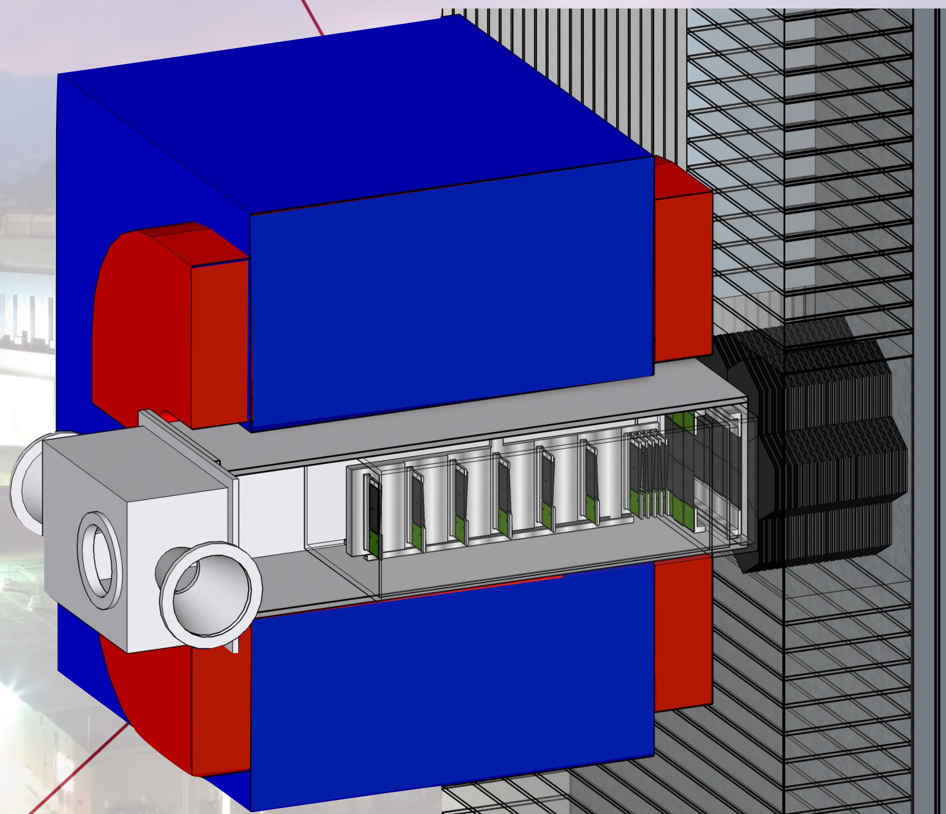
DASEL: Hunting for Dark Sectors at SLAC



Tim Nelson

SLAC Experimental Seminar

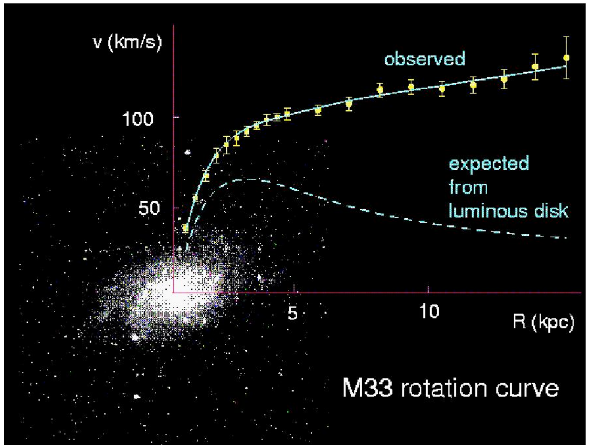
January 31, 2017

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

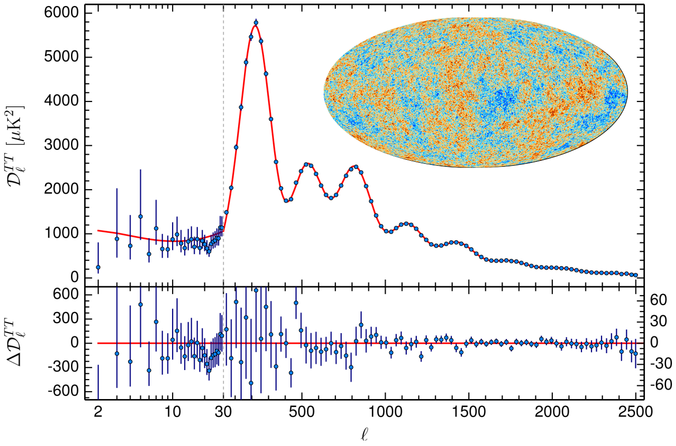
DM Orthodoxy

Galactic Rotation Curves



Gravitational Lensing

Structure of CMB



We know there is Dark Matter.

We know the vast majority is some new form of matter.

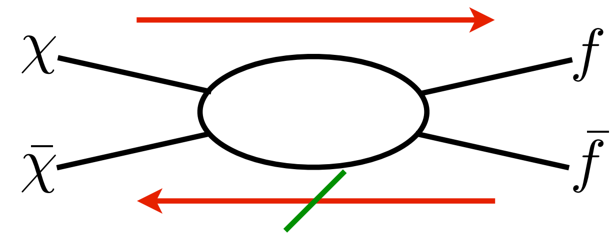
The particle nature of Dark Matter is a central puzzle in particle physics.

Thermally Produced Dark Matter

Extremely general and well motivated theory for production of DM in the early universe:

1. Assume DM is in thermal equilibrium with regular matter in hot "soup" of early universe
2. Universe cools so SM no longer energetic enough to produce massive DM pairs, DM begins annihilating away
3. Universe expands so DM stops annihilating

"freeze-out"

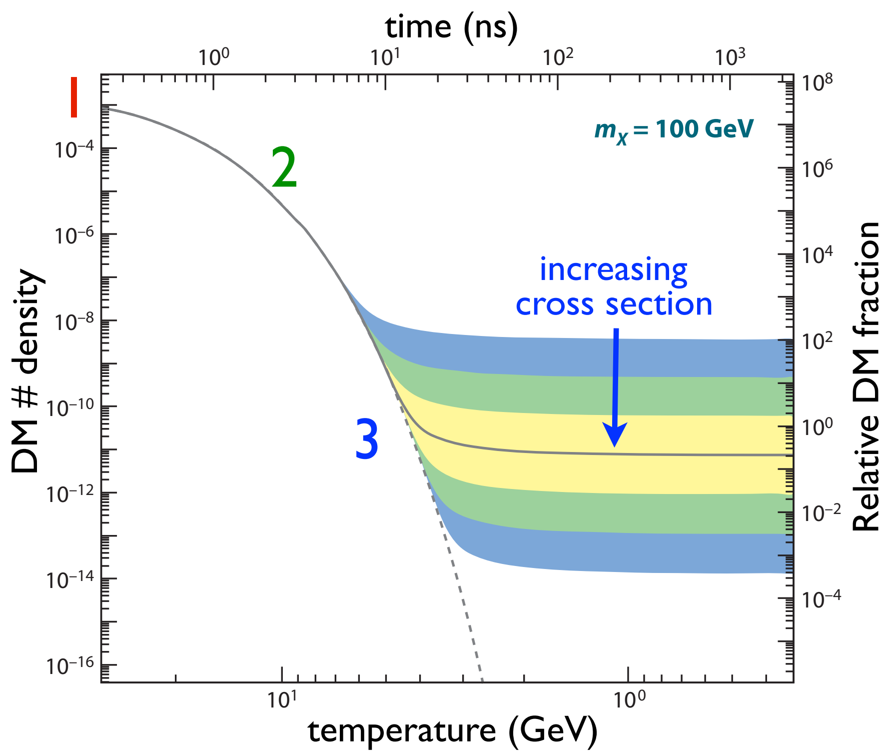


$$\Omega_\chi h^2 \simeq \frac{0.1\ \mathrm{pb} \cdot c}{\langle \sigma v \rangle}$$

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

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

"WIMP Miracle"

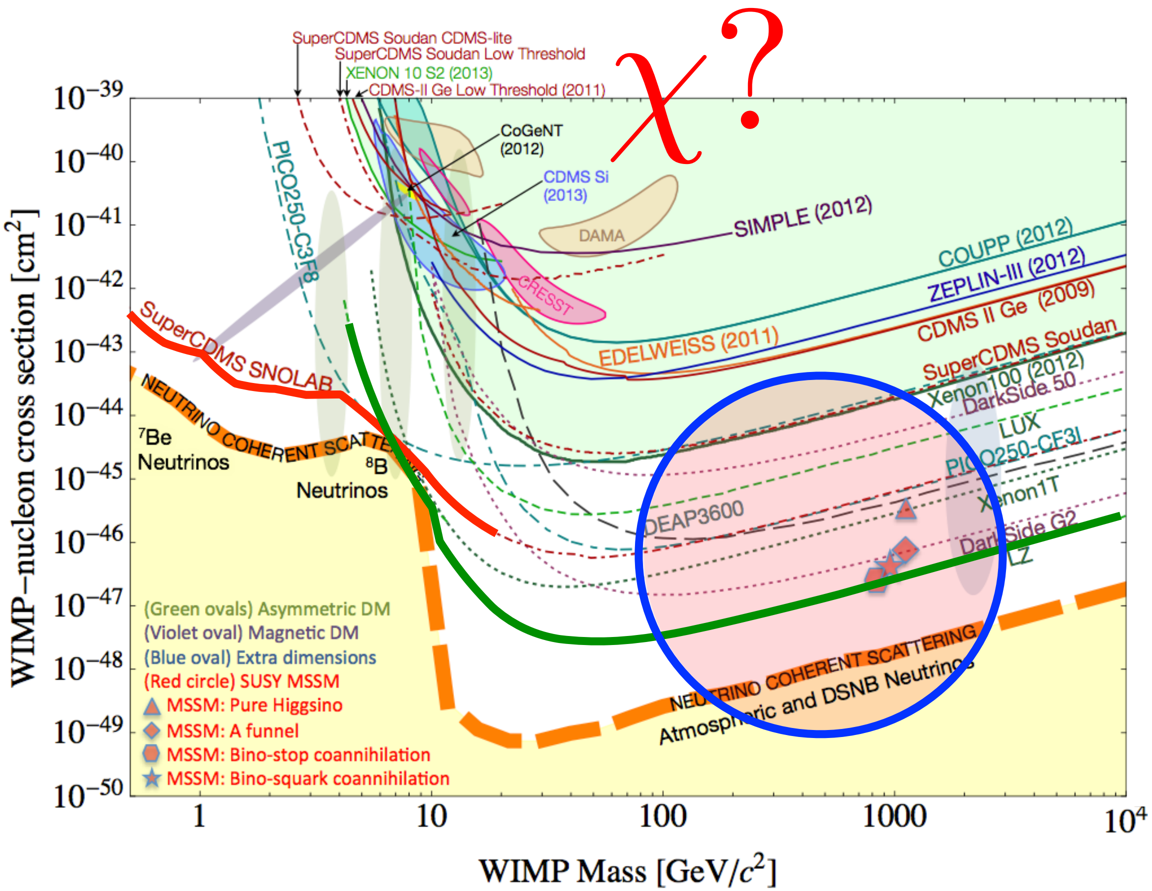


The Search for WIMPs

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

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

Where else should we look?



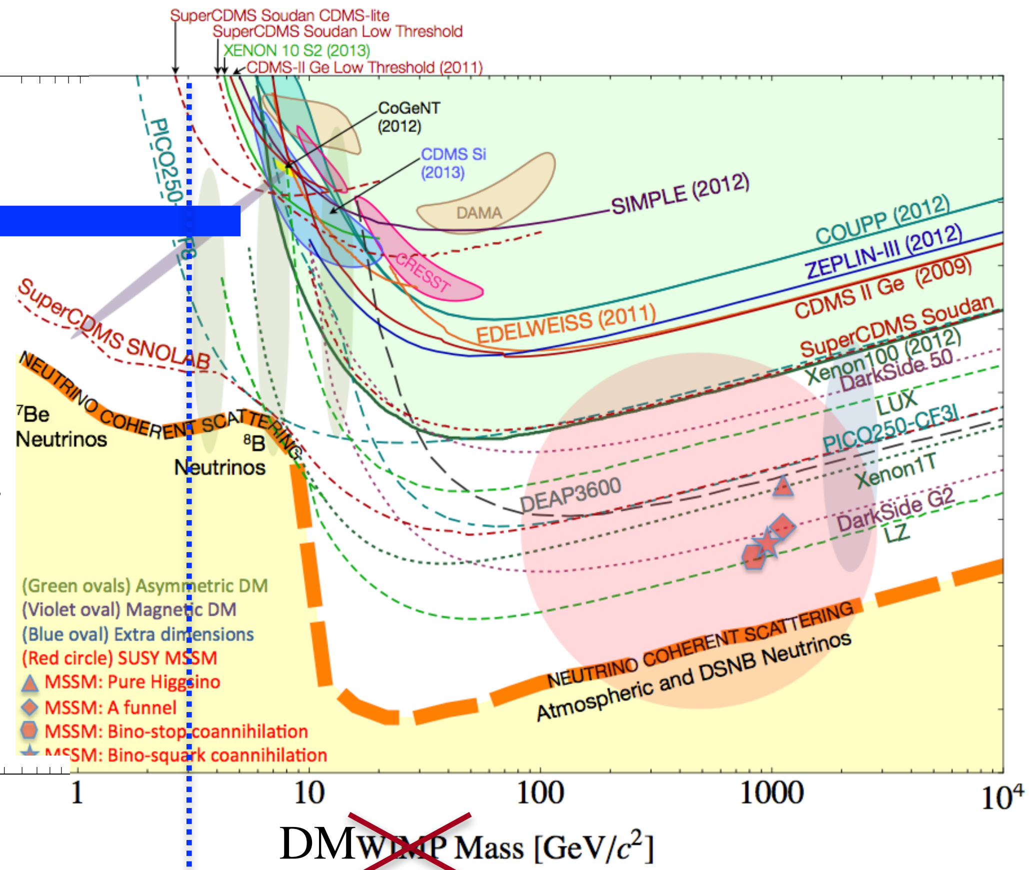
Light Dark Matter?

??

In principle, lower masses are fine, but suggest a new, light force carrier to achieve required annihilation rate.

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

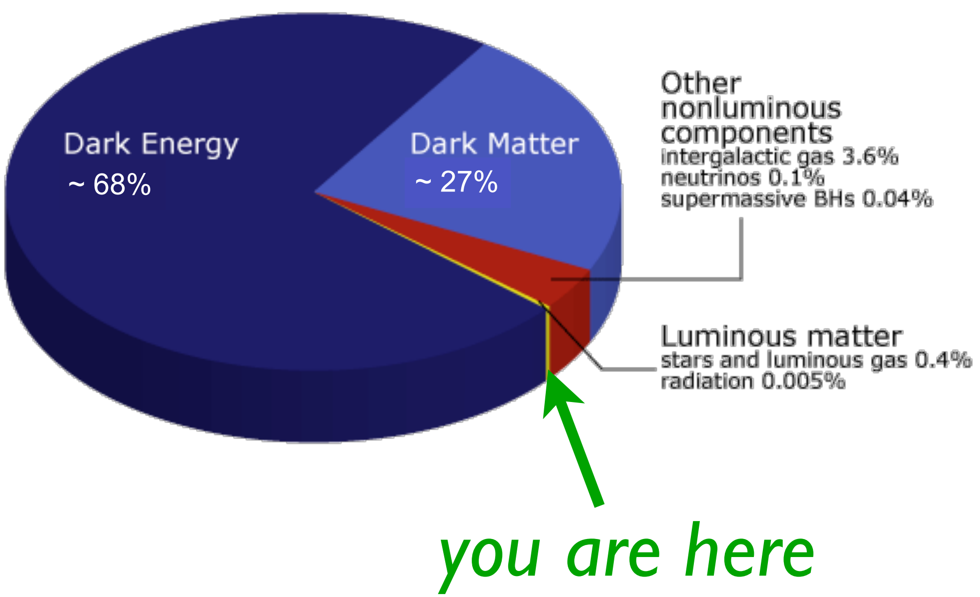
"Lee-Weinberg Bound"

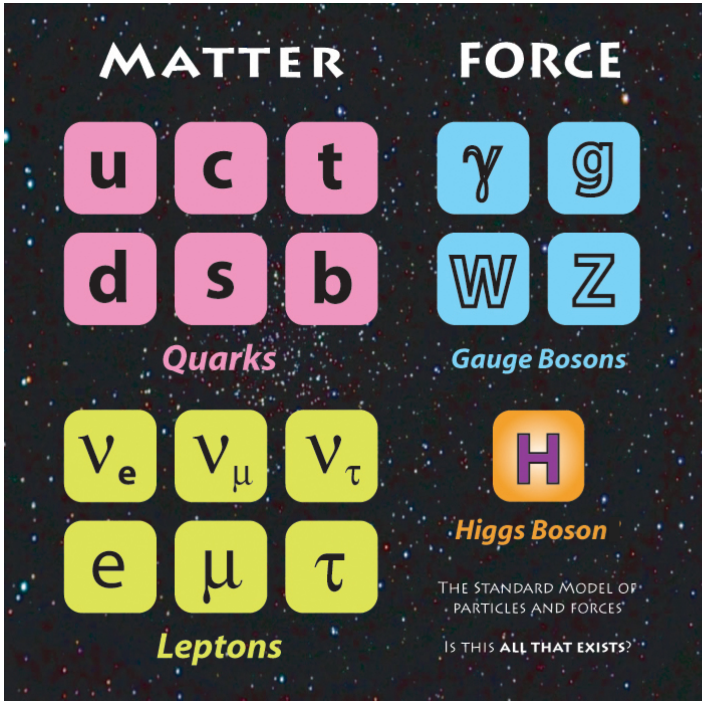


"Light Dark Matter" WIMPs

A New Force? Why Not?

The Standard Model is only 5% of the universe and still quite baroque!





Why should the 27% that is Dark Matter be any simpler?

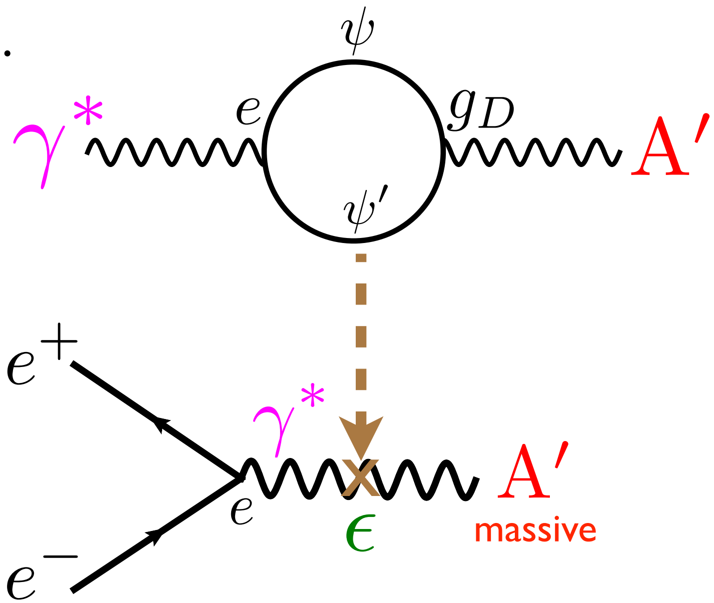
What would a "dark force" look like?

Dark Forces Primer

simplest case is a $U(1)'$ analogous to EM: a "dark photon"

The "dark photon" A' can mix with the SM photon.

This kinetic mixing $F_{\mu\nu}F'^{\mu\nu}$ creates "vector portal"…
(N.B. also allowed by gauge and Lorentz invariance: higgs portal, neutrino portal, gauge portal)



…generating an ϵe coupling to SM fermions:

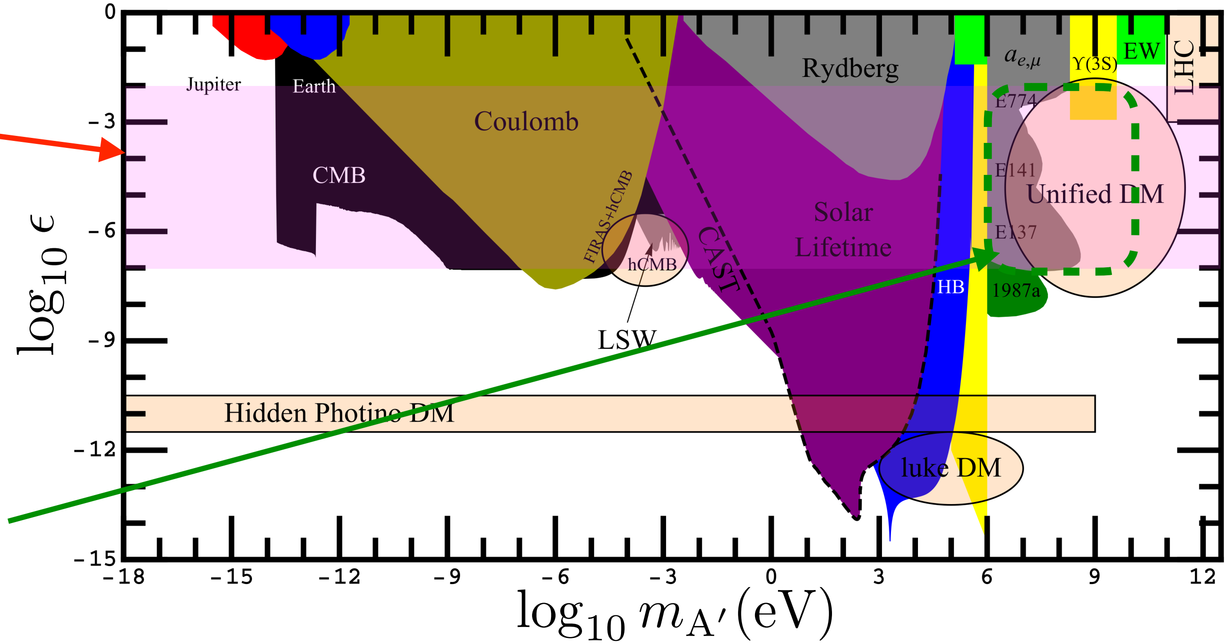
$$\epsilon \sim \frac{e g_D}{16\pi^2} log \frac{M_{\psi'}}{M_\psi} \sim 10^{-4} - 10^{-2}$$

If SM in GUT $\epsilon \sim 10^{-5} - 10^{-3}$ and
as small as 10^{-7} if both U(1) in unified groups.

$U(1)'$ can be broken $\Longrightarrow M_{A'} > 0$, avoids concerns that DM coupled to A' could have strong self-interactions: *"heavy photons"*

Dark Photon Parameter Space

$\epsilon \sim 10^{-2} - 10^{-7}$



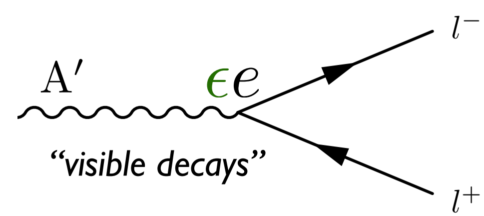
Possible origin for mass: related to m_Z by small parameter

e.g. SUSY+kinetic mixing
⇒ scalar coupling to SM Higgs:
$m_{A'} \sim \sqrt{\epsilon}\, m_Z \approx \mathrm{MeV} - \mathrm{GeV}$

SM-like mass range! Two possible signatures:

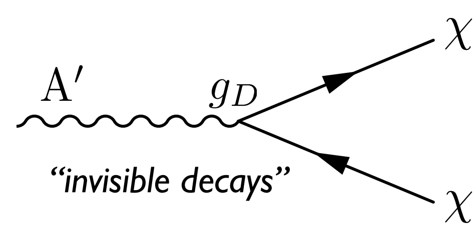
$2M_{ee} < M_{A'} < 2M_{DM}$: A' favors decay to SM fermions

⇒search for visibly decaying Dark Photons



If $M_{A'} > 2M_{DM}$: presume $g_D \gg \epsilon e$ so A' favors decays to DM.

⇒search for ~~Photonically Interacting Massive Particles~~ Light Dark Matter

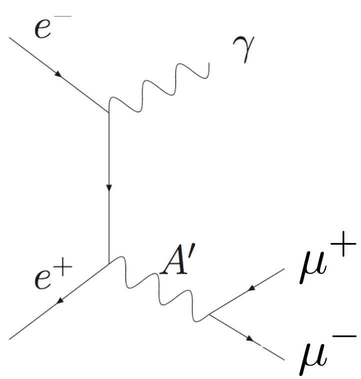


Searching for Low-mass, Weakly Coupled New Particles

Low-energy, high-intensity machines are the right tool.

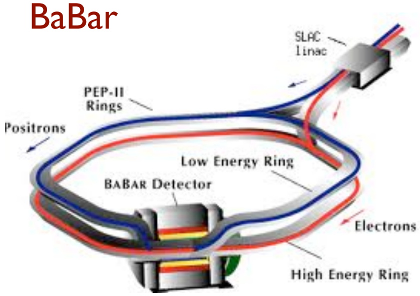
Rule of thumb: where there are photons, there are dark photons.

e^+e^- colliders

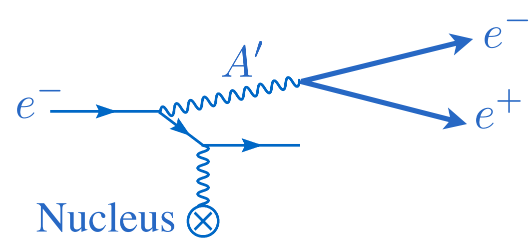


$$\sigma \propto \frac{\epsilon^2}{E^2_{\rm cm}}$$

BaBar

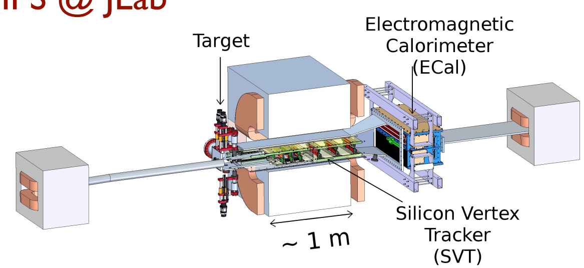


e^- fixed target



$$\sigma \propto \frac{Z^2\epsilon^2}{m^2_{A'}}$$

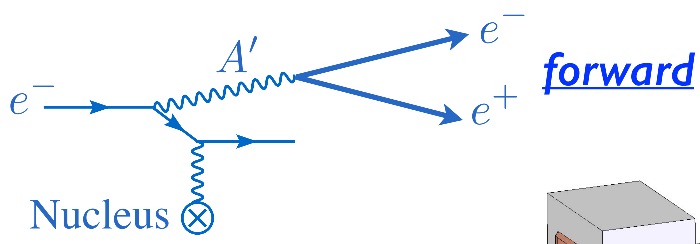
HPS @ JLab

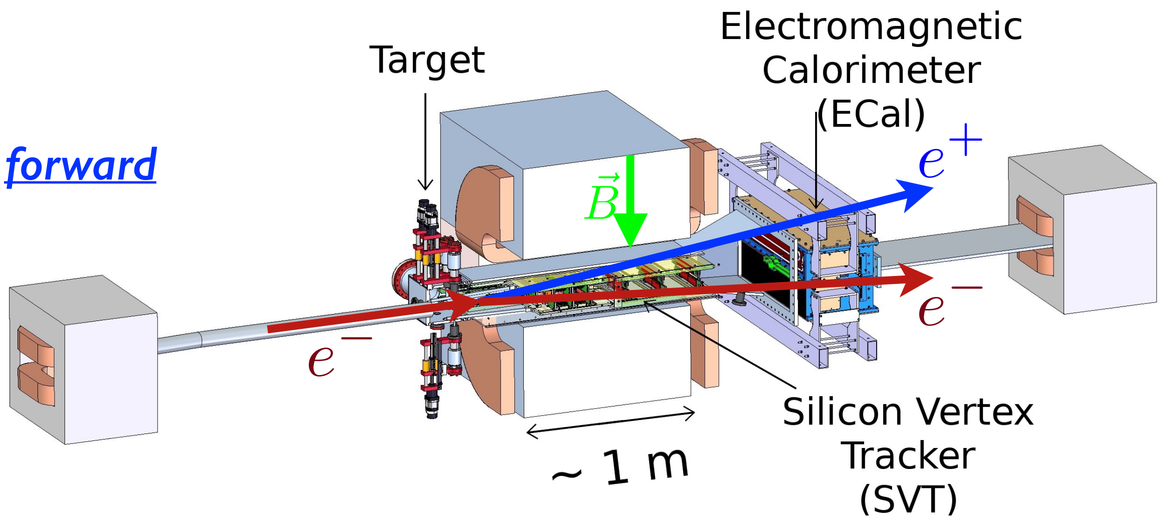


Example: HPS at JLab

*(Graf, Graham, **Jaros**, Maruyama, Moreno, Nelson, Schuster, Solt, Toro)*

HPS is an e^- fixed-target search for visibly decaying dark photons using the CEBAF12 (1-12 GeV) beam in Hall B at JLab.





Signal peaks in far forward spray of scattered electrons where occupancies are extreme (~4 MHz/mm^2 in silicon tracker) ⟹ truly the "intensity frontier"

- *CEBAF is a key tool*: near continuous beam of small bunches (1000-10000 e-/bunch @ 2 ns) with fast detectors and electronics mitigate extreme occupancies.
- Detector installed in Spring 2015. 2015/2016 Engineering Runs total ~170 hours of data.

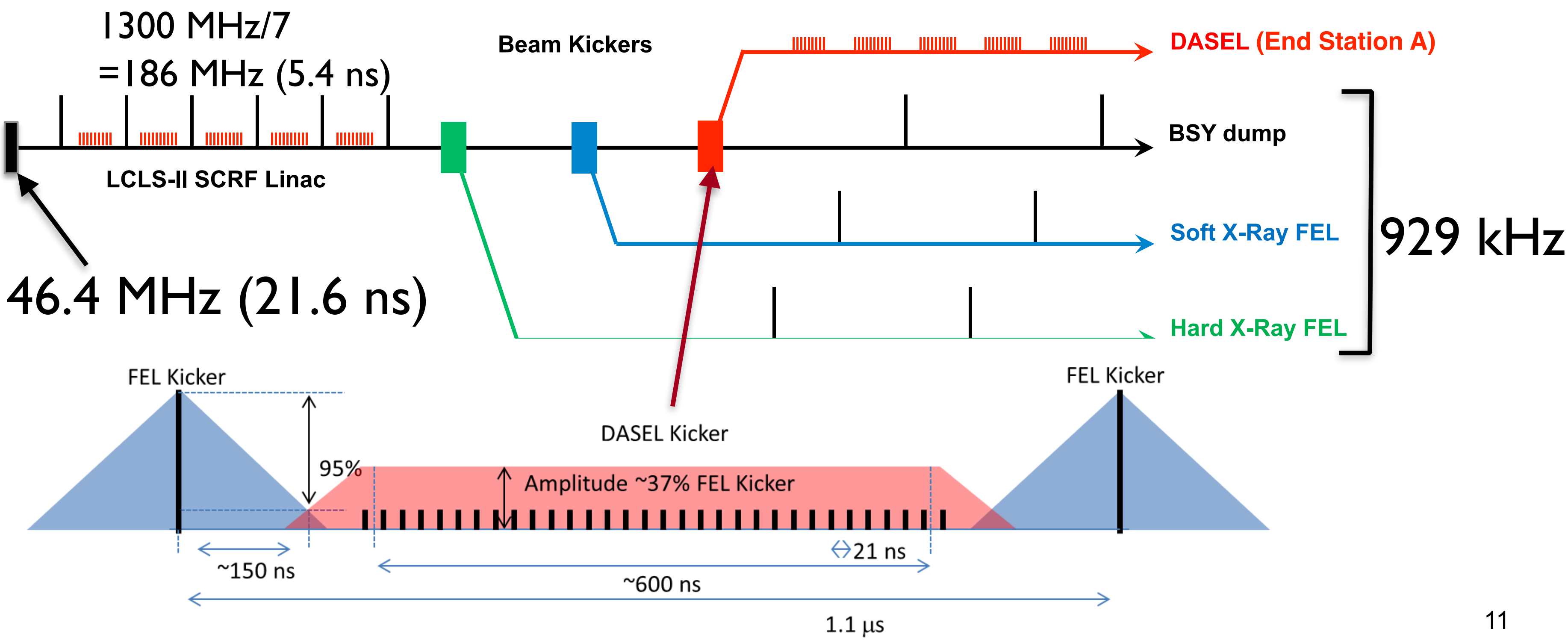
Dark Sector Experiments at LCLS-II (DASEL)

(Beukers, Fry, Hast, Markiewicz, Nelson, Nosochkov, Phinney, Raubenheimer, Schuster, Toro)

SLAC

LCLS-II produces a very similar e^- beam

LCLS-II: 4 GeV e^- $\Rightarrow$ LCLS-II-HE: 8GeV



Dark Sector Experiments at LCLS-II (DASEL)

(Beukers, Fry, Hast, Markiewicz, Nelson, Nosochkov, Phinney, Raubenheimer, Schuster, Toro)

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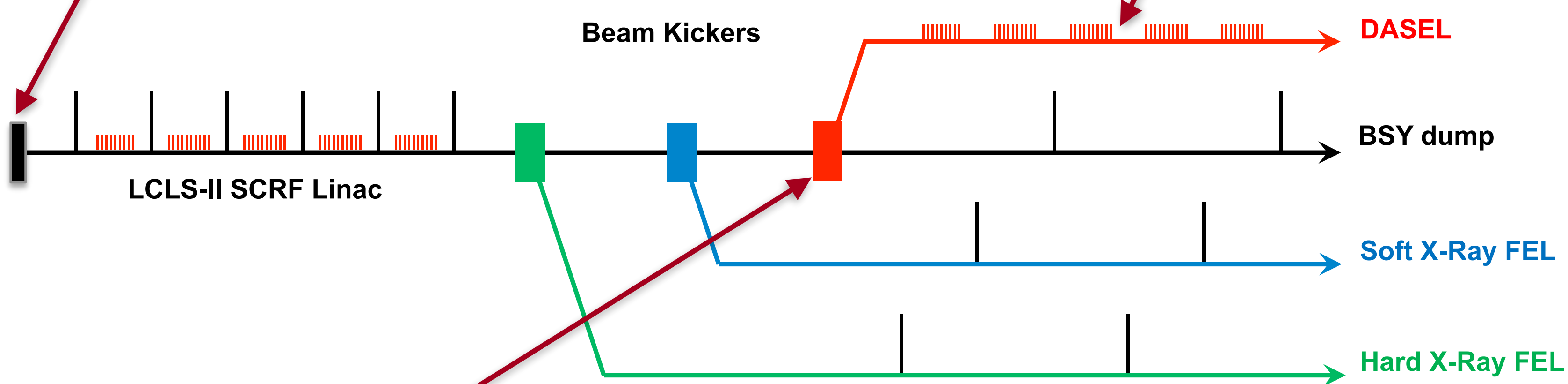
Laser system to fill "unused" buckets with electrons for DASEL

- Use rejected pulses from LCLS-II laser (46 MHz) *(or upgrade to 186 MHz laser)*

Beamline connecting to ESA line

- 3 dipoles & 11 quads (all refurbished)



DASEL kicker/septum system downstream of FEL kickers to minimize interference

- Based on LCLS-II design but with longer kicker pulse

HPS already has a home at JLab: what else would we like to do?

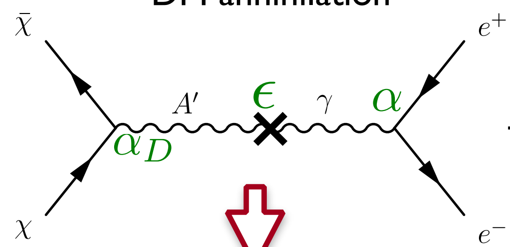
What about $M_{A'} > 2M_{DM}$?

Assume abundance of light dark matter with dark photon interaction is determined by thermal origins.

Can calculate minimum cross section allowed to avoid producing too much DM.

Defines a parameter space with clear targets for light DM searches.

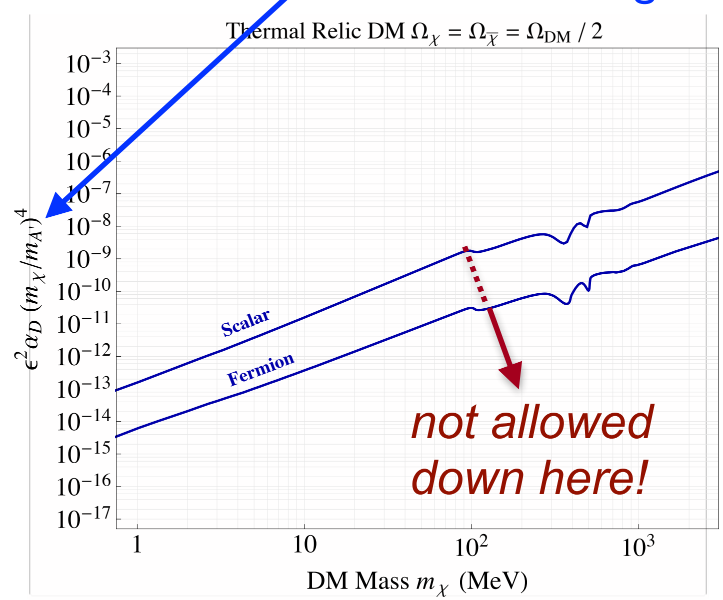
DM annihilation



+ other modes

$$\sigma v \sim \alpha_D \epsilon^2 \alpha \times \frac{m_\chi^2}{m_{A'}^4} \times m_\chi^2 \times \frac{1}{m_\chi^2}$$

y ≡ dimensionless parameter controlling cross-section



Searching for Light Dark Matter at Accelerators

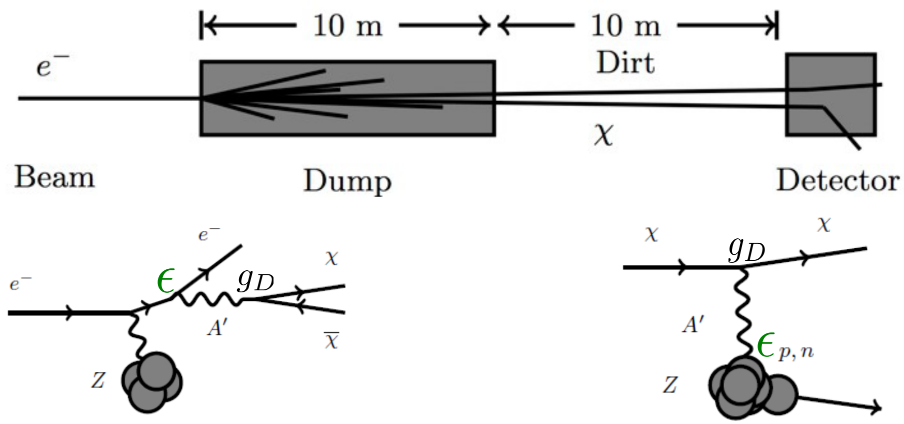
Beam Dump Experiment:

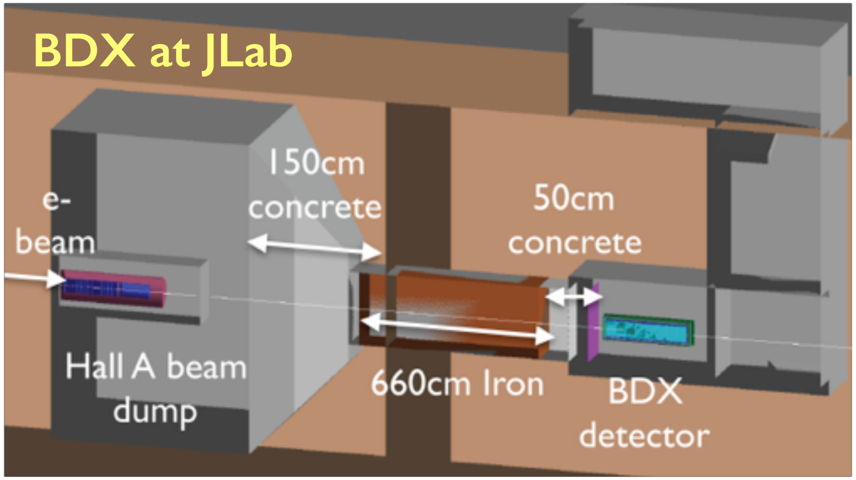
Produce a beam of DM and detect the DM particles downstream.

- convincing discovery signature
- can use very high beam intensities
- … rates are still low: $\sigma \propto \epsilon^4$

Proposed: BDX experiment at JLab

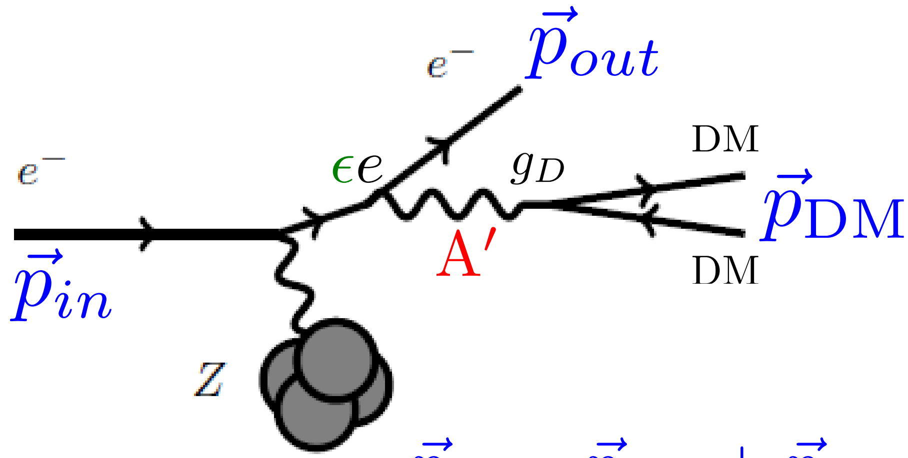
Protons work too! MiniBoone at FNAL





Missing Momentum Experiment:

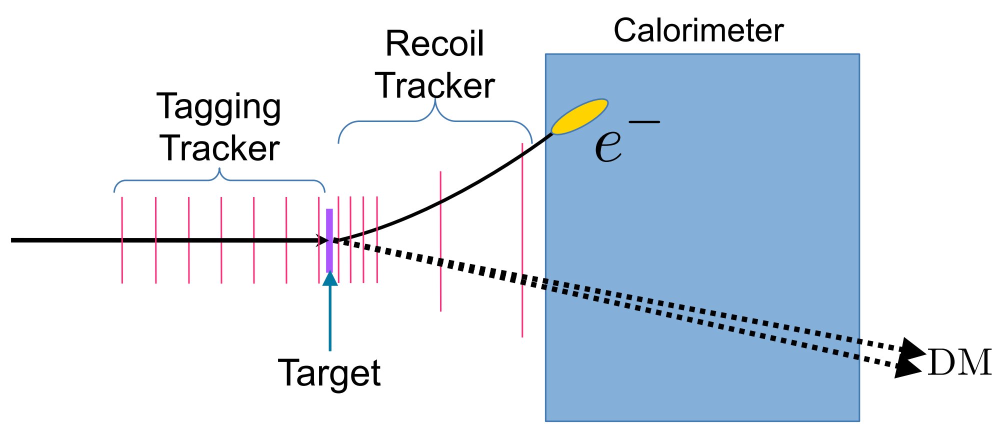
$\vec{p}_{\rm out} \neq \vec{p}_{\rm in}$ and *nothing else in detector* indicates production of invisible state $\Longrightarrow$ DM



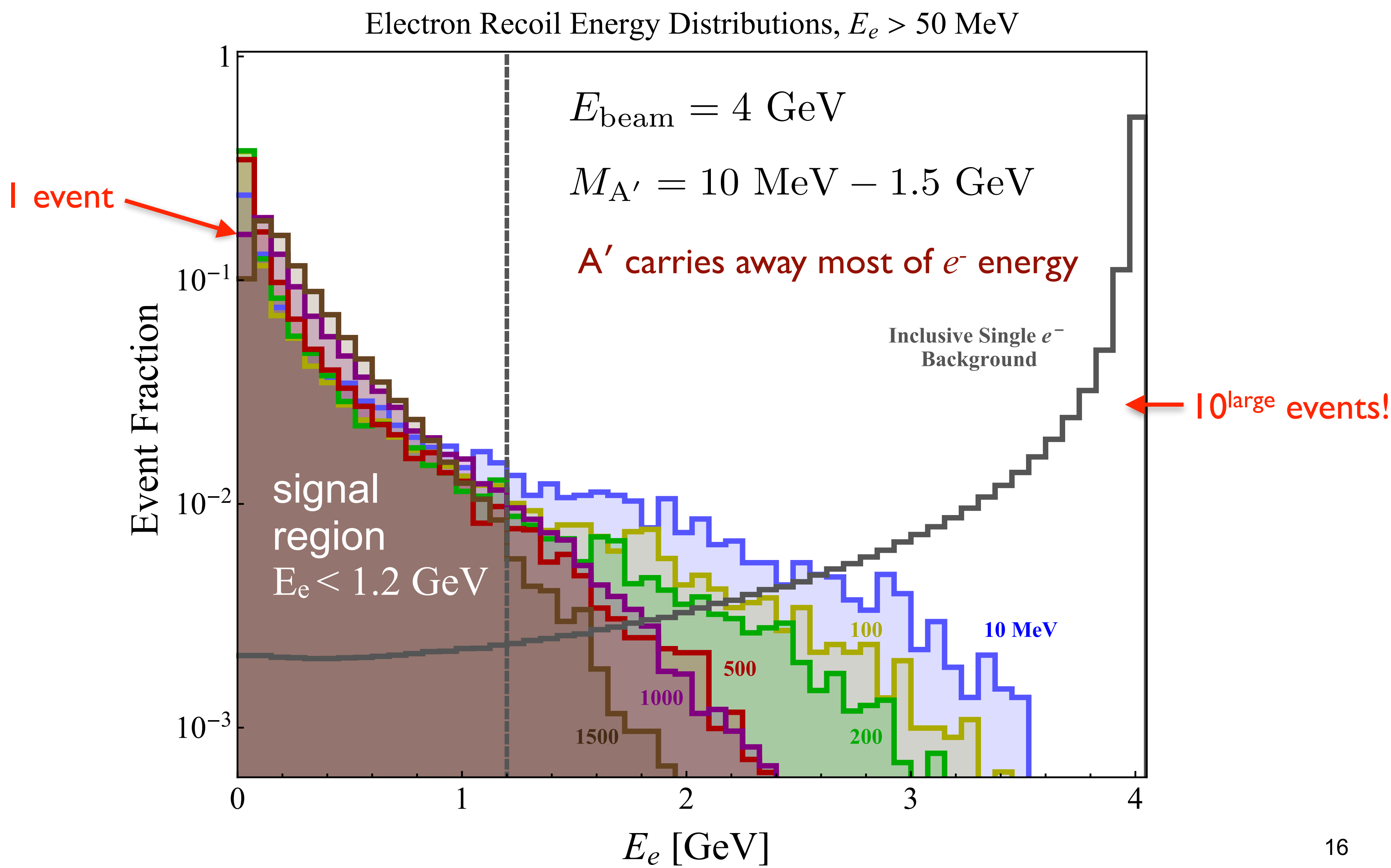
$$\vec{p}_{\rm in} = \vec{p}_{\rm out} + \vec{p}_{\rm DM}$$

- higher rates: $\sigma \propto \epsilon^2$
- requires low beam intensity (~1 e^-/bunch)
- less convincing discovery signature

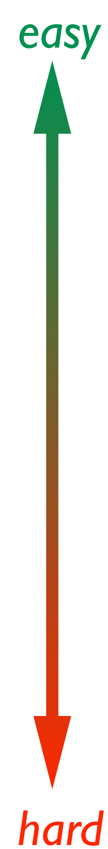
Light Dark Matter eXperiment (LDMX) at DASEL!



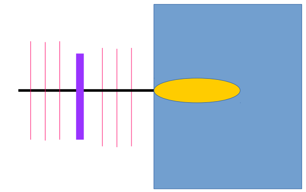
Signal and Background Kinematics I



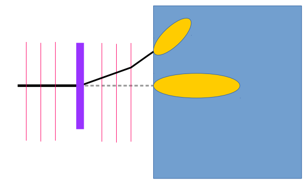
Backgrounds for Missing Momentum Experiments



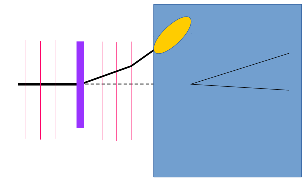
Non-interacting electrons $\mathcal{O}(1)/e^-$



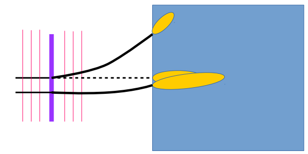
Electron+hard brem $\mathcal{O}(10^{-1})/e^-$



Electron+hard brem,
hard brem $\longrightarrow$ photonuclear $< \mathcal{O}(10^{-4})/e^-$
$\longrightarrow$ *($\pi^+ n$, nn, etc...)* $\lesssim \mathcal{O}(10^{-7})/e^-$



Overlapping the above depends on beam intensity



For an electron beam, irreducible neutrino background at ~10^{-16}

First Proof of Principle

NA64 missing *energy* experiment

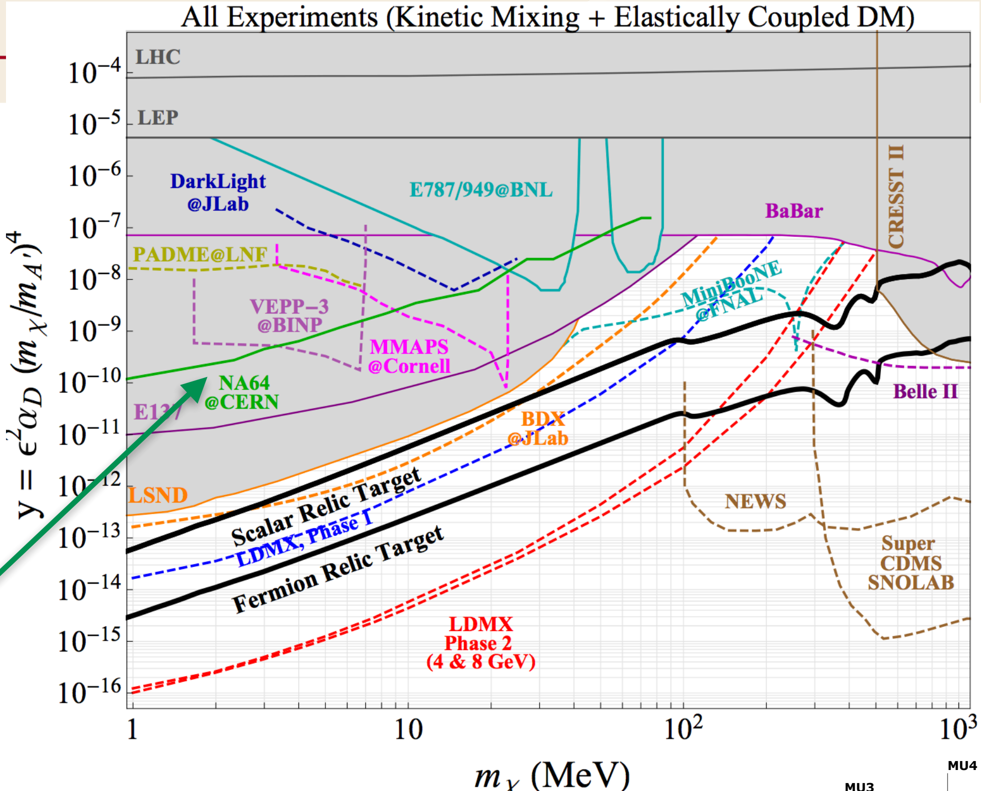
(no tracking for recoil electron)

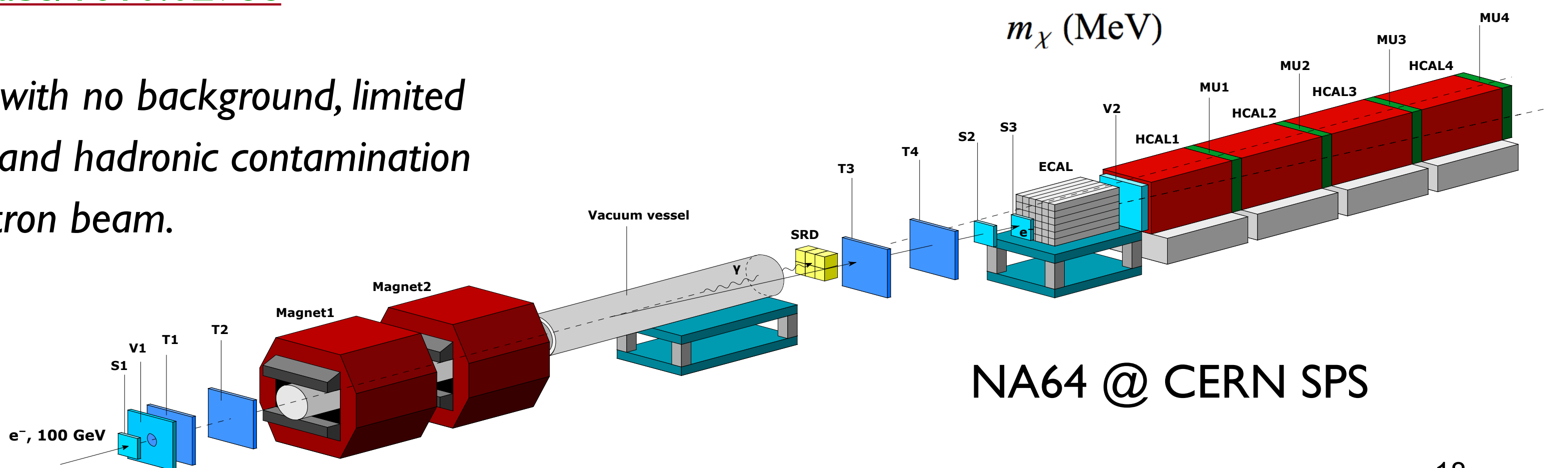
- measure energy of incoming 100 GeV e^-
- measure energy deposited in active ECal target and downstream Muon/HCAL

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

Results for 10^{10} electrons on target (EOT):
https://arxiv.org/abs/1610.02988

Goal is 10^{12} EOT with no background, limited by rate capability and hadronic contamination of secondary electron beam.

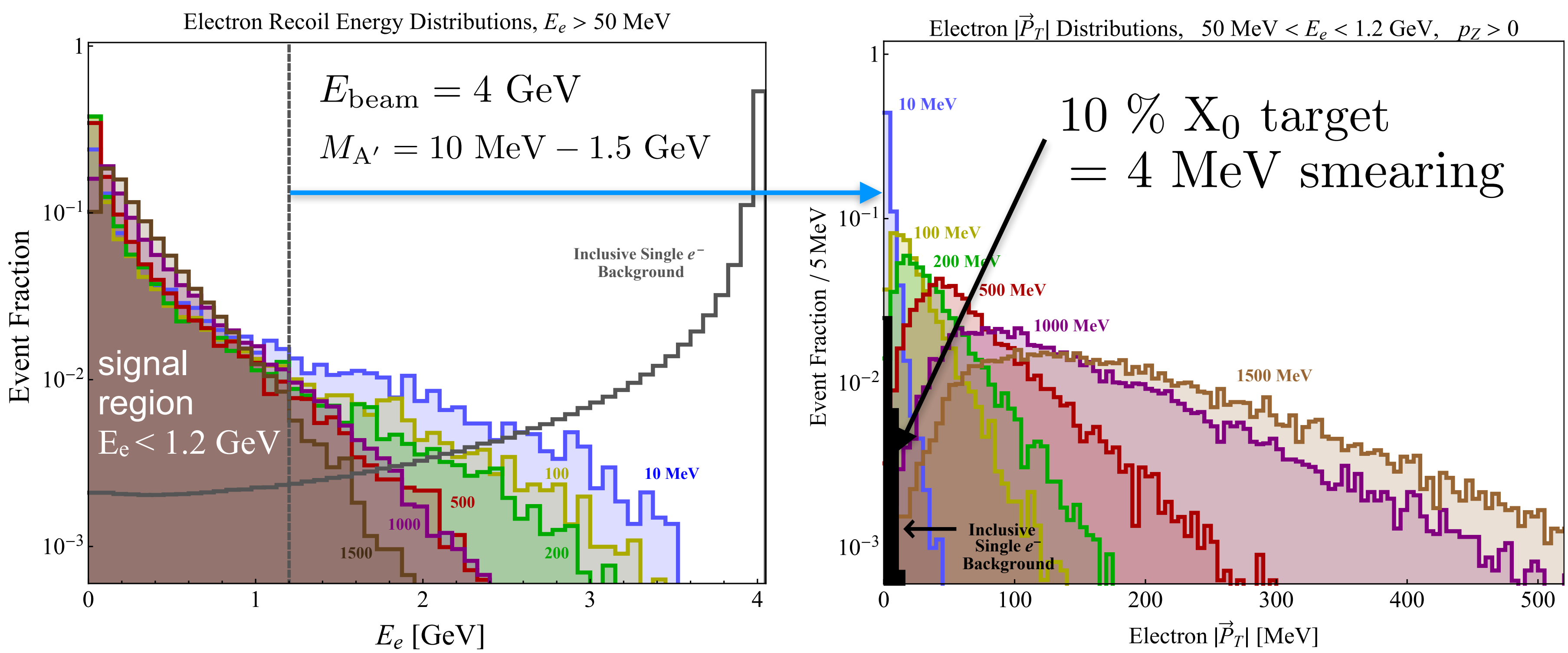




NA64 @ CERN SPS

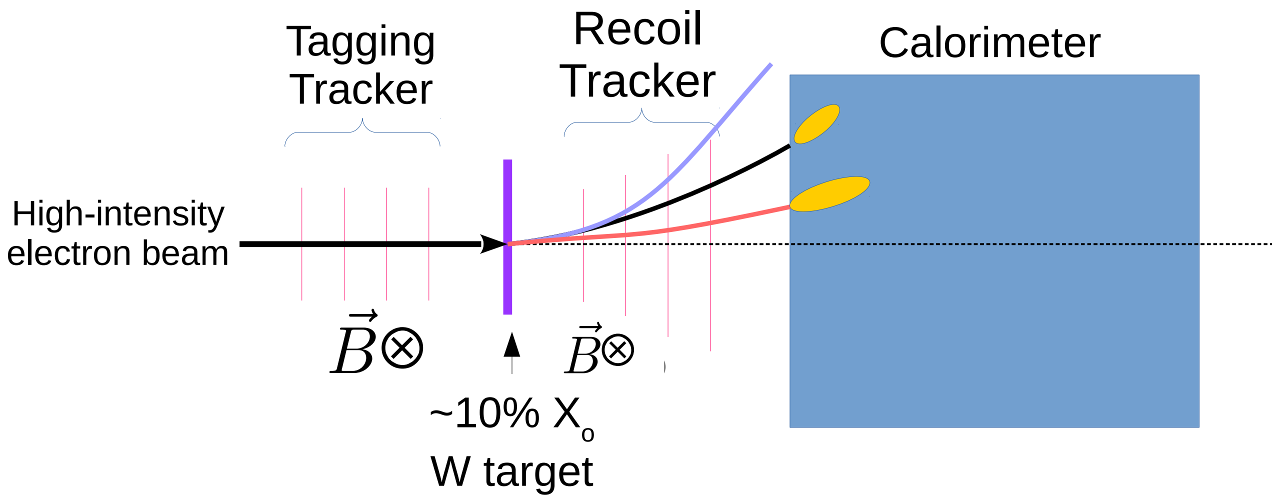
Signal and Background Kinematics II

Measuring p_T change across target adds powerful lever for background suppression.



What would it take to get to 10^{-16} "neutrino floor"?

Ingredients for a 10^{16} EOT Missing Momentum Experiment



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

- low-current, multi-GeV, e^- beam with high repetition rate (10^{16}/year ≈ 1 e^-/3 ns)
- large beamspot (~10 cm^2) to spread out these rates and radiation doses

Tracking and calorimetry capable of very high rates and radiation tolerance

- requirements for 10^{16} experiment push limits of available technologies

➡ Two-stage approach to LDMX: 4×10^{14} "Phase I" followed by 10^{16} "Phase II"

1 e^- / 21.6 ns bunch *a few e^-* / 5.4 ns bunch?

LDMX Phase I Detector Concept

*(Graf, Jaros, Maruyama, Moreno, Nelson, **Schuster**, Toro)*

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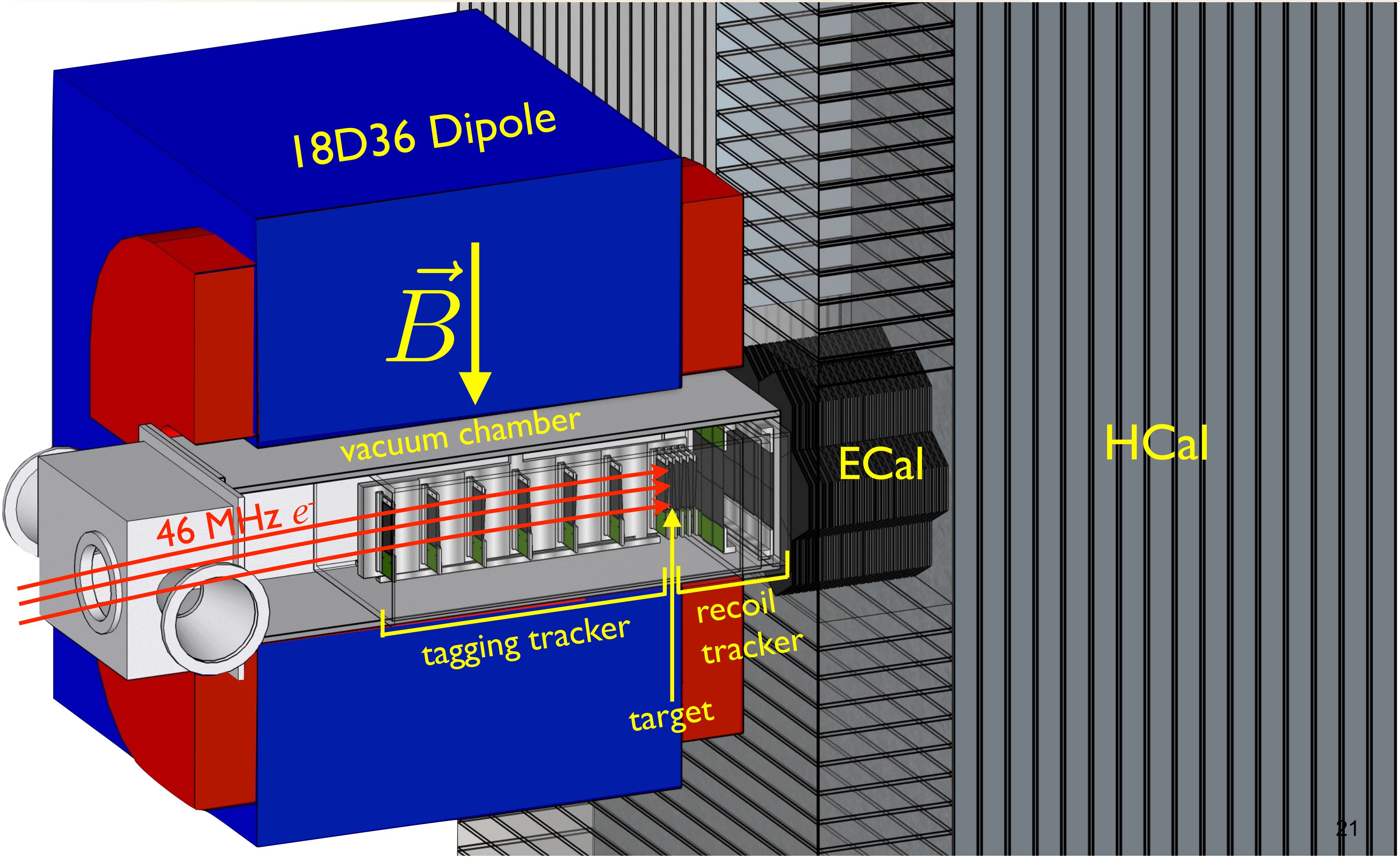


LDMX Spectrometer

(SLAC w/ UCSC - Fadeyev, Grillo, Johnson)

18D36 Magnet with 14" vertical gap @ 1.5 T

One magnet, two fields:

Tagging Tracker in central field for p_e = 4 GeV

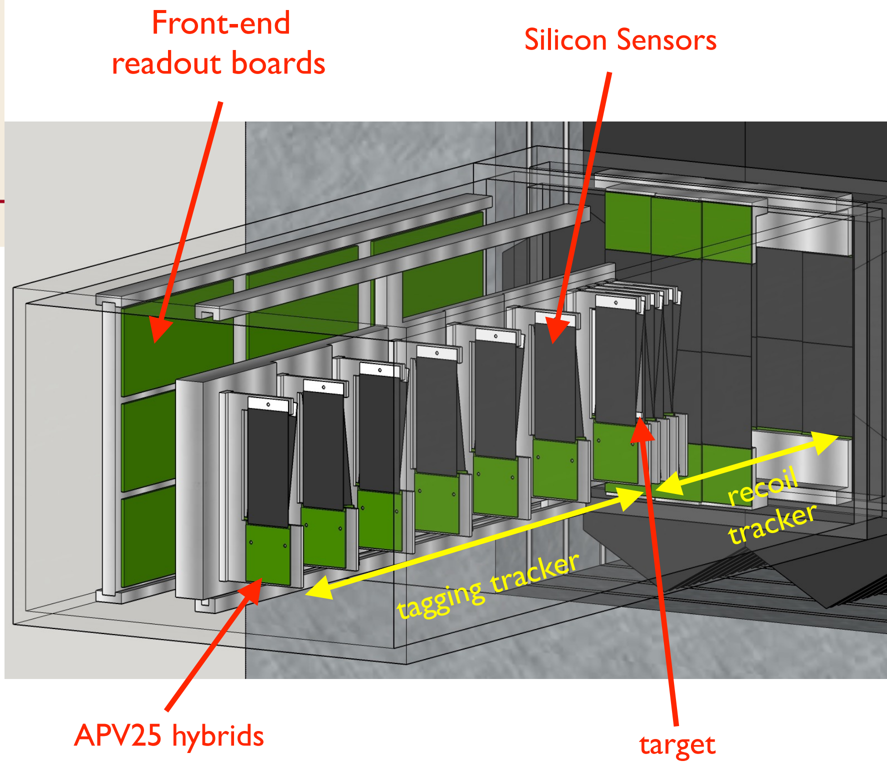
- reconstructs e^- position and momentum at upstream face of target
- long/narrow to select against off-energy e^-

Recoil Tracker in fringe field for p_e = 50-1200 MeV

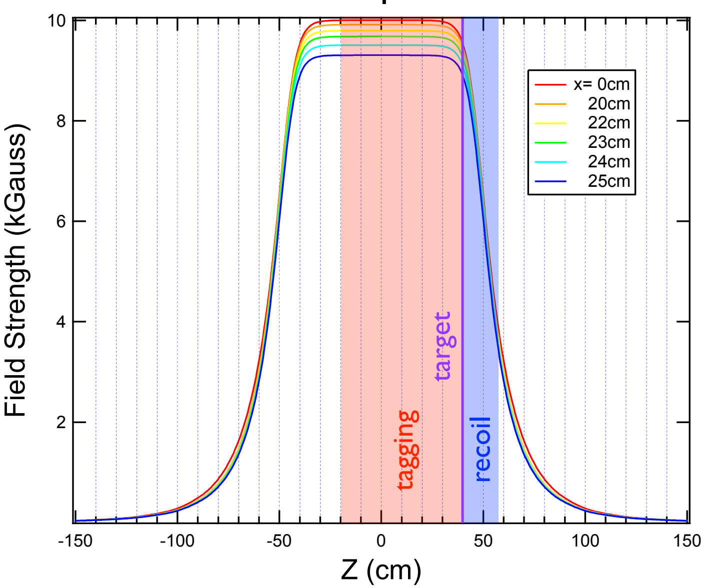
- reconstructs e^- position and momentum at downstream face of target
- vetoes events with additional tracks (e.g. tridents)
- short/wide to maximize acceptance and allow ECal close to target

Target between trackers

- 10% X_0 tungsten balances signal rate against MS
- scintillator vetoes ECal trigger on empty buckets



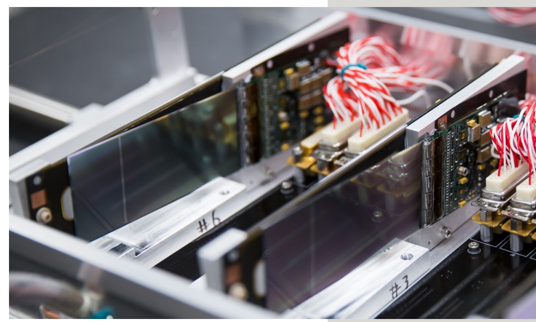
18D36 Dipole Field

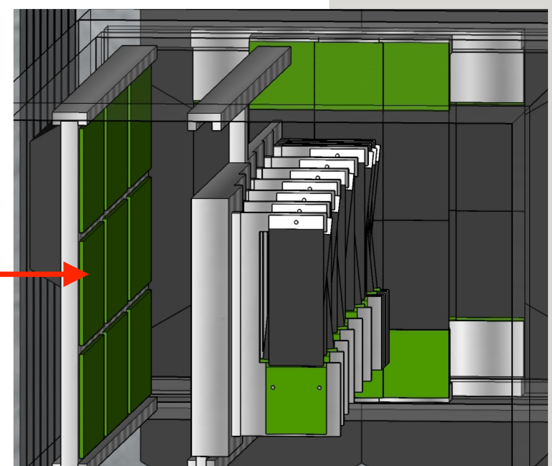


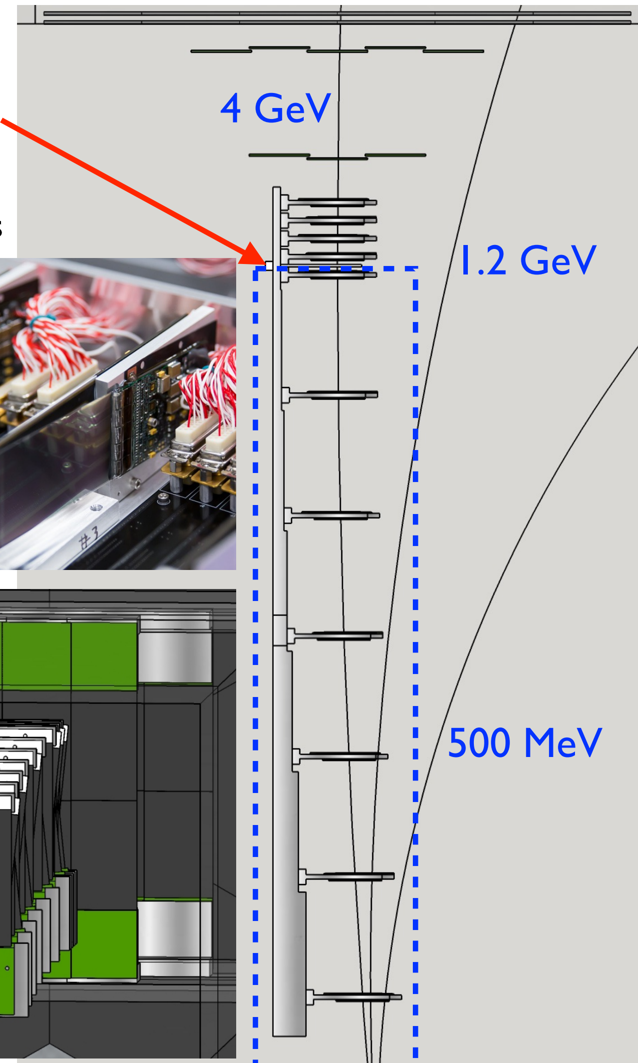
Tagging Tracker

Designed around trajectory of 4 GeV e^-

- 7 layers, every 10 cm from 7.5 mm to 607.5 mm upstream of target
- Silicon modules are similar to those built for HPS SVT
  - 0.7% X_0 / 3d measurement
  - 2 ns hit time resolution
- Digitization, zero-suppression on Front End Boards (FEBs), same as HPS SVT

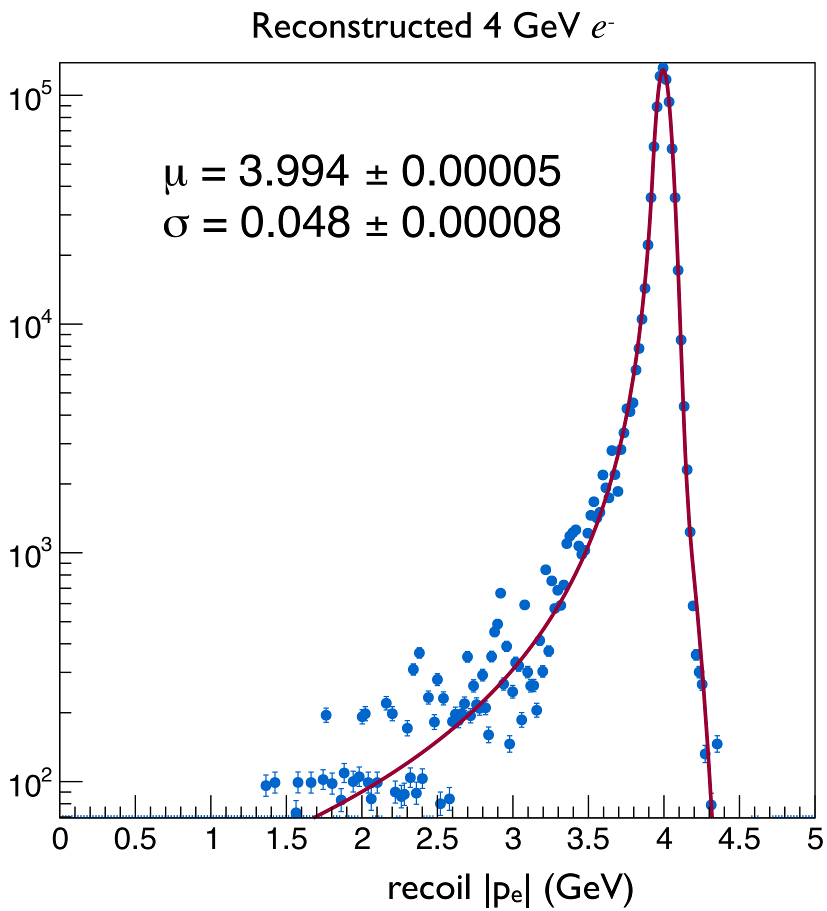


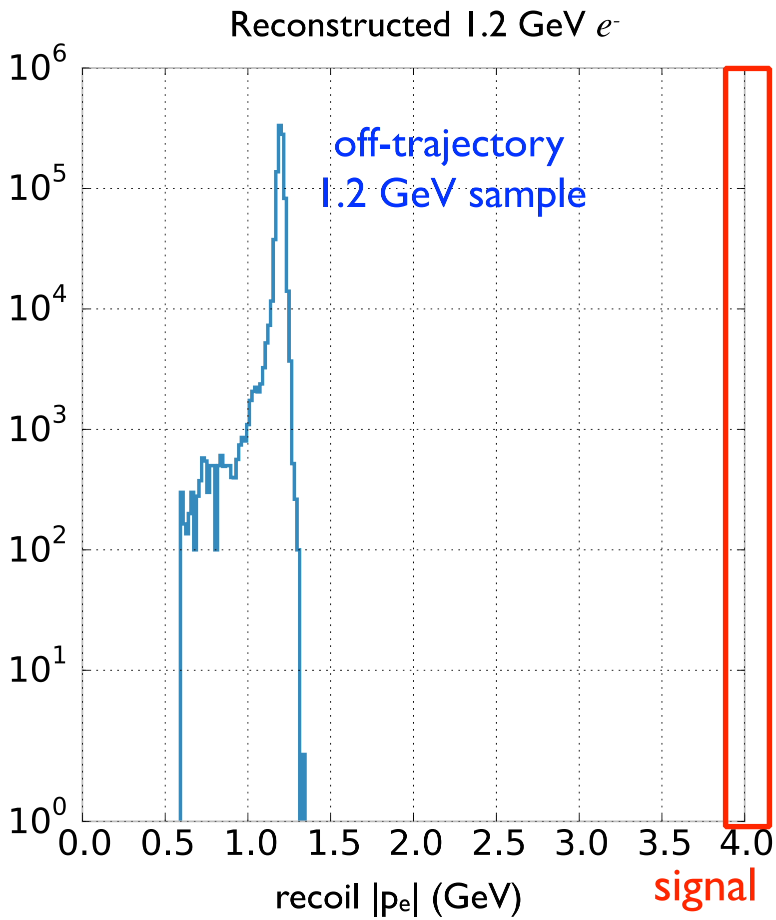




Tagging Tracker Performance

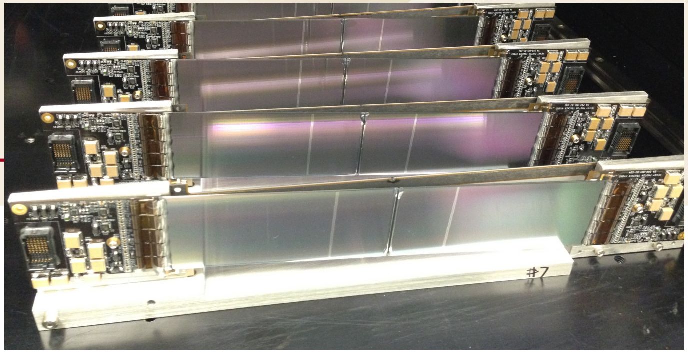
Critical: tagger tracker strongly selects against any off-energy component in beam.





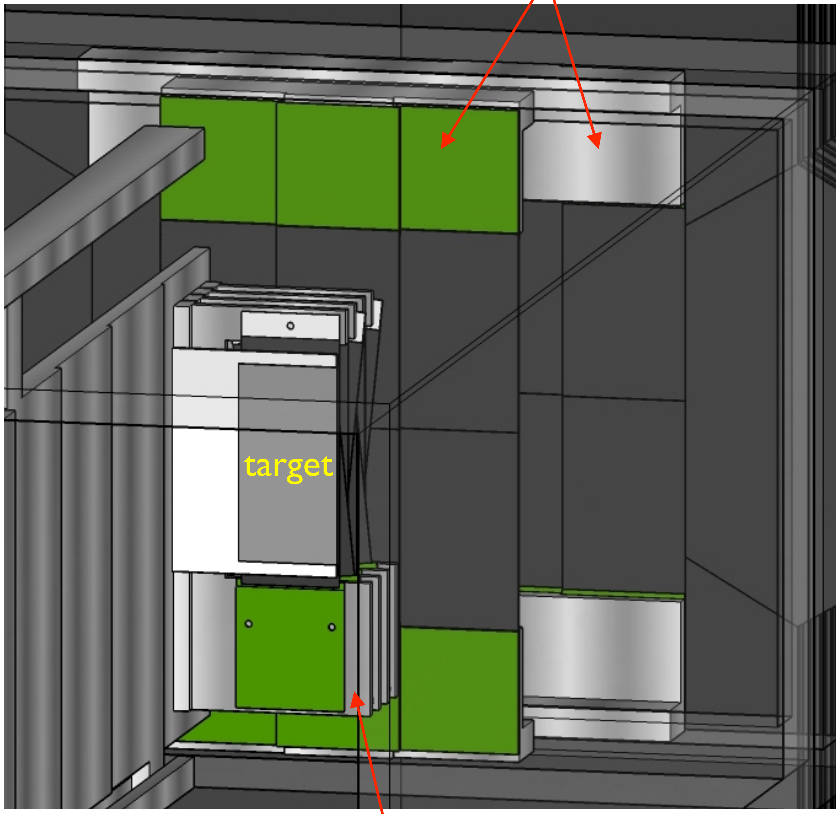
Recoil Tracker

HPS L4-6 modules



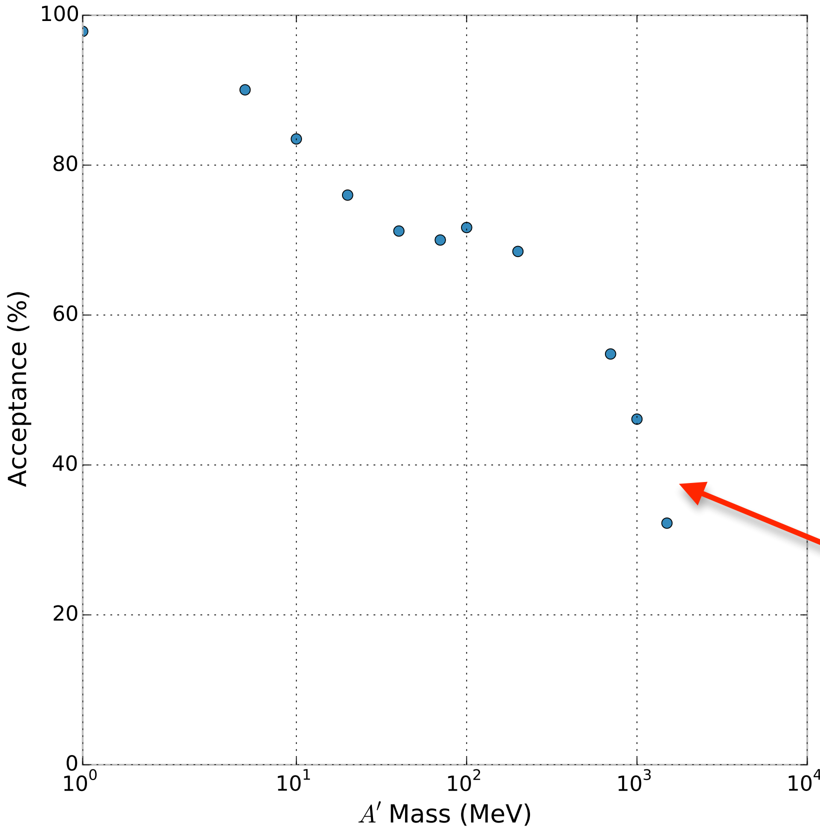
Designed for large angular and momentum acceptance in limited longitudinal space

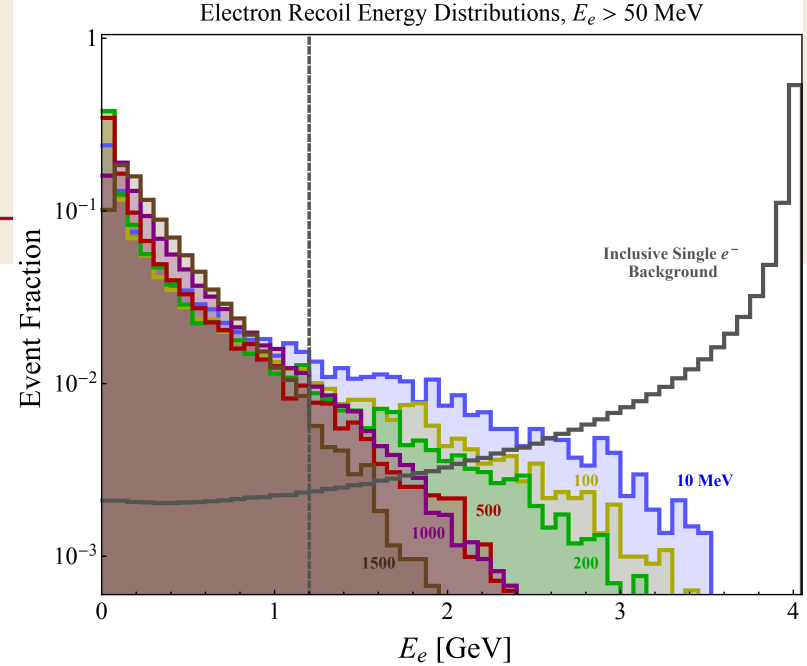
- 4 layers every 15mm from 7.5mm to 52.5mm downstream of target.
    - Same modules as tagging tracker
    - Mounted on the same support/cooling
- 2 larger-area axial layers (vertical strips) at 90mm and 180mm downstream of target (ECal face @ ~200mm)
    - 0.35% X_0 / layer
    - critical for momentum measurement

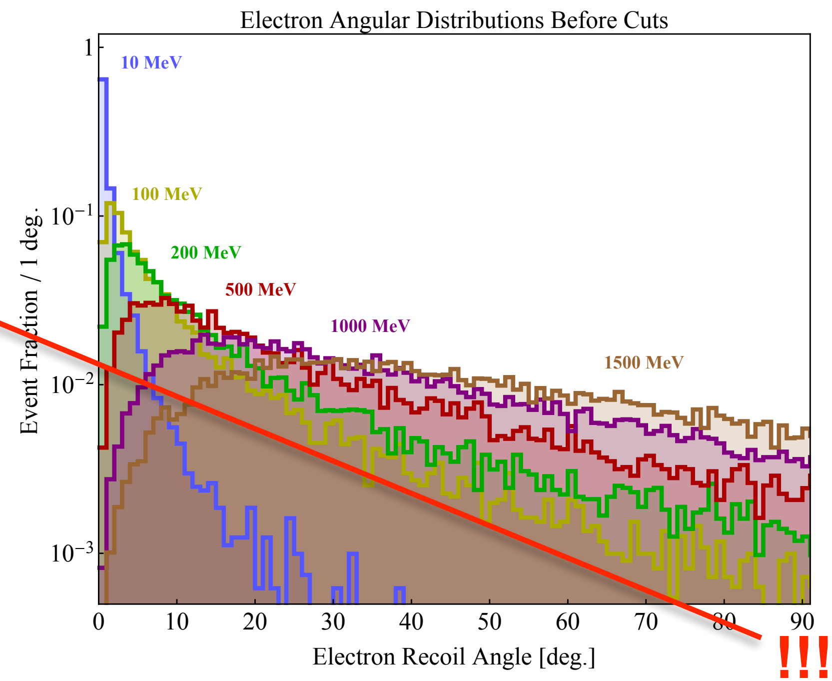


Recoil Tracker Acceptance

Acceptance for recoils findable with good vertex and p_T resolution





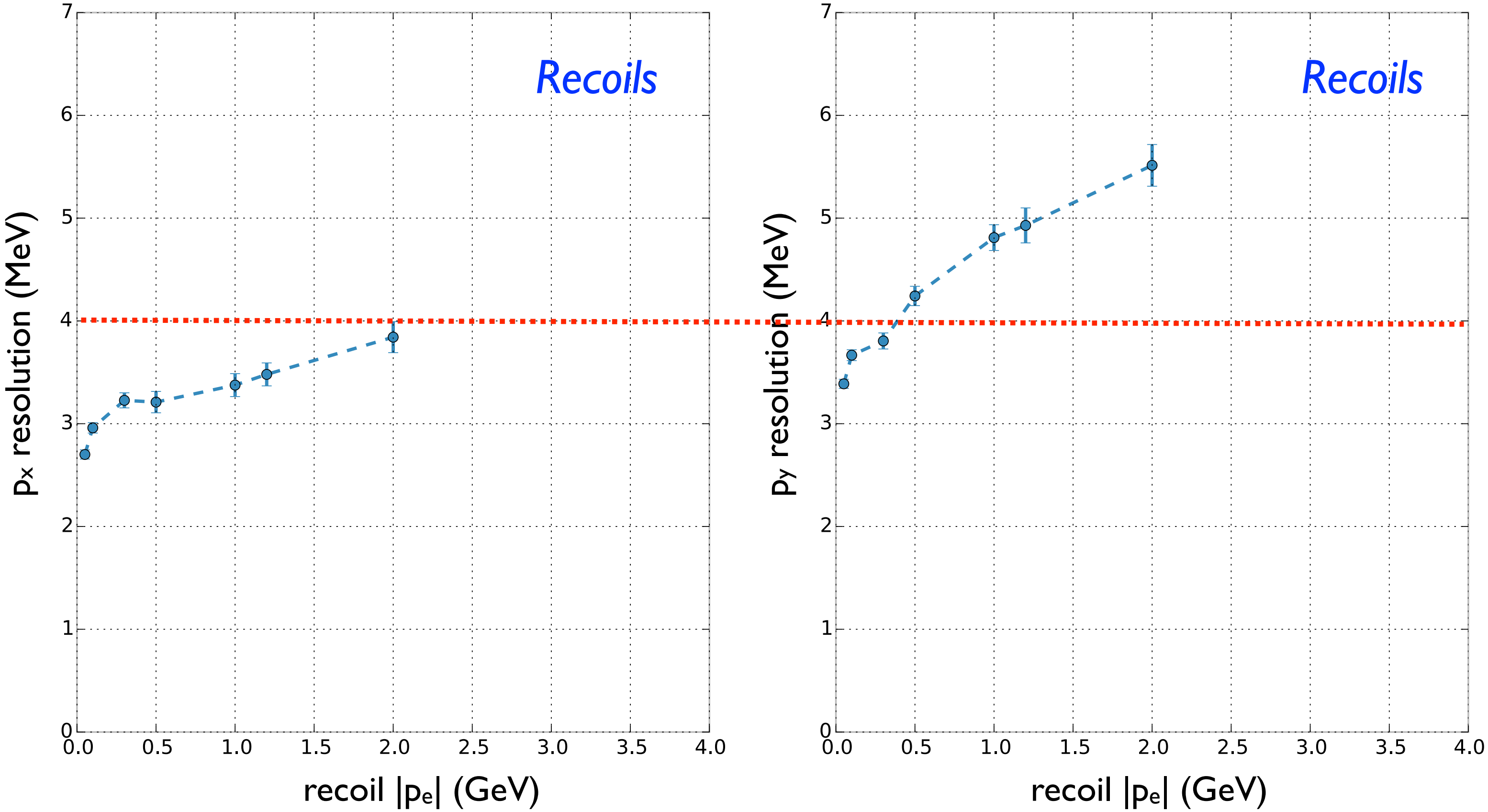


Good acceptance over a wide range of A' masses despite soft, wide-angle signal recoil distributions.

Tracker pT Resolutions

Tagger (px, py) resolutions are target are (1.0,1.4) MeV.

Recoil (px,py) resolutions are limited by 4 MeV scattering in 10% X_0 target (included here)

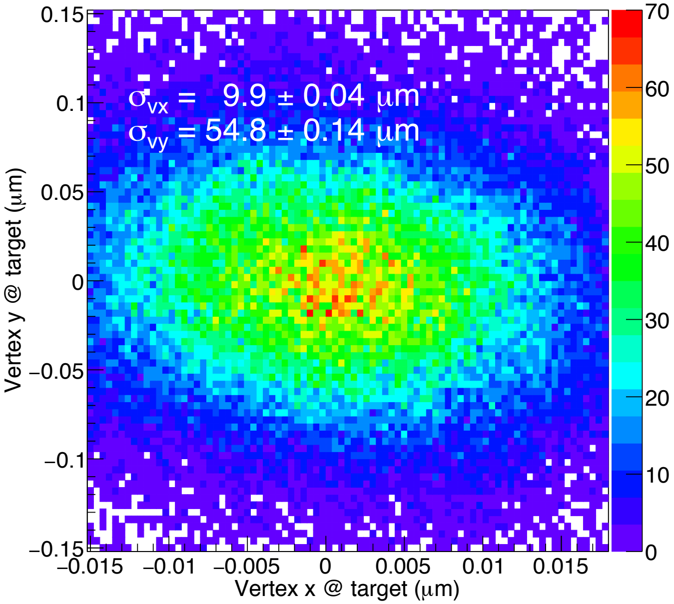


Performance of p_T cuts is limited by target material.

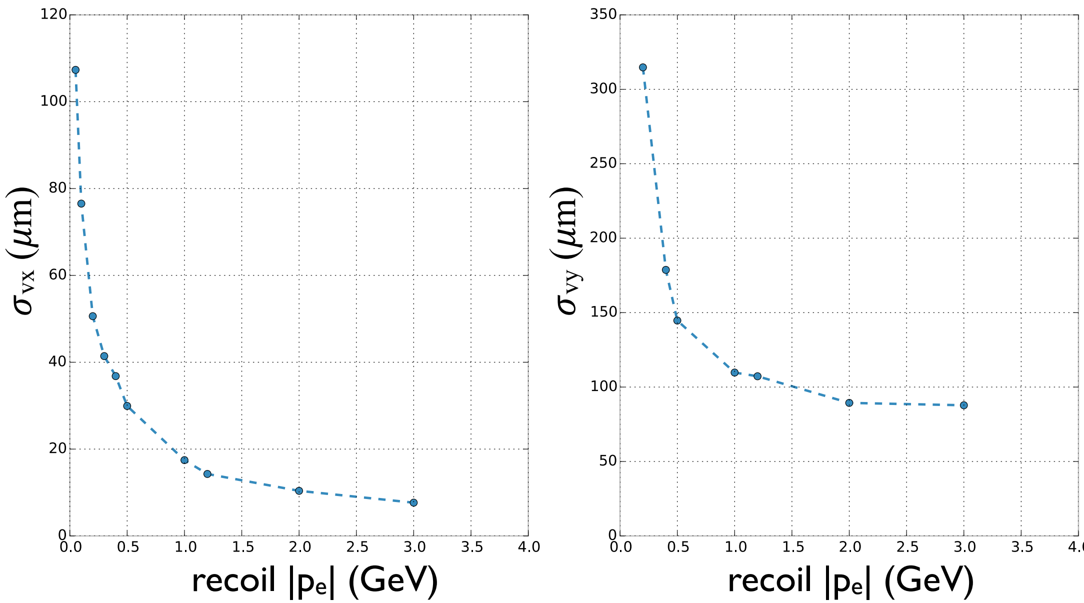
Impact Parameter Resolutions

SLAC

tagger e^- position at target



recoil e^- resolutions at target



Enables tight tag/recoil matching criteria relative to 10cm² beam spot:

- at E_R = 50 MeV: 3σ region for tagger/recoil consistency = 0.67 mm² $\Longrightarrow$ $<10^{-4}$ rejection
- at E_R = 1.2 GeV: 3σ region for tagger/recoil consistency = 0.026 mm² $\Longrightarrow$ $<10^{-5}$ rejection

LDMX ECal

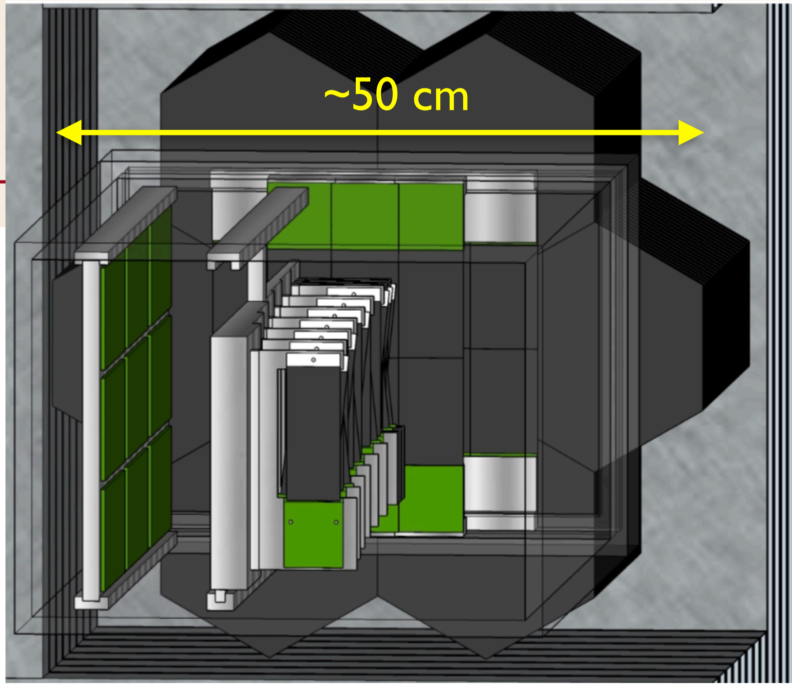
(UCSB - Incandela, Colegrove)

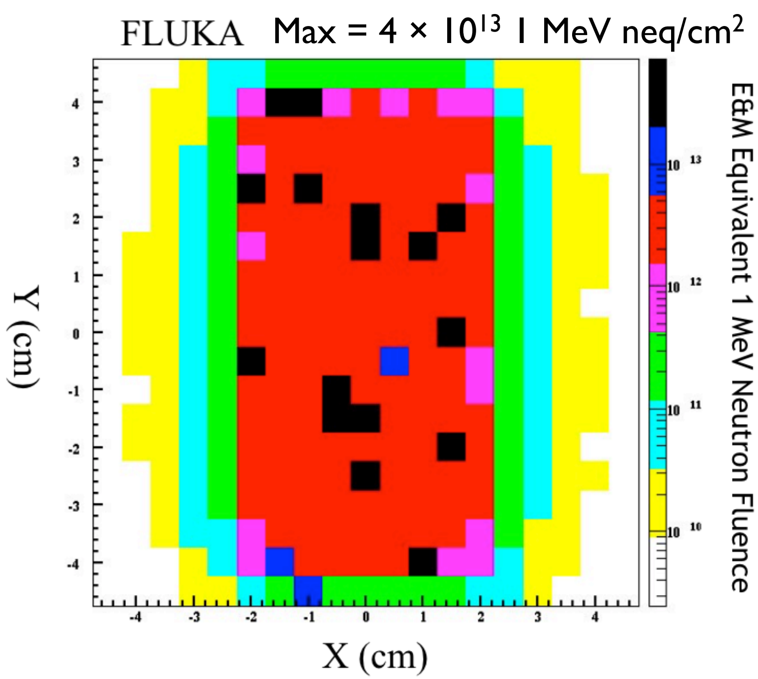
Si-W calorimeter developed for CMS upgrade

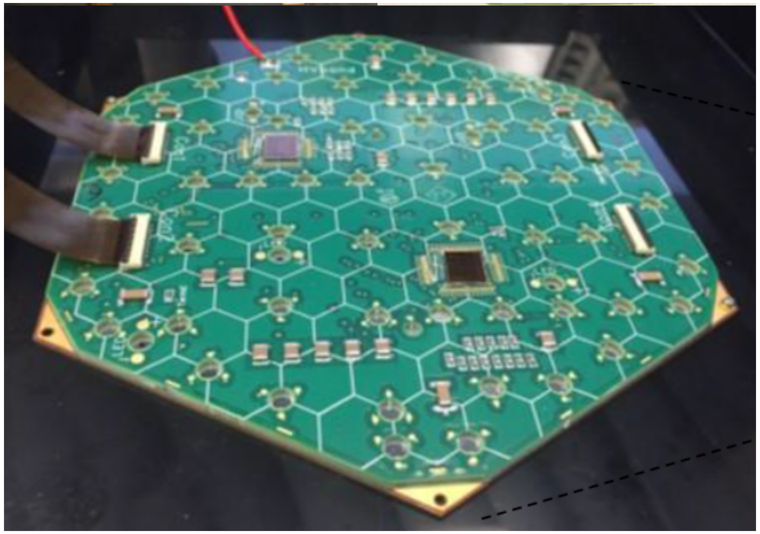
- fast, dense, granular for high occupancies
- deep (40 X_0) for extraordinary EM containment

For LDMX Phase I:

- easily exceeds radiation tolerance required
- meets rate requirement
- capable of providing fast trigger for trackers







Trigger

(UMN - Mans, Hiltbrand)

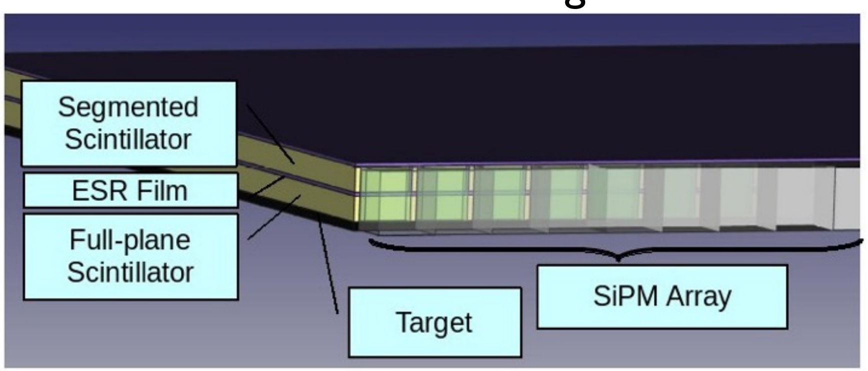
To reject beam-energy backgrounds

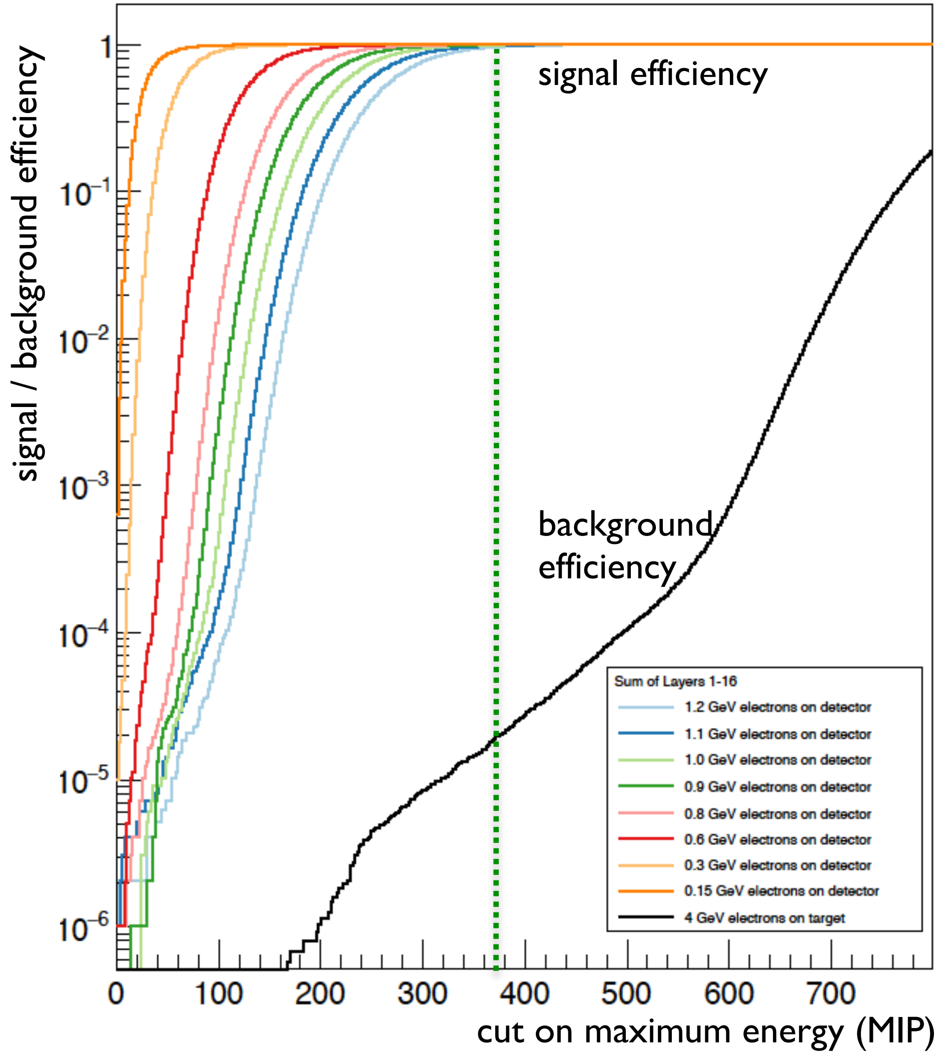
- cut on ΣE in first 16 ECal layers
- veto on empty target scintillator

Fully efficient at 2×10^{-5} rejection

($\sim3\times10^{-4}$ required for Phase I DAQ)

Instrumented Target





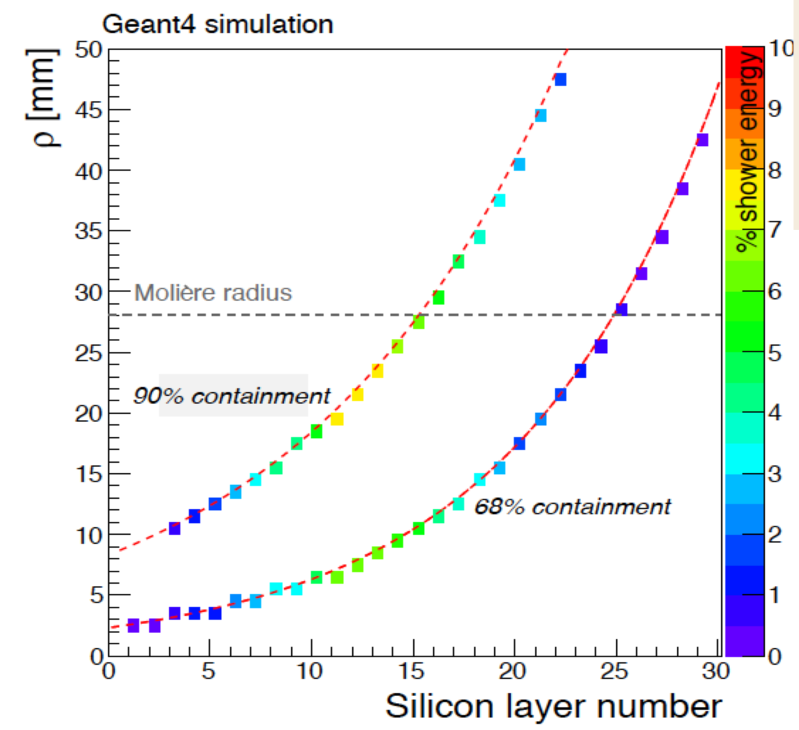
ECal Performance

Small Molière radius provides separation between recoils and high-rate e^-/γ pileup.

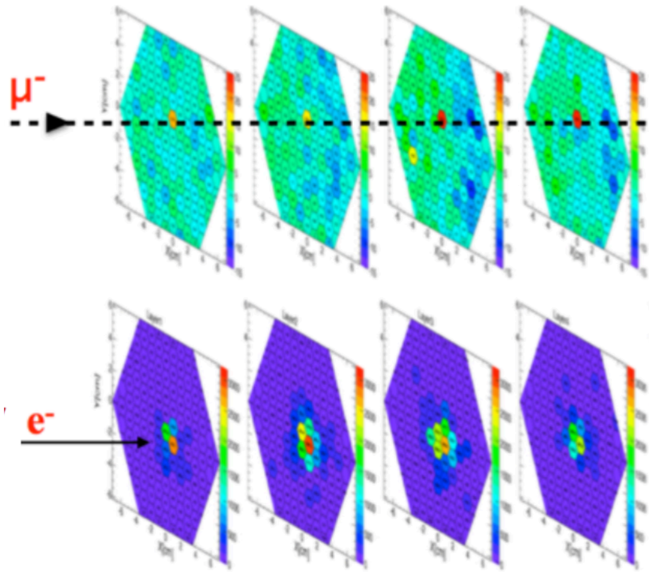
Sufficient energy resolution to separate beam energy from signal recoils reconstructed by tracker.

$$17\%/\sqrt{E} \oplus 1.4\%$$

Ability to track minimum ionizing particles (MIPs), helpful for photonuclear rejection



CERN Test Beam Data

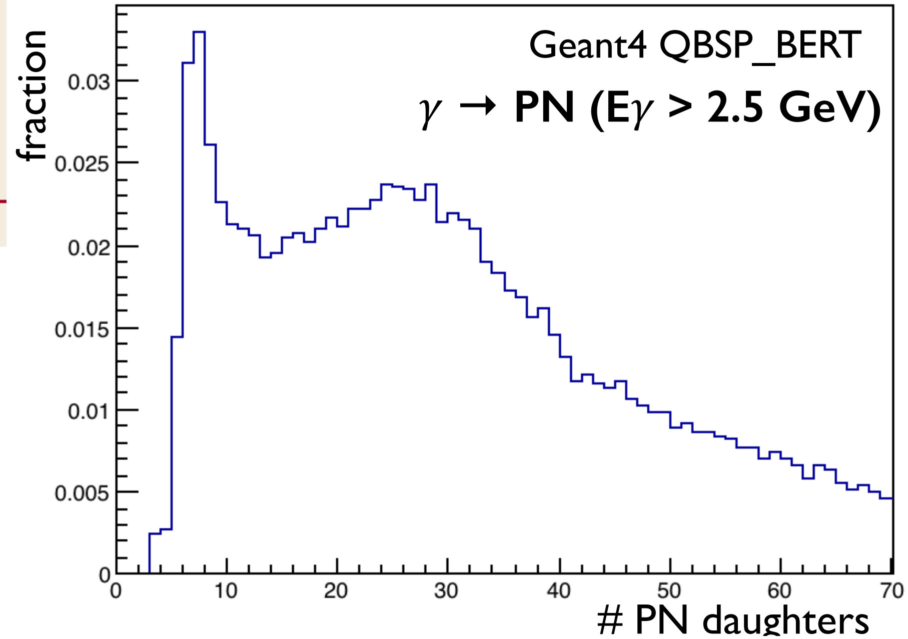


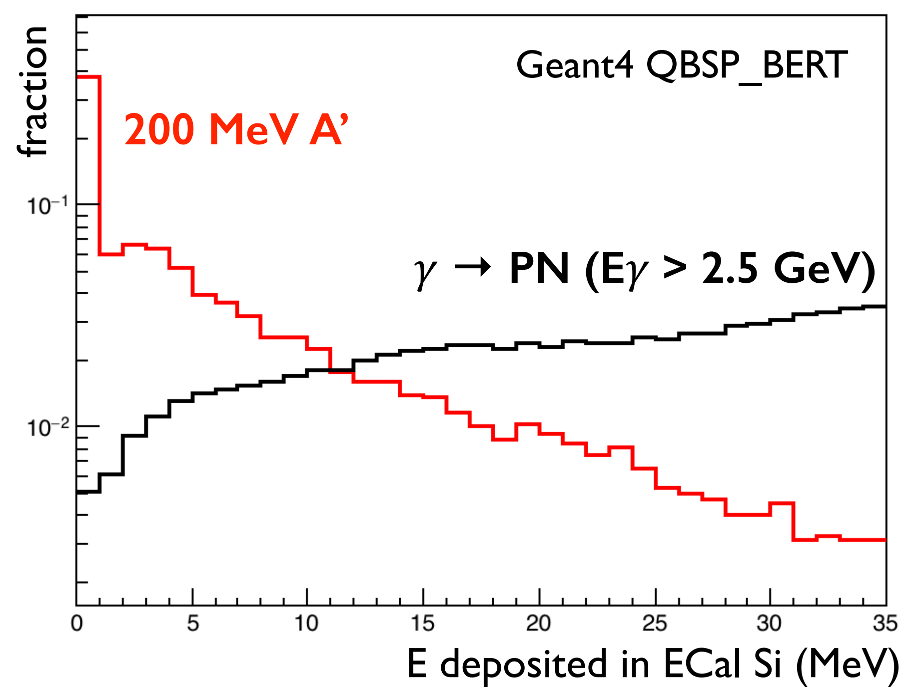
Photonuclear Backgrounds

Clearly the most challenging background

- 10^{14} EOT produce ~3×10^9 photonuclear events with $E_\gamma > 2.5$ GeV (i.e. $E_e \lesssim 1.5$ GeV)
- Mostly generated in the first few X_0 of ECal
- lower rate from target and recoil tracker

The ECal optimized to improve detection, final states with few/no charged particles in final state often escape detection.





LDMX HCal

*(FNAL - Tran, Whitbeck; Caltech - Echenard, **Hitlin**)*

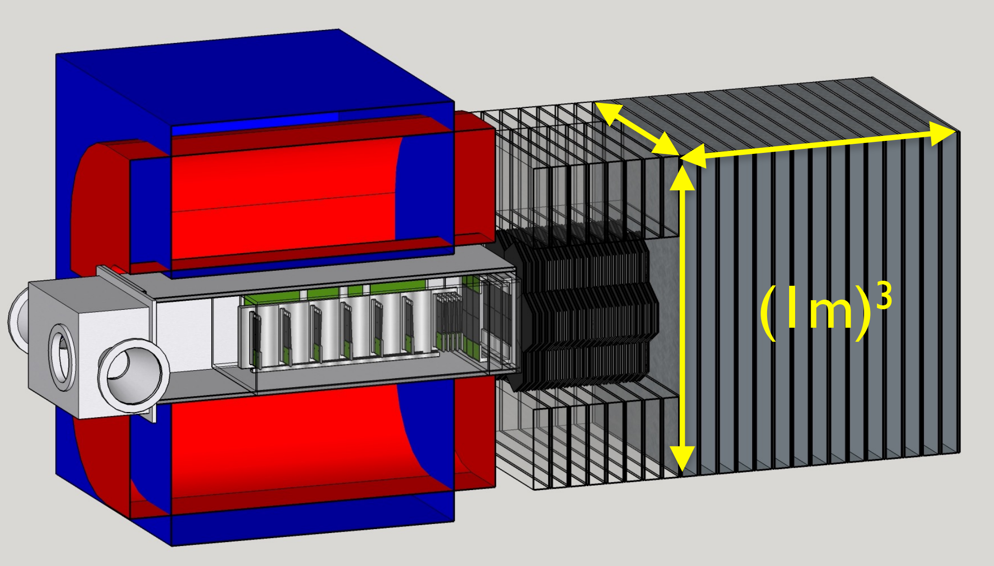
CMS upgrade hardware

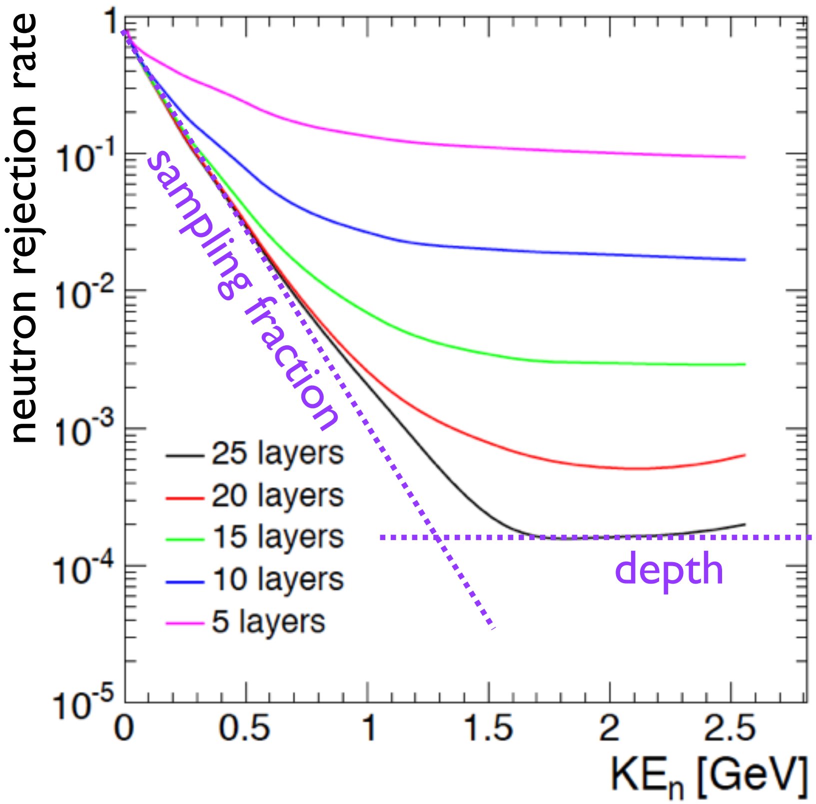
- Steel absorber/plastic scintillator
- SiPM readout via WLS fibers

Surround ECal as much as possible

- PN events with high-multiplicity of soft neutral hadrons
- Wide-angle brems (≳ 25 deg.)

HCal wants to be deeper/wider with thinner absorber layers for photonuclear rejection.





LDMX HCal!!! (?)

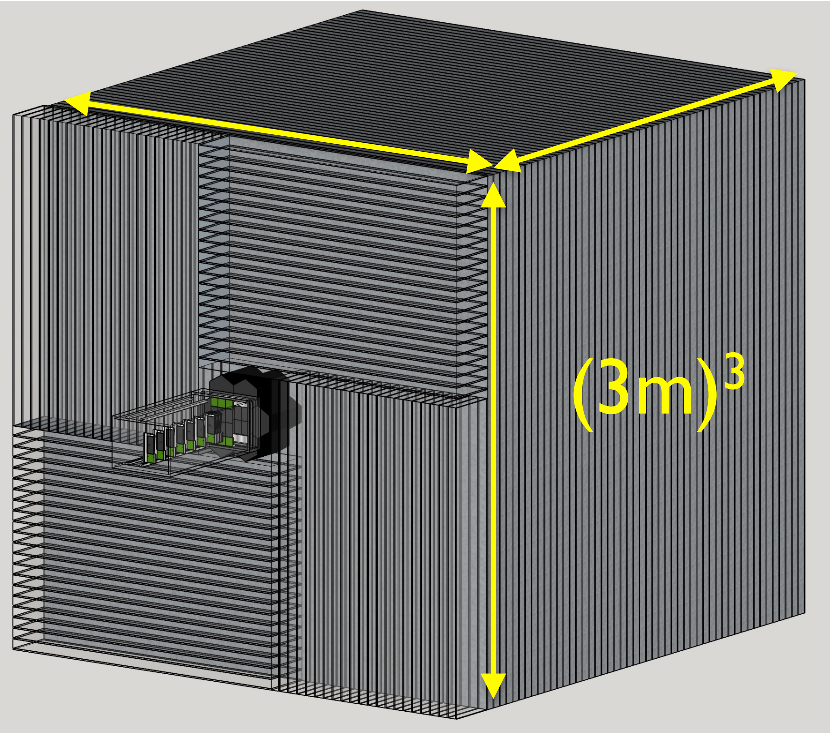
Big, beautiful HCal…IT'S YUUUGE!

- NOT a proposal, but a simulation testbed to explore HCal design
- This design vetoes Geant4 background at 10^{10} EOT. 10^{12} sample is under study.

Geant4 produces challenging backgrounds, and we are still exploring how to mitigate them

- 2 neutrons at large angles ($\gtrsim 60°$)
- only energetic particle emitted backwards!?

8 GeV beam (LCLS-II HE) would greatly reduce such backgrounds



Understanding Rare Photonuclear Events

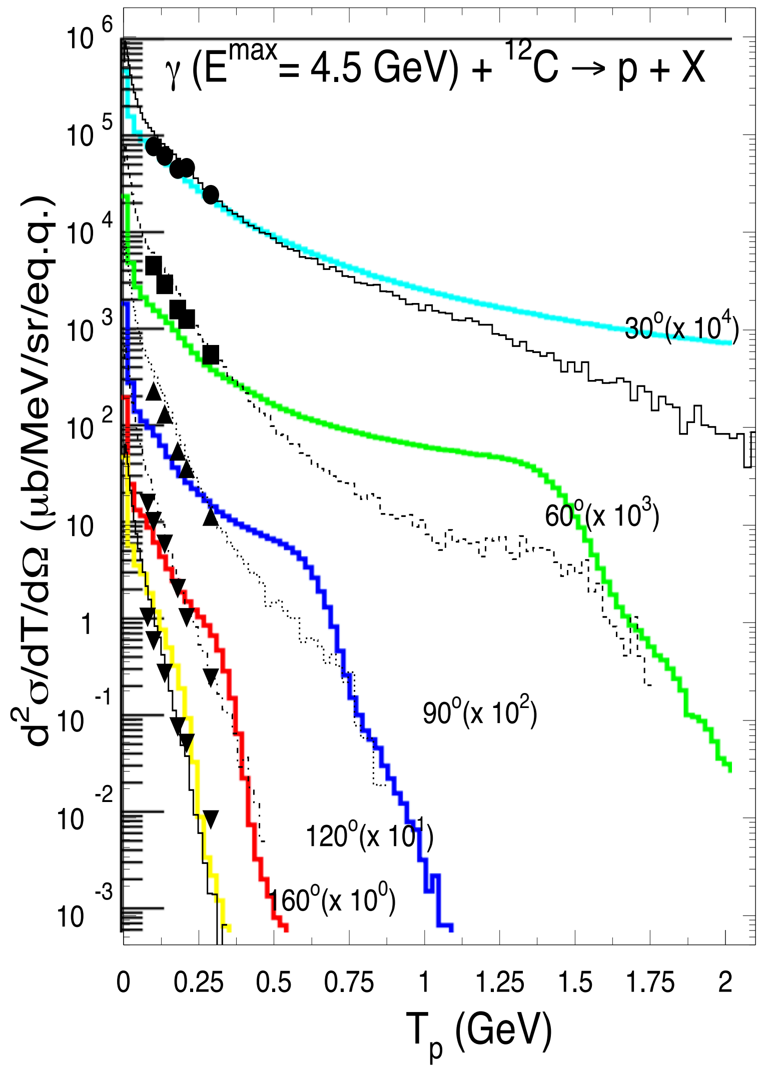
Bertini cascade model in Geant4 (colored lines at right) not tuned to data

Los Alamos code (LAQGSM) (black lines at right) is dedicated photonuclear simulation, tuned to data.

Data for high-energy photonuclear secondaries is sparse to nonexistent, especially at large angles.

*The validity of **all** simulations is questionable: talking to JLab colleagues to identify possibly useful datasets.*

Inclusive PN p+ spectra

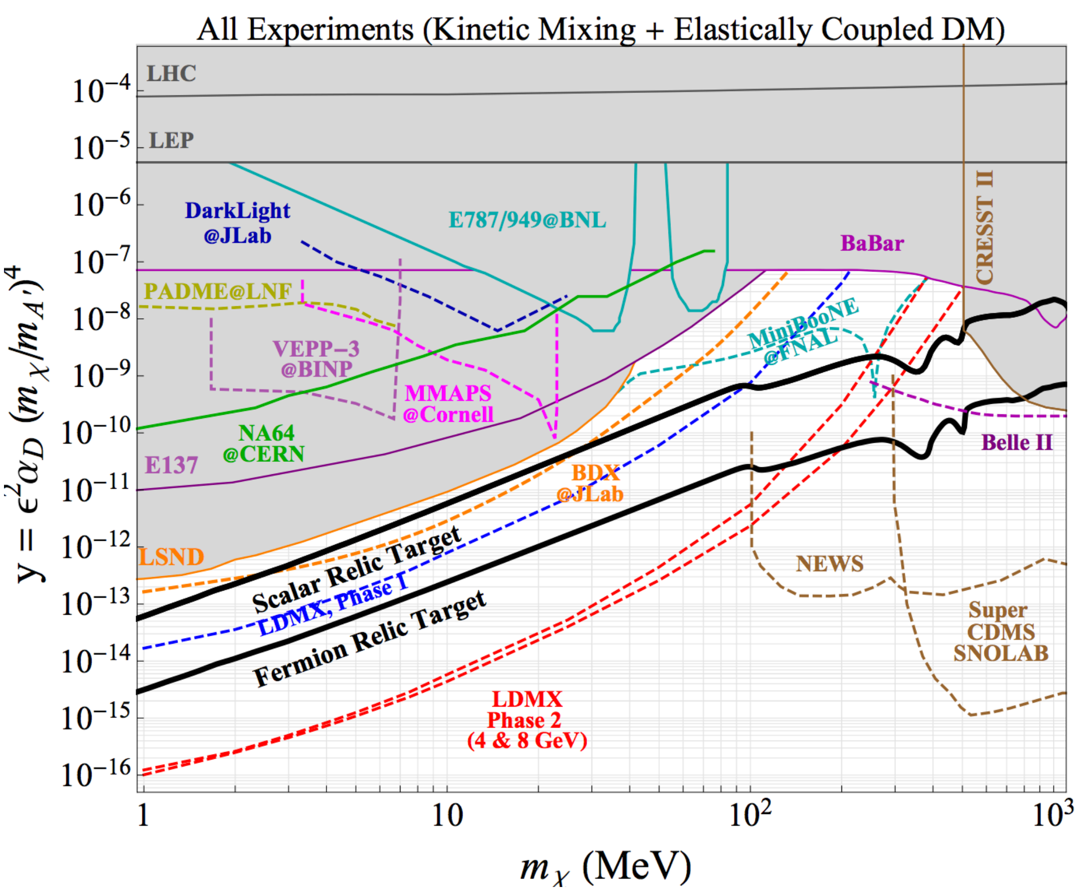


LDMX Phase I ⟹ Phase II

SLAC

LDMX for 10^{16} EOT poses additional challenges

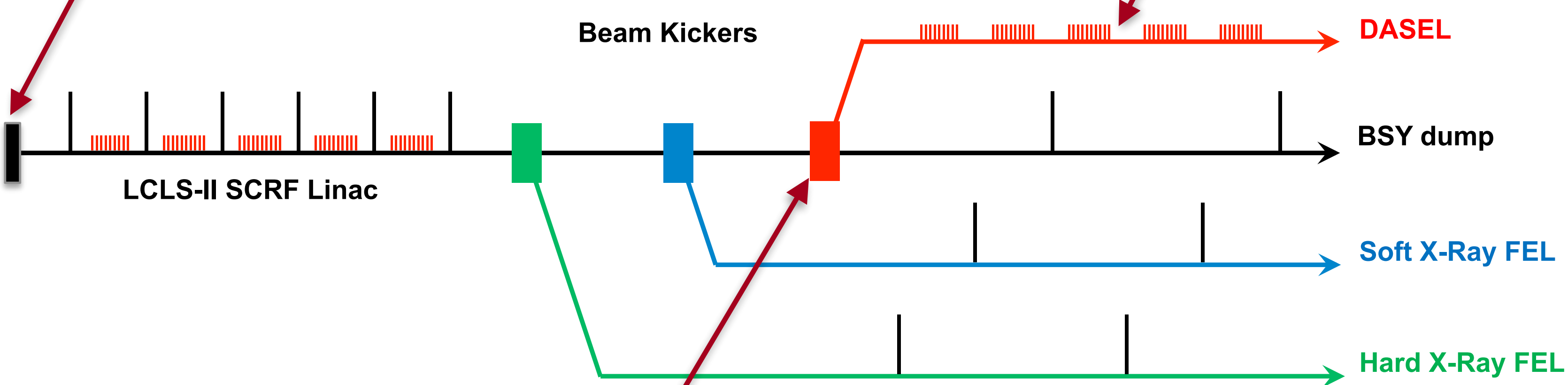
- ~ 1e^-/ns means tracking and ECal must disentangle multiple interactions with very high purity, requiring faster and more granular detectors
- Sensitive to even more exotic backgrounds than Phase I
- Likely requires upgrade of DASEL for186 MHz beam, perhaps rastering.



DASEL Phase I

Laser system to fill "unused" buckets with electrons for DASEL
- Use rejected pulses from LCLS-II laser (46 MHz)

Beamline connecting to ESA line
- 3 dipoles & 11 quads (all refurbished)

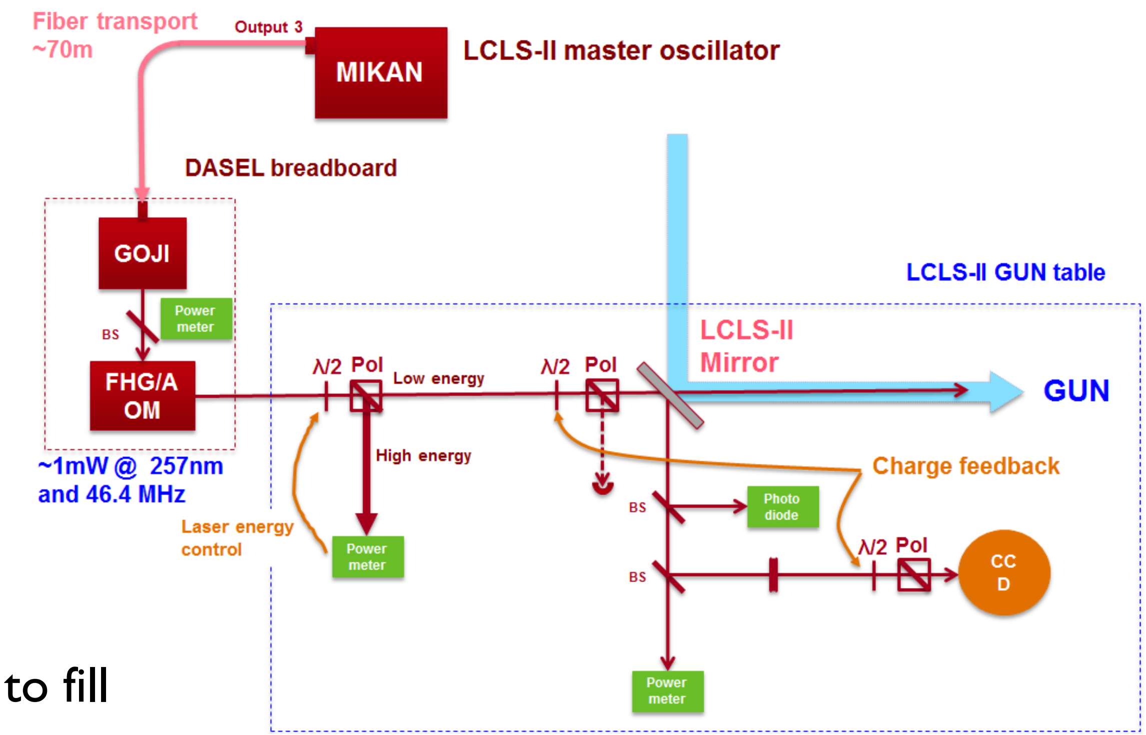


DASEL kicker/septum system downstream of FEL kickers to minimize interference
- Based on LCLS-II design but with longer kicker pulse

DASEL Laser System

Modification of LCLS-II laser system

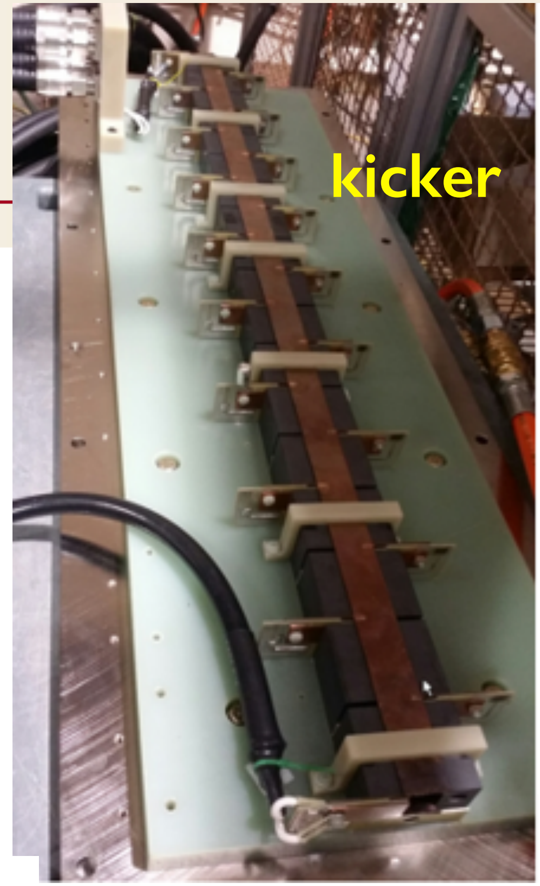
- For LDMX, dark current produces more than enough beam, but not controllable
- Instead, modify laser system to fill bunches for DASEL at 46.4 MHz (22 ns), use spoiler to reduce intensity for LDMX to ~1e⁻/bunch.
- A new laser would be needed to fill bunches at 186 MHz: likely needed for LDMX Phase II.

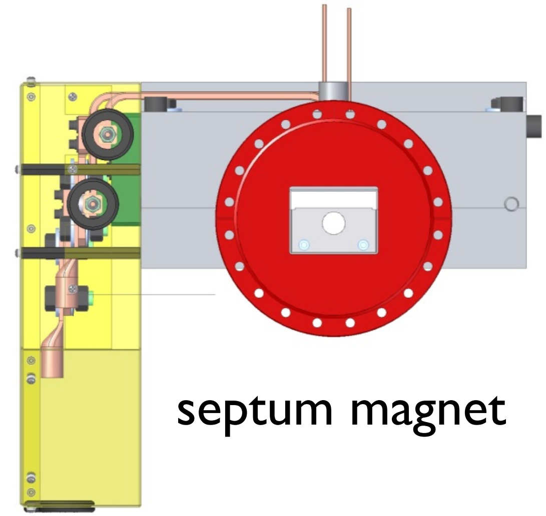


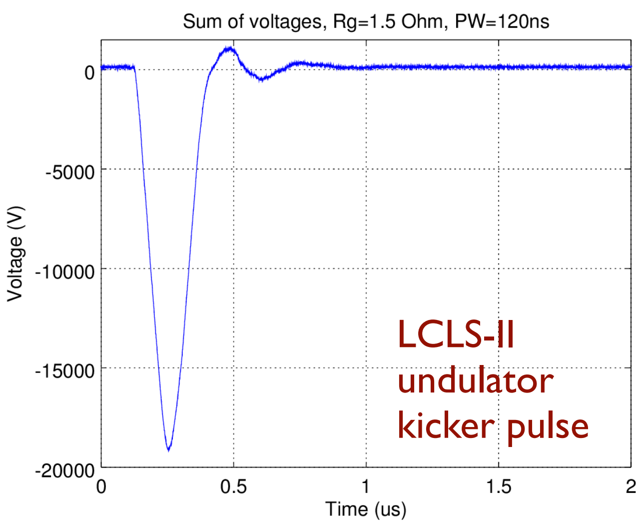
DASEL Kicker & Septum

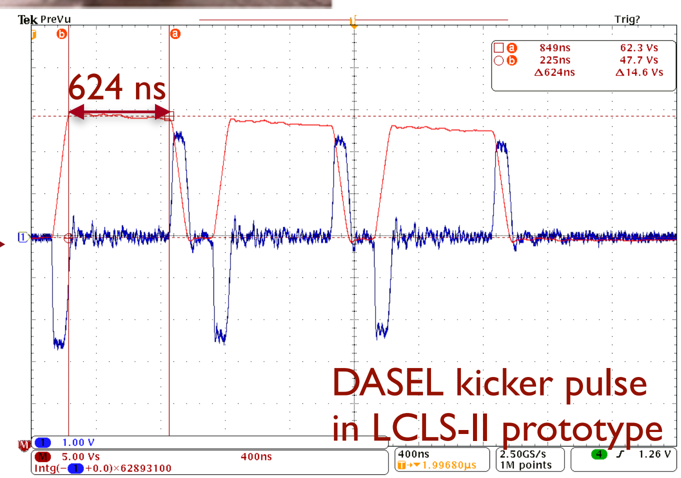
Kicker with 600 ns flattop based on LCLS-II kickers is being developed for DASEL.

Septum magnet is a copy of LCLS-II design







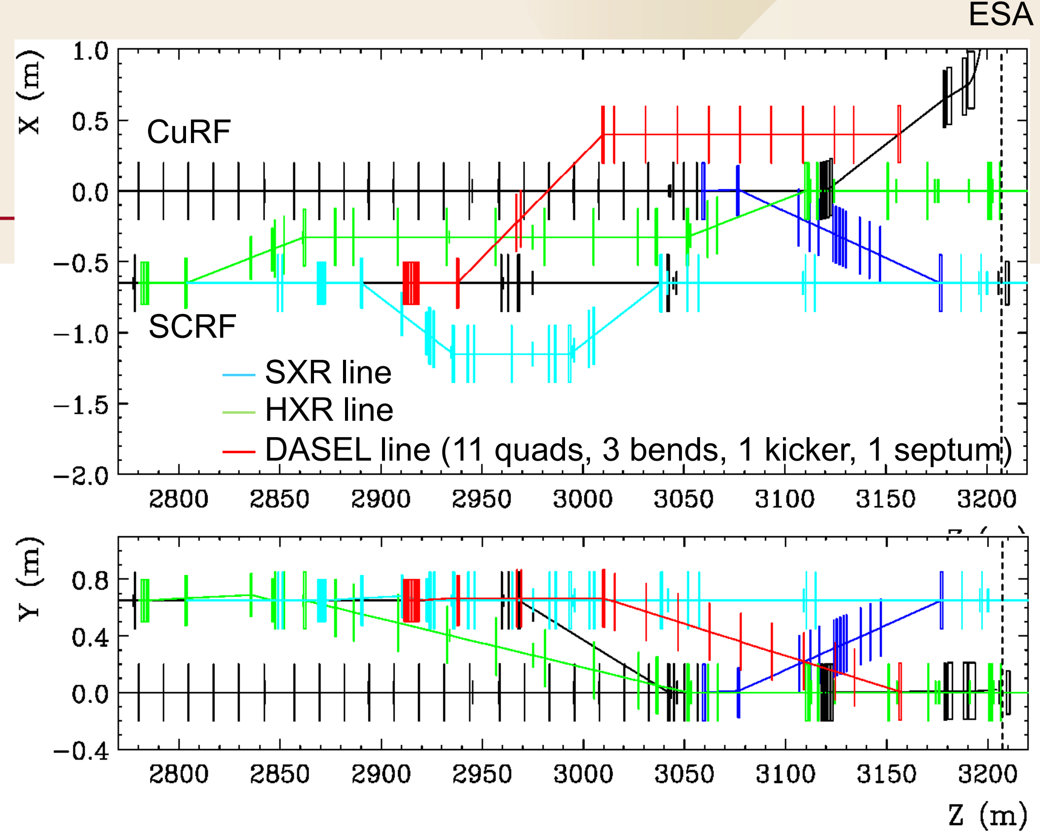


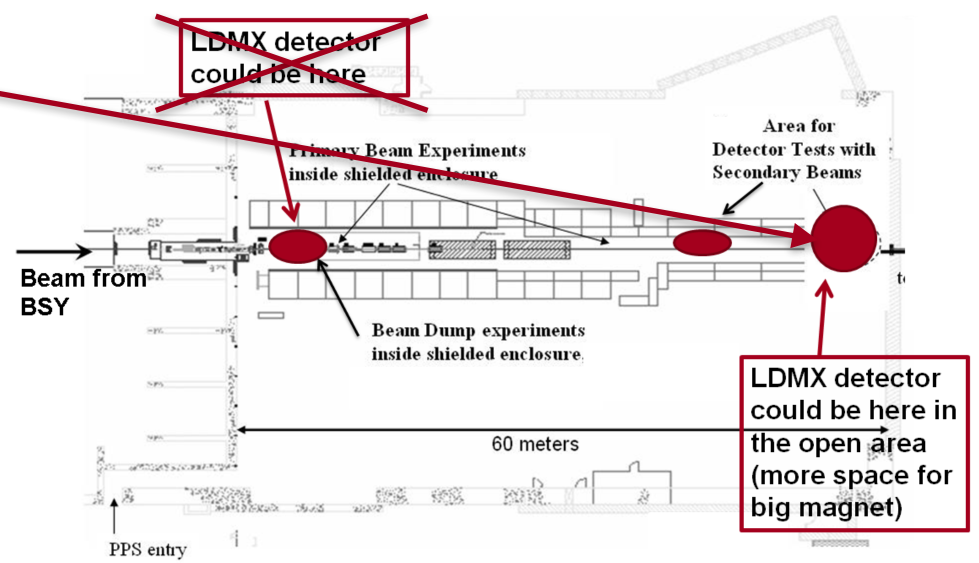
DASEL Beamline

DASEL beamline will connect the LCLS-II dump line to ESA transport line

Likely LDMX location at end of current shielding in ESA

Capable of delivering 8 GeV beam by doubling 2 quads and upgrading kicker.





DASEL After LDMX?

Experiments for visibly/invisibly decaying A′

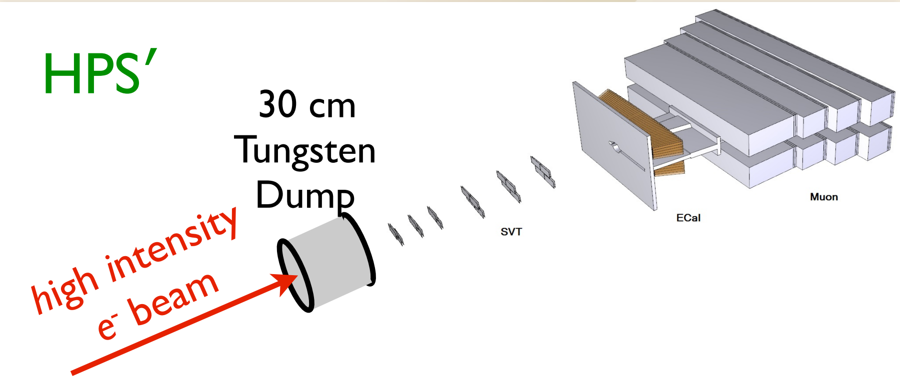
- “Super HPS”, “HPS′”
- BDX at SLAC?

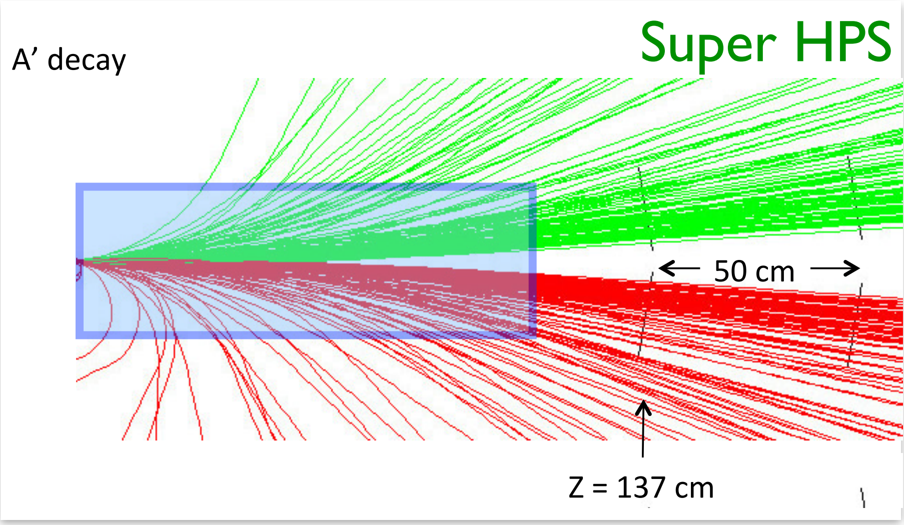
These require DASEL upgrades for higher currents and repetition rates.

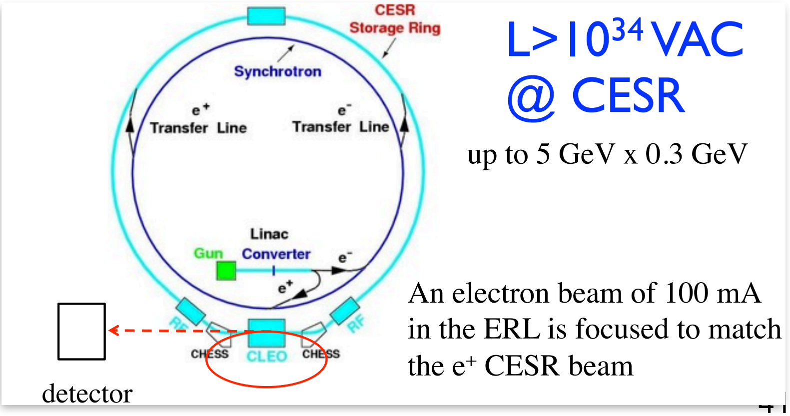
Low-energy, “Very Asymmetric Collider” (VAC): the ultimate tool for Dark Sector physics?

- CESR Concept being explored at JLab
- SLAC knows how to make positrons too

LCLS-II plans to build new undulators/ beamlines in ESA after 2025. Future DASEL experiments would need a new home.







Summary and Outlook

Dark Sectors are an interesting alternative to the minimal WIMP explanation for Dark Matter.

DASEL aims to bring accelerator based particle physics back to SLAC to study Dark Sector physics with LCLS-II.

LDMX is the flagship DASEL experiment, which will definitely test vector portal, thermally produced DM in the MeV-GeV range.

A number of other ideas for DASEL-based experiments have already been discussed, with the possibility that DASEL can be a long term pursuit at SLAC.

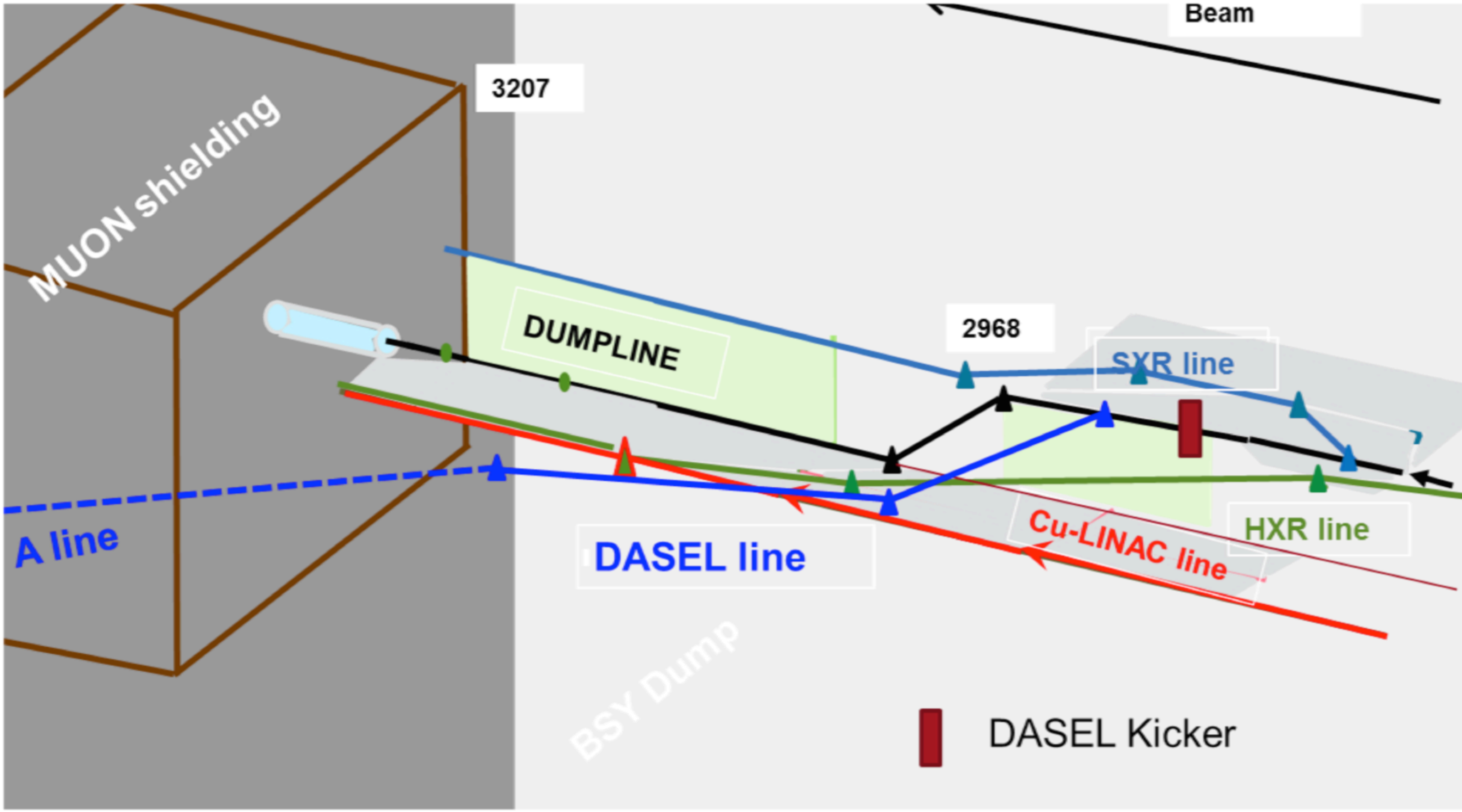
Extra Slides

DASEL Parameters

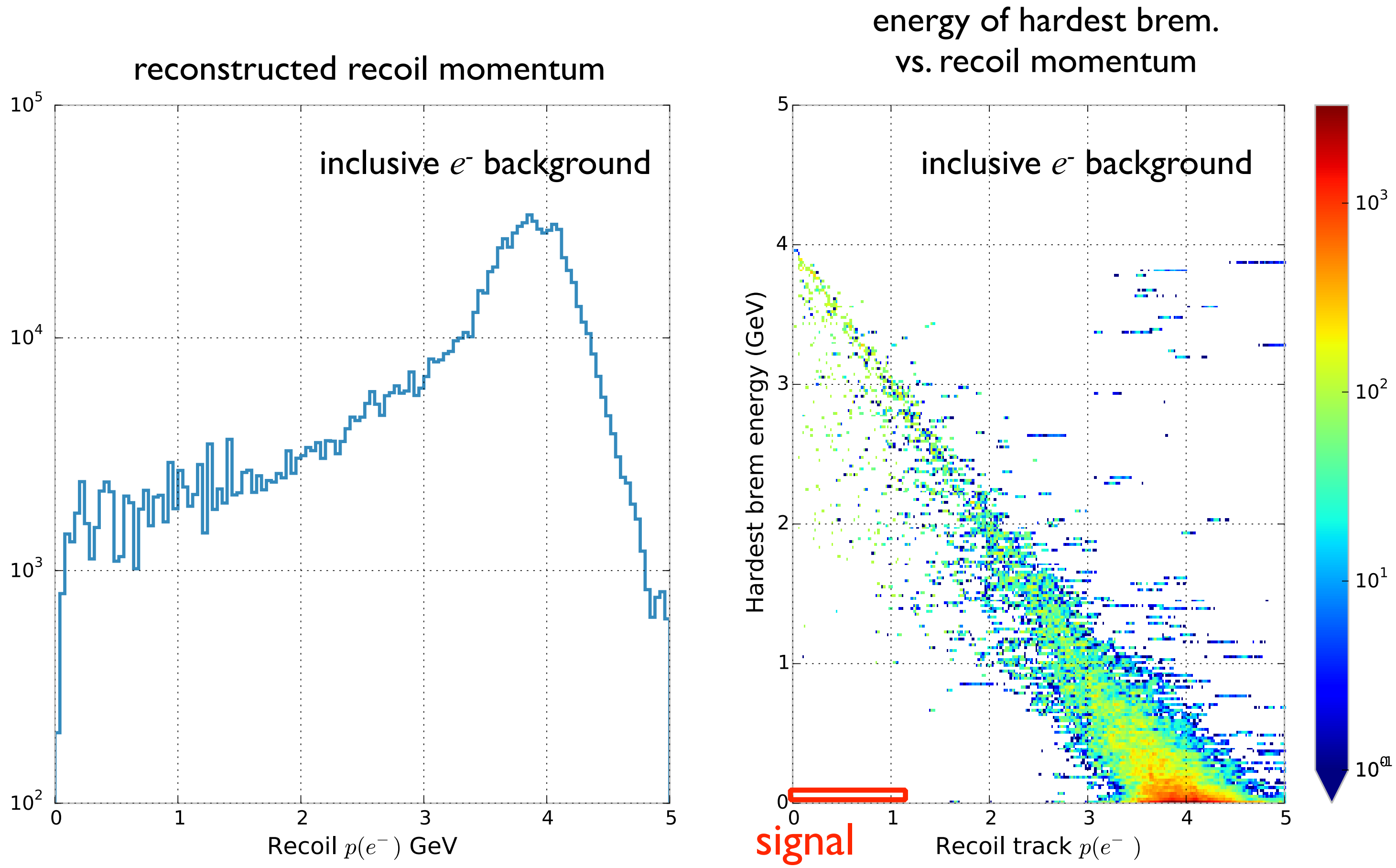
SLAC

Experiment Parameters	LDMX experiment (~2020)	Super-HPS-style upgrade (~2025)
Energy	4.0 GeV (possible to upgrade to 8.0 GeV)	4.0 GeV (possible to upgrade to 8.0 GeV)
Bunch spacing	21.5 ns	5.4 ns ←
Bunch charge	0.05 – 20 e-	70,000 e- (10 fC) ←
Macro pulse beam current	0.1 – 150 pA	2 uA ←
Duty cycle	55% (600 ns out of 1.1 us)	55% (600 ns out of 1.1 us)
Beam norm. emittance (rms)	~100 um; < 1000 um	~1 um ←
Bunch energy spread	<1%	<1%
IP spot size	4 cm x 4 cm (rastering at 40 MHz could be used)	<250 um including jitter ←
Max beam power	0.6 W	5 kW ←
ESA Spoiler Parameters		
Charge reduction	0 – 99.99%	N/A
Emittance increase	1 - 1000x	N/A
Max beam power	55 W	N/A
Spoiler thickness	0 – 0.5 r.l.	N/A
Accelerator Parameters		
Macro pulse beam current	0 – 25 nA	2 uA ←
Beam norm. emittance (rms)	~1um; < 25 um	~1um; < 25 um
Beam admittance (edge)	<50 nm; defined by LCLS-II collimators	<50 nm; defined by LCLS-II collimators
Bunch energy spread (FWHM)	<2% ; defined by LCLS-II collimators	<2%; defined by LCLS-II collimators
Bunch length (rms)	<1 cm	<1 cm
Max beam power	55 W	5 kW ←

DASEL Beamline in 3d



Recoil Tracker Momentum Resolution



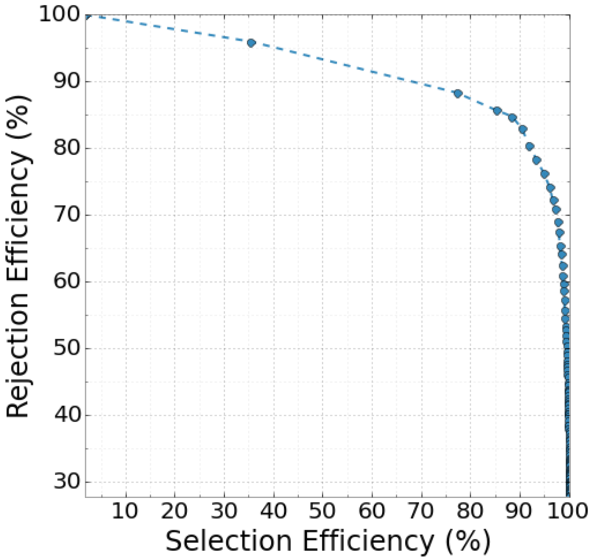
Despite compact size, recoil tracker has sufficient resolution to distinguish even non-interacting 4 GeV electrons from low-momentum signal recoils.

Rejecting Photonuclear Reactions in Target and Recoil Tracker

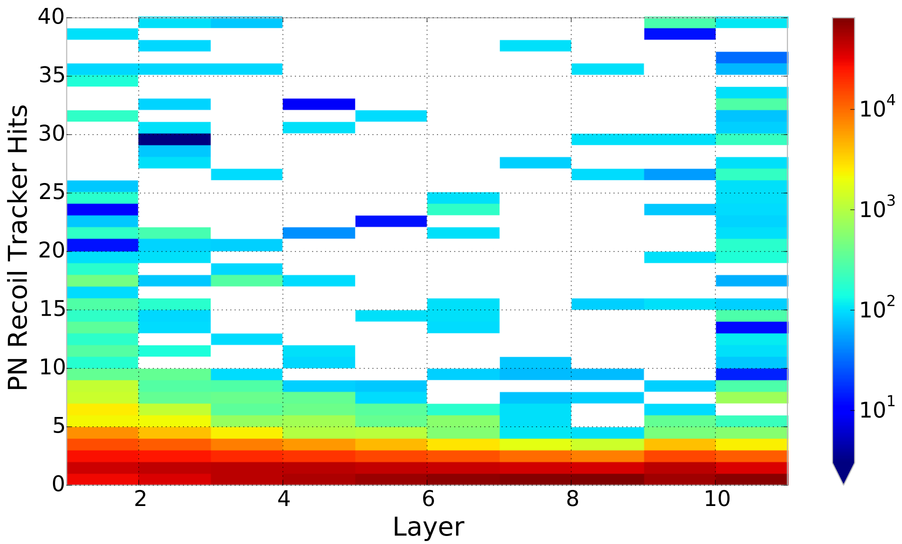
Trigger scintillator and recoil tracker can be used to reject events where a hard bremsstrahlung photon undergoes a photonuclear reaction in the target.

An active target gives nearly orthogonal information and would also be effective against events that produce only neutrals.

efficiency vs. rejection for cut on *trigger pad* energy



Recoil tracker occupancy from PN products (recoil hits excluded)



efficiency vs. rejection for cut on *target* energy