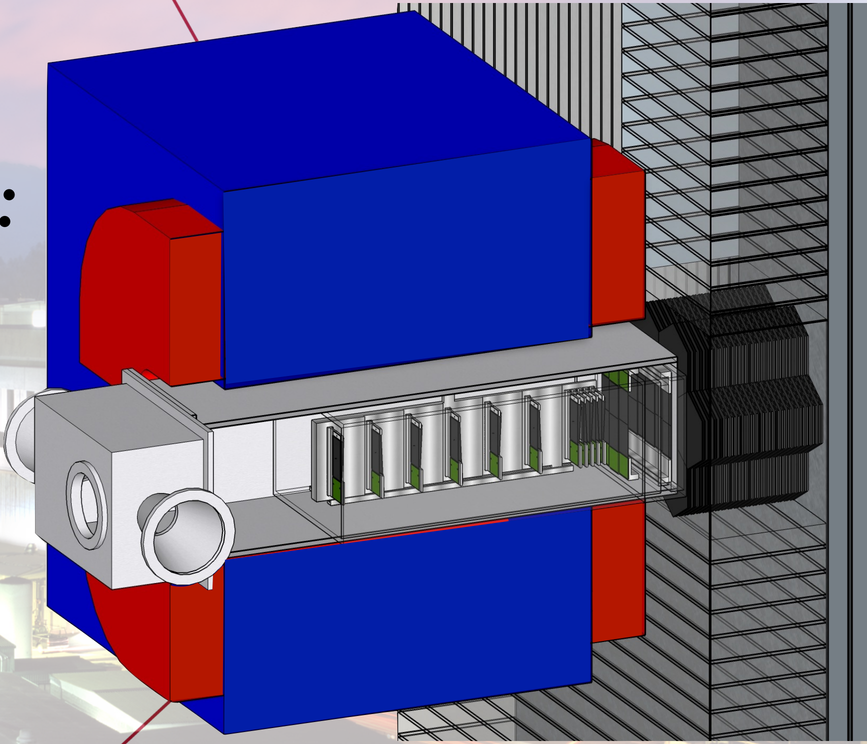
Light Dark Matter eXperiment: A Missing Momentum Search for Light Dark Matter



Tim Nelson, *on behalf of LDMX*

US Cosmic Visions: New Ideas in Dark Matter

University of Maryland - March 24, 2017

U.S. DEPARTMENT OF ENERGY
Office of Science

LDMX

SLAC NATIONAL ACCELERATOR LABORATORY

UCSB

Fermilab

Caltech

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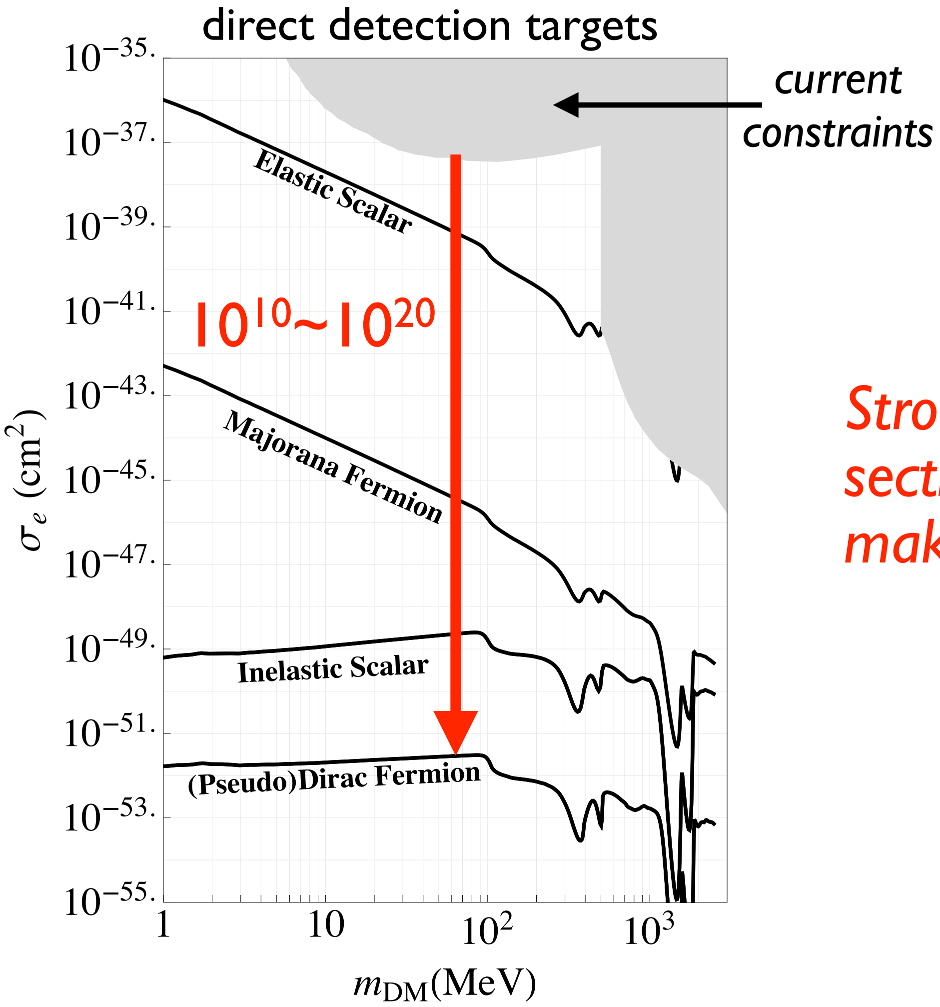
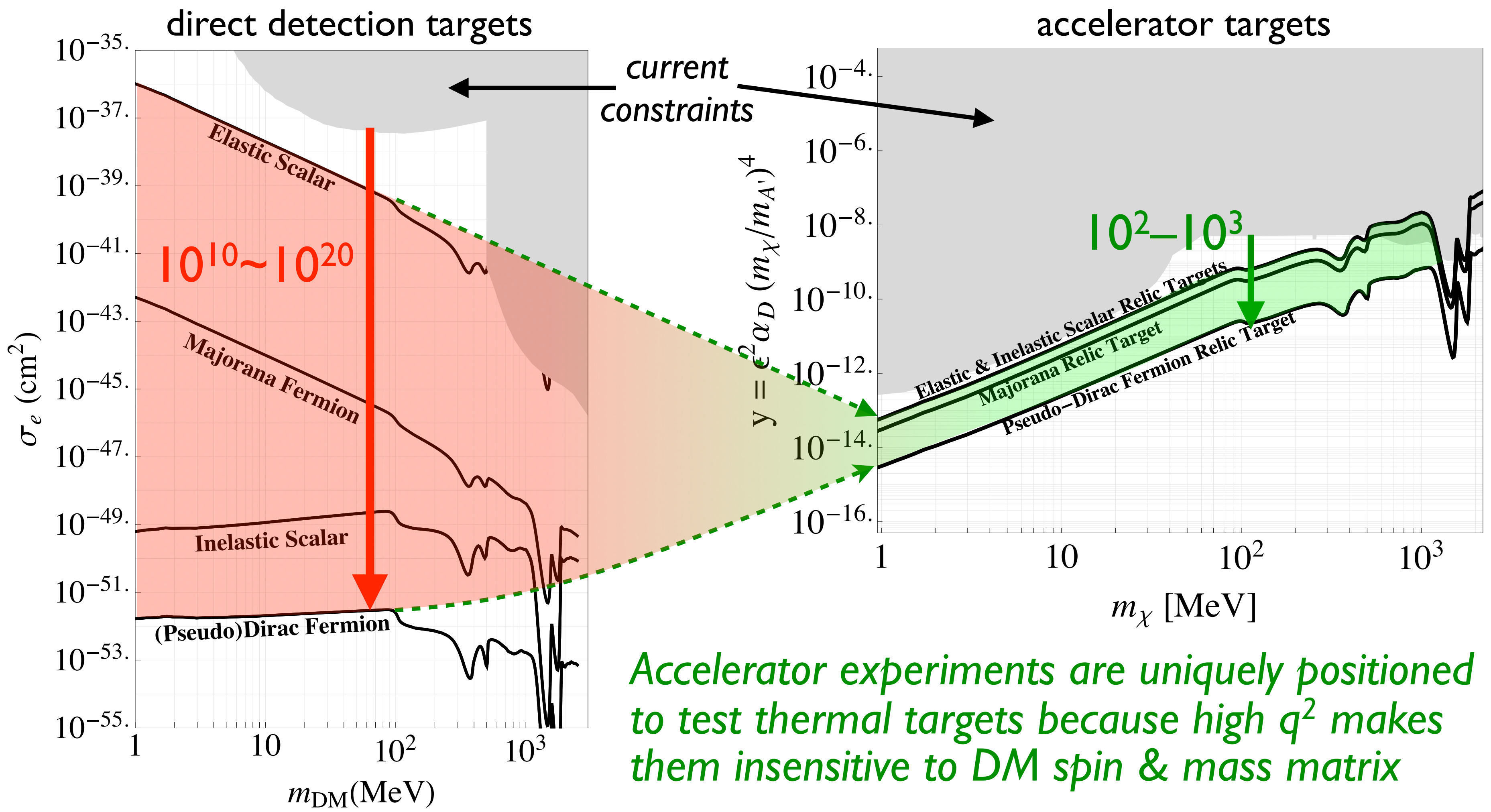
Goal: Test *all* Thermal DM Scenarios in MeV-GeV Range



Strong velocity dependence in cross section for all but the elastic scalar case makes direct detection very challenging.

Goal: Test *all* Thermal DM Scenarios in MeV-GeV Range



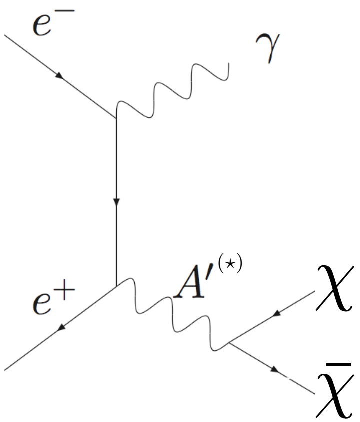
Accelerator experiments are uniquely positioned to test thermal targets because high q^2 makes them insensitive to DM spin & mass matrix

Maximizing Sensitivity for Accelerator Searches

Maximize DM yield $\Longrightarrow$ maximize dark mediator production

"where there are photons, there are dark photons"

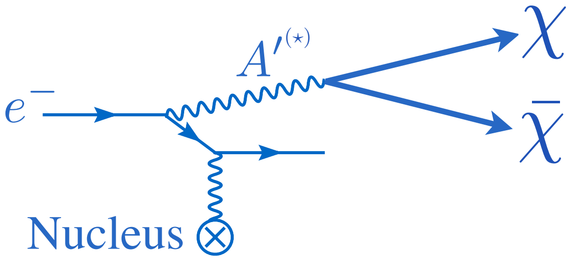
colliders



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

$$\ll$$

fixed target



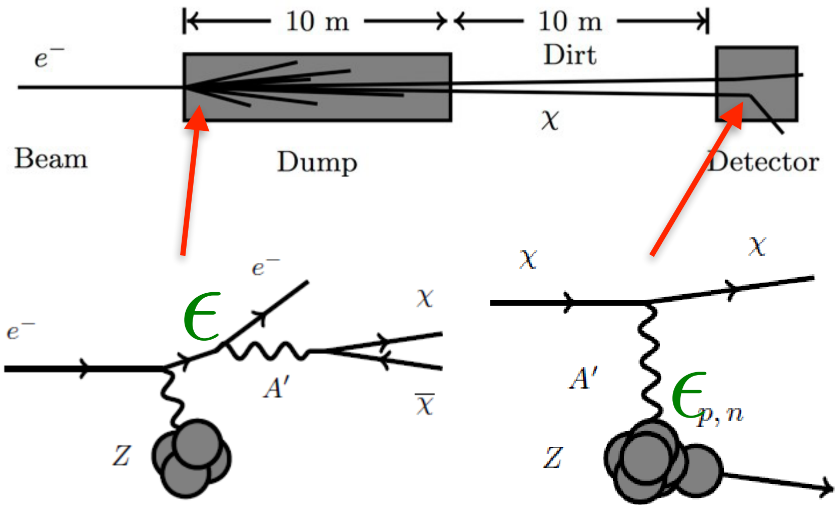
$$\sigma \propto \frac{Z^2\epsilon^2}{m_{\rm A'}^2}$$

Dark bremsstrahlung is the simplest way to generate large yields of light DM

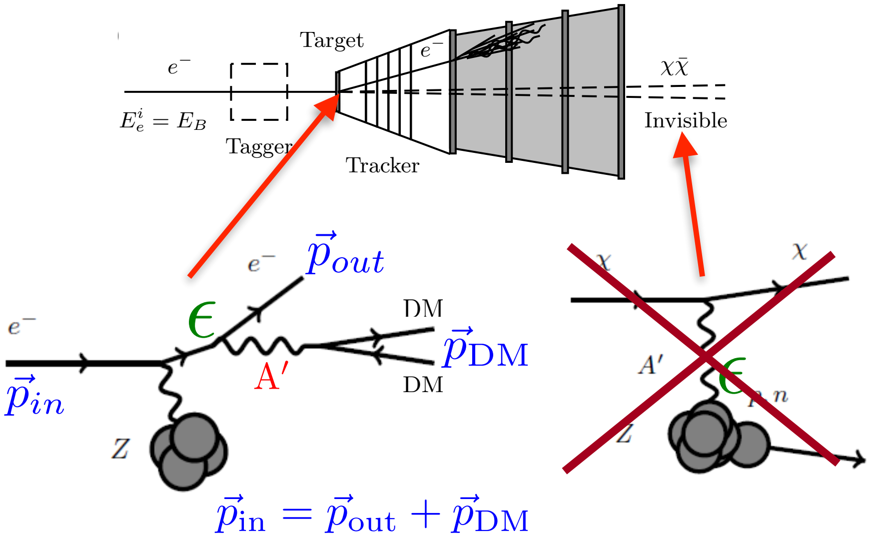
Maximizing Sensitivity for Accelerator Searches

Maximize DM detection efficiency

beam dump



missing momentum

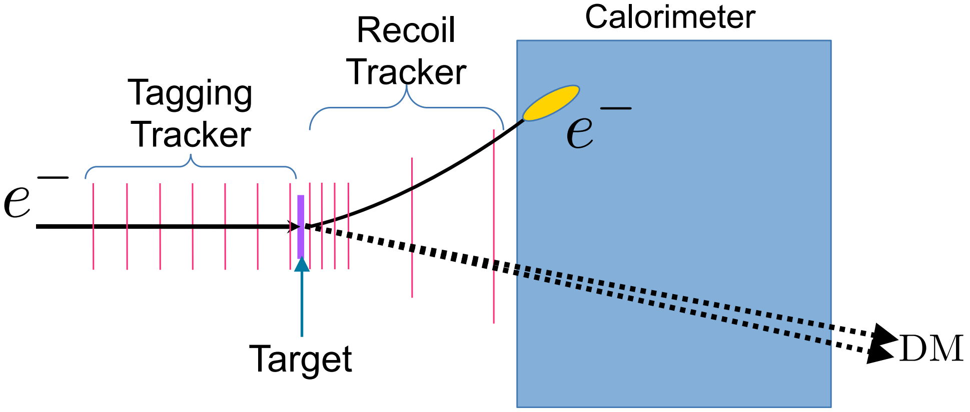


$$N \propto \epsilon^4 \quad \ll \quad N \propto \epsilon^2(1-\epsilon^2) \approx \epsilon^2$$

Missing momentum approach results in highest signal yields

The Light Dark Matter eXperiment

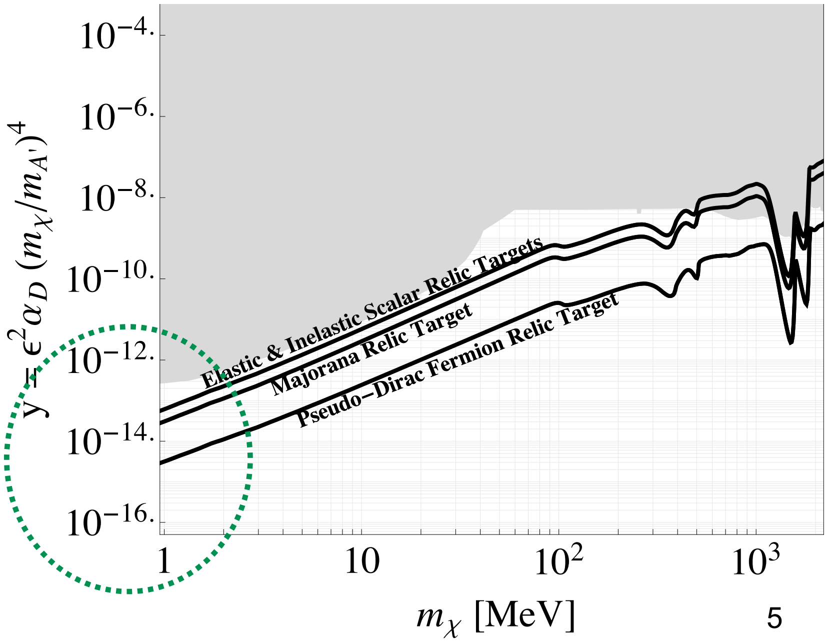
LDMX is an e^- fixed-target missing momentum search for light dark matter.



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

➡ a zero background experiment can definitively test thermal DM over most of MeV-GeV range with ~10^{16} e^-

*IF that experiment has high signal efficiency!

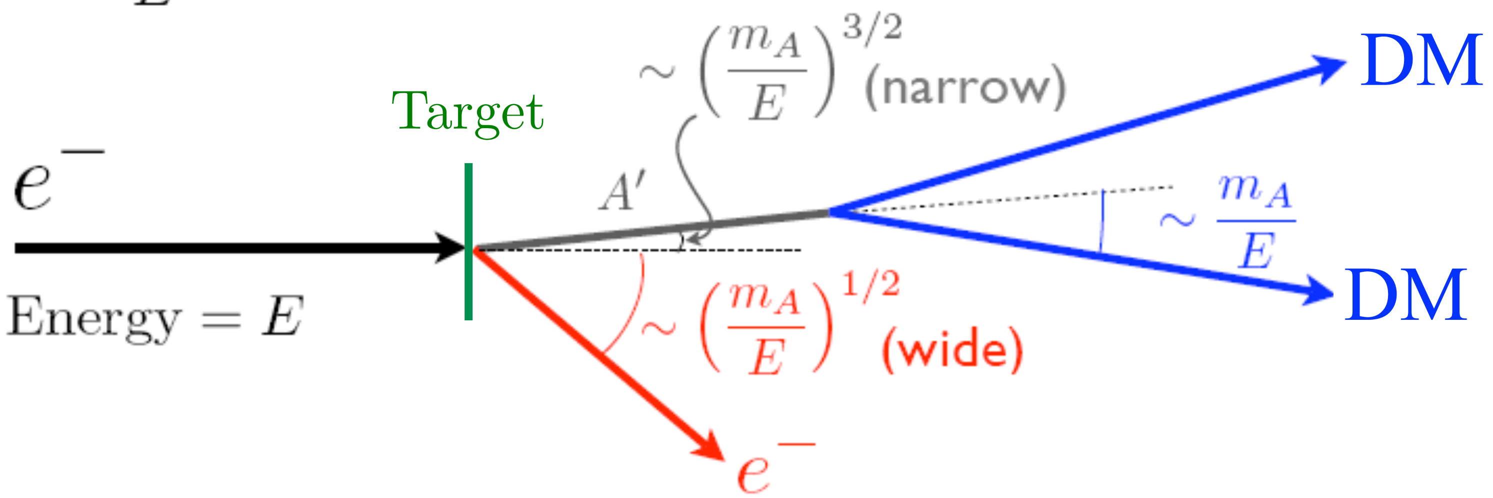


Dark Bremsstrahlung Kinematics

$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + \boxed{m_A^2(1-x)/x}}$$

$$x = \frac{E_A}{E}$$

Kinematics **very different** from massless photon bremsstrahlung



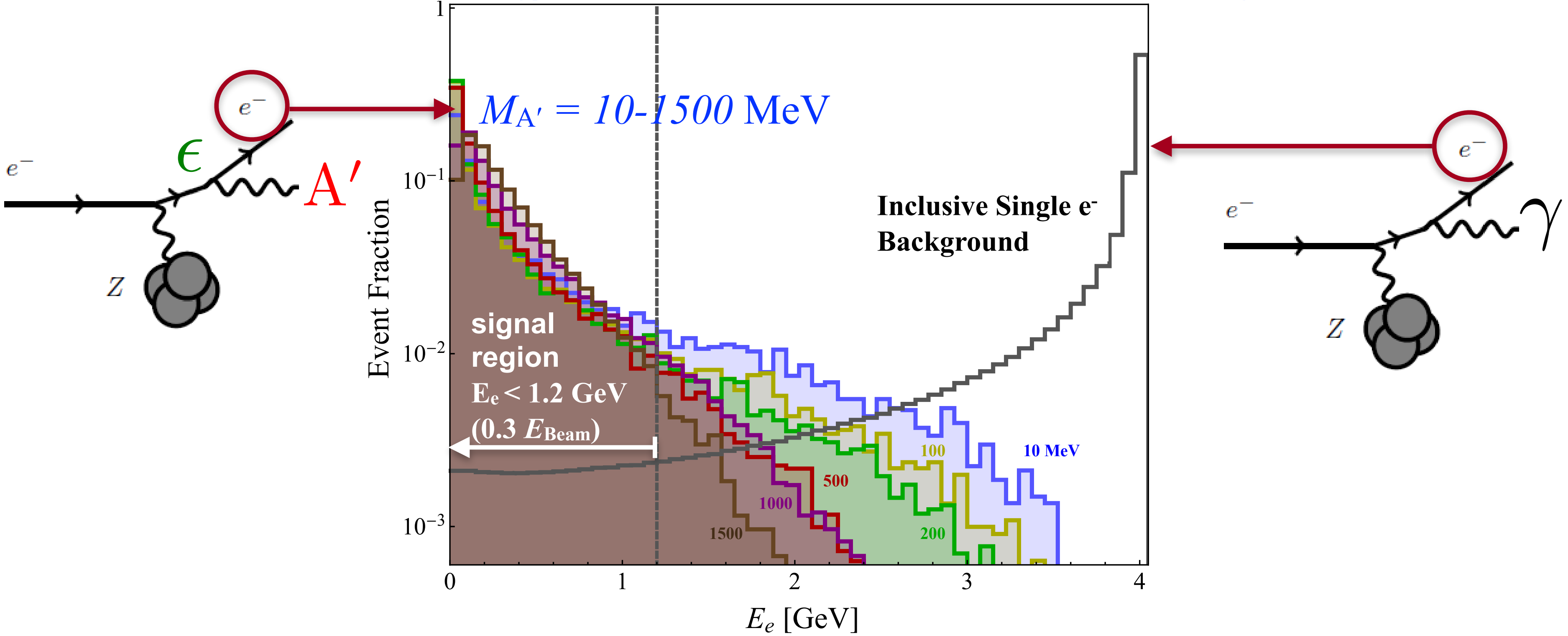
Heavier product (A′) carries away most of the beam energy

$\Longrightarrow$ recoil electron is soft — large missing energy

$\Longrightarrow$ recoil electron emerges at wide angle — large missing *momentum*

Dark Bremsstrahlung (signal) vs. Bremsstrahlung (background)

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

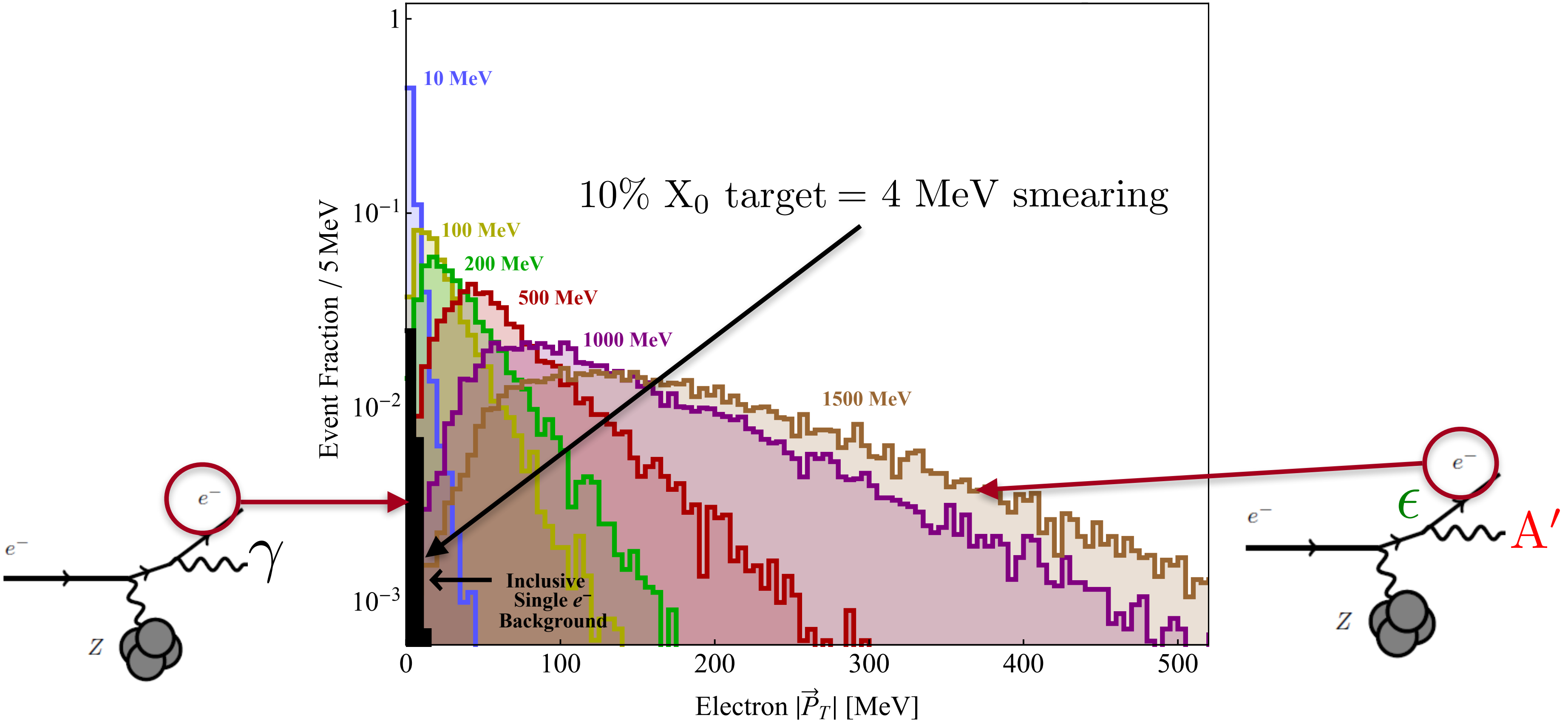


Recoil kinematics allow efficient signal definition providing ~30× background rejection

- *Tagging tracker:* track with $|p| = E_{\text{beam}}$ on expected trajectory
- *Recoil tracker:* single track, with $|p| < 0.3\ E_{\text{beam}}$, that points back to tag in target
- *Calorimeters:* shower consistent with recoil track and no other activity

Dark Bremsstrahlung (signal) vs. Bremsstrahlung (background)

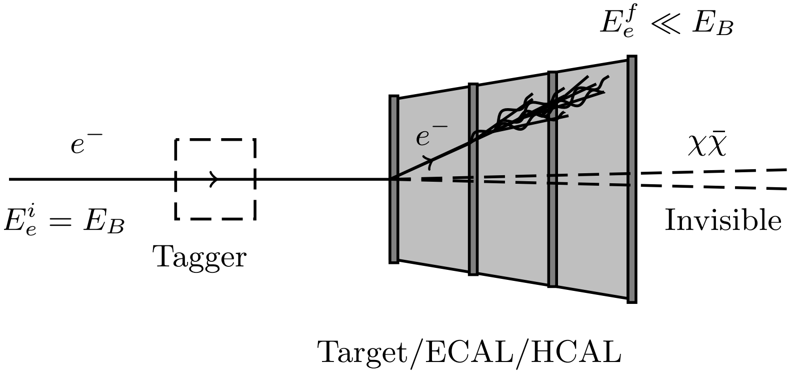
recoil p_T distributions, 4 GeV e^- on 10% X_0 target

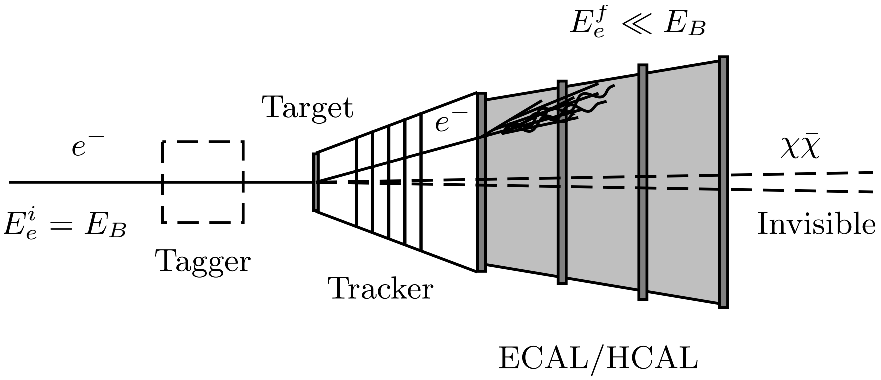


$10\%\ X_0$ target $=$ 4 MeV smearing

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

Missing Energy vs. Missing Momentum





Missing energy experiments…

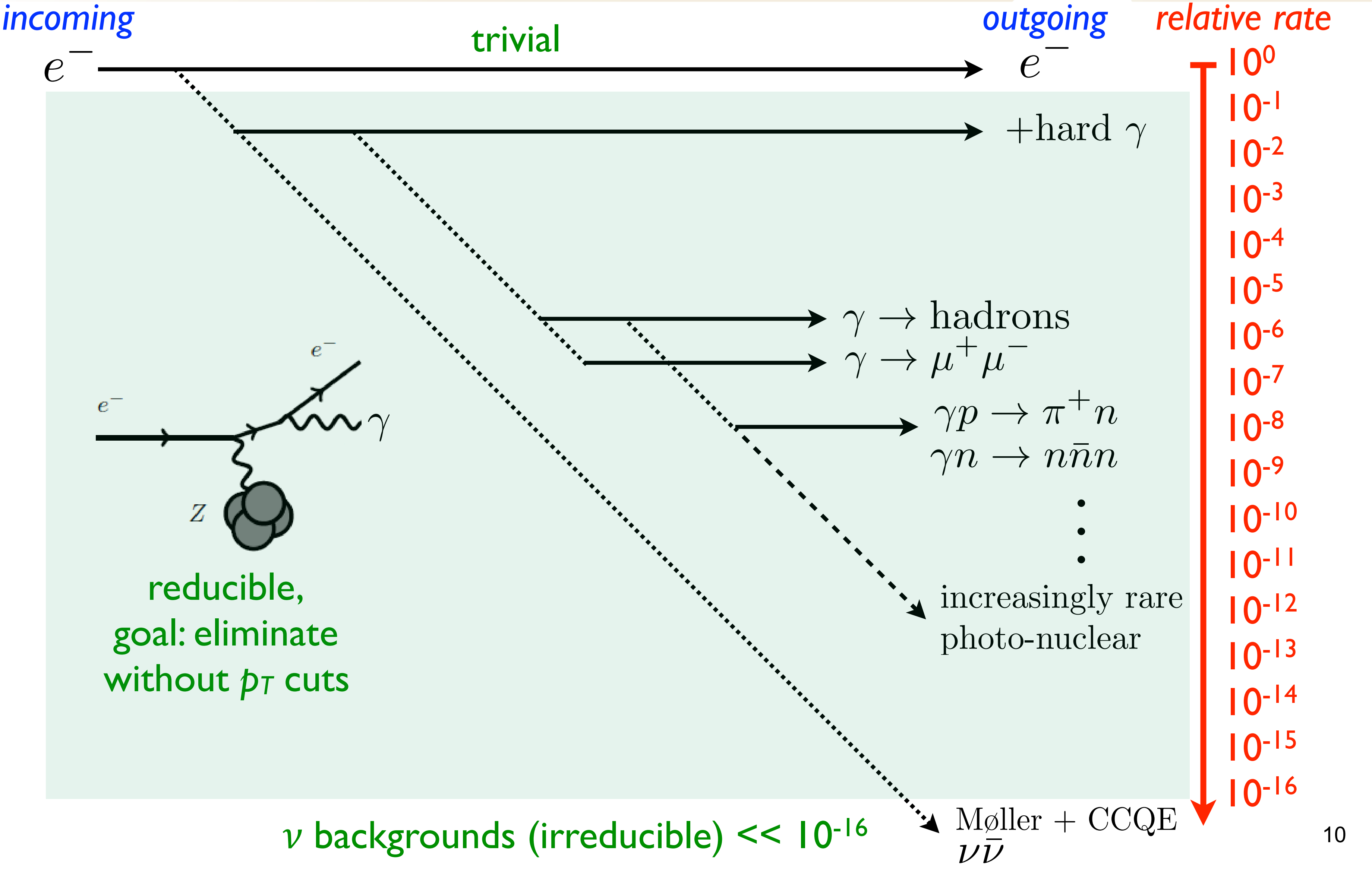
- have higher signal yields/EOT
- have greater acceptance
- *are challenged by backgrounds beyond 10^{14} EOT that require e-γ particle ID*

Missing momentum experiments…

- have p_T as a signal discriminator
- have p_T as a signal *identifier*, sensitive to $m_{A'}/m_\chi$
- *are equipped for e-γ particle ID*
- ***include a missing energy experiment***

Nothing prevents LDMX from doing a "missing energy" analysis, which probes backgrounds 3~10× beyond missing momentum statistics.

Backgrounds for Missing *Momentum* Experiments



incoming

trivial

outgoing

relative rate

e^- → e^-

+hard γ

$\gamma \rightarrow$ hadrons

$\gamma \rightarrow \mu^+\mu^-$

$\gamma p \rightarrow \pi^+ n$

$\gamma n \rightarrow n\bar{n}n$

⋮

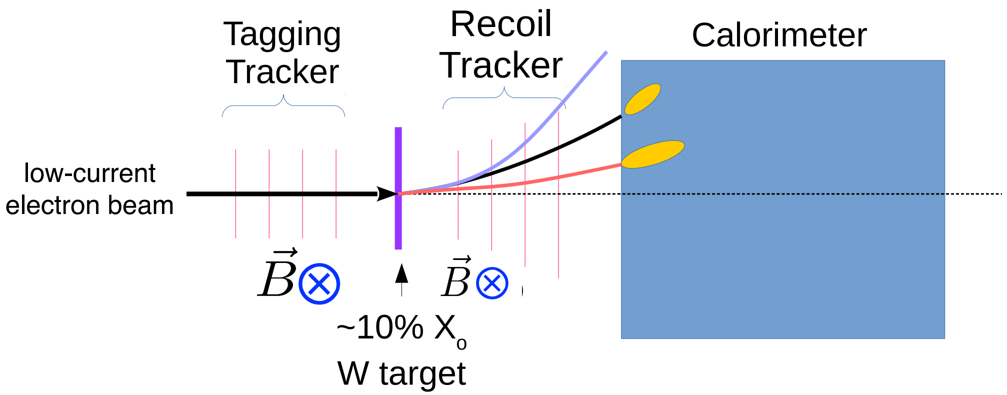
increasingly rare photo-nuclear

Møller + CCQE $\nu\bar{\nu}$

reducible,
goal: eliminate
without p_T cuts

ν backgrounds (irreducible) << 10^{-16}

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



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 CEBAF @ JLab (up to 11 GeV).
- large beamspot (~10 cm^2) to spread out otherwise extreme rates and radiation doses

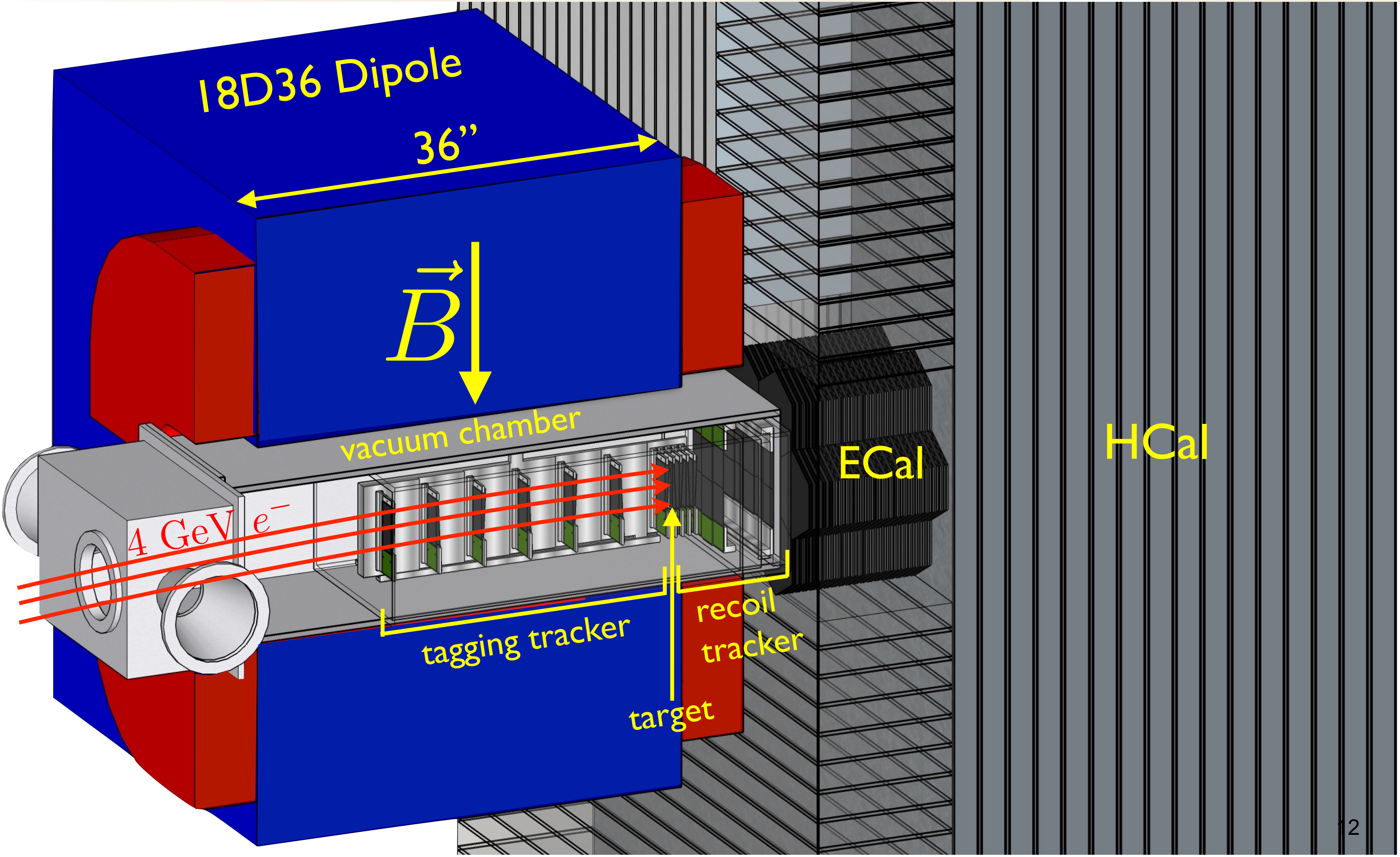
Tracking and calorimetry capable of high rates and radiation tolerance

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

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

~1e^- / 25 ns @ 4 GeV $\mathcal{O}$(1e^-/ns) , ≳8 GeV

LDMX Phase I Detector Concept



Tracking Spectrometers

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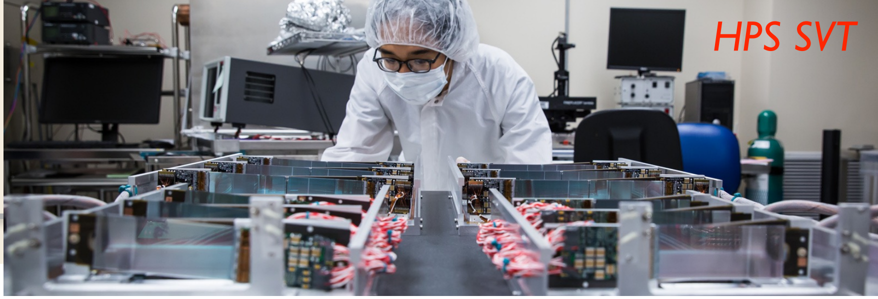


Silicon trackers similar to HPS SVT

- fast (2 ns hit timing)
- meets requirement for radiation tolerance

Single dipole magnet - two field regions

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

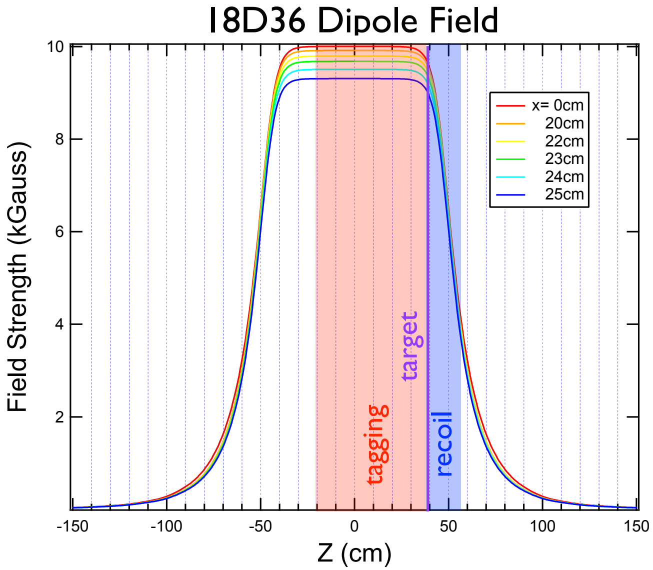
- 7 layers, long/narrow to select against off-energy e^-

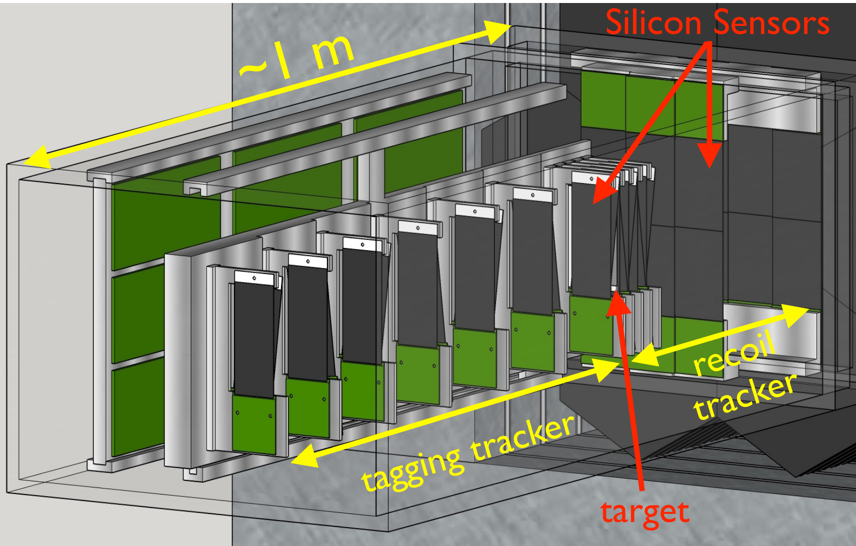
Recoil Tracker in fringe field for p_e = 50~1200 MeV

- 6 layers, short/wide to maximize acceptance for both recoil tracker and ECal

Tungsten target (0.1-0.3 X_0) between trackers

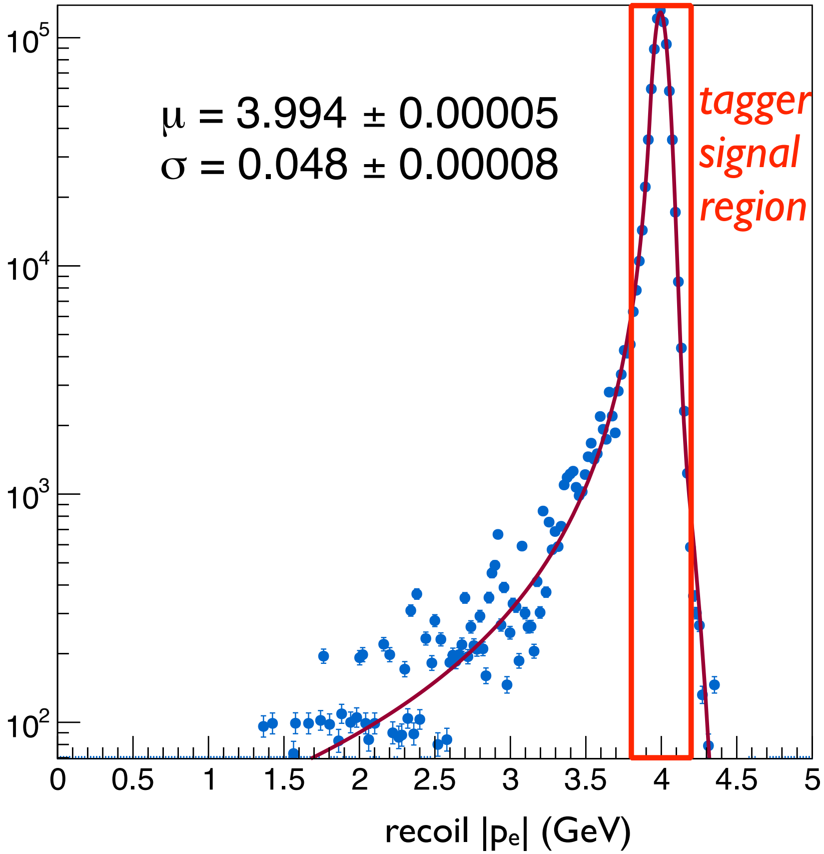
- thickness balances signal rate against p_T from MS
- scintillator vetoes ECal trigger on empty buckets



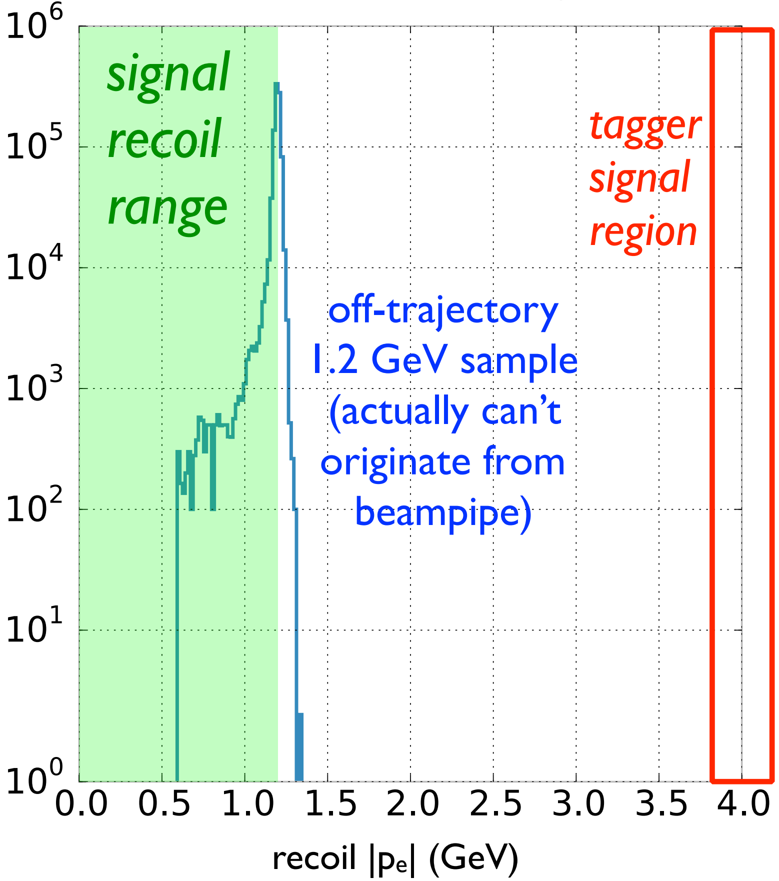


Tagging Rejection of Off-energy Beam

reconstructed 4 GeV beam e^-



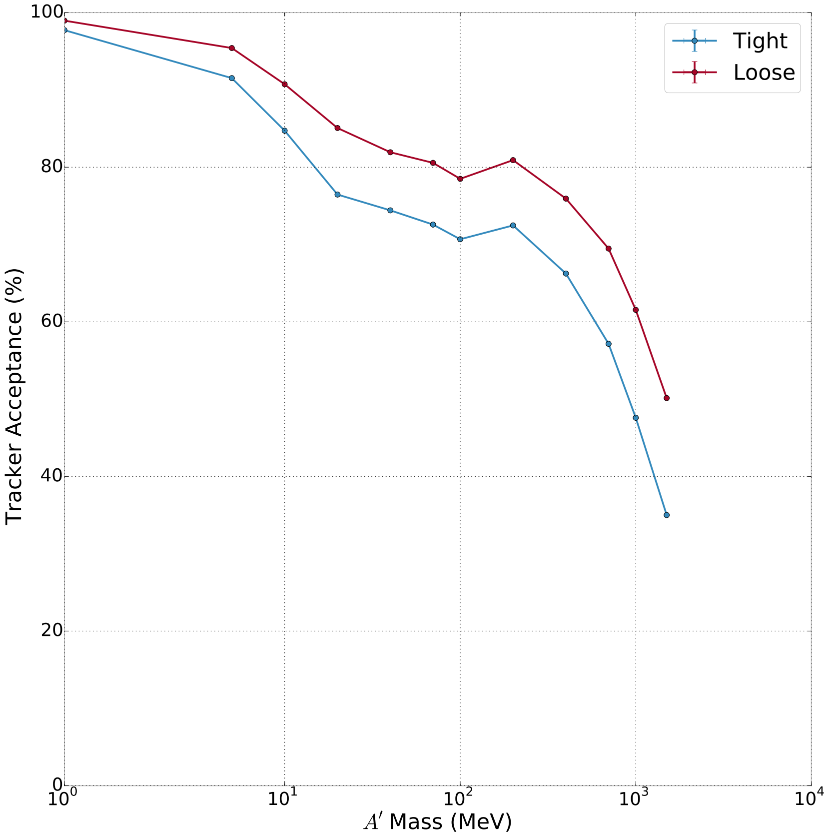
worst-case beam background

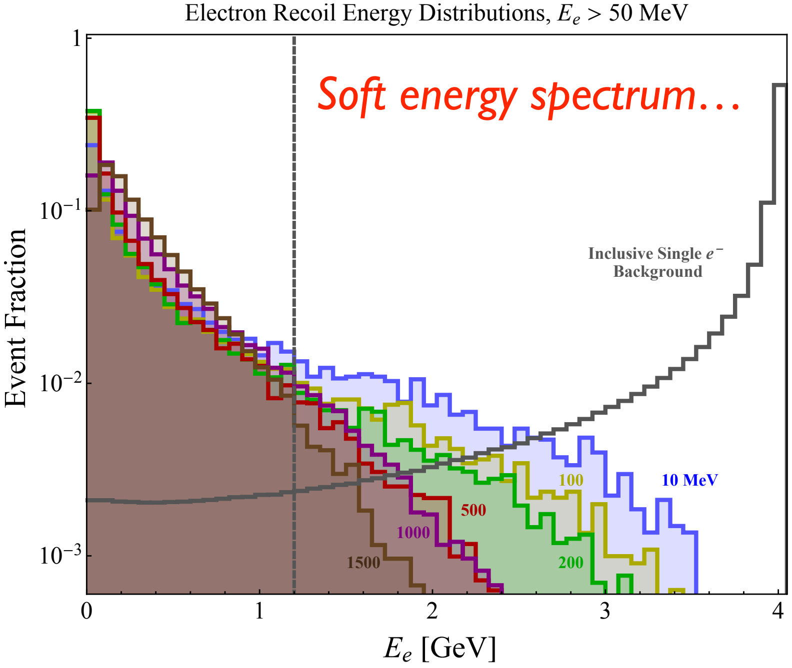


☑ *tagger tracker powerfully selects against any off-energy component in beam.*

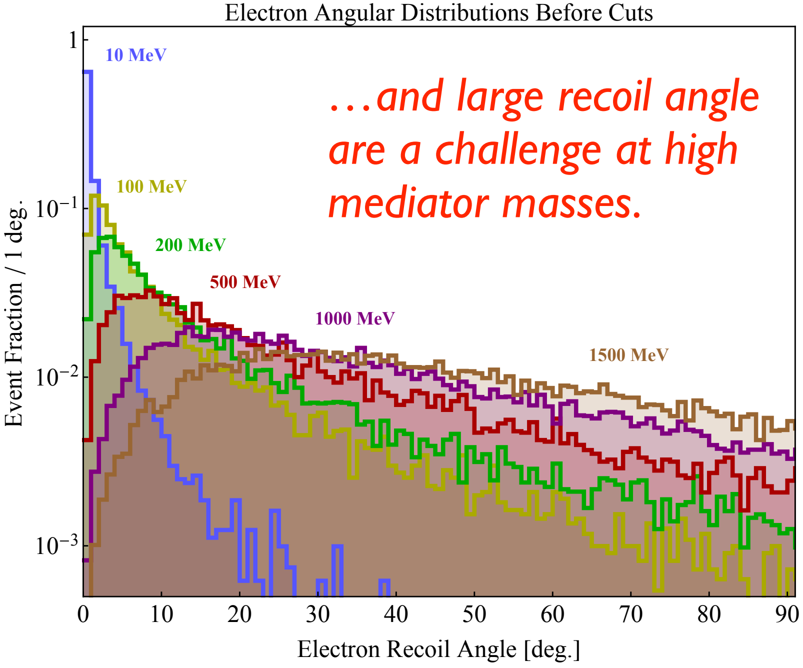
Recoil Tracker Acceptance

acceptance for recoils,
and those with best vertex and p_T resolution





Soft energy spectrum…



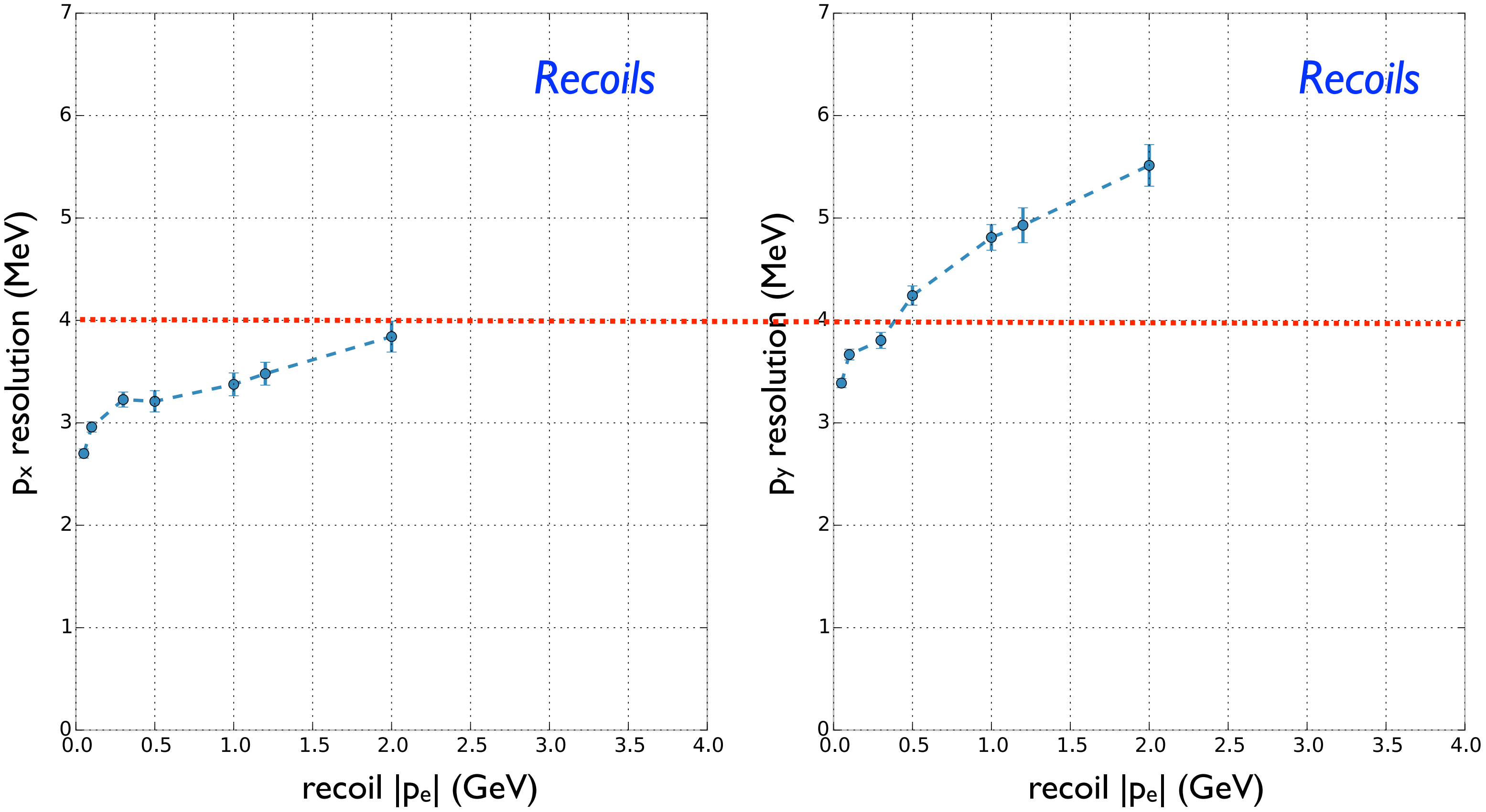
…and large recoil angle are a challenge at high mediator masses.

✓ *Good acceptance over a wide range of A′ masses*

Tracker p_T Resolutions

Tagger (p_x, p_y) resolutions at target are (1.0,1.4) MeV.

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



☑ *Tracker delivers best possible resolution for p_T*

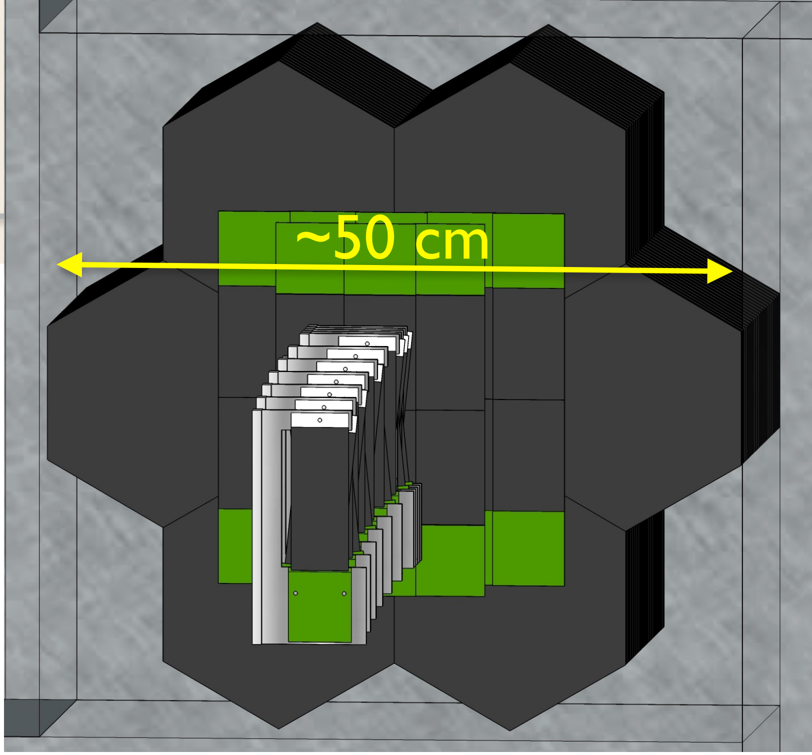
Electromagnetic Calorimeter

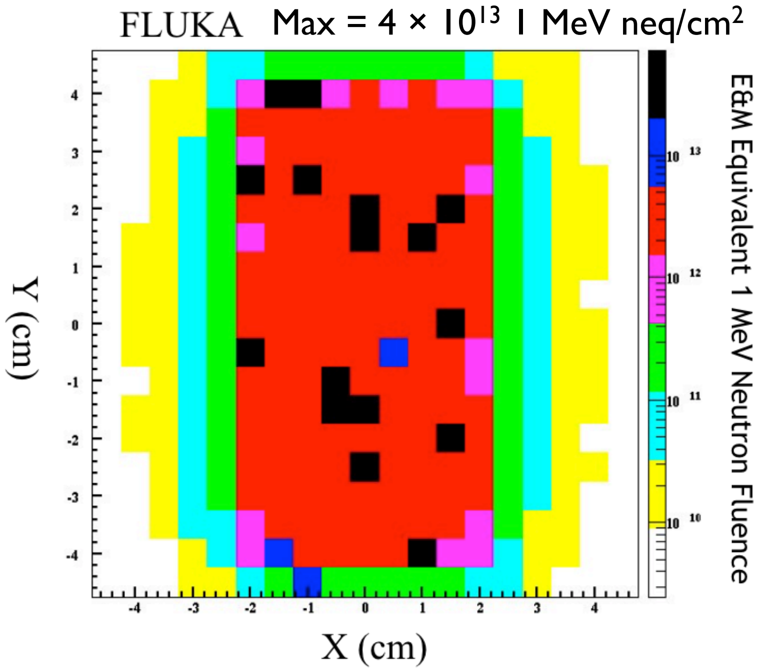
Si-W calorimeter developed for CMS upgrade

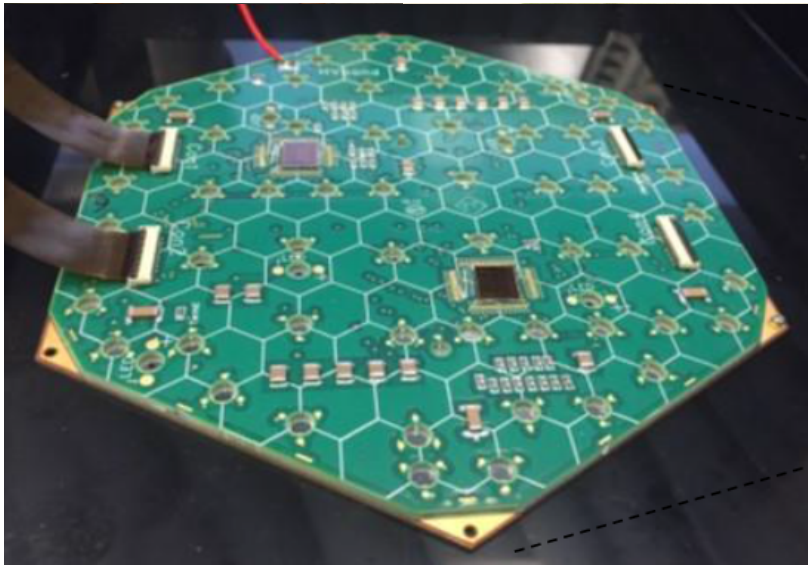
- fast, dense, granular for high occupancies
- deep (40 X_0) for extraordinary EM containment

For LDMX:

- easily exceeds radiation tolerance required
- meets rate requirement
- can provide fast trigger for trackers (3 μs)





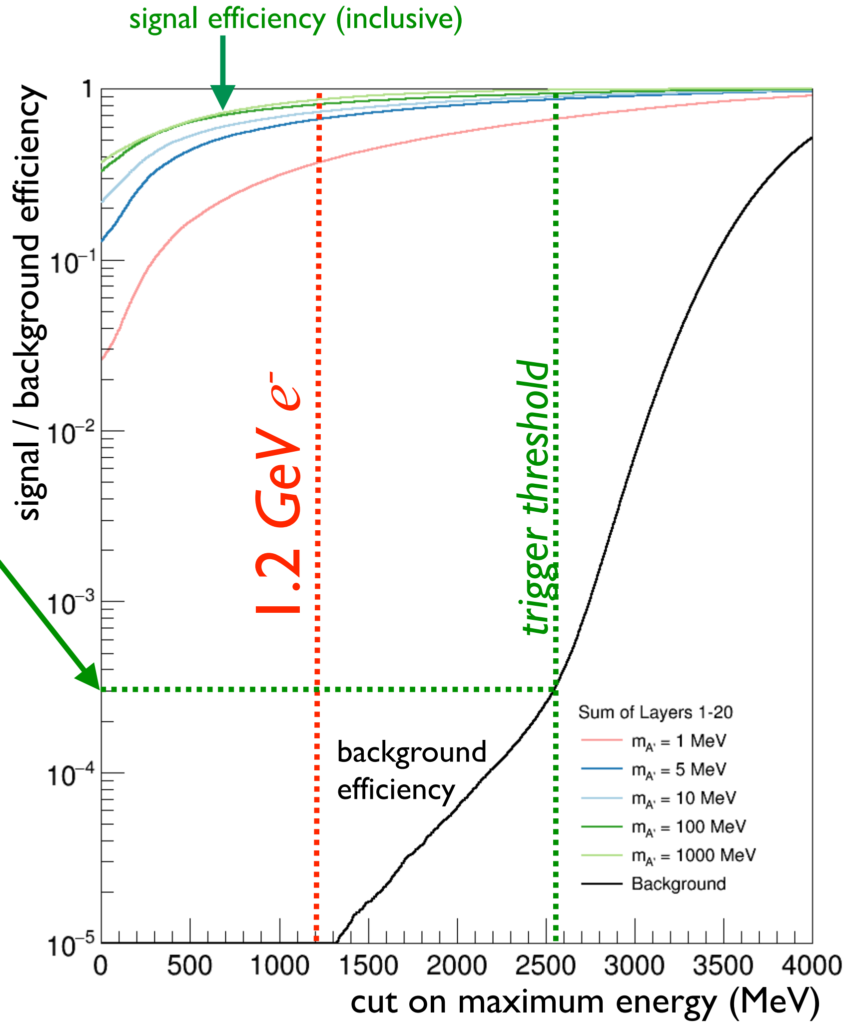


Trigger

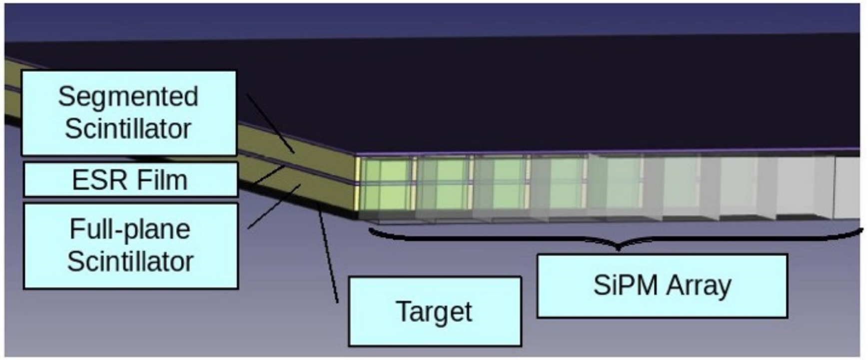
To reject beam-energy backgrounds

- cut on ΣE in first 20 ECal layers
- veto on empty target scintillator

☑ *Highly efficient at 3×10^{-4} rejection, needed for Phase I DAQ @ 5 kHz*

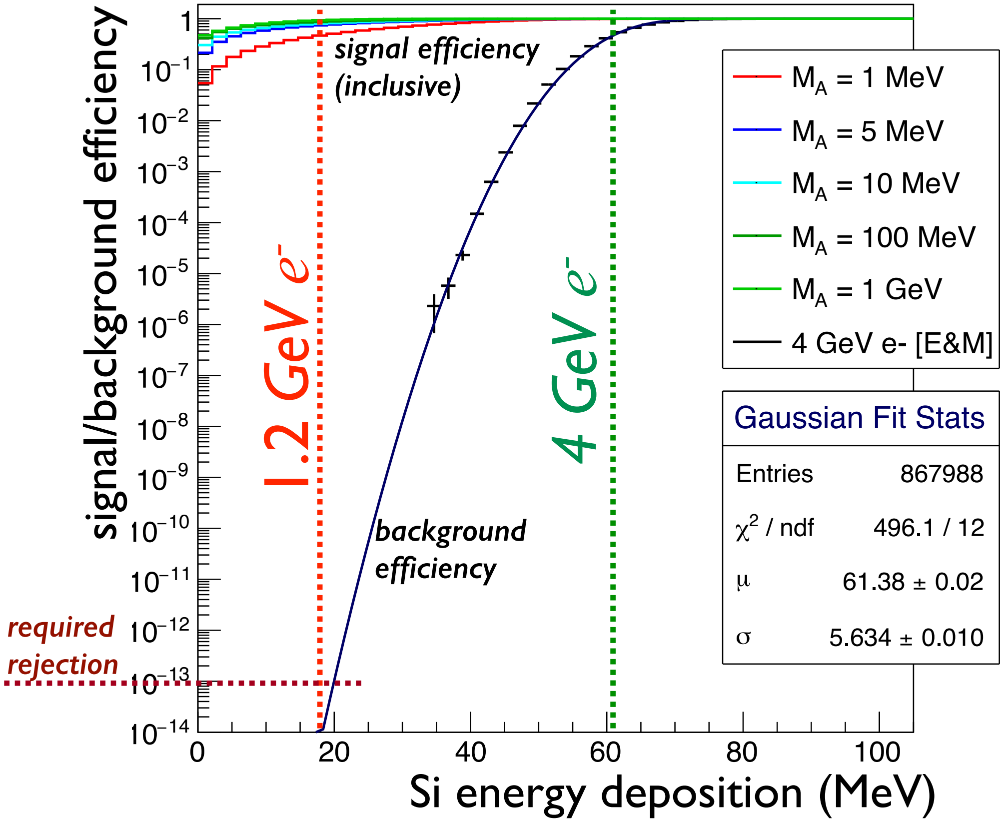


Target w/ Scintillator Pads

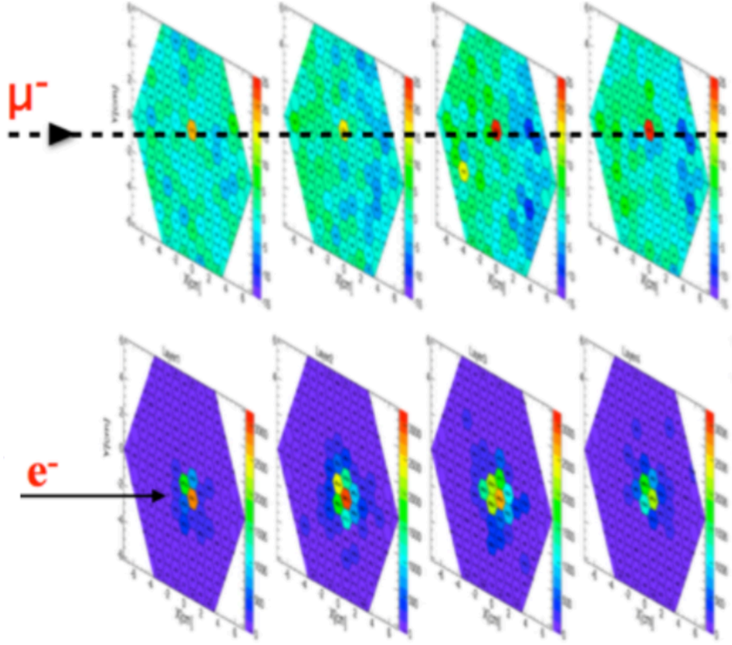


ECal Performance

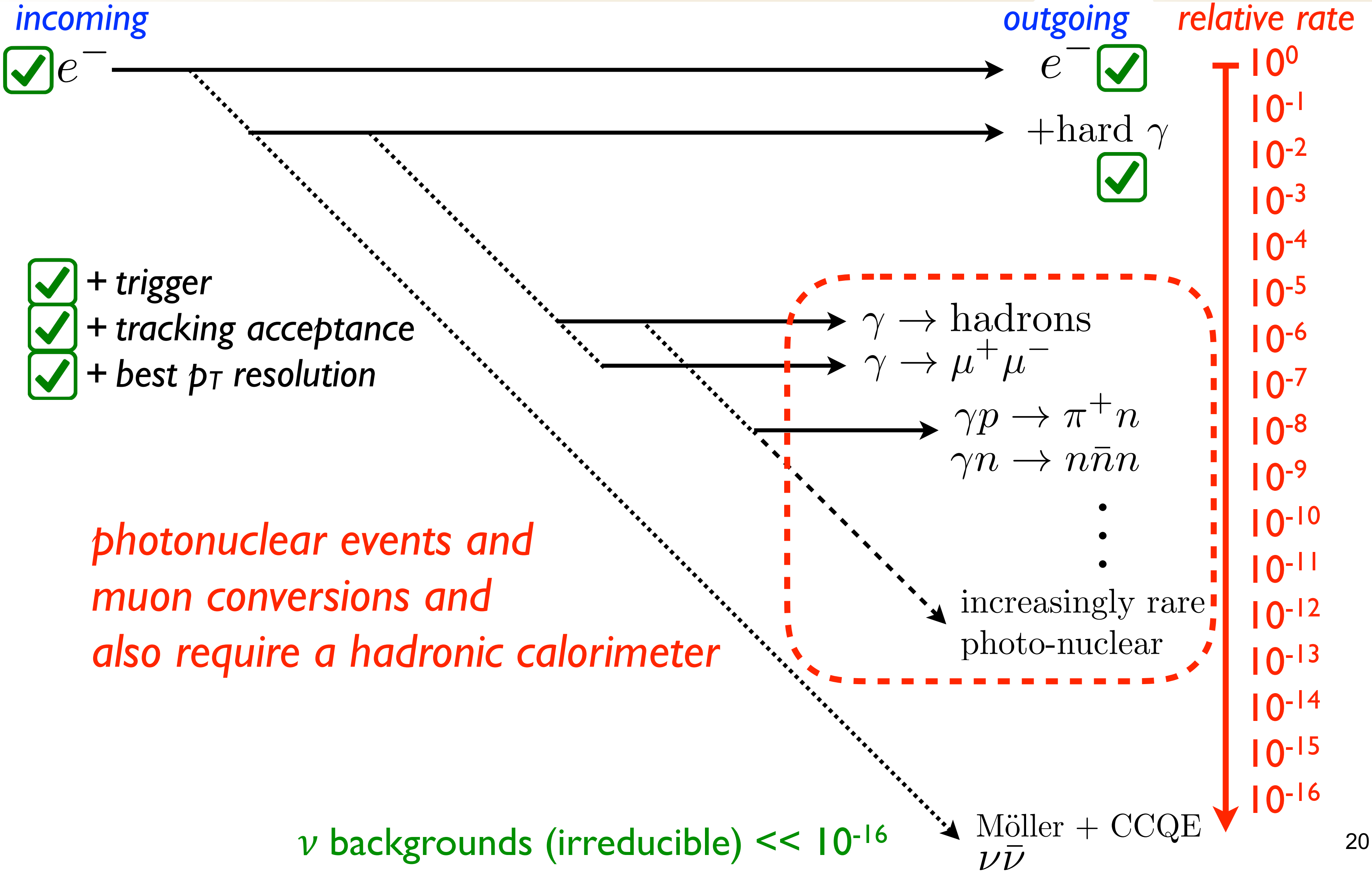
☑ *Even without using shape, ECal can distinguish EM-showering backgrounds (4 GeV $e^-+\gamma$) from signal (<1.2 GeV e^-) for Phase I*



ECal can track minimum ionizing particles (MIPs), important for rejection of $\gamma\to\mu^+\mu^-$ and $\gamma\to$photonuclear events.


CERN Test Beam Data

What's Left?



incoming

☑ e^-

outgoing

e^- ☑

$+\text{hard } \gamma$ ☑

relative rate

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}

☑ + *trigger*
☑ + *tracking acceptance*
☑ + *best p_T resolution*

$\gamma \rightarrow \text{hadrons}$

$\gamma \rightarrow \mu^+\mu^-$

$\gamma p \rightarrow \pi^+ n$

$\gamma n \rightarrow n\bar{n}n$

$\vdots$

increasingly rare
photo-nuclear

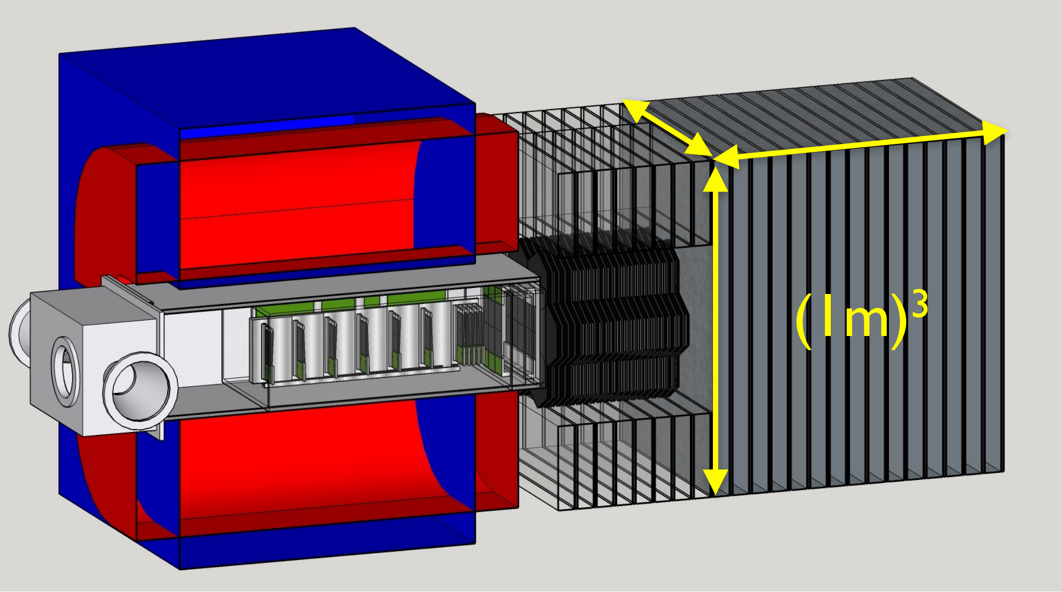
photonuclear events and
muon conversions and
also require a hadronic calorimeter

Möller + CCQE
$\nu\bar{\nu}$

ν backgrounds (irreducible) << 10^{-16}

Hadronic Calorimeter

Fermilab Caltech



CMS upgrade hardware

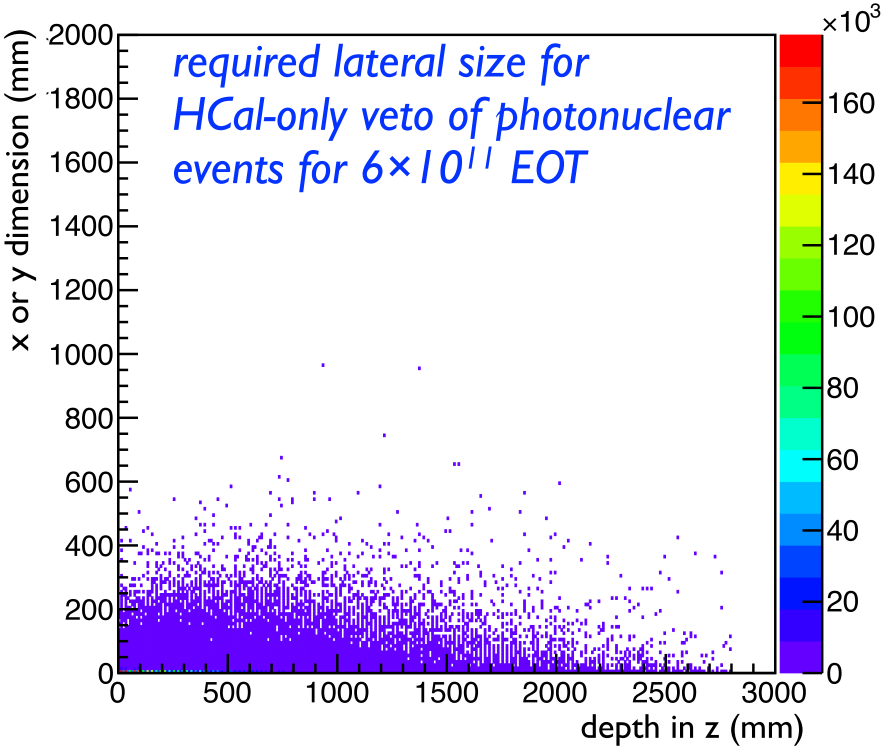
- Steel absorber/plastic scintillator
- SiPM readout via WLS fibers

Surround ECal as much as possible

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

Initial studies indicate that HCal will need to be larger than $(1m)^3$.

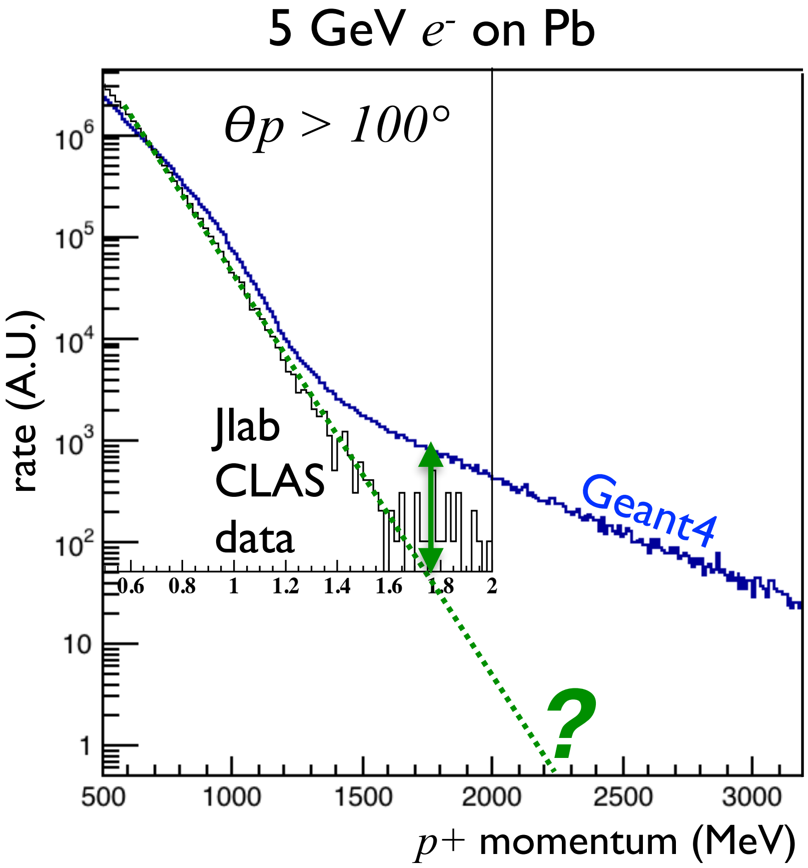
Testing rejection for a larger HCal in MC, which will be sculpted down by dropping hits once the photonuclear veto has been optimized.


required lateral size for HCal-only veto of photonuclear events for 6×10^{11} EOT

Simulating Rare Photonuclear Events in Geant4

Geant4 produces surprising number of events with enormous momentum transfer to recoiling nucleus.

- With high energy secondaries emitted at large angles, these are very difficult events to veto.
- Geant4 is not tuned to data in this regime, which is sparse in the literature.
- Energy/angle spectra from data provide evidence for a universal exponential fall-off, suggesting that Geant4 rates in this regime are overestimated by orders of magnitude.



*The validity of **all** simulations is questionable, so we are working to identify data we can use as a reference point to tune the MC and validate our photonuclear rejection performance.*

Photonuclear Backgrounds in Geant4

Can occur in target, recoil tracker, or ECal

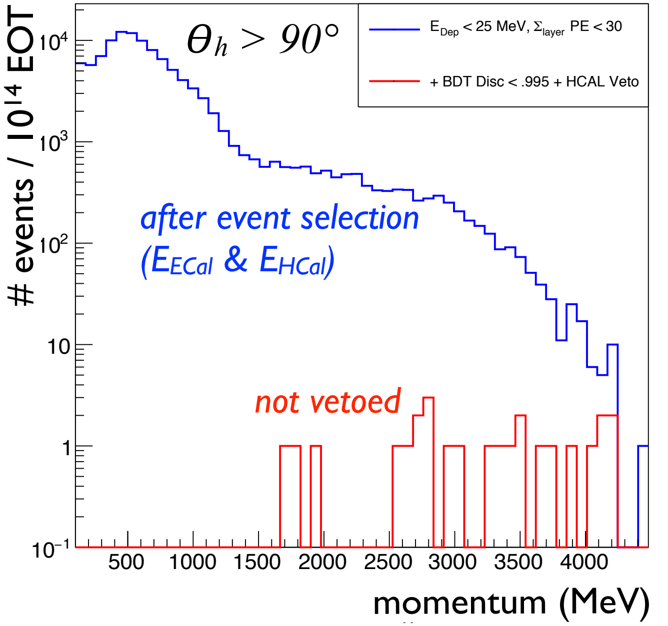
Multiple handles available for veto

- trigger pad (for PN in target)
- recoil tracker (for PN in target and recoil tracker)
- ECal
- HCal

An initial veto that using some of the information from each subsystem eliminates all but a few events with extremely large momentum transfer at ~10^{13} EOT.

We expect to eliminate photonuclear backgrounds without using p_T.

highest-momentum backwards hadron

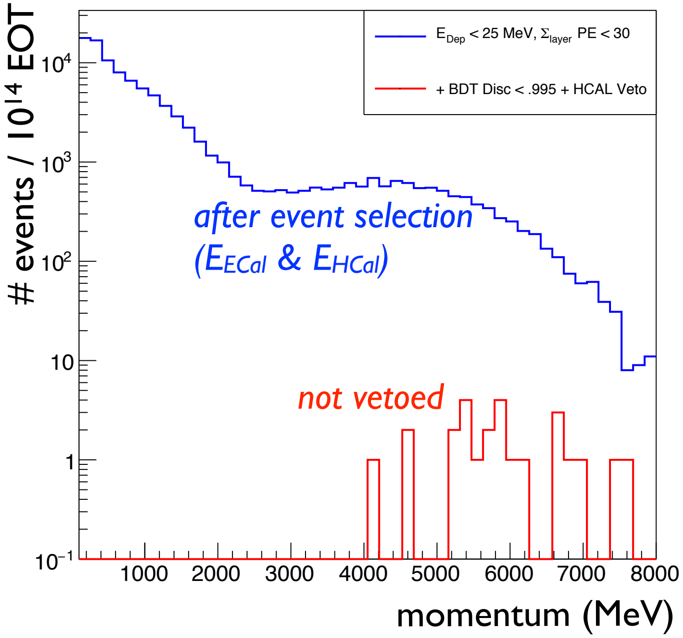


$\theta_h > 90°$

after event selection (E_{ECal} & E_{HCal})

not vetoed

p_z of recoiling nucleus



after event selection (E_{ECal} & E_{HCal})

not vetoed

Muon Conversion Backgrounds in Geant4

Can occur in target, recoil tracker or ECal.

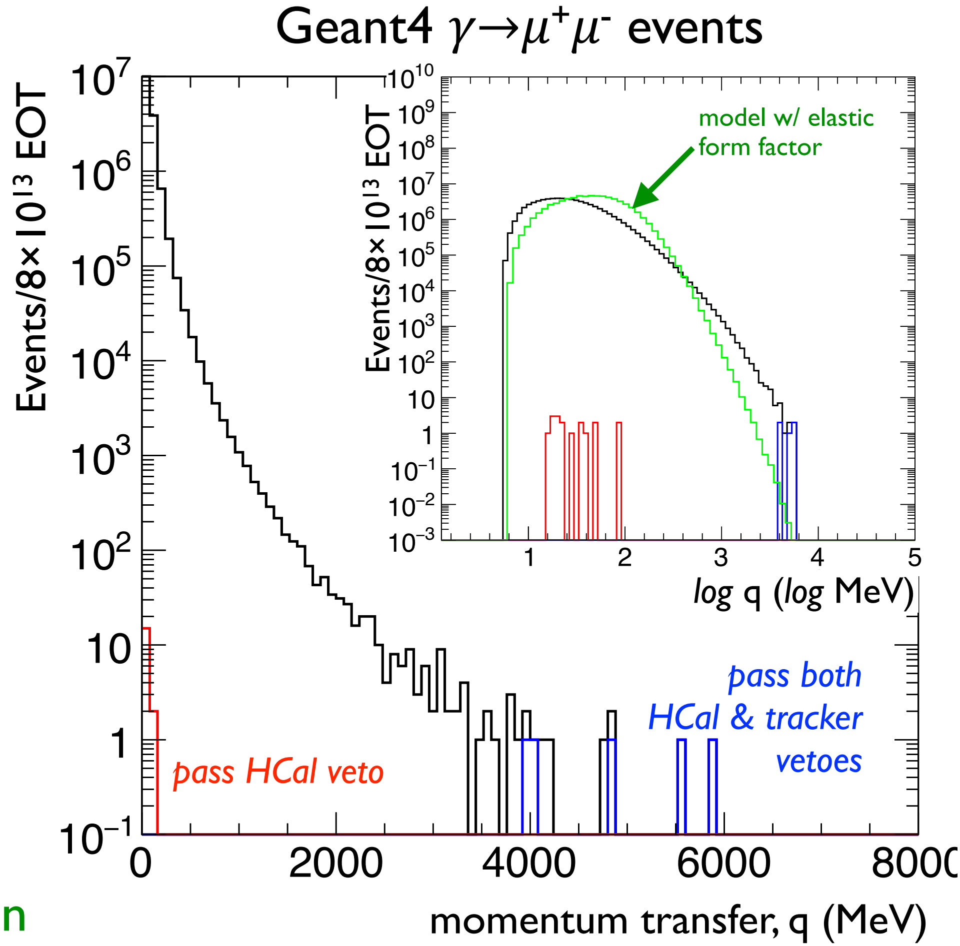
Multiple handles available for veto:

- recoil tracker (for $\gamma \to \mu^+\mu^-$ in target & recoil tracker)
- ECal
- HCal

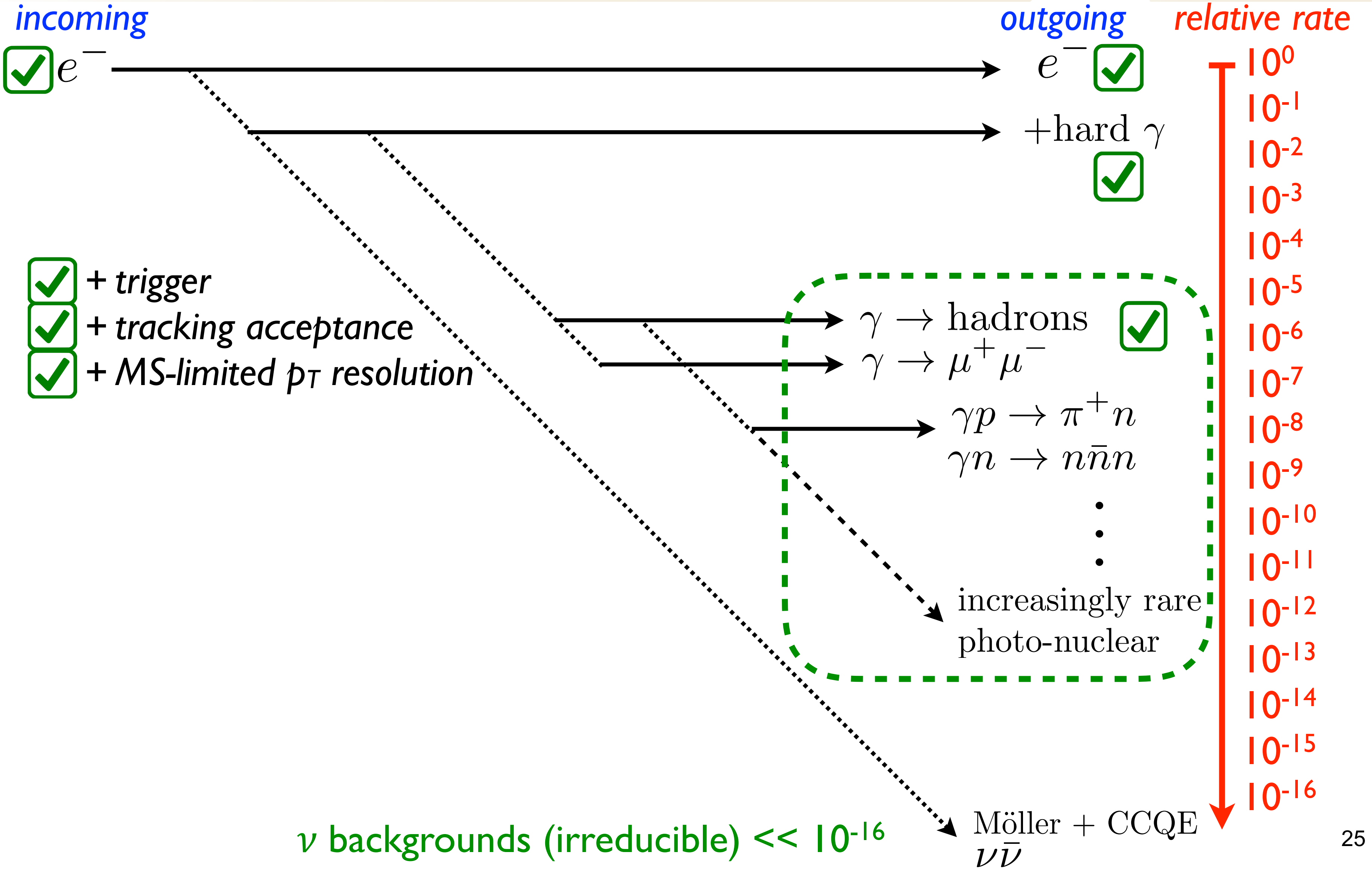
An initial veto using only tracker and HCal eliminates all but a few events where both muons are emitted at ≳90° for ~10^{14} EOT.

Geant4 also grossly overestimates rate of $\gamma \to \mu^+\mu^-$ events with extremely high q^2.

We expect to eliminate muon conversion backgrounds without using p_T.



What's Left? Nothing.



incoming

☑ e^-

outgoing

e^- ☑

+hard γ ☑

☑ + *trigger*

☑ + *tracking acceptance*

☑ + *MS-limited p_T resolution*

$\gamma \rightarrow$ hadrons ☑

$\gamma \rightarrow \mu^+\mu^-$

$\gamma p \rightarrow \pi^+ n$

$\gamma n \rightarrow n\bar{n}n$

$\vdots$

increasingly rare photo-nuclear

Möller + CCQE $\nu\bar{\nu}$

ν backgrounds (irreducible) << 10^{-16}

relative rate

10^{0}

10^{-1}

10^{-2}

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10^{-4}

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10^{-6}

10^{-7}

10^{-8}

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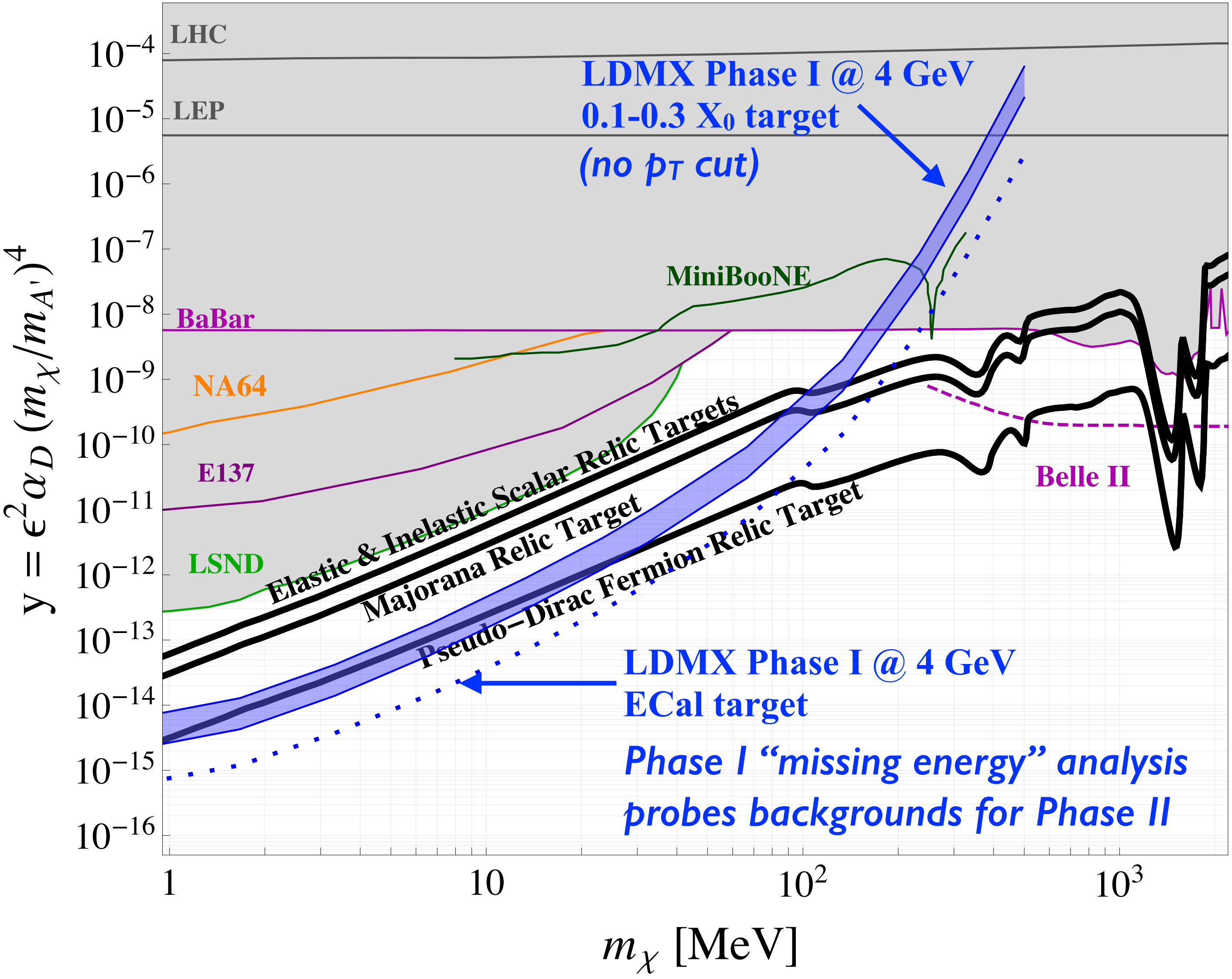
10^{-16}

LDMX Phase I Reach



LDMX Phase I @ 4 GeV
0.1-0.3 X_0 target
(no p_T cut)

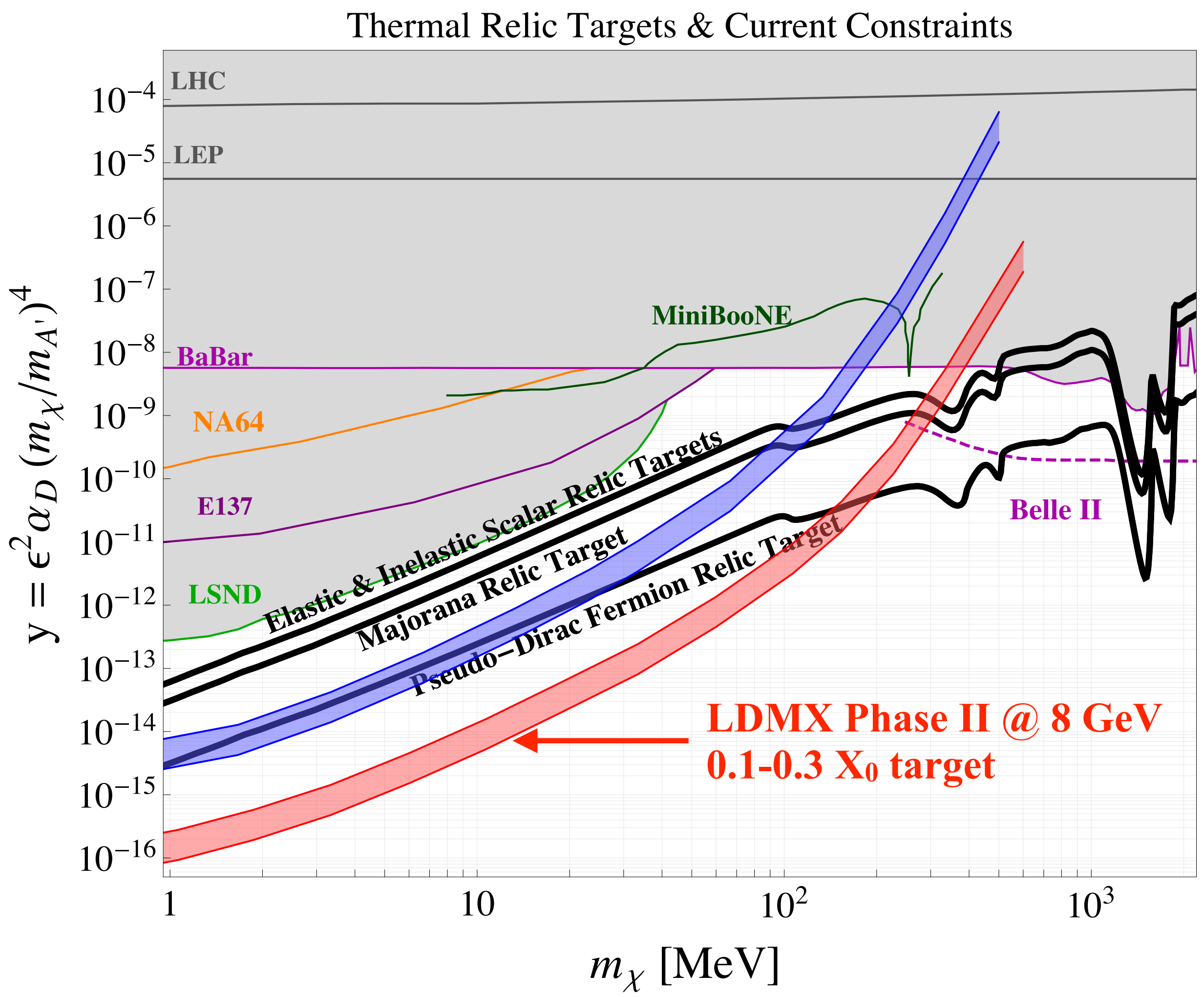
LDMX Phase I @ 4 GeV
ECal target

Phase I “missing energy” analysis probes backgrounds for Phase II

LDMX Phase II

may require faster and more granular detectors, more sophisticated trigger

Higher beam energy (e.g. 8 GeV DASEL) would mitigate the most difficult backgrounds.


Thermal Relic Targets & Current Constraints

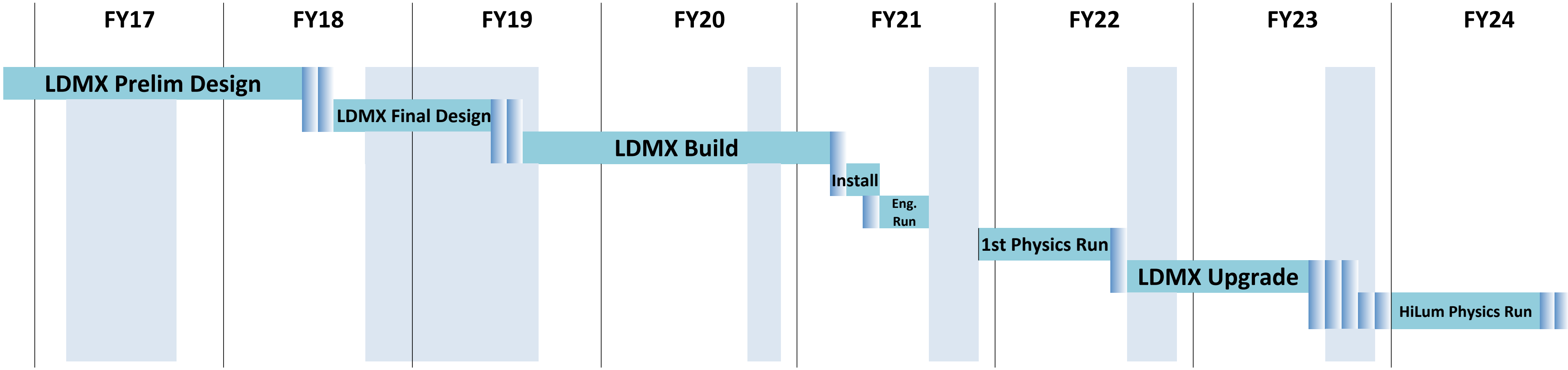
LDMX Phase II @ 8 GeV 0.1-0.3 X_0 target

Schedule and Budget

Anticipate 2 years to complete design + 2 years for construction

Phase I Run beginning in late 2021. Phase 2 two years later.

Details depend upon accelerator schedules.



LDMX Phase I+II costs are <$10M.

Funding in FY18 is critical to support engineering and technical design.

LDMX Collaboration

LDMX

SLAC NATIONAL ACCELERATOR LABORATORY	Norman Graf, Jeremy McCormick, Takashi Maruyama, Omar Moreno, Tim Nelson, Philip Schuster, Natalia Toro
UCSB	Owen Colegrove, Joe Incandela
UNIVERSITY OF MINNESOTA	Josh Hiltbrand, Jeremy Mans
Fermilab	Gordan Krnjaic, Nhan Tran, Andrew Whitbeck
Caltech	Bertrand Echenard, David Hitlin
UC SANTA CRUZ	Robert Johnson

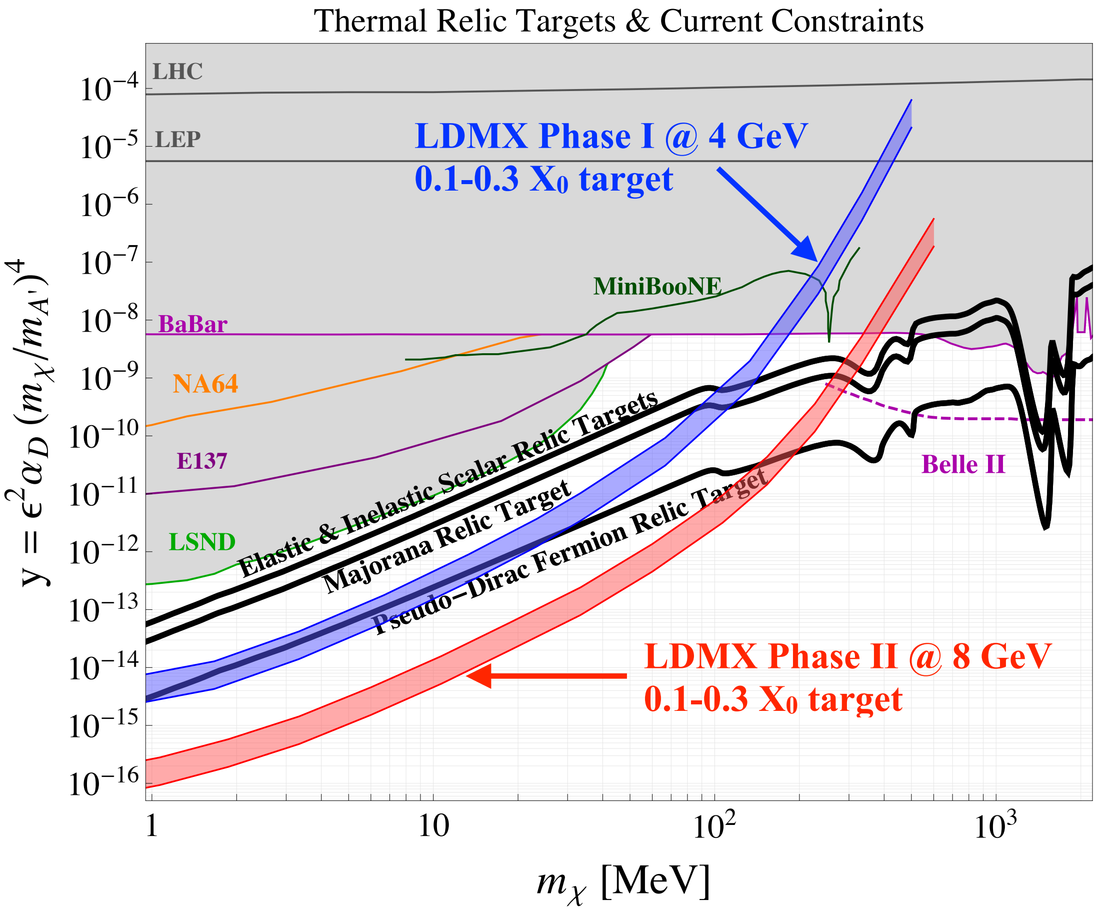
Summary and Outlook

Accelerator-based DM searches have unique sensitivity in the MeV-GeV range.

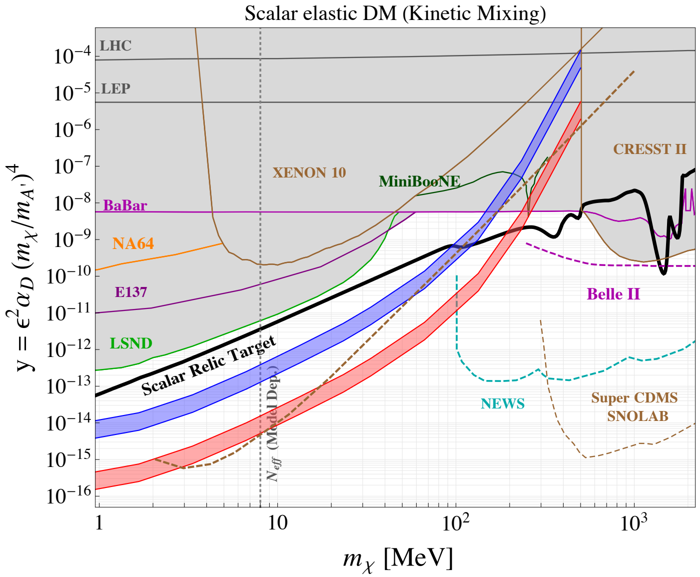
Missing Energy/Momentum experiments provide best sensitivity per luminosity.

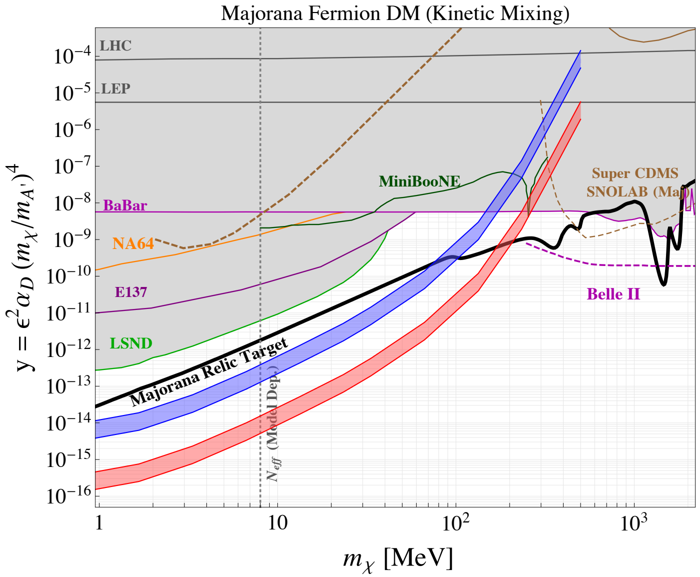
LDMX can robustly reach all thermal targets over most of the MeV-GeV range.

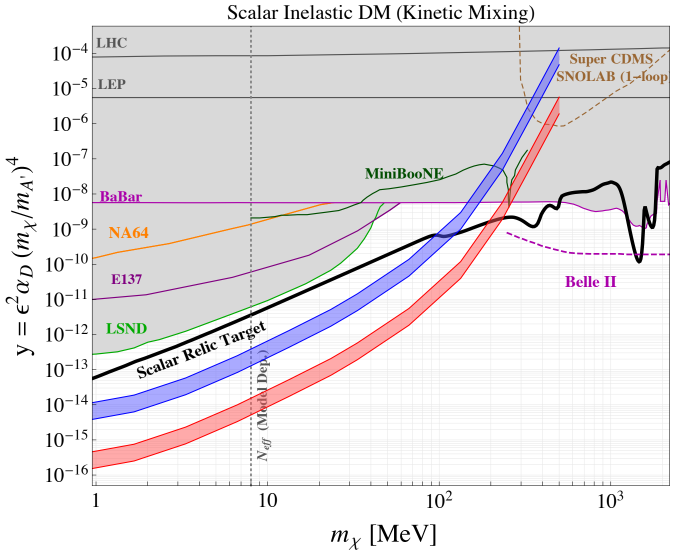
LDMX can complete this program within the next decade at reasonable cost.

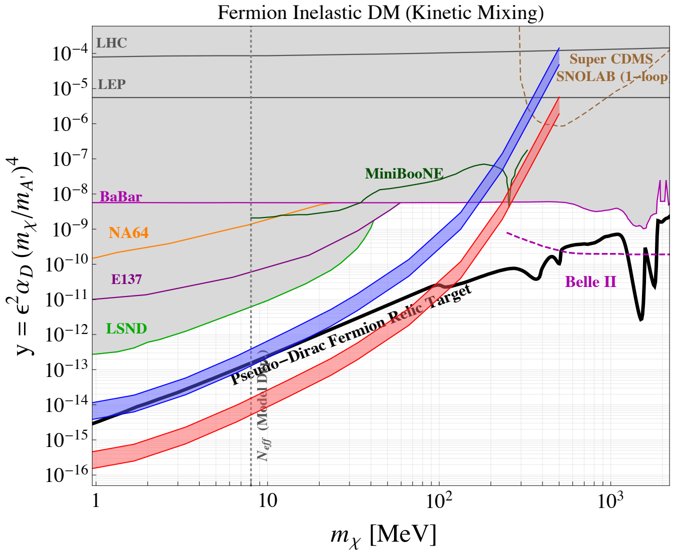


DM Targets and Sensitivities

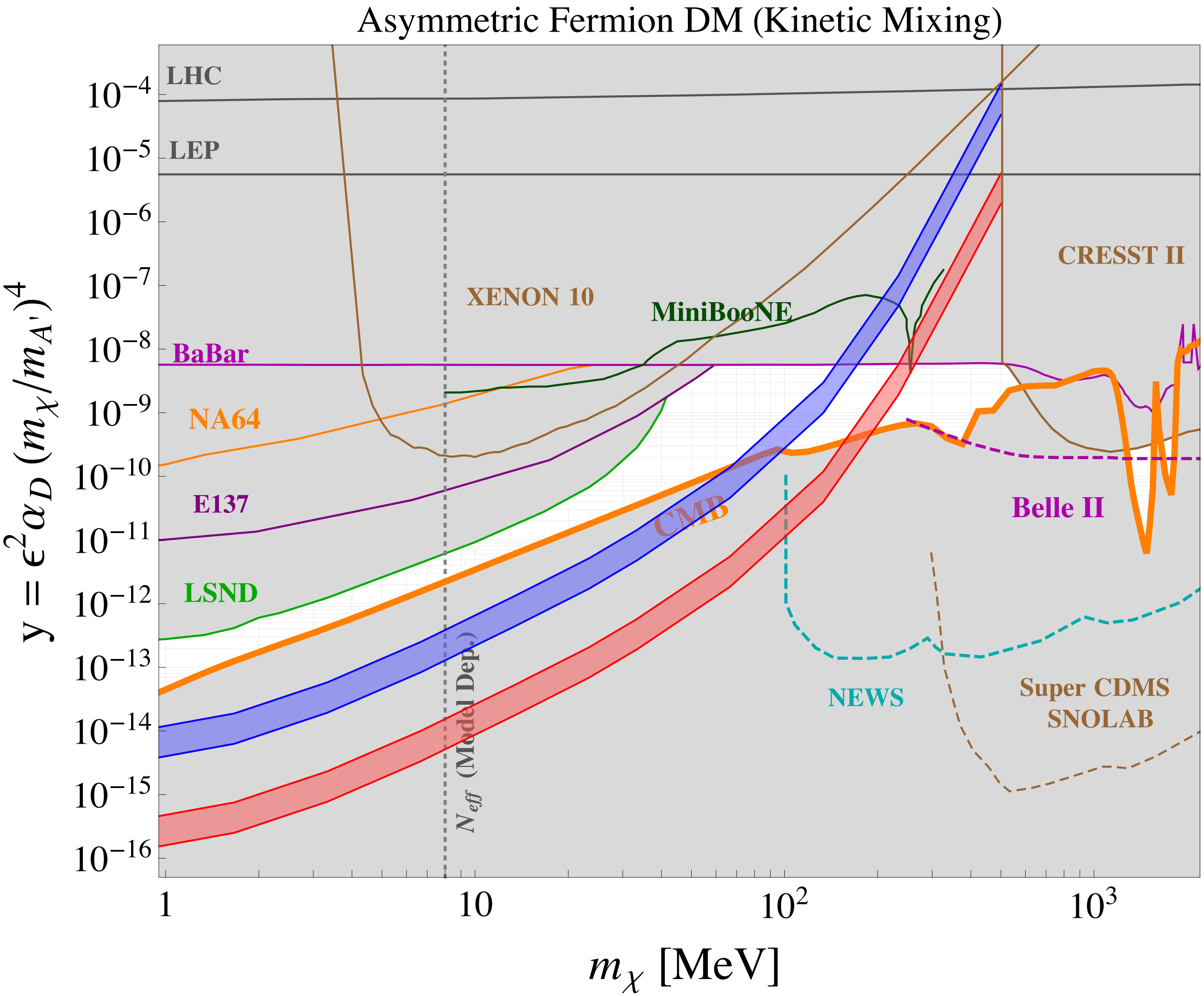

Scalar elastic DM (Kinetic Mixing)


Majorana Fermion DM (Kinetic Mixing)

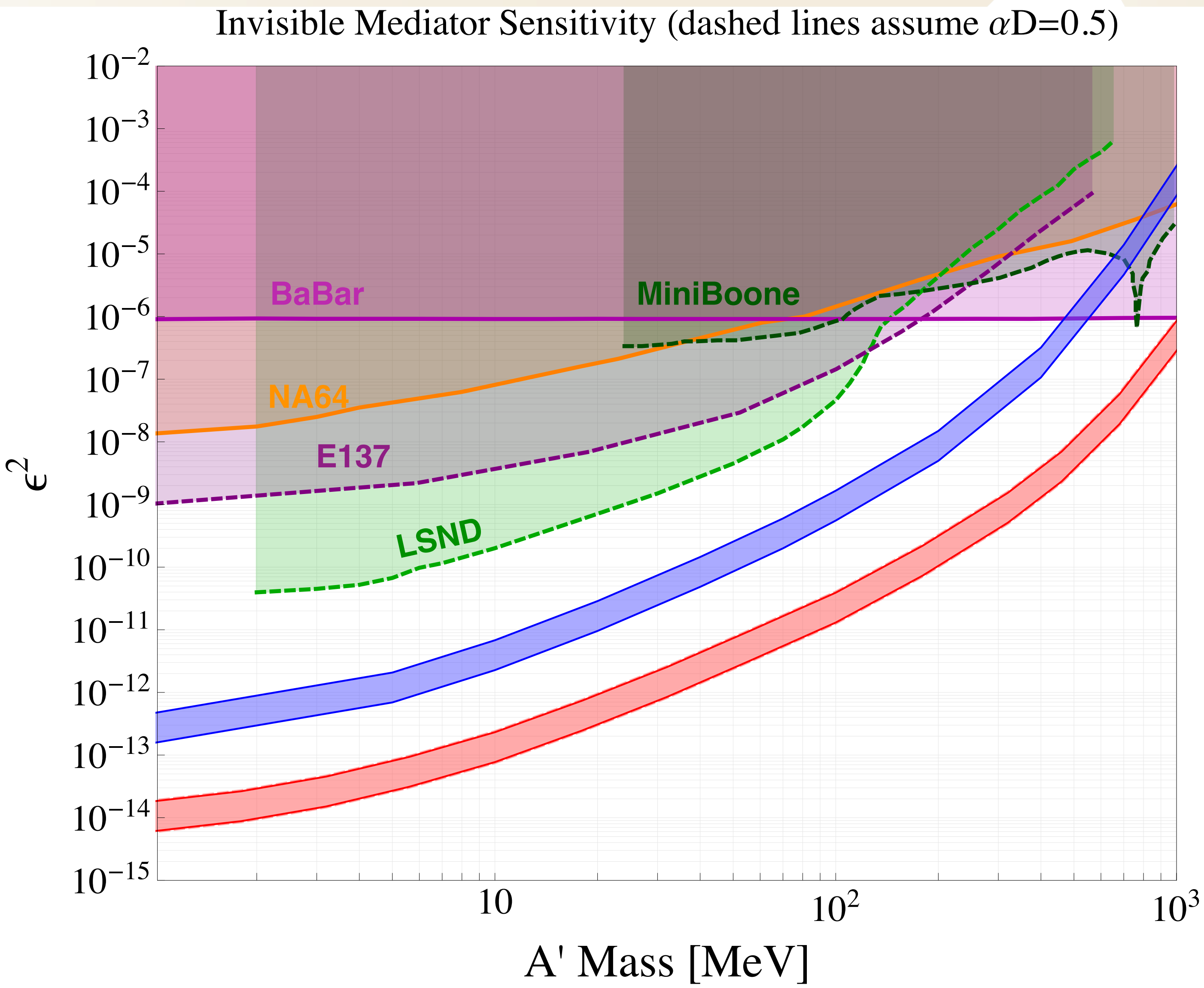

Scalar Inelastic DM (Kinetic Mixing)


Fermion Inelastic DM (Kinetic Mixing)

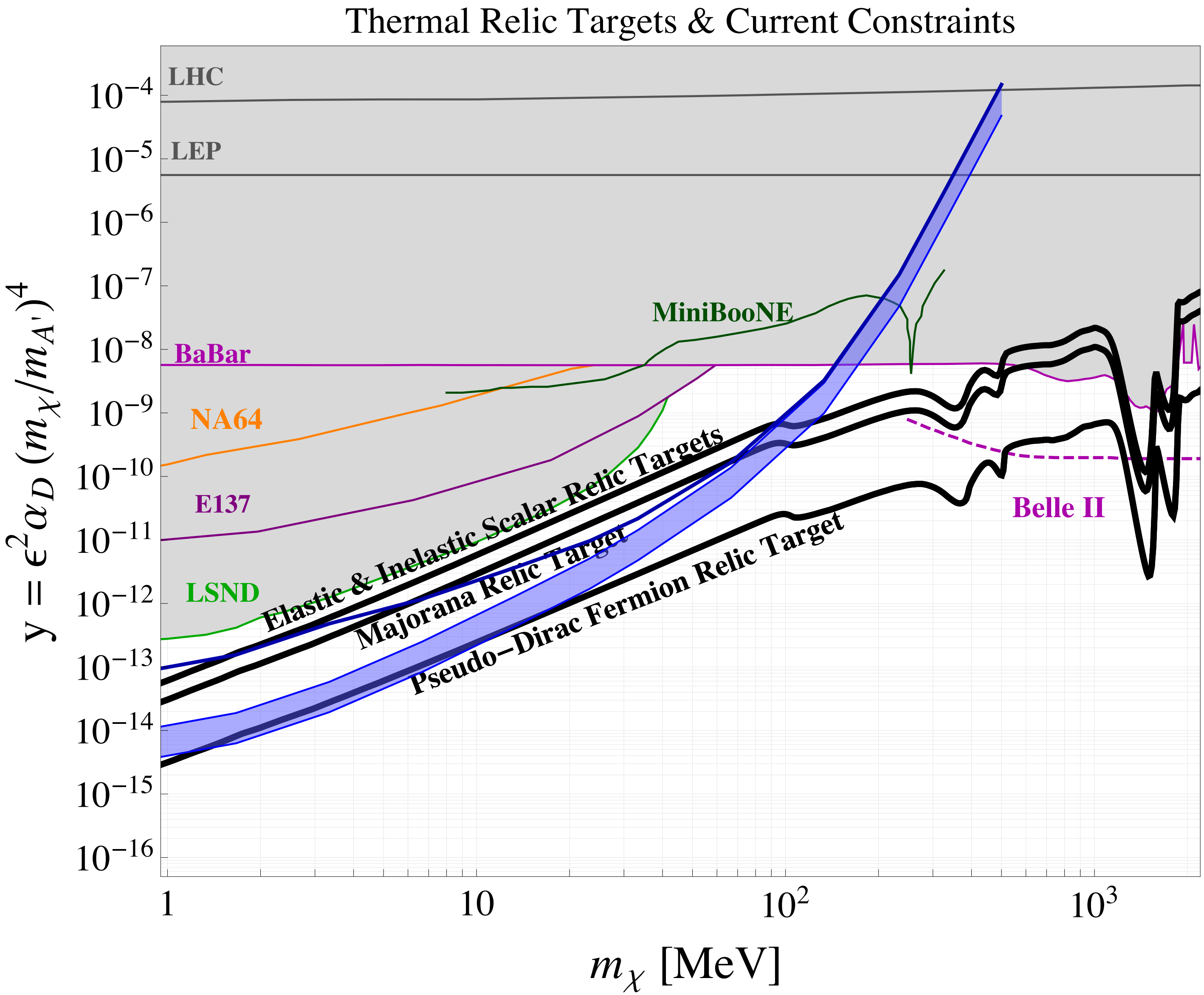
Asymmetric DM Sensitivity



Mediator Sensitivity



Effect of p_T Cut with 100 Background Events

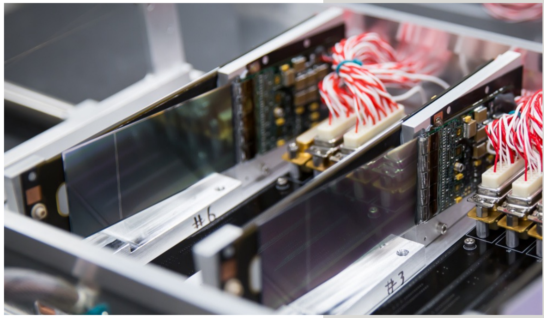


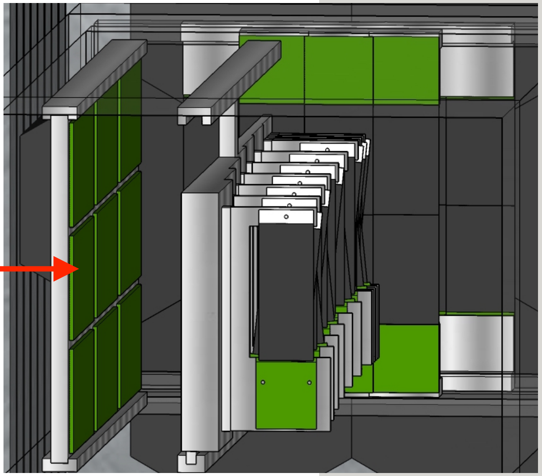
Tagging Tracker

Designed around trajectory of 4 GeV e^-

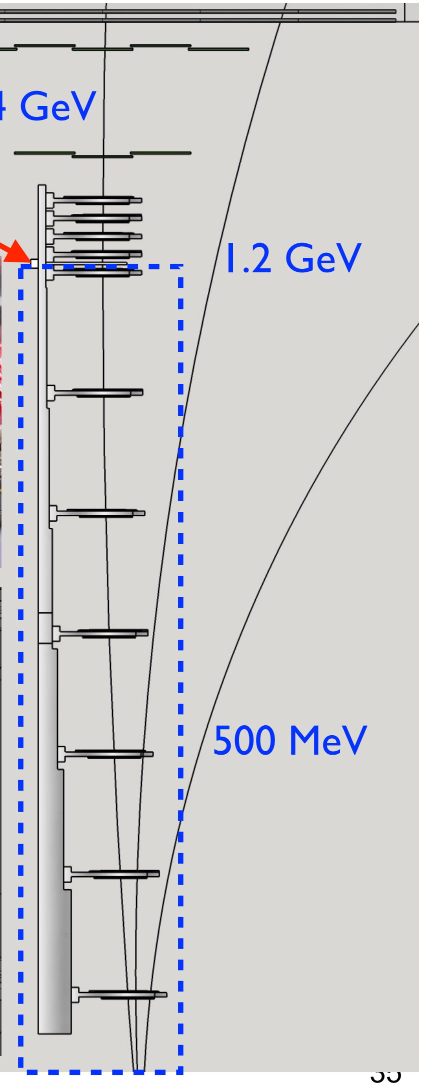
- 7 layers, every 10 cm from 7.5 mm to 607.5 mm upstream of target
- Silicon modules are similar to those built for HPS SVT
  - 0.7% X_0 / 3d measurement
  - 2 ns hit time resolution
- Digitization, zero-suppression on Front End Boards (FEBs), same as HPS SVT

HPS L1-3 modules





target

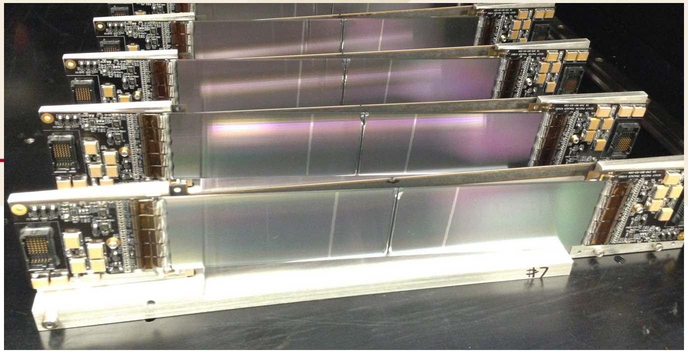


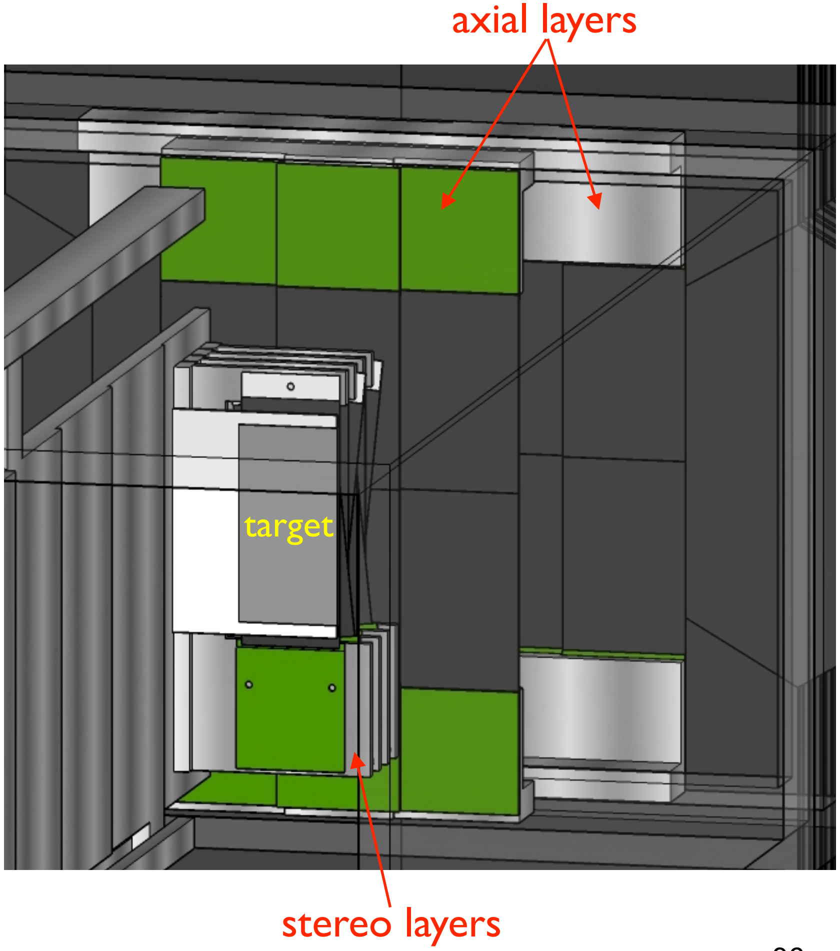
Recoil Tracker

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

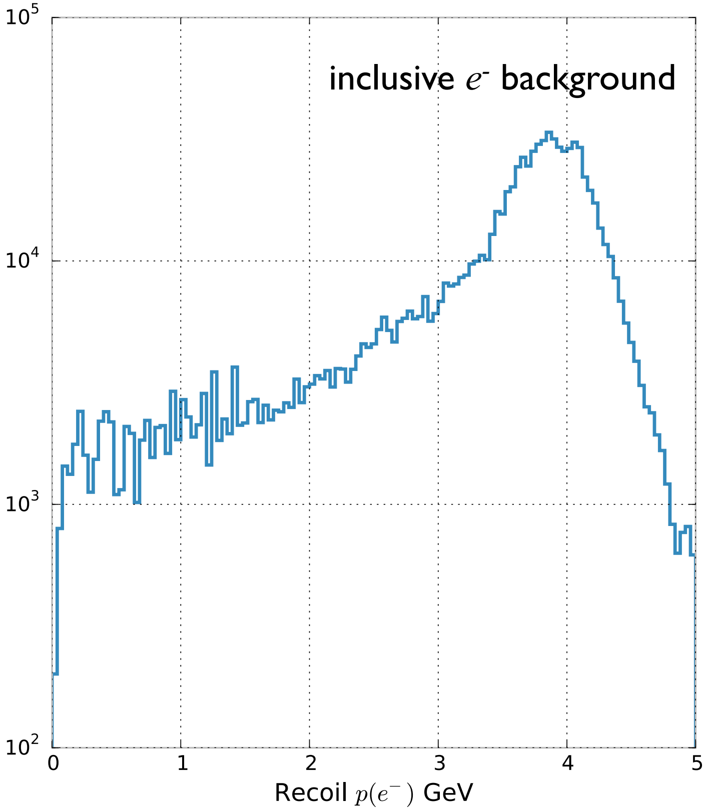
HPS L4-6 modules



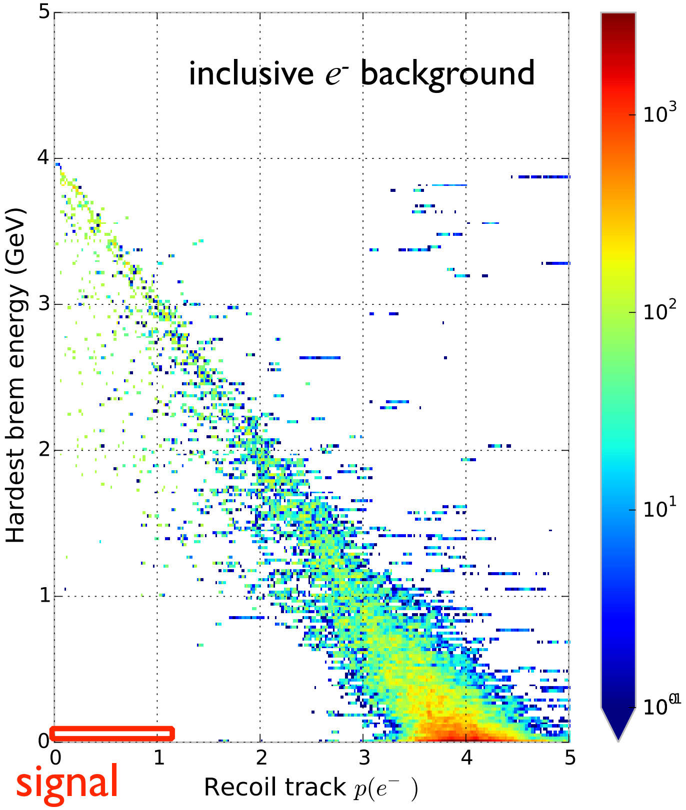


Recoil Tracker Momentum Resolution

reconstructed recoil momentum



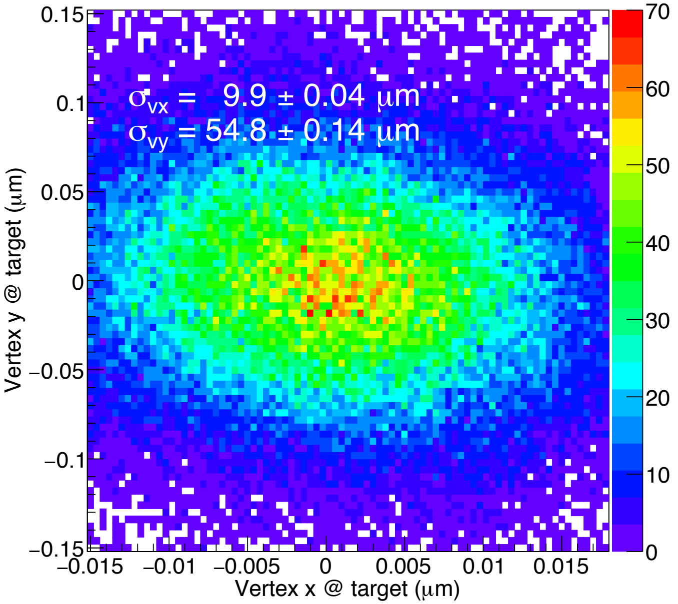
energy of hardest brem.
vs. recoil momentum



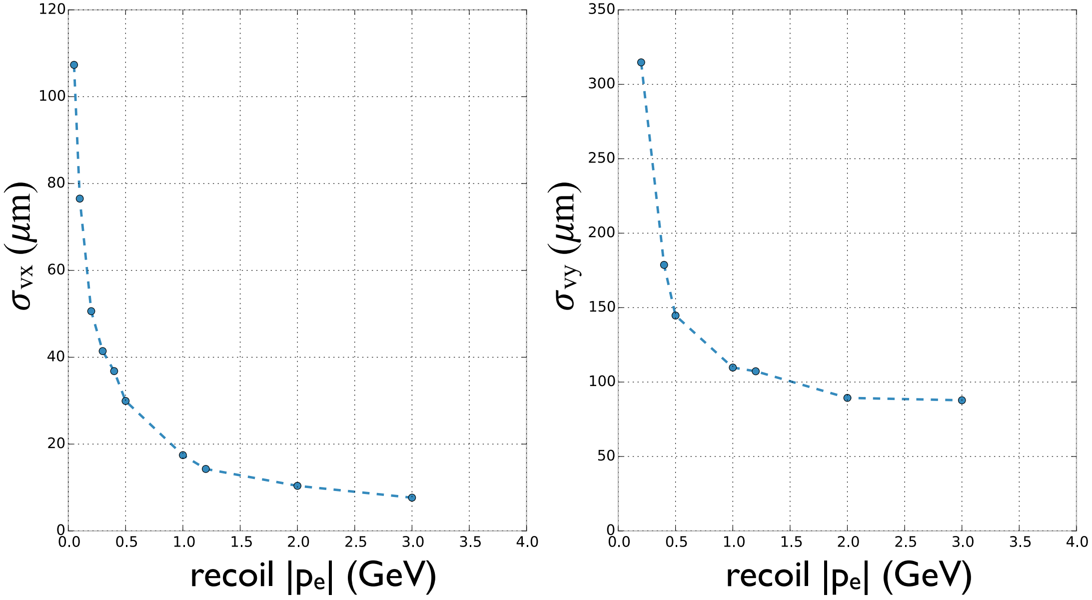
Despite compact size, recoil tracker has sufficient resolution to distinguish even non-interacting 4 GeV electrons from low-momentum signal recoils.

Impact Parameter Resolutions

tagger e^- position at target



recoil e^- resolutions at target



Enables tight tag/recoil matching criteria relative to 10cm^2 beam spot:

- at E_R = 50 MeV: 3σ region for tagger/recoil consistency = 0.67 mm^2 $\Longrightarrow$ $<10^{-4}$ rejection
- at E_R = 1.2 GeV: 3σ region for tagger/recoil consistency = 0.026 mm^2 $\Longrightarrow$ $<10^{-5}$ rejection

Understanding Rare Photonuclear Events

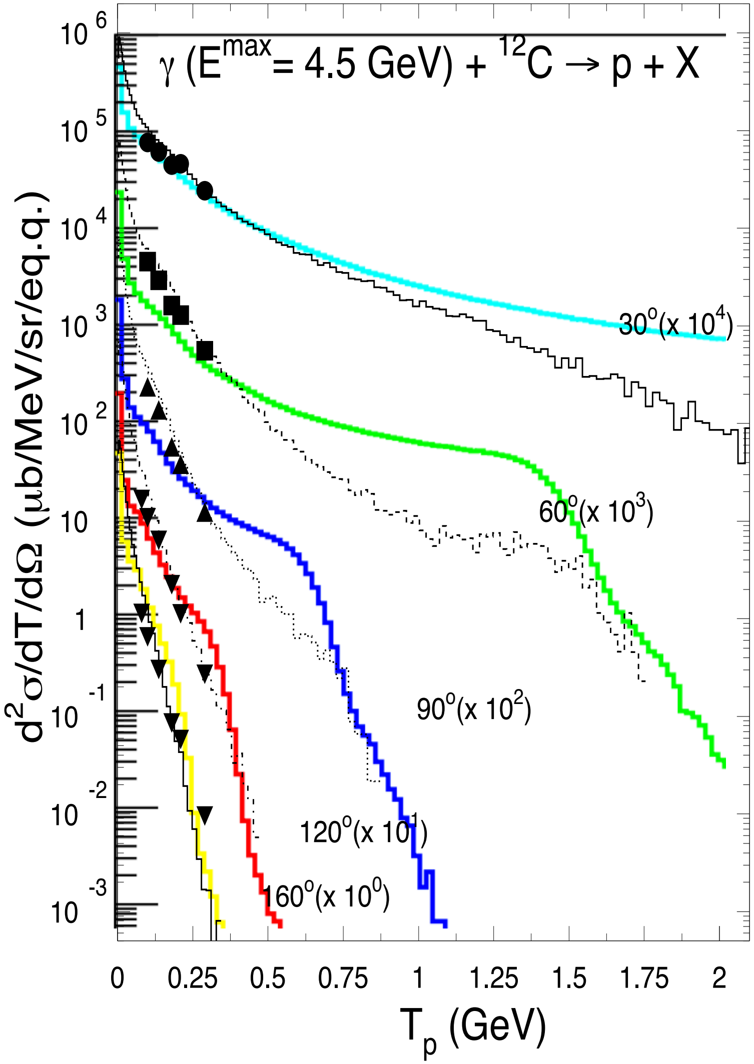
Bertini cascade model in Geant4 (colored lines at right) not tuned to data

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

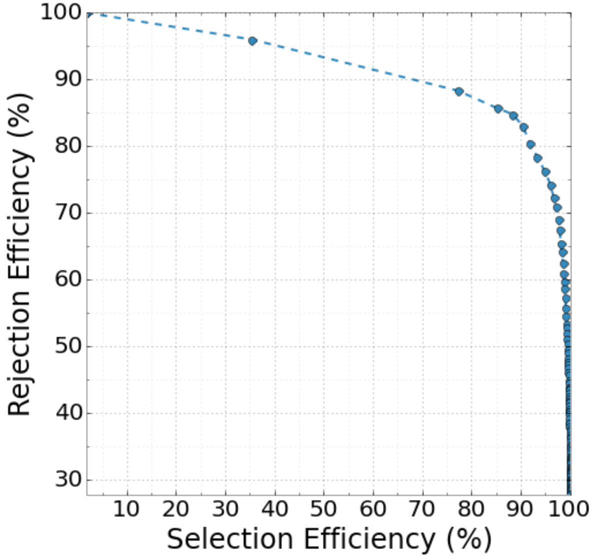


Rejecting Photonuclear Reactions in Target and Recoil Tracker

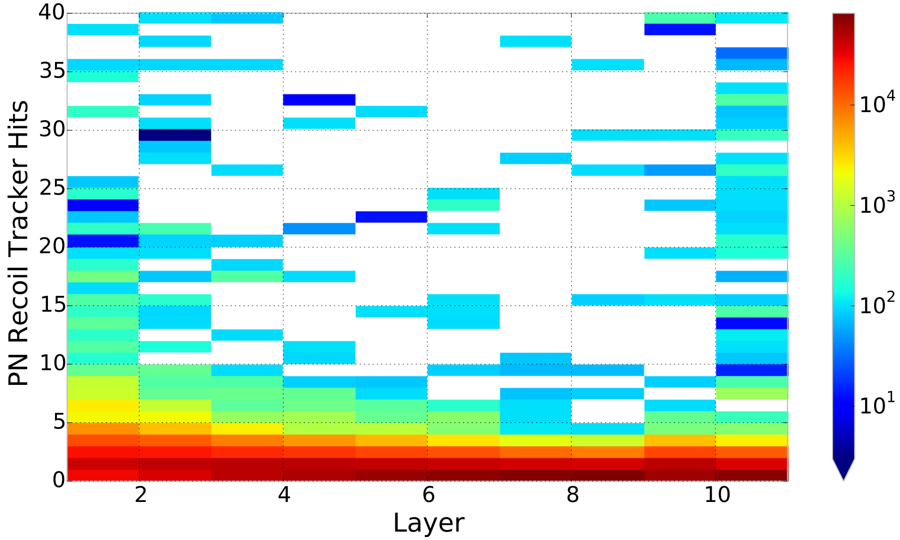
Trigger scintillator and recoil tracker can be used to reject events where a hard bremsstrahlung photon undergoes a photonuclear reaction in the target.

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

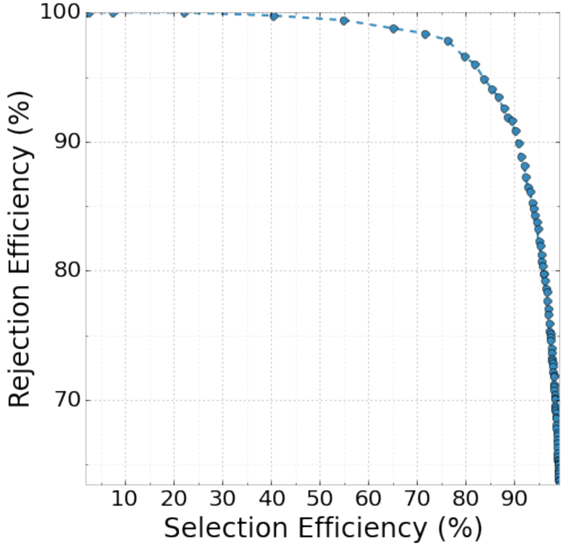
efficiency vs. rejection for
cut on *trigger pad* energy



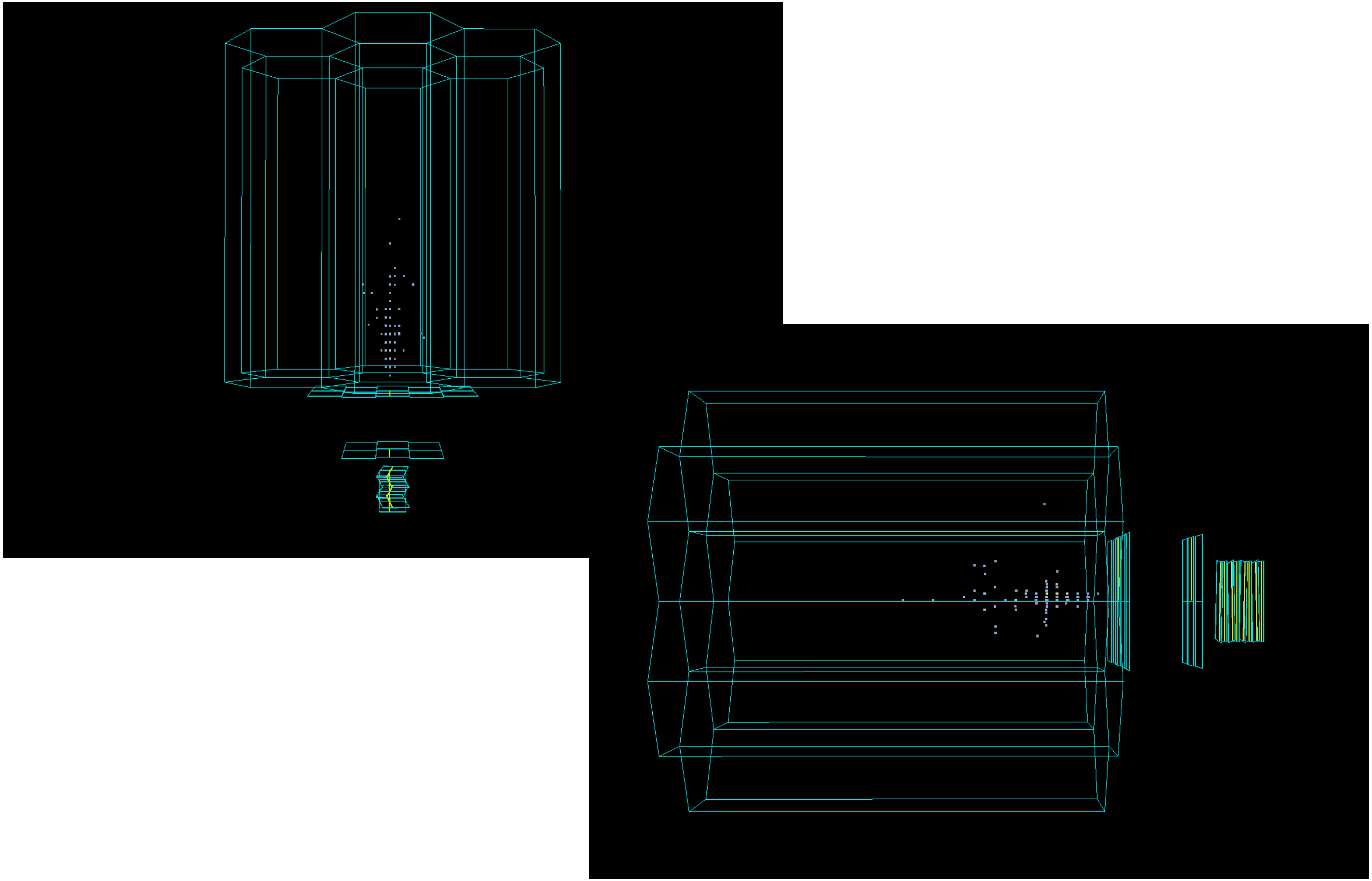
Recoil tracker occupancy from PN products
(recoil hits excluded)



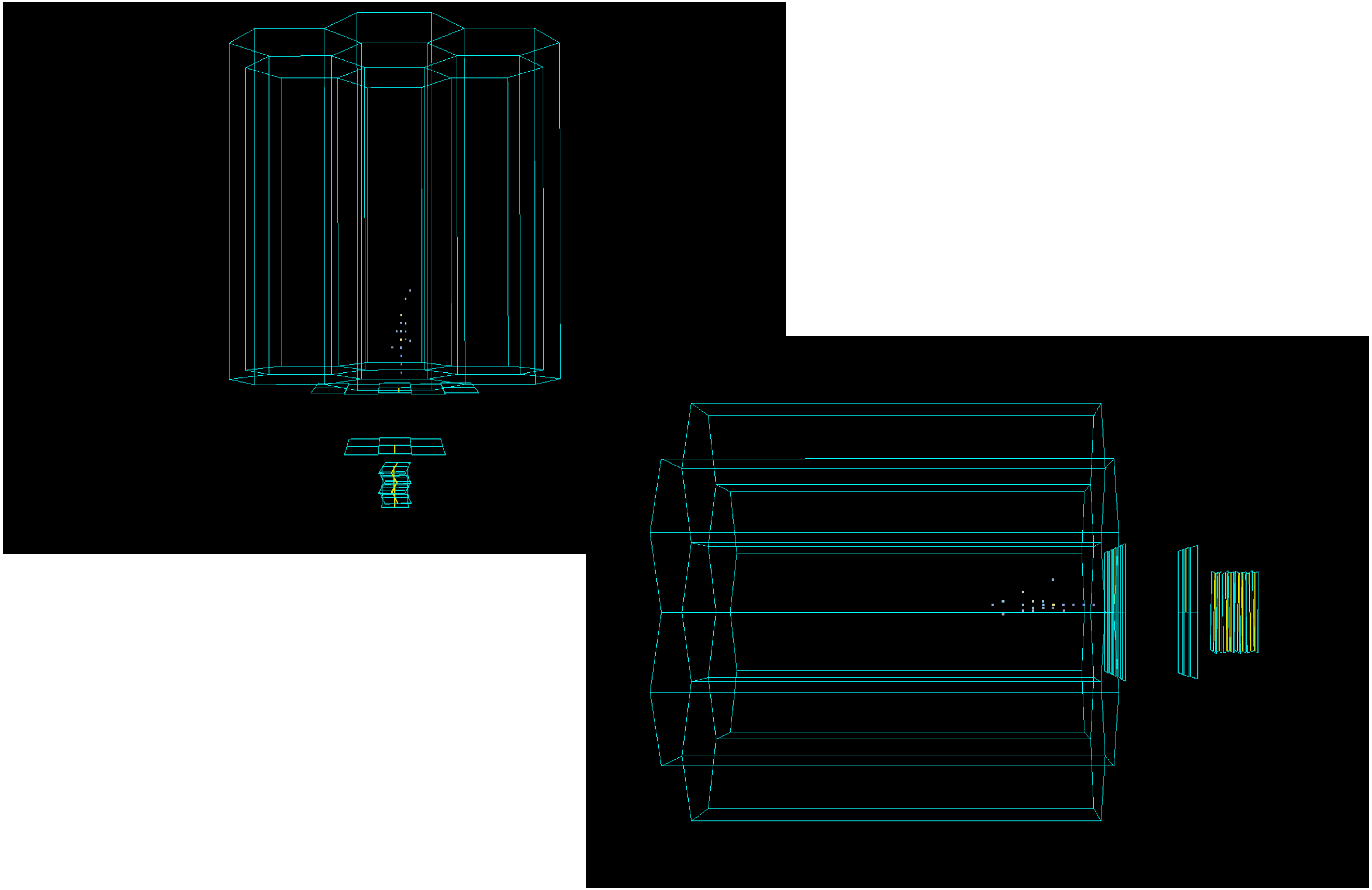
efficiency vs. rejection for
cut on *target* energy



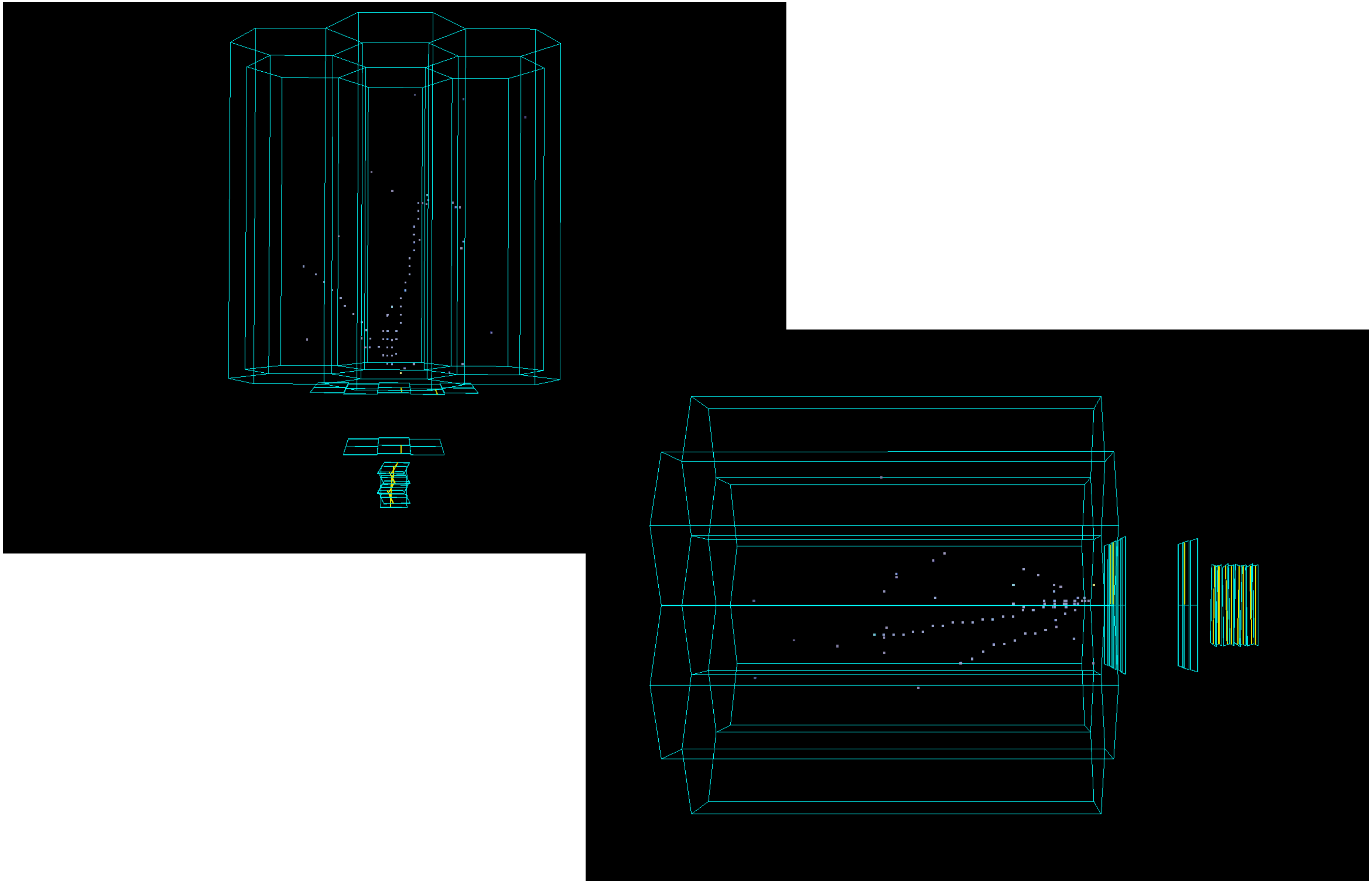
4 GeV Electron on Target



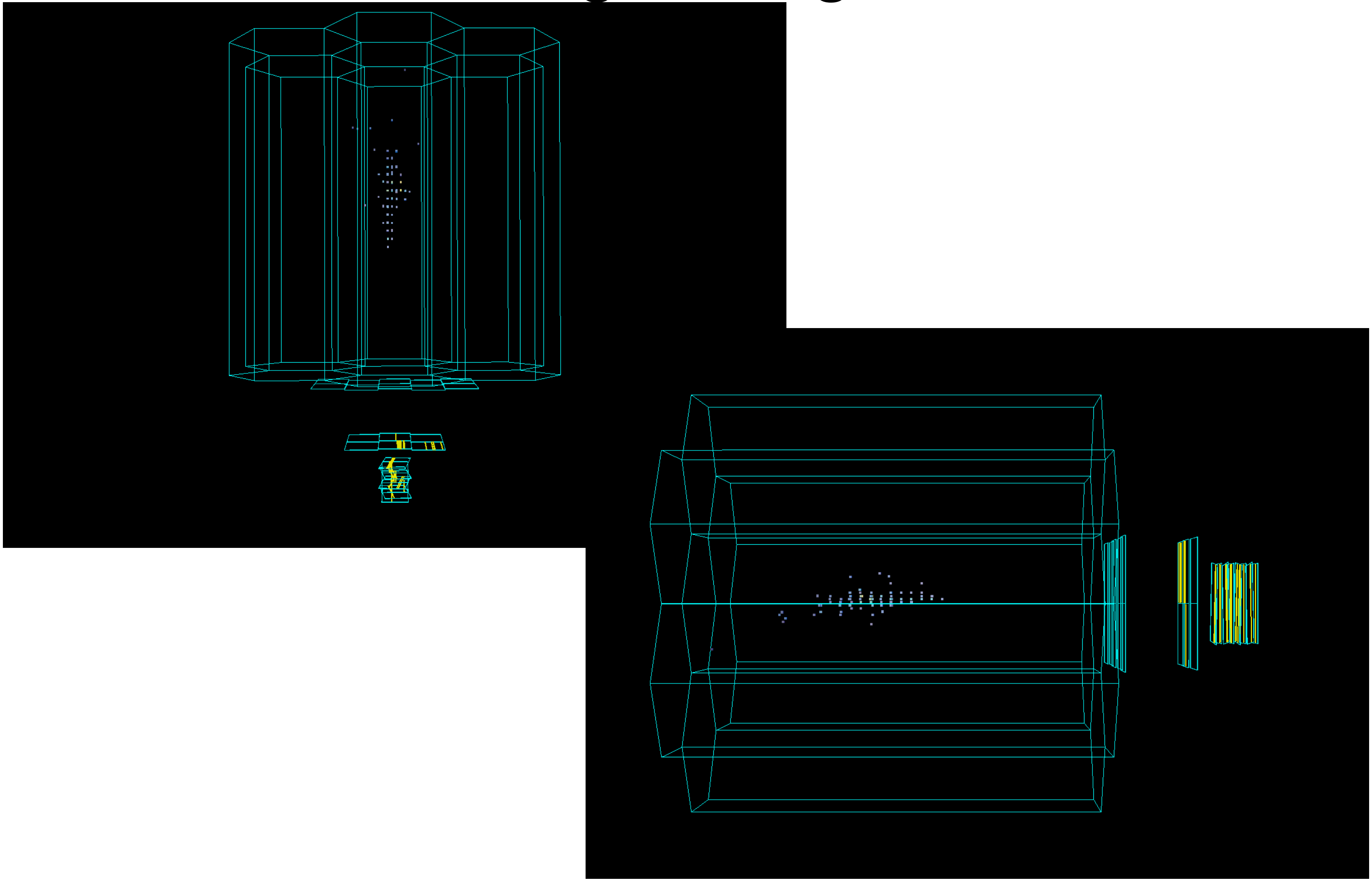
Signal, $m_{A'}$= 100 MeV



Interesting Background 1



Interesting Background 2



Interesting Background 3