The LDMX experiment:
search for light thermal dark matter

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LBL – September 2017

Special thanks to T. Nelson

Outline

Introduction

Thermal dark matter
Direct detection and accelerators

Light dark matter at accelerators

Colliders, fixed target and beam dump experiment
A recent B*A*B*AR* result

The LDMX proposal

Design and sensitivity

Summary

Dark matter: an 80 years old puzzle

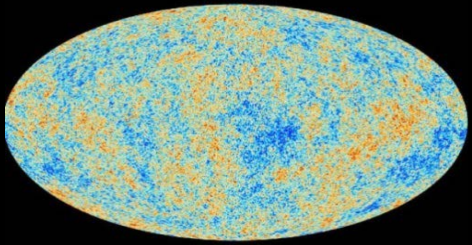
In 1933, F. Zwicky posited the existence of unseen “dark” matter after analyzing the velocity dispersion of galaxies in the coma cluster

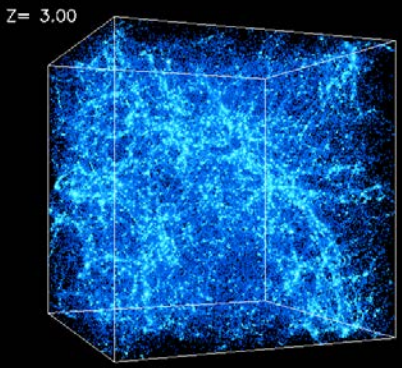
Coma cluster SDSS

Since then, we have collected strong evidence for dark matter

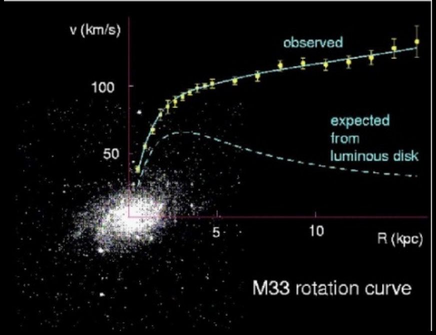
Lensing

CMB





Structure

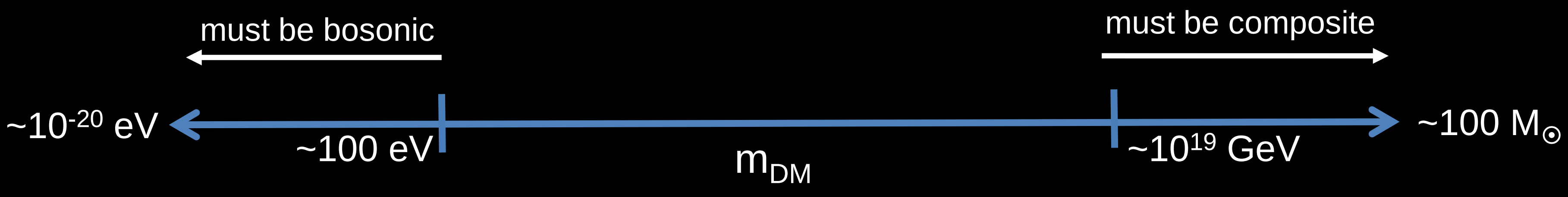


Rotation curve

One name, many possibilities

What we know: its equation of state (ρ_{DM}) and it interacts through gravity.

This allows for a wide range of possibilities…



must be bosonic

must be composite

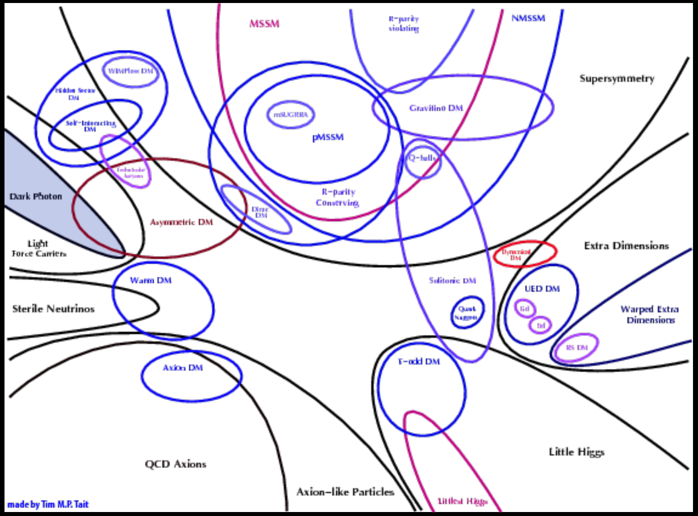
~10^{-20} eV

~100 eV

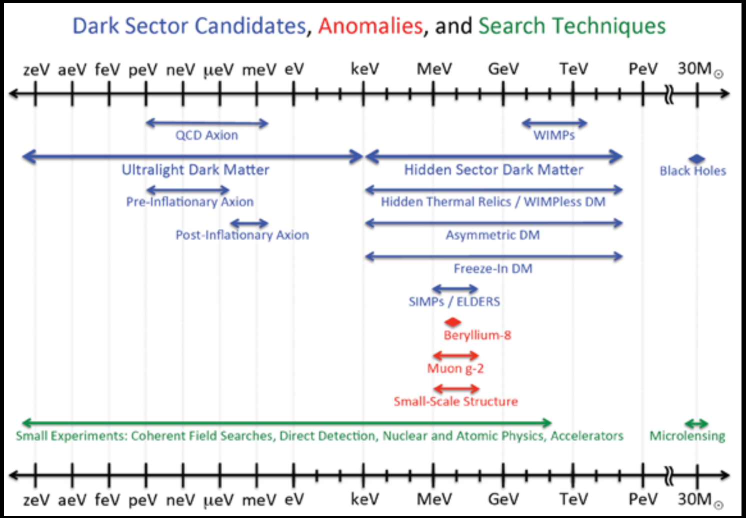
m_{DM}

~10^{19} GeV

~100 $M_\odot$



Tim Tait



U.S. cosmic visions report

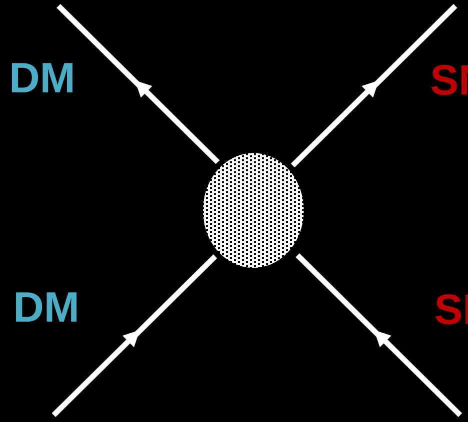
Thermal dark matter

Thermal dark matter, originating as a relic in the early Universe, is arguably one of the most compelling paradigms

Simple: requires only that non-gravitational interaction rate between dark and familiar matter exceed the Hubble expansion. Compatible with nearly all UV scenarios.

Generic: Applies to nearly all models with coupling large enough to allow detection (rare counter-example: axion).

Reasonable: Evidence from CMB and BBN for hot and dense thermal phase of early Universe. Don't need to speculate too much!



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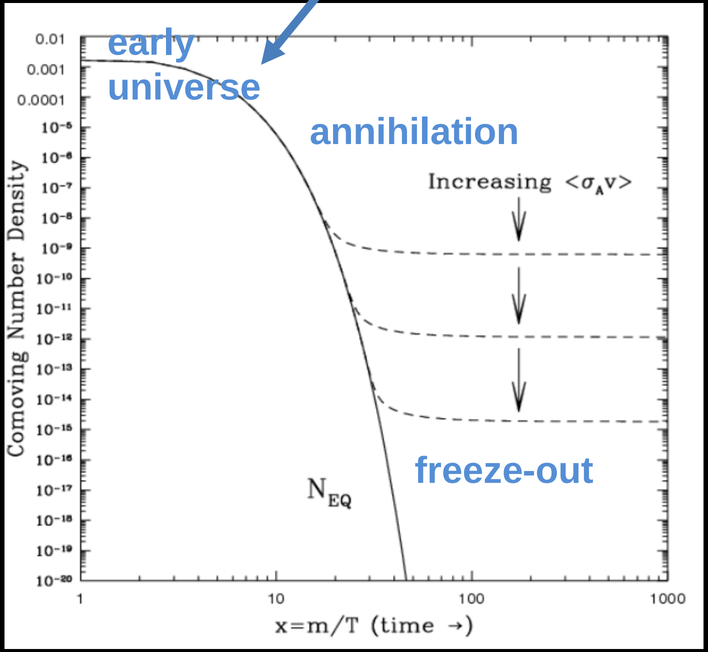
Predictive: DM mass and coupling with SM set abundance → target

$$n_{\mathrm{DM}}^{(\mathrm{eq.})} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \sim T^3$$



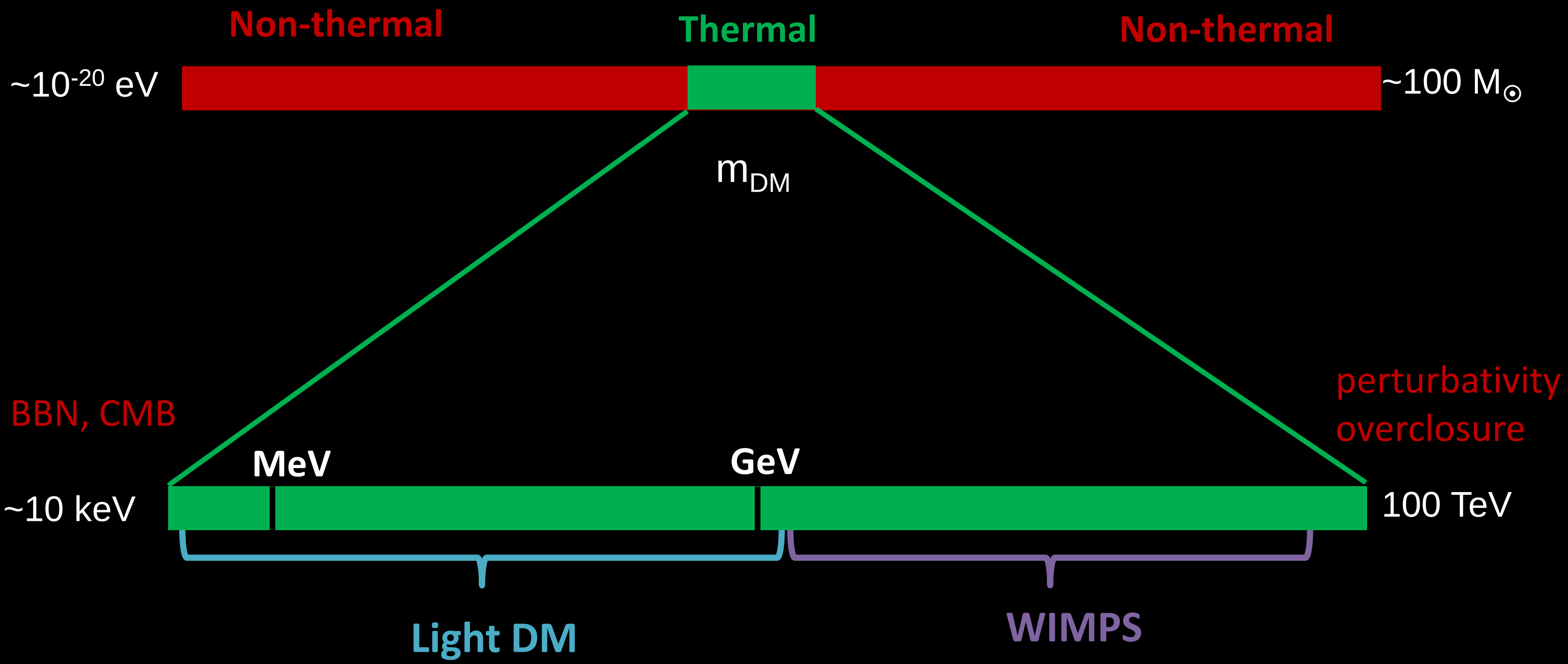
Thermal DM

$\sigma v_{\mathrm{sym}} \sim 3\mathrm{x}10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$ (symmetric)
$\sigma v_{\mathrm{asym}} > 3\mathrm{x}10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$ (asymmetric)

There is a target!

Thermal dark matter

The thermal hypothesis greatly restricts the range of allowed DM masses



Non-thermal **Thermal** **Non-thermal**

$\sim 10^{-20}$ eV $\sim 100\ M_{\odot}$

m_{DM}

BBN, CMB

perturbativity
overclosure

MeV **GeV**

~10 keV 100 TeV

Light DM

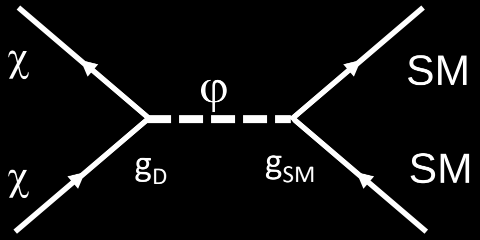
WIMPS

Thermal contact implies new mediator
Hidden sector light DM well-motivated model

Thermal freeze-out for weak scale masses
Driven DM searches for last ~30 years

Light thermal dark matter

Freeze-out scenario with light dark matter (χ) requires new light mediator to explain the relic density, or dark matter is overproduced



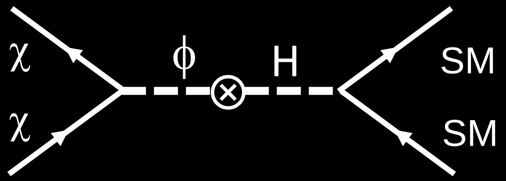
$$< \sigma v >_{relic} \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

$$m_\varphi^4 \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{<\sigma v>} \leq \frac{m_x^2}{<\sigma v>} \qquad \text{since } g \leq O(1)$$

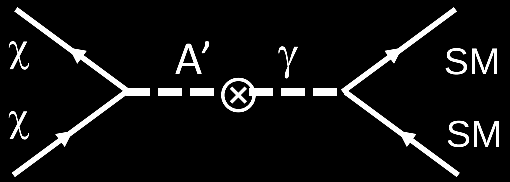
What kind of mediator?

Must be neutral under the SM and renormalizable. Simplest choices:

New scalar (ϕ) with Higgs coupling



New vector (A’) with photon coupling



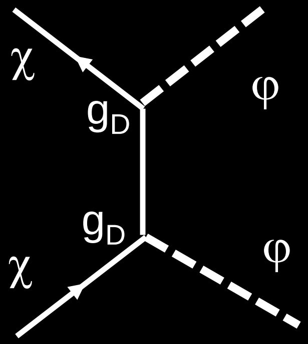
Naturally realized in the context of hidden sectors

Light thermal dark matter

The DM / mediator mass ratio determines the type of annihilation and the mediator decay

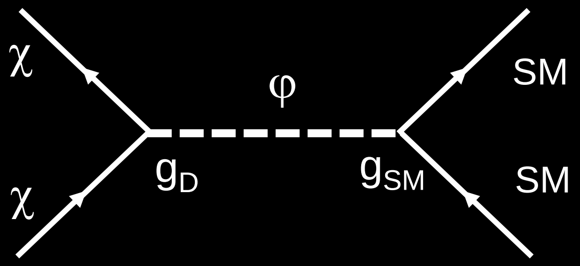
Secluded decay

$m_\chi > m_\varphi$



Direct annihilation

$m_\chi < m_\varphi$

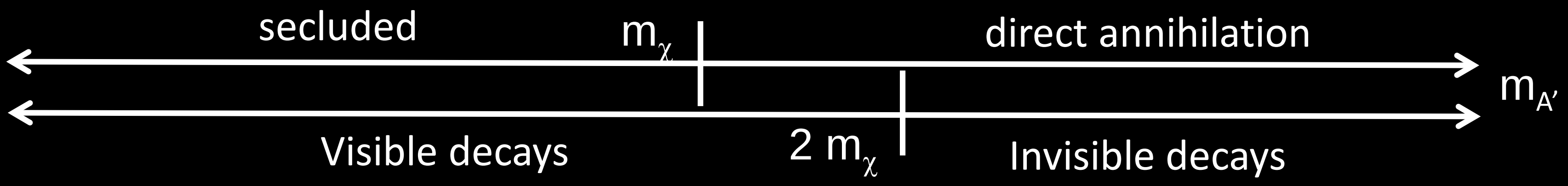


Independent of mediator decays to SM
→ no specific target

Not further considered

Define specific target
almost ruled out for scalar mediator

Direct annihilation with vector mediator



secluded

m_χ

direct annihilation

$m_{A'}$

Visible decays

$2\ m_\chi$

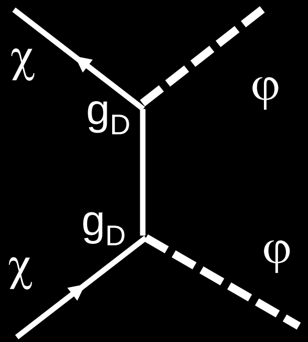
Invisible decays

Light thermal dark matter

The DM / mediator mass ratio determines the type of annihilation and the mediator decay

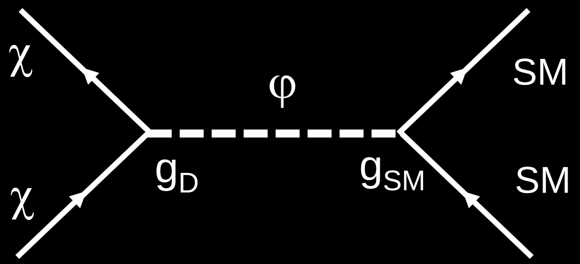
Secluded decay

$m_\chi > m_\varphi$



Direct annihilation

$m_\chi < m_\varphi$



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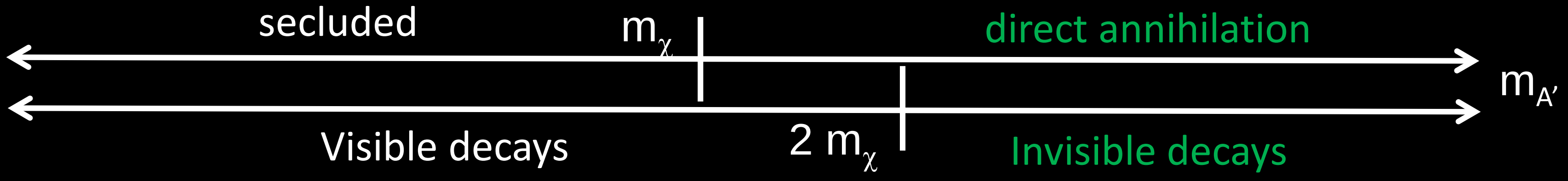
Direct annihilation with vector mediator



secluded

m_χ

direct annihilation

$m_{A'}$

Visible decays

$2\,m_\chi$

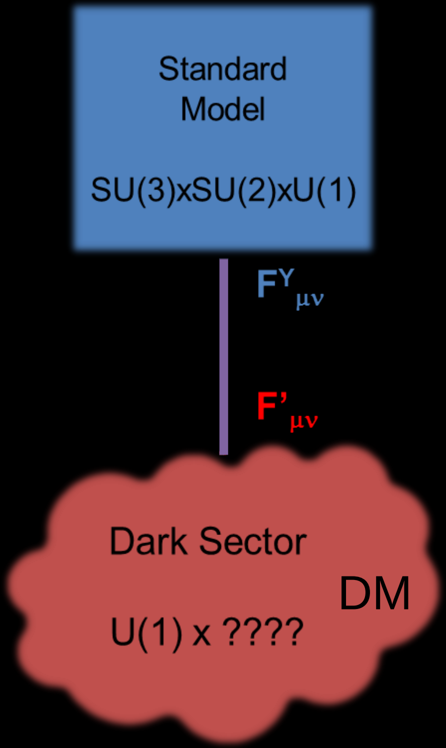
Invisible decays

Hidden sector and vector portal

Hidden sector: sector with new particles - and possible forces - that don't couple directly to the SM, but via new mediators (aka portals).

VECTOR PORTAL

- Hidden sector with a new gauge group U(1)' and a corresponding gauge boson, the dark photon A'
- There is a generic interaction (kinetic mixing) between the SM hypercharge and U(1)' fields with a mixing strength ε.
- Could be realized by new heavy particles charged under both gauge groups.
- This induces a dark photon – SM fermion coupling $\alpha' = \varepsilon^2\alpha$

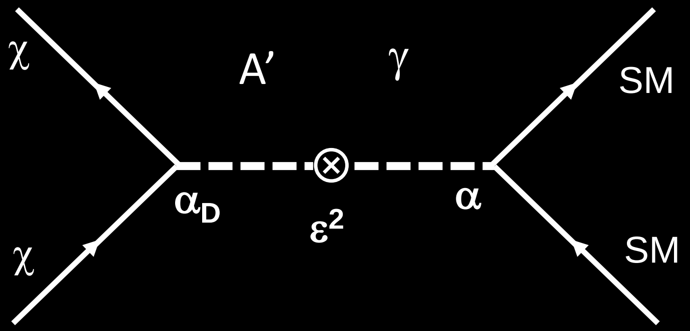


$$\Delta\mathcal{L} = \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

Holdom, Galison, Manohar

LDM scenario

Hidden sector thermal LDM with vector portal.



$$< \sigma v > \sim \alpha_D \varepsilon^2 \frac{m_x^2}{m_A^4} \sim \alpha_D \varepsilon^2 \frac{m_x^4}{m_A^4} \frac{1}{m_x^2} = y \frac{1}{m_x^2}$$

$$\boxed{y = \alpha_D \, \varepsilon^2 \frac{m_x^4}{m_A^4}}$$

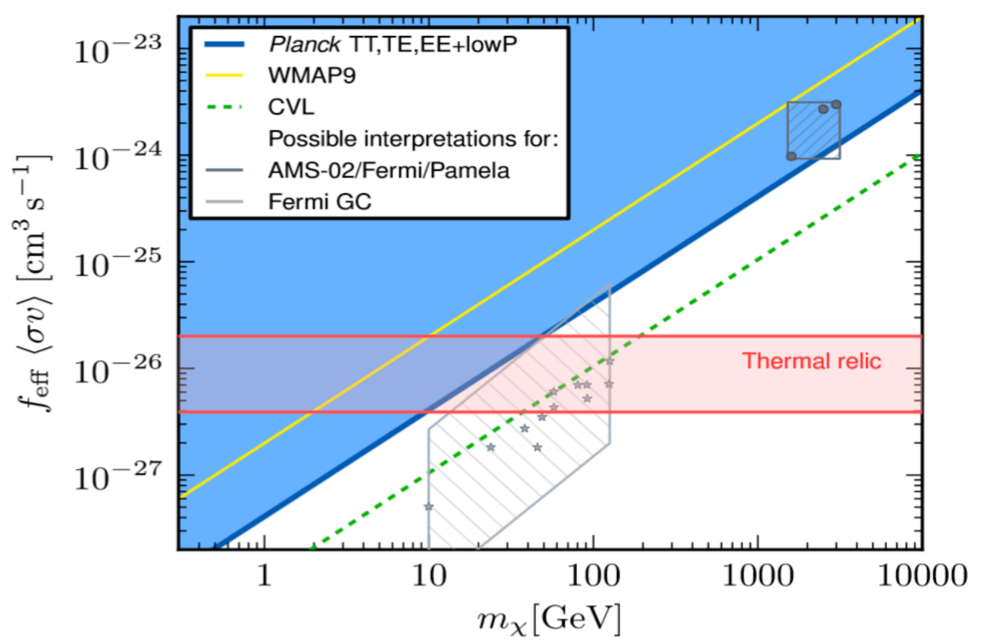
Dimensionless variable

Definitive predictions as a function of mass and particle type !!!

Cosmological constraints

Primordial DM annihilation injects energy in the CMB $\rightarrow$ distorts CMB spectrum

Constraints on the self-annihilation cross-section at recombination x efficiency parameter



Planck collaboration, 1502.01589

Rules out Dirac fermion DM, which proceeds via s-wave annihilation.

Remaining possibilities

(1) p-wave annihilation

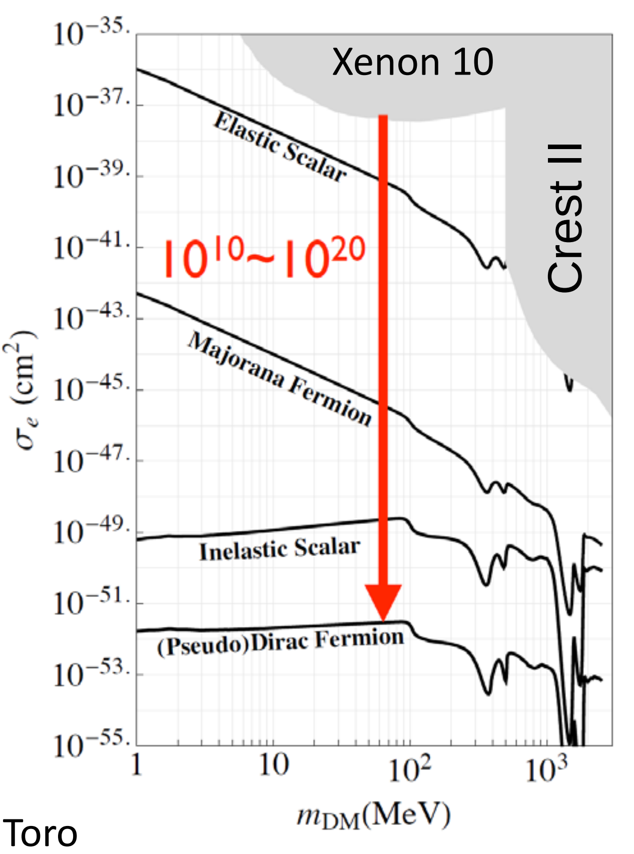
OR

(2) annihilation shuts off before CMB

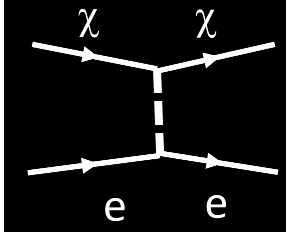
Scalar, Majorana and inelastic DM are possible candidates

Direct detection and accelerators

Direct detection targets

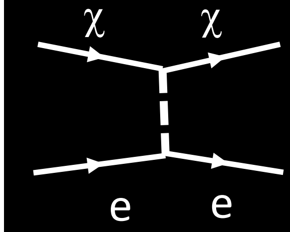


Toro



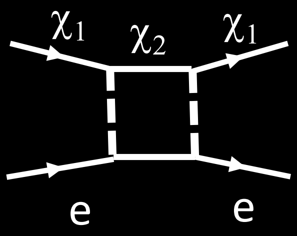
SCALAR

$\sigma_e \sim 10^{-39}$ cm^2



MAJORANA

$\sigma_e \sim 10^{-39}$ v^2 cm^2 $v \sim 10^{-3}$



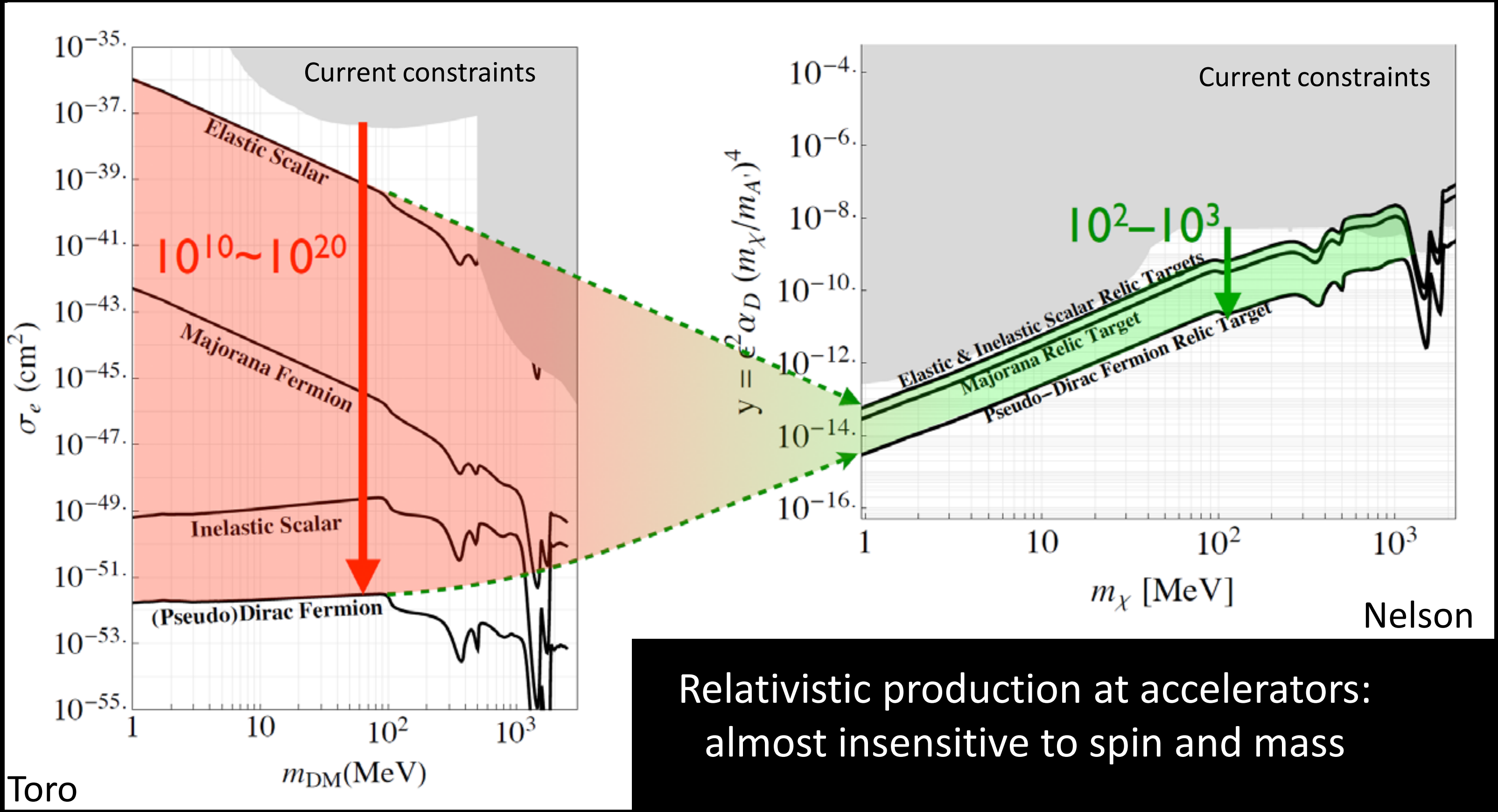
INELASTIC

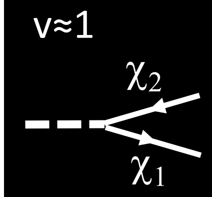
$\sigma_e \sim 10^{-50}$ cm^2 loop diagram

Is there a way to put these on the same footing?

Direct detection and accelerators

Direct detection targets **Accelerator targets**





Relativistic production at accelerators: almost insensitive to spin and mass

Accelerators uniquely positioned to probe directly annihilating thermal LDM

More generally…

The scope of accelerator-based experiments is much more extensive, and encompass models such as

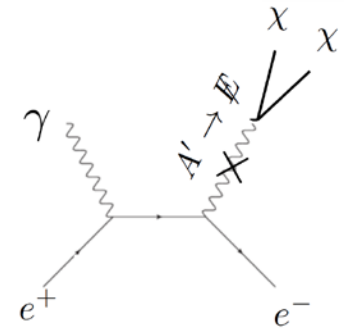
- Quasi-thermal DM, such as asymmetric DM and ELDER DM
- New long-lived resonances produced in the dark sector (SIMP)
- Freeze-in models with heavy mediators
- New force carriers coupling to electrons, decaying visibly or invisibly
- Milli-charged dark sector particles
- ….

In essence, exploring physics that couples to electrons in the sub-GeV mass range is well-motivated and important, and accelerator based experiments could generically probe a vast array of possibilities in addition to light thermal DM.

Light dark matter at accelerators

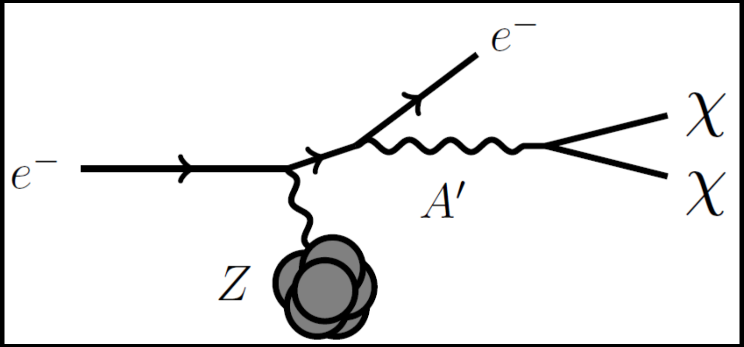
Accelerator approaches

Missing mass



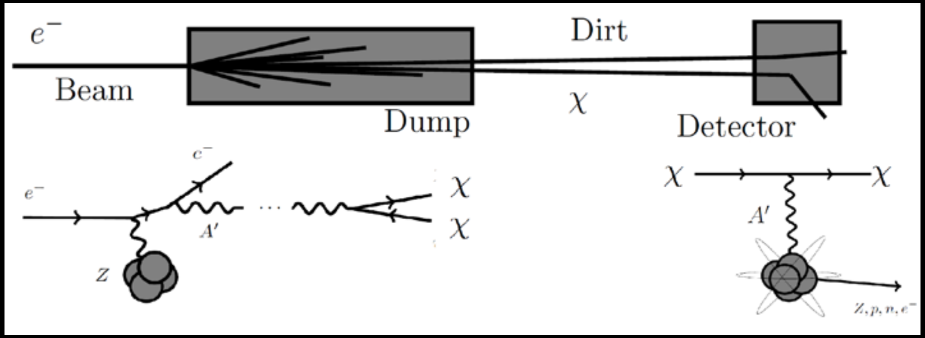
Resonant signal

Missing energy / momentum



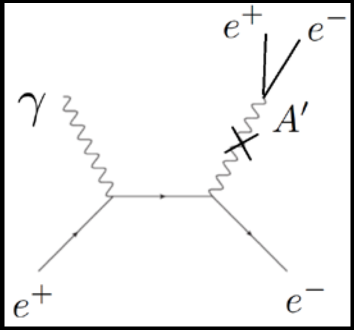
Large yield at low $m_{A'}$

Beam dump



Probes DM interaction twice

Direct mediator search

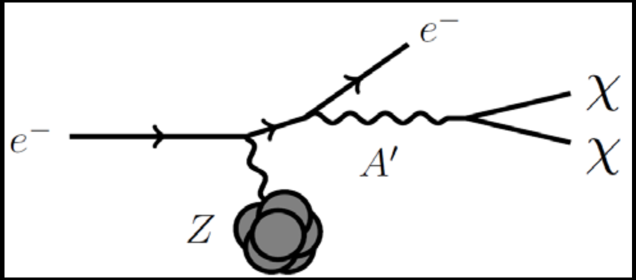


Visible decay $m_{A'} < 2m_\chi$

Accelerators can access explore the physics in detail ($\varepsilon, m_{A'}, m_\chi, \alpha_D$),
direct detection needed to establish cosmological stability

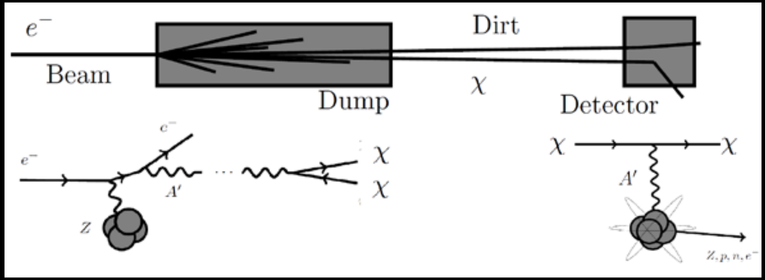
Maximizing dark photon detection

Missing energy / momentum



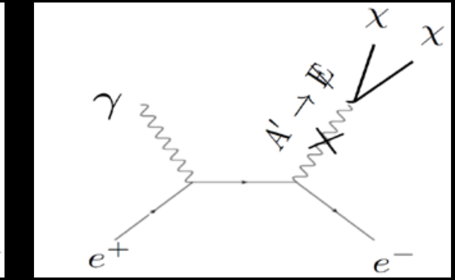
$\sigma \sim Z^2 \varepsilon^2 / m_A^2$

Beam dump



$\sigma \sim \alpha_D \varepsilon^4$

Missing mass



$\sigma \sim \varepsilon^2/s \quad m_A \ll s$

$\sigma \sim \varepsilon^2/(s-m_A^2) \quad m_A \sim s$

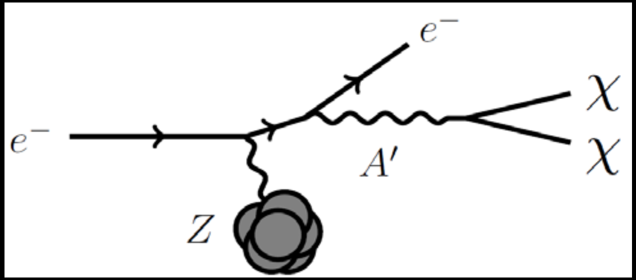
Fixed target
  large dark photon yield production for low mediator masses

Missing energy/momentum:
  large “detection” yield

Missing energy / momentum maximizes low mass dark matter production and detection. Missing mass provides best yield for larger masses.

Maximizing dark photon detection

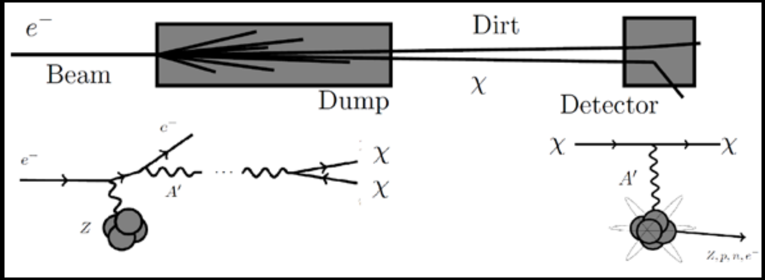
Missing energy / momentum



$\sigma \sim Z^2 \varepsilon^2 / m_A^2$

$$N_{signal} \approx N_e \left. y \right|_{1\ MeV}$$

Beam dump



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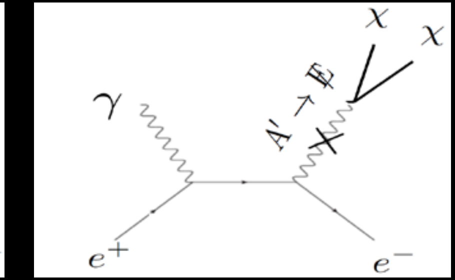
Missing mass

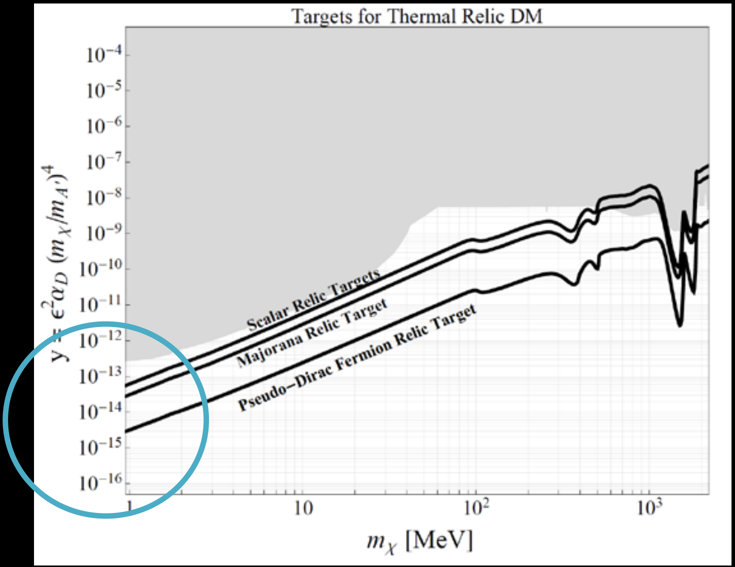


$\sigma \sim \varepsilon^2/s \qquad m_A \ll s$

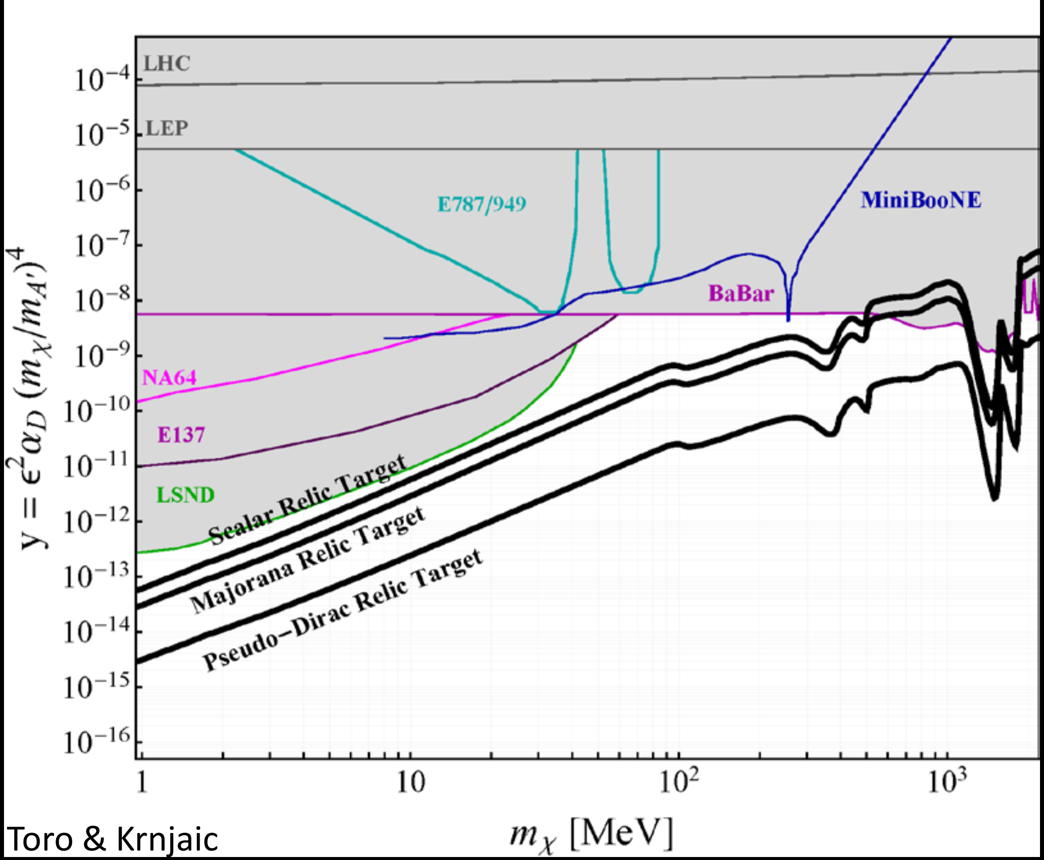
$\sigma \sim \varepsilon^2/(s-m_A^2) \qquad m_A \sim s$

A zero background experiment can definitely test the light thermal DM over a large fraction of the allowed mass range with 10^{16} EOT.

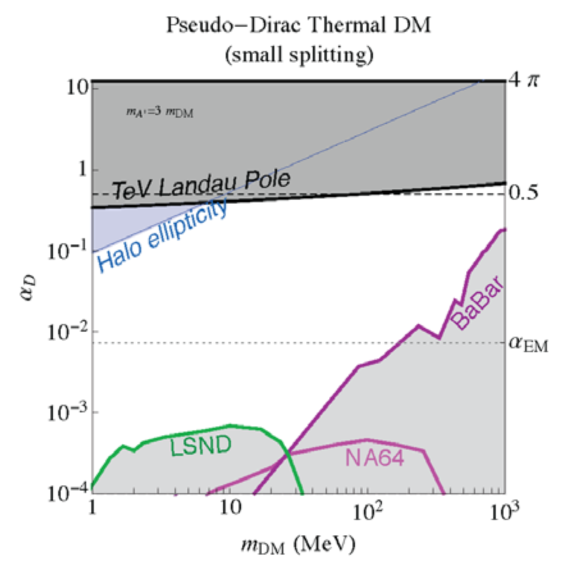
A missing mass experiment with a large luminosity could cover the remaining range.



Current constraints



Toro & Krnjaic



Some assumptions need to be made to plot constraints from missing mass / momentum / energy experiments. We pick very conservative parameters: $\alpha_D = 0.5$ and $m_A/m_\chi = 3$.

These parameters lead to weak(est) constraints. For smaller values of α_D or larger mass ratio, the constraints go down while the targets are invariant.

pseudo-Dirac DM: Dirac fermion whose two Weyl states are split by a small Majorana term

Missing mass approach:
light dark matter search at B*A*B*AR*

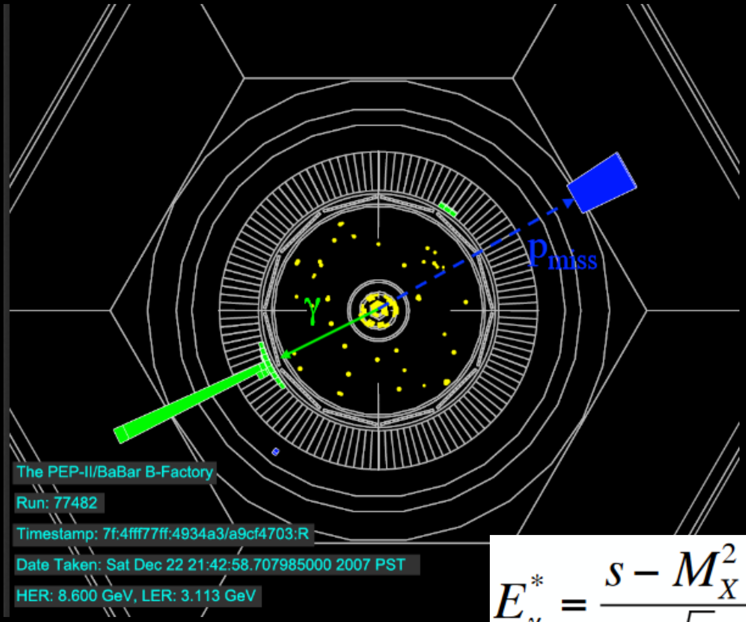
Search for invisible A’ decay at BABAR

At e^+e^- colliders, we can search for $e^+e^- \to \gamma\ A'\ ,\ \ A' \to \text{invisible}$ by tagging the recoil photon in “single photon” events.

BABAR collected ~53 fb^{-1} of data with dedicated single photon triggers during its last year of data taking.

Analysis overview

- Missing energy and momentum is best signature
- Hermeticity is key, but need to allow some machine background
- Search strategy: select single-photon final state, then look for a bump in missing mass M_X (or $E\gamma$)
- Main backgrounds: $e^+e^- \to \gamma\gamma$ and $e^+e^- \to \gamma\ e^+e^-$ with particles outside detector acceptance
- Selection variable categories: photon quality, number of tracks, extra calorimeter energy, missing four-vector and IFR information



$$E_\gamma^* = \frac{s - M_X^2}{2\sqrt{s}}$$

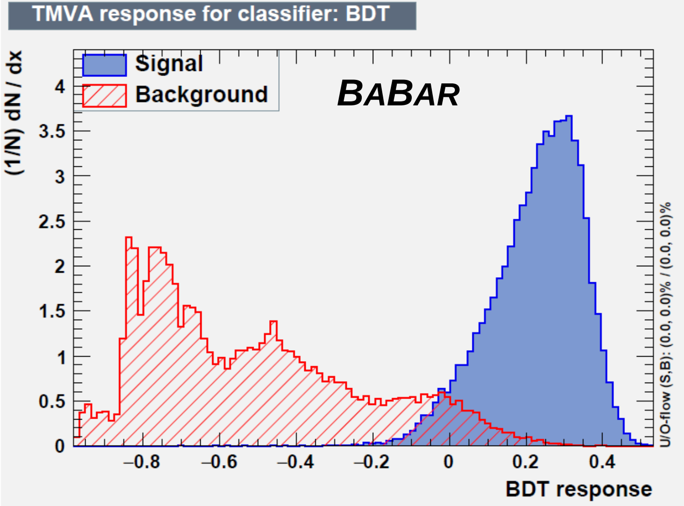
Search for invisible A' decay at BABAR

Train BDT to separate signal from background in two separate regions:

Low-mass: $-4 < M_X^2 < 36$ GeV^2, residual background from $e^+e^- \to \gamma\gamma$ limits sensitivity

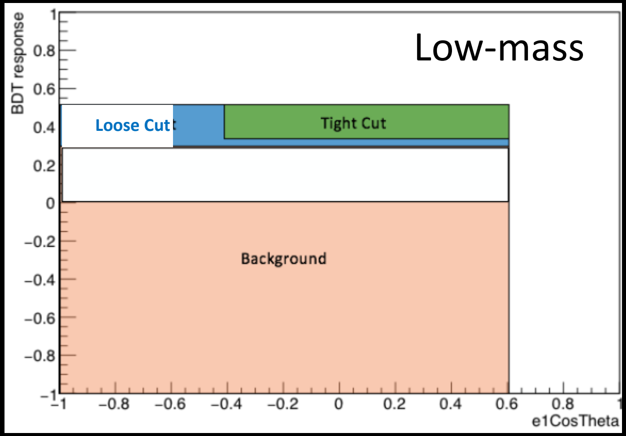
High-mass: $36 < M_X^2 < 69$ GeV^2, smooth background

BDT output low-mass region



Output independent of photon energy

Define several signal regions in the bi-dimensional space of BDT output vs the photon angle to optimize the analysis:



Split data into four non-overlapping regions for each datasets taken at different energies:

Low-mass + tight, low-mass + loose and Not tight, high-mass + loose, background

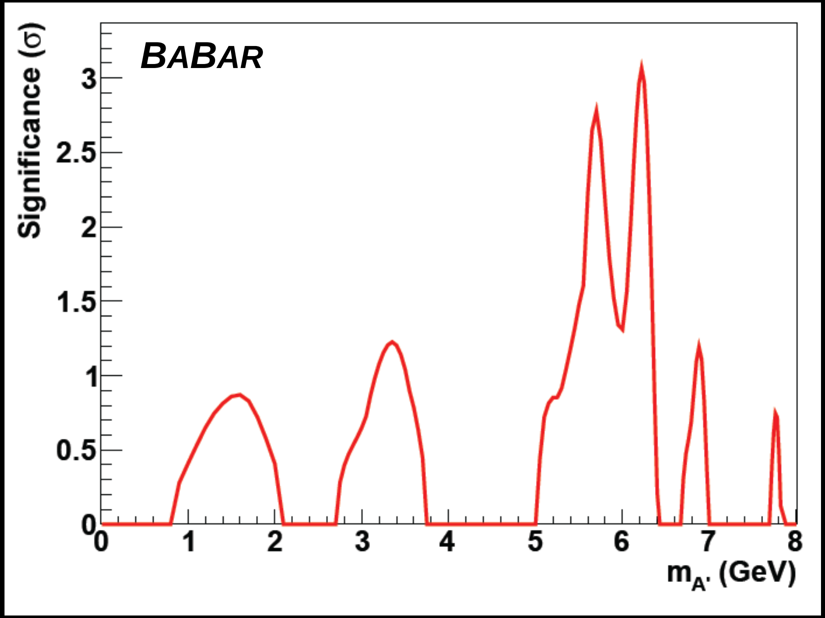
Total of 9 low-mass datasets and 4 high-mass datasets.

Search for invisible A’ decay at BABAR

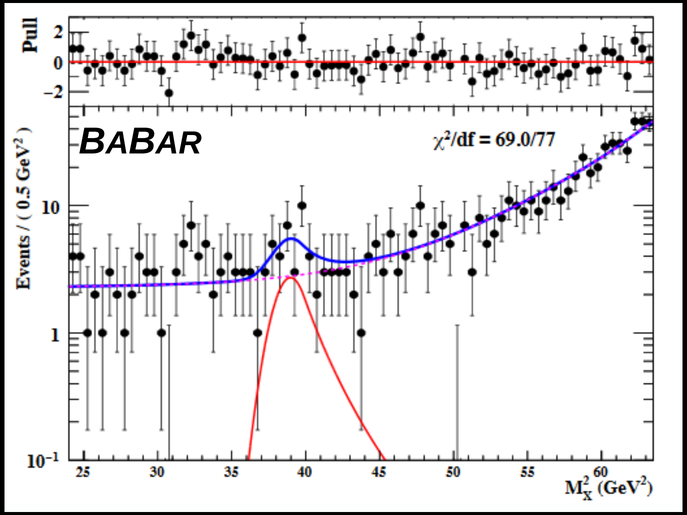
We extract the signal by a simultaneous fit to these independent regions for each beam energies. We probe a total of 166 mass hypotheses.

For each fit, we fix the background shape using the background region, and float the signal yield, peaking and continuum background contributions.

Signal significance distribution



Most significant fit m_A = 6.22 GeV



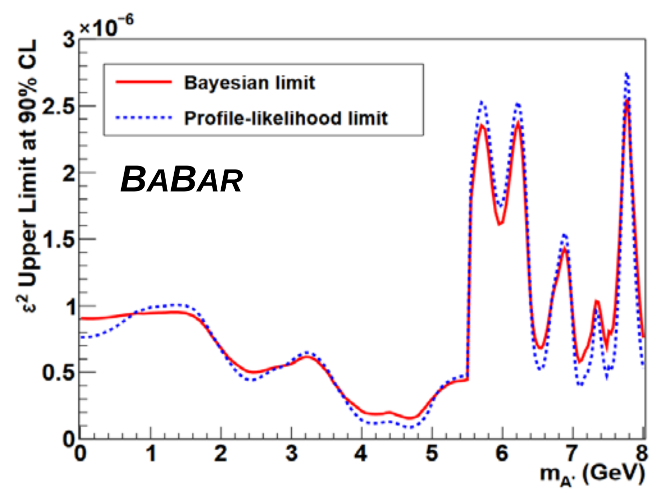
Local (global) significance: 3.1σ (2.6σ)
Global p-value ~ 1%

No significant signal

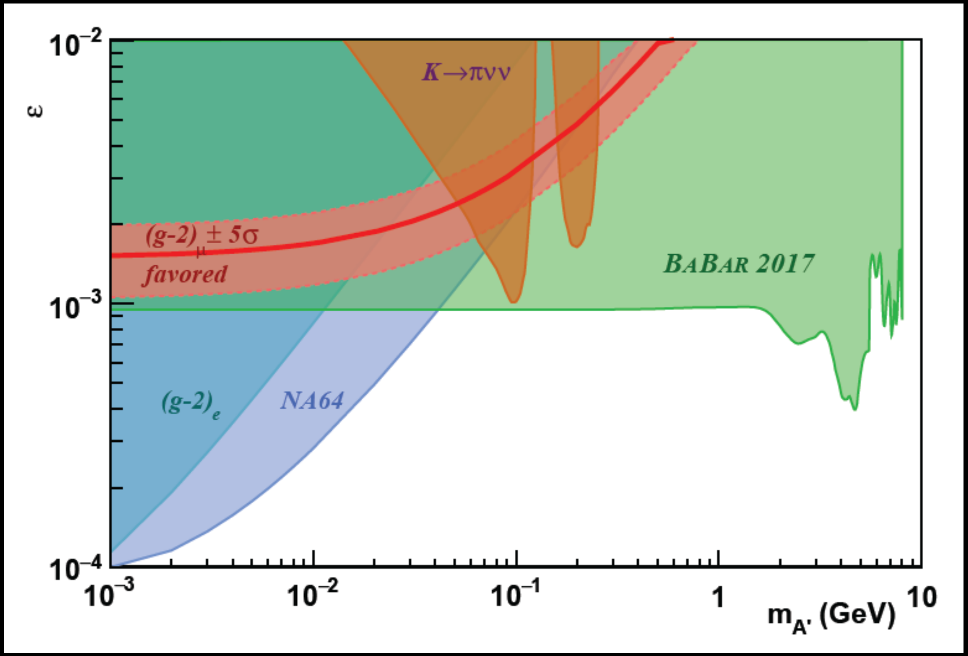
Search for invisible A' decay at BABAR

arXiv:1702.03327
Accepted to PRL
and PRL highlights

Limit on mixing parameter



Limits (90% CL) on mixing parameter



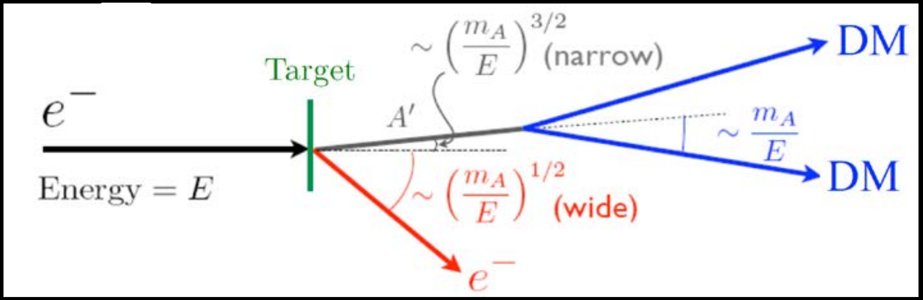
Large improvement over previous measurements, especially at higher masses

Rules out the entire region preferred by $(g\text{-}2)_\mu$ anomaly

Belle-II should further improve

Missing momentum approach: the LDMX experiment

Missing momentum kinematics

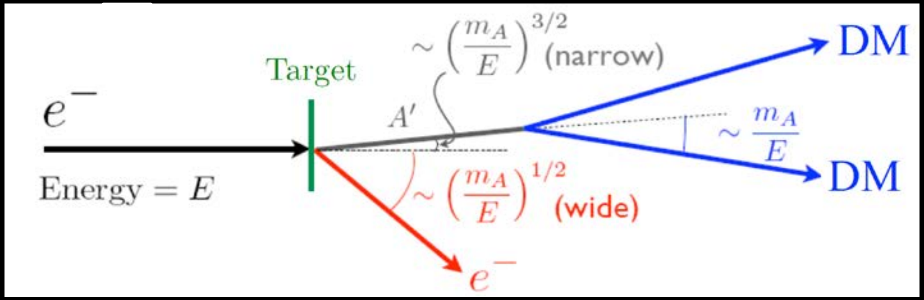


$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + \boxed{m_A^2(1-x)/x}}$$

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

The kinematics is very different from bremsstrahlung emission.

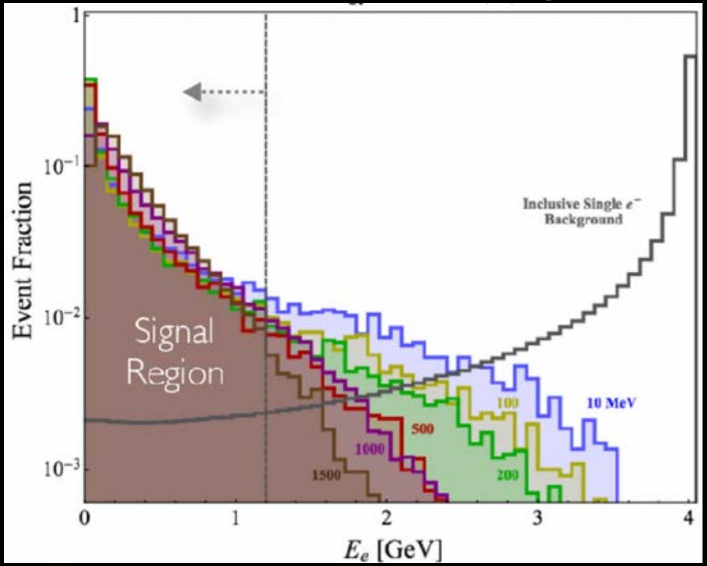
Missing momentum kinematics



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

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

Recoil energy,
4 GeV *e-* on 10% X_0 target



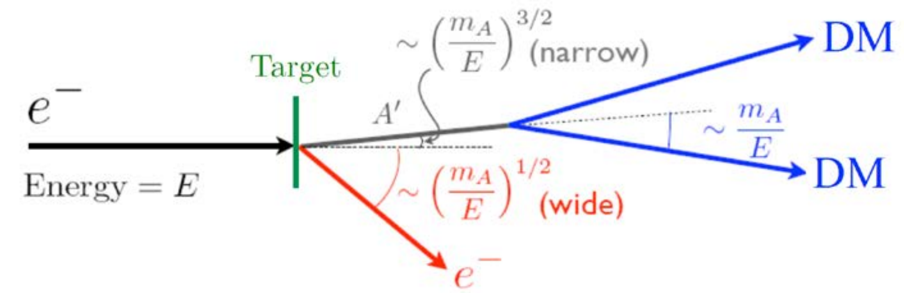
Bremsstrahlung suppressed by factor ~30 is signal region

The kinematics is very different from bremsstrahlung emission.

The A’ is emitted at low angle and carries most of the energy, so

- large missing energy, the recoil electron is soft

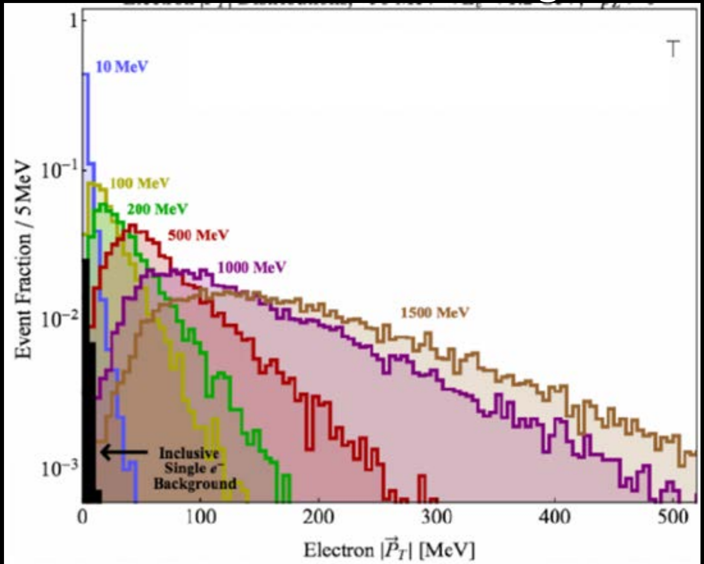
Missing momentum kinematics



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

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

Recoil p_T,
4 GeV *e-* on 10% X_0 target



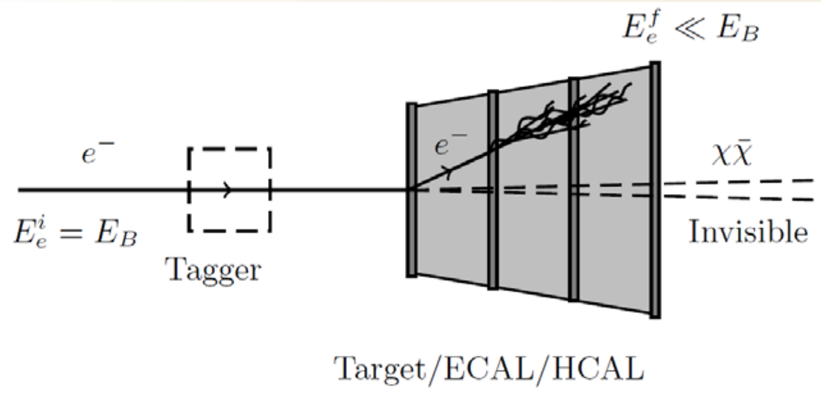
Clear separation from
Bremsstrahlung background

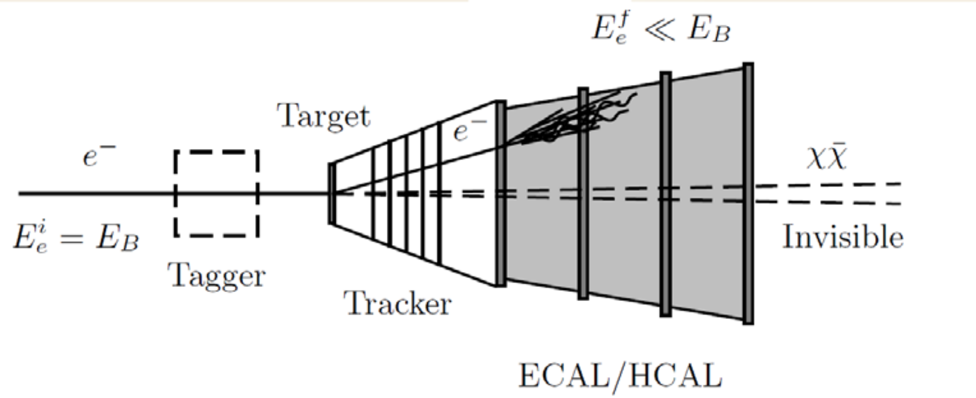
The kinematics is very different from bremsstrahlung emission.

The A’ is emitted at low angle and carries most of the energy, so

- large missing energy, the recoil electron is soft
- large missing p_T, the recoil electron is emitted at large angle

Missing energy / momentum





Missing energy:

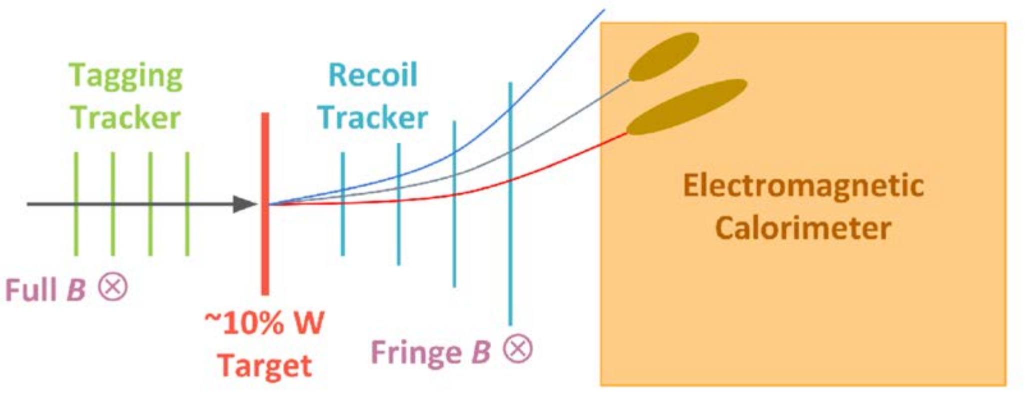
- Higher signal yields / EOT
- Greater acceptance
- Backgrounds beyond 10^{14} EOT might require e-γ identification

Missing momentum:

- Reconstruct outgoing electron, better bkg rejection
- p_T spectrum sensitive to $m_{A'}/m_\chi$
- Lower signal yield / ETO

A missing momentum experiment can also perform a missing energy measurement!

A successful missing momentum design



Beam allowing individual reconstruction of each incident electron

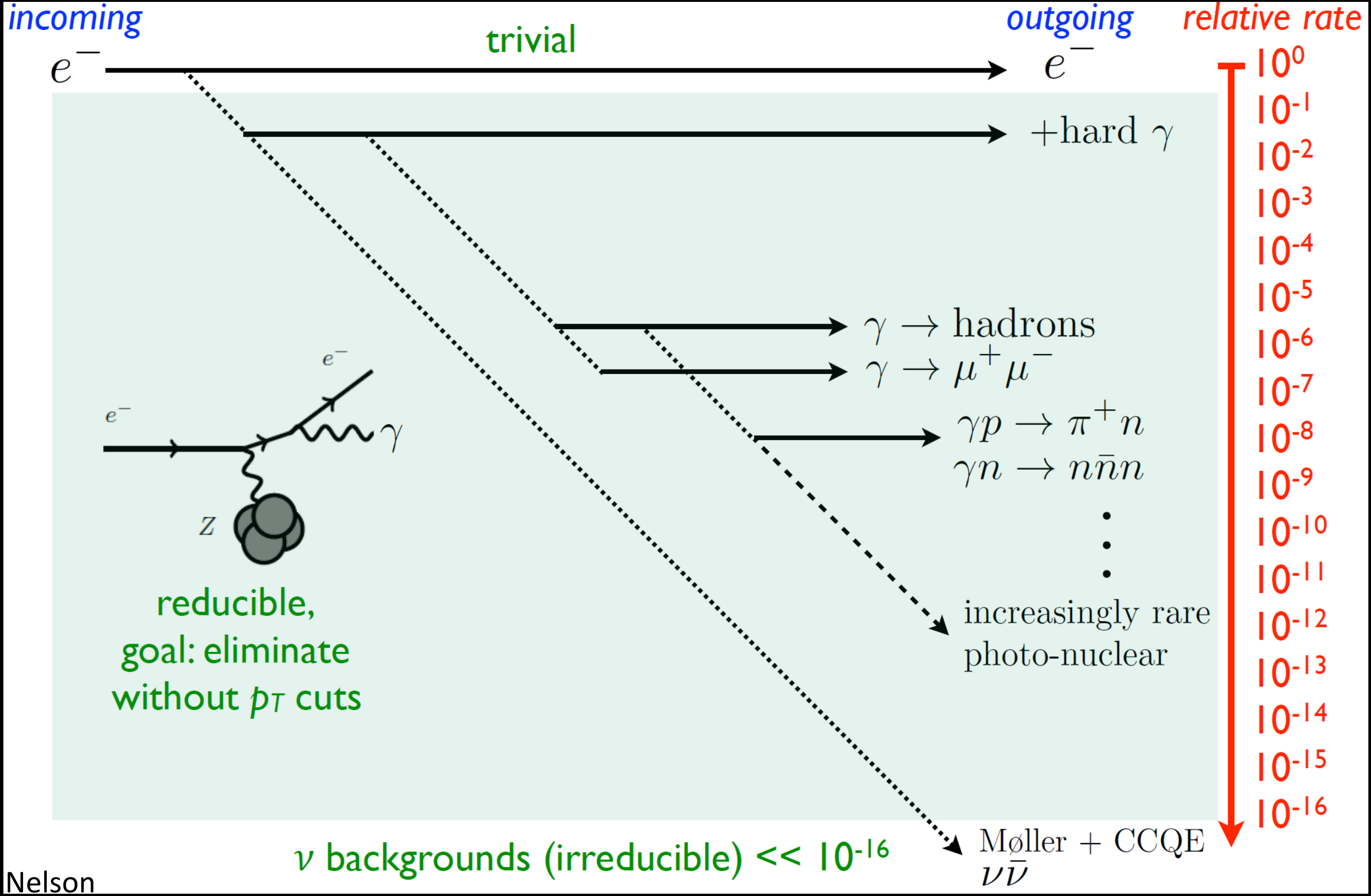
- A multi-GeV, low-current, high repetition rate (10^{16} EOT / year ≈ 1e / 3 ns) beam with a large beam spot to spread out the occupancy / radiation dose.
- The candidates are DASEL @ SLAC (4/8 GeV) and CEBAF @ JLab (up to 12 GeV).

Detector technology with high rate capabilities and high radiation tolerance

- Fast, low mass tagger / recoil tracker to tag each electron with good momentum resolution
- Fast, granular, radiation hard EM calorimeter

The LDMX experiment has been proposed to realize these design requirements in two phases: Phase-I with 10^{14} EOT (1e- / 25 ns) , and Phase-II with 10^{16} EOT (1e- / 3 ns)

Backgrounds



incoming

e^-

trivial

outgoing

e^-

$+\text{hard } \gamma$

$\gamma \rightarrow \text{hadrons}$

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

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

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

⋮

increasingly rare photo-nuclear

Møller + CCQE $\nu\bar{\nu}$

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}

reducible,
goal: eliminate
without p_T cuts

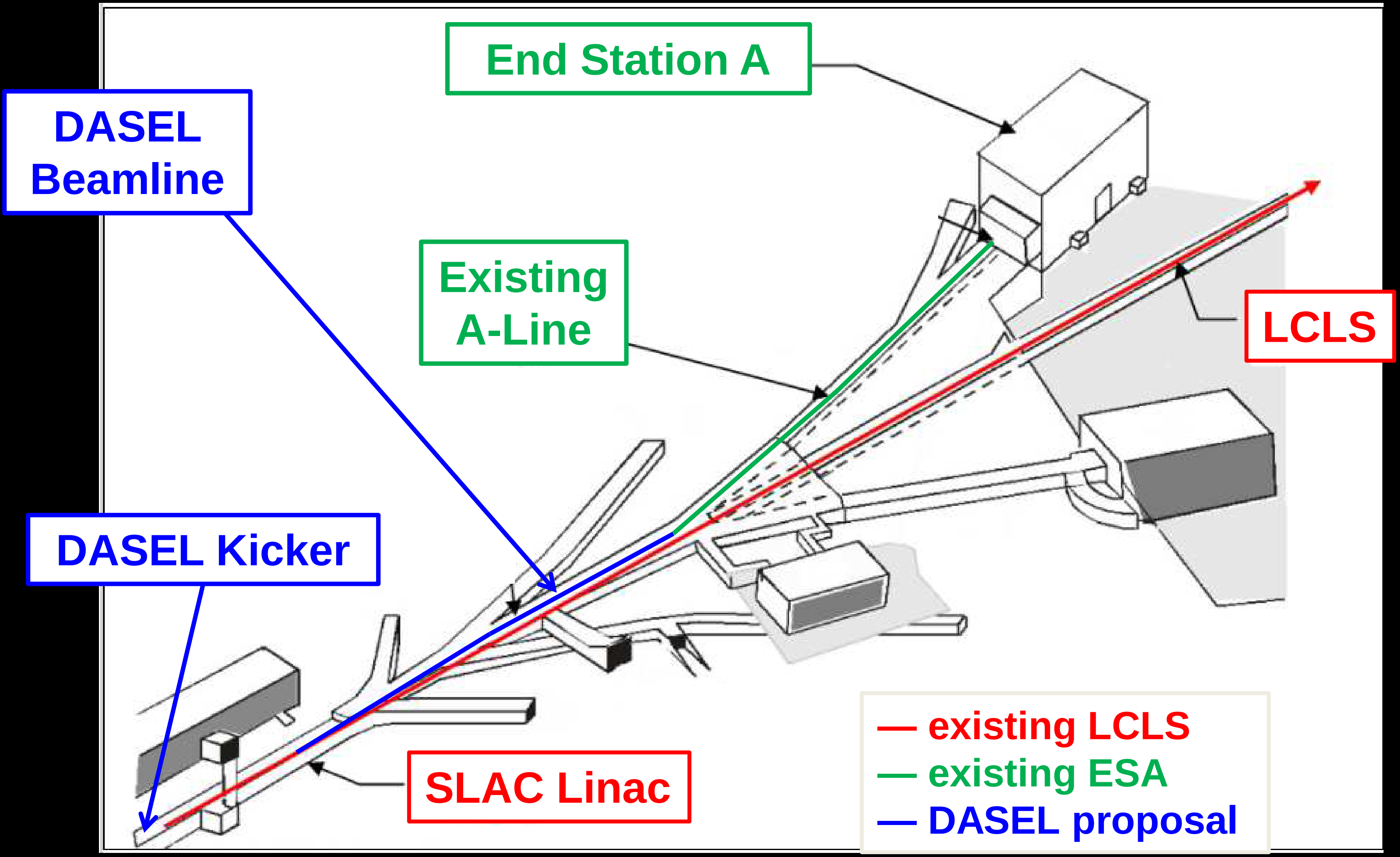
ν backgrounds (irreducible) << 10^{-16}

Nelson

DASEL proposal

DASEL (Dark Sector at LCLS)

T. Raubenheimer



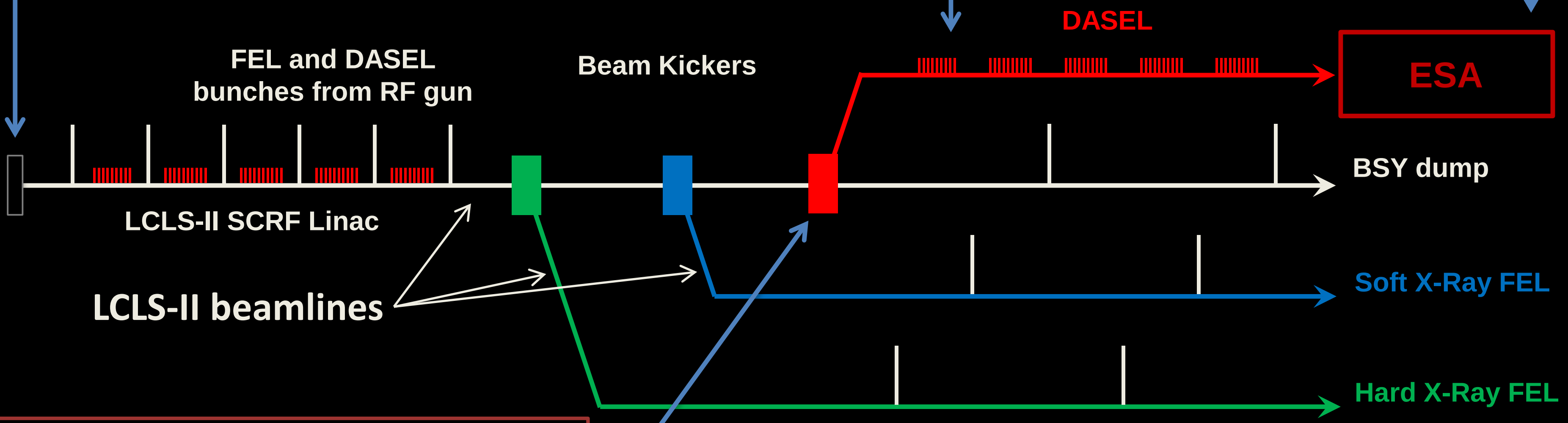
DASEL proposal

T. Raubenheimer

Experimental Facilities
- Small upgrades to ESA systems

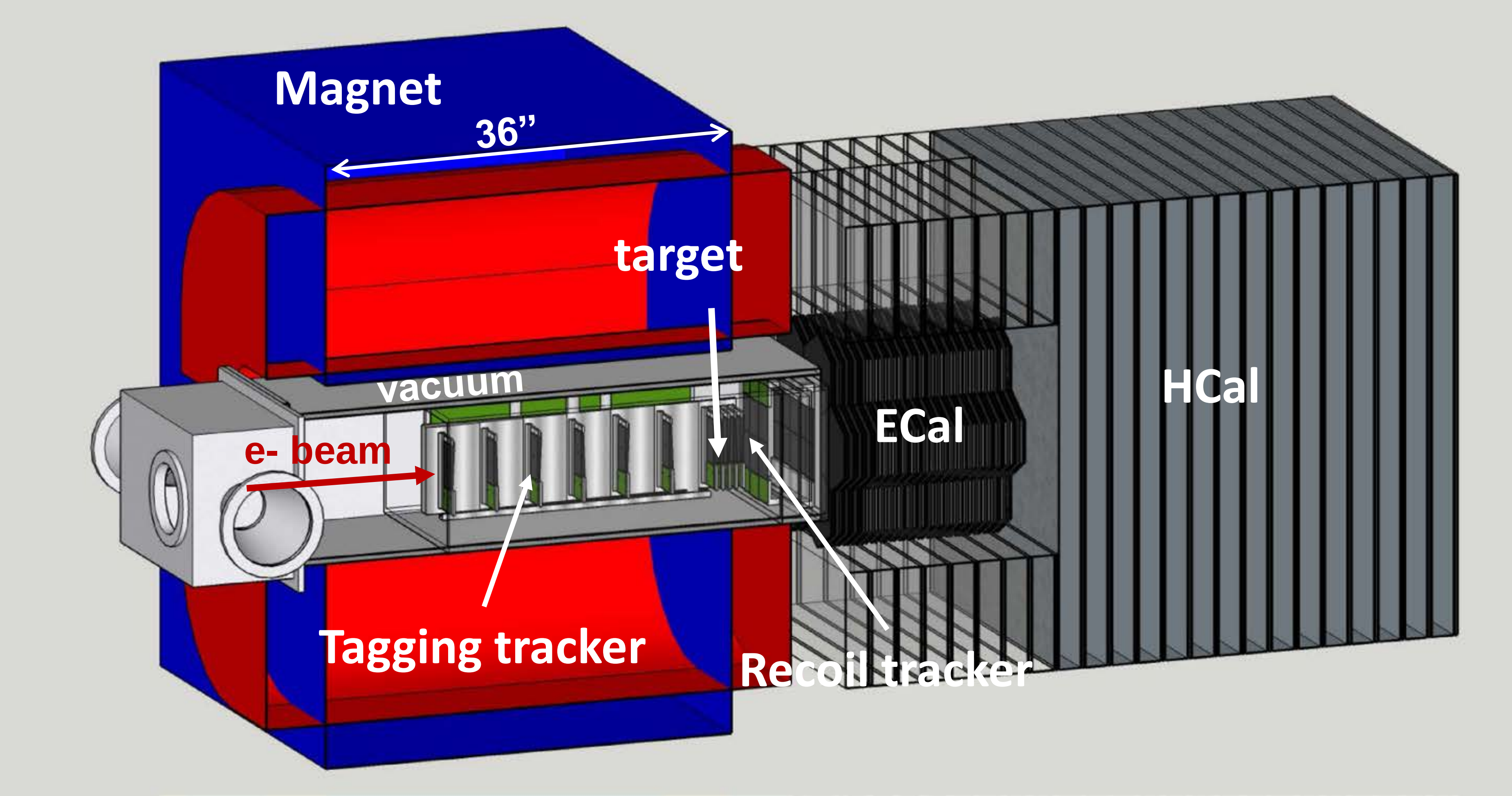
DASEL Beamline connecting to ESA line
- 3 dipoles & 14 quads (all refurbished)

Laser system to fill “unused” buckets with electrons for DASEL



DASEL kicker/septum system downstream of FEL kickers to eliminate interference
- Based on LCLS-II design

LDMX detector concept – Phase I



Tracking system

Two tracking systems:

- Tagging tracker to measure incoming e-
- Recoil tracker to measure scattered e-

Single dipole magnet, two field regions

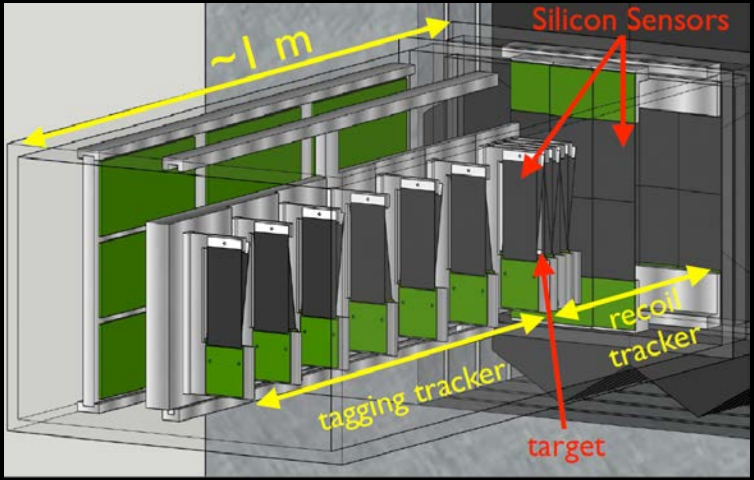
- Tagging tracker placed in the central region for p_e = 4 GeV,
- Recoil tracker in the fringe field for p_e ~ 50 – 1200 MeV

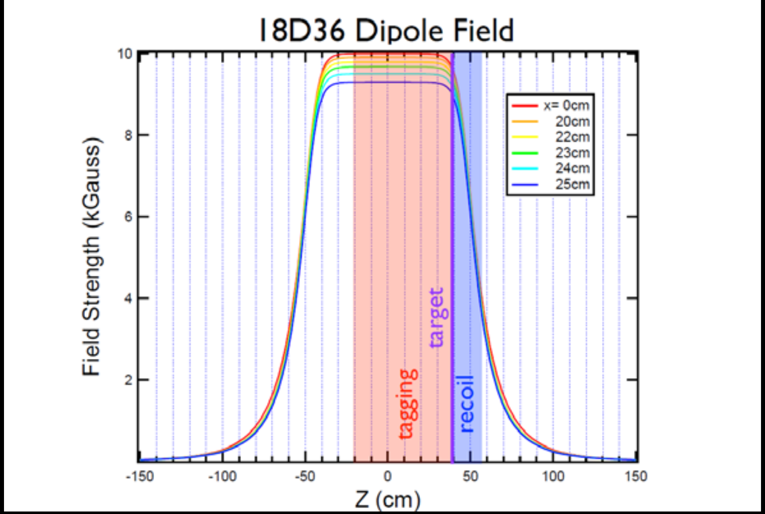
Silicon tracker similar to HPS SVT

- Fast (2ns hit time) and radiation hard

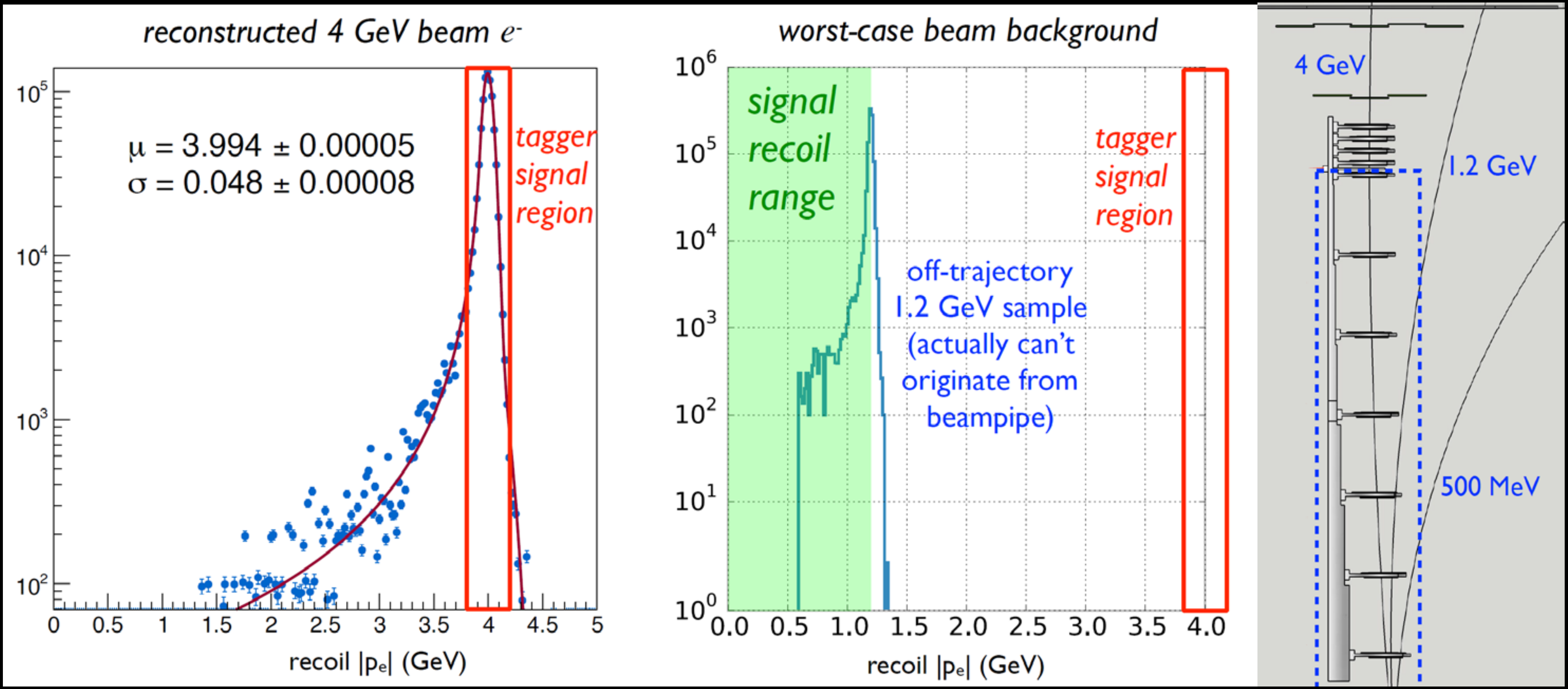
Tungsten target between the two trackers

- 0.1-0.3 X_0 thickness to balance between signal rate and momentum resolution
- Scintillator pads at the back of target to veto empty events





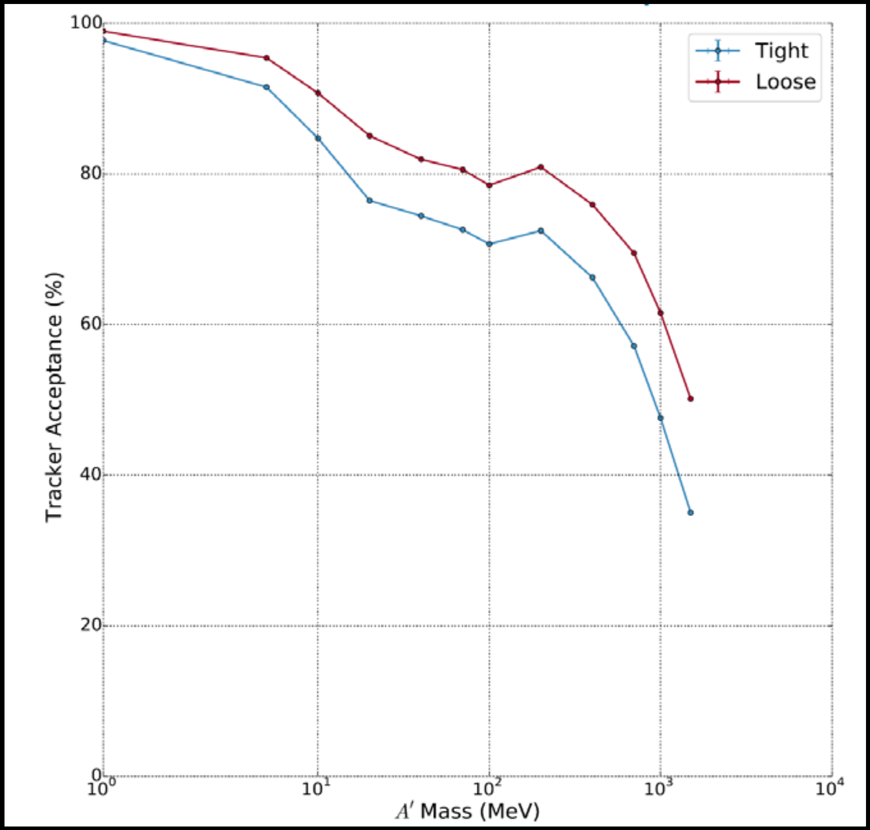
Tracking system

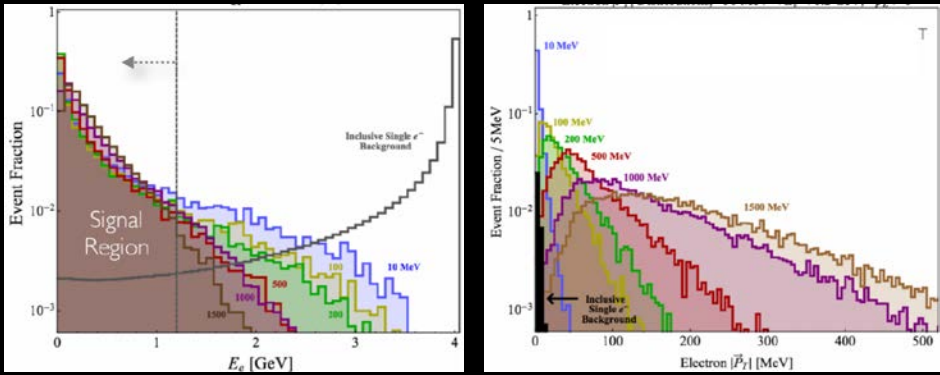


Tagging tracker efficiently rejects beam-induced background

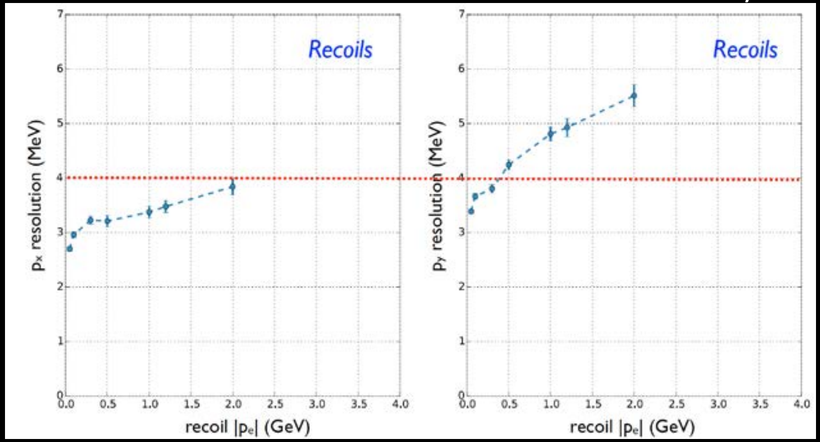
Tracking system

Acceptance for recoil electrons





Recoil momentum resolution (p_x,p_y)



Good acceptance, limited at high masses by kinematics,

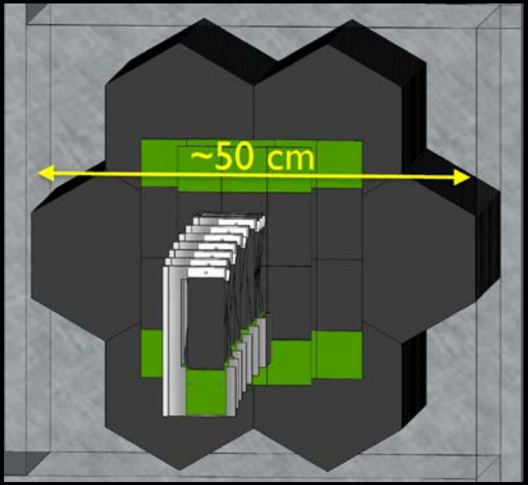
Recoil momentum resolution limited by multiple scattering in target

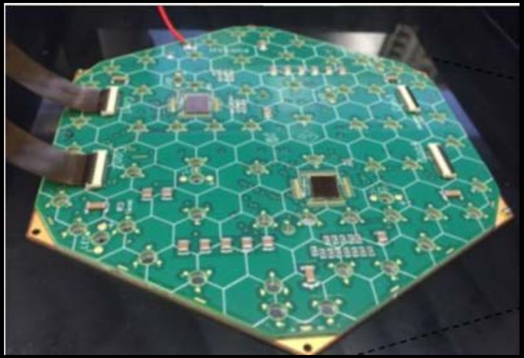
EM calorimeter

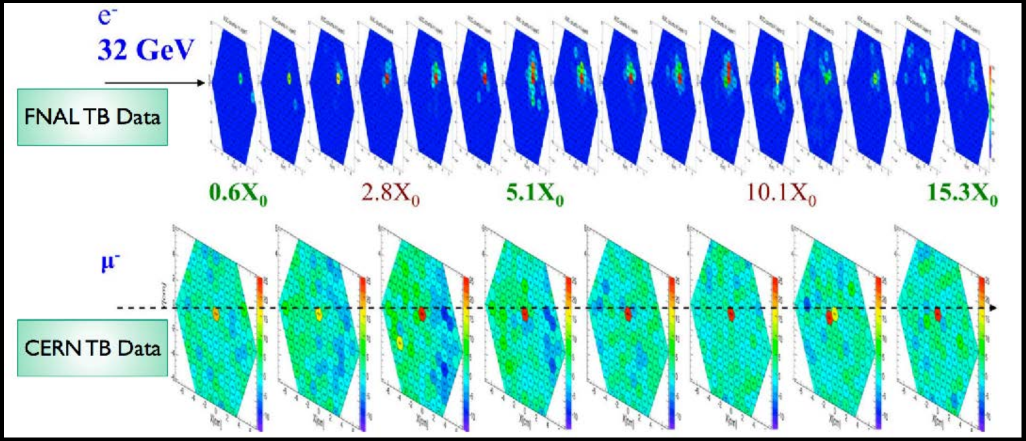
Si-W sampling calorimeter

- Fast, dense and radiation hard
- 40 X_0 deep for extraordinary containment
- High granularity, exploit transverse & longitudinal shower shapes to reject background events
- Can provide fast trigger

Currently developed for CMS upgrade, adaptable to LDMX

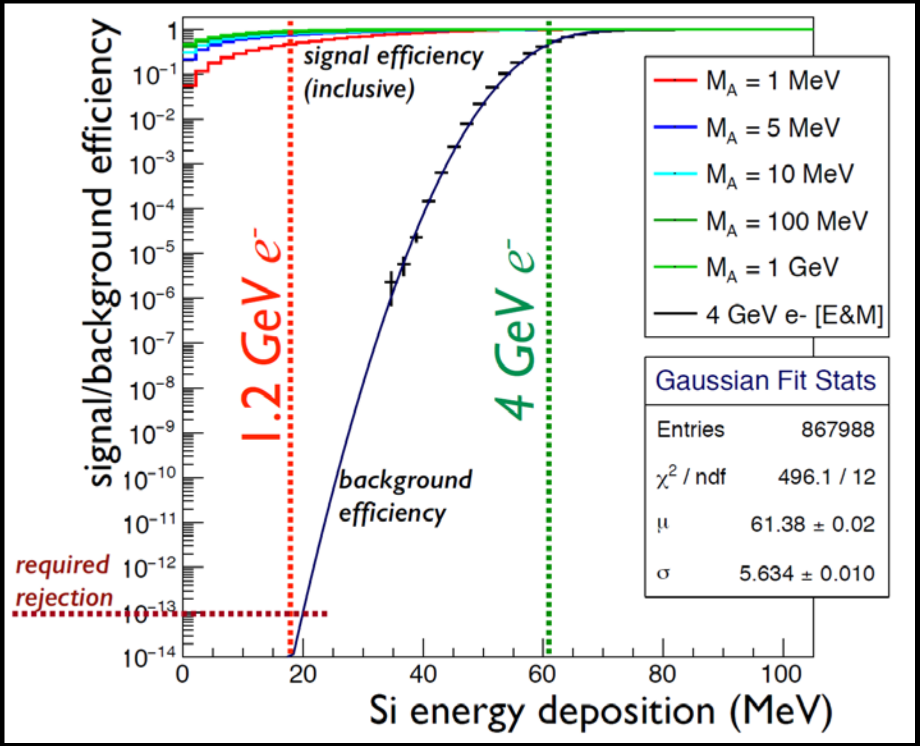






High granularity enables muon vs. electron discrimination, important to reject $\gamma \rightarrow \mu\mu$ bkg

EM calorimeter



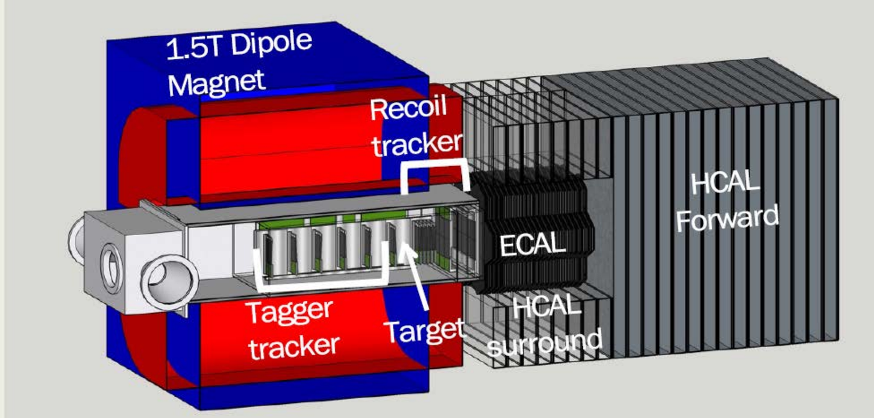
Preliminary studies show that even without using shower shape, the ECAL can reject EM background (4 GeV e- + γ) from signal (E_e < 1.2 GeV) at the level required for Phase I.

On-going work to include shape information and substantially improve the ECAL performance

Hadronic calorimeter

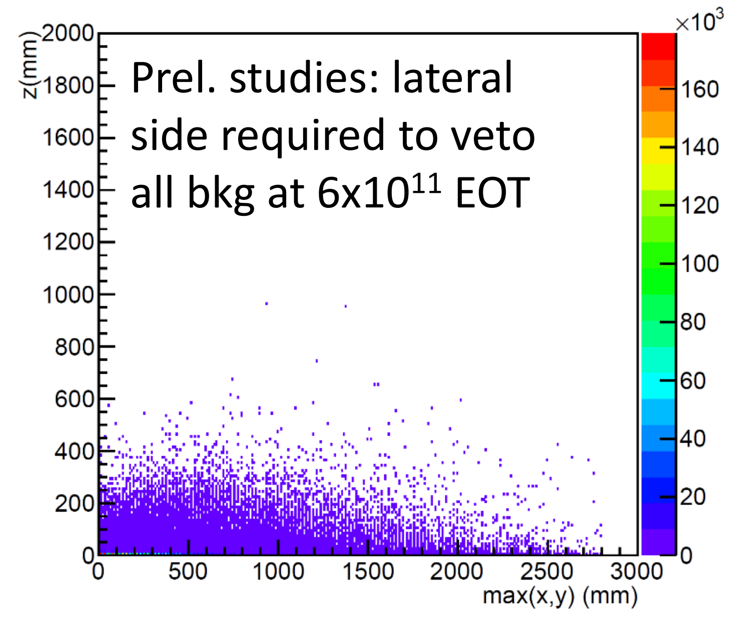
Steel / plastic scintillator sampling calorimeter

- Surround ECAL as much as possible
- Catch hadrons from PN events, in particular PN events emitting several hard neutrons (e.g. $\gamma n \rightarrow n\bar{n}n$) or many soft neutrons
- Catches wide angle bremsstrahlung, and generally help with overall veto



On-going studies to determine the best absorber material (steel, uranium), scintillator thickness and general layout. Scintillator read out by SiPM and WLS fibers.

Initial studies indicate that the HCAL size might be larger than 1m x 1m x 1m, currently use a wider geometry that will be sculpted down when the ECAL veto has been optimized.



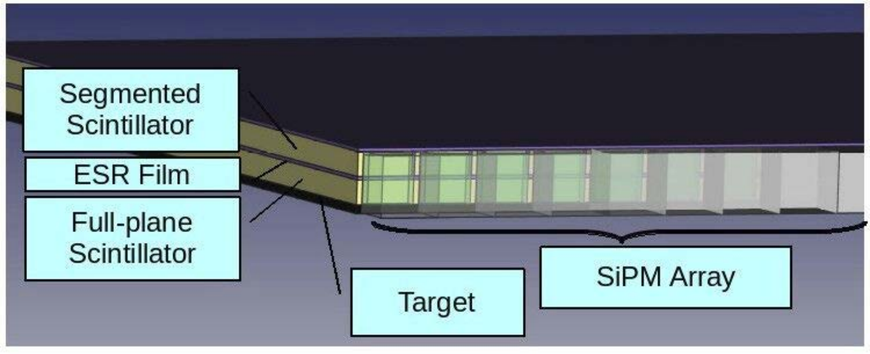
Prel. studies: lateral side required to veto all bkg at 6×10^{11} EOT

Trigger

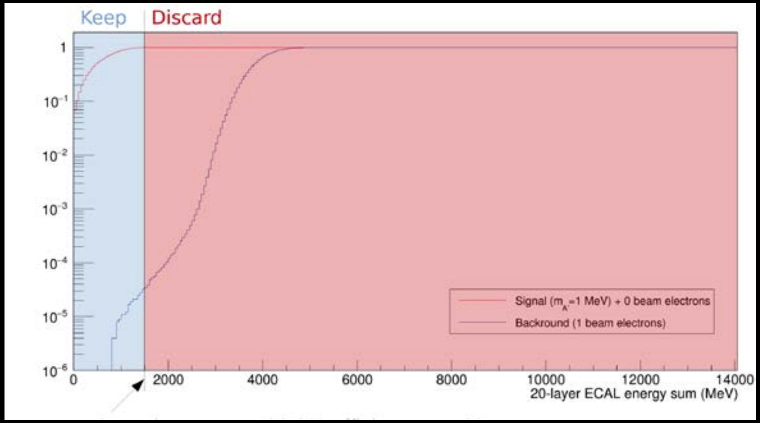
Trigger systems

- Reject beam-energy backgrounds (non-interacting e-, bremsstrahlung,…)
- Sum energies of the first 20 layers of Ecal
- Scintillator behind target to suppress empty events

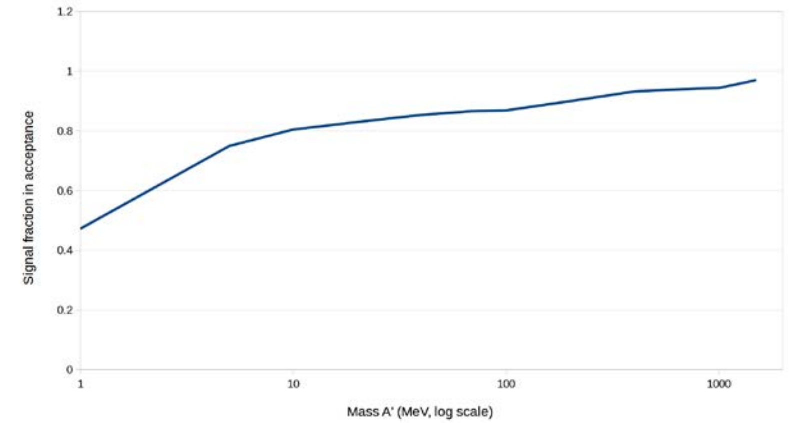
Signal efficiency 50-100% with 10^{-4} bkg rejection



Sum energies of the first 20 layers of Ecal with recoil electron E < 1.2 GeV



Signal acceptance



Photonuclear background

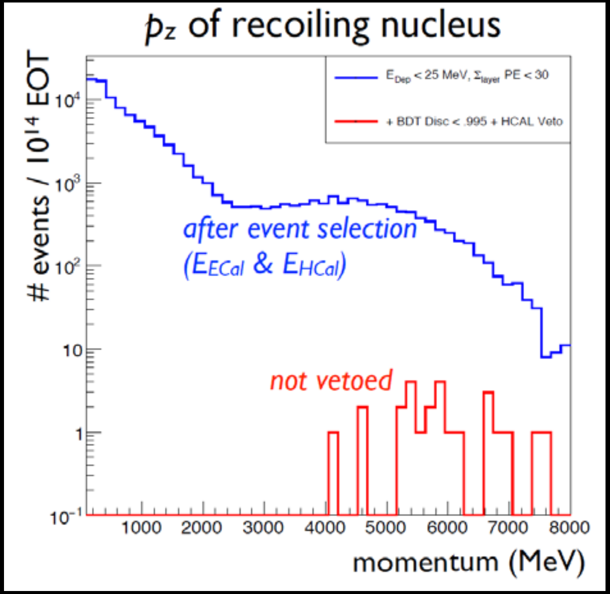
A photon can induce PN reactions in the target, recoil tracker or ECAL. These must be efficiently vetoed.

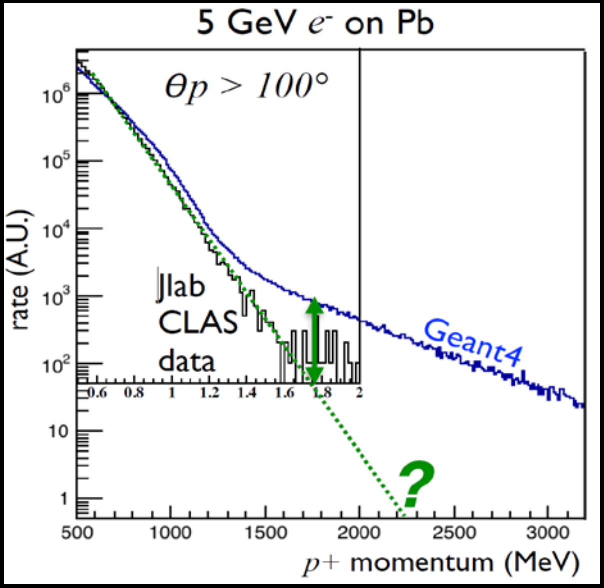
An initial veto that using information from each sub-detector eliminates all but a few events with extremely large momentum transfer to the nucleus at ~10^{13} EOT.

Geant4 produces a large number of this type of events:

- Not tuned to data in this regime (sparse data available)
- Energy/angle spectra from data suggests that these rates might be overestimated by orders of magnitude.

Working on improving our understanding of these type of events and validating the simulation



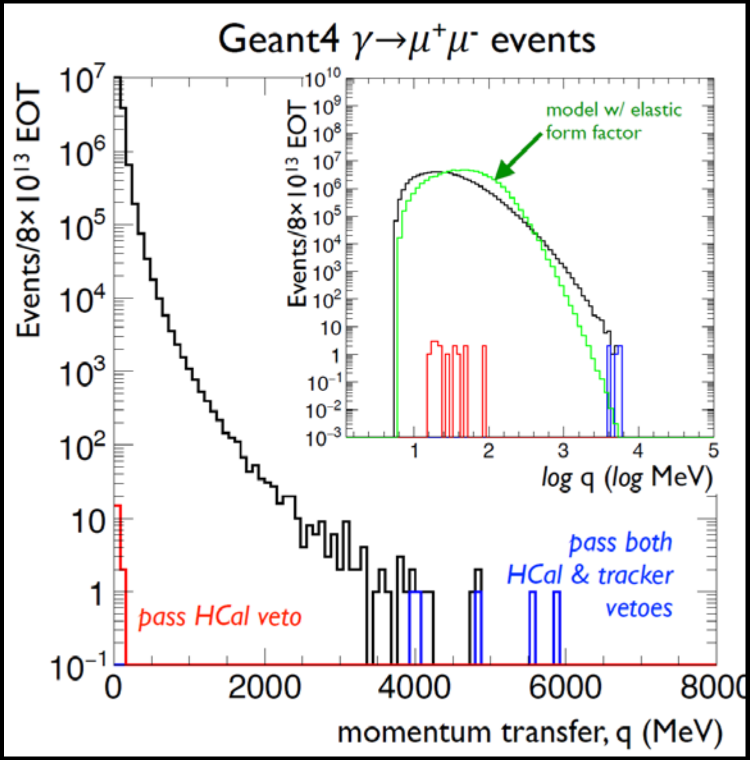


Photon conversion

A photon can convert to a muon pair in the target, recoil tracker or ECAL. These must be efficiently vetoed.

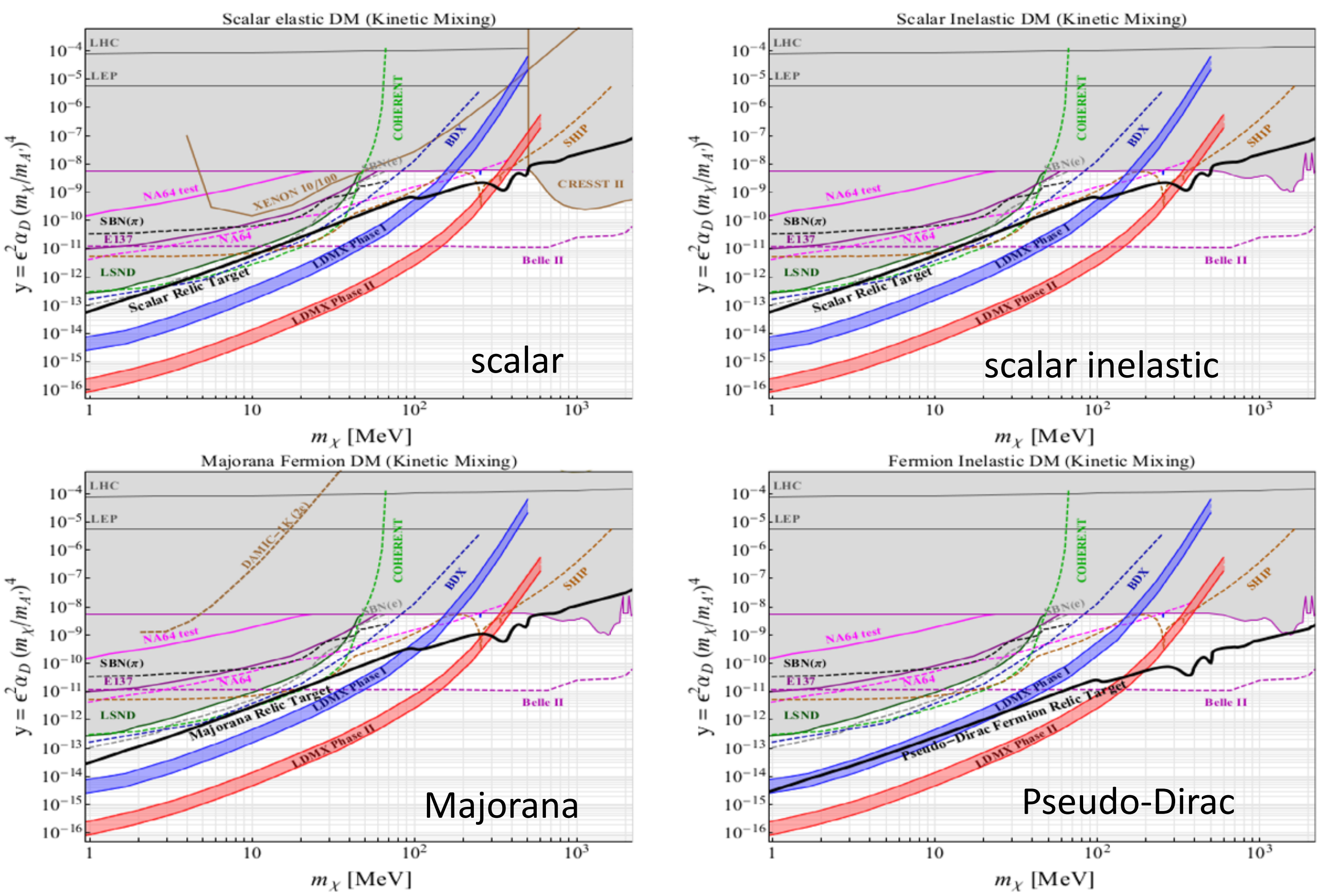
An initial veto based on the tracker and HCAL eliminates all but a few events at ~10^{14} EOT.

Geant4 also overestimates the rate of $\gamma \to \mu^+\mu^-$ events with very large momentum transfer q^2.



Working on improving our understanding of these type of events and validating the simulation

Sensitivity estimates

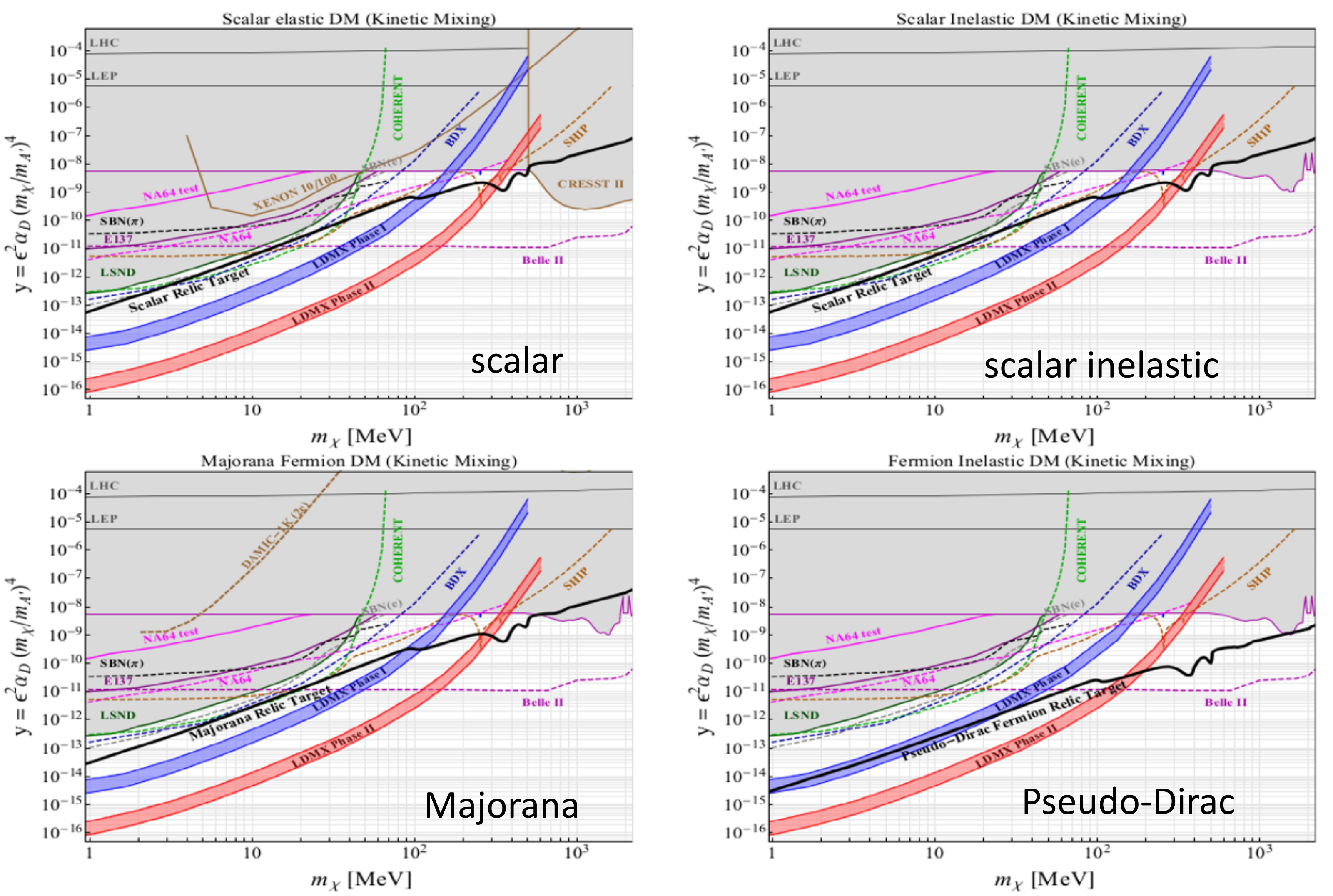


No bkg
$\alpha_D = 0.5$
$m_A/m_\chi = 3$

Phase I 10^{14} EOT @ 4 GeV probes scalar, Majorana and scalar inelastic DM

Phase II 10^{16} EOT @ 8 GeV probes Pseudo-Dirac DM

Sensitivity estimates



No bkg

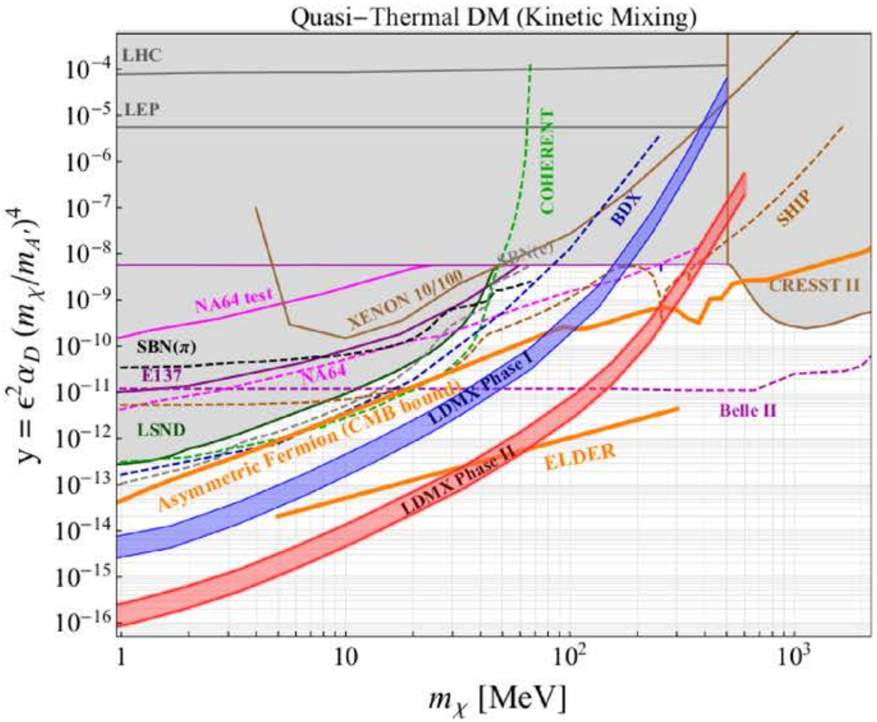
$\alpha_D = 0.5$

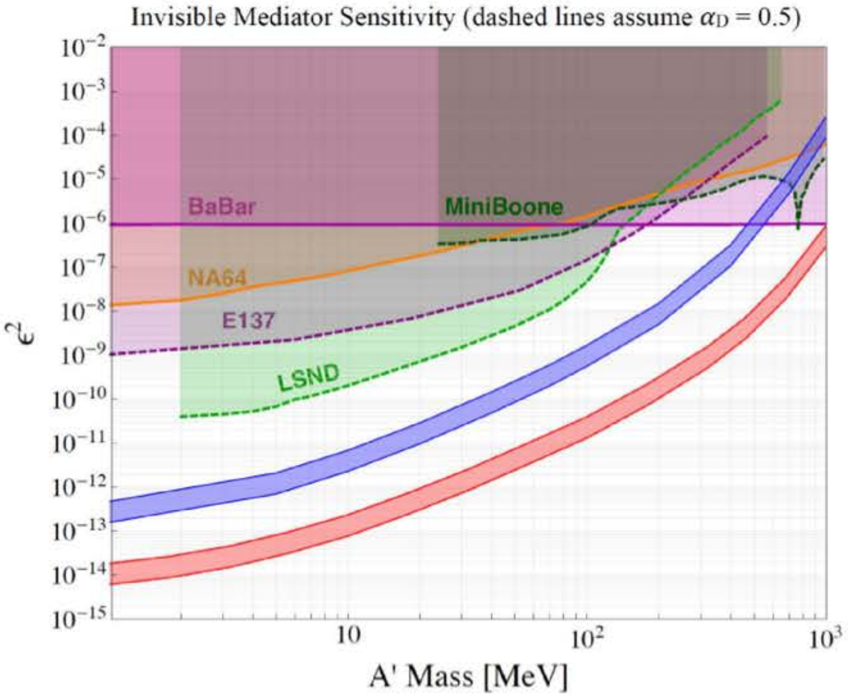
$m_A/m_\chi = 3$

Unprecedented sensitivity surpassing all existing and projected constraints by orders of magnitude for DM masses below a few hundred MeV.

Sensitivity estimates

US cosmic vision report arXiv: 1707.04591





LDMX can also explore DM with quasi-thermal origins, e.g. asymmetric DM or SIMP/ELDER scenarios, and improve the sensitivity on invisible A’ decays.

And other interesting possibilities

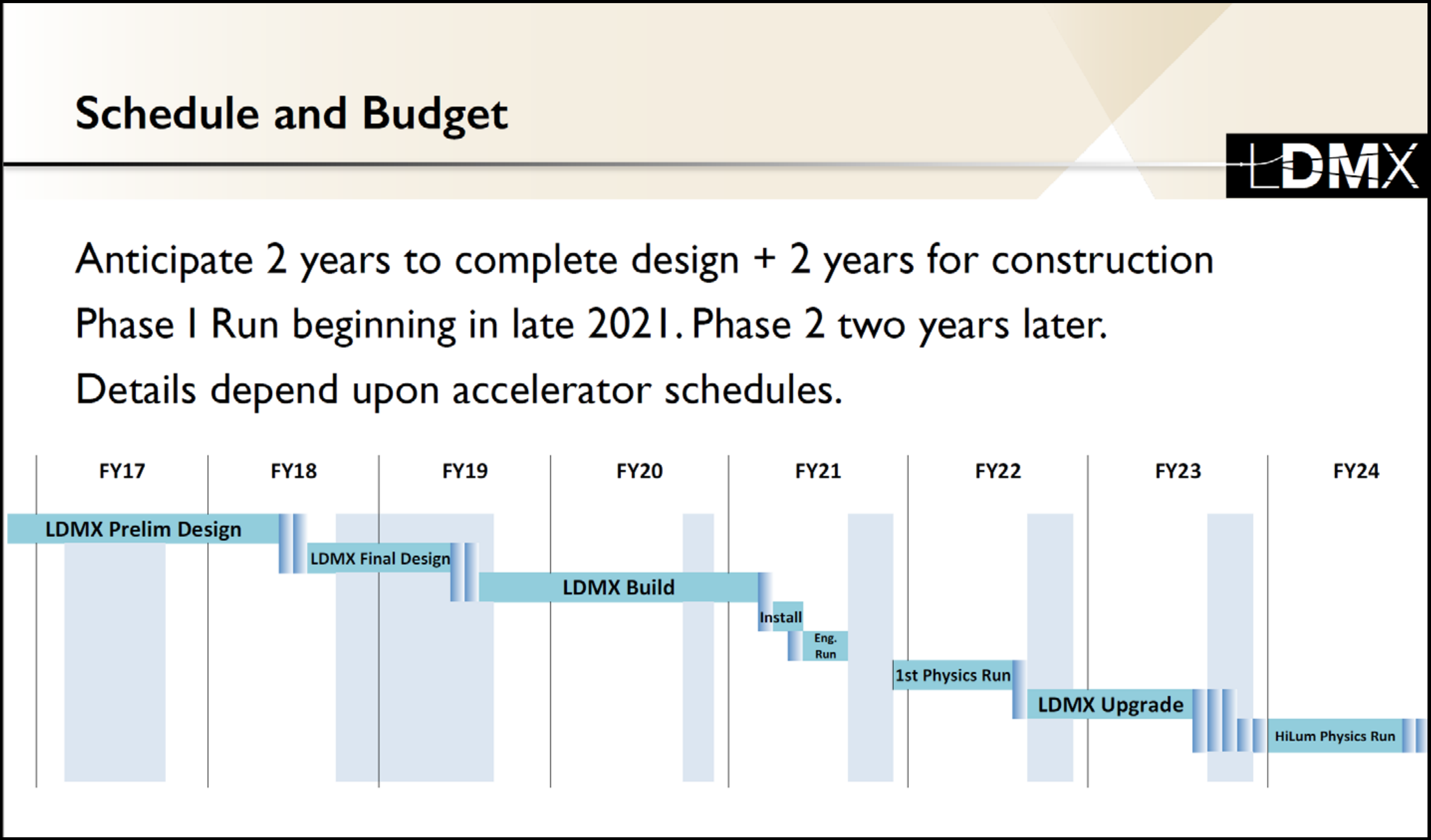
LDMX would also be sensitive to:

- New mediators decaying invisibly
- Displaced vertex signature from 'DM co-annihilation' models
- Displaced vertex signature from SIMP models
- Milli-charge particles

And could perform photonuclear & electronuclear measurements useful for future neutrino experiments.

Schedule

Tim Nelson at US cosmic visions workshop



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 collaboration

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

Conclusion

The thermal paradigm is arguably one of the most compelling DM candidate, and the broad vicinity of the weak scale is a good place to be looking – logical extension of WIMP

Accelerator based experiments are in the best position to decisively test all simplest scenarios of light dark matter - and could reveal much of the underlying dark sector physics together with direct detection experiments

Among potential approaches, missing energy / momentum provide the best luminosity per sensitivity.

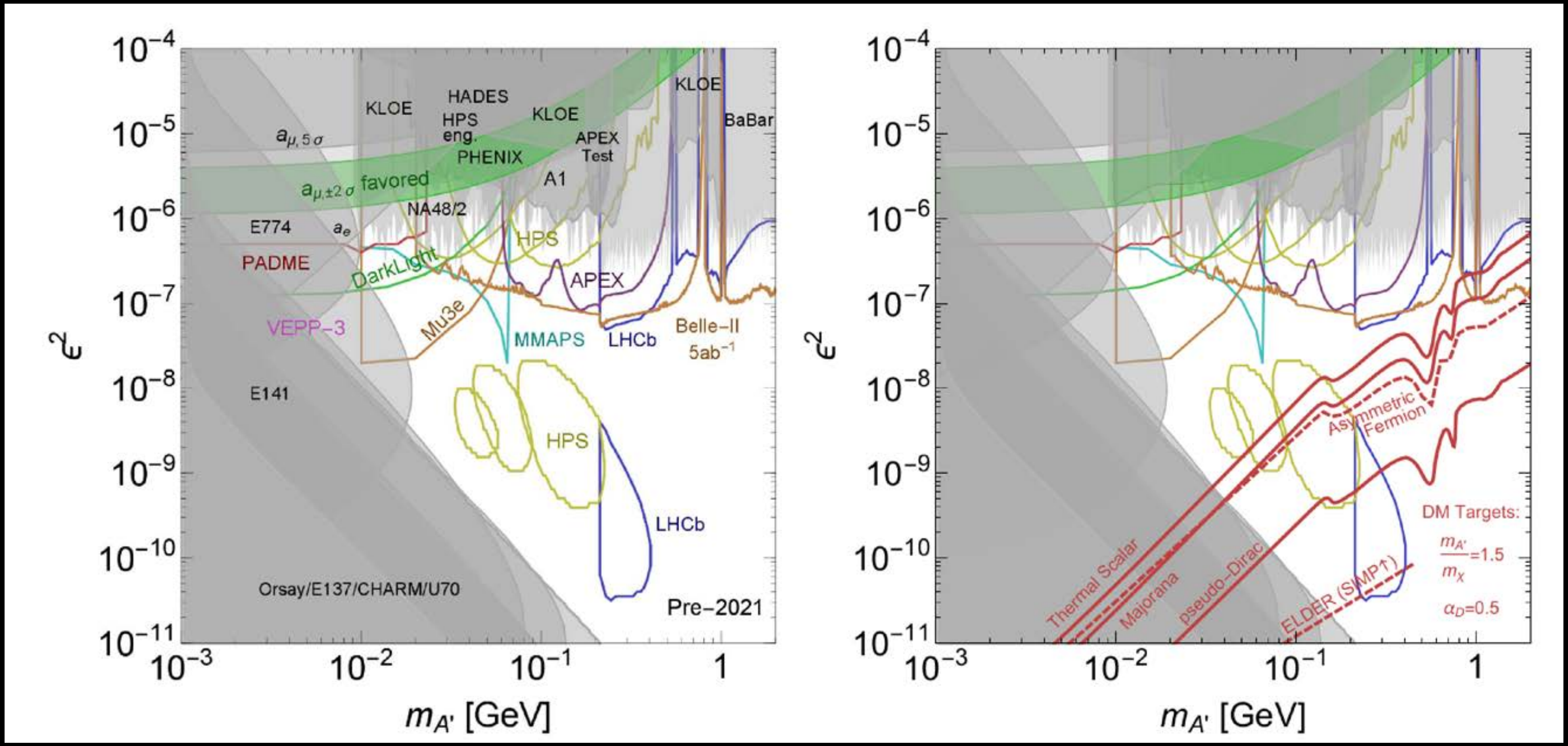
LDMX would offer unprecedented sensitivity to light DM, surpassing all existing and projected constraints by orders of magnitude for DM masses below a few hundred MeV. The experiment could also perform photonuclear & electronuclear measurements useful for planned neutrino experiments.

LDMX can complete this program within the next decade at reasonable cost, and potentially result in a groundbreaking discovery.

Extra material

Sensitivity estimates

Toro & Essig



Visible decays searches ($m_\chi<m_{A'} < 2m_\chi$) will start probing the thermal DM, asymmetric and ELDER targets in the near future as well