Dark Sectors in Electron Fixed-Target Experiments

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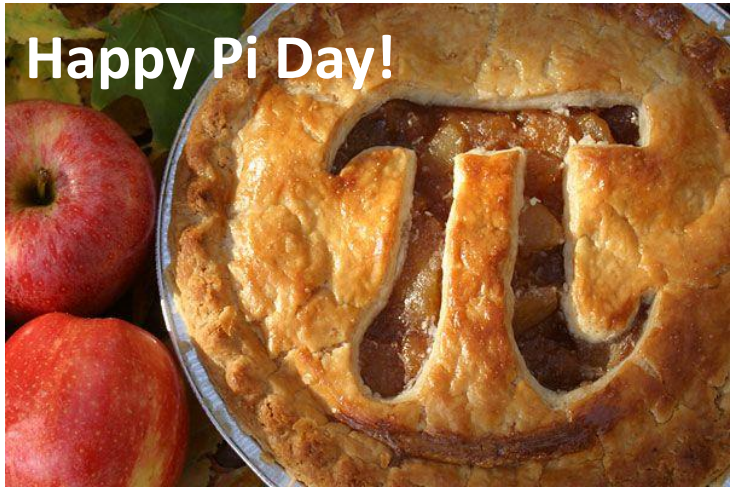
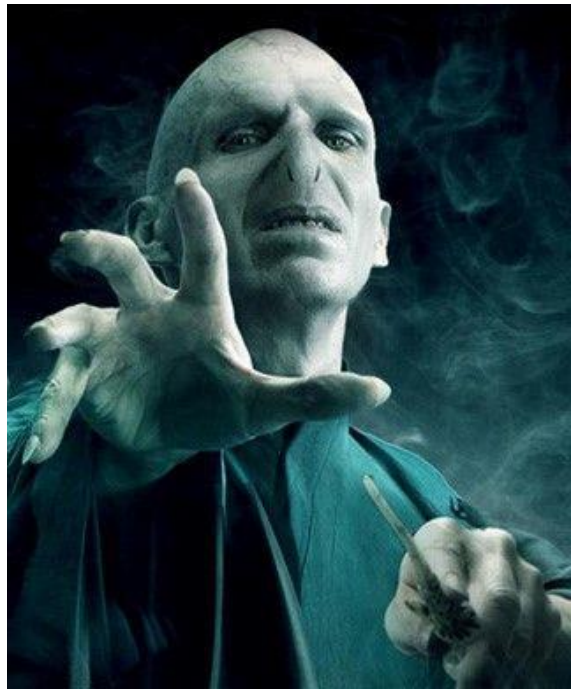
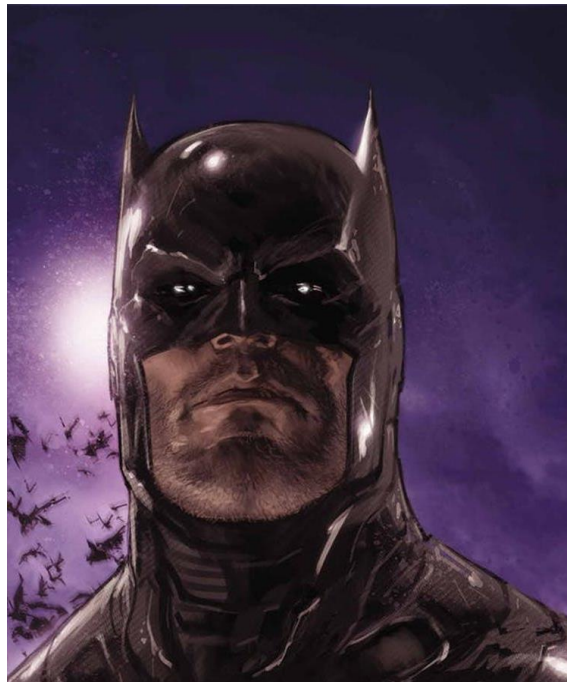


… or, Unlocking the Dark Side

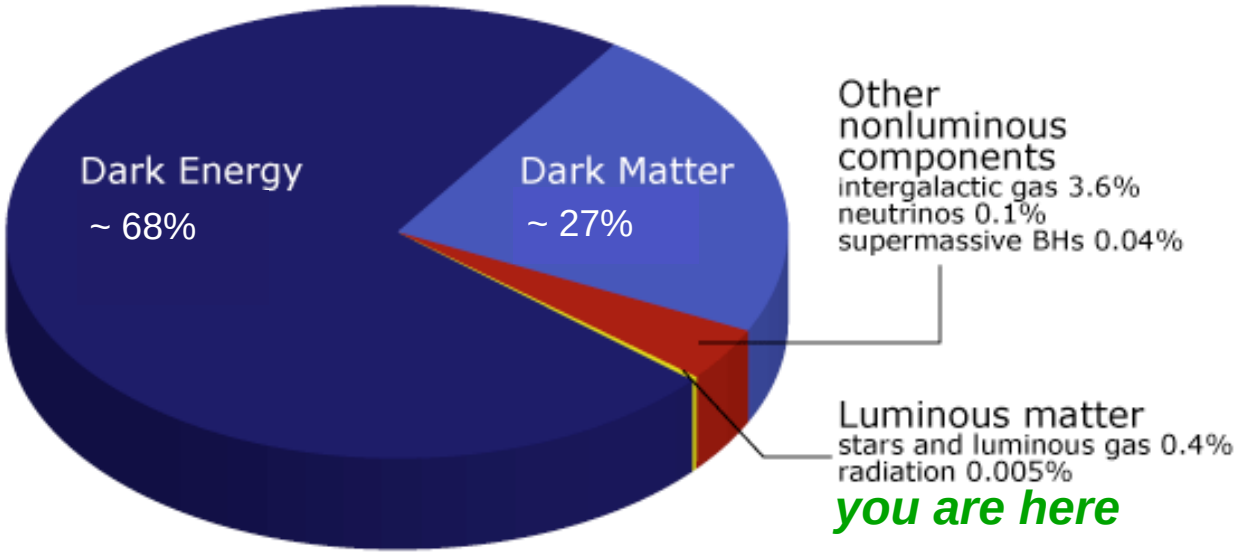


Outline

- Dark Sector Search Motivations
  - Dark Photons
- Search Strategies
  - Fixed Target
- Heavy Photon Search (HPS)
  - Concept & Experimental Setup
  - Engineering Run Results: Resonance & Displaced-Vertex Searches
  - Upcoming Physics Runs
- Light Dark Matter Search (LDMX)
  - Concept & Experimental Setup
  - Projected Reach

Dark Sector Search Motivations



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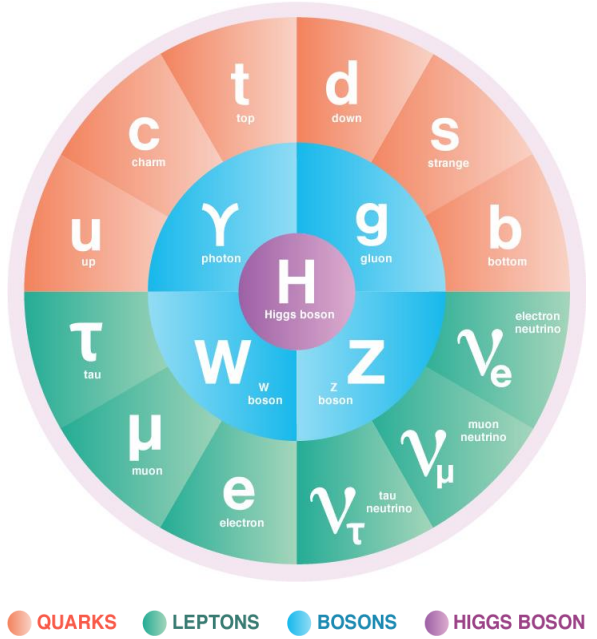

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What is the particle composition of DM?

What are its interactions?

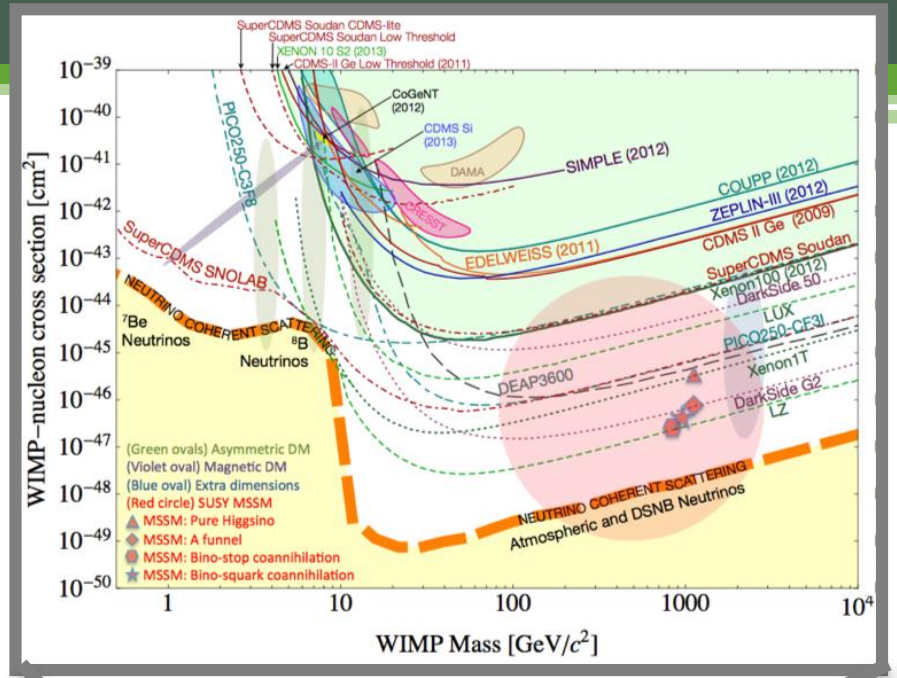
What mechanism(s) set the amount of dark matter?

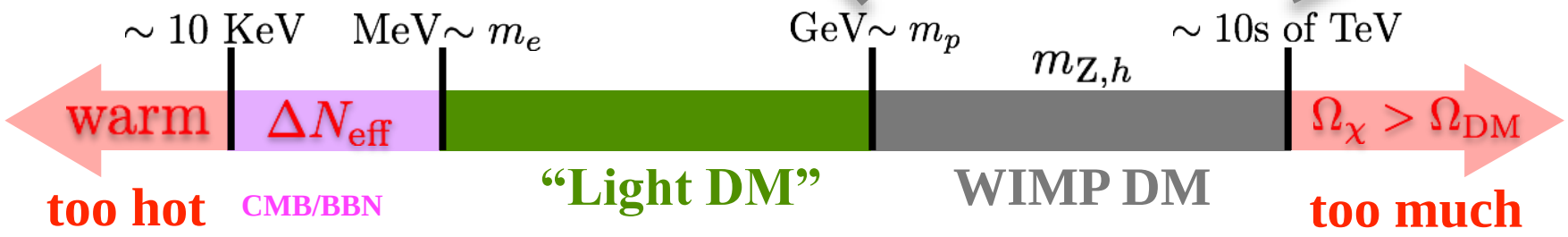
And its ratio to the amount of regular matter?

How did this amount change over cosmic timescales?

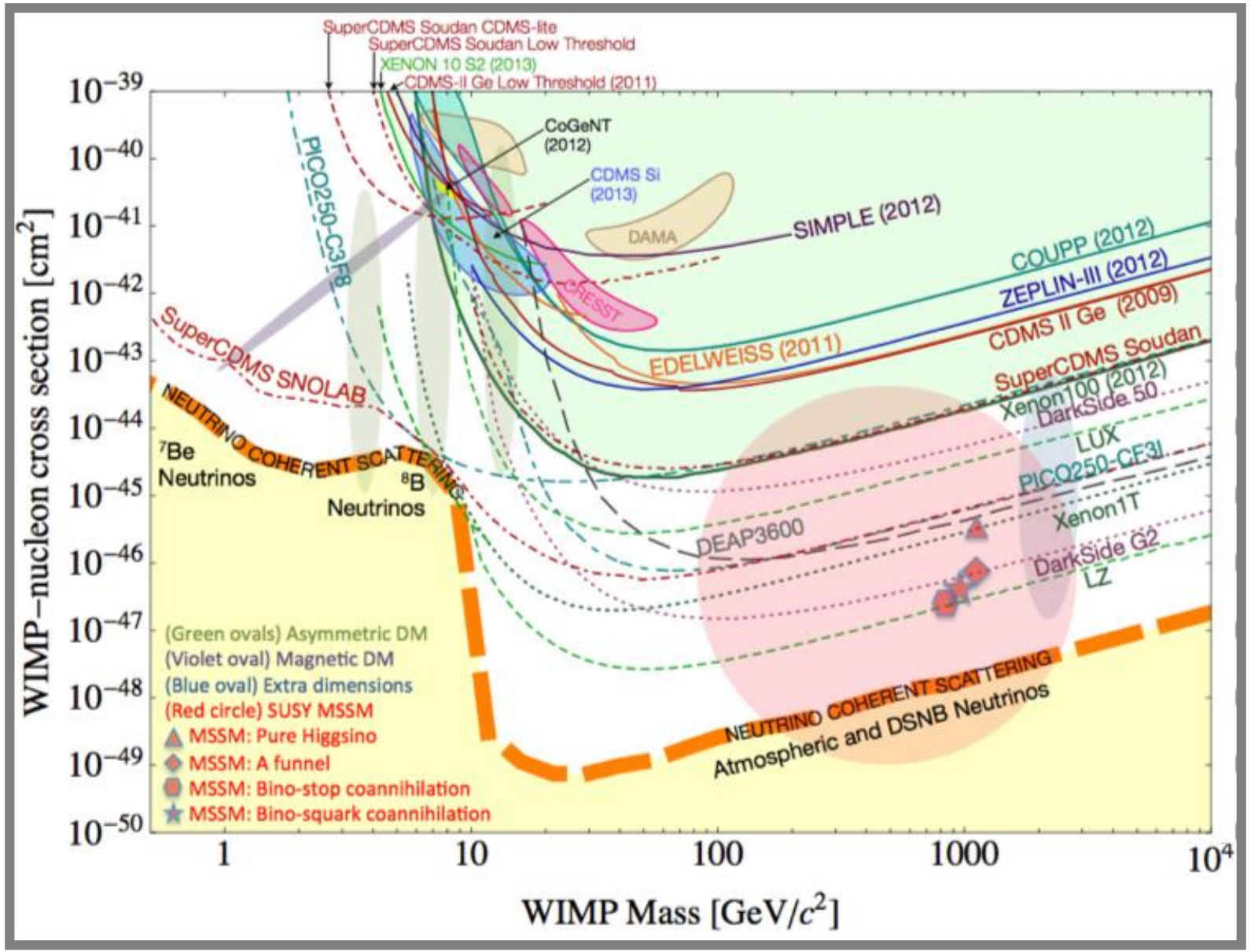
Dark Sector Search Motivations

- "Thermal Relic" Weakly Interacting Massive Particles: seemingly the simplest scenario
- But haven't shown up in mass range where we most expected them!





Dark Sector Search Motivations



Dark Sector Search Motivations

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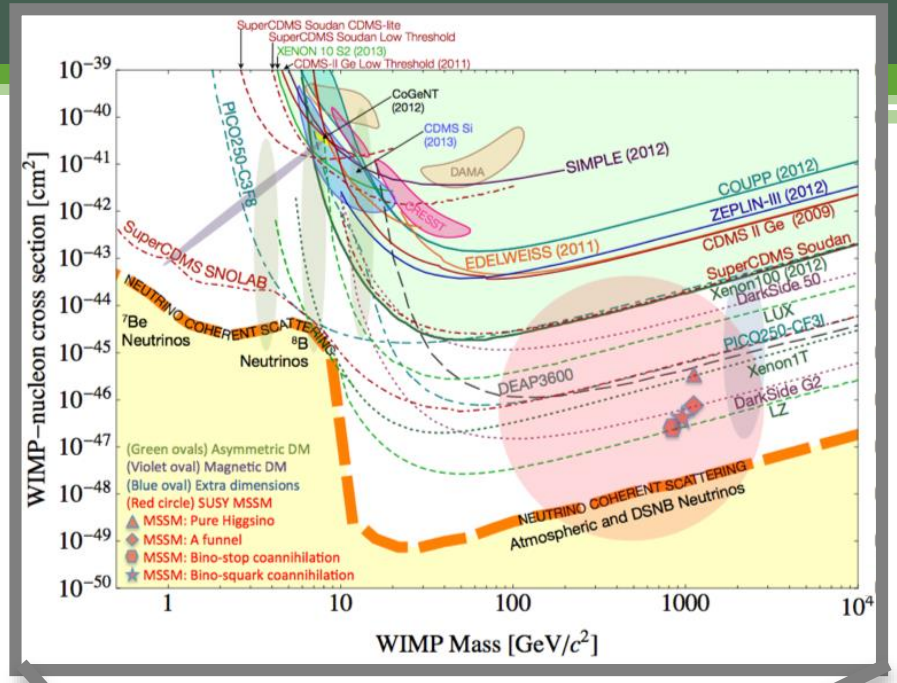
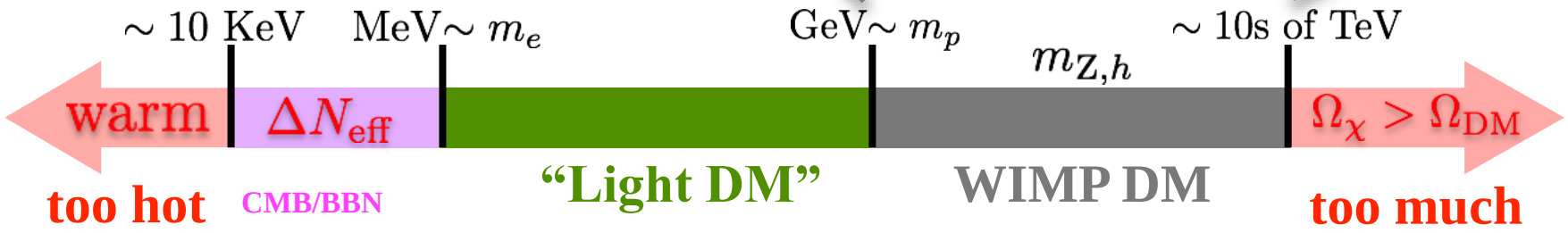




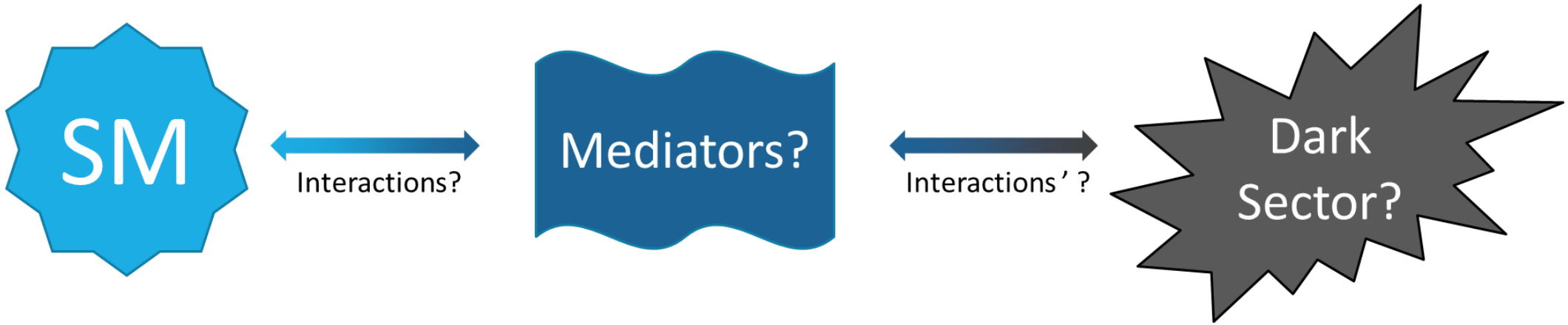
- Thermal Relic DM actually works fine at least down to $2m_e$
- But "light DM" requires new, comparably low-mass mediators to achieve required annihilation cross-section for thermal relics

Dark Sector Search Motivations

The Standard Model is only ~5% of the universe.
It includes 3 forces.

Why should the ~25% that is Dark Matter be any simpler?
Dark Forces?

How would DM interact with the SM?
Mediator particles?

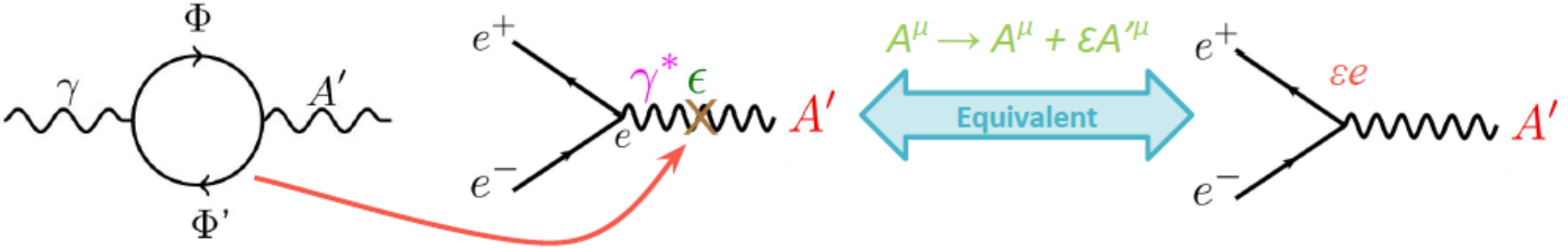


Dark Sector Search Motivations

- Vector Portal: Add a U(1)' whose massive "dark" gauge boson (A' / Z_D / γ_d) mixes kinetically with SM photon

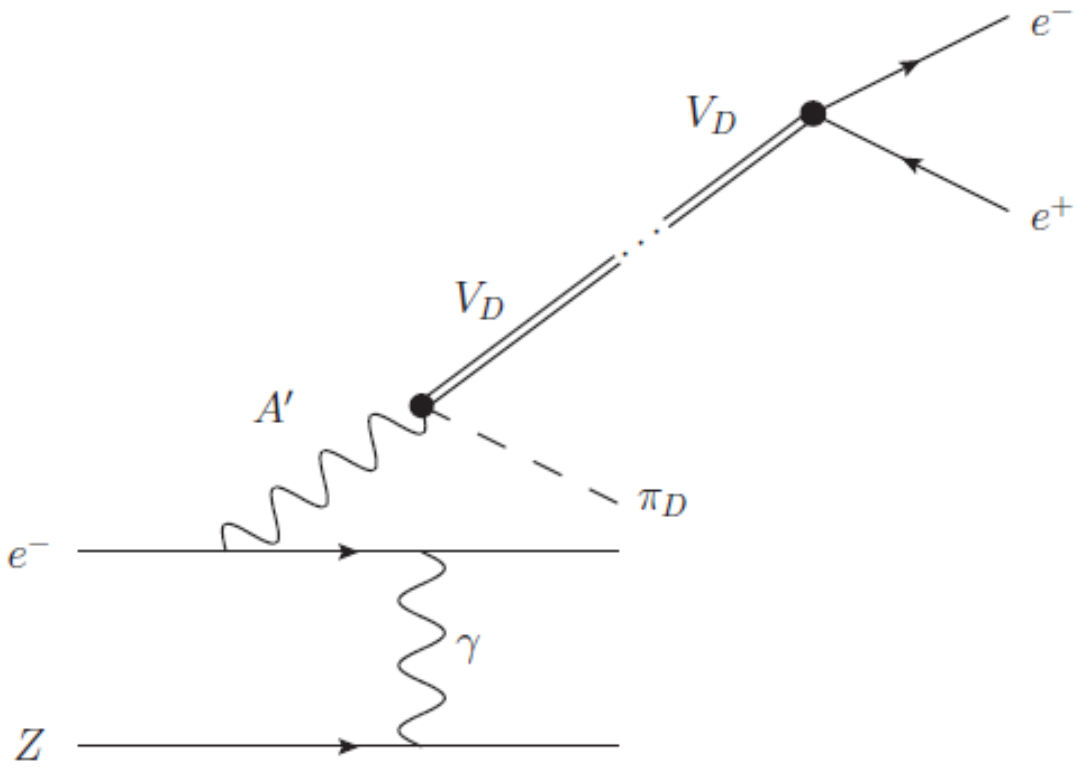
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

kinetic mixing → induces weak coupling to electric charge



Dark Sector Search Motivations

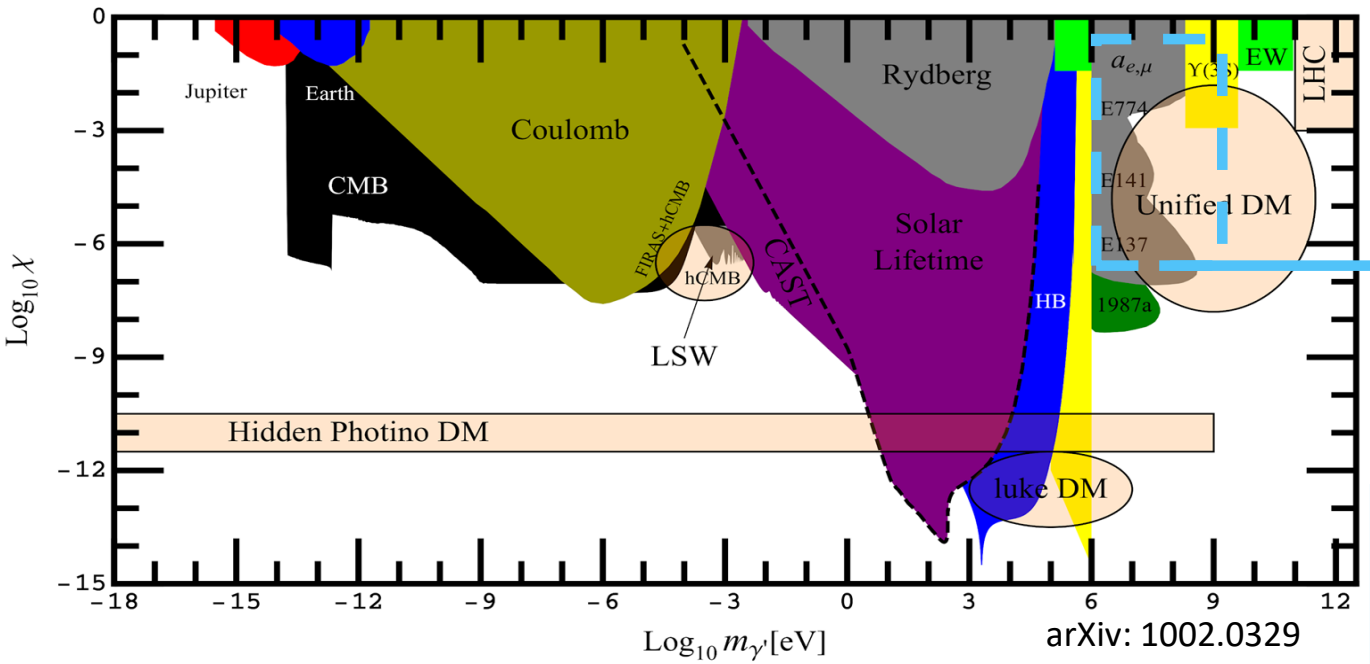
- Hidden Valley: sector of dark particles, interacting amongst themselves, weakly coupled to SM through loops of TeV-scale particles or marginal operators
  - Lowest particle in Valley forced to decay to SM due to mass gap or symmetry
  - "Portal" couples both to SM and Valley operators
- "Bottom-up" astrophysics models with *A'*:
  - Inelastic DM
  - Exciting DM
  - Secluded DM
  - Strongly Interacting Massive Particles
    - "Dark quarks" charged under new confining gauge group ("dark QCD") *and* new U(1)
    - Dark pions (π_D), dark vector mesons (V_D), etc. can be long-lived and interact with *A'*

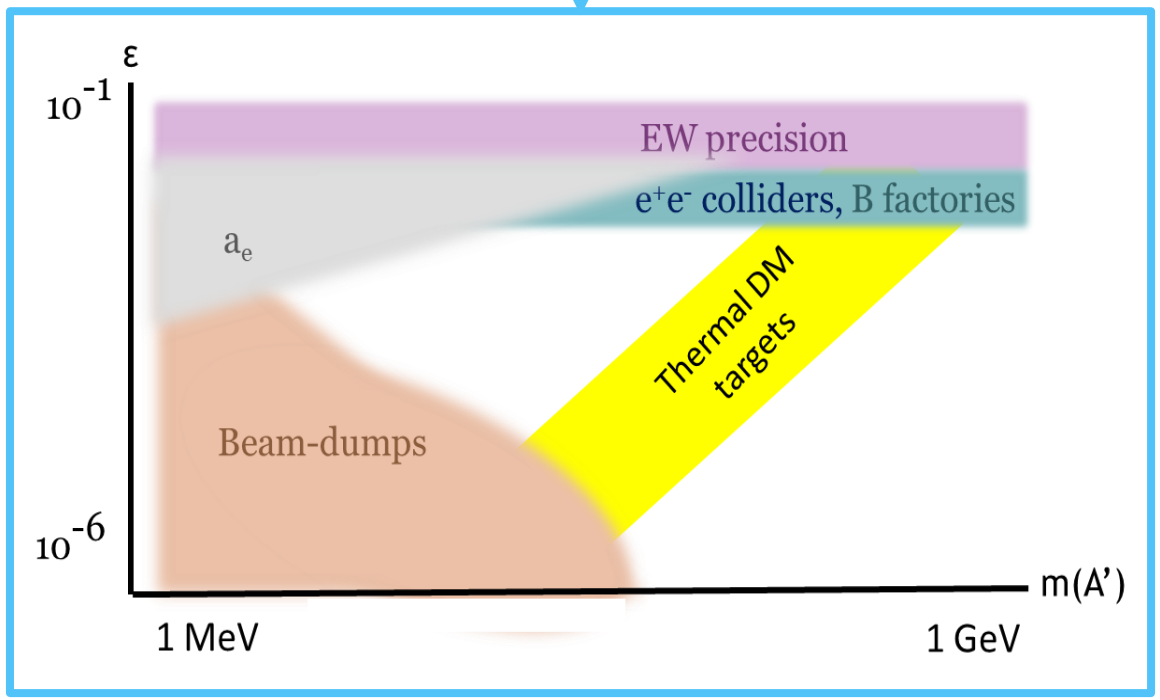


Dark Photon Search Motivations

Look for the Portal

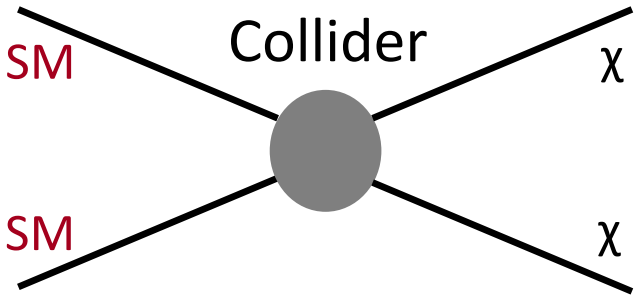
Dark Photon Search Motivations

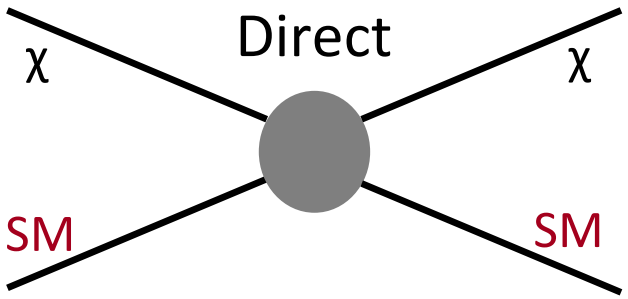


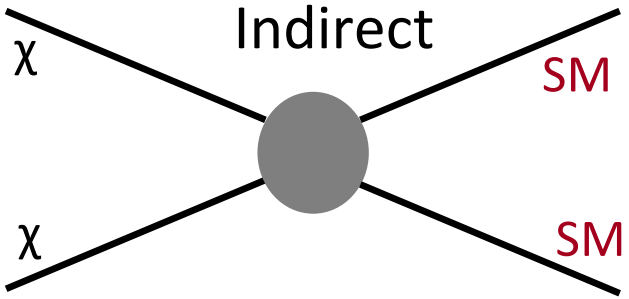


Dark Sector Search Strategies

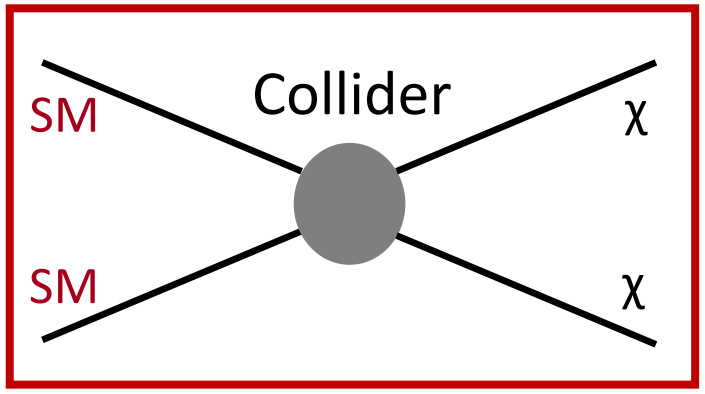
Complementarity between different types of experiments:



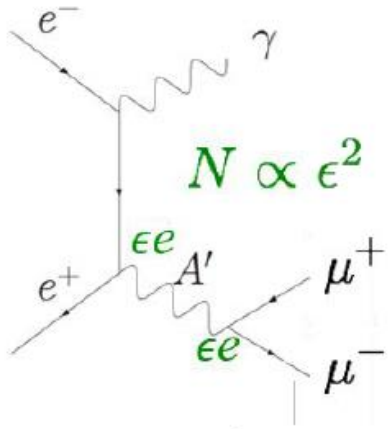




Dark Sector Search Strategies

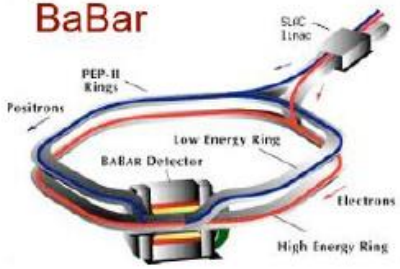


e^+e^- colliders

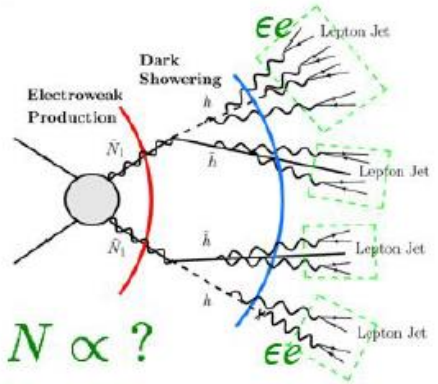


+ meson decays

BaBar

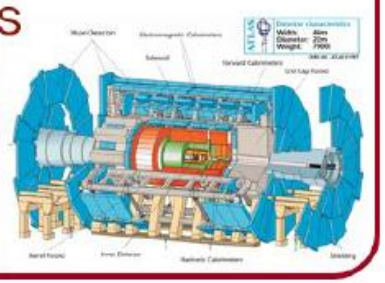


pp collider

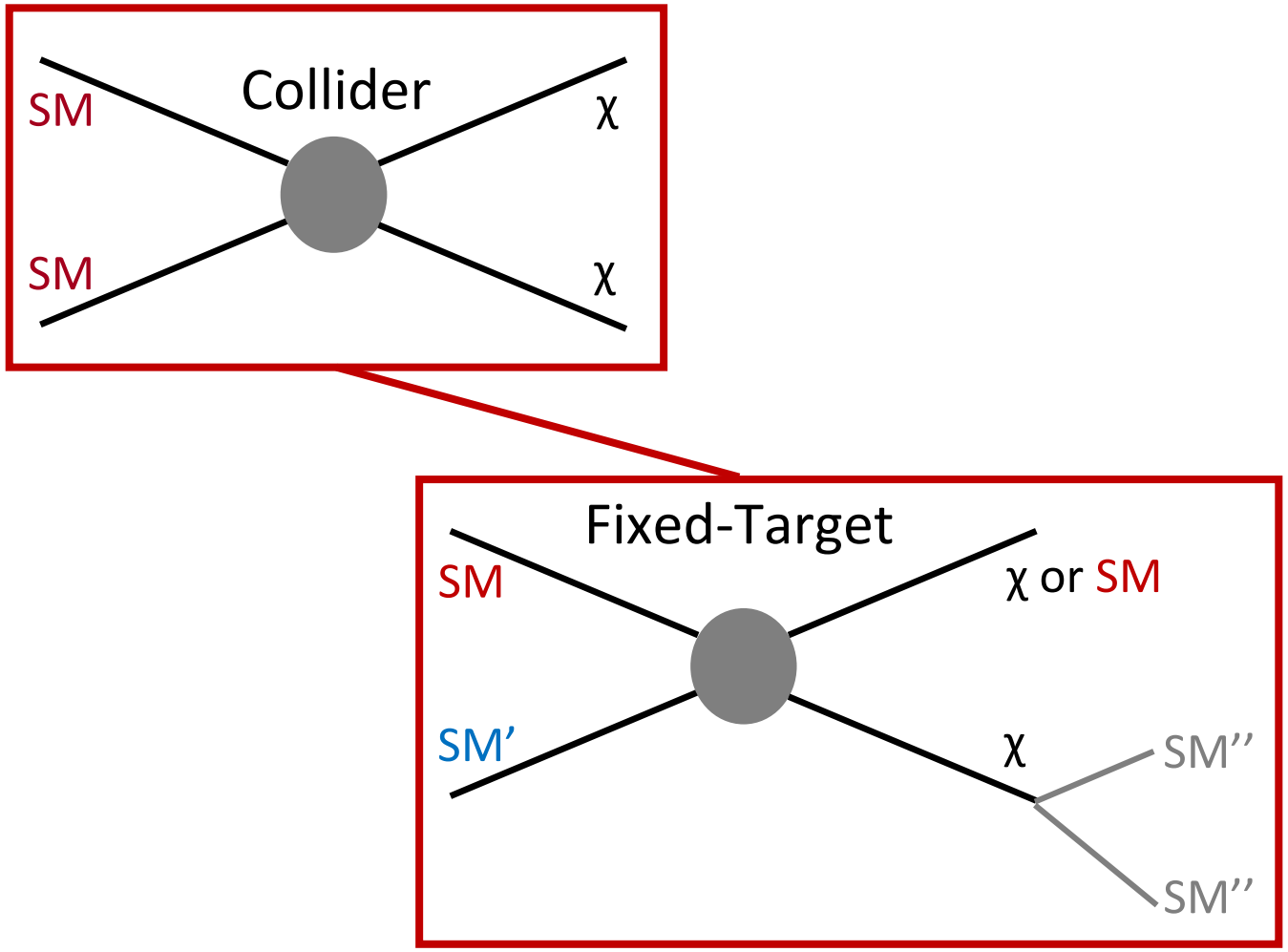


"lepton jets"
+ meson decays

ATLAS
CMS
LHCb

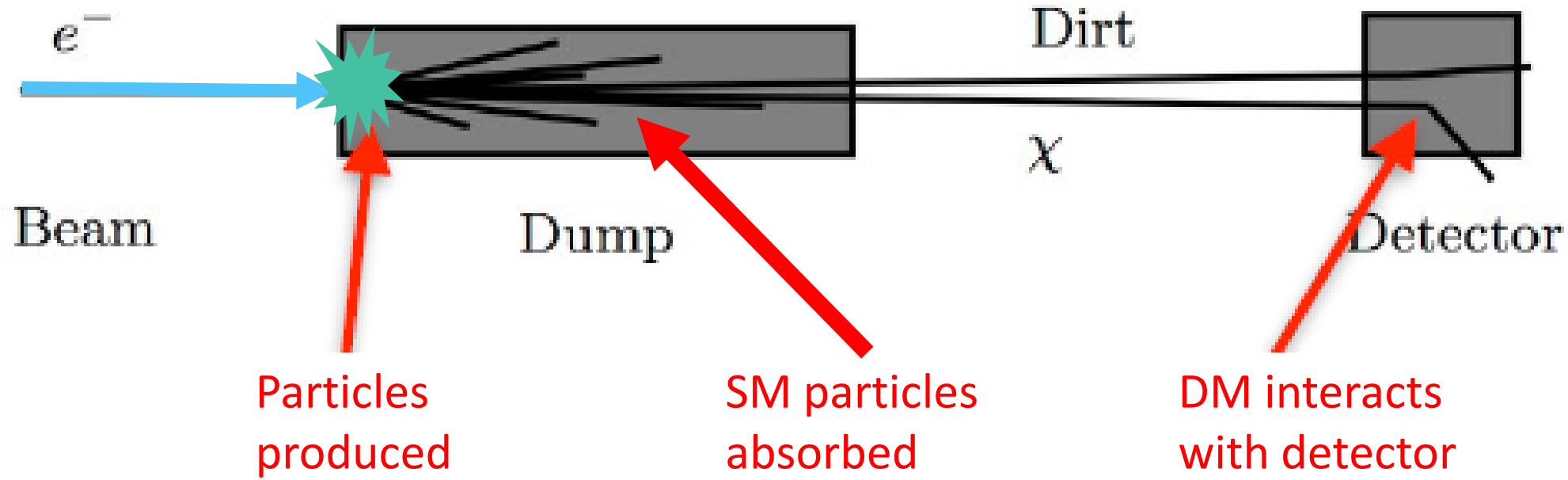


Dark Sector Search Strategies



Dark Sector Search Strategies

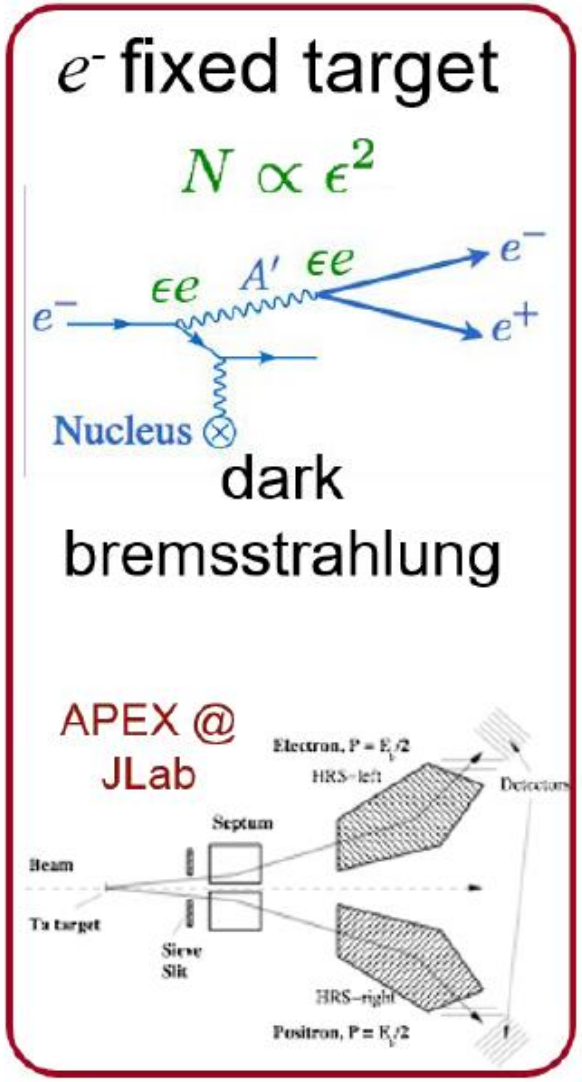
Simplest fixed-target experiment: “beam dump”

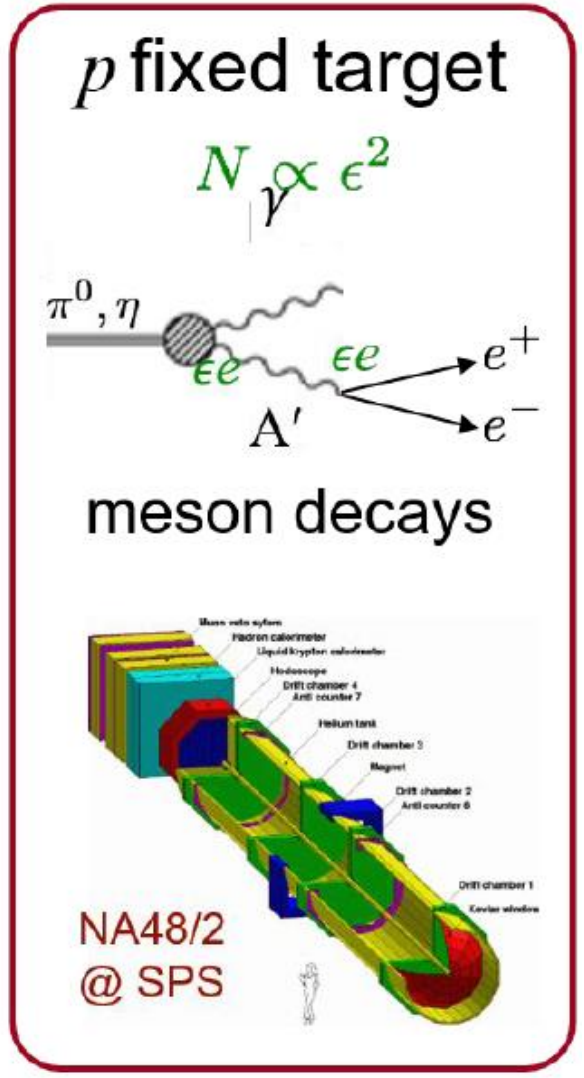


- When particle beam collides with fixed target, DM produced in association with visible SM particles
- Only the DM reaches detector behind “beam dump” and dirt

Dark Photon Search Strategies

- More complex setups target final-state dilepton signatures for *A'* as lowest-mass dark state
- *A'* lifetime varies with mass and ε

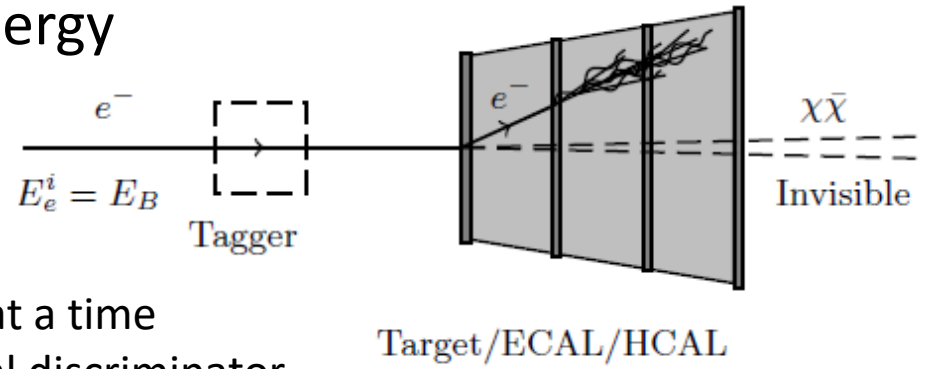




Dark Photon Search Strategies

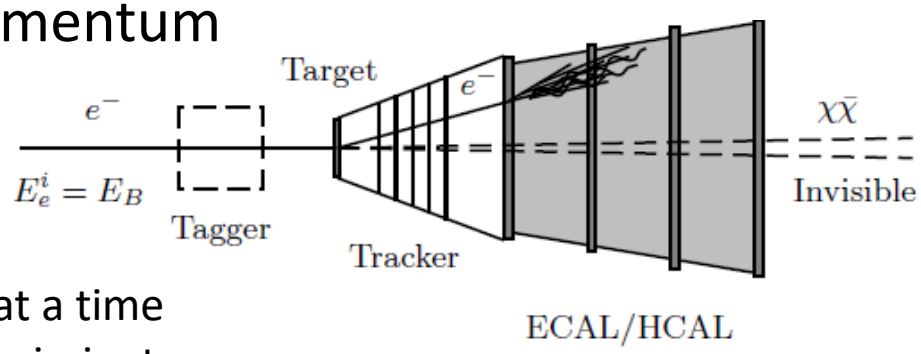
Even more sophisticated: also look for signatures of invisible A' decay products in final state, where other dark sector particles are lighter than A'

Missing Energy



One electron at a time
Only one signal discriminator
Insensitive to nature of interactions
Challenging backgrounds

Missing Momentum



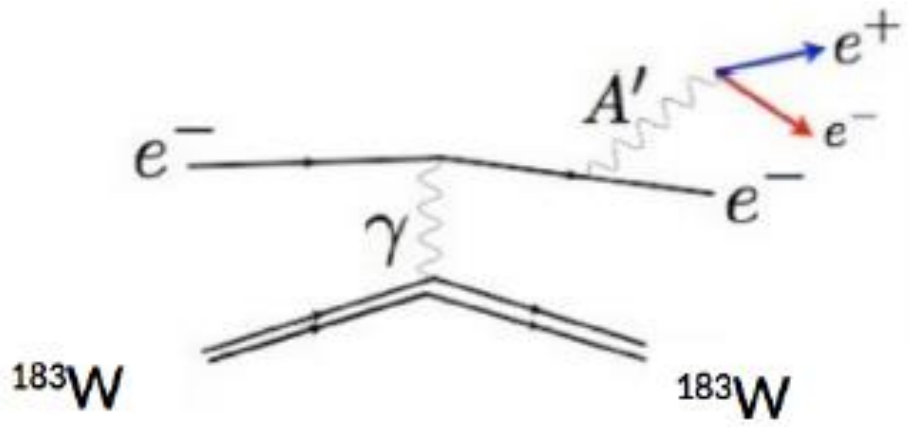
One electron at a time
Two signal discriminators
Sensitive to *A'* mass
"Zero-background"

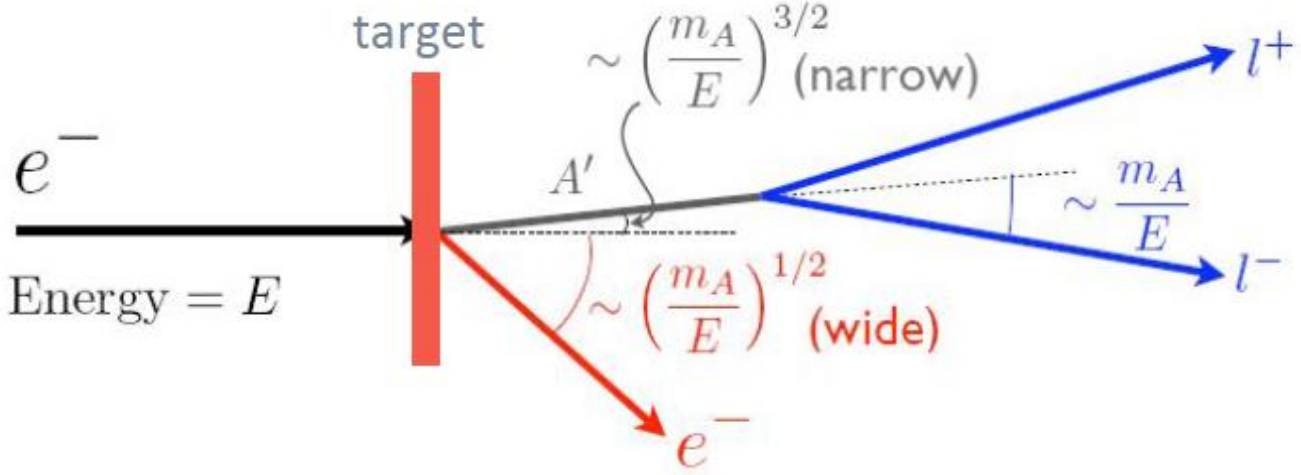
Heavy Photon Search Concept

arXiv:1505.02025

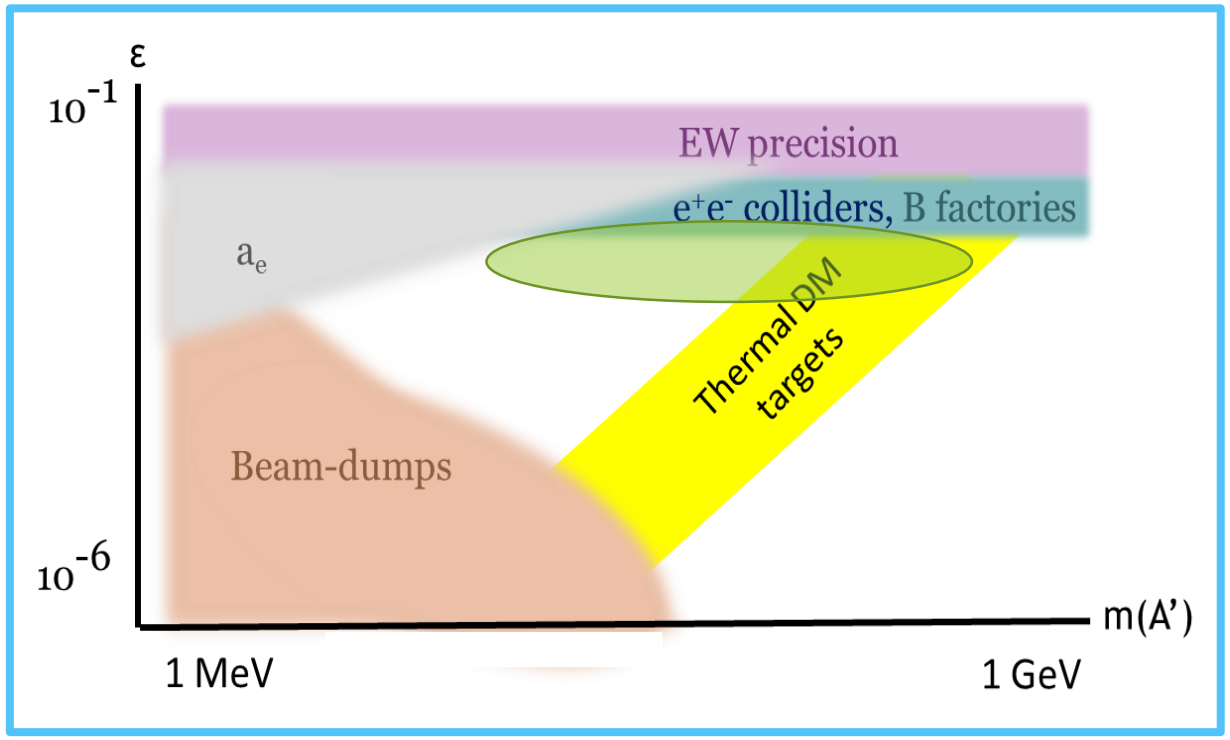
- *A'* takes most of beam energy
- e^+e^- opening angle ~ $m_{A'} / E_{beam}$

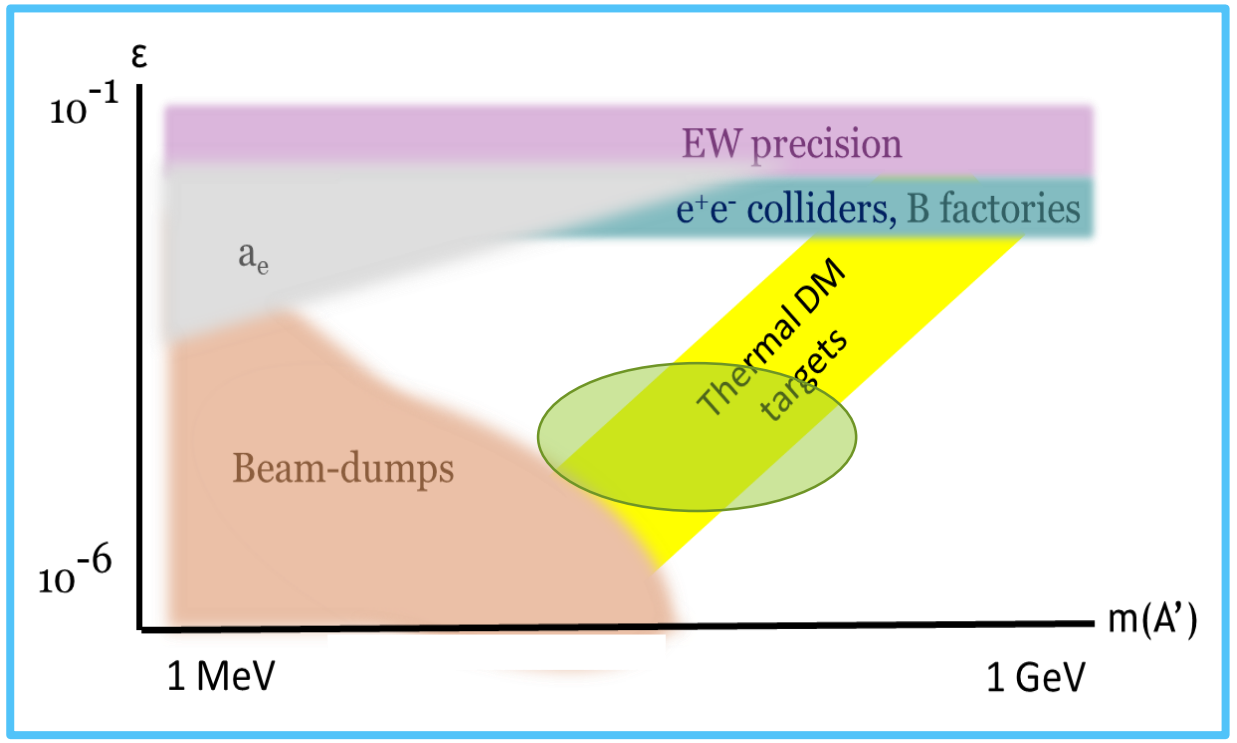
- Keys:
  - High intensity (luminosity)
  - Beam: use timing for background mitigation
  - Thin target: minimize scattering
  - Vacuum: eliminate secondaries
  - Magnetic field: spread e^+e^- pairs
  - Tracker: narrow displaced vertices
  - Electromagnetic Calorimeter: fast, high-rate e^+e^- triggering





HPS Concept





Resonance Search

- Prompt *A'*
- Excess in $m(e^+e^-)$ above large QED bg

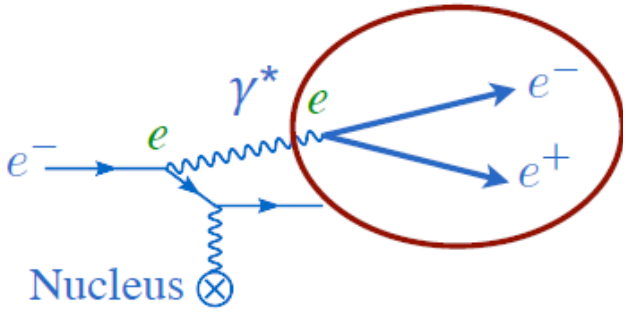
Displaced Vertex Search

- Longer-lived *A'*
- Lower background, smaller signal

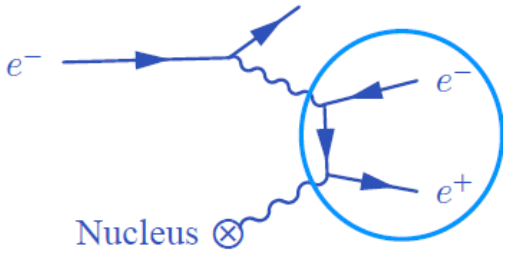
HPS Concept

Backgrounds

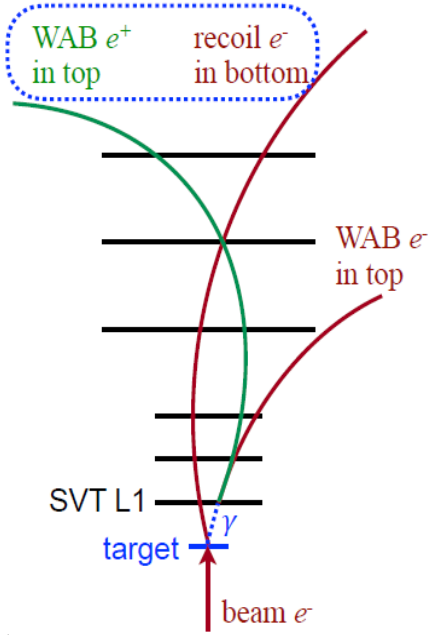
- Radiatives (irreducible)
  - Turn into tool for studying *A'* rates



- Bethe-Heitler Tridents
  - Reduce using kinematic cuts



- Wide-Angle Brem
  - Reduce using kinematic and tracking cuts



- Beam Background (Accidentals)
  - Reduce using timing and goodness-of-fit cuts

HPS Experimental Setup

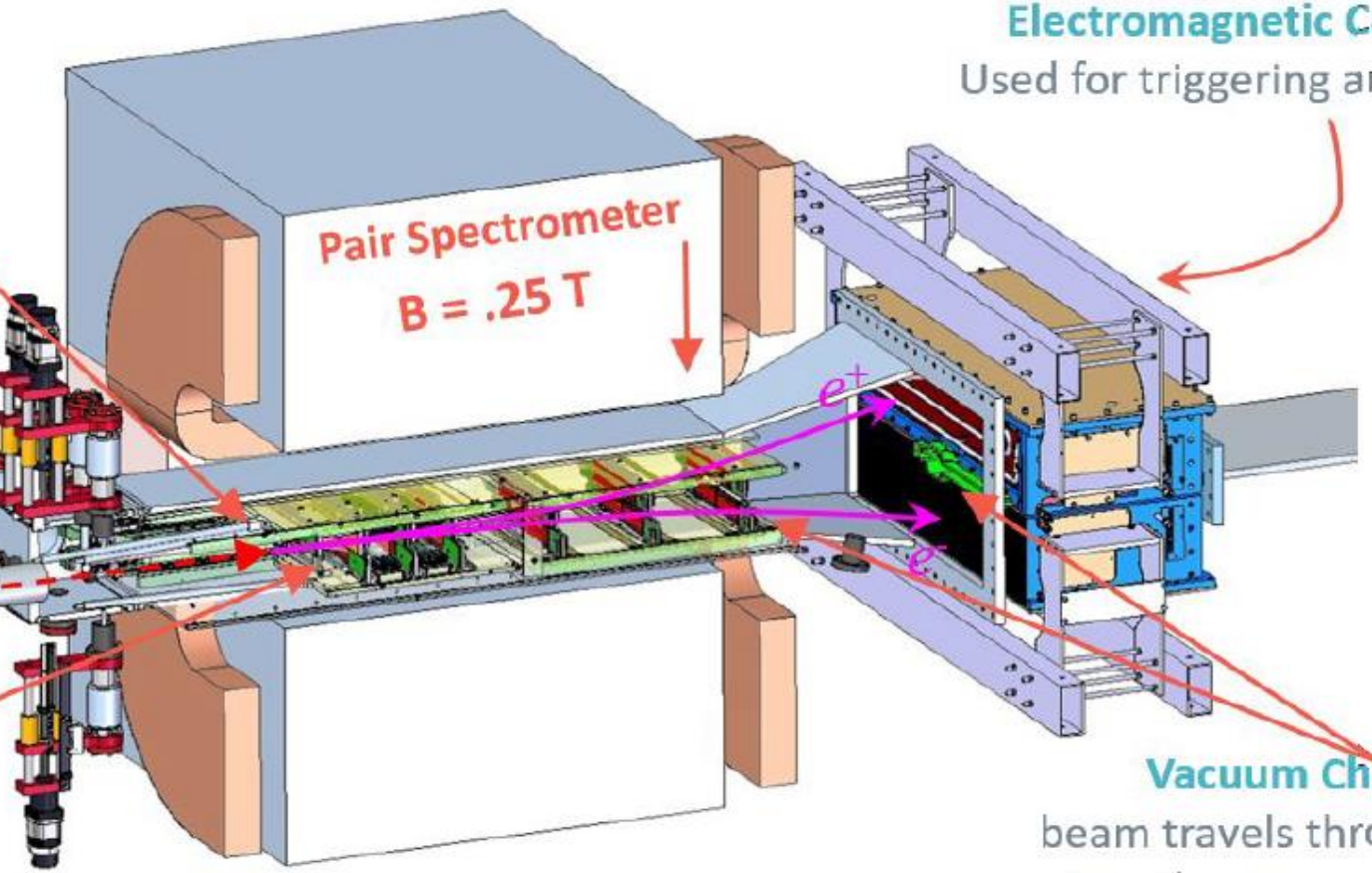
NIM publications
arXiv: 1406.6115
arXiv: 1610.04319
arXiv: 1612.07821

~10^{-3} X_0 Tungsten Target
Thin target to reduce multiple scattering

Linear Shift Motion System
Allows adjustment of deadzone between SVT volumes

High intesity e^- beam
Courtesy of CEBAF @ JLab

Silicon Vertex Tracker (SVT)
Split into two volumes to avoid intense flux of scattered beam electrons. Measures momentum and vertex precisely.



Electromagnetic Calorimeter
Used for triggering and particle ID

Vacuum Chambers
beam travels through vacuum in order to avoid beam-gas interactions

SVT + ECal DAQ capable of 50 kHz

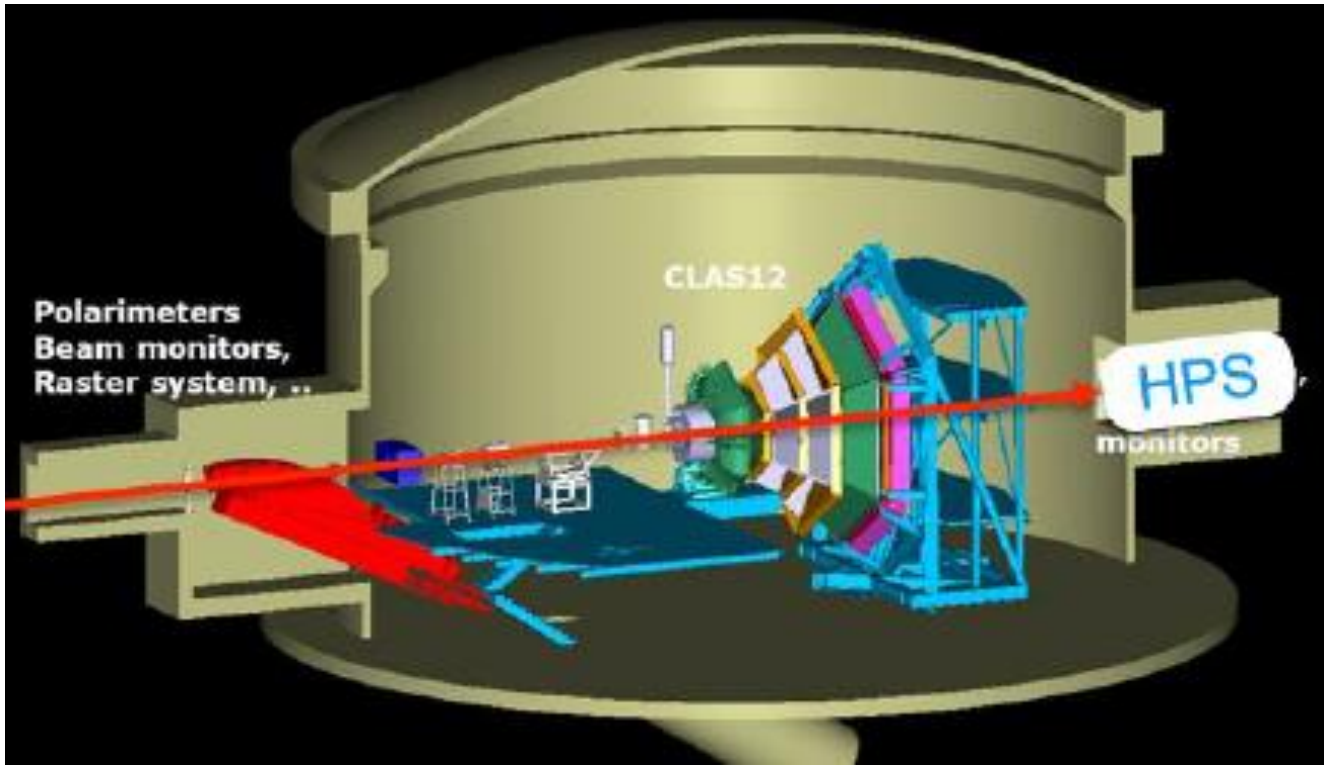
Installed within the Hall B alcove at Jefferson Lab downstream of the CLAS12 detector

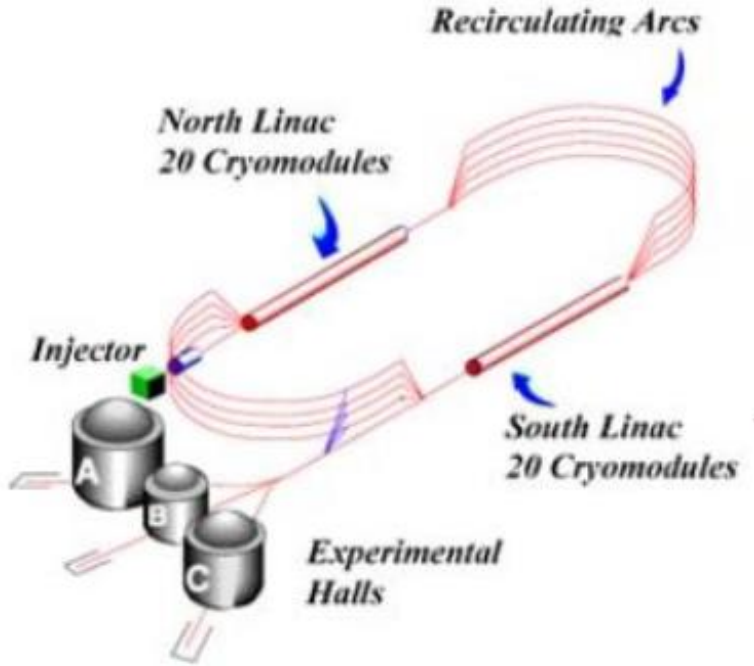
HPS Experimental Setup

arXiv:1612.07821

Beam

- Continuous Electron Beam Accelerator Facility @ JLAB
- HPS runs parasitically in Hall B
- 2 ns bunch pulse
- σ_x ~100 - 500 μm, σ_y < 50 μm



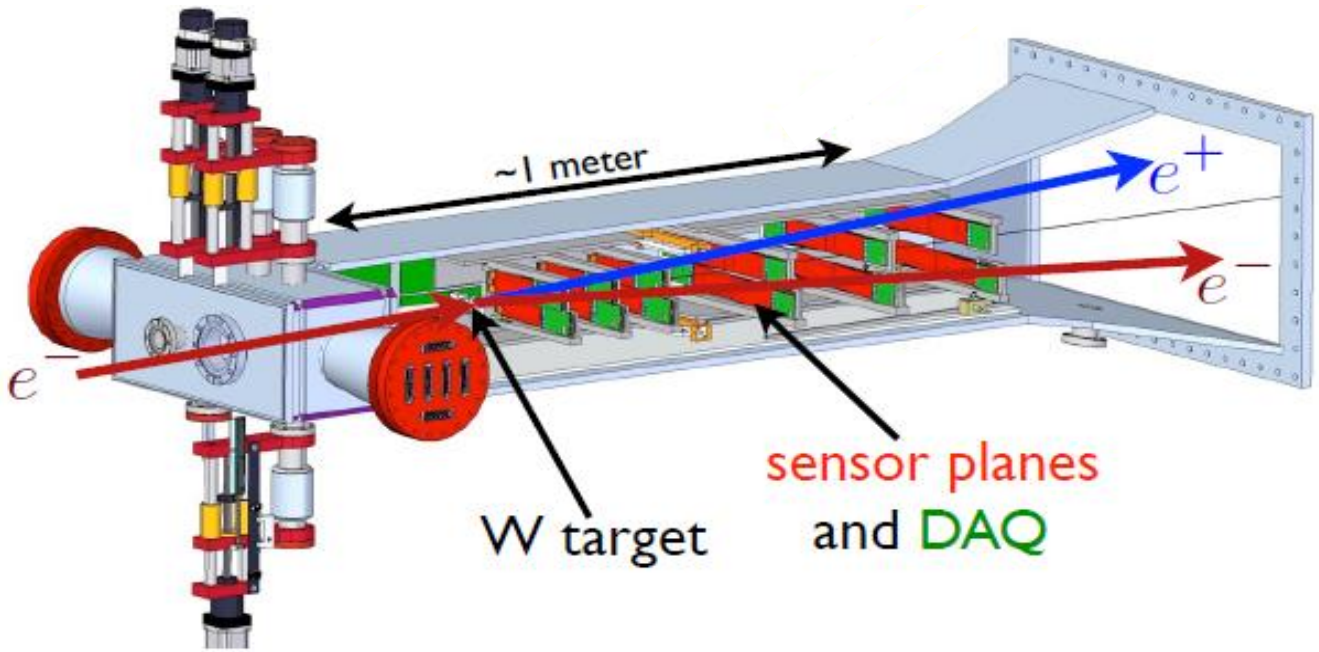


HPS Experimental Setup

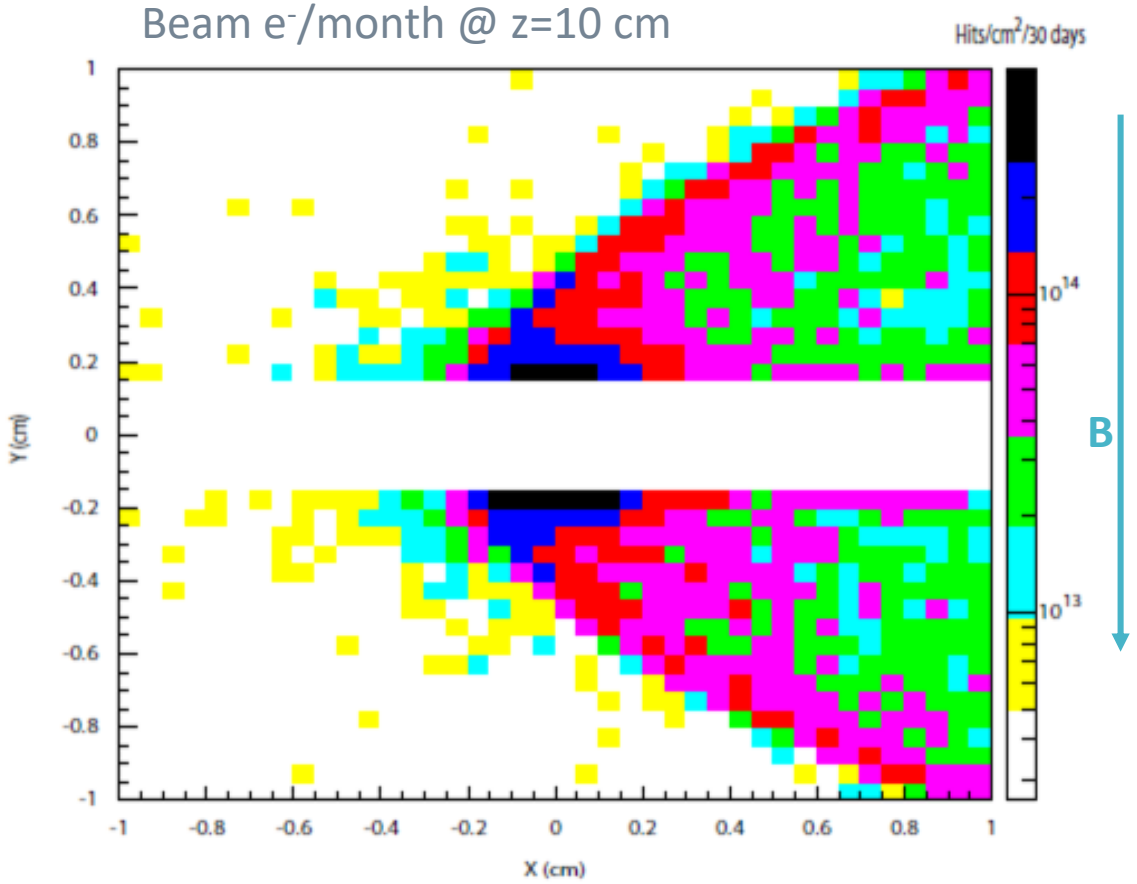
Silicon Vertex Tracker (SVT)

- 6 layers of axial/stereo strips
- Segmented top/bottom
- 180 APV25 chips, 23004 channels
  - Radiation tolerant, low-noise (S/N>25)
  - 40 MHz readout, 2 ns resolution

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)	± 1.5	± 3.0	± 4.5	± 7.5	± 10.5	± 13.5
Material budget	.7%	.7%	.7%	.7%	.7%	.7%



Beam e^-/month @ z=10 cm

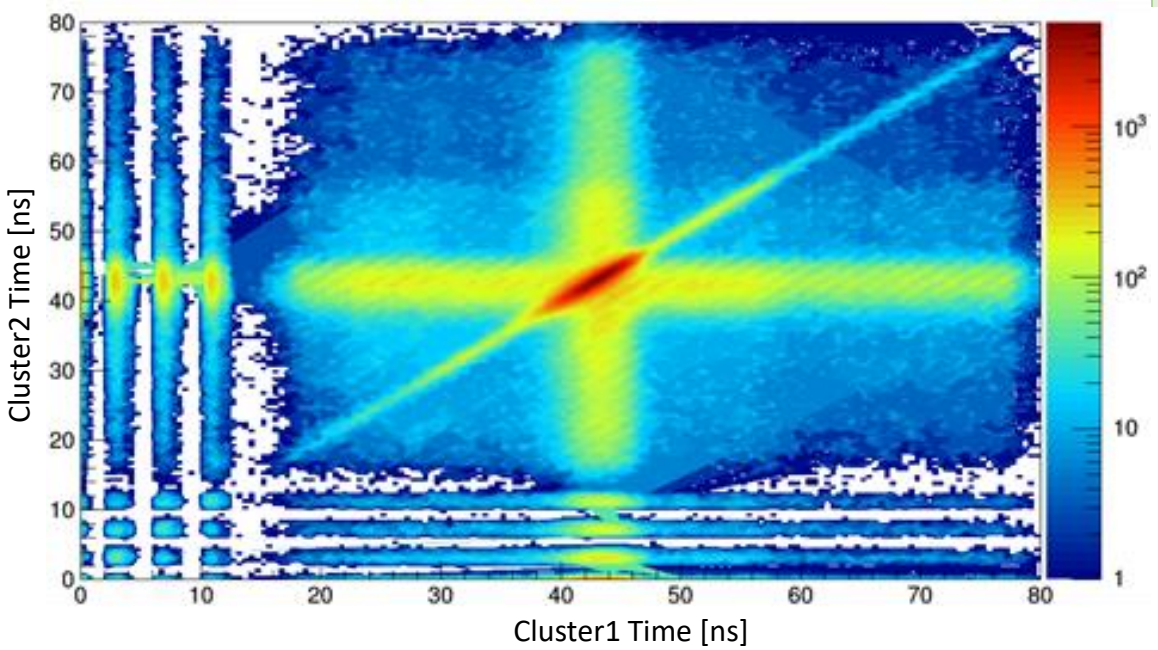


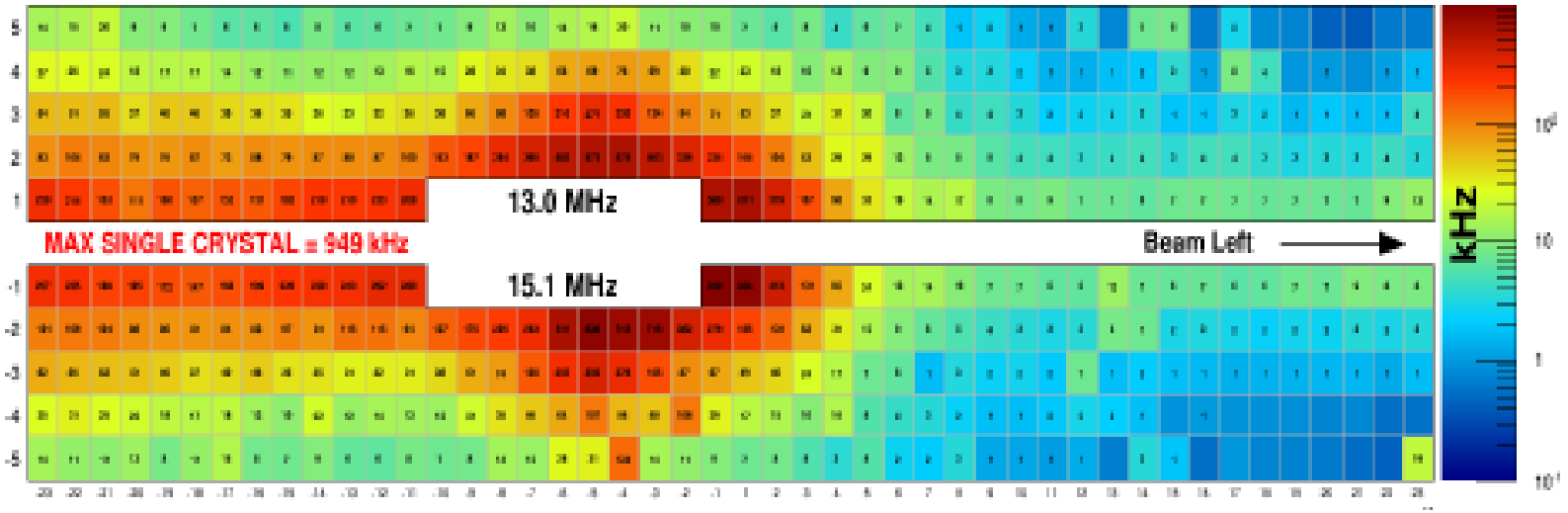
HPS Experimental Setup: ECal

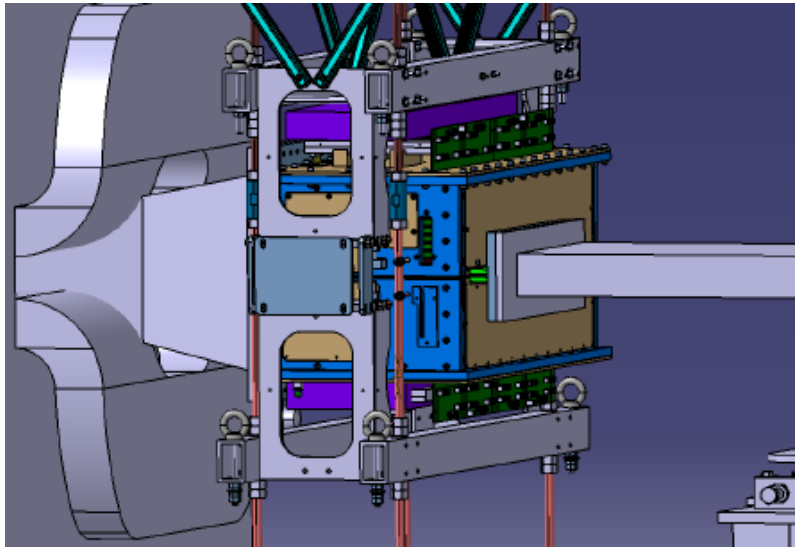
ECal

arXiv:1610.04319

- 442 $PbWO_4$ crystals in 5 layers
- Crystals coupled to avalanche photodiode readout
- Max energy deposition: ~4 GeV / crystal
- Time resolution allows for ns cluster coincidence



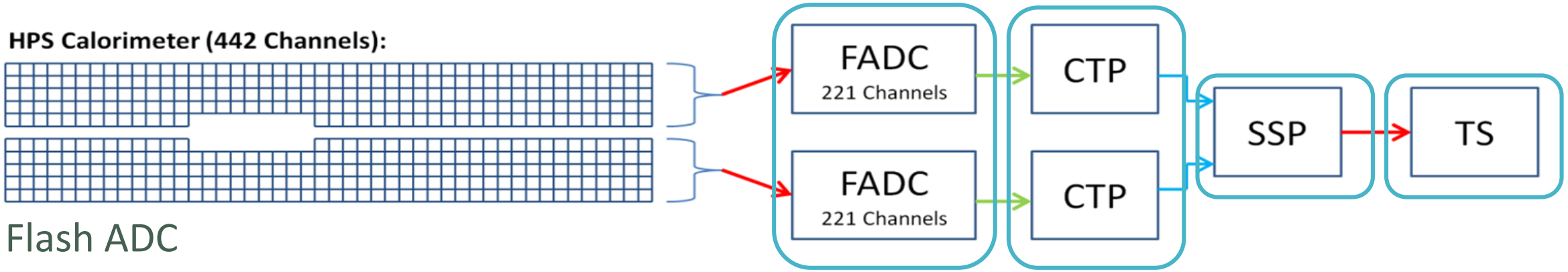




HPS Experimental Setup

Trigger

- Goal: two ECal clusters consistent with e^+e^- from A' decay

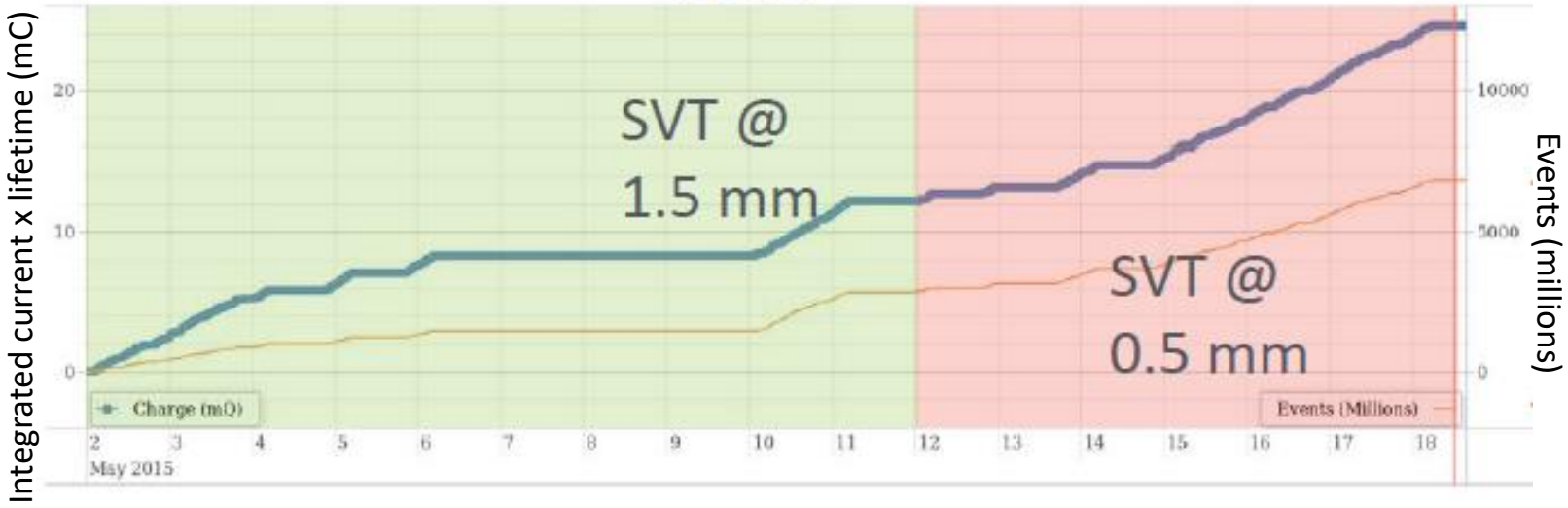


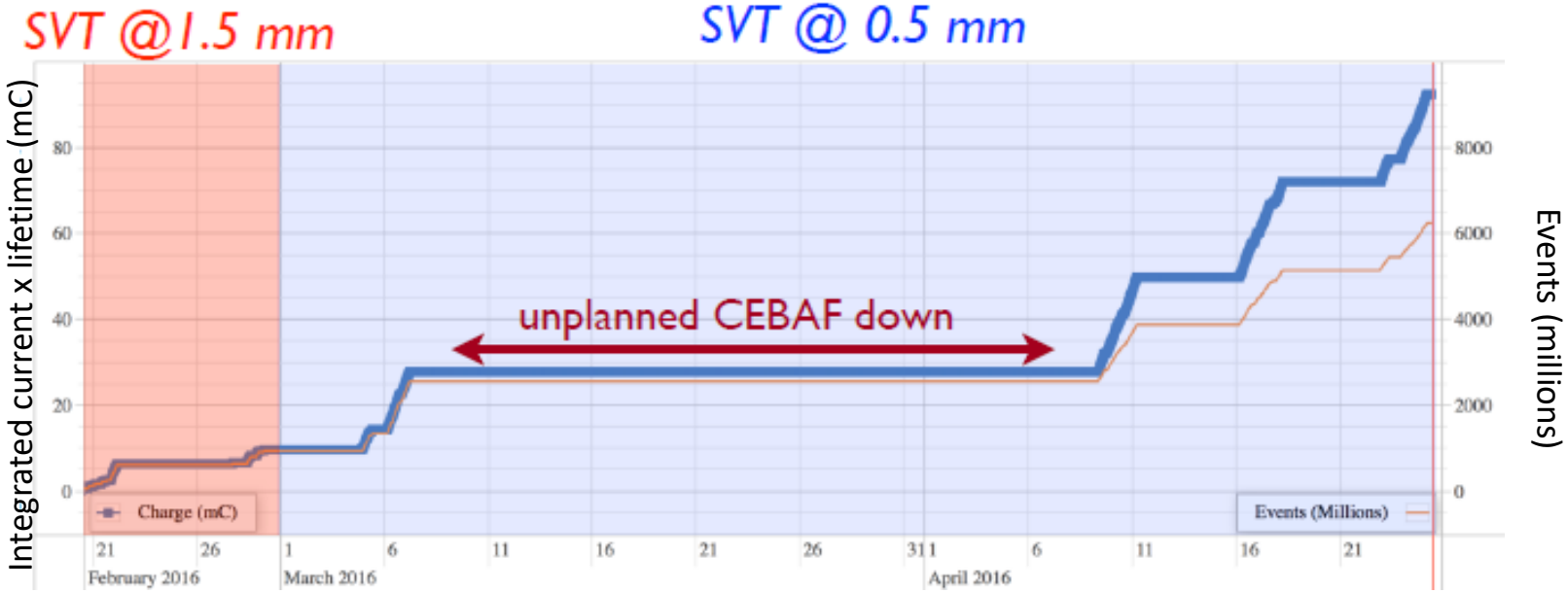
- Flash ADC
  - 250 MHz crystal sampling
  - For signal > threshold: integrates amplitude, sends crossing time
- Crate Trigger Processor
  - Cluster-finding in every 3x3 array of crystals
  - For isolated cluster-sum > threshold: reports amplitude, position, time
- Sub-System Processor
  - Searches for pairs in 8 ns window
  - Topological selection
- Trigger Supervisor
  - Generates trigger signal

HPS Engineering Runs

- **Two SVT configurations:** active edge at 1.5 mm and 0.5 mm from beam plane

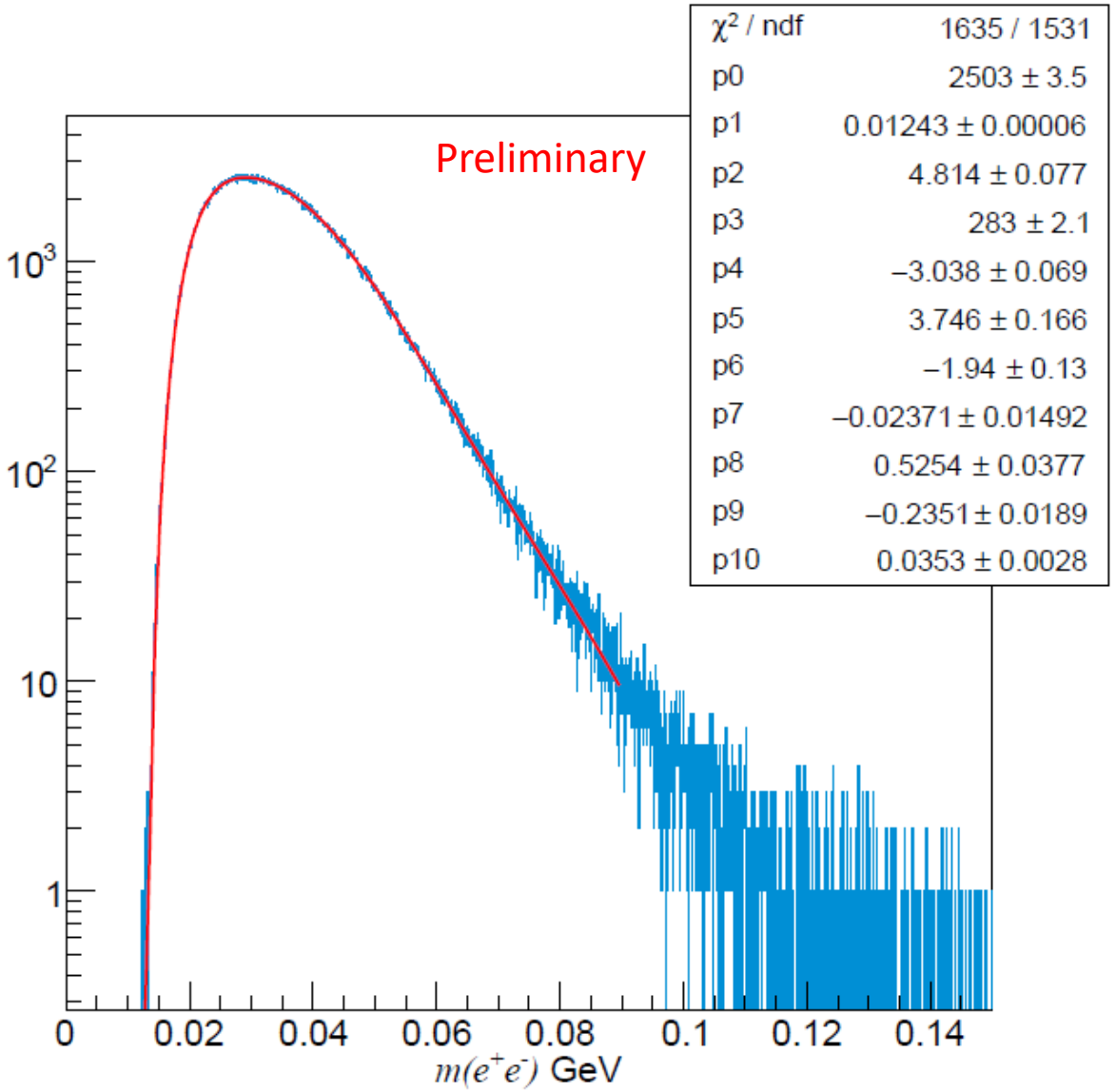
- **May 2015:**
  - 50 nA, 1.056 GeV e^- beam
  - 10 mC in each config
- **Spring 2016:**
  - 200 nA, 2.3 GeV e^- beam
  - 92.5 mC in 0.5 mm config





HPS Resonance Search

arXiv:1807.11530

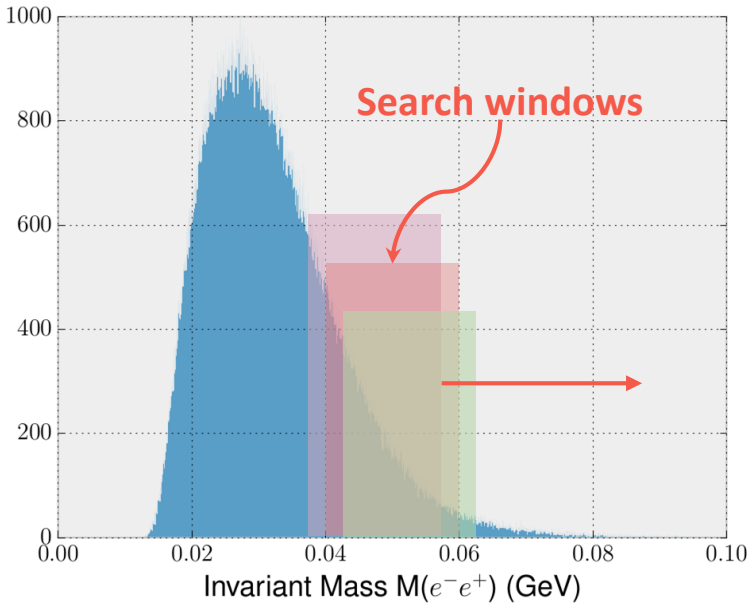


- Search for Gaussian signal ϕ:

  mean = $m_{A'}$, width = experimental mass resolution $\sigma_{m_{A'}}$

  $$P(m_{e^+e^-}) = \mu \cdot \phi(m_{e^+e^-}|m_{A'}, \sigma_{m_{A'}}) + B \cdot p(m_{e^+e^-}|\mathbf{t})$$

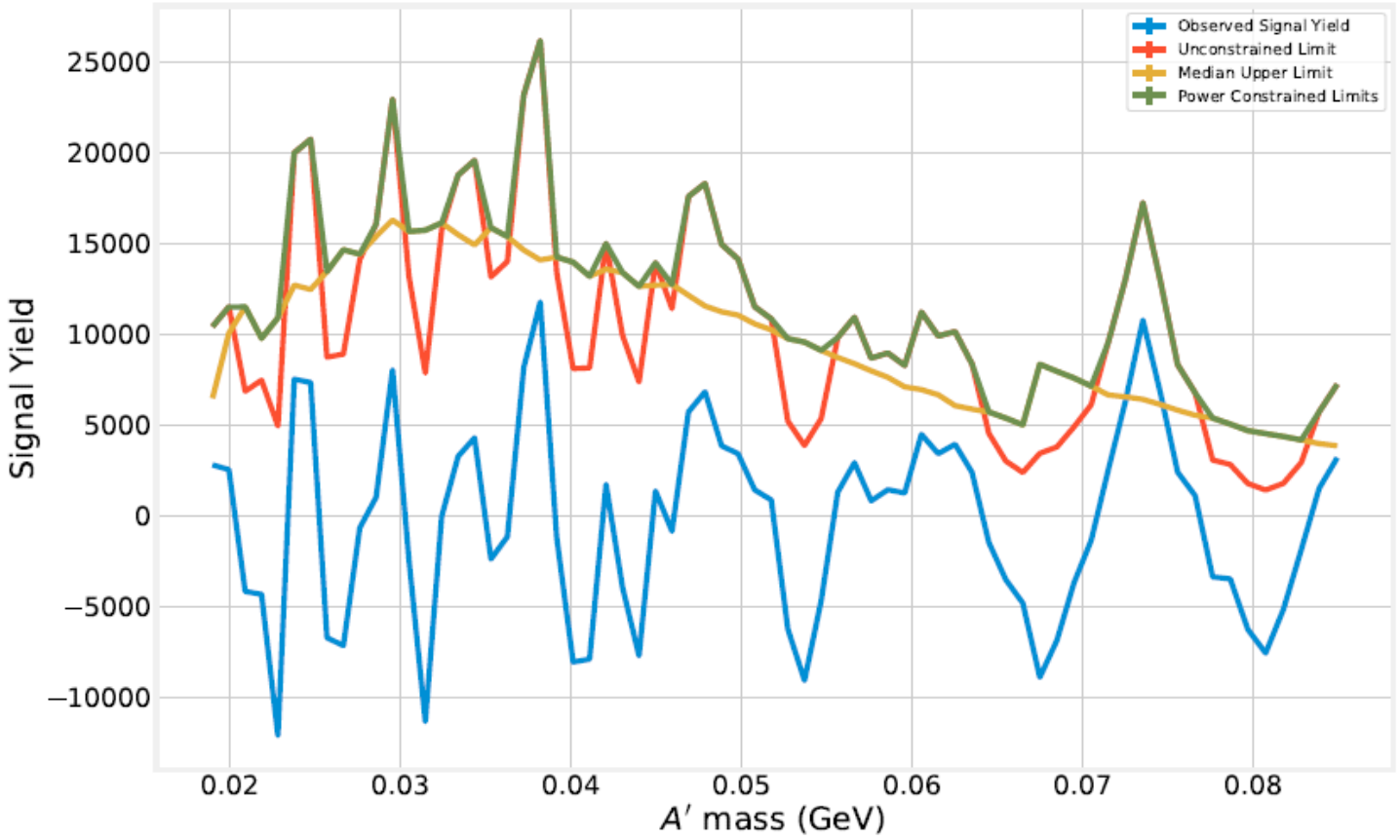
  - B: #background events in window around hypothesized $m_{A'}$
  - p: background distribution (exponential x polynomial)
- Binned maximum likelihood fit

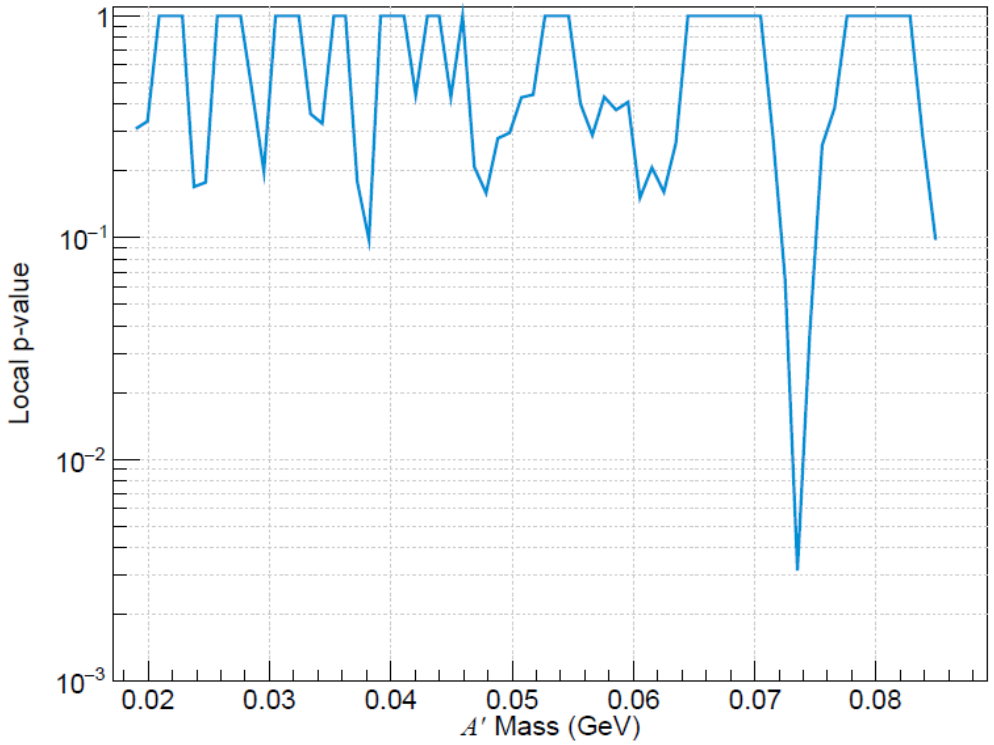


- Look Elsewhere Effect for scanning over many mass windows
- Used 10% of dataset to test fit procedures & parameters before unblinding

HPS Resonance Search

Signal upper limits:





Most significant mass point: 73.5 MeV (local *p*-value 0.0032, global 0.1)

No significant signal found

HPS Resonance Search

A’ Upper Limits:

- Observed # radiative QED events related to expected # *A’* events

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

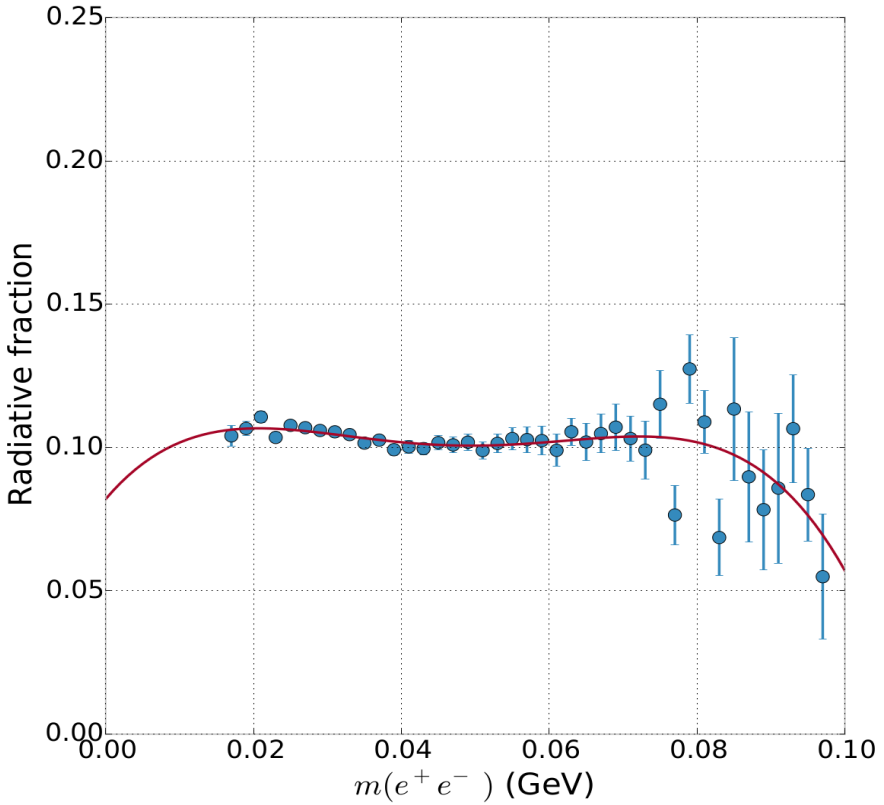
- Transform signal upper limit to ε upper limit:

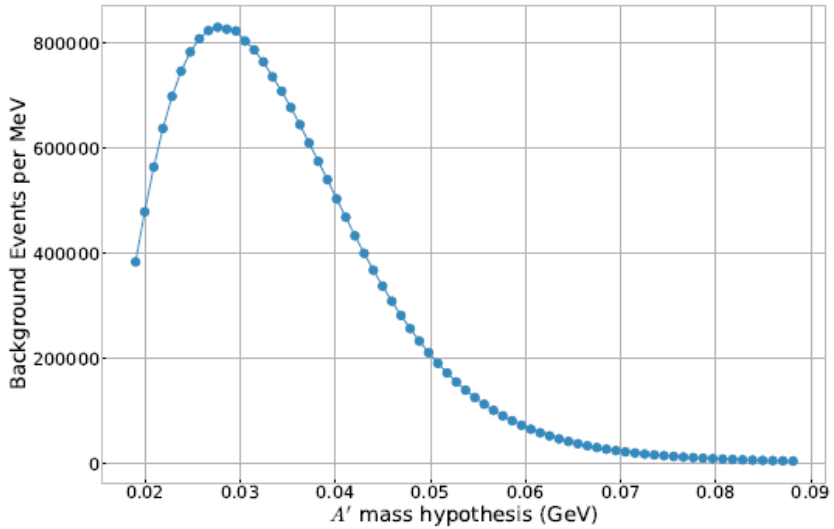
$$\epsilon^2 = \left(\frac{S_{\text{up}}/m_{A'}}{f\Delta B/\Delta m}\right)\left(\frac{2N_{eff}\alpha}{3\pi}\right)$$

where

$$f_{rad} = \frac{N_{rad}}{N_{tri} + N_{cWAB}} = \frac{\frac{N_{rad}}{N_{tri}}}{1 + \frac{N_{cWAB}}{N_{tri}}}$$

  - *N* ratios taken from MC
  - $\Delta B/\Delta m$ from integrating $m(e^+e^-)$ spectrum in $2.5\sigma_{mA'}$ window around hypothesized $m_{A'}$



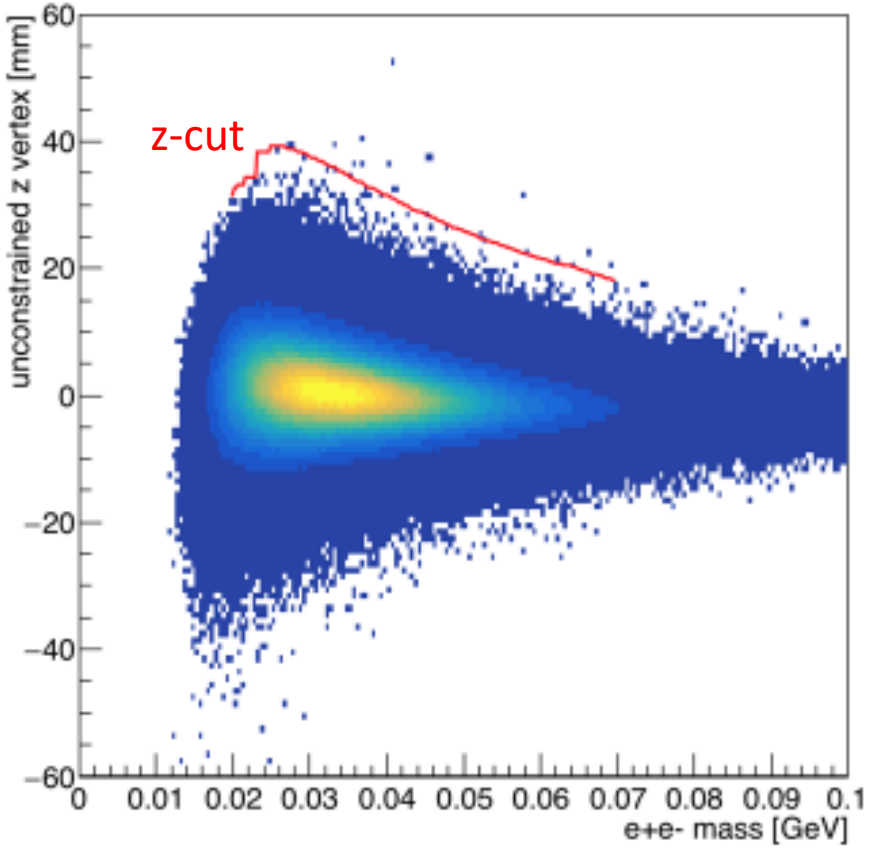


HPS Displaced Vertex Search

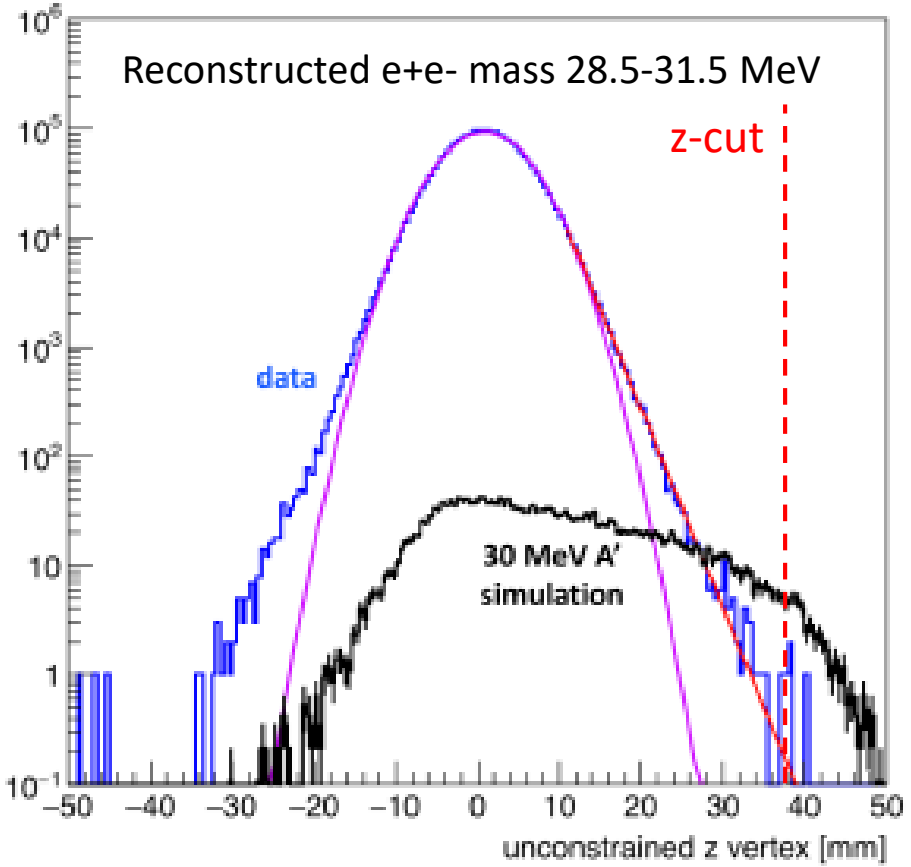
PoS(ICHEP2018)076

- Search for events with reconstructed vertex several mm downstream of target ("past z-cut")
- Calculate signal distribution past z-cut that would be expected from A' of a given mass
  - Repeat for various A' masses

Data



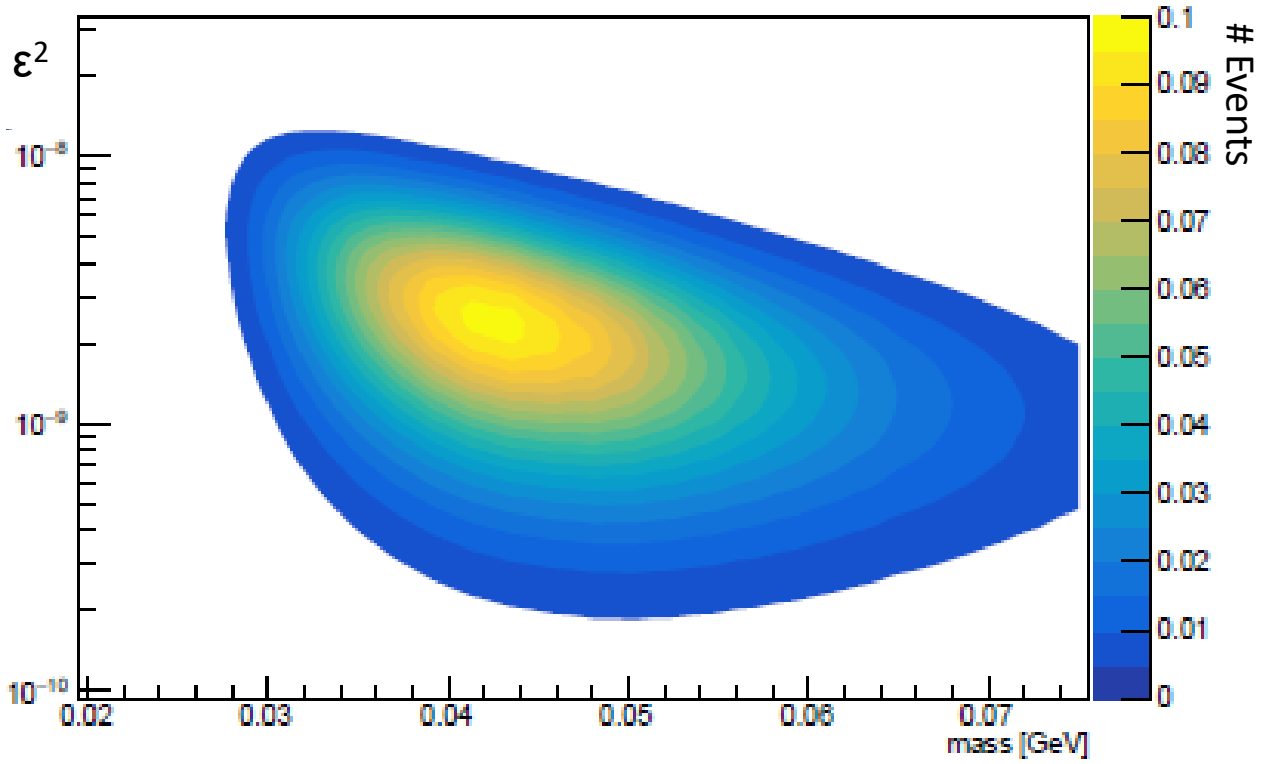
Simulated Signal



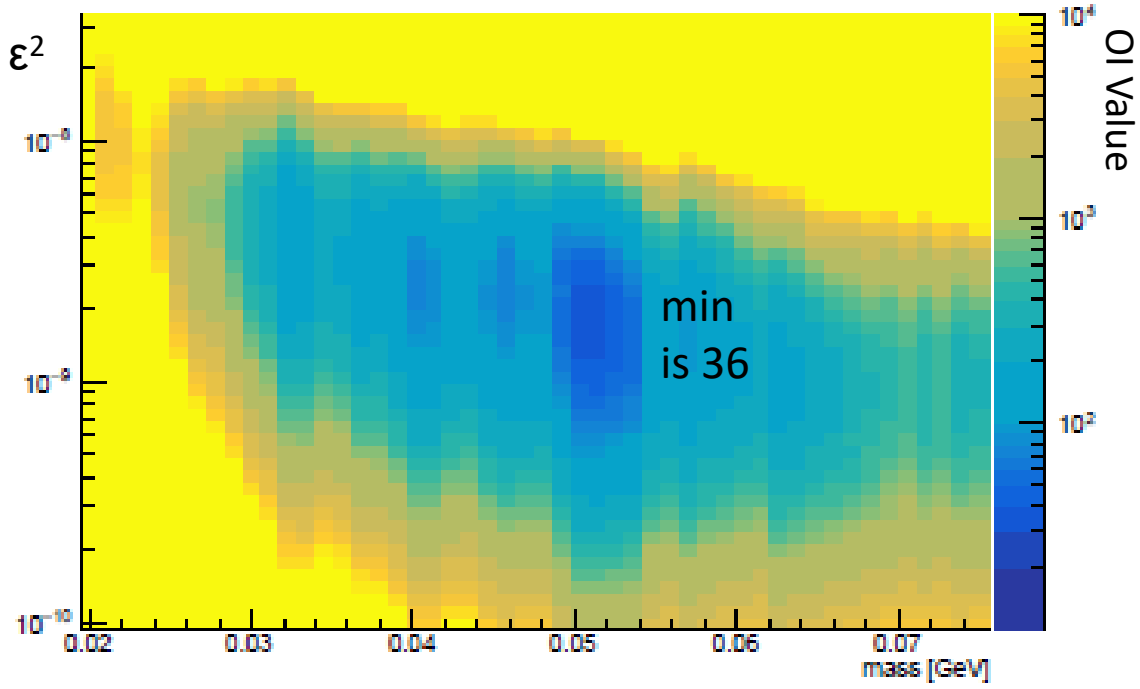
HPS Displaced Vertex Search

- Optimum Interval Method: for limit-setting with small signals of known shape, but unknown backgrounds
  - OI Value below 1 would indicate: excluded with 90% confidence
  - No 90% exclusion limit achieved with 2015 run – just proof-of-concept

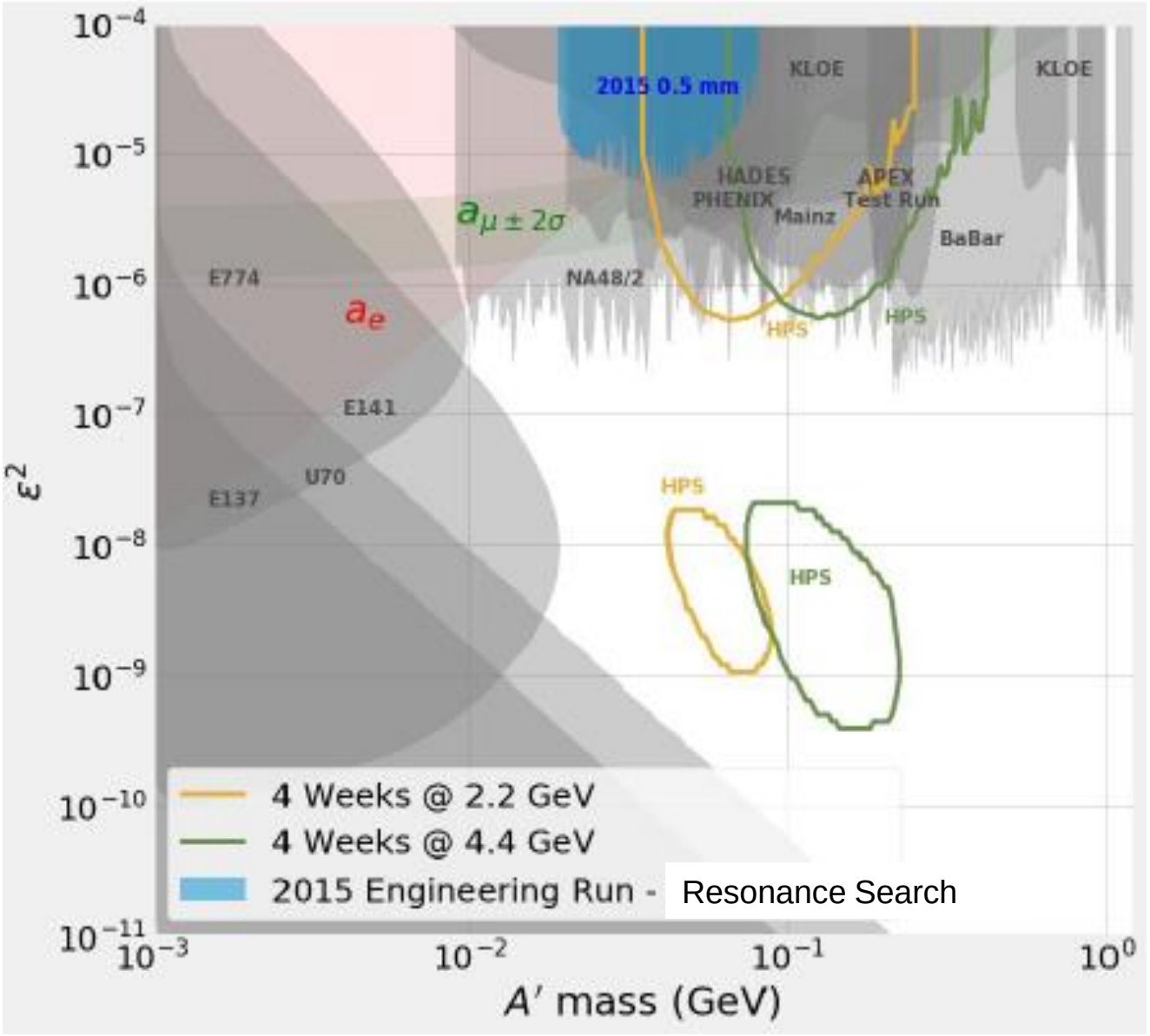
Expected A' Events Detected Past z-cut



Optimum Interval Value



HPS Upcoming Physics Run



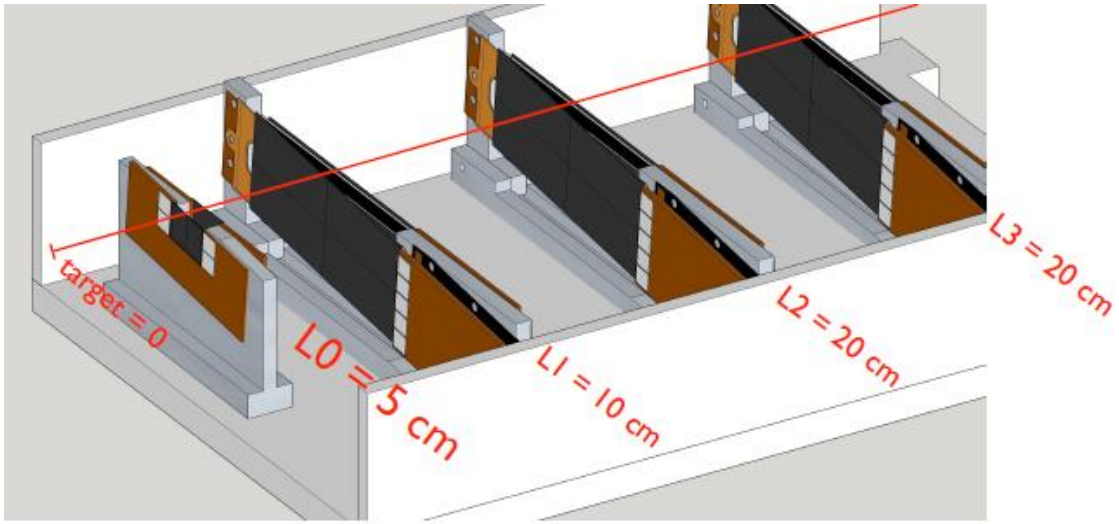
- Proof-of-concept: 2015 data
- Soon to come: analysis with 2016 data included

- Allows us to generate realistic projections of reach for a full run
- 180 more data-taking days (~20x existing datasets) approved by JLab
  - Starting June 2019

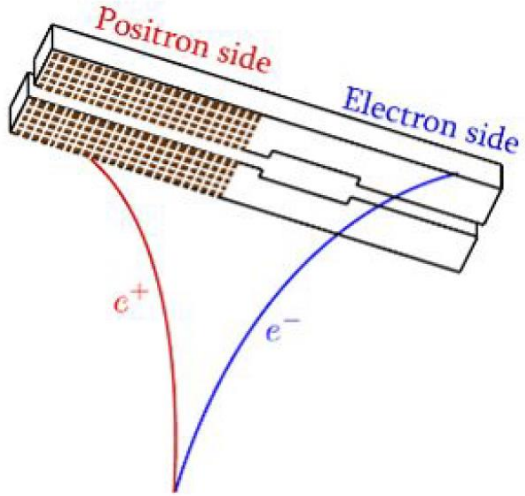
HPS Upcoming Physics Run

Upgrades!

- Install additional layer “L0” in SVT
  - Between target and current Layer 1
  - Will greatly improve vertex resolution
    ☺ **L0 sensors purchased with NSERC PDF $**
- Move SVT Layers 2-3 toward beam
  - Will improve acceptance for longer-lived *A’*



- Add positron hodoscope in front of ECal
  - Implement “positron-only” trigger to improve trigger efficiency
  - Covering x > 90mm catches almost all e^+, with manageable trigger rate (< 4KHz)



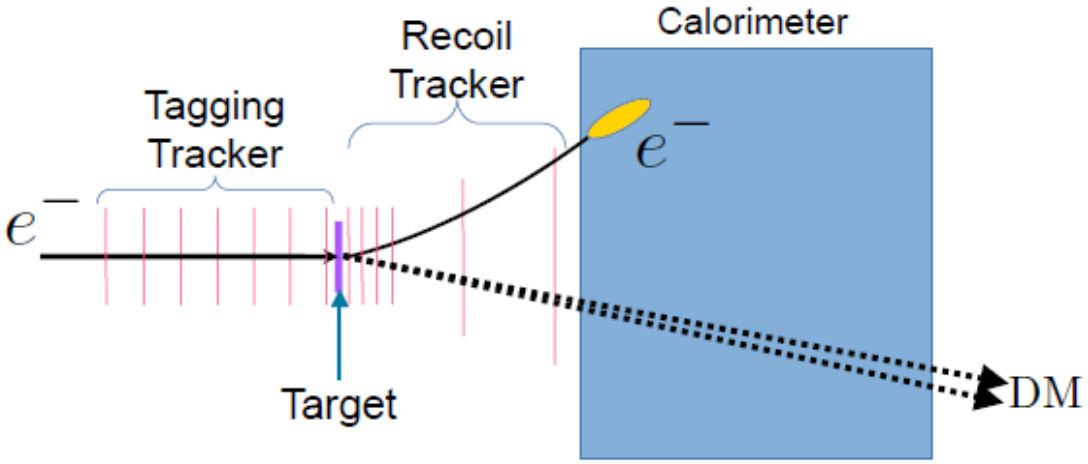
LDMX Concept

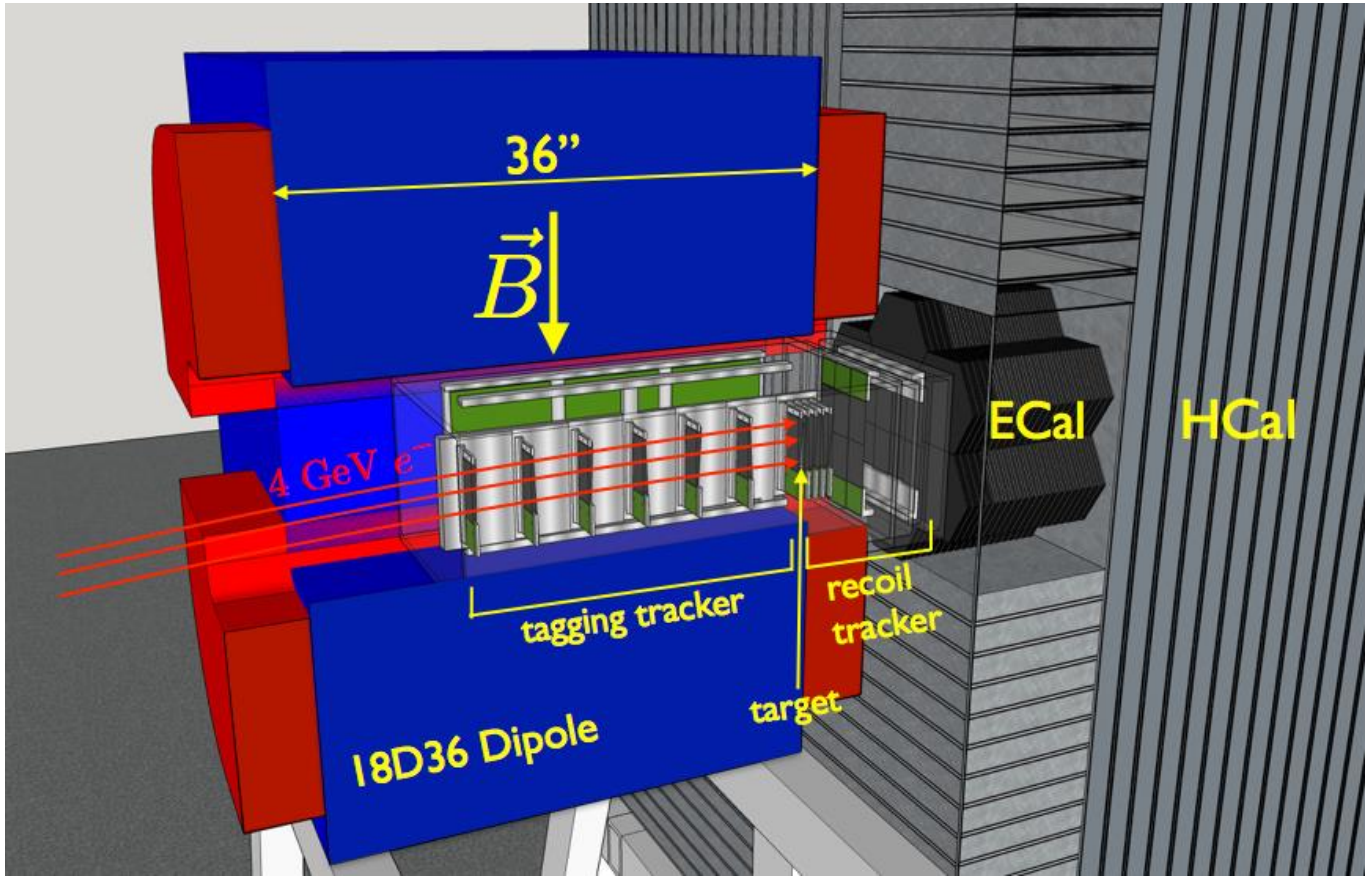
arXiv:1808.05219

So far, have only looked for the visible A' decay products. What about the invisibles?

Light Dark Matter Experiment (LDMX): Proposal for "zero-background" missing momentum experiment

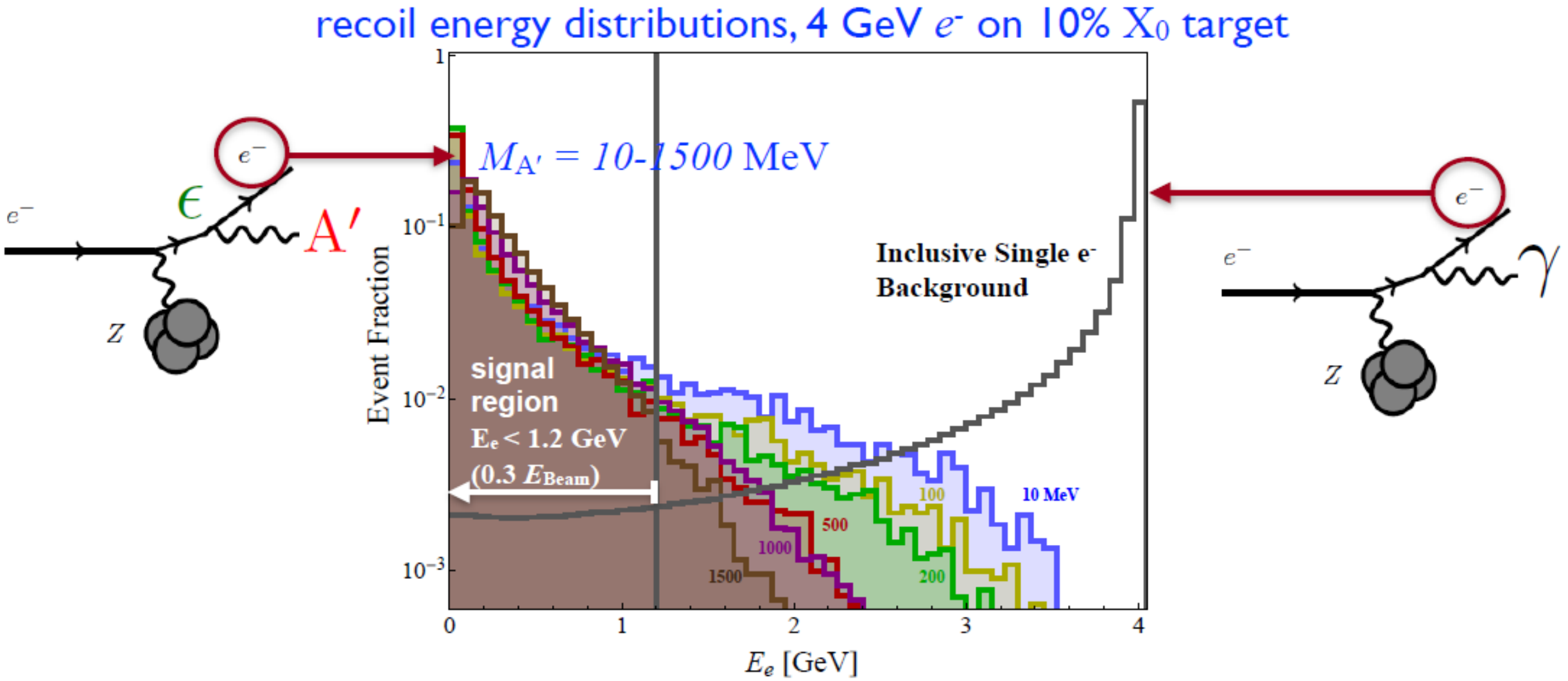
Could be hosted at SLAC, JLab, or CERN





- Tagging tracker: track carrying beam energy, on expected trajectory
- Recoil tracker: single low-momentum track pointing back to tag
- Calorimeter: shower consistent with recoil track and no other activity

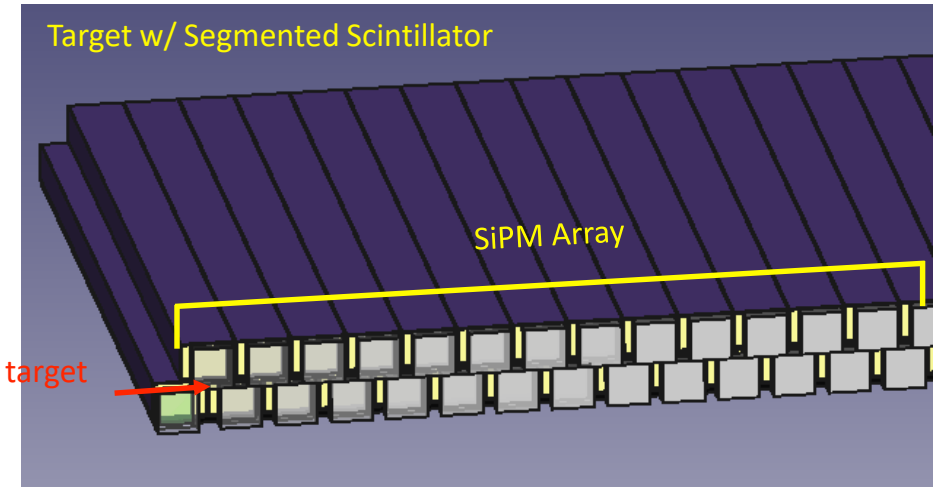
LDMX Concept

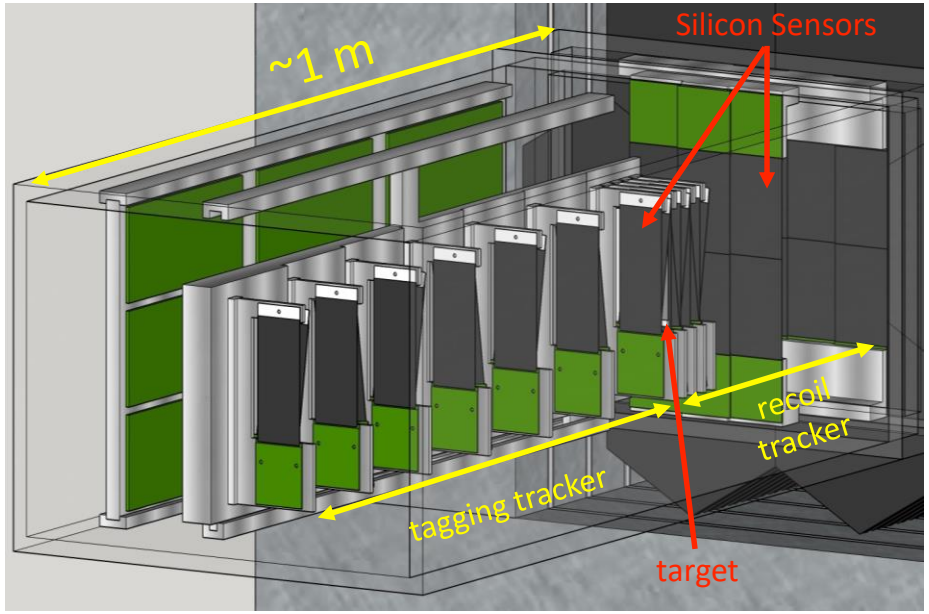


LDMX Experimental Setup

Si Trackers

- Similar to HPS
- Tagging Tracker in central dipole field: robust tag of incoming electrons
- Recoil Tracker in fringe field: measures recoiling electrons with good resolution, large acceptance
- Tungsten target between trackers
- Scintillator counts electrons for trigger

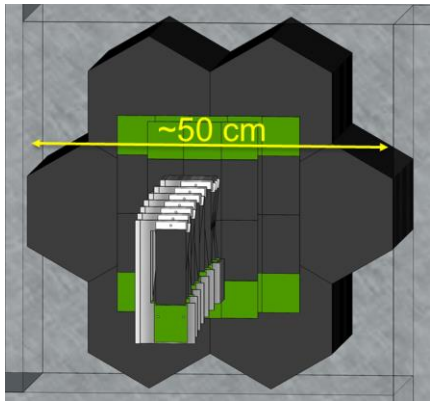


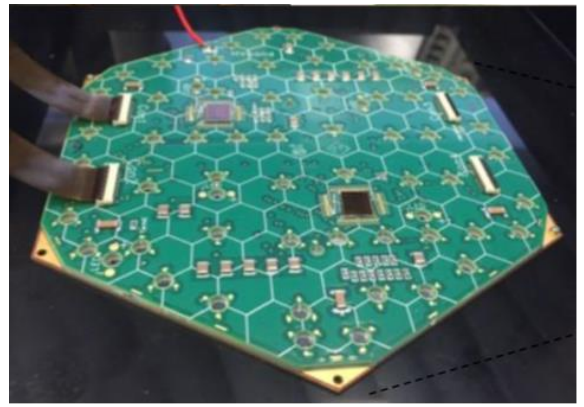


LDMX Experimental Setup

Electromagnetic Calorimeter

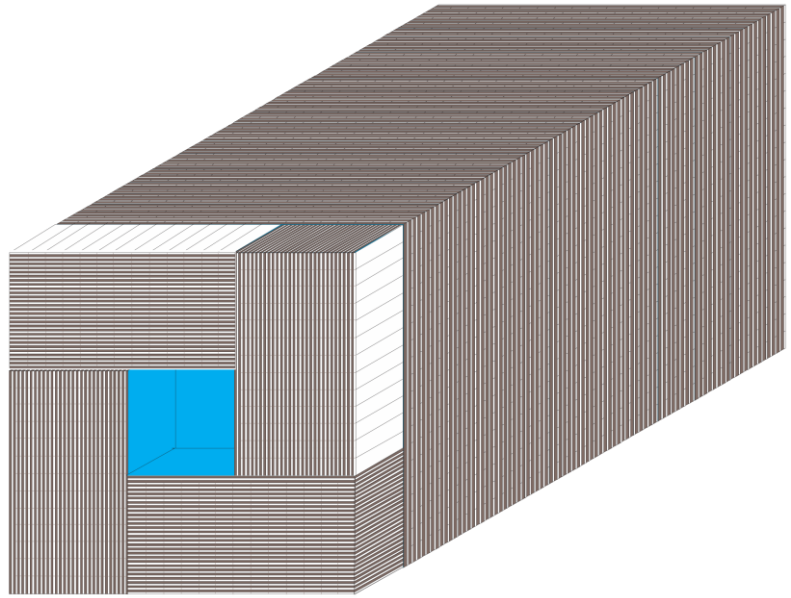
- Si-W, developed for CMS
- Fast, dense, granular for high occupancies
- Very deep for EM containment
- High rate/radiation tolerance
- Fast enough to provide trigger
- Powerful tool for rejection of rare backgrounds





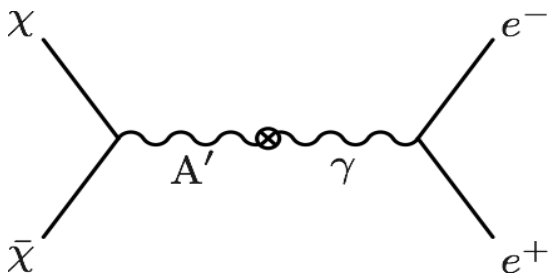
Hadronic Calorimeter

- Steel absorber/plastic scintillator
- Surrounds ECal (required size still being studied)
- Optimized for high multiplicity of soft neutral hadrons from photonuclear events
- Catches rare wide-angle bremsstrahlung events



LDMX Projected Reach

Parameterize in terms of y:

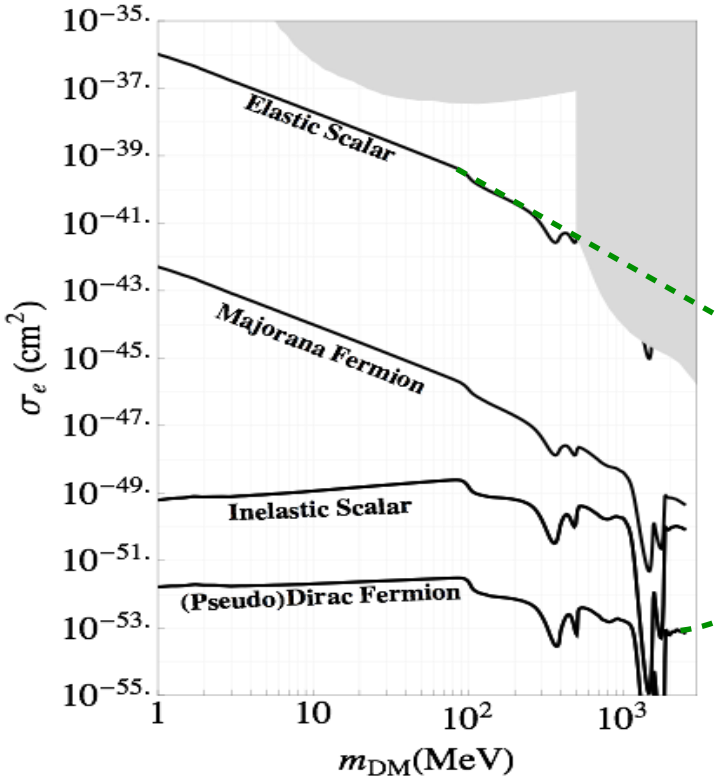


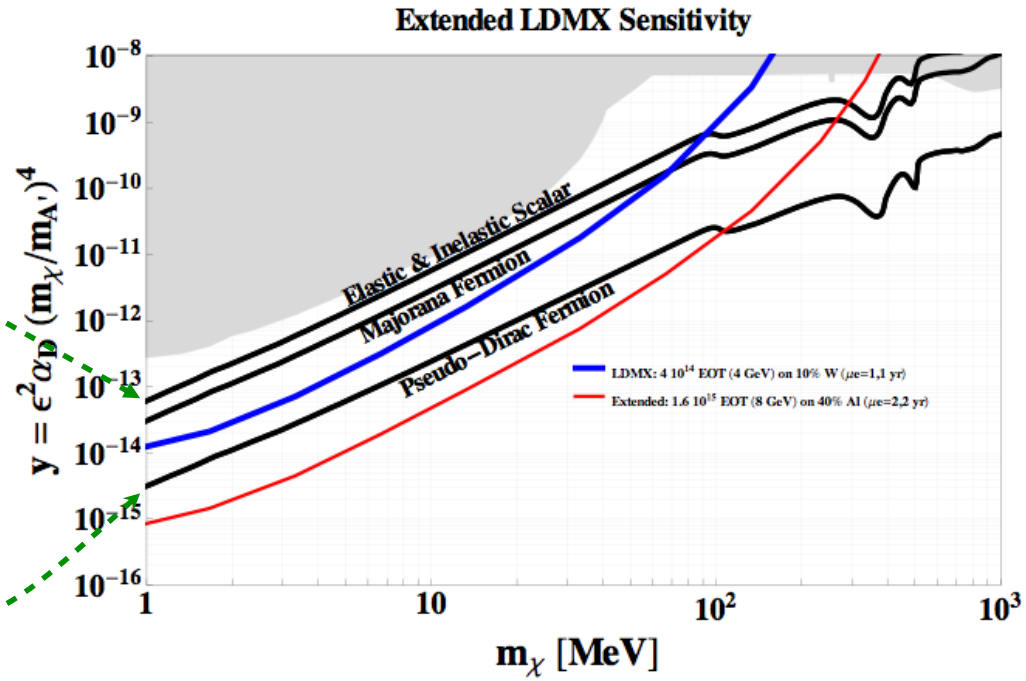
$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

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

"Thermal limits" depend upon nature of χ

- Scalar (elastic, inelastic)
- Fermion (Majorana, pseudo-Dirac, Dirac)





Conclusions

- The particle nature of DM is among the greatest puzzles in physics
- For decades, WIMPs have been the leading paradigm
- Beyond WIMPs, light thermal relic DM is simple and well-motivated, requiring a new light mediator (~MeV-GeV)
- In both “visible” and “invisible” decay searches for dark photons, much of parameter space is still unconstrained
- Electron fixed-target experiments have a key role to play

- HPS: has unique reach in the next 3-5 years, with apparatus already working well in engineering runs
- LDMX: can reach key thermal relic targets with a relatively simple apparatus