Accelerating Dark Matter

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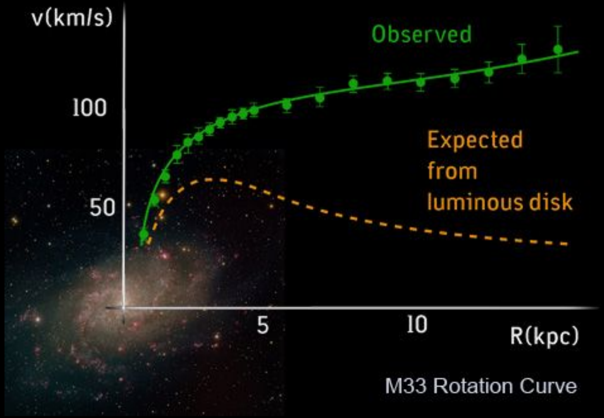
UNIVERSITÀ DEGLI STUDI DI GENOVA

Experimental Seminar
September 13, 2018

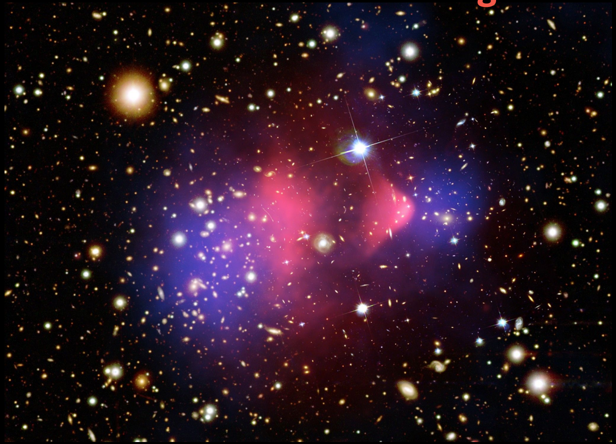
The Evidence for Dark Matter

There is plenty of evidence for the existence of Dark Matter!

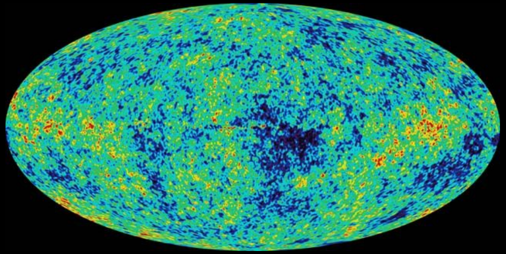
Galactic Rotation Curves



Gravitational Lensing

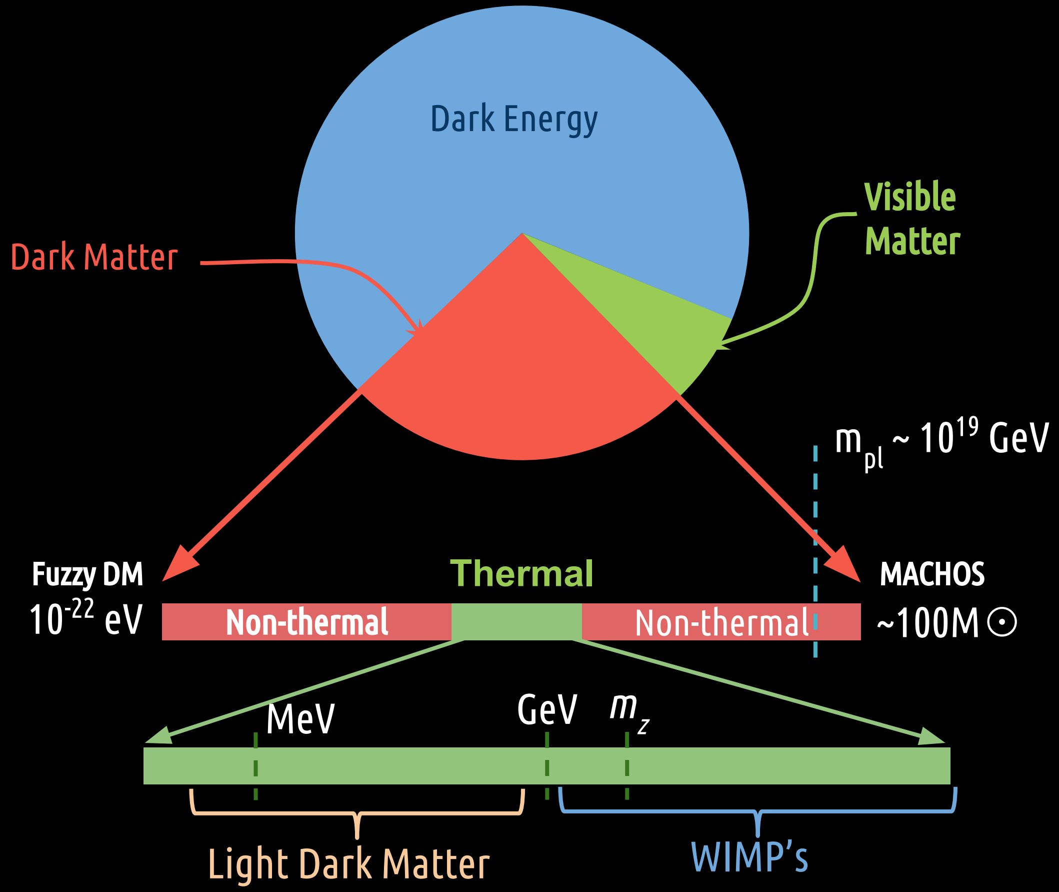


Structure of Cosmic Microwave Background



The particle nature of Dark Matter is a central puzzle in particle physics.

What is Dark Matter?



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Thermal Dark Matter

1) The early universe is very hot so DM is in thermal equilibrium with regular matter

2) As the universe cools, SM no longer energetic enough to produce massive DM, DM begins to annihilate away

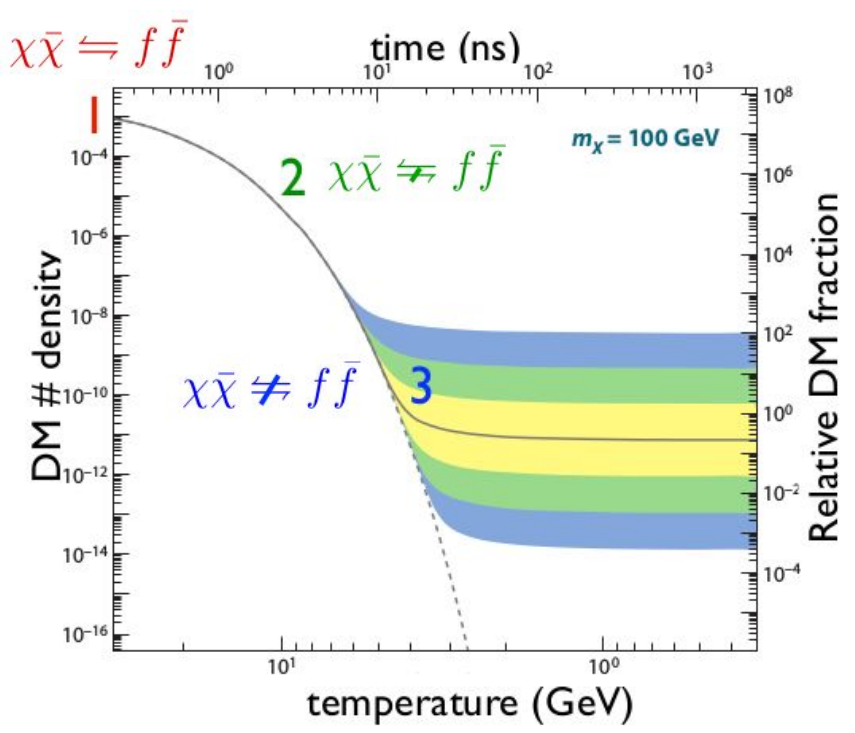
3) Universe expands so DM stops annihilating "freeze-out"

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

$$\Omega_\chi h^2 \approx 0.1 \implies \langle\sigma v\rangle \approx 3\times10^{-26}\ \mathrm{cm^3\ s^{-1}}$$

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

"WIMP Miracle"



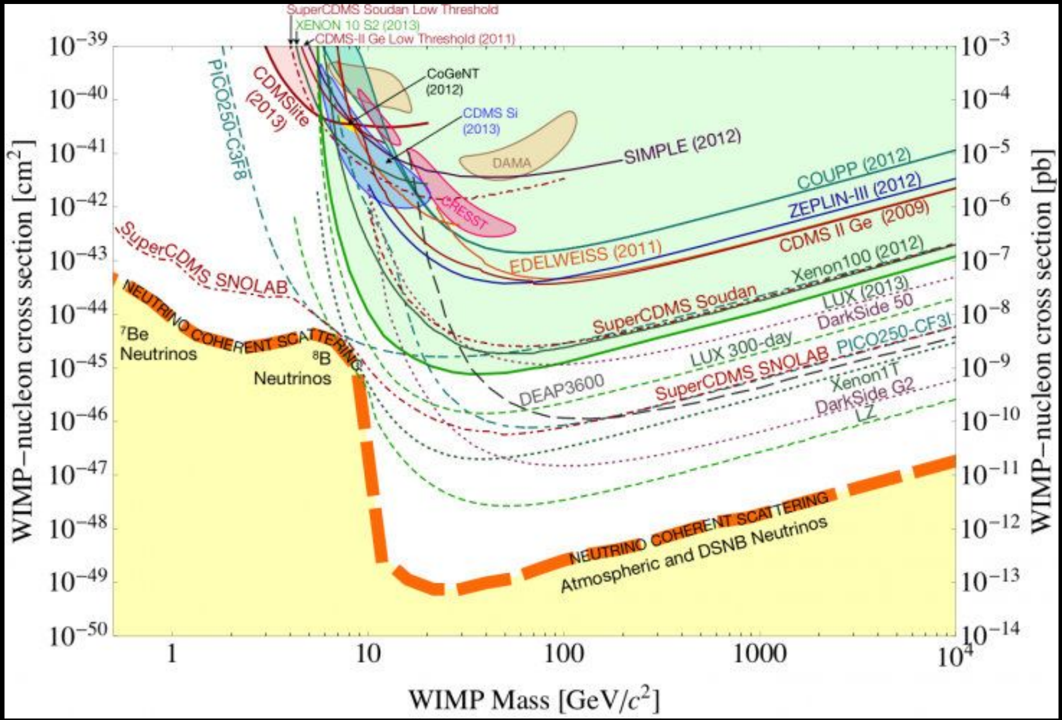
Where Do WIMP Searches Stand?

Broad and impressive program has been built to understand ~GeV - TeV WIMP Dark Matter, but searches for them in the most favorable areas have yielded nothing … will be ruled out or found in the coming years by next gen experiments (e.g. SuperCDMS, LZ or LHC)

Going lower in mass and cross-section gets harder for direct detection because of the need to contend with more backgrounds ⟶ Need to lower thresholds

- e^- - DM Scattering
- Semiconductors

So where else do we look?

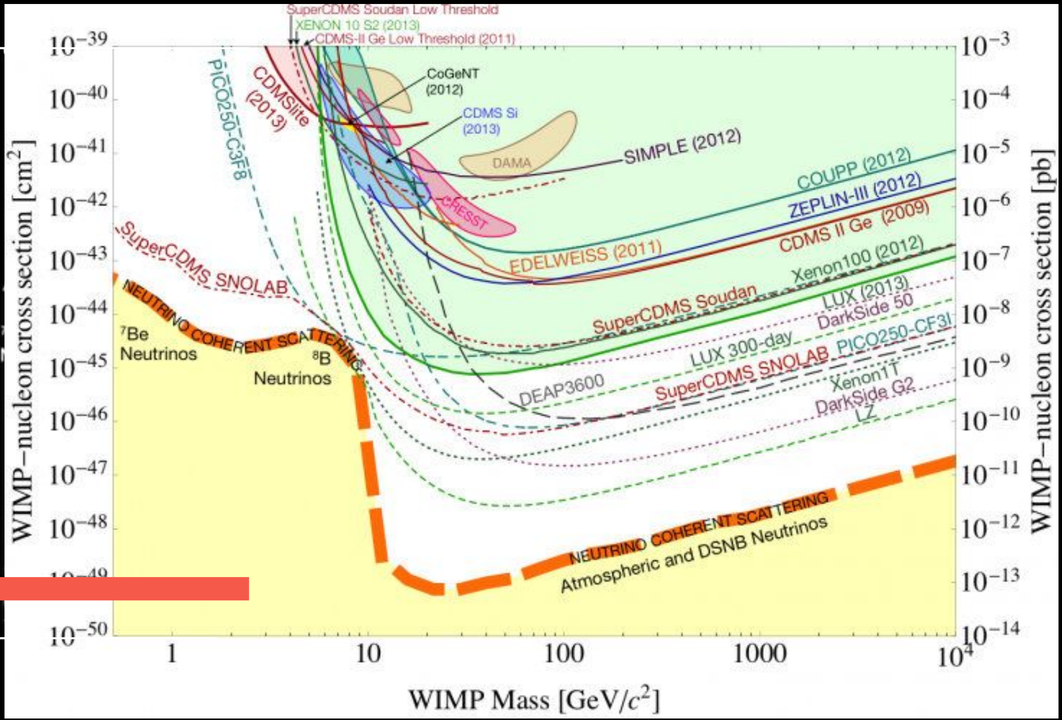


So Where Else Can We Look?

Light Dark Matter in the broad vicinity of the weak scale is a natural and simple generalization of WIMPs. **Light thermal dark matter requires a new force** to achieve the correct thermal relic abundance.

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

(WIMP's limited by Lee-Weinberg Bound to 2 GeV).
Phys. Rev. Lett. 39, 165



Given the complex structure of the Standard Model, a "Dark Sector" where dark matter interacts via a light mediator is an obvious scenario to test. It has been the focus of a broad array of searches and experiments for many years now.

Possible Mediators

$F'_{\mu\nu}F^{\mu\nu}$ A dark photon kinematically mixes with the SM photon

Induces a small coupling between DM and SM

$V_\mu J^\mu_{\mathrm{SM}}$ A new force directly couples DM and 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.

Possible Mediators

$$F'_{\mu\nu}F^{\mu\nu}$$

A dark photon kinematically mixes with the SM photon

Induces a small coupling between DM and SM

Benchmark Scenario!

$$V_\mu J^\mu_{\mathrm{SM}}$$

A new force directly couples DM and 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.

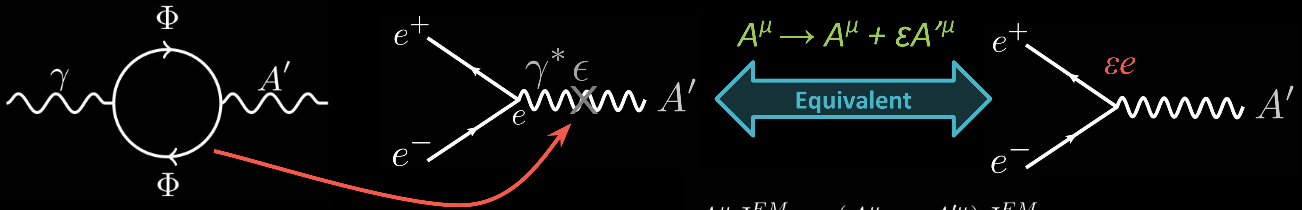
Dark Photon Primer

If nature contains an additional Abelian gauge symmetry, *U'(1)*

Holdom, Phys. Lett. B166, 1986

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \boxed{\frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

This gives rise to a **kinetic mixing** term where the photon mixes with a new gauge boson ("dark/heavy photon" or *A'*) through the interactions of massive fields → **induces a weak coupling to electric charge**



$$A^\mu J^{EM}_\mu \to (A^\mu + \epsilon A'^\mu) J^{EM}_\mu$$

Coupling strength can have a wide range.
If *U'(1)* is embedded in a Grand Unified Theory (e.g. *SU(5)*) then the kinetic mixing can be generated through the interaction of split multiplets

$$\epsilon \sim \frac{g_Y g_D}{16\pi^2} \ln \Lambda \sim 10^{-3} - 10^{-1}$$

Signatures

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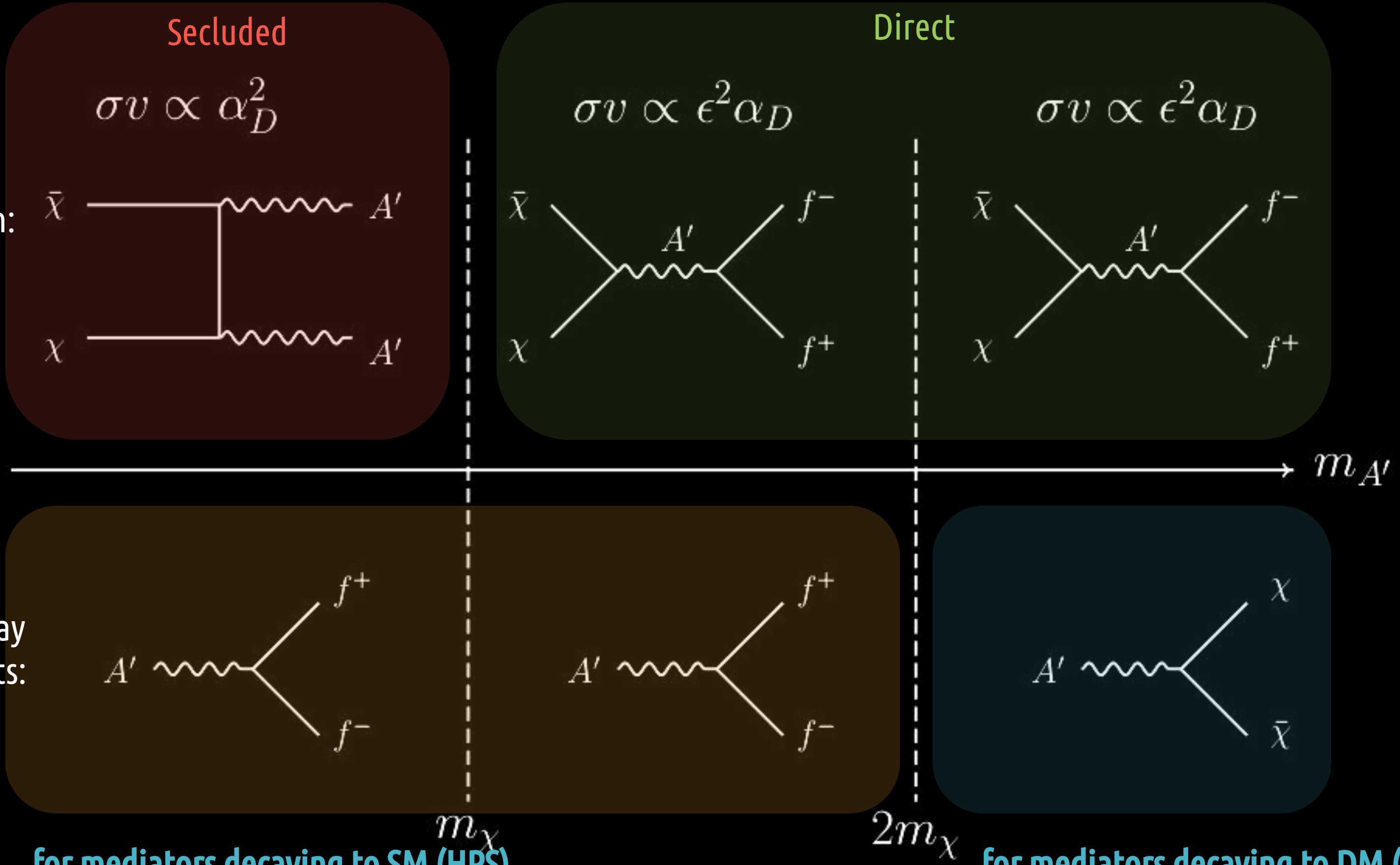
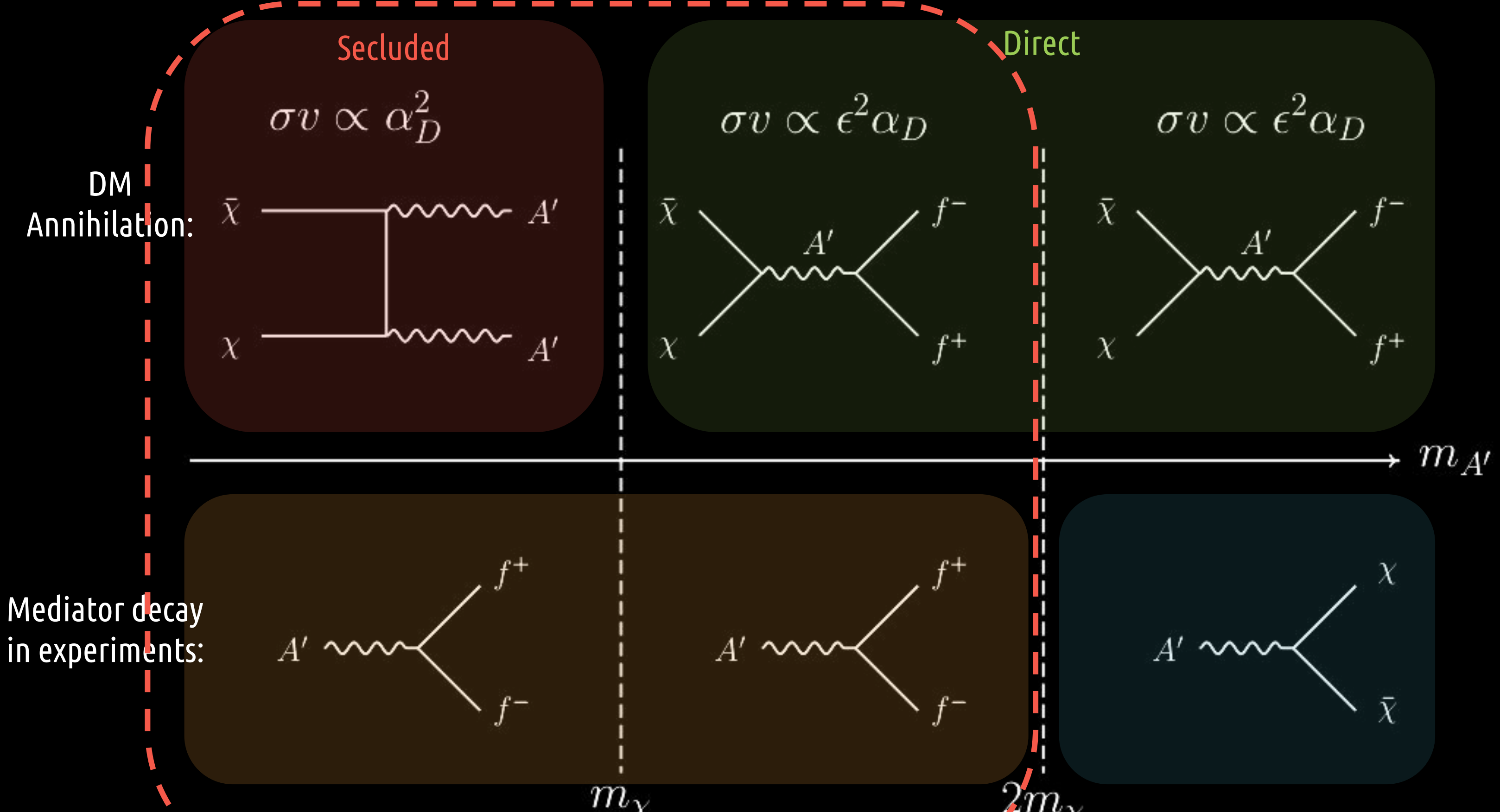
DM Annihilation:

Mediator decay in experiments:



Search: for mediators decaying to SM (HPS) for mediators decaying to DM (LDMX)

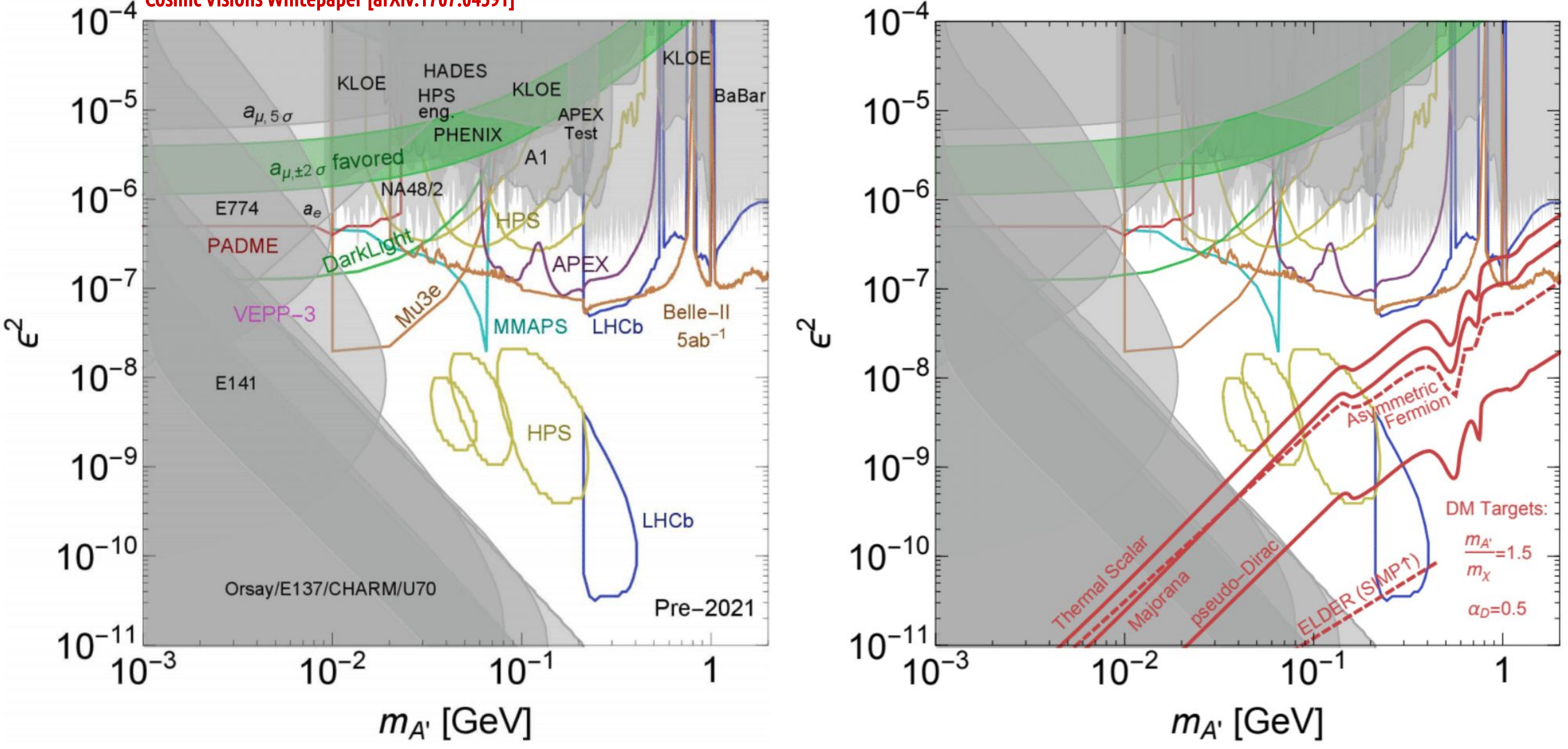
Signatures



Search: for mediators decaying to SM (HPS) — for mediators decaying to DM (LDMX)

Visible Decay Parameter Space

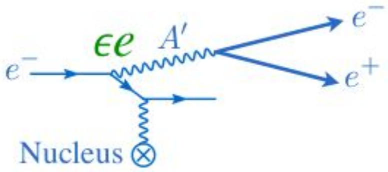
Cosmic Visions Whitepaper [arXiv:1707.04591]



How Do You Search for a Dark Photon?

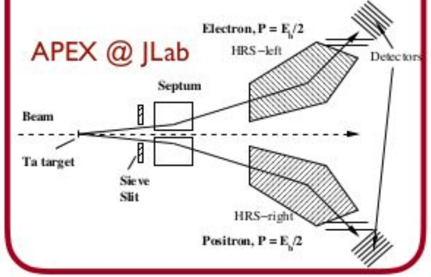
e^- fixed target

$N \propto \epsilon^2$



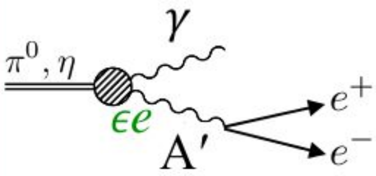
dark bremsstrahlung

APEX @ JLab

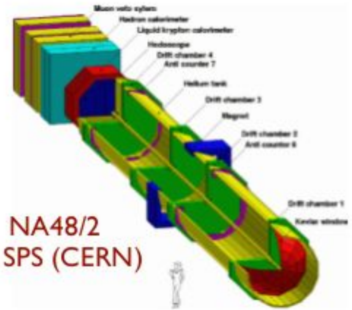


p fixed target

$N \propto \epsilon^2$

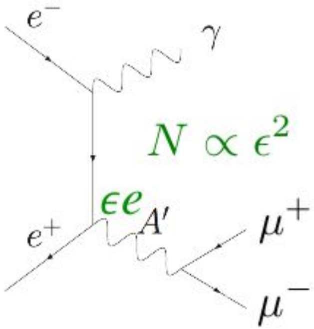


meson decays



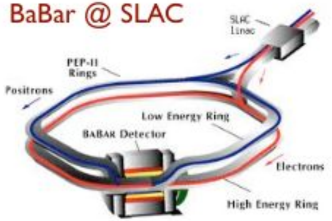
NA48/2 @ SPS (CERN)

e^+e^- colliders

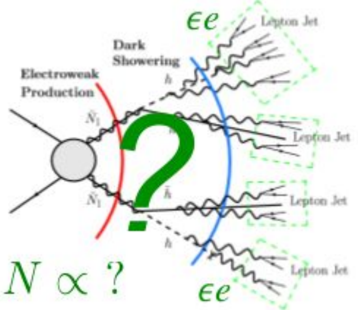


+ meson decays

BaBar @ SLAC

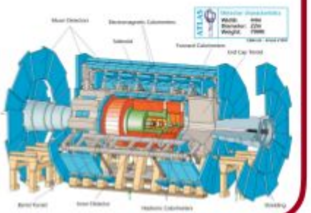


pp collider



"lepton jets" + meson decays

ATLAS
CMS
LHCb
@LHC



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Fixed Target Kinematics

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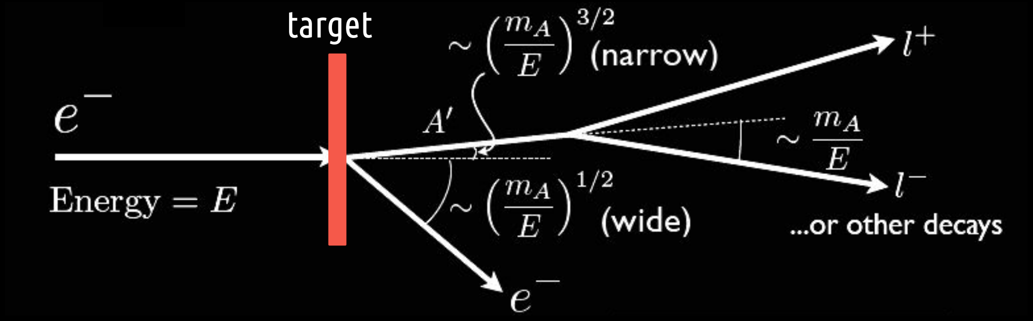
Since dark photons couple to electric charge, they will be produced through a process analogous to bremsstrahlung off heavy targets subsequently decaying to l^+l^-



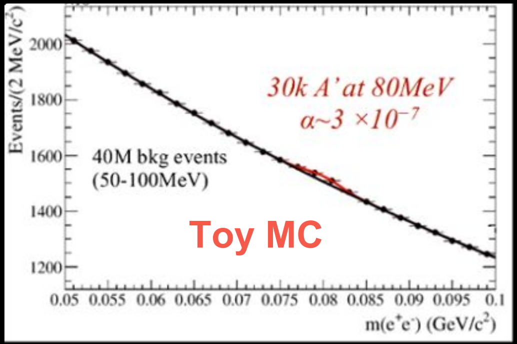
Kinematics are very different from bremsstrahlung

- Production is sharply peaked at x ≈ 1 ⟶ A' takes most of the beam energy
- A' decay products opening angle, $m_{A'}/E_{beam}$

The HPS experiment was designed to make use of such a production mechanism to search for a heavy photon using two methods:

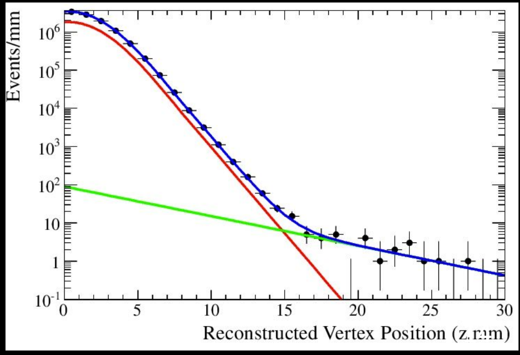
Resonance Search (Bump Hunt)

Look for an excess above the large QED background ⟶ Large signal required so limited to large coupling.

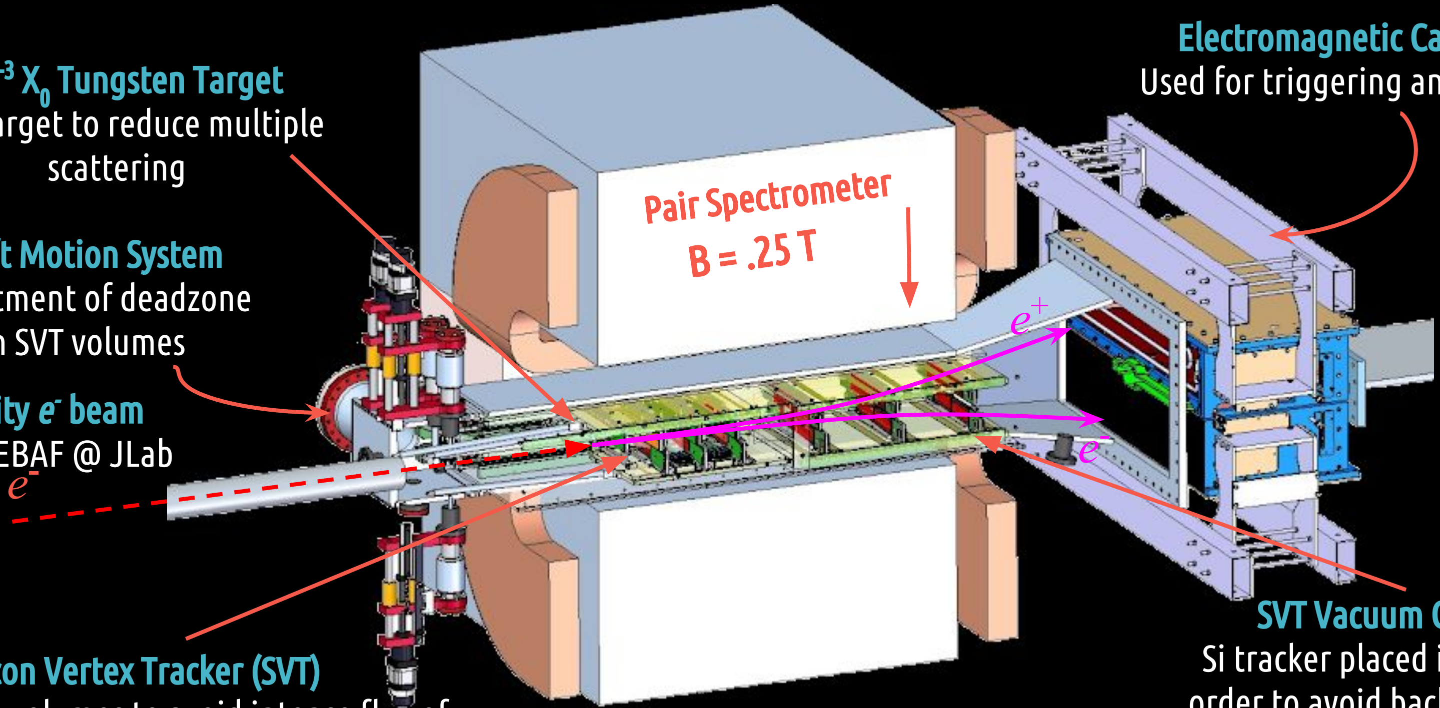


Displaced Vertex + Bump Hunt

Long lived A' will have a displaced vertex ⟶ Will help cut down prompt backgrounds but limited to small coupling



The HPS Apparatus



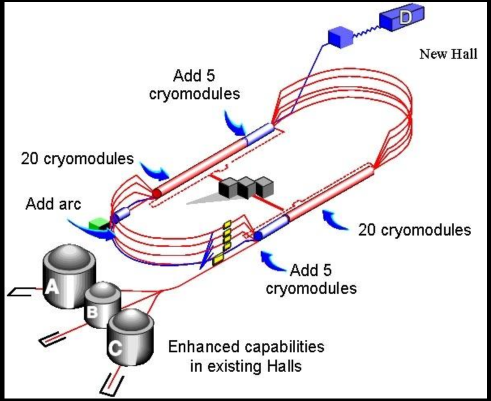
SVT + ECal DAQ capable of 50 kHz

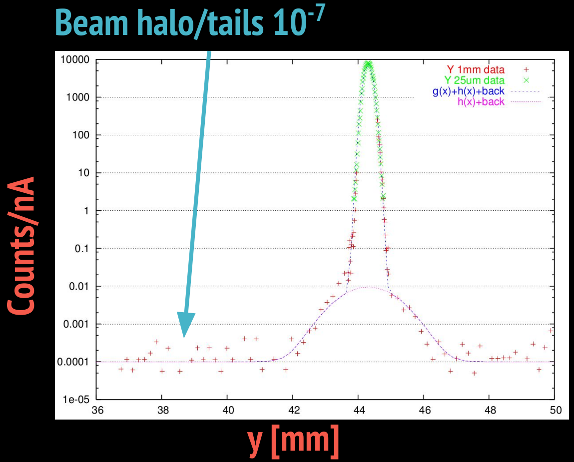
Installed within the Hall B alcove at Jefferson Lab upstream of the CLAS12 detector

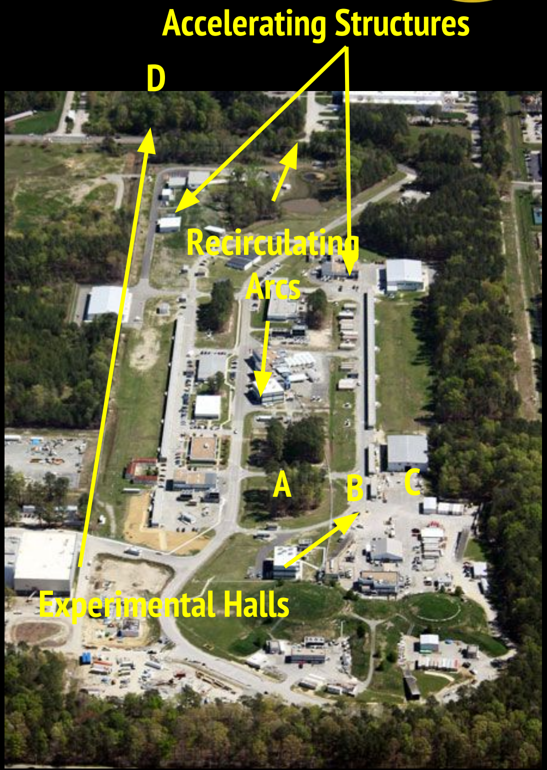
Continuous Electron Beam Accelerator Facility

Simultaneous delivery of **intense** electron beams of different energies to four experimental halls.

- **Hall A, C:** I_{beam} < 100 μA, **Hall D:** I_{beam} < 5 μA, **Hall B:** I_{beam} < 500 nA
- With energy upgrade, $E_{beam} = n \times 2.2$ GeV, $n \leq 5$ up to a maximum of 11 GeV (12 GeV for Hall D)
- Beam delivery is nearly continuous → 2 ns bunch structure
- Capable of providing small beam spot with small tails

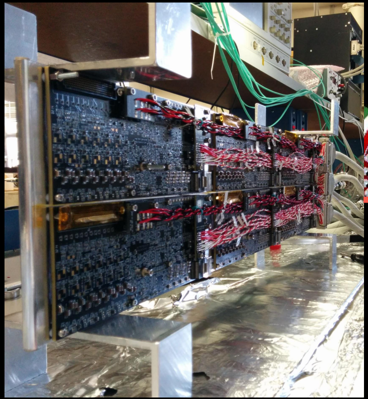


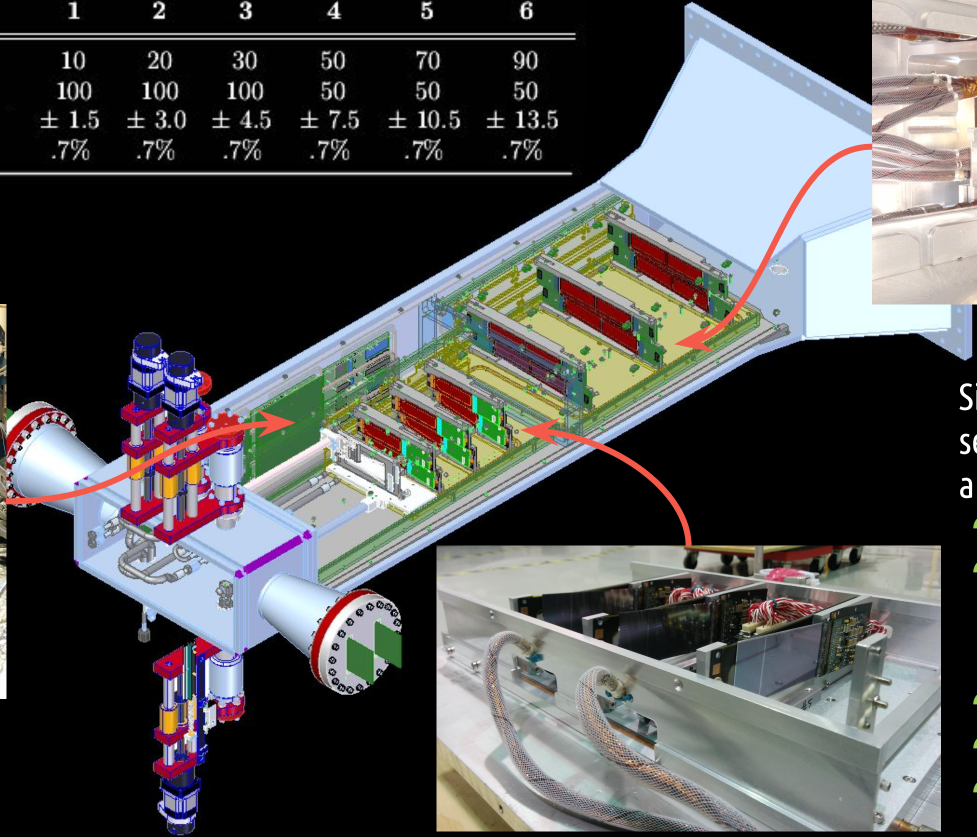


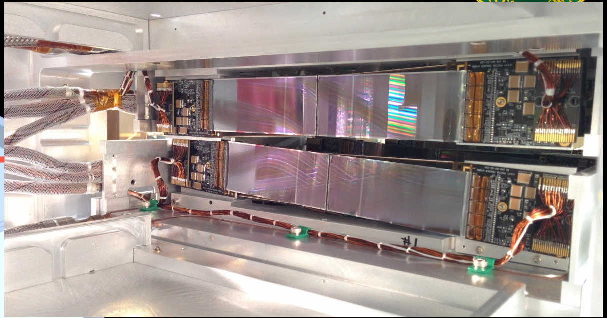


Silicon Vertex Tracker

Layer	1	2	3	4	5	6
z position from target (cm)	10	20	30	50	70	90
Stereo angle (mrad)	100	100	100	50	50	50
Nominal dead zone in y (mm)	$\pm$ 1.5	$\pm$ 3.0	$\pm$ 4.5	$\pm$ 7.5	$\pm$ 10.5	$\pm$ 13.5
Material budget	.7%	.7%	.7%	.7%	.7%	.7%

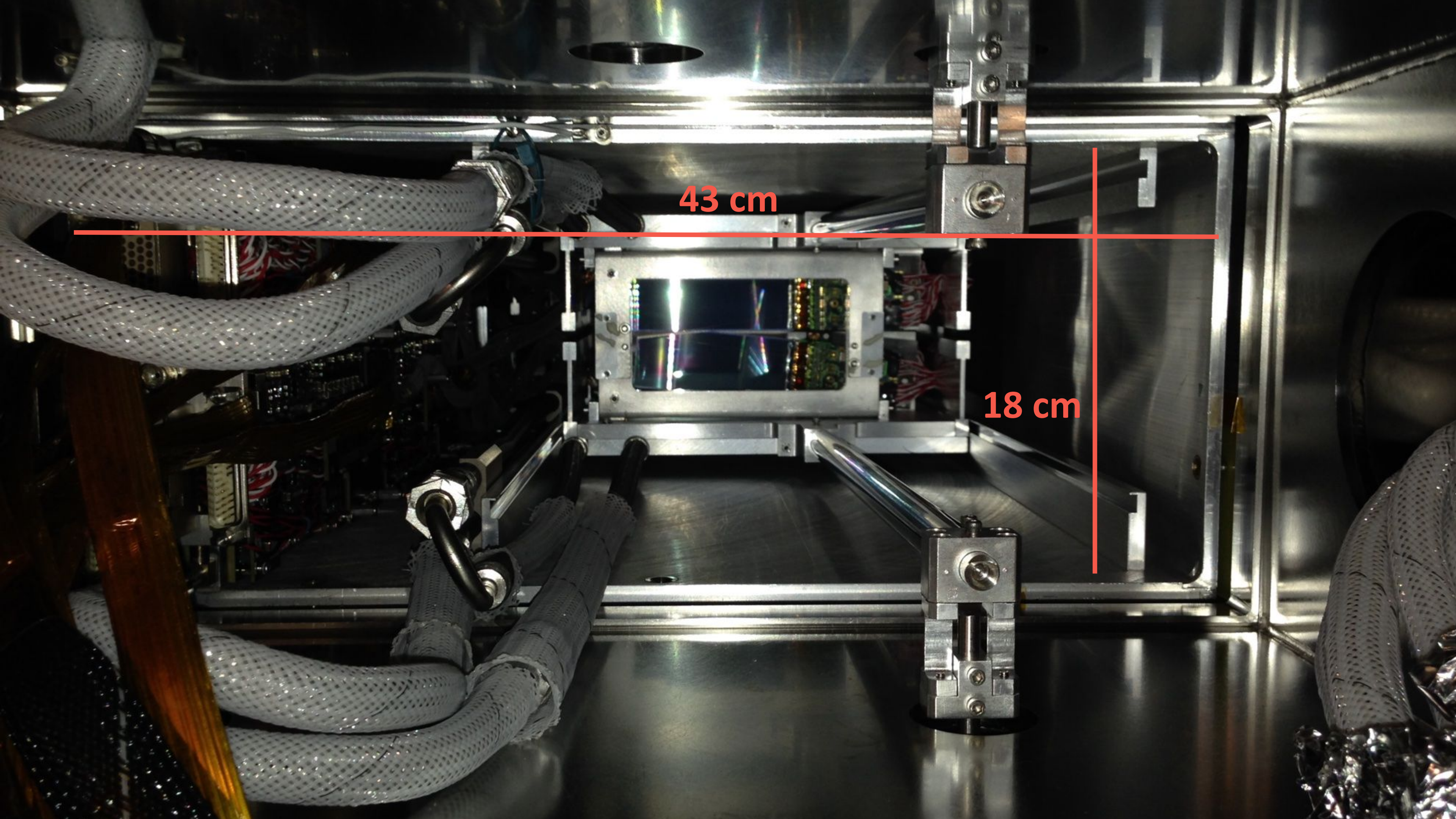






Six layers of pairs of Si microstrip sensors ⟶ One axial and the other at small angle stereo (50 & 100)

- Layer 1-3: single sensor
- Layer 4-6: double width coverage to better match Ecal acceptance
- 36 sensors
- 180 APV25 chips
- 23,004 channels


43 cm
18 cm

Electromagnetic Calorimeter

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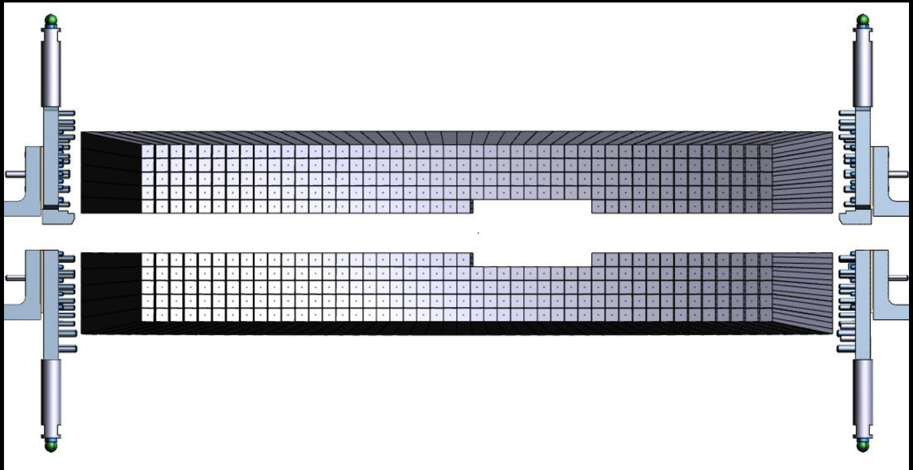
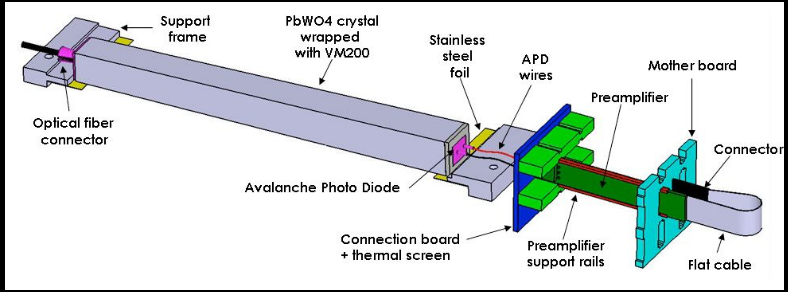
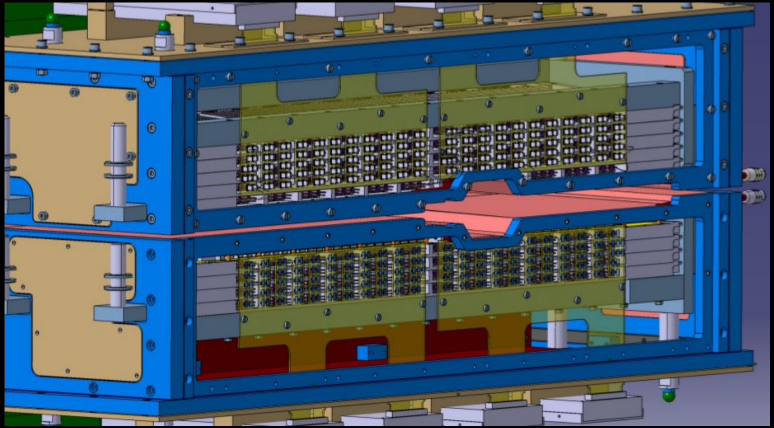






- 442 $PbWO_4$ crystals coupled to avalanche photodiode readout
- FADC readout at 250 MHz ⟶ allows for a narrow trigger window (8ns)
- Trigger and DAQ capable of a rate > 100 kHz

The HPS Engineering Runs

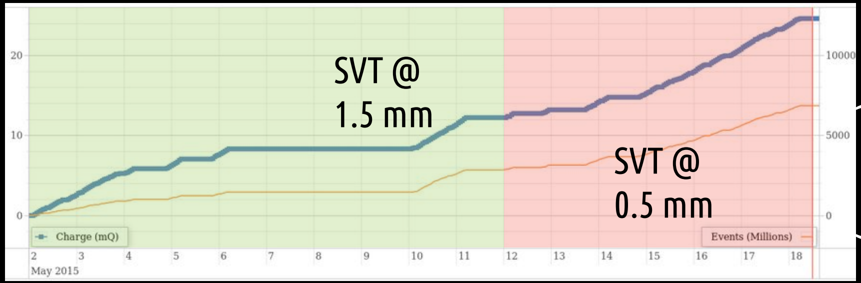
Two successful JLab engineering runs

- **Spring 2015:** 50 nA, 1.056 GeV electron beam (night and weekend running)
- **Spring 2016:** 200 nA, 2.3 GeV electron beam (weekend running)

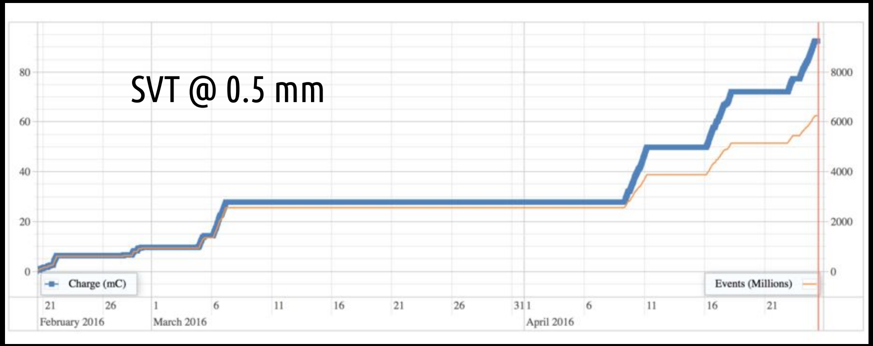
Goal: Understand the performance of the detector and take physics data.

- For the 2015 run, data was taken with the Silicon Vertex Tracker (SVT) in two configurations: inactive edge at 1.5 mm and 0.5 mm from the beam plane
- **2015:** 10 mC with the SVT at 1.5 mm and 10 mC (**1.7 PAC days**) at 0.5 mm
- **2016:** 92.5 mC (**5.4 PAC days**) with the SVT at 0.5 mm

2015



2016

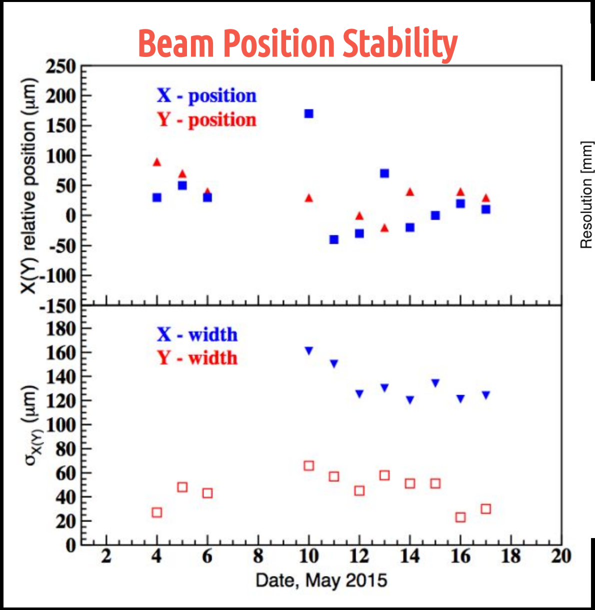


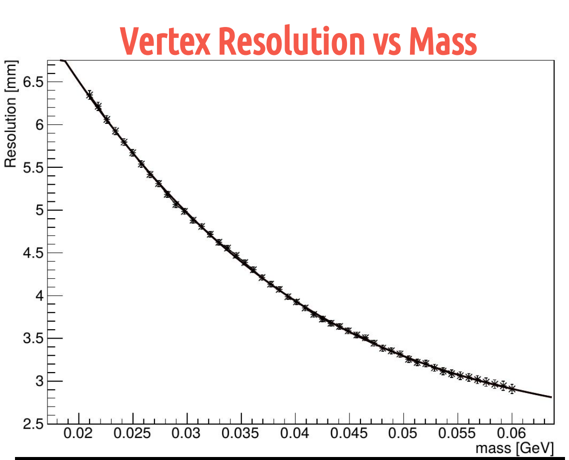
The results shown in this talk used the full 0.5 mm 2015 Engineering run dataset.
First 2016 results expected in early 2019.

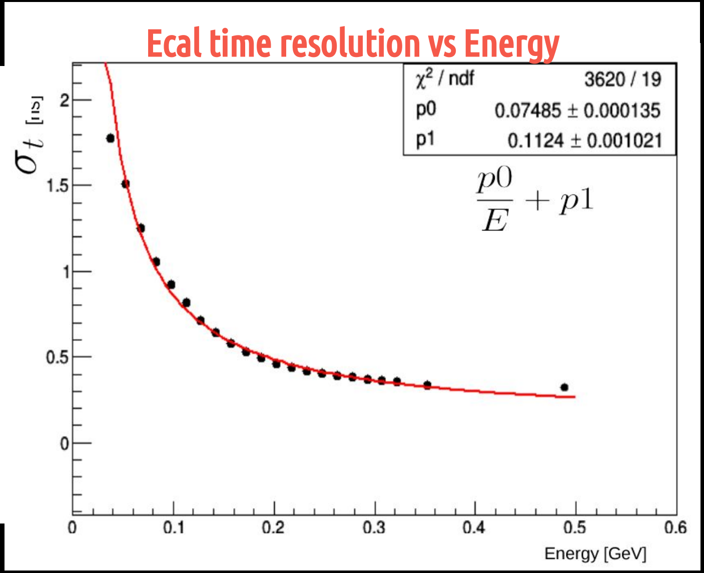
2015 Engineering Run Performance

The 2015 engineering run has demonstrated that HPS is ready to do a meaningful search for heavy photons

- Hall B beamline was capable of delivering a small beam spot , low beam halo with high stability → allowed placing tracker 0.5 mm from the beam
- Excellent Ecal time and energy resolution allows for the efficient selection of true e+e- pairs
- Vertex resolution was as expected and sufficient to conduct a search for a displaced *A'*





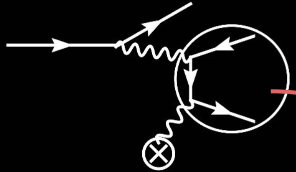


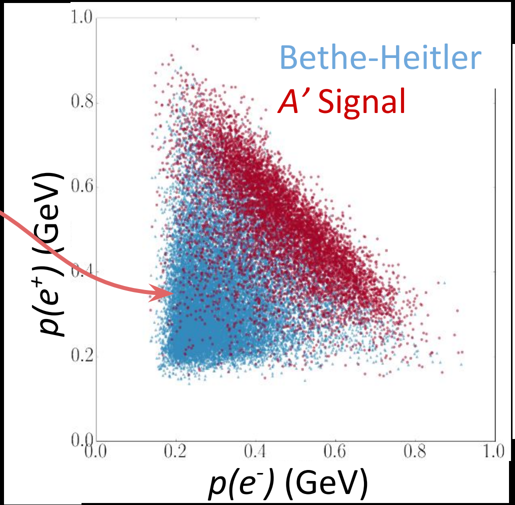
Backgrounds

The search for an *A′* involves looking for a narrow resonance in the e^+e^- invariant mass spectrum on top of a large, continuous background composed of several components

Physics Backgrounds

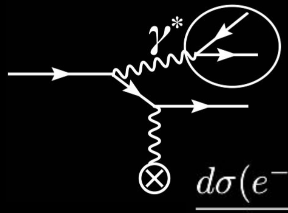
Bethe-Heitler





Dominant, but most lies below the A′ signal region.

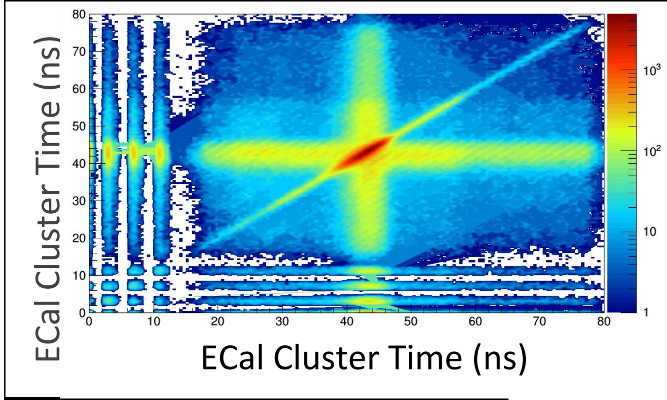
Radiative



Irreducible. Kinematically identical to A′ but can be used to understand expected *A′* rates.

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

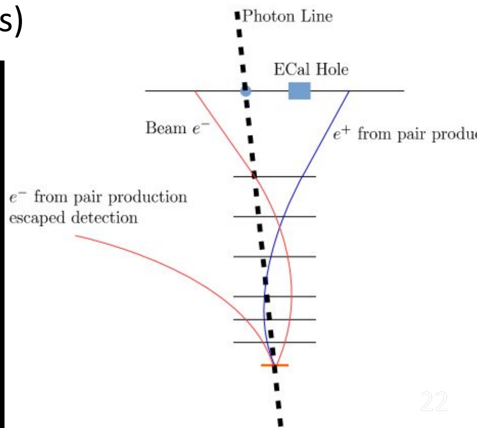
Accidentals



True e+e- pairs will have time-coincident clusters in the calorimeter. Can be suppressed using time cuts and cuts used to remove scattered beam electrons.

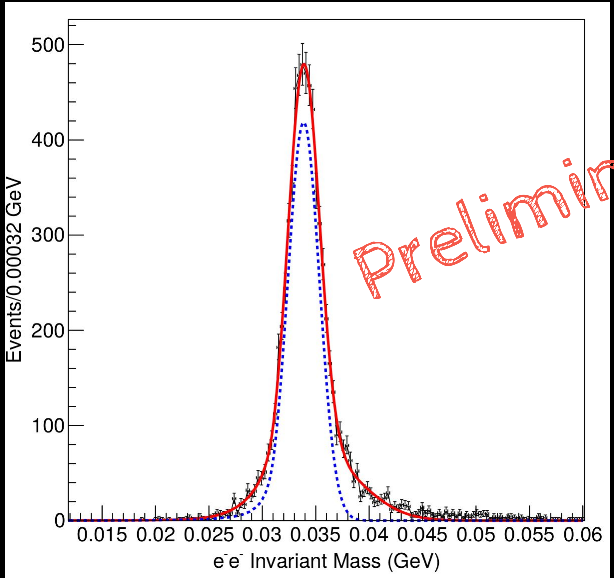
Wide Angle Bremsstrahlung (WAB)

Conversions of photons produced in the target and first few layers of the SVT can mimic a trident e+e- pair

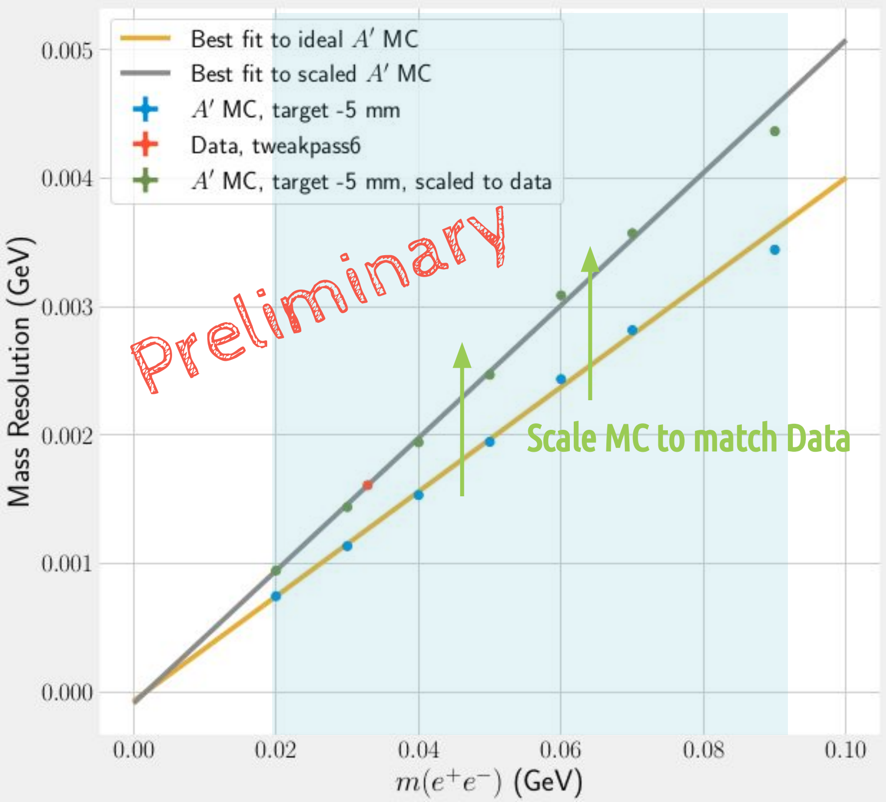


e^+e^- Mass Resolution

- Determined the resolution as a function of mass using A' and Møller Monte Carlo
- From data, use the Møller invariant mass distribution to measure the mass resolution
- Scale the MC mass resolution parameterization to match the data observation.



Discrepancy between data and MØller Monte Carlo is due to mismatch of momentum resolutions



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Searching for a Resonance

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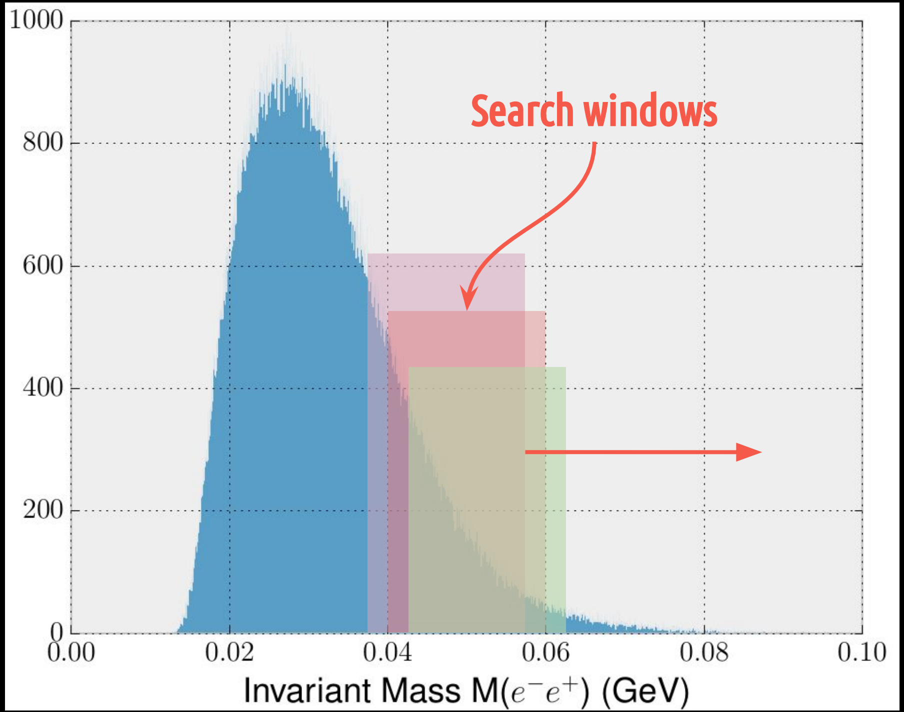
- Search for a resonance within a window in the mass range between 19 MeV and 81 MeV by scanning the e^+e^- invariant mass spectrum in 0.5 MeV step sizes.
- Maximize the Poisson likelihood within the range using a composite model with the signal described as a **Gaussian** and an **exponential of a Chebychev polynomial to model the background**
  - Mass < 39 MeV: exp(5th order), window size: $14\sigma_{mass}$
  - Mass >= 39 MeV: exp(3rd order), window size: $13\sigma_{mass}$
- Use Likelihood ratio to quantify significance of any excess i.e. "bump"
- Determine the 2σ signal upper limit at each mass hypothesis by inverting the likelihood ratio
- Translate the signal upper limit into the coupling-mass phase space



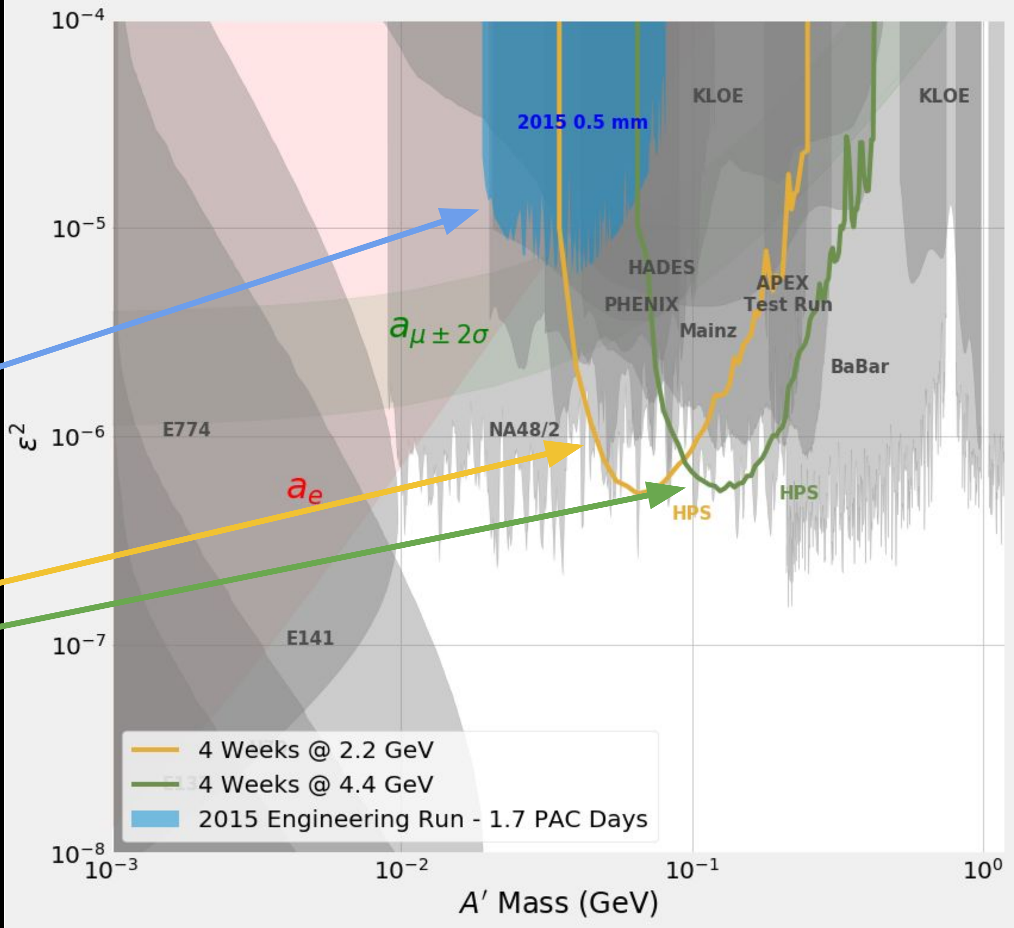
2σ Upper Limit on ε

2015 bump hunt paper is currently under review for PRD RC!

arXiv: 1807.11530

2015 Engineering Run
1.7 PAC days @ 1.05 GeV

2018-2020 Physics Run
4 Weeks @ 2.2 GeV
4 Weeks @ 4.4 GeV



HPS Going Forward

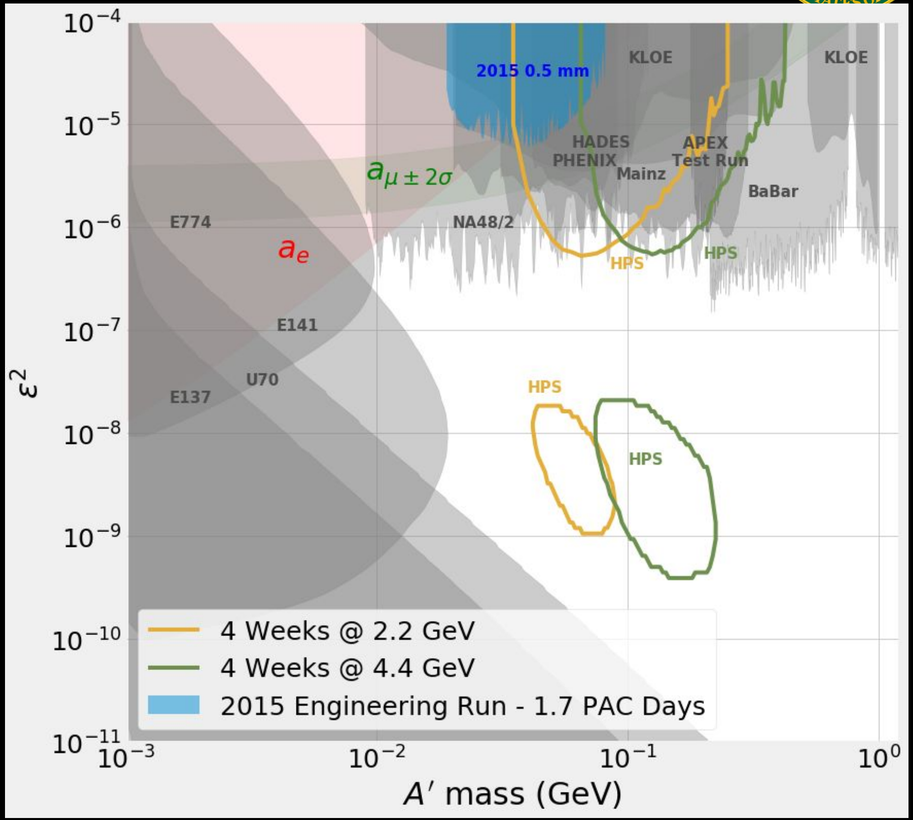
Several analyses are ongoing

- 2016 Bump hunt analysis and 2015/16 Vertex analysis are ongoing

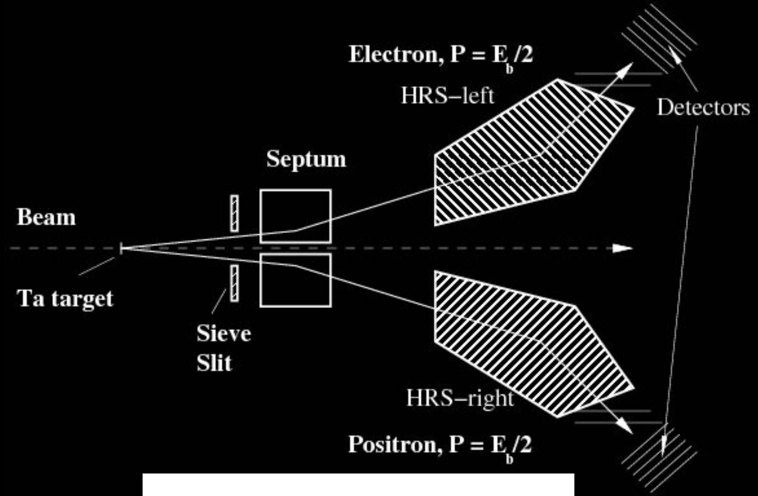
Upgrades to trigger and SVT are being built and will be installed Jan '19

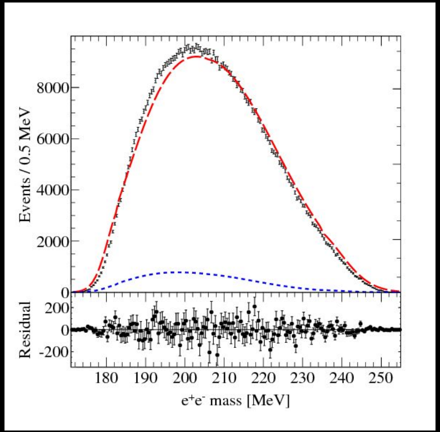
- Will significantly extend the reach of HPS

Next run planned for summer of 2019 at 4.4 GeV



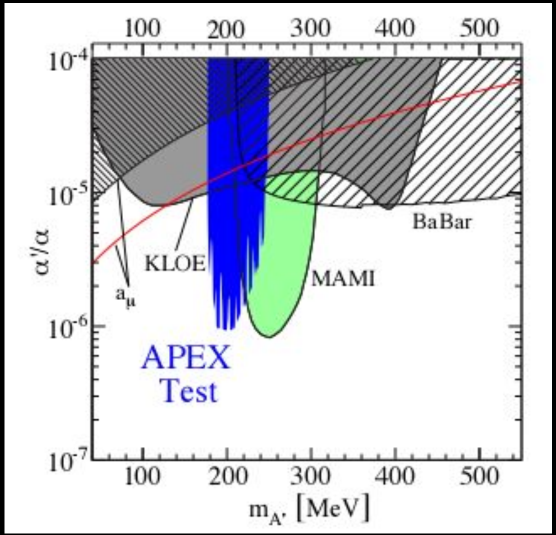
The *A* Prime EXperiment (APEX)





- Spectrometer-based search for 50-500 MeV *A'* decaying promptly to e^+e^-
- Test run took place in 2010
- Run planned in February of 2019

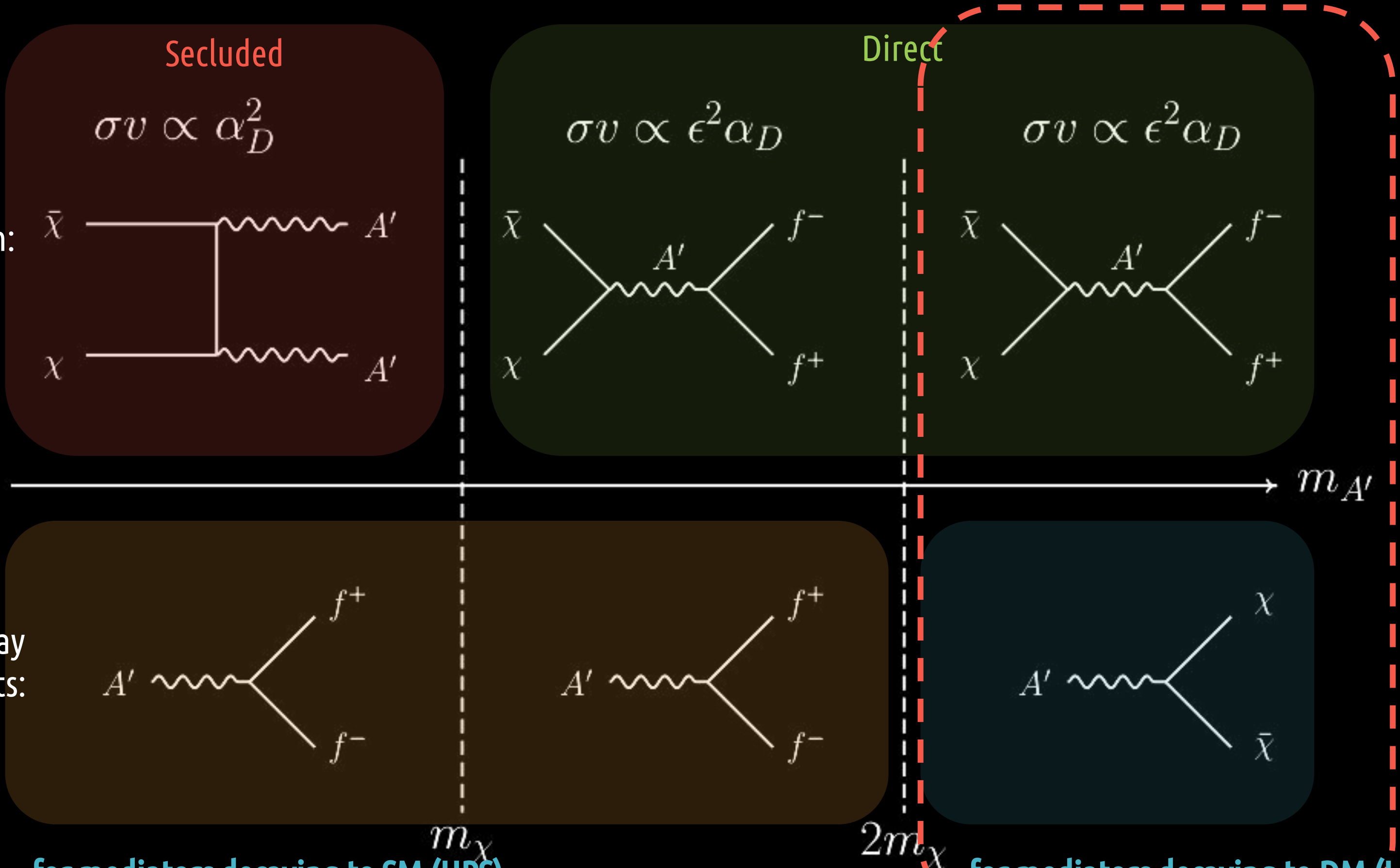
Looking for collaborators! Contact me at omoreno@slac.stanford.edu if interested!



Signatures

DM Annihilation:

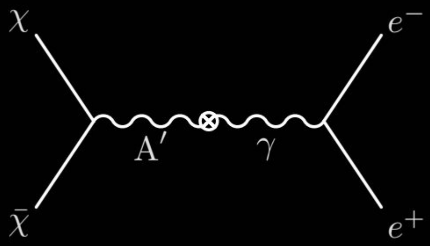
Mediator decay in experiments:



Search: for mediators decaying to SM (HPS) for mediators decaying to DM (LDMX)

Thermal DM Targets at Accelerators

O. Moreno (SLAC National Accelerator Laboratory) INFN Genova Experimental Seminar September 13, 2018

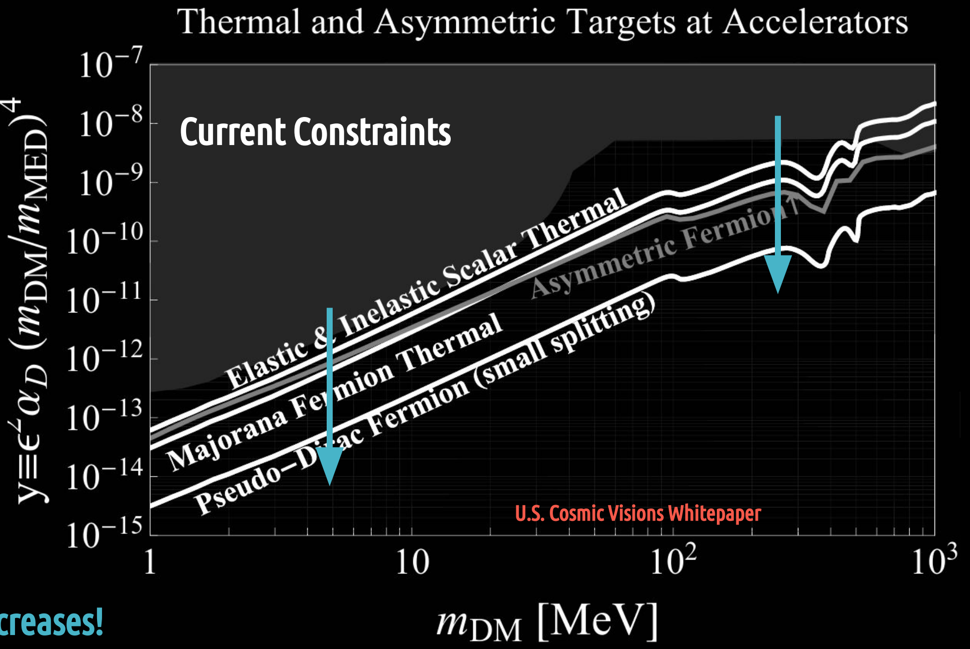


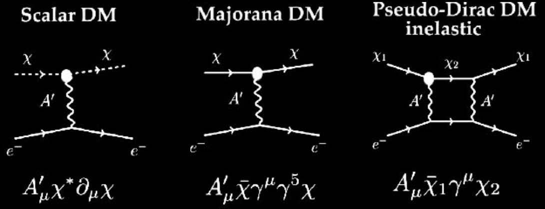
Need a way to estimate the reach of searches ⟶
Introduce dimensionless interaction strength, y

$$\sigma v(\chi\chi \to A'^* \to f\bar{f}) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2} \quad , \quad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

Uses **conservative** values for $\alpha_D (= .5)$ and $m_\chi / m_{A'}$ $(m_{A'} = 3m_\chi)$

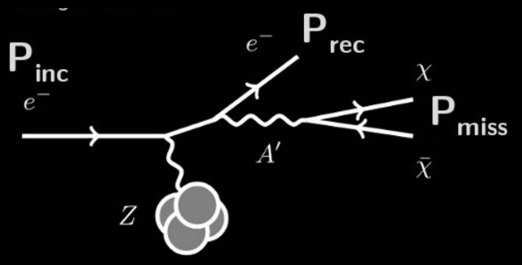
As α_D or $m_\chi / m_{A'}$ decreases, **the sensitivity of an experiment increases!**

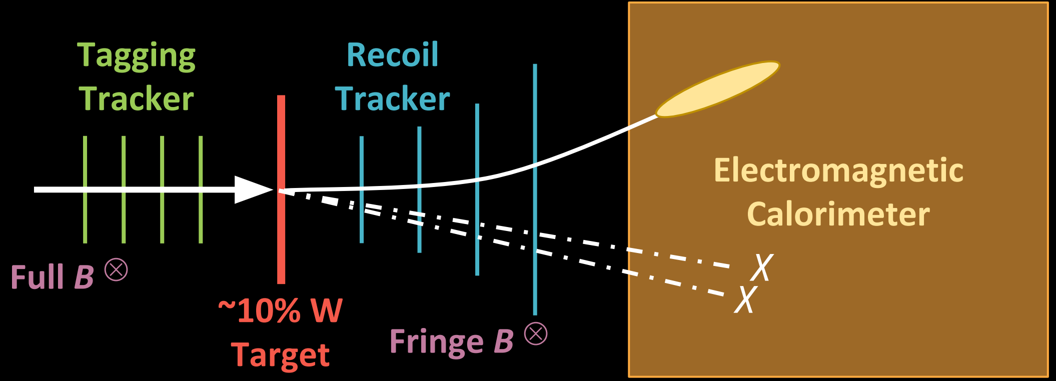




The Light Dark Matter eXperiment

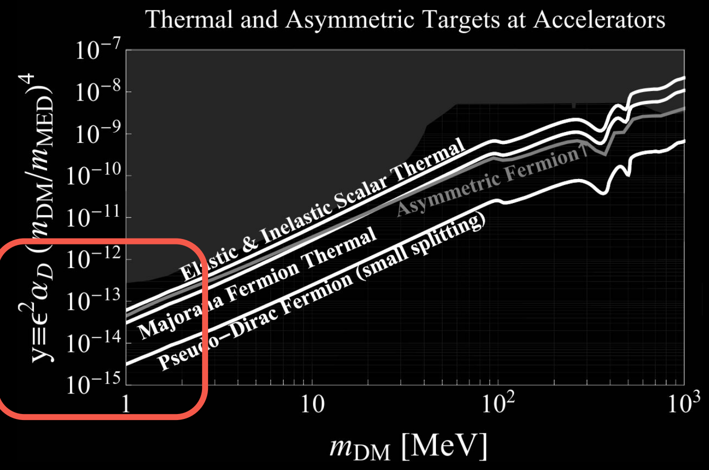
The Light Dark Matter eXperiment is a e^- fixed target missing momentum search for light dark matter



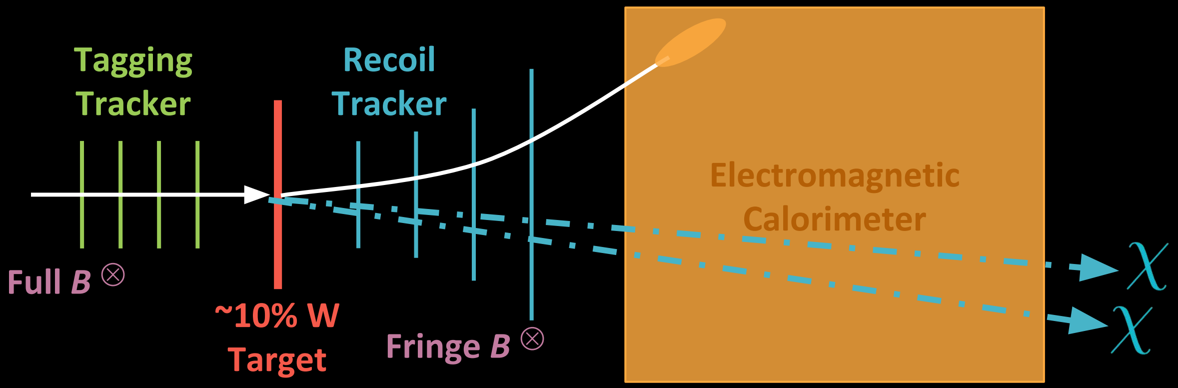


$\sigma \propto \epsilon^2 \rightarrow N_{signal} \simeq N_{e-} \times y|_{1\ MeV}$

A zero background experiment can test all thermal targets over most of the MeV-GeV range (with 10^{16} e^- on target)!



LDMX Design Considerations



Beam that allows individual tagging and reconstruction of 10^{16} incident e^-

- A low-current, multi-GeV, e^- beam with high repetition rate (10^{16}/year ≈ 1 e^-/3 ns).
  - The possibilities are DASEL @ SLAC (4/8 GeV) and CERN and CEBAF @ JLab (< 11 GeV)
- large beamspot (~10 cm^2) to spread out otherwise extreme rates and radiation doses

Tracking and calorimetry capable of high rates and radiation tolerance

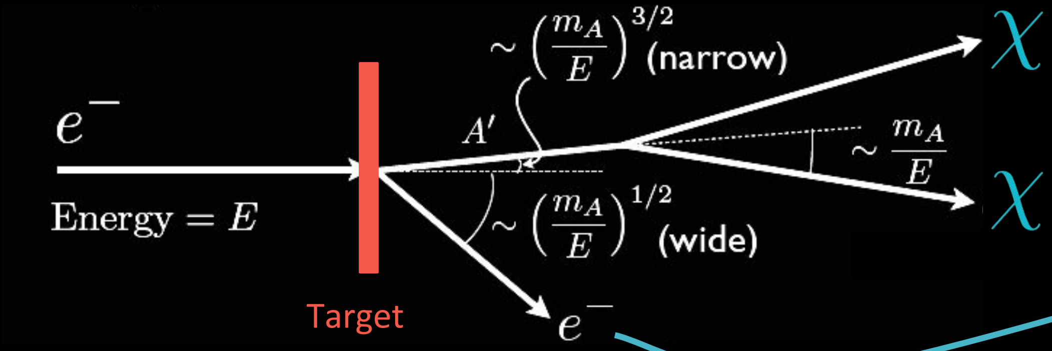
- High resolution, low mass tagging/recoil trackers
- High energy resolution EM calorimeters

Requirements for 10^{16} experiment close to limits of available technologies ➡ Two-stage approach to LDMX: **4×10^{14} "Phase I" (1 e^-/25 ns @ 4 GeV)** followed by **10^{16} "Phase II" (O(1 e^-/ns) @ >8 GeV)**

SLAC

Dark Bremsstrahlung Kinematics

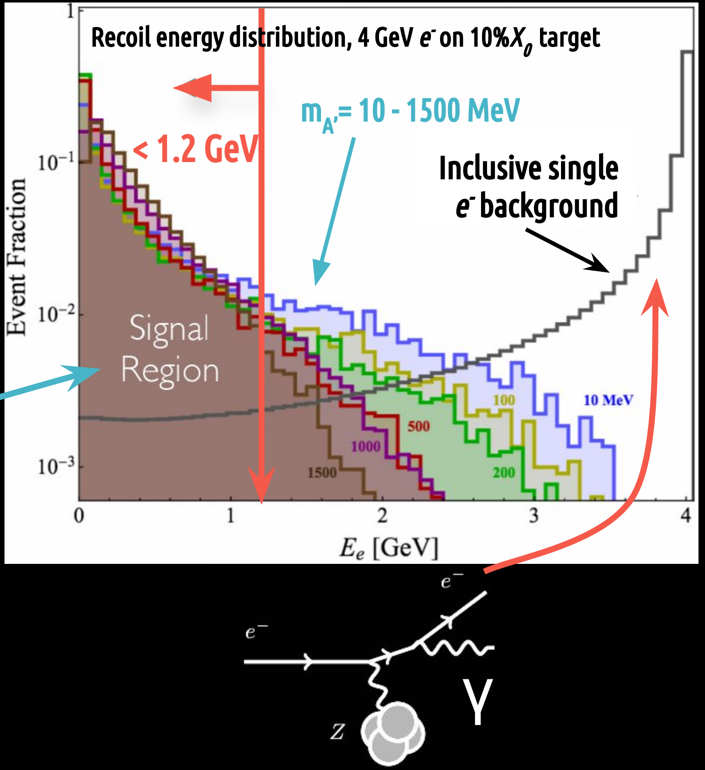
Since dark photons couple to electric charge, they will be produced through a process analogous to bremsstrahlung off heavy targets



but with different rates and kinematics

- Production is sharply peaked at x ≈ 1 ⟶ A' takes most of the beam energy
- Recoil is produced very soft and at wide angles ⟶ Large missing momentum

Recoil kinematics allow efficient signal definition providing a factor of 30 background rejection!



Dark Bremsstrahlung Kinematics

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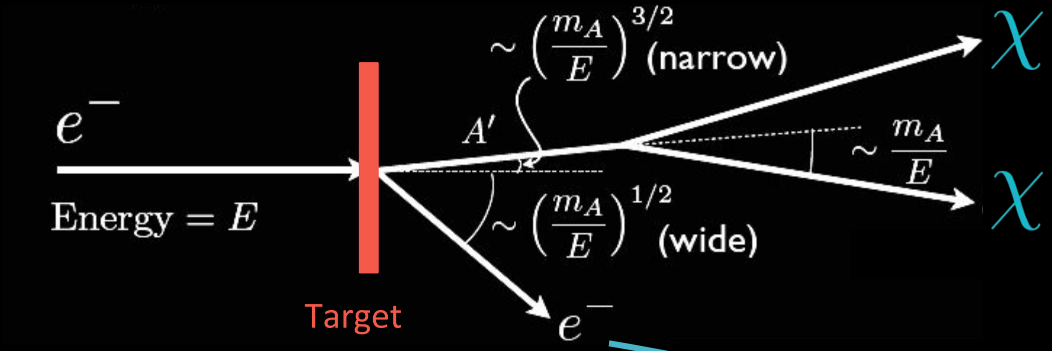

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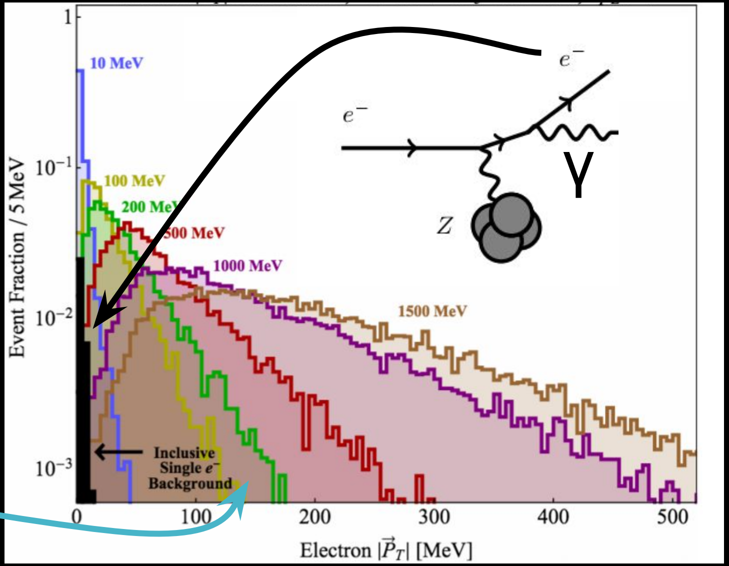
p_t is also an important experimental handle as it depends on the mass of the A'



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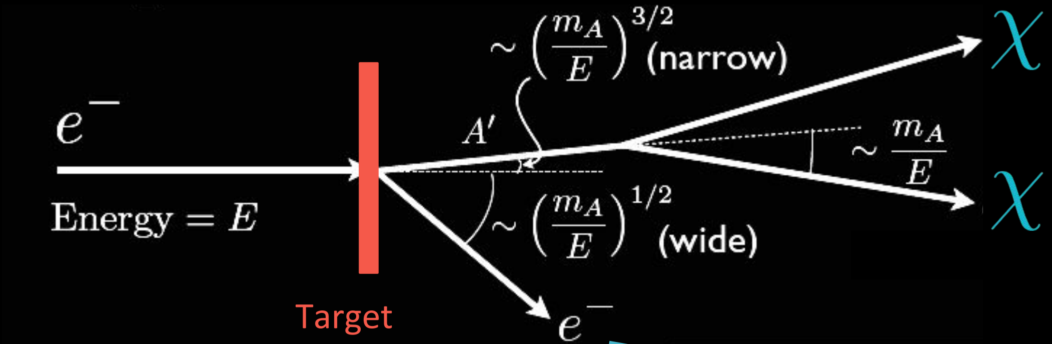

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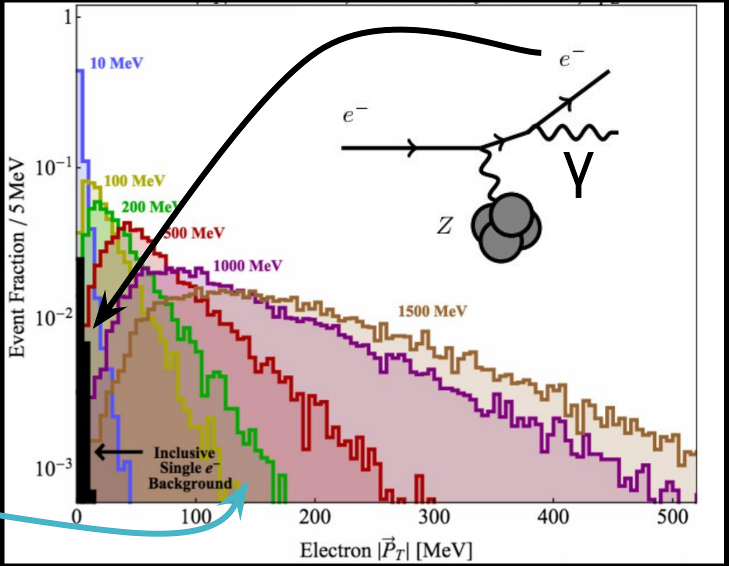
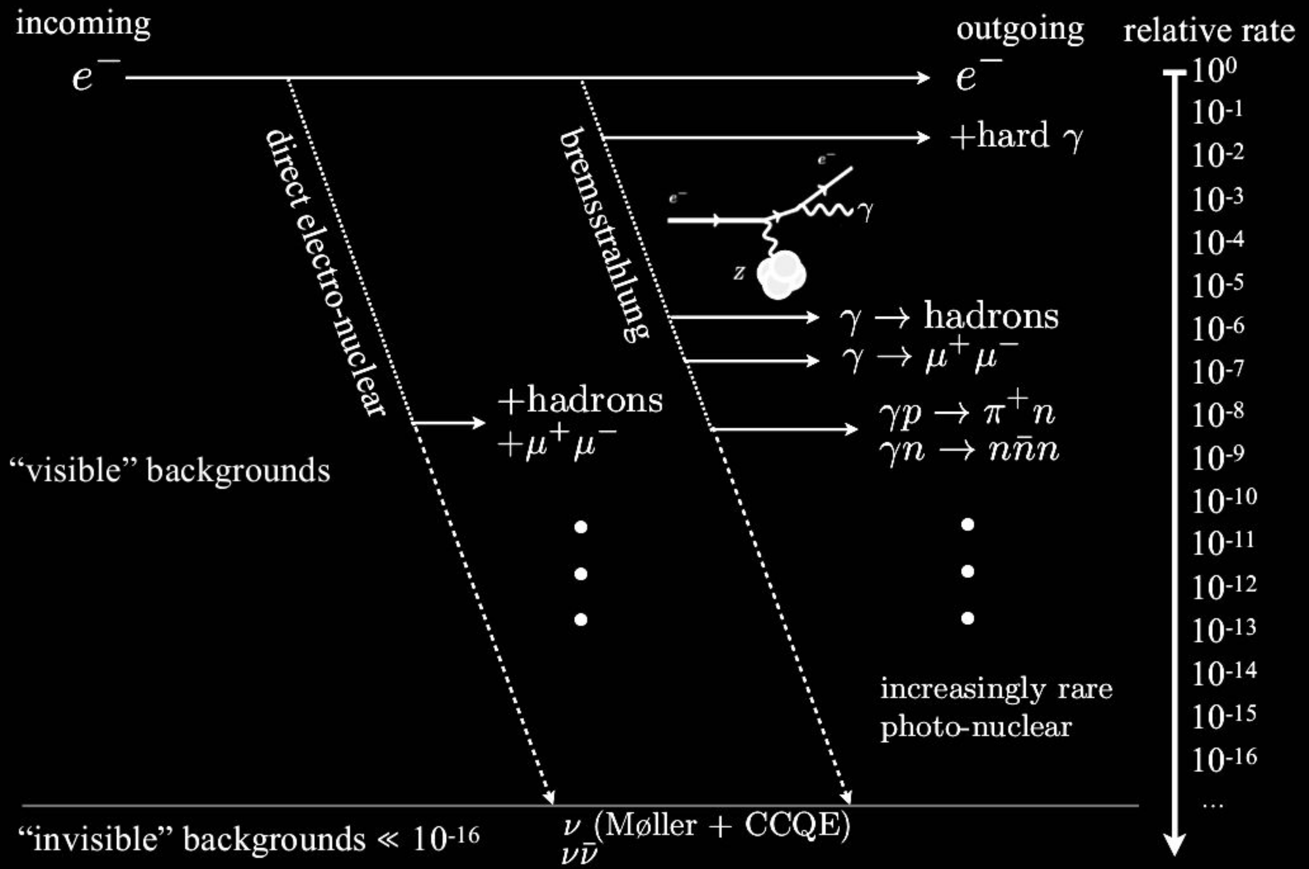
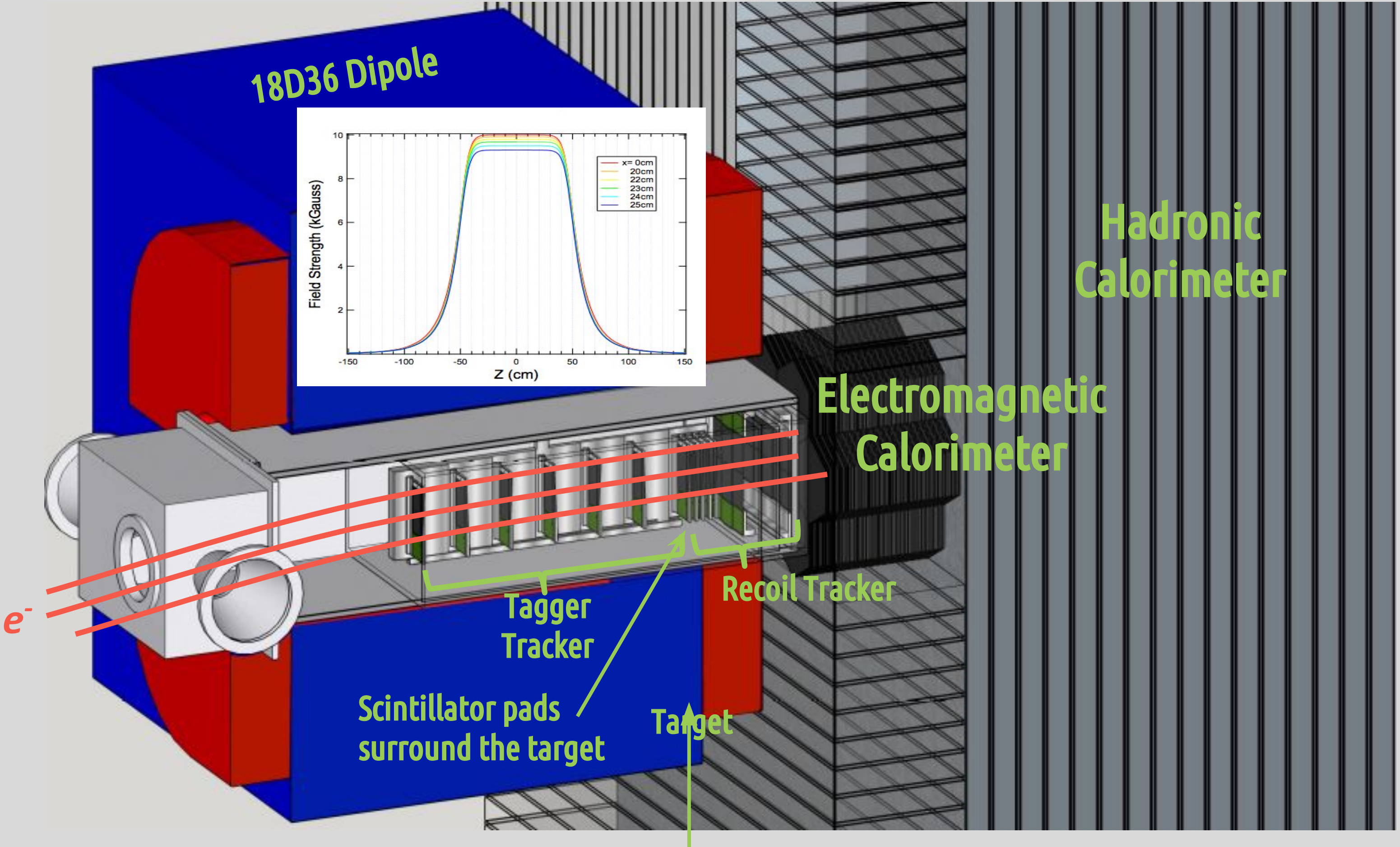


Goal: achieve zero background without using p_T as a signal discriminator

Missing Momentum Backgrounds



LDMX Phase I Detector Concept



Tagger and Recoil Trackers

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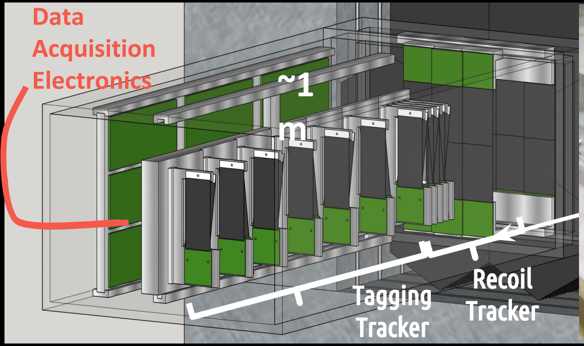
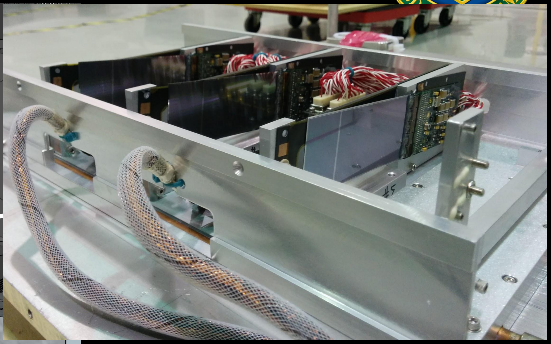
Silicon strip trackers will be similar to the HPS Silicon Vertex Tracker
- Fast (2 ns time resolution)
- Meets radiation tolerance requirements

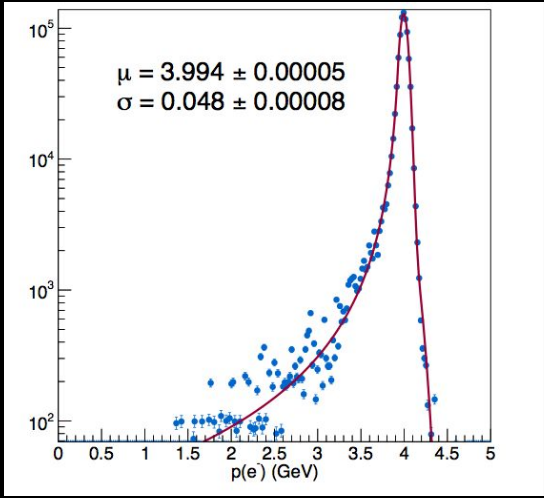
Tagging tracker → 7 measurement stations composed of two sensors at small angle stereo
- Used to select against off-energy e^-

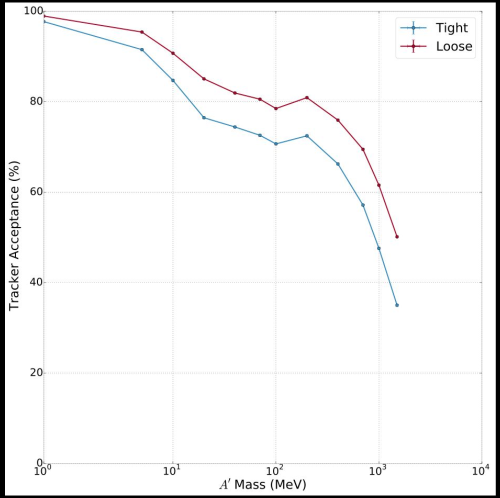
Recoil tracker → 4 stations composed of sensor pairs at small angle stereo + 'axial only' layers

Single 18D36 dipole magnet → Two field regions
- Tagging tracker in central 1.5T field
- Recoil Tracker in fringe field





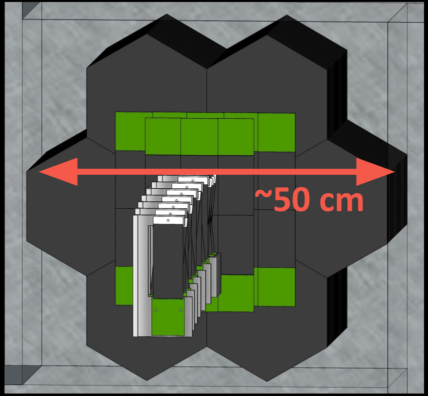




Electromagnetic Calorimeter

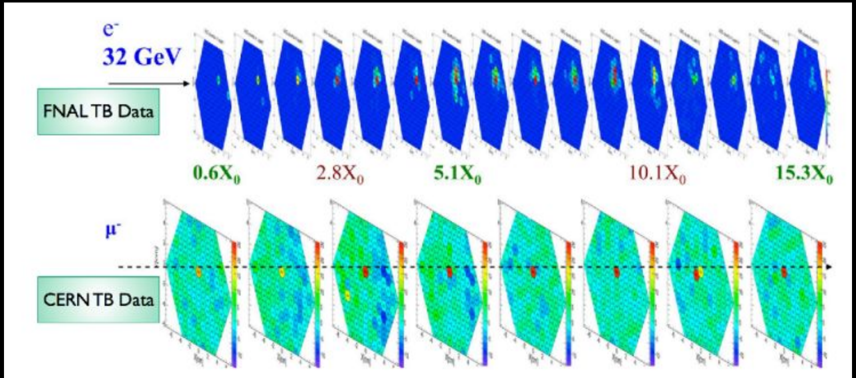
Si-W calorimeter developed for CMS upgrade

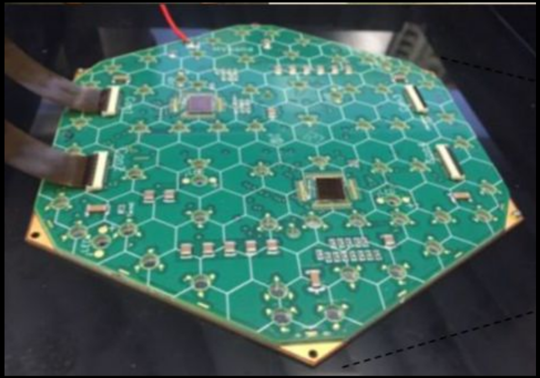
- Fast, dense, granular for high occupancies ⟶ Allows for exploitation of both longitudinal and transverse shower shapes
- Deep (40 X_0) for extraordinary EM containment



For LDMX

- Easily withstands the effective fluence of 10^{13} n/cm^2 caused by 10^{14} e^-'s on target
- Can provide fast trigger for trackers (~3 μs)
- Is capable of MIP tracking which will help with background rejection.





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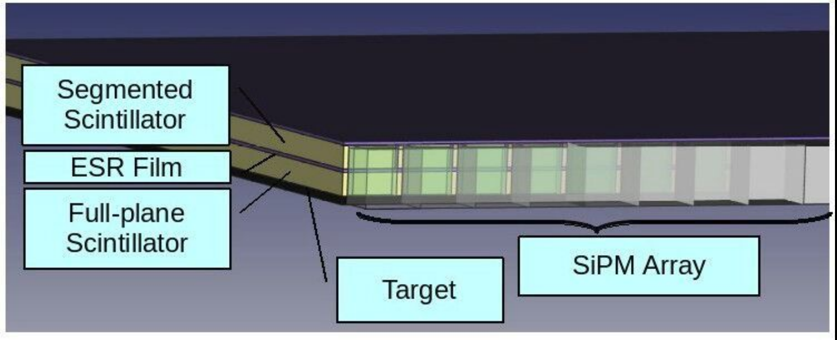
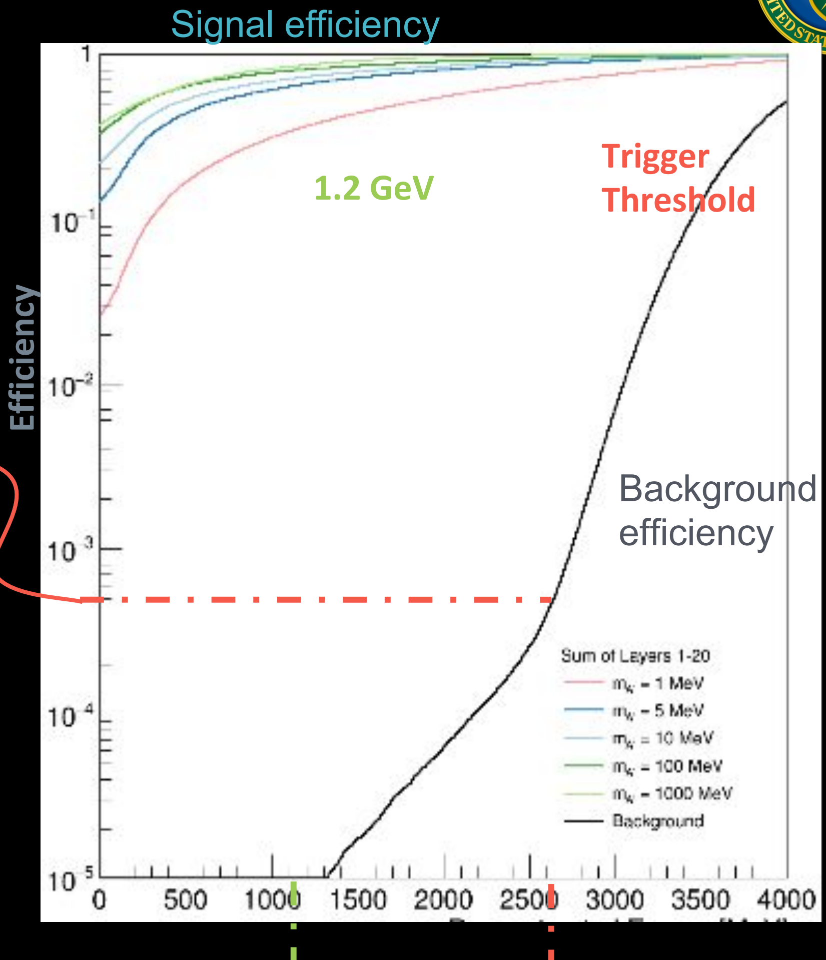
Trigger

Trigger makes use of Ecal and trigger scintillator pad downstream of the target to reject beam backgrounds

- Apply a cut on the sum of the first 20 Ecal layers
- Scintillator pad used to count the number of incident electrons → Allows setting of trigger threshold

3 x 10^{-4} background rejection!





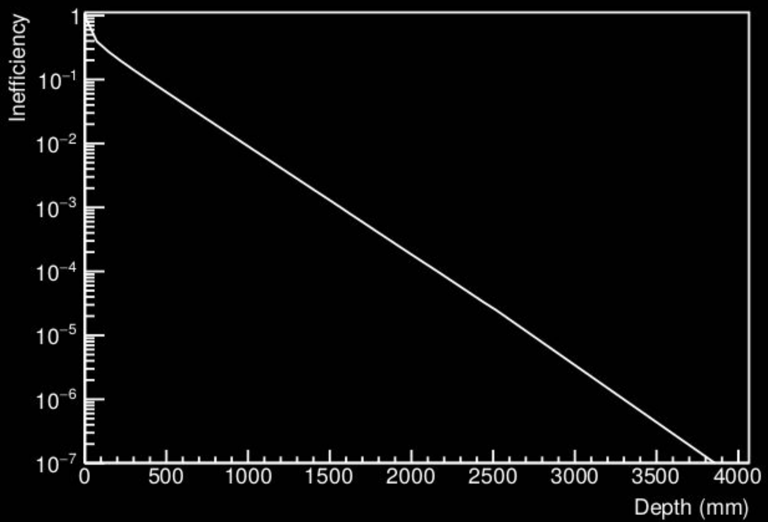
Hadronic Calorimeter

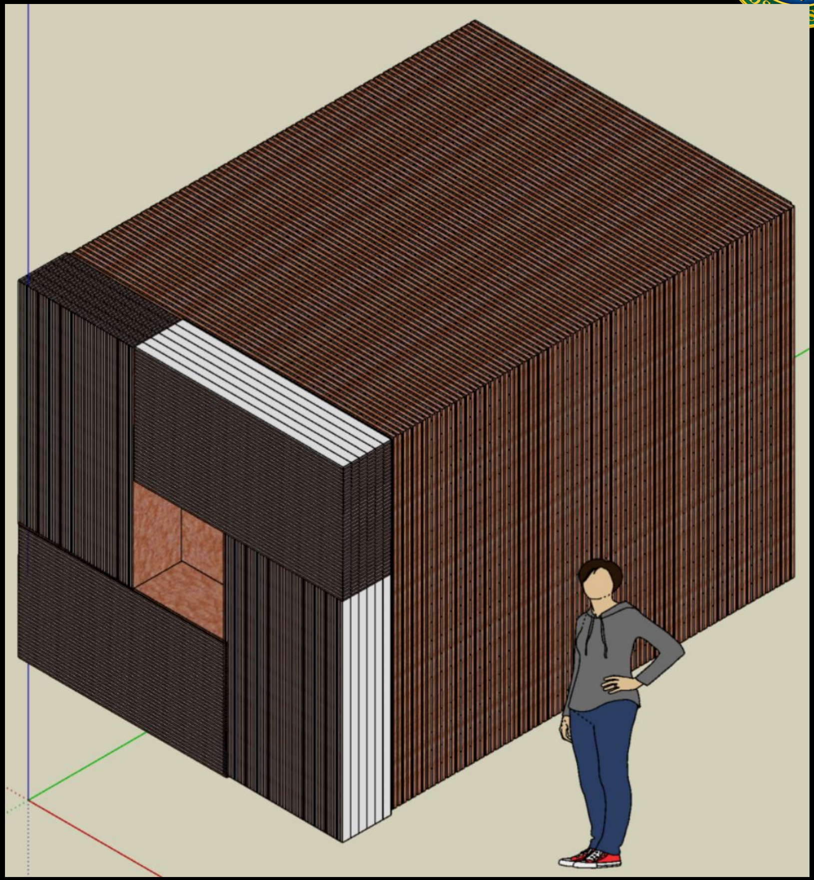
Makes use of CMS upgrade hardware

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

Surround ECal as much as possible

- Many PN events have a high multiplicity of soft neutral hadrons
- Also catches wide-angle brems (≳ 25 deg.)





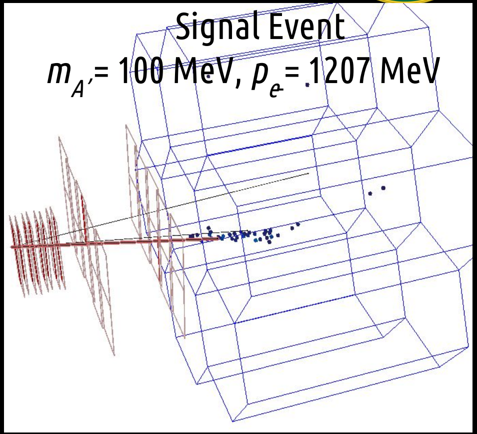
Rejecting Backgrounds

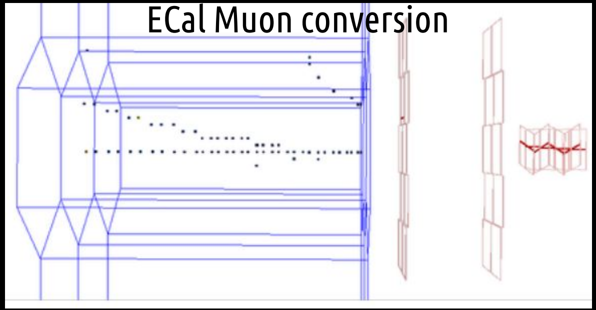
Photo/electronuclear as well as muon conversion backgrounds can occur in the target, recoil tracker or Ecal

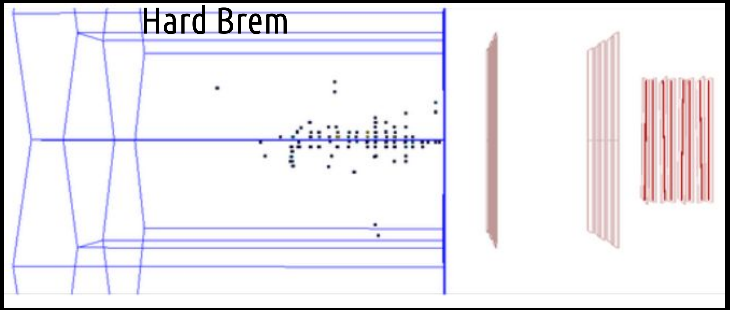
Have several handles that can be used to veto these backgrounds

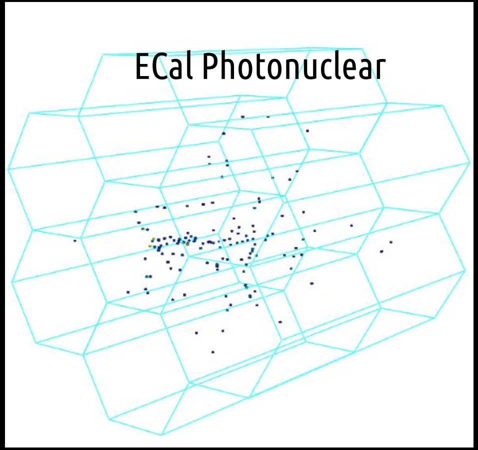
- Last layers of Tagger tracker→ used to reject PN/EN from the target
- Recoil tracker → used to reject PN/EN and muon conversions that occur the target and recoil tracker
- Ecal - Use boosted decision tree to reject both target PN/EN and Ecal PN → Ecal EN is not a concern
- Hcal can be used to reject all backgrounds types

Initial studies using a veto making use of information from each subsystem was able to eliminate all photonuclear events from a sample equivalent to 10^{14} e^- on target!

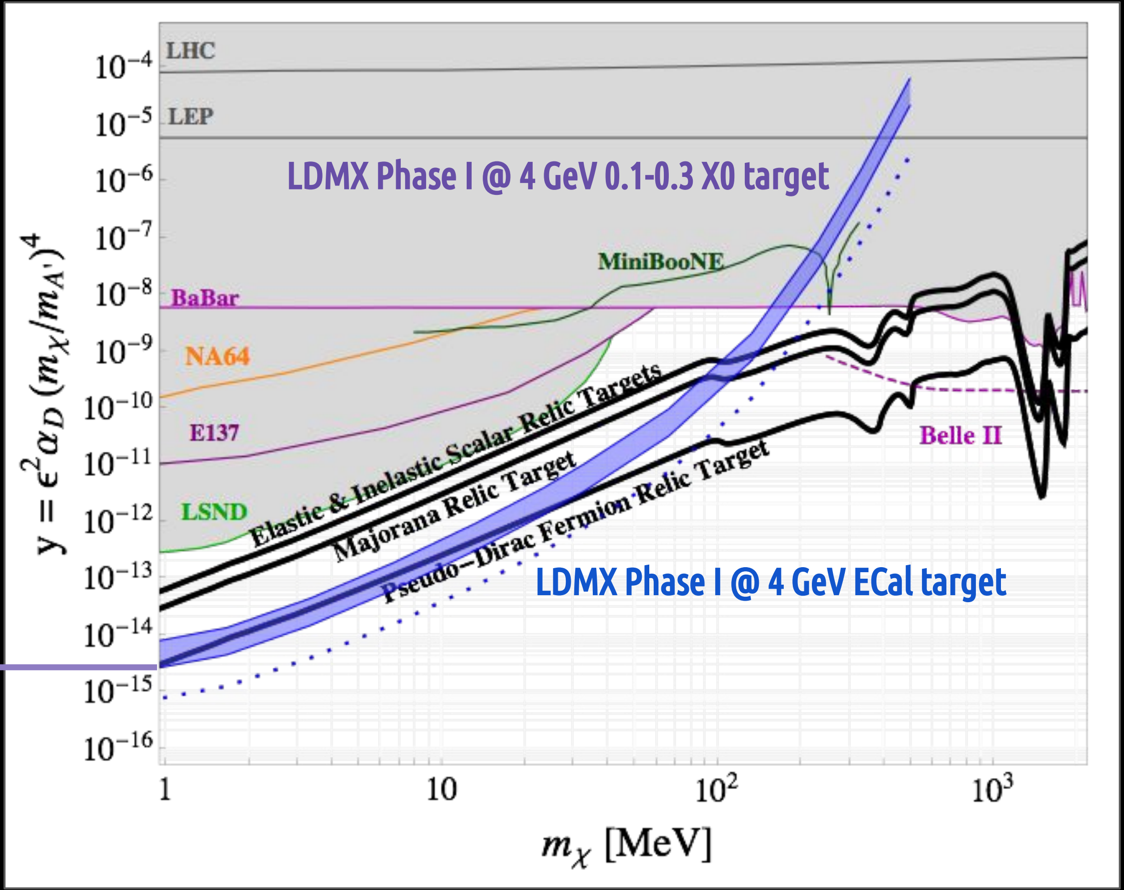








LDMX Phase I Reach



Sensitivity extends to lower masses

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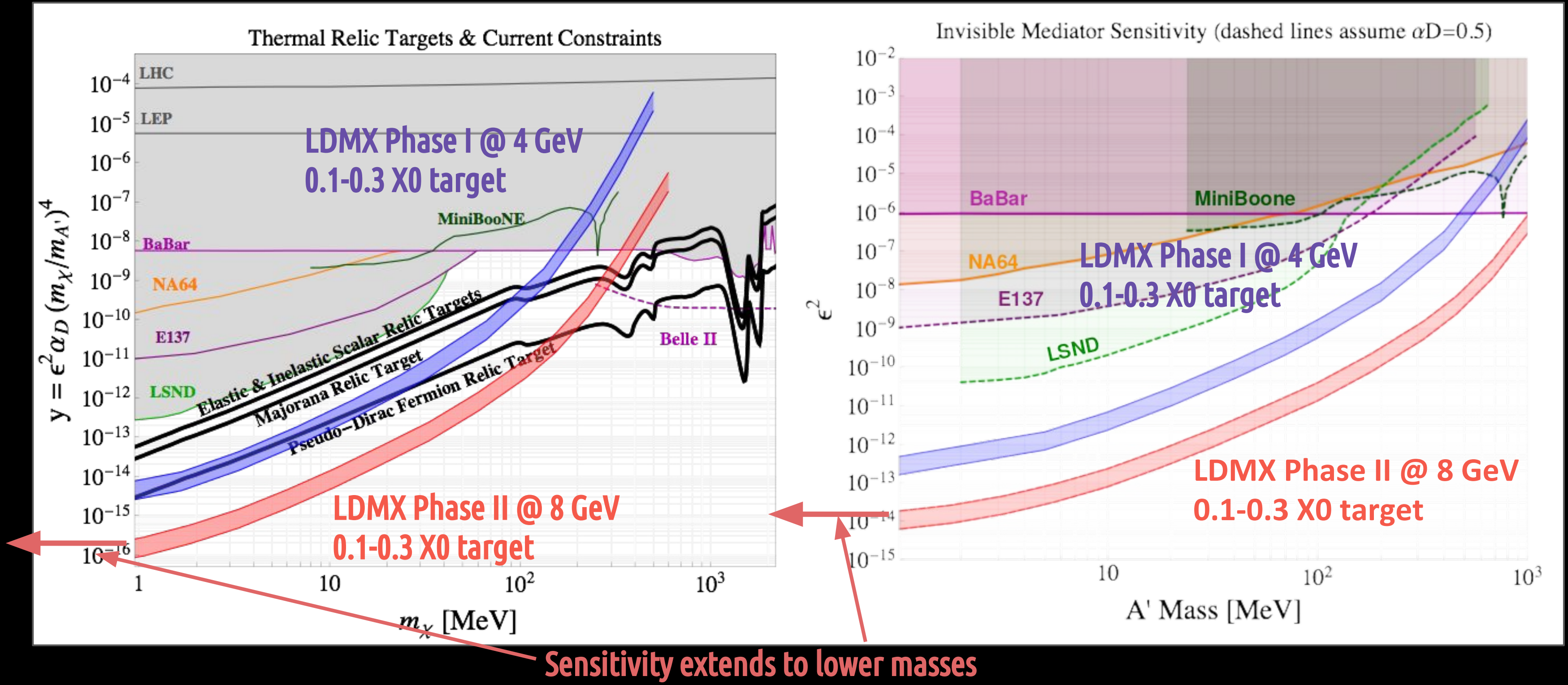
LDMX Phase II Reach



Conclusion

- Beyond WIMPs, the general case of thermal relic dark matter is a simple and motivated scenario, requiring only a new, light mediator over the remaining mass range for viable candidates (~MeV-GeV).

- This leads to two kinds of searches, for the mediators and the light dark matter. For both, much of the parameter space is unconstrained, but the set of simple models is limited and there are clear targets.

- The mediator searches require accelerator experiments, where HPS has unique reach in the next 3-5 years. Despite many challenges, the apparatus is working exceptionally well and our first analyses are showing us what we need to improve to succeed.

- Accelerators have a unique ability to search broadly for thermal relic dark matter in the MeV-GeV range and the LDMX concept can reach key thermal relic targets with a relatively simple apparatus.

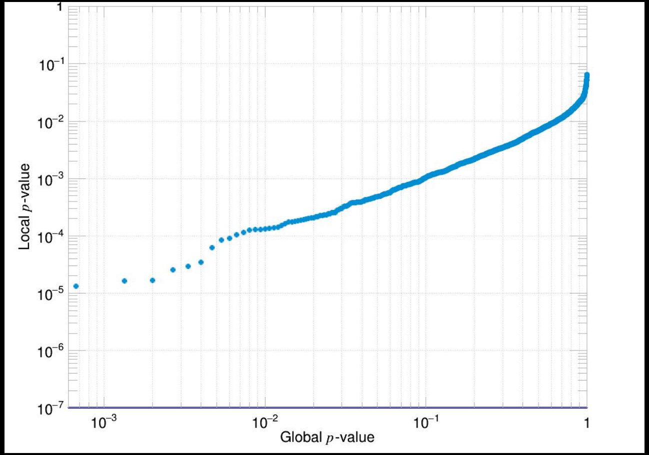
Backup

Fit Results

Establishing whether the signal+background model is significantly different from the background-only model is typically done using the profile likelihood ratio and test statistic q_0

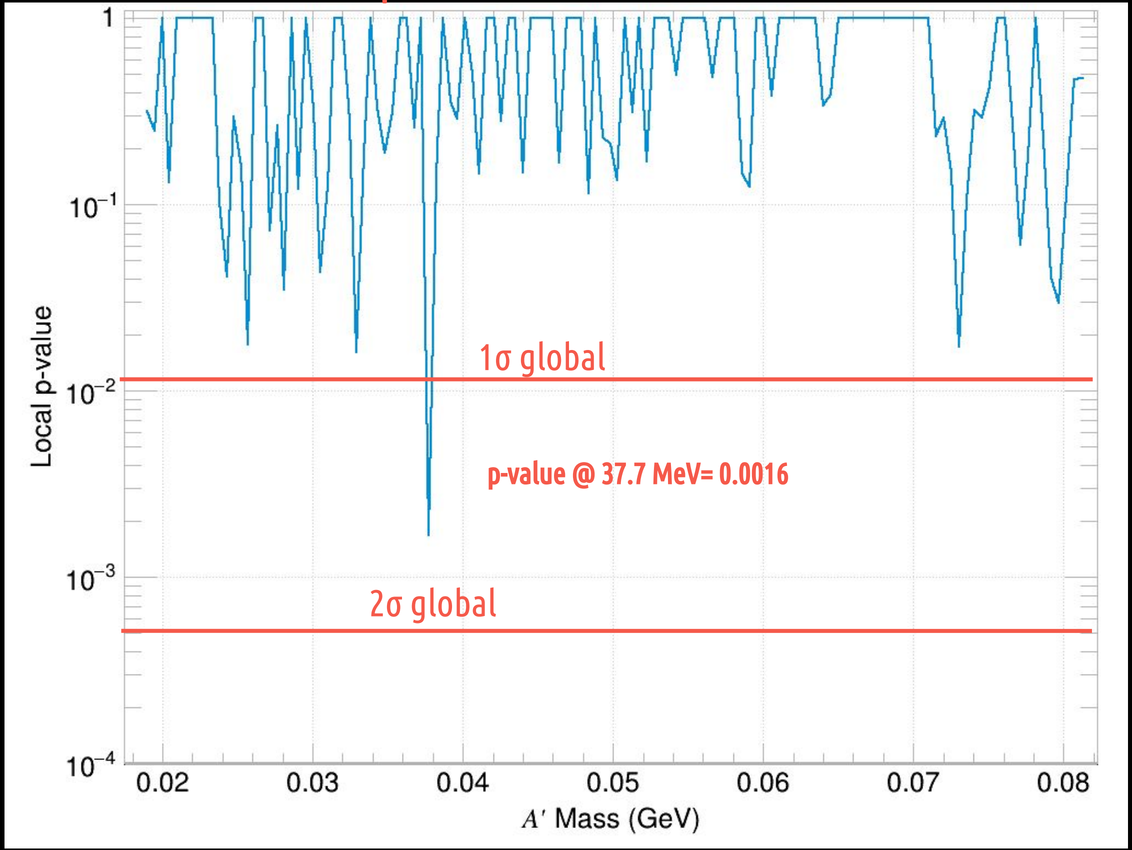
$$q_0 = \begin{cases} -2\ln \frac{\mathcal{L}(0,\hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu},\hat{\theta})} & \hat{\mu} > 0 \\ 0 & \hat{\mu} < 0 \end{cases} \quad p = \int_{q_{0,obs}}^{\infty} f(q_0|0)\,dq_0$$

Use toy MC to determine the look-elsewhere correction



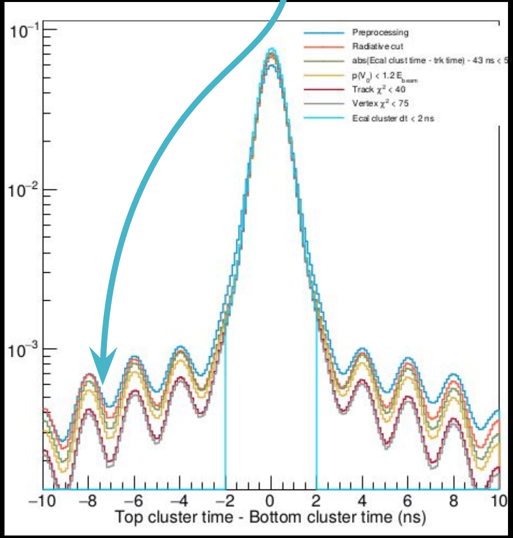
No significant bump was found!

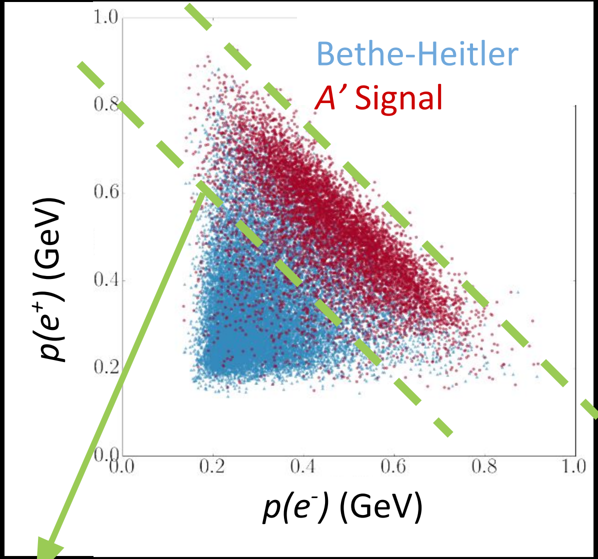
0.5 MeV Steps



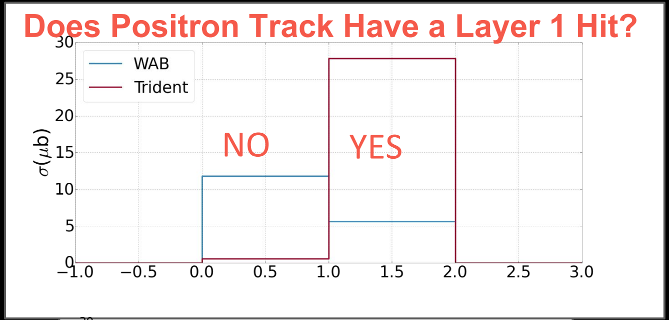
Bump Hunt Event Selection

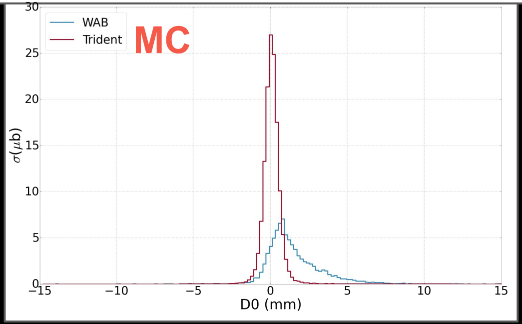
Apply kinematic and goodness of track and vertex fit cuts to clean up accidentals. **Reduces contamination from accidentals to < 1%.**





Requiring a **layer 1 hit removes 68% of WABS** from final event sample. Additional cuts on the distance of closest approach and p_t asymmetry **rejects WAB's by > 80% of WABs.**

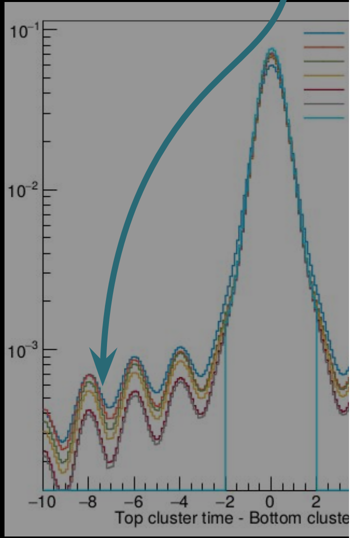




Requiring the sum of the e^+e^- pair momentum to be $0.8E_{beam} < p(e^+e^-) < 1.2E_{beam}$ GeV and greatly reduces the number of Bethe-Heitler background in our final sample.

Bump Hunt Event Selection

Apply kinematic and goo
accidentals. **Reduces con**



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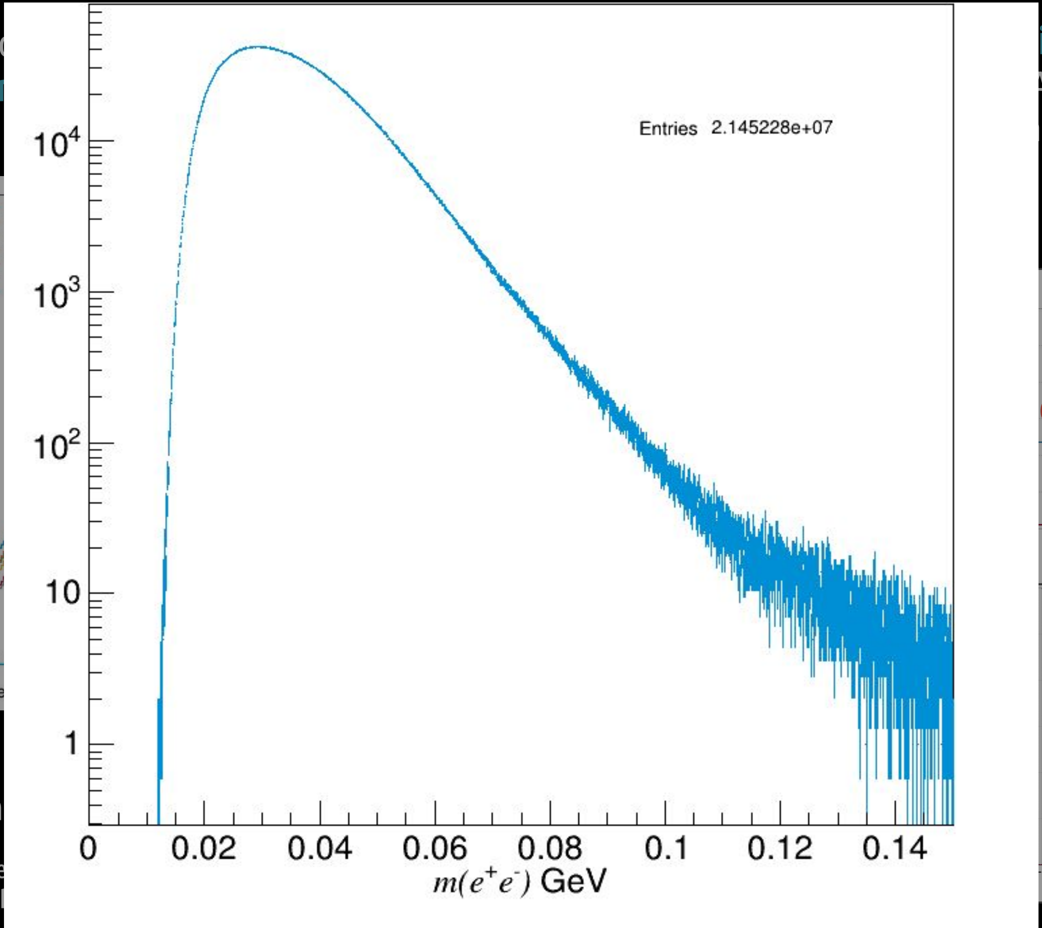
$0.8E_{beam} < p(e^+e^-) < 1.2E_{be}$
Bethe-Heitler backgrou



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