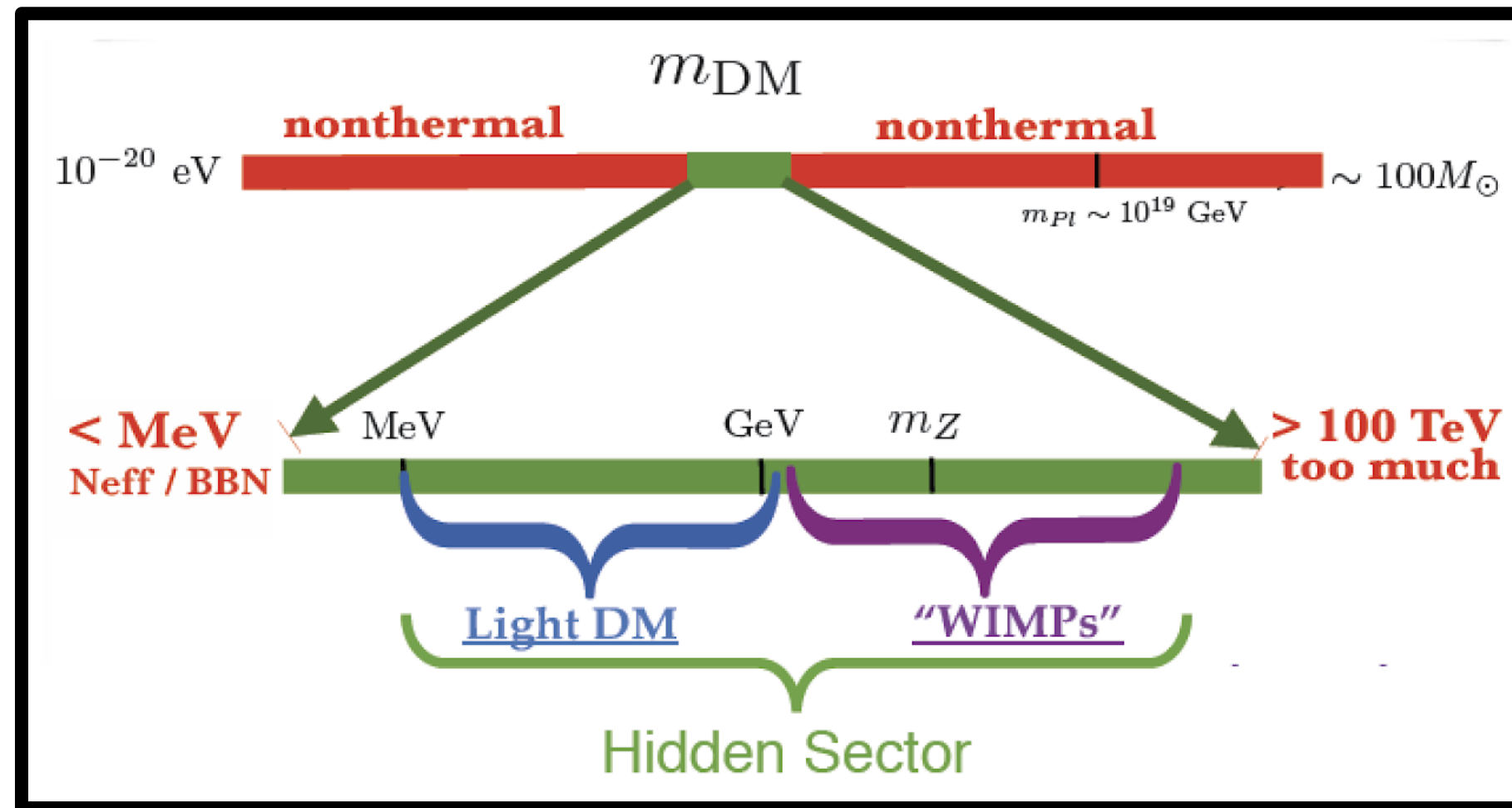


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- ★ Simple
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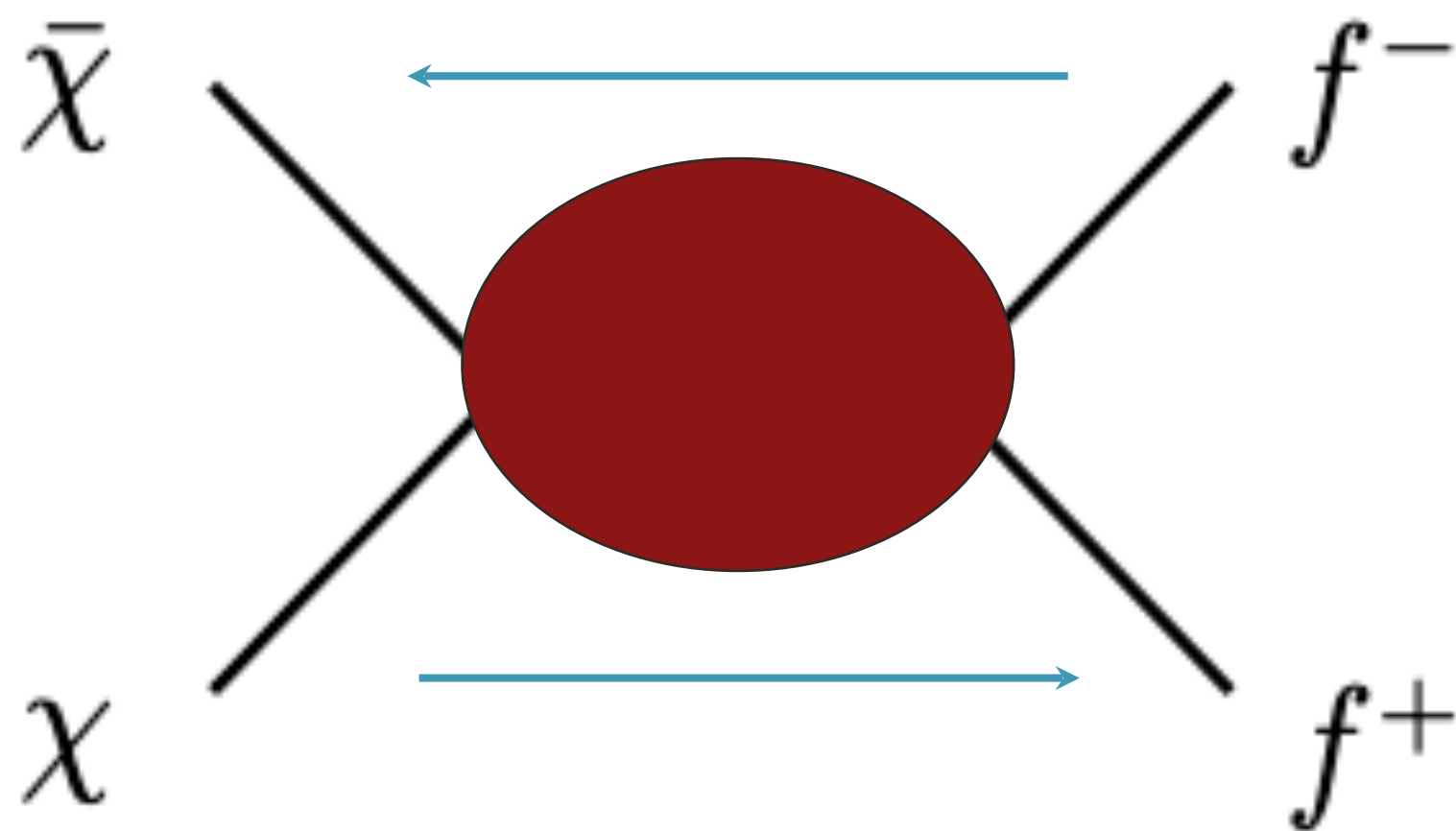


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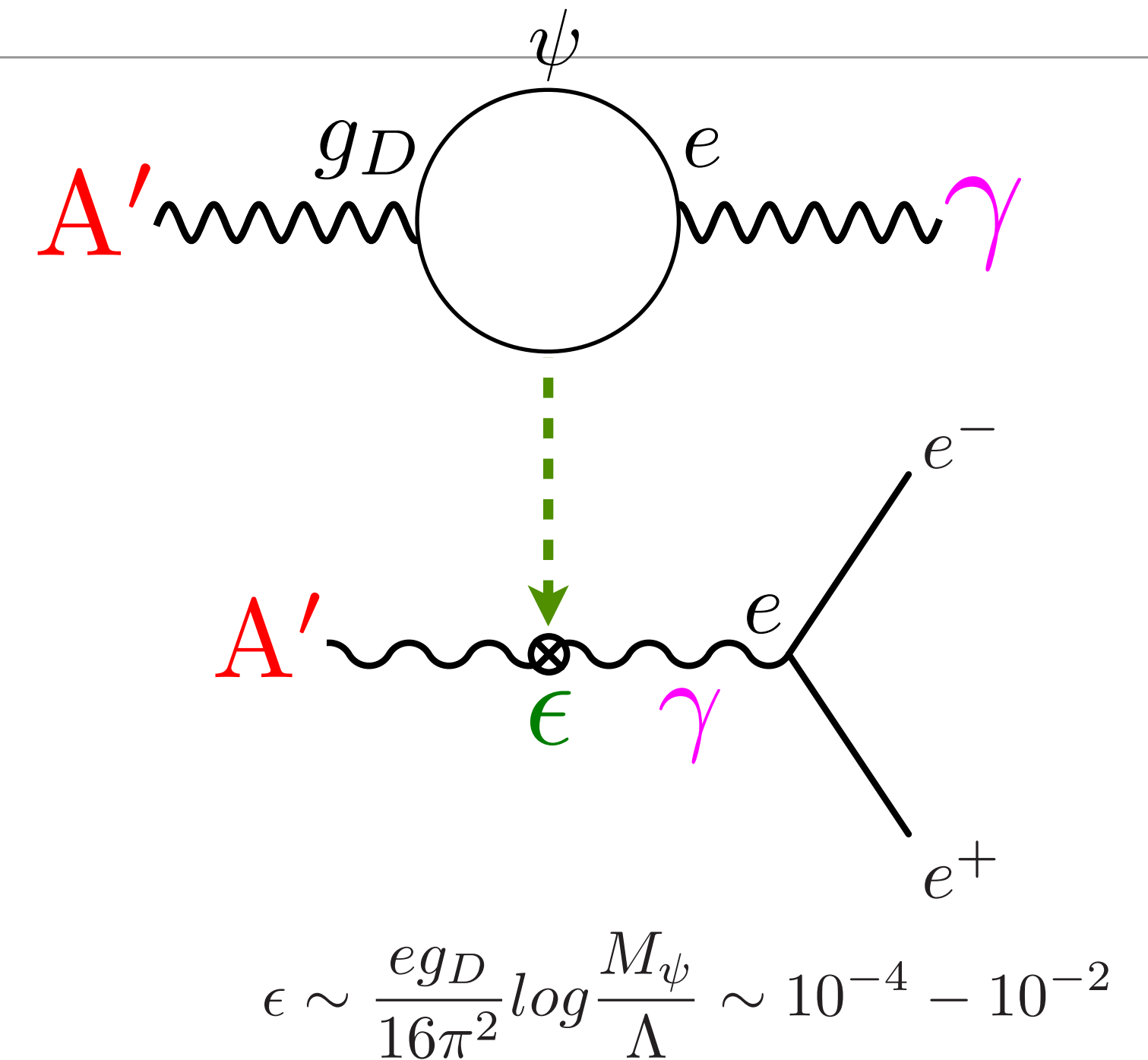
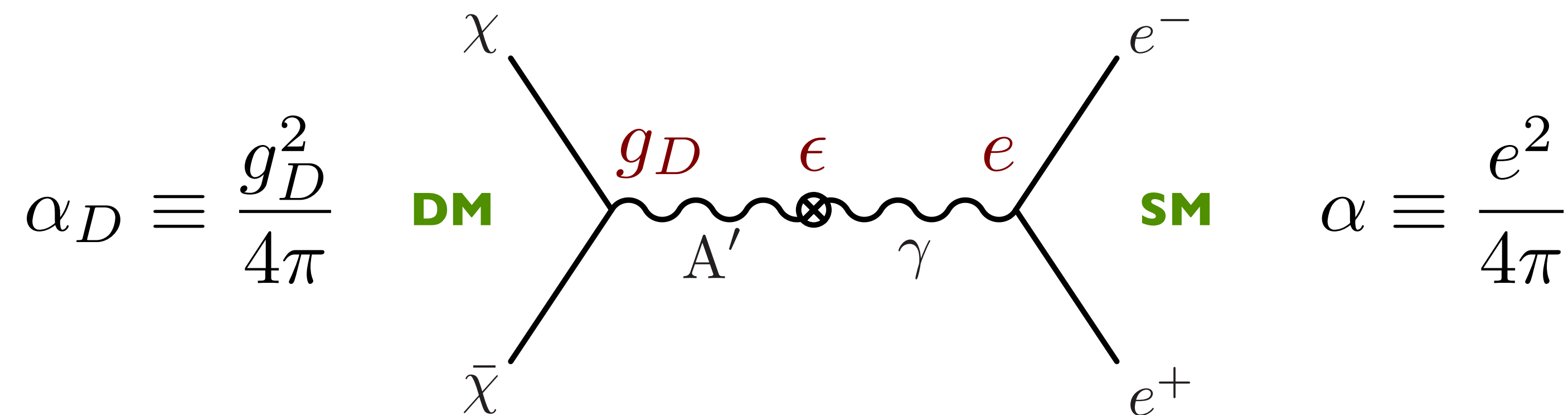
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- ★ Simple
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- ★ Consistent

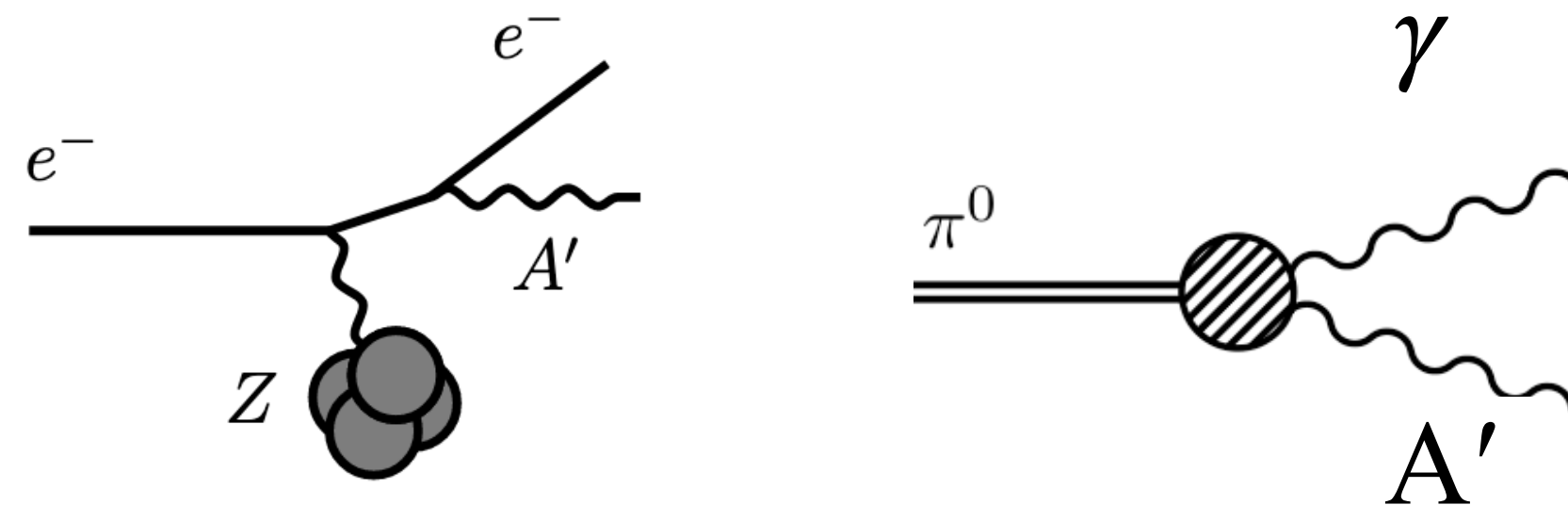


Dark photons as mediators

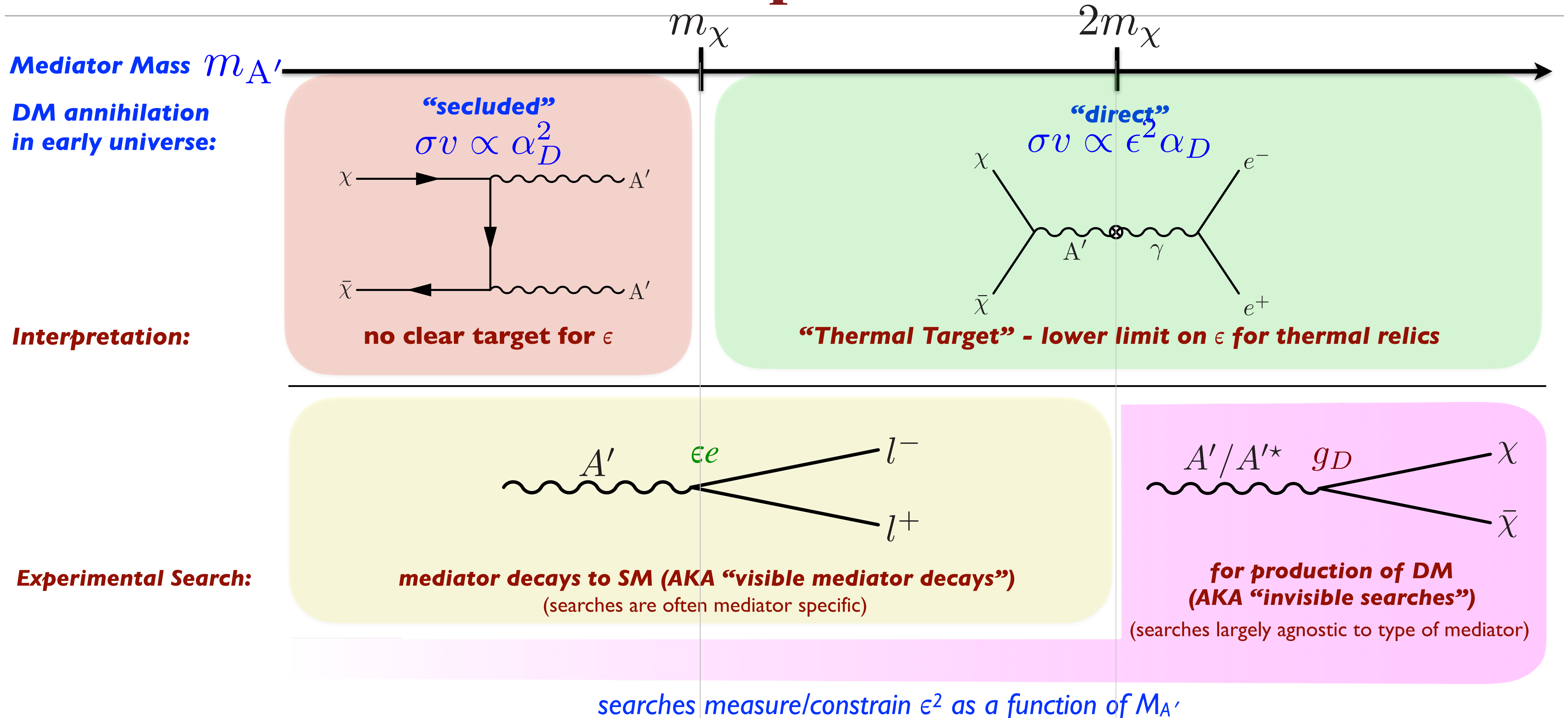
- New U(1) dark sector $\Rightarrow$ dark photon can kinetically mix with photon:



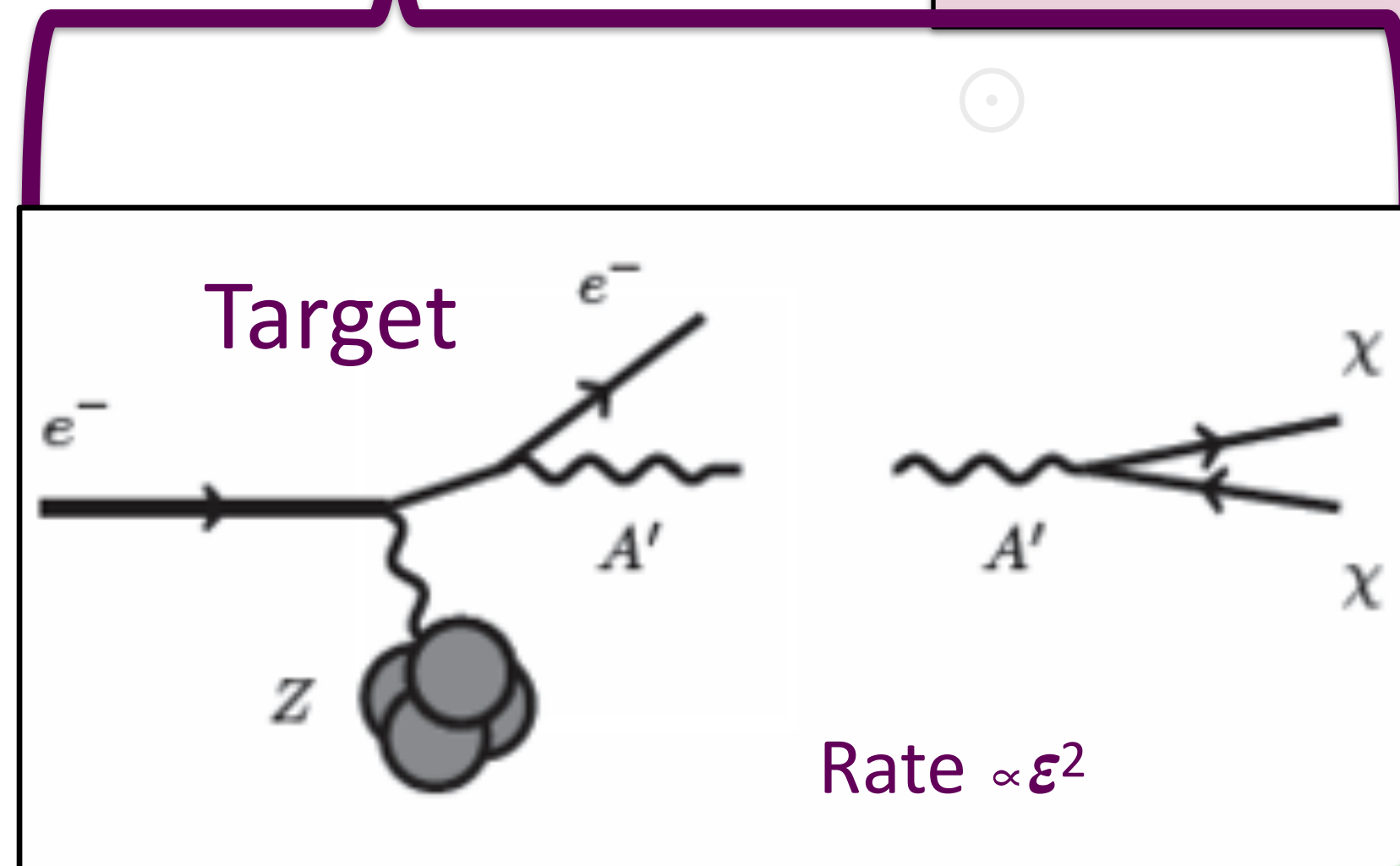
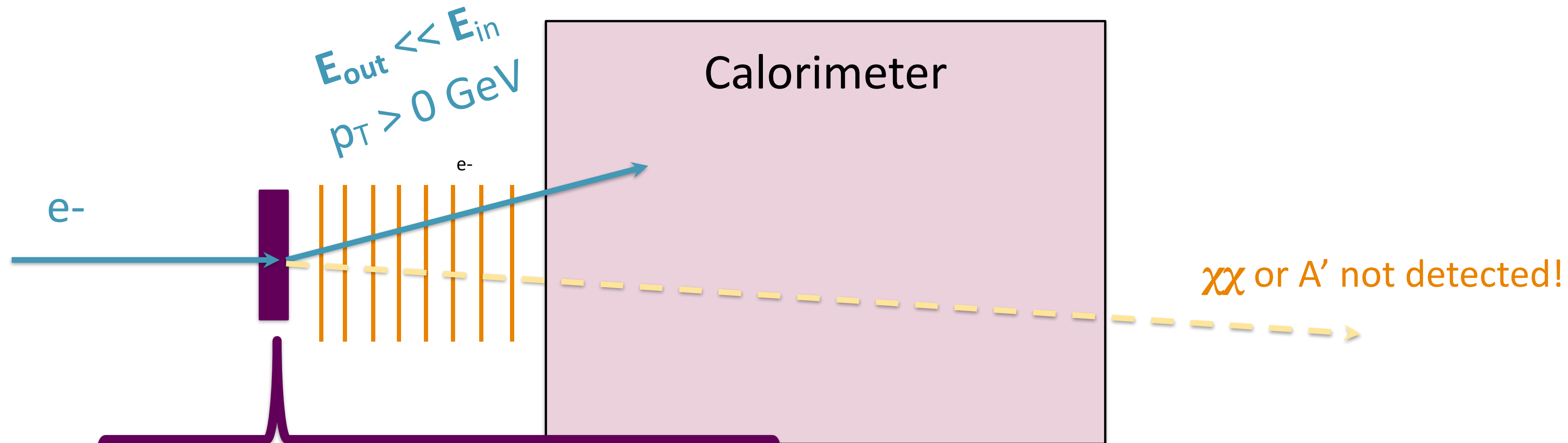
- Then can produce dark photons with production rate $\propto \epsilon^2$



Dark Photon Parameter Space



The missing momentum concept



Advantages of the missing momentum approach:

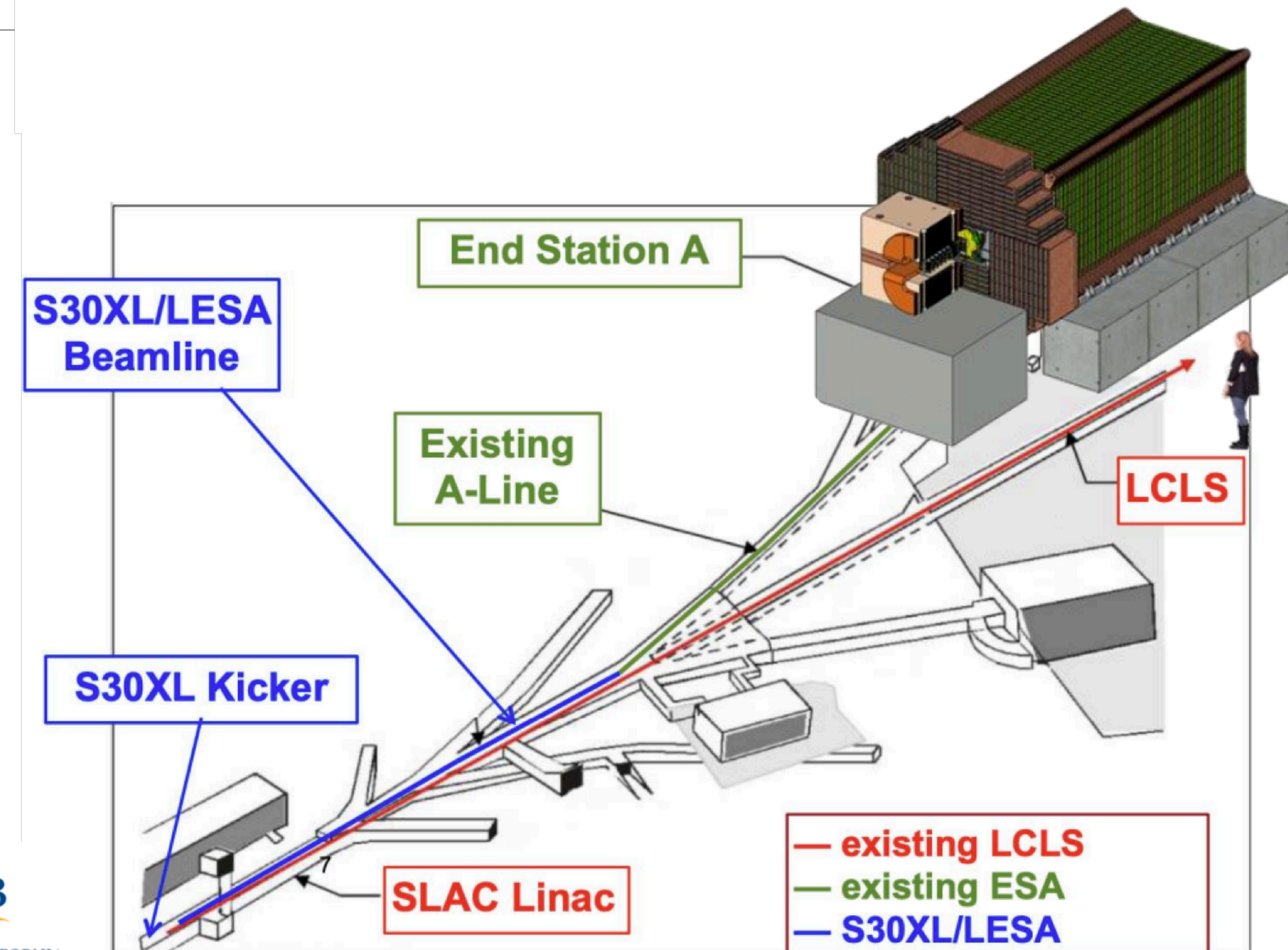
- A' only needs to interact once
- Precise recoil electron reconstruction is a powerful discriminant against backgrounds

Disadvantage: thin target means lower cross-section

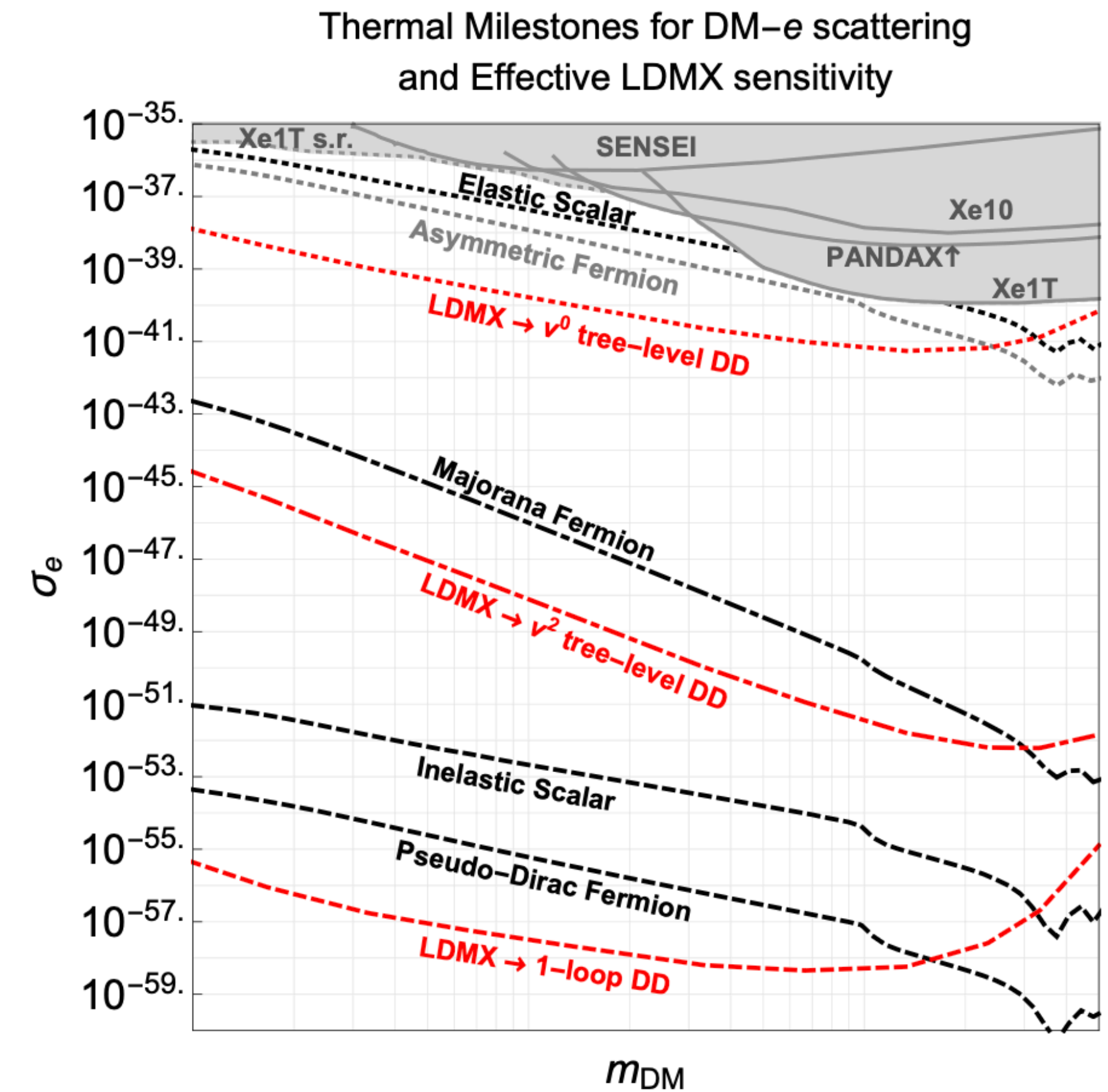
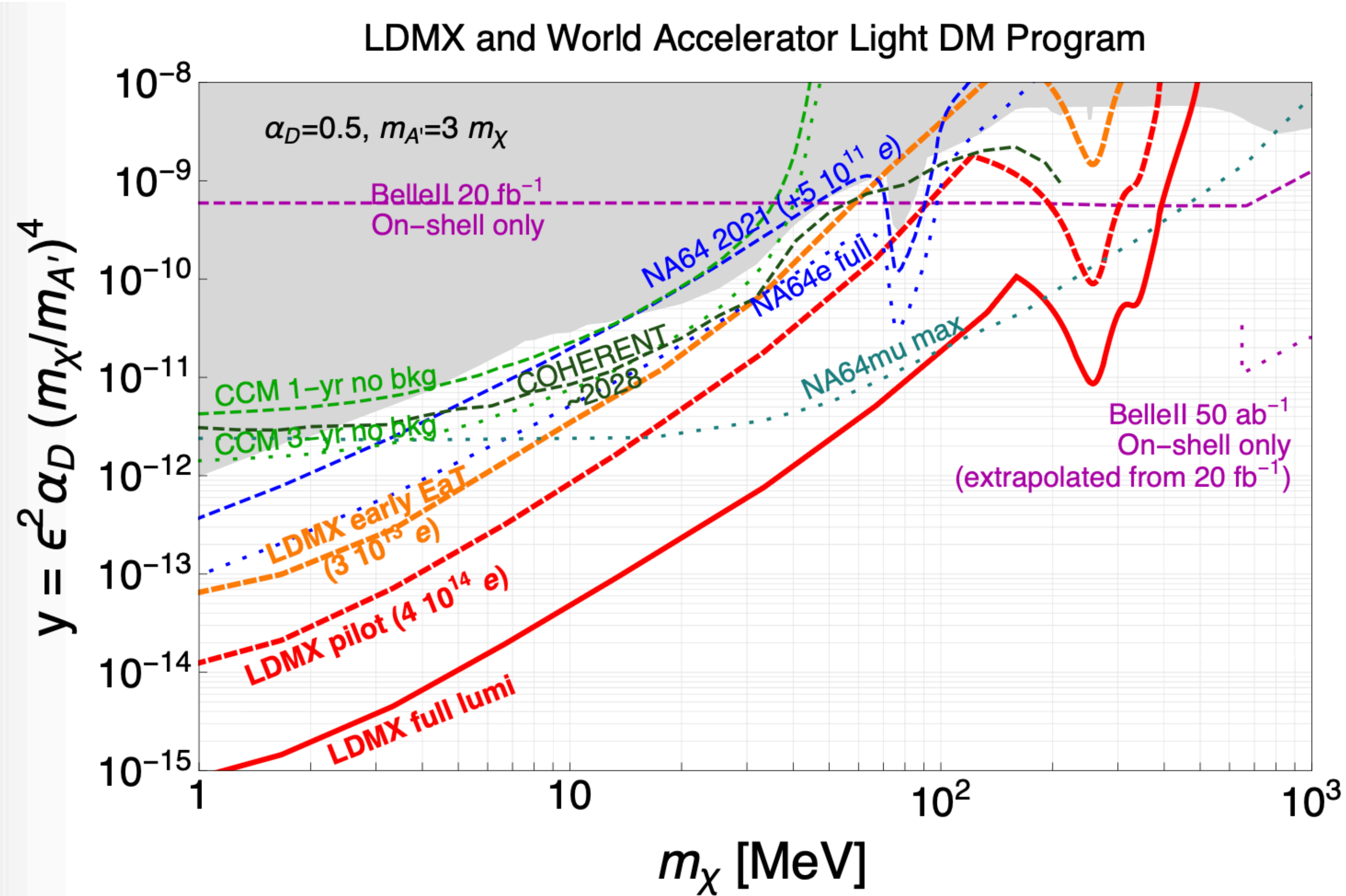
OK if you can still meet benchmark sensitivities

Light Dark Matter eXperiment

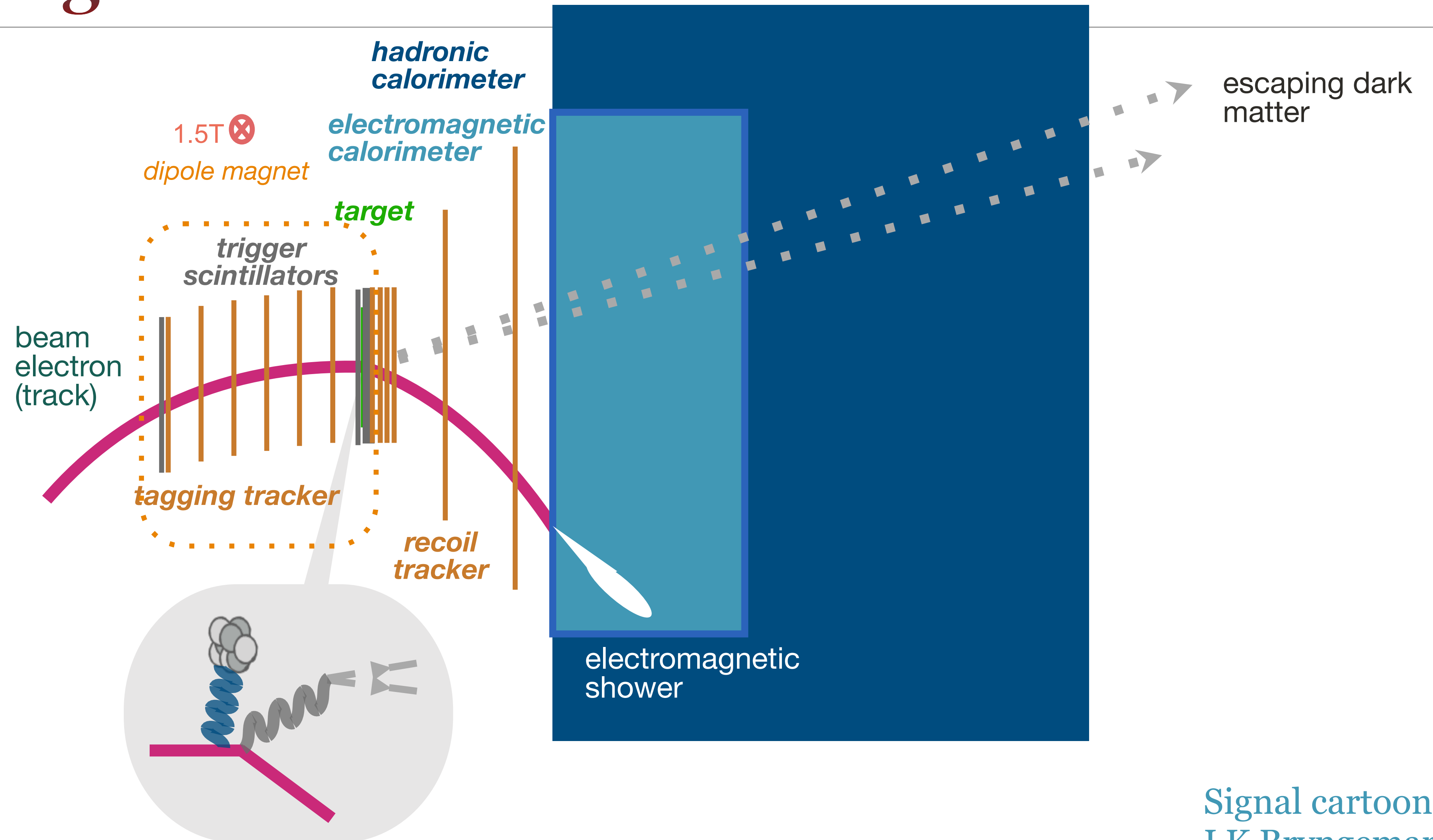
- Compact detector at SLAC's End Station A utilizing electron beam from LCLS-II
- Detector technology adapted from existing experiments (HPS, CMS, Mu2E)
 - Designed for 24-7 operation, 10^{16} EOT, 1-4 e at ~ 40 MHz
- Thin W, Ti, Al target: $.1 - .4 X^0$



Projected Power of the Approach



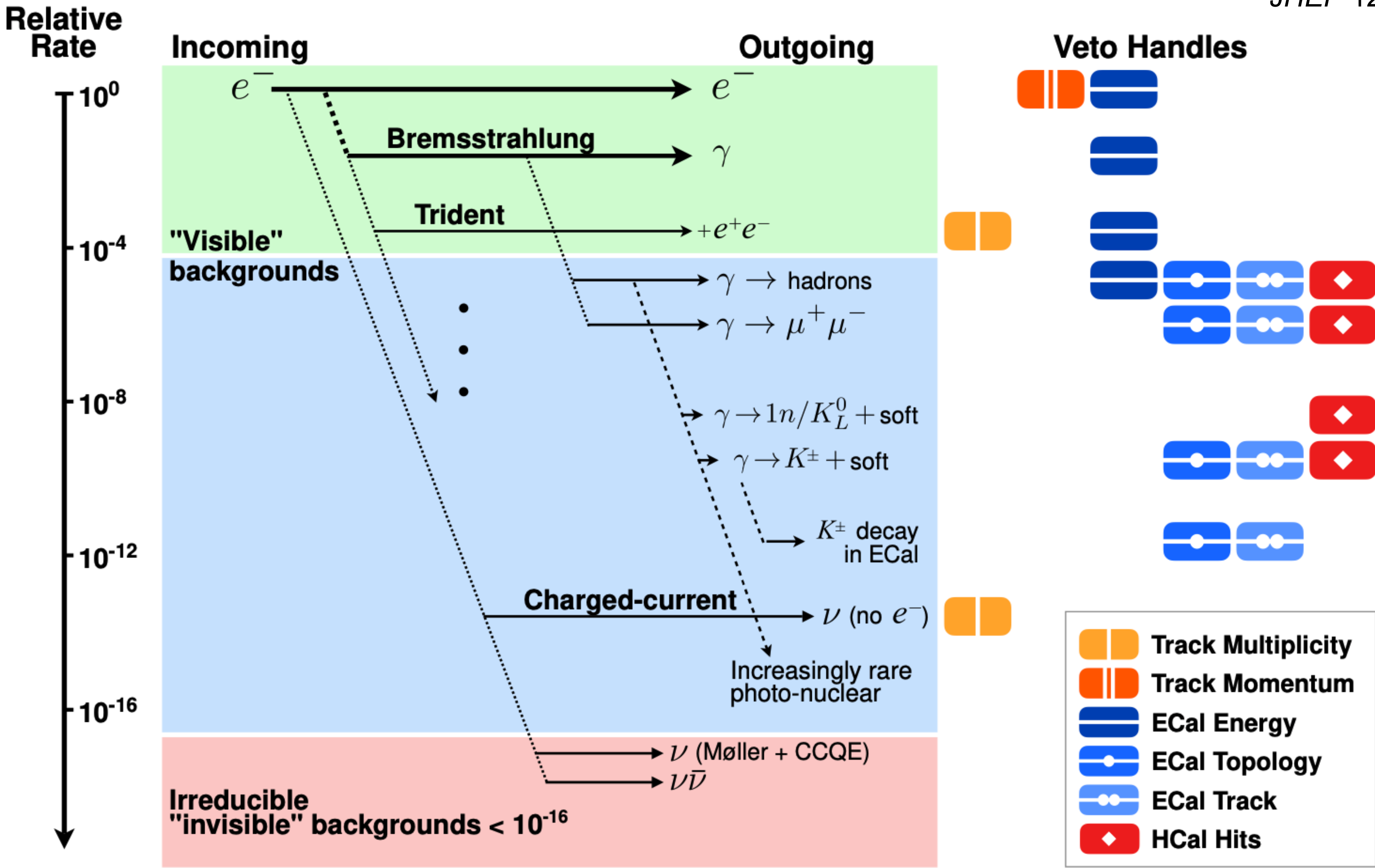
LDMX Design



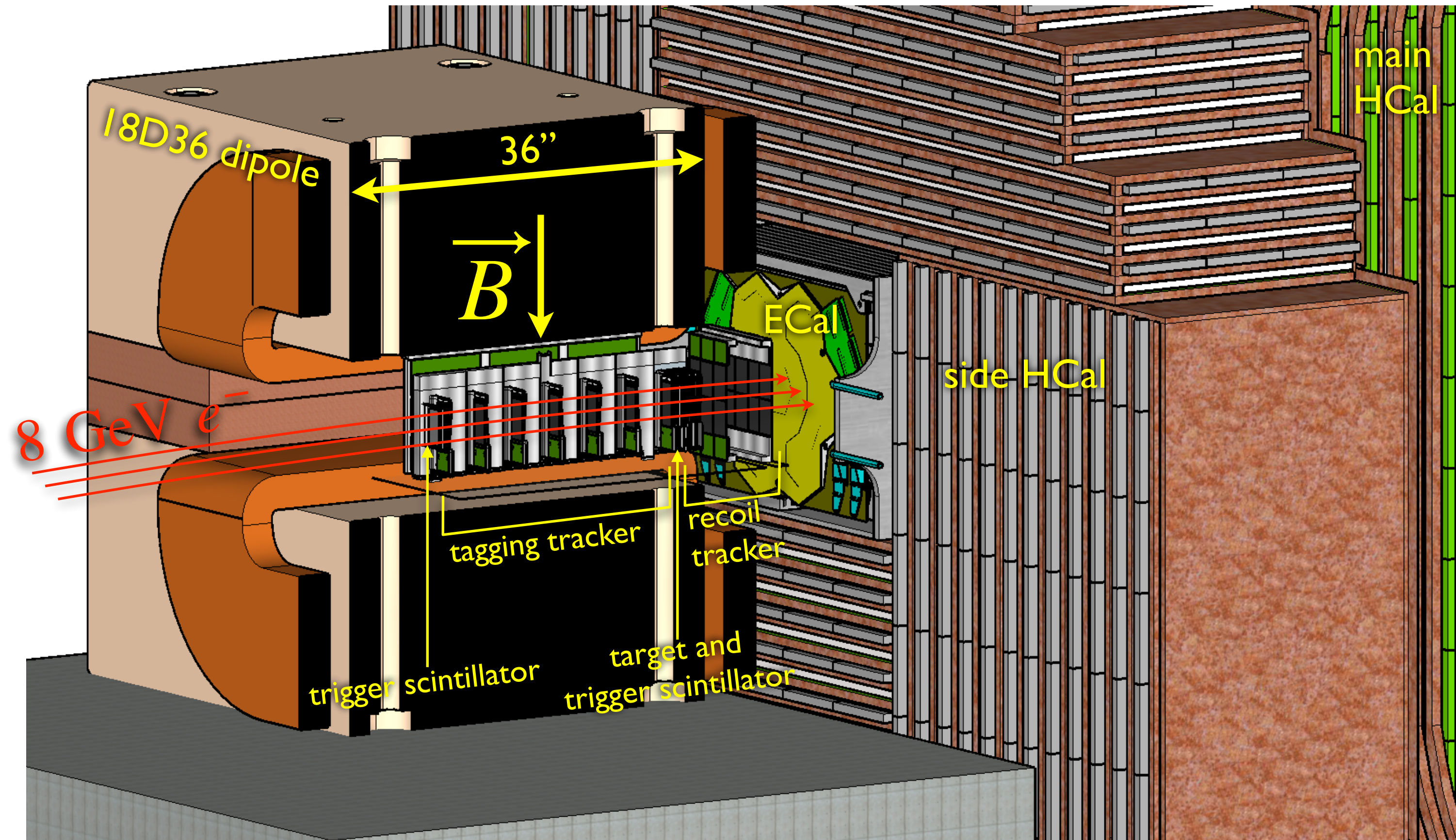
Signal cartoon
LK Bryngemark

The challenge: background reduction

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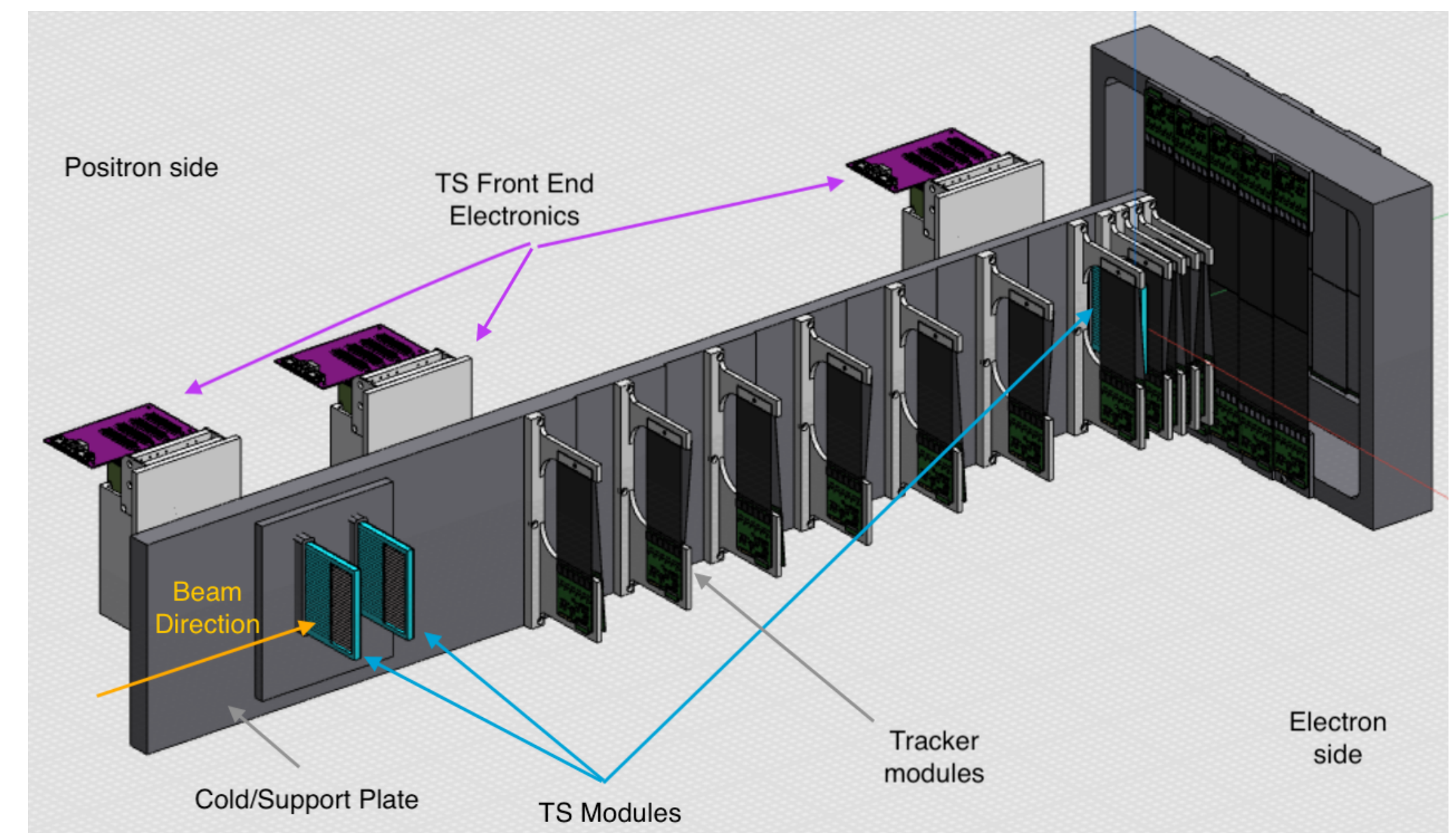
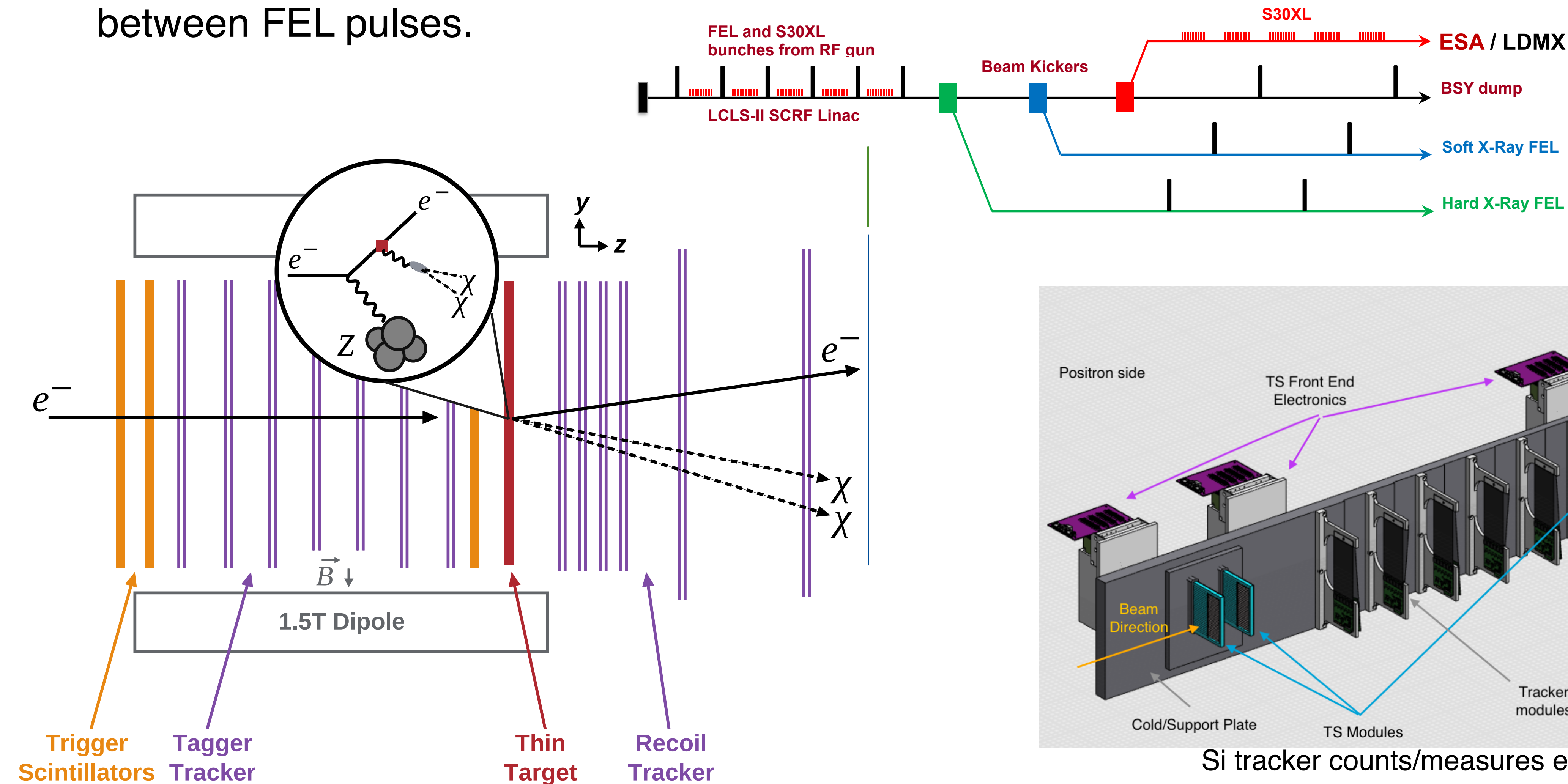


Experimental Setup



First step: Electron counting (real-time & offline)

LESA beamline short bunches every 27 ns w/ $\langle n_e \rangle \sim 1$, via spoiled laser driven dark current between FEL pulses.



Si tracker counts/measures electrons

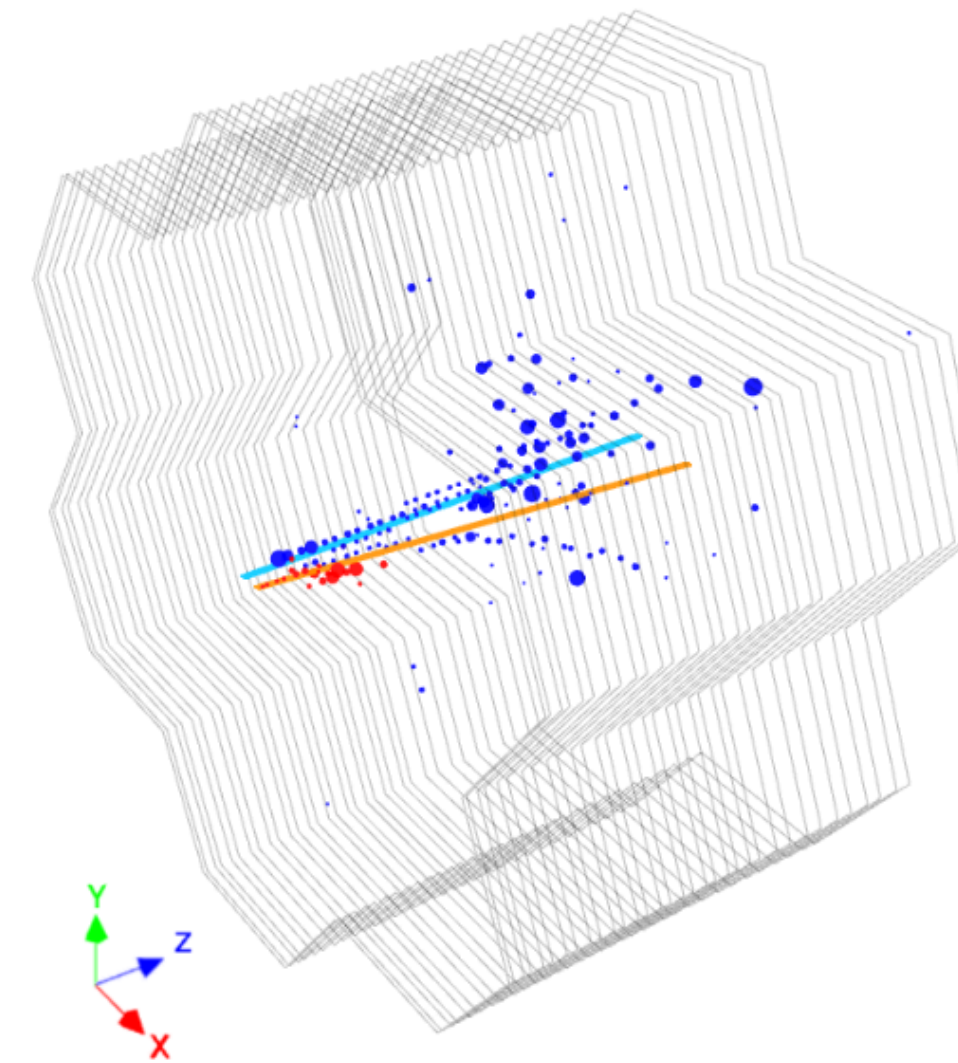
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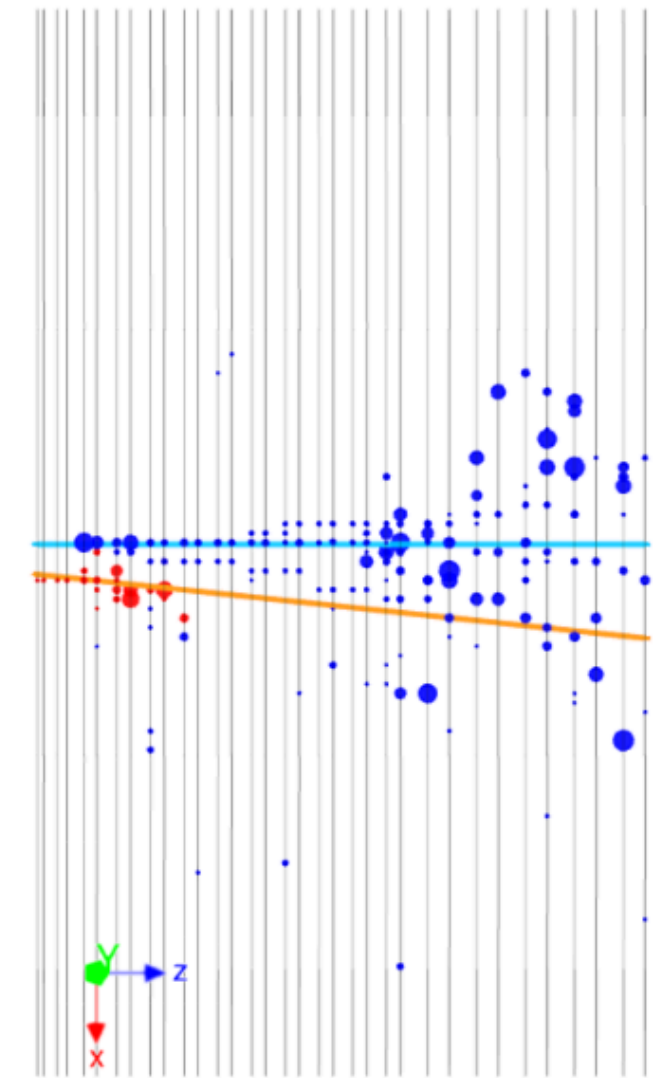
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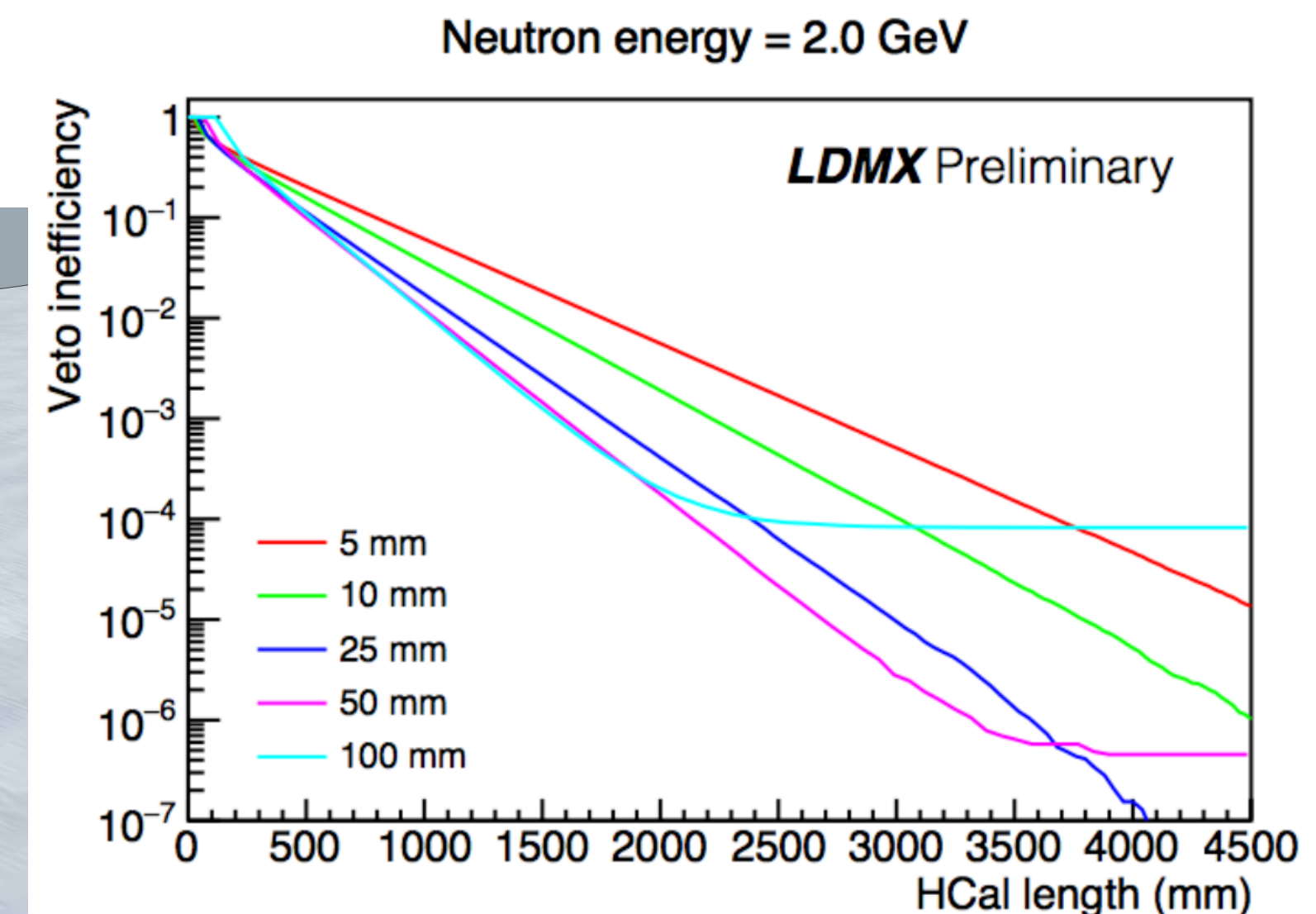
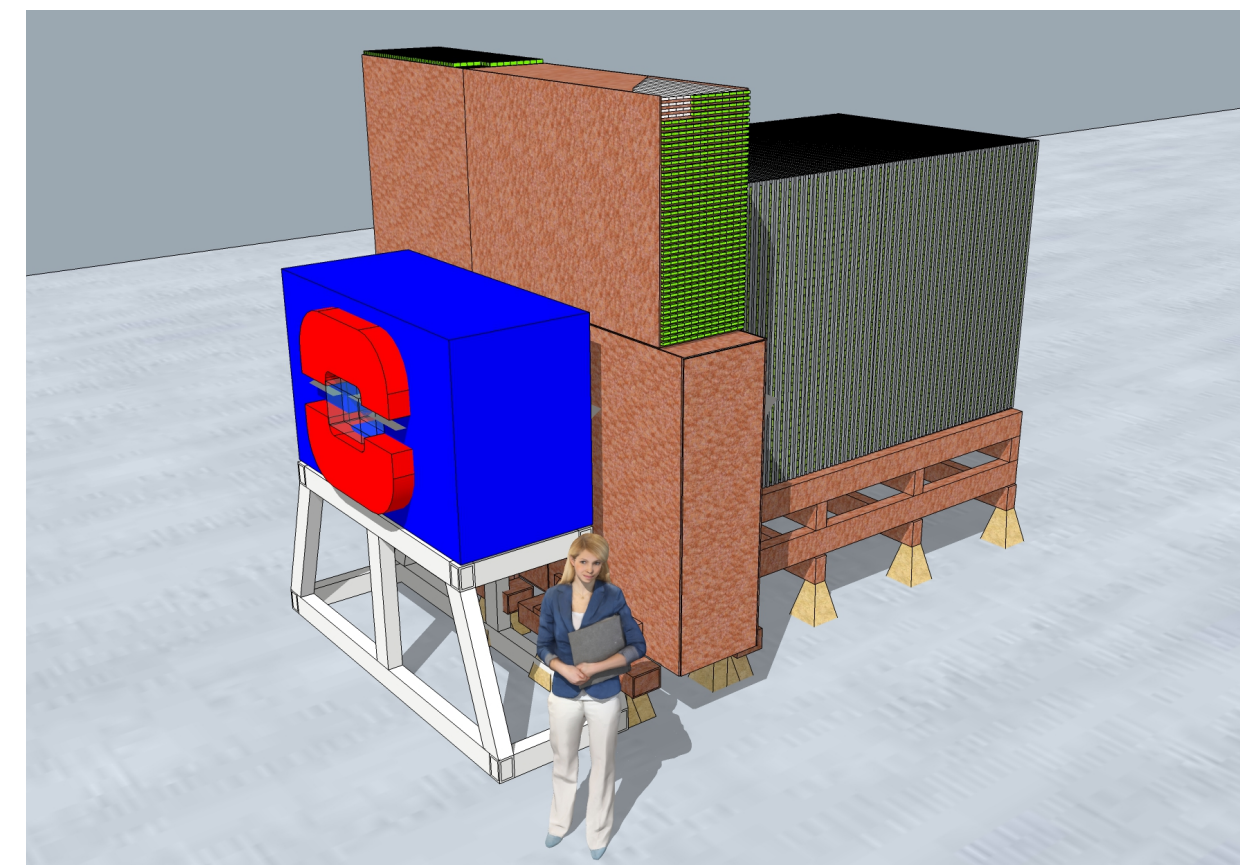


LDMX Simulation



Next: Calorimetry

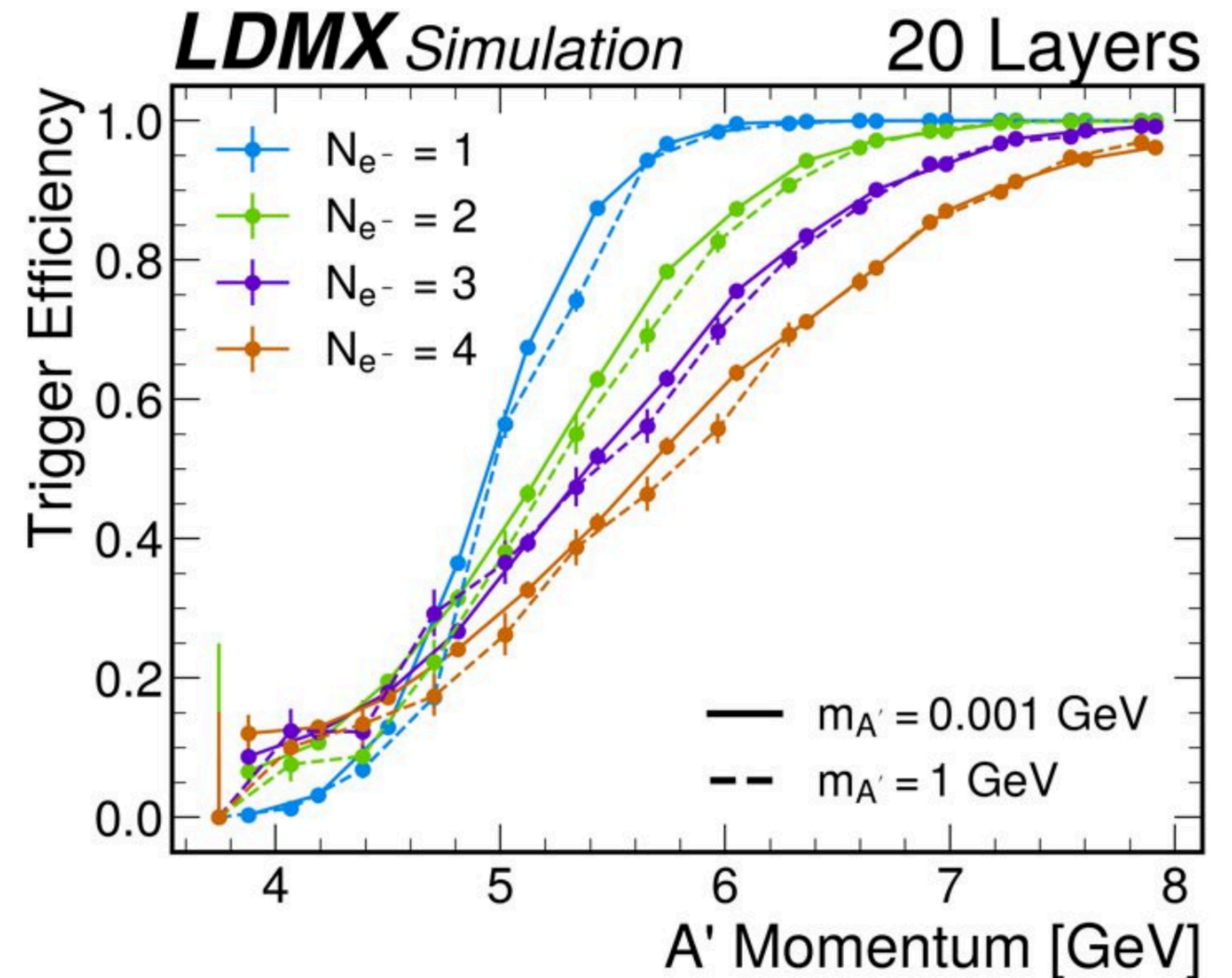
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Analysis Strategy

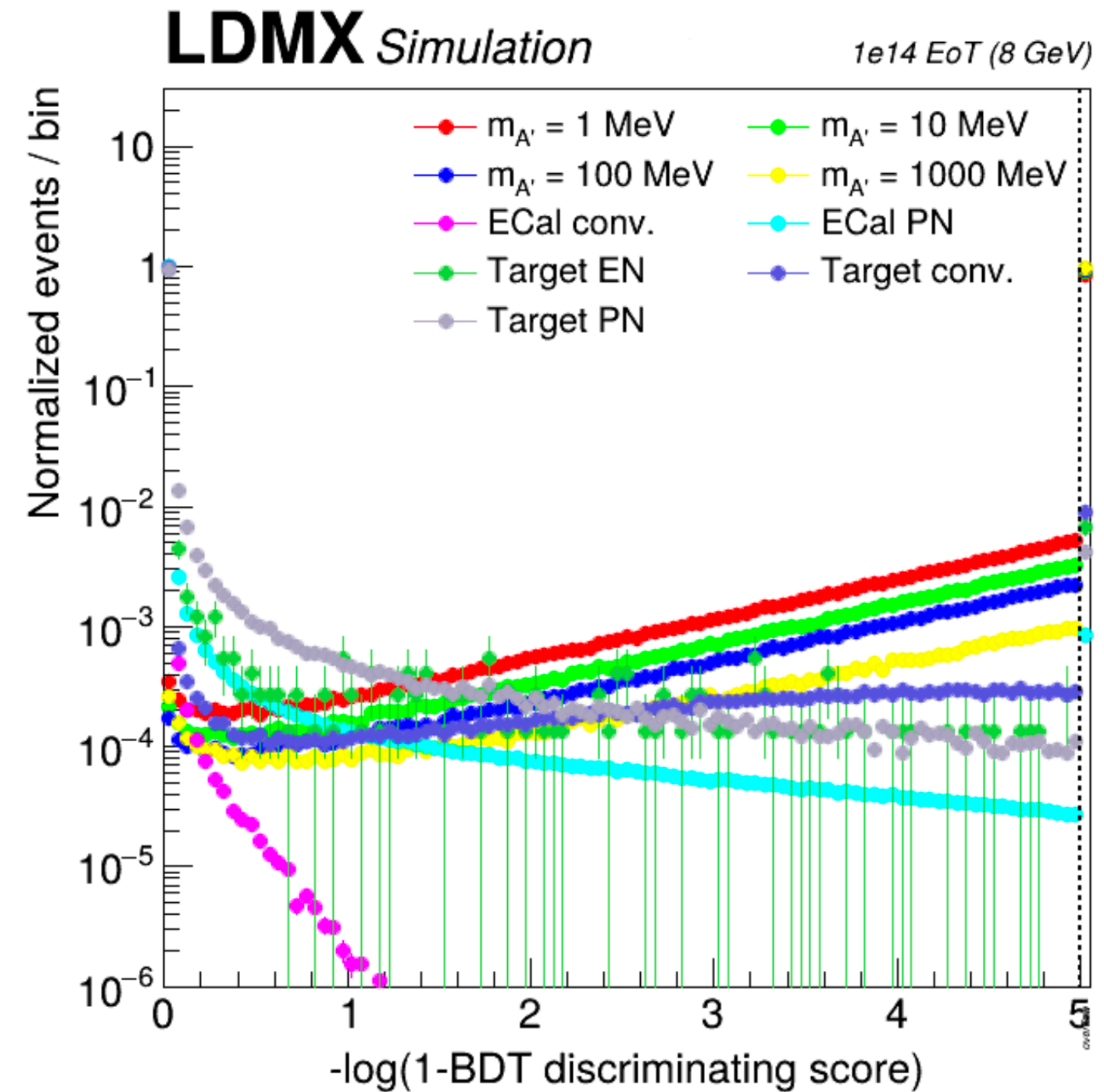
- Trigger on ECAL energy less than expected
- Require soft track
- Input high granularity ECAL features in BDT
- Veto on HCAL activity
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[Design Report](#)



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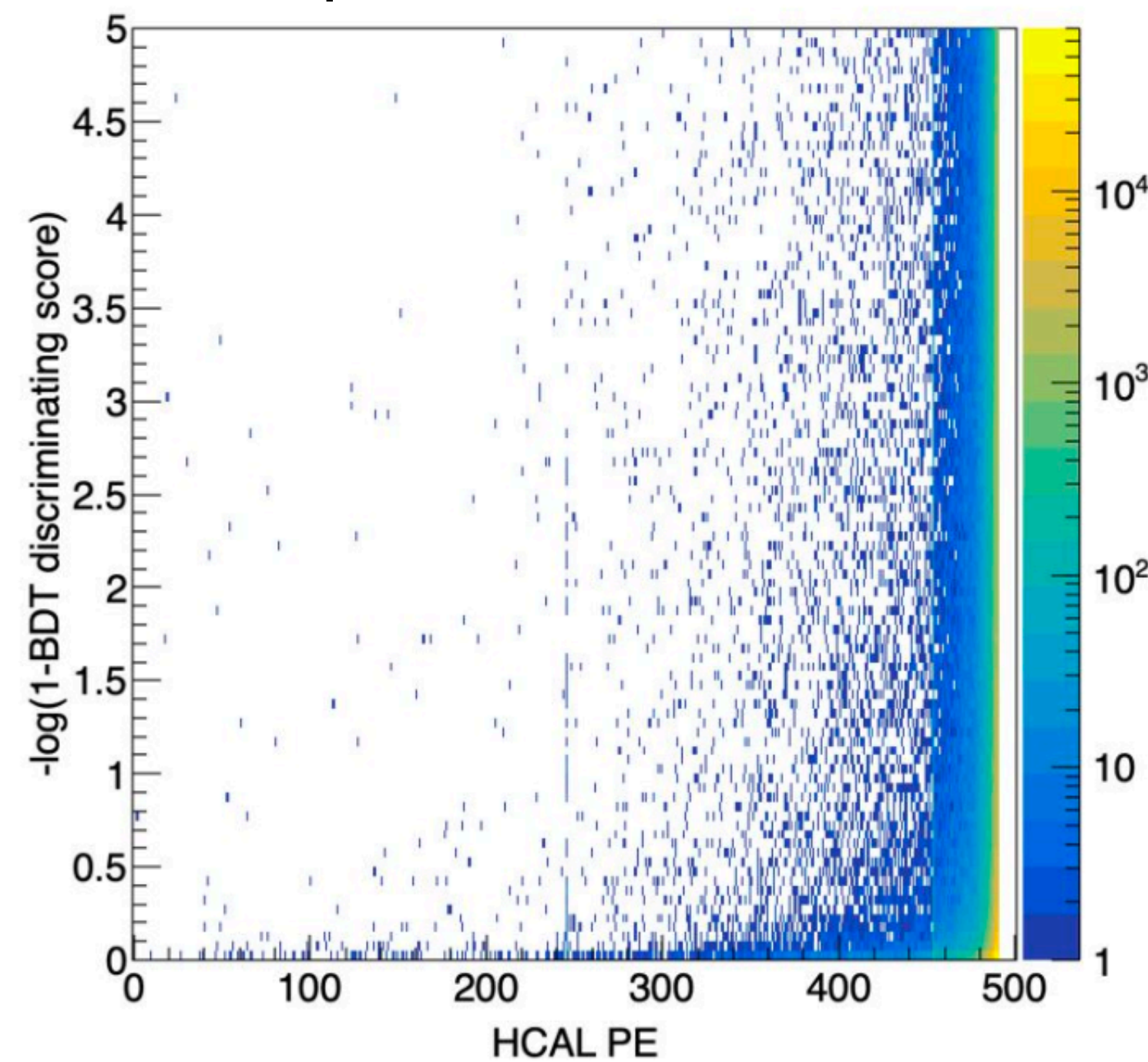
[Design Report](#)

Analysis Strategy

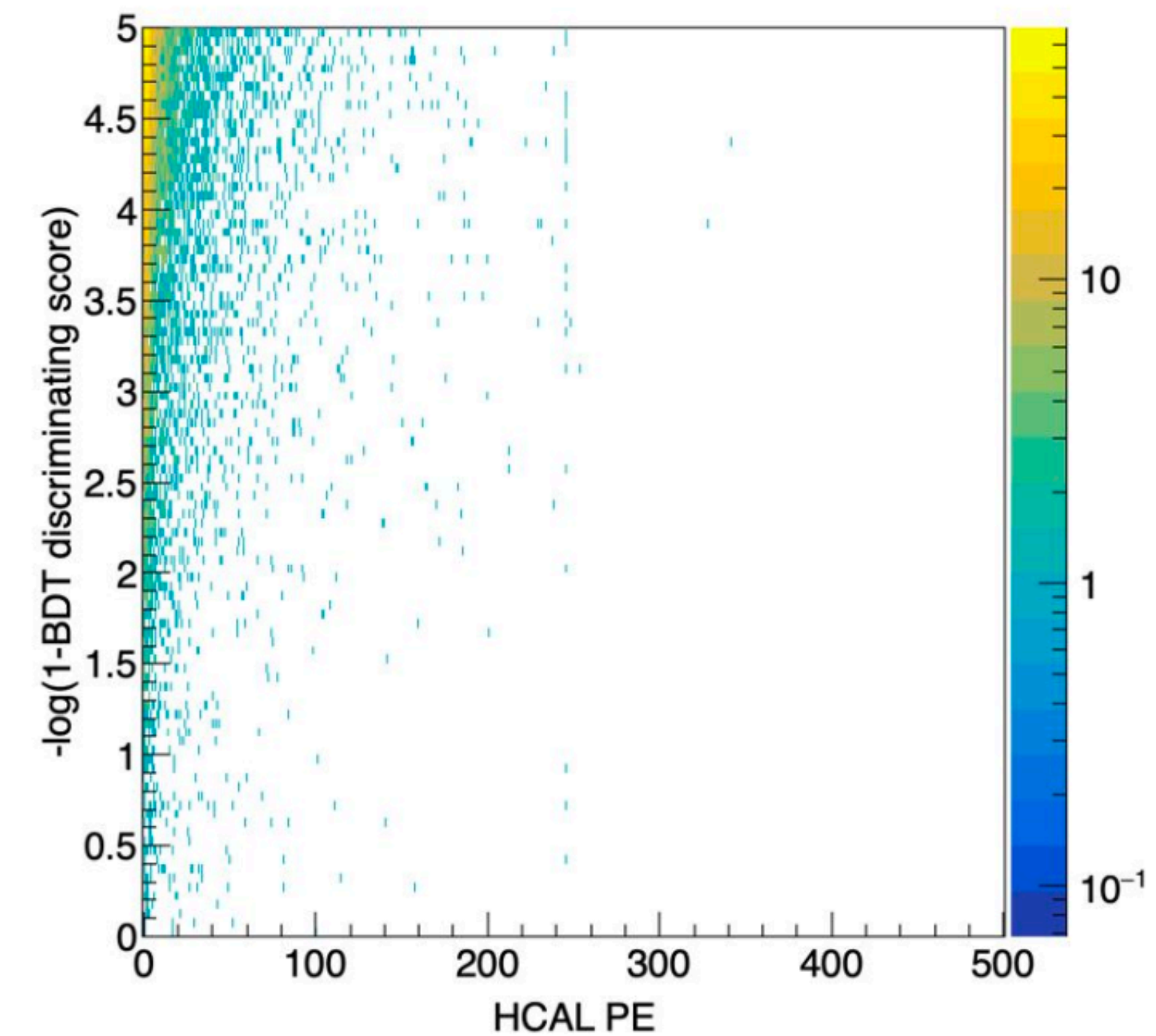
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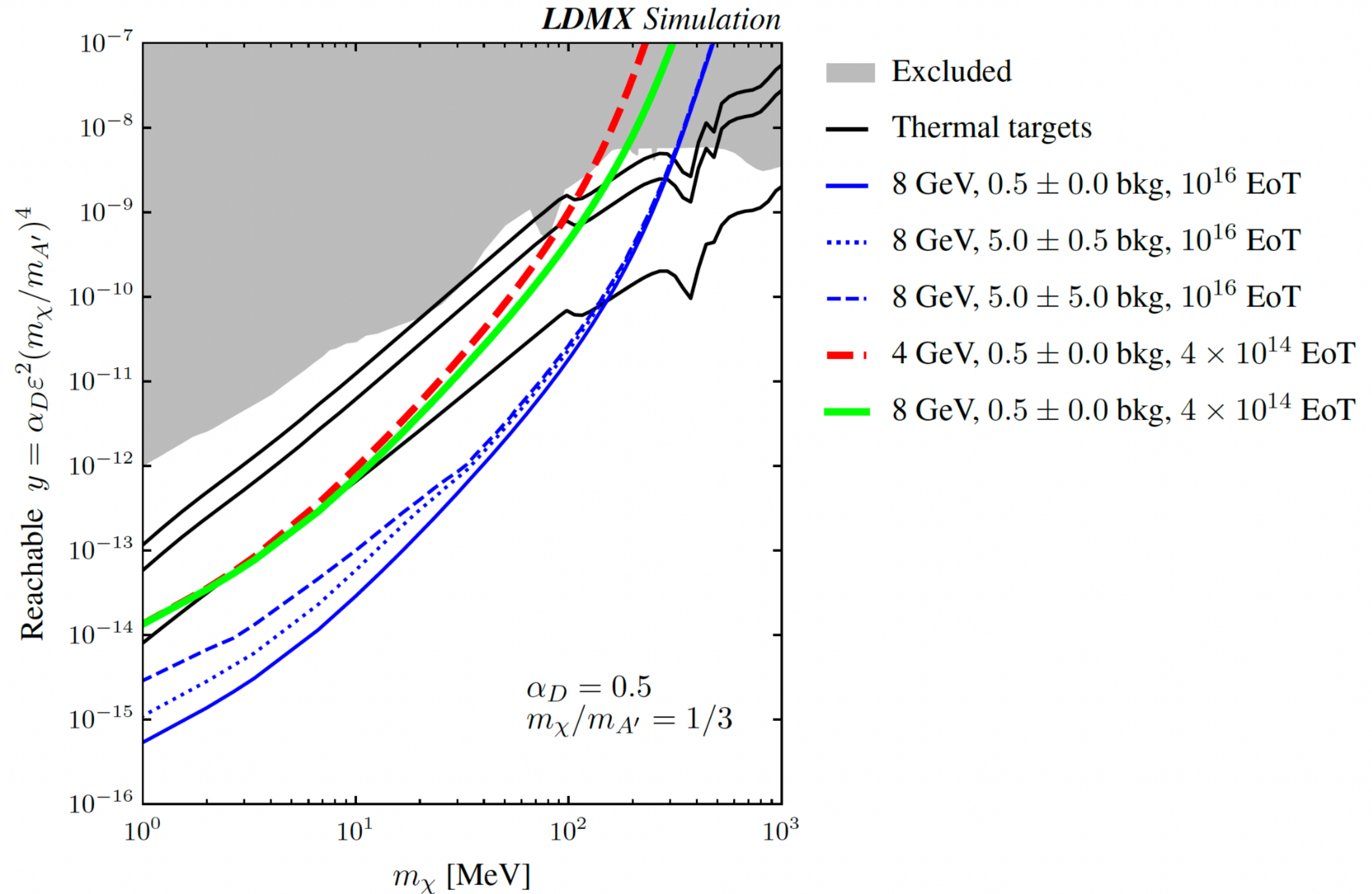
pN events



A' events

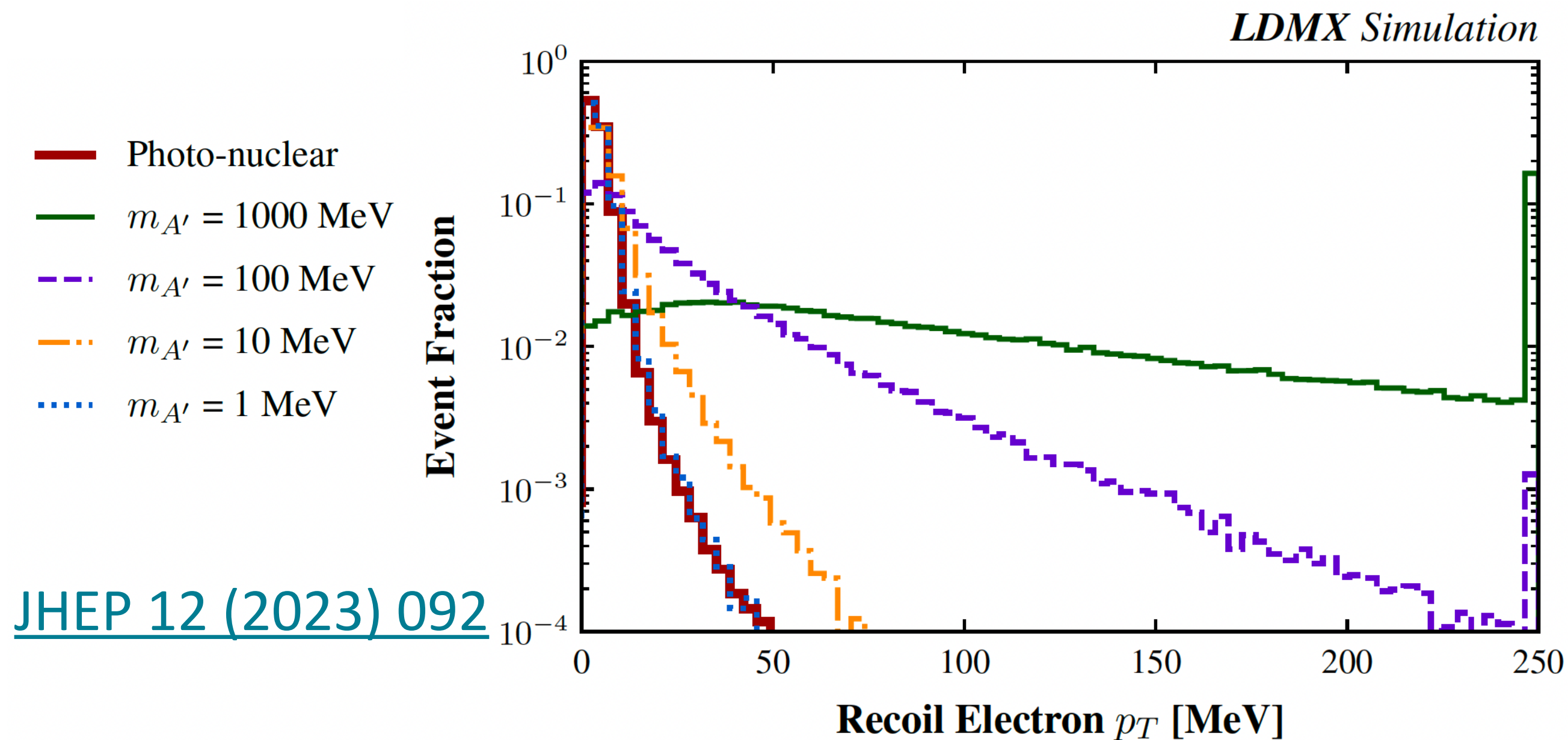


Projected Sensitivities

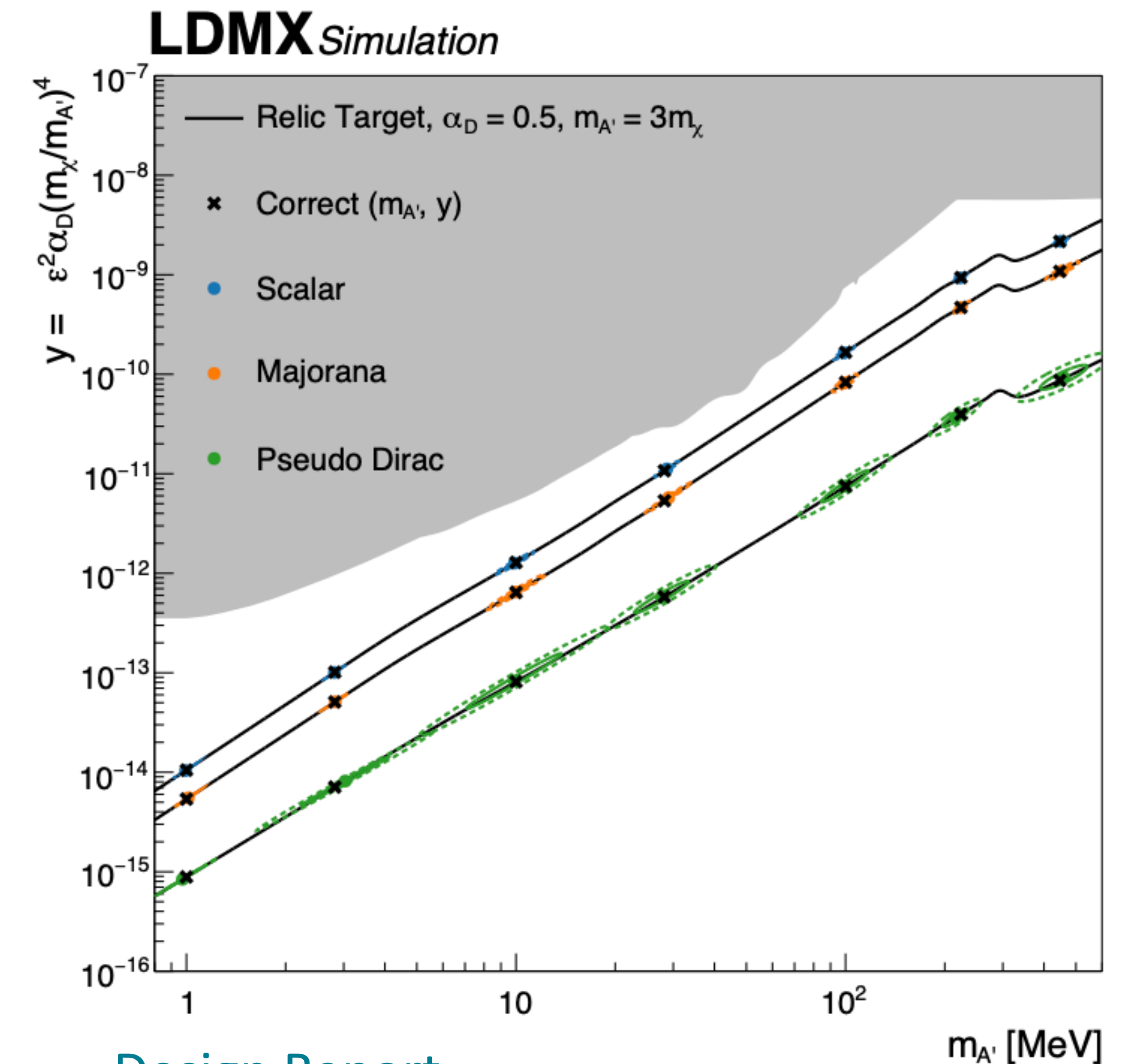
[Design Report](#)


Mass determination

- If events are found, joint fit to recoil e p_T and ECAL energy can constrain A' mass.



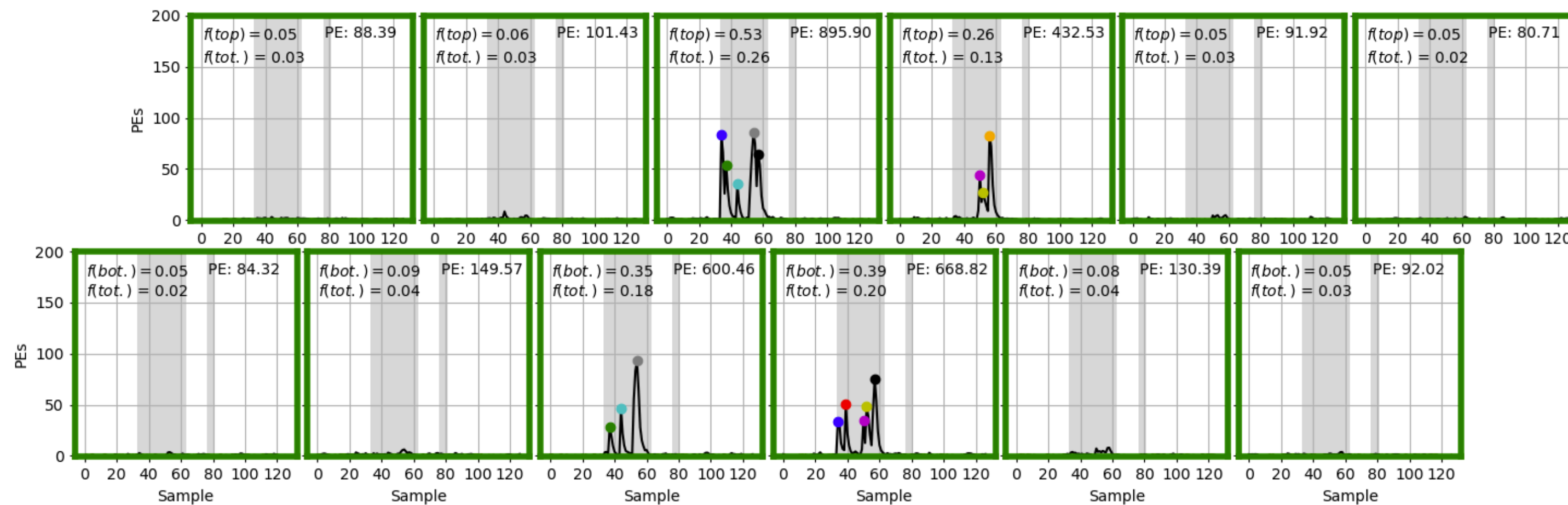
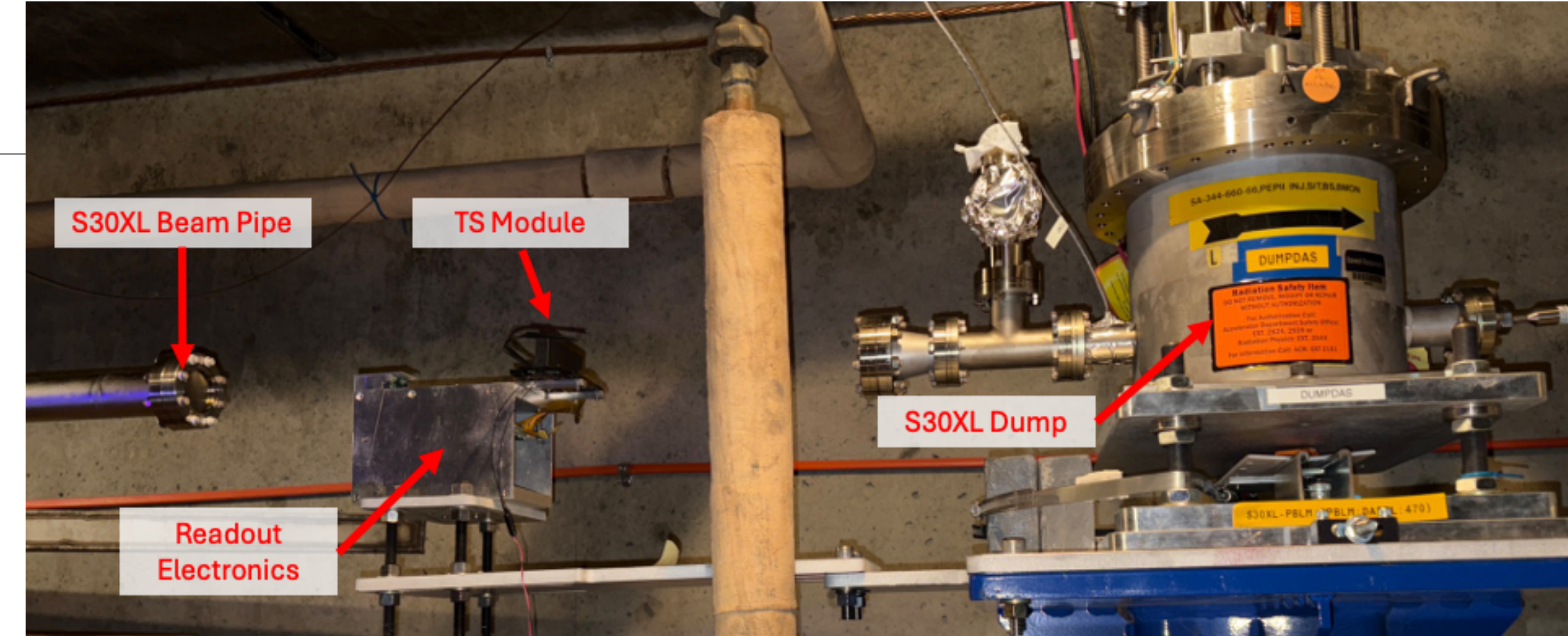
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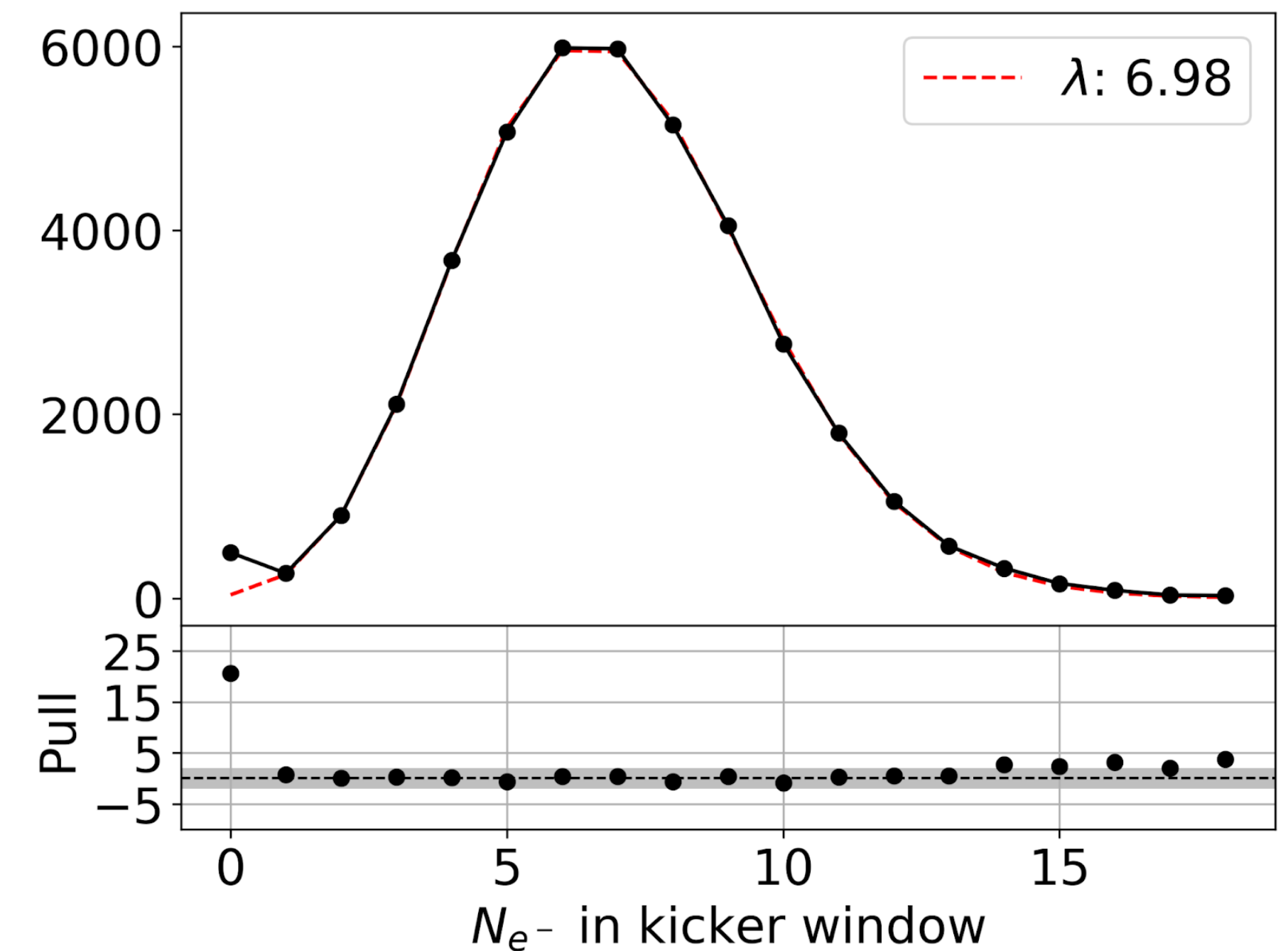
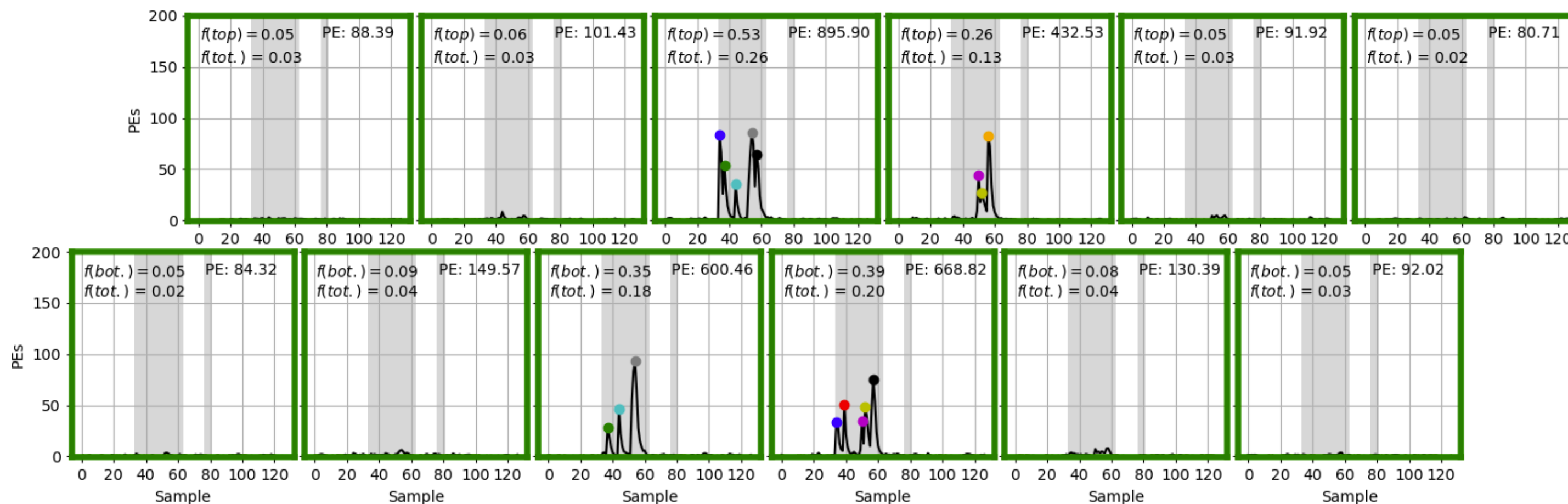
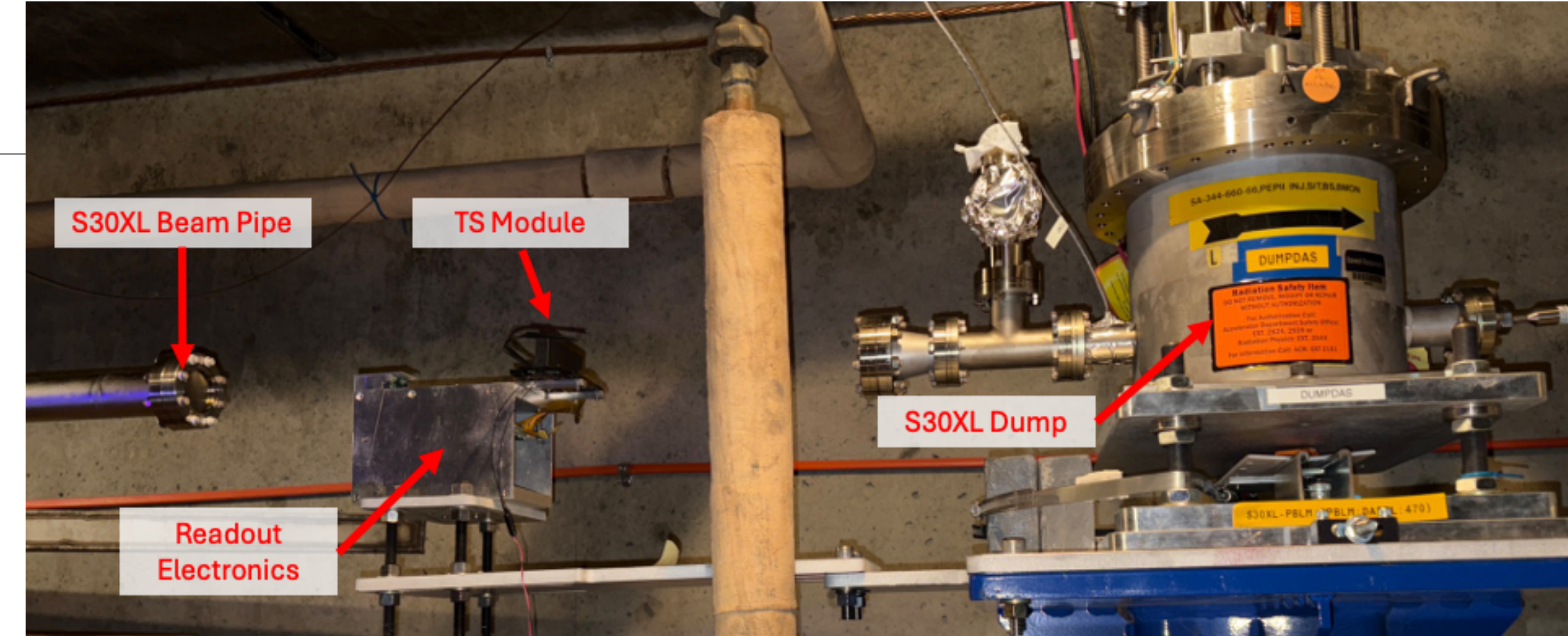
Prototyping & Prospects

- Installed one plane of Trigger Scintillators at in beamline.
- Measured dark current of LCLS-II beam is ~1.6pA (but varies). Published in NIM-A
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Dec 2025 End Station A Tests

Prototypes of all
subdetectors integrated

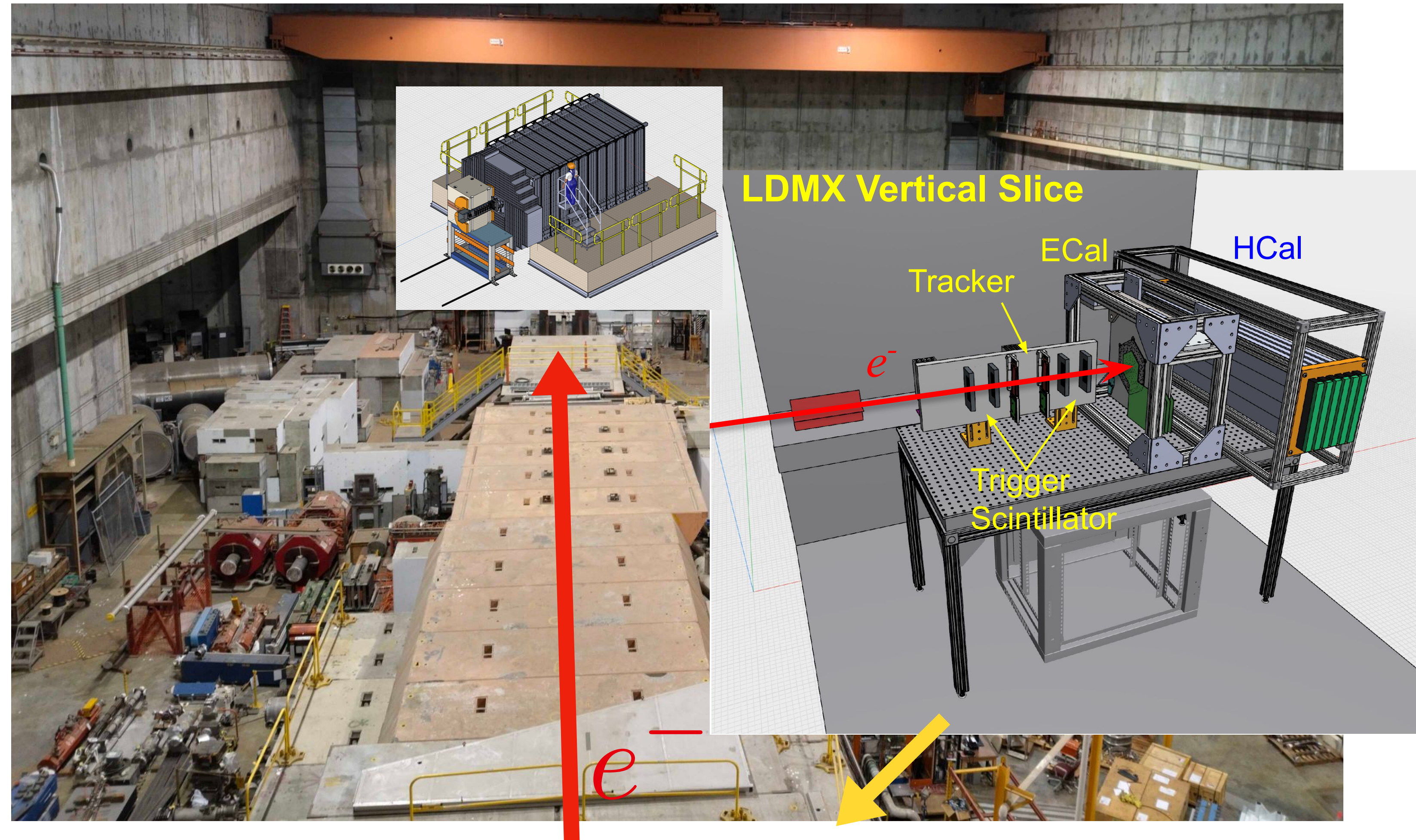
4 GeV LCLS-II beam in dark
current & “spoiled” mode



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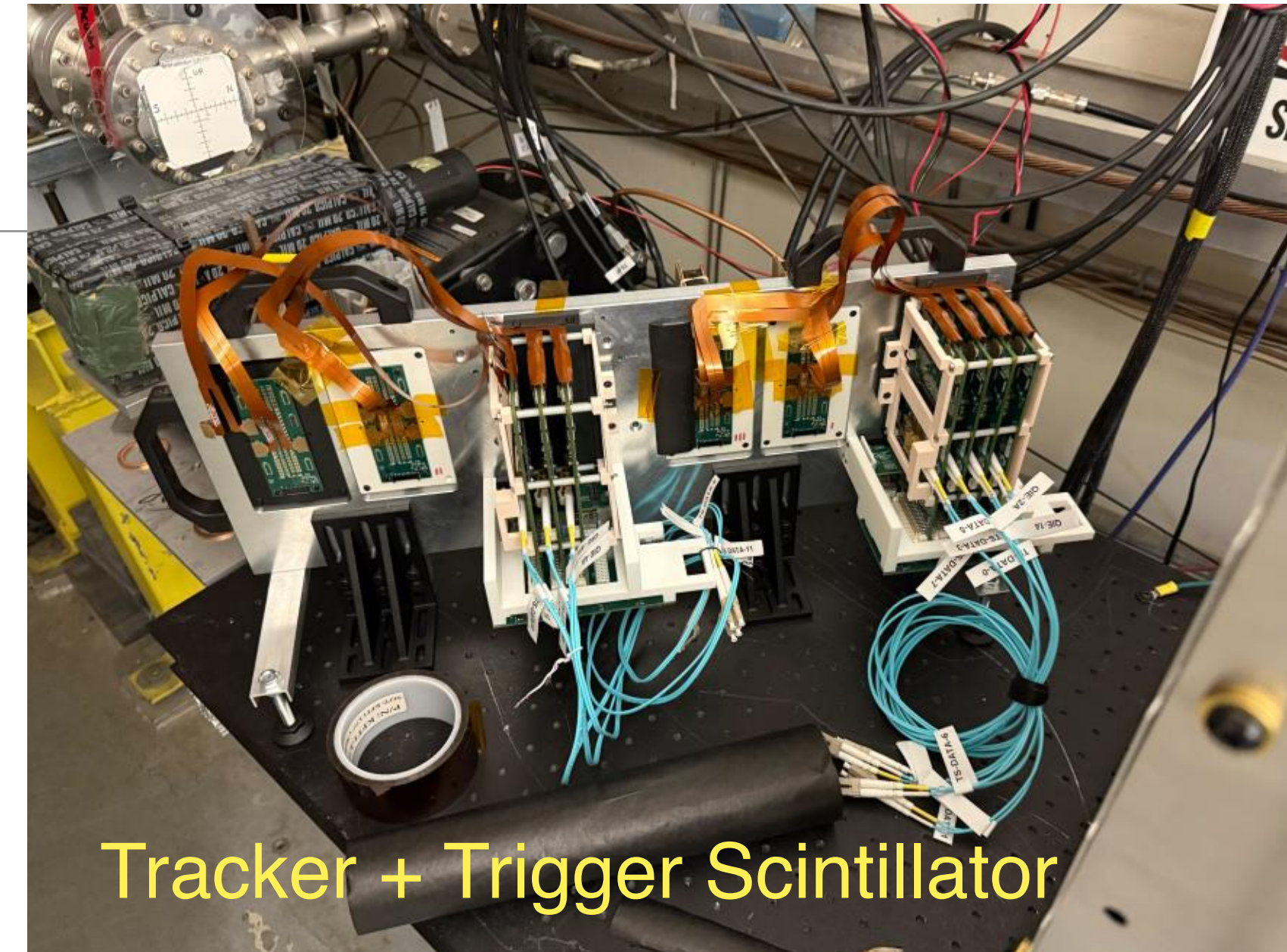
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Constructing the 'vertical slice'

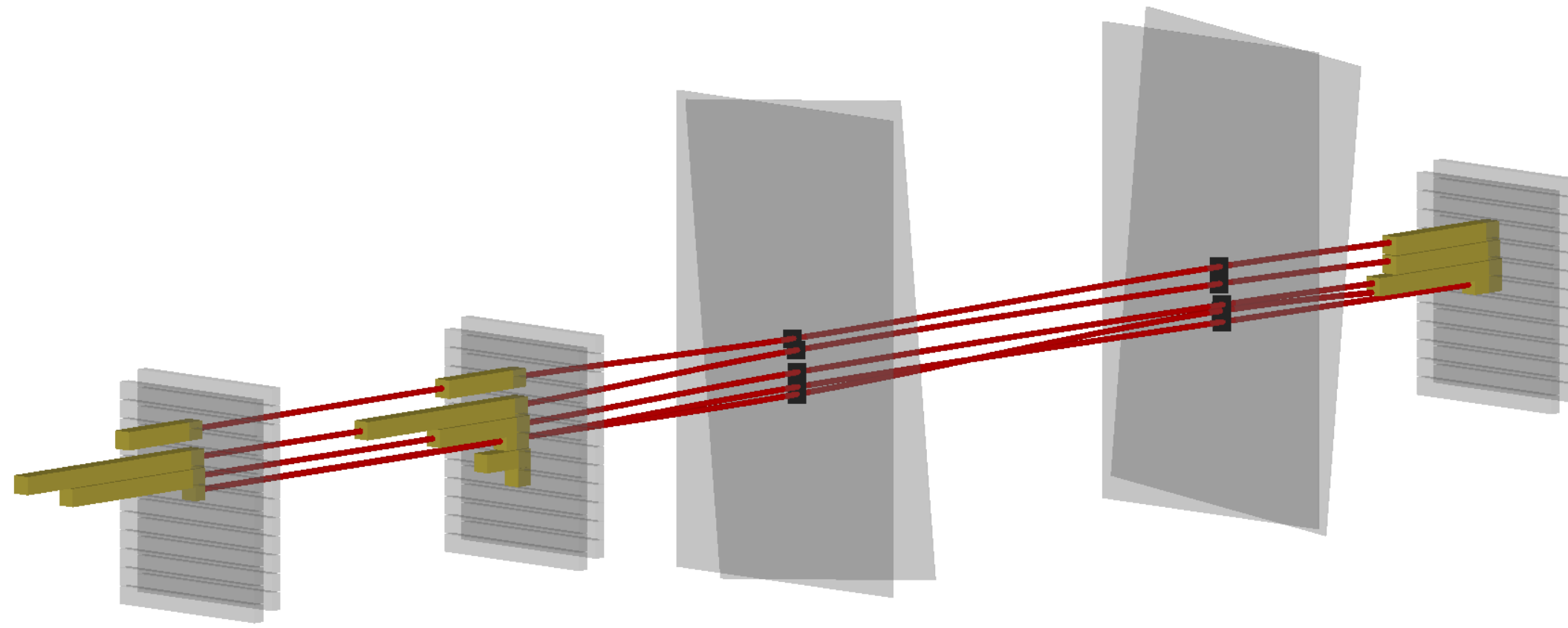
Integrated 3 TS planes + 1 LYSO plane, 4 tracker modules, several ECAL planes and HCAL quad-bars (no absorbers)

DAQ and Trigger was integrated with beamline, demonstrated electron track finding triggers

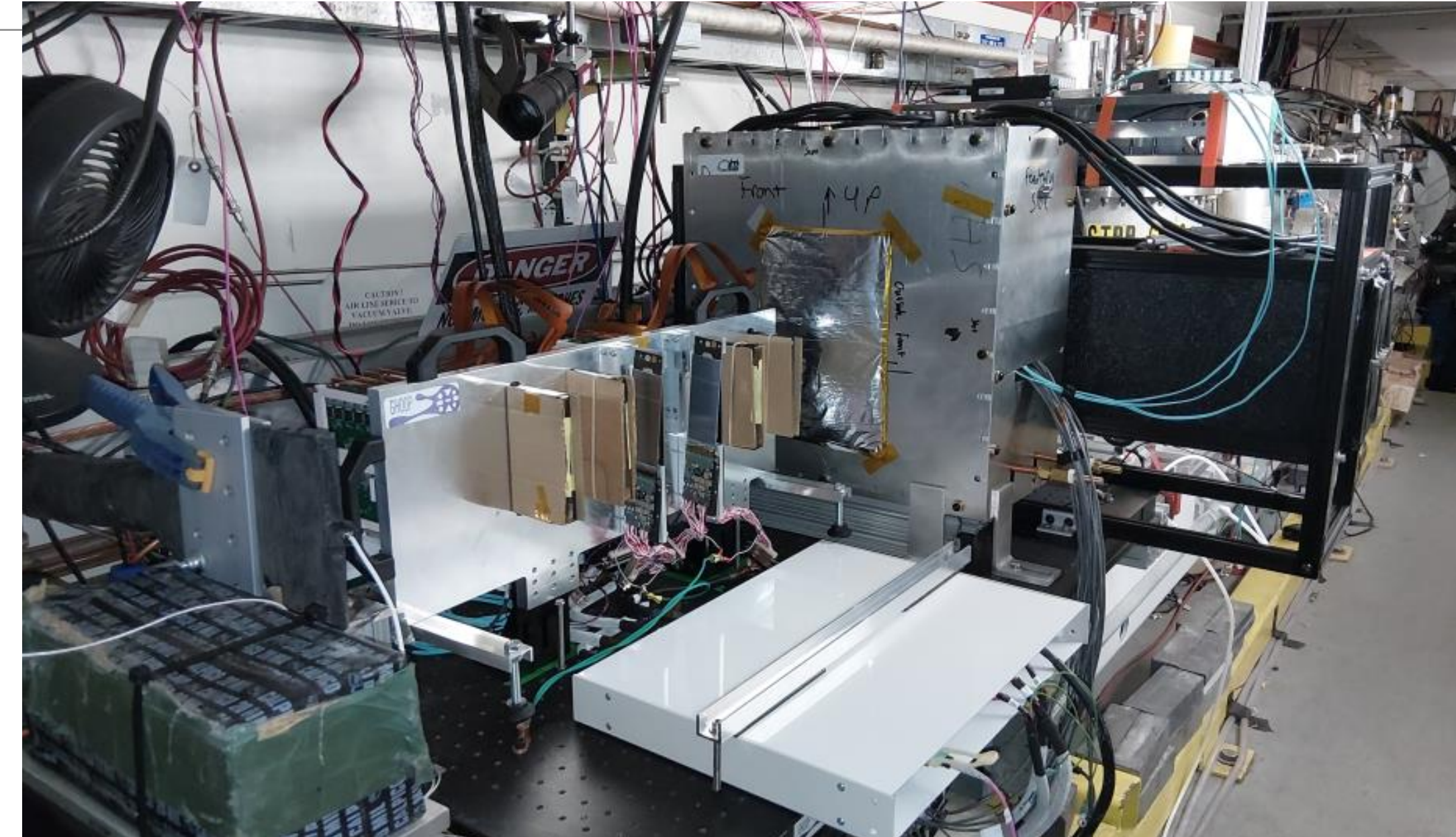


First data with 'vertical slice' of LDMX

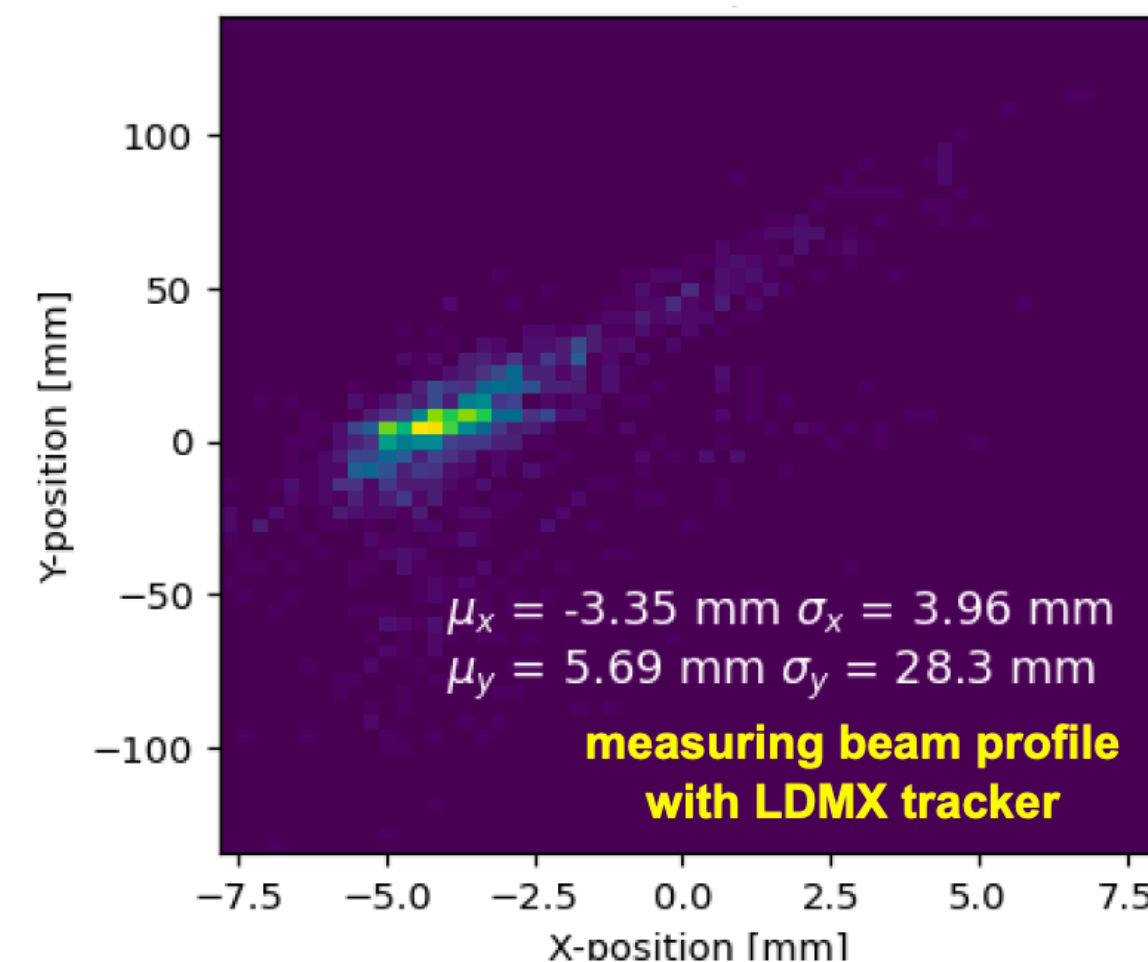
An early highlight:



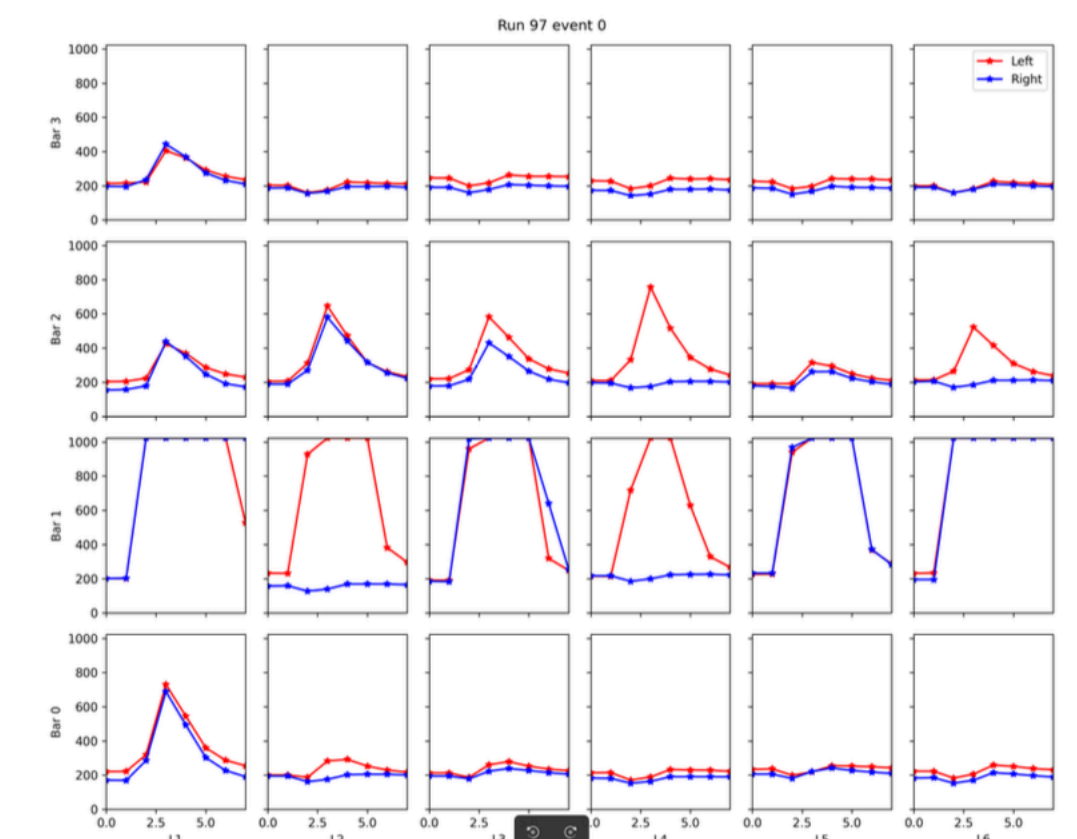
Combined **track reconstruction** with **scintillating trigger bars** and **silicon planes**.



Builds on CERN testbeam in 2022

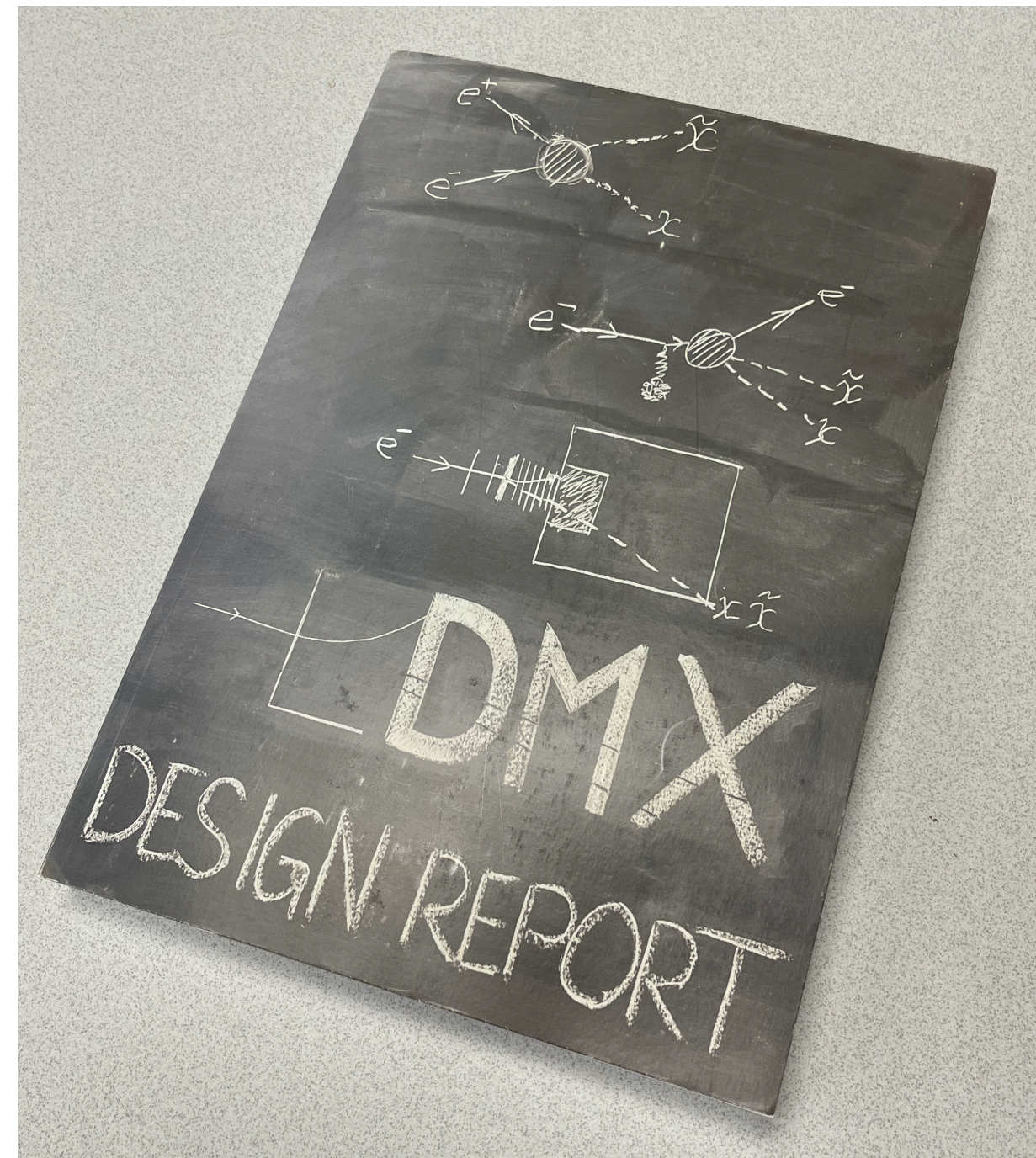


Externally triggered HCal readout

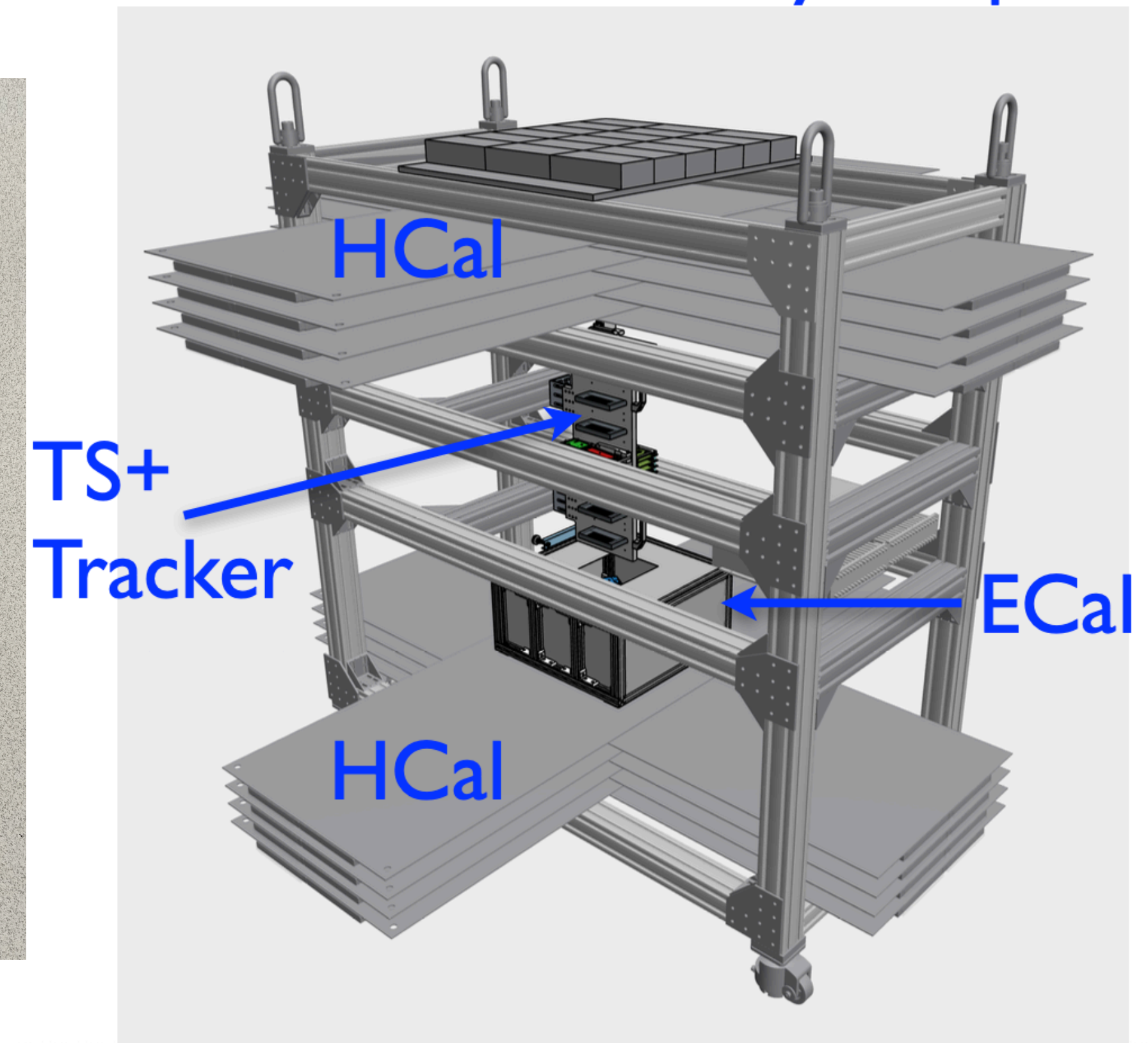


LDMX Status & Plans

- Design report published this summer
- Building cosmic ray test stand for operation this fall
- Producing plans for “mini-LDMX” when LCLS-II operations resume
- Ready to begin construction when funding available

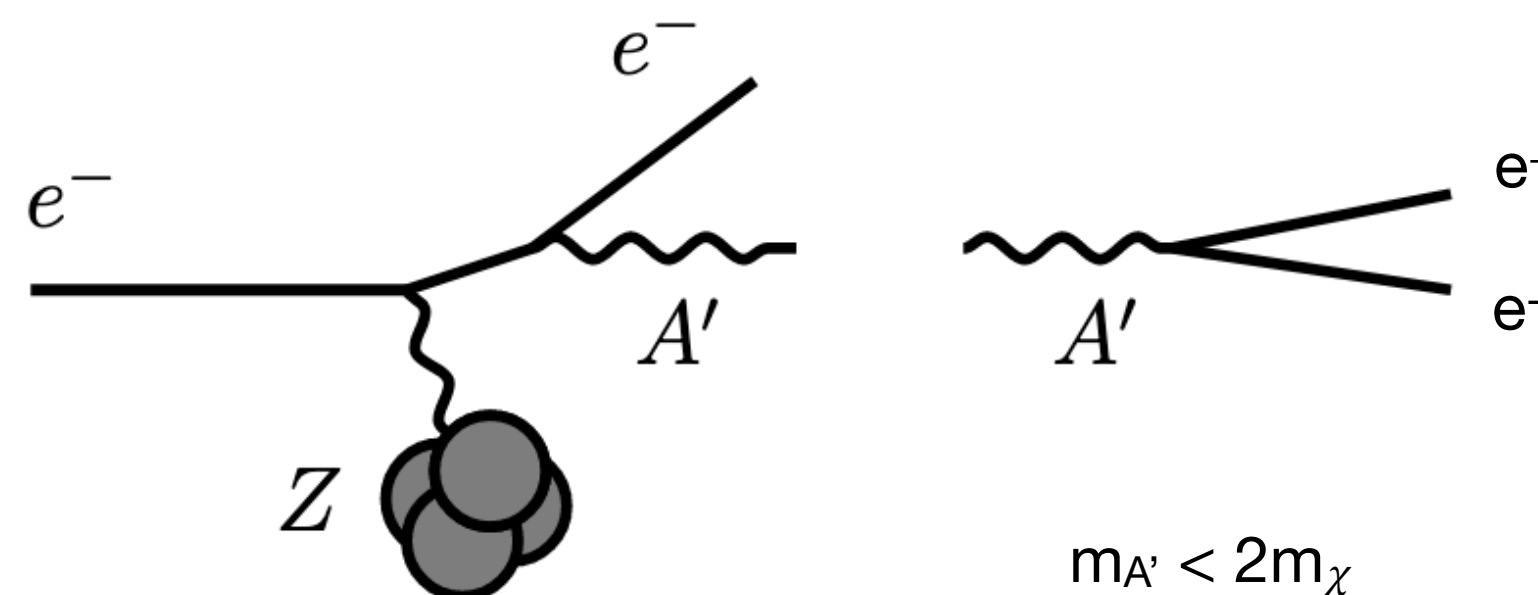
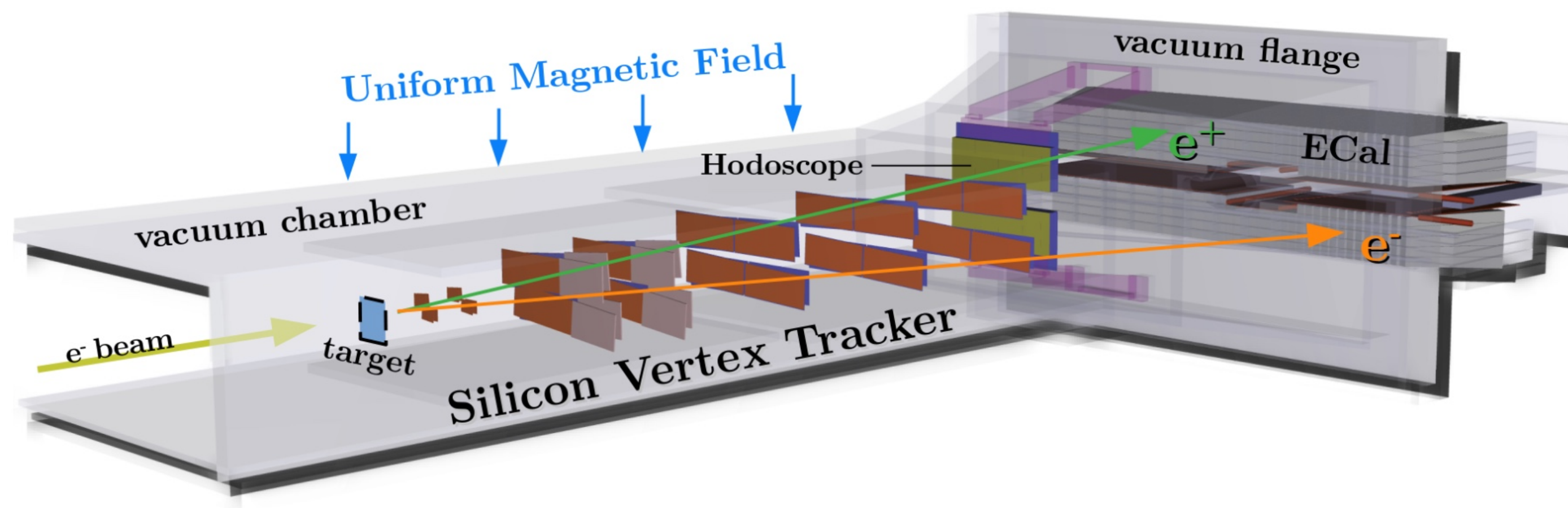


LDMX Cosmic Ray Setup



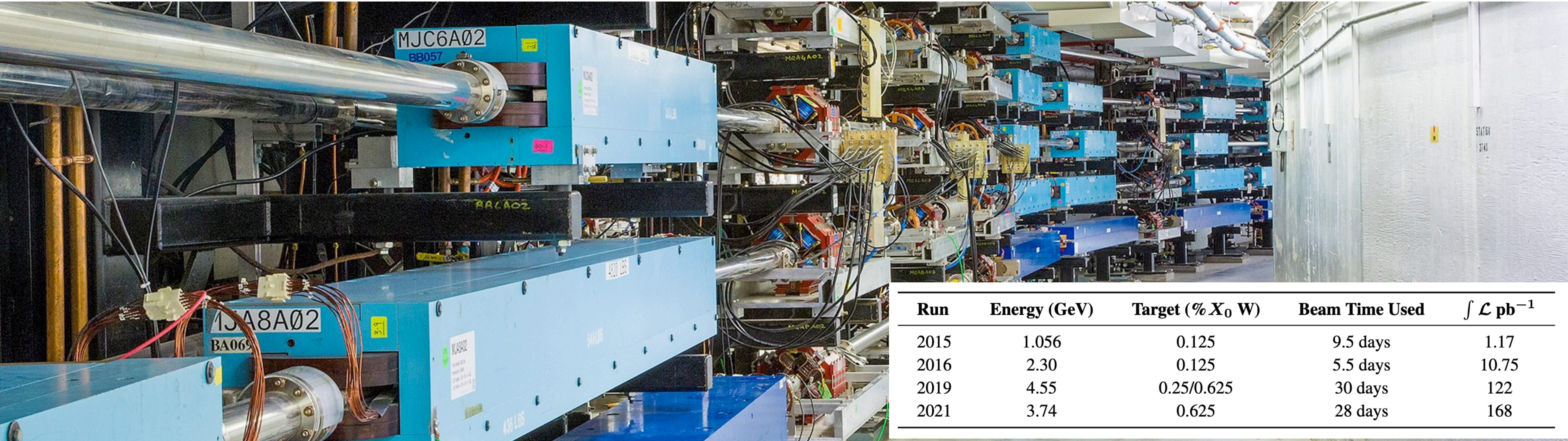
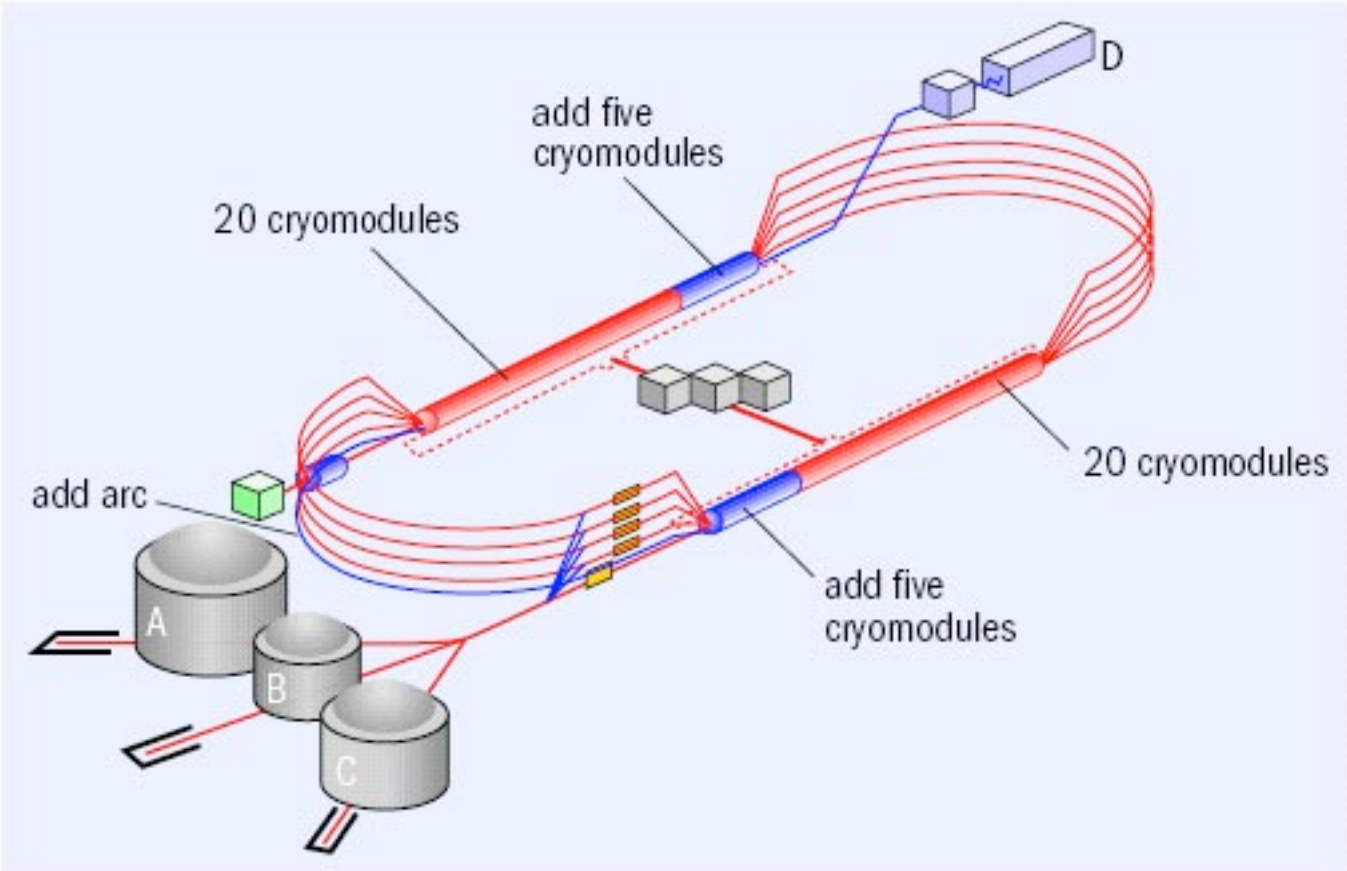
Heavy Photon Search Experiment

- Experiment to search for visible decays of dark photons produced by dark brems in thin tungsten target



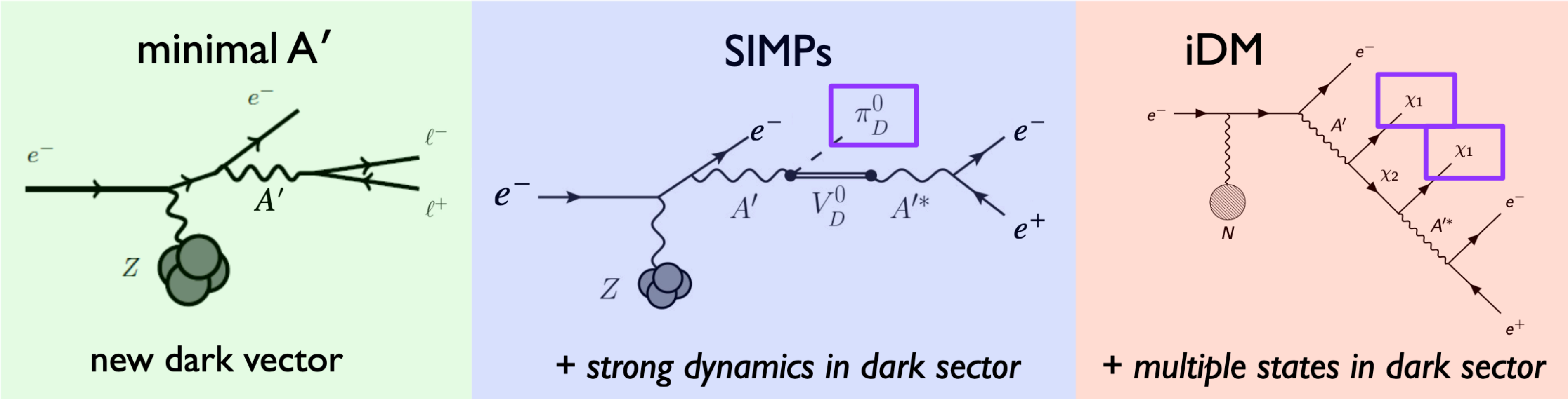
Continuous Electron Beam Accelerator Facility (CEBAF) @ JLab

- High intensity, multi-GeV beam with tunable energy
- Deliver continuous ~500nA electron beam to HPS
- HPS has had 4 runs so far, ~100 days left in program



Run	Energy (GeV)	Target (% X_0 W)	Beam Time Used	$\int \mathcal{L} \text{ pb}^{-1}$
2015	1.056	0.125	9.5 days	1.17
2016	2.30	0.125	5.5 days	10.75
2019	4.55	0.25/0.625	30 days	122
2021	3.74	0.625	28 days	168

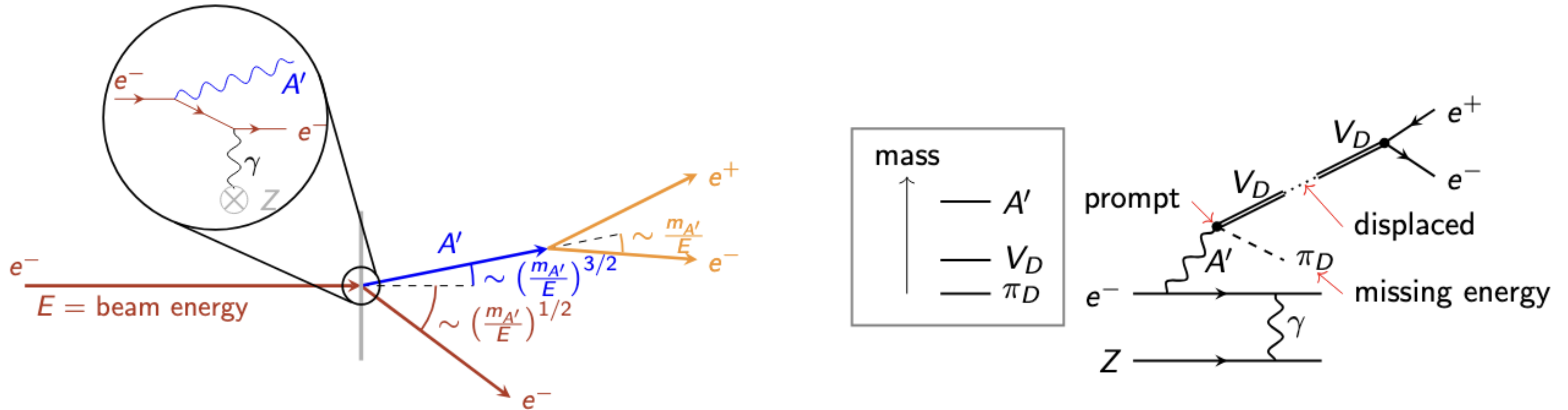
Physics Scope of HPS



	Signal			
	Minimal A'	Minimal A'	SIMPs	iDM
Signature	$\epsilon^2 \gtrsim 10^{-7}$	$\epsilon^2 \lesssim 10^{-8}$		
$x = \frac{ p_{e+} + p_{e-} }{E_{\text{beam}}}$	high	high	low	low
resonance	yes	yes	yes	no
prompt/displaced	prompt	displaced	displaced	displaced

- HPS sensitive to prompt and displaced resonant events
- Exploring sensitivity to non-resonant events, but ~~very challenging~~ likely impossible

HPS Expected Signal Yield

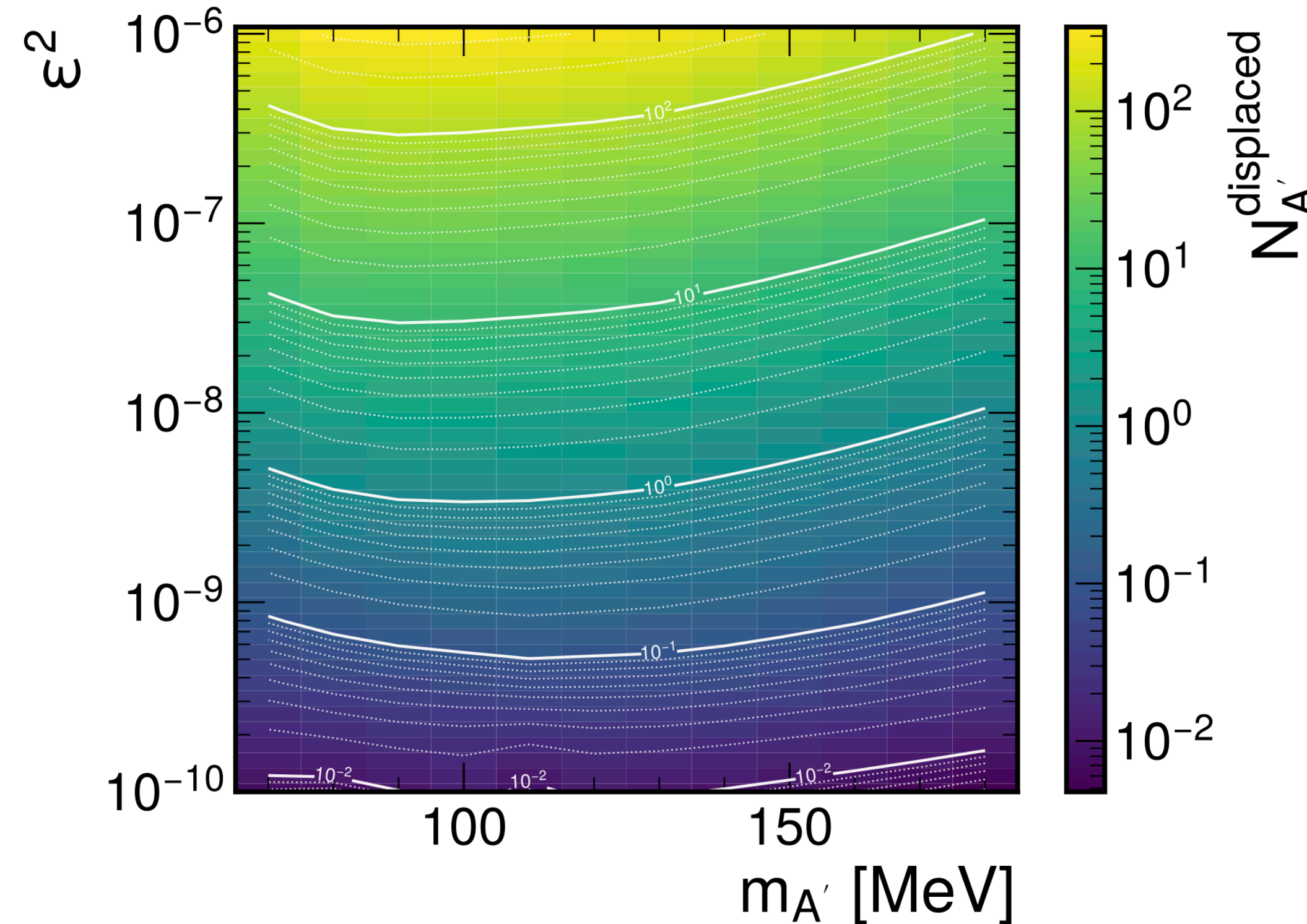


- Proportional rates of dark and regular bremsstrahlung

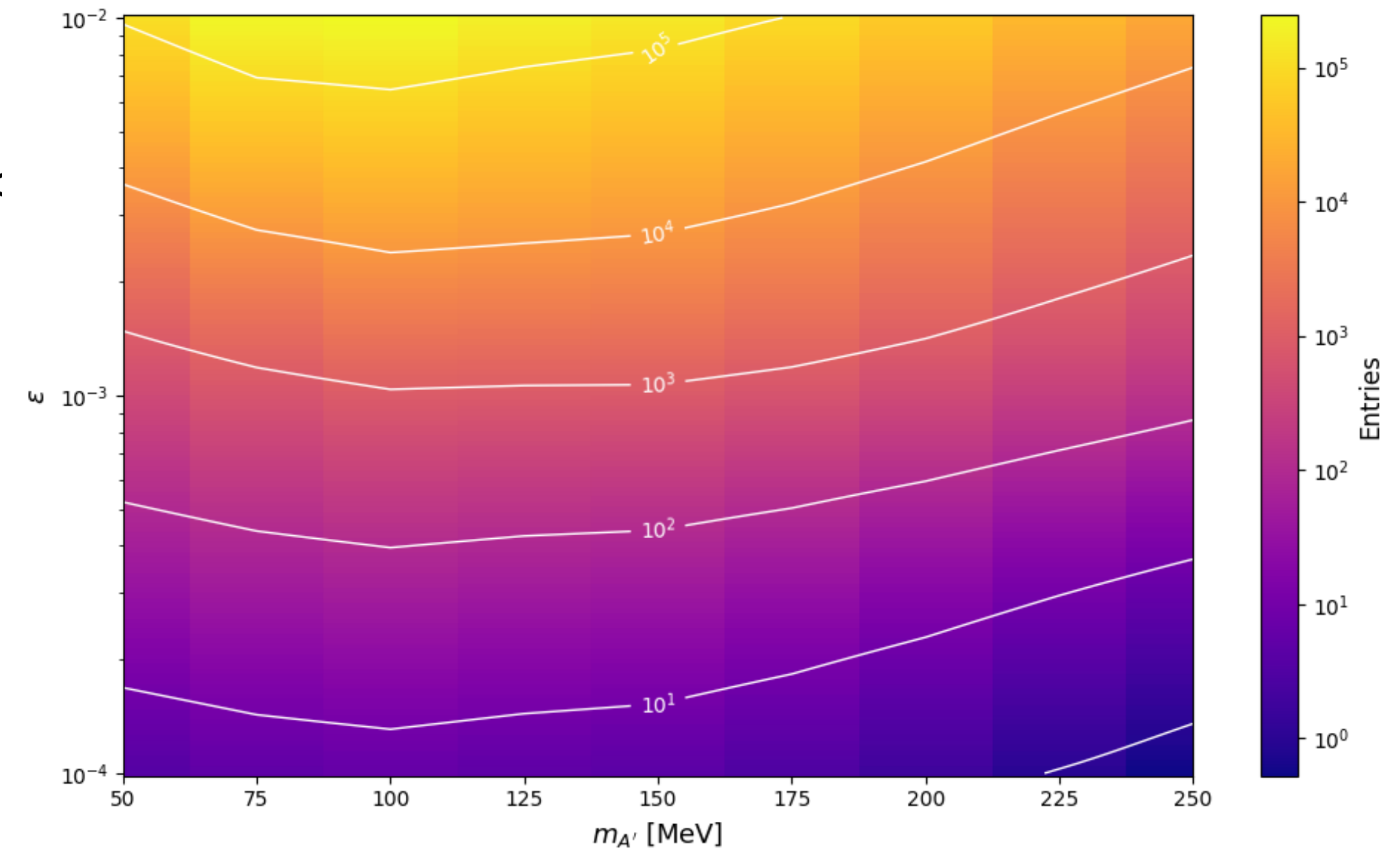
$$\frac{d\sigma(e^- Z \rightarrow e^- Z(A' \rightarrow l^+ l^-))}{d\sigma(e^- Z \rightarrow e^- Z(\gamma^* \rightarrow l^+ l^-))} = \left(\frac{3\pi\epsilon^2}{2N_{\text{eff}}\alpha} \right) \frac{m_{A'}}{\delta m}$$

- A' rate estimated by radiative trident rate
 - At HPS: MC-derived “radiative fraction” relates overall event rate to radiative trident rate
 - Need for accurate MC simulations
 - Expected event rate modified for complex dark sectors

Expected Signal Yield



1% luminosity

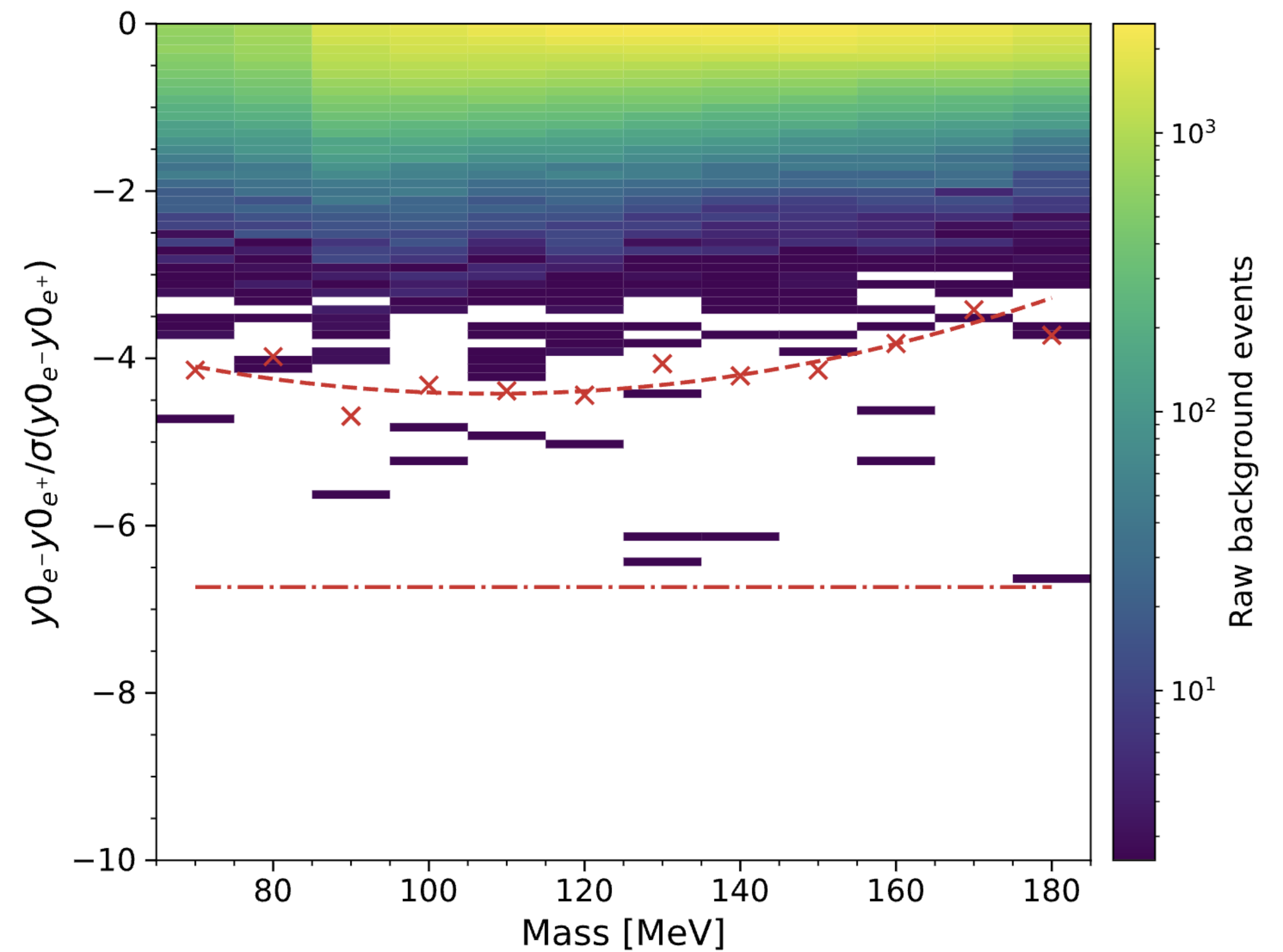


100% luminosity

- SIMP model depends on multiple parameters – can give much higher signal yield
- At 100% lumi: A' has max. 10^4 events, SIMP has max. 10^5 events

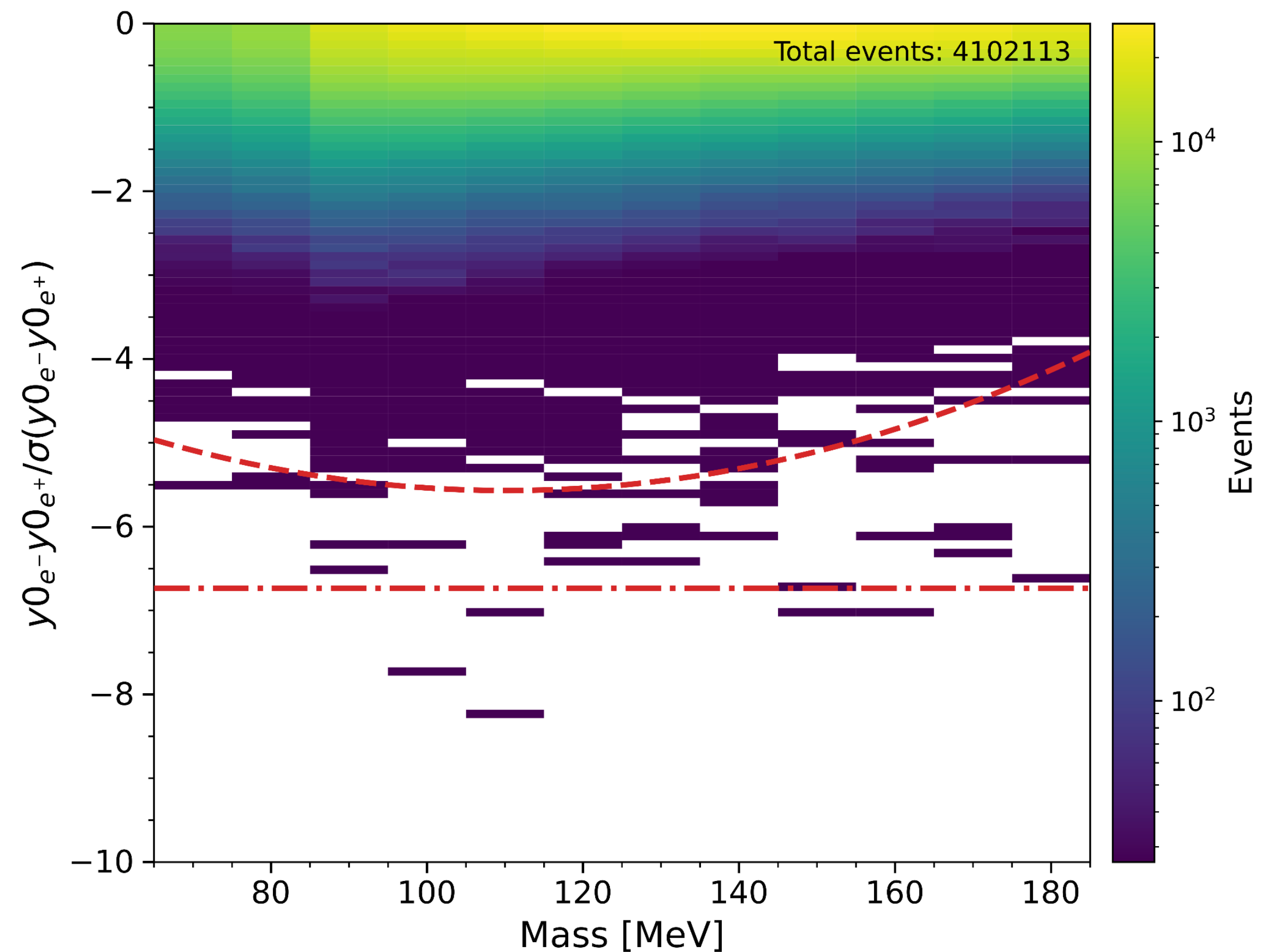
Background-free Search?

- Two scenarios:
 - Piecewise linear zero-background signal region (dashed-dotted)
 - Signal region defined by tail fit of background distribution (dashed)



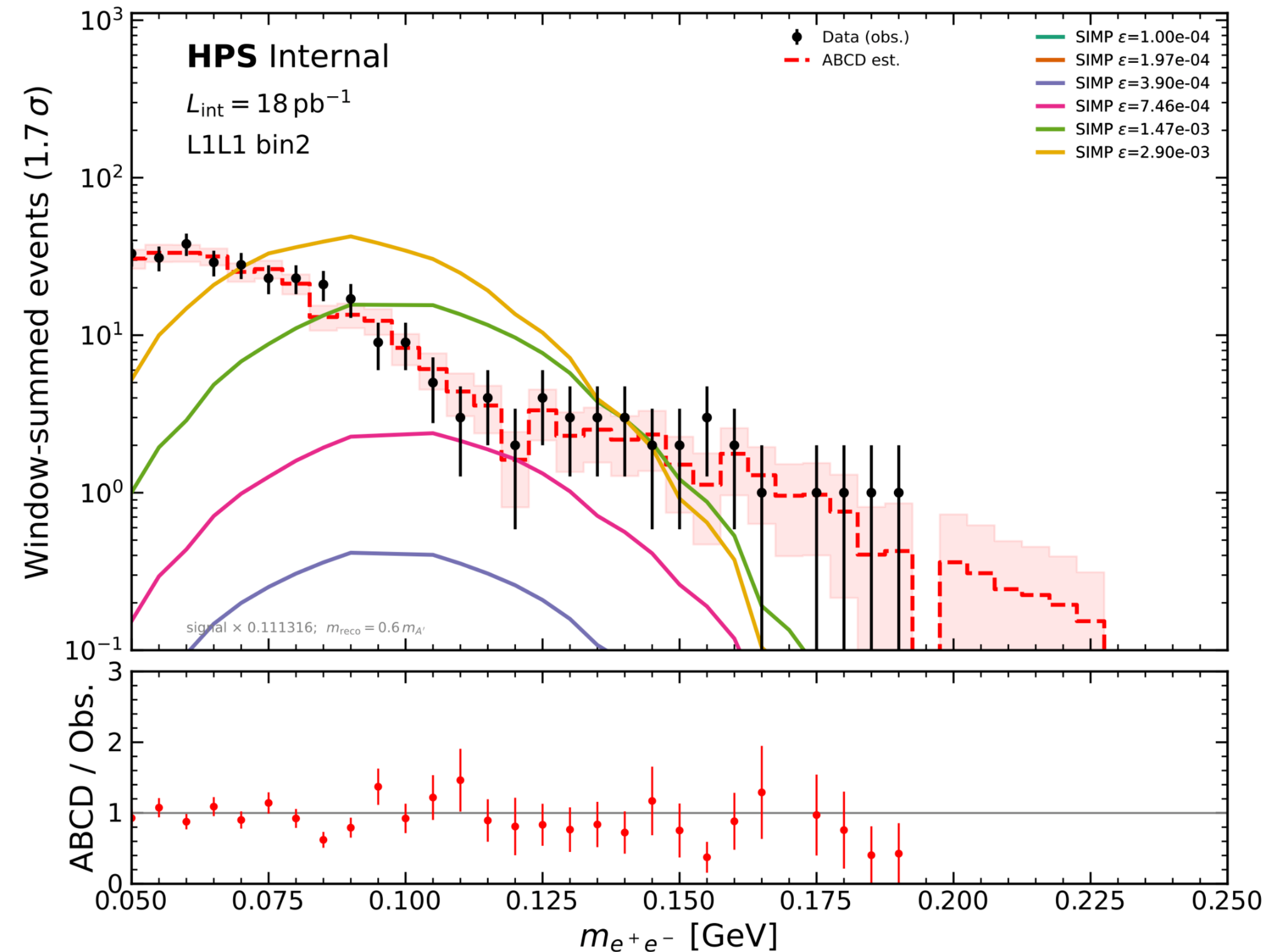
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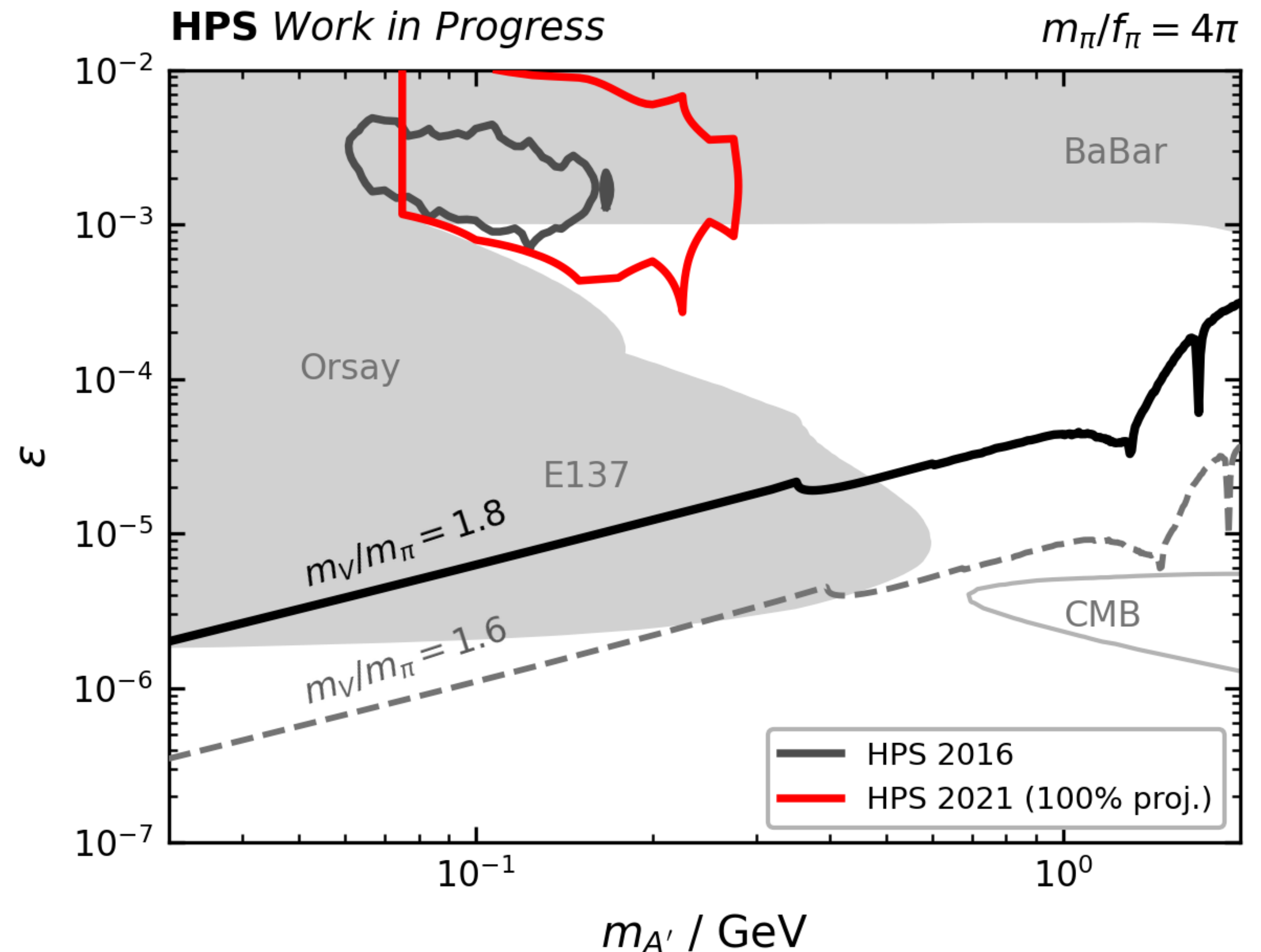
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- Problem: always some background in signal region
 - Harsher cuts reduce signal rate too much!
- For SIMP search: higher expected yield
 - Possible to compare data to background and signal estimates



Expected SIMP yield for HPS

- Studies on going to complete the SIMPS search with 2021 data.
 - Exploring ML techniques
- Expect publication in early 2027, with nominal displaced A' to follow



Conclusions

- LDMX design is mature and prototypes have performed well in beam tests
- HPS has shown us that zero background searches with accelerators are hard!

Back-up

Conclusions & Outlook

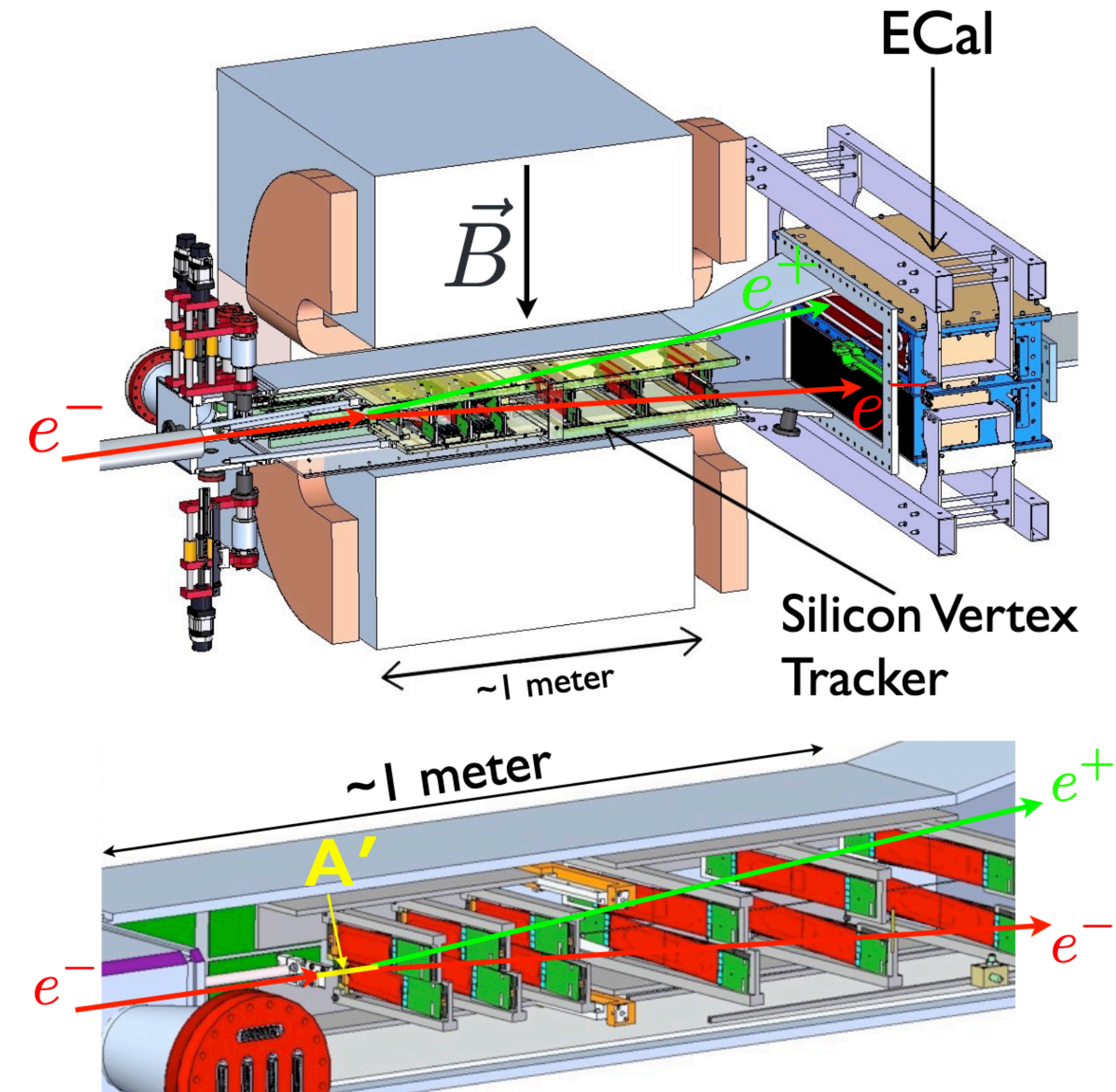
- Broad set of experiments looking for direct production of dark matter with accelerators
- Thin target experiments:
 - HPS has data to analyze & more to be taken
 - LDMX is ready to build
- Let's hope for a DM party in the next ~decade



Back up

HPS Detector Design

- 7-layer silicon strip detector with $\sim 60\mu\text{m}$ strip pitch
- Innermost layers are slim-edge for acceptance
- Edges 0.5mm from beam center
- Vertex resolution:
- Fast PbWO_4 ECal for triggering and electron positron ID
- Added positron hodoscope in front of ECal for positron-only trigger

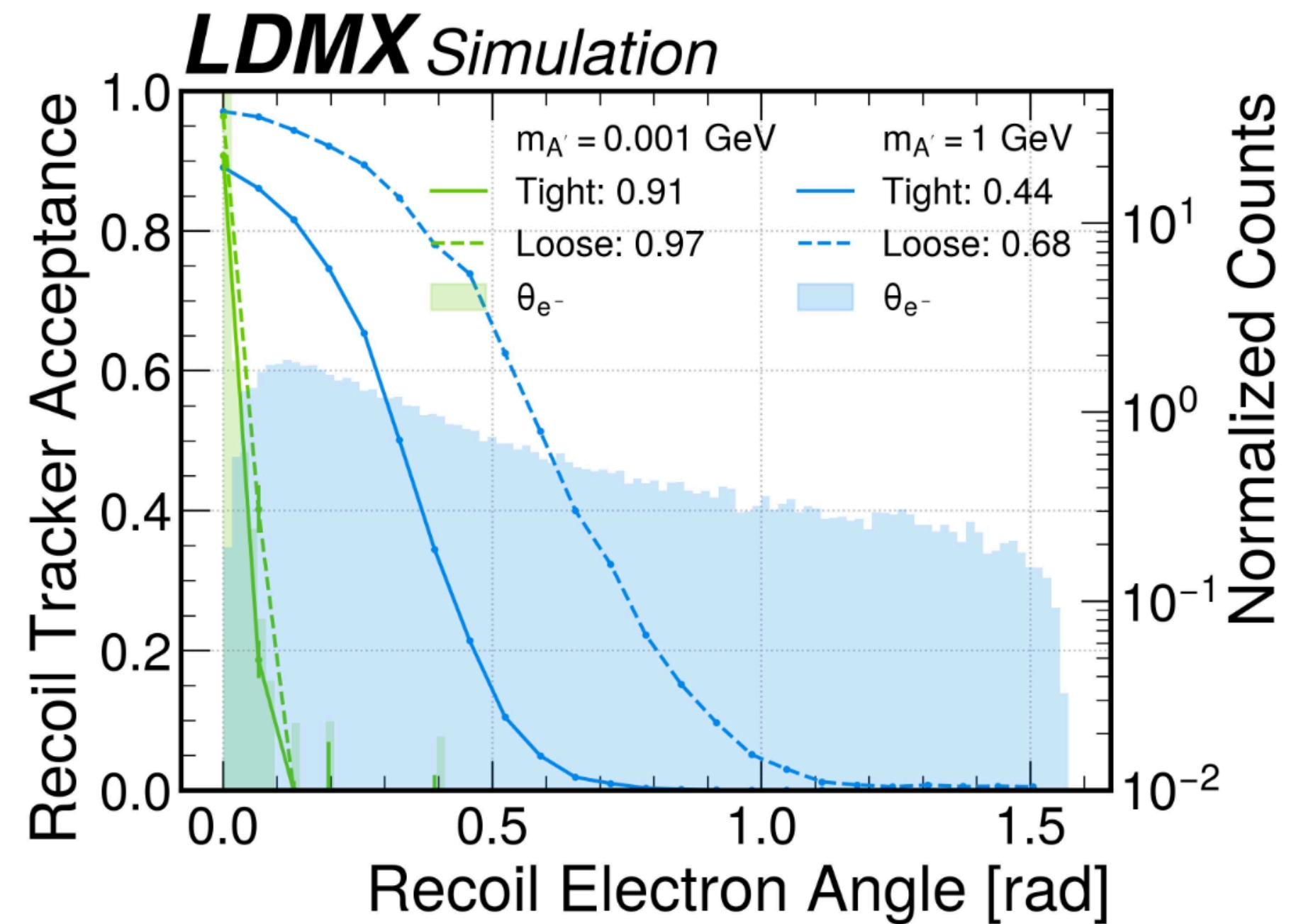
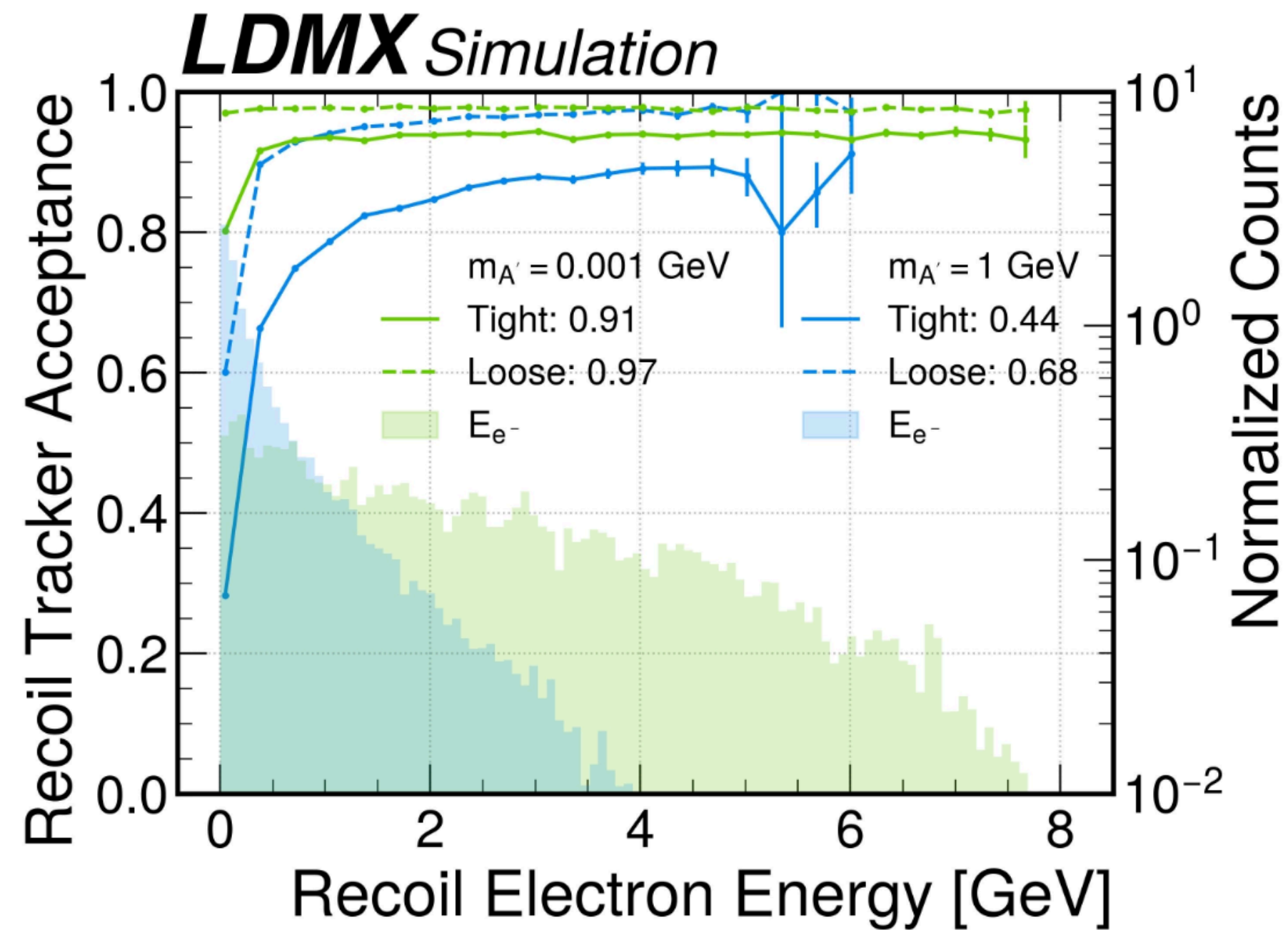


1e14 LDMX Cutflow (from design report)

Cut	Number of Background Remaining				Signal Efficiency for different $m_{A'}$			
	target PN	target conv.	ECal PN	ECal conv.	1 MeV	10 MeV	100 MeV	1000 MeV
EoT equivalent	10^{14}	10^{15}	10^{14}	10^{14}				
All / Acceptance	1,941,296	7,091,907	299,299,867	18,720,663	100%	100%	100%	100%
Triggered	756,661	4,280,536	170,993,364	14,042,193	78.2%	89.6%	91.3%	94.3%
$p_{\text{tagger}} > 5.6 \text{ GeV}$	745,494	4,224,191	168,725,637	13,856,953	77.1%	88.4%	90.0%	93.0%
$N_{\text{recoil}} = 1$	72,927	21,625	154,191,349	12,685,692	72.2%	82.4%	83.0%	72.4%
Ecal BDT > 0.9974	1,529	<1	64,353	<1	52.9%	68.6%	73.1%	67.8%
$N_{\text{straight}} < 3$	1,412	<1	61,771	<1	51.8%	67.2%	71.7%	64.3%
HCal maxPE < 8	<1	<1	2	<1	49.9%	64.3%	68.3%	59.3%

Table 4.2: Cutflow with trigger, tracker veto, ECal BDT, HCal veto and MIP tracking cuts, in the target / ECal conversion and photo-nuclear events, together with a target electro-nuclear sample as backgrounds, and signal samples with masses from 1 MeV to 1 GeV.

Design report Tracking Performance



Background modeling

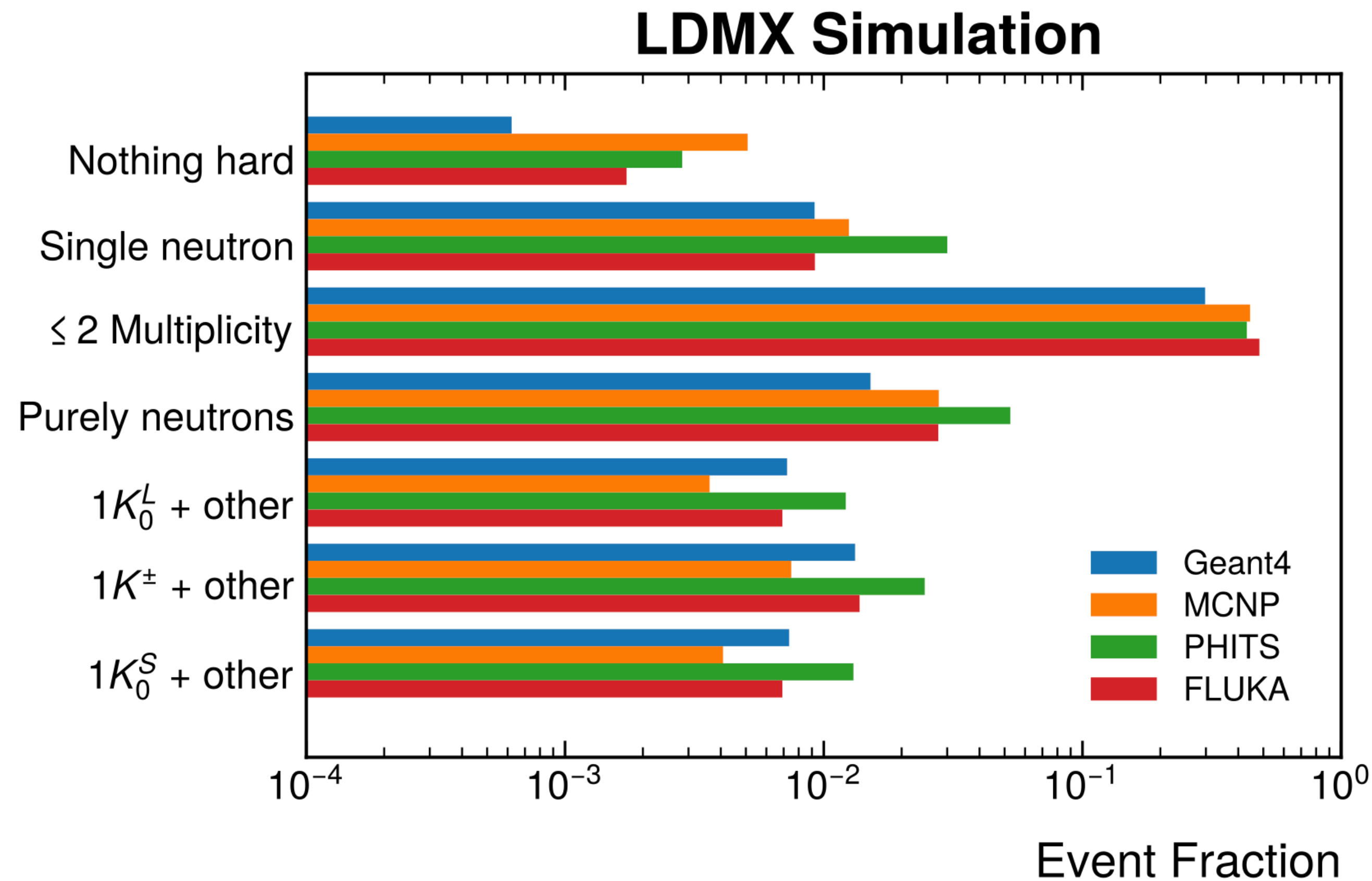
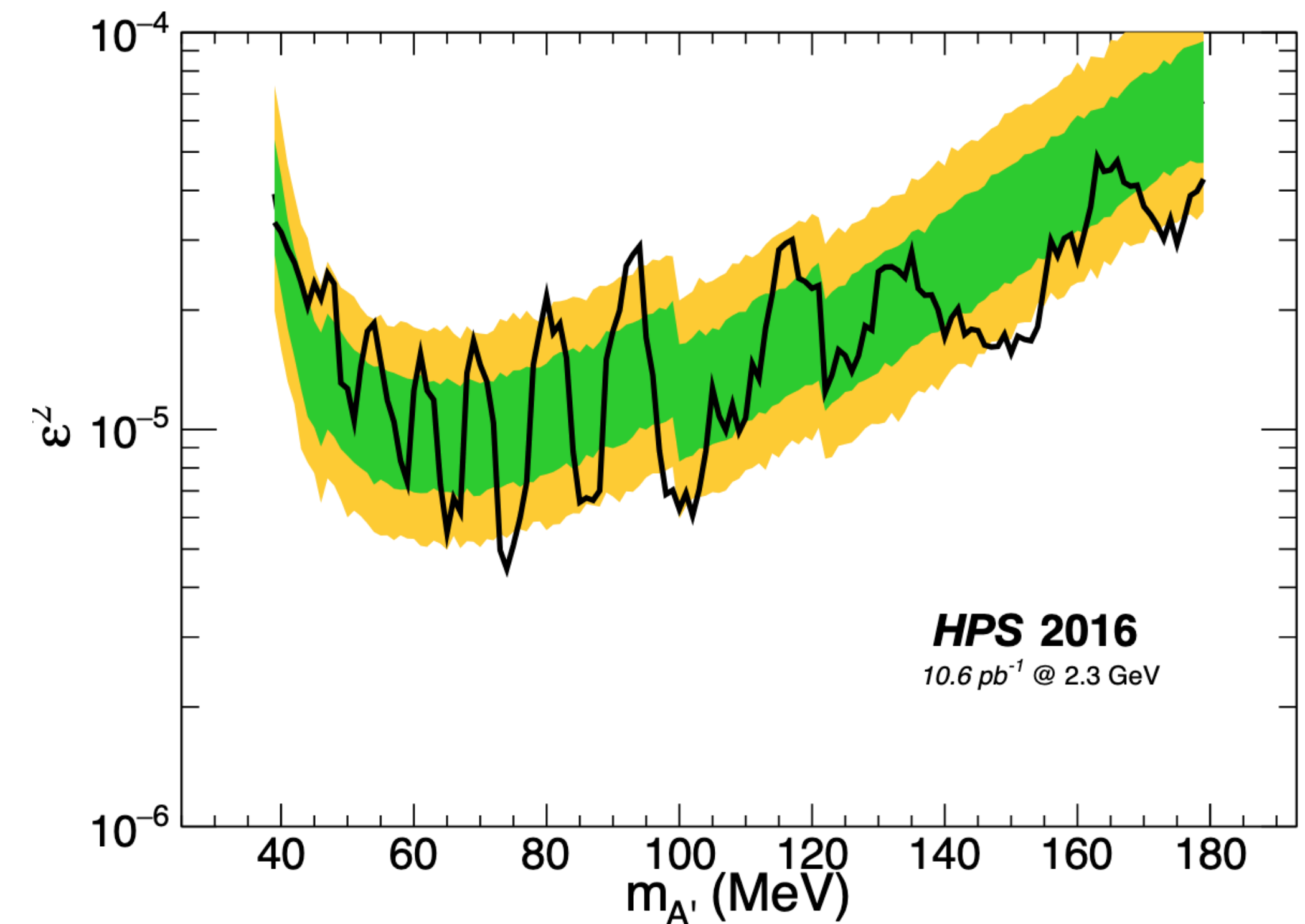
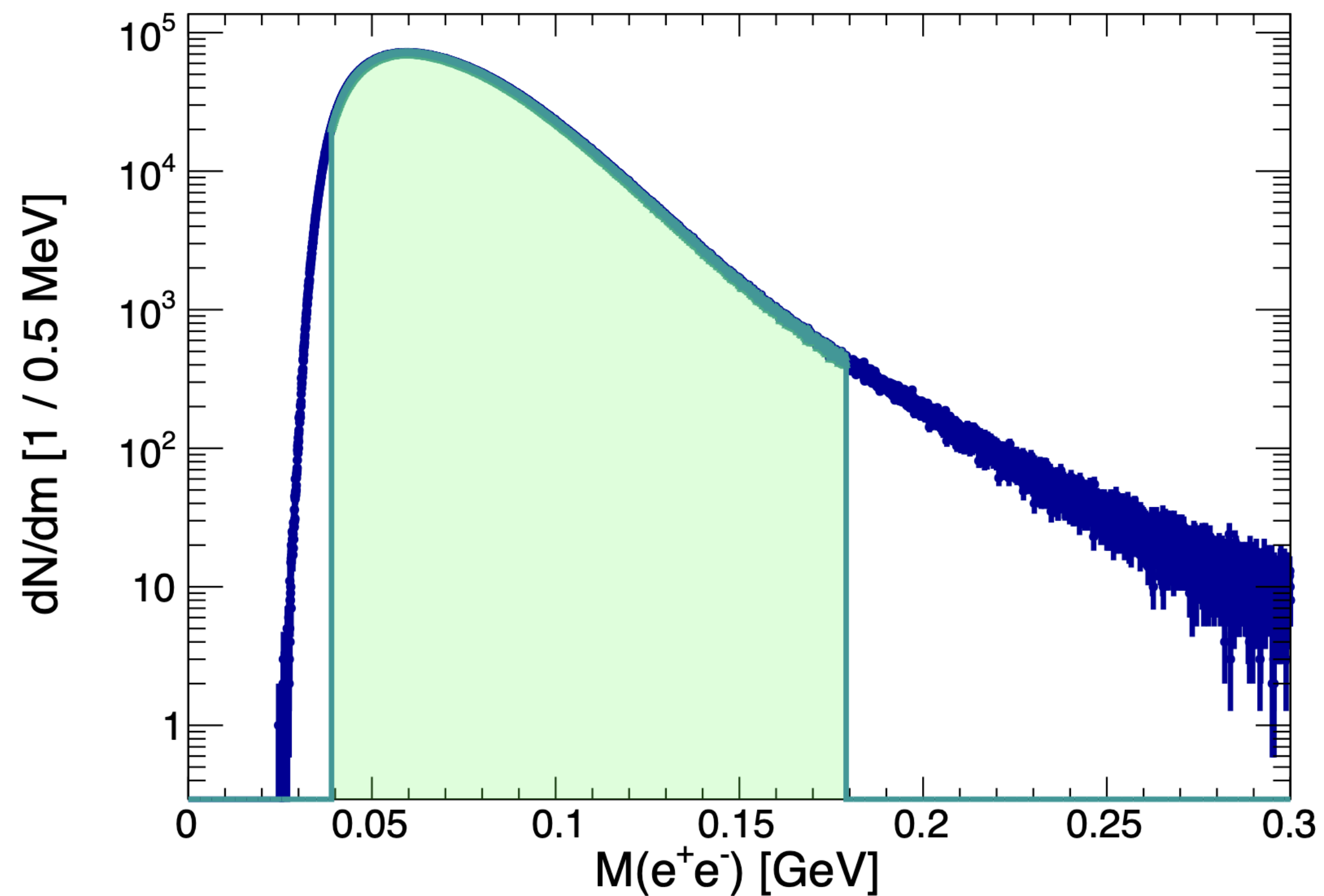


Figure 4.1: Predicted relative rates of photo-nuclear final states from 25000 events generated by the Bertini model in Geant4 (blue), the CEM model in MCNP (orange), the JAM model in PHITS (green), and the PEANUT model in FLUKA (red). Events are classified based on the multiplicity of different particle species with kinetic energy above 200 MeV.

HPS Prompt Search 2016 data

Phys. Rev. D 108, 012015



- “Bump hunt” looks for gaussian peak on Legendre polynomial background in varying mass windows
- Fitting method limits overall sensitivity, work is on-going to develop global background model

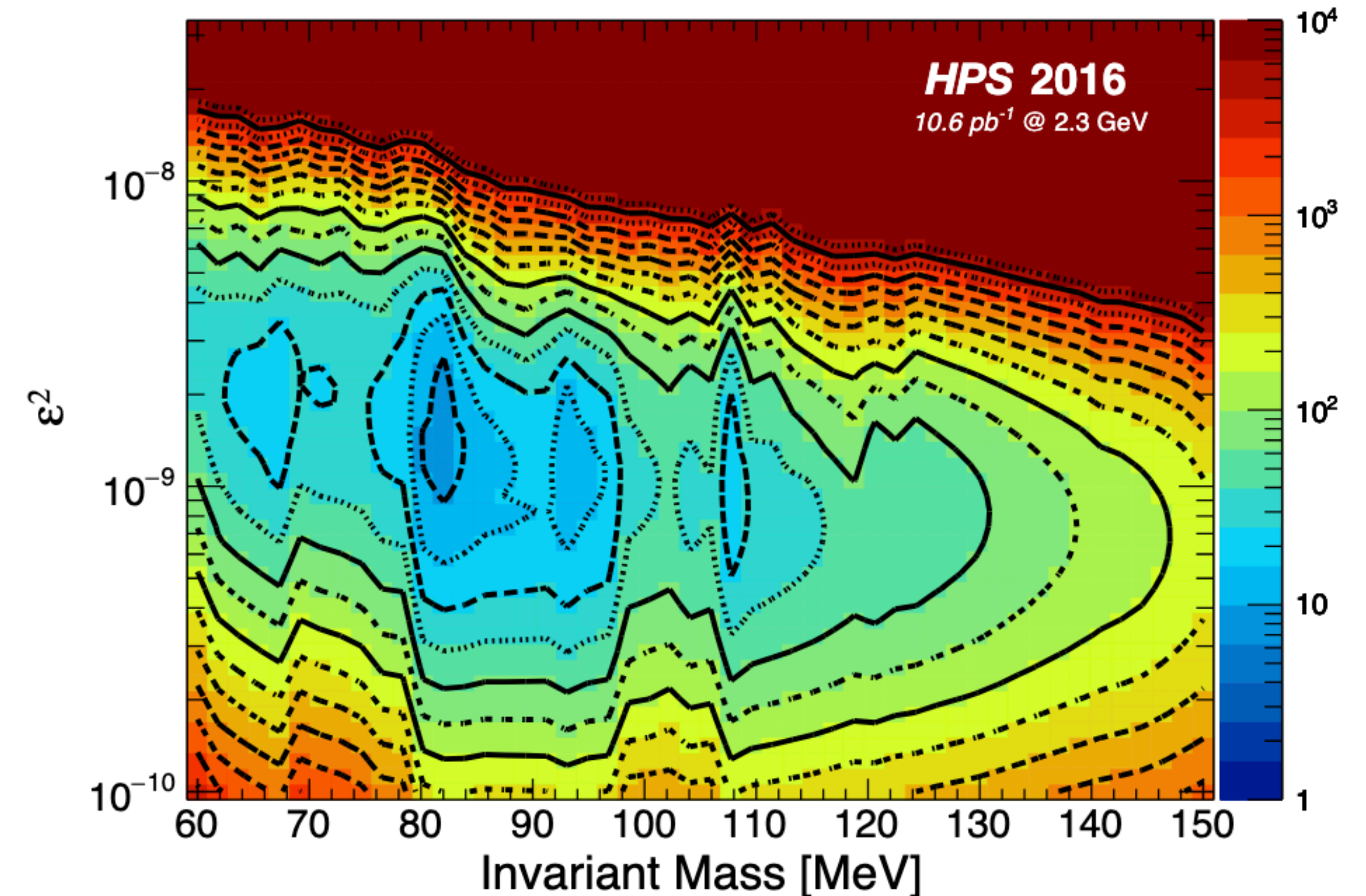
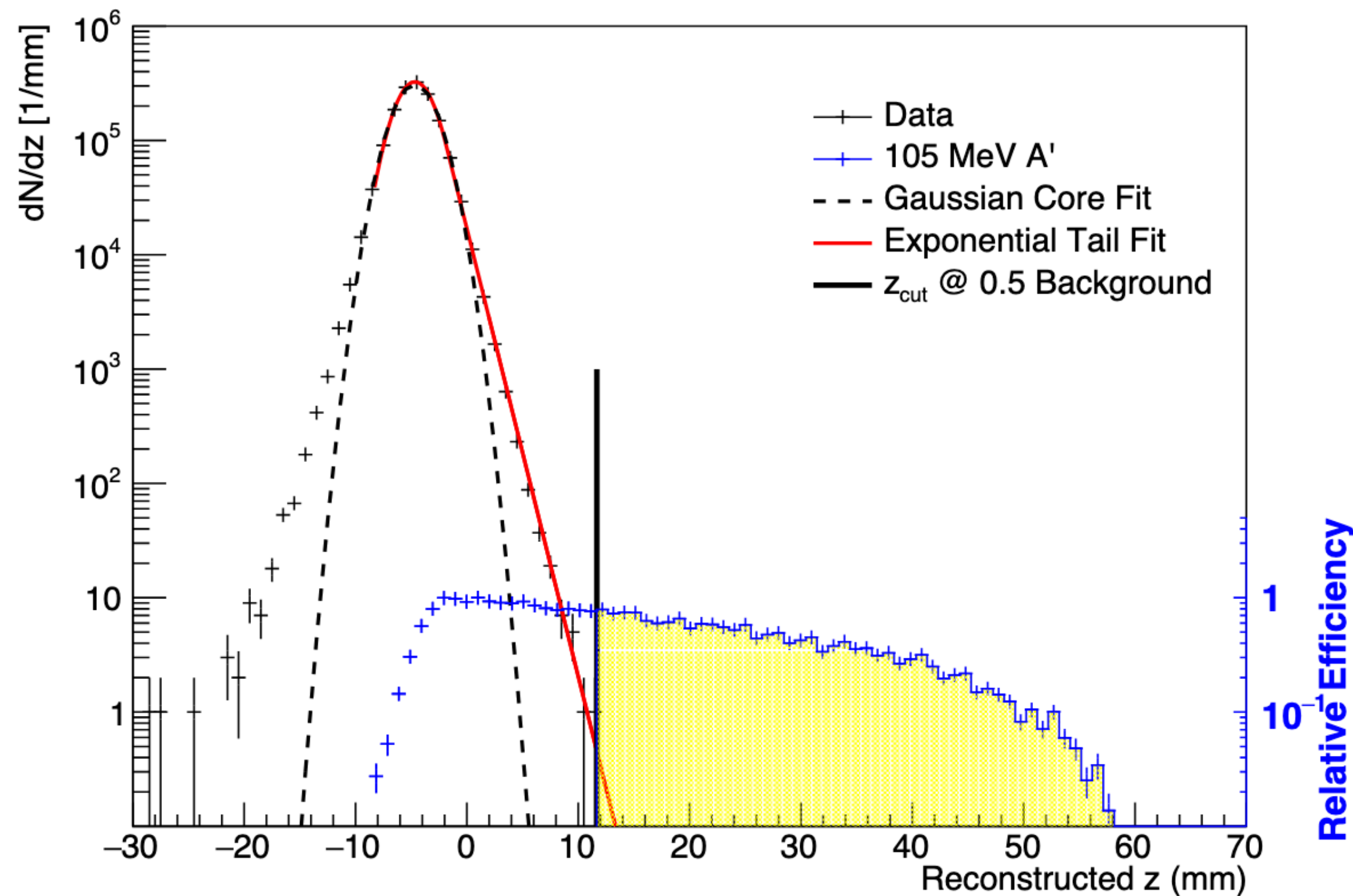
- HPS beam parameter requirements

Parameter	Requirement	Unit
Beam Energy (E)	1 to 6.6	GeV
$\delta E/E$	$< 10^{-4}$	
Beam Current	50 to 500	nA
Current Stability	~ 5	%
σ_x	< 300	μm
σ_y	< 50	μm
Position Stability	< 30	μm
Divergence	< 100	μrad
Beam Halo ($> 5\sigma$)	$< 10^{-5}$	

Table 1: Required beam parameters.

Displaced Search 2016 data

Phys. Rev. D 108, 012015



- Displaced search is very similar to SIMPs, just at higher P_{sum}
- No new sensitivity to A' in 2016 dataset but should have sensitivity in 2019/2021

A' Future Constraints

arXiv:2209.04671v1 [hep-ph] 10 Sep 2022

Dark Sector Physics at High-Intensity Experiments

Report of the RF6 Topical Group for Snowmass 2021

Stefania Gori¹ and Mike Williams²

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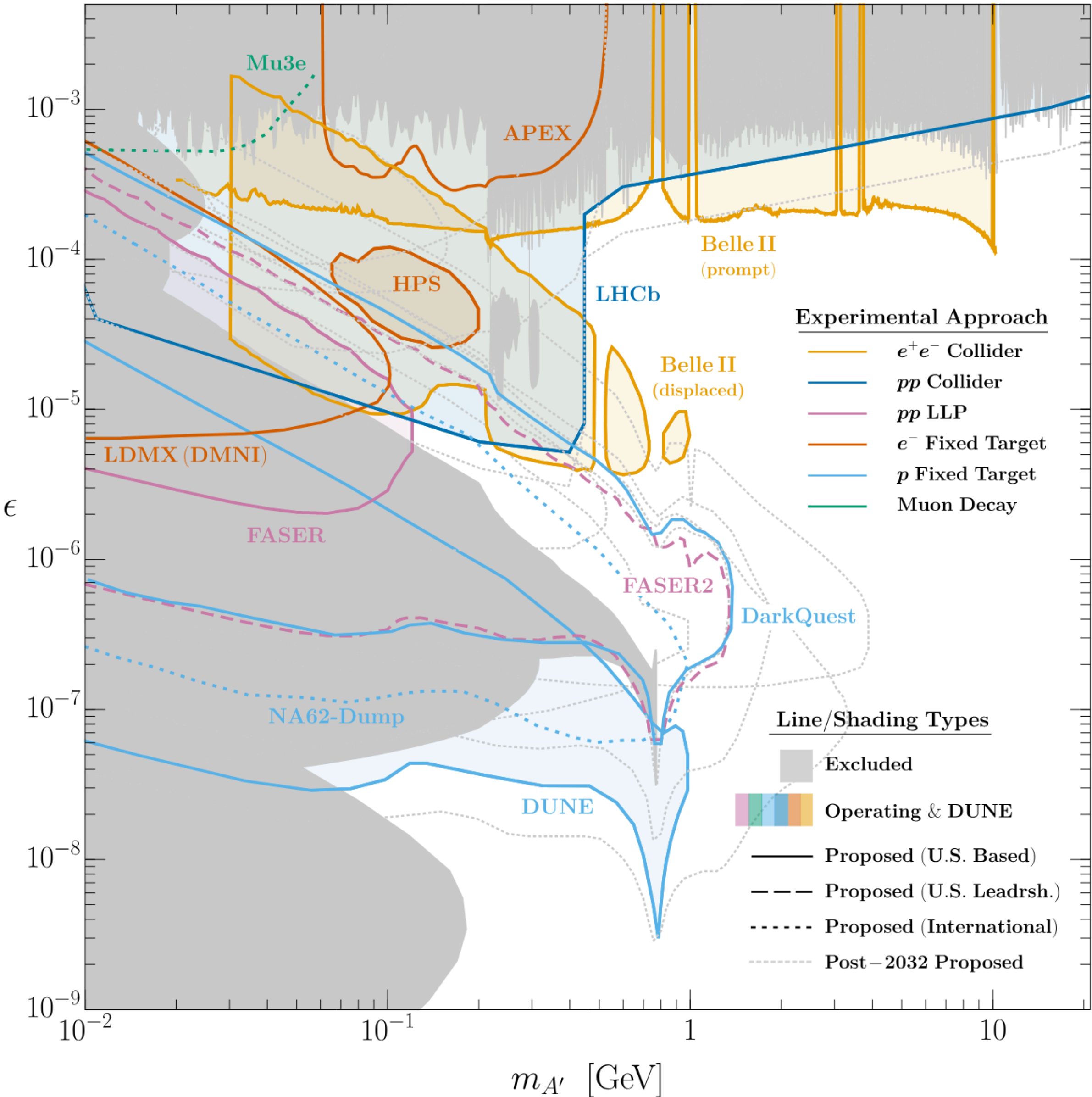
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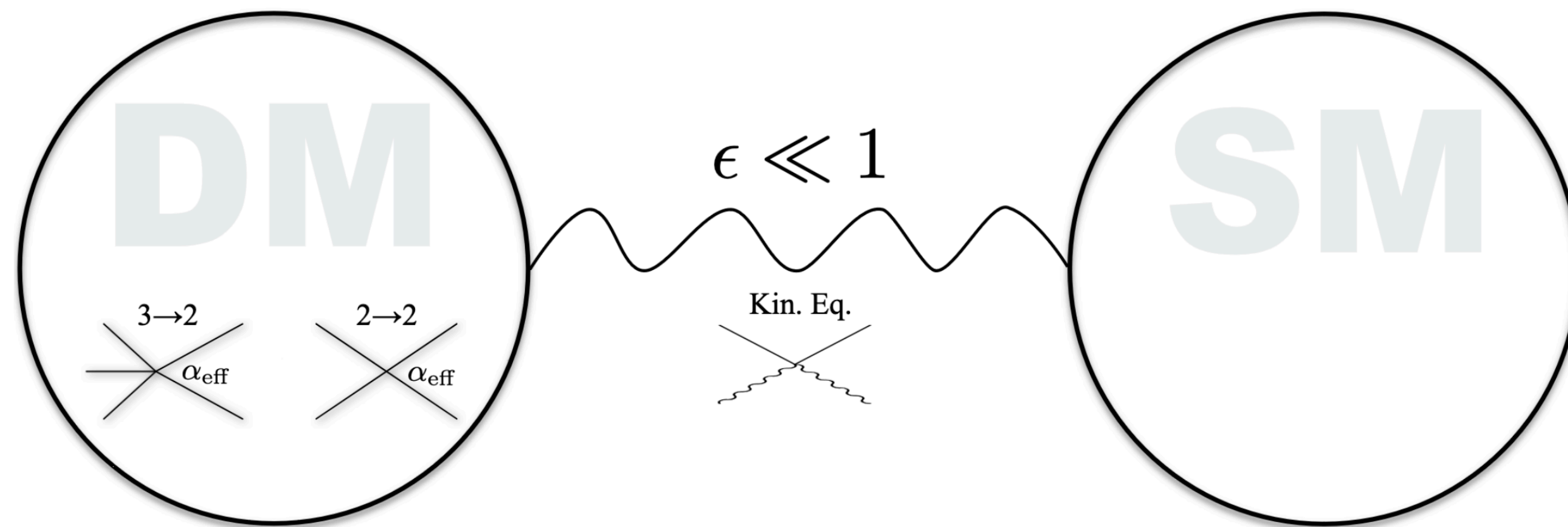
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Is Dark Matter part of a Dark Sector? The possibility of a dark sector neutral under Standard Model (SM) forces furnishes an attractive explanation for the existence of Dark Matter (DM), and is a compelling new-physics direction to explore in its own right, with potential relevance to fundamental questions as varied as neutrino masses, the hierarchy problem, and the Universe’s matter-antimatter asymmetry. Because dark sectors are generically weakly coupled to ordinary matter, and because they can naturally have MeV-to-GeV masses and respect the symmetries of the SM, they are only mildly constrained by high-energy collider data and precision atomic measurements. Yet upcoming and proposed intensity-frontier experiments will offer an unprecedented window into the physics of dark sectors, highlighted as a *Priority Research Direction* in the 2018 Dark Matter New Initiatives (DMNI) BRN report [1]. Support for this program—in the form of dark-sector analyses at multi-purpose experiments, realization of the intensity-frontier experiments receiving DMNI funds, an expansion of DMNI support to explore the full breadth of DM and visible final-state signatures (especially long-lived particles) called for in [1], and support for a robust dark-sector theory effort—will enable comprehensive exploration of low-mass thermal DM milestones, and greatly enhance the potential of intensity-frontier experiments to discover dark-sector particles decaying back to SM particles.

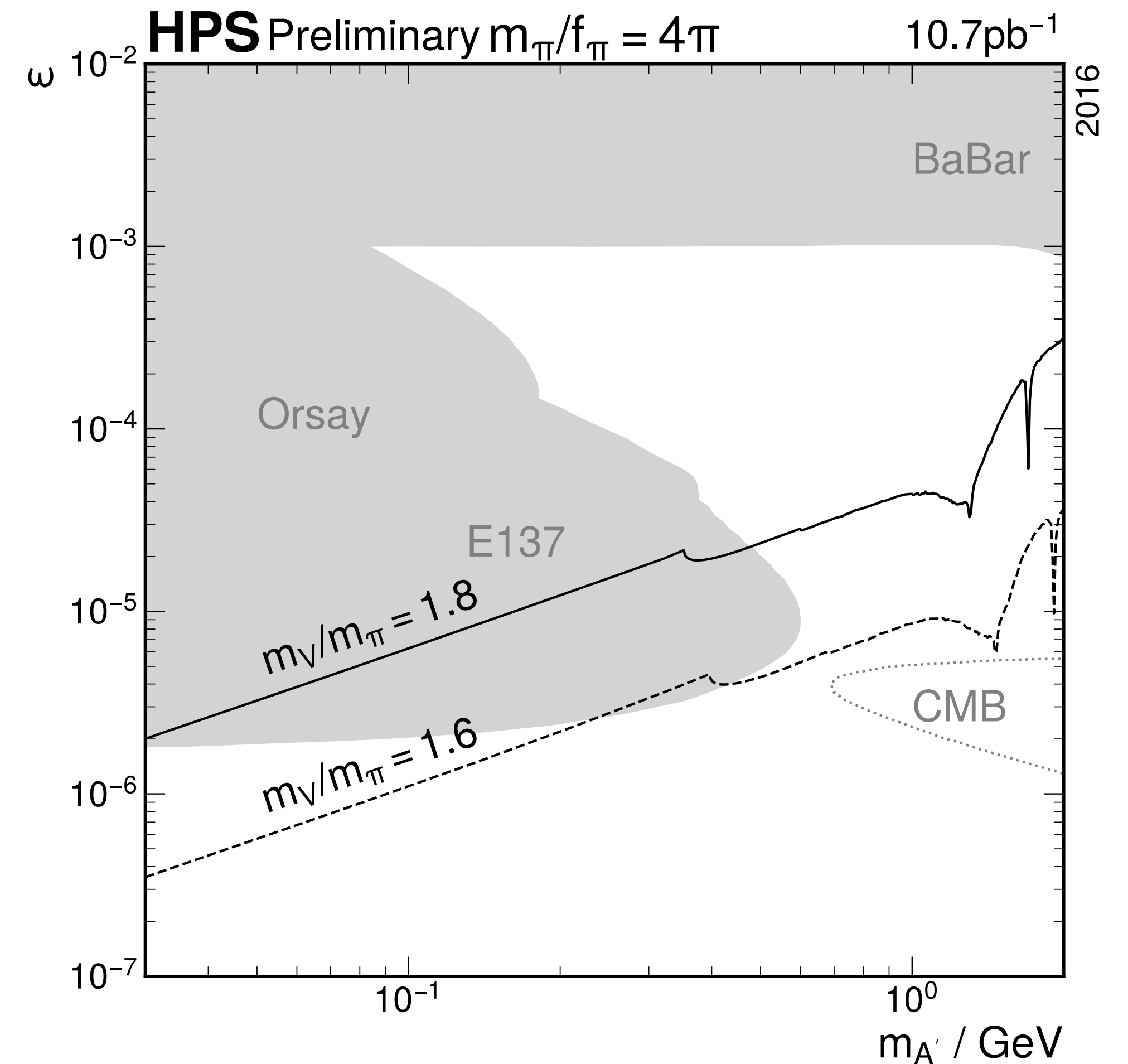


The SIMP Miracle arXiv:1402.5143

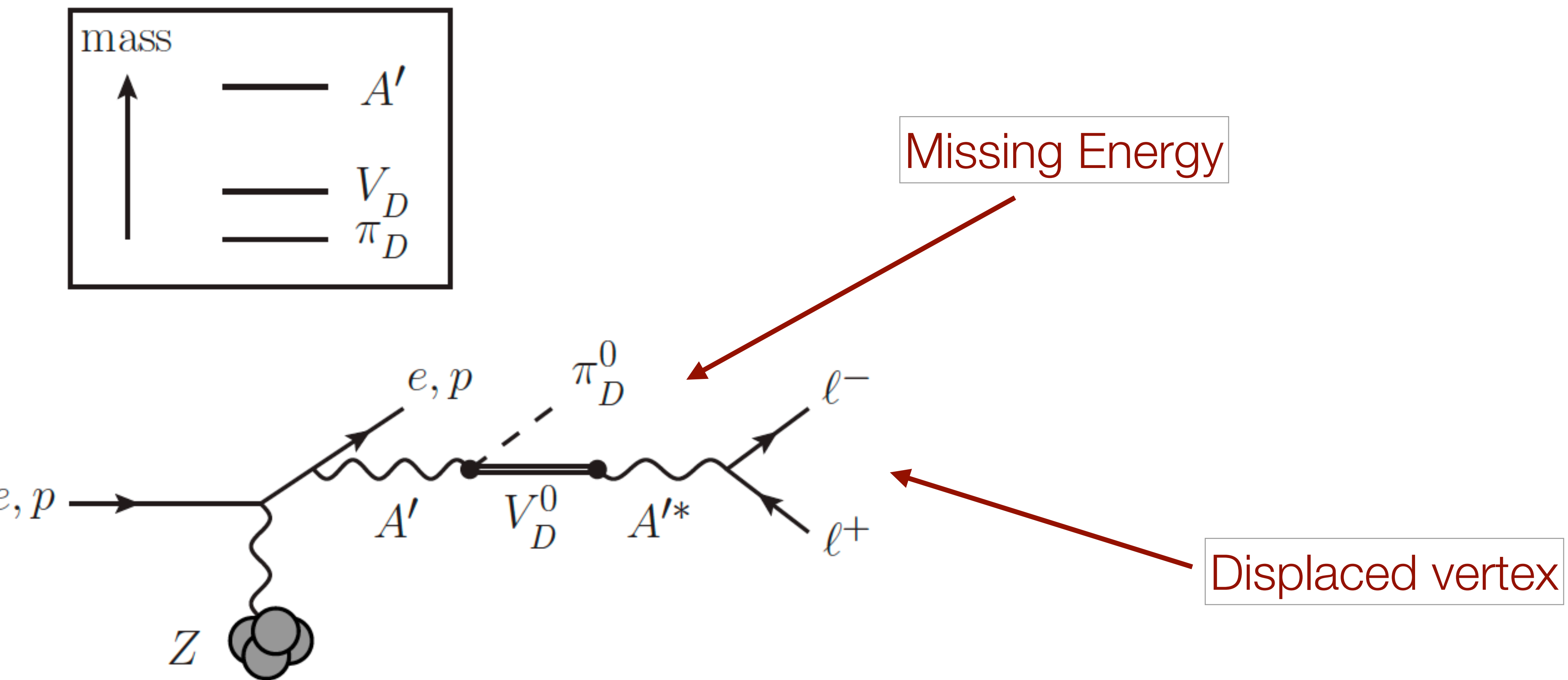
Yonit Hochberg, Eric Kuflik, Tomer Volansky, Jay G. Wacker



SIMPS: an alternative thermal relic dark matter model

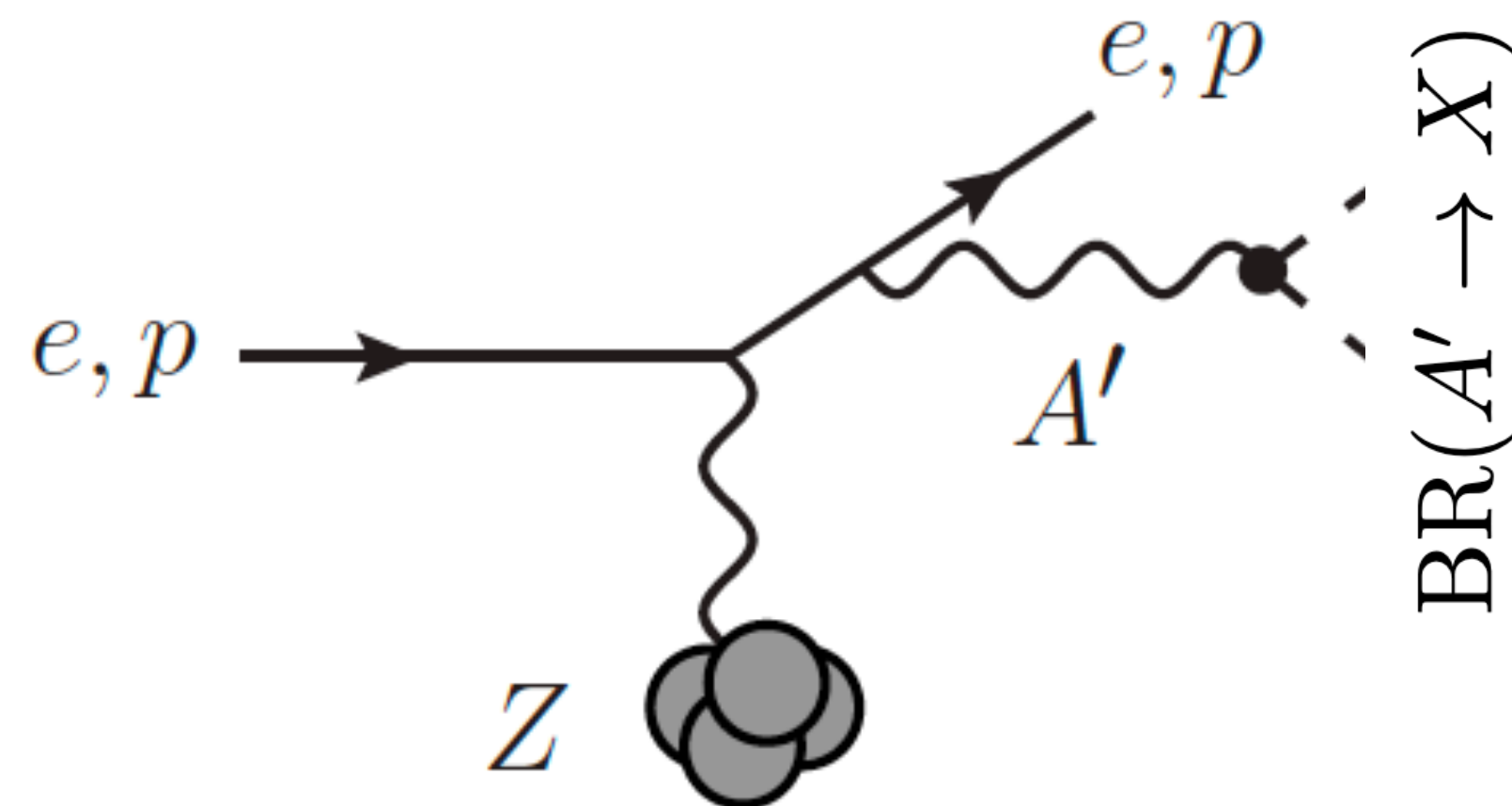
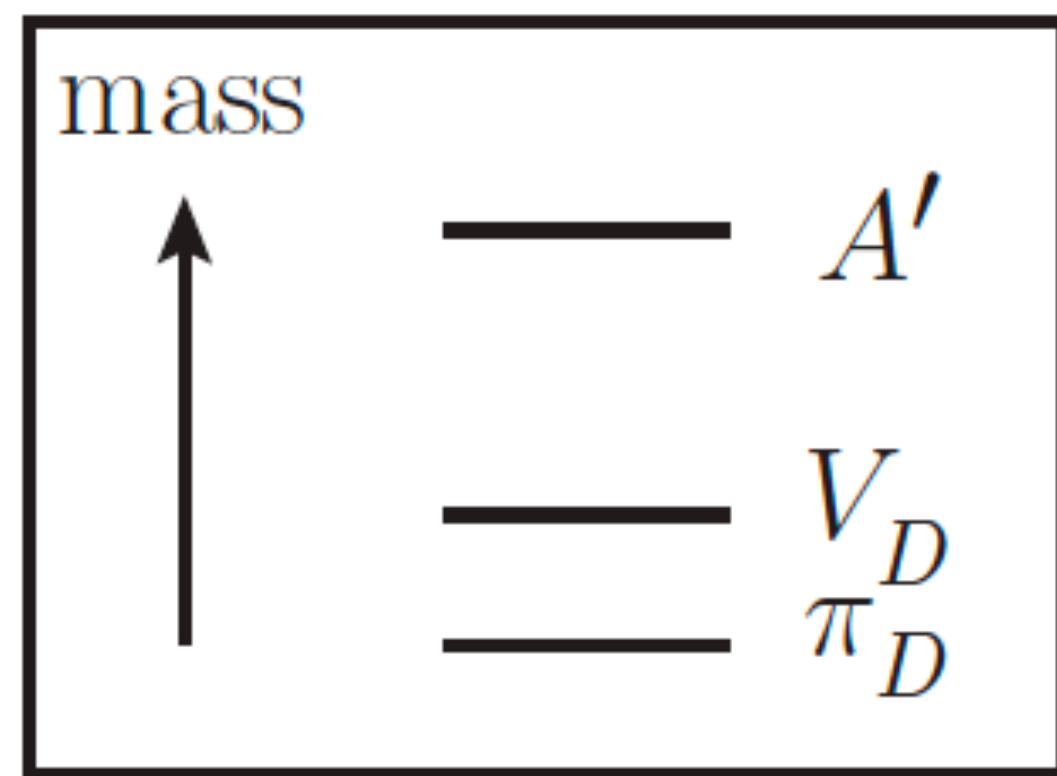


$3 \rightarrow 2$ & $2 \rightarrow 2$ annihilation mechanism for dark matter freeze-out
Equilibrium with SM through kinetic mixing

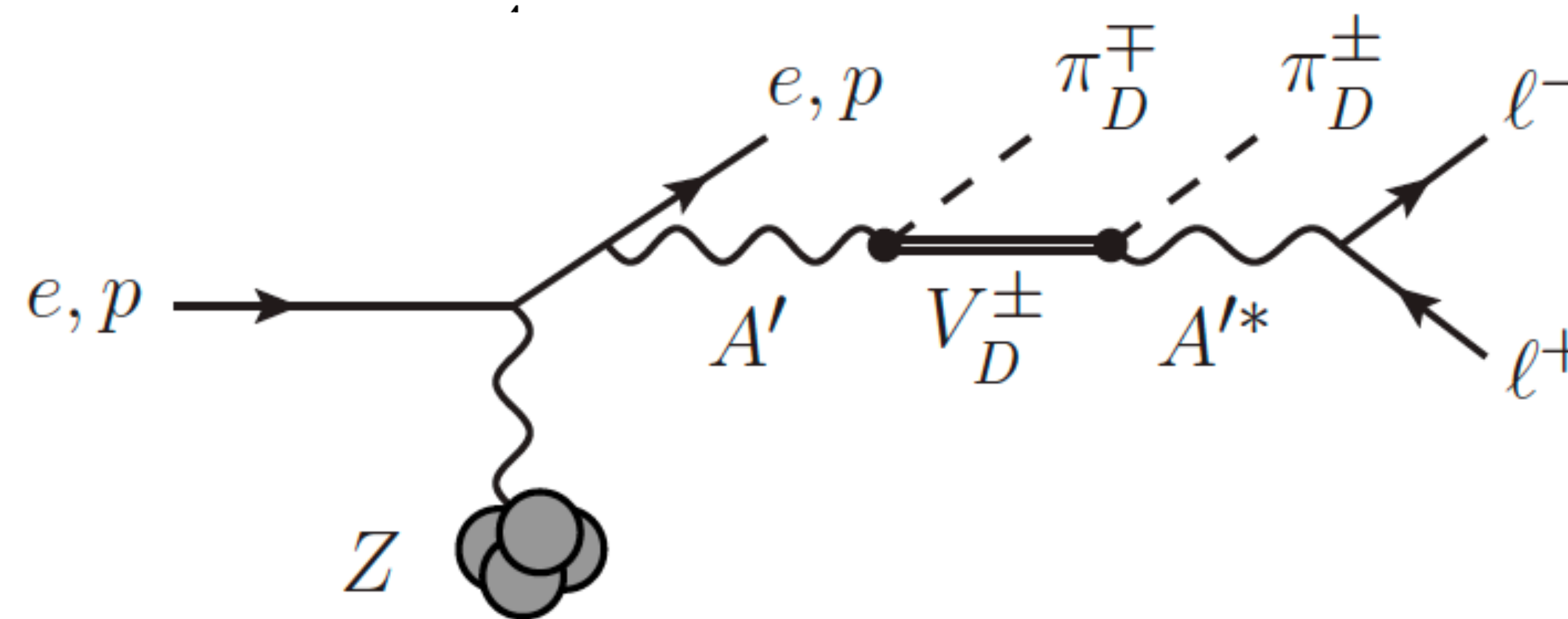
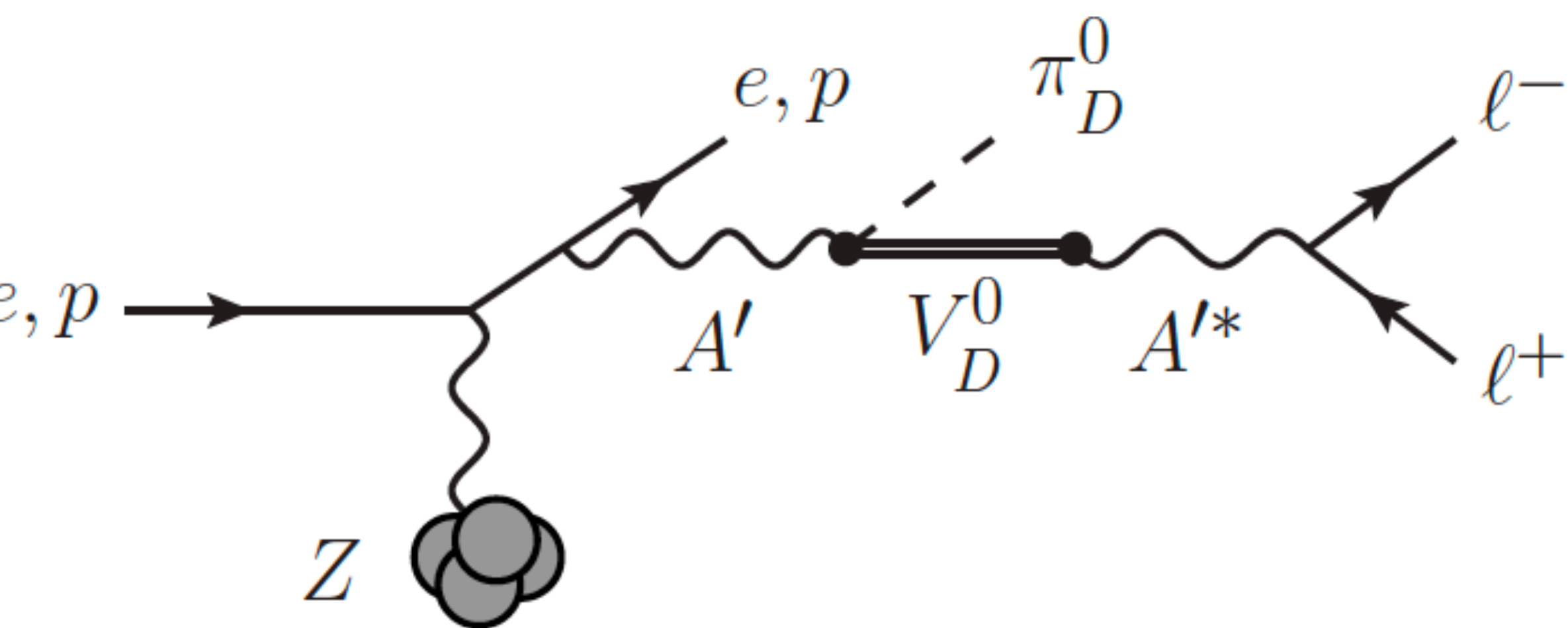
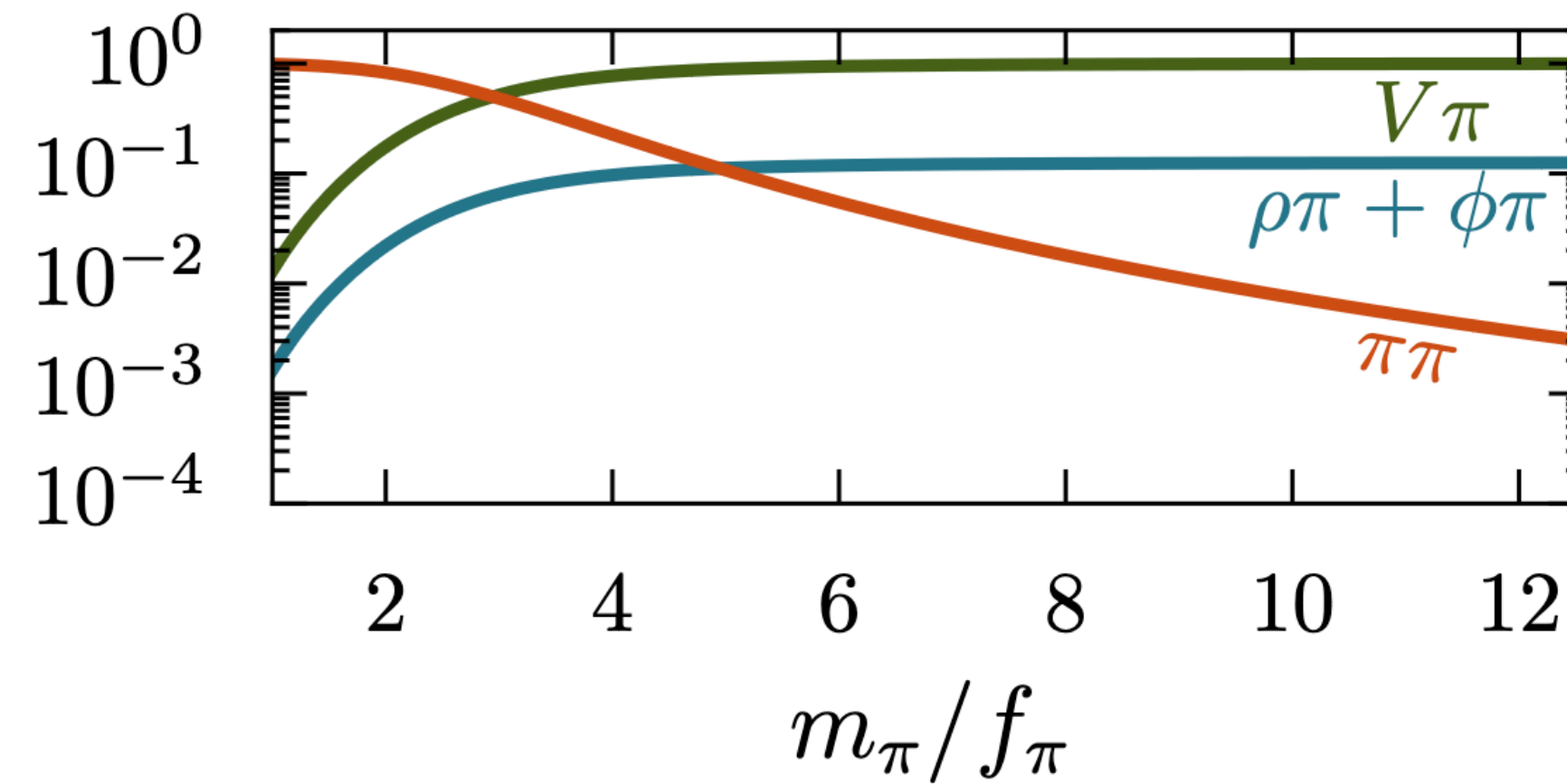


SIMPS
signatures

1 accessible to HPS:
Intermediate momentum,
displaced resonance



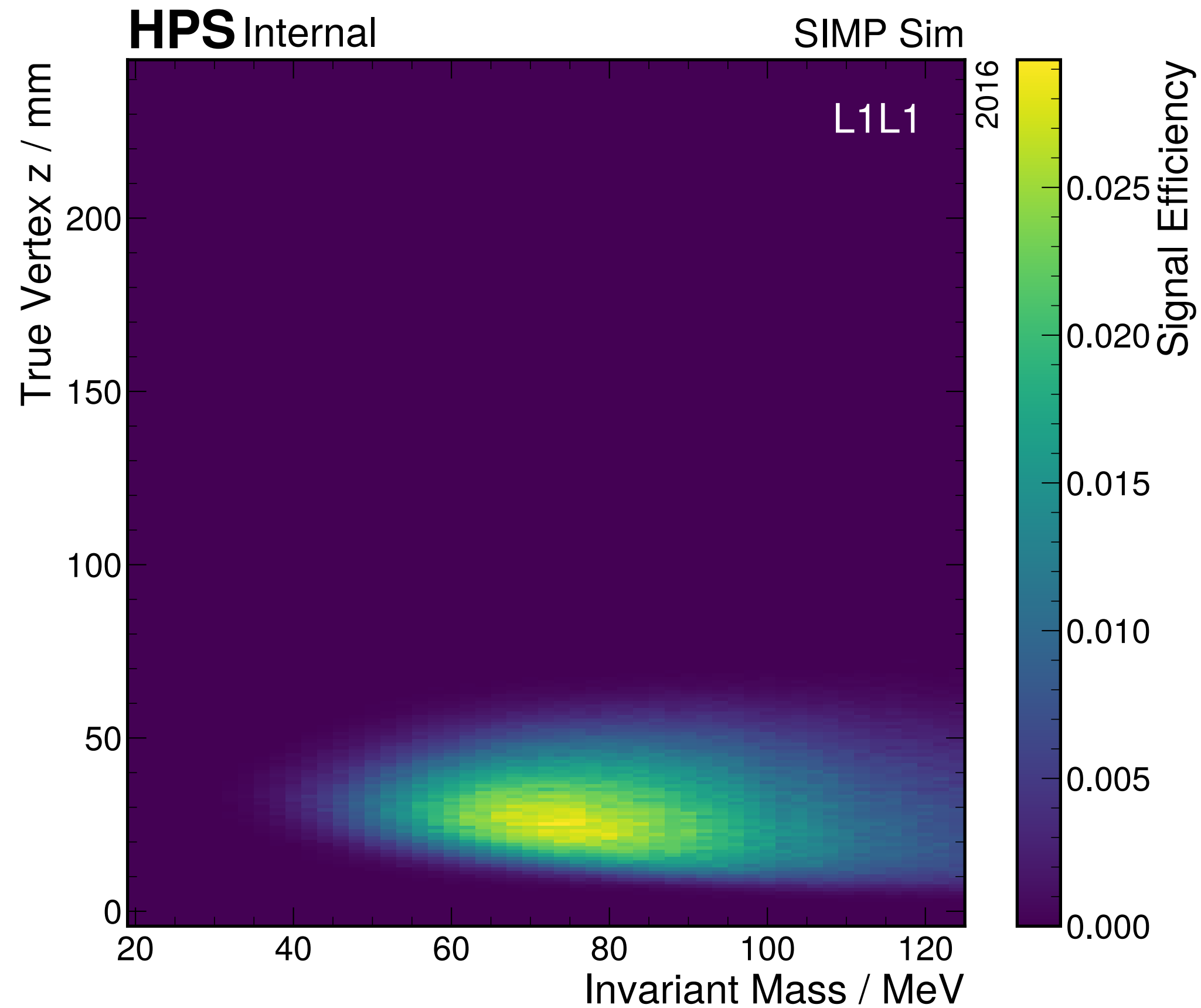
$\text{BR}(A' \rightarrow X)$



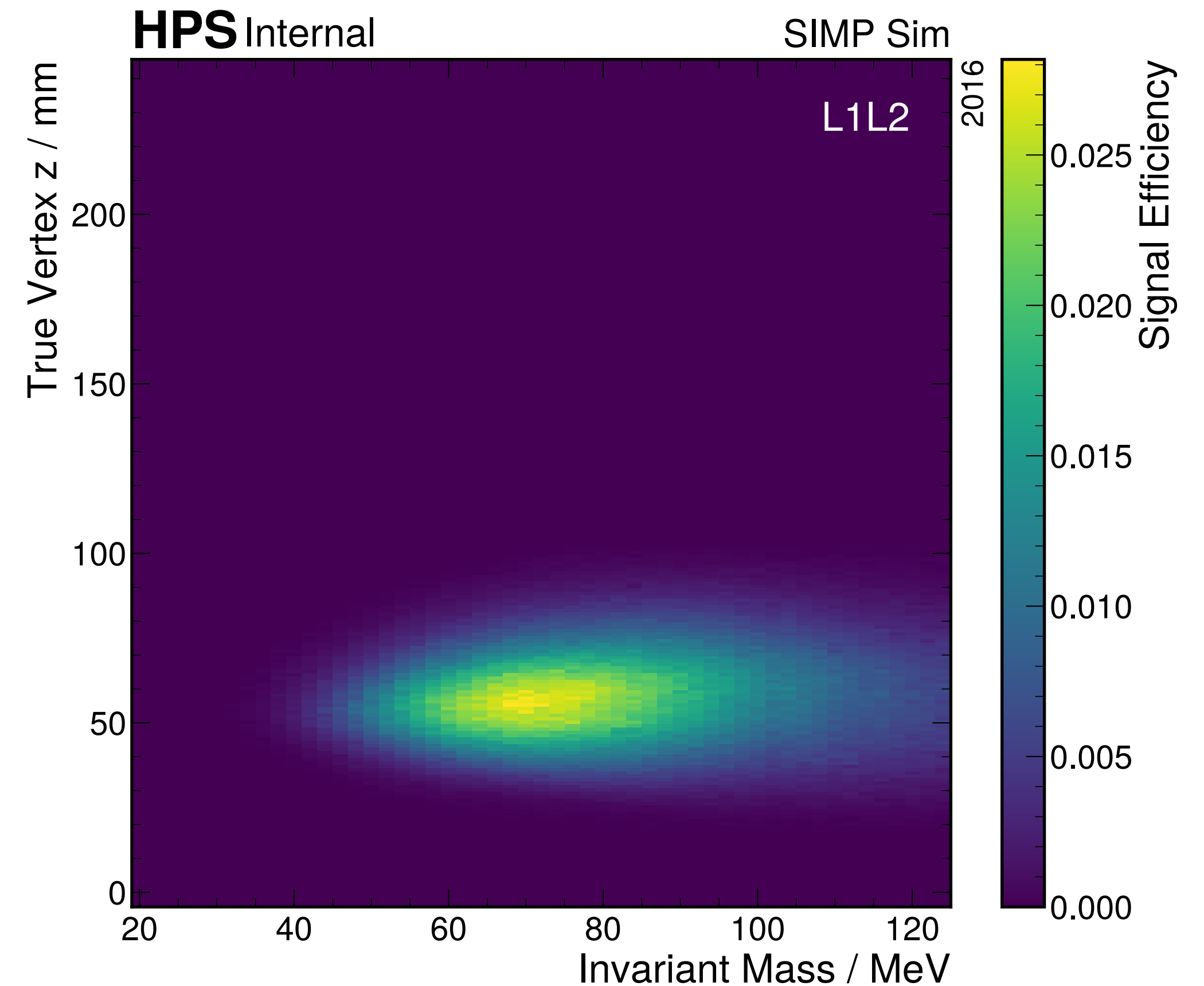
SIMPS
signatures

3 possible final states

L1L1



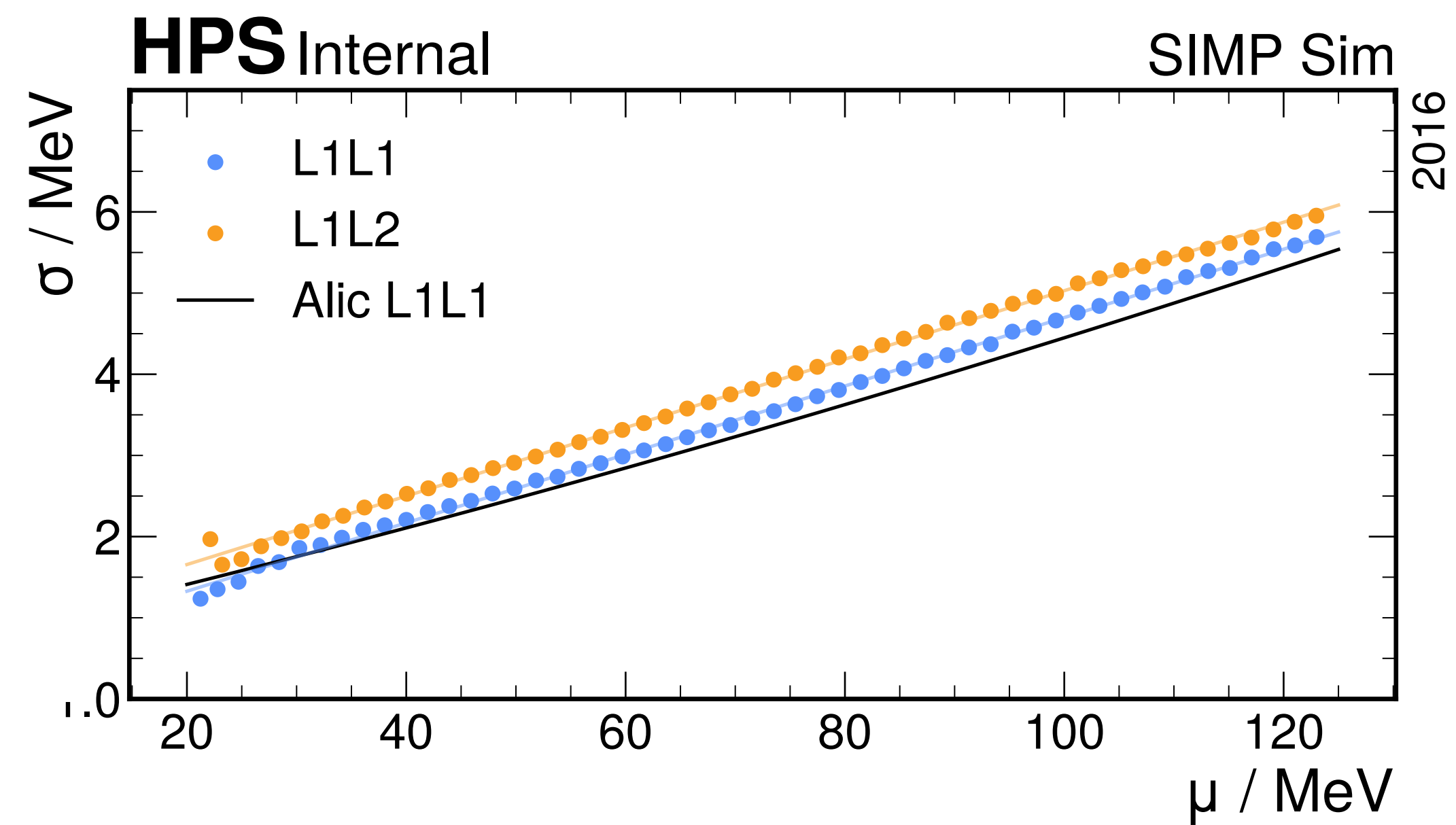
L1L2

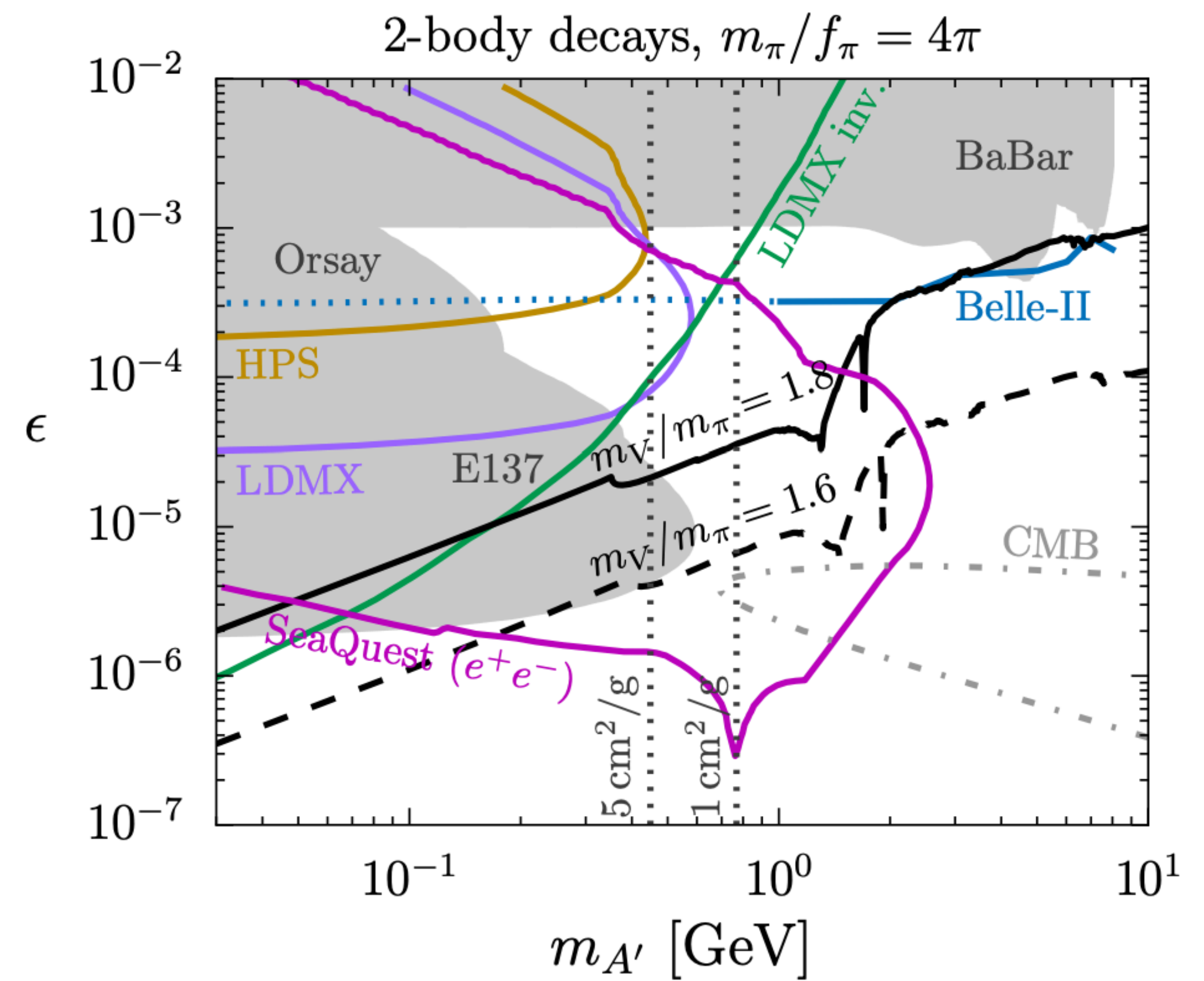
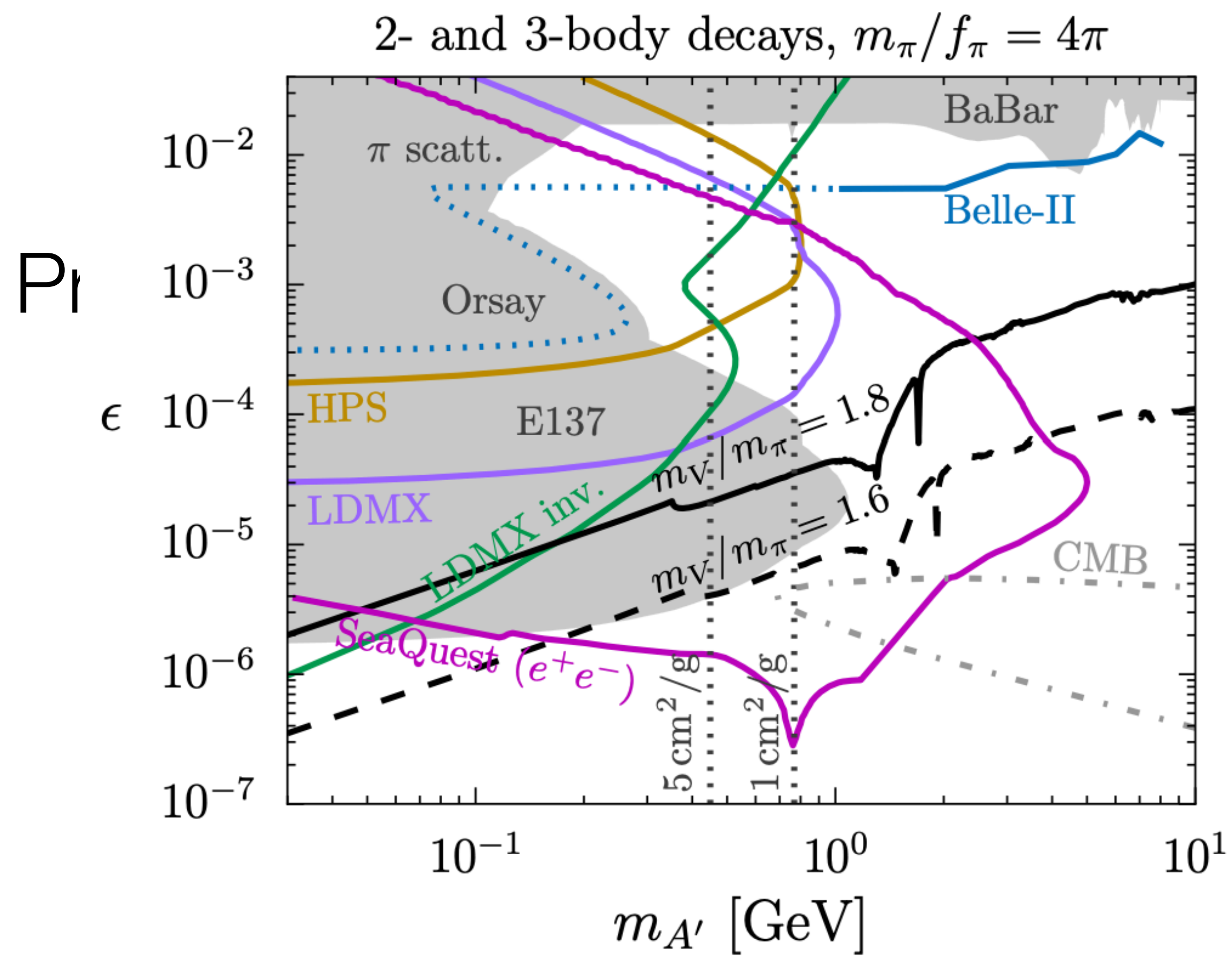


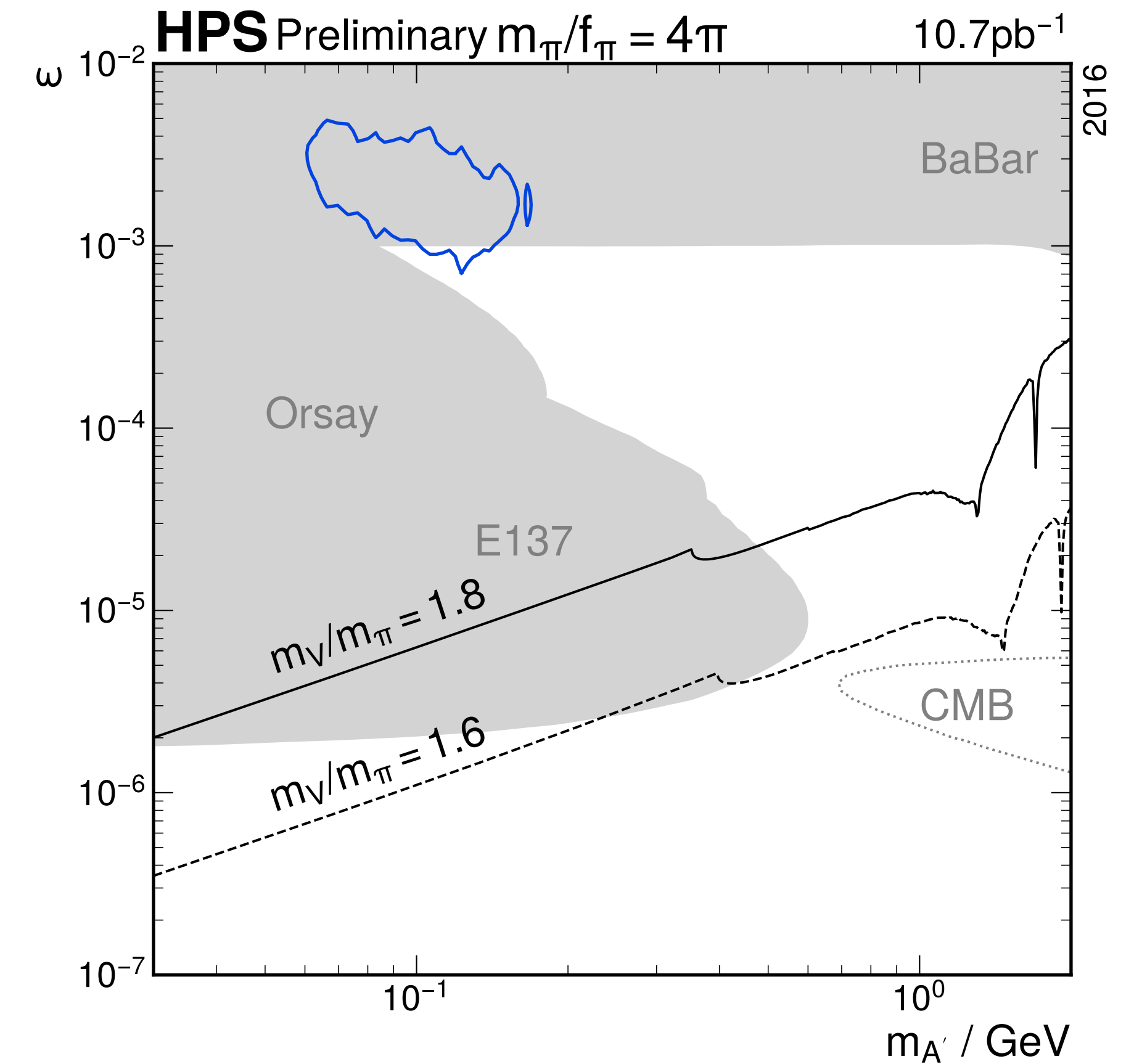
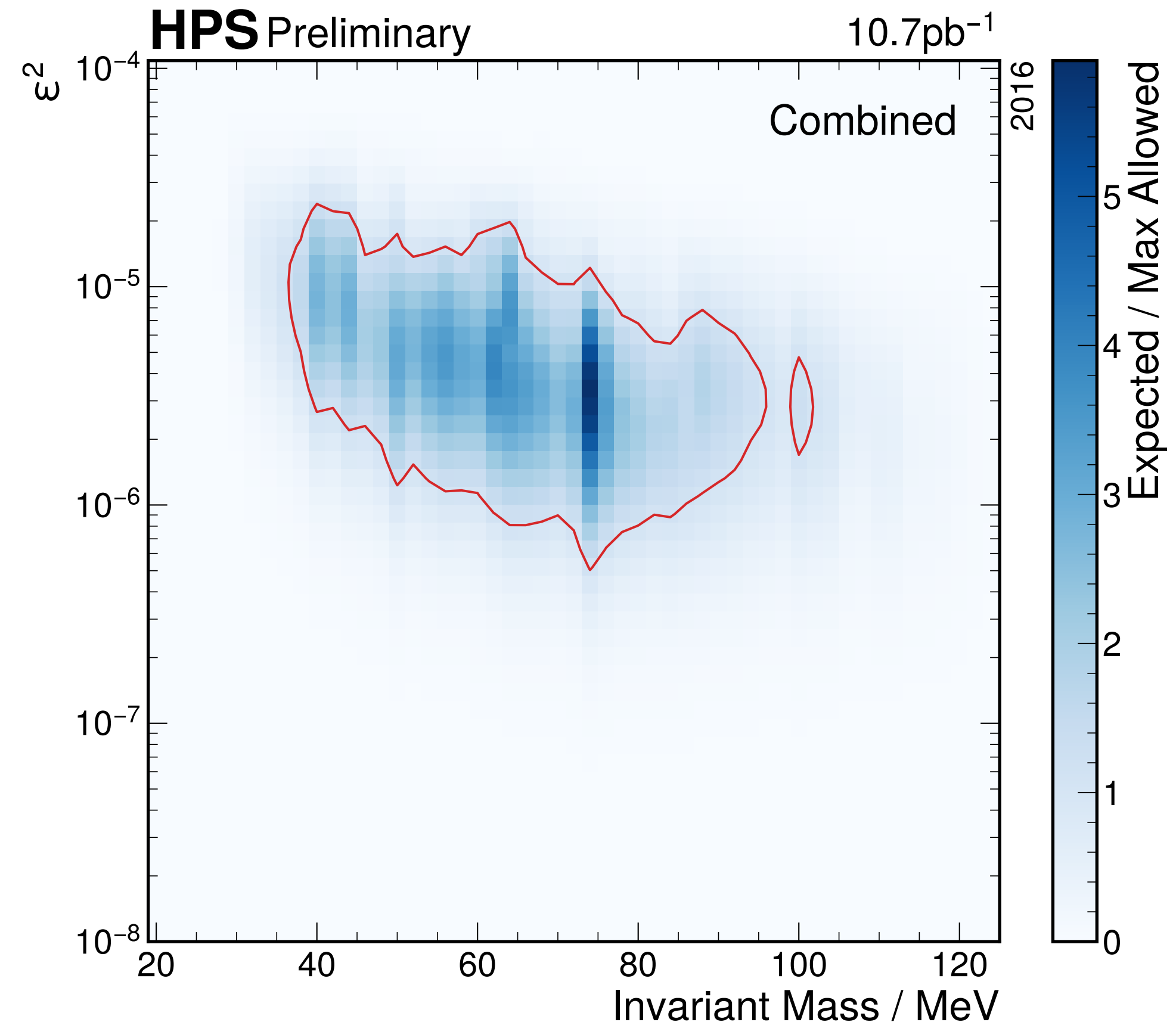
Selection Efficiency

L1L1 and L1L2 have
complementary acceptance

Mass Resolution







HPS SIMP Projections

Exclusions calculated using the Optimum Interval Method
 Majority of the exclusion coming from L1L1 events
 Statistics limited analysis! Will see more from 2019/2021 data.

HPS minimal A' sensitivity

	Minimal A'	Minimal A'
Signature	$\epsilon^2 \gtrsim 10^{-7}$	$\epsilon^2 \lesssim 10^{-8}$
$x = \frac{ p_{e+} + p_{e-} }{E_{\text{beam}}}$	high	high
resonance	yes	yes
prompt/displaced	prompt	displaced

