Fixed-target Searches for Dark Sectors

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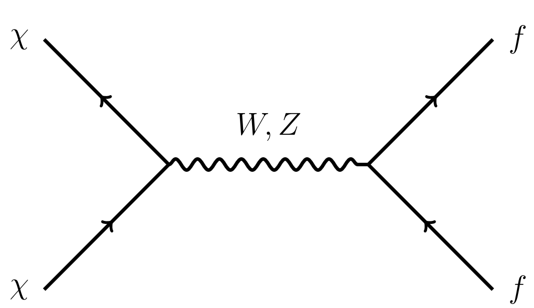
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

A Key Motivation: Low-mass Thermal Relics

Light DM requires new, comparably light mediators to achieve required annihilation cross-section for thermal relics.



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

Lee/Weinberg '79

Benchmark Scenario: Dark Photons

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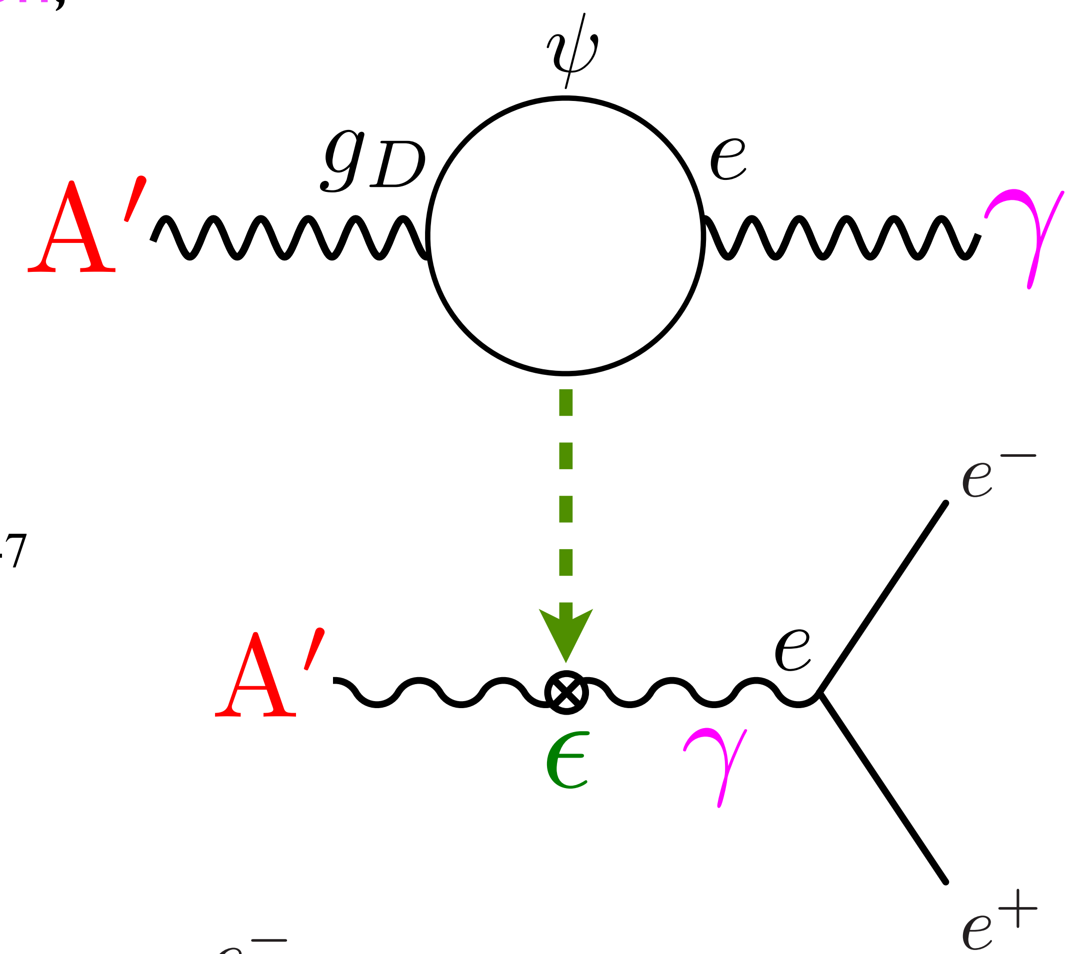
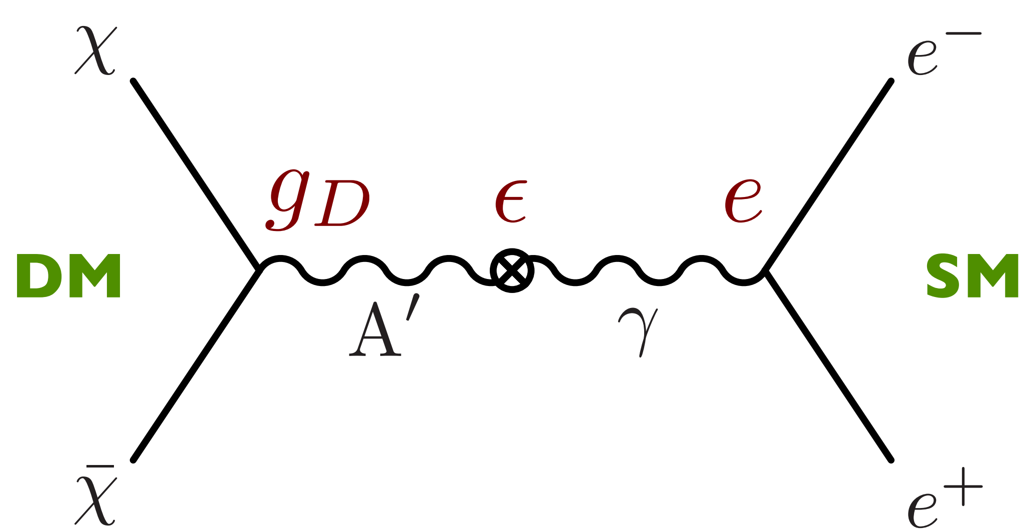
A dark photon, A′, can mix with the SM photon, generating an ϵe coupling to SM fermions:



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

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

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



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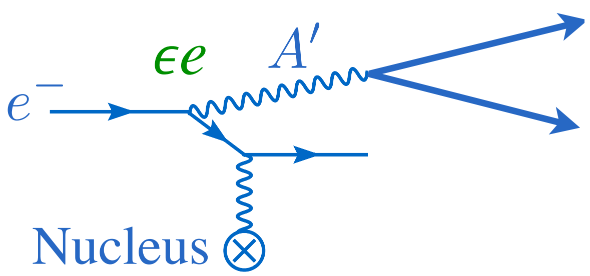
Dark Photon Production

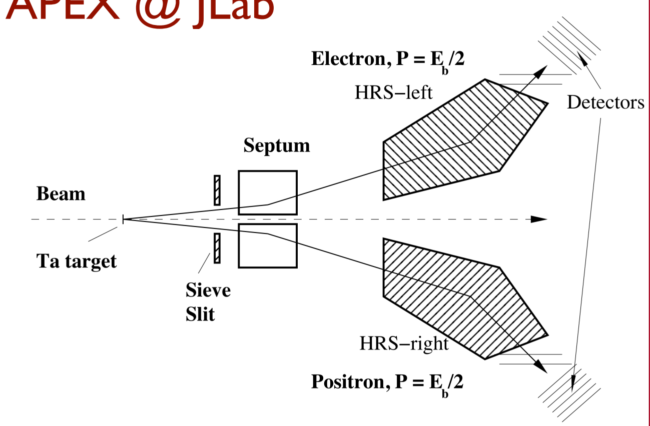
e fixed target



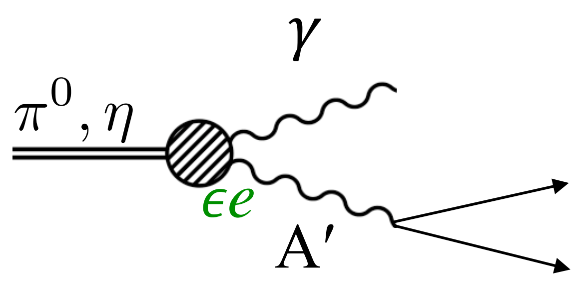
$N \propto \epsilon^2$

- dark bremsstrahlung
- $e^+e^- \to A'\gamma$

APEX @ JLab

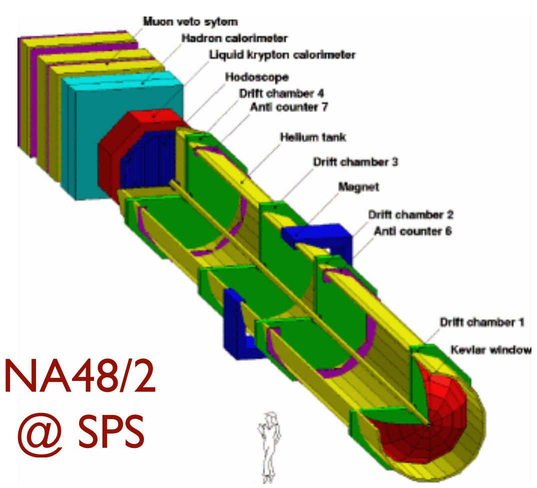


p fixed target



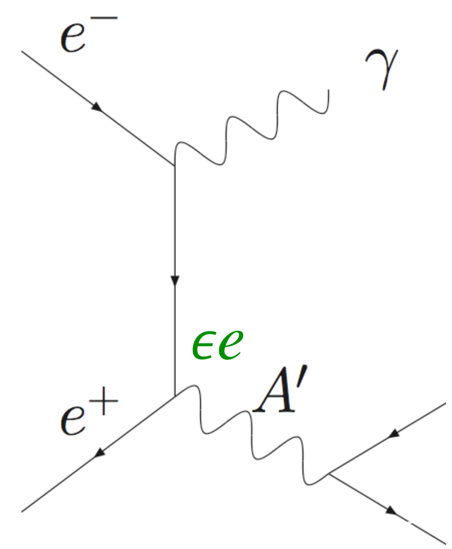
$N \propto \epsilon^2$

- meson decays
- dark bremsstrahlung



NA48/2 @ SPS

e^+e^- colliders



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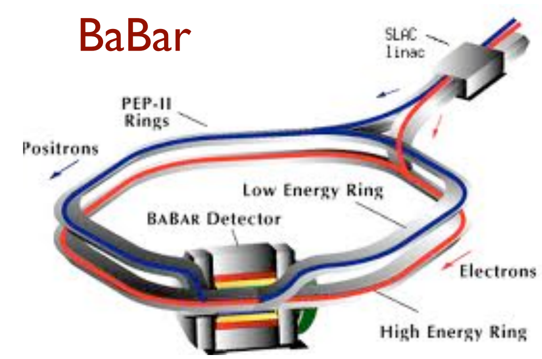
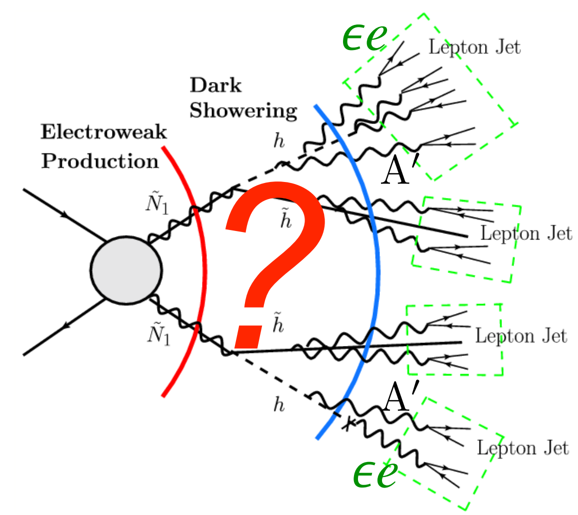
BaBar

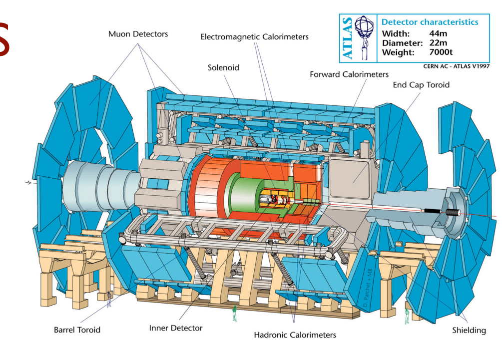


pp collider



- "lepton jets" $N \propto ?$
- meson decays $N \propto \epsilon^2$

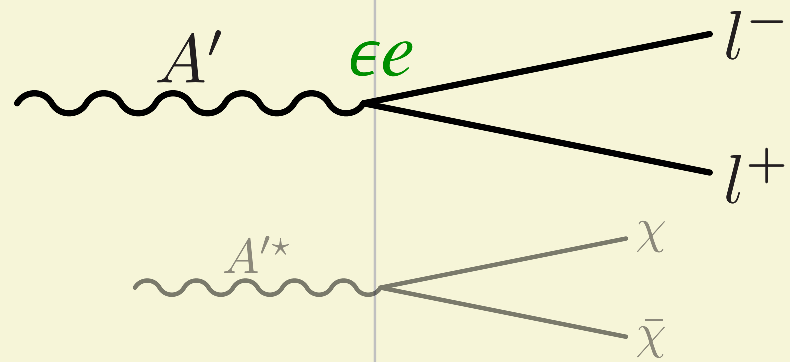
ATLAS
CMS
LHCb

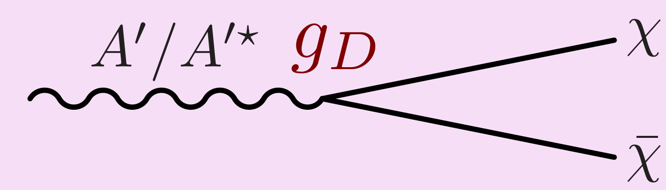


Analogous SM process is irreducible background but allows $(M_{A'}, N_{\text{observed}}) \Longrightarrow (M_{A'}, \epsilon)$

Mass Hierarchy Determines Search Strategy

Mediator decay in experiments





Search: ***for mediators decaying to SM*** ***for production of DM***

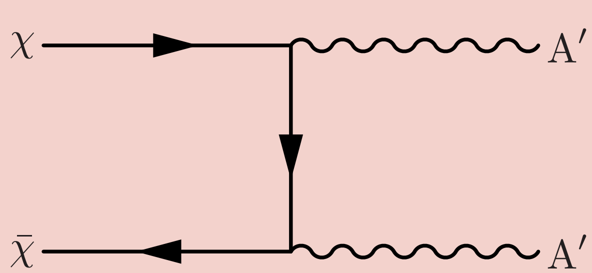
****or off-shell to DM***

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

Dominant DM annihilation:

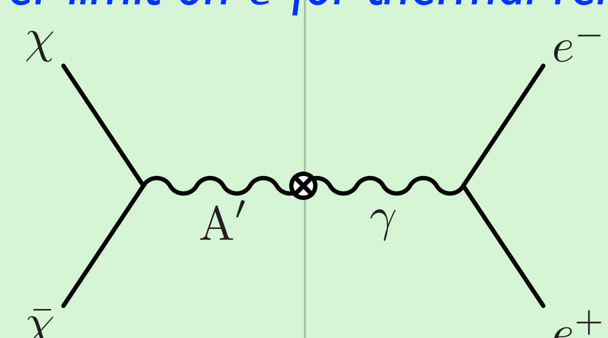
$\sigma v \propto \alpha_D^2$

no clear target for ϵ



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

lower limit on ϵ for thermal relics



Mass Hierarchy Determines Search Strategy

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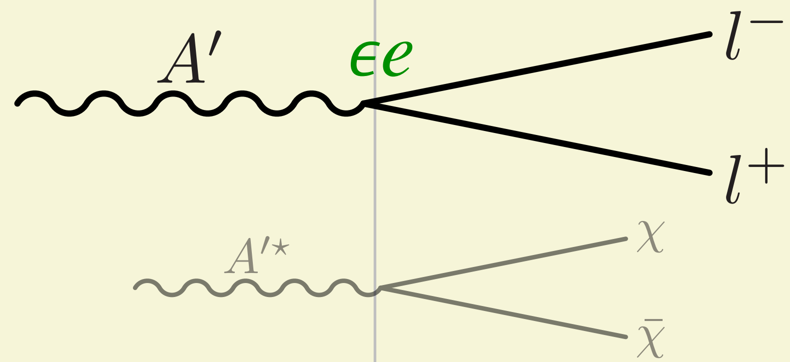
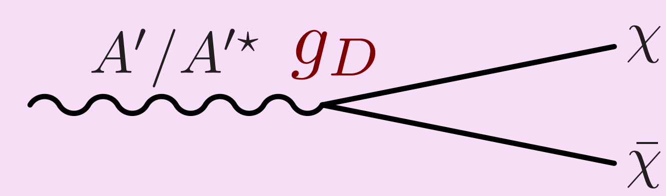
$m_{A'}$ — m_χ — $2m_\chi$

Mediator decay in experiments





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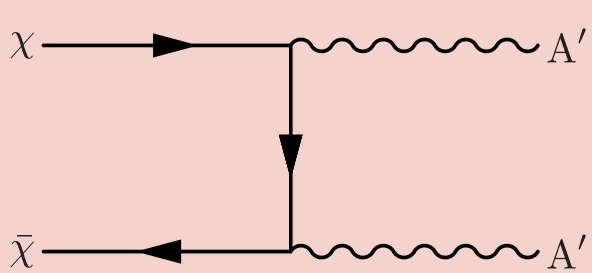

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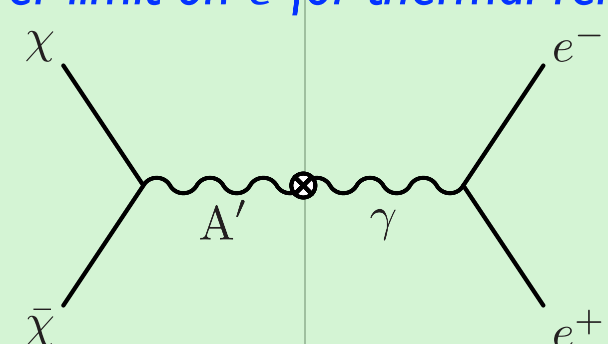
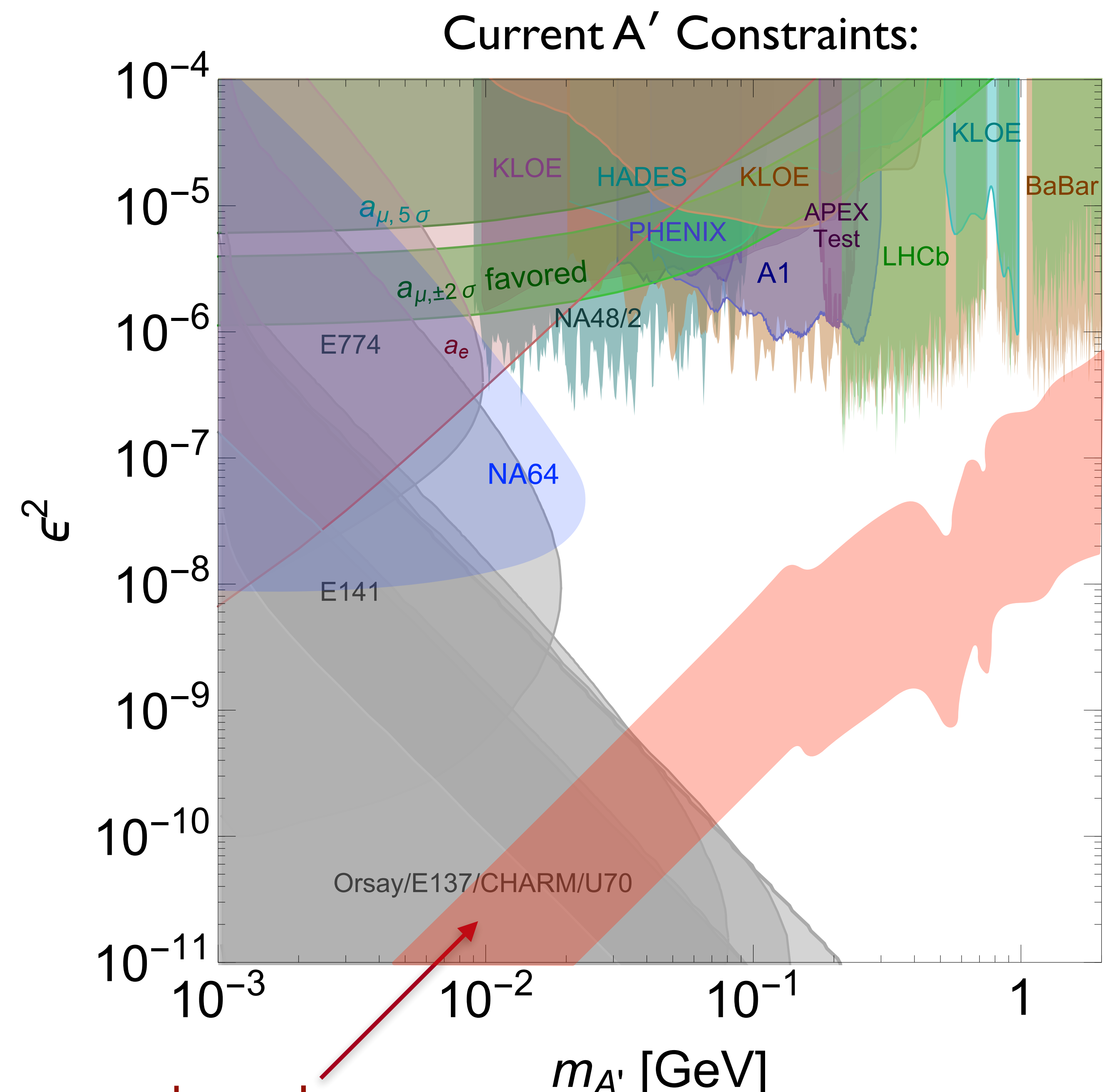


Parameter Space: Mediator Decays to SM

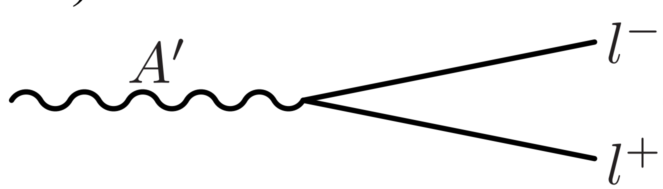


thermal targets

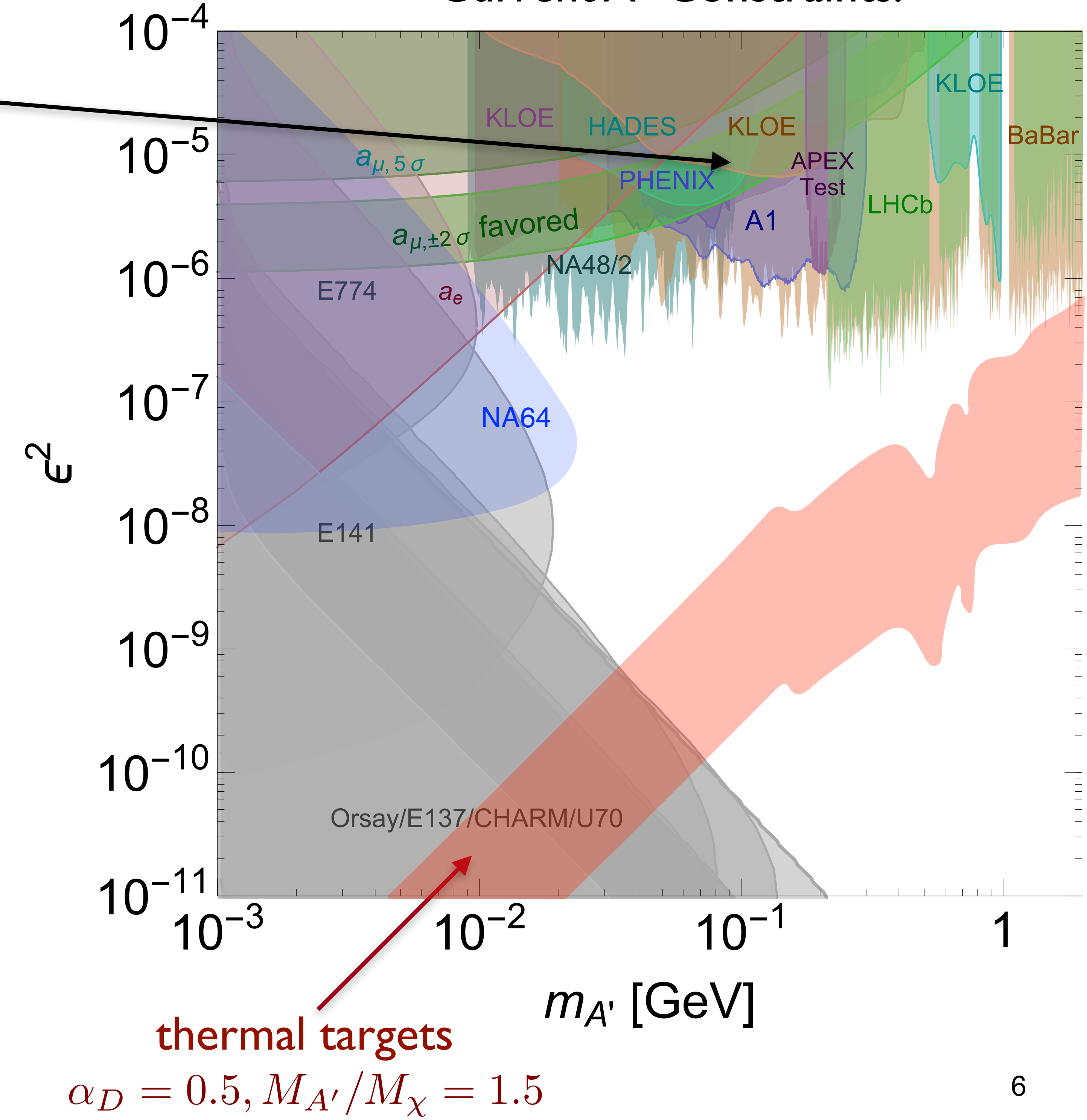
$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$

Parameter Space: Mediator Decays to SM

Generally, searches are "bump hunts" for $m(l^+l^-)$ resonances.



Current A′ Constraints:



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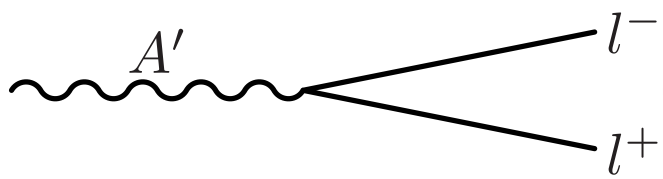
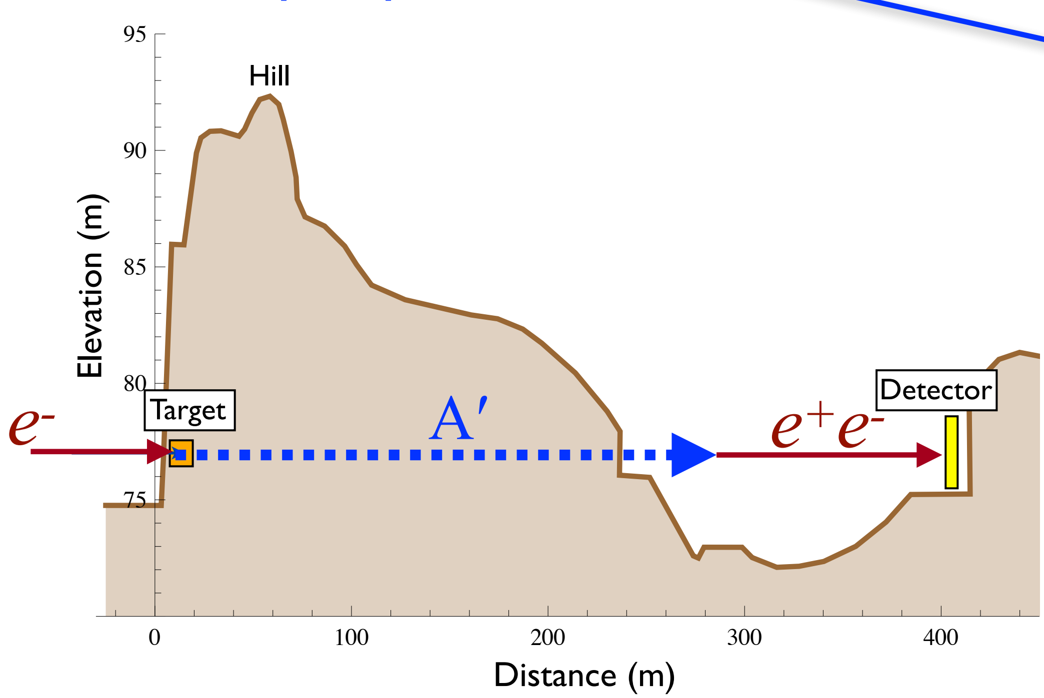


A′ becomes long lived at small couplings.

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

Leads to constraints from "beam dump experiments"



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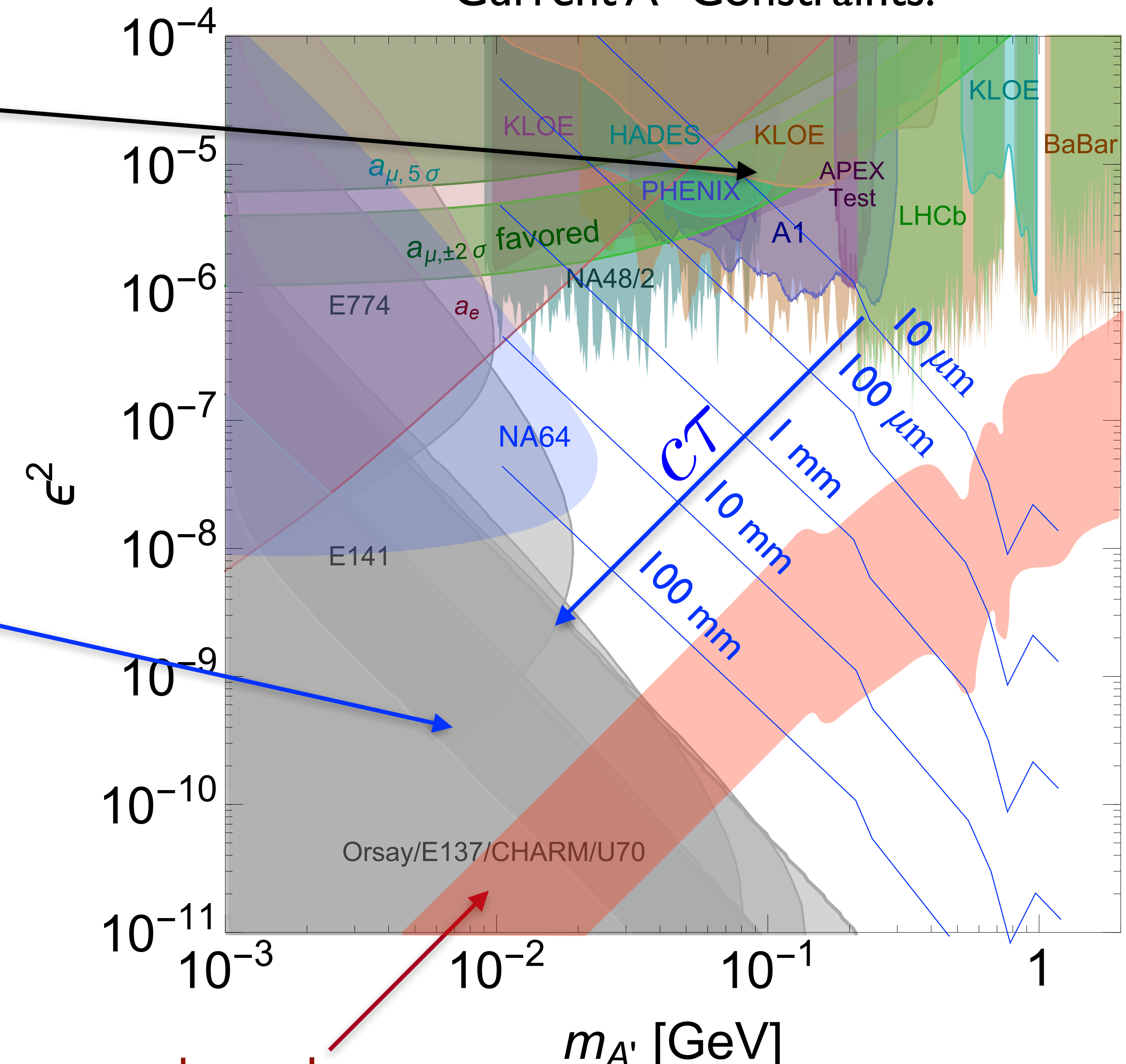

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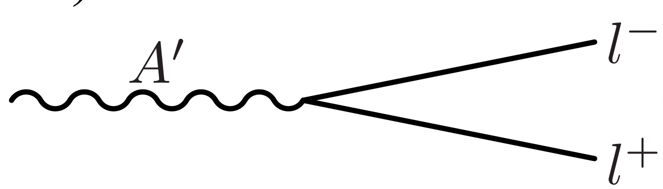

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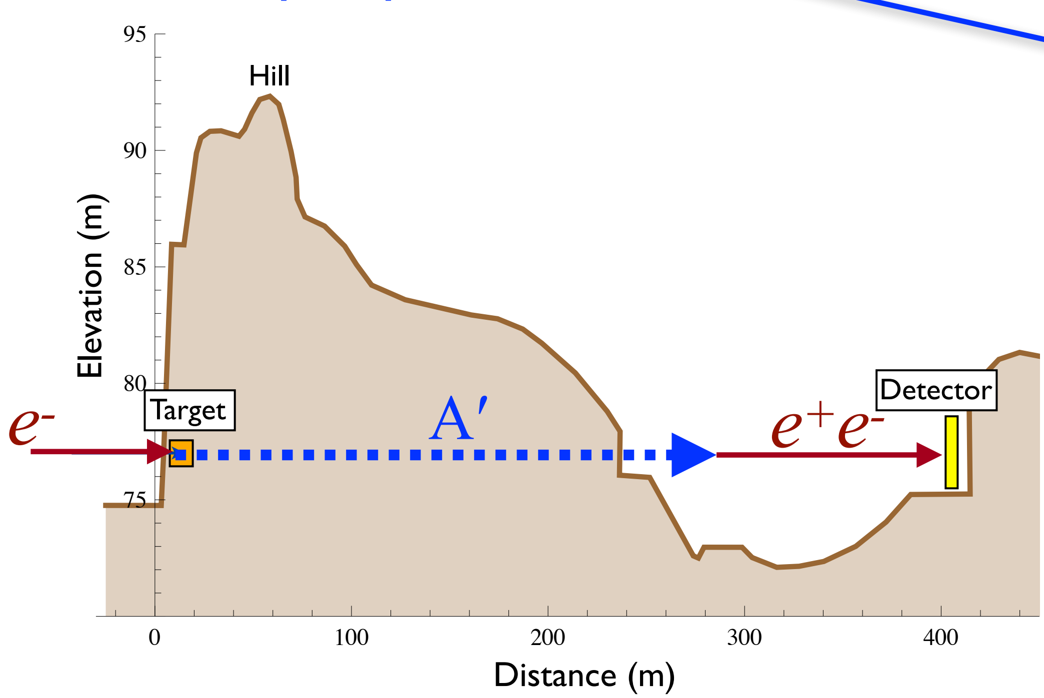

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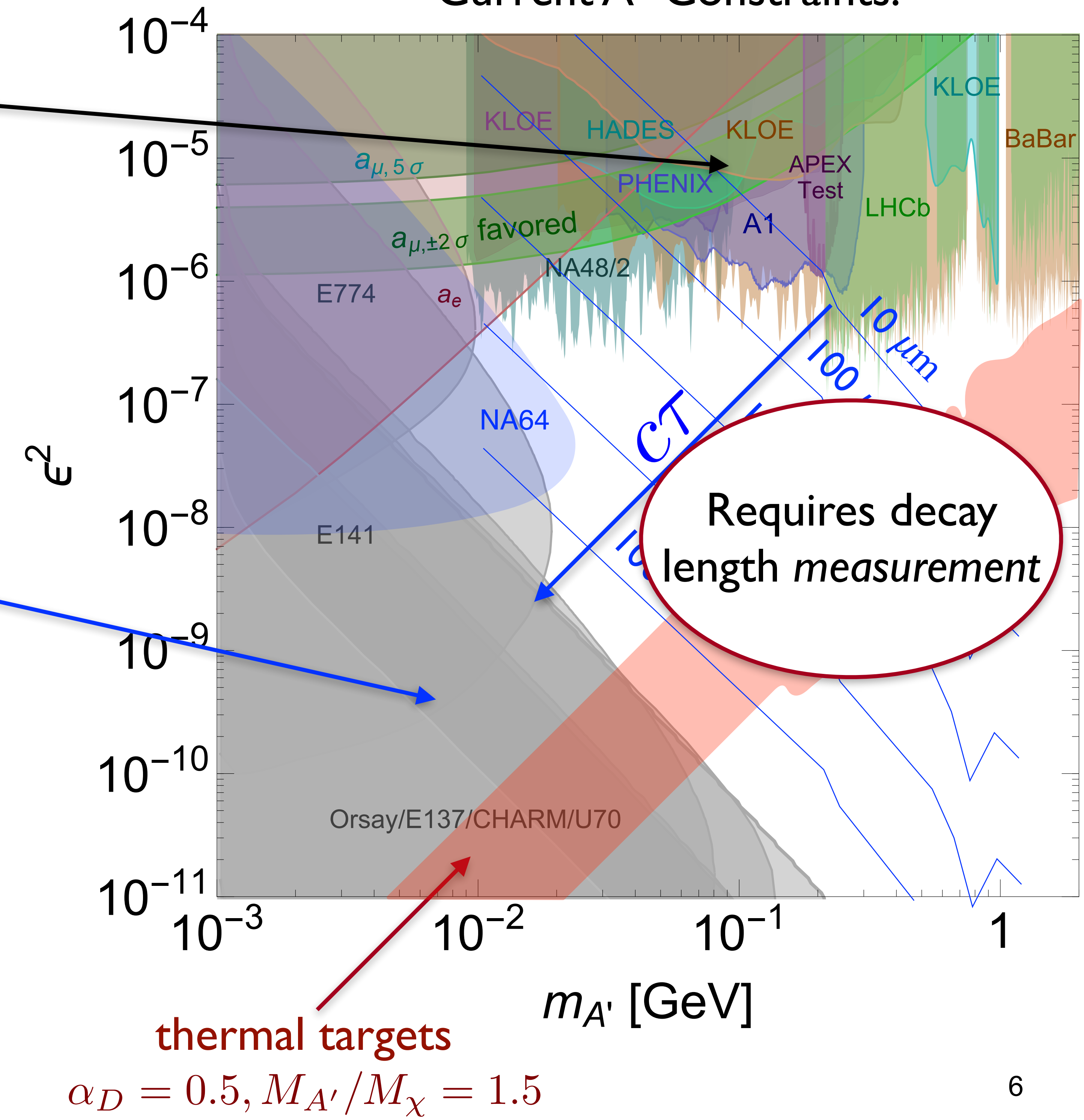
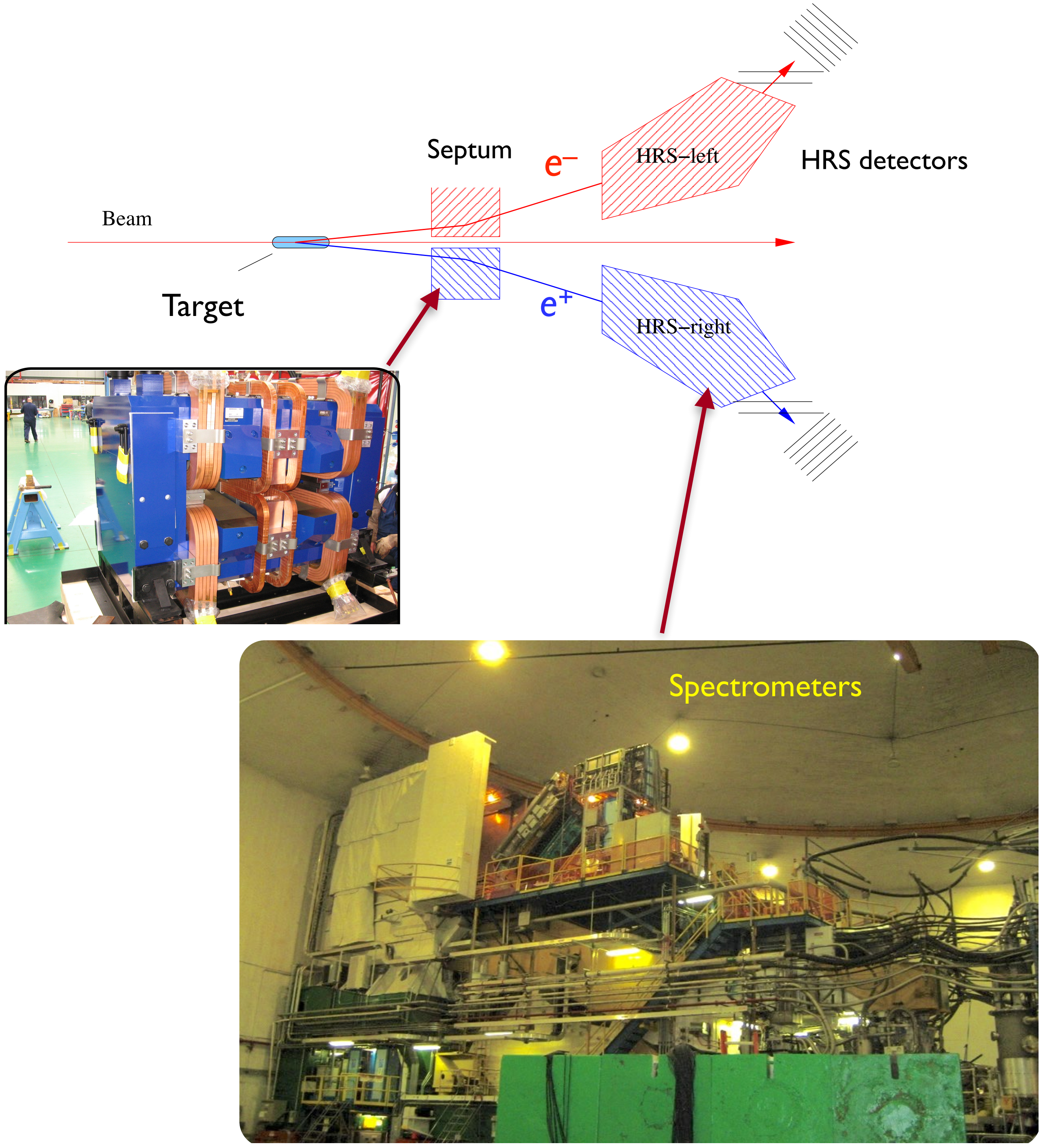
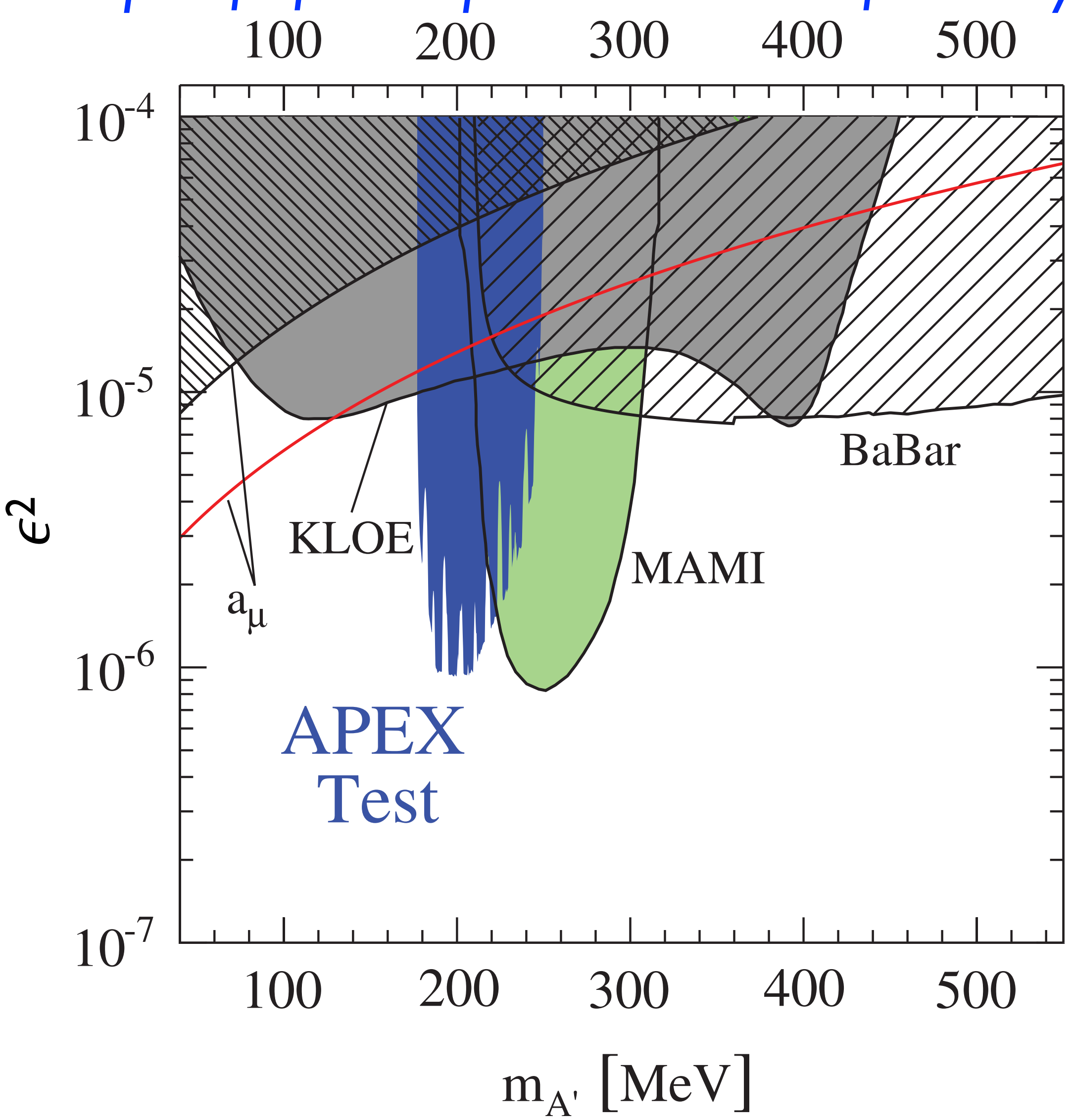


Present - e⁻ Fixed Target: APEX @ JLab CEBAF

Resonance search using Hall A High-Resolution Spectrometers, dark bremsstrahlung production from multi-GeV e⁻ beam



Test run in 2010: proof of concept and technical feasibility



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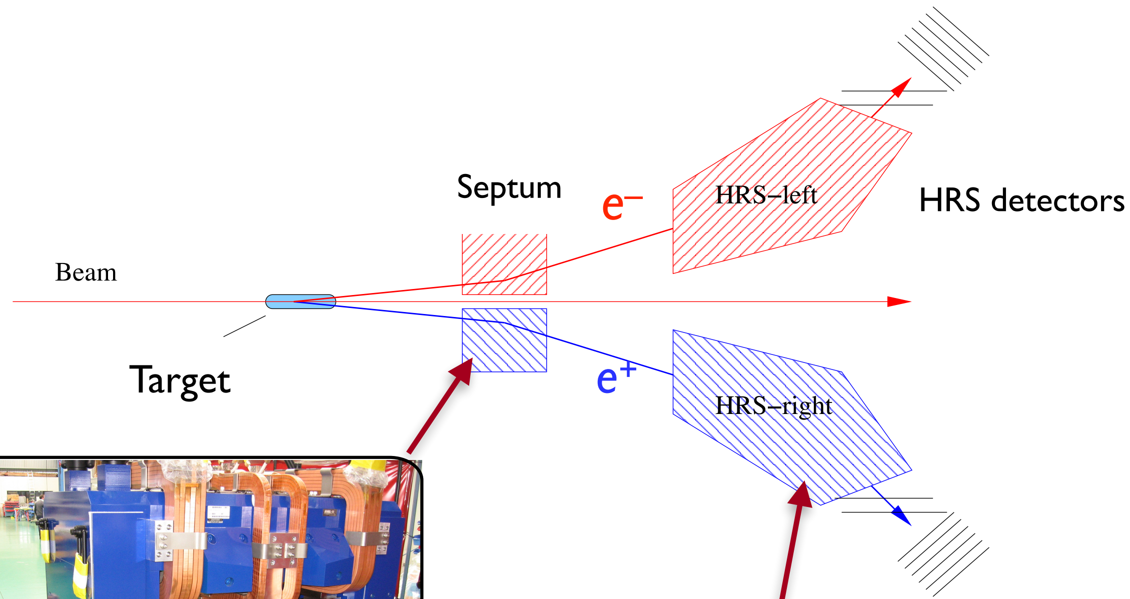
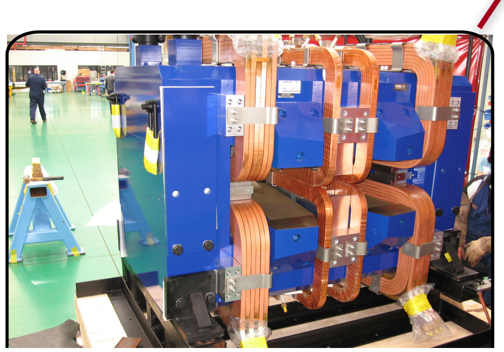
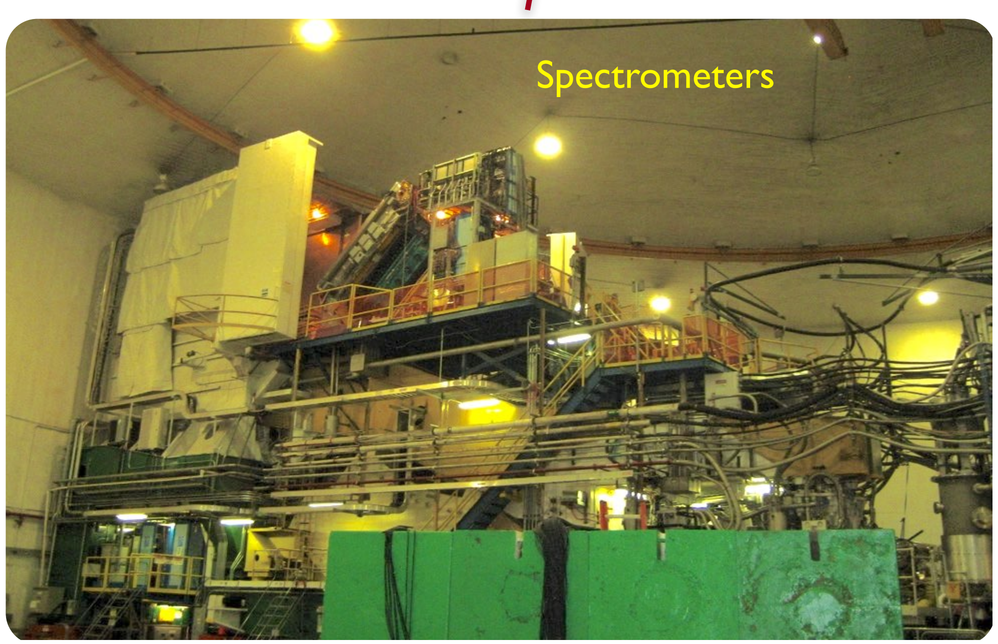
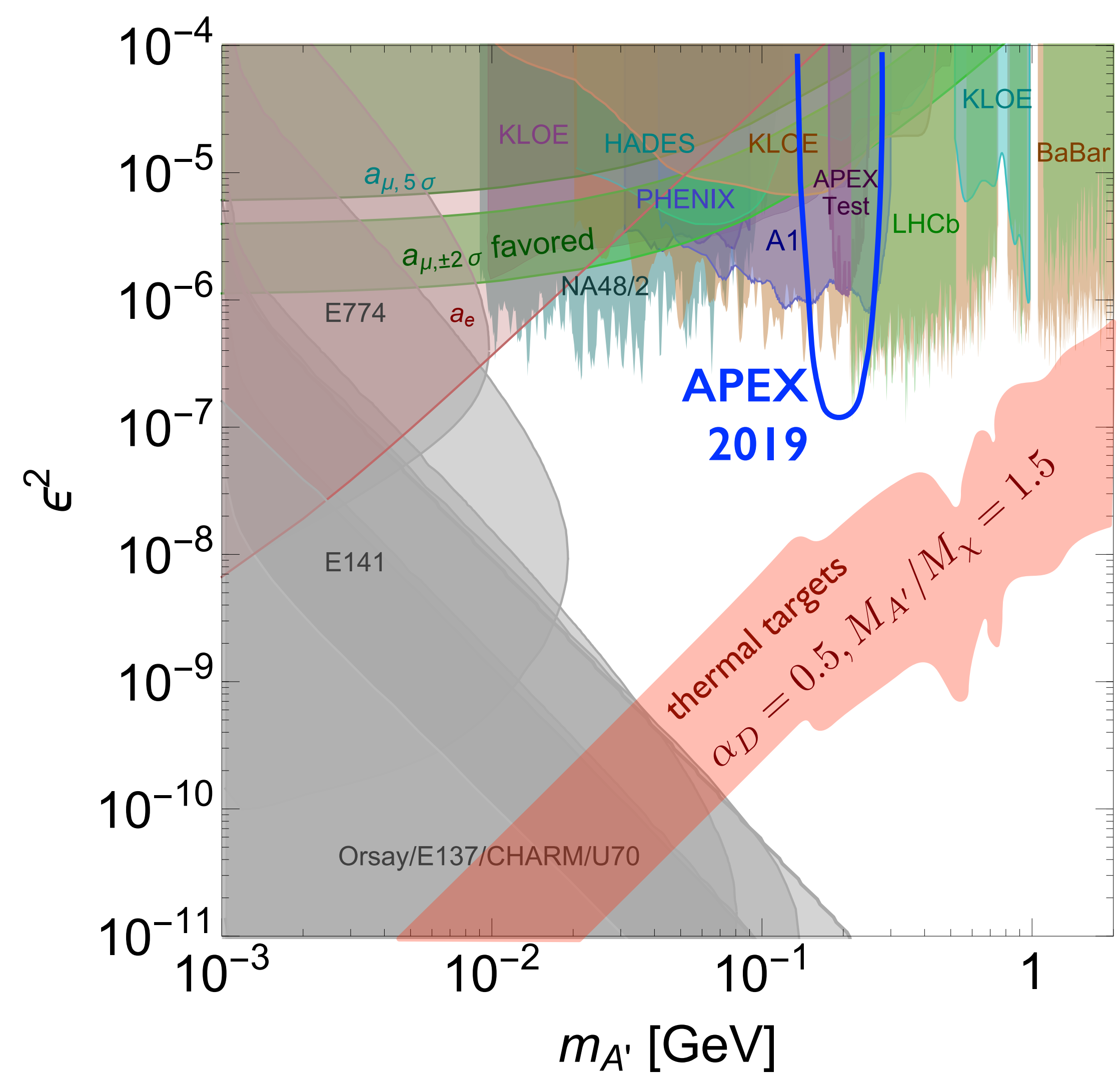






2019 Physics Run *(2/1 - 3/10 2019)*
15 days at E_{beam} = 2.2 GeV

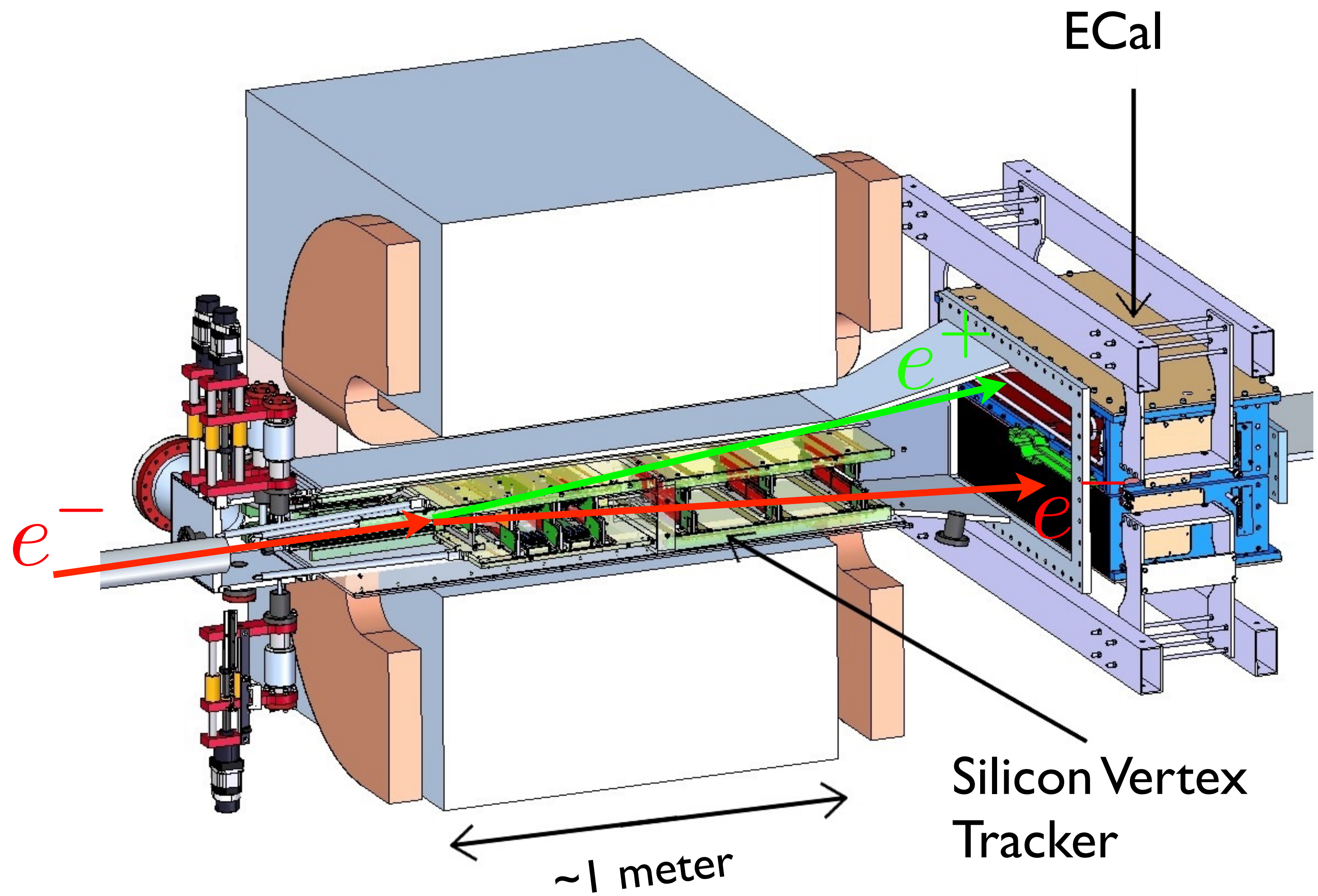


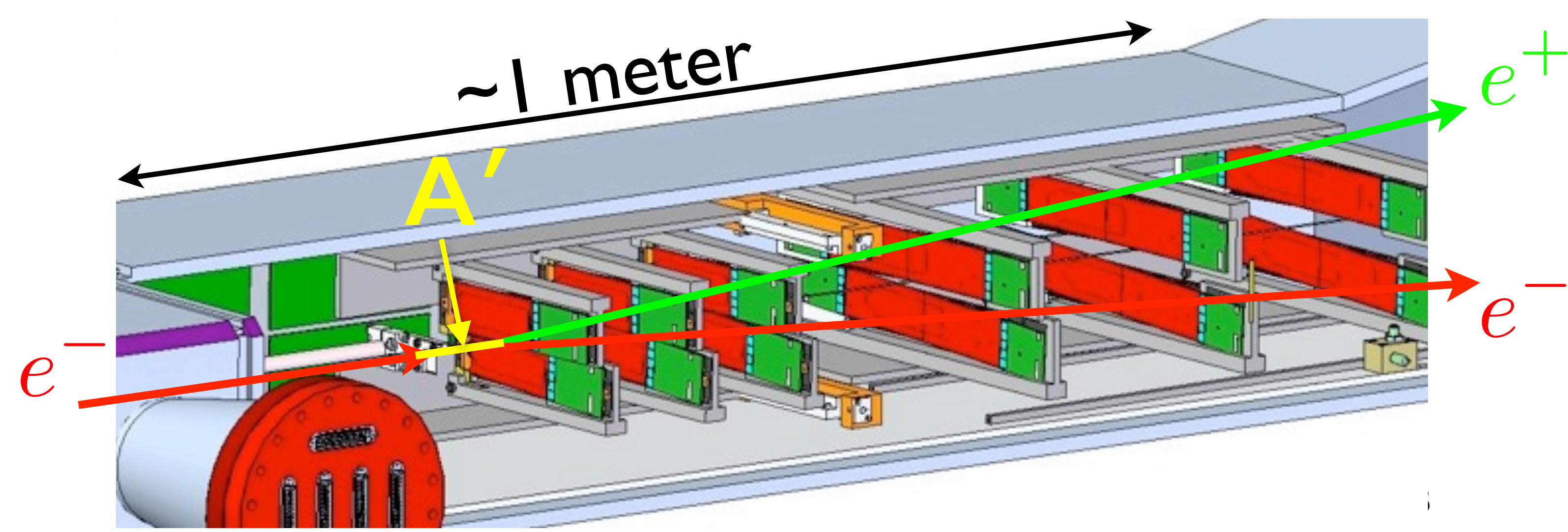
e^- fixed target:
HPS @ JLab CEBAF (present)

Compact e^+e^- spectrometer, immediately downstream of thin target in multi-GeV beam in Hall B.

- Low-mass, high-rate (up to 4 MHz/mm^2) silicon tracker (SVT) allows ***vertexing long-lived A′***. SVT must suppress SM tridents from target by factor ~10^7
- $PbWO_4$ ECal trigger eliminates 10's MHz scattered single e^-.

Short engineering runs in 2015 (1.7 days) and 2016 (5.4 days)





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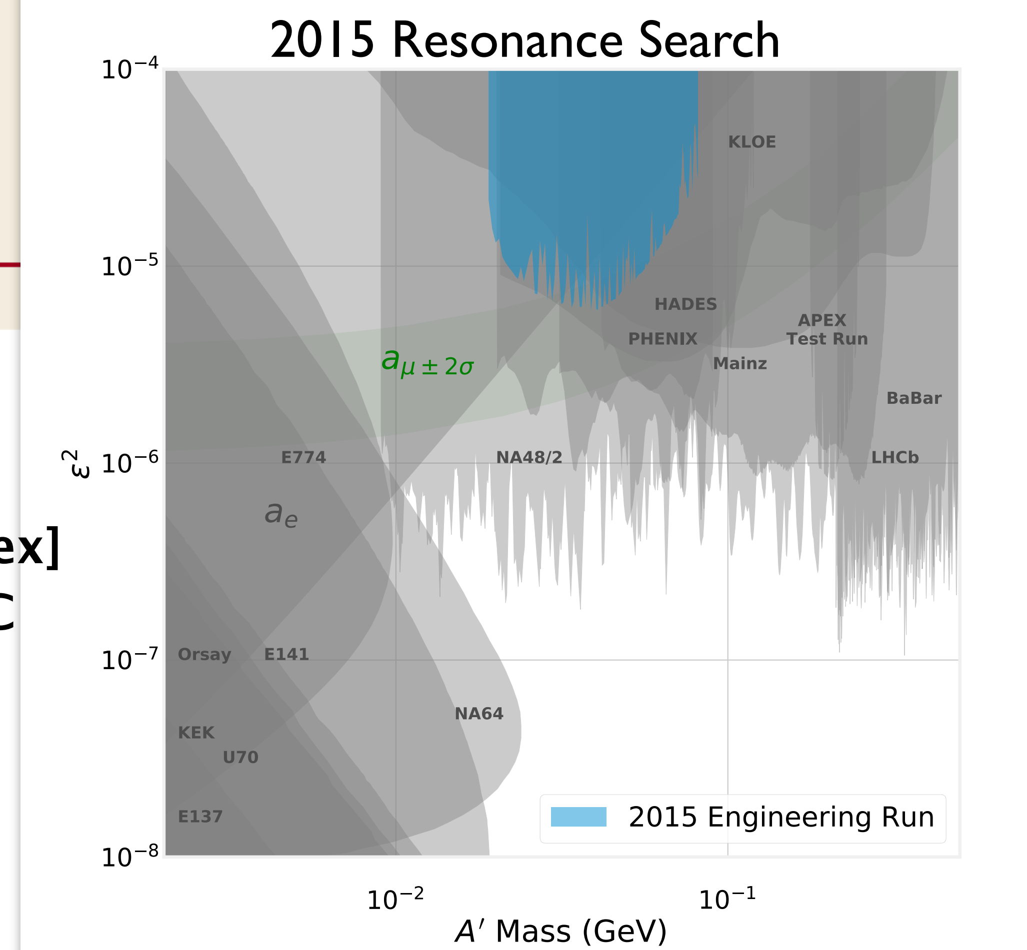
arXiv:1807.11530 **[hep-ex]**
under review for PRD RC



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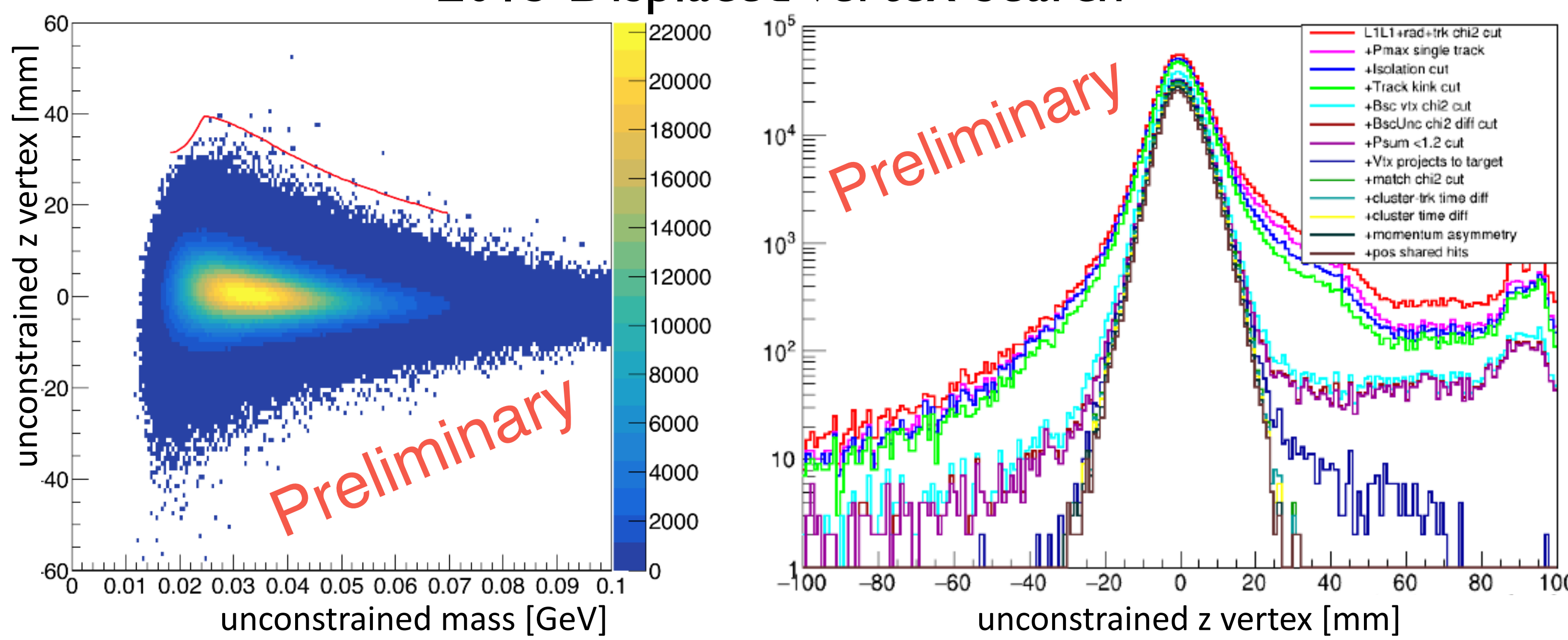
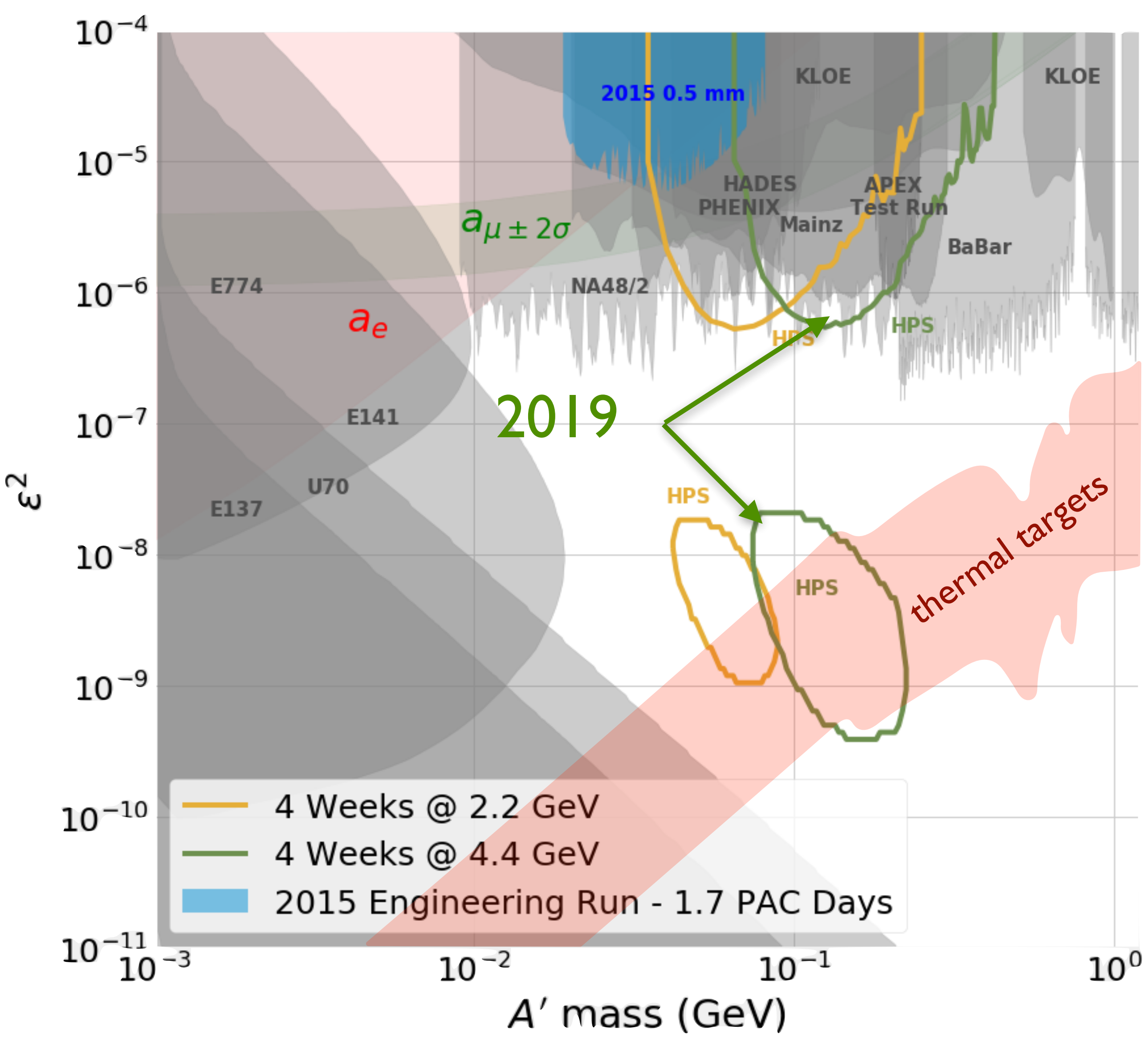
2015 Displaced Vertex Search



No new sensitivity for minimal dark photons, but analyses prove concept in advance of physics runs.

e⁻ fixed target: HPS @ JLab CEBAF (present)

First physics run scheduled for 6/10 — 8/4/2019
8 weeks at 4.55 GeV, ≈ 4 weeks of data = 0.7 C (50% typical duty cycle)

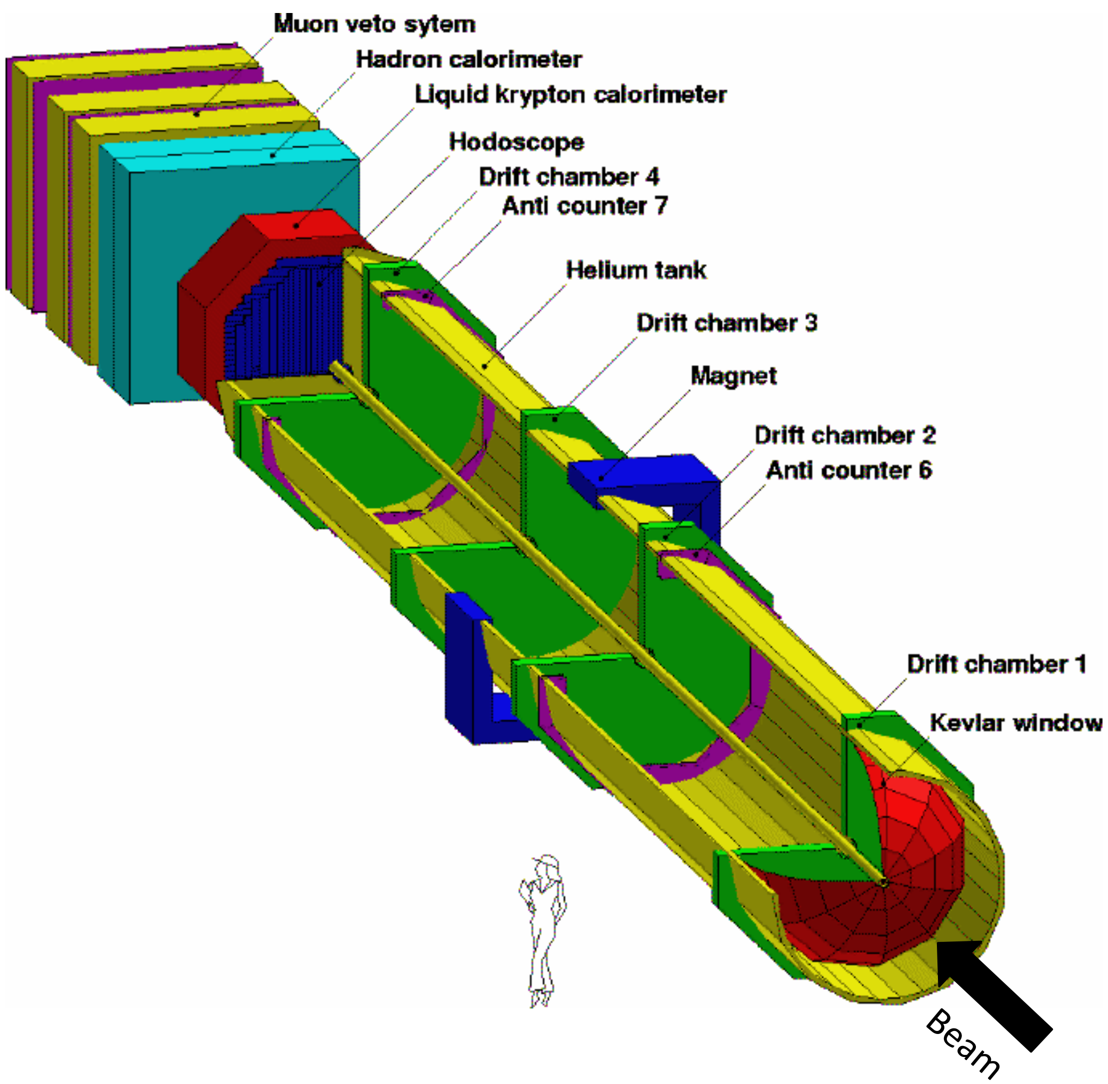


HPS will request similar runs in 2020 and 2021 at 2.2/6.6 GeV

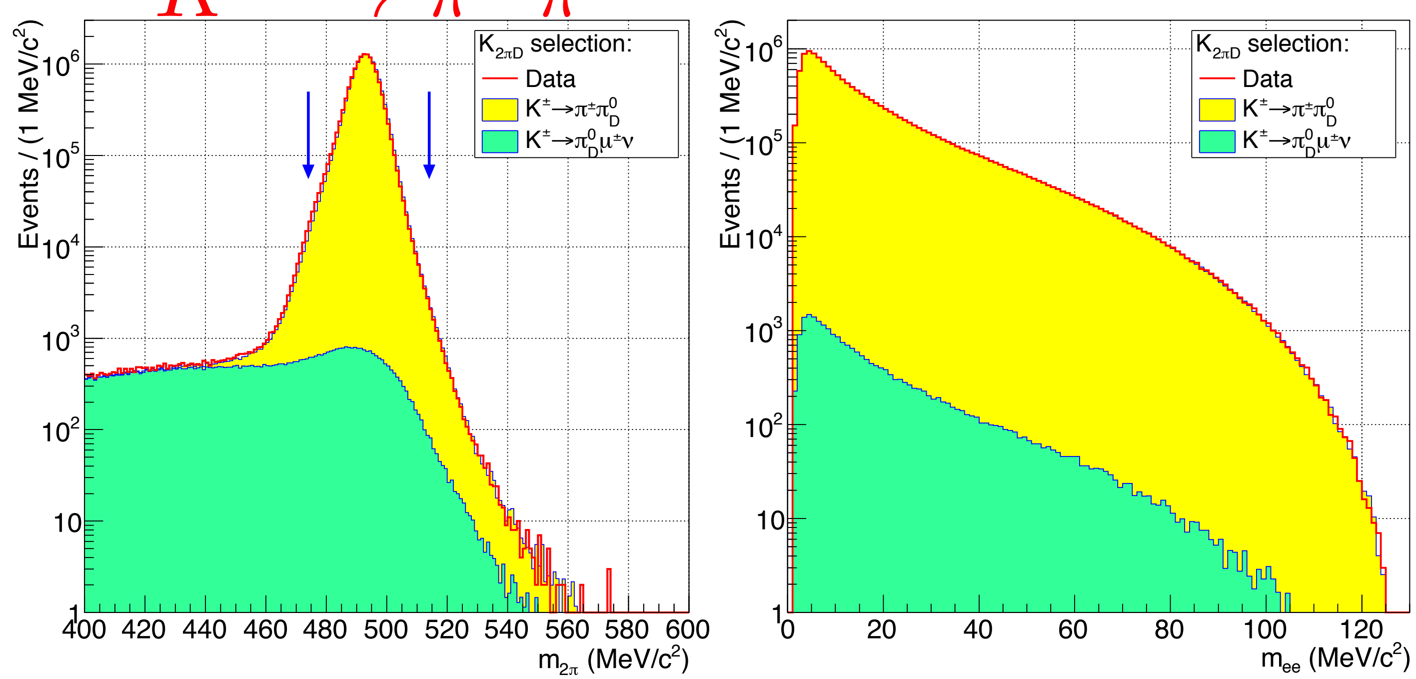
p^+ fixed target:
NA48/2 @ SPS (2015)

CERN SPS Kaon CP-violation/rare decay experiment collected a large sample of π^0

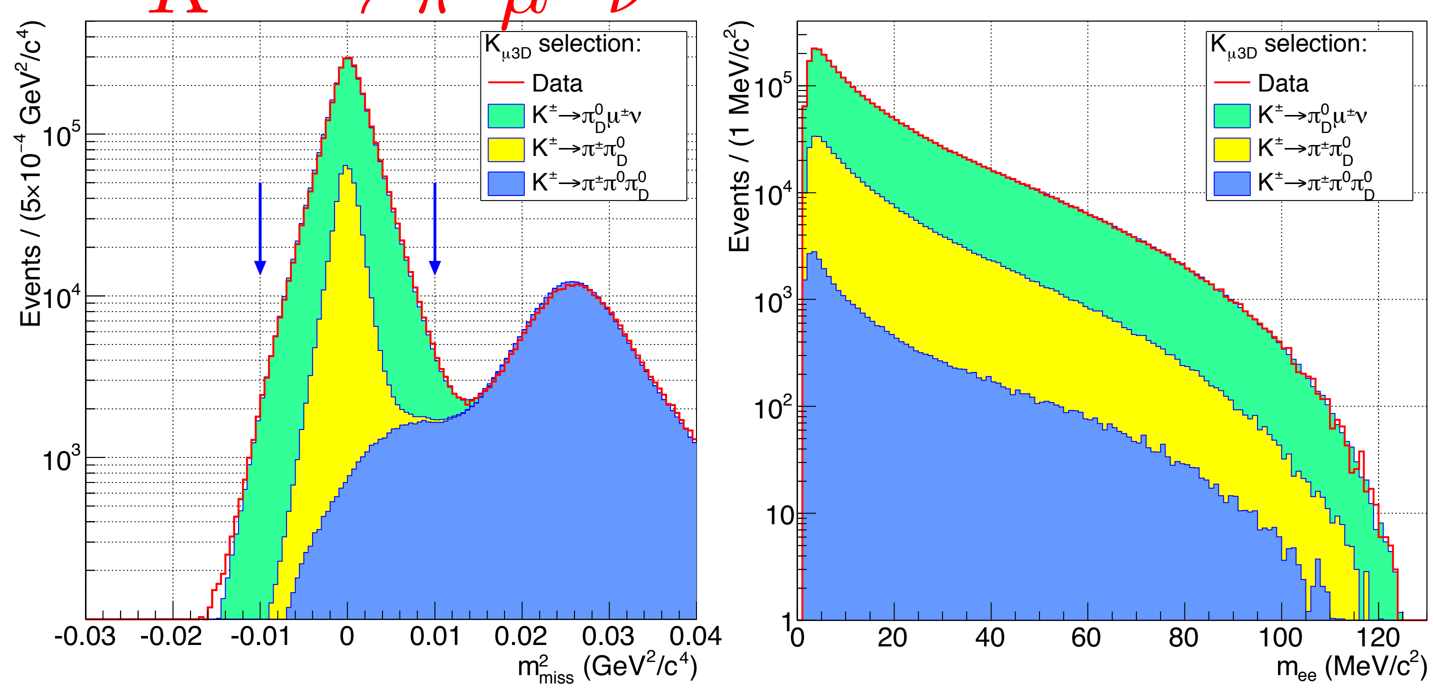
$$\pi^0 \to \gamma A' \to \gamma e^+ e^-$$



$K^\pm \to \pi^\pm \pi^0$



$K^\pm \to \pi^0 \mu^\pm \nu$



The NA48/2 Collaboration, Phys. Lett. B 746 (2015) 178

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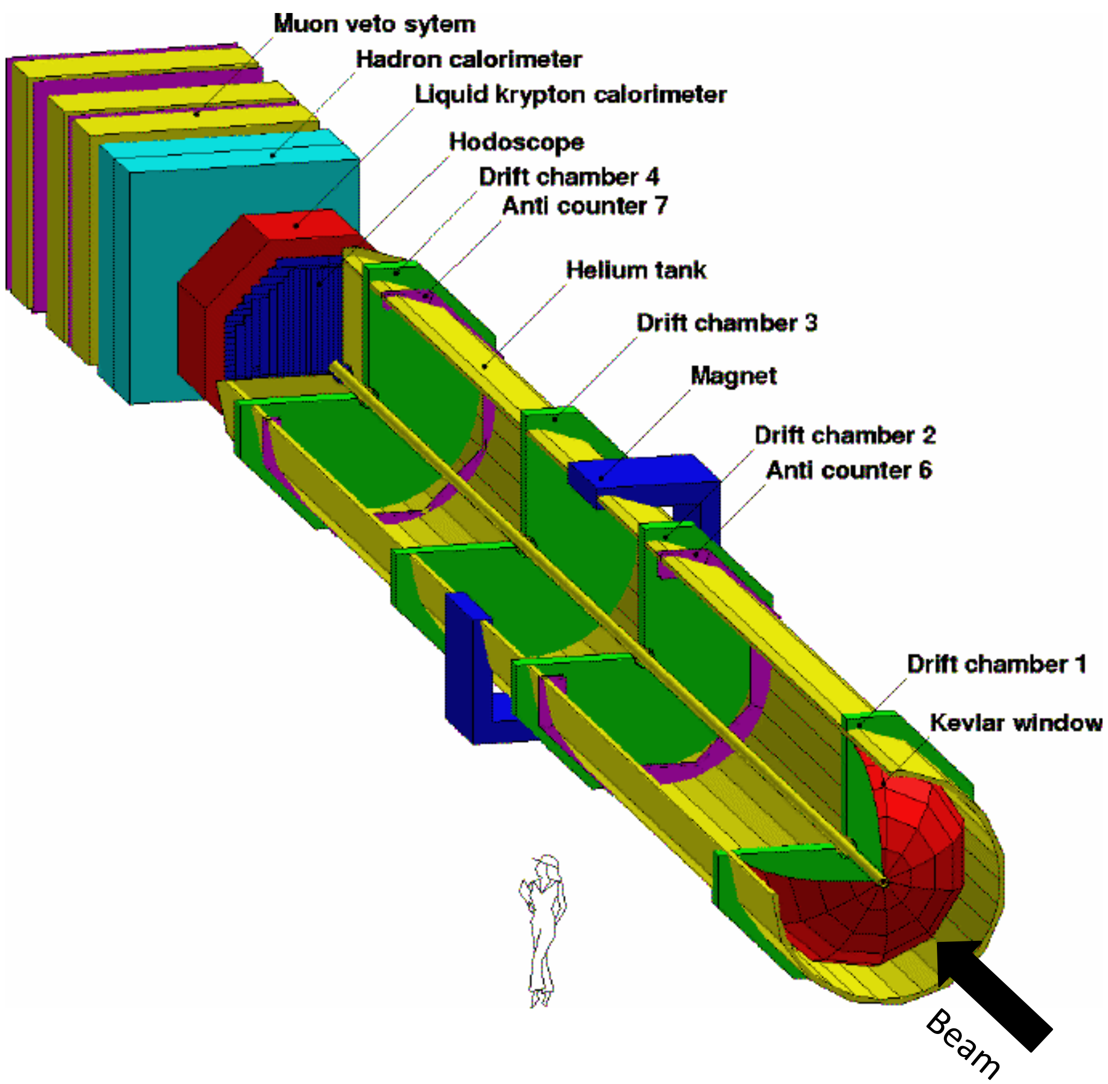

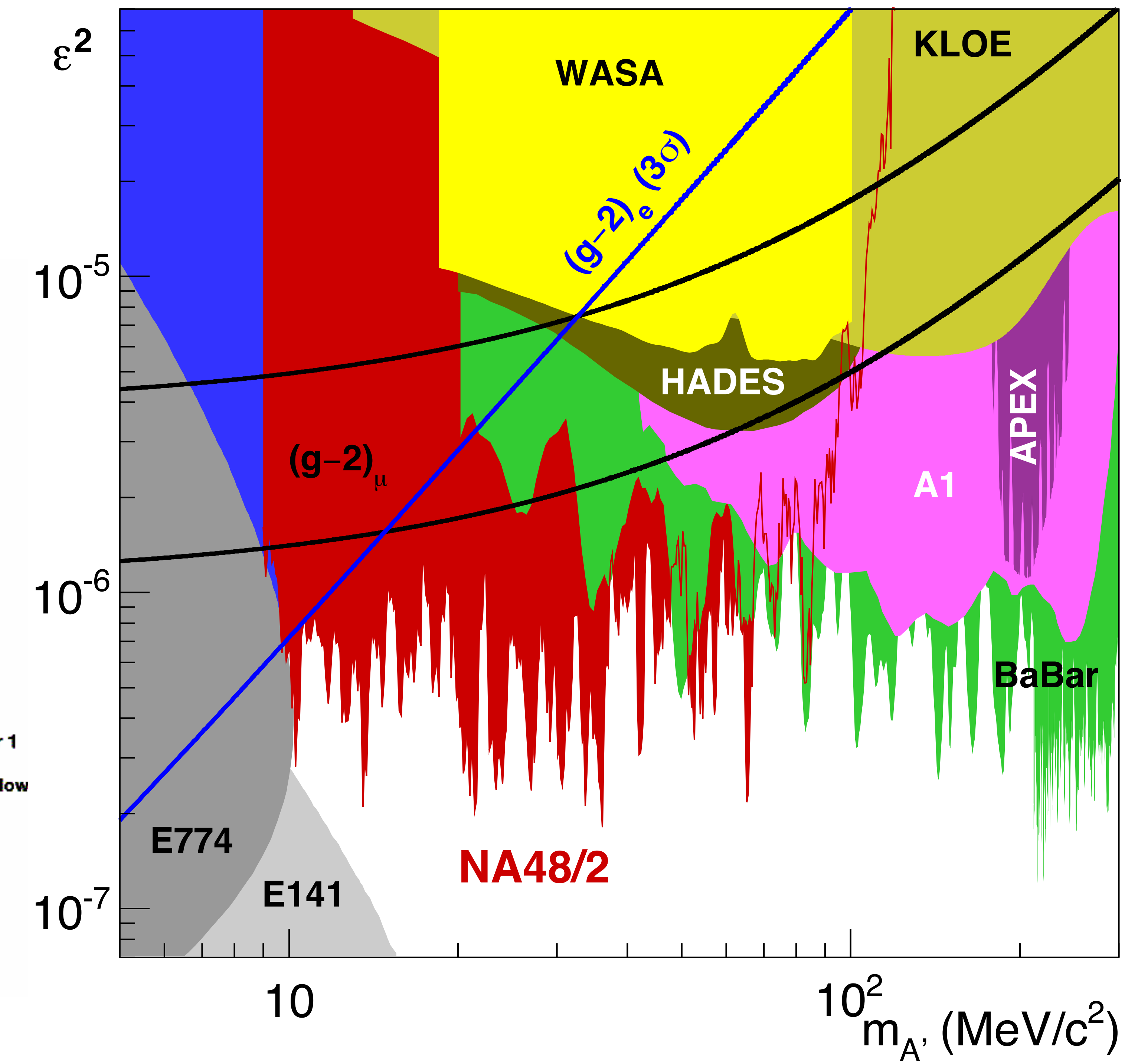

The NA48/2 Collaboration, Phys. Lett. B 746 (2015) 178

e^+ fixed target:
PADME @ Frascati (present), VEPP-3 @ BINP(?), MMAPS @ Cornell (?)

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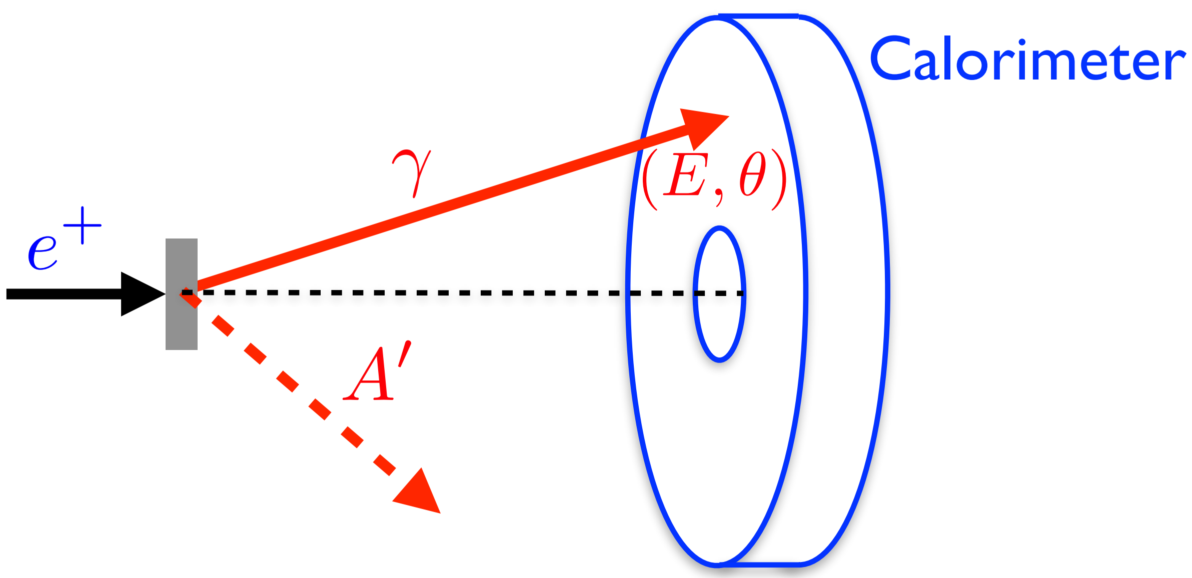
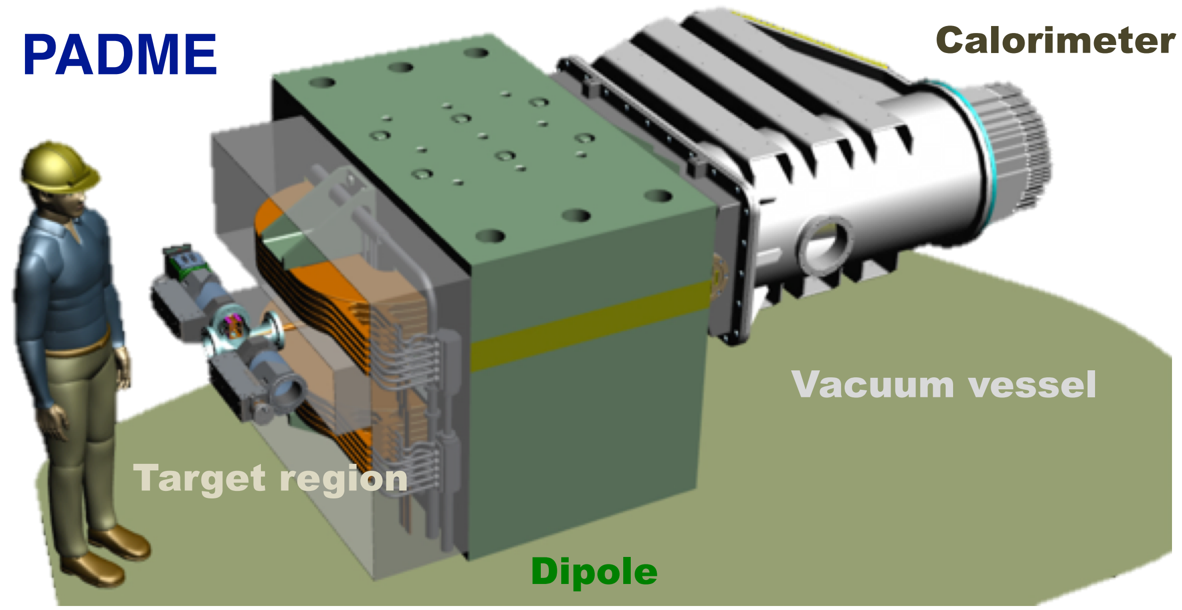
Reconstruction of A' mass without measurement of decay products. Sensitivity to both visible and invisible mediator decays.

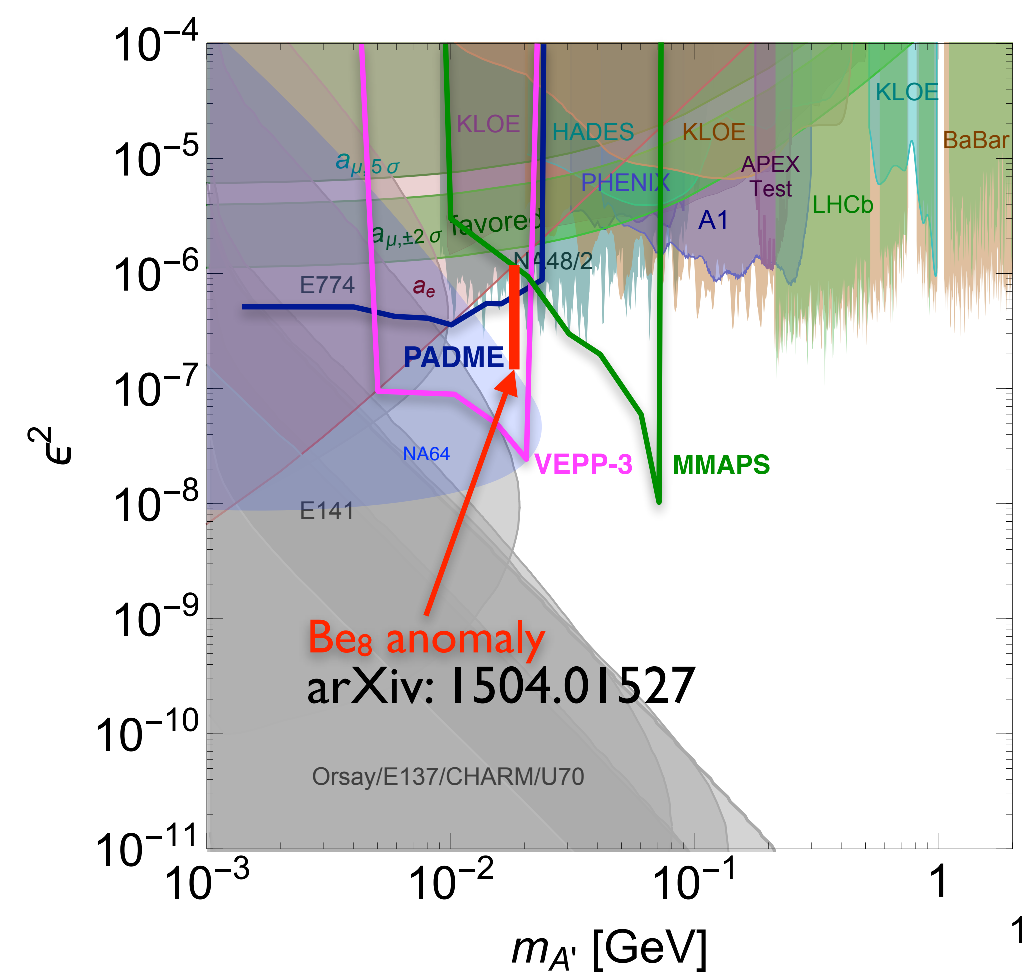
$$e^+e^- \to \gamma + X$$



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

Missing mass also proposed by VEPP-3 @ BINP and MMAPS @ Cornell

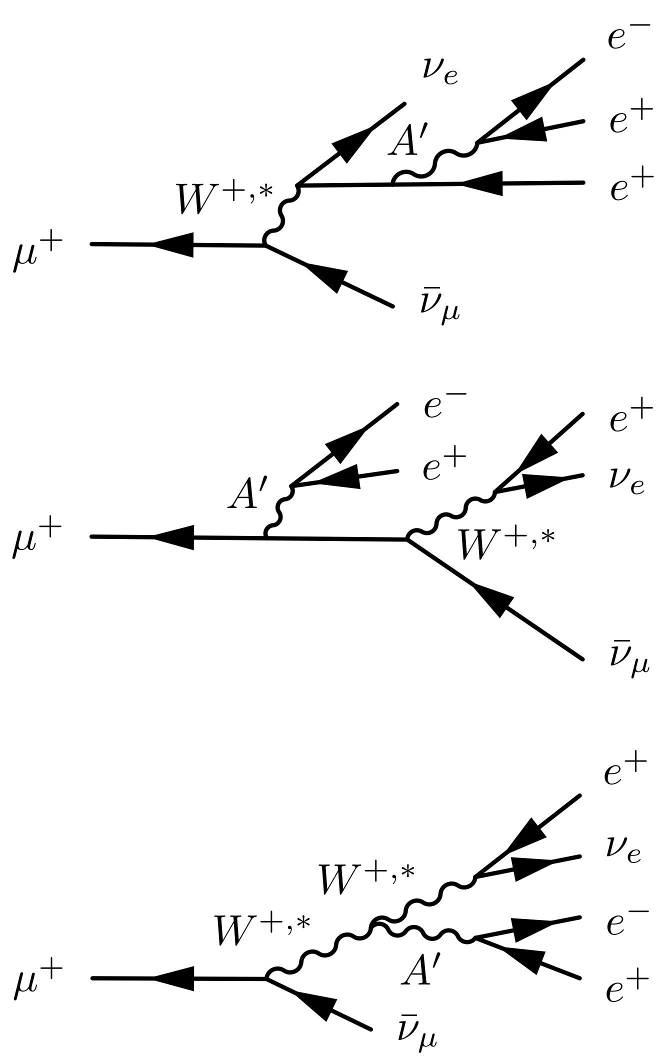


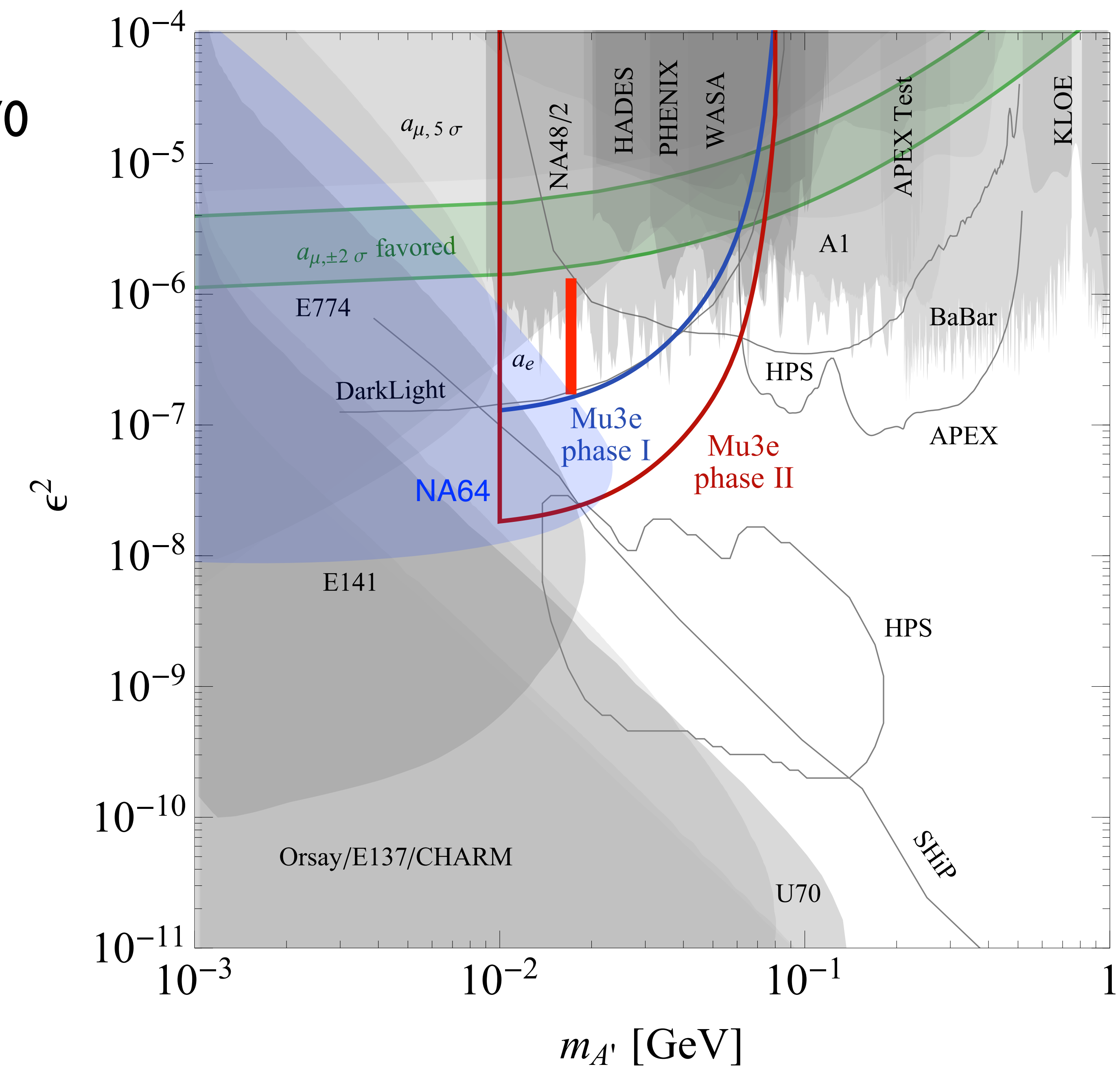


μ^+ beam ISR/FSR: mu3e (2020?)

Experiment at PSI using secondary muon beam to search for $\mu^+ \to e^+ e^- e^+$ with up to 5×10^{16} μ

arXiv: 1411.1770





Can definitively cover Be_8 anomaly

e^- beam dumps (1980-1991)

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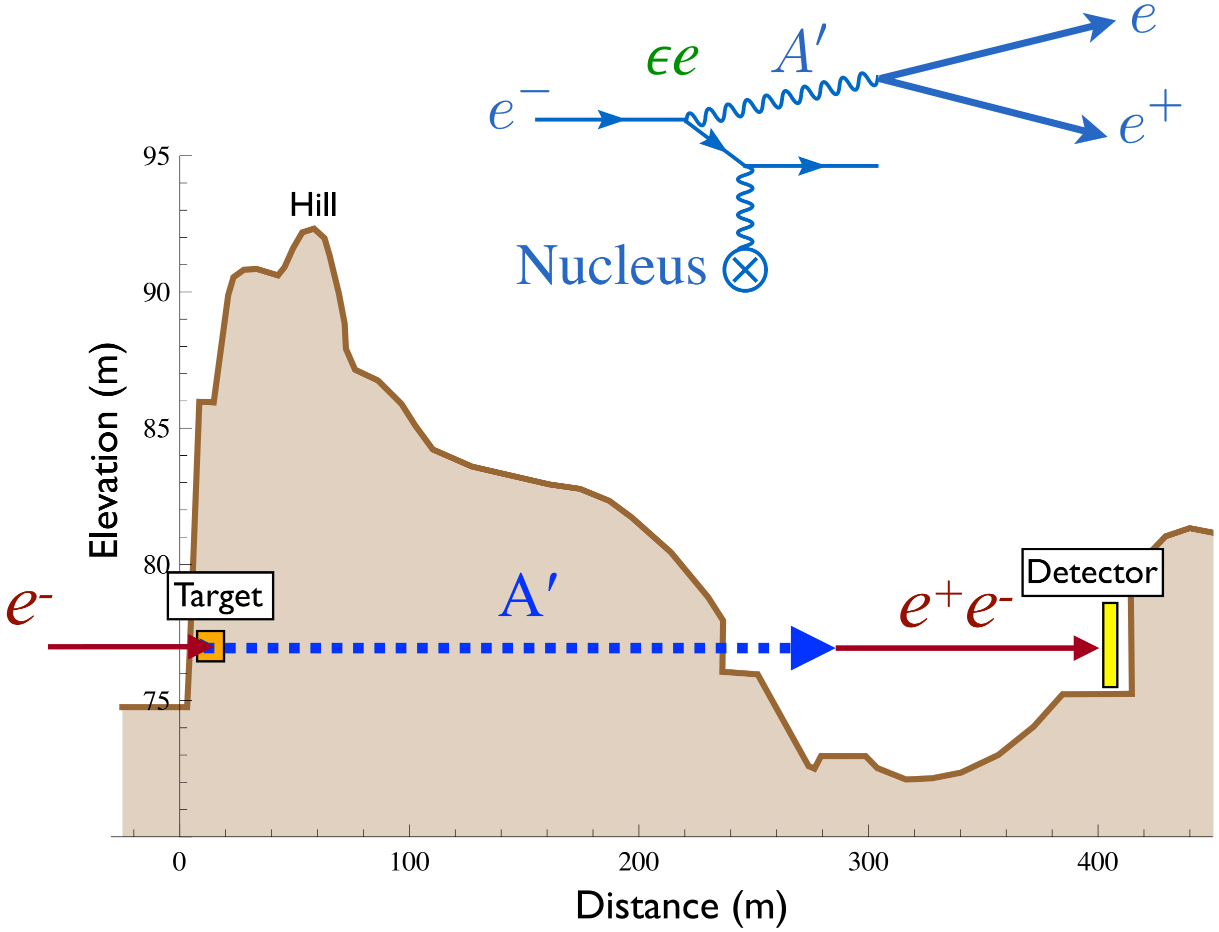
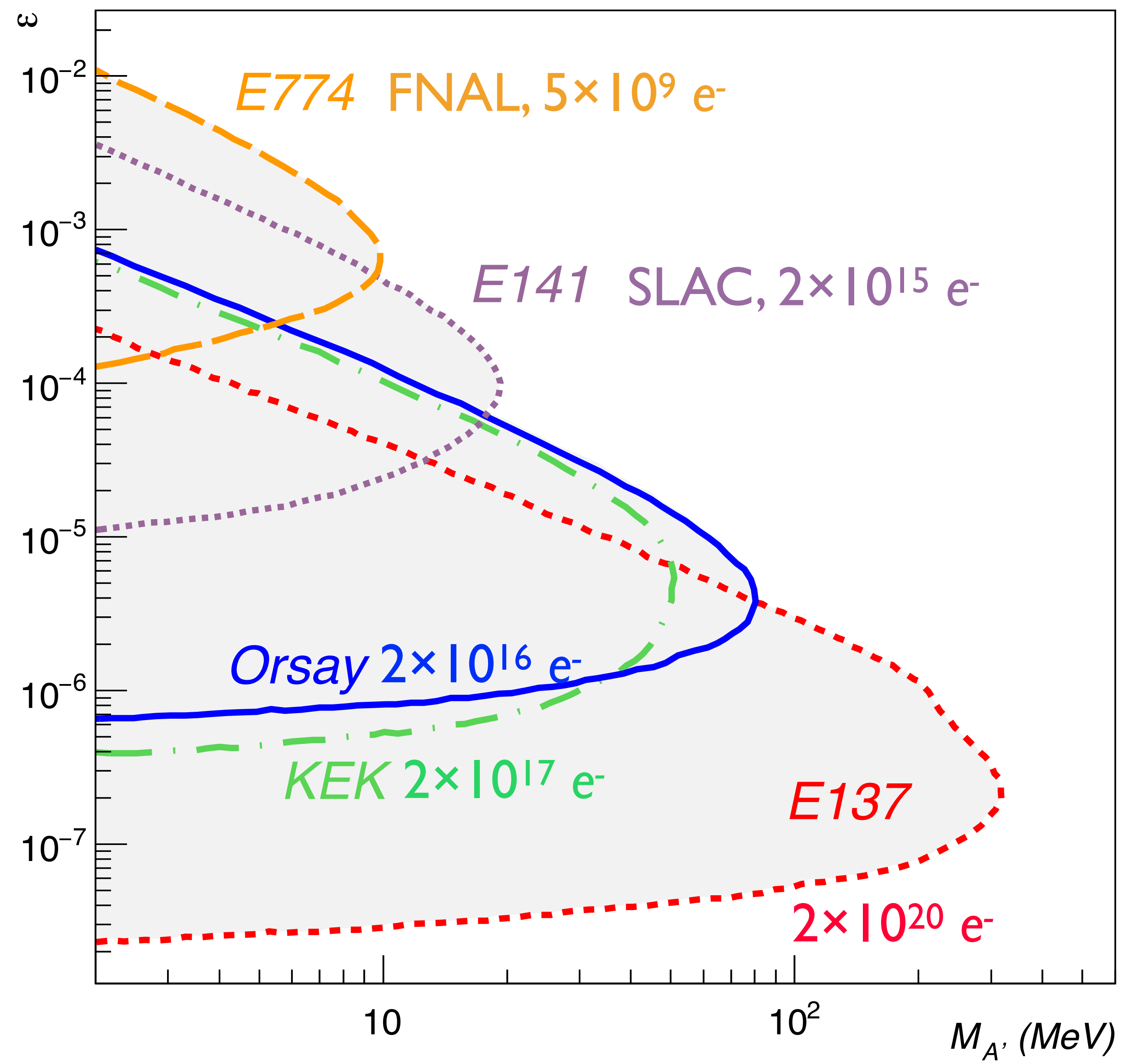
SLAC E137: search for metastable particles run during 1980-1982(!)

- 2×10^{20} e^- (30 C) @ 20 GeV
- 179 meter shield





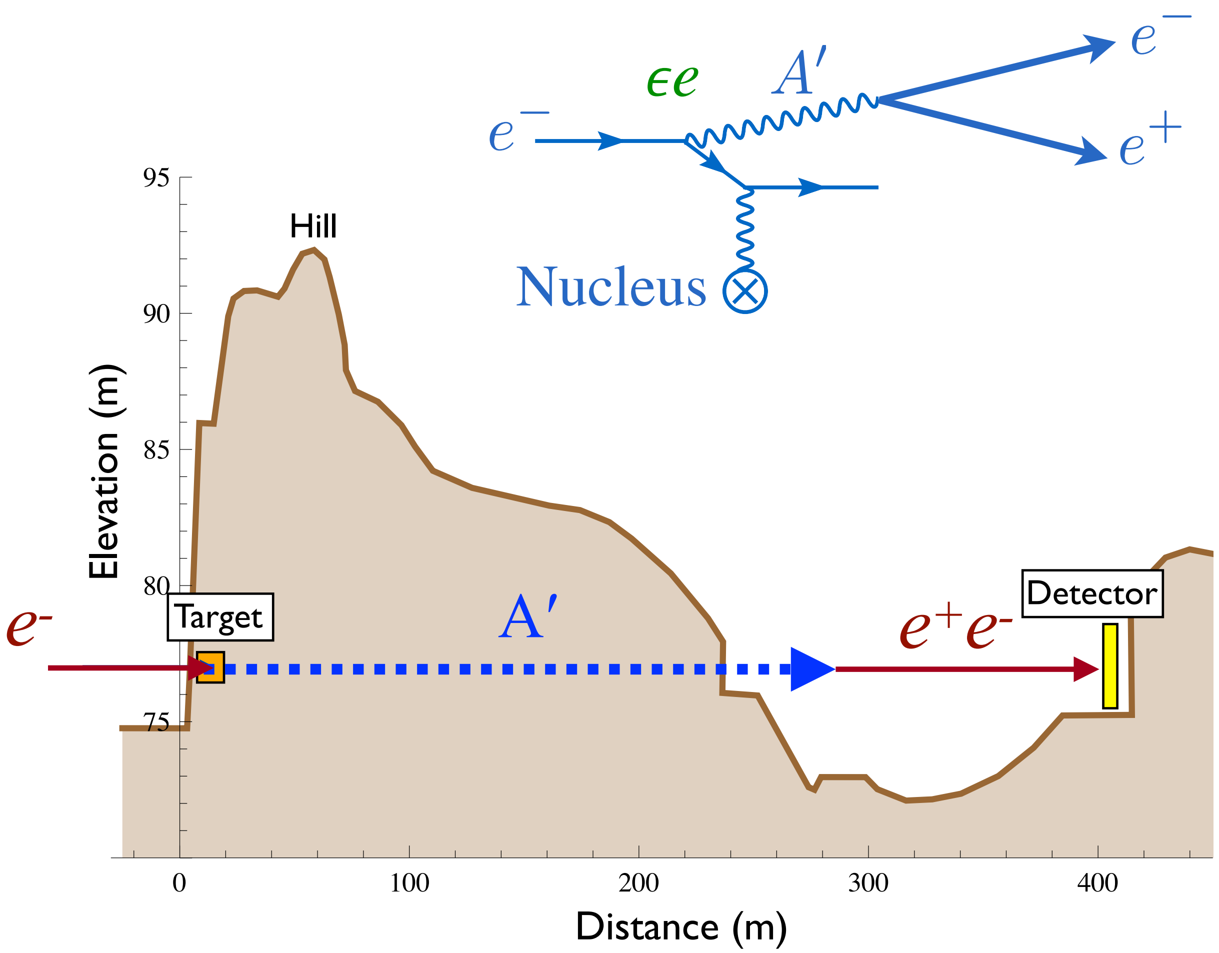
Still the best limits in parts of parameter space for many dark sector models!

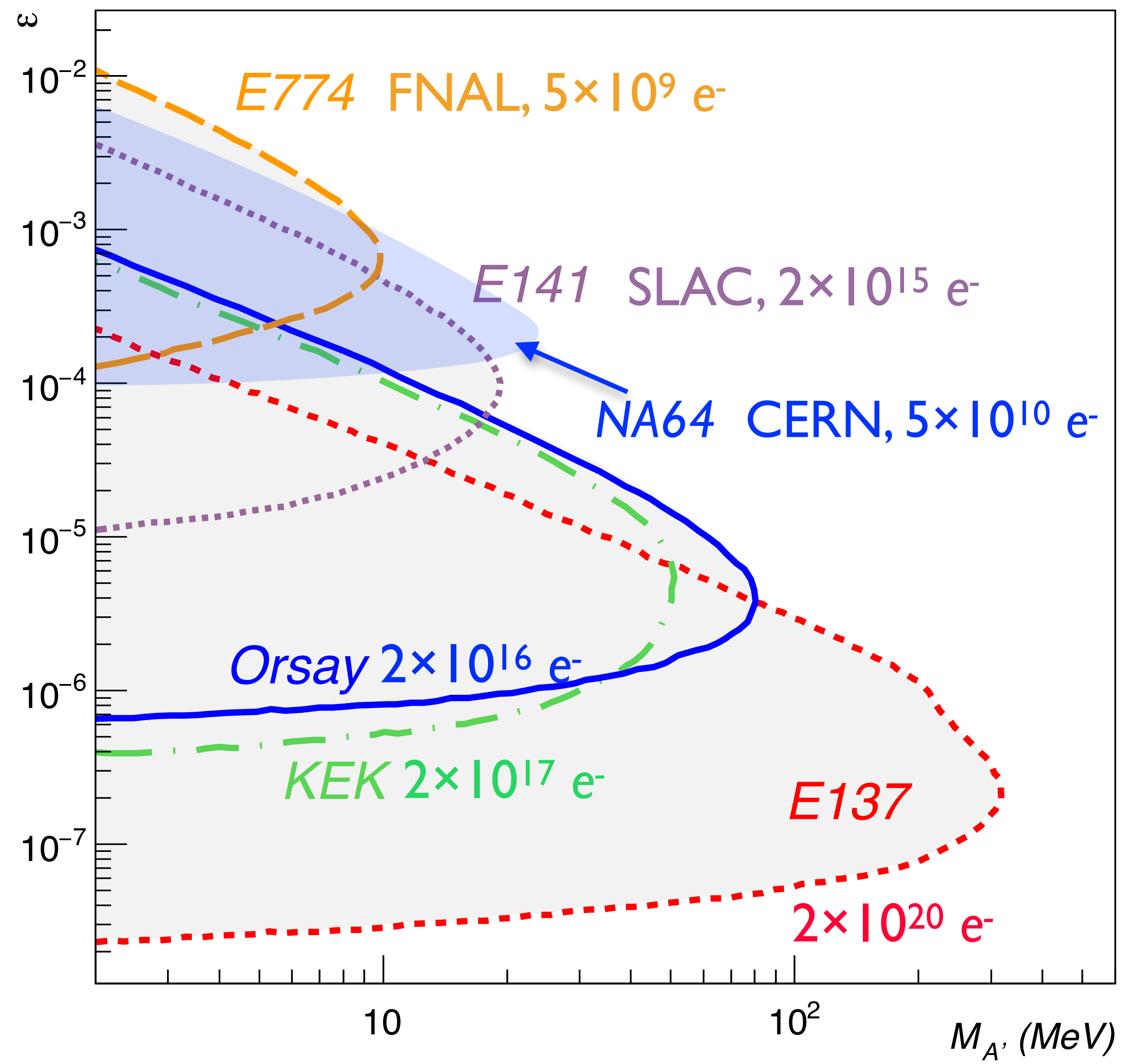
e.g. arXiv: 1209.6083, 1406.2698, 1802.03794

e⁻ beam dumps (1980-1991) + 2018

SLAC E137: search for metastable particles run during 1980-1982(!)

- 2×10^{20} e⁻ (30 C) @ 20 GeV
- 179 meter shield





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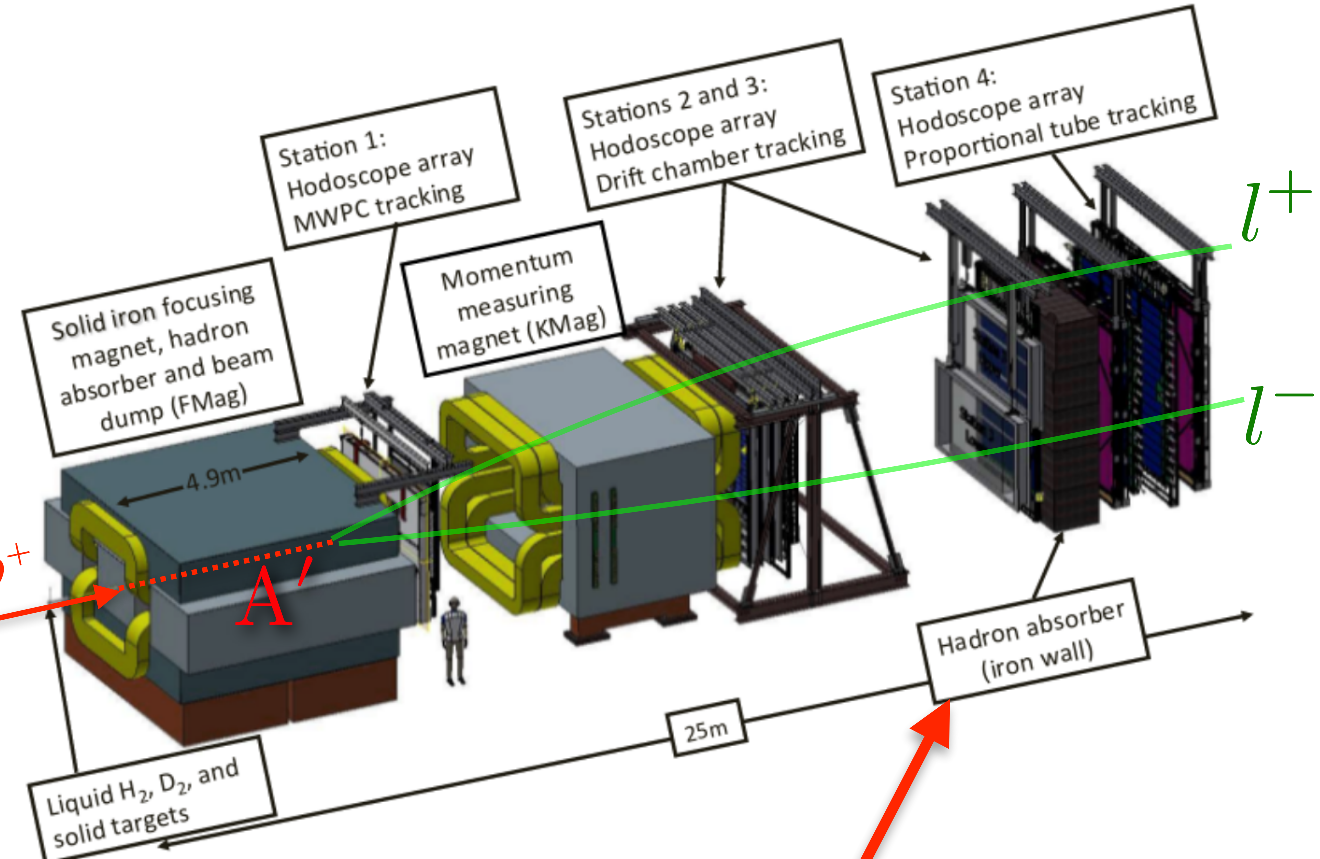
p^+ beam dump:
SeaQuest @ FNAL (2019 $\mu^+\mu^-$) (2021? e^+e^-)

SLAC

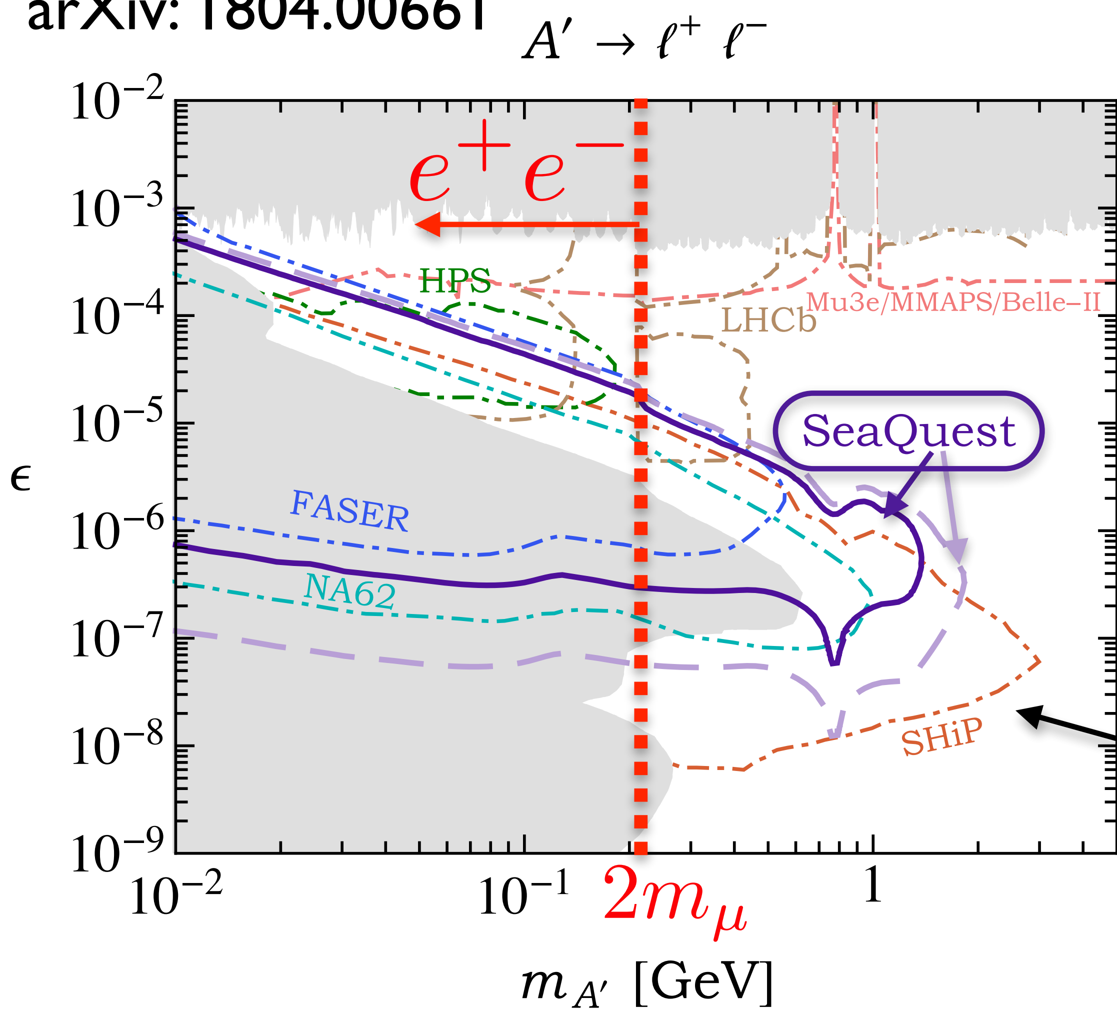
Fixed target muon spectrometer for Drell-Yan sea quark measurements at FNAL

Parasitic program of dark photon searches with addition of displaced vertex trigger.

Shallow dump + large boost accesses larger couplings than previous dump experiments



arXiv: 1804.00661



Potential future upgrade to replace Hadron absorber with EMCal to enable reach below $2m_\mu$

Very similar: NA62, SHiP

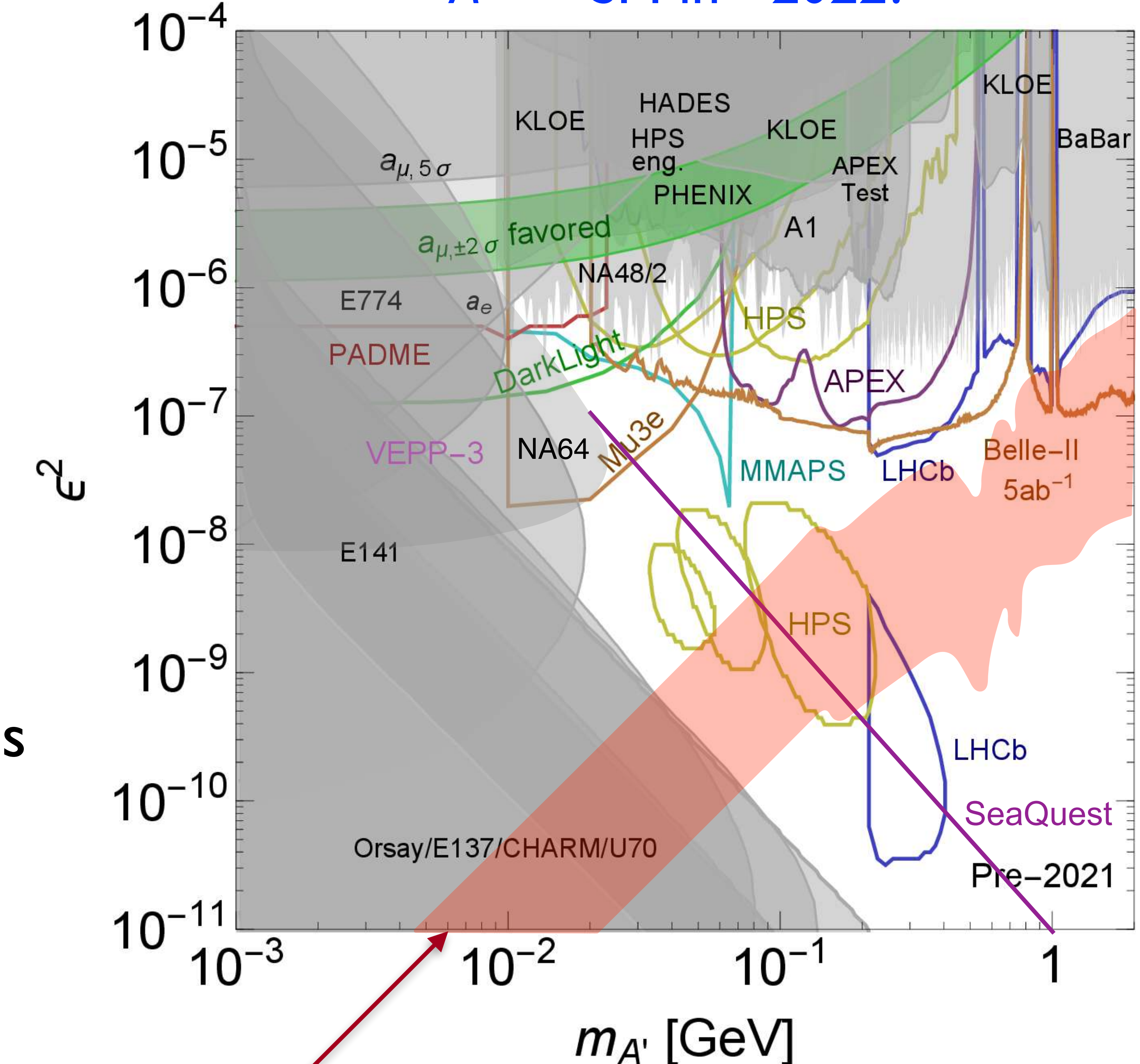
Summary: Dark Mediator Decays to Standard Model

A number of initiatives are making progress

In the next few years, much of this territory will be explored.

With LHC Run 3 data, LHCb may cover most of what remains here w/ $M_{A'} < 500$ MeV

$A' \to$ SM in ~2022?



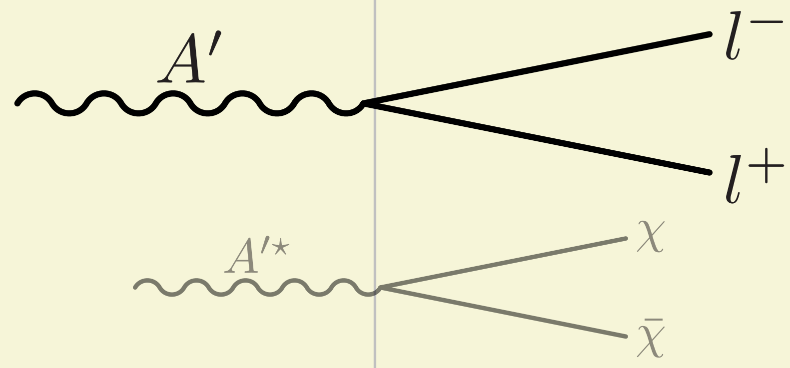
thermal targets
$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$

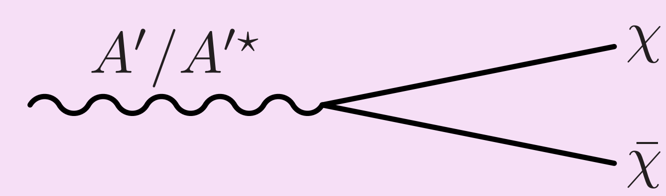
Mass Hierarchy Determines Search Strategy

SLAC

$m_{A'}$ — m_χ — $2m_\chi$

Mediator decay in experiments





Search: ***for mediators decaying to SM***

****or off-shell to DM***

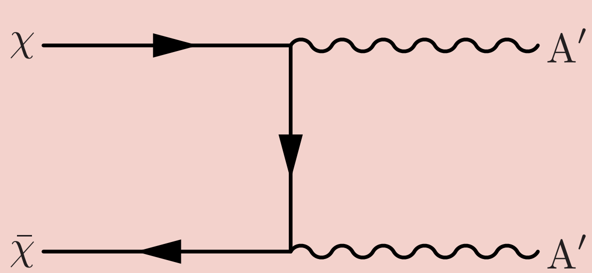
for production of DM

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

Dominant DM annihilation:

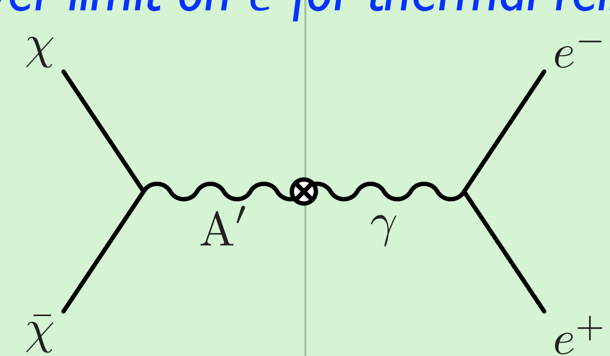
$$\sigma v \propto \alpha_D^2$$

no clear target for ϵ



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

lower limit on ϵ for thermal relics



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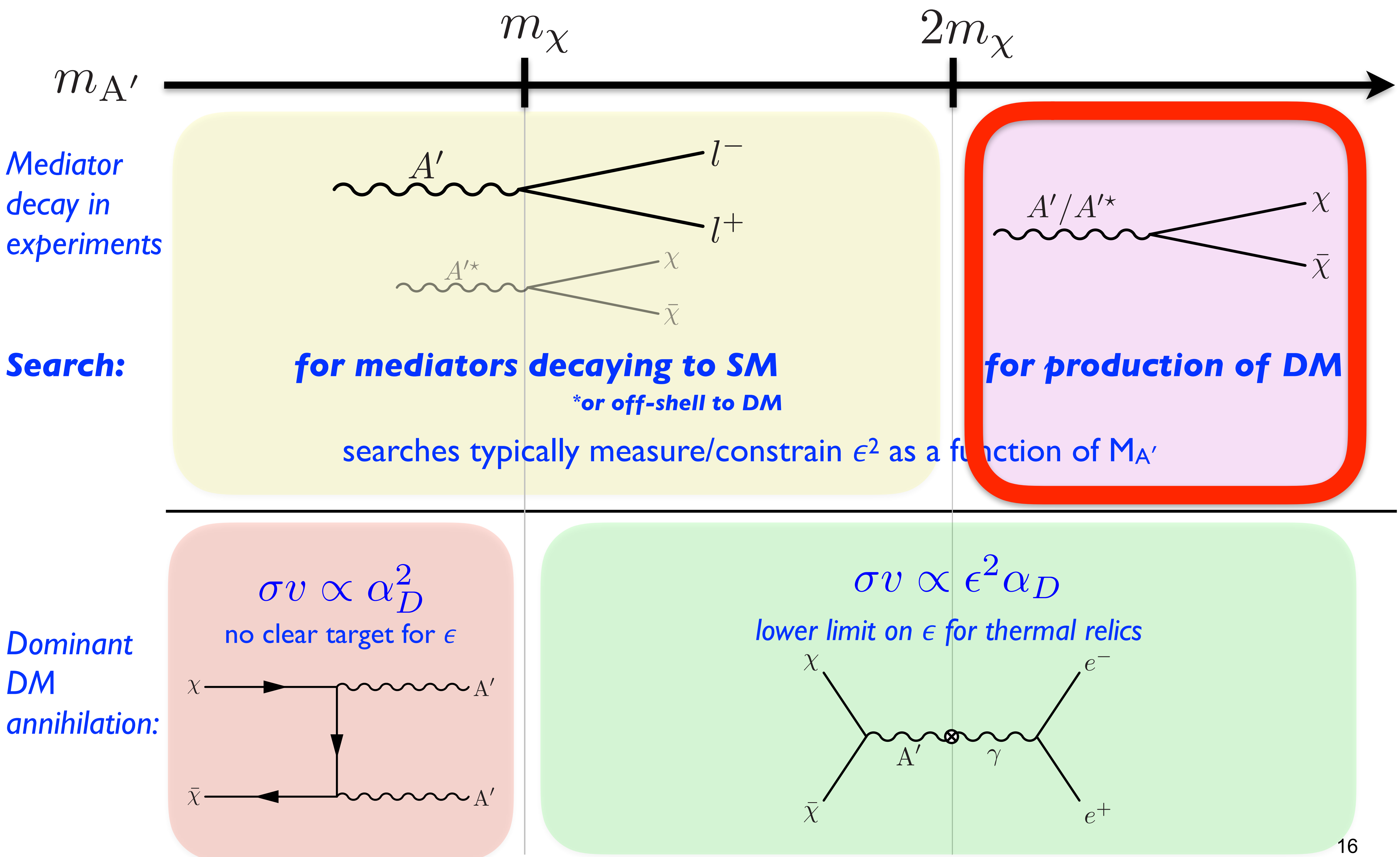
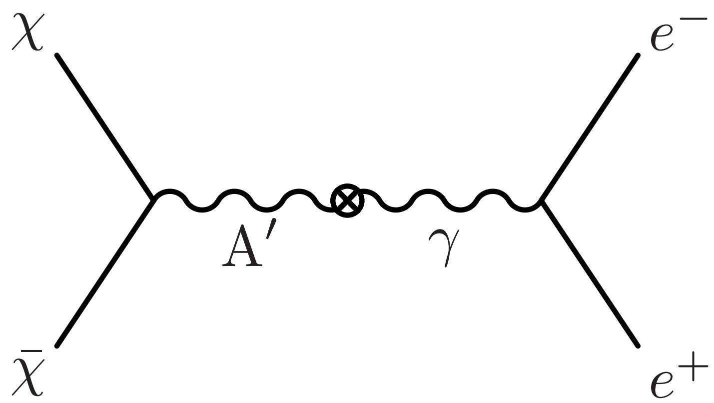


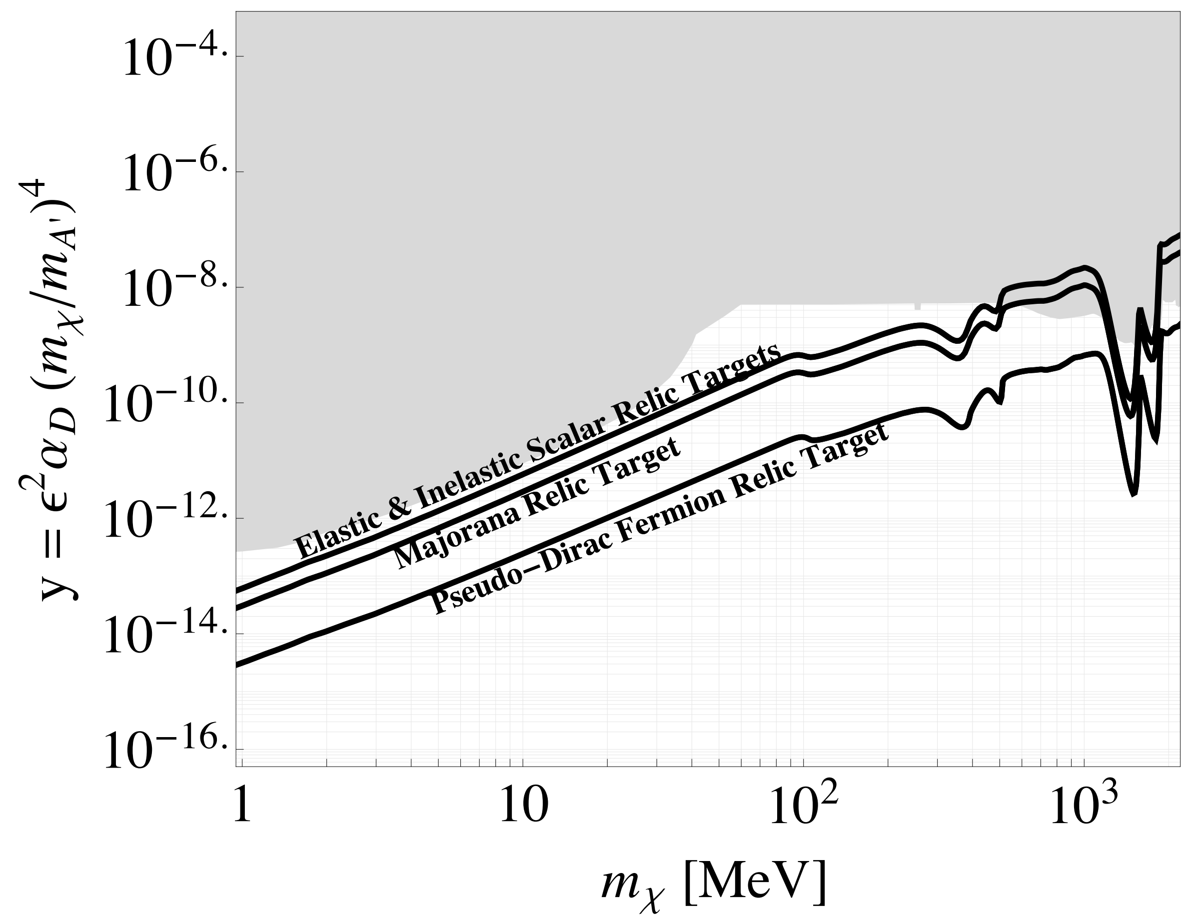
Searches for Production of Light Dark Matter

Want a way to conservatively estimate reach of searches



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

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



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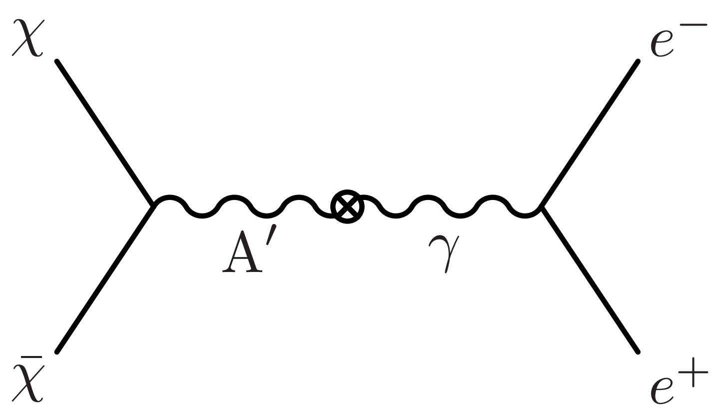

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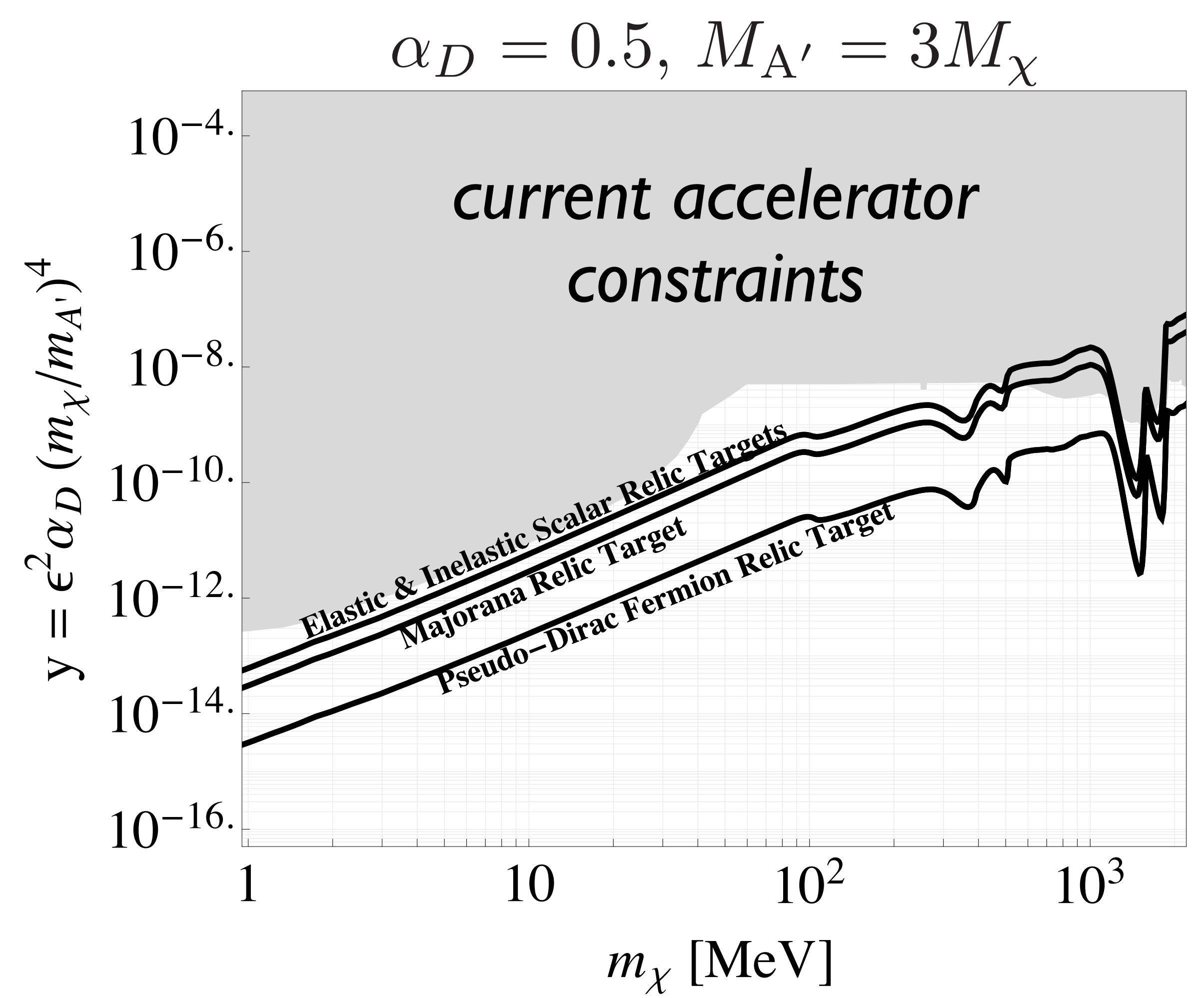
Choose conservative values of α_D, $M_{A'}/M_\chi$ for converting $(M_{A'},\epsilon) \Longrightarrow (M_\chi, y)$



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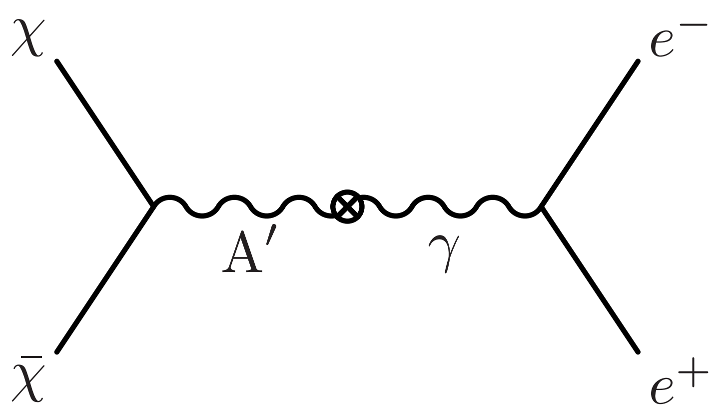

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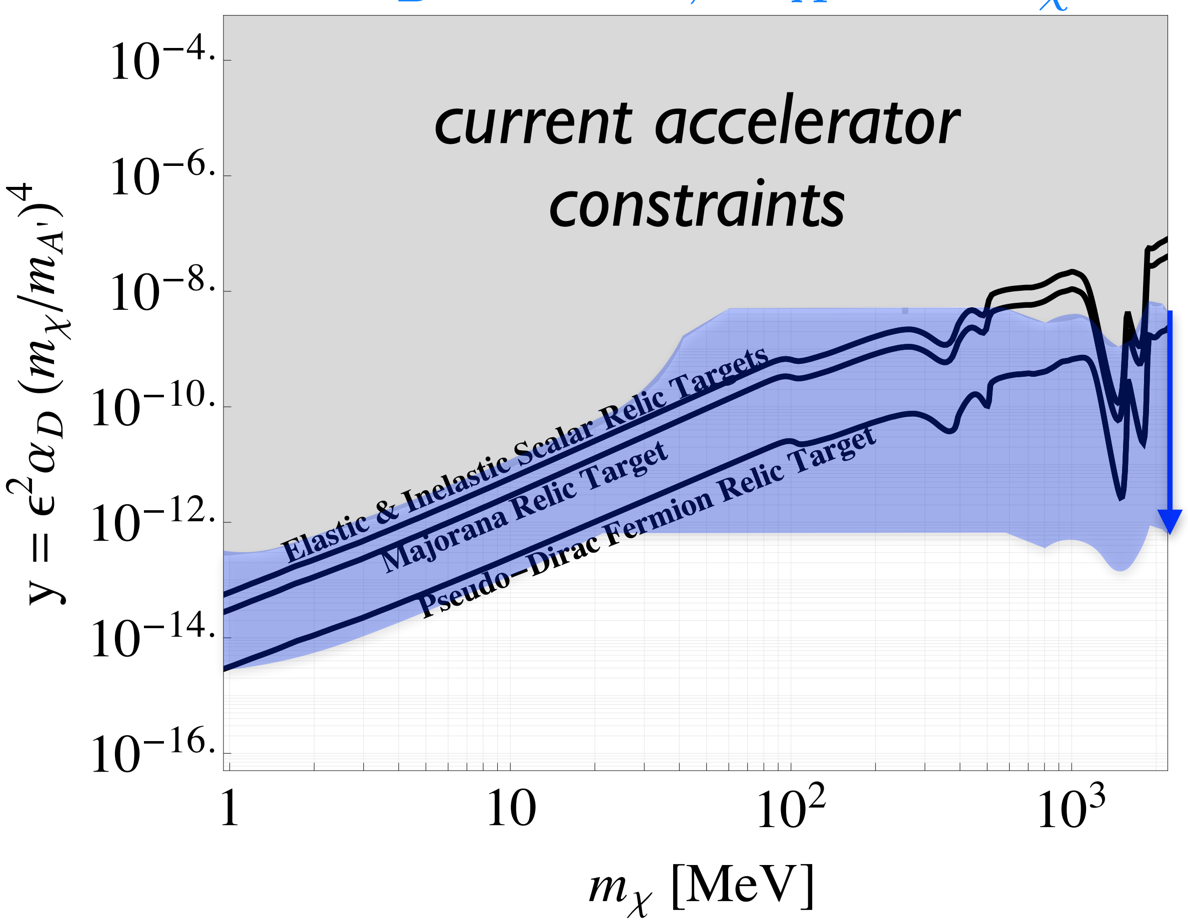
$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

$\alpha_D = 0.005,\ M_{\mathrm{A}'} = 3M_\chi$

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

If α_D more like α_{EM}, sensitivity gets better



Searches for Production of Light Dark Matter

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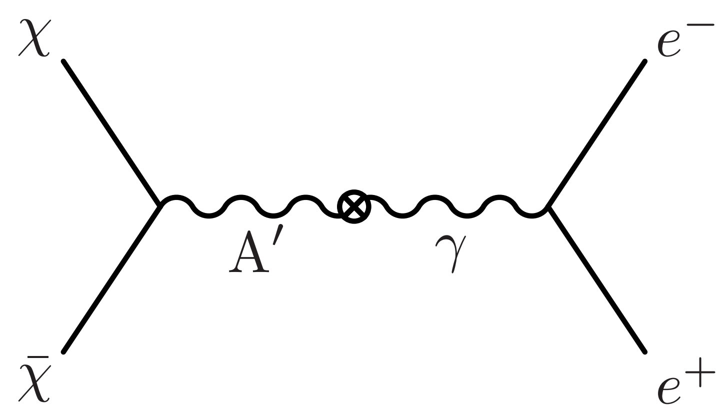

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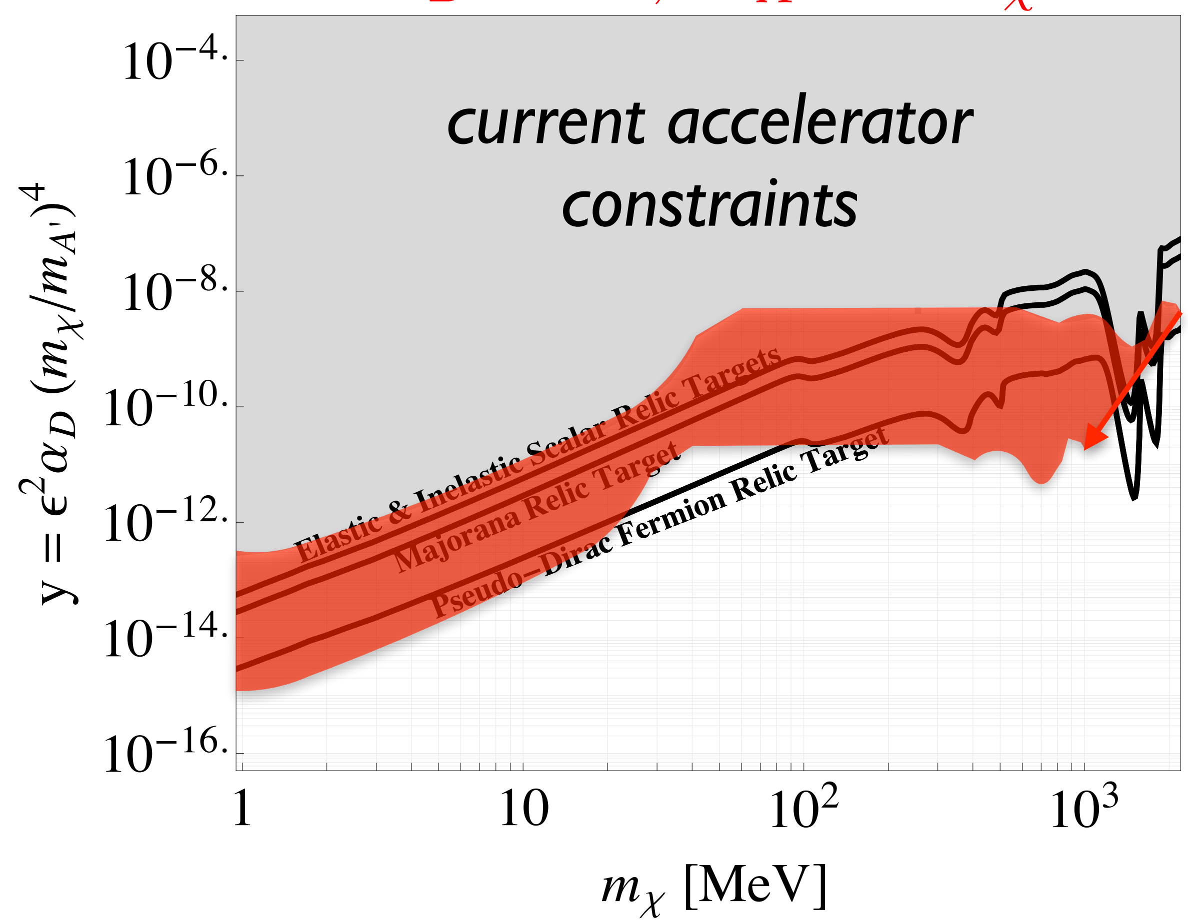
$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

$\alpha_D = 0.5,\ M_{A'} = 6M_\chi$

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

If α_D more like α_{EM}, sensitivity gets better

If $M_{A'}/M_\chi$ larger, sensitivity gets better.

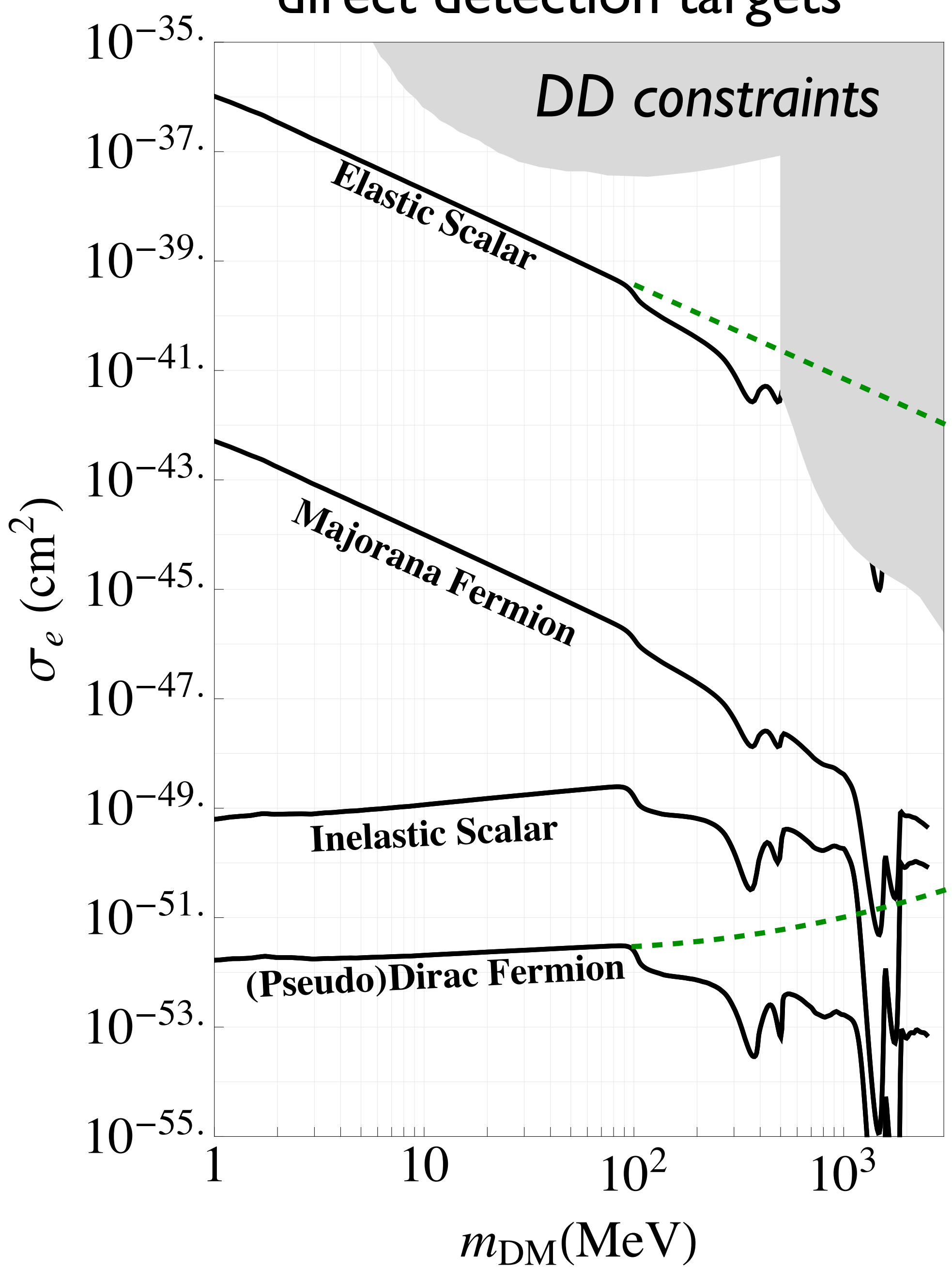


Comparing to Direct Detection

SLAC

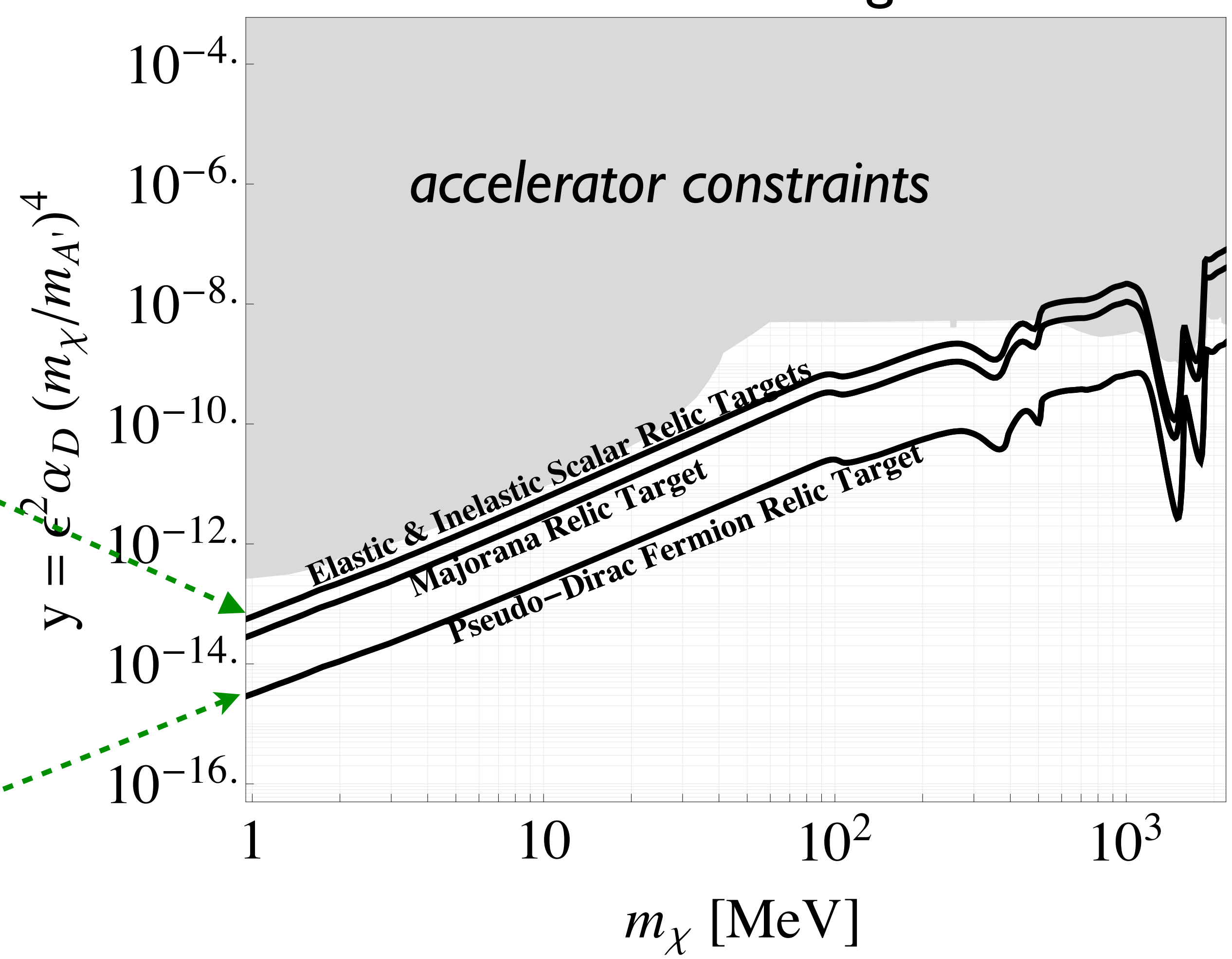
$q^2 \ll q^2\big|_{\text{freeze-out}}$

direct detection targets



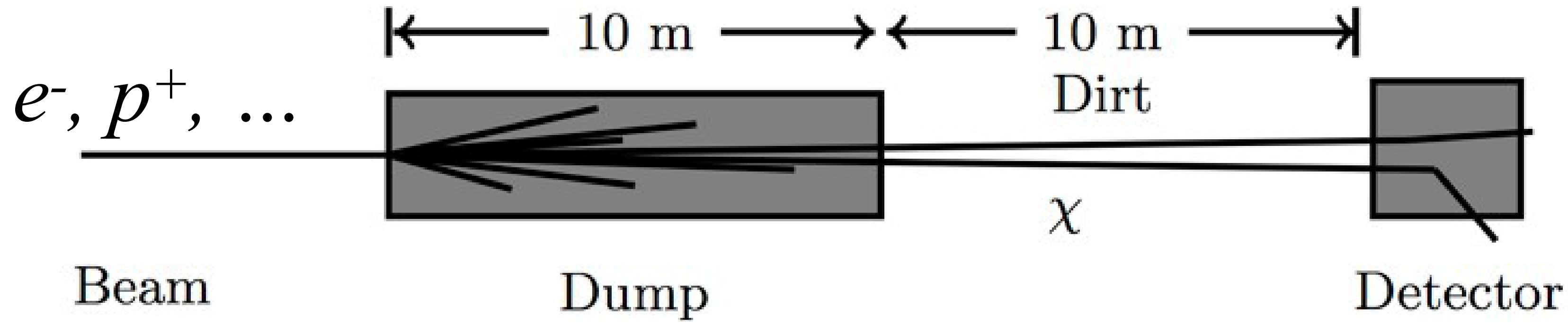
$q^2 \approx q^2\big|_{\text{freeze-out}}$

accelerator targets



Sensitivities for direct detection and accelerators can only be compared one target at a time!

Beam Dumps



Boosted $A' \rightarrow \chi\bar{\chi}$ *makes a dark matter beam!*

- very convincing discovery signature
- possible to investigate nature of DM-SM interactions
- can use very high beam intensities and run parasitically

BDX @ JLab CEBAF (e^- beam dump)

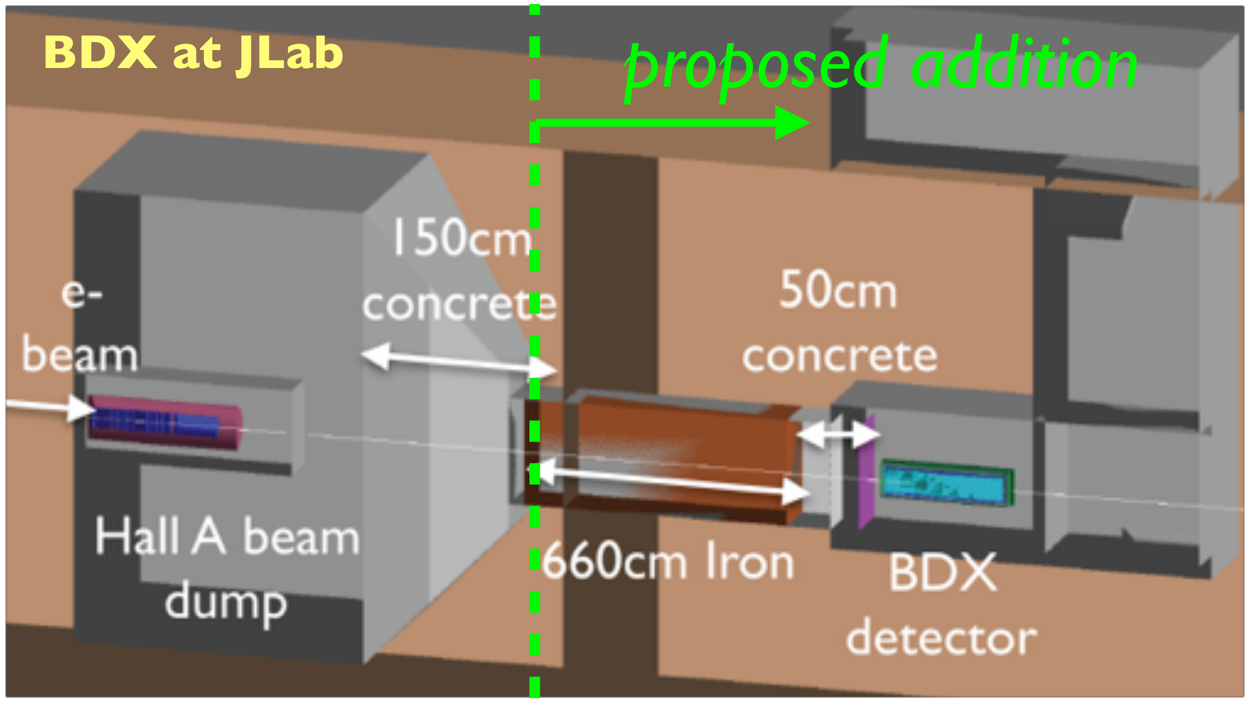
small calorimeter behind Hall A dump (~10^{22} EOT)

MiniBoone/SBN @ FNAL (p^+ beam dump)

Infrastructure from neutrino program (~10^{20} POT)

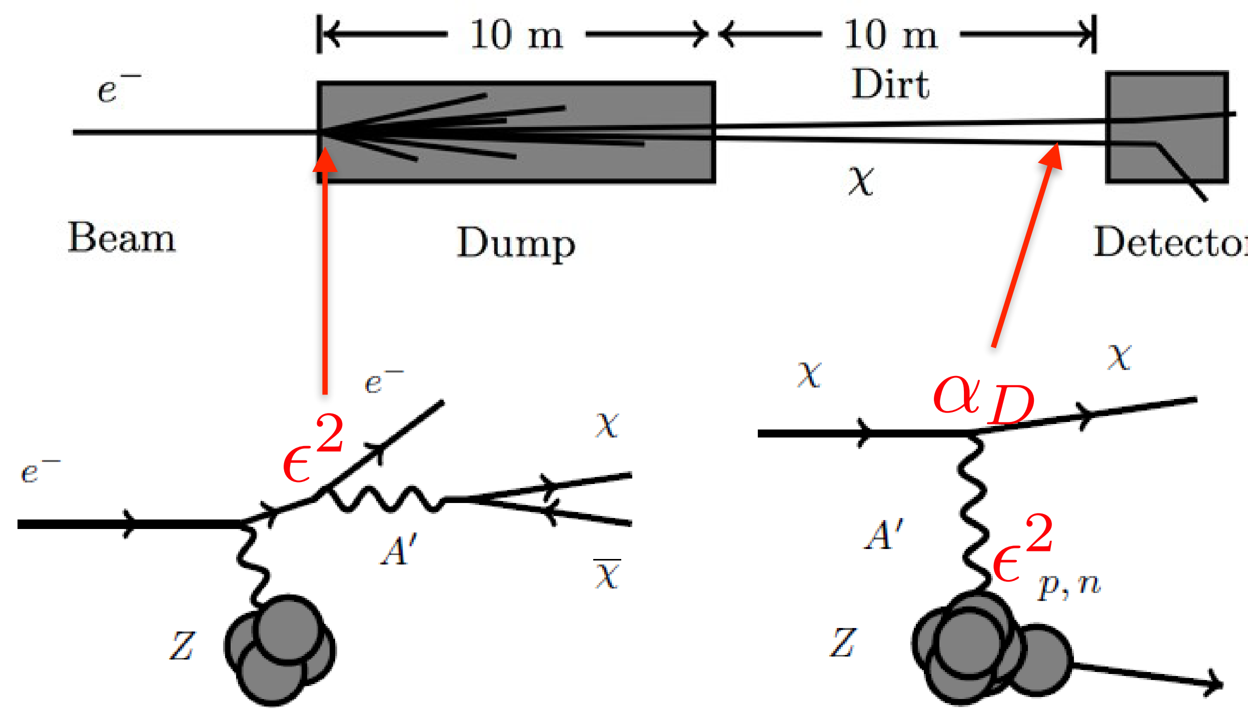
Coherent @ ORNL SNS (p^+ beam dump)

Infrastructure from ν scattering program (~10^{23} POT)



Beam Dump Limitations

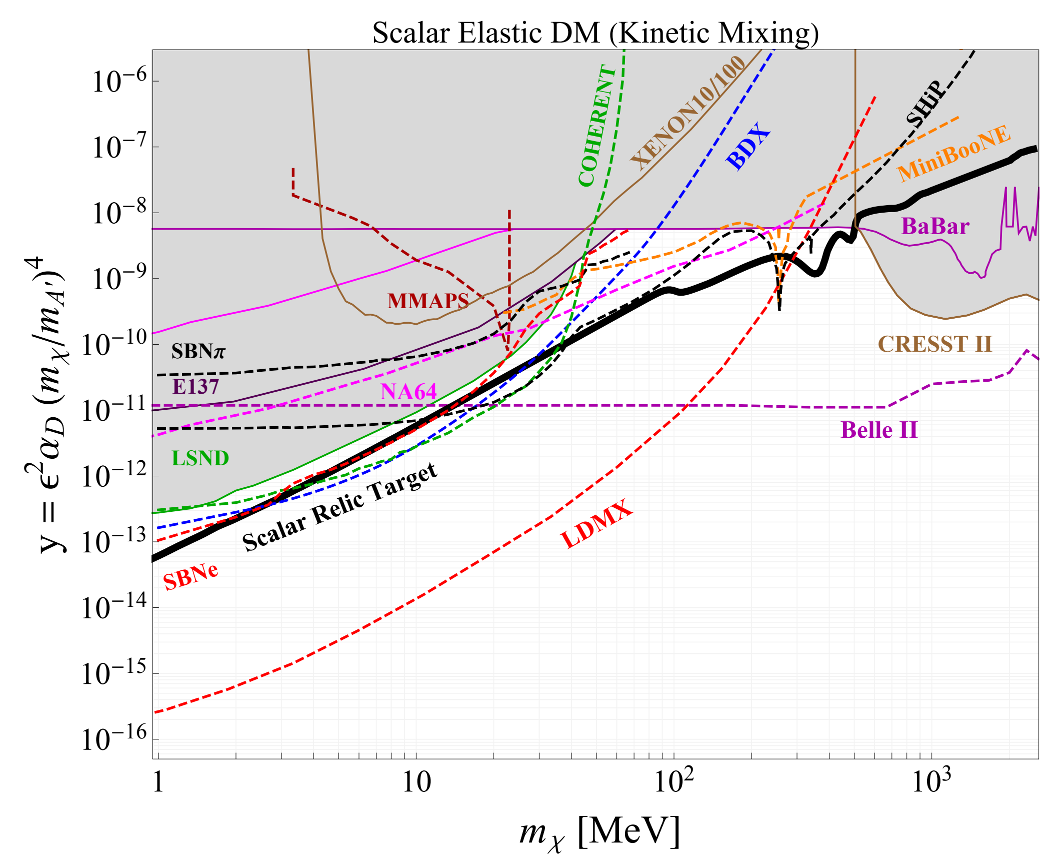
Next generation beam dumps cover only scalar target with expected yields, where neutrino backgrounds can already be a problem.



Signal yield scales as $\alpha_D \epsilon^4$

$\Longrightarrow$ reach in $y \; \alpha \; (\#\mathrm{EOT})^{1/2}$ *(no background)*

$\Longrightarrow$ reach in $y \; \alpha \; (\#\mathrm{EOT})^{1/4}$ *(w/ background)*



Reaching all thermal targets convincingly with beam dumps looks very difficult.

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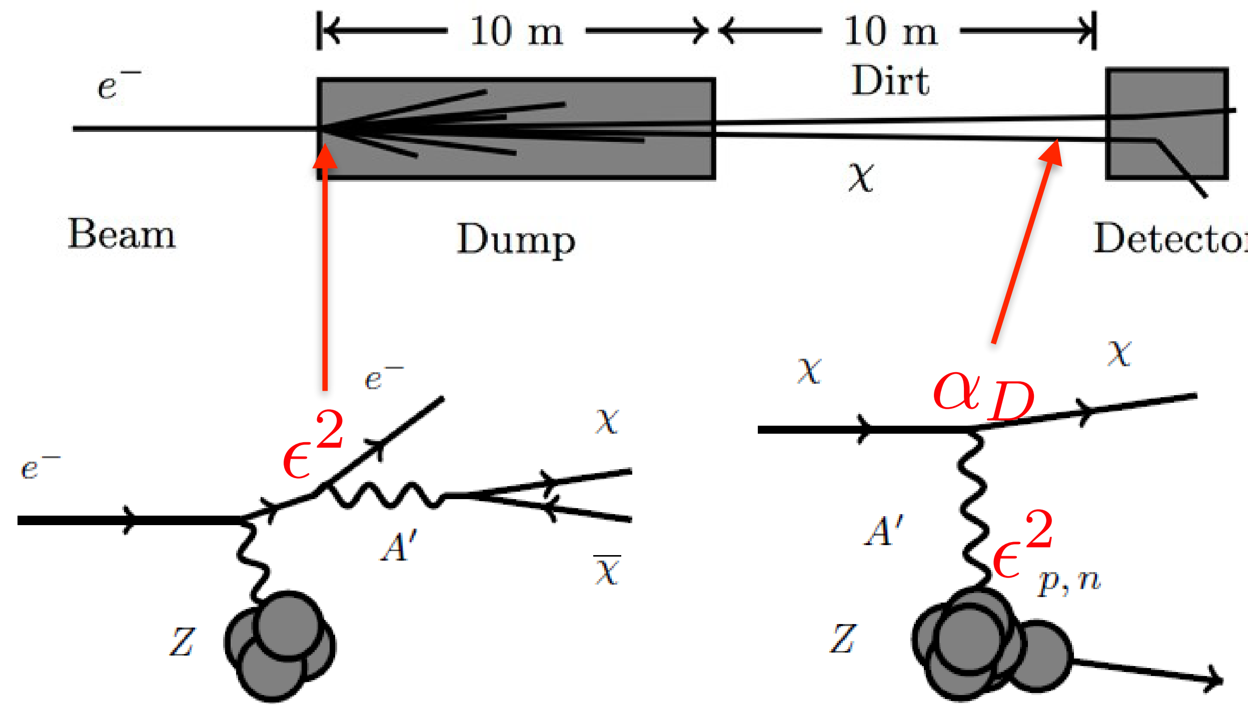

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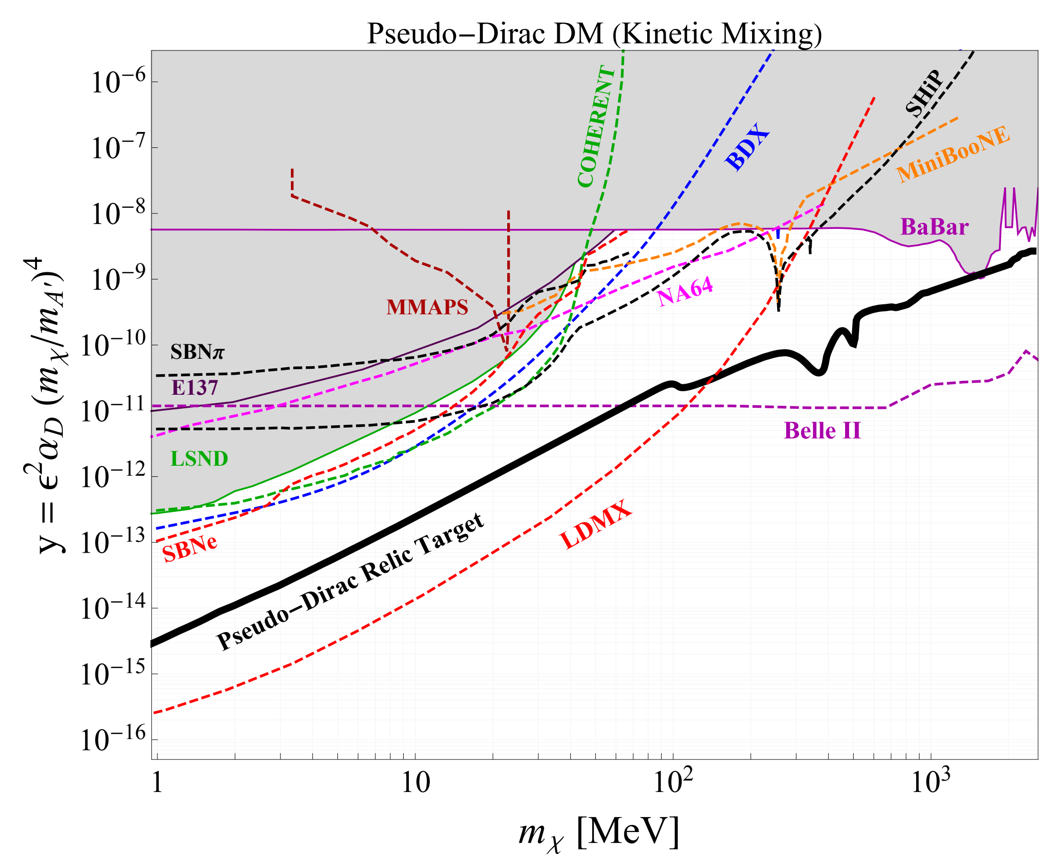

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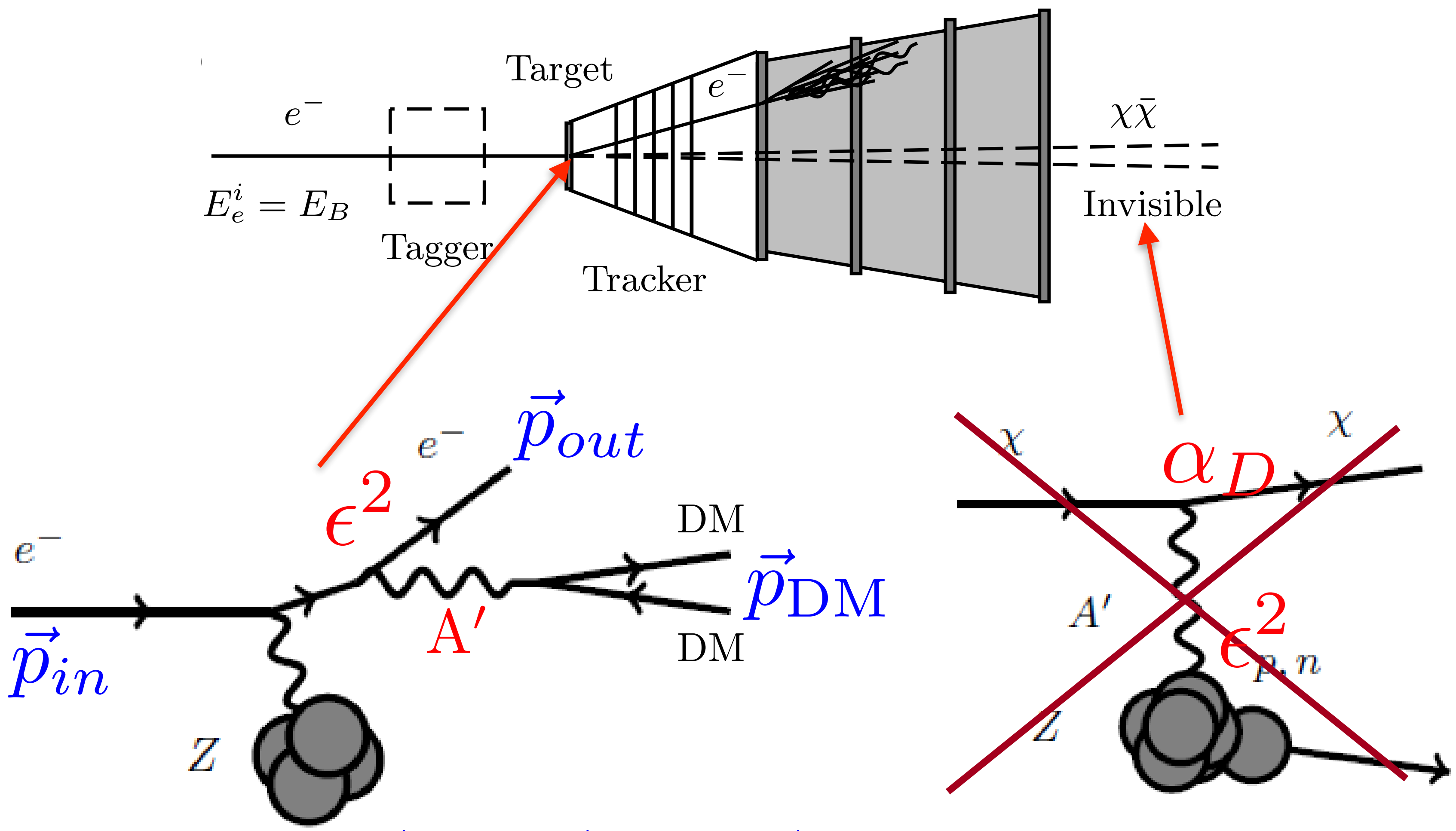
Missing Energy/Momentum



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

$$N \propto \epsilon^2$$

➡ only electrons are clean enough

➡ one electron at a time - must uniquely associate e^-_{out} with e^-_{in}

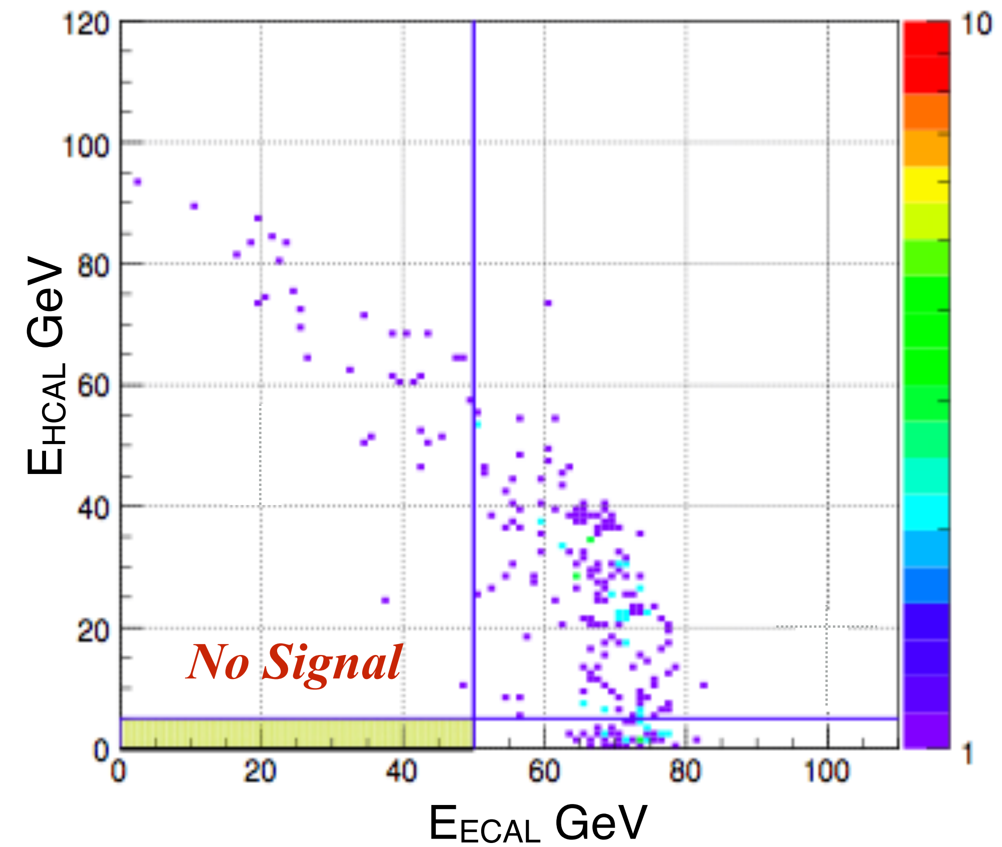
e^- missing energy:
NA64 @ SPS (present)

NA64 missing ***energy*** experiment

(no tracking for recoil electron)

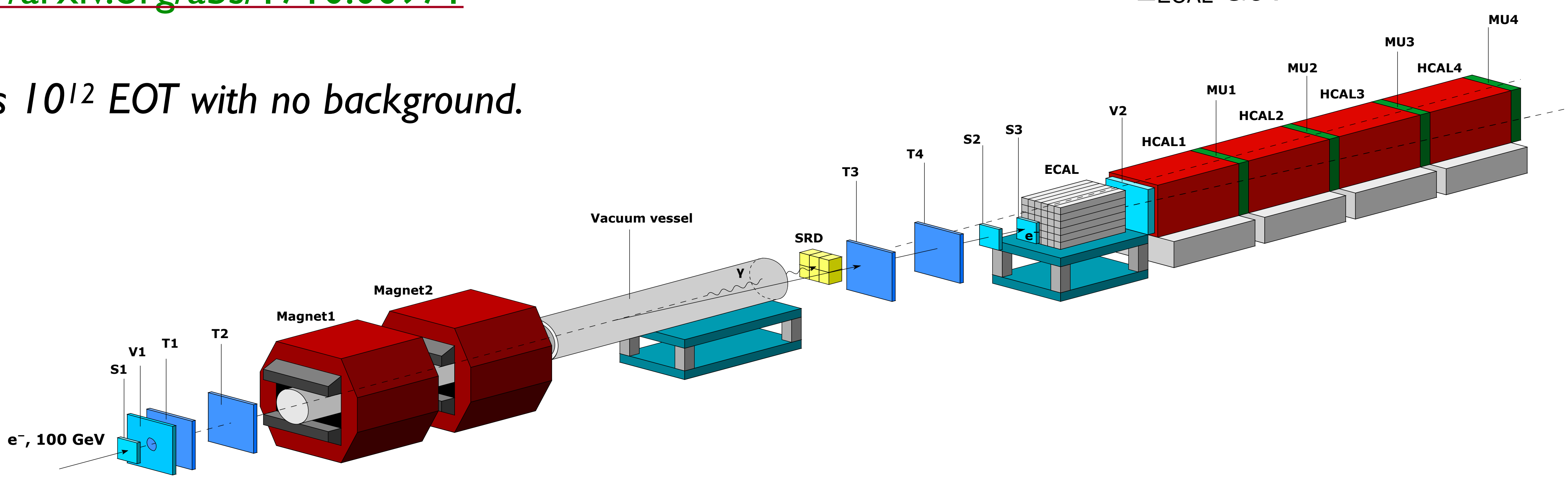
- measure **energy** of incoming 100 GeV e^-
- measure **energy** deposited in active ECal target and downstream Muon/HCAL

Look for excess of events with large E_{in} - E_{out}



Results for 4.3×10^{10} electrons on target (EOT):
https://arxiv.org/abs/1710.00971

Goal is 10^{12} EOT with no background.



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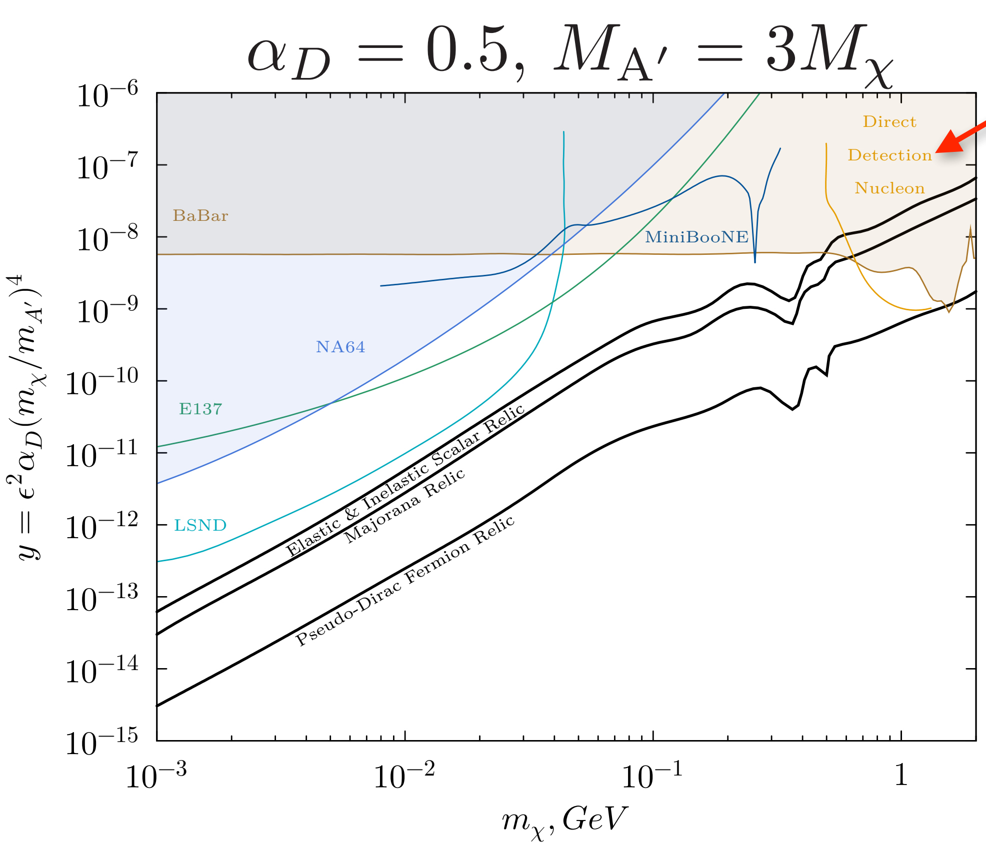
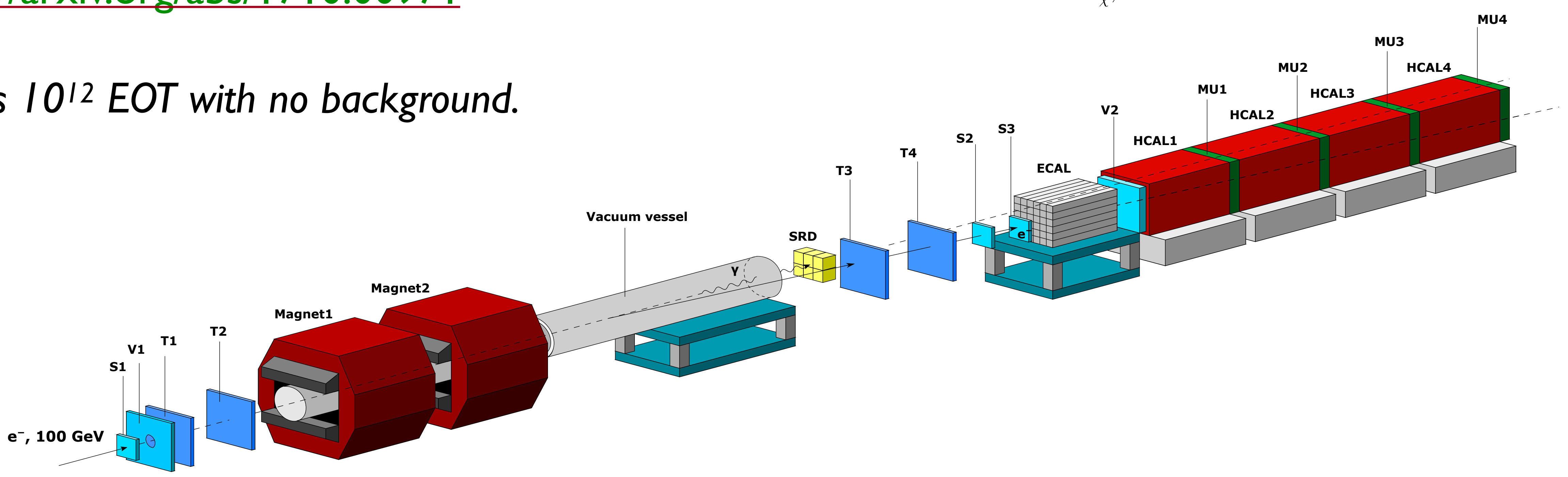
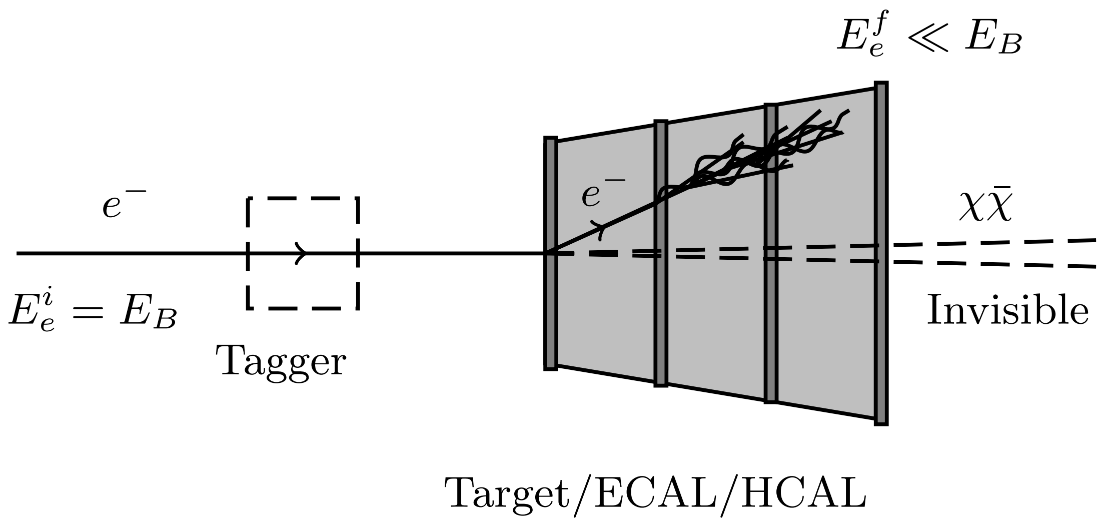


warning! can only compare to Scalar Target



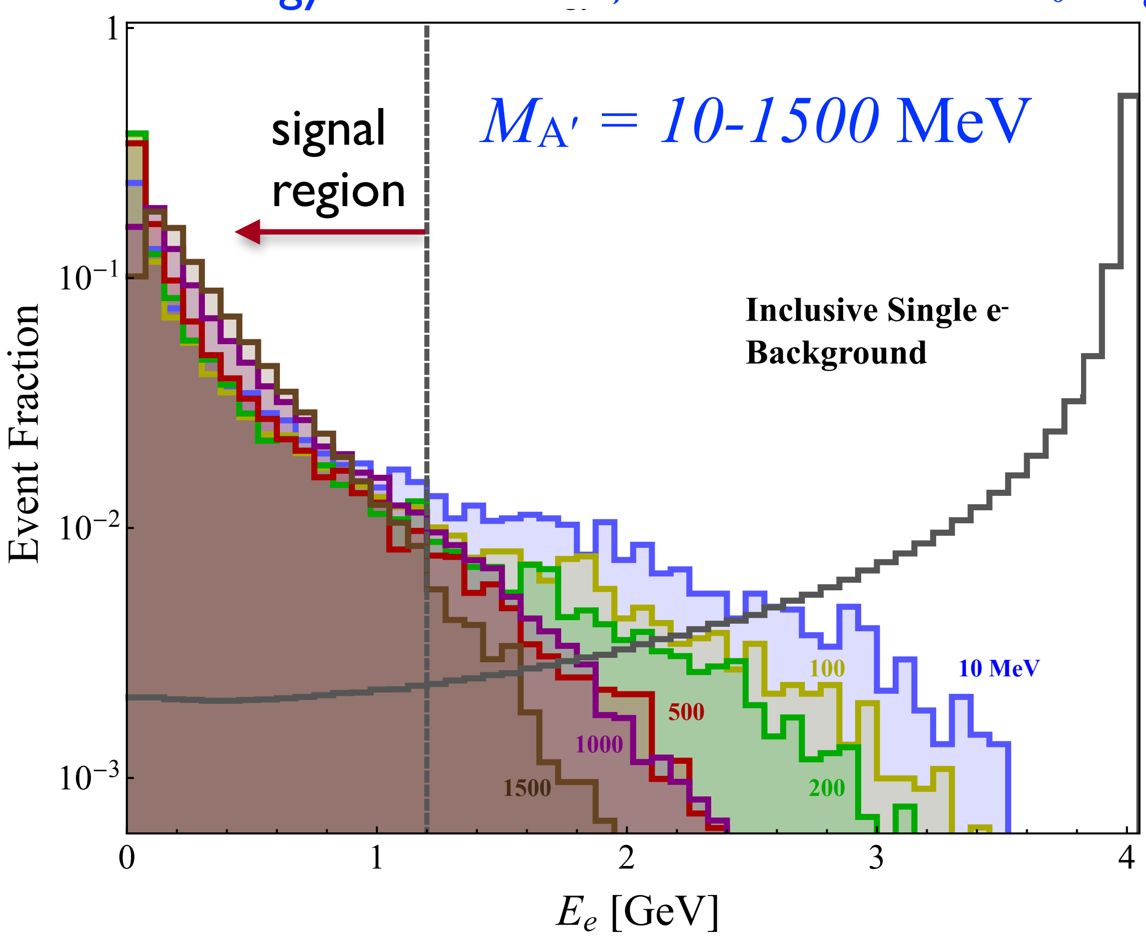
Missing *Energy* vs. Missing *Momentum*



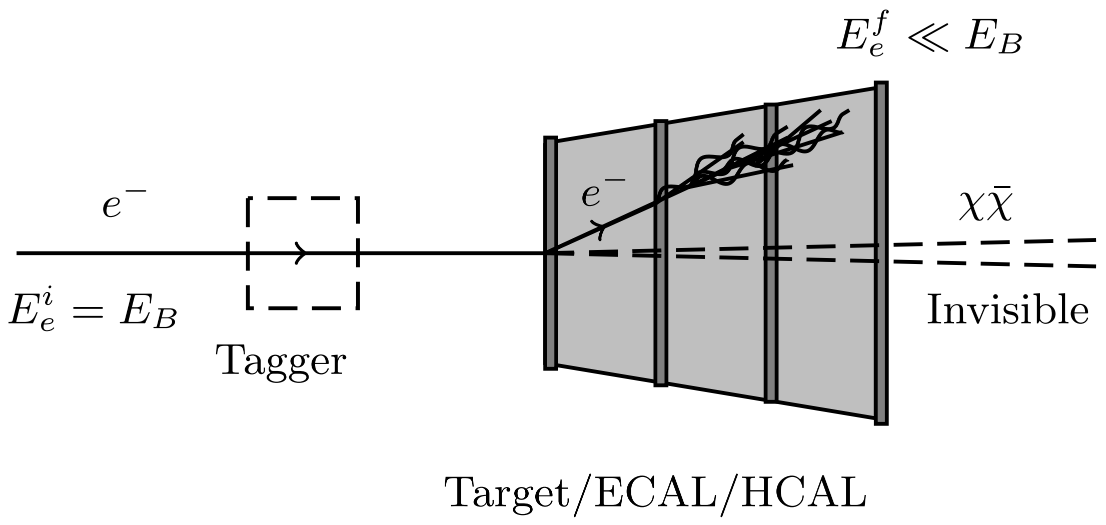
Missing energy experiments…

- *have only one signal discriminator*
- *have no way to probe mediator physics*
- *are challenged by backgrounds beyond 10^{14} EOT that require e-γ particle ID*

recoil energy distributions, 4 GeV e^- on 10% X_0 target



Missing *Energy* vs. Missing *Momentum*



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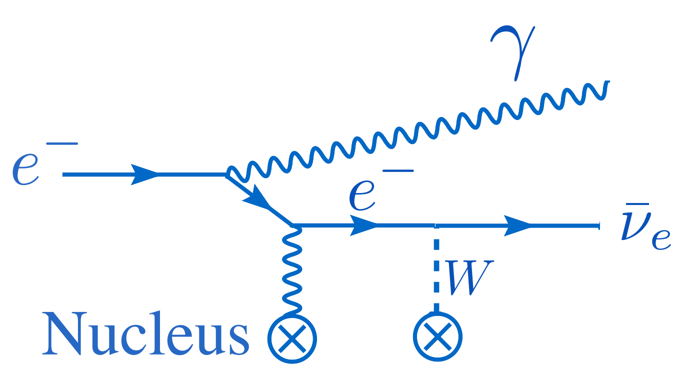

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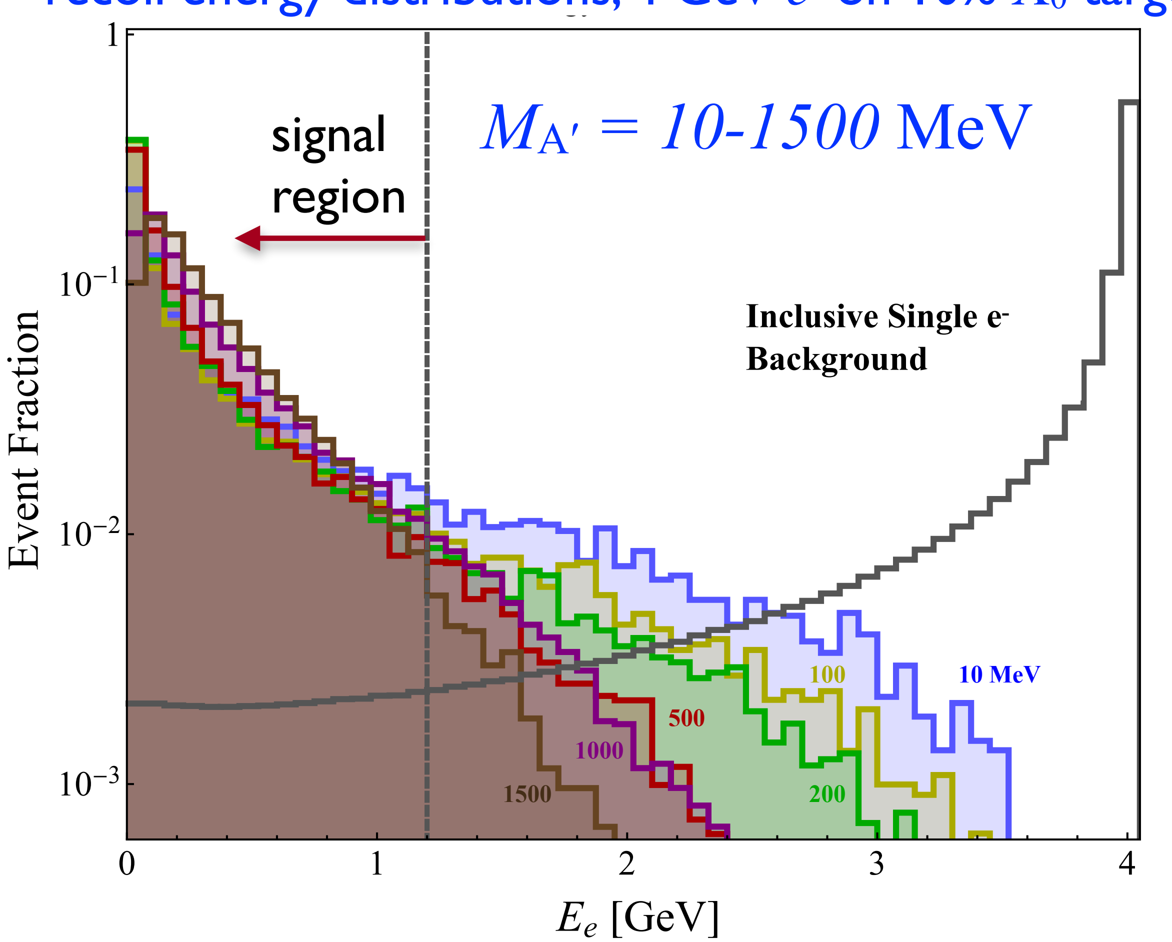
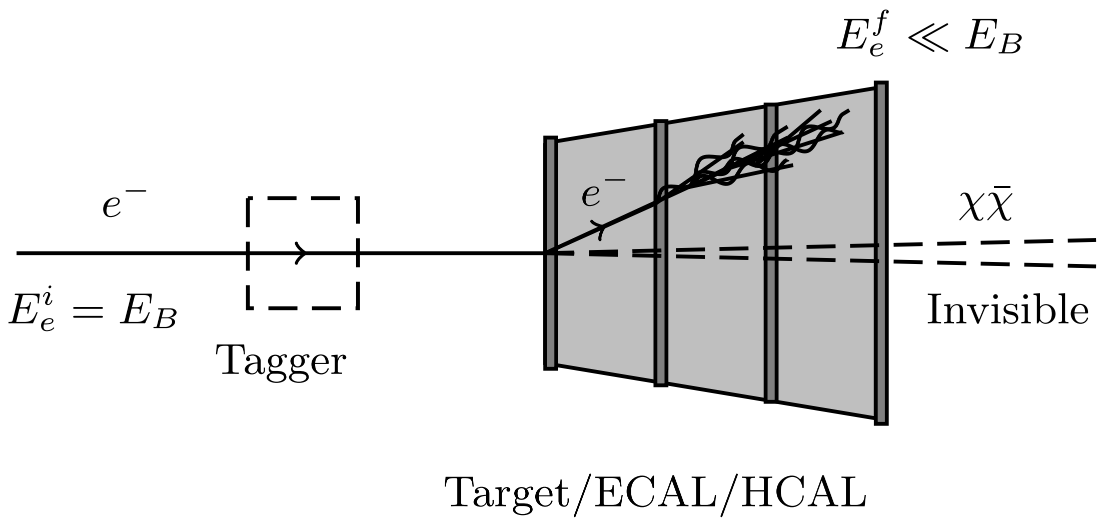
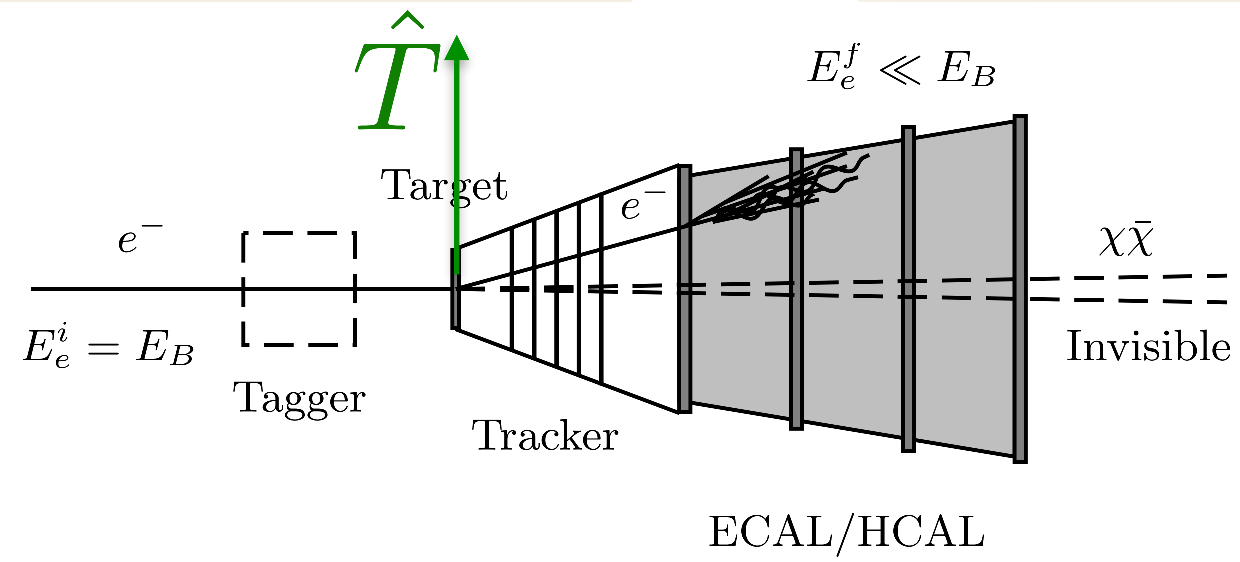
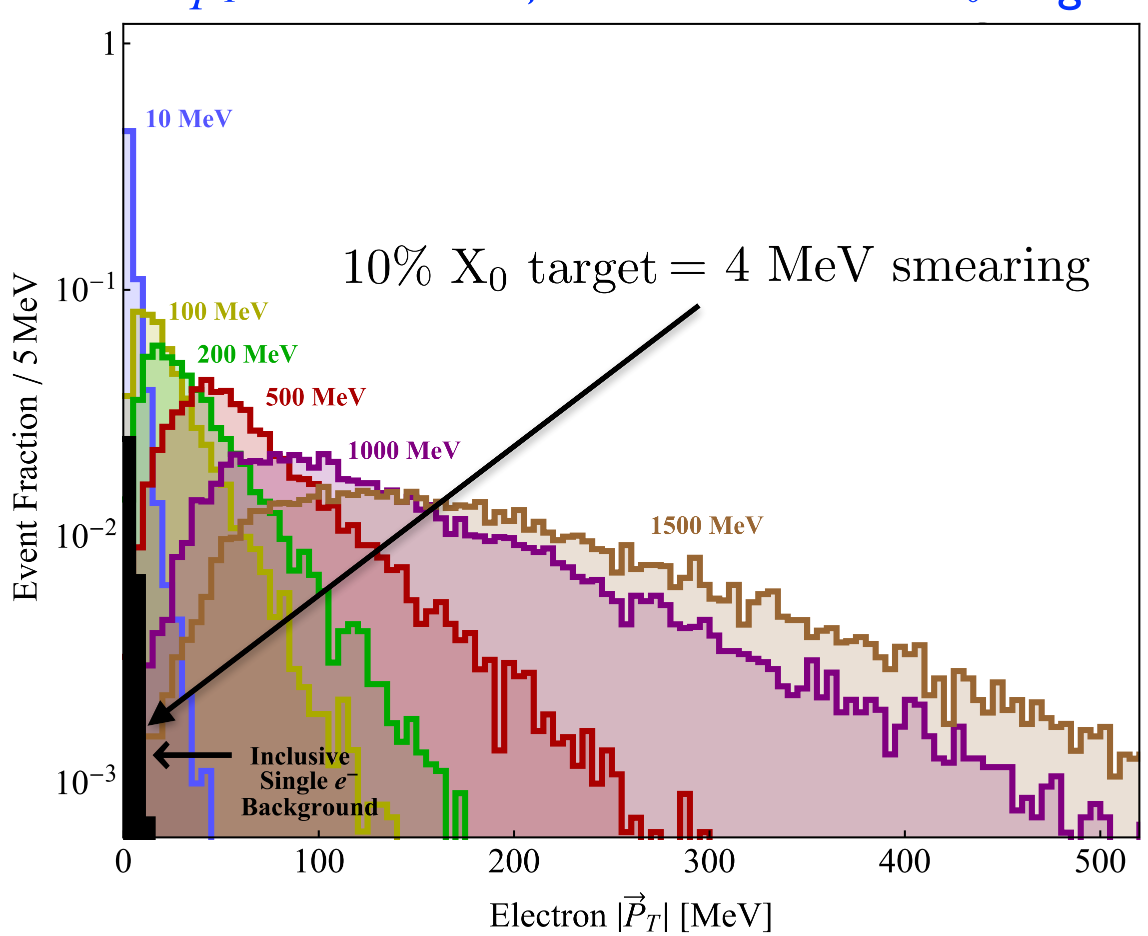


Missing *Energy* vs. Missing *Momentum*





recoil p_T distributions, 4 GeV e^- on 10% X_0 target



Missing momentum experiments…

- also have Δp_T as a signal discriminator
- have Δp_T as a signal *identifier*, sensitive to $m_{A'}$
- have tracking for e-γ particle ID so that no irreducible backgrounds beyond 10^{16} EOT.

e^- missing momentum: LDMX @ SLAC, JLab, or CERN (future?)

Compact missing momentum experiment for up to 10^{16} EOT.

Employs technology from CMS upgrades (HGC ECal) and HPS (tracking).

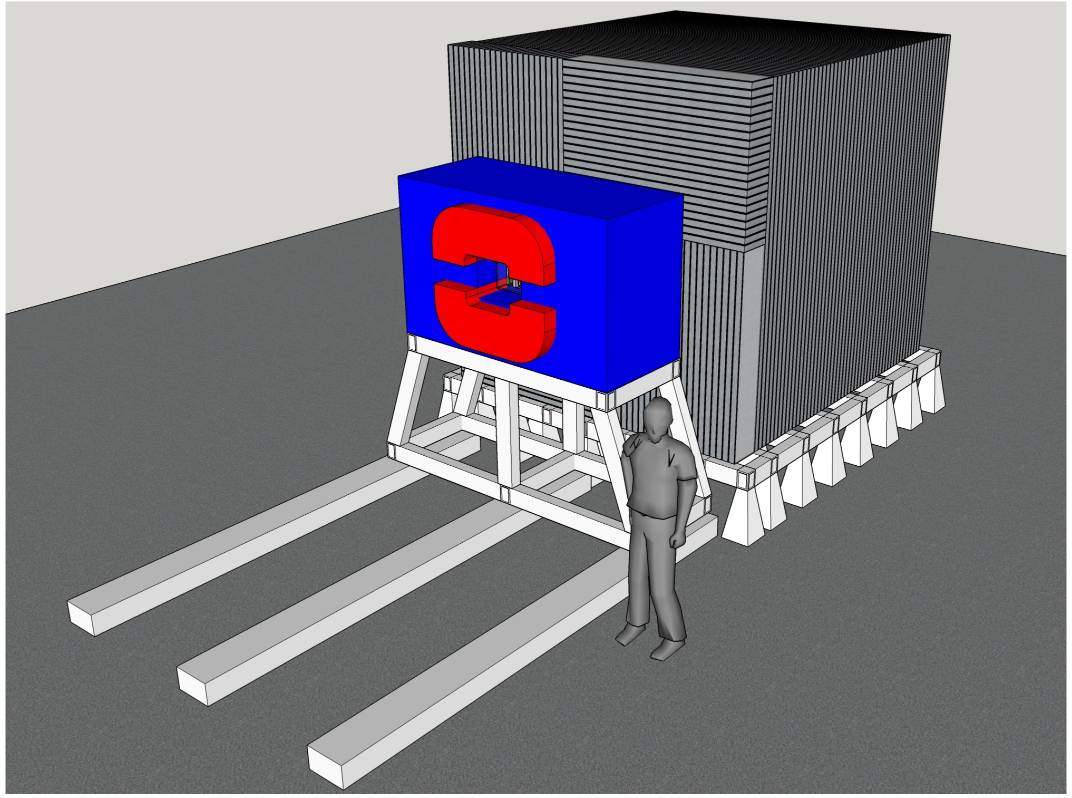
Possible host laboratories:

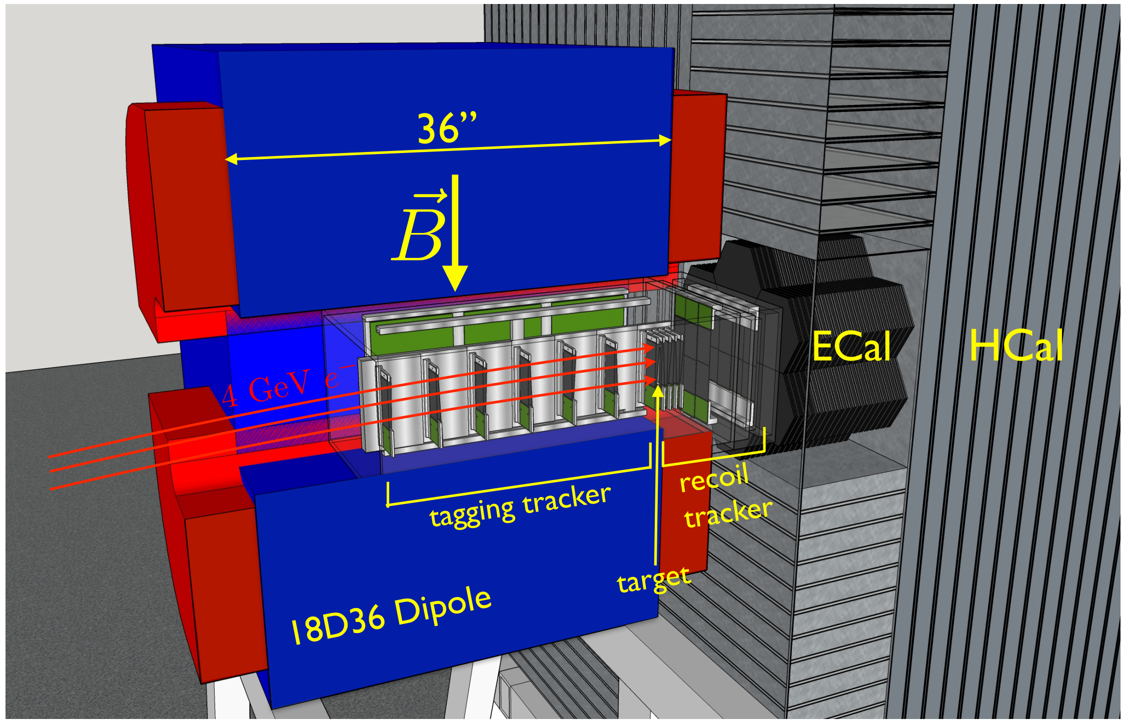
- SLAC End Station A, LCLS-II parasitic @ 4/8 GeV
- JLab CEBAF at @ 11/12 GeV
- CERN "eSPS" @ 16 GeV

A physics study of operation at SLAC demonstrates reach of a "Phase I" experiment with 4×10^{14} EOT

arXiv:1808.05219 [hep-ex]

Work continues to understand requirements for "Phase II", to cover all thermal targets.





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arXiv:1808.05219 [hep-ex]

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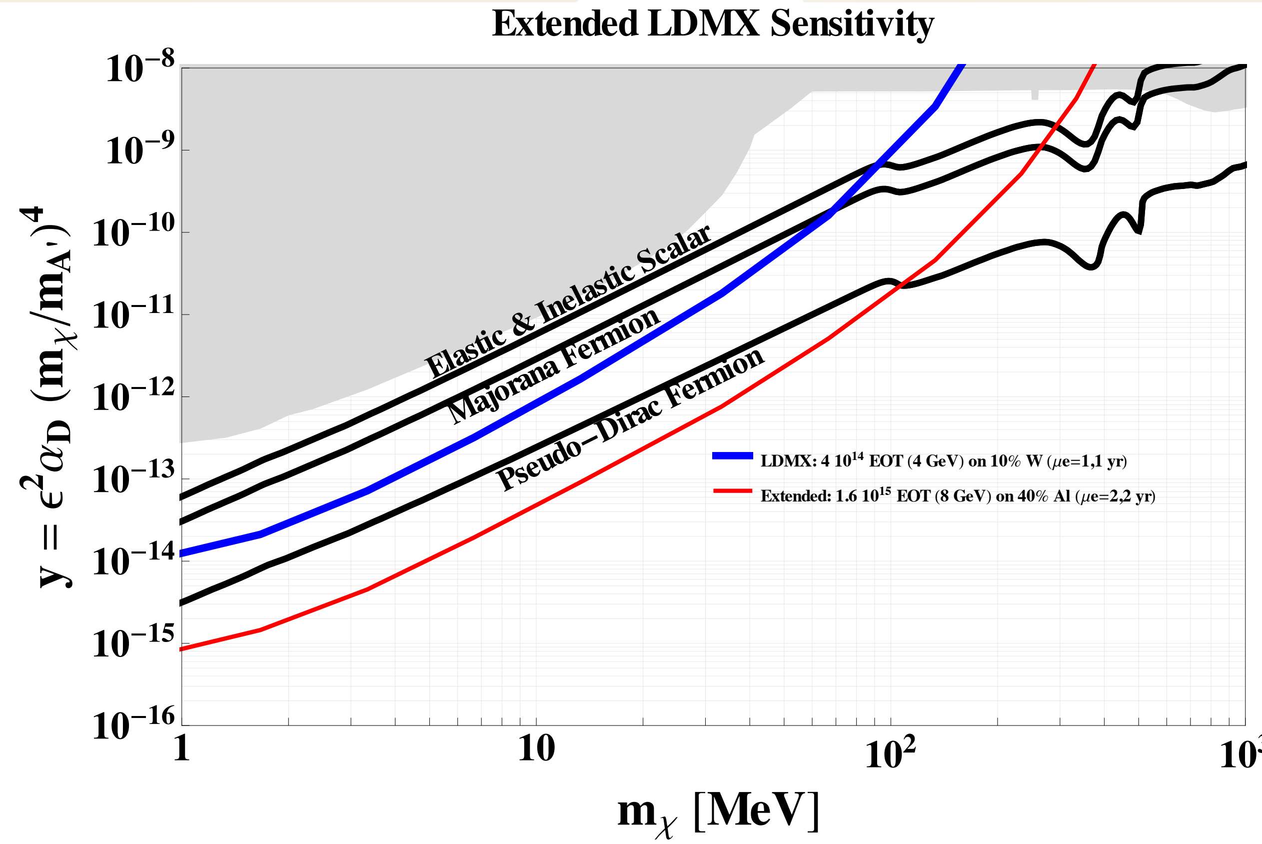

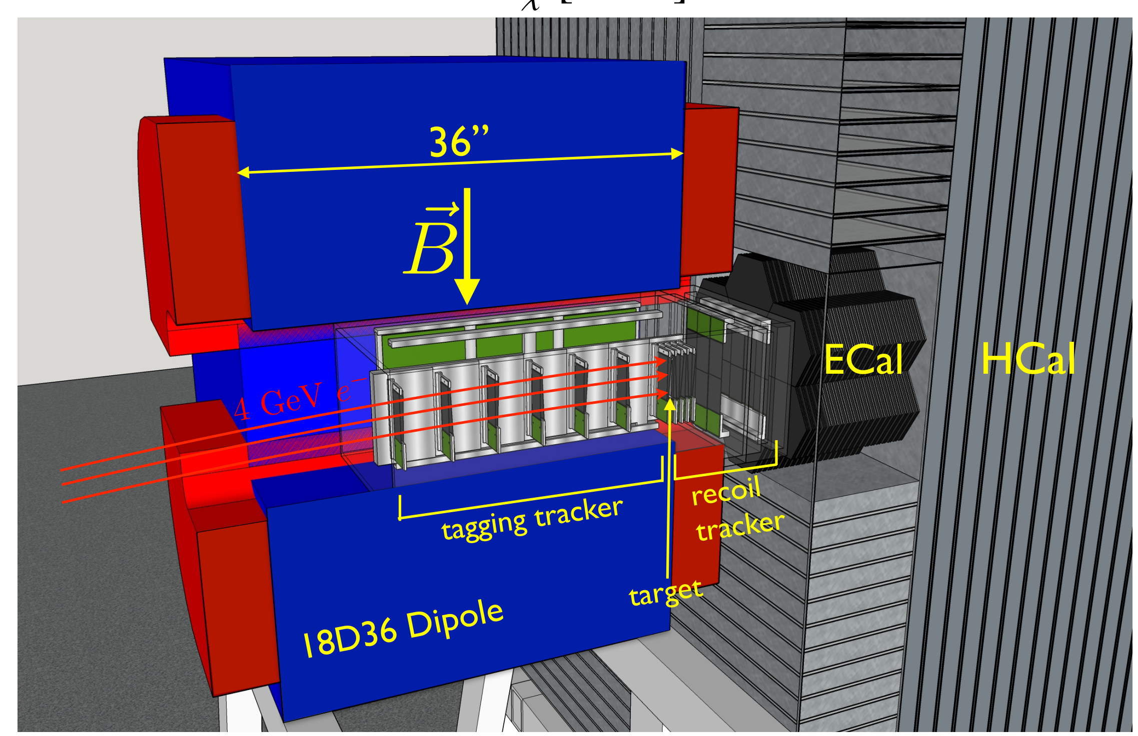

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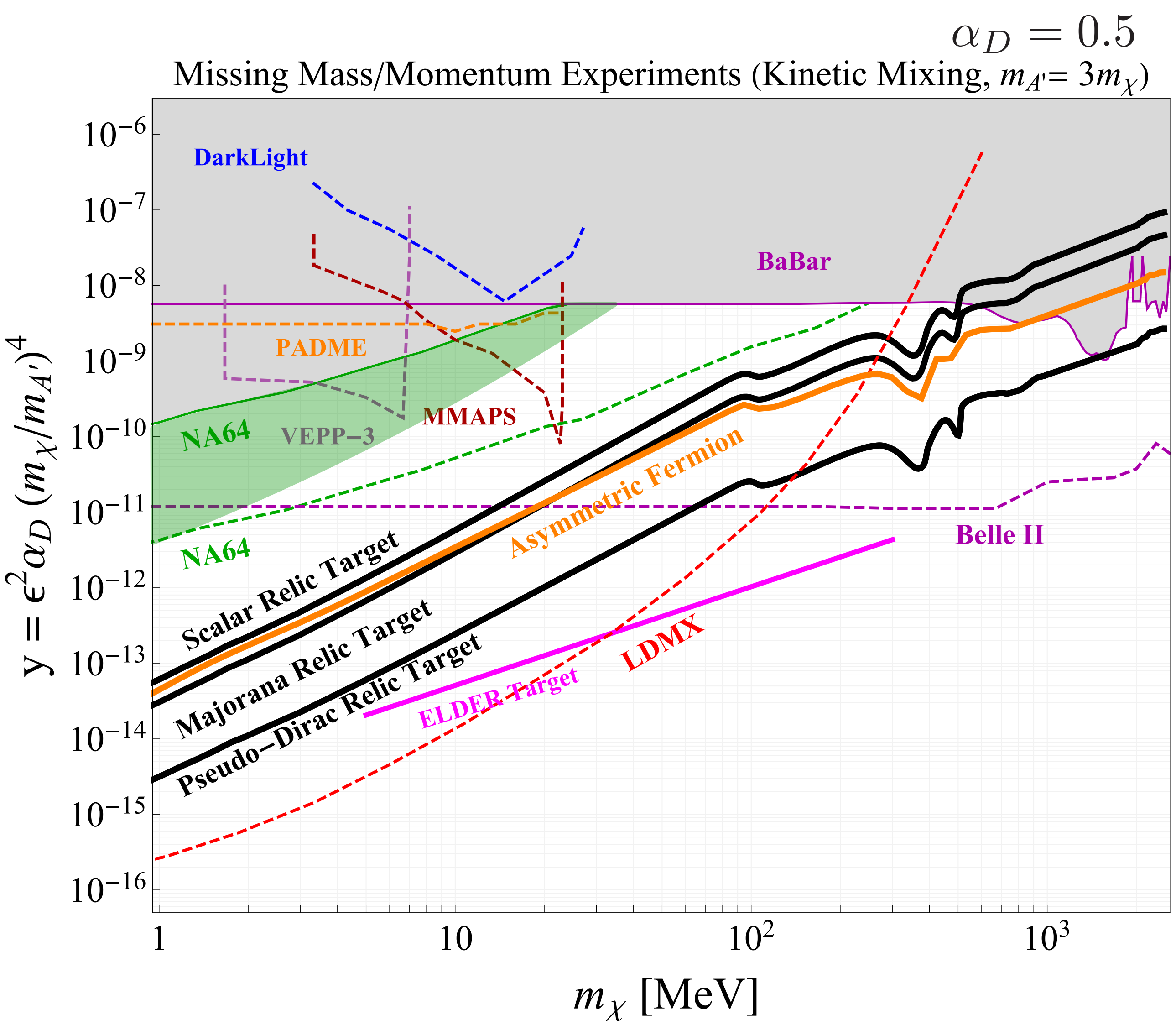
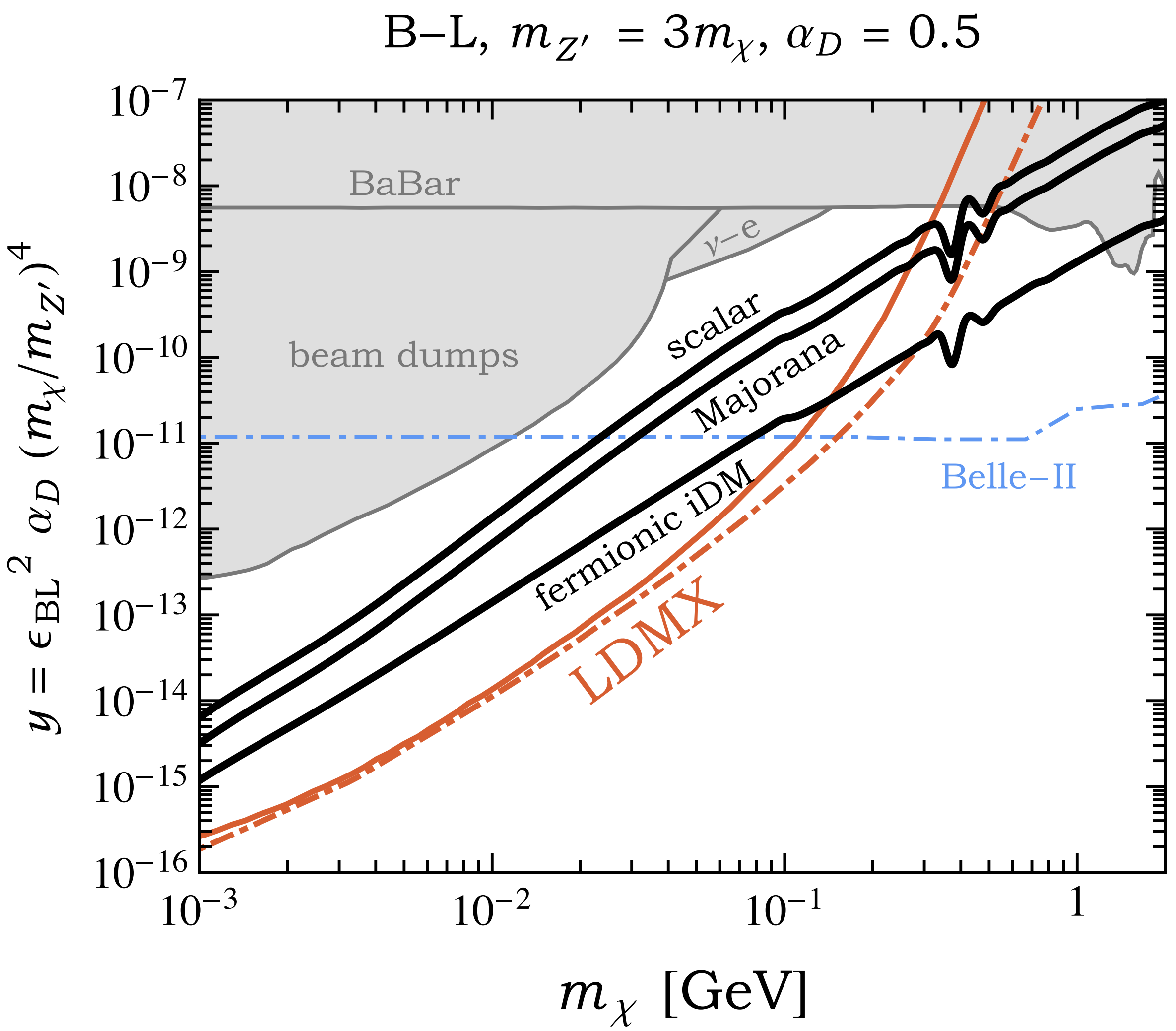


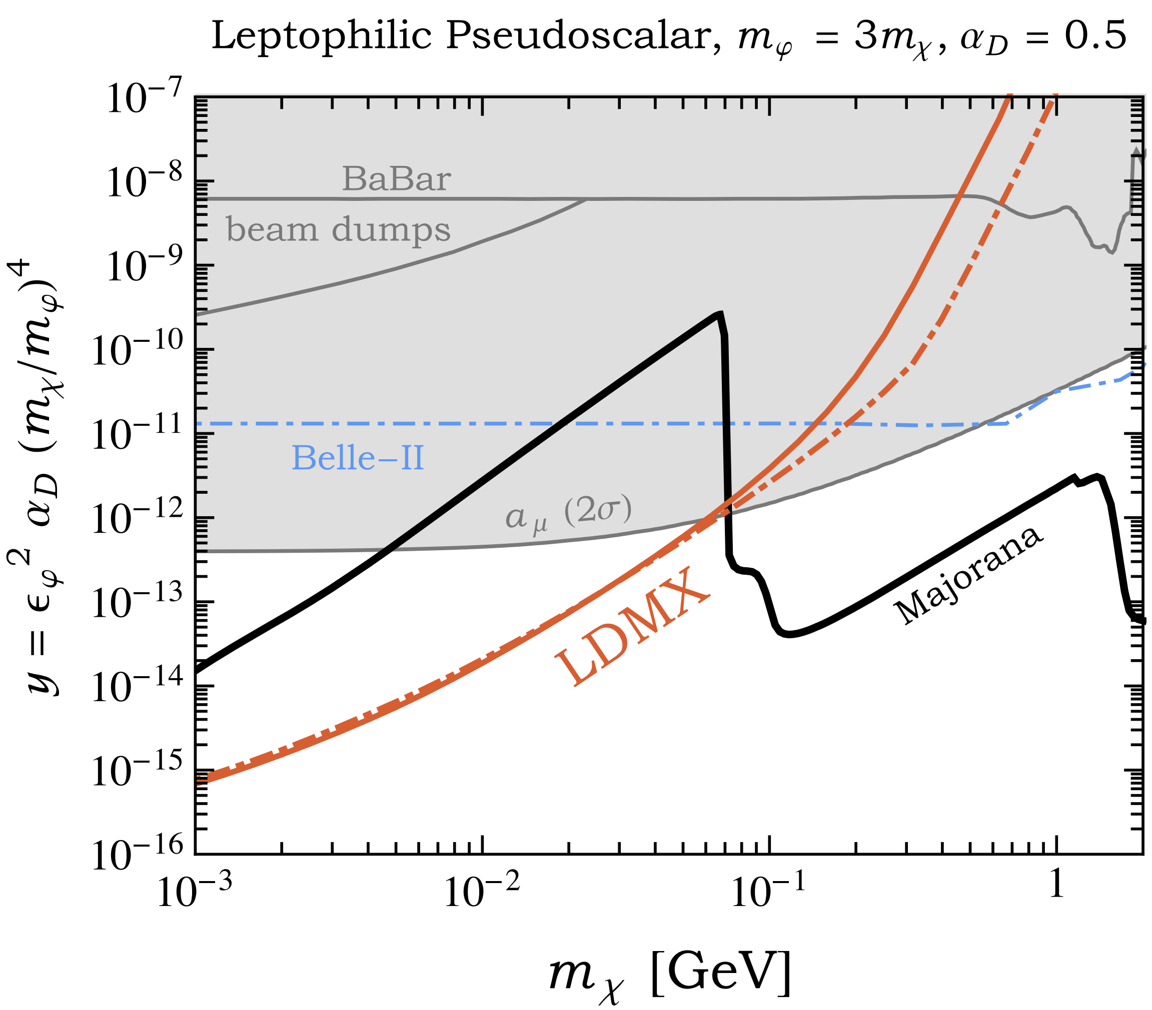
Together with Belle-II, can comprehensively probe low-mass thermal relics.

LDMX: One More Thing…

LDMX physics covers a lot more ground than minimal models!

Some of it is obvious.





arXiv:1807.01730 [hep-ph]

LDMX: One More Thing…

LDMX physics covers a lot more ground than minimal models!

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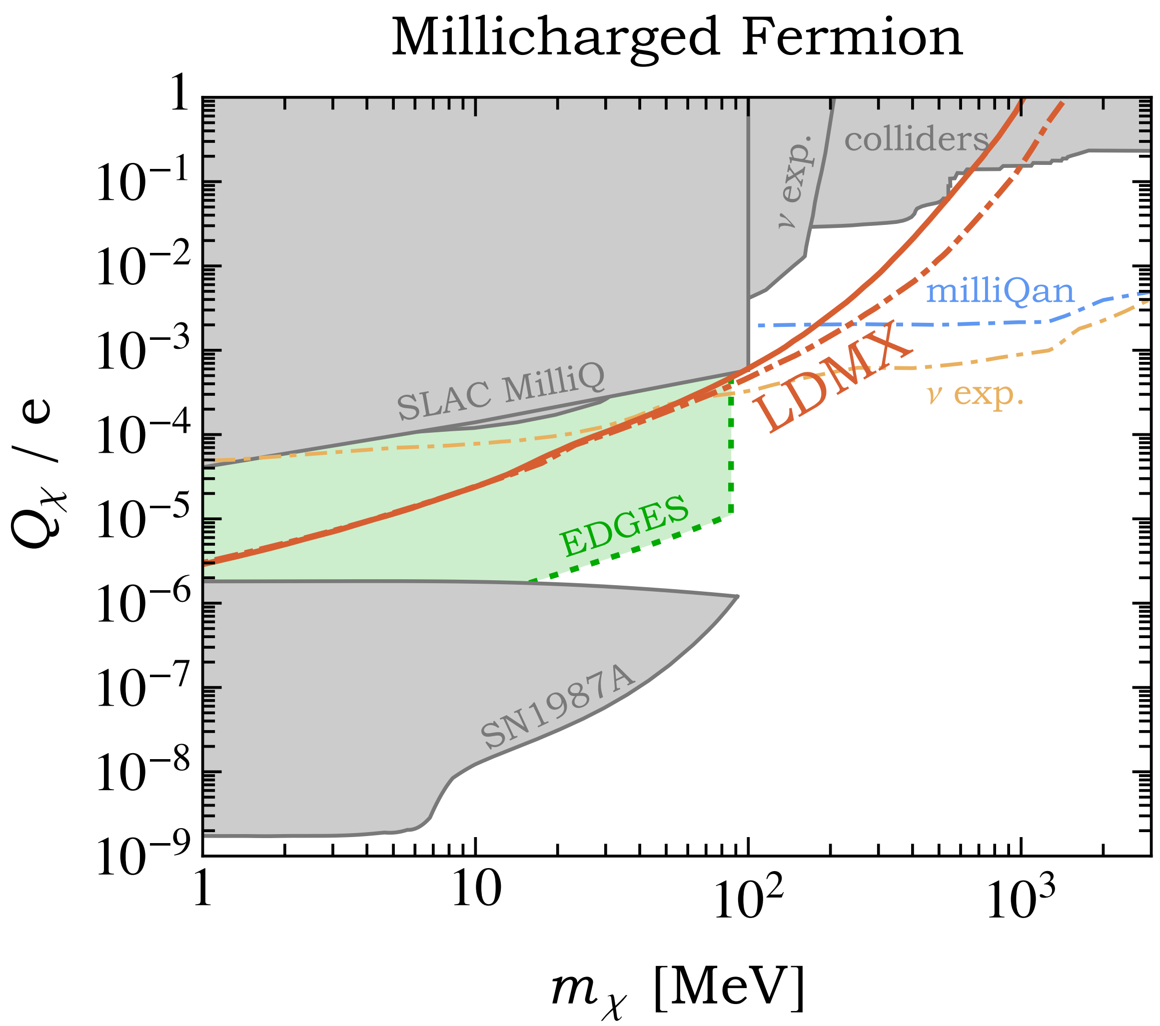

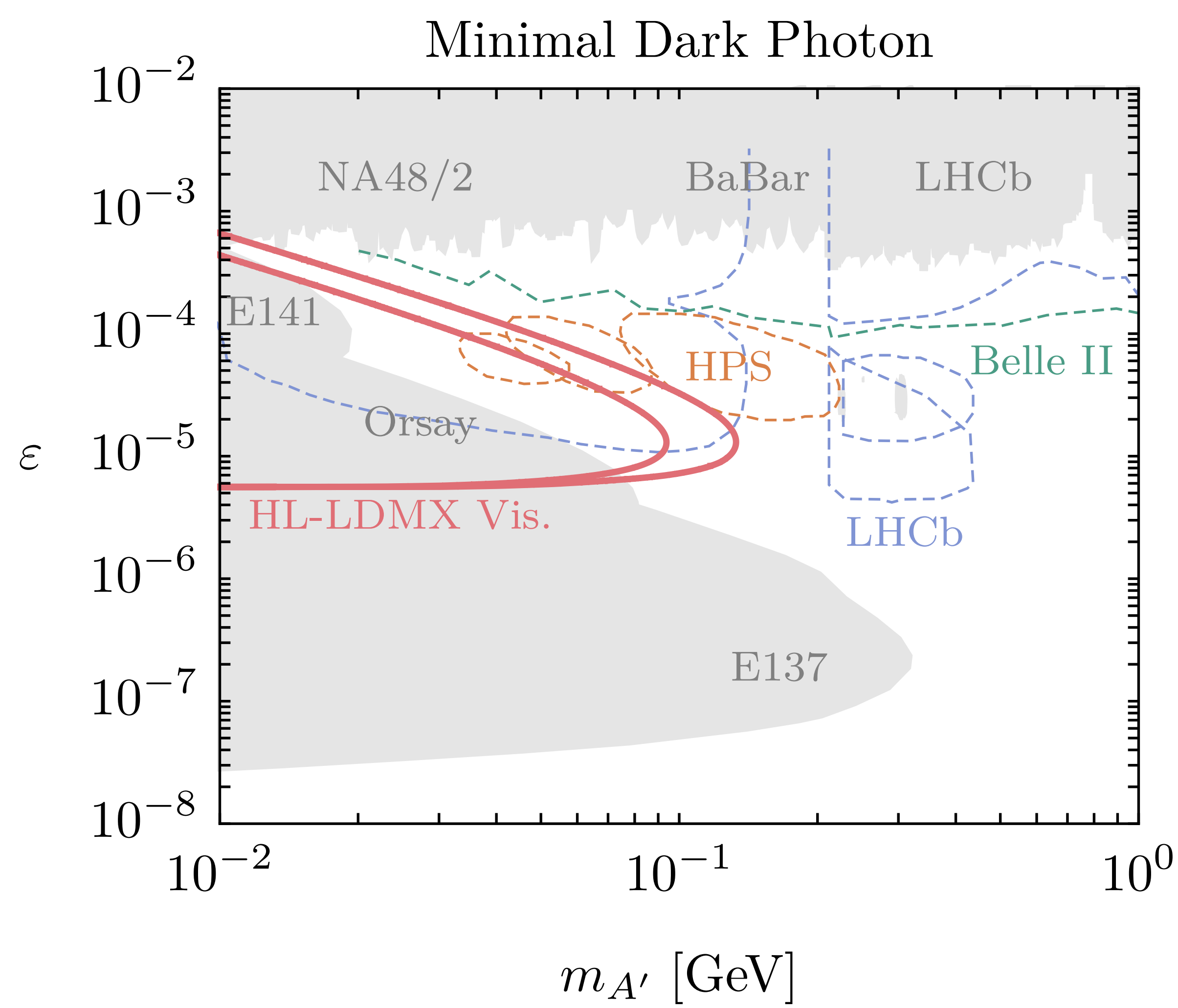

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Summary

SLAC

Accelerators have unique capabilities in exploring hidden sectors, whether motivated by thermal dark matter or on general grounds.

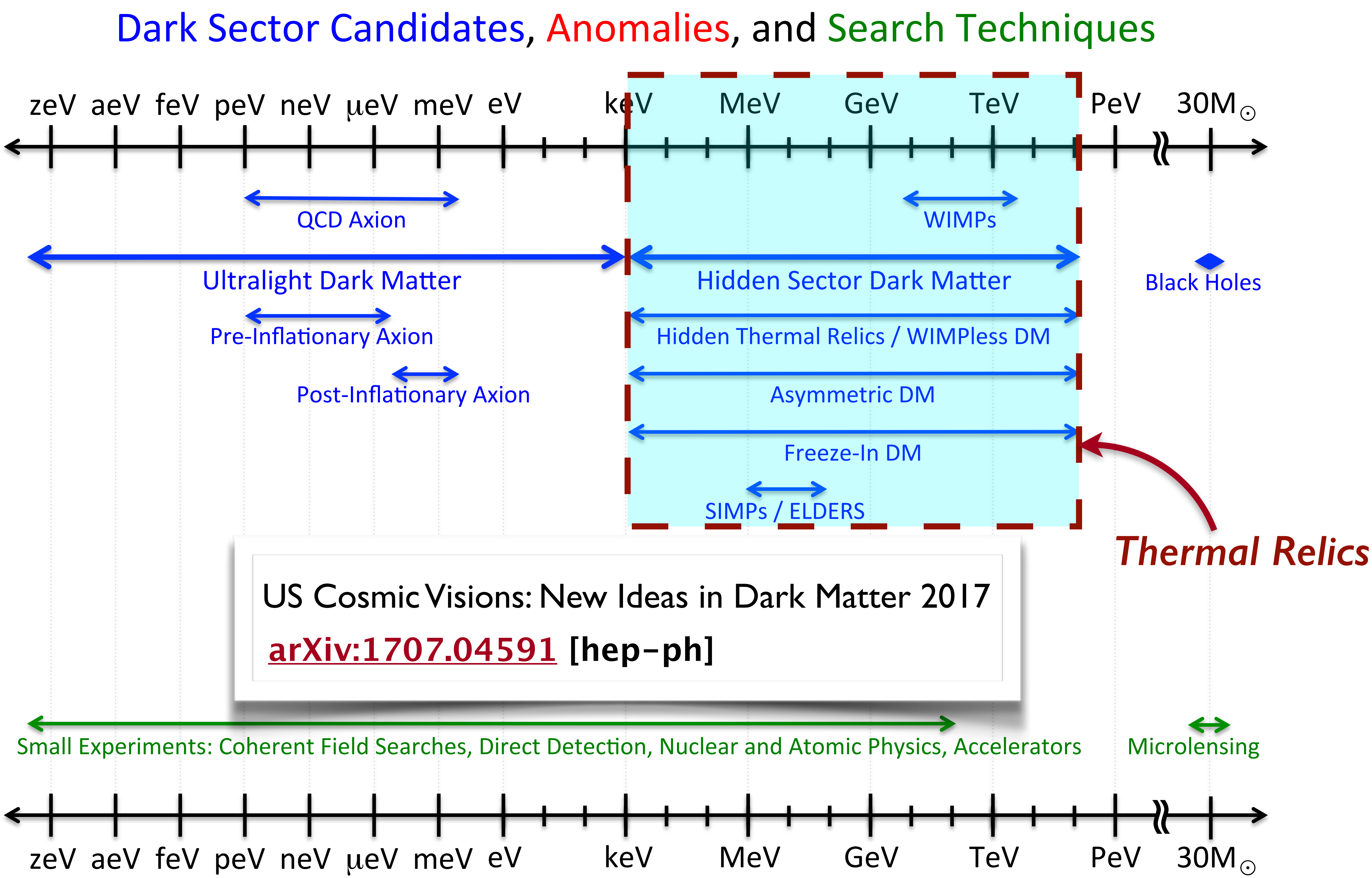
Work begun on developing mediator searches starting almost ten years ago is bearing fruit in exploring the top-down motivated parameter space for mediator decays to SM.

Work is underway to define a search program for MeV-GeV thermal dark matter, which can cover highly motivated targets.

Many experiments have sensitivity to non-minimal models, other mediators, and DM candidates - especially true of missing energy/momentum which have sensitivity for thermal relic DM that is relatively independent of mediator and DM candidate.


Extra Slides

Broadening Our Perspective



US Cosmic Visions: New Ideas in Dark Matter 2017

arXiv:1707.04591 [hep-ph]

Possible Mediators

The complete list of options:

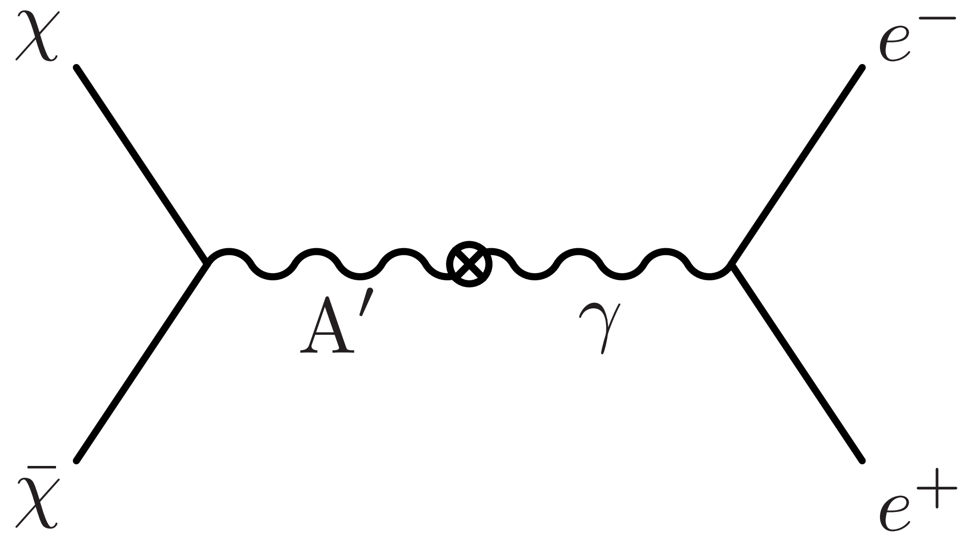
$F'_{\mu\nu}F^{\mu\nu}$ A dark photon kinetically mixes with the SM photon
induces a small coupling between DM and SM

$V_\mu J^\mu_{\mathrm{SM}}$ A new force directly couples to DM to SM
Gauge SM quantum numbers (B-L, etc…)

LHN New neutral fermion N mixes with neutrinos
Scenarios for stable, thermal DM are highly constrained.

$\phi H^\dagger H$ A new scalar mixes with the SM Higgs
The most predictive scenarios are ruled out.

Direct Annihilation Thermal Targets



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

$\Omega_\chi/\Omega_{\rm DM} < 1 \implies$ there is a minimum cross section compatible with thermal DM

perturbativity/unitarity $\implies \alpha_D \lesssim 1$

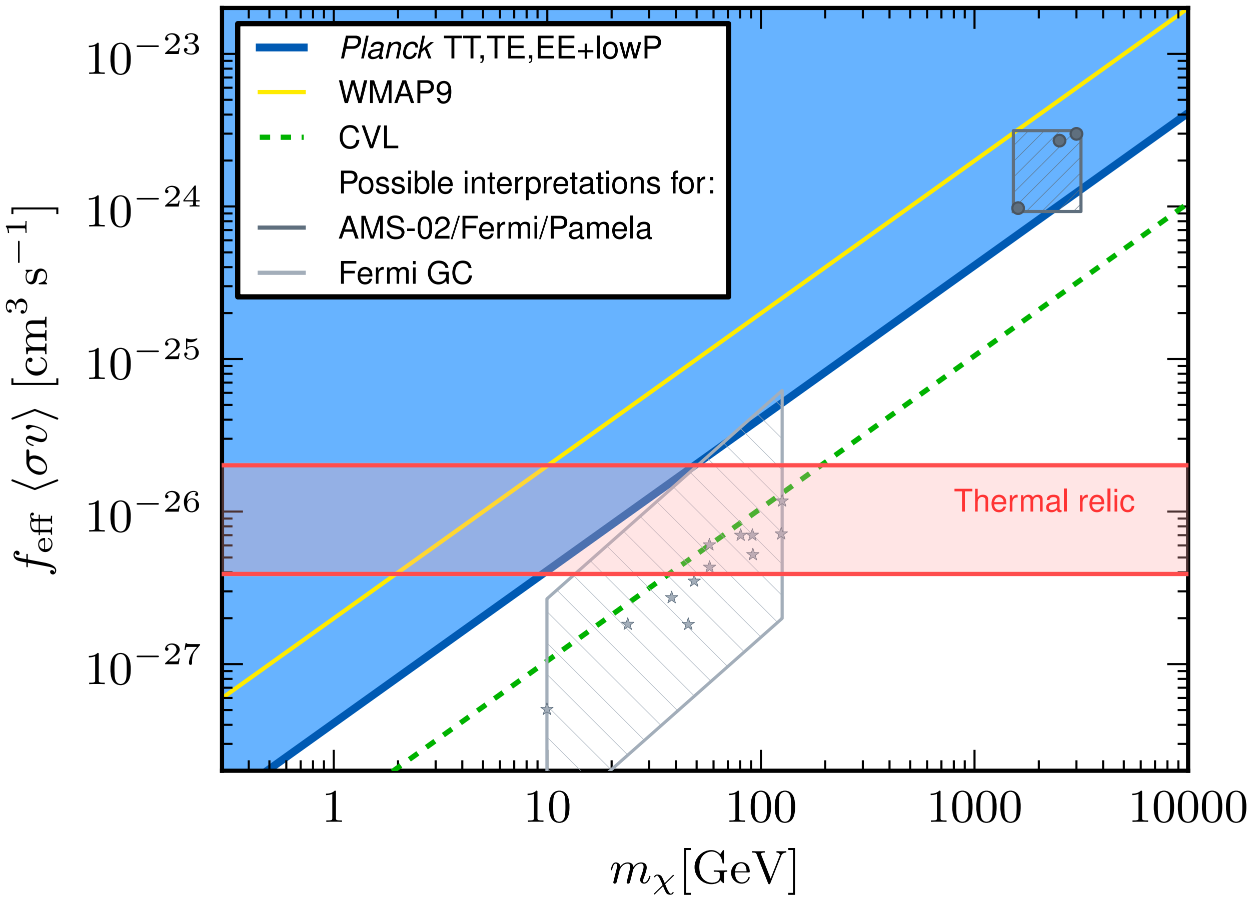
direct annihilation $\implies m_\chi/m_{\rm A'} < 1$

$\implies$ there is a minimum value of ϵ motivated by thermal DM!

What Kind of DM?

SLAC

Annihilation during recombination (T = eV) affects CMB power spectrum



$$\mathcal{L} \supset g_D A'_\mu J^\mu_\chi$$

$$J^\mu_\chi = \begin{cases} \overline{\chi}\gamma^\mu\chi & \text{Asym. Dirac} \\ \overline{\chi}_1\gamma^\mu\chi_2 & {}^*\text{Pseudo}-\text{Dirac} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{Majorana} \\ i\chi^*\partial_\mu\chi & \text{Scalar} \end{cases}$$

*Dirac + small Majorana mass

Rules out thermal relic DM below ~10 GeV unless annihilation suppressed relative to freeze-out:

$$\langle\sigma v\rangle\big|_{T={\rm eV}} \ll \langle\sigma v\rangle\big|_{T=m_\chi}$$

p-wave annihilation (Scalar, Majorana)

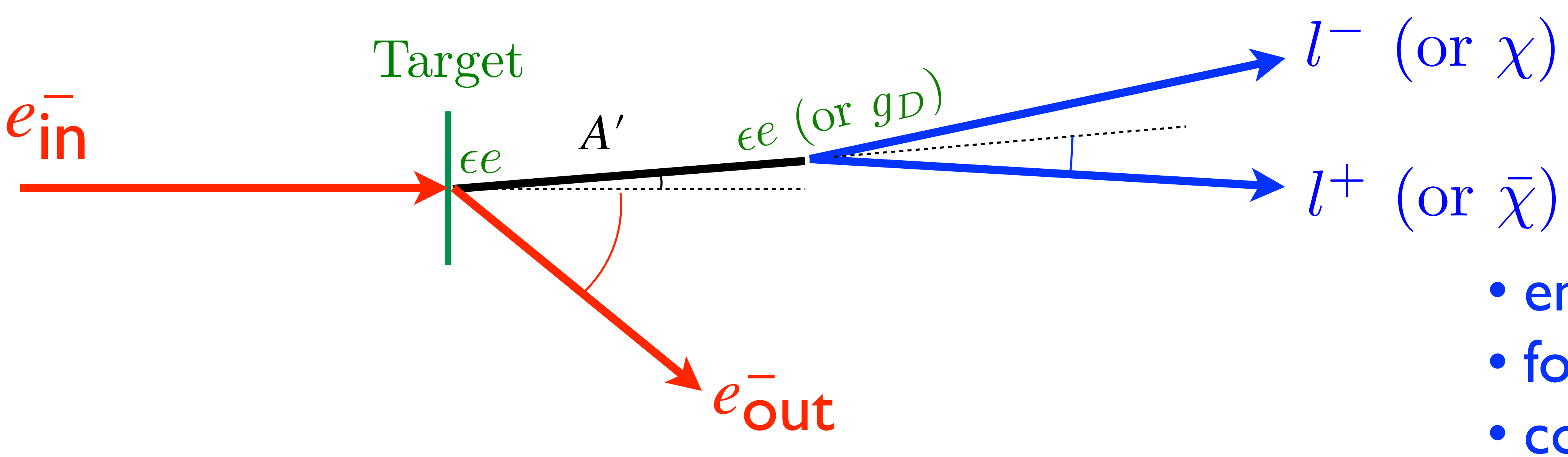
$$n_\chi\big|_{T=eV} < n_\chi\big|_{T=m_\chi}$$

Asymmetric or Pseudo-Dirac

N.B. Related considerations may suppress direct-detection cross-sections.

Dark Bremsstrahlung

Heavier product (here A′) takes most of beam energy

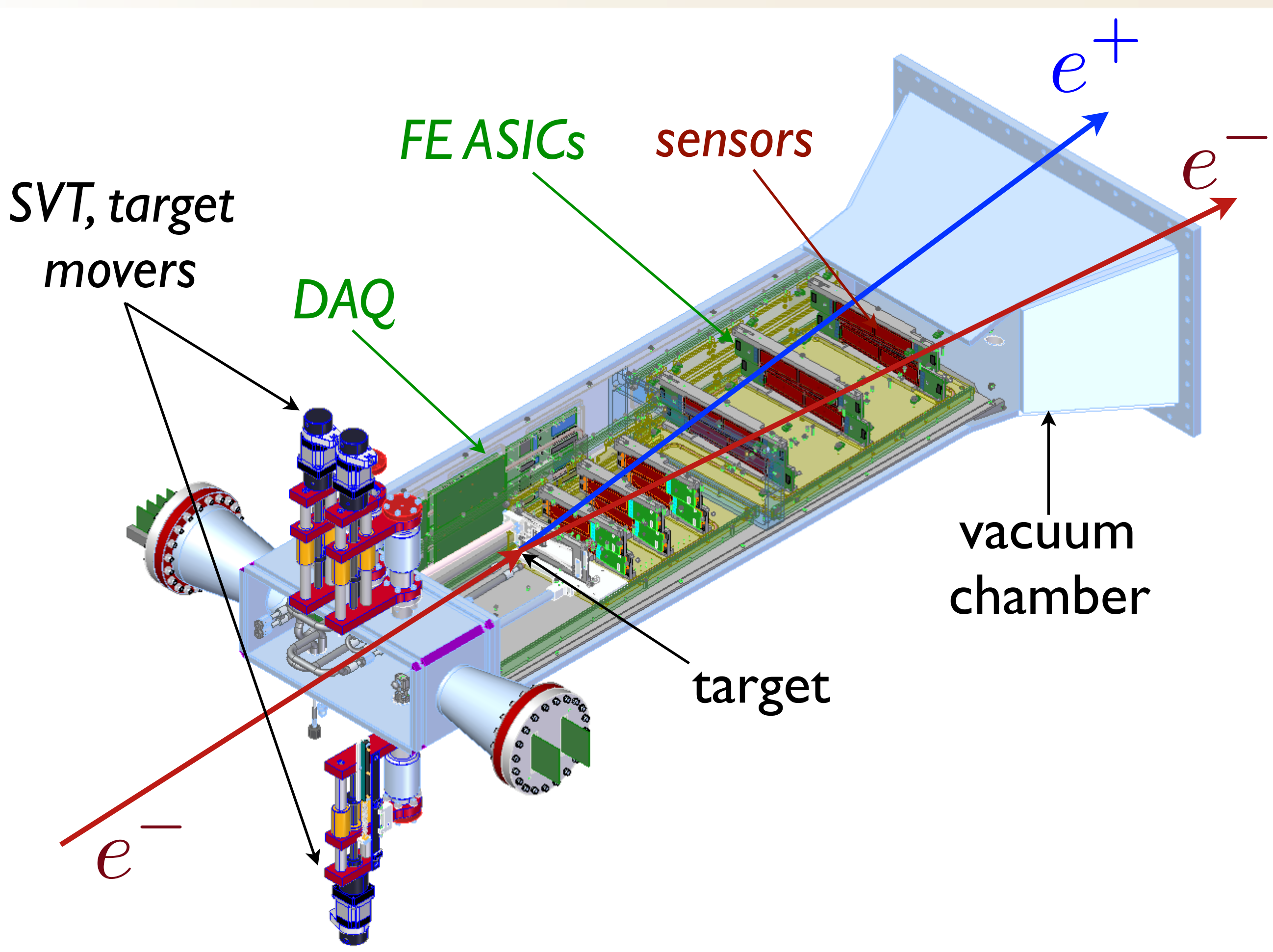


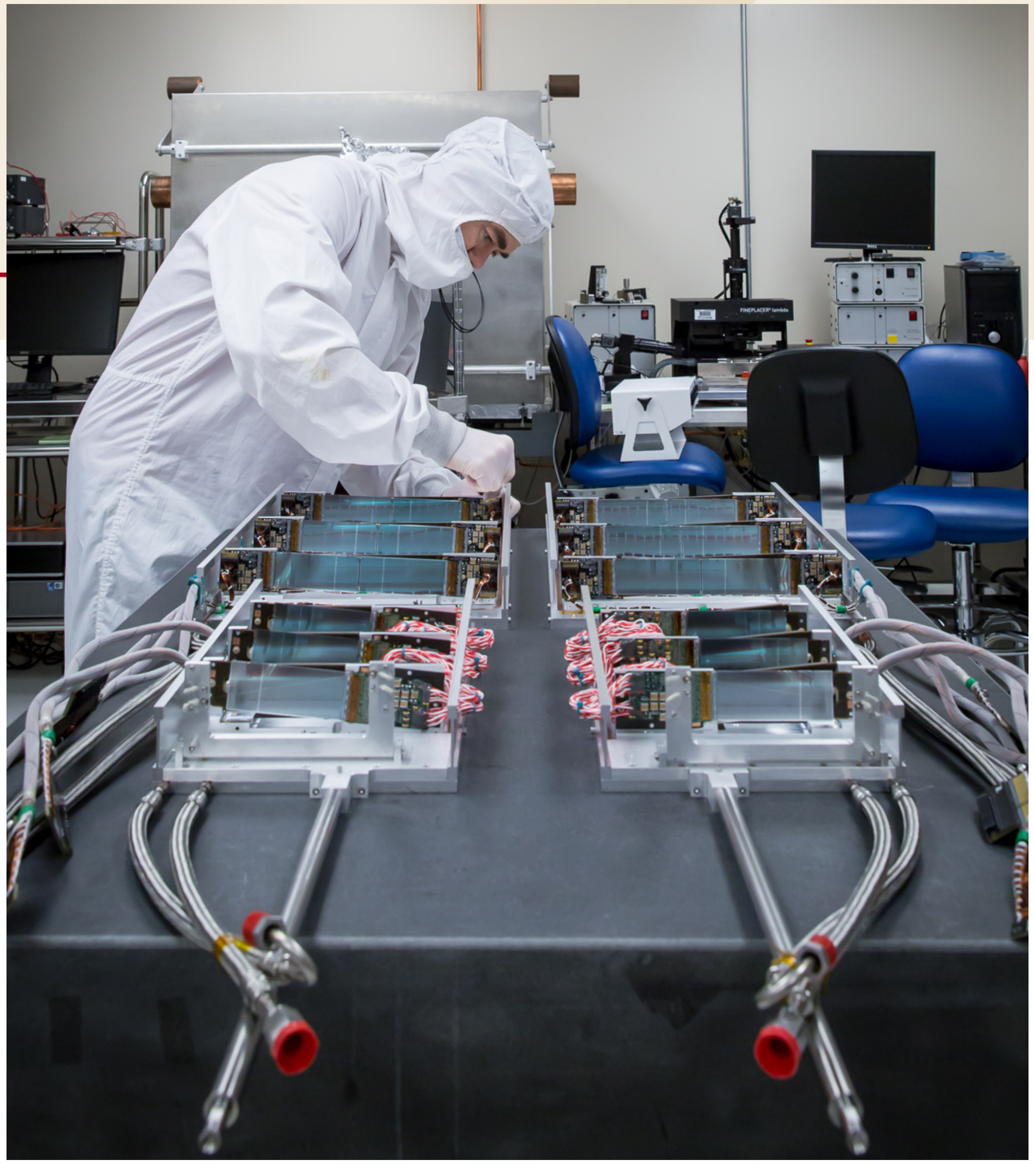
- energetic
- forward
- collimated

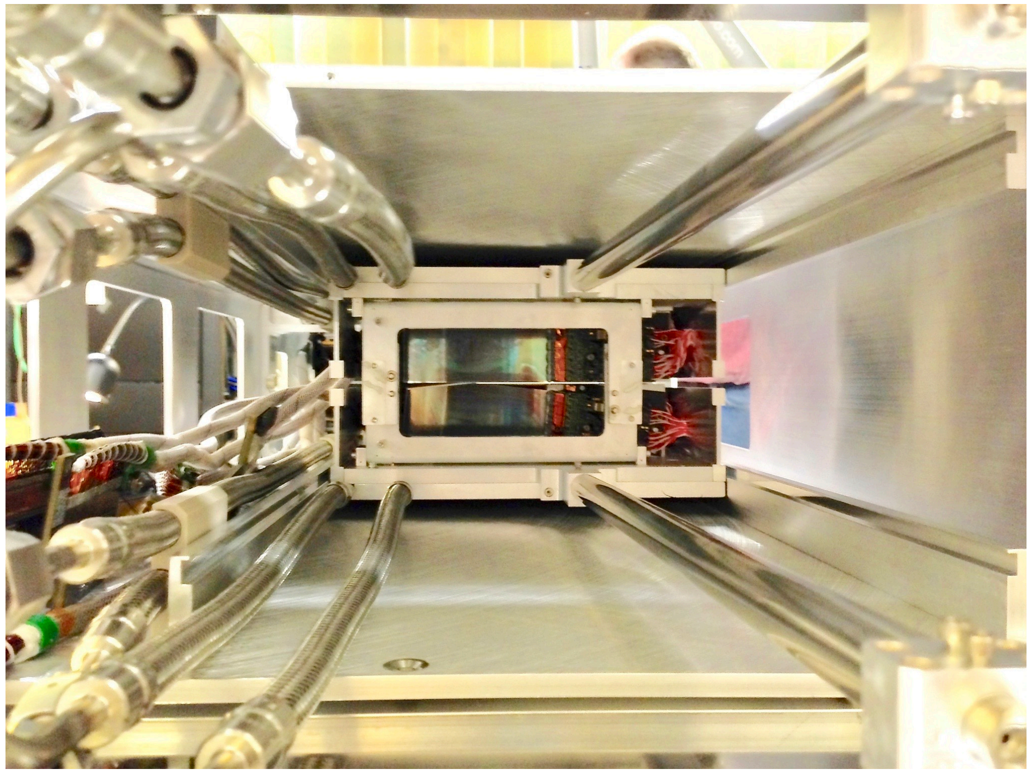
- soft
- wide-angle

This shapes the designs of many experiments.

HPS SVT

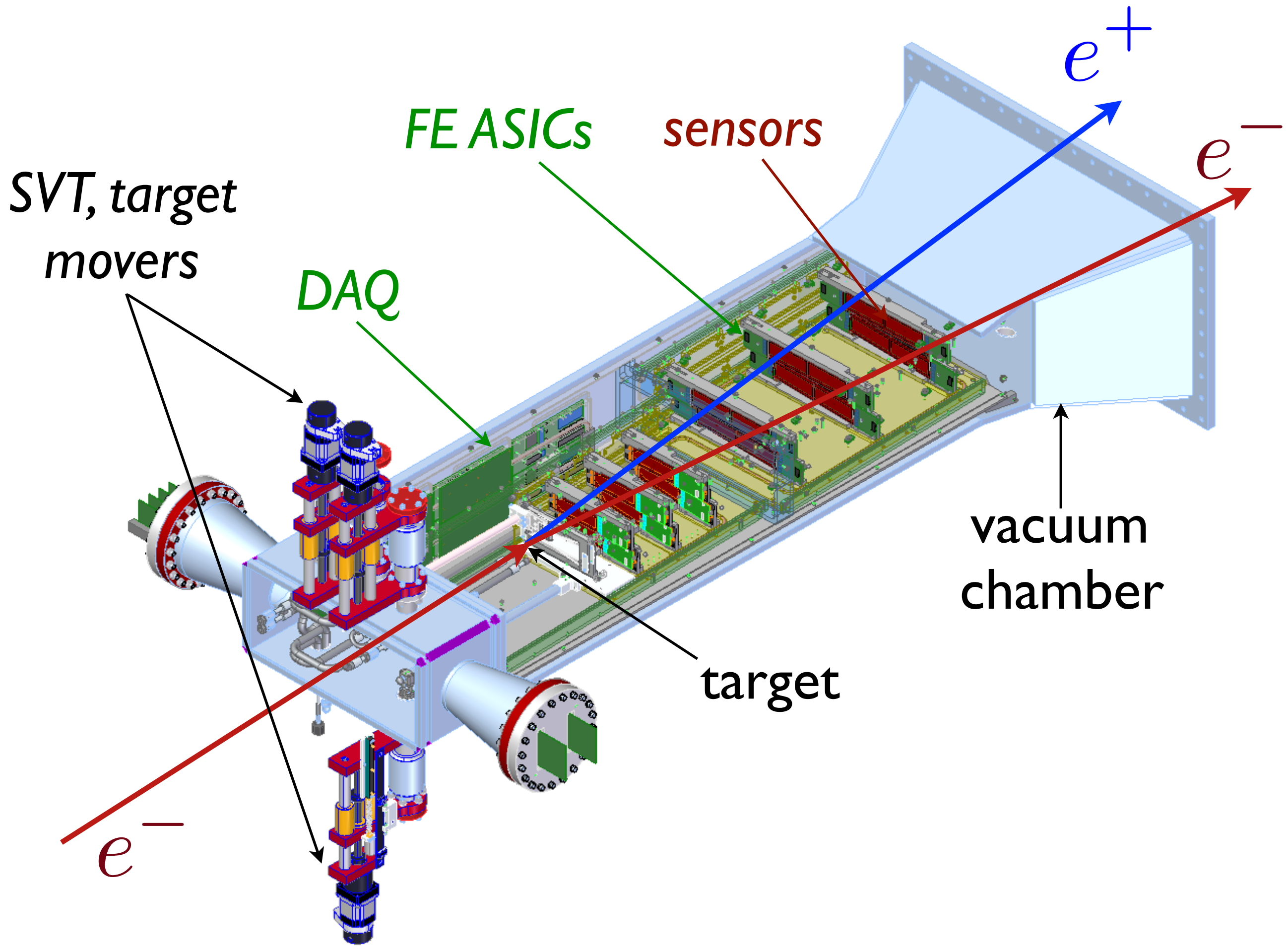


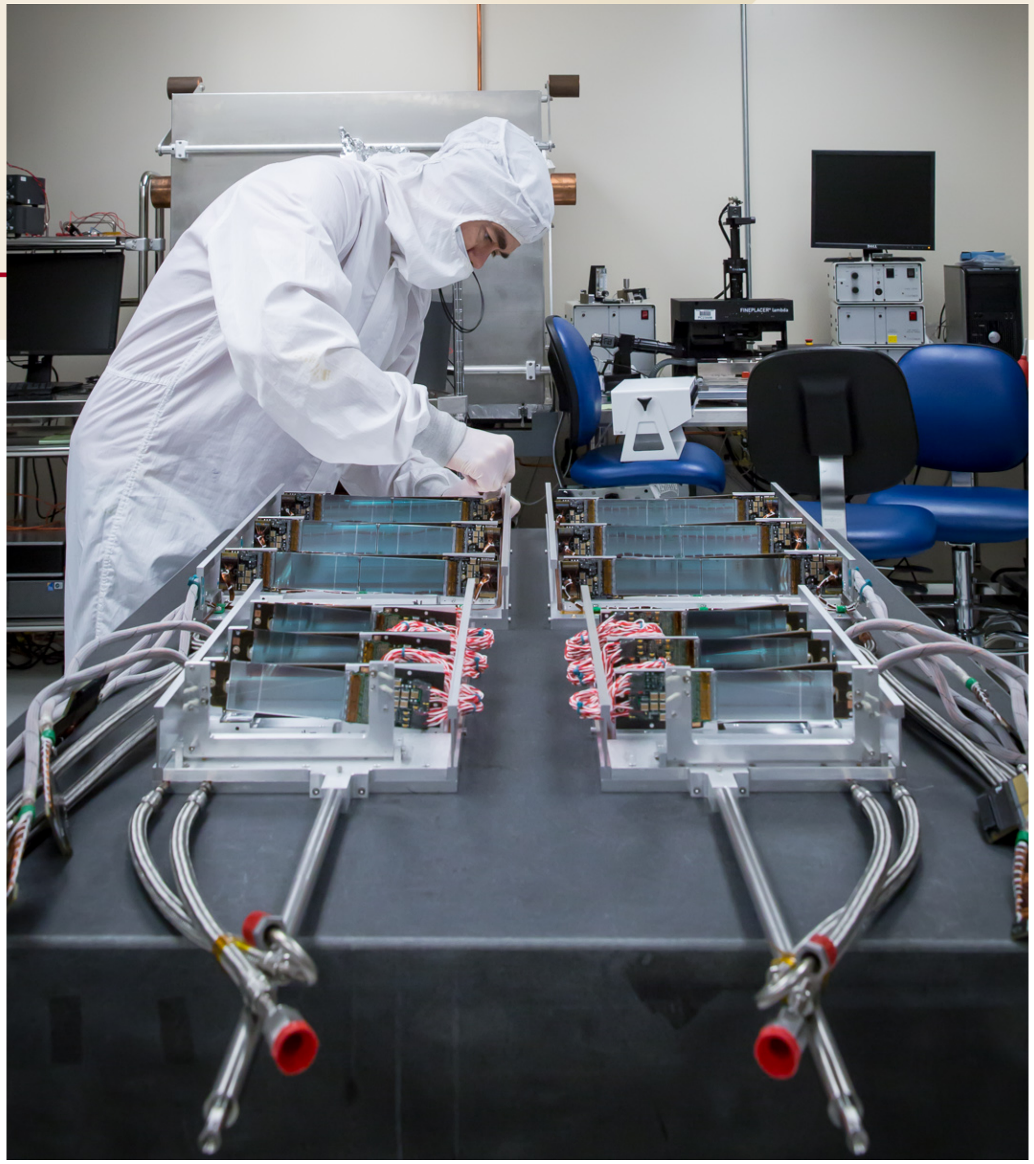




- 6-layer Si microstrip tracker, inside beam vacuum
- Cooled to -20C, radiation tolerant
- existing components: DØ RunIIb Si, CMS APV25
- SLAC RCE DAQ (also ATLAS, LSST, DUNE, LCLS)
- Layer 1 silicon 0.5 mm from primary beam!
- vertically retractable

HPS SVT





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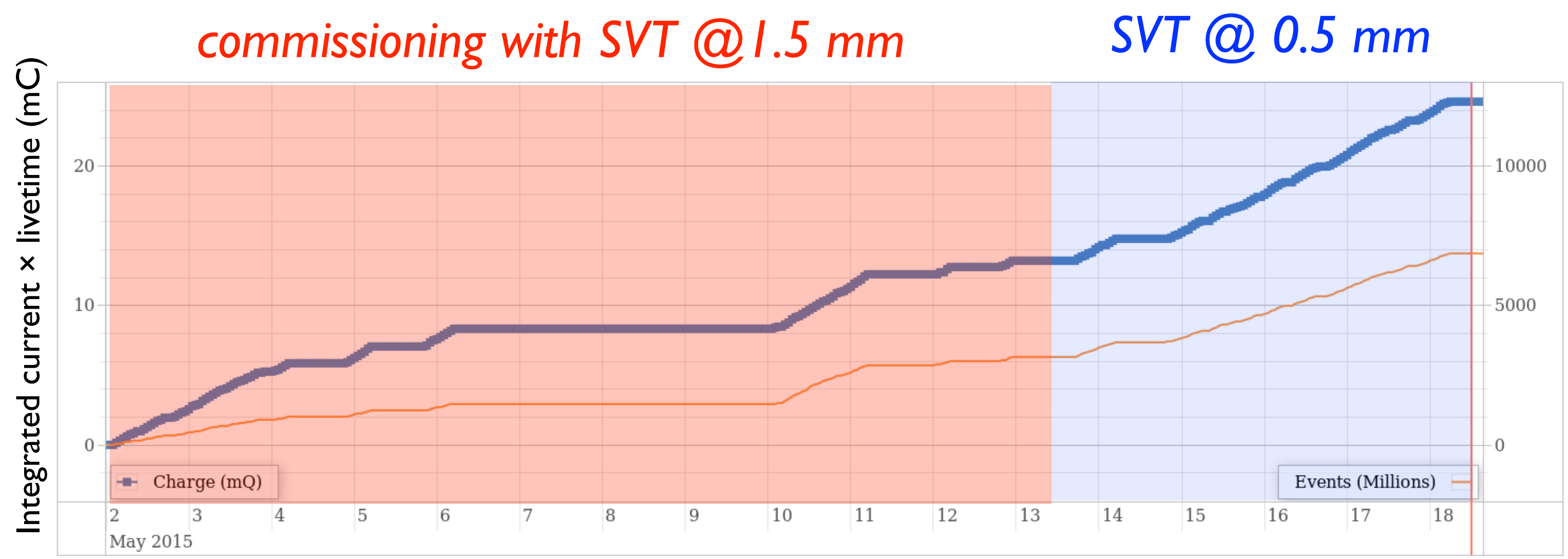
- Cooled to -20C, radiation tolerant
- existing components: DØ RunIIb Si, CMS APV25
- SLAC RCE DAQ (also ATLAS, LSST, DUNE, LCLS)
- Layer 1 silicon 0.5 mm from primary beam!
- vertically retractable
- 0.7% X_0/3d measurement
- $\sigma_y = 6\ \mu m$, $\sigma_x = 60(120)\ \mu m$ in L1-3 (L4-6)
- $\sigma_{\text{hit time}} = 2$ ns (offline)
- 50 kHz max trigger rate
- 200 gb/sec max data rate
- as built: 3/23004 bad channels, 75 um alignment

HPS Engineering Runs

2015 Engineering Run

50 nA @ 1.06 GeV

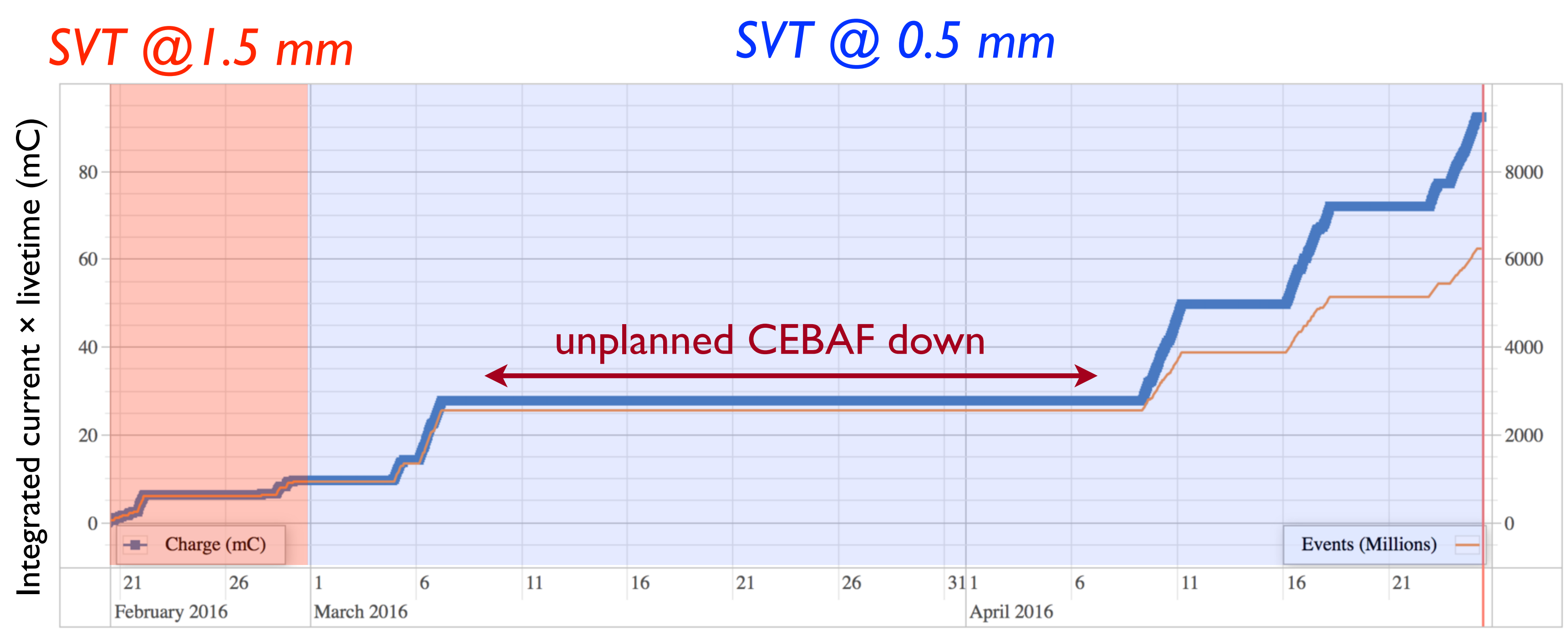
1.7 days (10 mC) of physics data



2016 Engineering Run

200 nA @ 2.3 GeV

5.4 days (92.5 mC) of physics data



- The HPS apparatus, including the SVT, has performed exceptionally well.
- *HPS still approved for 165 more days of beam time: a long way to go!*

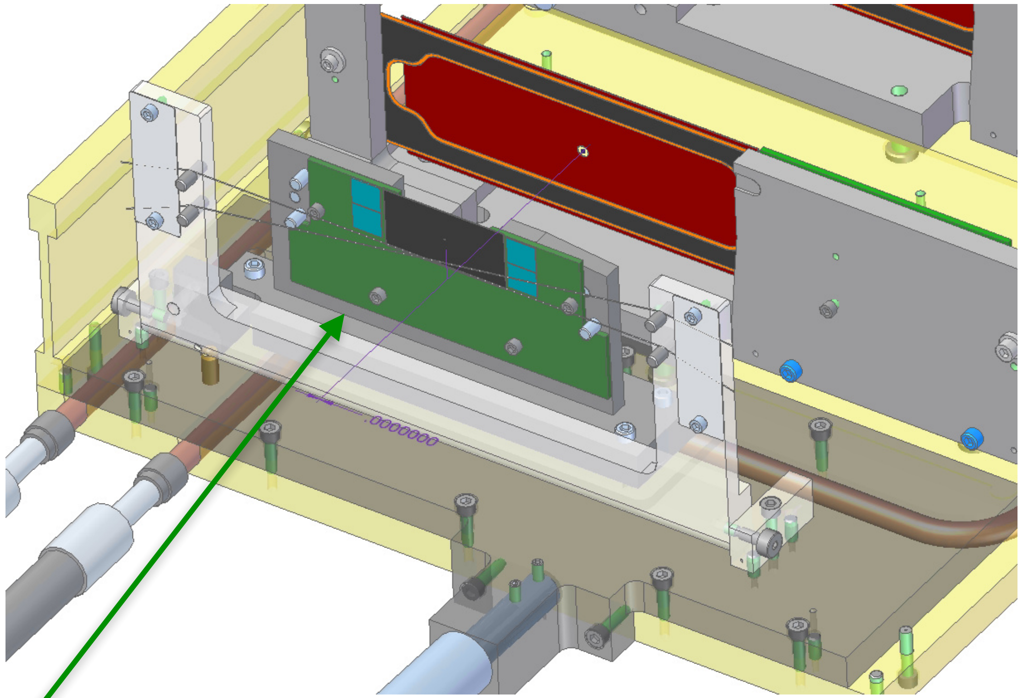
HPS Upgrade

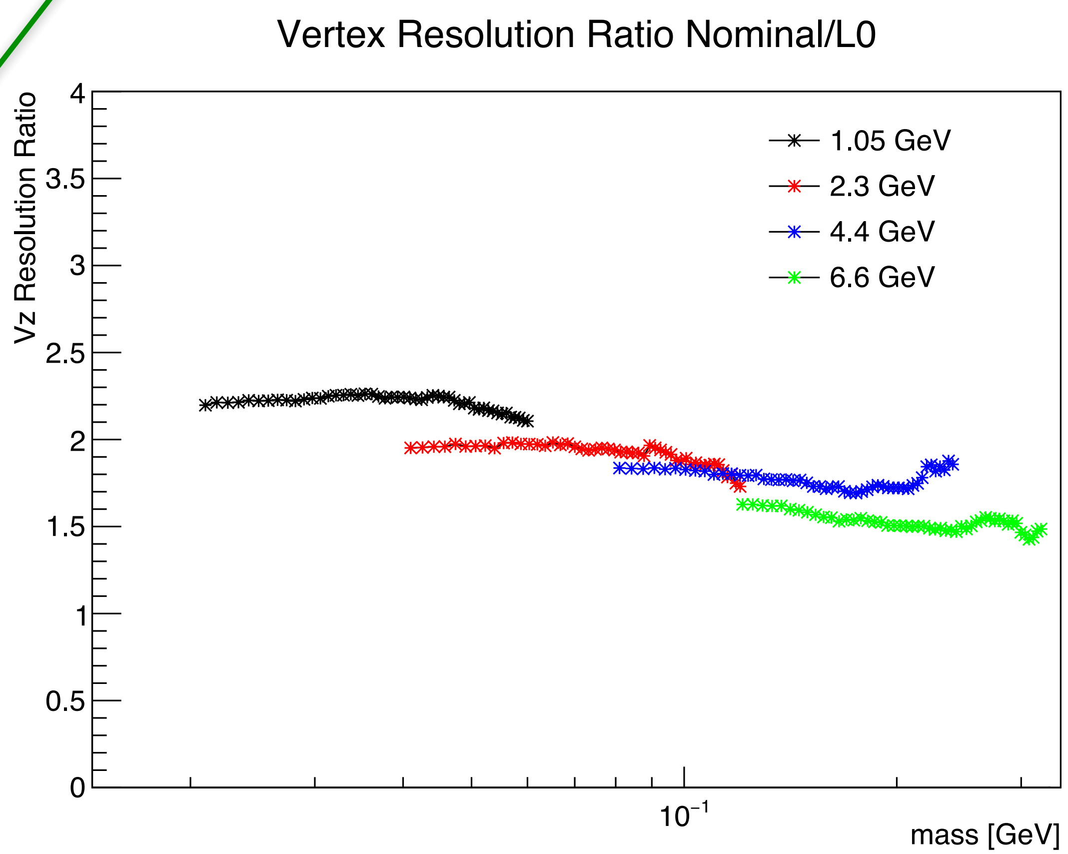
Engineering Run analyses showed where HPS can be improved.

- High-occupancy crystals removed from ECal design are important for triggering e^- from low-mass A′.
- angular acceptance of SVT for long-lived A′ previously overestimated

Both are addressable.

- New hodoscope provides positron-only trigger.
- New SVT Layer 0, thinner and closer to the target allows SVT to access shorter decays lengths





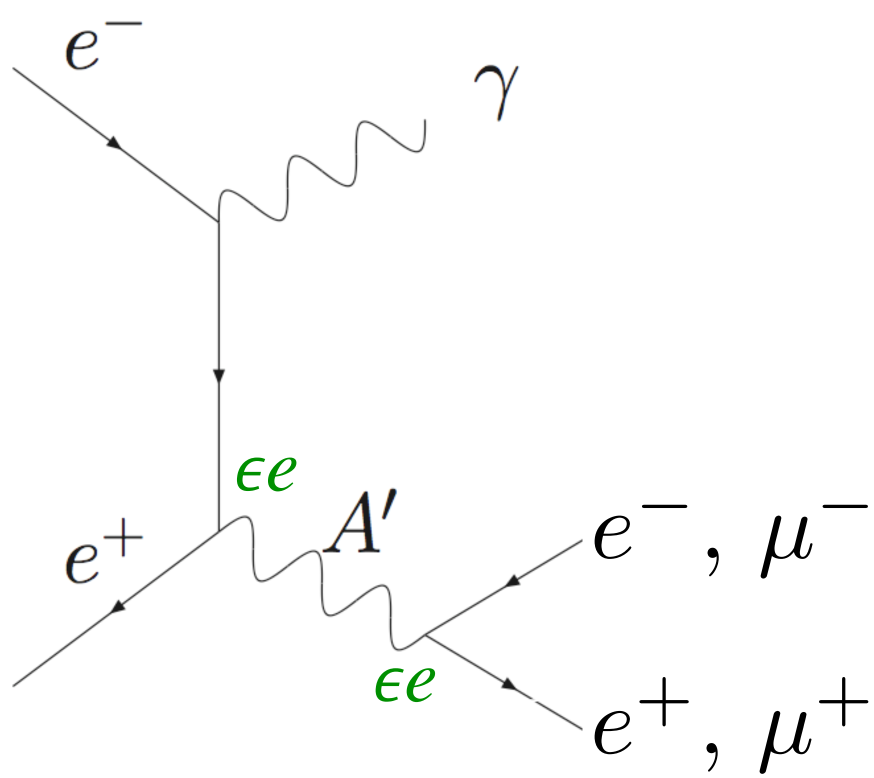
Past, Present & Future - e^+e^- Colliders: Babar & Belle-II

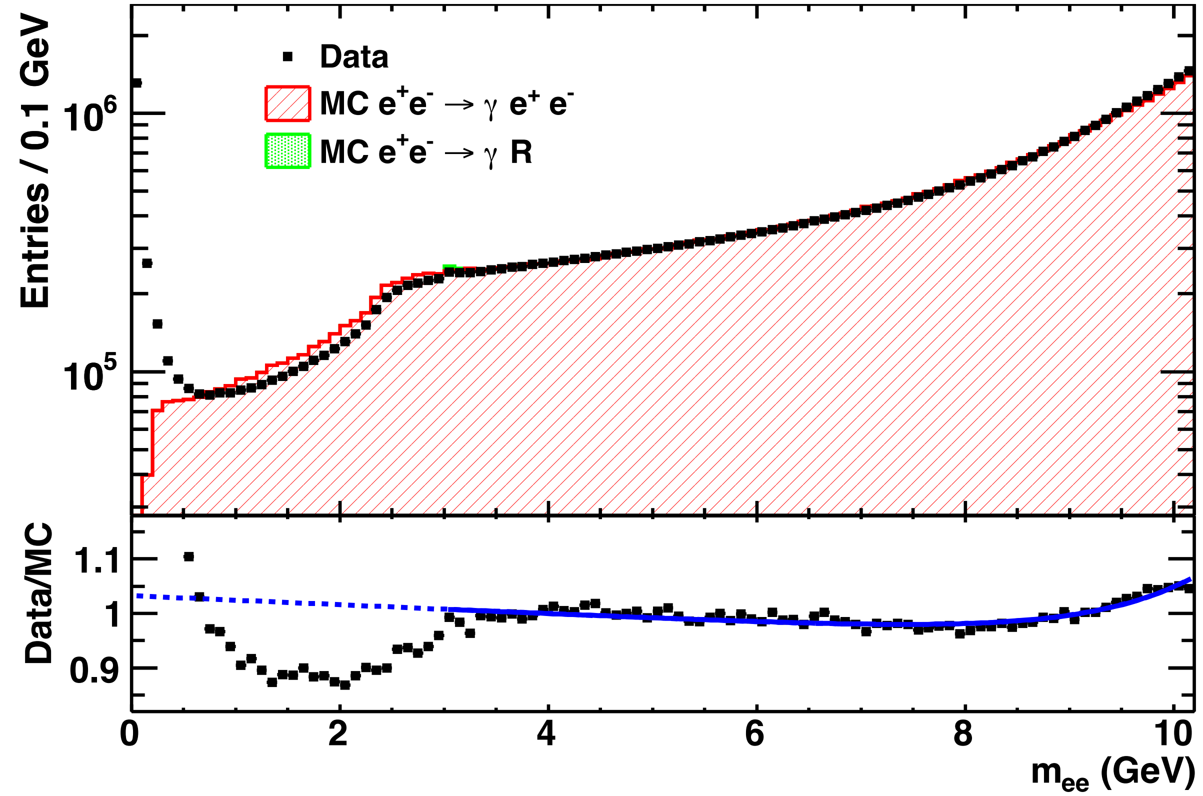
SLAC

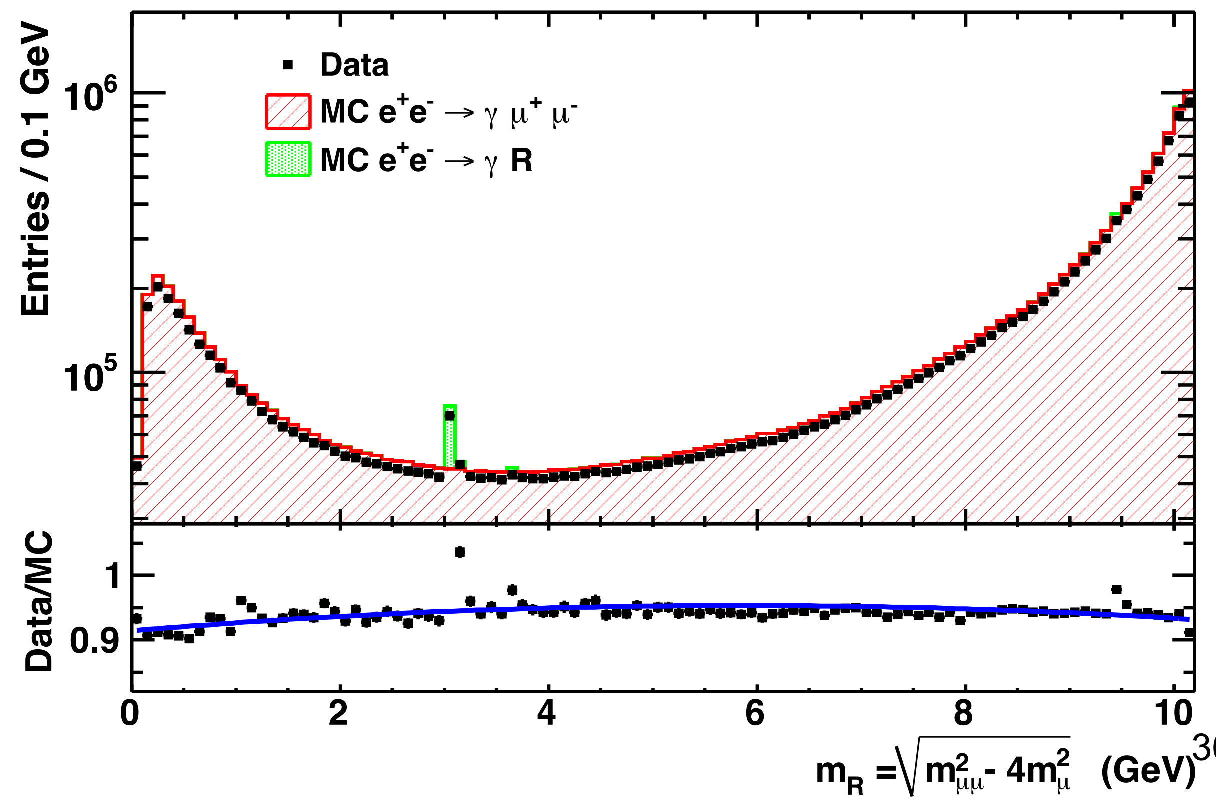
e^+e^- @ Υ(2s,3s,4s) $\approx$ 10 GeV

Full BaBar dataset, 514 fb^{-1}

arXiv: 1406.2980







Belle-II may ultimately do about 10× better in ϵ^2 with 50 ab^{-1}.

Past, Present & Future - e^+e^- Colliders: Babar & Belle-II

e^+e^- @ $\Upsilon(2s,3s,4s) \approx 10$ GeV

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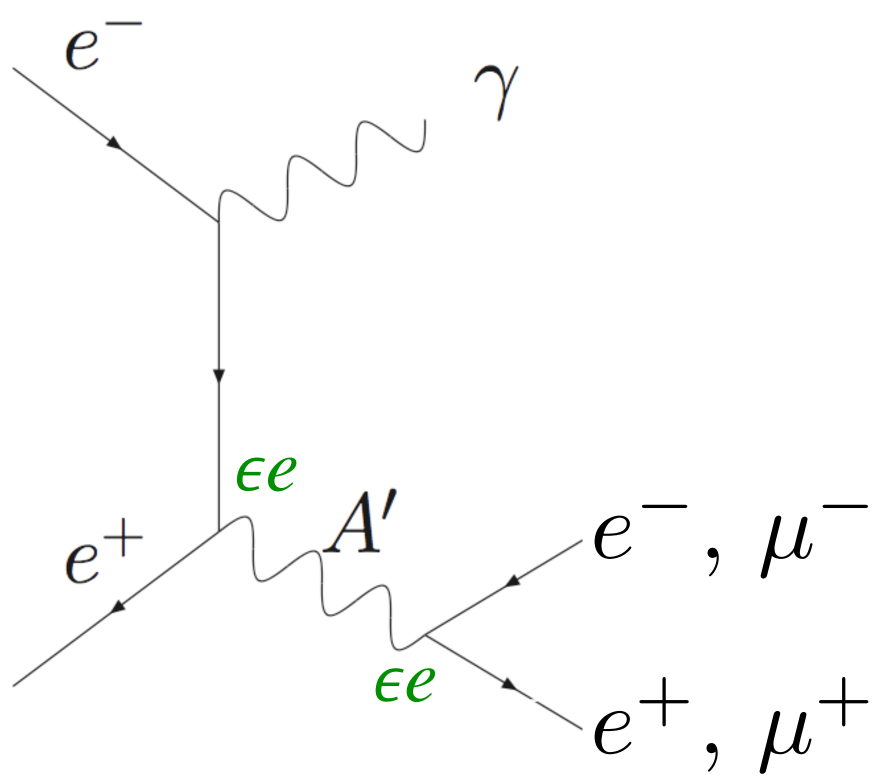

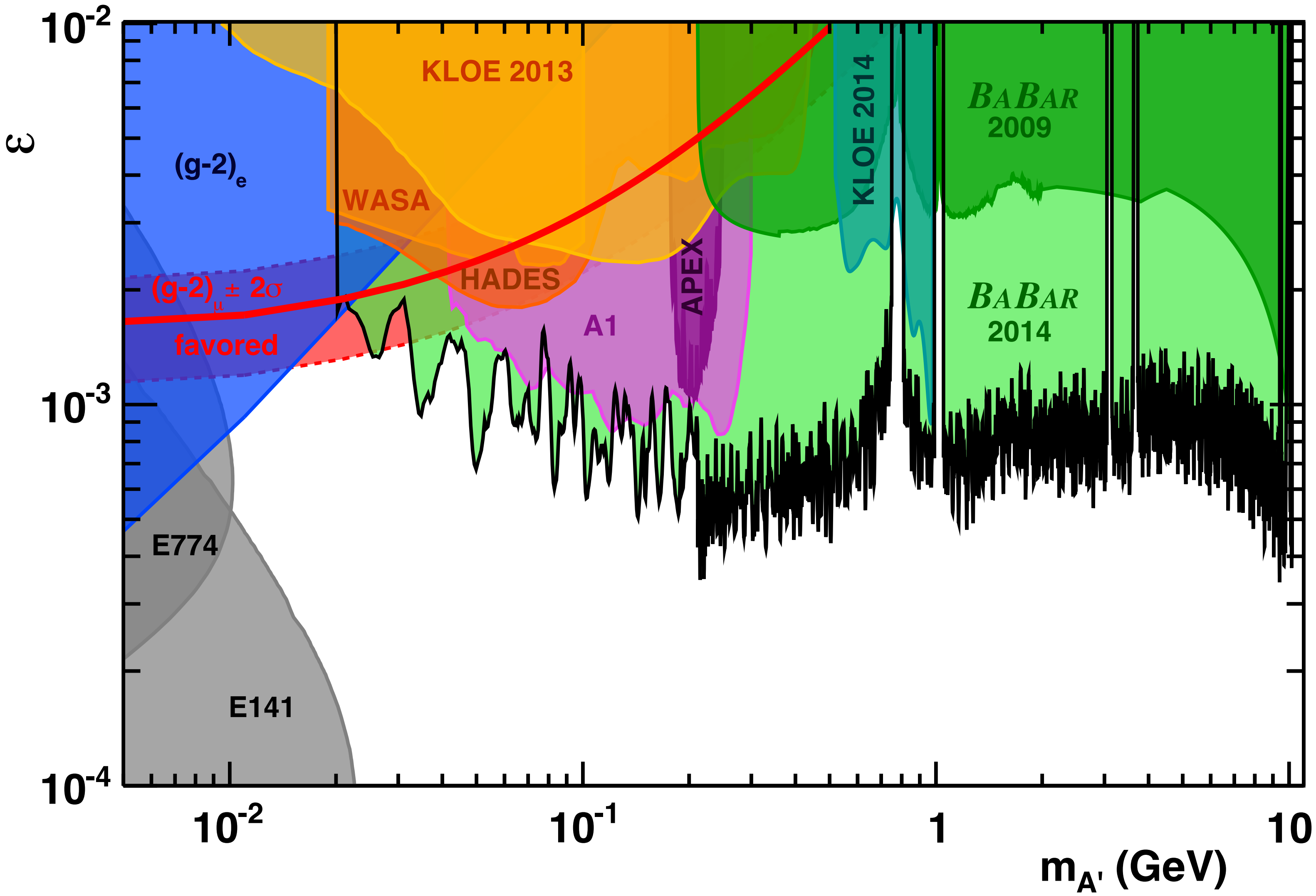

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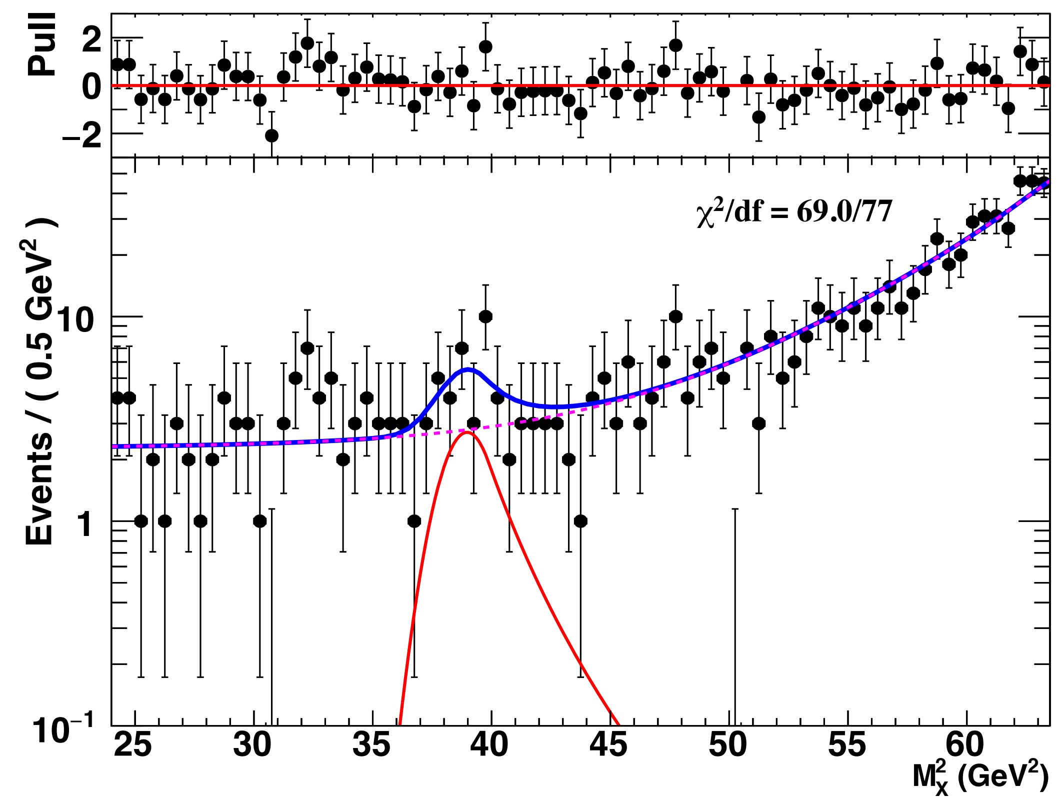
Colliders - Past/Present/Future: BaBar/Belle-II Missing Mass

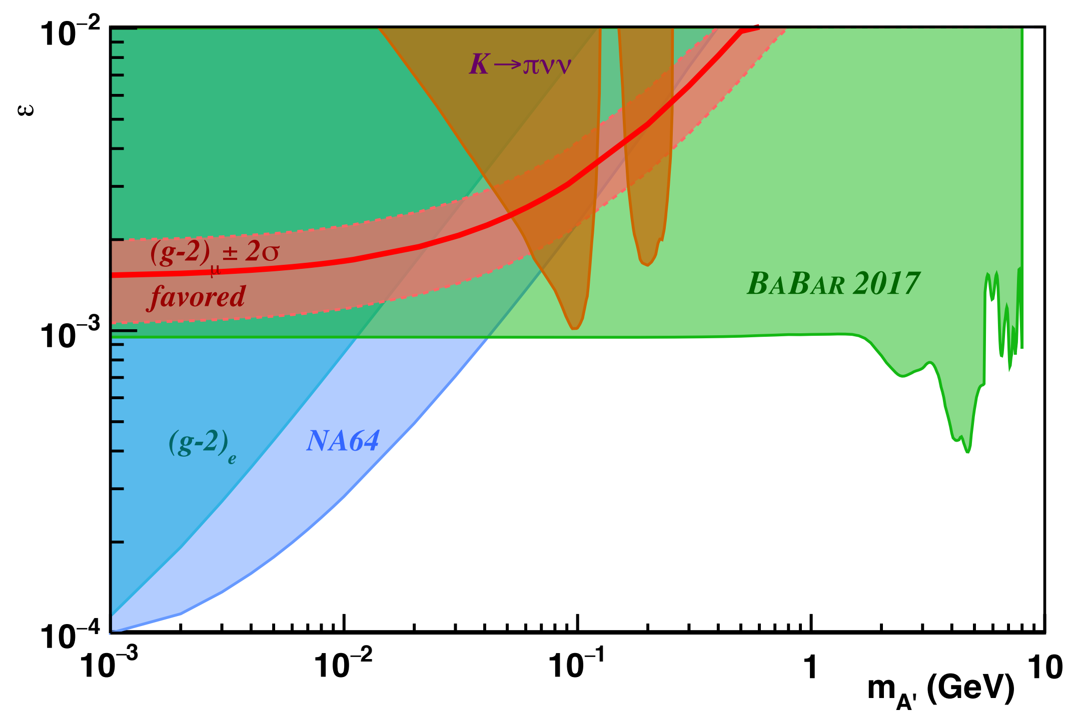
BaBar 2017 result using 53 fb^{-1} collected with special single-photon trigger in 2007-2008.

arXiv: 1702.03327



Initial state at e+e- collider so well known can employ missing mass

$$e^+e^- \to \gamma + X$$
$$m_{\text{miss}} = E_{\text{CM}} - m(\gamma X)$$



Belle-II is working to ensure collection of these events, can hope to do three orders of magnitude better in ϵ^2 / y with 50 ab^{-1}

LDMX Physics Potential

Key backgrounds are e^- + low multiplicity:

$$e^- \to e^- + \text{hard } \gamma$$
$$\gamma \to \mu^+\mu^-$$
$$\gamma \to \text{hadrons}$$

…and direct electro-nuclear analogues

A physics study of operation at SLAC has demonstrated reach of a "Phase I" experiment with $4{\times}10^{14}$ EOT.

arXiv:1808.05219 [hep-ex]

Work continues to understand requirements for "Phase II", to cover all thermal targets.

Cutflow and event yields

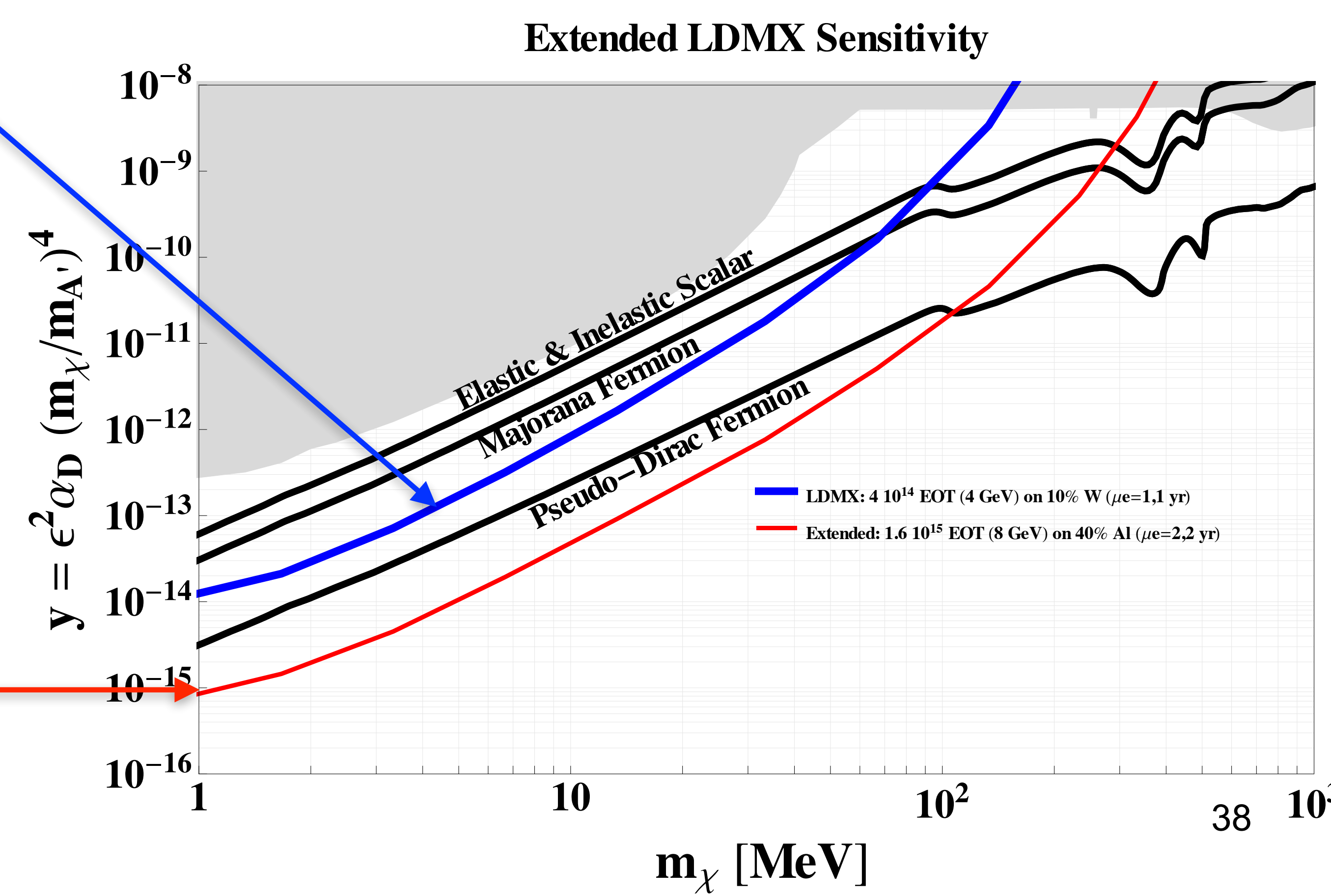
	Target-area $\mu\mu$	ECal $\mu\mu$
EoT equivalent	1.1×10^{15}	6.6×10^{14}
Events passing trigger	2.14×10^{7}	1.50×10^{8}
Passing HCal veto	36	169
Passing N_{track} veto	2	169
Passing ECal BDT veto	0	1

Cutflow and event yields

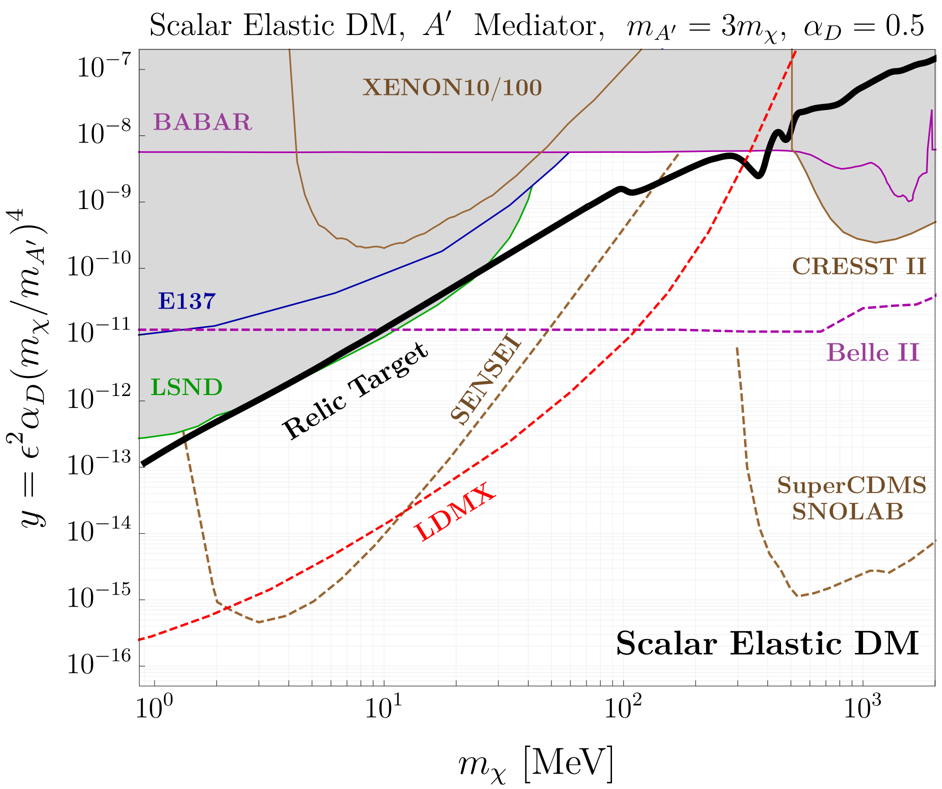
	ECal PN	Target-area PN
EoT equivalent	4×10^{14}	4×10^{14}
$E_{recoil} < 1.5$ GeV, trigger requirement	2.7×10^{8}	2.2×10^{7}
ECal Shower-Profile BDT	2×10^{6}	8.2×10^{5}
HCal Max PE < 3	0.55	28
Single track with $p < 1.2$ GeV	0.51	23
Recoil activity Cut	0.41	23
ECal activity cut	0.24	23
Tagging tracker activity cut	0.24	0

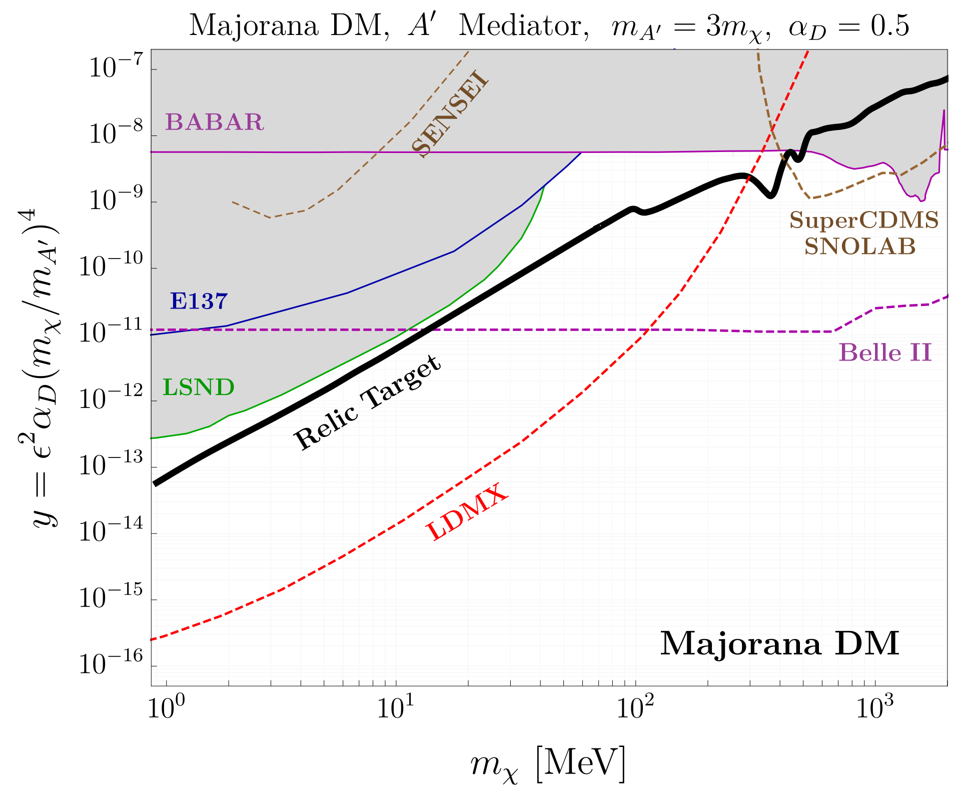
Cutflow and event yields

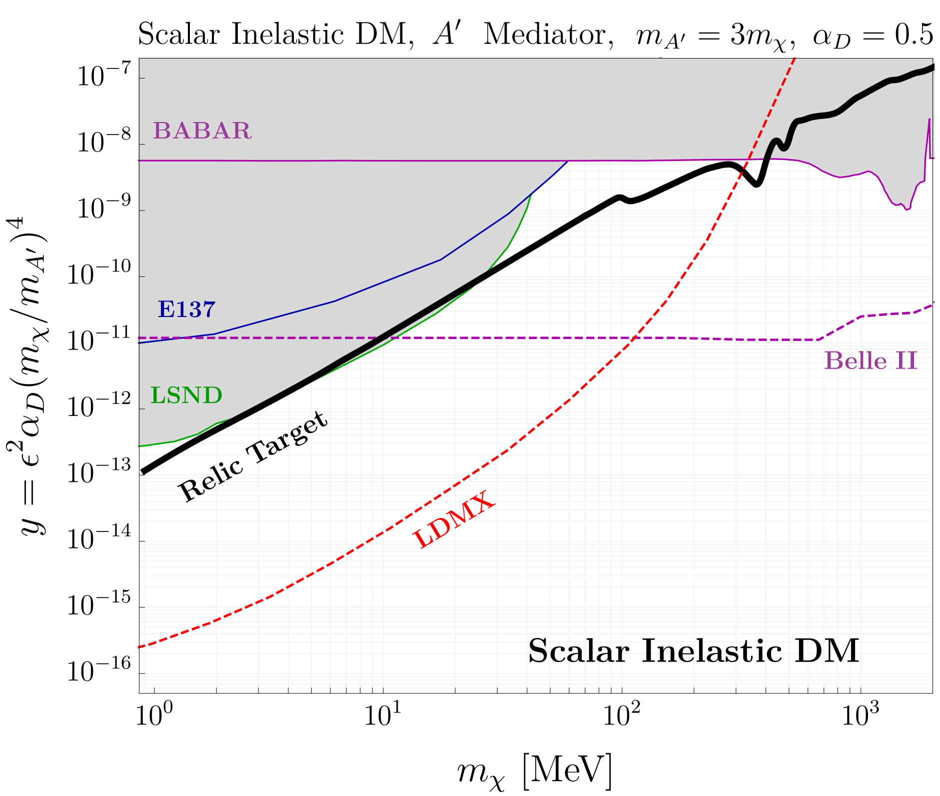
	Target-area EN
EoT equivalent	4×10^{14}
$E_{recoil} < 1.5$ GeV, trigger requirement	1.4×10^{7}
ECal Shower-Profile BDT	6.2×10^{5}
HCal Max PE < 3	26
Single track with $p < 1.2$ GeV	13
Tagging tracker activity cut	0.0127

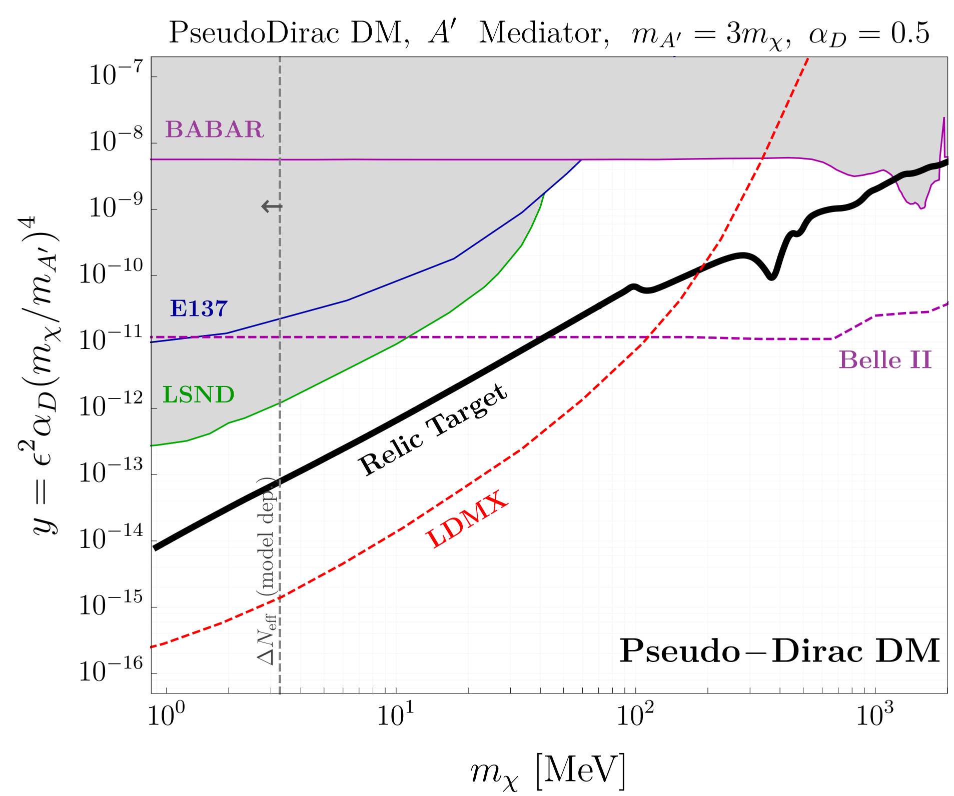


Thermal Targets - Accelerators and Direct Detection

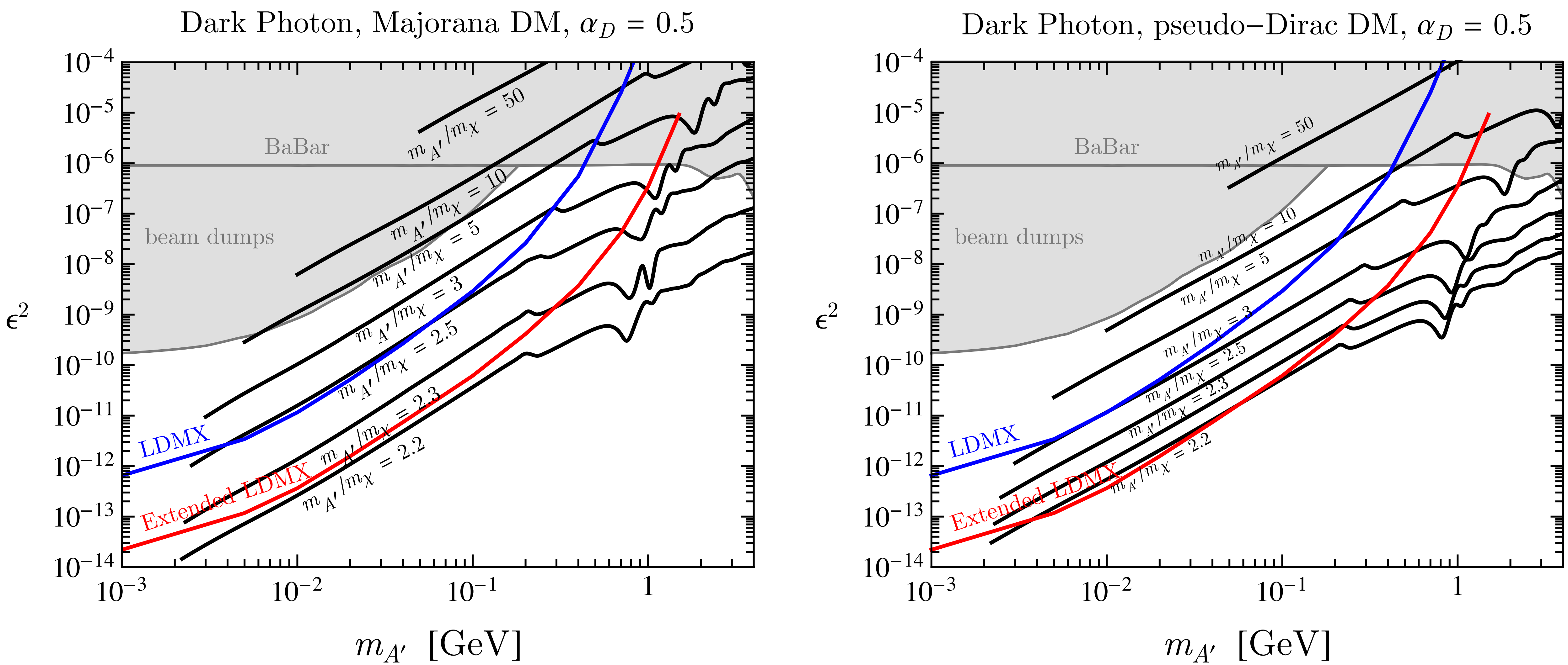








Resonance Effects



LDMX has good sensitivity even for finely tuned mass ratio.

How to Discover Something Invisible?

25 years before the neutrino was observed in scattering experiments, Pauli successfully predicted it’s existence.

“I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle.”

- Pauli, in open letter December 4, 1930

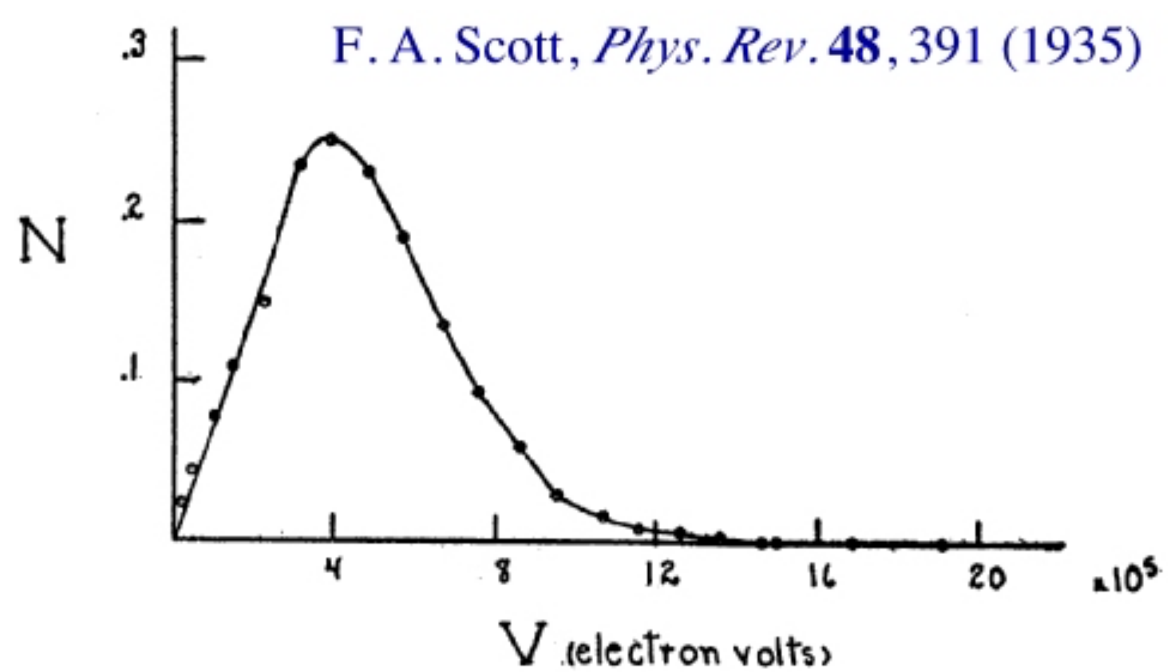
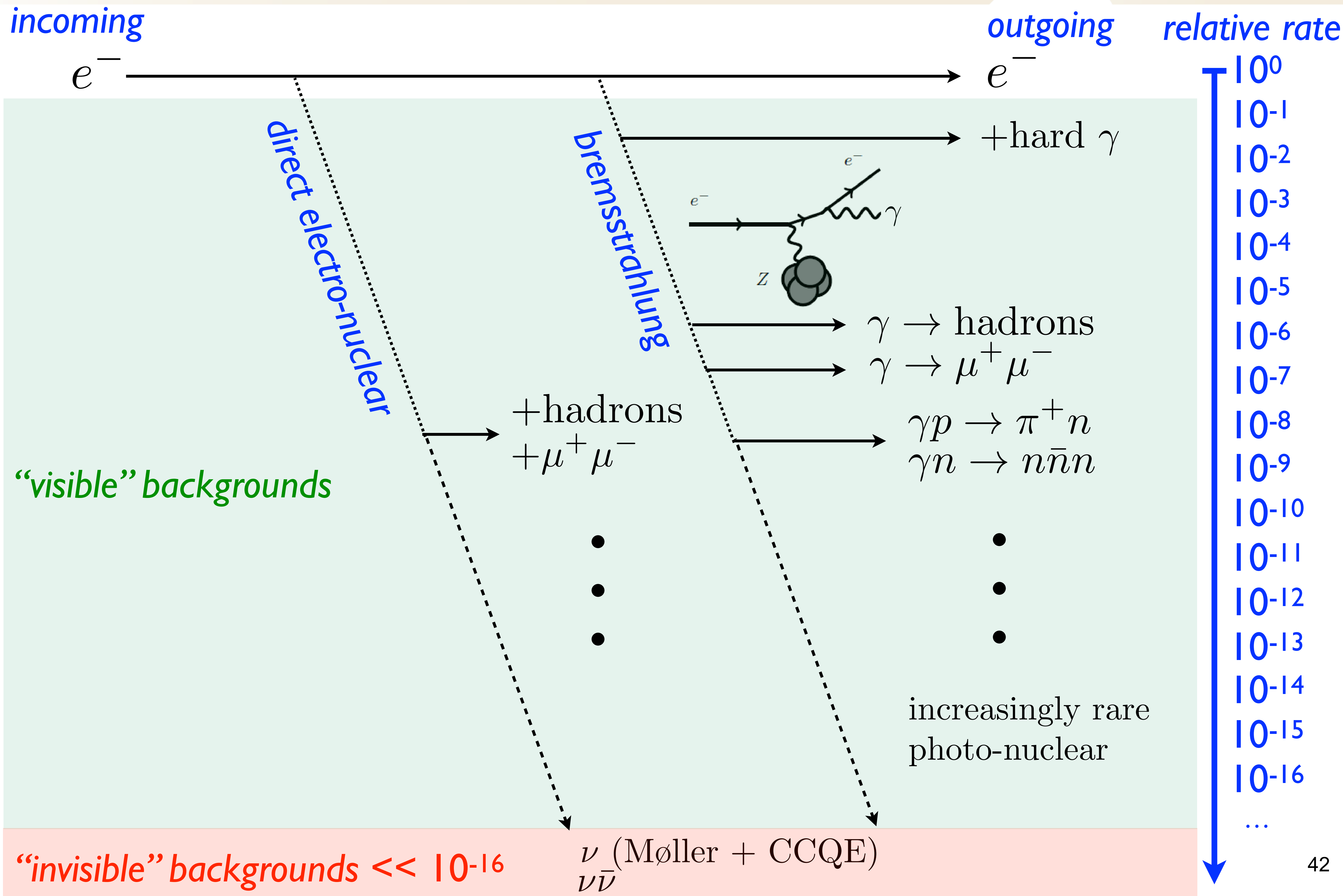


FIG. 5. Energy distribution curve of the beta-rays.

Take same approach as mono-photon/monojet searches: missing momentum!

Missing Momentum Backgrounds

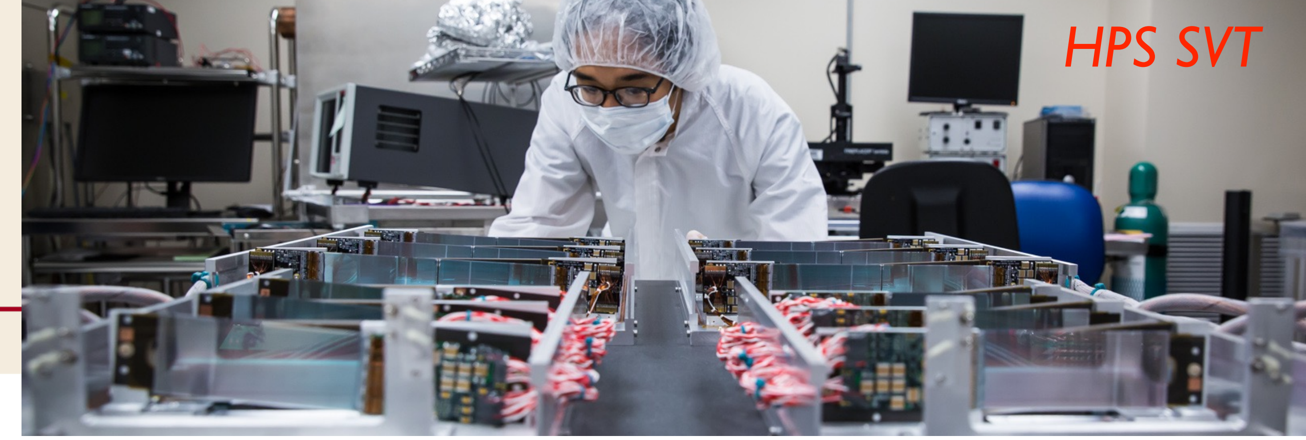
SLAC



LDMX Tracking

SLAC NATIONAL ACCELERATOR LABORATORY

UC SANTA CRUZ



Si trackers similar to HPS SVT built by SLAC/UCSC

- low mass, fast (2 ns hit timing)

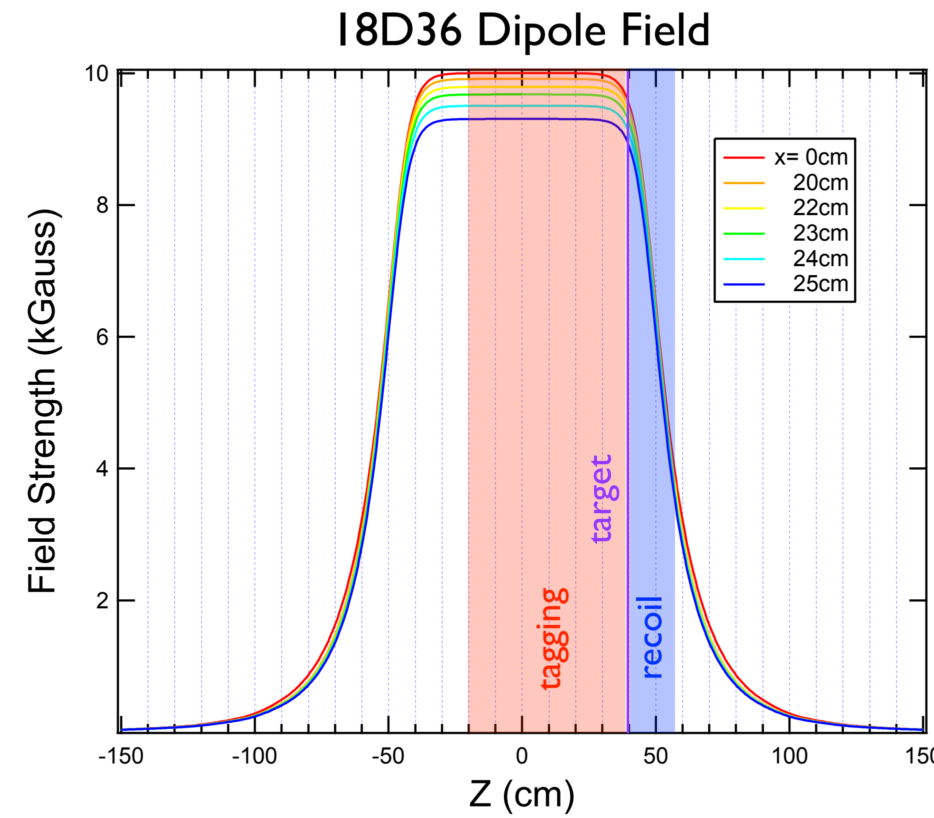
Single dipole magnet - two field regions

Tagging Tracker in central 1.5 T field for p_e = 4 GeV

- provides robust tag of incoming electrons

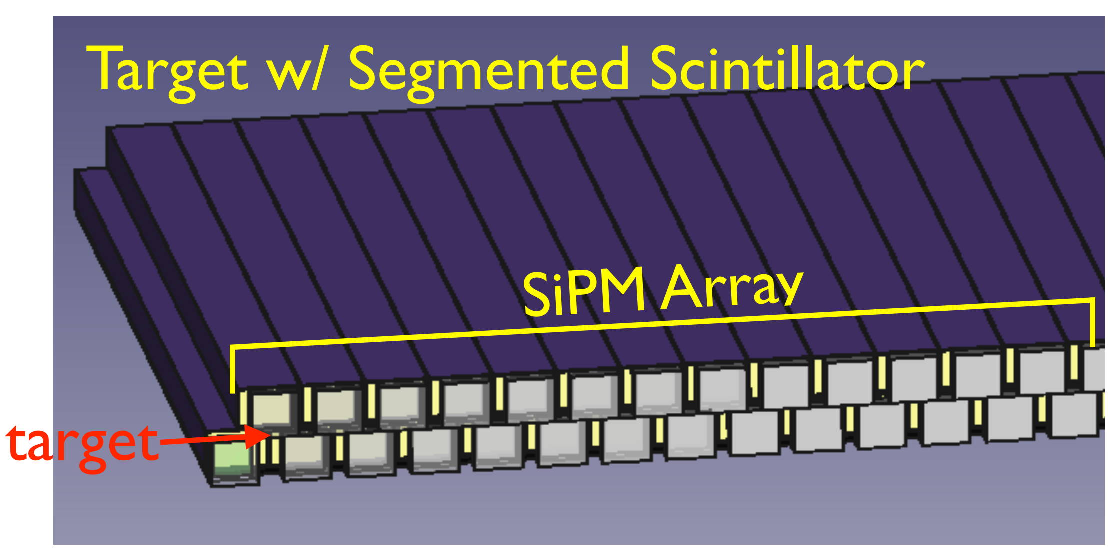
Recoil Tracker in fringe field for p_e = 0.05 - 1.2 GeV

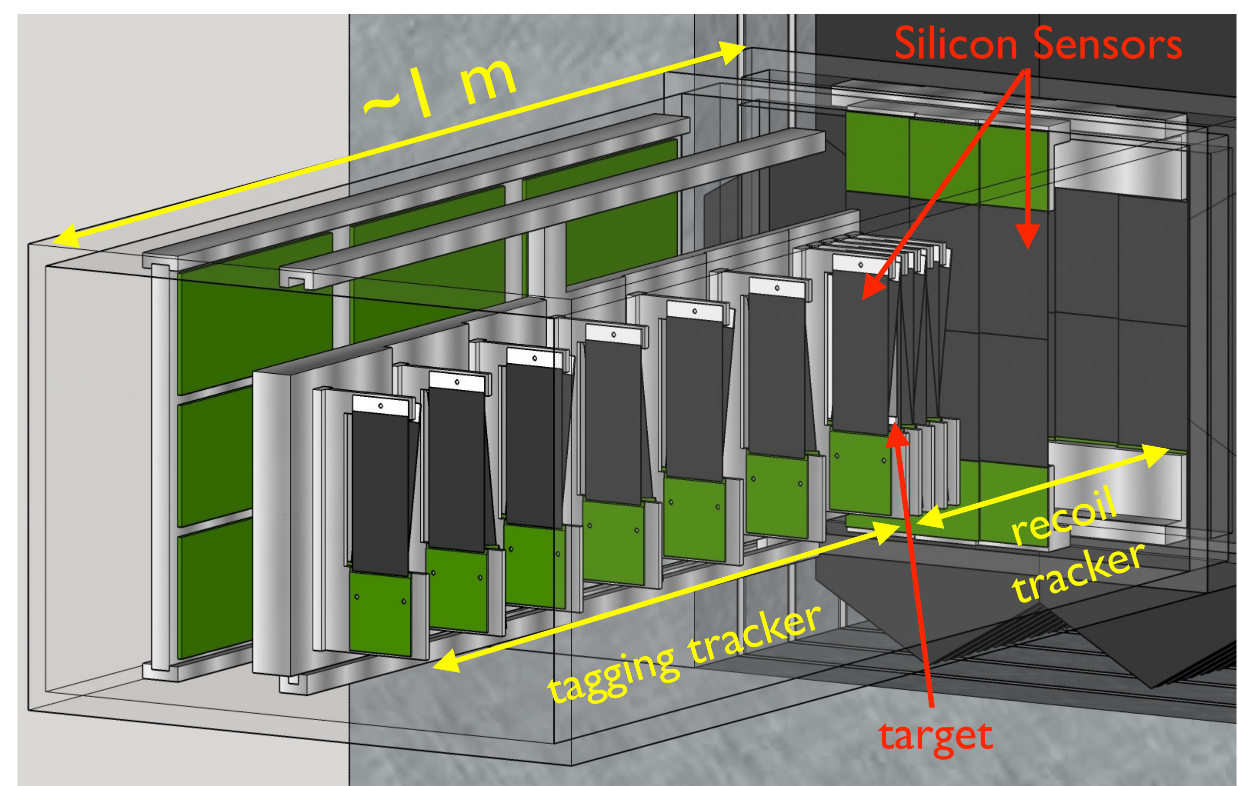
- measures recoils with good resolution, large acceptance



Tungsten target (0.1-0.3 X_0) between trackers

- scintillator counts electrons/bunch for trigger



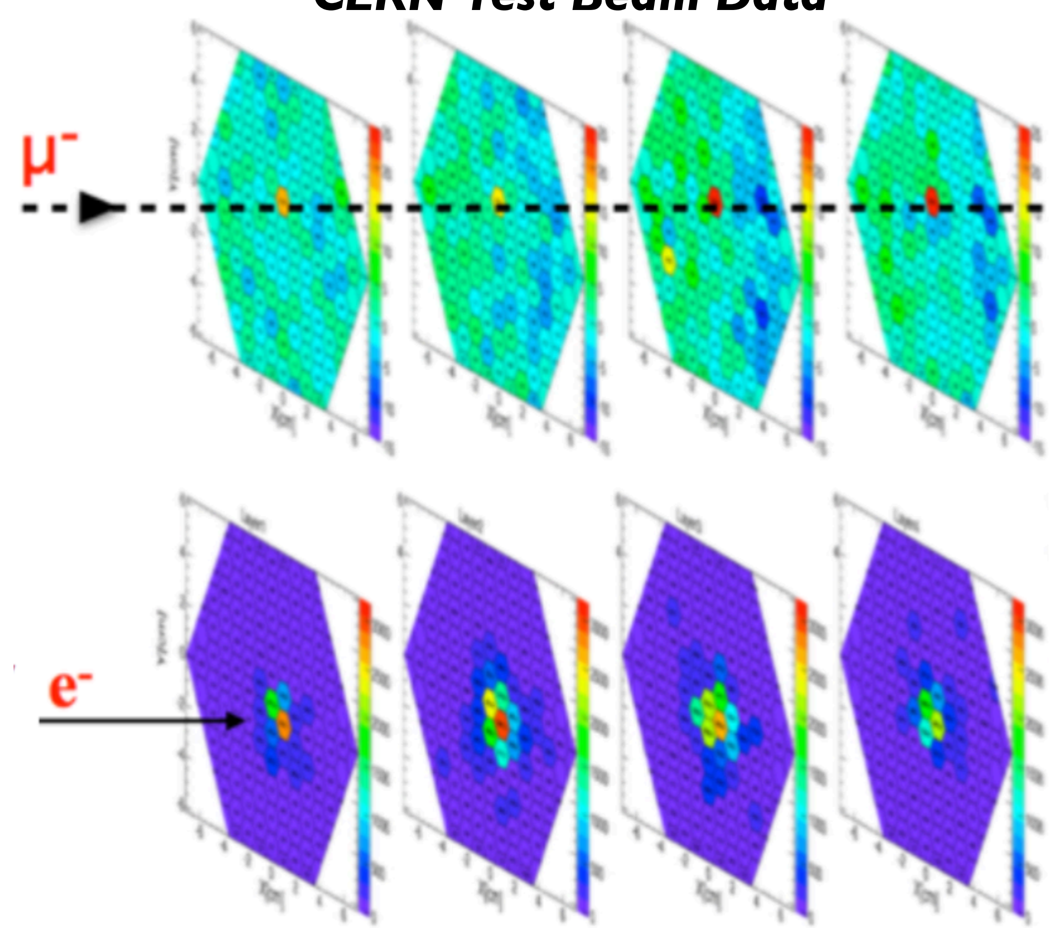


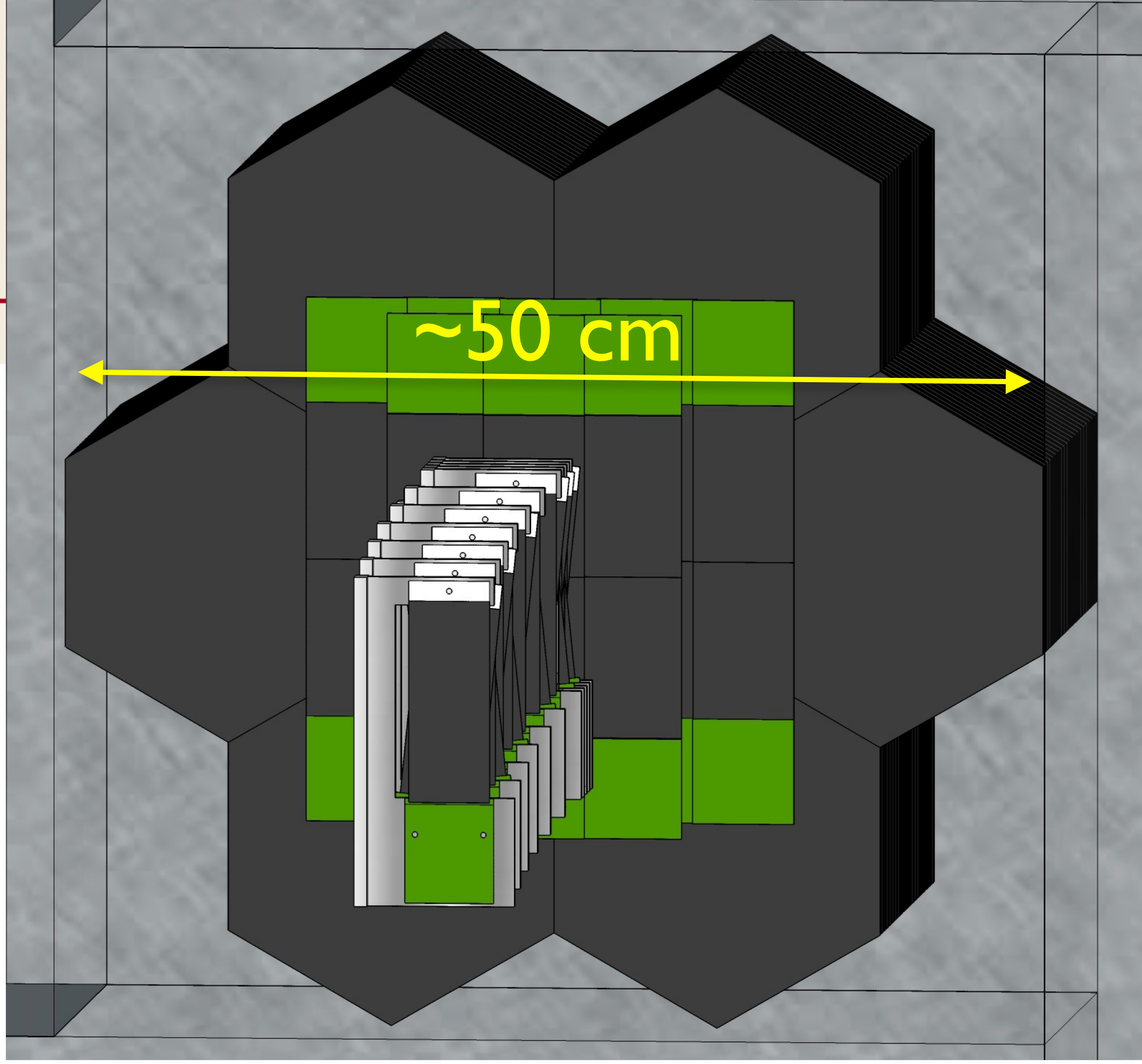
LDMX ECal

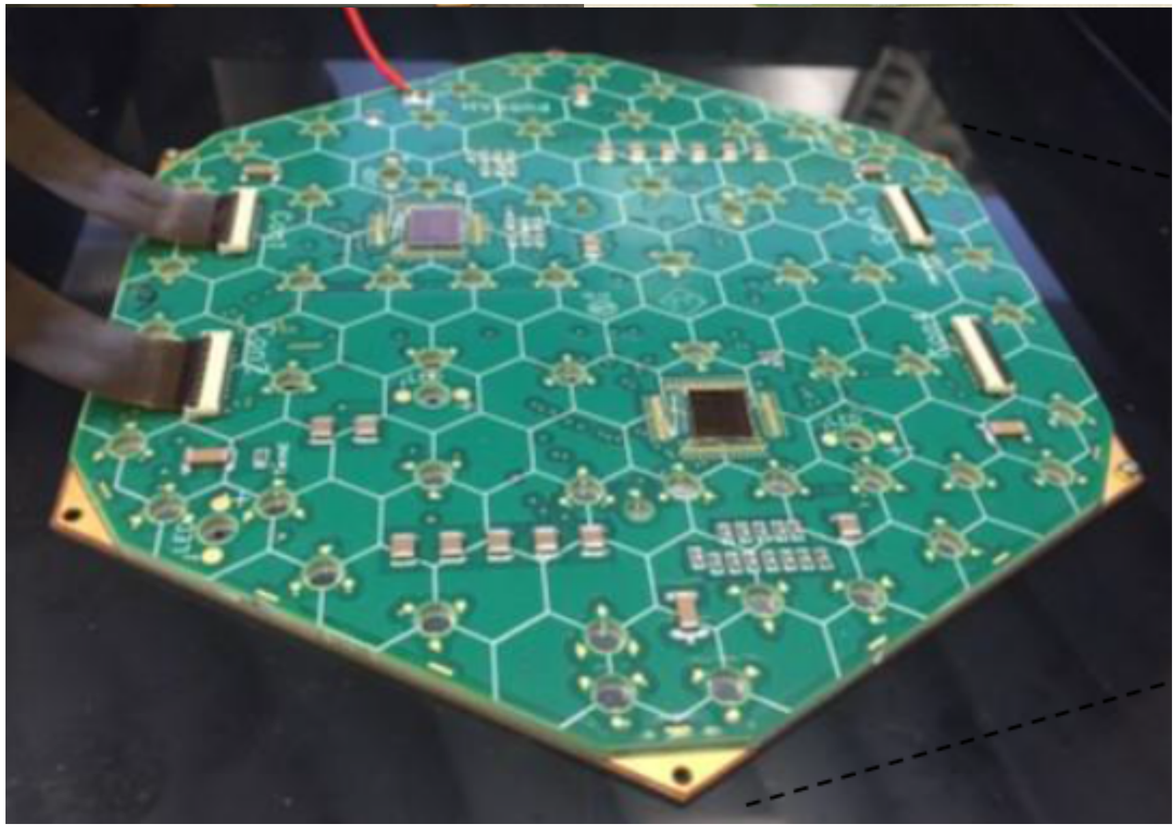
Si-W calorimeter developed for CMS upgrade (HGC)

- fast, dense, granular for high occupancies
- deep (40 X_0) for extraordinary EM containment
- meets difficult rate/radiation tolerance requirements
- can provide fast trigger for trackers (3 μs)
- *very powerful tool for rejection of rare backgrounds*

CERN Test Beam Data







LDMX HCal

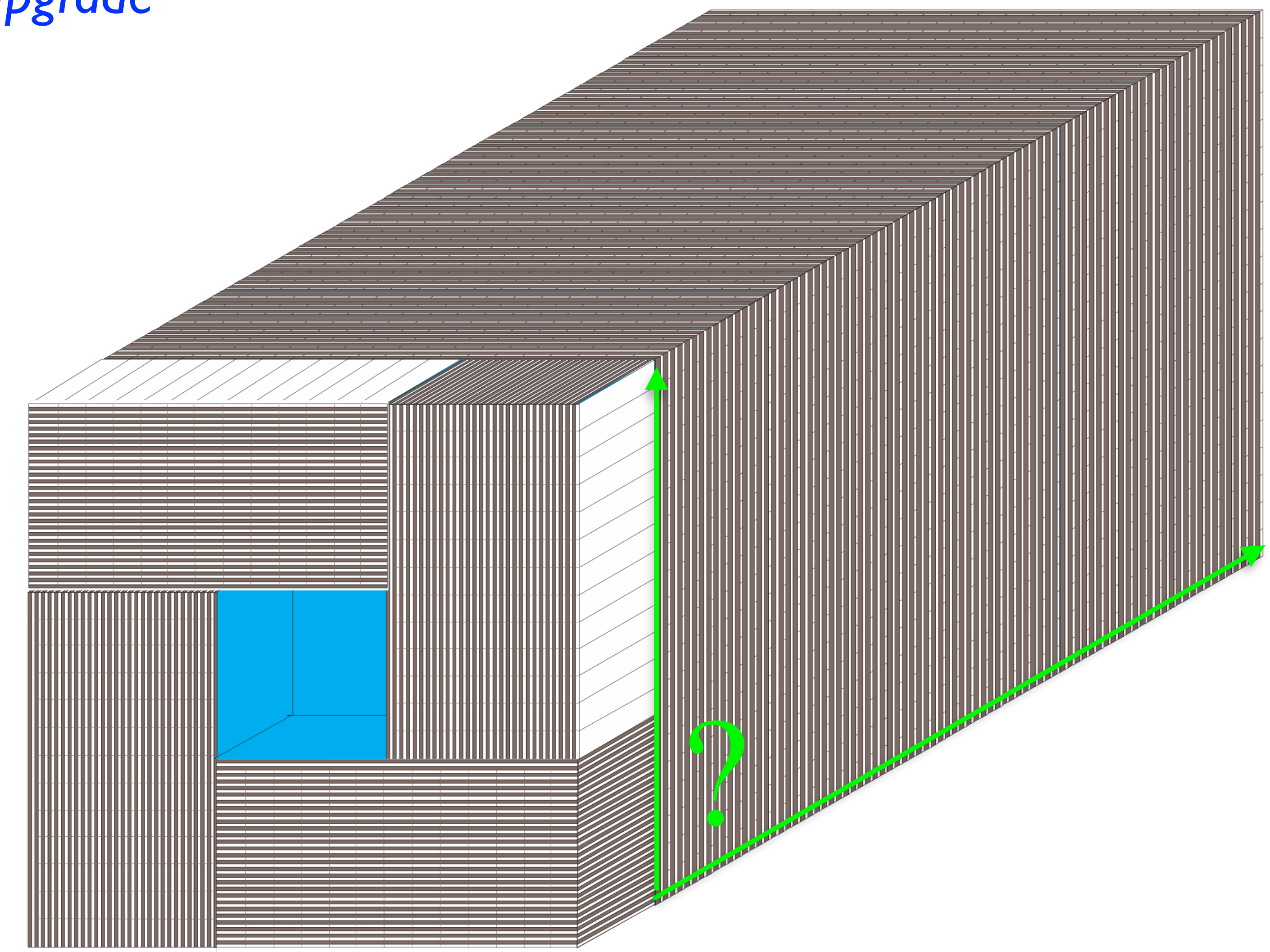
Baseline design employs technology from CMS upgrade

- Steel absorber/plastic scintillator
- SiPM readout via WLS fibers

… but other possibilities are being explored.

Surrounds ECal as much as possible

- Many photonuclear events have a high multiplicity of soft neutral hadrons
- Catch rare wide-angle brems (≳ 25°)



Size of HCal required is a key question for simulation studies.

Sector 30 Beam Transfer Line

LCLS-II produces an ideal e^- beam, mostly to the dump!

LCLS-II: 4 GeV e^- ⇒ LCLS-II-HE: 8GeV