Accelerator-based Searches for Sub-GeV Dark Matter

Tim Nelson - SLAC

6th Workshop on Applications of Dielectric Laser Accelerators

February, 21 2023

U.S. DEPARTMENT OF ENERGY

Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Wait…wasn't this supposed to be a talk about LDMX?

LDMX (Light Dark Matter eXperiment) is a great experiment in this space.

There are others, each having somewhat unique beam requirements.

Snowmass taught me more communication is needed to identify opportunities.

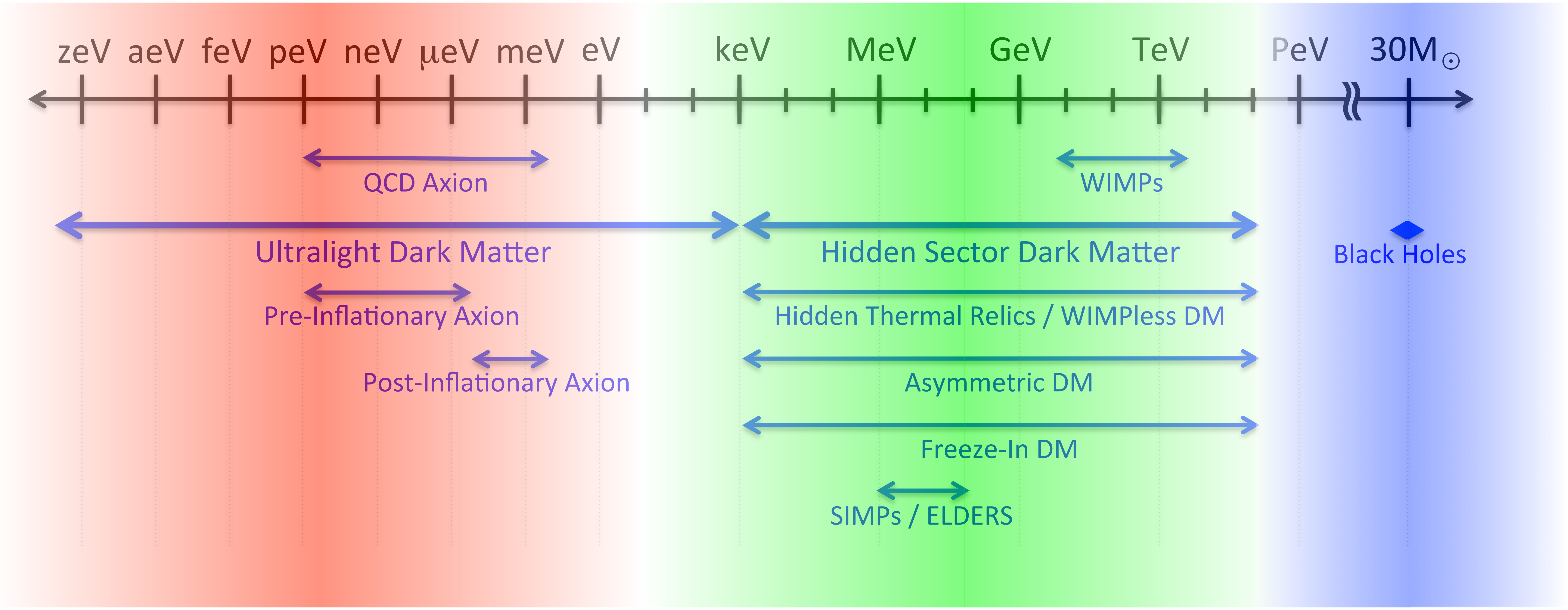
I'll get to LDMX, but will more generally survey…

- Light (sub-GeV) particle Dark Matter and dark forces
- fixed-target accelerator based searches
    - *what are the goals?*
    - *how do they work?*
    - *what are the beam requirements?*

Dark Matter

Everything we know about the mass of Dark Matter

too diffuse



too lumpy

waves

particles

stars

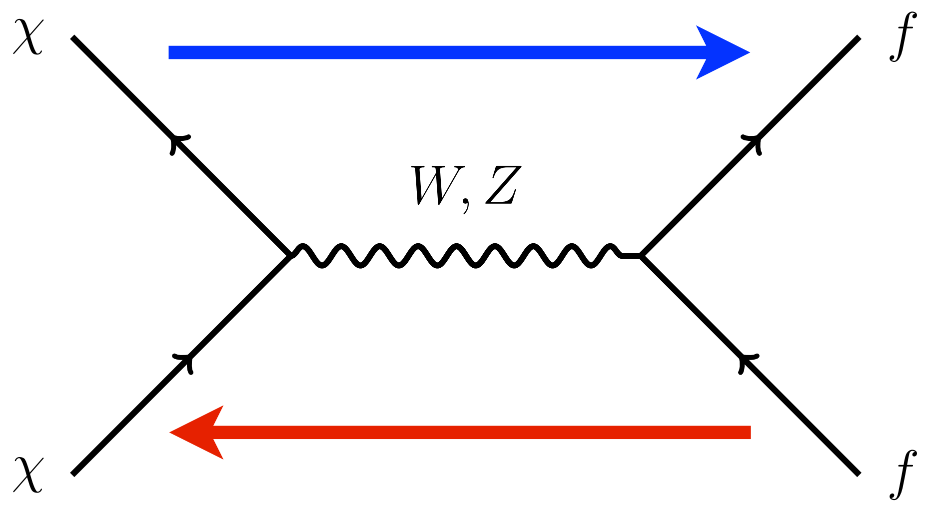
Particle DM and Thermal Contact

Discoverable particle DM has significant non-gravitational interactions with visible matter.

$\Longrightarrow$ most discoverable candidates for particle Dark Matter had thermal contact with visible matter in early universe.

Contact between Dark Matter and visible matter plays a role in generating the observed abundance, often leading to testable predictions.

A particularly simple and predictive mechanism for generating the Dark Matter abundance is "thermal freeze-out":



relic density

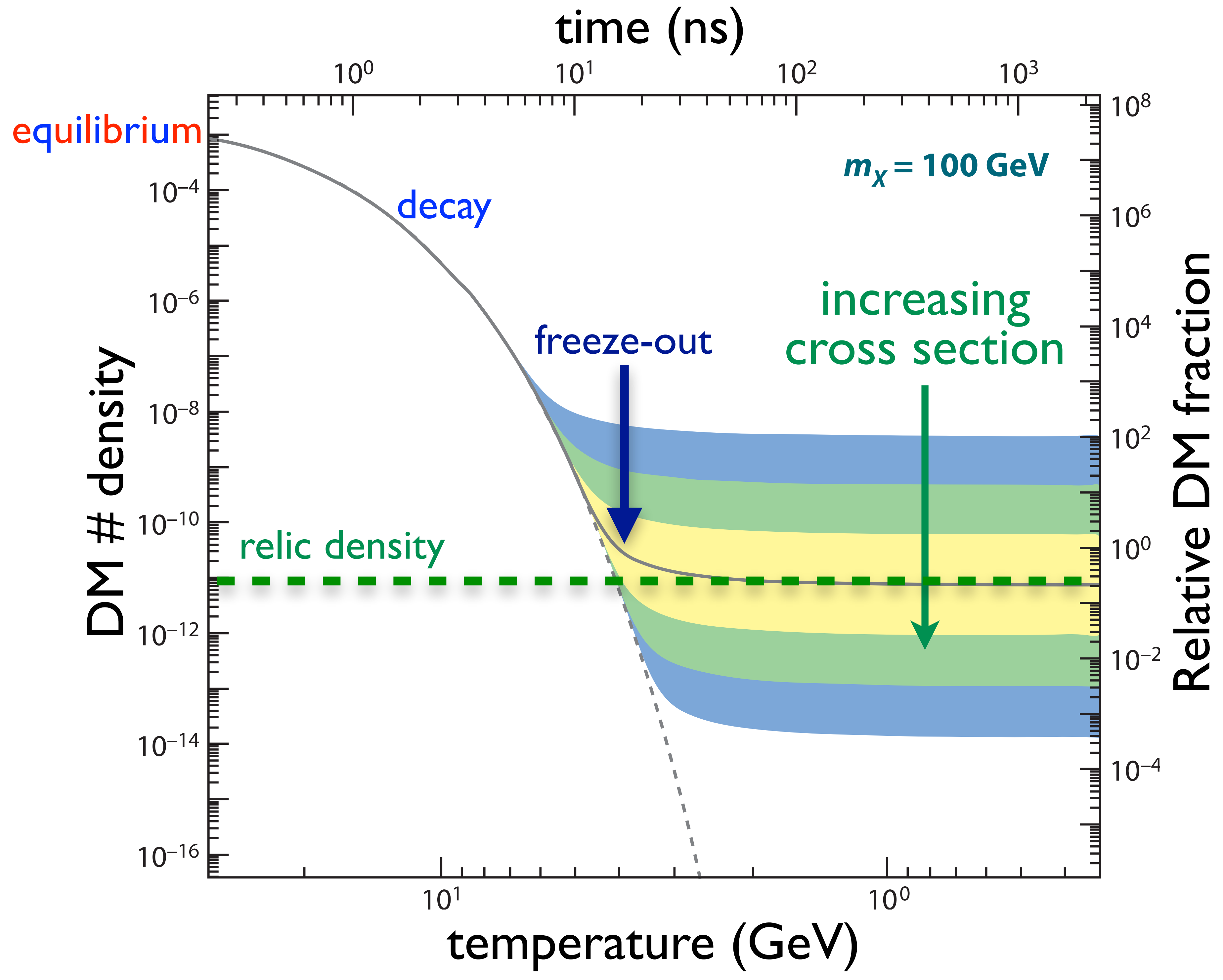
$$\Omega_\chi h^2 \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma v \rangle}$$

cross section

$$\Omega_\chi h^2 \approx 0.1 \Longrightarrow \langle \sigma v \rangle \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

$$\langle \sigma v \rangle \propto \frac{m_\chi^2}{m_Z^4} \Longrightarrow m_\chi \approx 100 \text{ GeV}$$

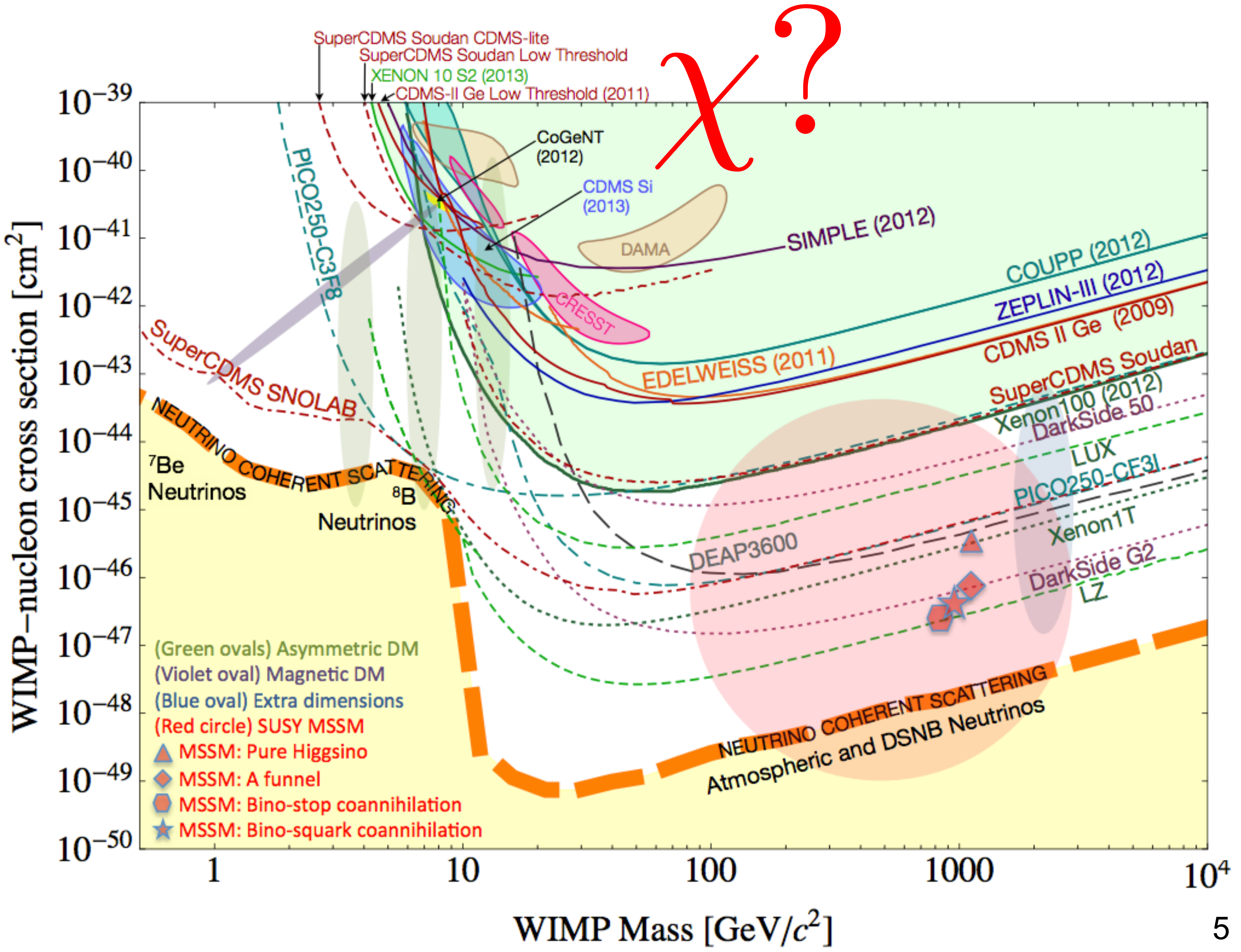
"WIMP Miracle"



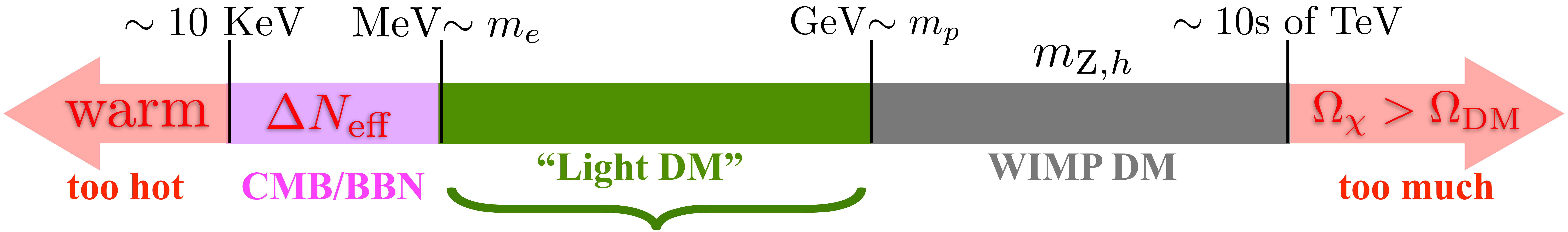
30 Years of WIMP Searches

Searches for WIMPs where we most expect to find them haven't seen anything.

Within next few years, will either find WIMPs or rule out most of the accessible parameter space.

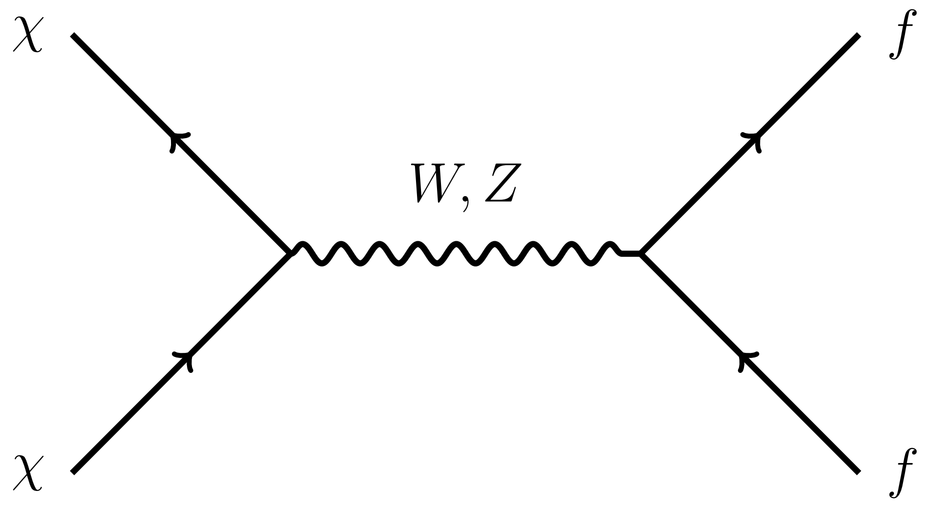


Broadening the Search for Thermal Relic DM



Production rates in MeV-GeV range are large at accelerators, esp. fixed target!

MeV-GeV thermal relic DM requires new, comparably light mediators to achieve required annihilation cross-section for thermal freeze-out.



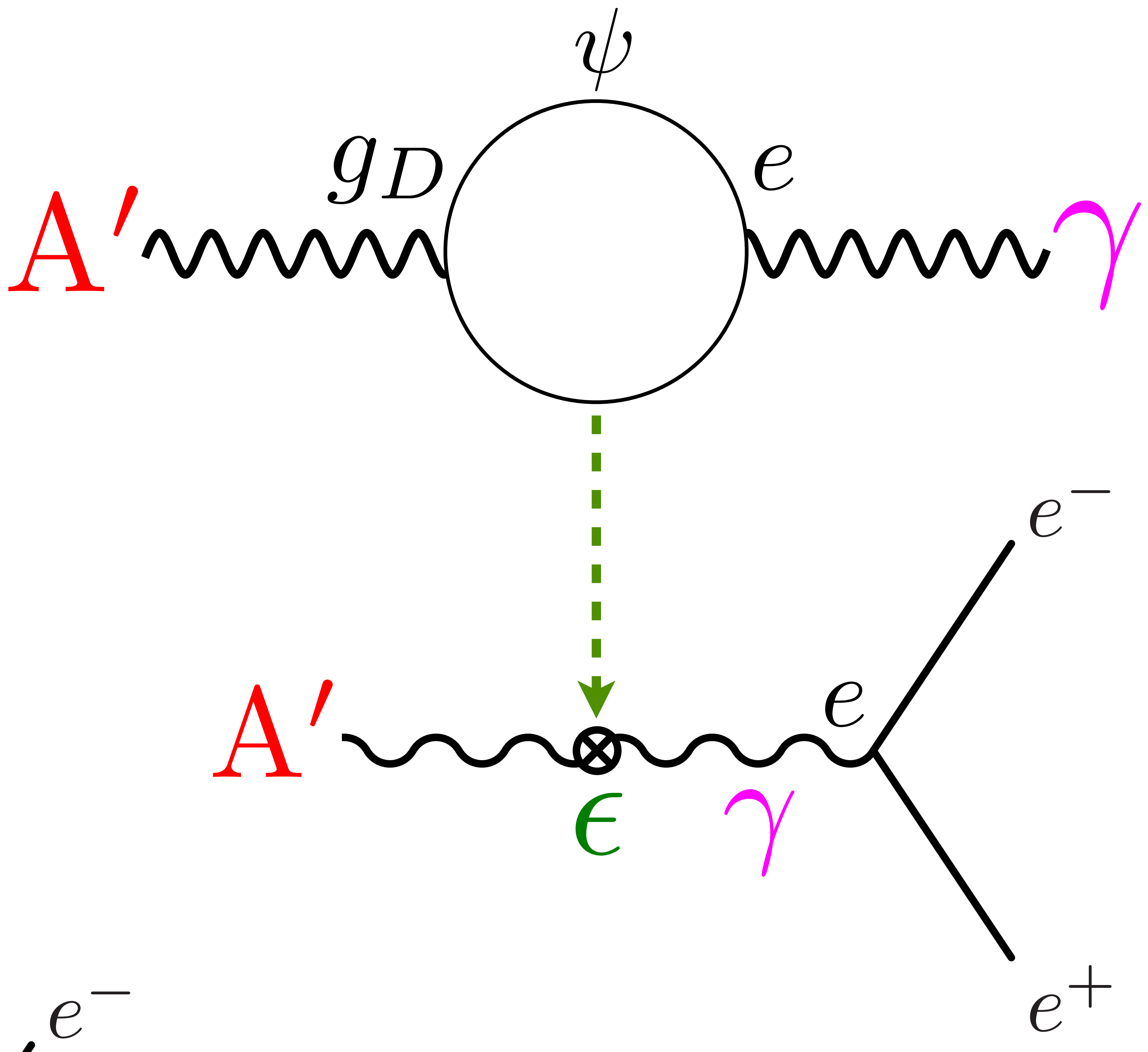
$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}{\rm cm}^3{\rm s}^{-1}\left(\frac{m_\chi}{\rm GeV}\right)^2$$

Lee/Weinberg '79

$$\implies m_\chi \gtrsim 2 \text{ GeV}$$

Benchmark Example: Dark Photon Mediator

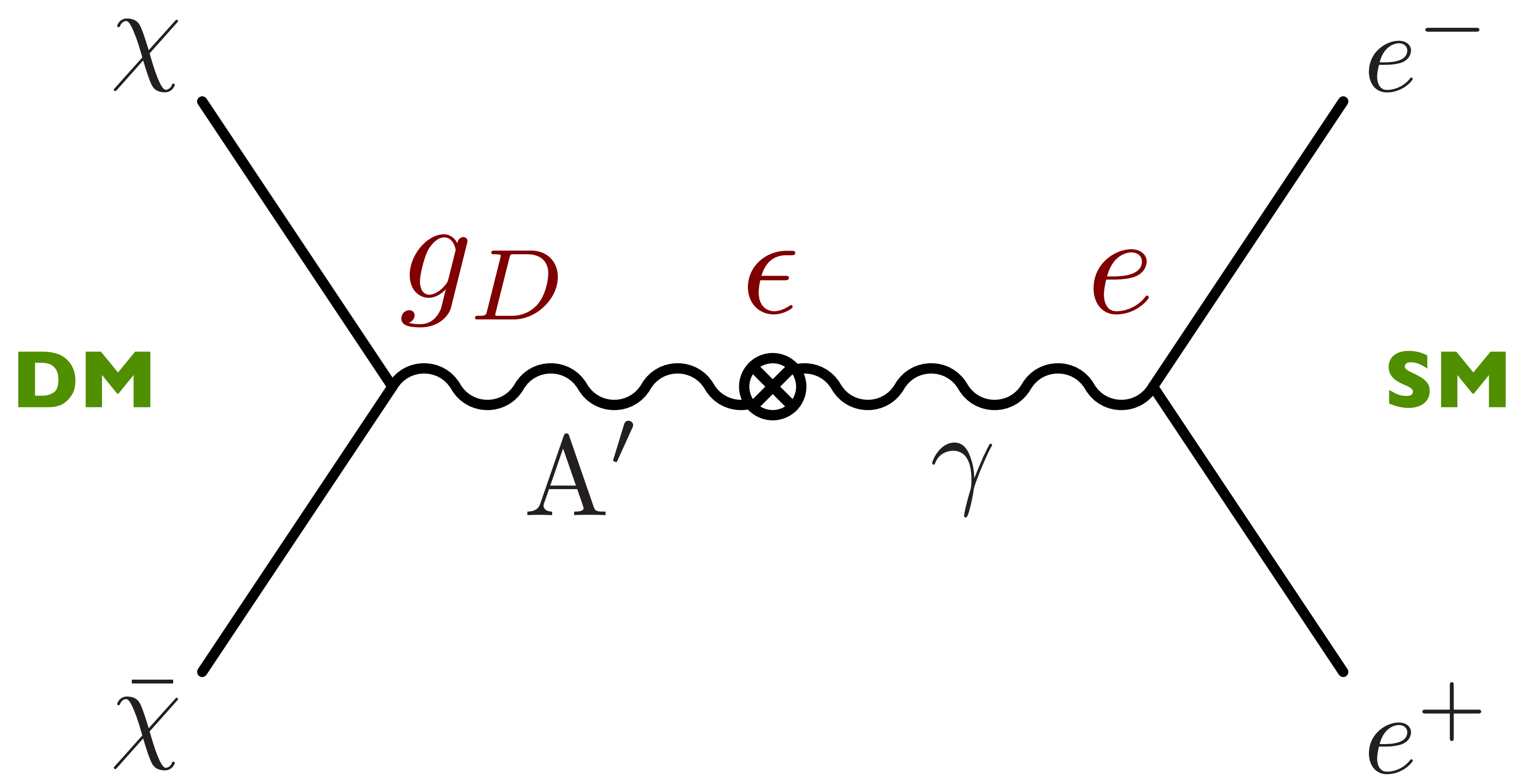
A dark photon, A′, can mix with the SM photon, generating an ϵe coupling to SM fermions:



$$\epsilon \sim \frac{e g_D}{16\pi^2} log \frac{M_\psi}{\Lambda} \sim 10^{-4} - 10^{-2}$$

If one or both U(1) in GUT, ϵ as small as 10^{-7}

$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$



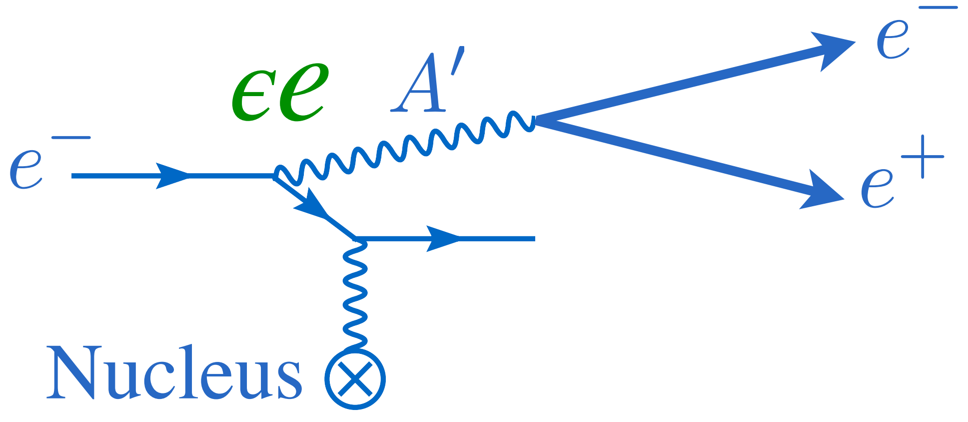
$$\alpha \equiv \frac{e^2}{4\pi}$$

Producing Dark Photons

Where there are photons, there are dark photons!

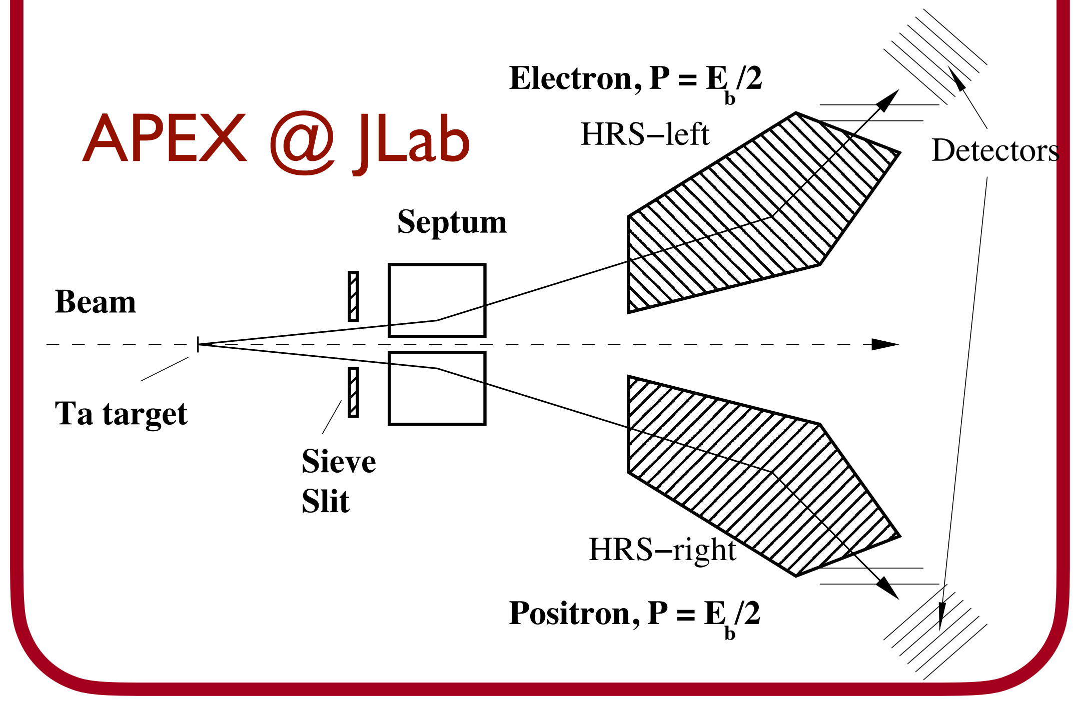
e^- fixed target

$N \propto \epsilon^2$



dark bremsstrahlung

APEX @ JLab



p fixed target

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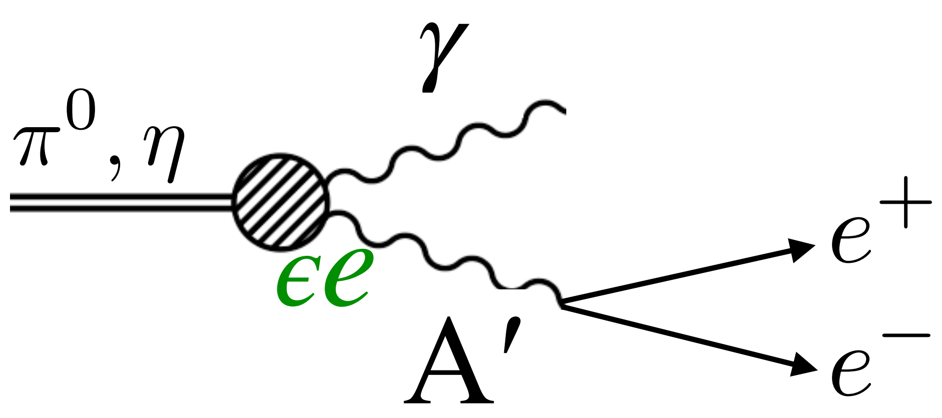
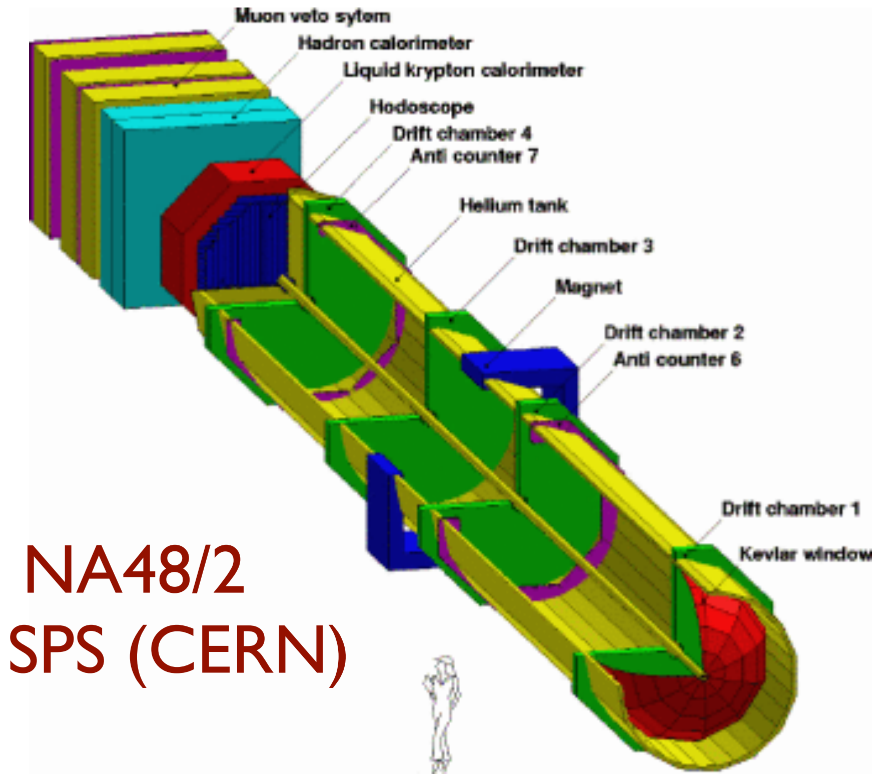
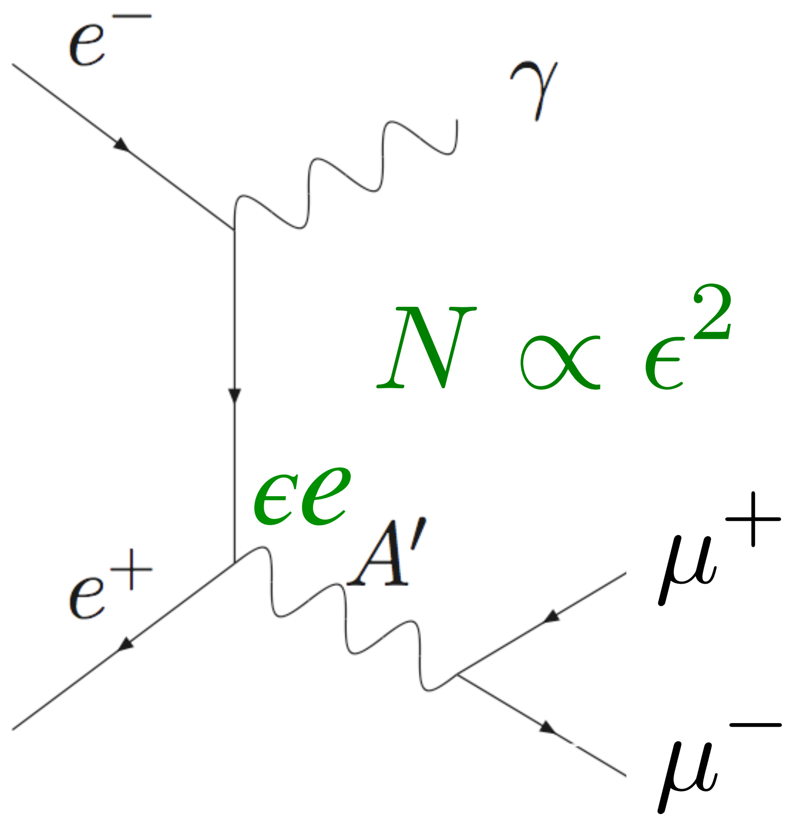


meson decays



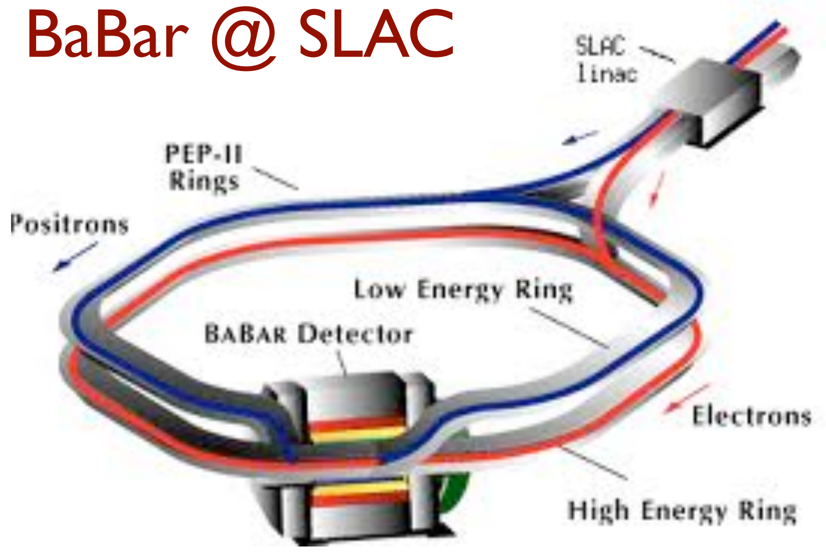
NA48/2 @ SPS (CERN)

e^+e^- colliders

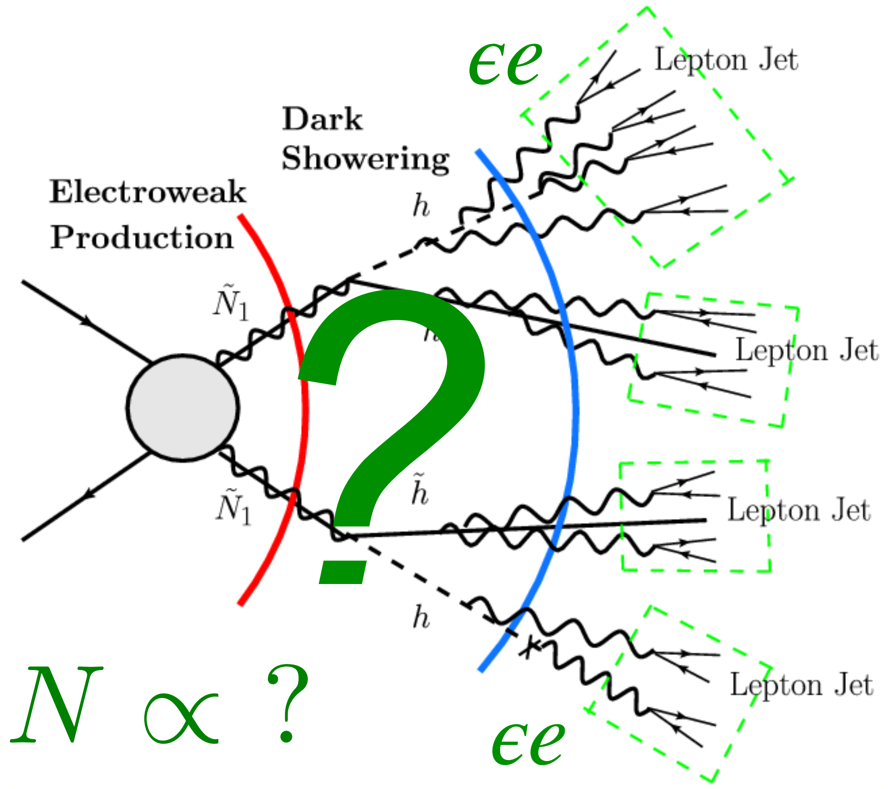


+ meson decays

BaBar @ SLAC

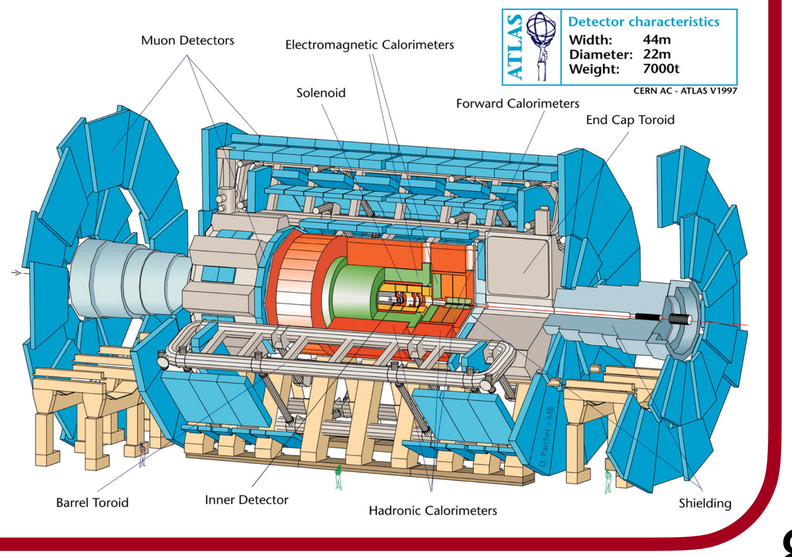


pp collider



"lepton jets"
+ meson decays

ATLAS
CMS
LHCb
@LHC



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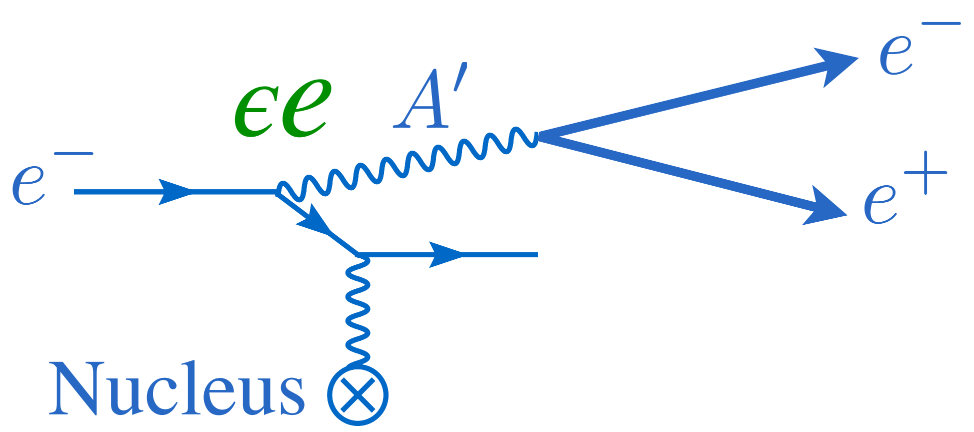
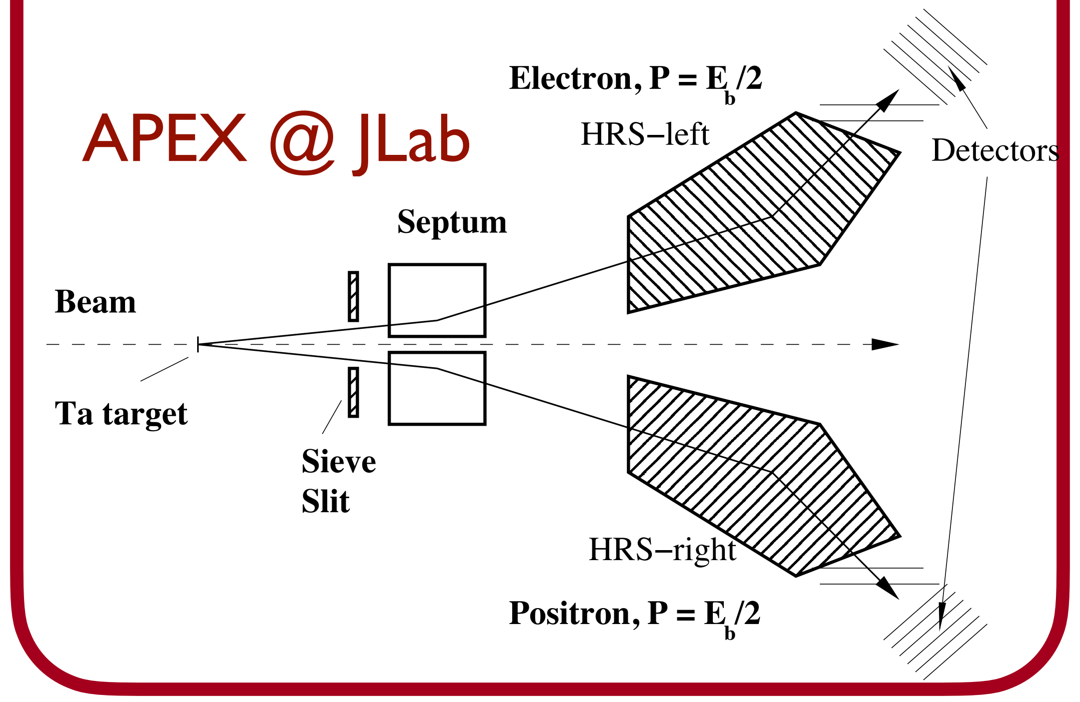


dark bremsstrahlung

APEX @ JLab



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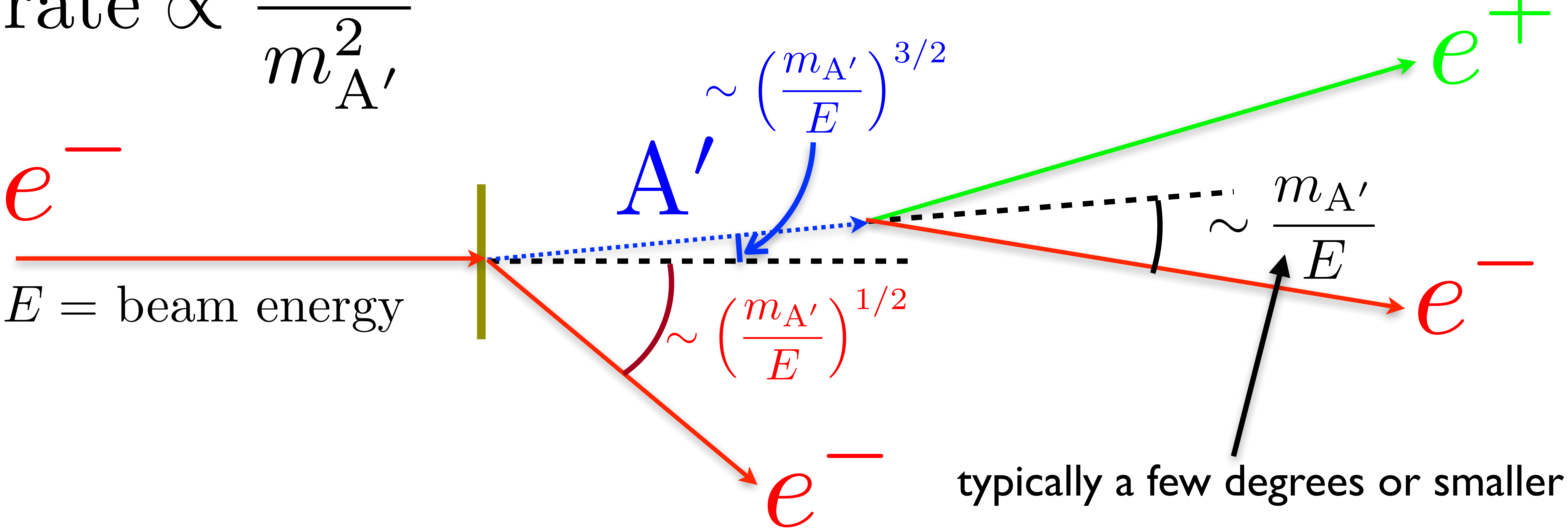
Dark Bremsstrahlung Kinematics

Heavier product (here A′) takes most of beam energy: $E_{A'} \approx E$

$$\text{rate} \propto \frac{Z^2 \epsilon^2}{m_{A'}^2}$$



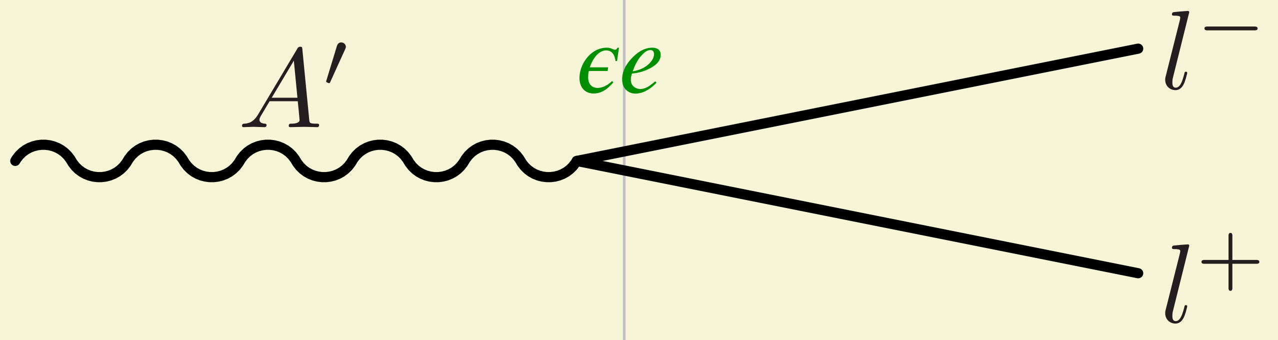
This shapes the designs of many experiments.

Mass Hierarchy Determines Search Strategy & Interpretation

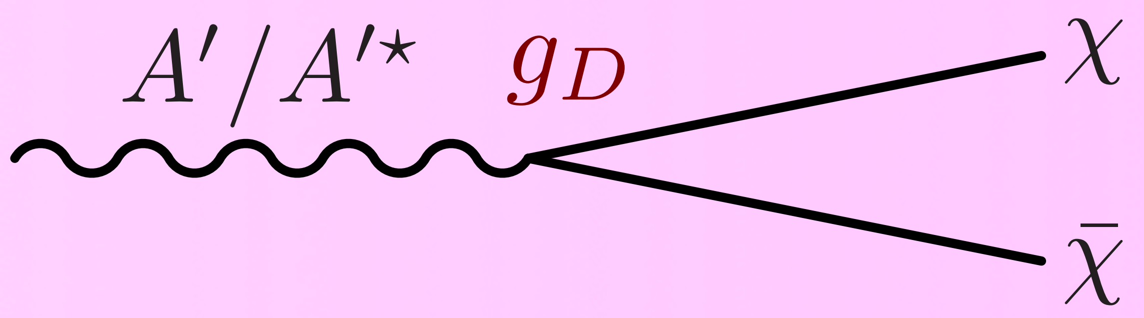
SLAC

Mediator Mass $m_{A'}$ — m_χ — $2m_\chi$ →

Experimental Search:



mediator decays to SM (AKA "visible mediator decays")
(searches are often mediator specific)

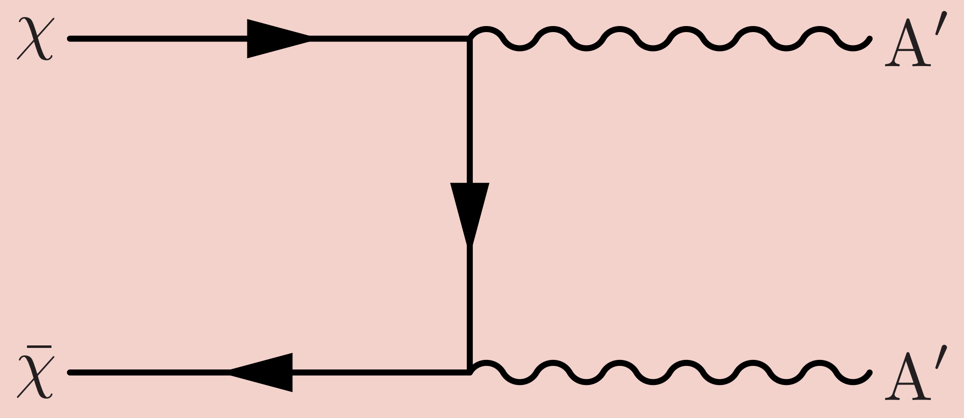


for production of DM
(AKA "invisible searches")
(searches largely agnostic to type of mediator)

searches measure/constrain ϵ^2 as a function of $M_{A'}$

DM annihilation in early universe:

"secluded"
$\sigma v \propto \alpha_D^2$



"direct"
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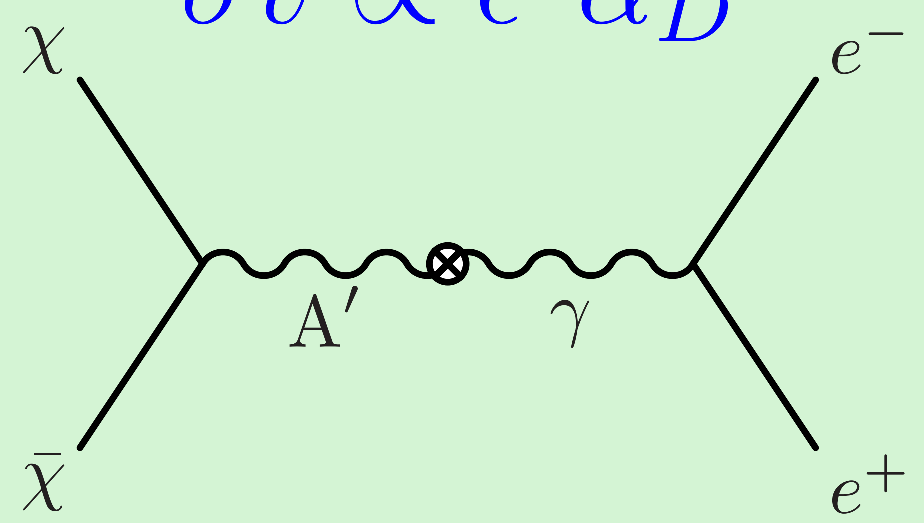

Interpretation:

no clear target for ϵ

"Thermal Target" - lower limit on ϵ for thermal relics

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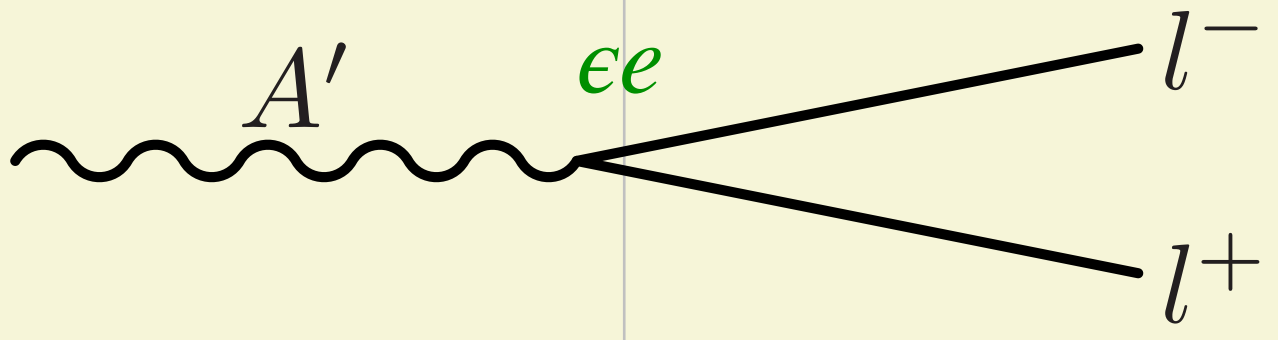

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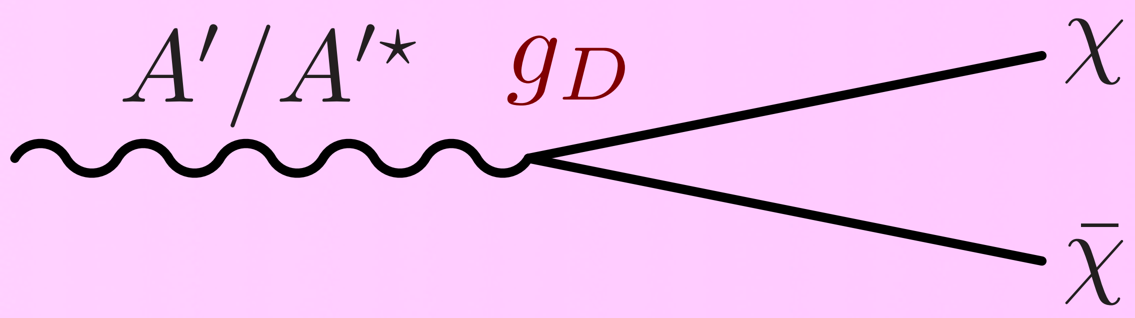

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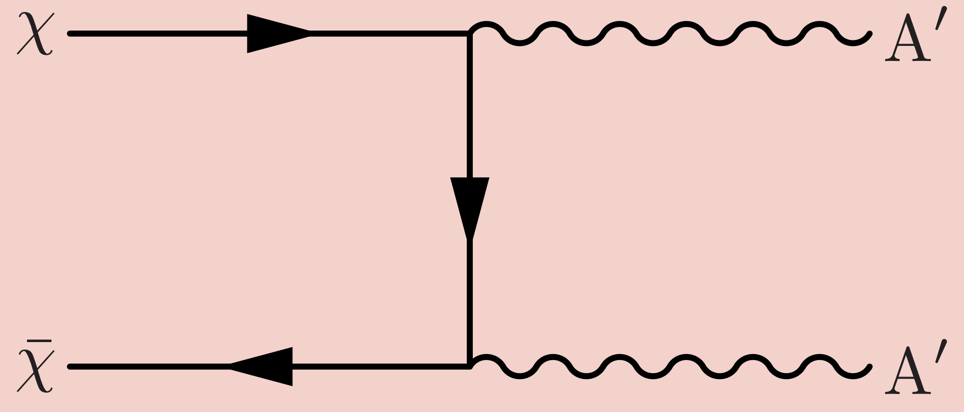

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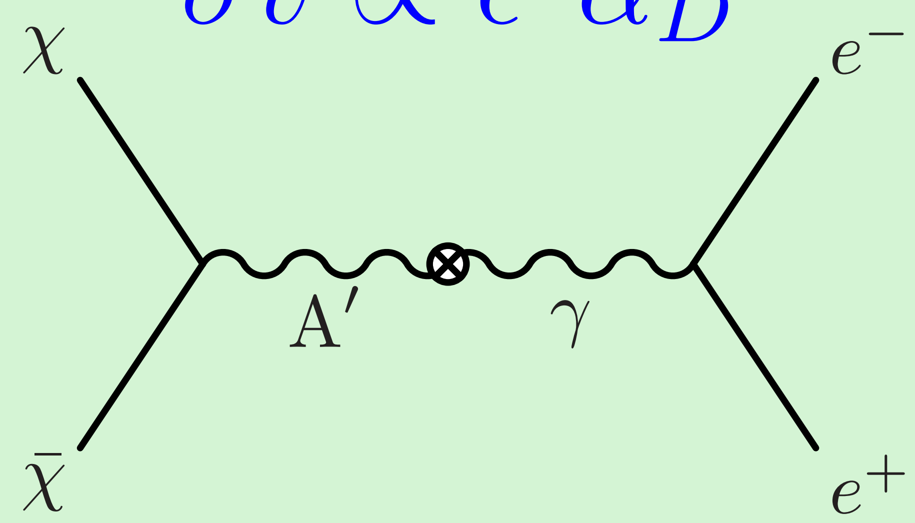

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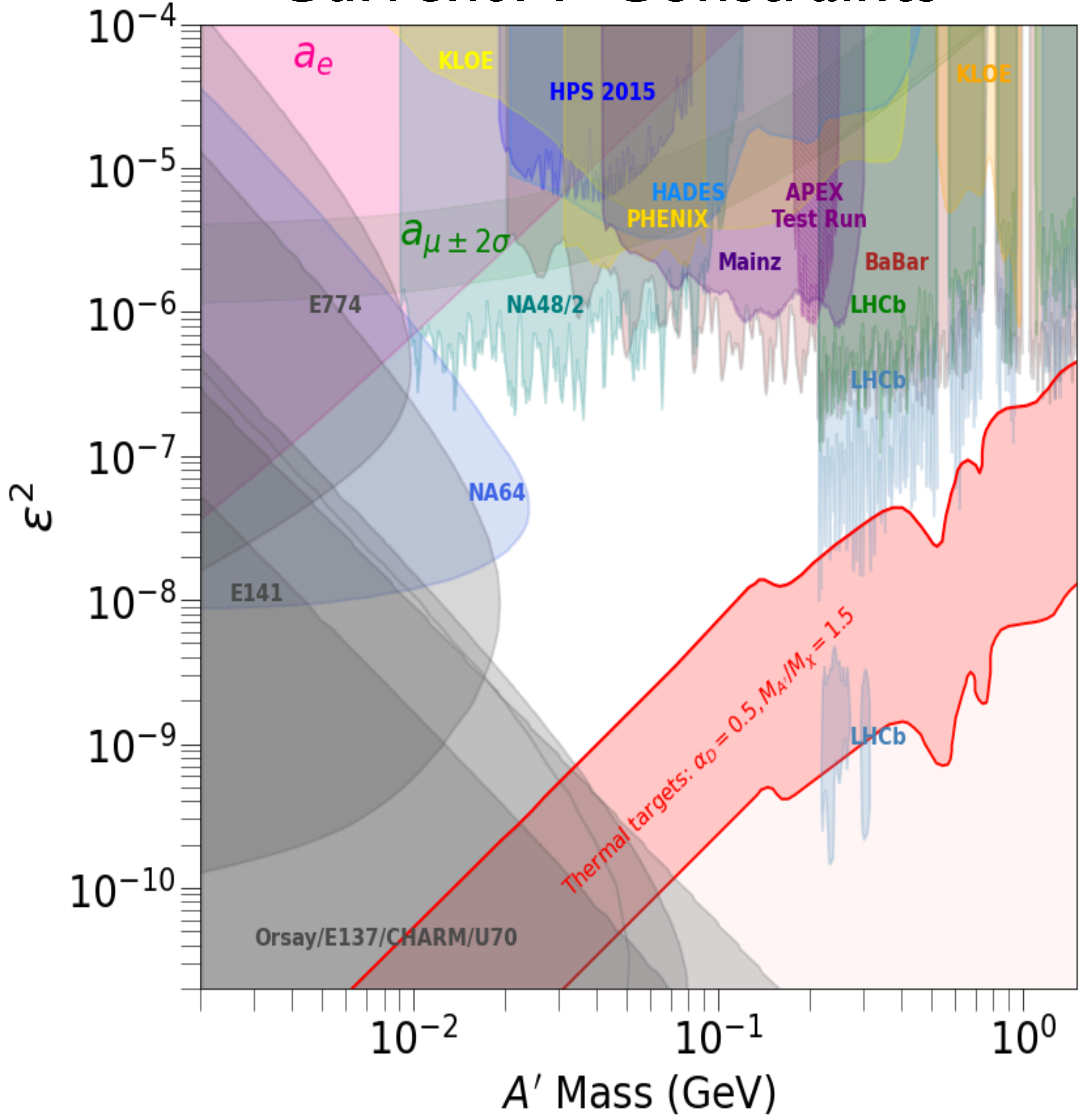
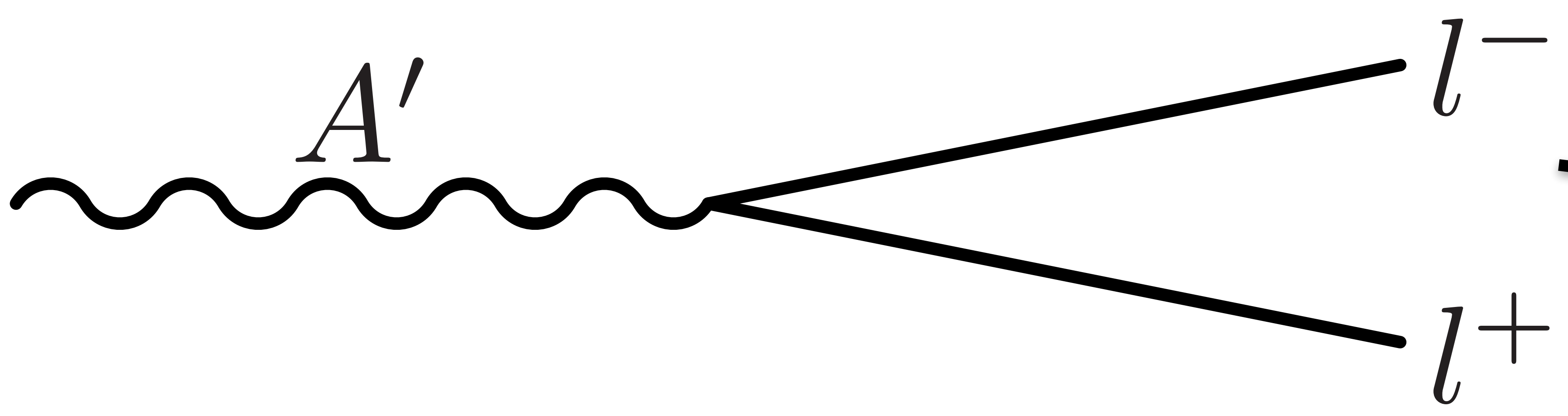
Searching for Dark Photons Decaying Visibly to SM

Current A′ Constraints



Searching for Dark Photons Decaying Visibly to SM

Many searches are simply for $m(l^+l^-)$ resonances.



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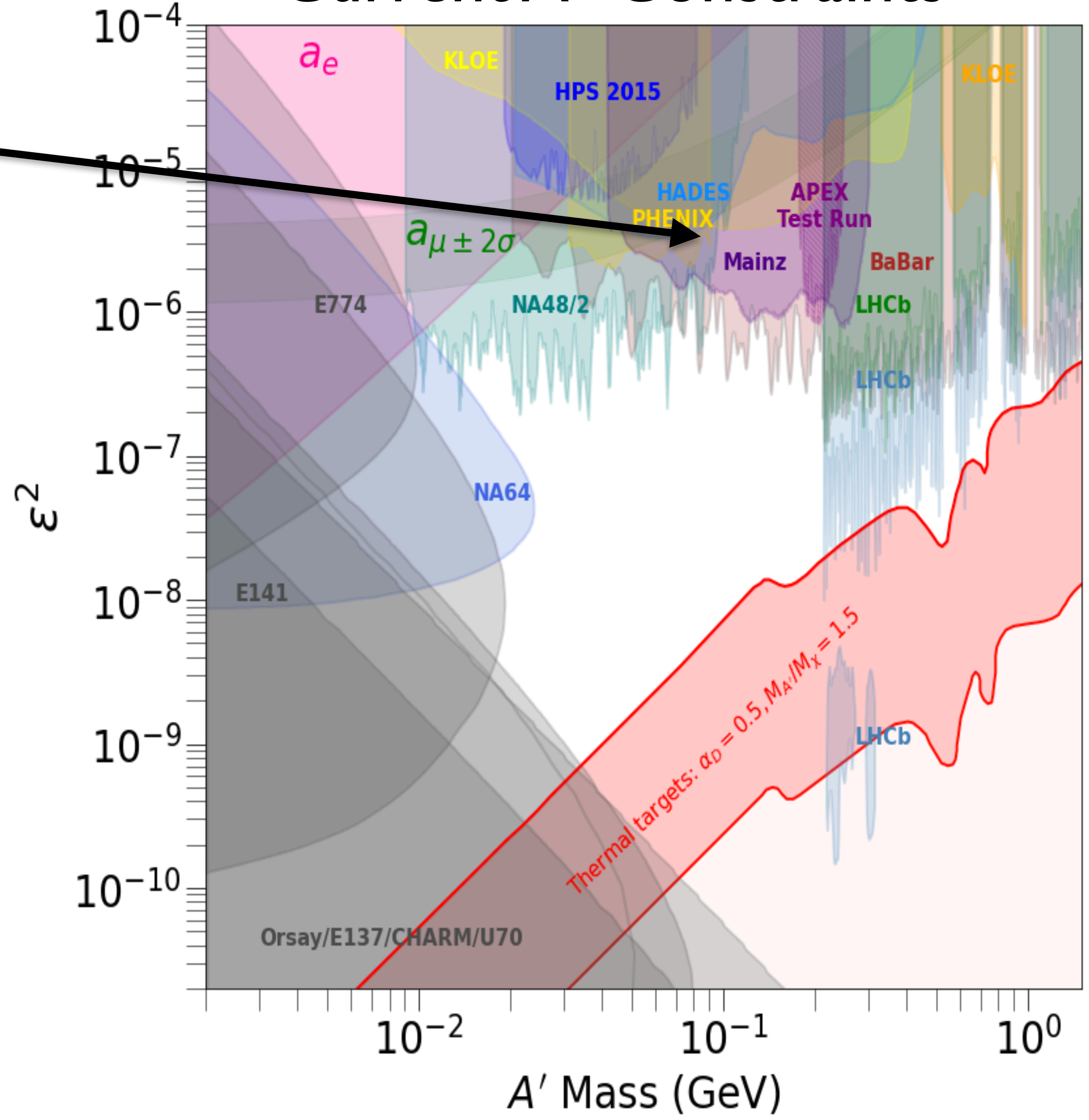

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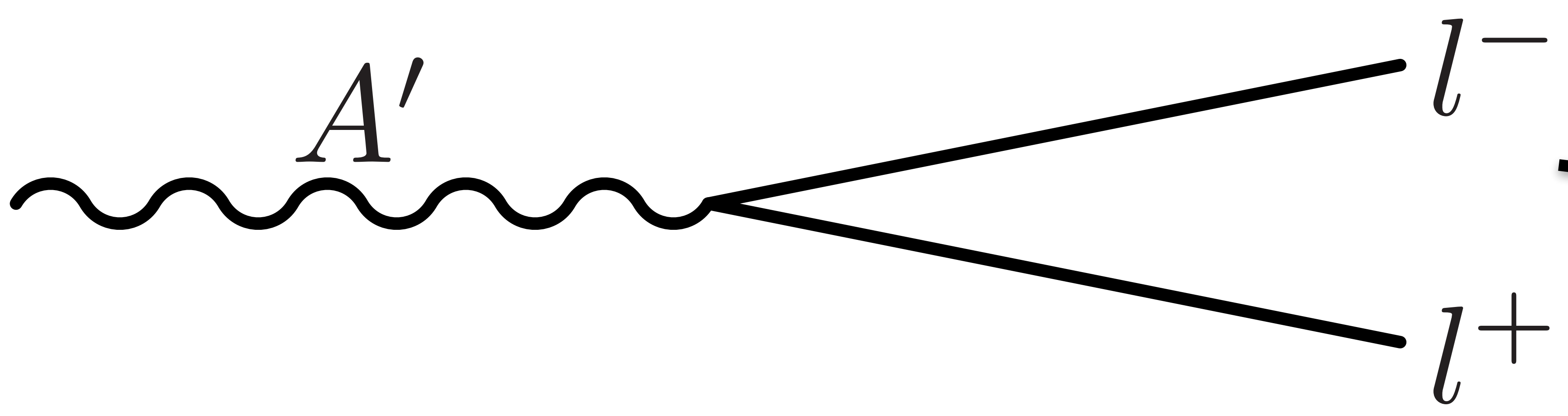
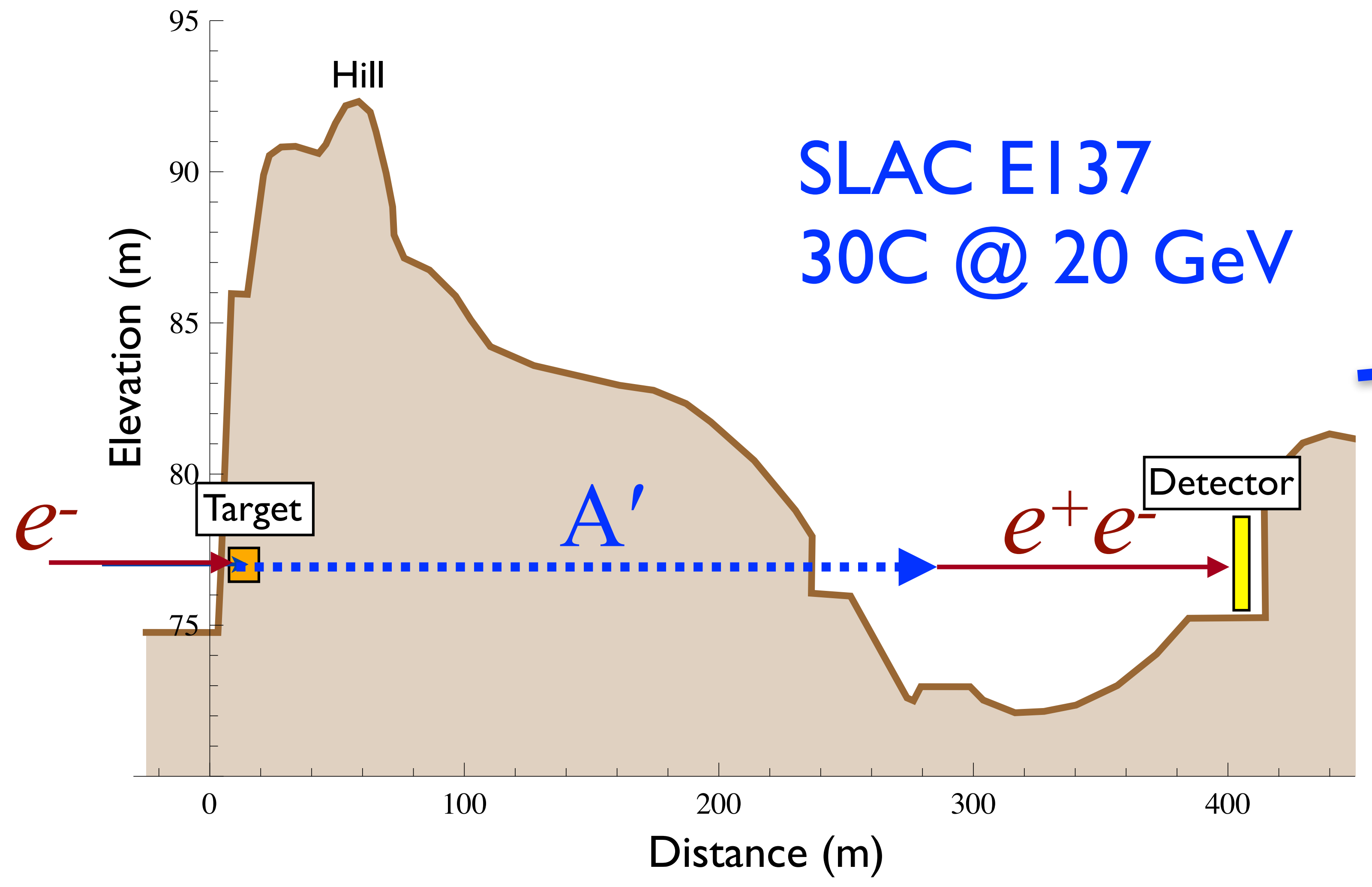


A′ becomes long lived at small couplings.

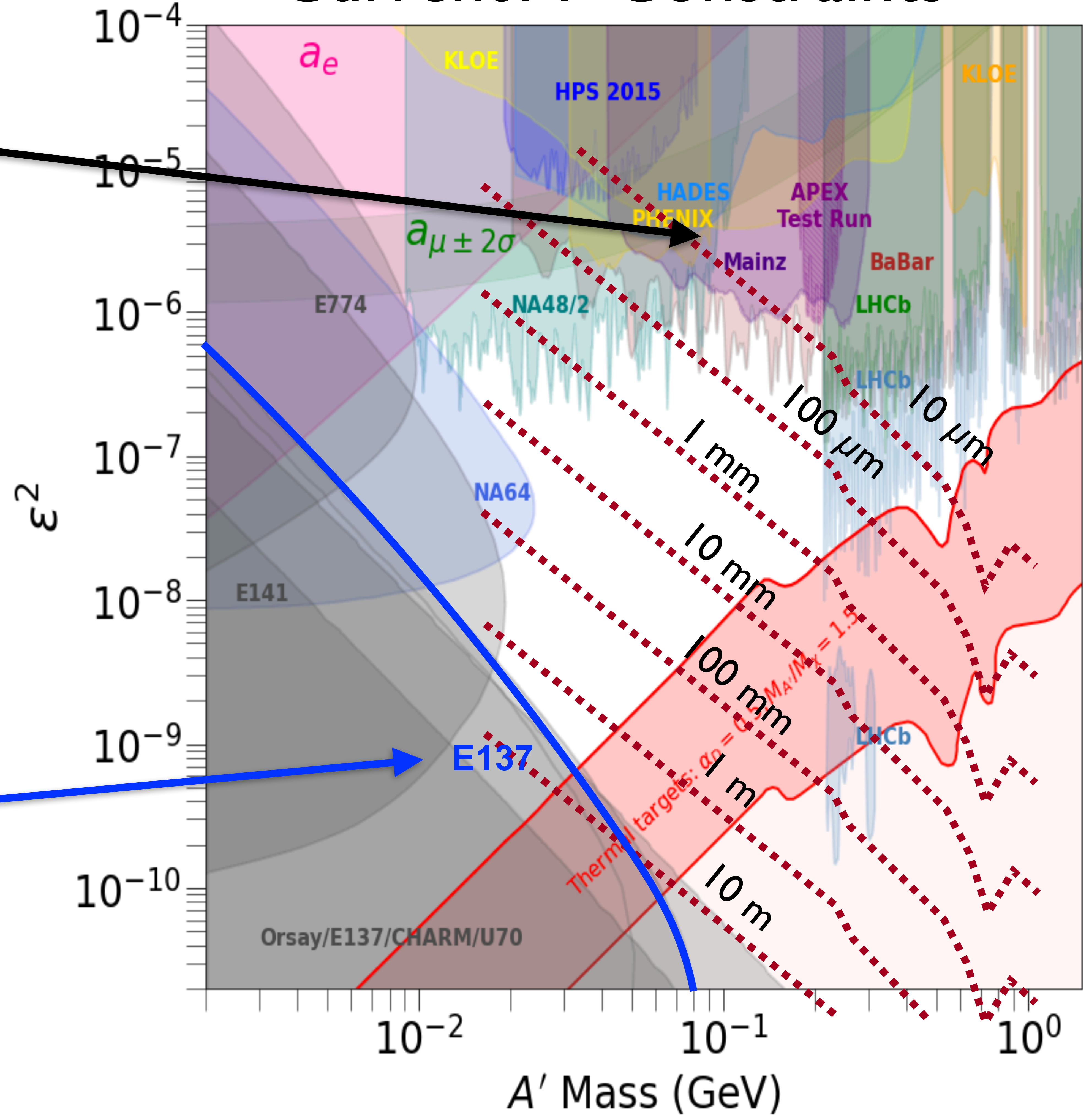
$$\gamma c\tau \propto \frac{1}{\epsilon^2 m^2_{A'}}$$

Leads to constraints from beam dump experiments



SLAC E137
30C @ 20 GeV

Current A′ Constraints



typical decay length for E_{beam} = 20 GeV

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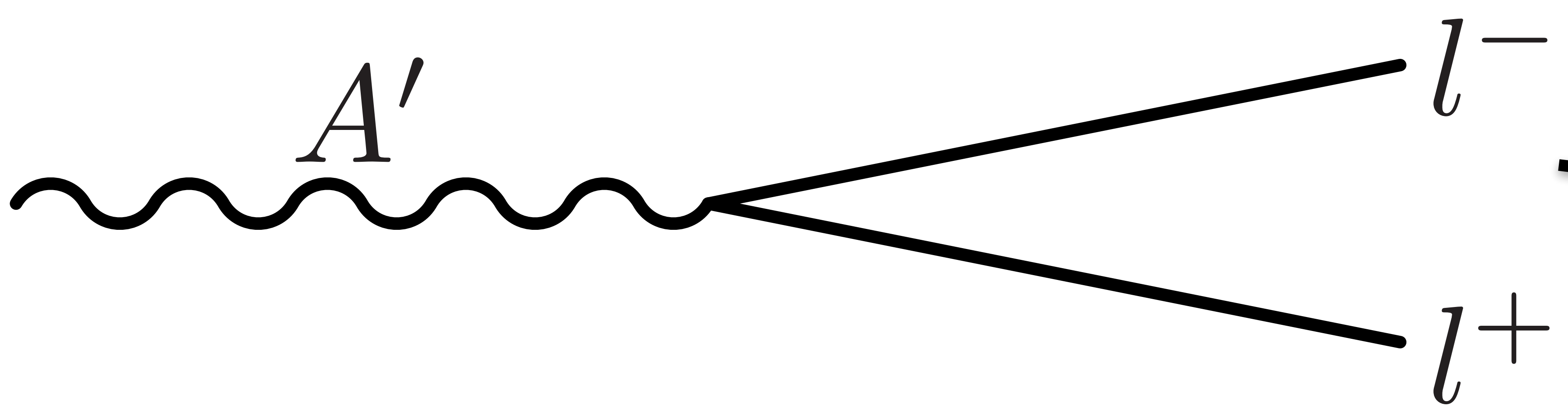

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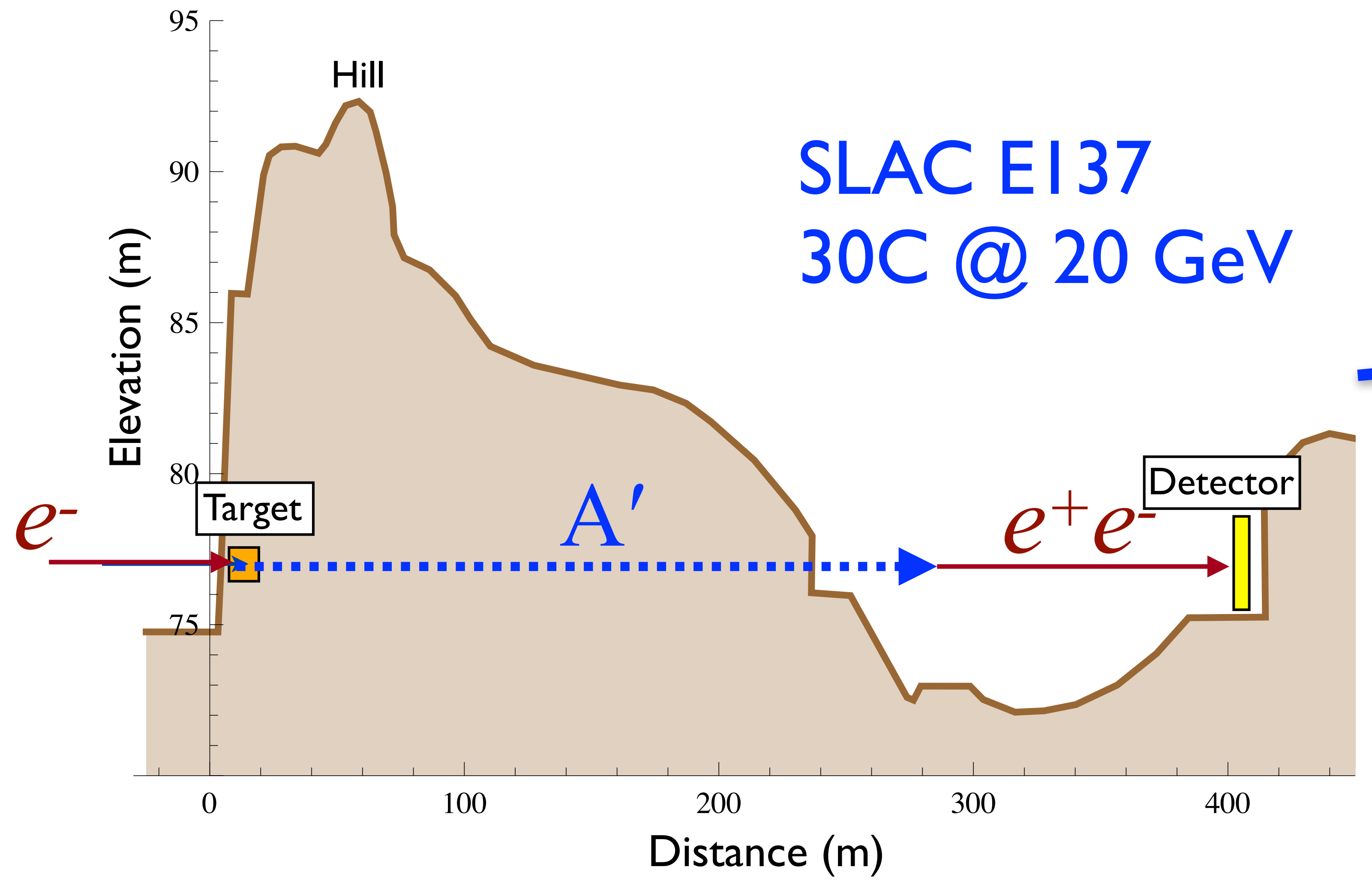

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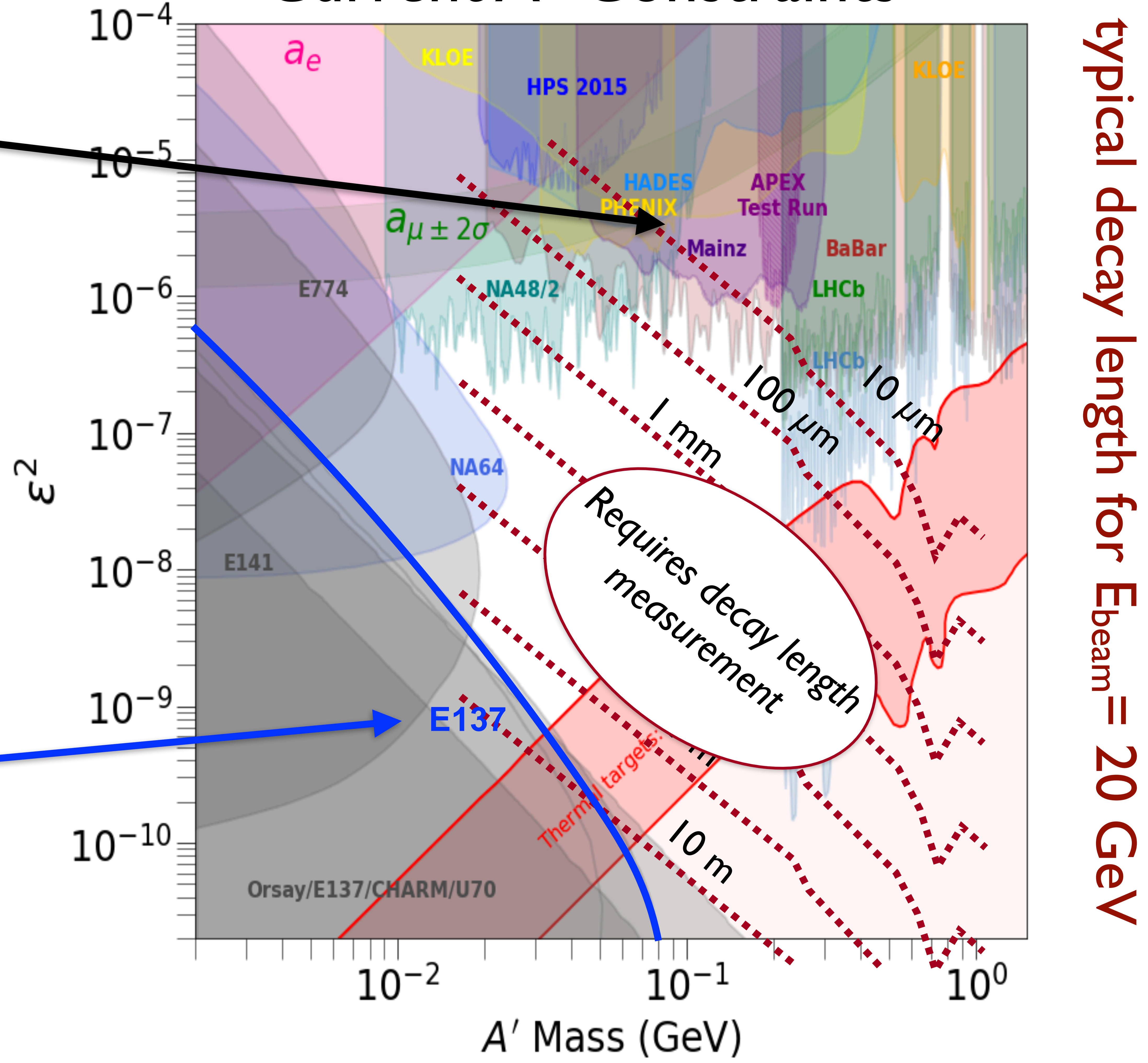


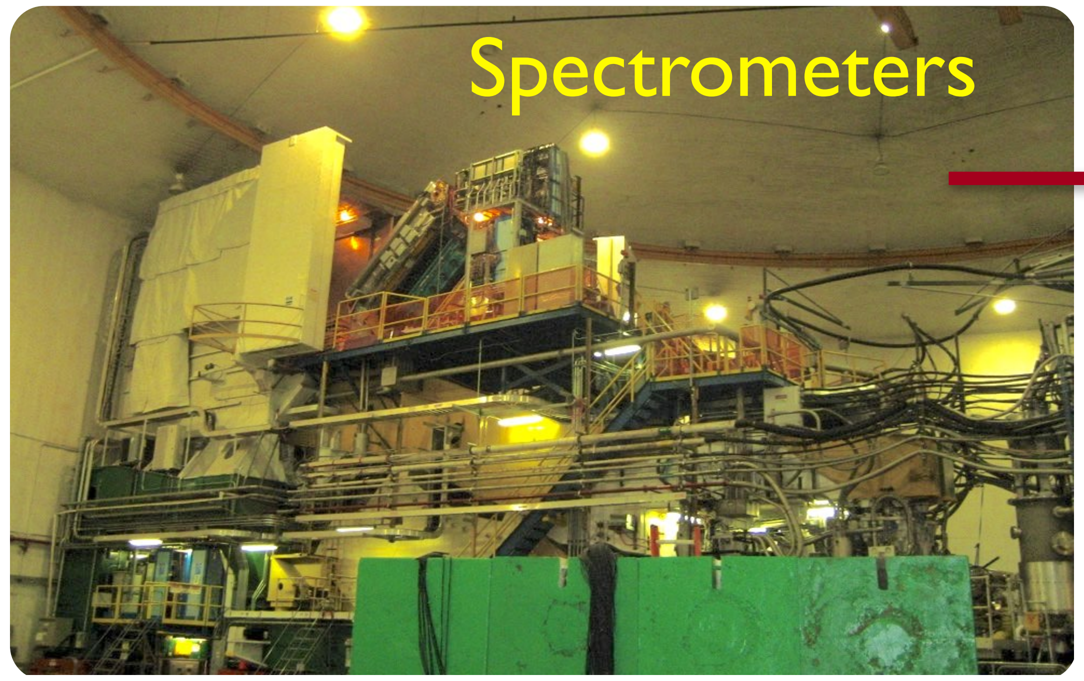
Resonance Search

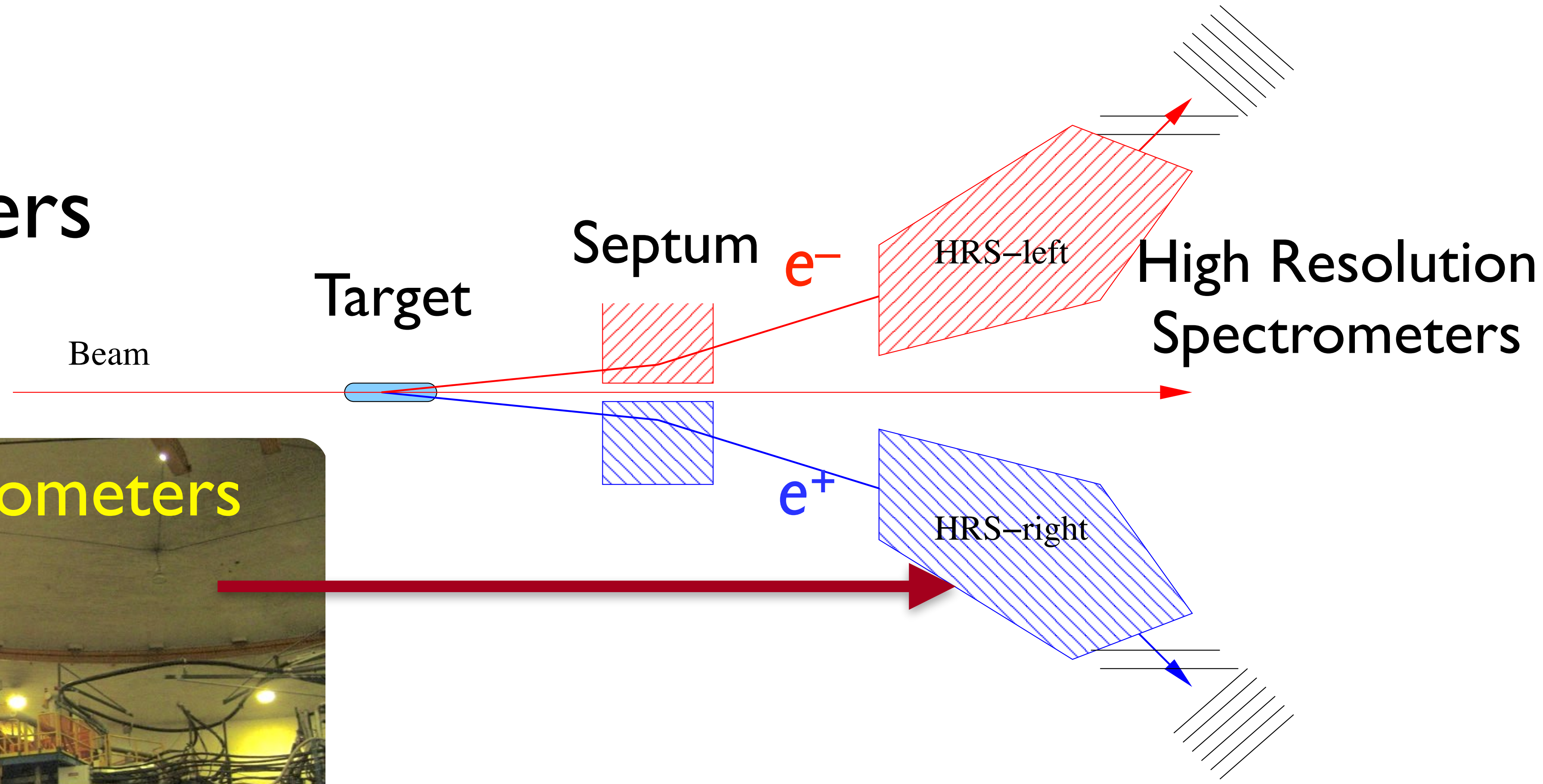
Example: APEX @ JLab (SLAC is a collaborator)

Resonance search w/ thin target, Hall A High-Resolution Spectrometers

Key background: SM tridents (irreducible)

Beam Energy	Beam Current	Rep. Rate	Bunch Charge (e^-)	Spot Size
1.1 GeV	50 μA	2 ns	6.25E+05	<1 mm
2.2 GeV	70 μA	2 ns	8.75E+05	<1 mm
3.3 GeV	80 μA	2 ns	1E+06	<1 mm
4.4 GeV	60 μA	2 ns	7.5E+05	<1 mm

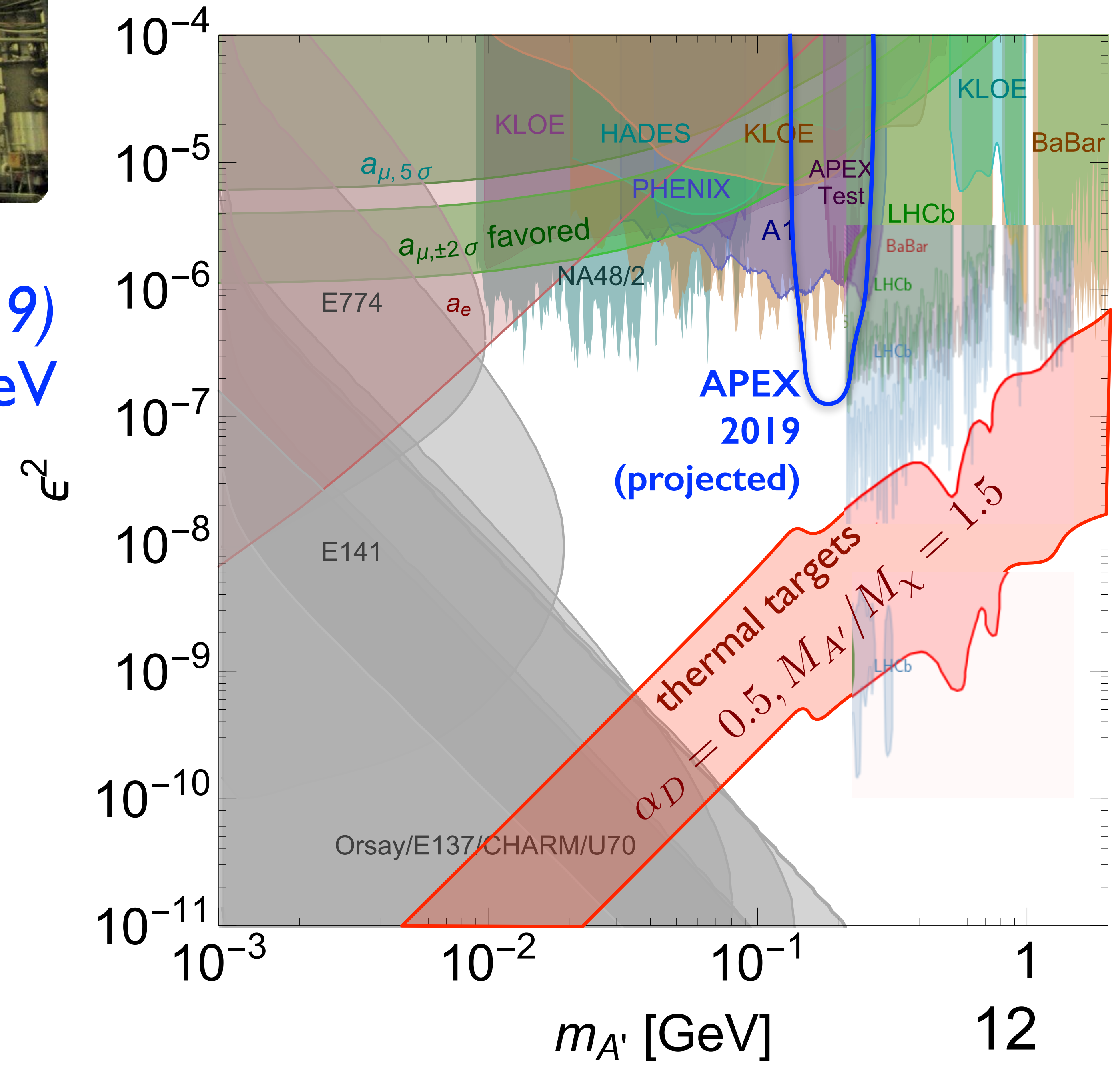




Considerations:

- beam energy determines mass window
- very small momentum acceptance of spectrometers allows high currents
- detector occupancy limits beam current given rep rate
- spectrometer optics require small, low-emittance beam

2019 Physics Run *(Jan. - Mar. 2019)*
15 days at E_{beam} = 2.2 GeV



Other experiments (e.g. A1 @ Mainz) are similar.

Resonance Search + Precision Vertexing

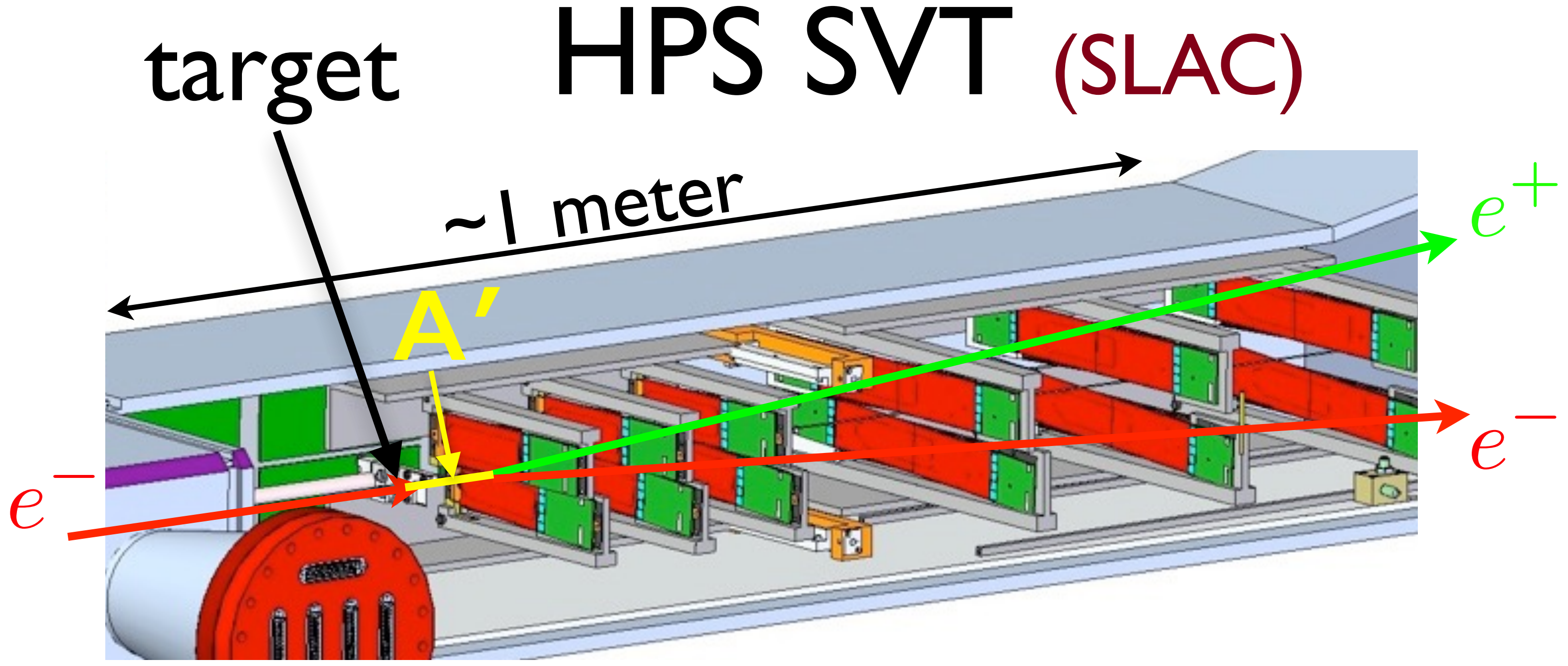
SLAC

Example: HPS @ JLab (SLAC-led collaboration)

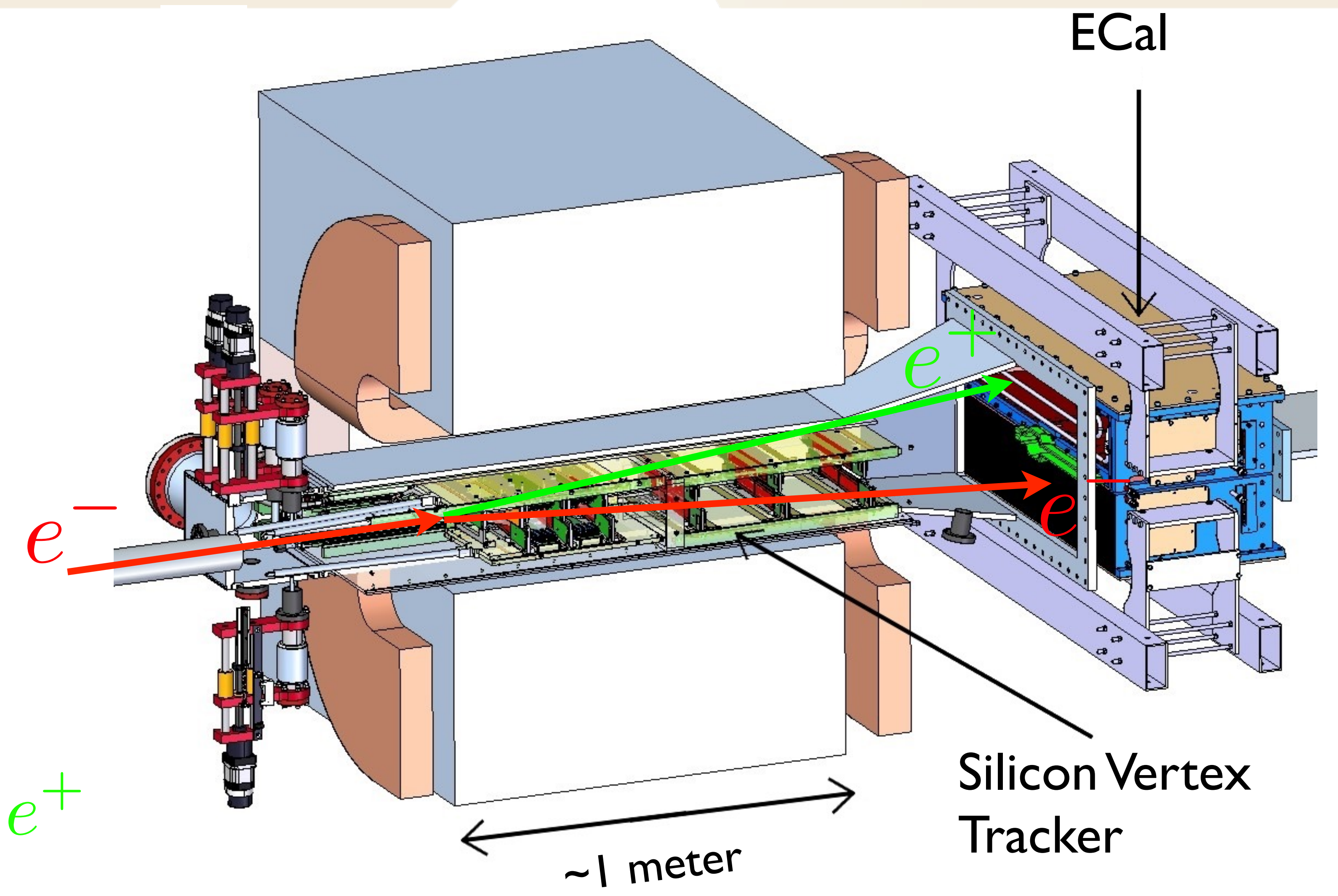
Resonance search with thin target using compact, high rate spectrometer: Silicon Vertex Tracker (SVT) / ECal trigger with ~2 ns resolution

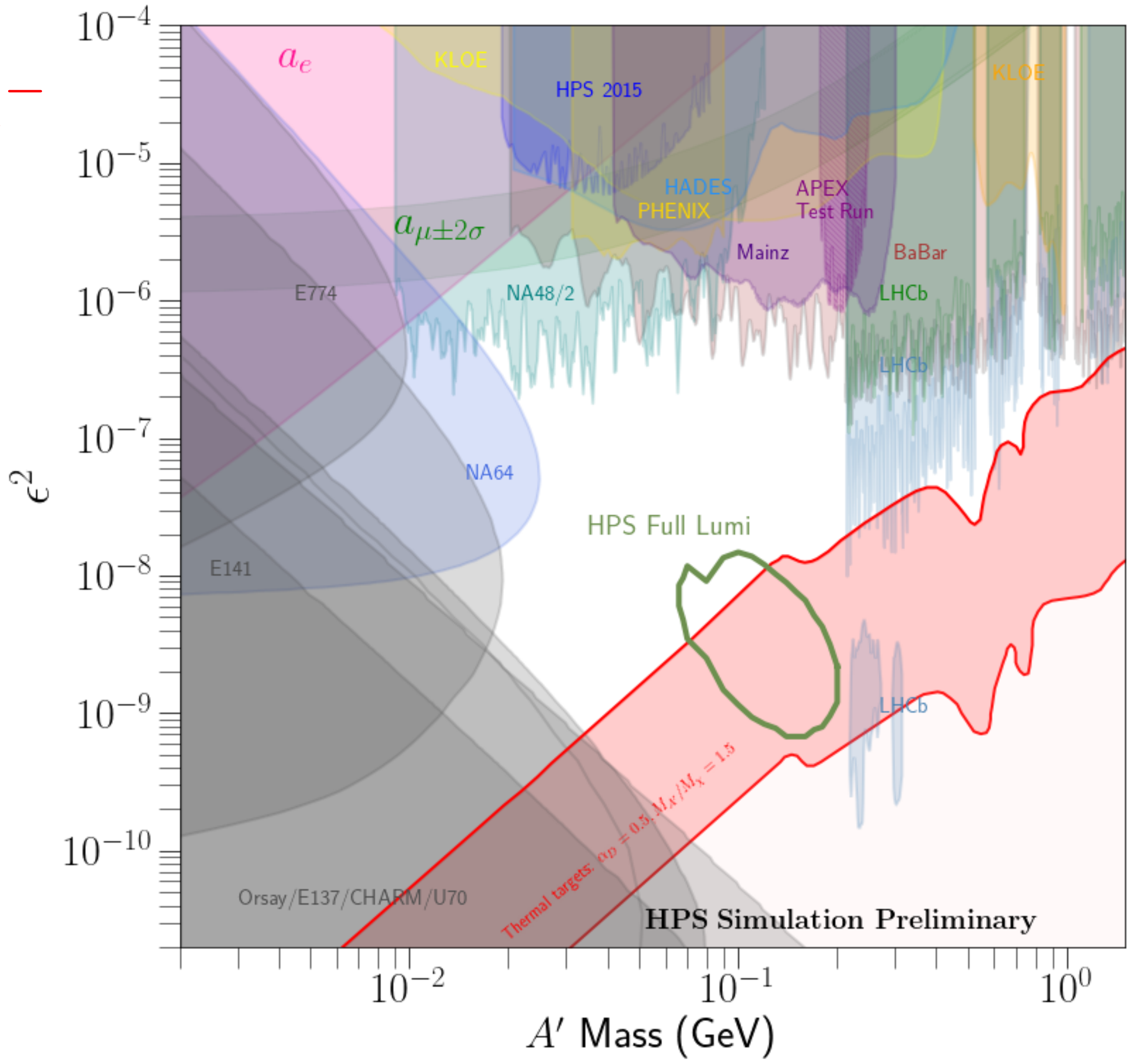
Key background: SM tridents from target

Beam Energy	Beam Current	Rep. Rate	Bunch Charge (e^-)	Spot Size
2.2 GeV	50 nA	2 ns	625	<50 μm
4.4 GeV	120 nA	2 ns	1500	<50 μm
6.6 GeV	120 nA	2 ns	1500	<50 μm



Si 0.5mm from beam axis!!





Considerations:

- beam energy determines mass window
- occupancy in high-acceptance detector limits bunch charge
- SVT requires very small, clean, and stable beam spot.

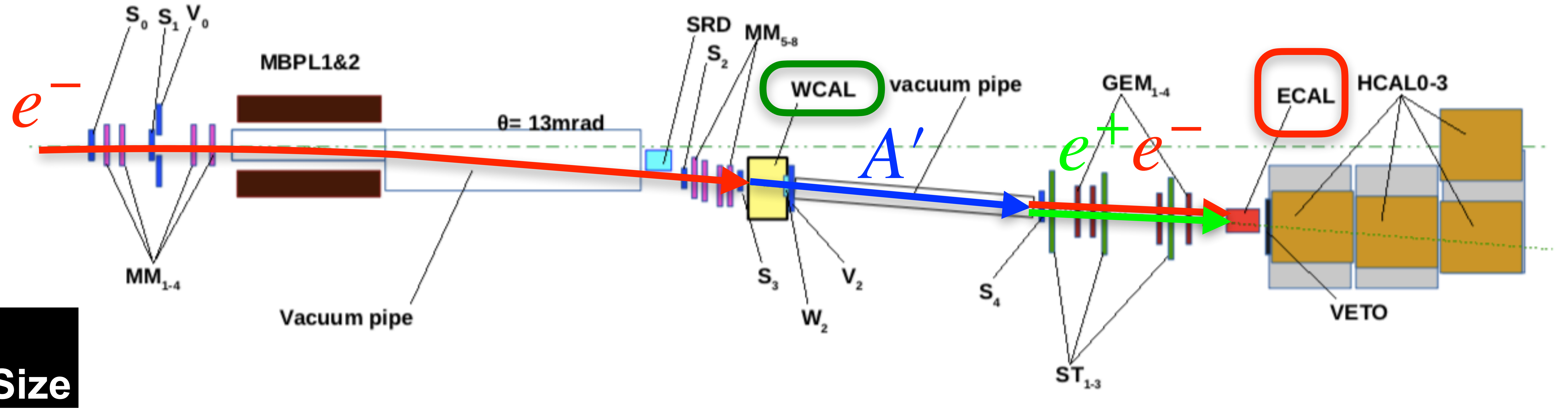
Active Beam Dump

Example: NA64 @ CERN

Search for long-lived particles decaying to electrons

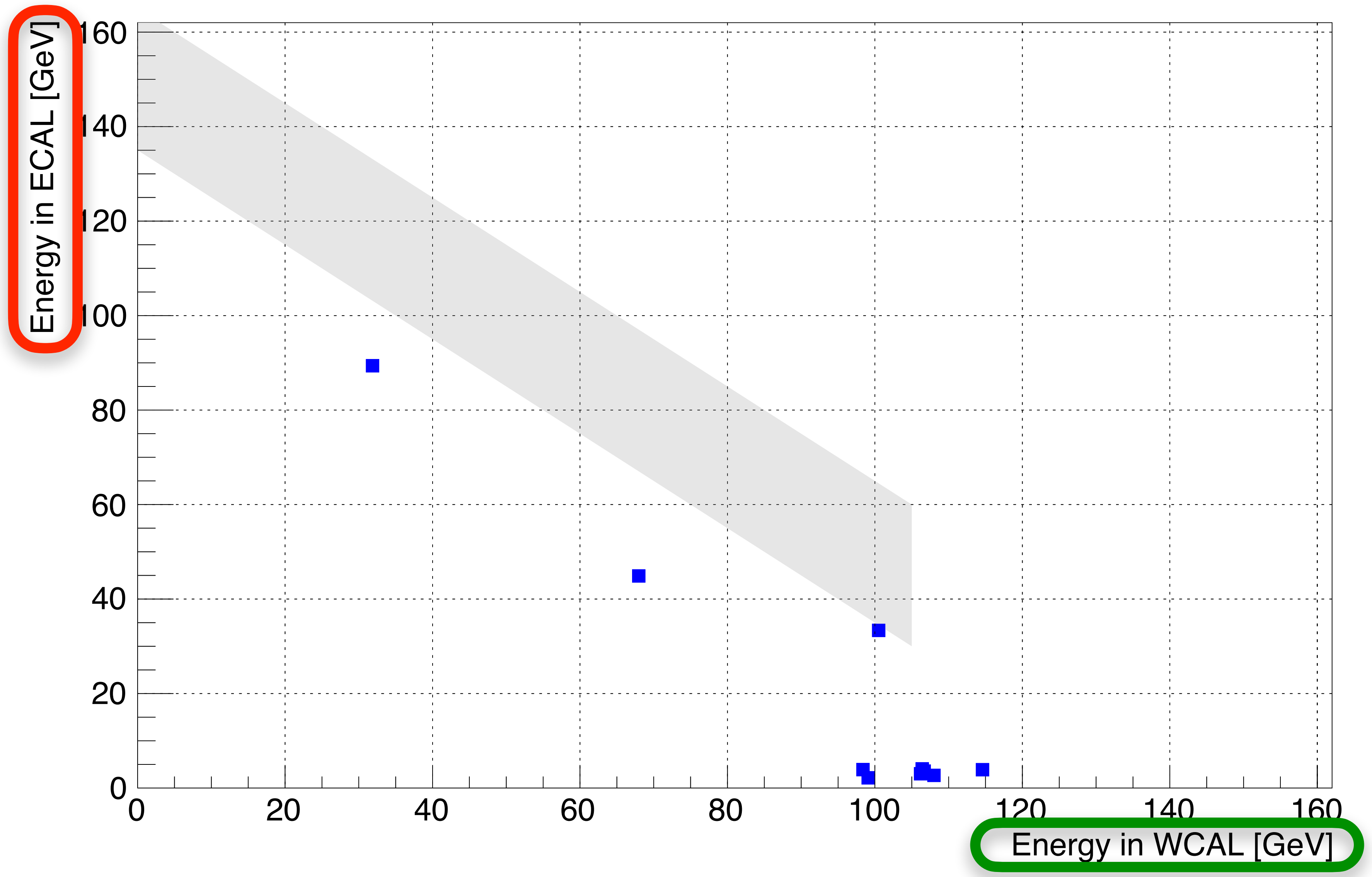
Key background: hadronic contamination in secondary electron beam

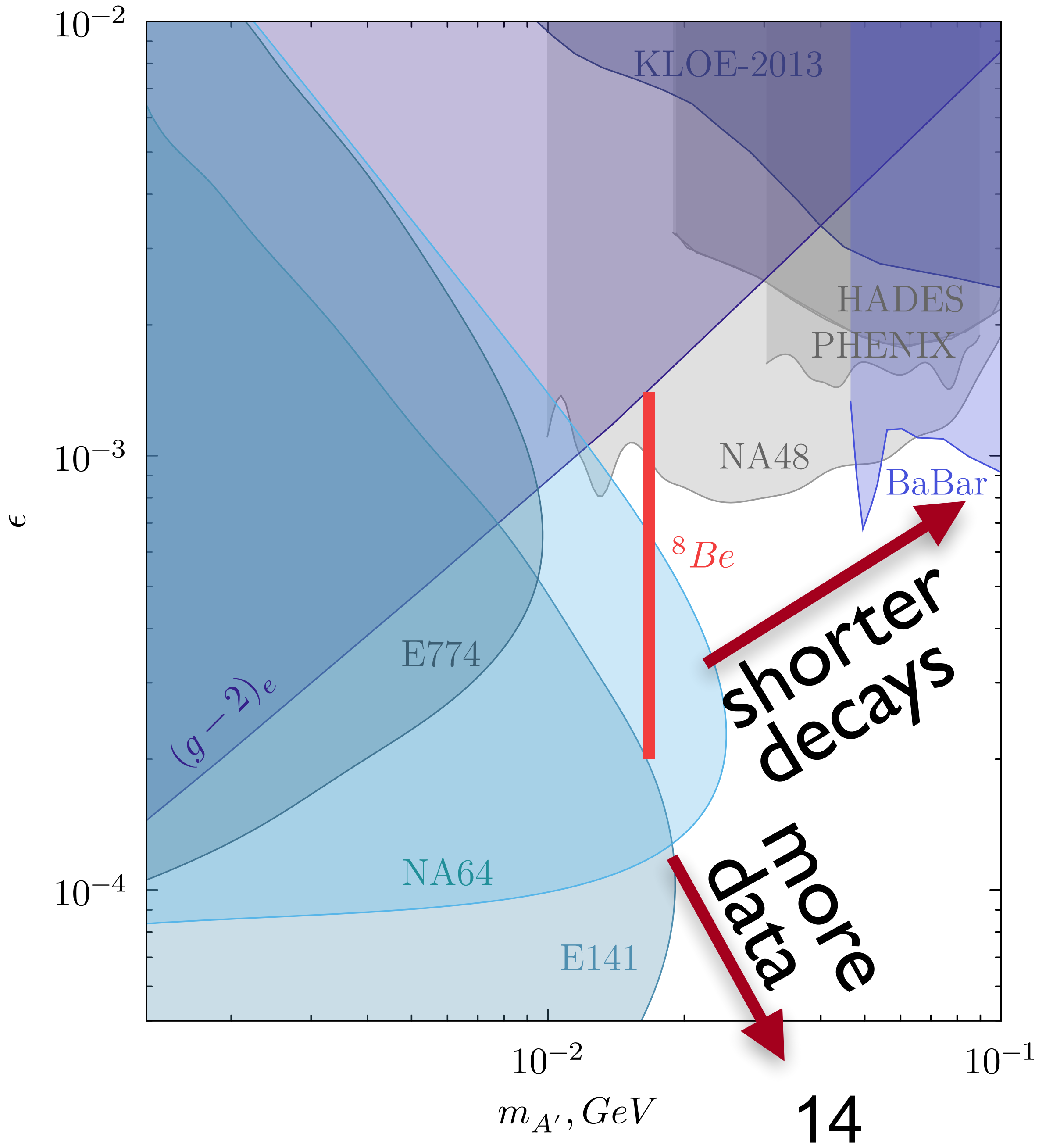
Beam Energy	Beam Current	Rep. Rate	Bunch Charge (e^-)	Spot Size
150 GeV	200 fA	continuous spill	continuous spill	~mm-cm



Considerations:

- high energy boosts decay length
- sensitivity limited by current
- low charge/time is critical – need single-electron events (~1 e^-/μsec)





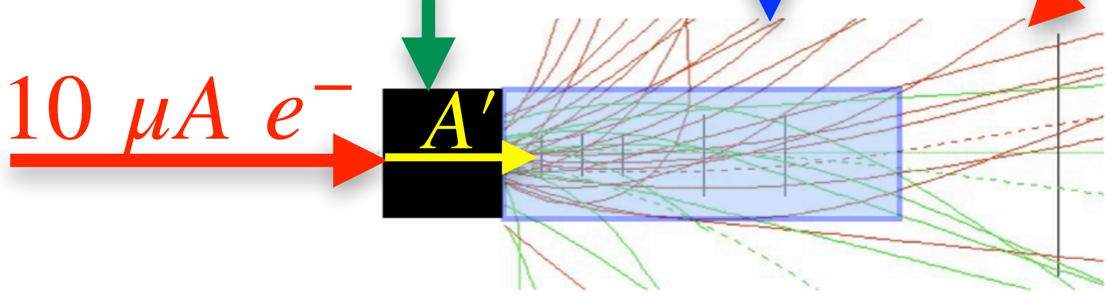
Shallow Dump + Spectrometer w/ Vertexing

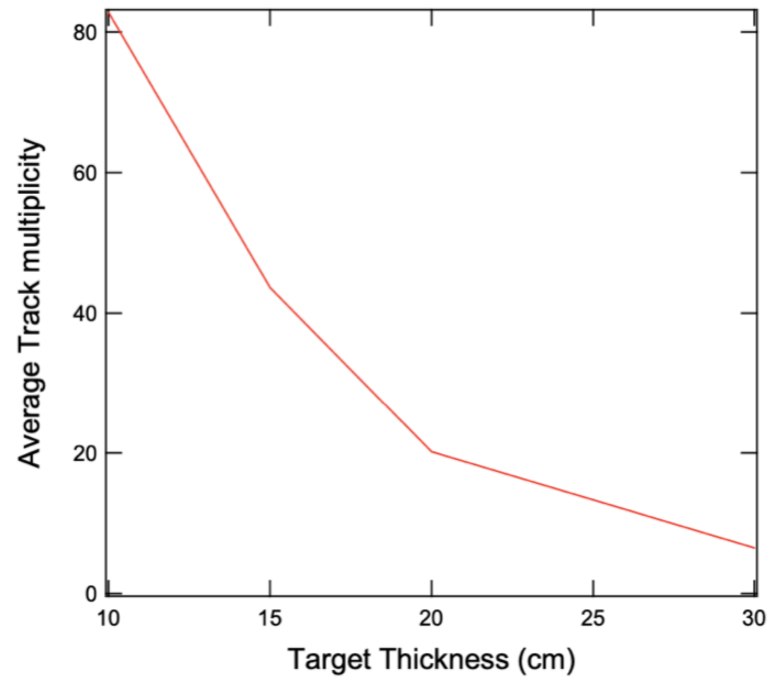
Examples: high-intensity HPS, AWAKE (concepts)

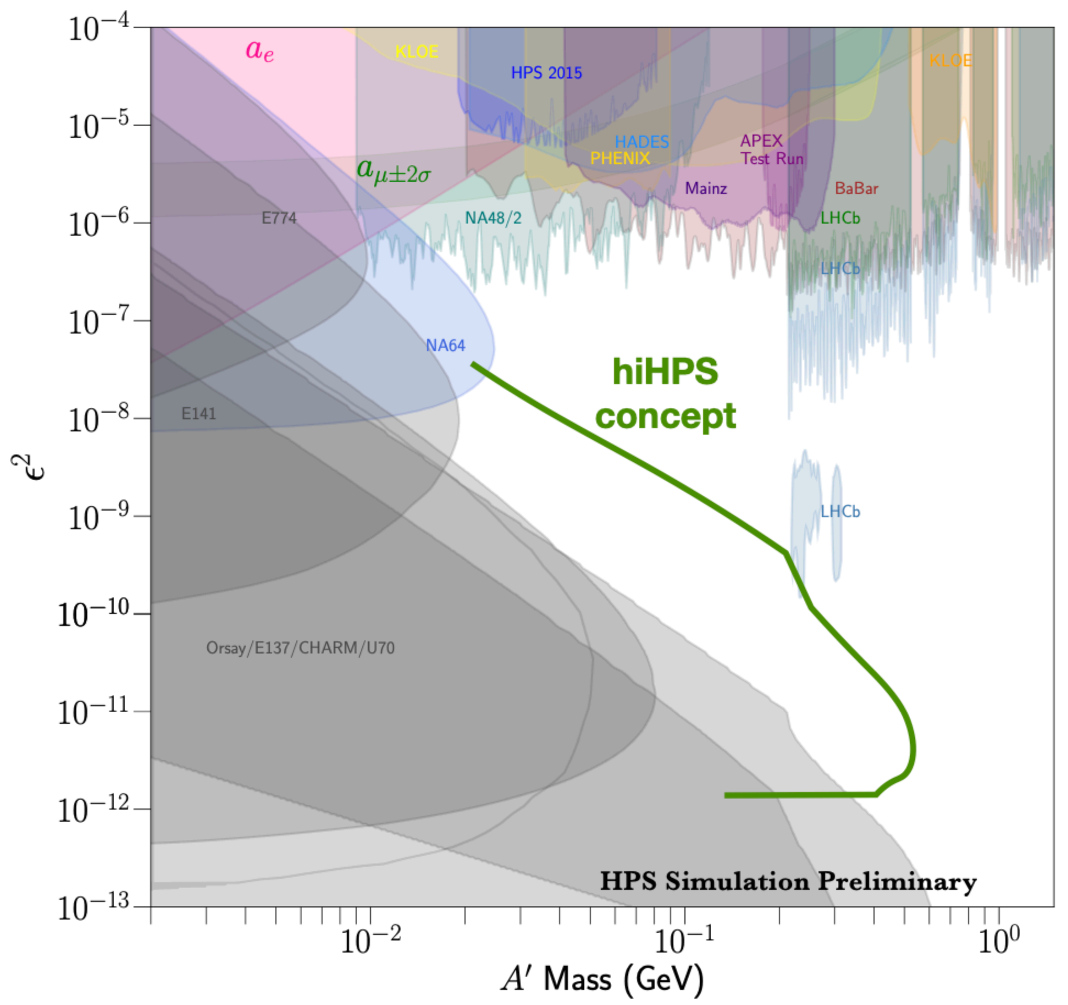
Search for long-lived dark photons with spectrometer downstream of shallow dump

Key background: fake vertices from leakage of charged particles

	Beam Energy (GeV)	Beam Current	Rep. Rate	Bunch Charge (e-)	Spot Size
hiHPS	6.6	10 μA	2 ns	1E+05	~cm
AWAKE	50-1000	300 pA (avg)	25 ns (min)	1.5E+07 (min)	~cm



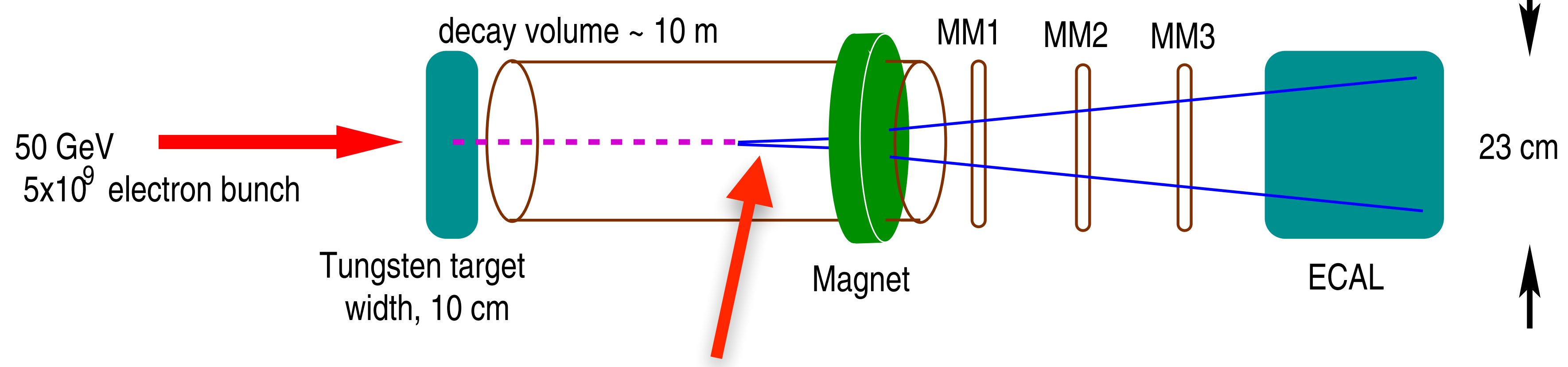




Considerations:

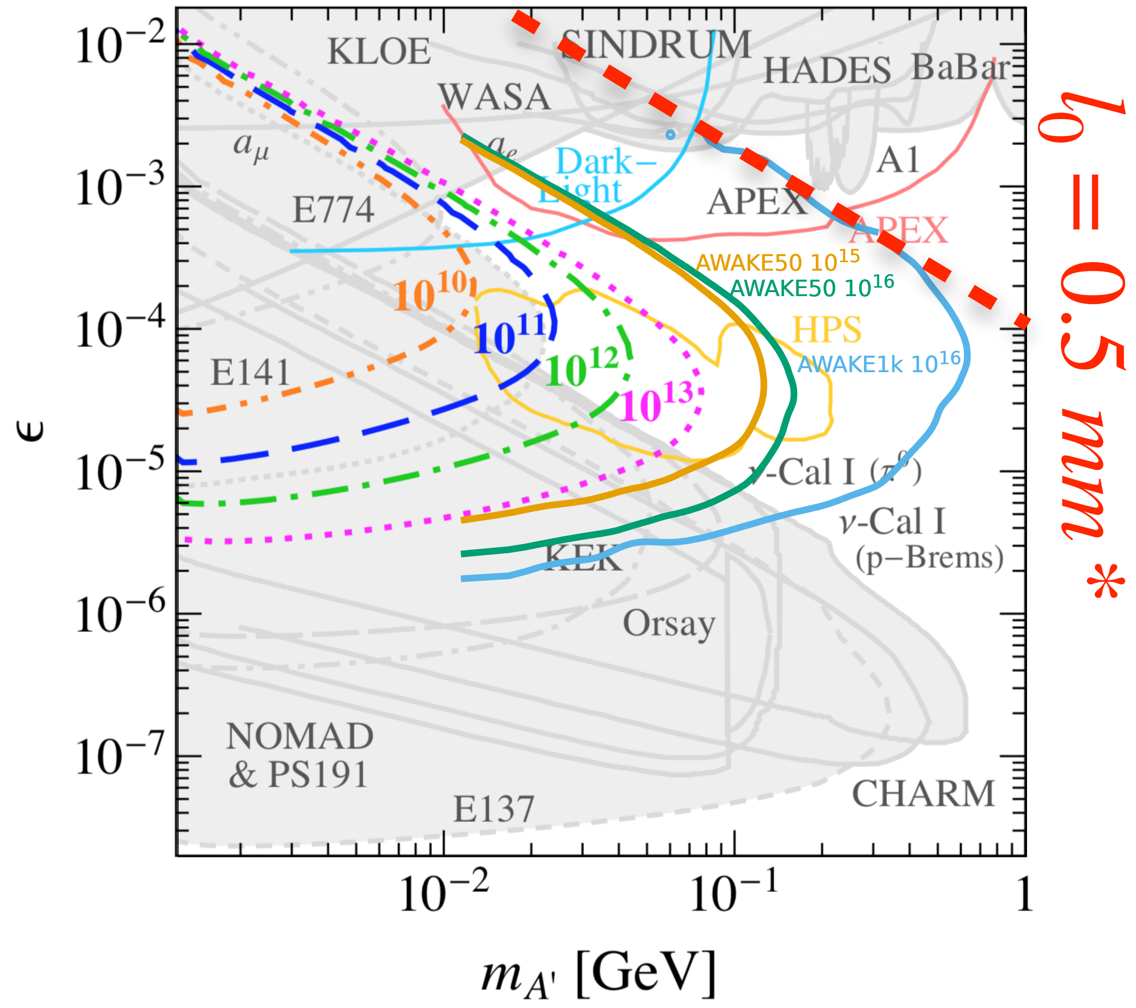
- high energy boosts decay length*
- high-rate beam with fast detectors*
- Radiation hardness is a serious issue

Fierce competition from similar p^+ beam experiments (NA62, FASER, DarkQuest,…)



Expect at least 3000 tracks/bunch!*

**concept needs a closer look*



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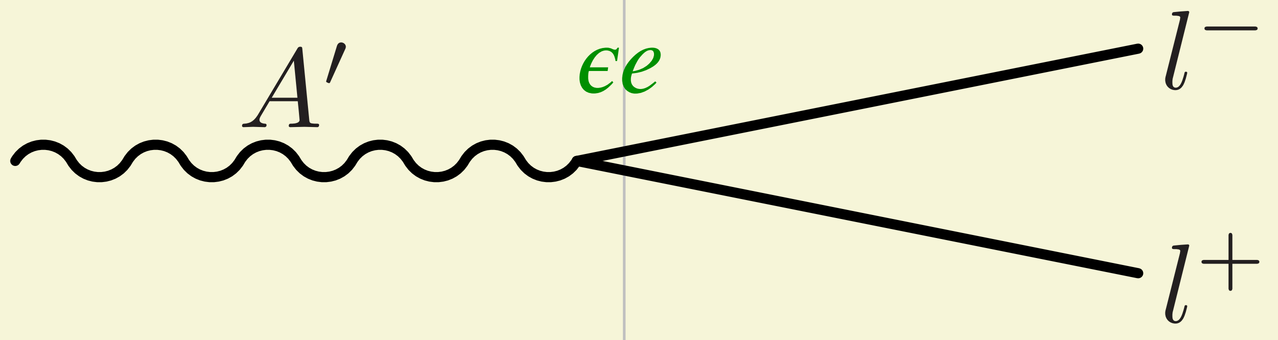

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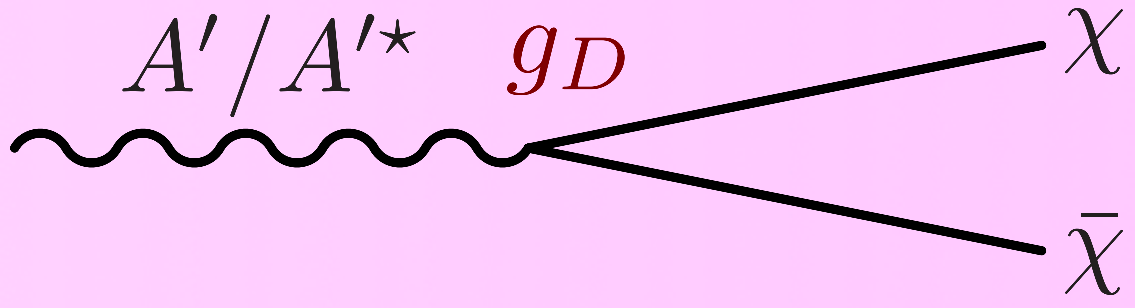

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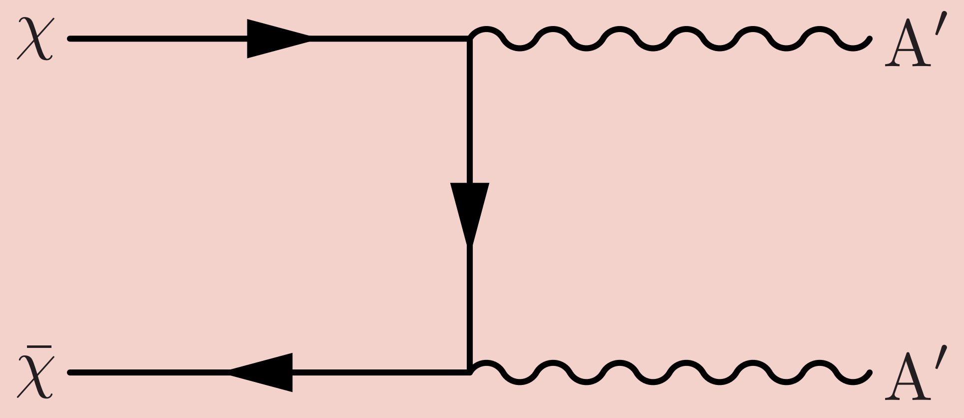
DM annihilation in early universe:

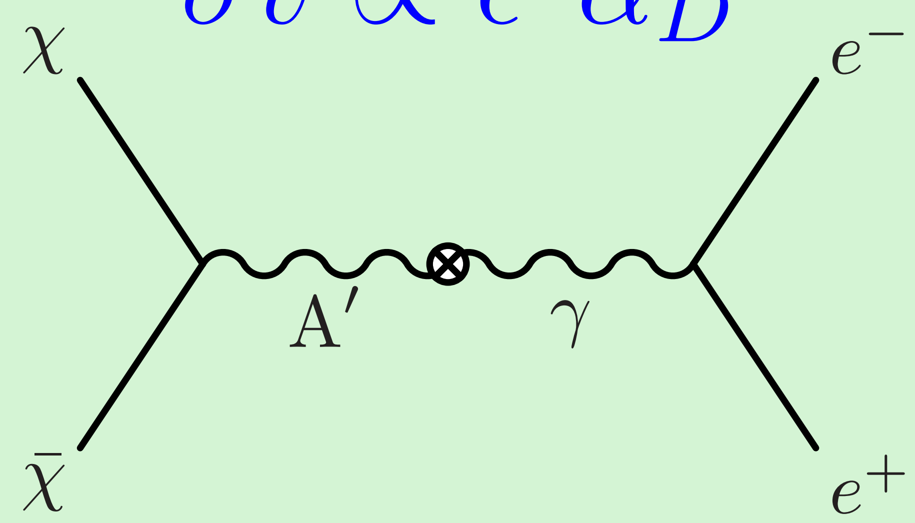
"secluded"

$$\sigma v \propto \alpha_D^2$$



"direct"

$$\sigma v \propto \epsilon^2 \alpha_D$$



Interpretation:

no clear target for ϵ

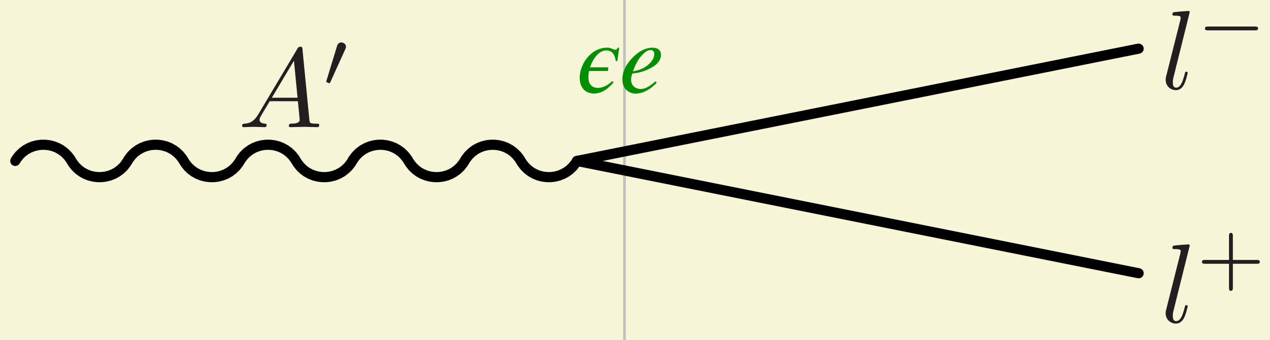
"Thermal Target" - lower limit on ϵ for thermal relics

Mass Hierarchy Determines Search Strategy & Interpretation

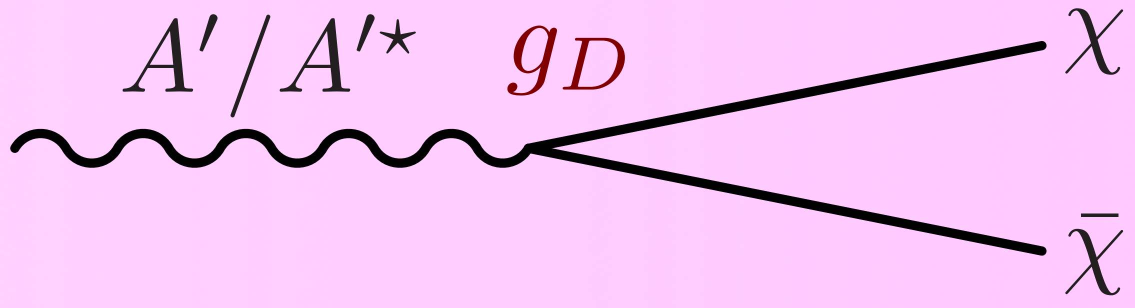
SLAC

Mediator Mass $m_{A'}$ — axis marks: m_χ, $2m_\chi$

Experimental Search:



mediator decays to SM (AKA "visible mediator decays")
(searches are often mediator specific)



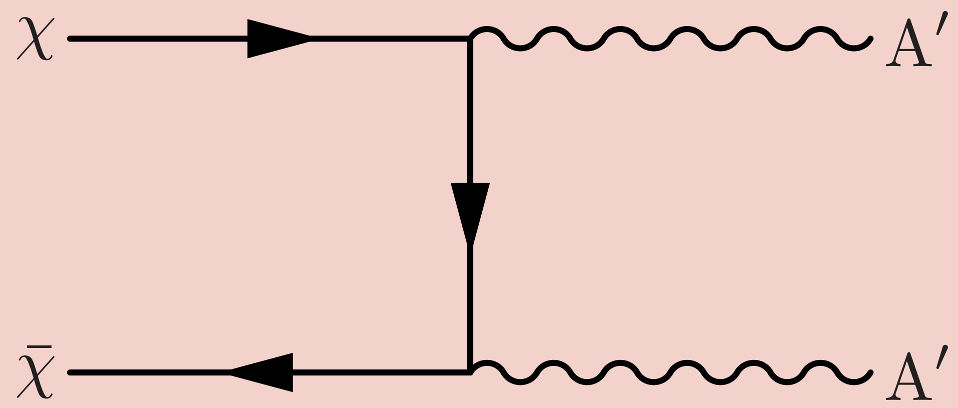
for production of DM
(AKA "invisible searches")
(searches largely agnostic to type of mediator)

searches measure/constrain ϵ^2 as a function of $M_{A'}$

DM annihilation in early universe:

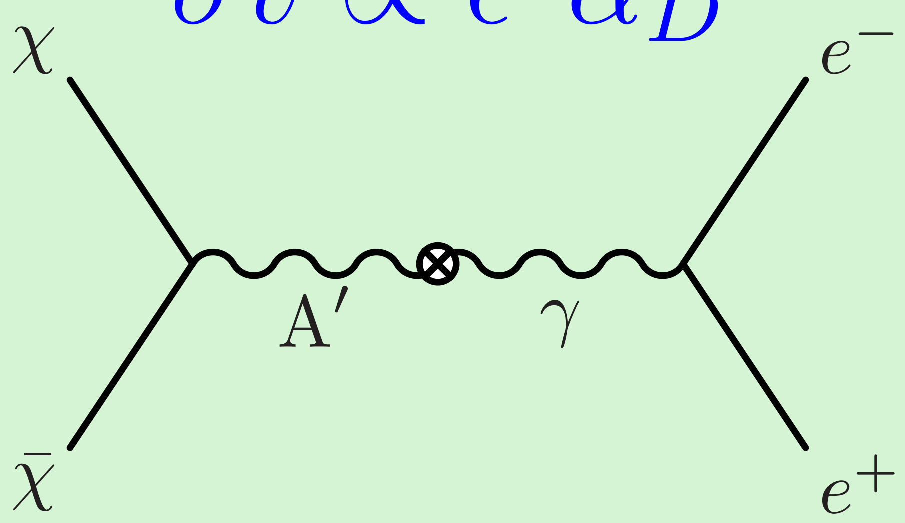
"secluded"

$$\sigma v \propto \alpha_D^2$$



"direct"

$$\sigma v \propto \epsilon^2 \alpha_D$$



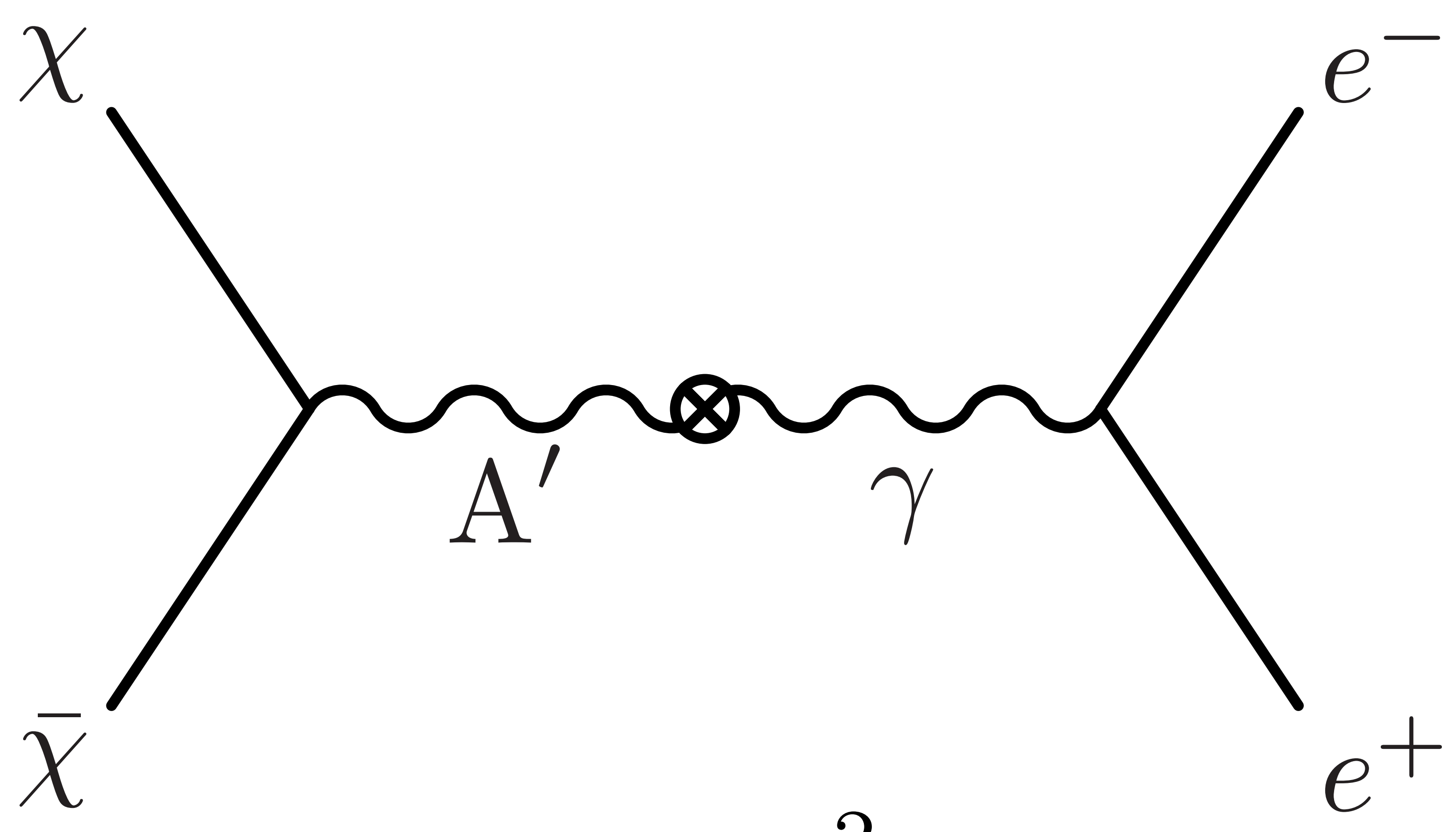
Interpretation:

no clear target for ϵ

"Thermal Target" - lower limit on ϵ for thermal relics

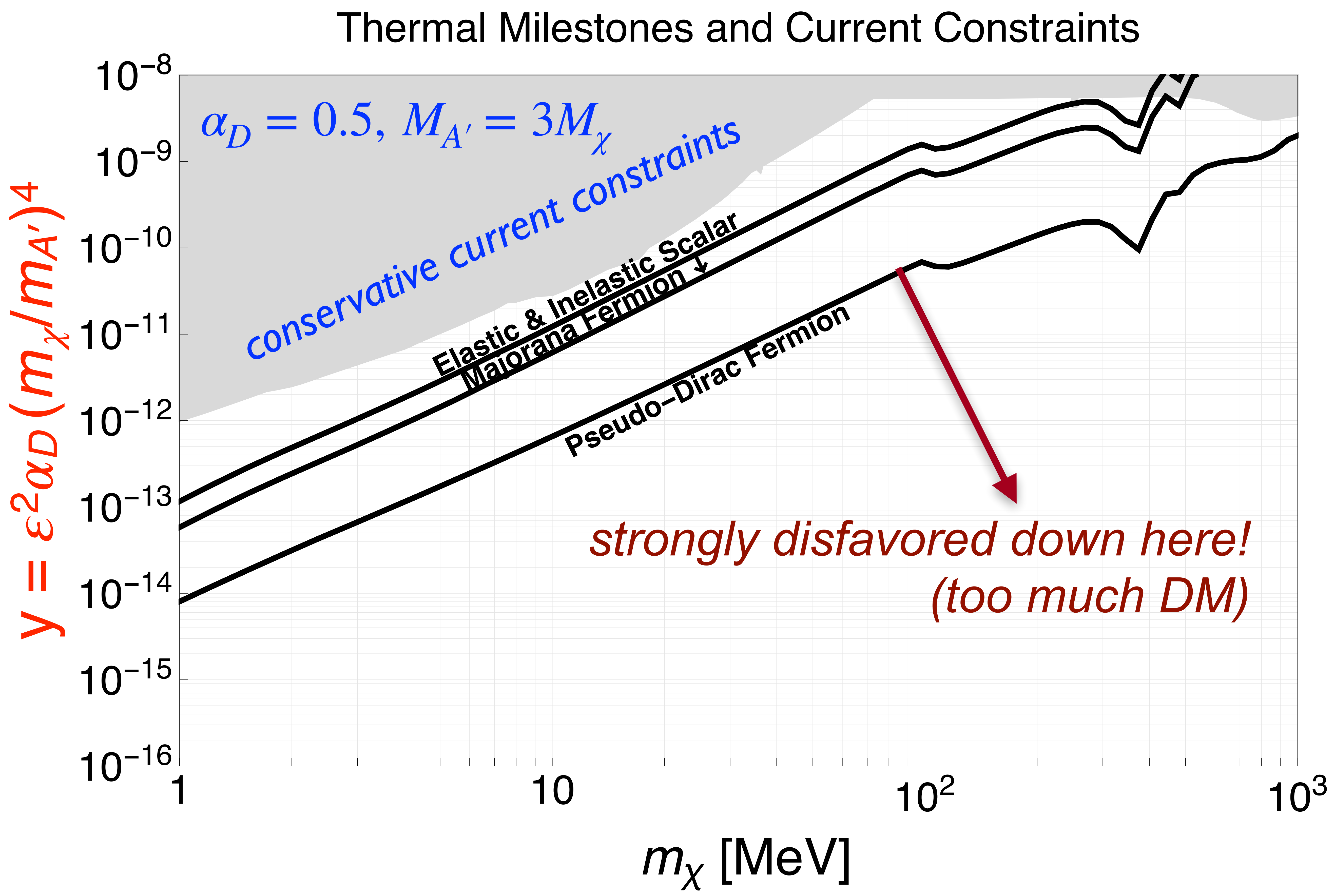
Searches for Production of Light Dark Matter

Want parameter space more natural for DM searches



$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

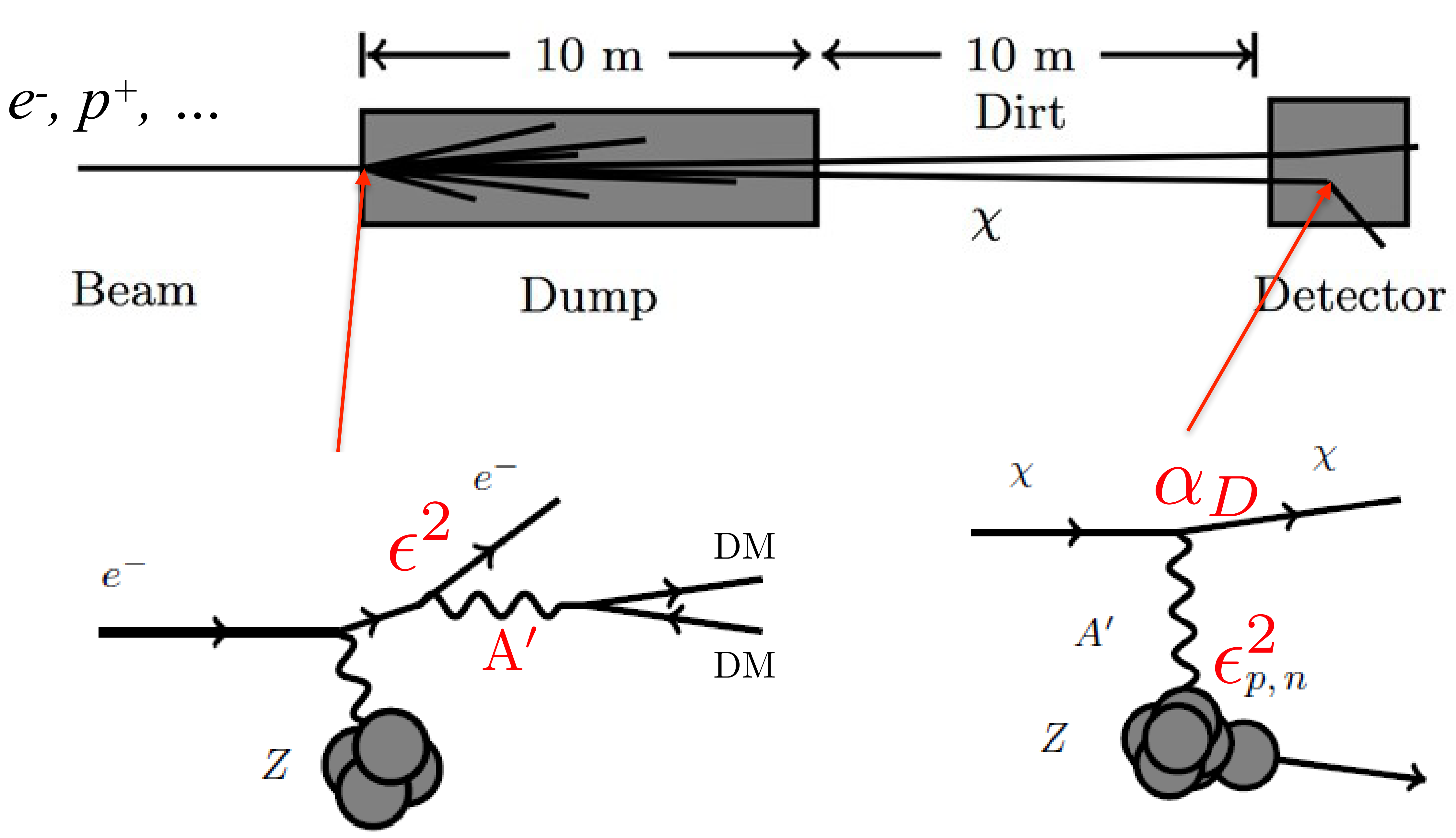


Choose "conservative" values of α_D, $M_{A'}/M_\chi$ for converting $(M_{A'},\epsilon) \Longrightarrow (M_\chi, y)$

Fixed Target Dark Matter Search Approaches

SLAC

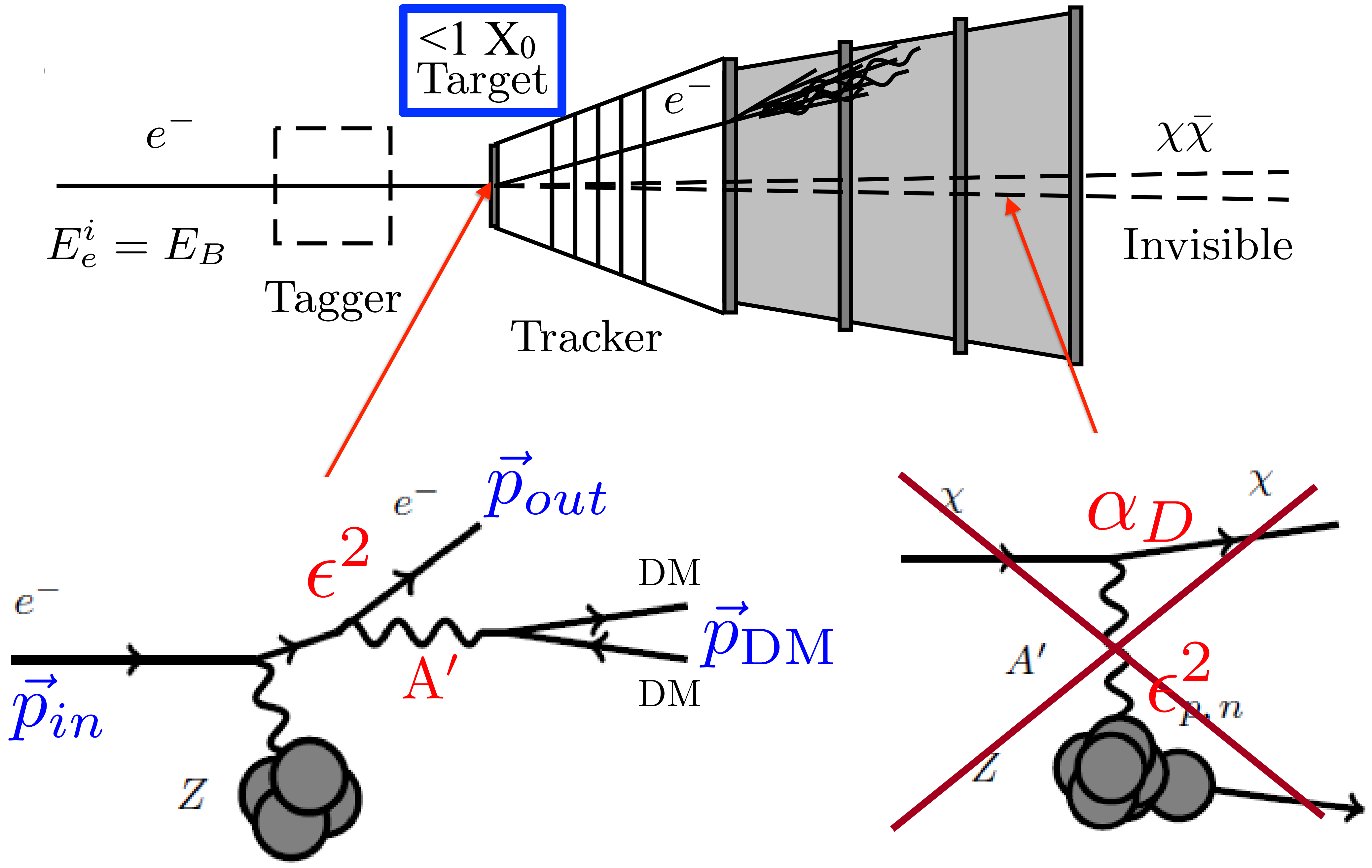
Beam Dumps: Produce and detect DM



$$N \propto \epsilon^4$$

Interesting sensitivity for ~10^{22} particles on target

Missing Momentum: Detect the production of DM



$$\vec{p}_{\rm in} = \vec{p}_{\rm out} + \vec{p}_{\rm DM}$$

$$N \propto \epsilon^2$$

Interesting sensitivity for ~10^{12} particles on target

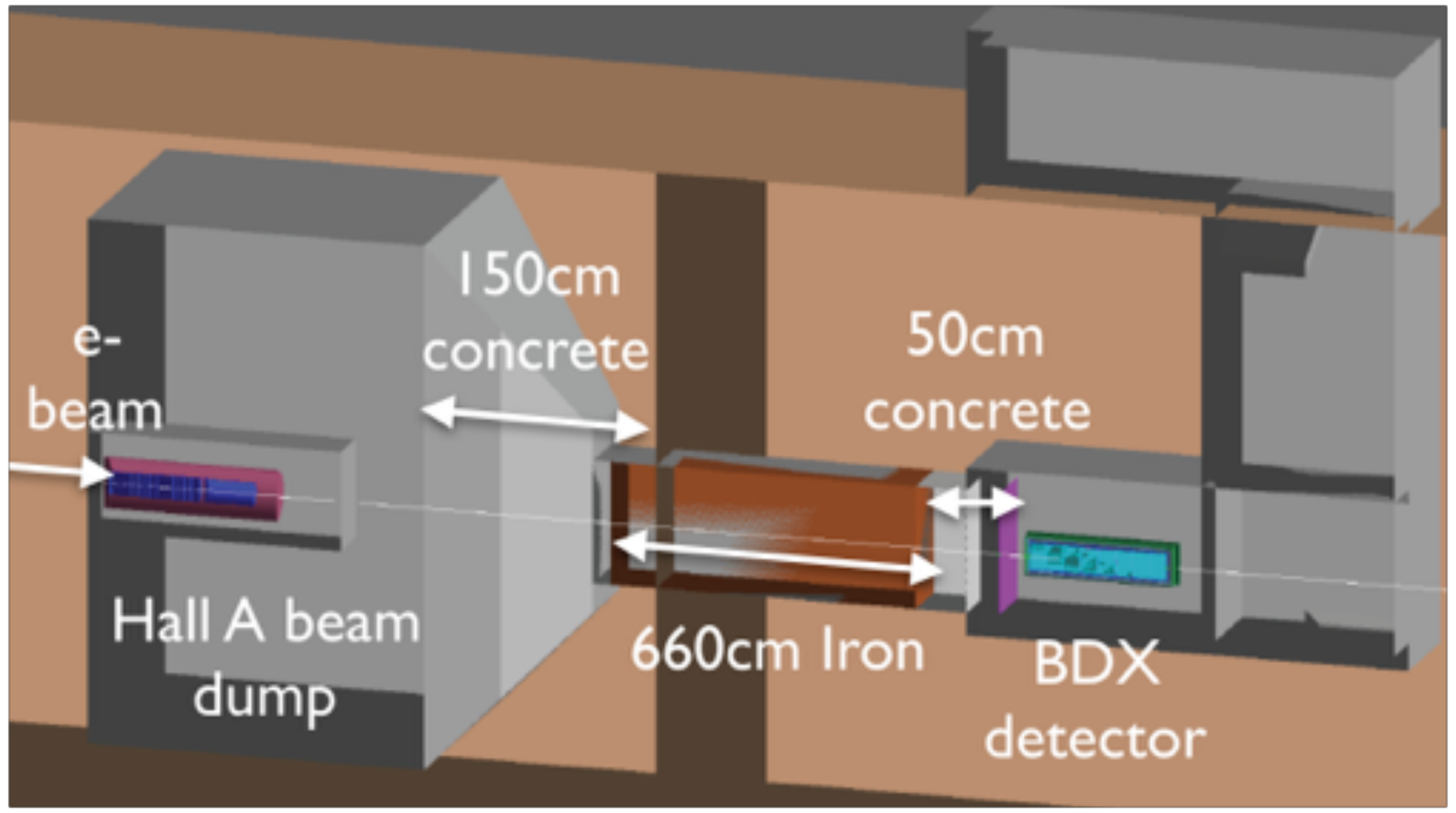
Beam Dump

Example: BDX @ JLab (proposed)

Search for production and re-scattering of weakly interacting particles behind high-power beam dump

Key background: Cosmics and neutrinos

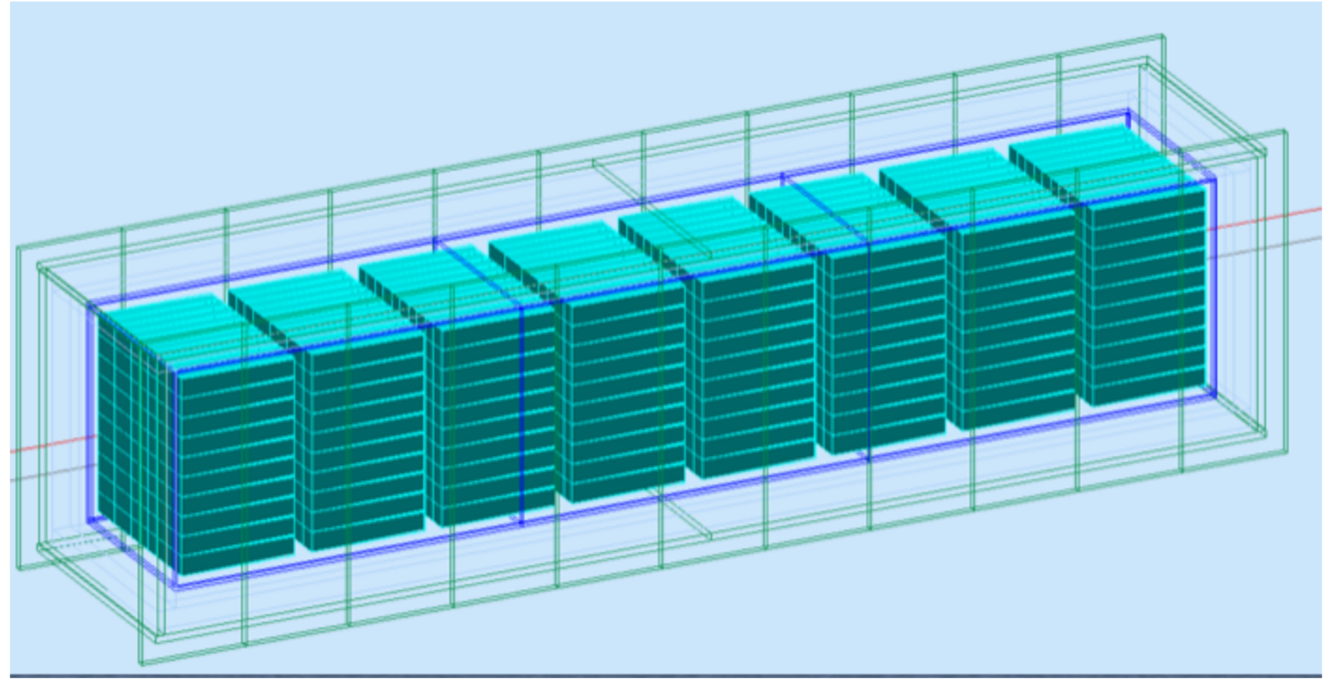
Beam Energy	Beam Current	Rep. Rate	Bunch Charge (e-)	Spot Size
11 GeV	60 μA	2 ns	few E11	~cm

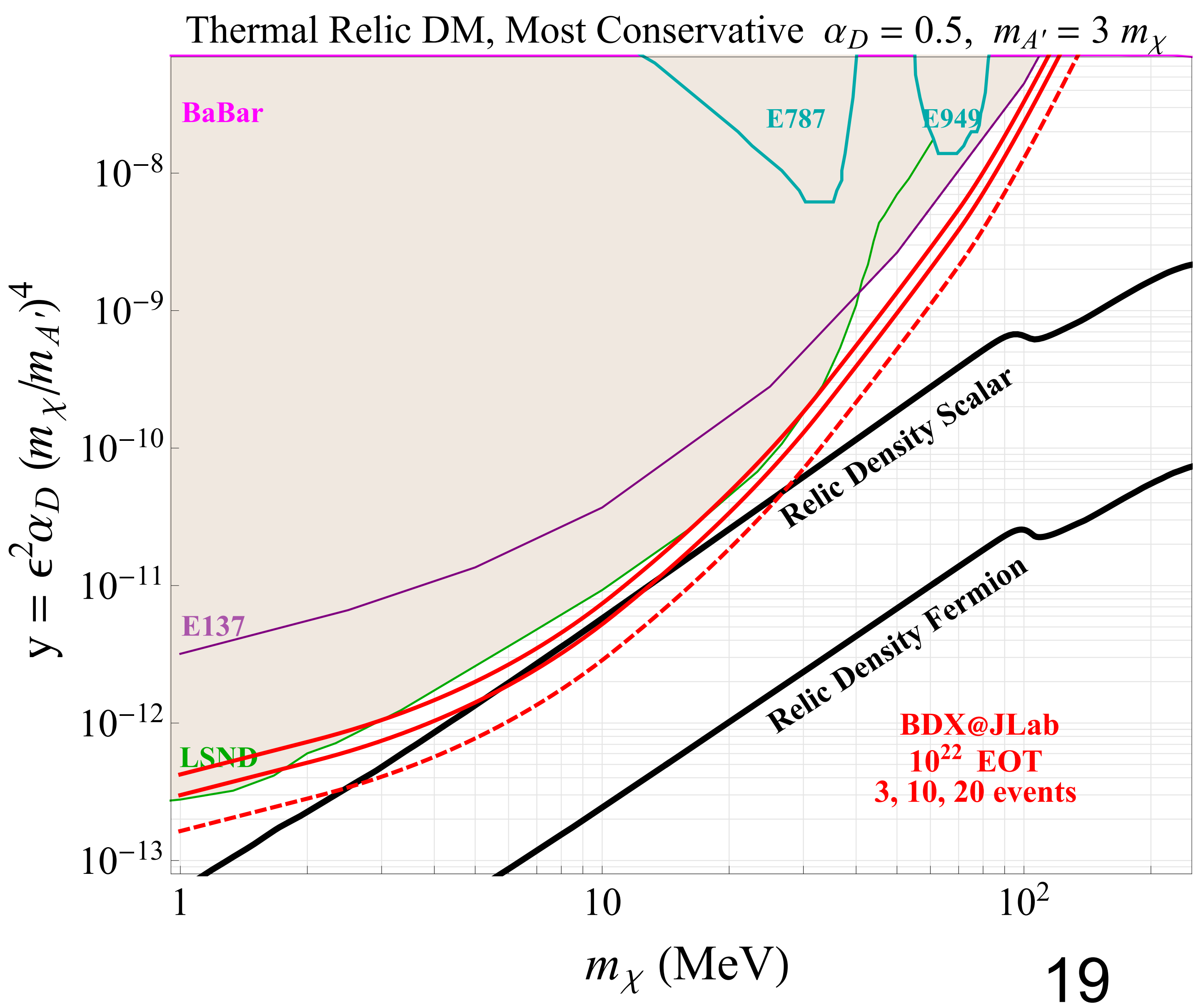


Considerations:

- higher energy is better
- huge total charge required (~1000 C)
- higher bunch charge / lower rep rate would minimize cosmics
- In concepts with longer baselines and low repetition rate, time-of-flight can be used to reduce neutrino backgrounds

CsI calorimeter w/ cosmic veto





Concept also considered for ILC

Missing Momentum/Energy

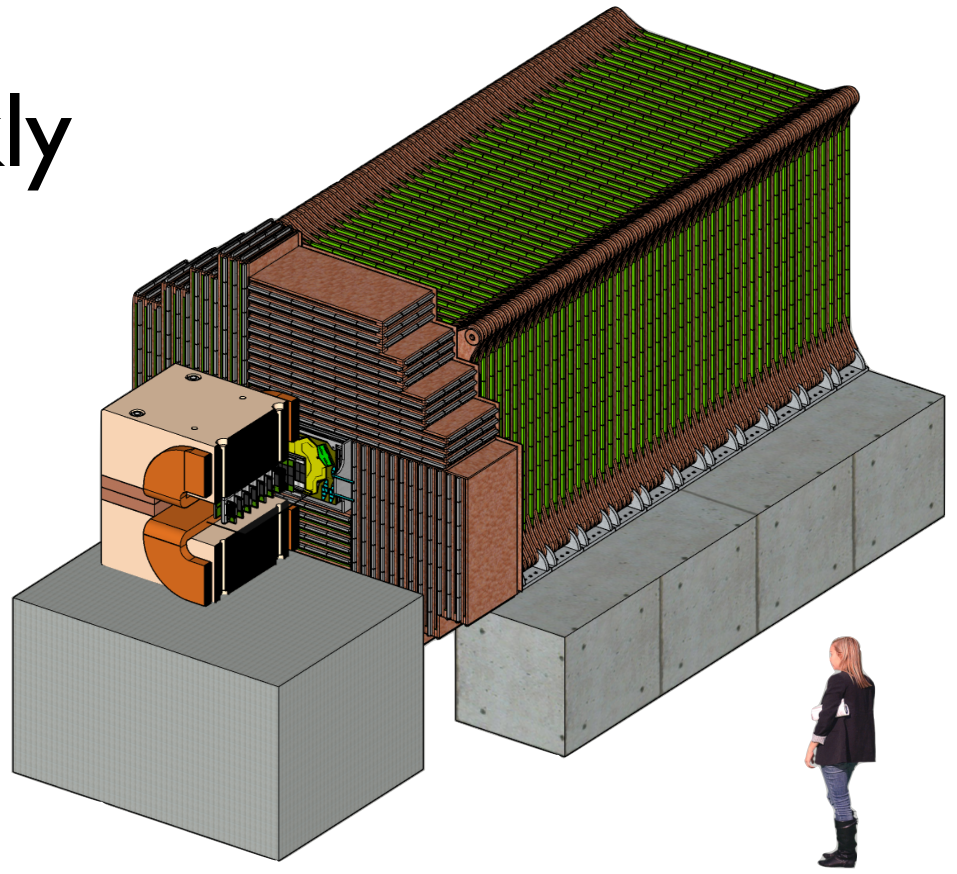
SLAC

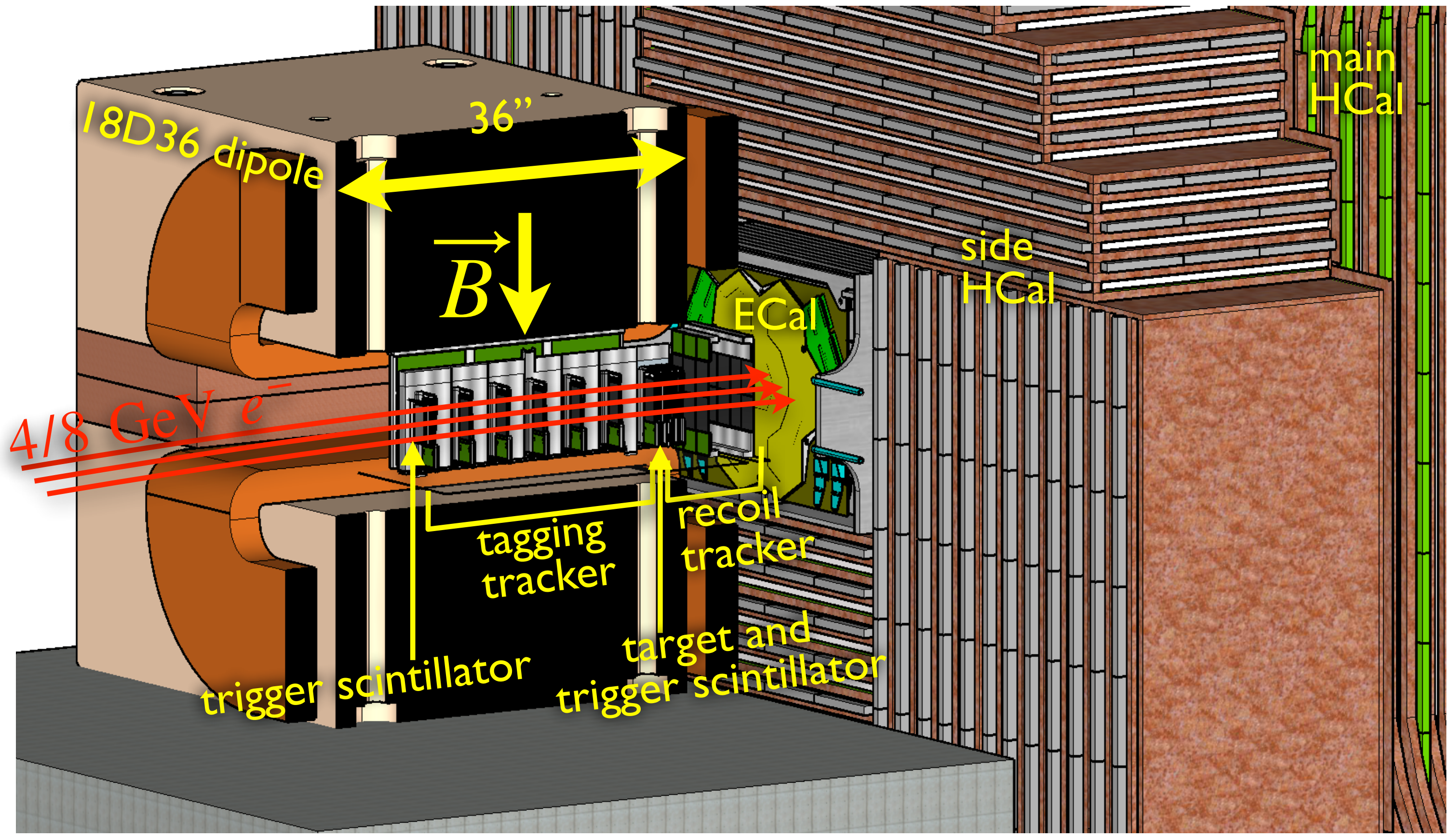
Example: LDMX @ SLAC (proposed)

Search for missing momentum in production of weakly interacting particles using LCLS-II drive beam

Key background: hard brem → rare photo-nuclear

Beam Energy	Beam Current	Rep. Rate	Bunch Charge (e^-)	Spot Size
4/8 GeV	6-30 pA	27 ns	~1 e^-	~ 5 cm

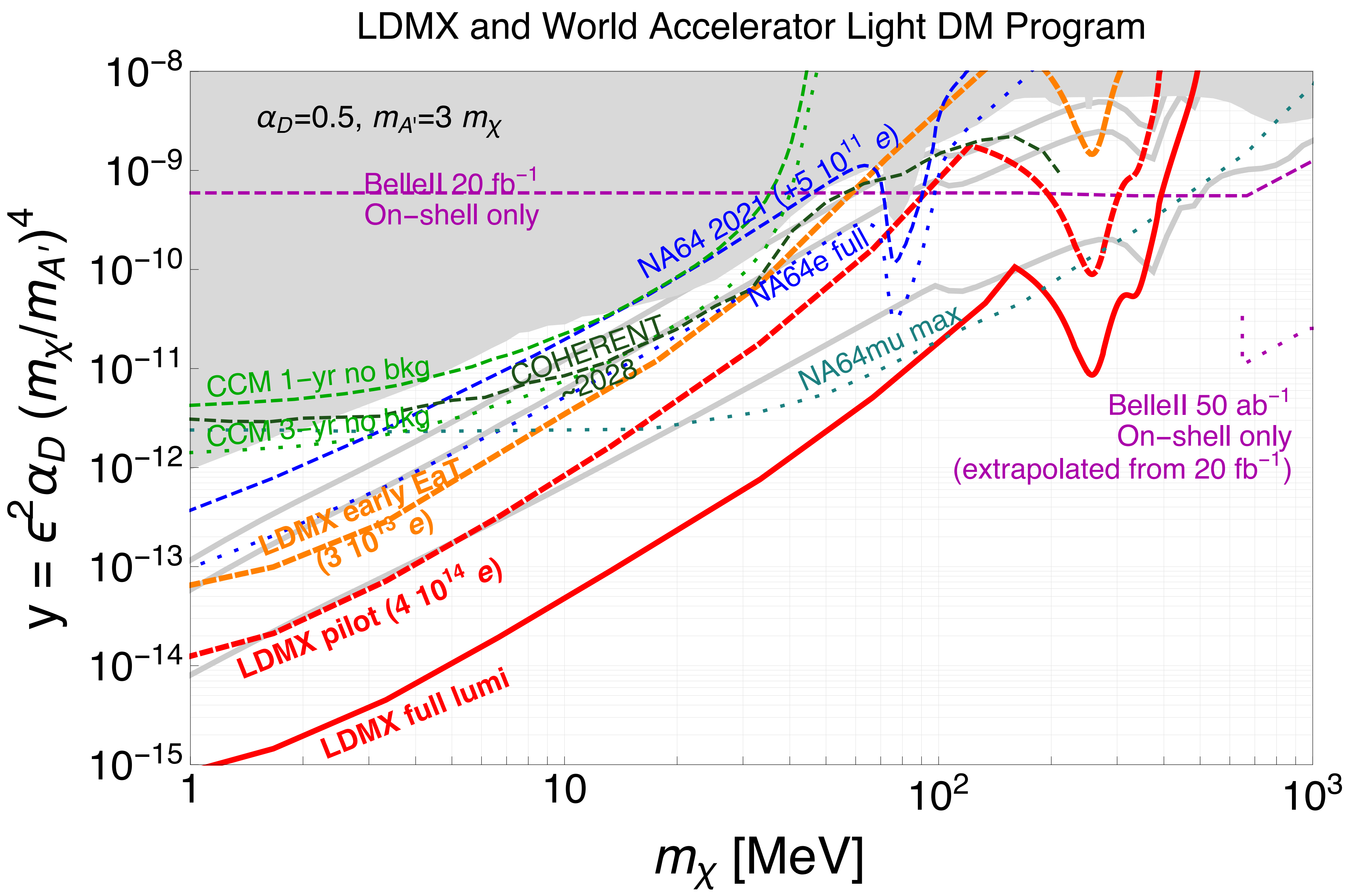




Considerations:

- higher energies are beneficial (up to at least ~20 GeV)
- achieves full potential at ~10^{16} EOT
- need ~single electron events: high rep-rate, low-current beam and fast detectors
- pure e^- beam with small energy spread is important

Beamline construction at SLAC is underway, development of LDMX supported as a DOE "Dark Matter New Initiative"



Summary of Beam Requirements (most challenging)

SLAC

Searches for Visibly Decaying Mediators

	Beam Energy	Beam Current	Bunch Charge / Rep Rate	Beam Spot Size
Resonance Search (e.g. APEX)	Tuned according to spectrometer acceptance and desired mass range	As high as possible, limited by detector occupancy	low charge / high rep rate (detector occupancy)	<1mm
Resonance Search + Precision Vertexing (e.g. HPS)	Tuned according to spectrometer acceptance and desired mass range	As high as possible, limited by detector occupancy	low charge / high rep rate (detector occupancy)	<50 μm
Simple Beam Dump (e.g. E137 - in backup)	As high as possible	As high as possible (need >100 C)	As high as possible (cosmic backgrounds)	can be large
Active Beam Dump (e.g. NA64)	As high as possible	As high as possible, limited by detector occupancy	Requires O(1) e^- per detector integration time (1-100 ns)	can be large
Beam Dump + Spectrometer w/Vertexing (e.g. AWAKE concept)	As high as possible	As high as possible, limited by detector occupancy	low charge / high rep rate (detector occupancy)	can be large
Positron missing mass (e.g. PADME - in backup)	As high as possible	As high as possible, limited by detector occupancy	low charge / high rep rate (detector occupancy)	<1mm

Searches for Dark Matter

	Beam Energy	Beam Current	Bunch Charge / Rep Rate	Beam Spot Size
Beam Dump (e.g. BDX)	As high as possible	As high as possible (need >100 C)	Prefer high charge / Low rep-rate (cosmic backgrounds)	can be large
Missing Energy/Momentum (e.g. LDMX)	As high as possible	As high as possible, limited by detector occupancy	Requires O(1) e^- per detector integration time (1-100ns)	can be large

Conclusions

- Fixed target experiments are good candidates for early deployment of new accelerator technologies. (Colliding beams are hard!)
- Electron fixed-target searches for dark matter / mediators utilize a wide variety of techniques with widely varying beam parameters.
- In general, the demands are extreme in at least one of…
  - highest possible current (total charge is king)
  - highest possible repetition rate (low charge/bunch to reduce pileup)

No experimental concept obviously stands out as ideal for early application of PWA or ACHIP, but we should keep exploring the possibilities.

Additional Slides

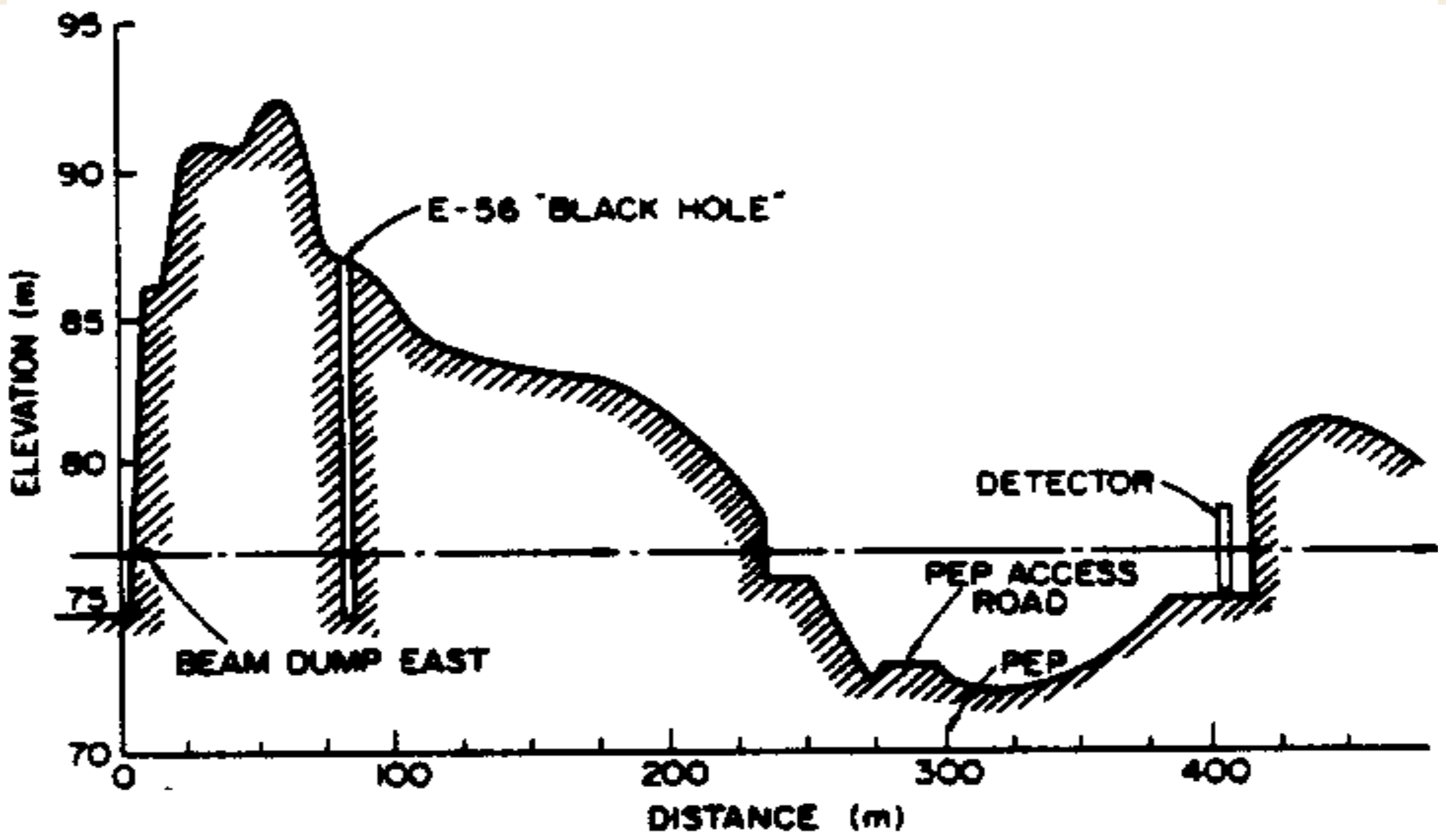
Simple Beam Dump

Example: E137 @ SLAC (1980-1982!!)

Search for long-lived particles with high-power H_2O-Al dump using large wire chambers and scintillator hodoscope

Key background: Cosmics and other accidentals

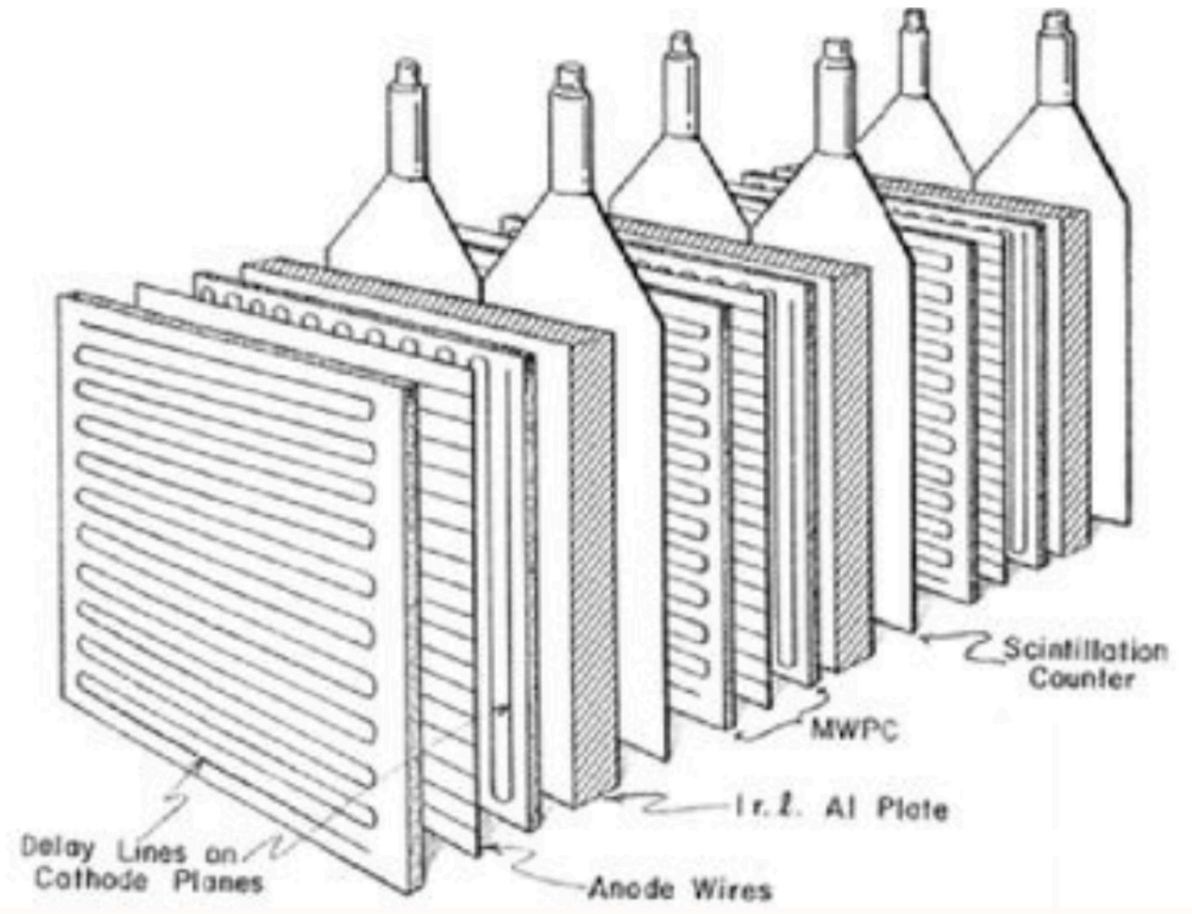
Beam Energy	Beam Current	Rep. Rate	Bunch Charge (e^-)	Spot Size
20 GeV	high (30C total)	120 Hz	few E11	~cm

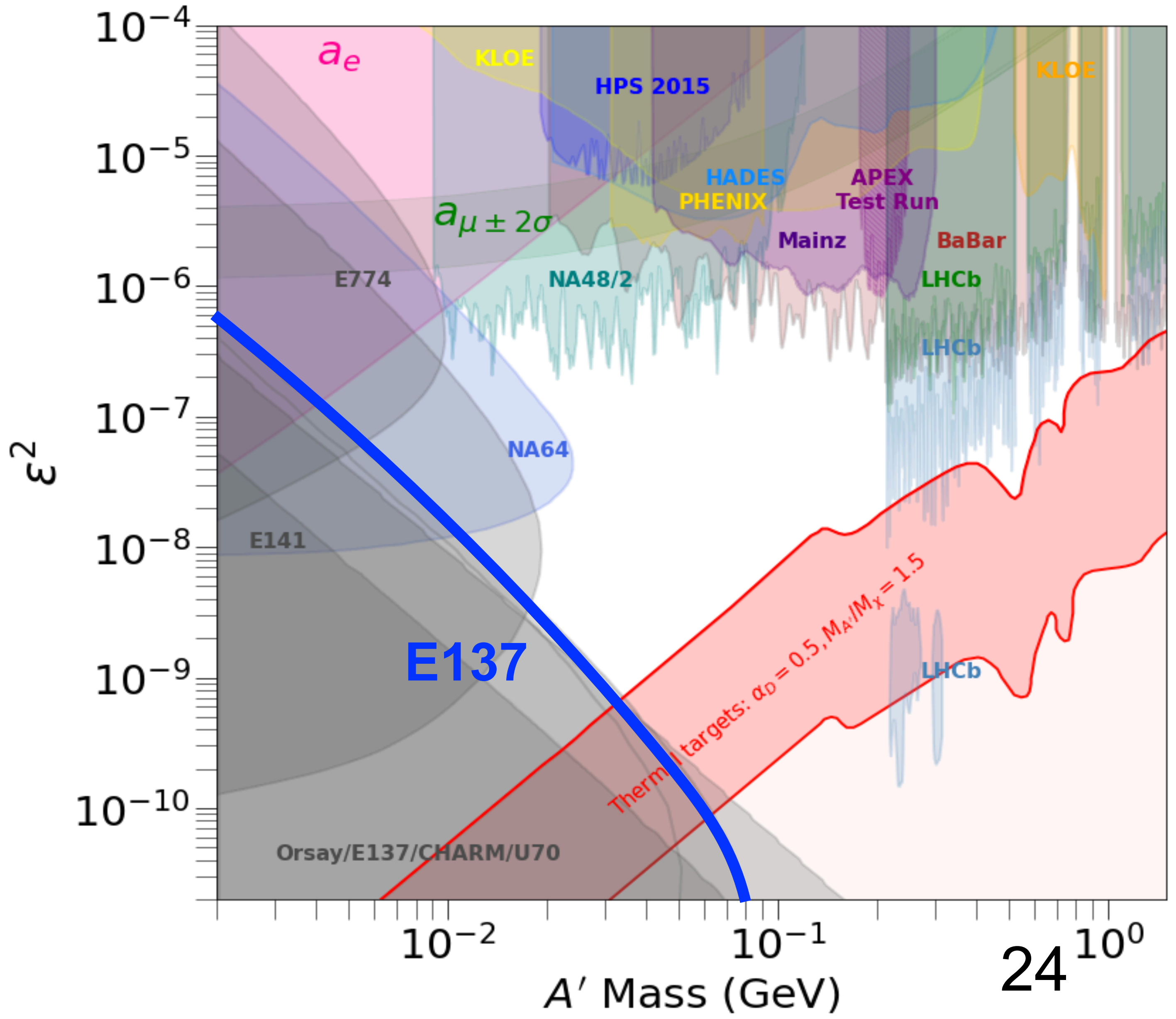


Considerations:

- Total charge is king
- high bunch charge / low duty cycle minimizes cosmics and other environmental accidentals
- Nature of target / detector allows relatively large beams

E137 and similarly un-subtle experiments continue to have best sensitivity to some models!





Positron Missing Mass

Example: PADME @ LNF, JLab, …

"Missing mass" search for resonances in e+e- annihilation in fixed target.

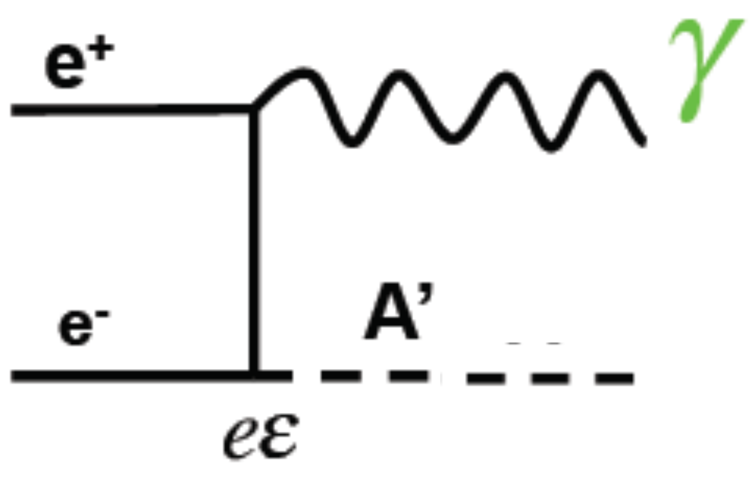
Key background: continuum of missing energy from limited acceptance

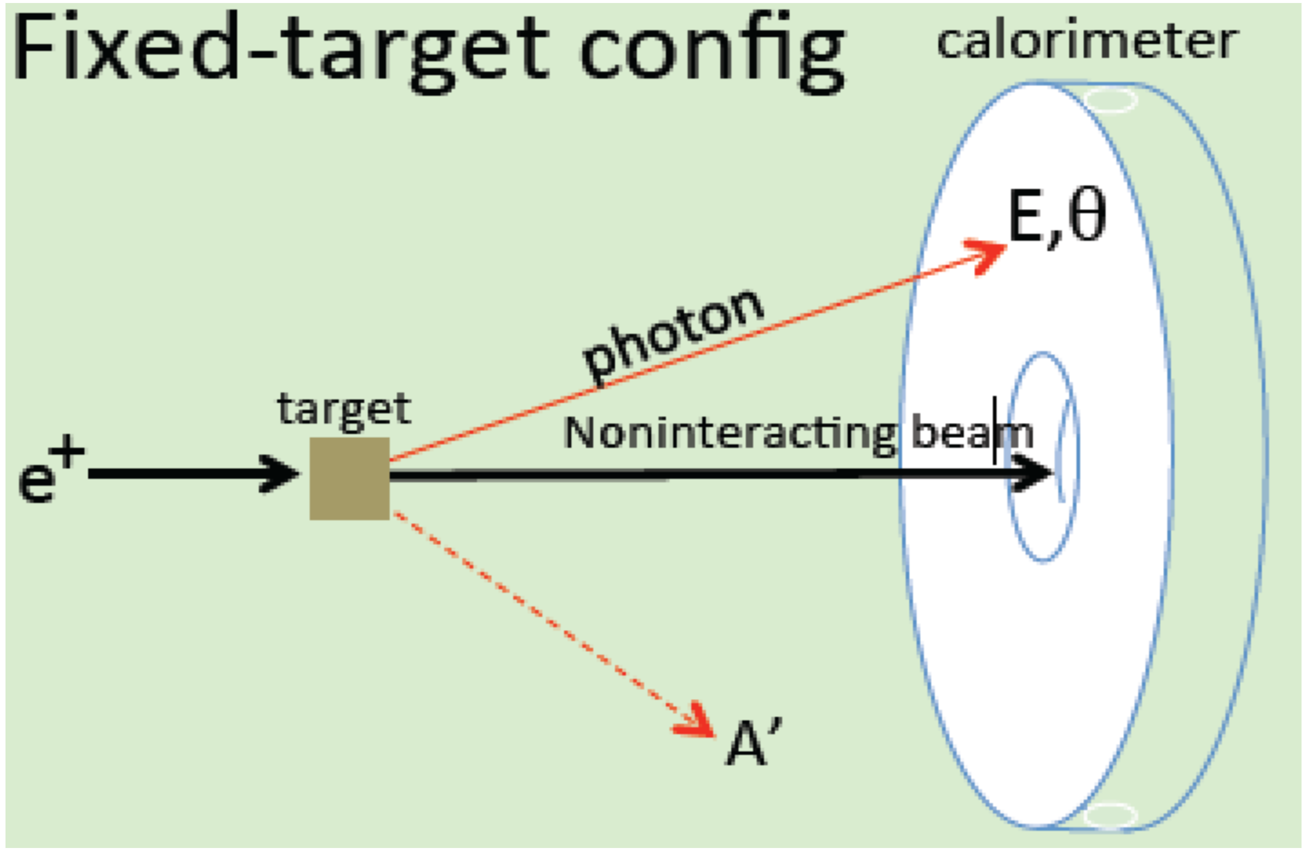
Beam Energy	Beam Current	Rep. Rate	Bunch Charge (e^-)	Spot Size
550 MeV	250 fA	50 Hz	3E4 in 250 nS	~mm

Considerations:

- higher energies are beneficial
- low charge/time is critical to avoid pileup

Pushing concept further requires high-rate, low-current beam, fast detectors, higher energy

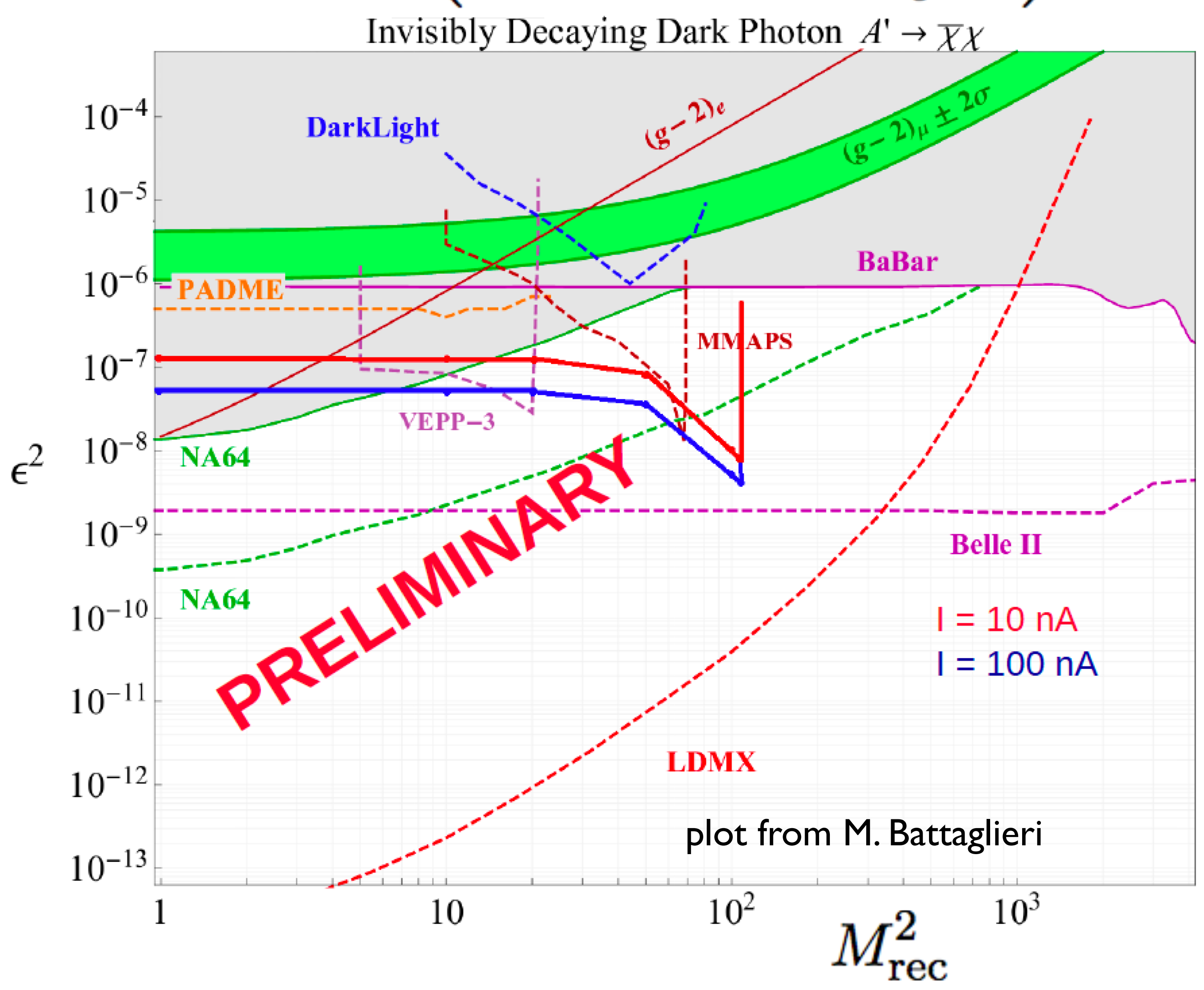




$$M_{\rm rec}^2 = 2m_e\left(E_+ - E_\gamma\left(1+\frac{E_+}{2m_e}\theta_\gamma^2\right)\right)$$

Reconstruction of mass without measurement of decay products.

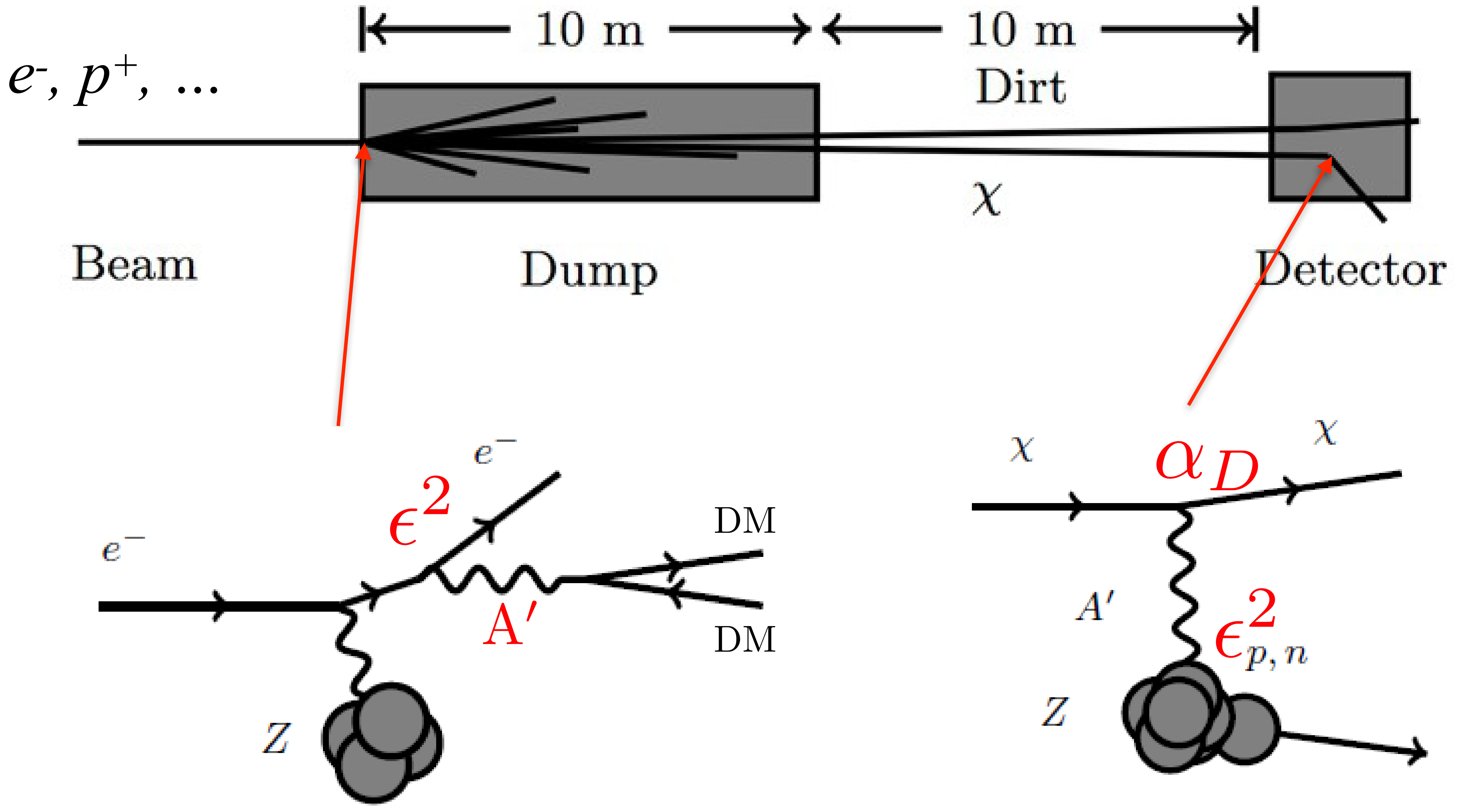
Sensitive to both visible and invisible decays of on-shell mediators.

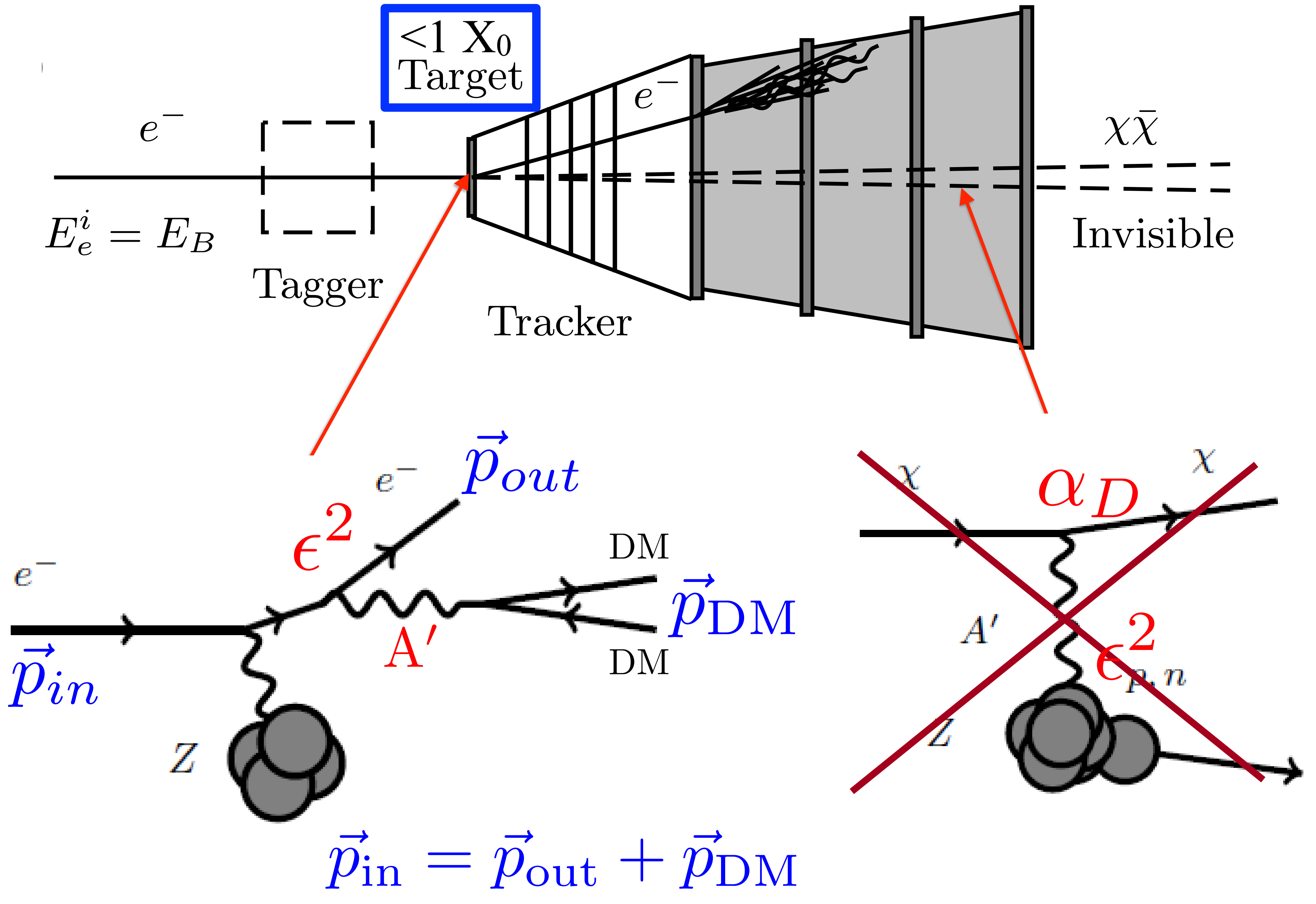


DM at Accelerators

Beam Dumps: Produce and detect DM

Missing Momentum: Detect the production of DM





$$N \propto \epsilon^4$$

$$N \propto \epsilon^2$$

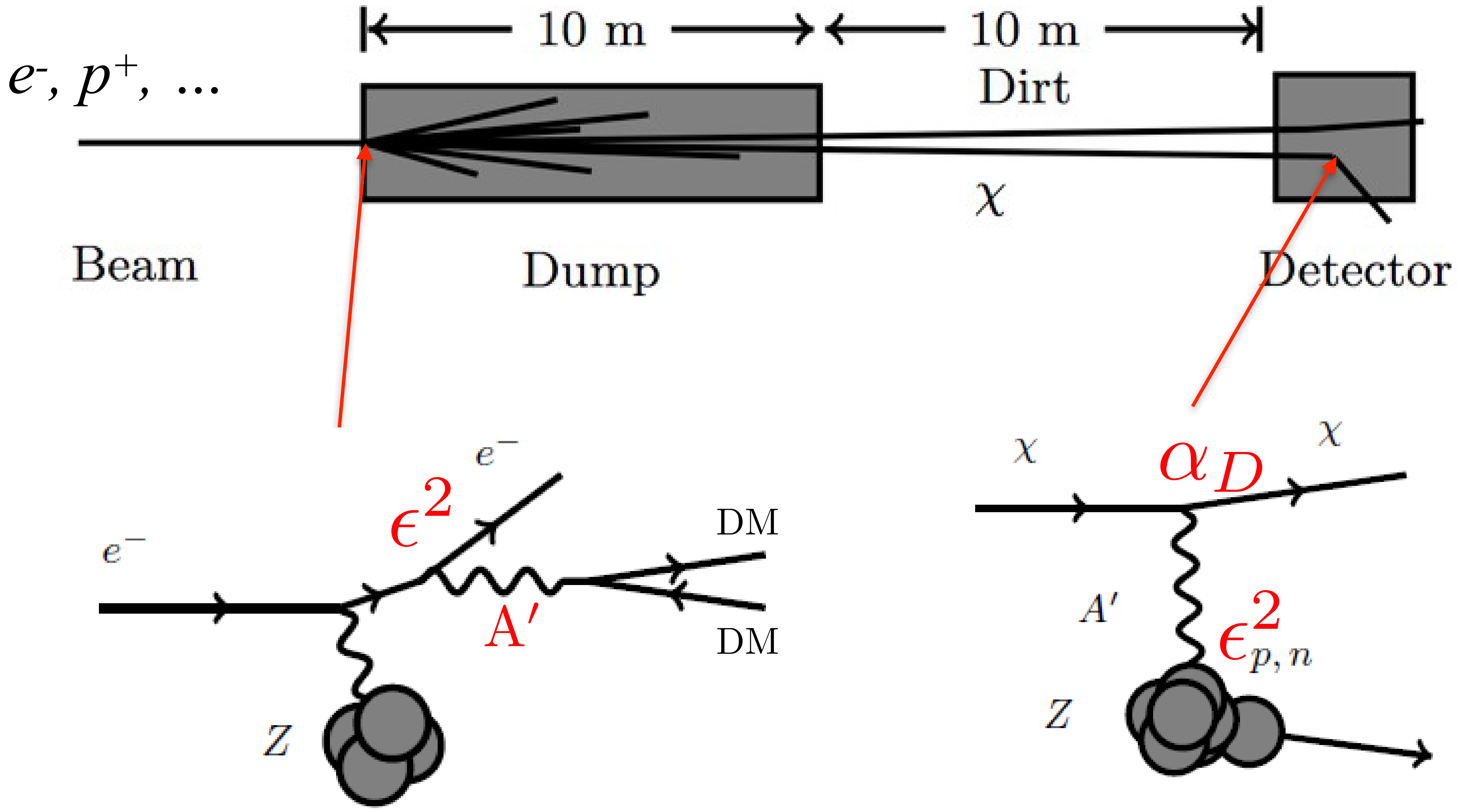
Interesting sensitivity for ~10^{22} particles on target

Interesting sensitivity for ~10^{12} particles on target

DM at Accelerators

LDMX

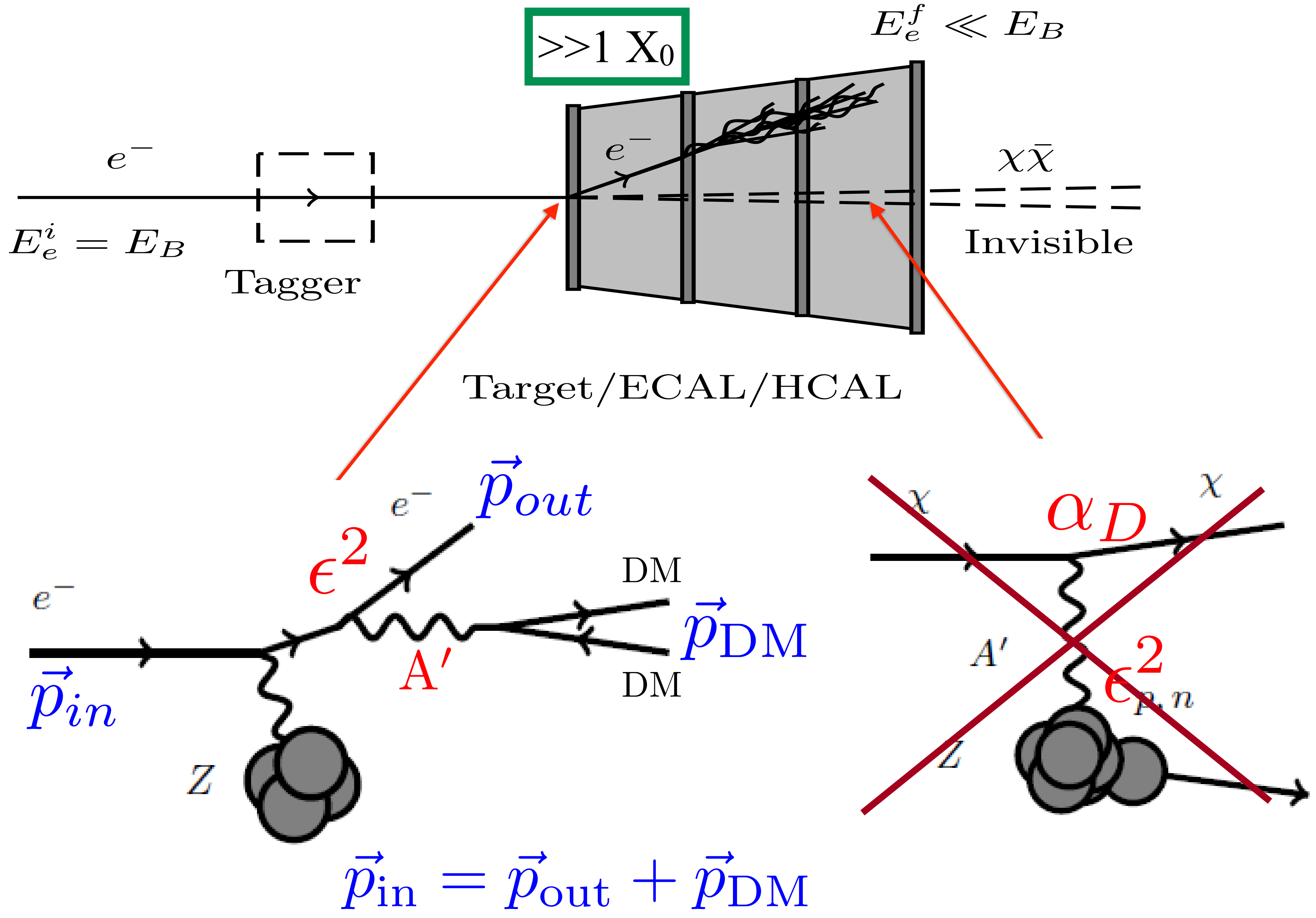
Beam Dumps: Produce and detect DM



$$N \propto \epsilon^4$$

Interesting sensitivity for ~10²² particles on target

Missing Energy: Detect the production of DM

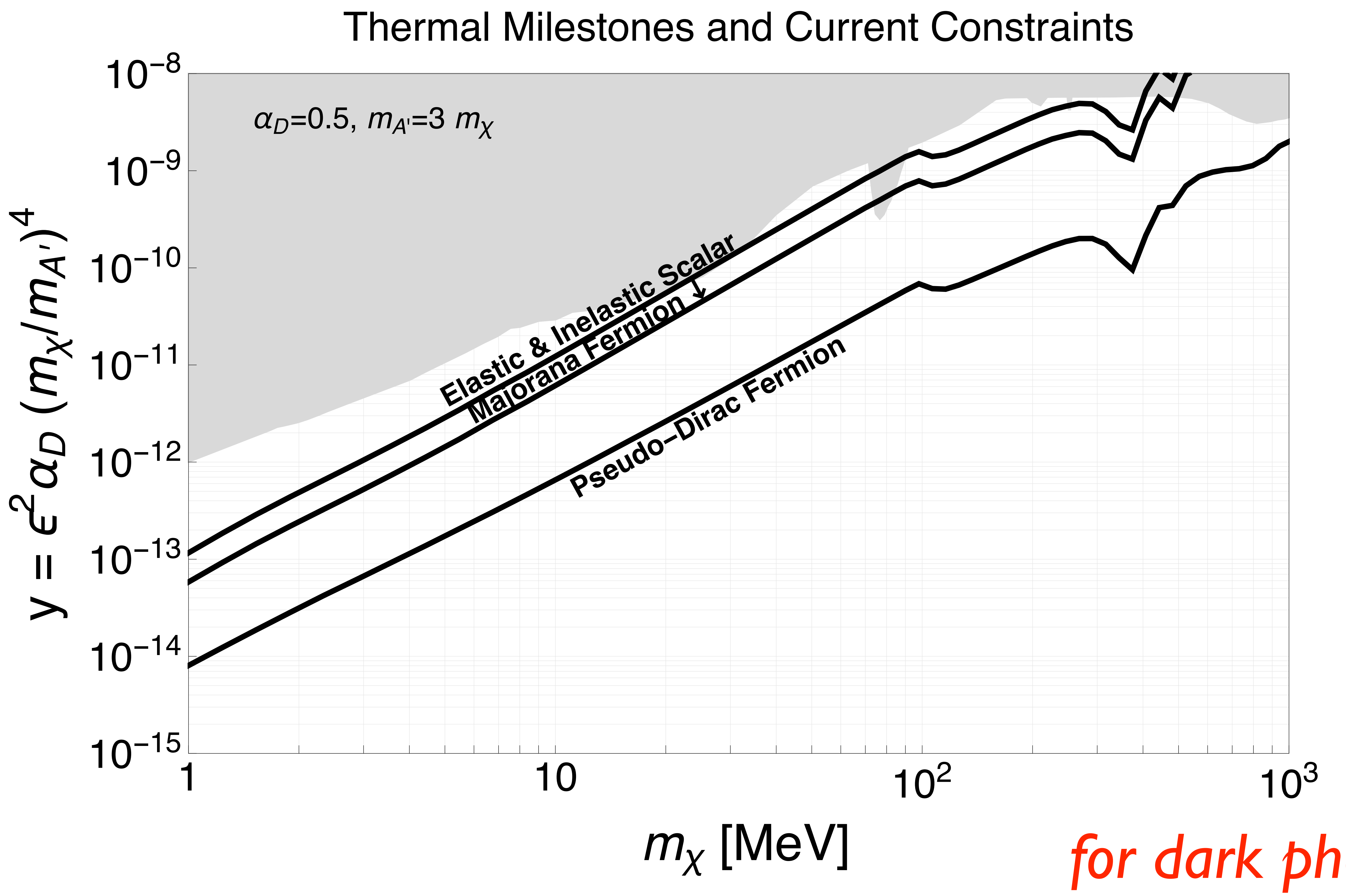


$$N \propto \epsilon^2$$

Interesting sensitivity for ~10¹¹ particles on target
(but backgrounds beyond ~10¹⁴ particles on target)

Sensitivity: Missing Energy/Momentum, Beam Dumps, and Direct Detection

Missing momentum experiments, using modern detectors operating directly in a low-current lepton beam, identify dark matter production events based on the kinematics of visible particles recoiling from the production event. Such experiments in a continuous-wave electron beam offer a path to reach 1000-fold improvement in sensitivity over a broad mass range …



for dark photon mediator

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LDMX

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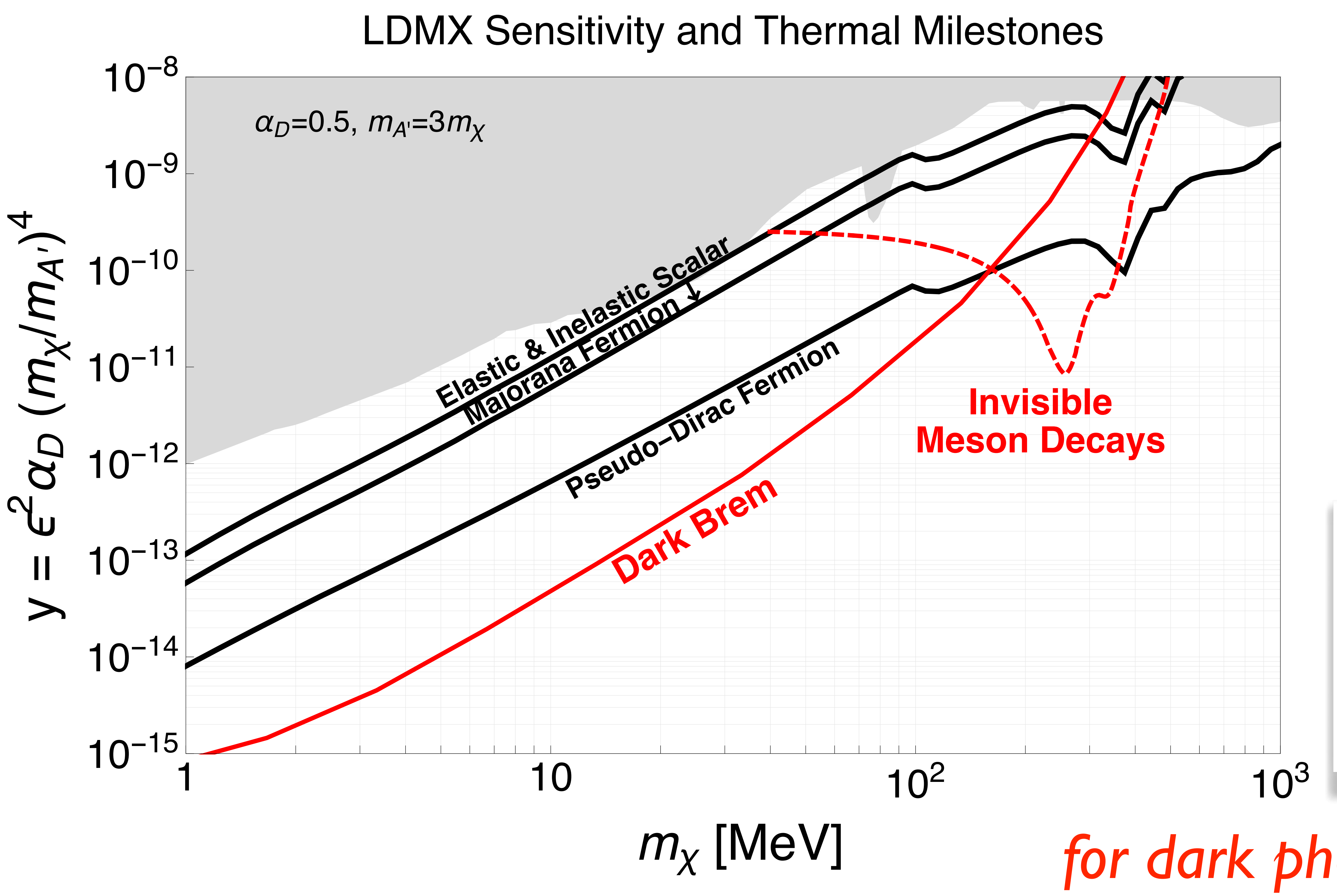
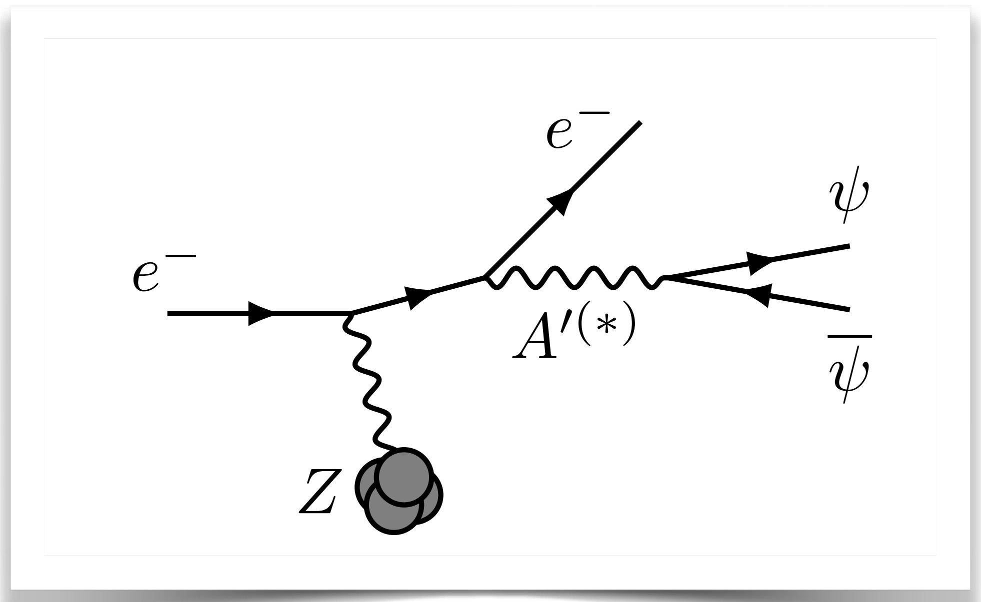
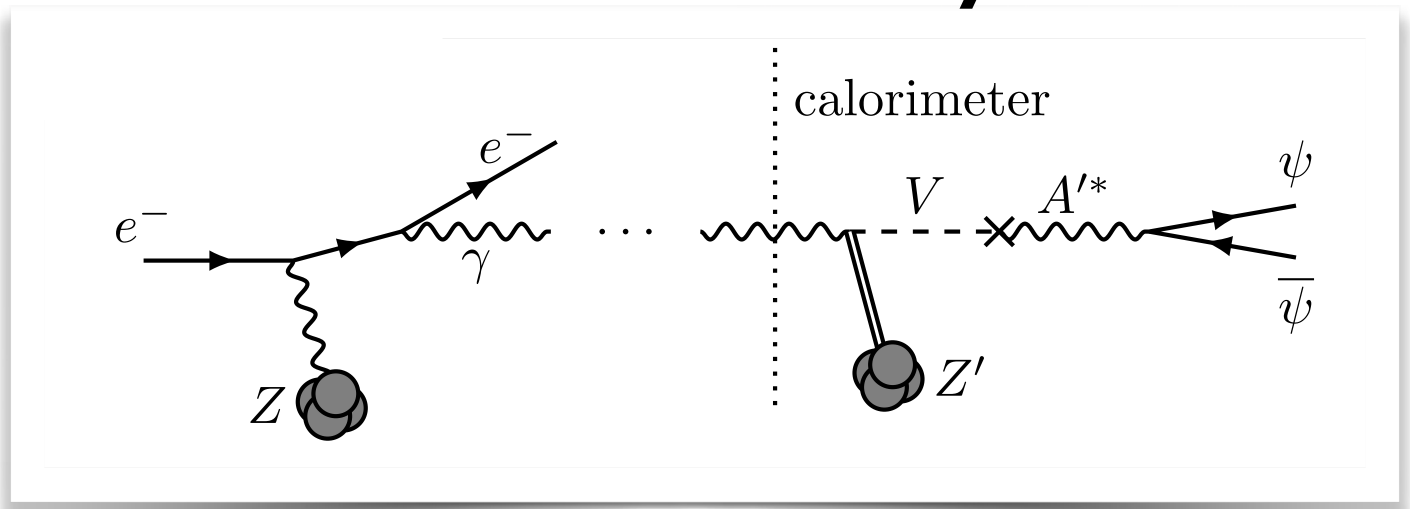


dark brem



meson decays



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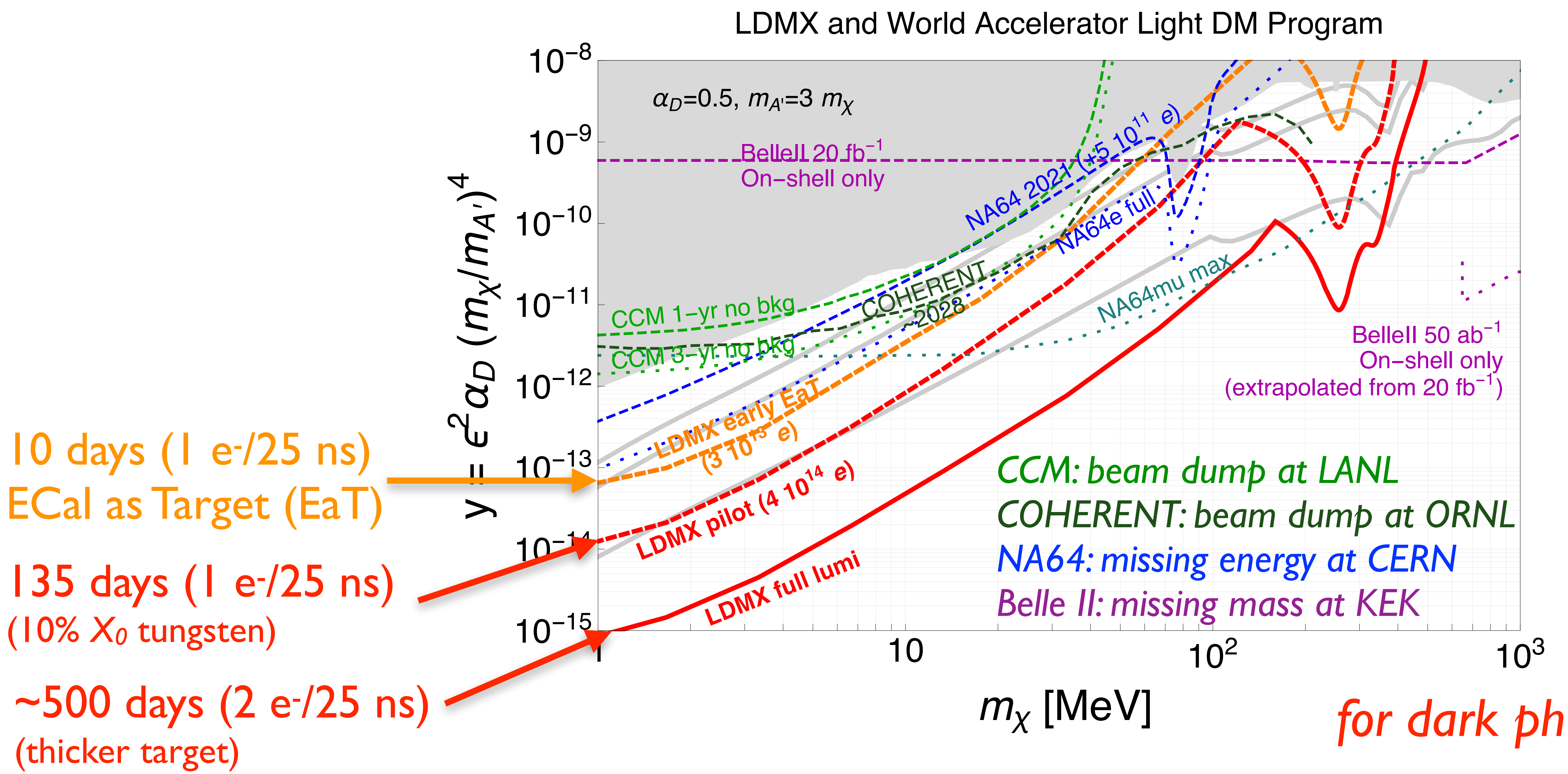

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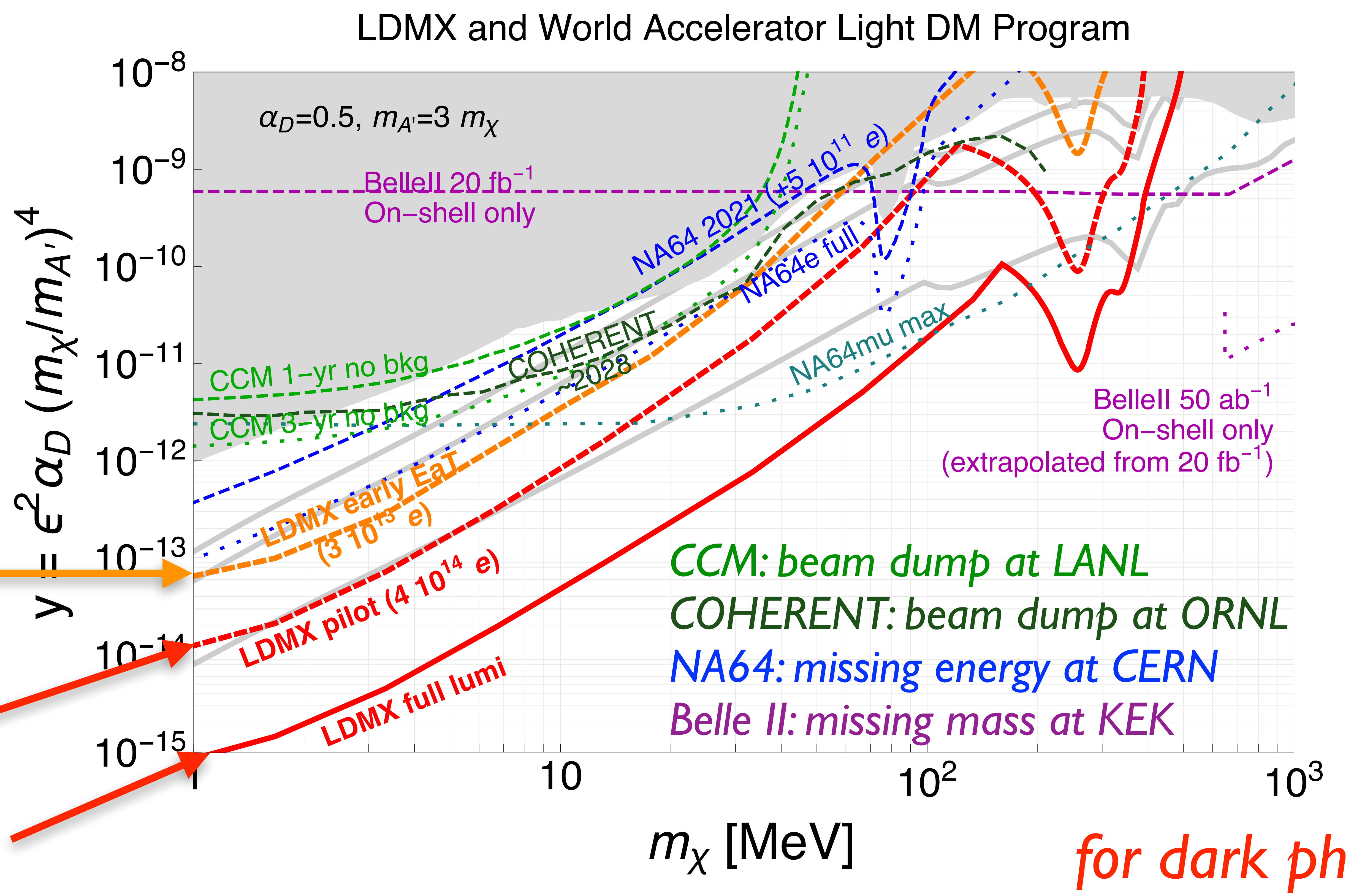
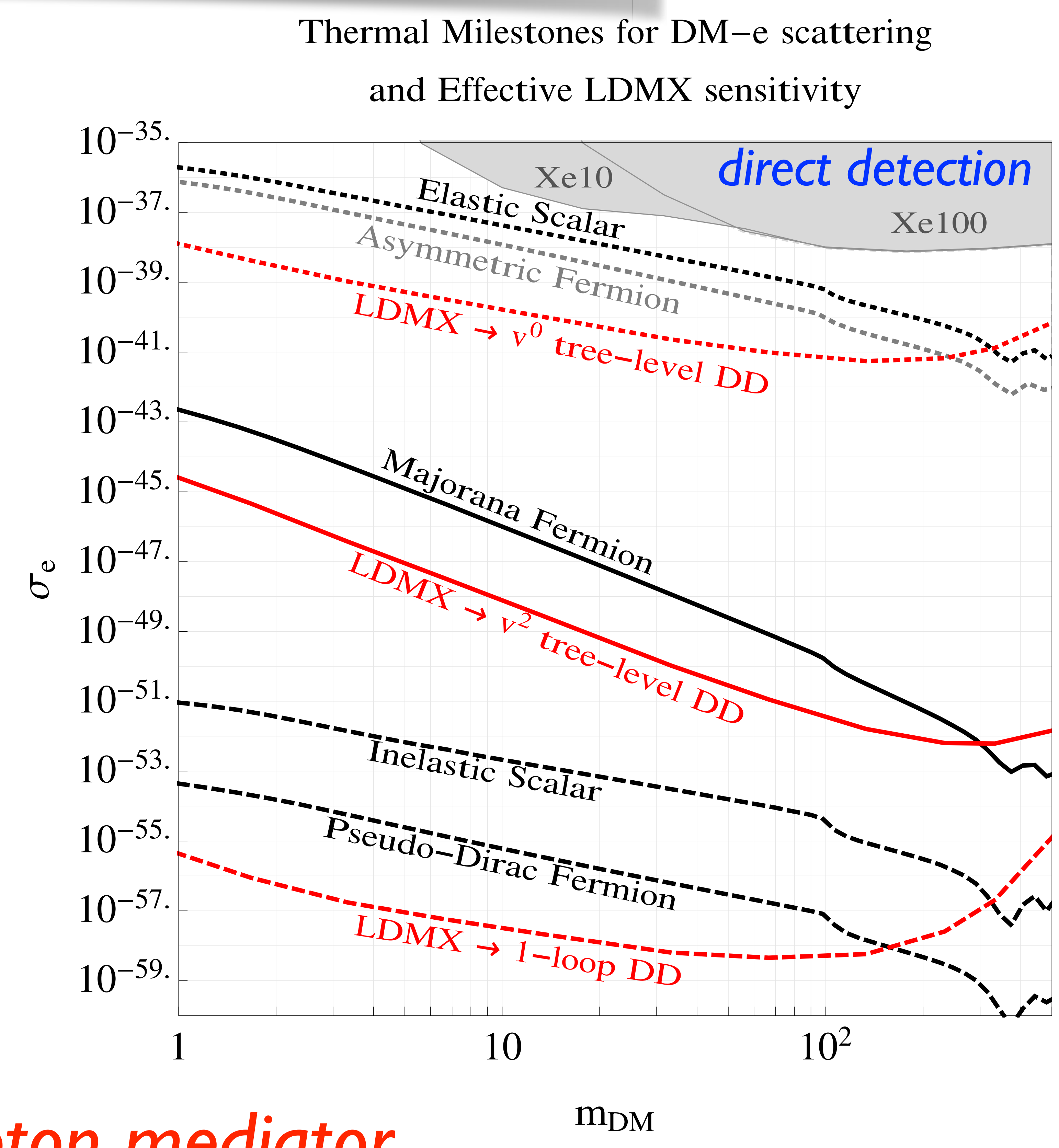


10 days (1 e-/25 ns)
ECal as Target (EaT)

135 days (1 e-/25 ns)
(10% X_0 tungsten)

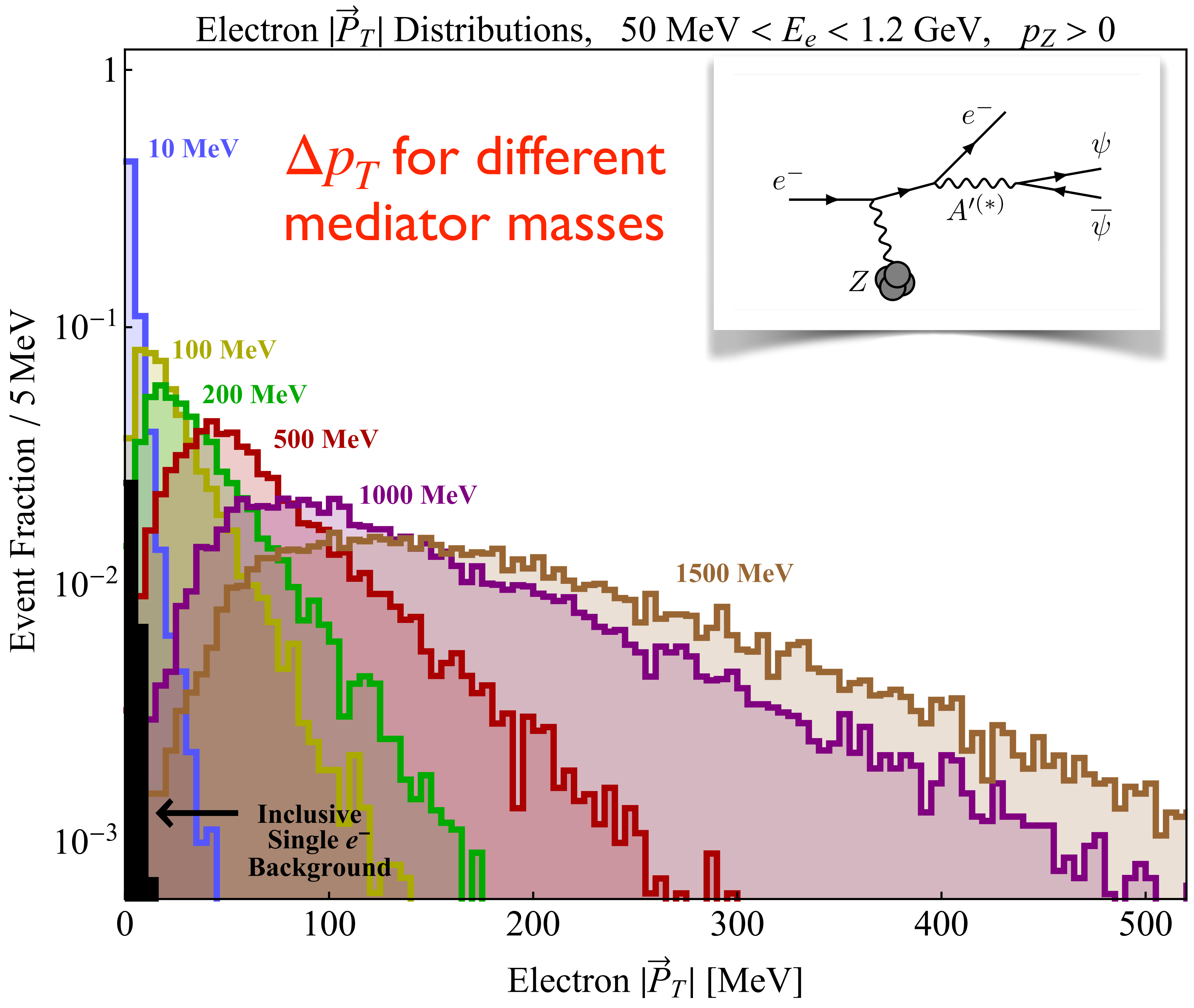
~500 days (2 e-/25 ns)
(thicker target)

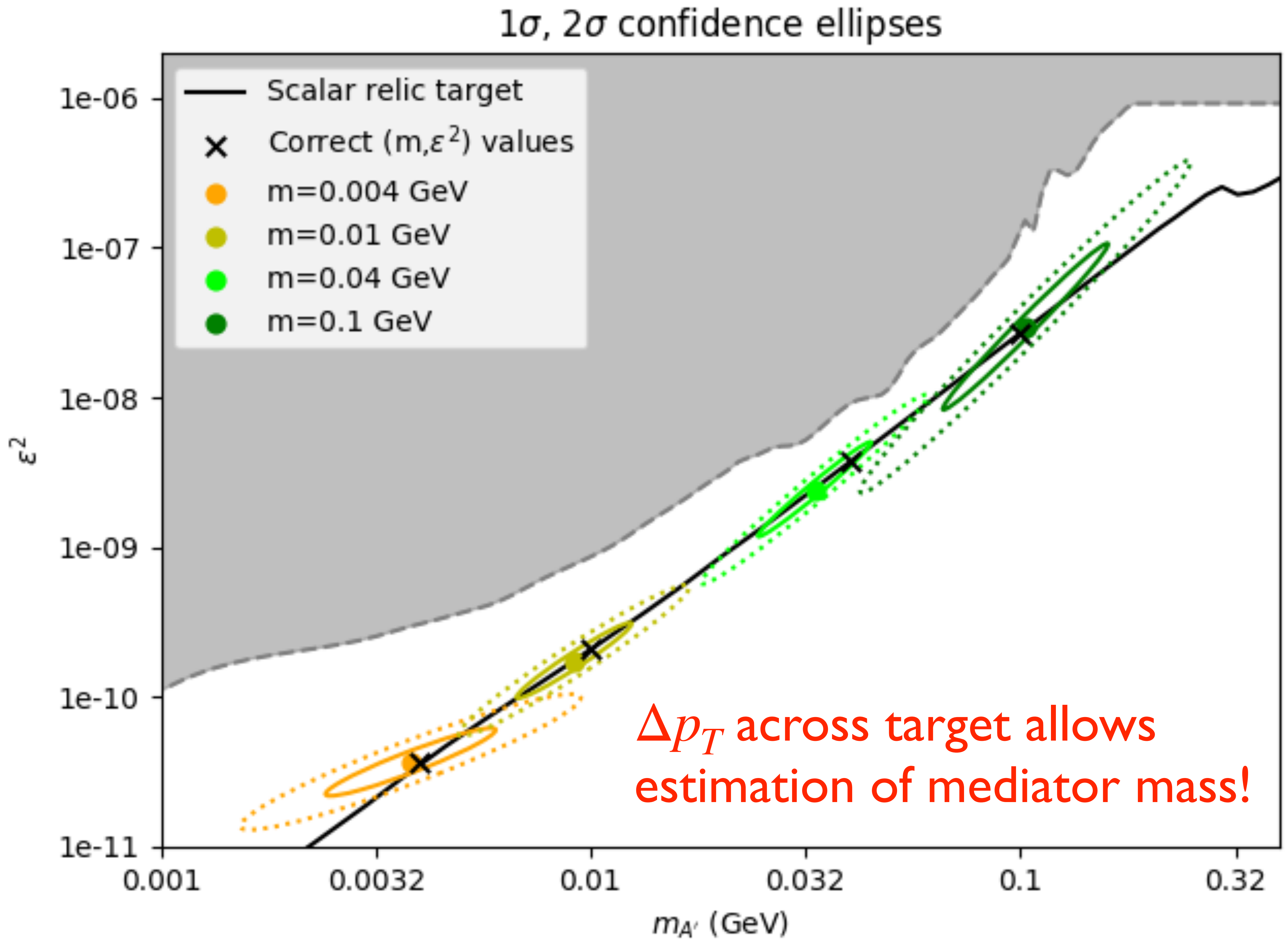


for dark photon mediator

Sensitivity: Missing Energy/Momentum, Beam Dumps, and Direct Detection

LDMX measures the kinematics of dark matter production, enabling detailed study of the dark sector!





for dark photon mediator

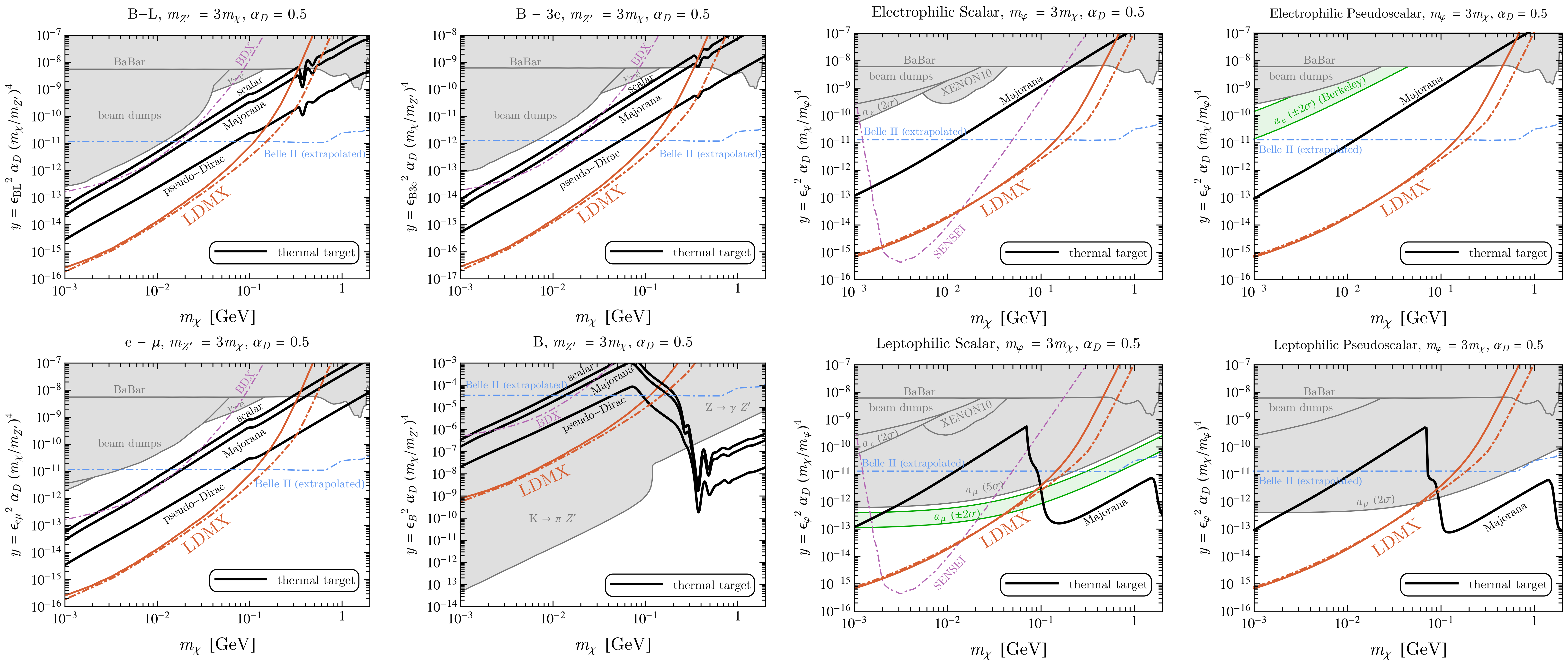
LDMX: The Broader Physics Case (other examples in backup)

Invisible Signatures

- other mediators →
- QCD axions
- millicharged 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 (DMNI PRD 1,Thrust 2)

- Dark Photons
- Axion-like particles (ALPs)



arXiv:1807.01730 [hep-ph]

LDMX: The Broader Physics Case (other examples in backup)

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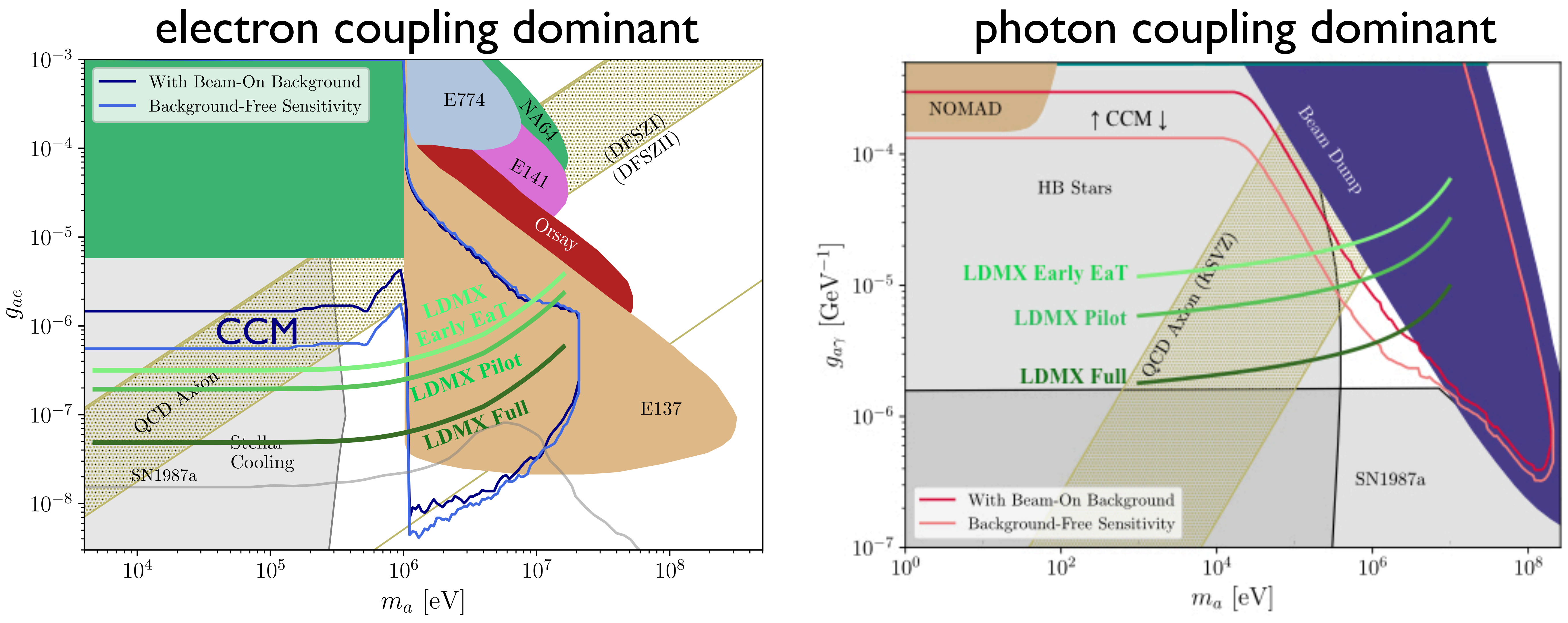

adapted from https://arxiv.org/abs/2112.09979

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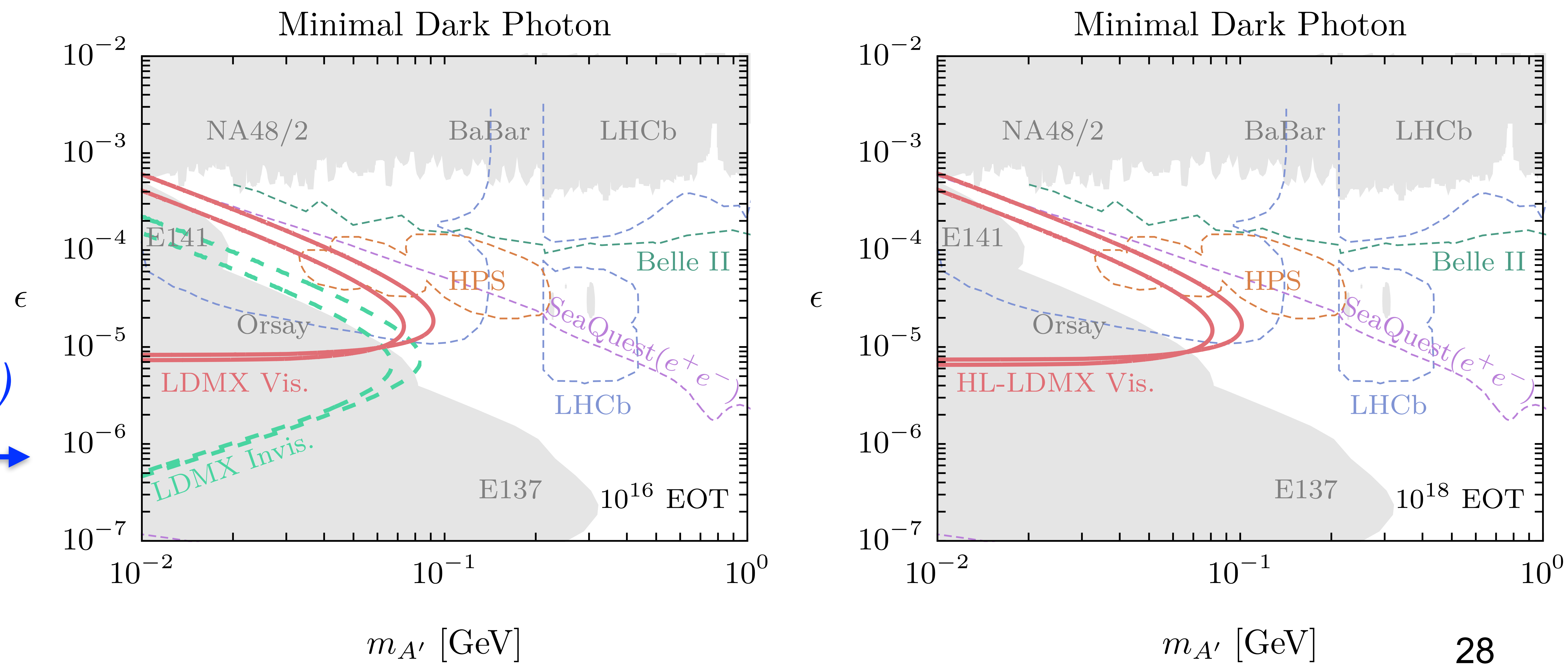

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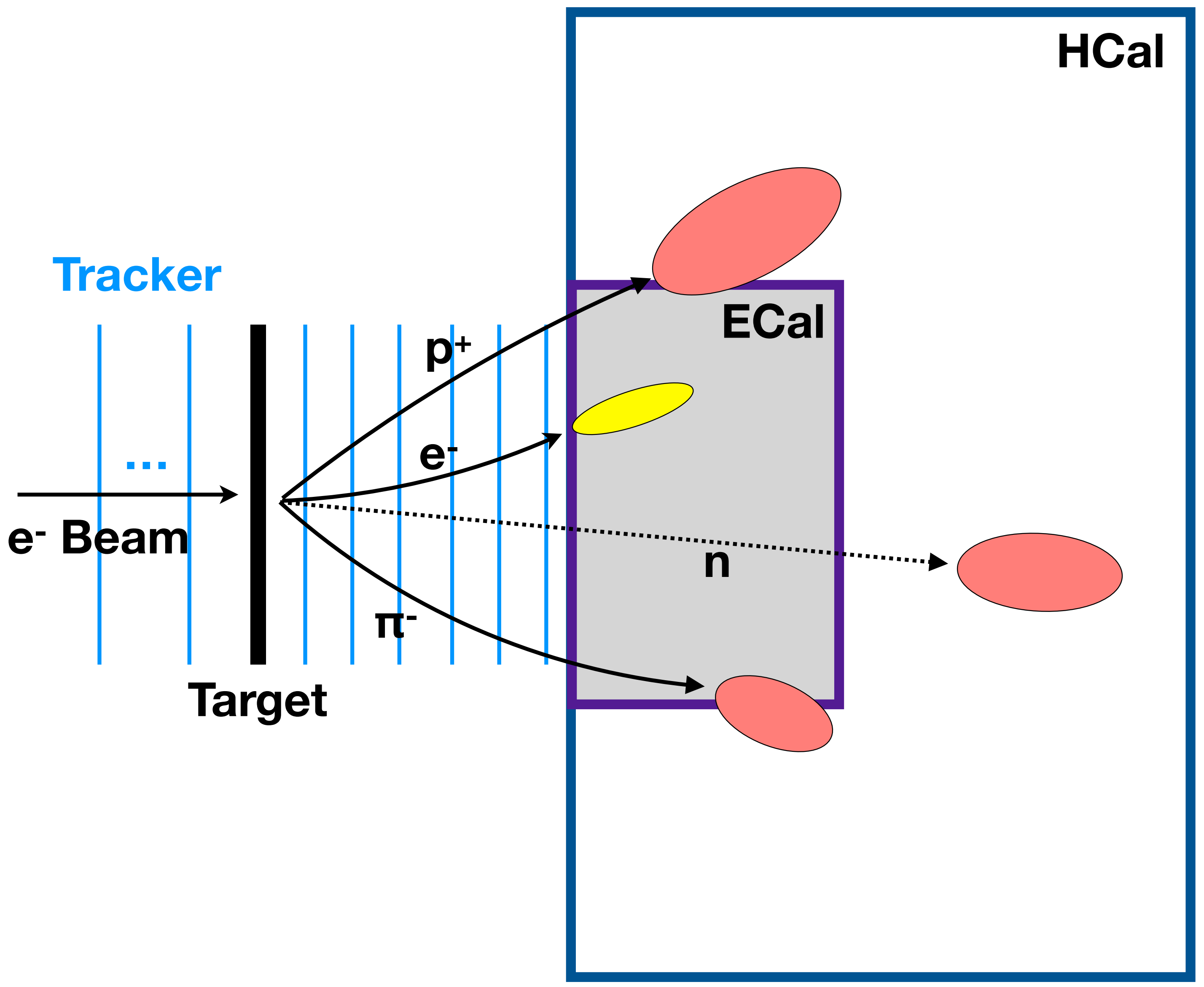
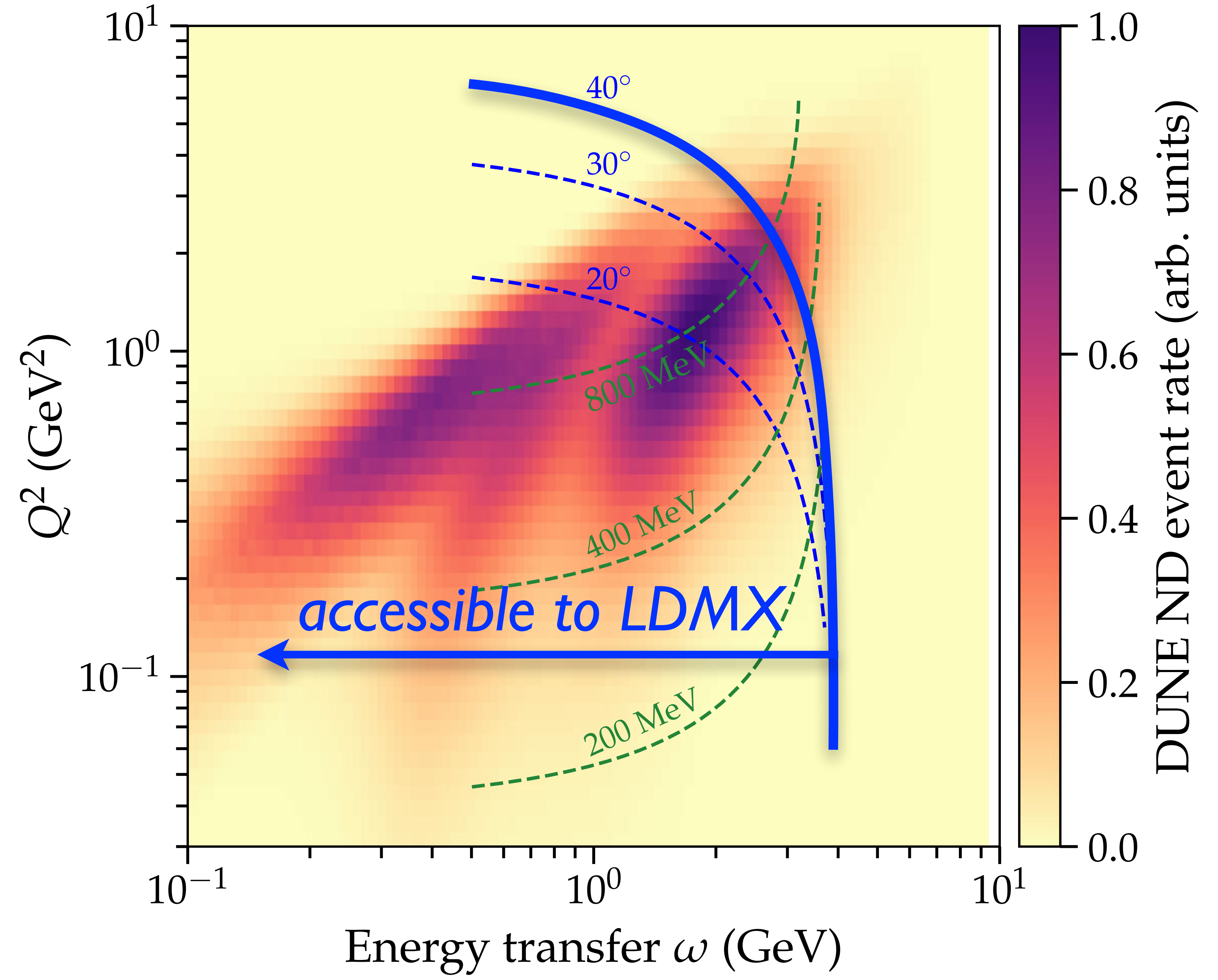
Visible Signatures (DMNI PRD 1,Thrust 2)

- Dark Photons
- Axion-like particles (ALPs)

arXiv:1807.01730 [hep-ph]

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





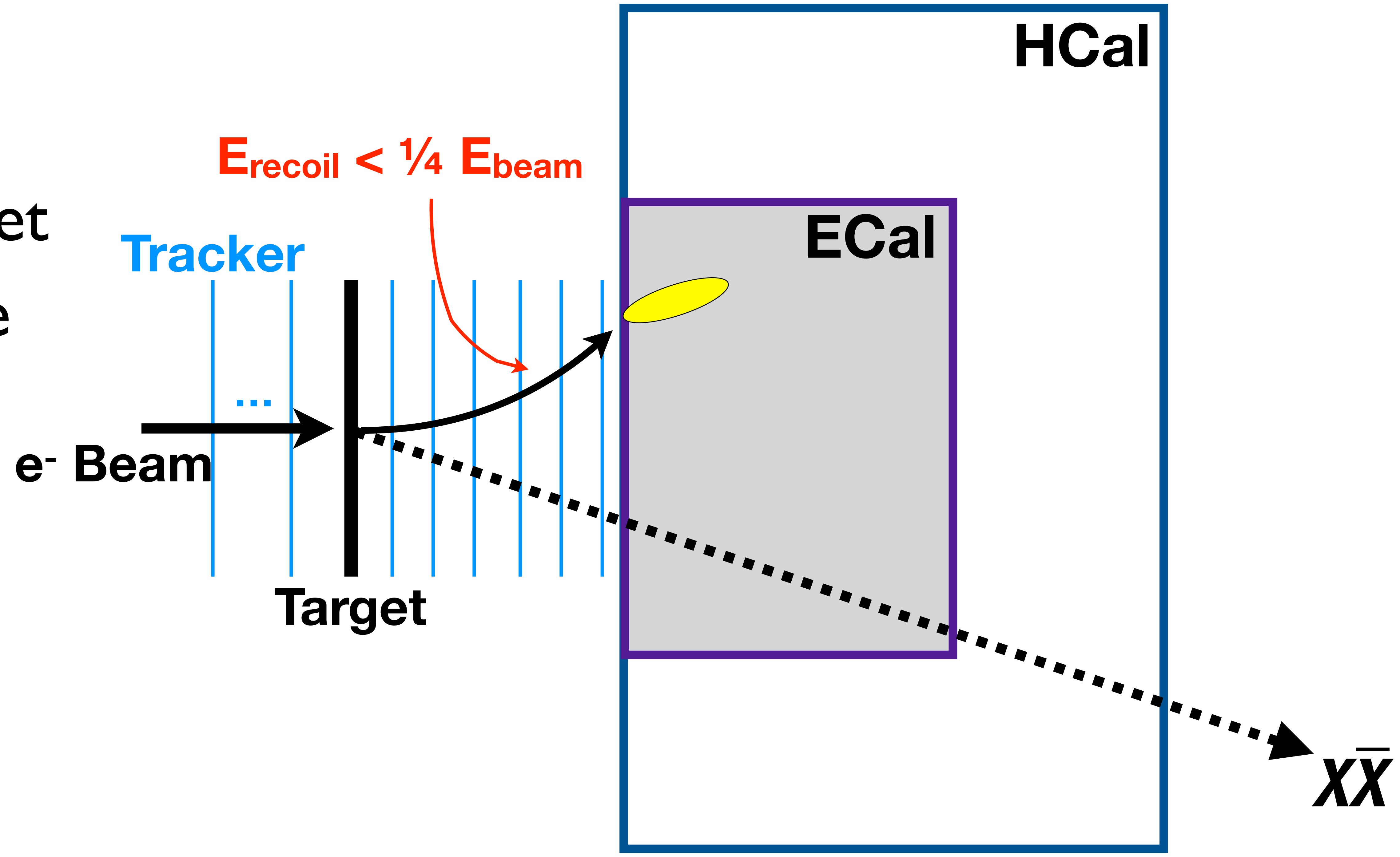
PHYSICAL REVIEW D 101, 053004 (2020)

Missing Momentum: Operational Design Drivers

Signature:

1. substantial energy loss by incoming beam electron
2. substantial transverse momentum change across target
3. no other particles with significant energy in final state

Goal: low background from ~10^{16} e^-



Accelerator Requirements:

- Low-intensity multi-GeV beam (10^{16} e^- = *50 pA-years*)
- Spread out beam in space/time (large beamspot ~ 20 cm^2, high repetition-rate ~ 40 MHz)

➡ allows individual events to be distinguished at higher rate (a few electrons/pulse) in detectors with fine granularity and resolution in both space and time

➡ spreads out peak radiation doses so radiation tolerance is less an issue for tracking and ECal

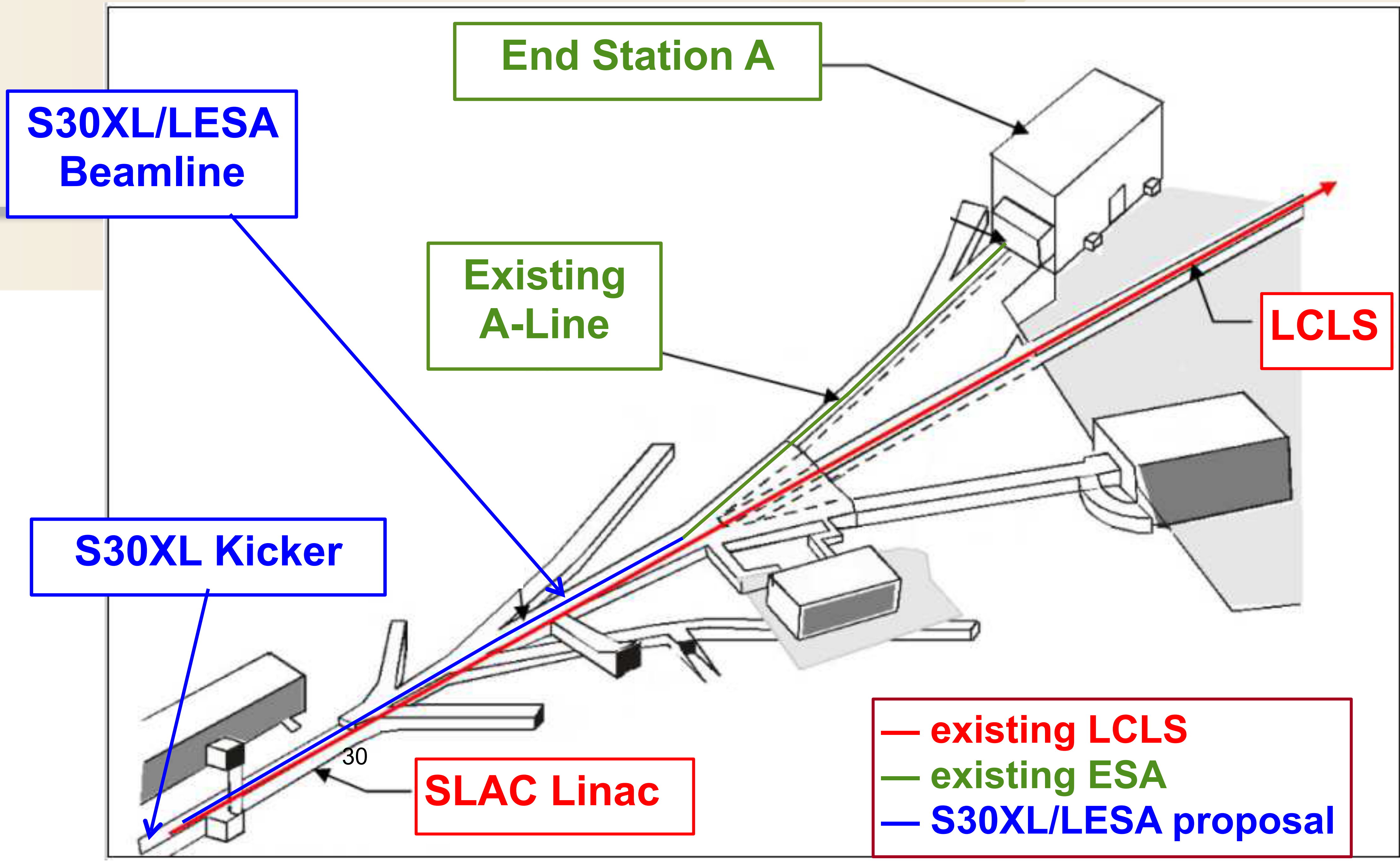
Linac to End Station A (LESA) at SLAC

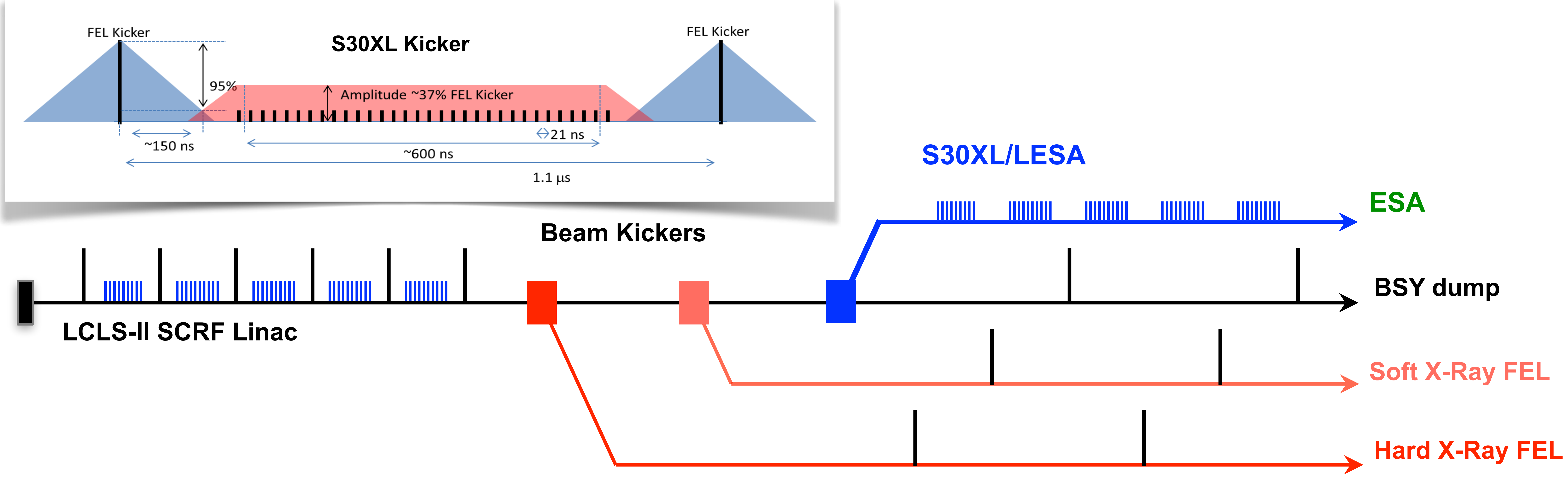
LCLS-II 4 GeV drive beam accelerates 186 MHz bunches

- ~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 primary user.
- LCLS-II-HE upgrade to 8 GeV in ~2026-2028

S30XL AIP is currently under construction alongside LCLS-II.

LESA is expected to deliver beam to End Station A in late FY23.



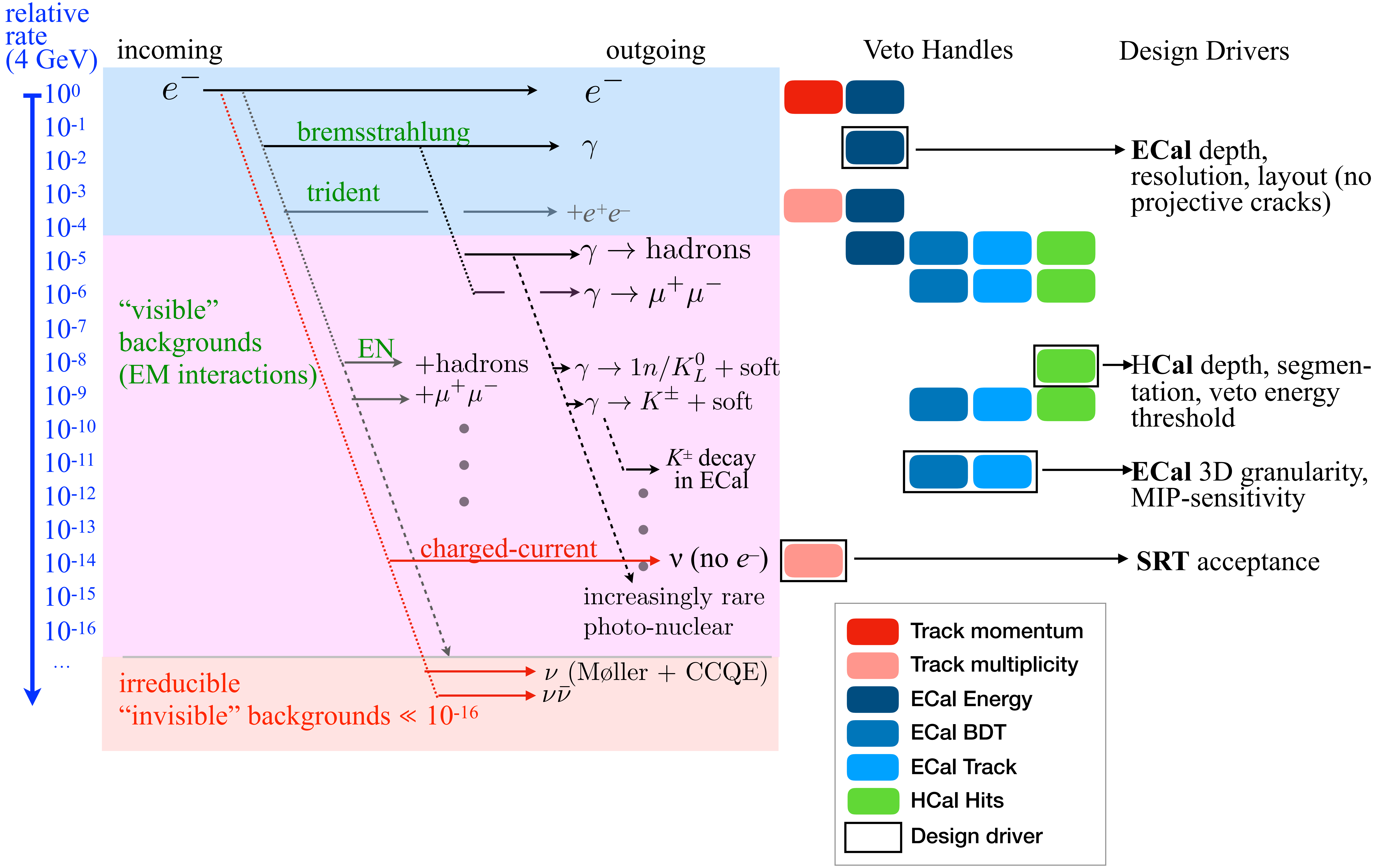


Missing Momentum: Physics Design Drivers

Gaussian energy fluctuations

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

Irreducible prompt $\not{E}$

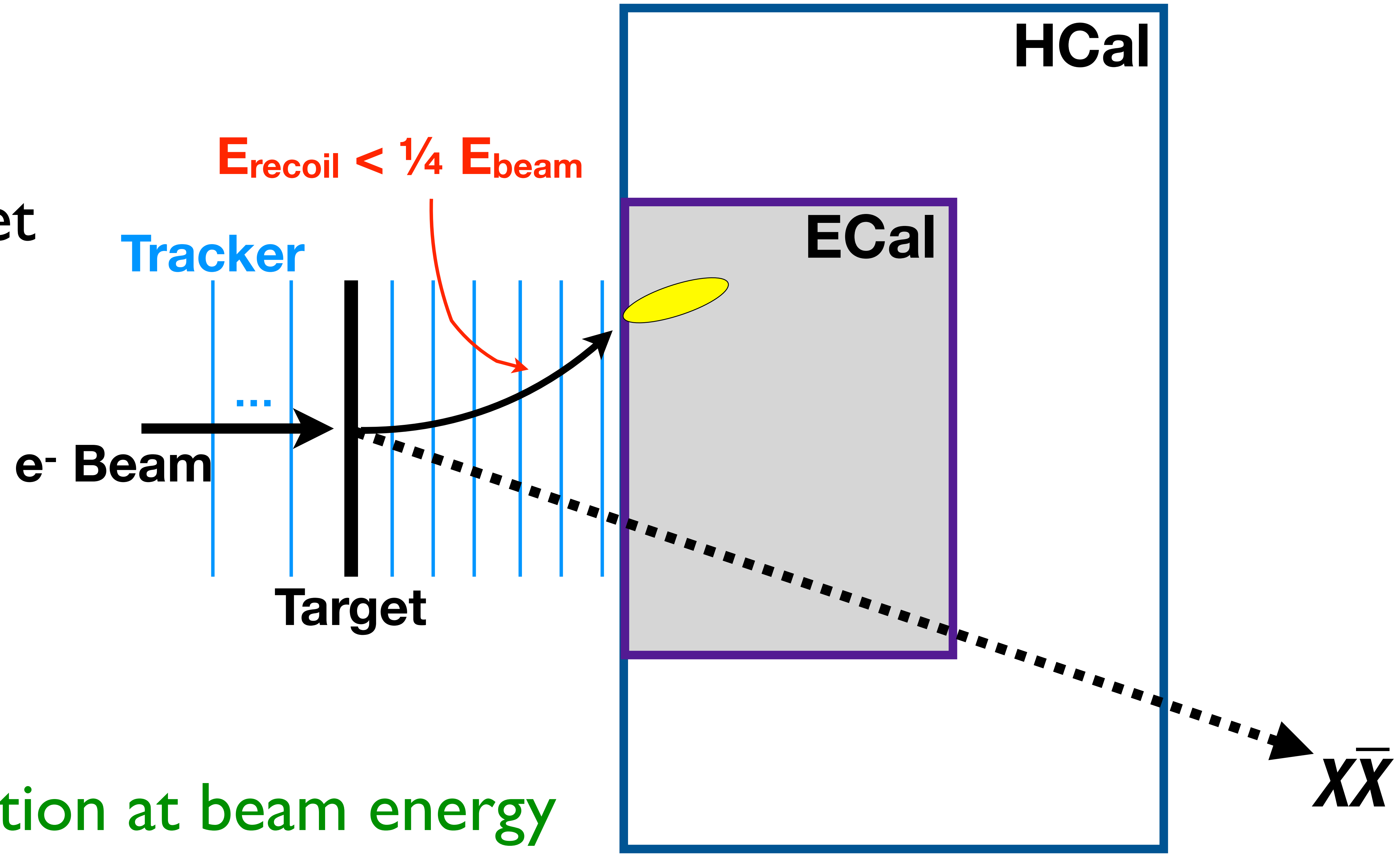


Missing Momentum: Physics Design Drivers

Signature:

1. substantial energy loss by incoming beam electron
2. substantial transverse momentum change across target
3. no other particles with significant energy in final state

Goal: low background from ~10^{16} e^-

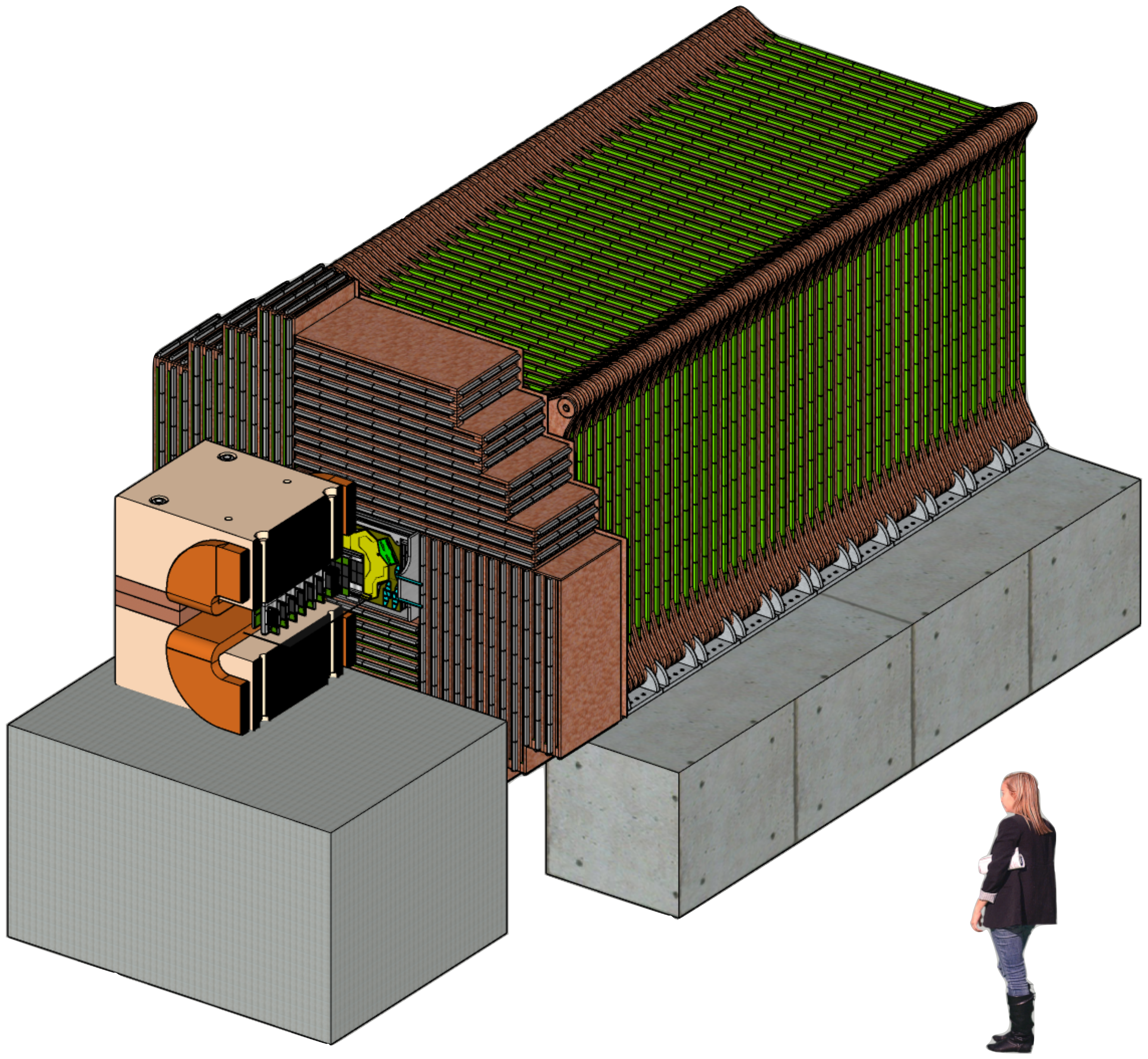


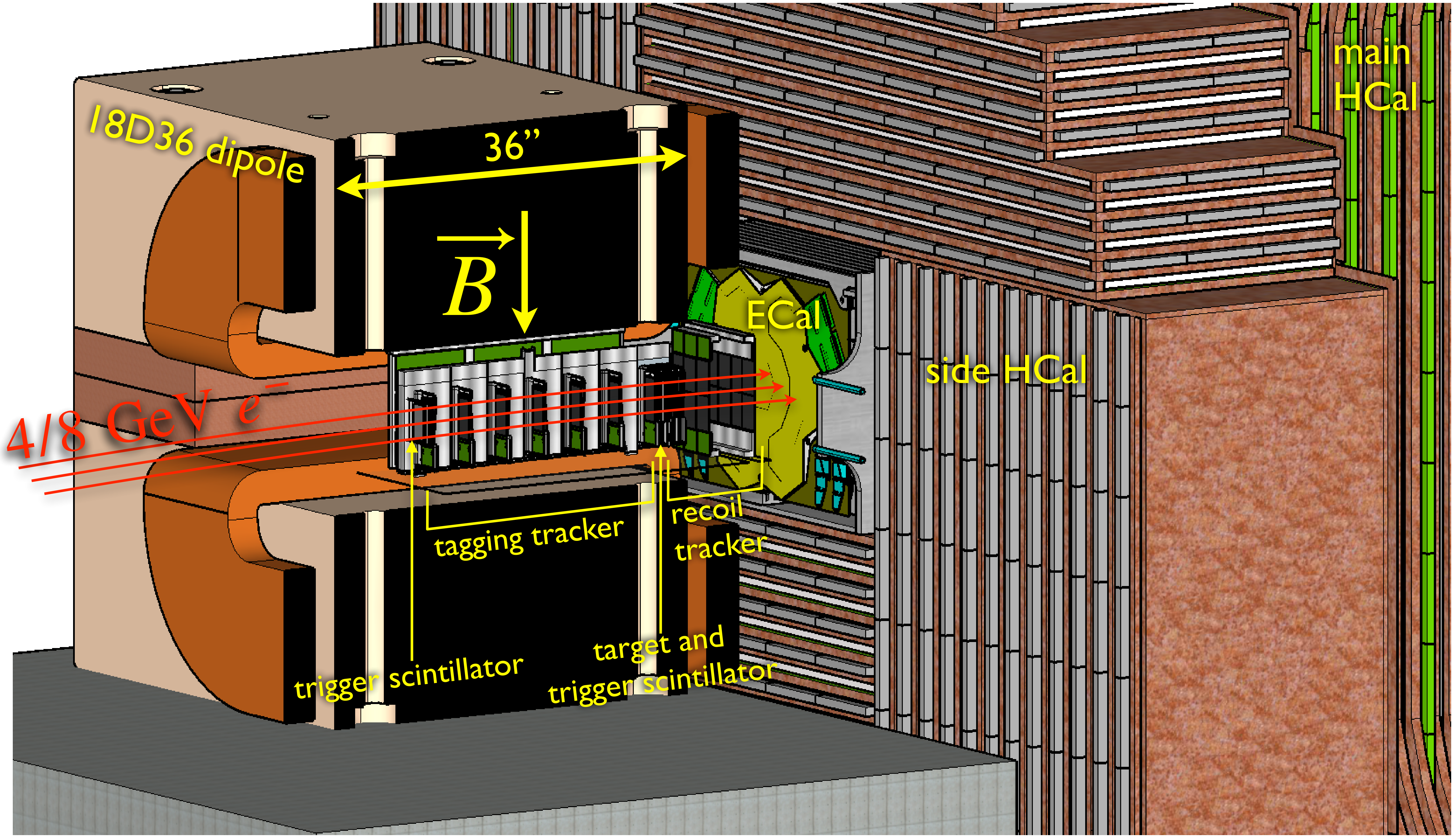
Detector Requirements:

- Tagging tracker with small acceptance and good resolution at beam energy
- Recoil tracker with large acceptance and good resolution at low momentum
- Deep ECal with good resolution and no projective cracks
- ECal with excellent granularity and sensitivity for distinguishing EM/Had showers and tracking muons
- Deep HCal with good segmentation and low veto energy threshold for neutral hadrons
- Efficient missing energy trigger and high-rate data acquisition

LDMX Detector Overview

LDMX Whitepaper arXiv:1808.05219

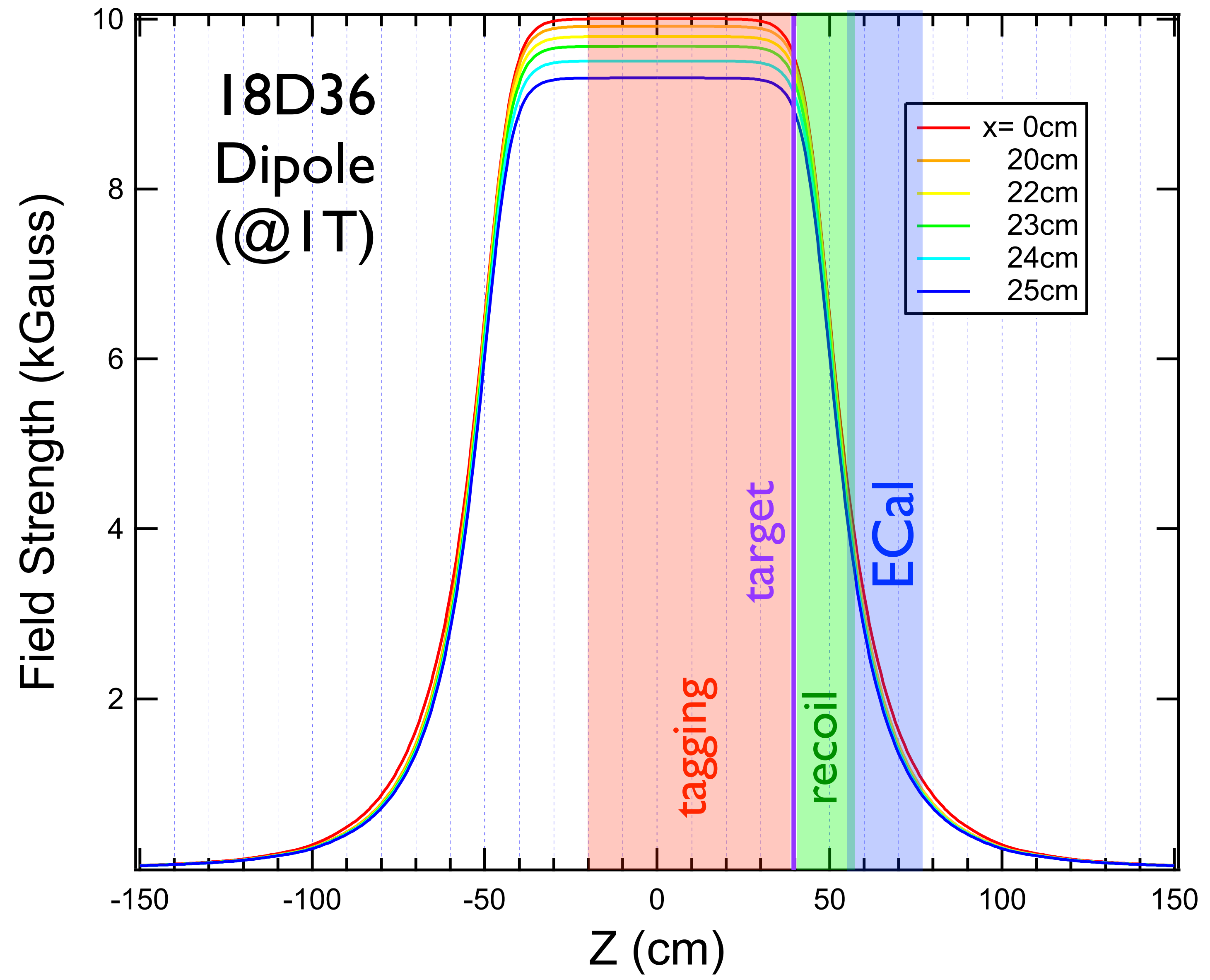




LDMX Subsystems and Technology Choices

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^-



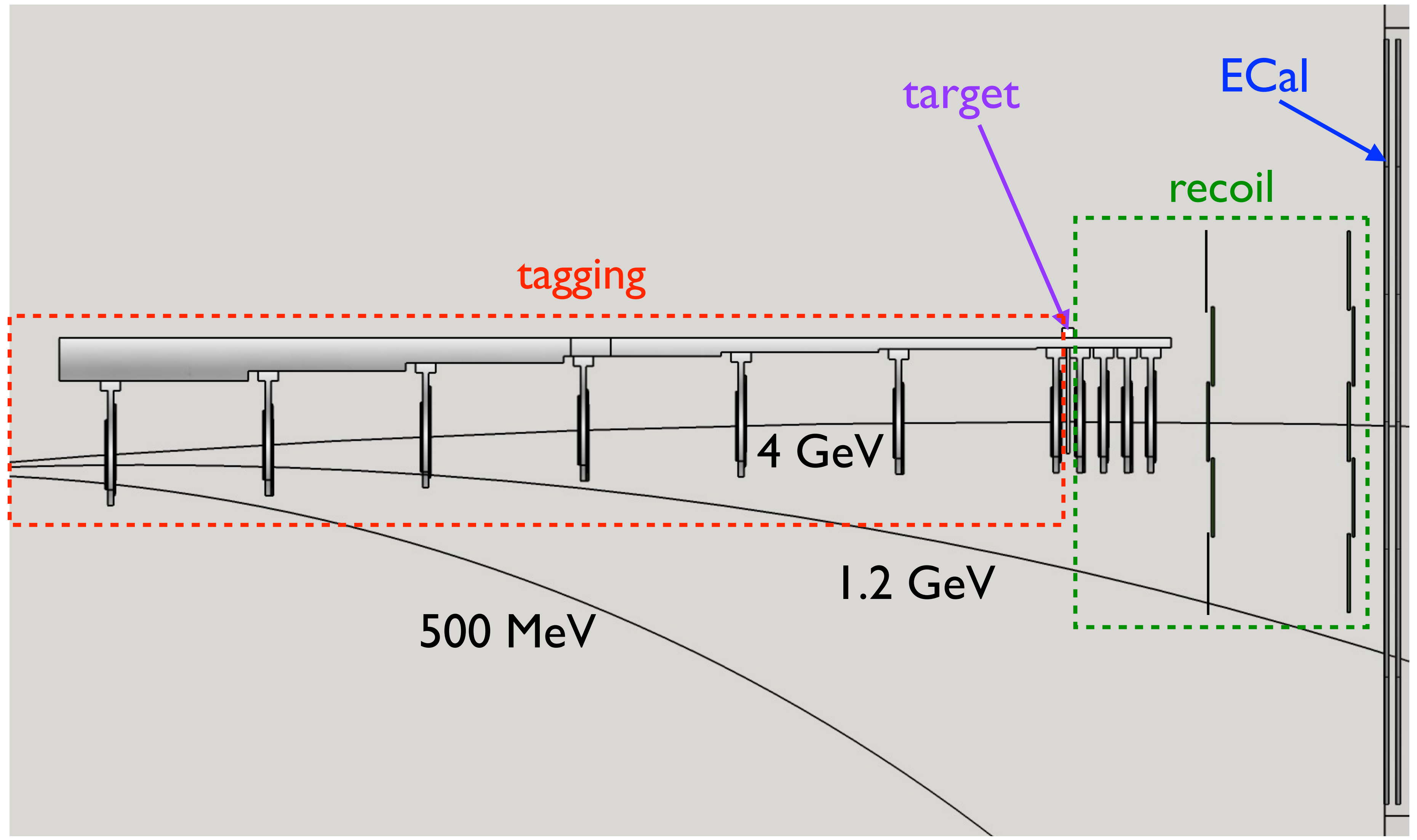
WBS 1.3 – Trackers: (from HPS Silicon Vertex Tracker built at SLAC)

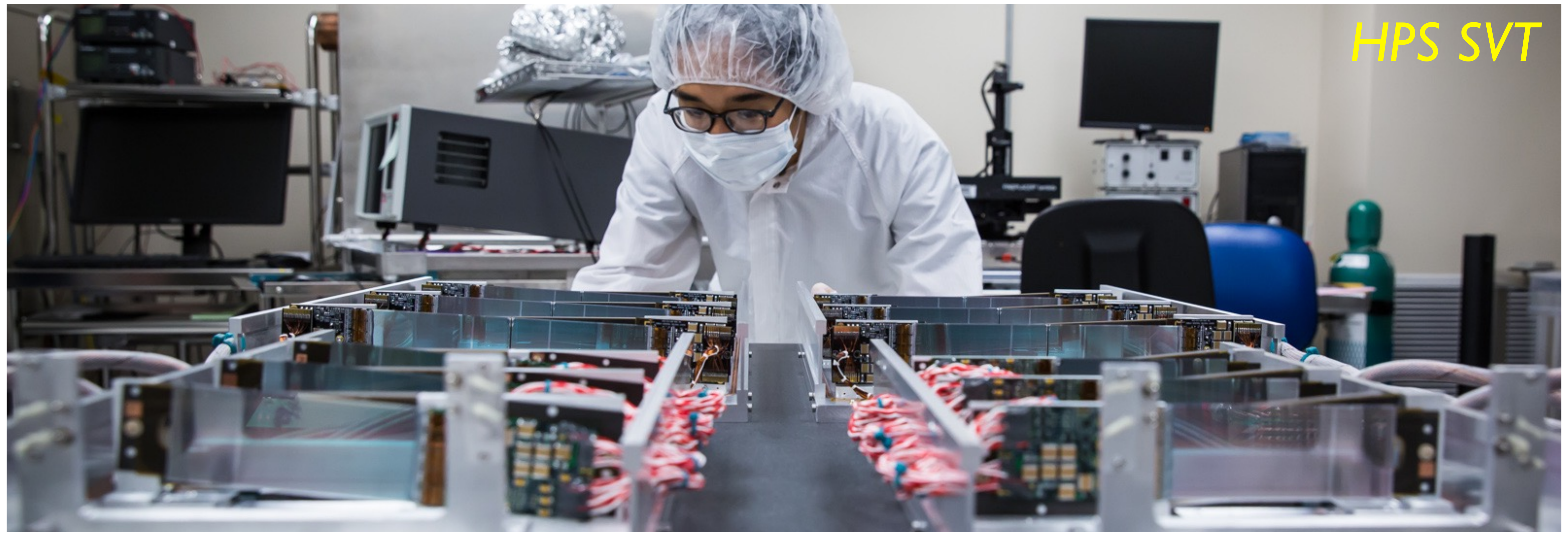
Tagging Tracker: long, narrow, in uniform 1.5 T field for p_e = 4 GeV

- 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

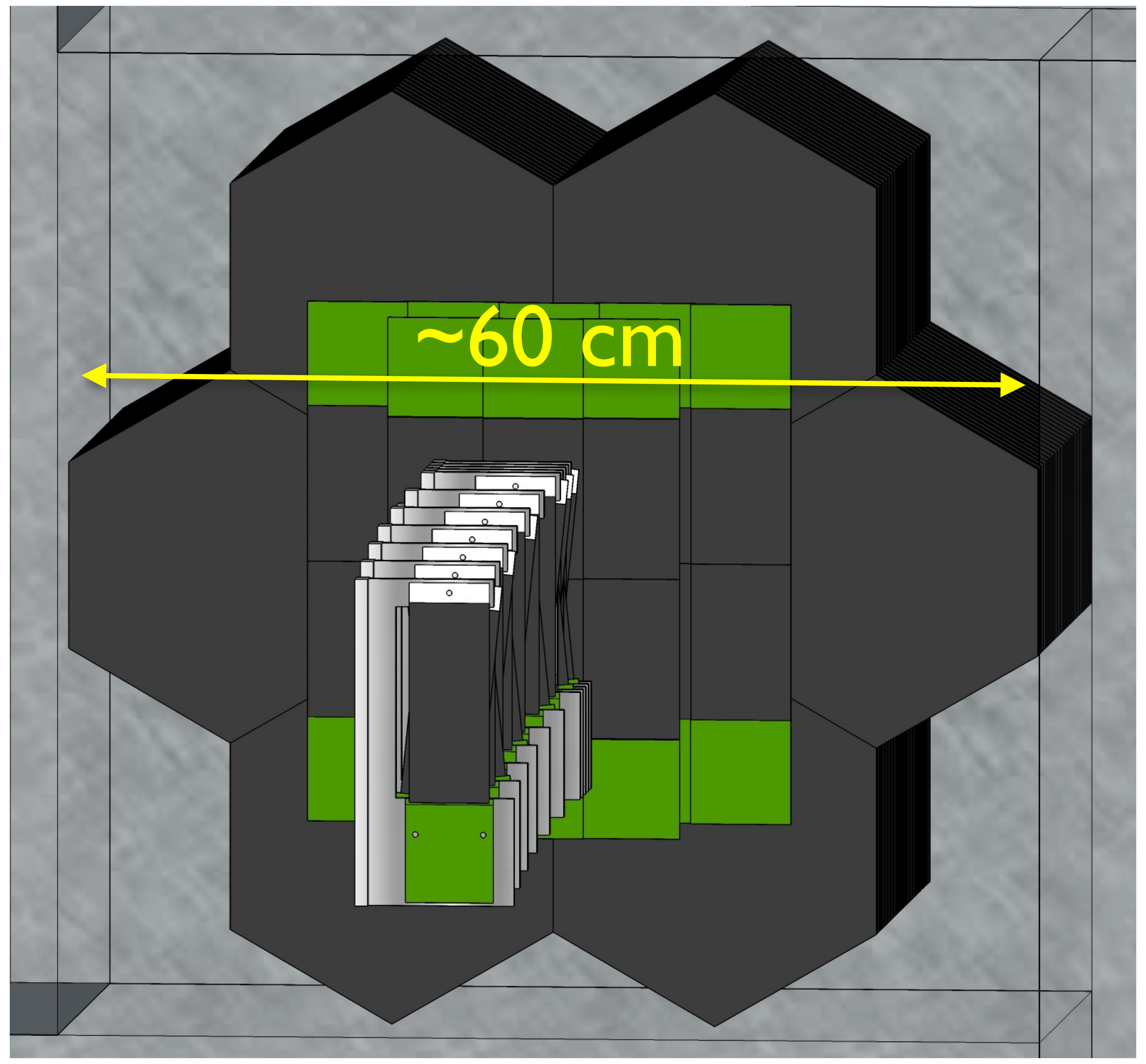


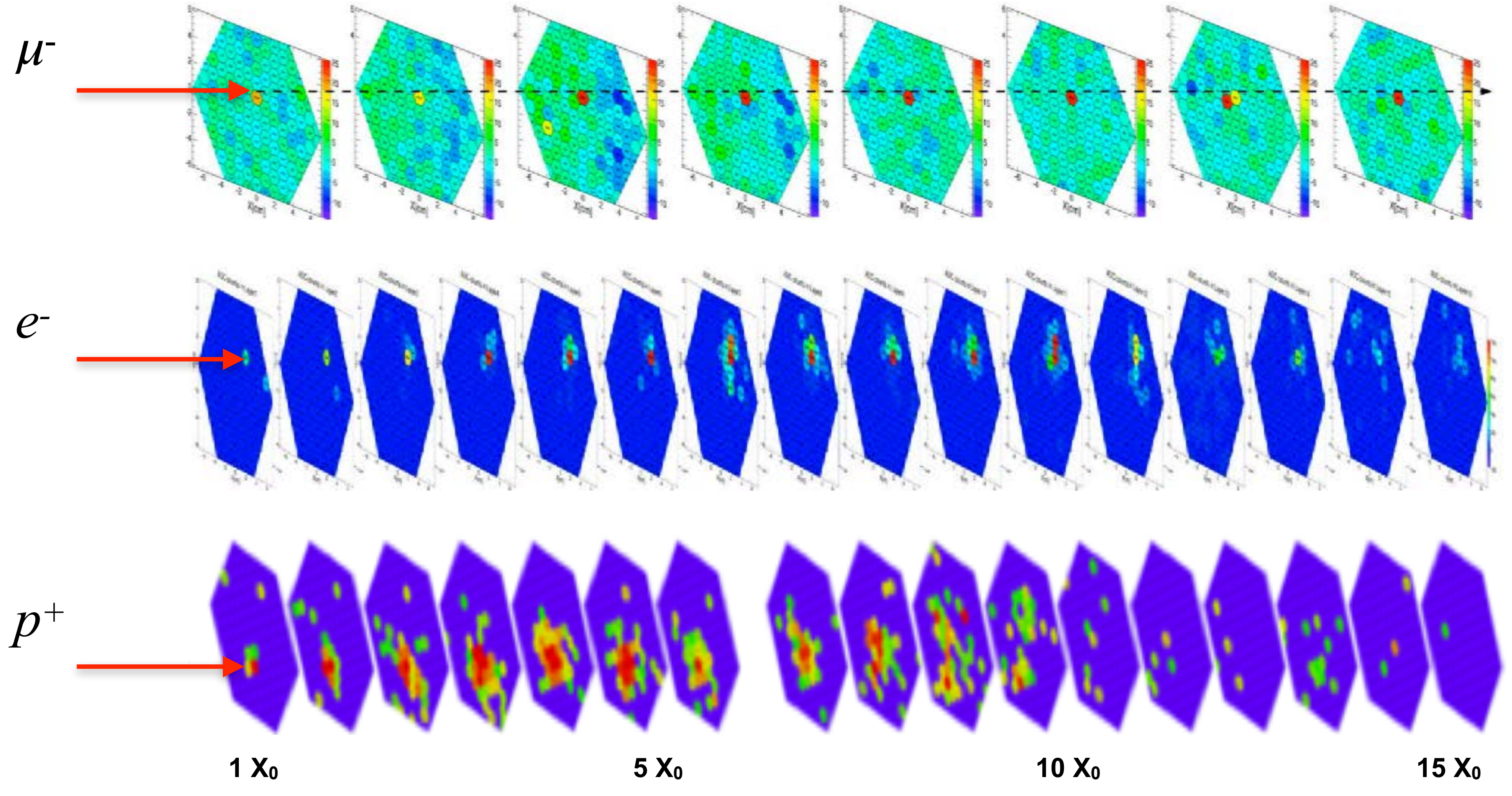


LDMX Subsystems and Technology Choices

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

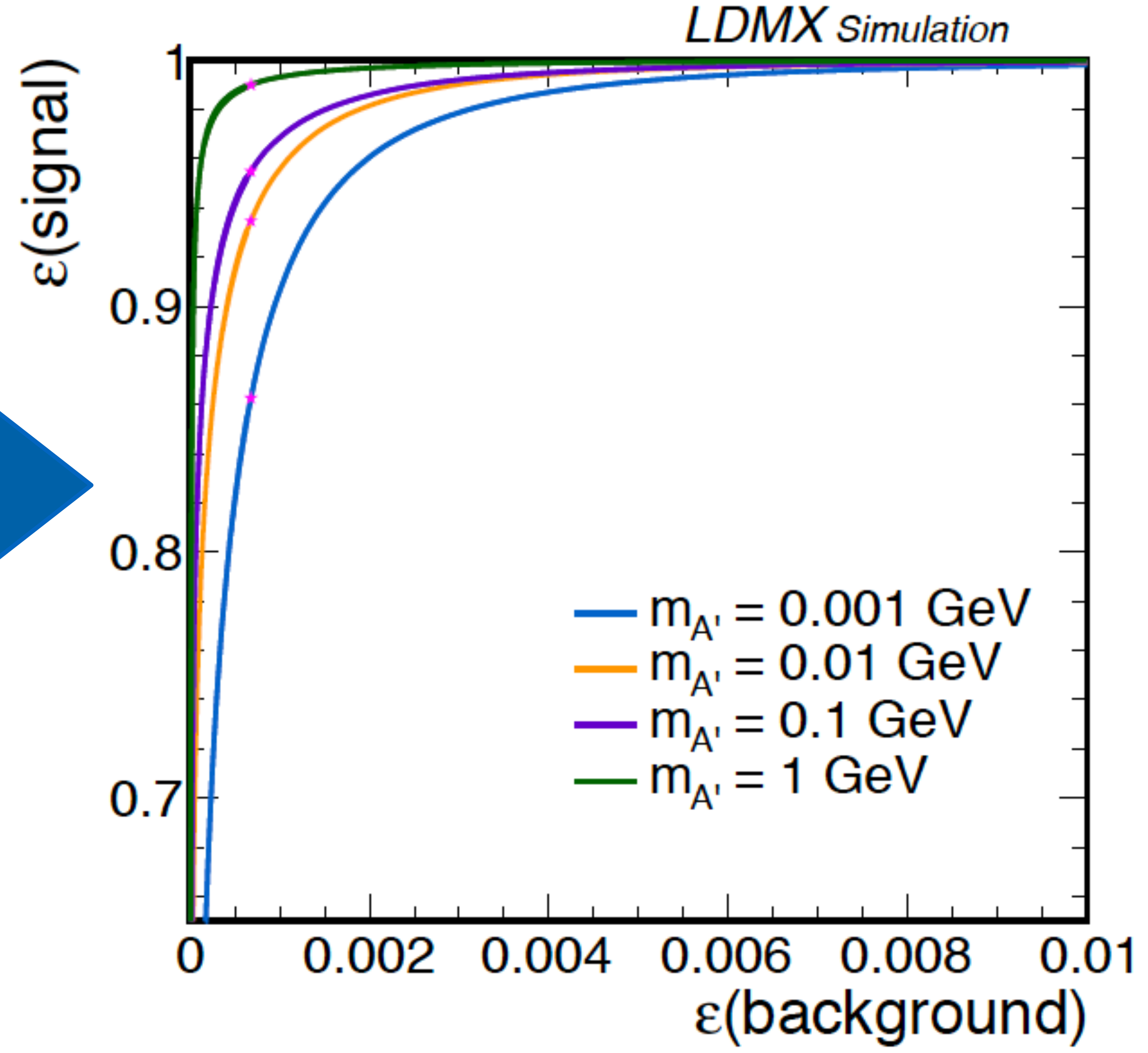
- Si-W sampling calorimeter: fast, dense, high radiation tolerance
- 40 X_0 deep: excellent containment of EM showers
- Granularity and MIP sensitivity: imaging and MIP tracking are powerful for rejecting rare backgrounds (e.g. photonuclear reactions and $\gamma \rightarrow \mu\mu$)
- designed to provide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

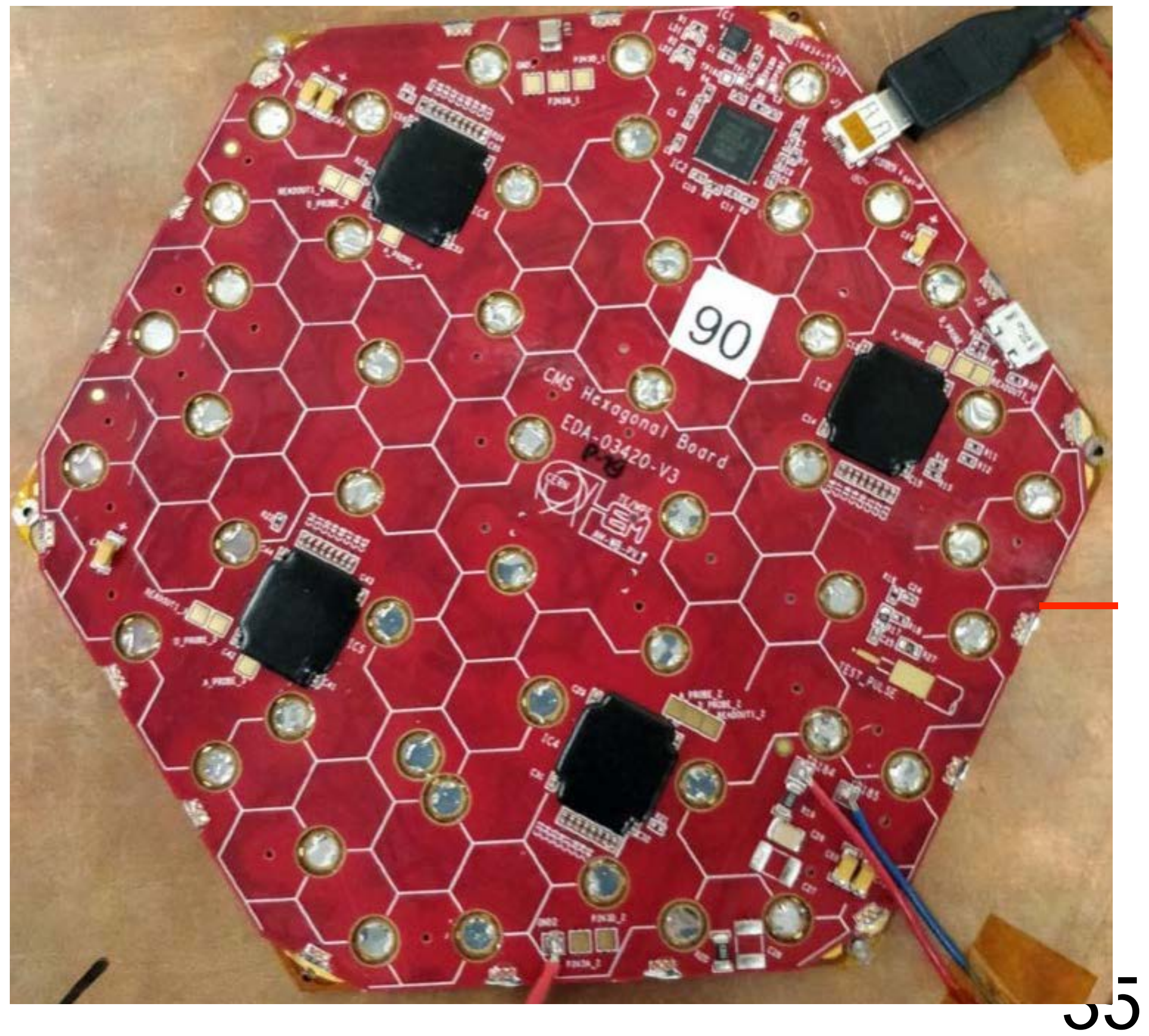




CERN Test Beam Data

Boosted Decision Tree

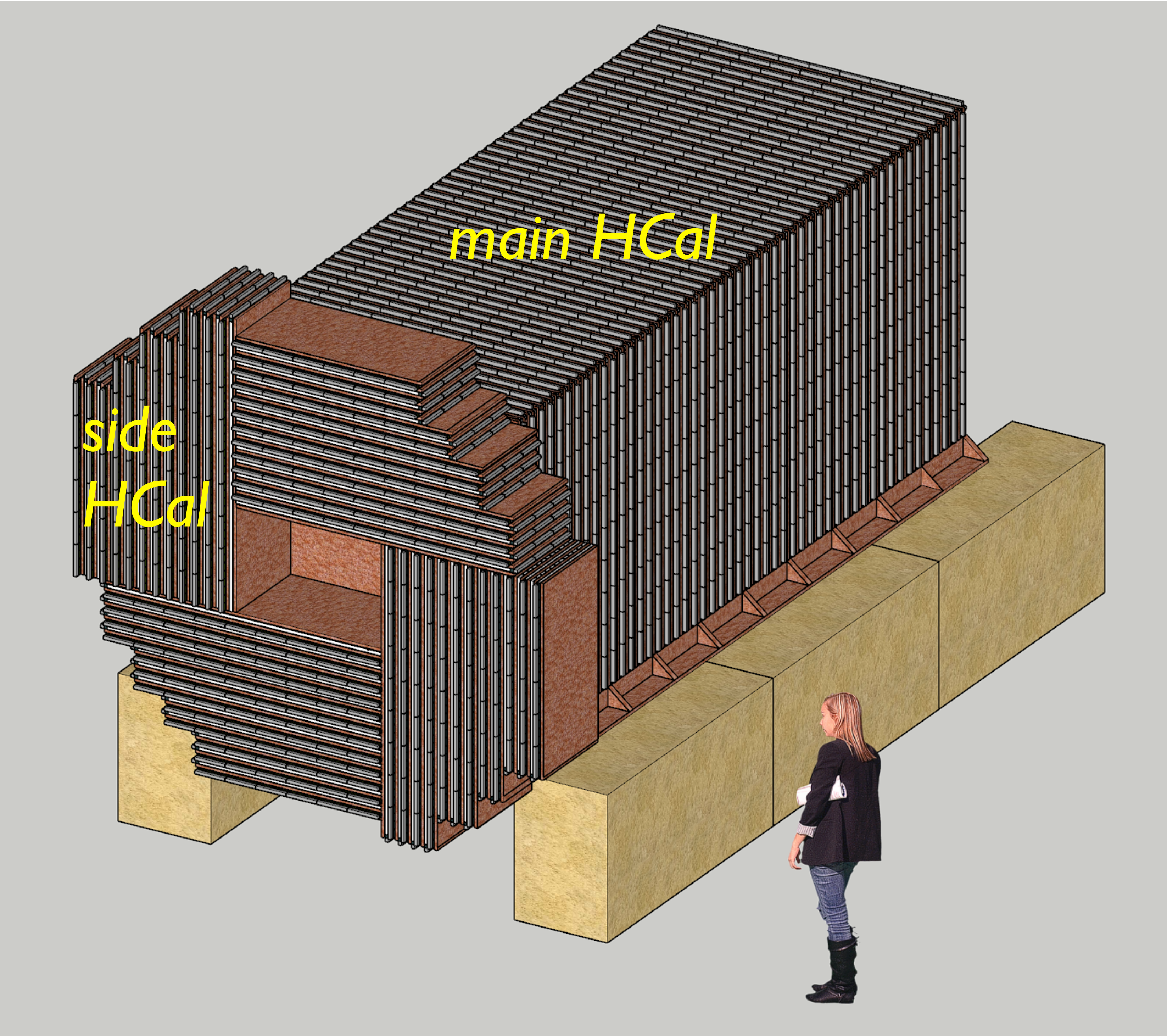


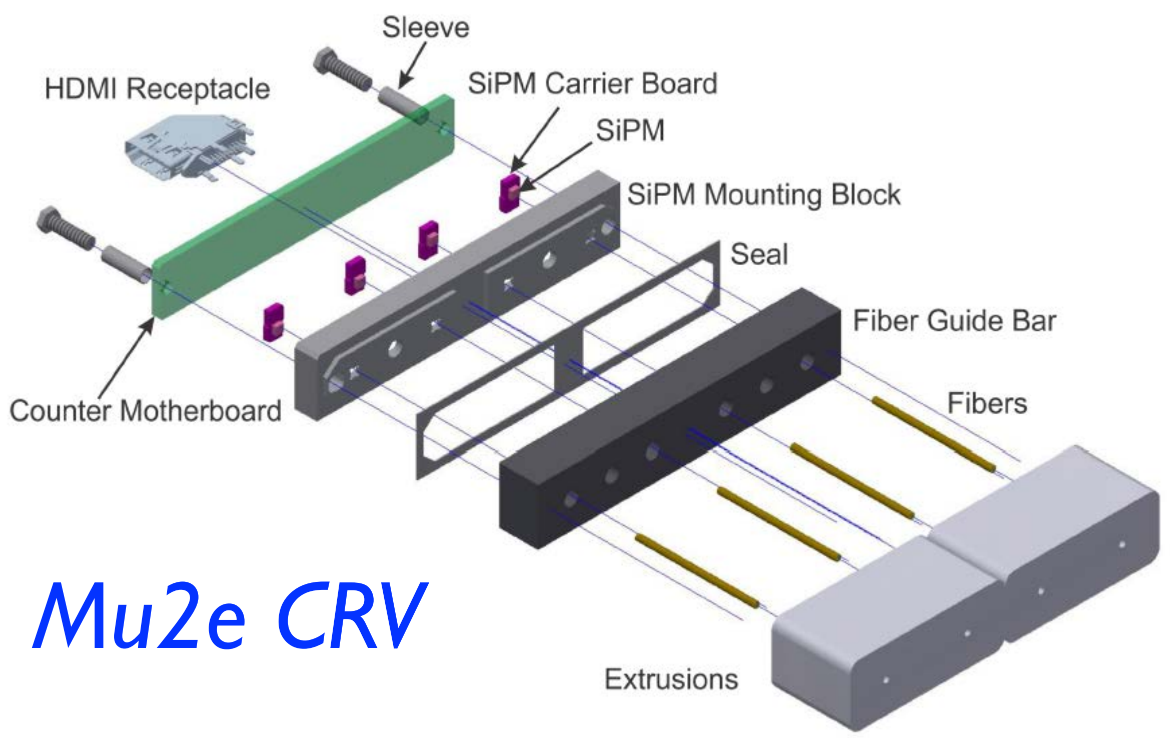


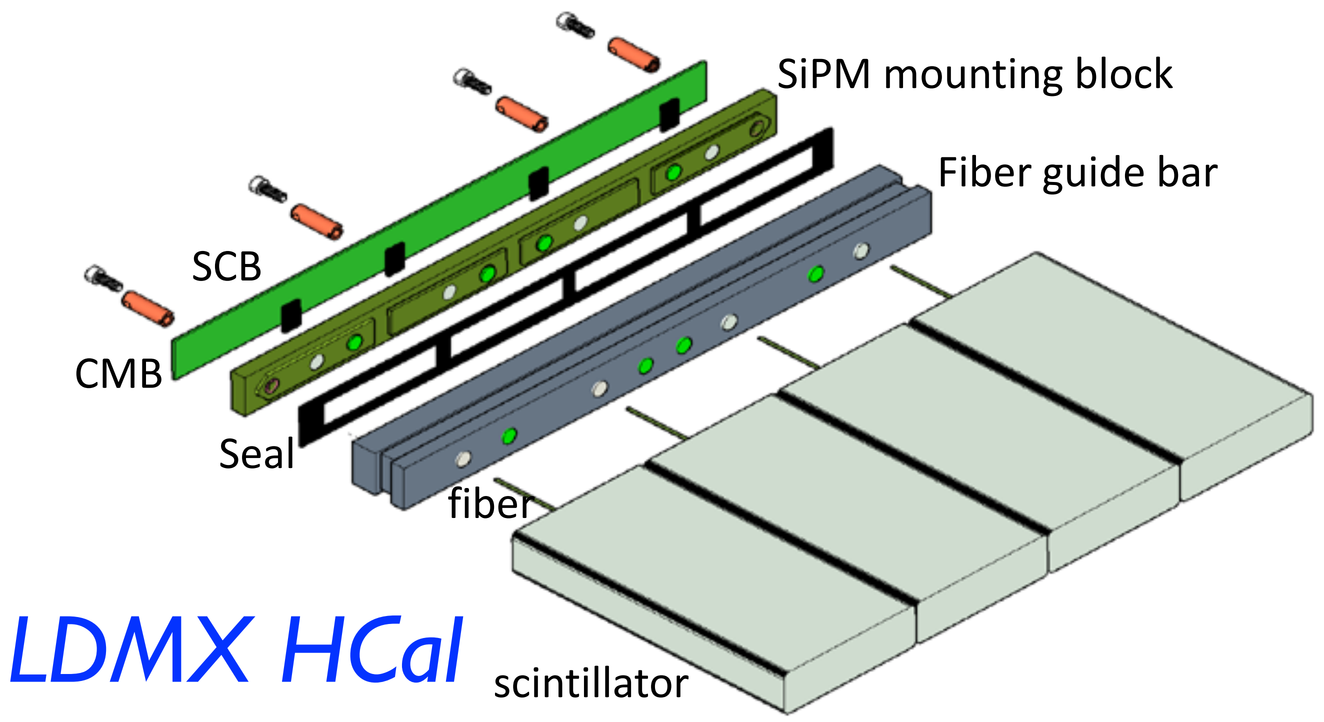
LDMX Subsystems and Technology Choices

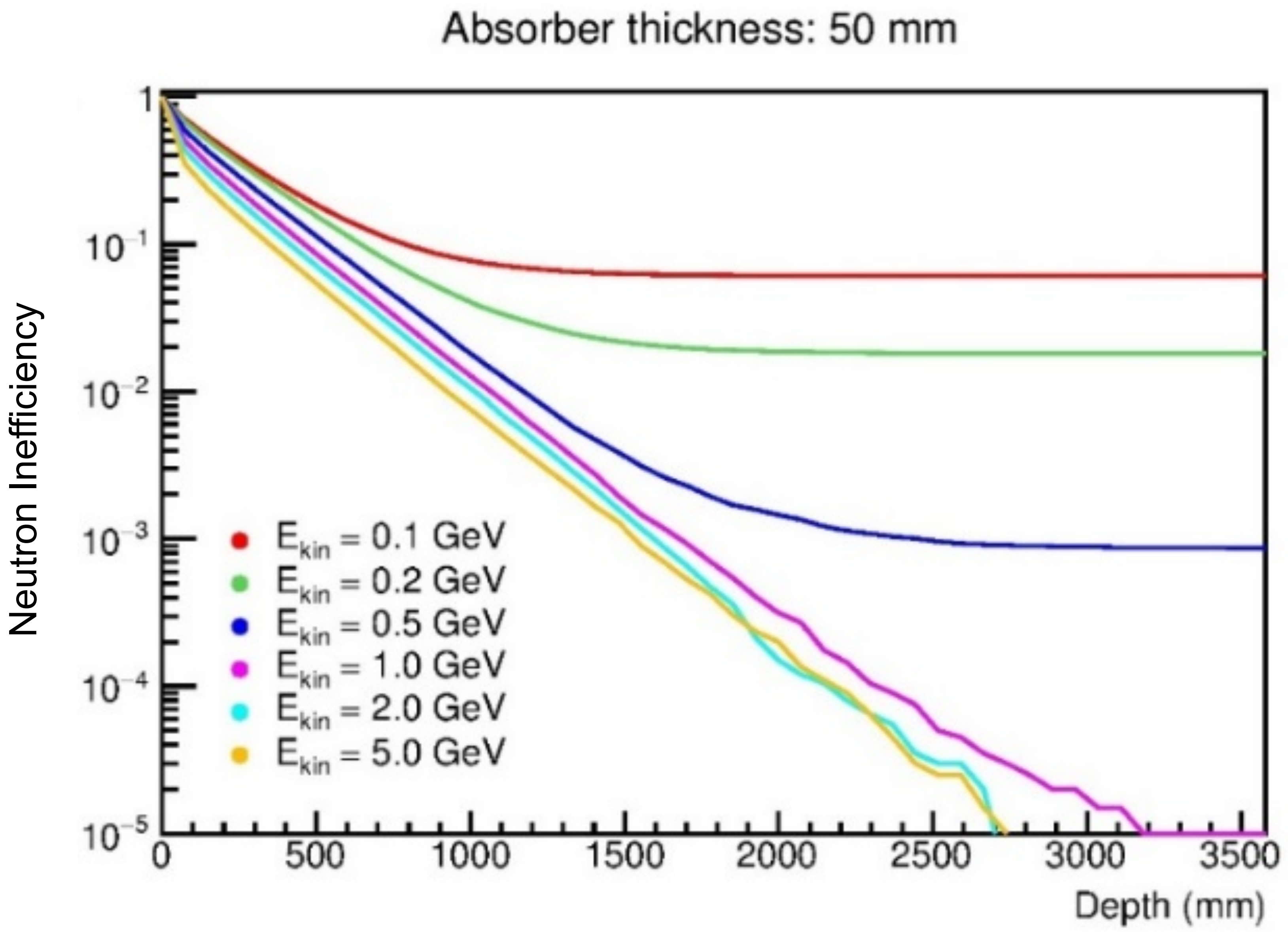
WBS 1.5 – HCal: from Mu2e Cosmic Ray Veto (UVA – Group)

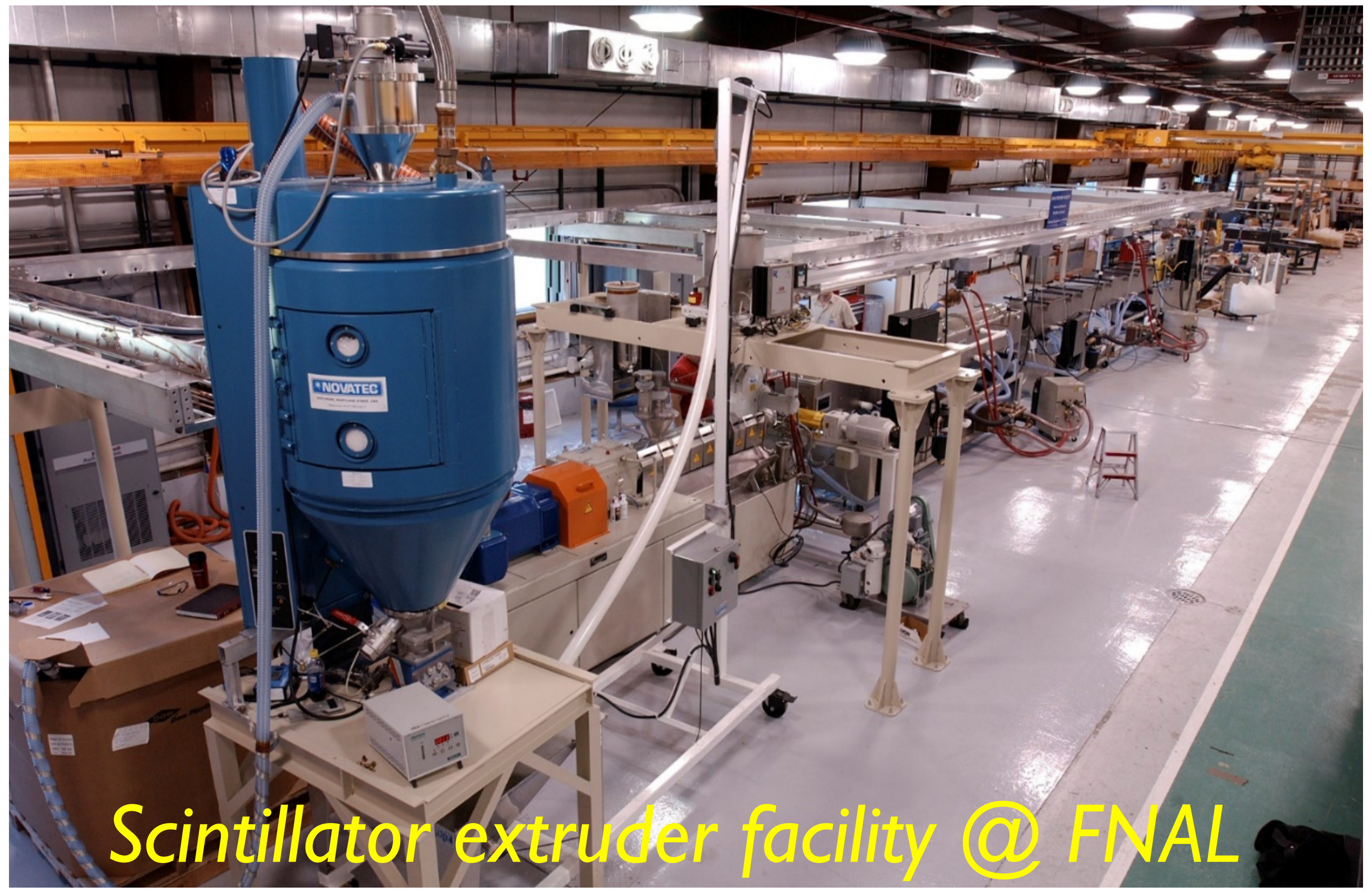
- extruded polystyrene scintillator with WLS fibers and SiPM readout
- main HCal: sufficient depth for rare events with very hard neutrons ($E_n \sim E_\gamma$)
- side HCal: important for high-multiplicity final states and wide-angle brems







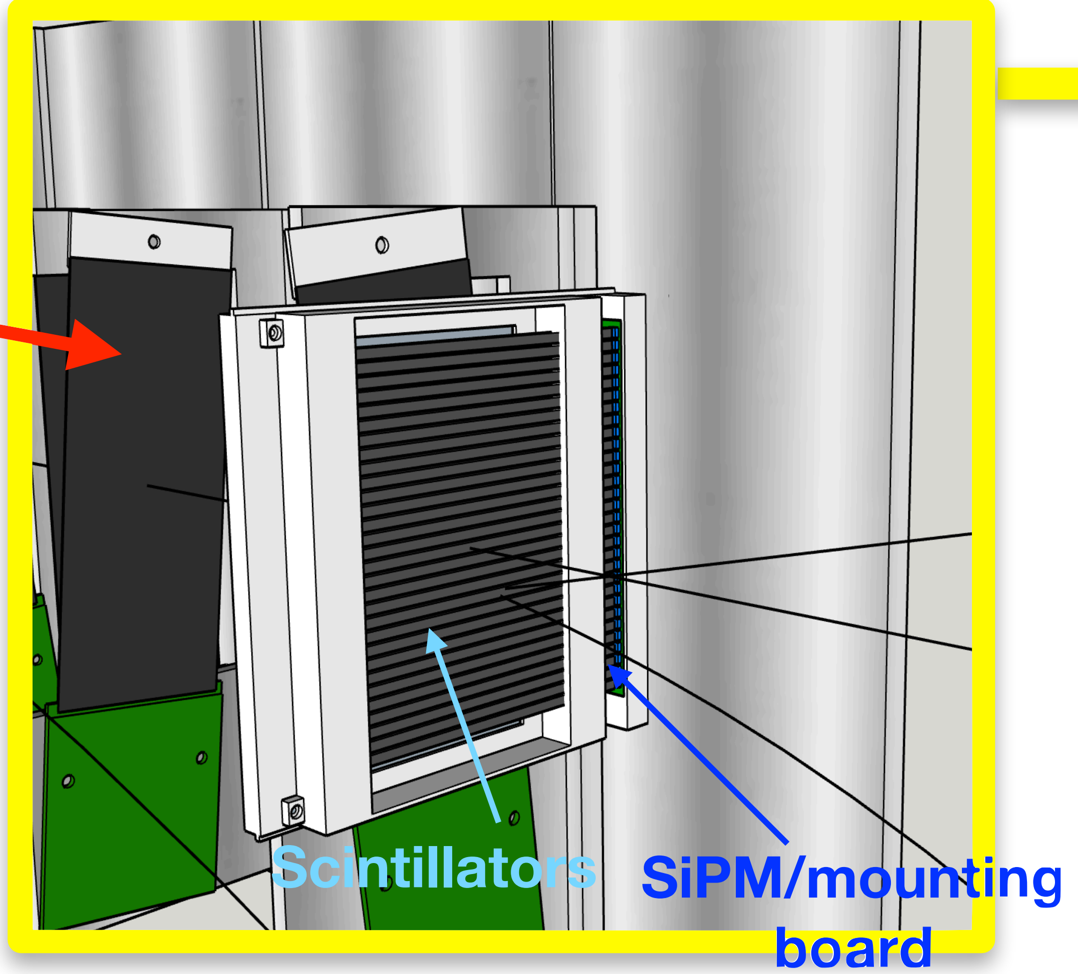


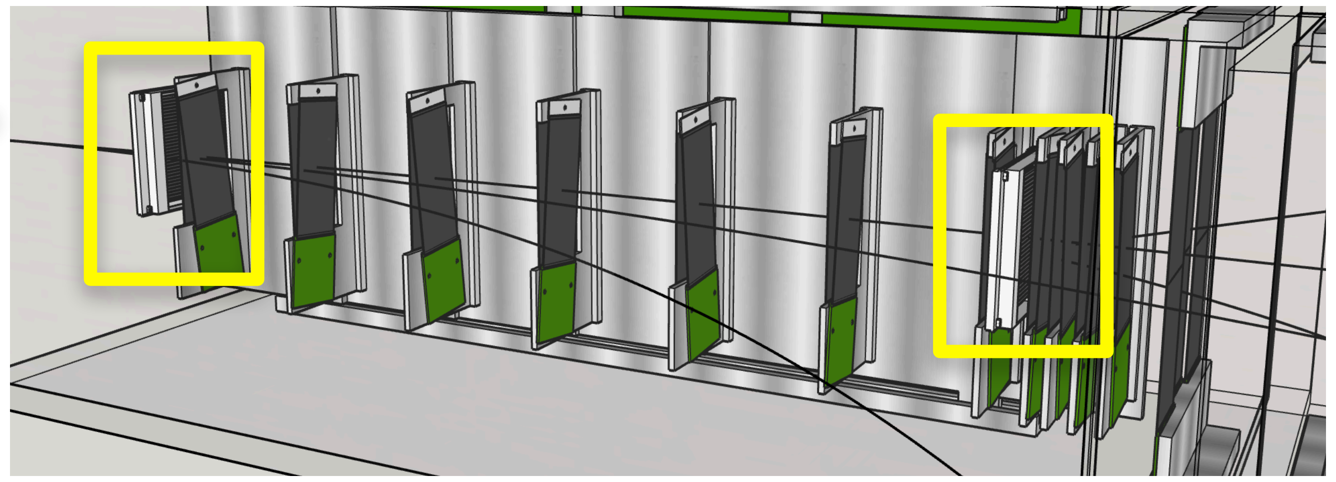


LDMX Subsystems and Technology Choices

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



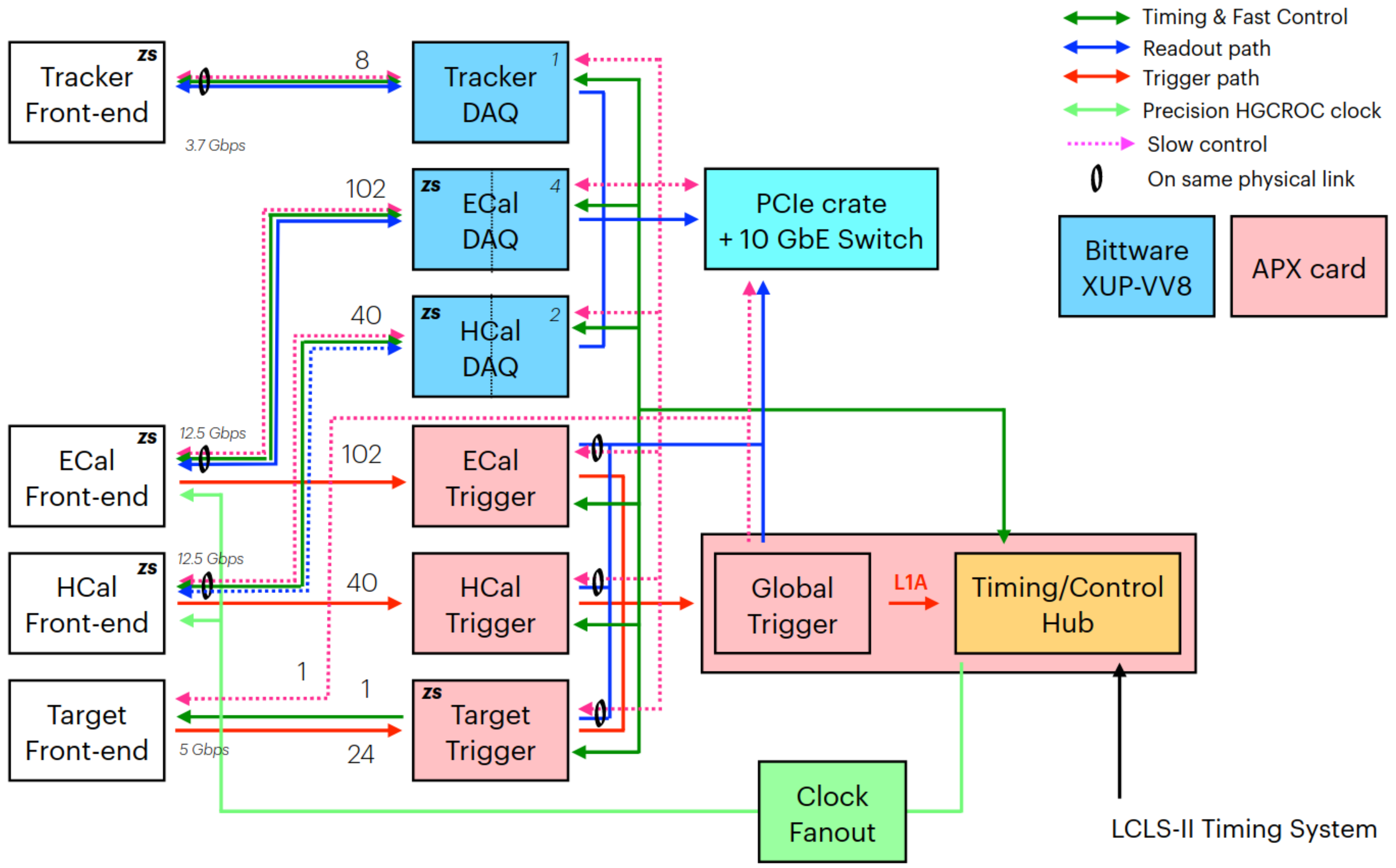


4 GeV trigger summary

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%

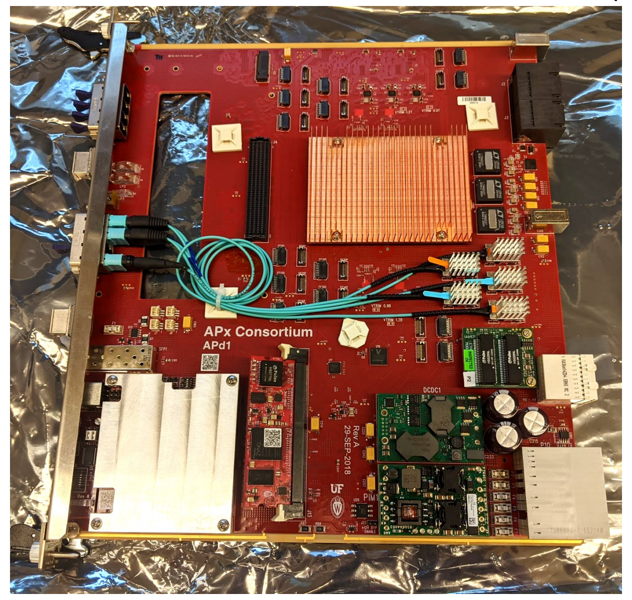
WBS 1.6 – Trigger and DAQ: from SLAC/FNAL tech

- 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

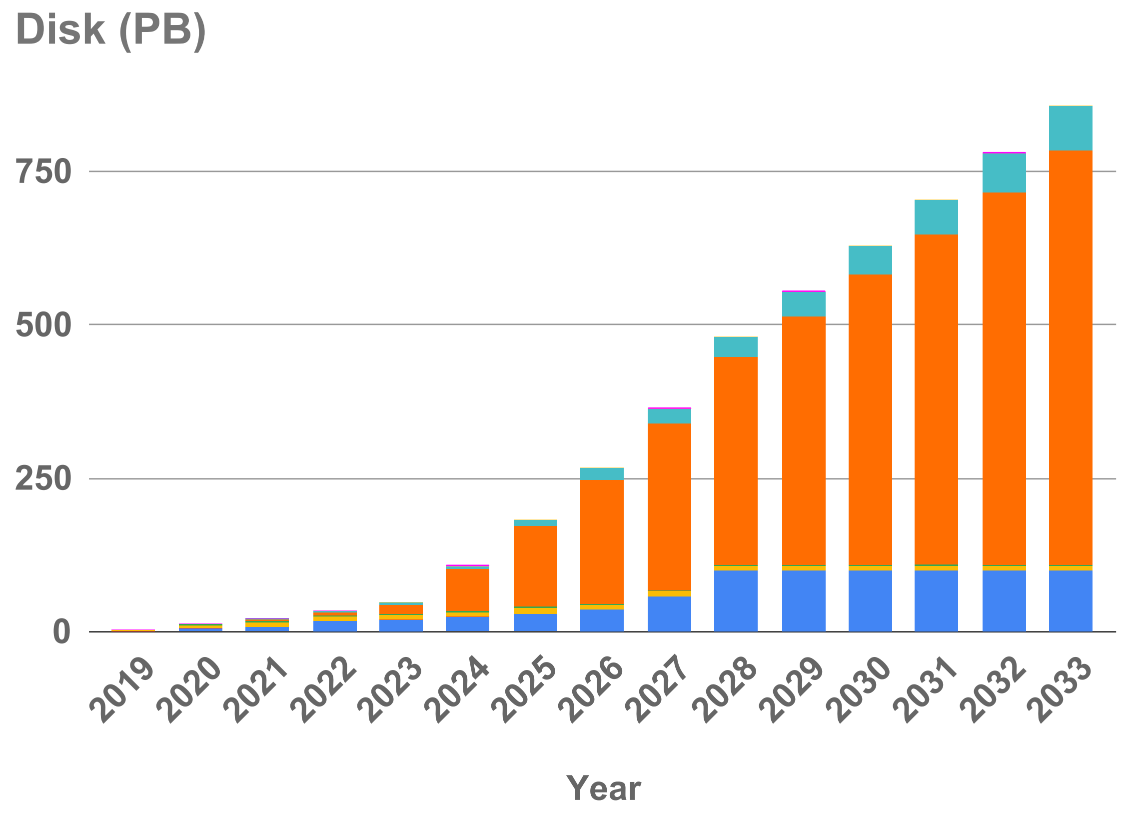
LDMX requires significant computing resources: Datasets and MC will total ~8 PB (disk+tape) after filtering and require ~15M CPU hours to process.

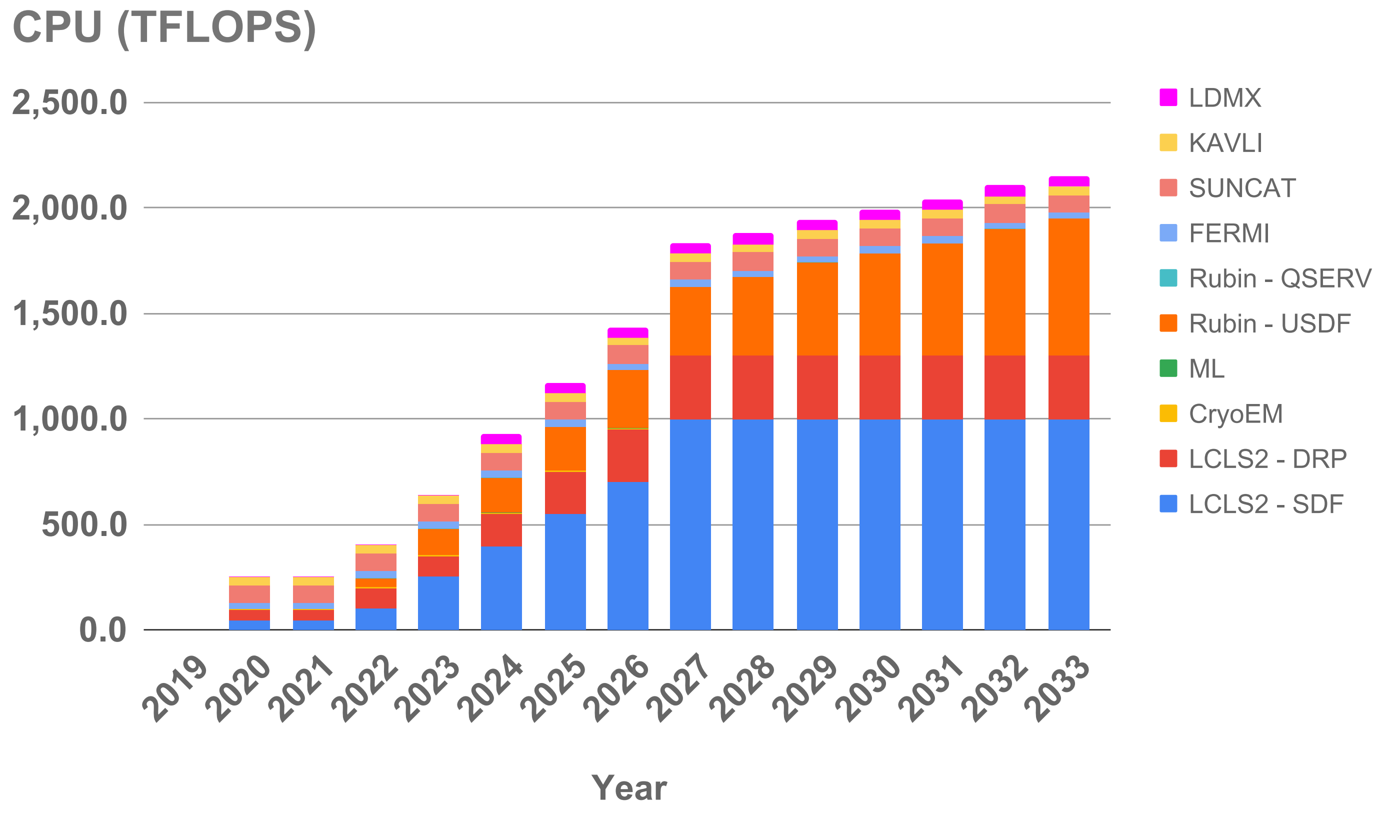
- SLAC Shared Scientific Data Facility (SDF)
- LDMX distributed computing pilot project: *Lightweight Distributed Computing System (LDCS)* arXiv:2105.02977 **[hep-ex]**

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

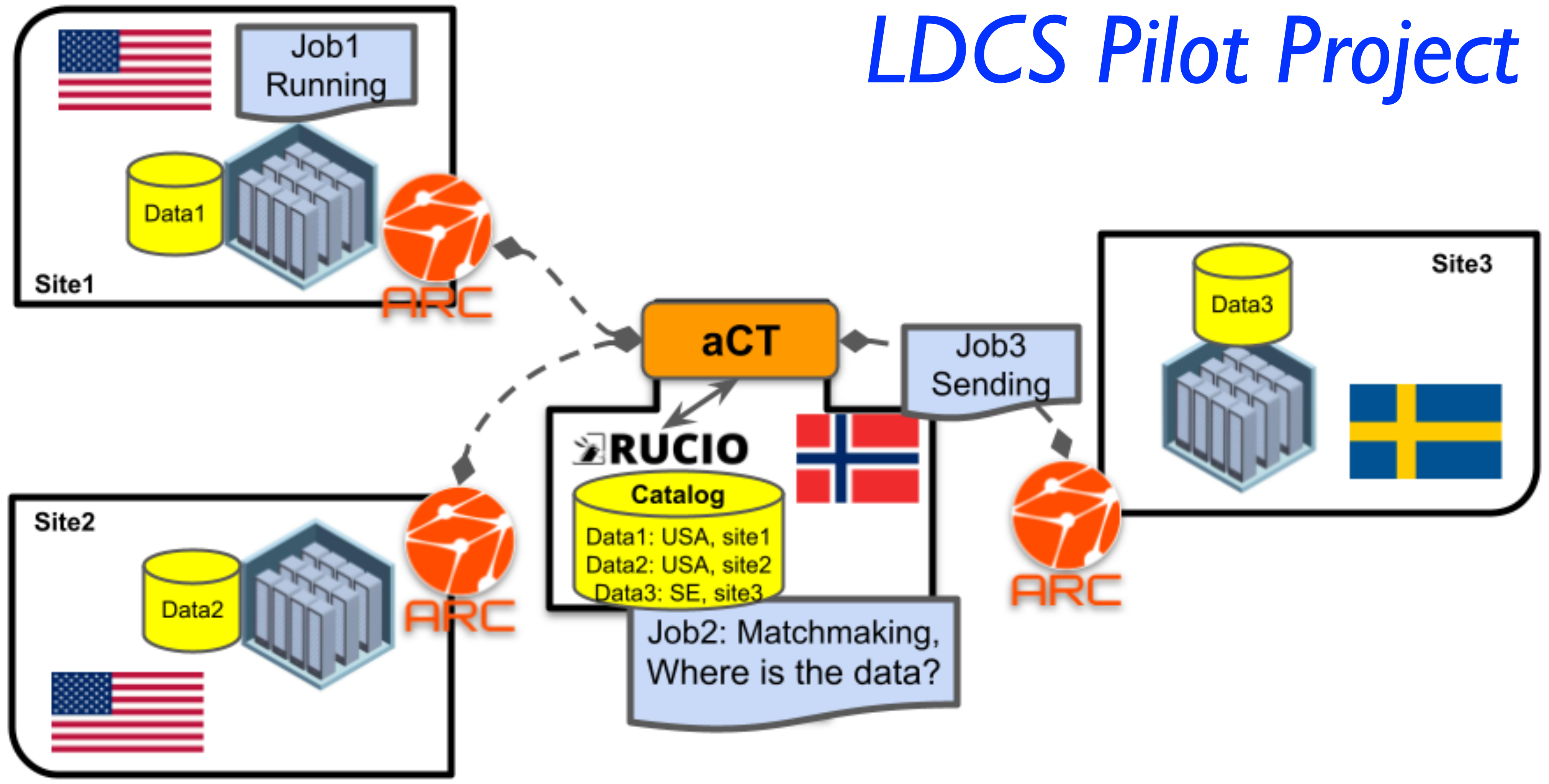
https://github.com/LDMX-Software/ldmx-sw/

SLAC Shared Scientific Data Facility (SDF)





LDCS Pilot Project

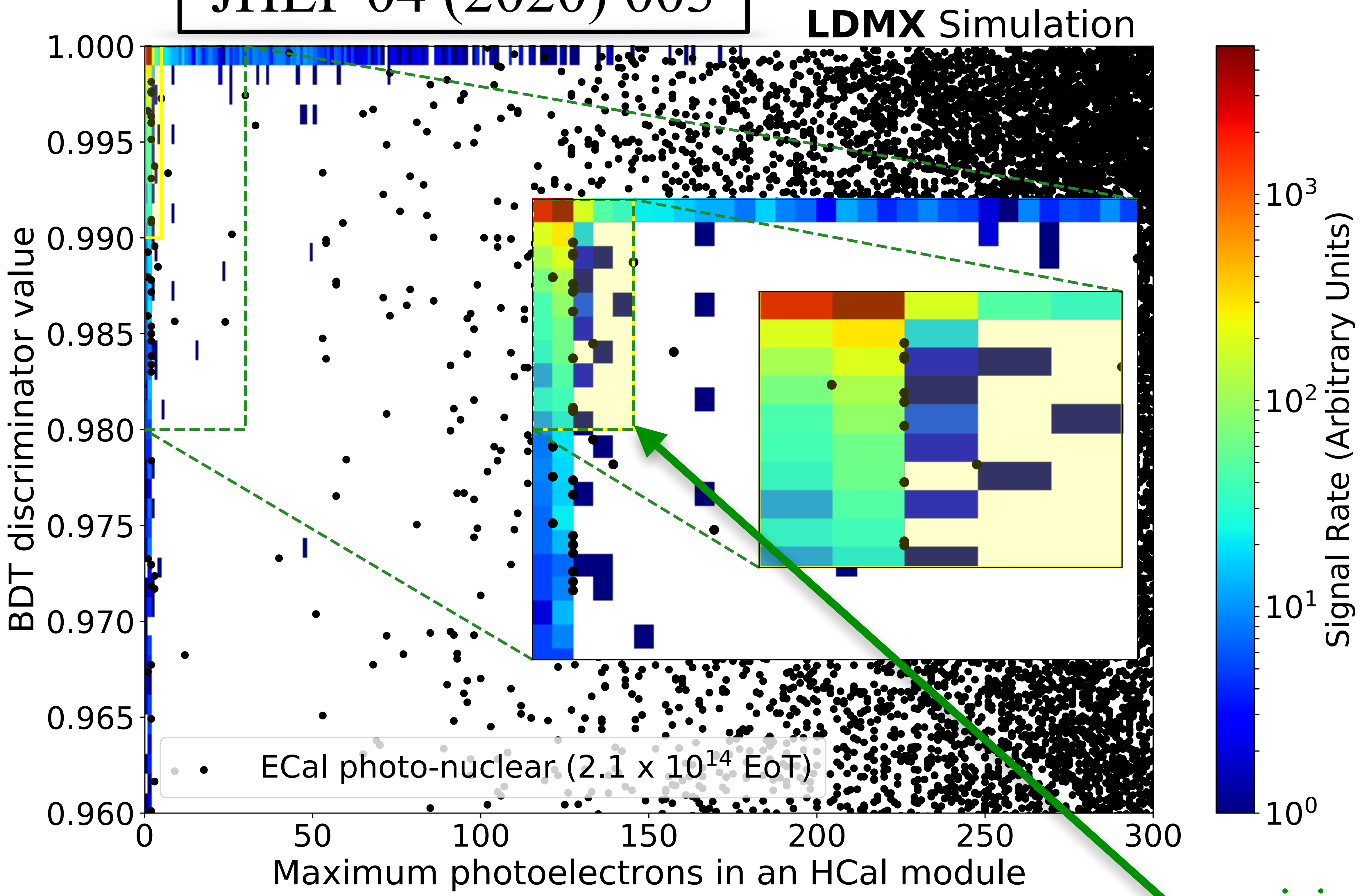


LDMX Physics Studies

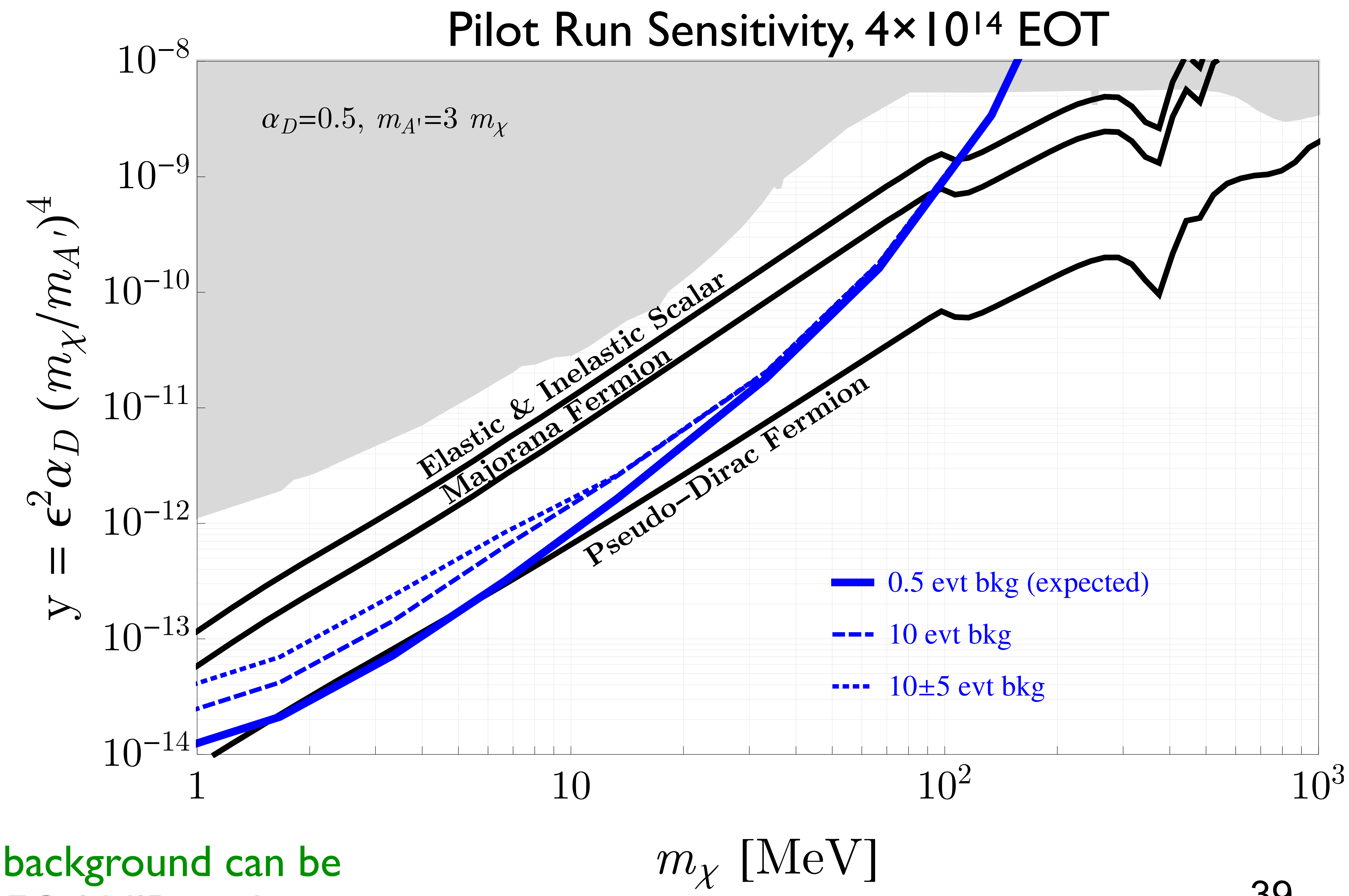
Robust software and computing infrastructure have enable detailed, high-statistics performance studies, largely driven by an active team of Ph.D. students and postdocs.

Study of dominant photo-nuclear backgrounds:
1.5M CPU hours, 1.3 PB data

JHEP 04 (2020) 003



remaining background can be vetoed by ECal MIP tracking



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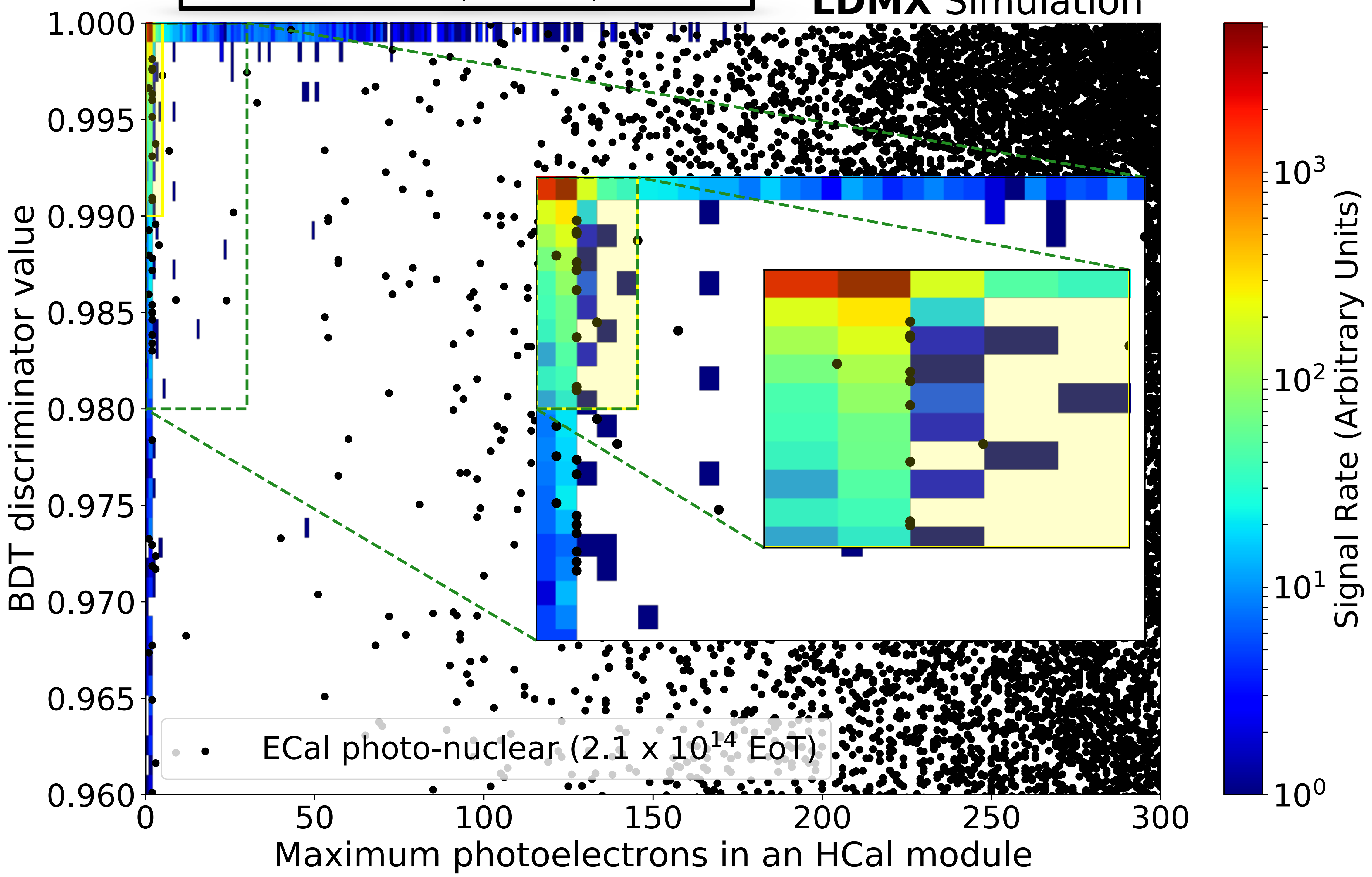
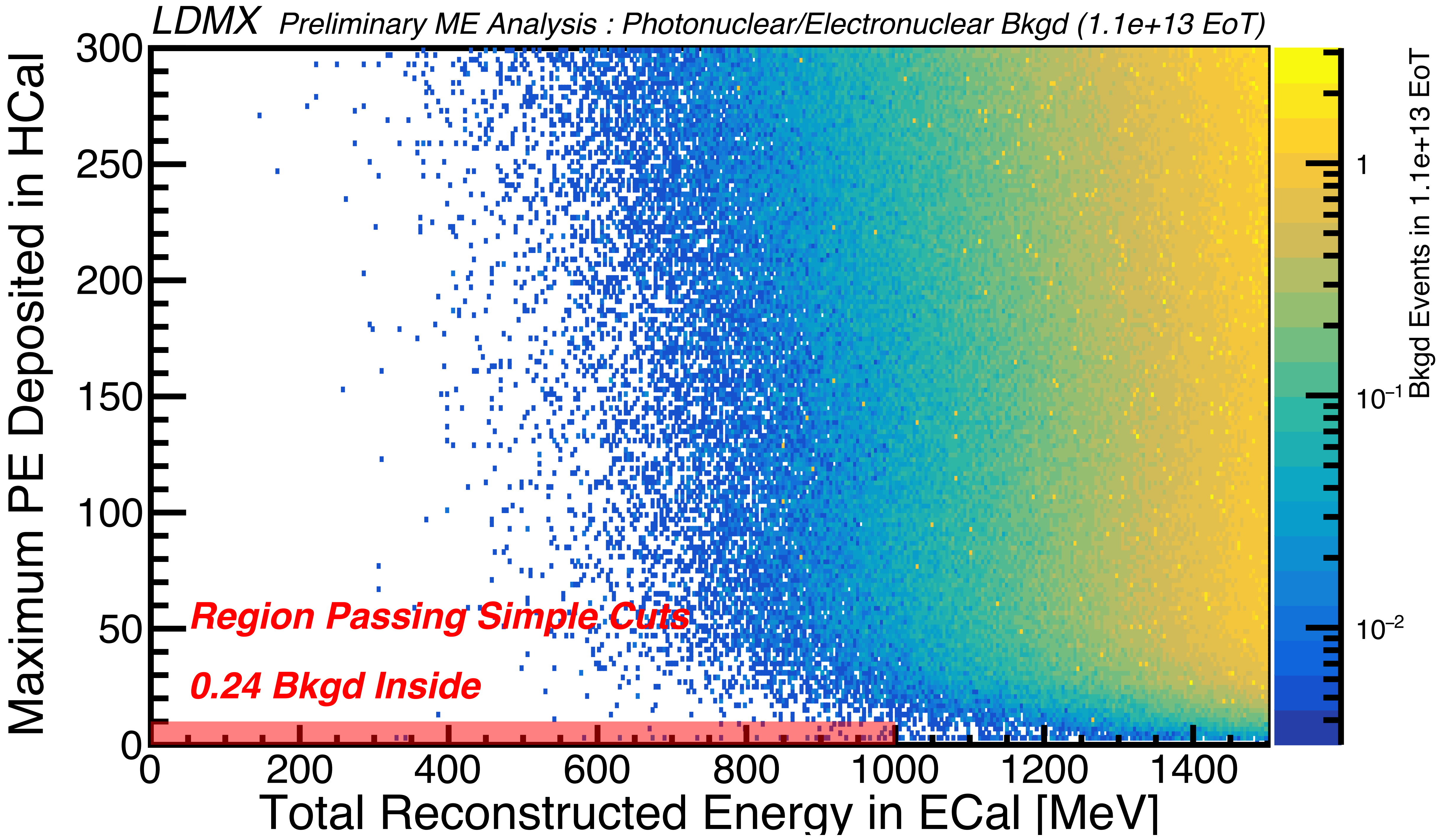


Preliminary ECal as Target missing energy study:
4.1M CPU hours, 1.1 PB data



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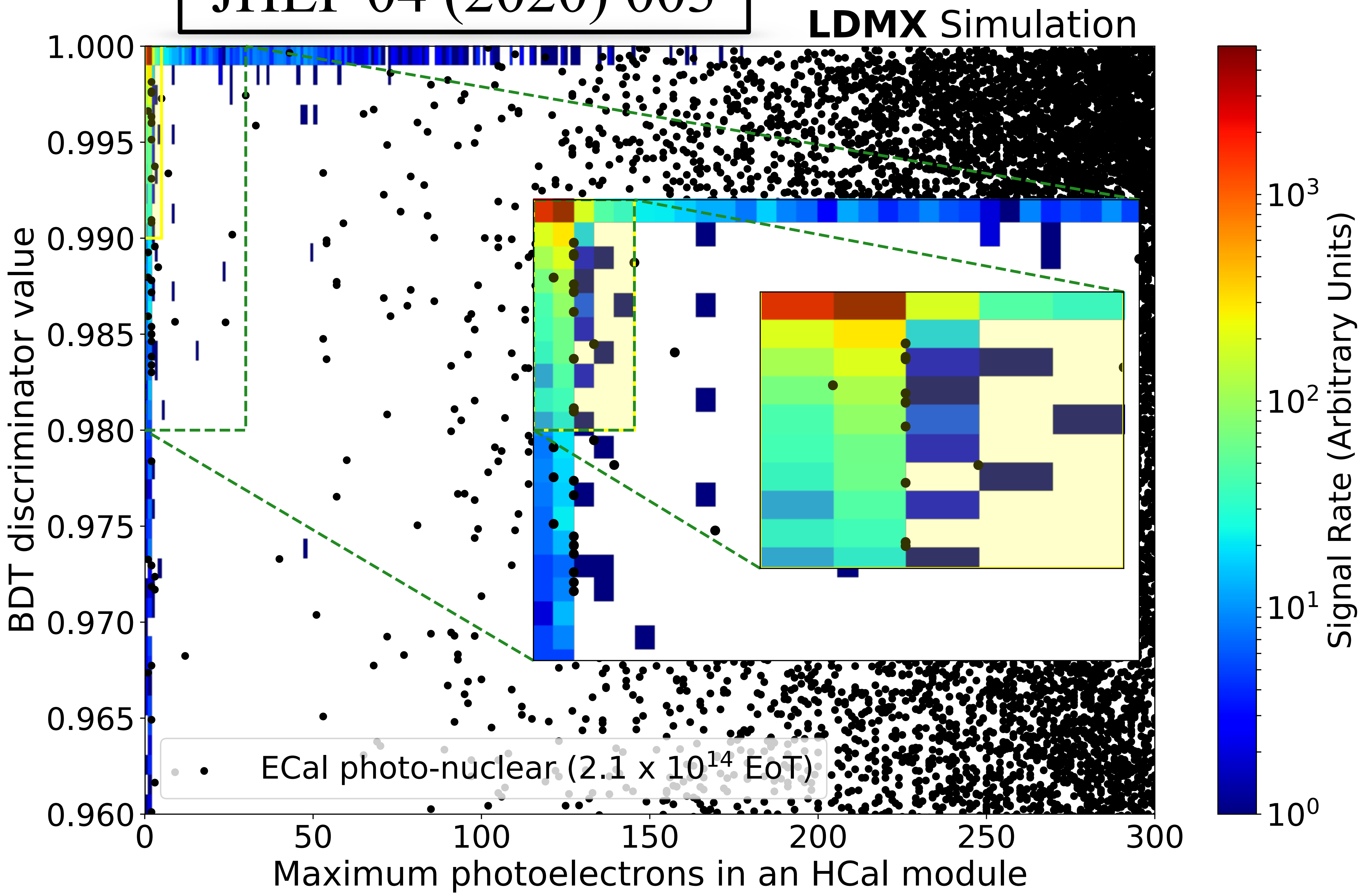
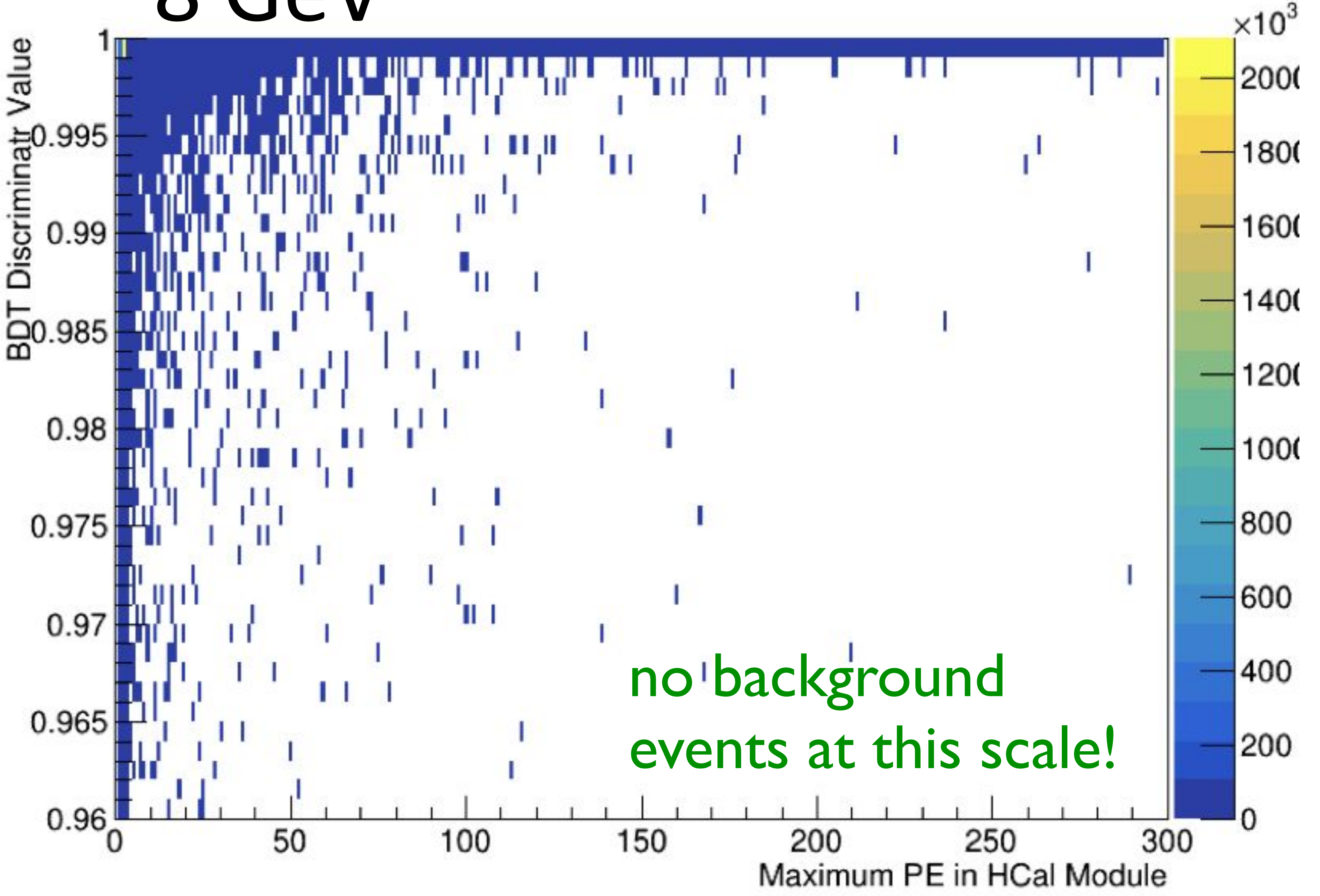


First Look at 8 GeV with 0.6×10^{14} EOT:
A full 10^{16} study is the next step!



LDMX Collaboration and DMNI Consortium

Collaboration, formed in Spring 2019…

Spokespersons
T. Nelson (SLAC)
T. Akesson (Lund)

Collaboration Board

*Chair:*J.Mans (UMN)

Technical Coordinator
D. Hitlin (Caltech)

Electronics Coordinator
J. Mans (UMN)

Physics Coordinators
P. Schuster (SLAC)
R. Pottgen (Lund)

Senior Investigators Board
Chairs
J. Incandela (UCSB)
B. Echenard (Caltech)

Conference Chair

C. Group (UVA)

CIDER Committee

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Trigger Scintillator
A. Whitbeck (TTU)

Tracker
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…maps onto DMNI Consortium

SLAC: PI Nelson *(HPS SVT)*
- Beamline/Magnet, Tracking, Computing, Project Management

UCSB: PI Incandela *(CMS HGCal modules)*
- ECal

U. Minn: PI Mans *(CMS HGCal electronics)*
- ECal

Caltech: PI Echenard
- HCal and Trigger Scintillator

U.VA: PI Group *(Mu2e CRV)*
- HCal

FNAL: PI Tran
- TDAQ

Texas Tech: PI Whitbeck
- Trigger Scintillator

Additional collaborators:
Lund: Åkesson, Pöttgen – (HCal, Computing)
Stanford: Tompkins – (TDAQ)