Opportunities for Fixed Target Experiments with ILC Beams

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LCWS Workshop, March 16 2021

ILC Fixed Target/Dark Sectors

- ILC Fixed Target/Dark Sectors informal study group has recently been formed, 2 Zoom meetings so far
- Theory, Experiment and Accelerator Physics participants
- Everyone interested in exploring these subjects is invited to join! Email me at mp325@cornell.edu to receive mailings
- Thanks to SG participants for discussions and ideas in this talk
- Any errors and omissions are mine alone

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Intro/Motivation

- Significant recent interest in searches for sub-GeV particles with feeble coupling to the SM

- Such particles can play the role of dark matter, escape direct detection in nuclear recoil searches

- Other motivations: axion-like particles (ALPs), light SM-singlet scalars from generalized Higgs sectors, etc.

- Benchmark Model: Dark Photon (DP) mediating interactions between SM and Dark Matter (DM) particle

DP - SM coupling strength, small parameter

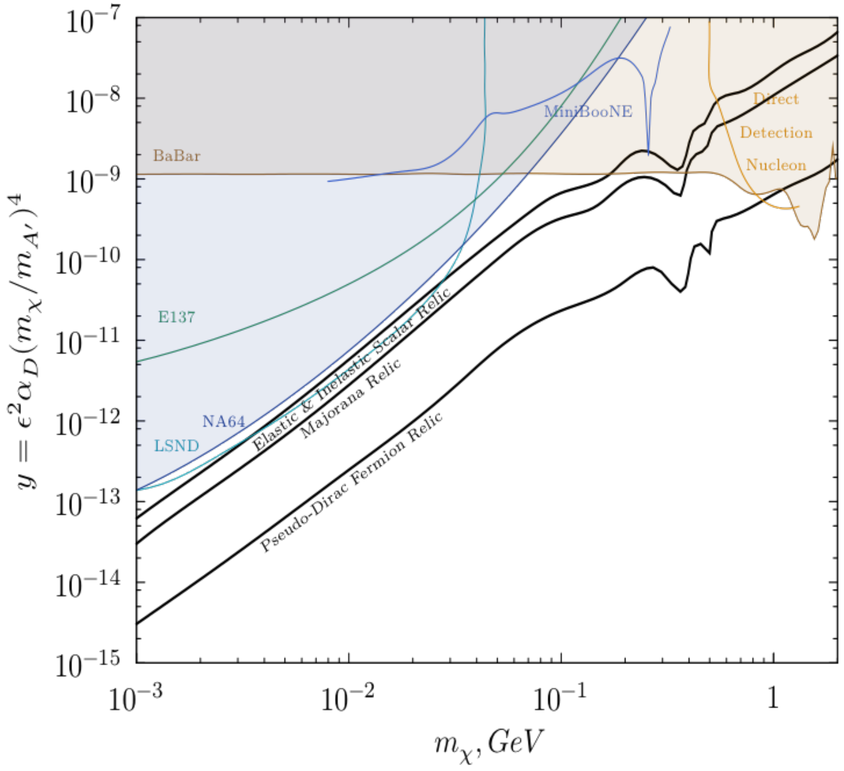
$$\mathcal{L}_{eff} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_{\mu}A'^{\mu} - \frac{\varepsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \\ + \overline{\chi}\left(i\not{D} - m_\chi\right)\chi\,,$$

DM particle mass

DP mass

Intro/Motivation

- For sub-GeV DM, interactions with the SM via DP “mediator” can provide thermal relic density - a robust target for experiments to discover of falsify



“benchmark” choices: e.g. $\alpha_D = 0.1$

$m_{A'} = 3 m_\chi$

$$\mathcal{L}_{eff} = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu - \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \\ + \overline{\chi} \left(i \not{D} - m_\chi \right) \chi \, ,$$

DM particle mass

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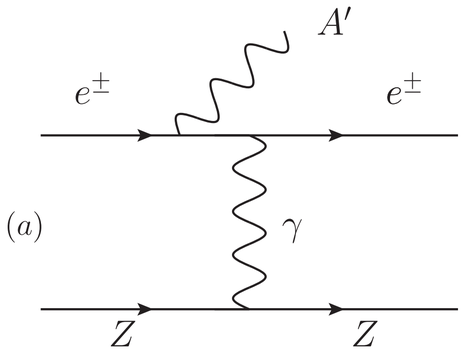
Target Parameter Space

$m_{A'} \leq 1 \text{ GeV}$

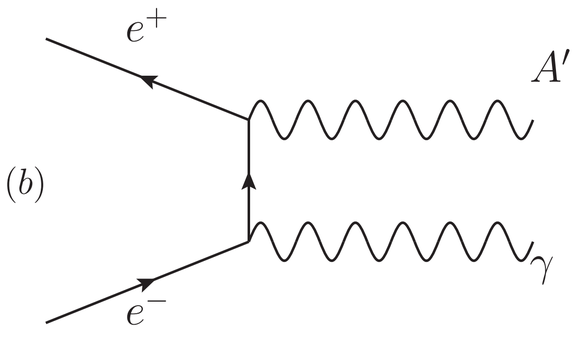
$\epsilon \leq 10^{-3}$

DP Phenomenology

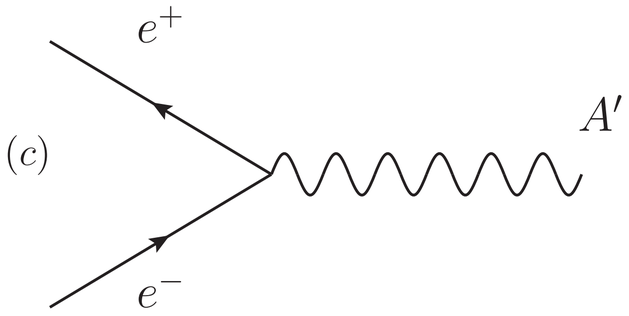
- If $m_{A'} > 2m_\chi$, DP will decay to “visible” (SM) final states **[see Yasuhito Sasaki’s talk]**
- If $m_{A'} \leq 2m_\chi$, DP will decay “invisibly” to DM pairs (prompt for $g_D \sim 1$)
- My talk will focus on opportunities for invisible DP searches at the ILC
- Three DP production mechanisms are relevant at the ILC:



Dark Brehmsstrahlung



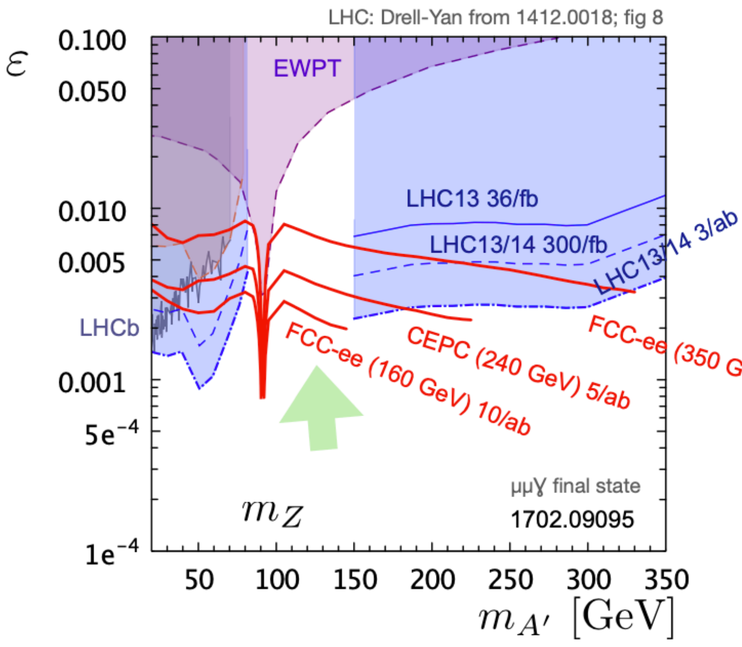
Associated Production (with SM photon)



Resonant Production

Collider vs. Fixed-Target

- At the ILC, Dark Photons may be produced in collisions at the main IP via $e^+e^- \to A' + \gamma$
- Traditional " $\gamma + \mathrm{MET}$ " searches sensitive to DP in the 0-250 GeV mass range, but don't reach below $\epsilon \sim 10^{-3}$
- For DP masses ~GeV or below, fixed-target setup offers huge improvement in sensitivity due to higher statistics
- High-energy, high-intensity positron beams available at the ILC offer an especially attractive opportunity due to enhanced DP production



[Plot: F. Tanedo]

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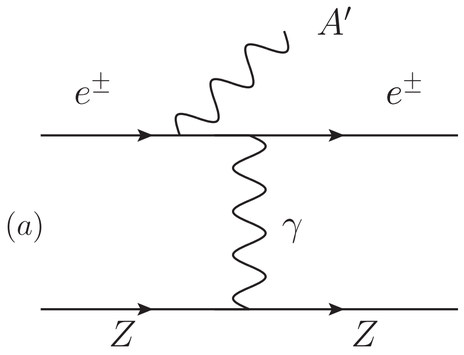
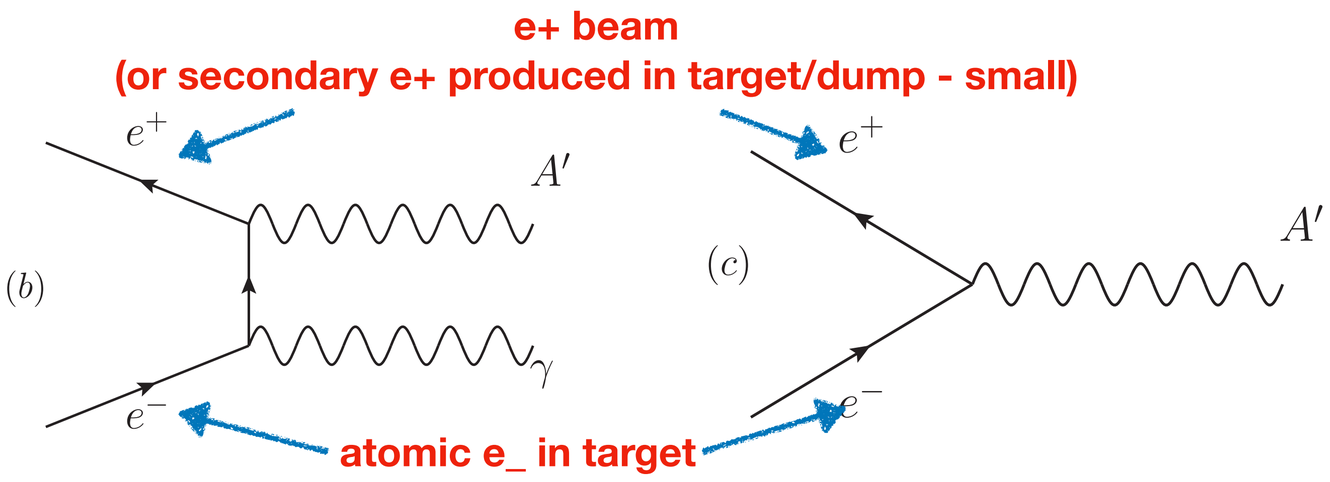


Dark Brehmsstrahlung



Associated Production (with SM photon)

Resonant Production

Main Beam Dump Experiments

- ILC Main Beam Dump: 125 GeV e-/e+ beams, 4*10^21 EOT/POT/year
- A' production in the dump (brem + Assoc/Res production with e+ beam)
- Prompt invisible decay to pair of DM particles, boosted along the beam axis
- Setup similar to BDX experiment planned at JLAB, with similar statistics, ~12x beam energy, and positron beam available
- A cavern with access from main ILC linac tunnel seems feasible in terms of costs and engineering.

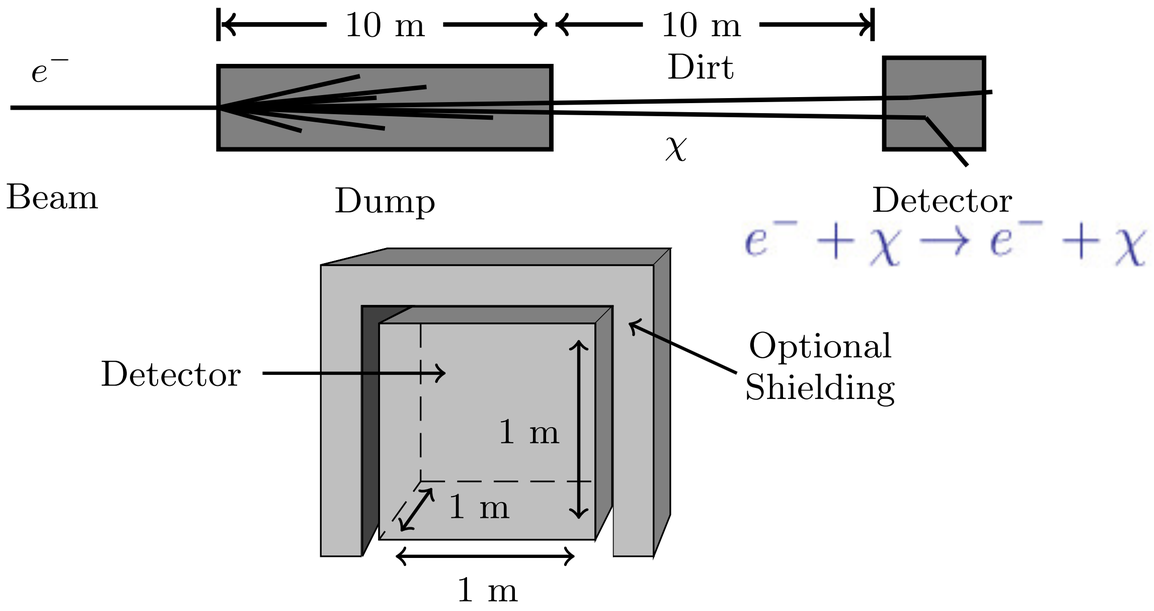
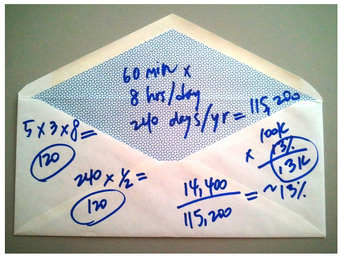
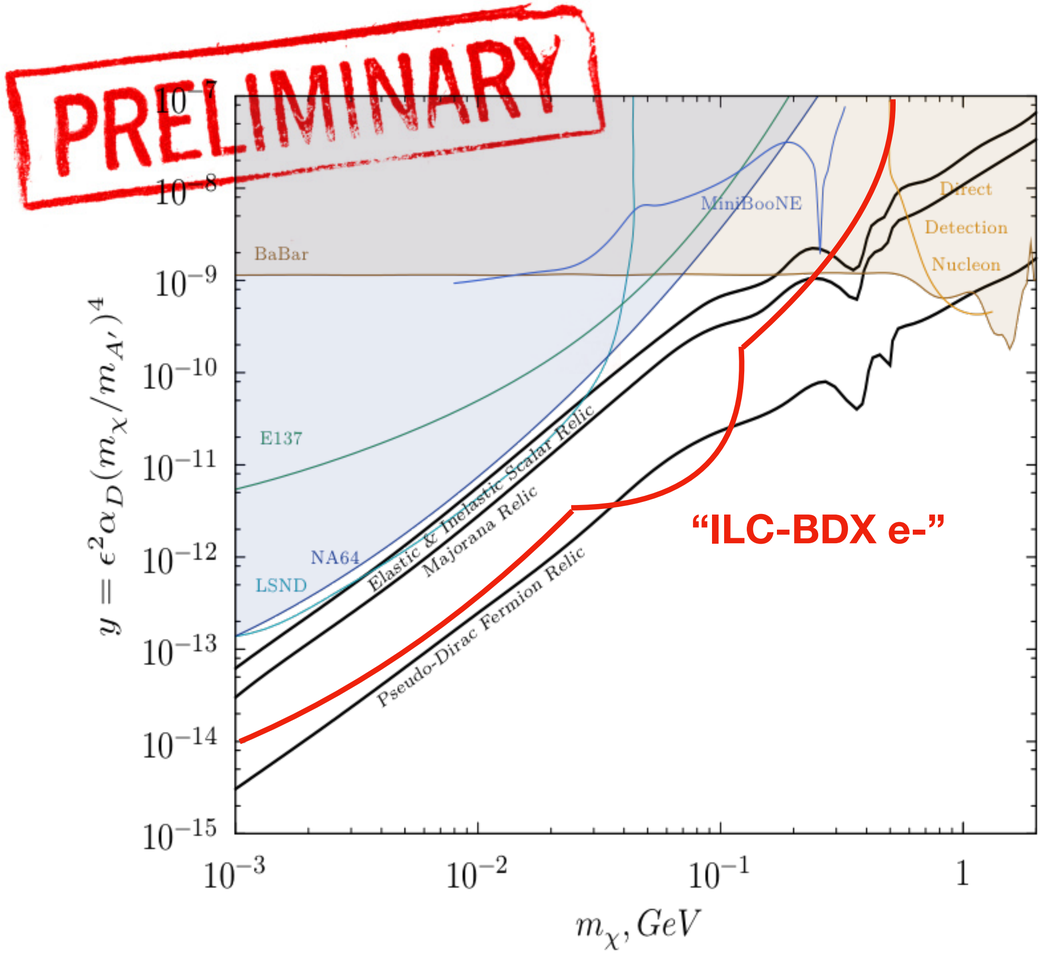
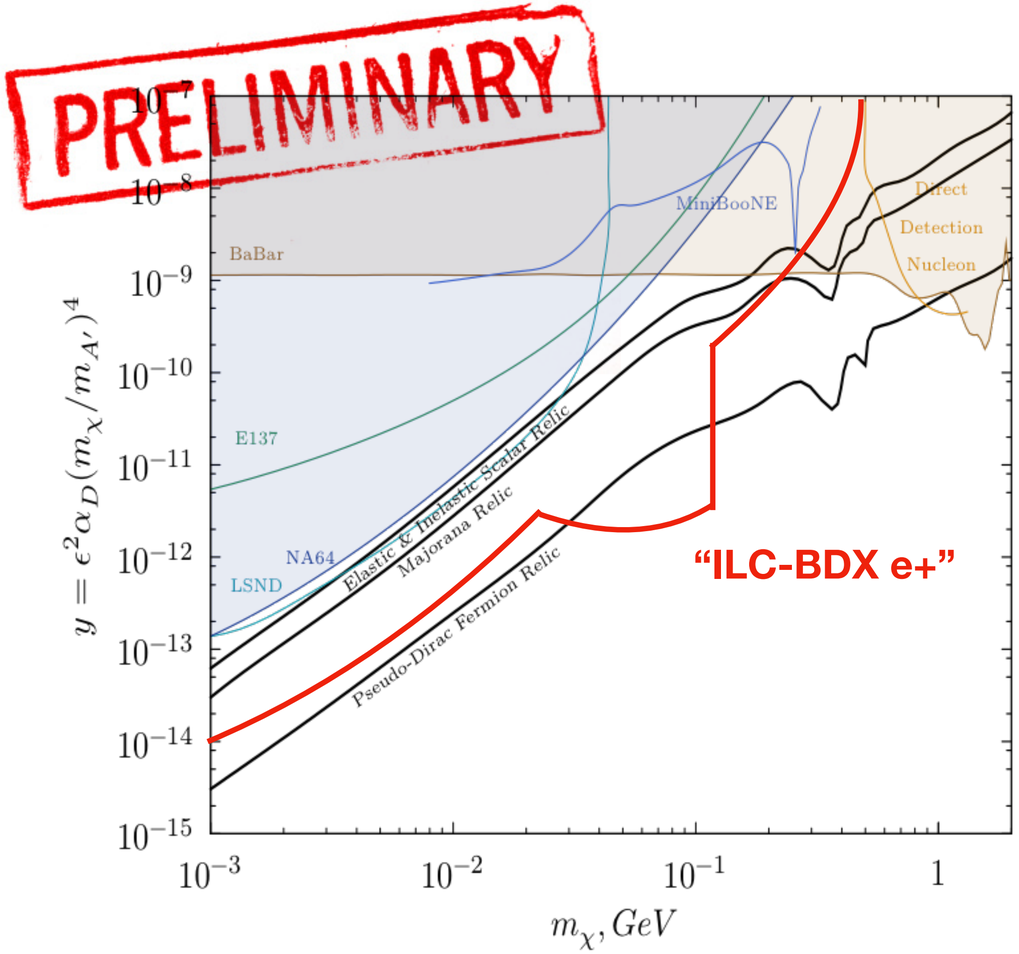


Figure: BDX, 1607.01390

Main Beam Dump Experiment







Scaling estimate based on Marsicano et.al., arXiv:1807.05884

Extracted Beam Experiments

- Missing Mass technique: positron beam on thin target, $e^+e^- \to A' + \gamma$
- Detect photons ~10 m downstream at 0.5-2 deg. angle
- Reconstruct MM: $m^2_{\text{miss}} = (p_{e^+} + p_{e^-} - p_\gamma)^2$
- Bump-hunt over SM bg: $2\gamma, 3\gamma, \text{ brem}, \ldots$
- Setup similar to PADME experiment running at Frascati, with ~500 x beam energy and large increase in statistics

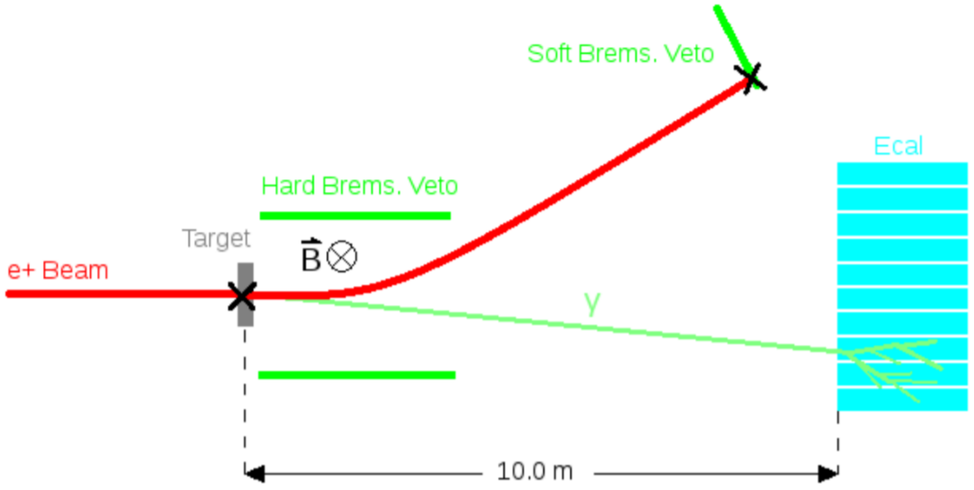
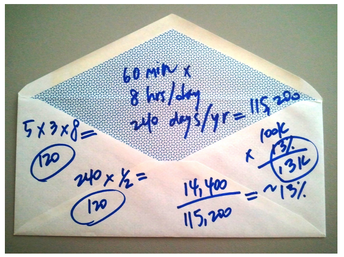


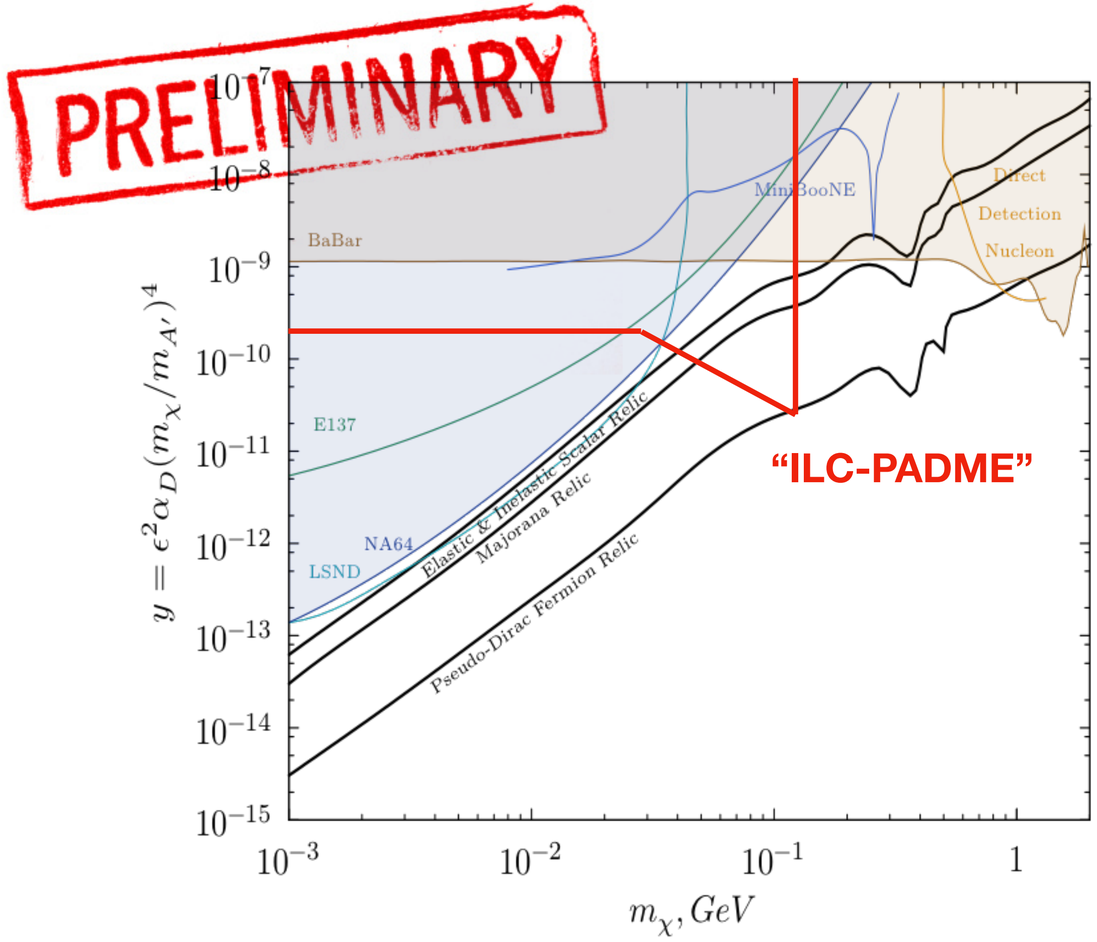
Figure: Marsicano et al, 2007.15081

Missing Mass Experiment

- Assume availability of extracted positron beam at 125 GeV.
- Major limitation is pileup in the detector. At most O(10) events in the detector per detector response time (~10 nsec)
- Viable experiment requires increased bunch frequency, reduced bunch charge compared to standard ILC beams
- Assume ~1 GHz bunches with ~10^6 positrons each, O(1) events per bunch with realistic target
- Beam energy known at ~1% level and angular dispersion <0.1 mrad required for missing-mass reconstruction

Extracted Beam Experiment: M-Miss





Kinematic Endpoint:

$$m_{A'} = \sqrt{2 m_e E_{e^+}} = 354 \text{ MeV}$$

Scaling estimate based on MMAPS proposal, J. Alexander et.al. and Marsicano et.al., in 2007.15081

Extracted Beam Experiments

- Missing energy/momentum technique: electron or positron beam on active target or thick target + hermetic detector downstream

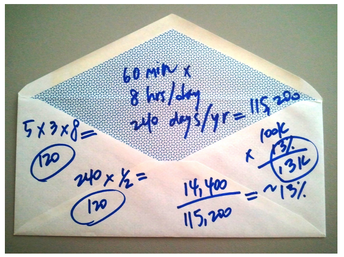
- O(1) incident particles per detector response time, measure total shower energy, look for large mismatch between beam and shower energy

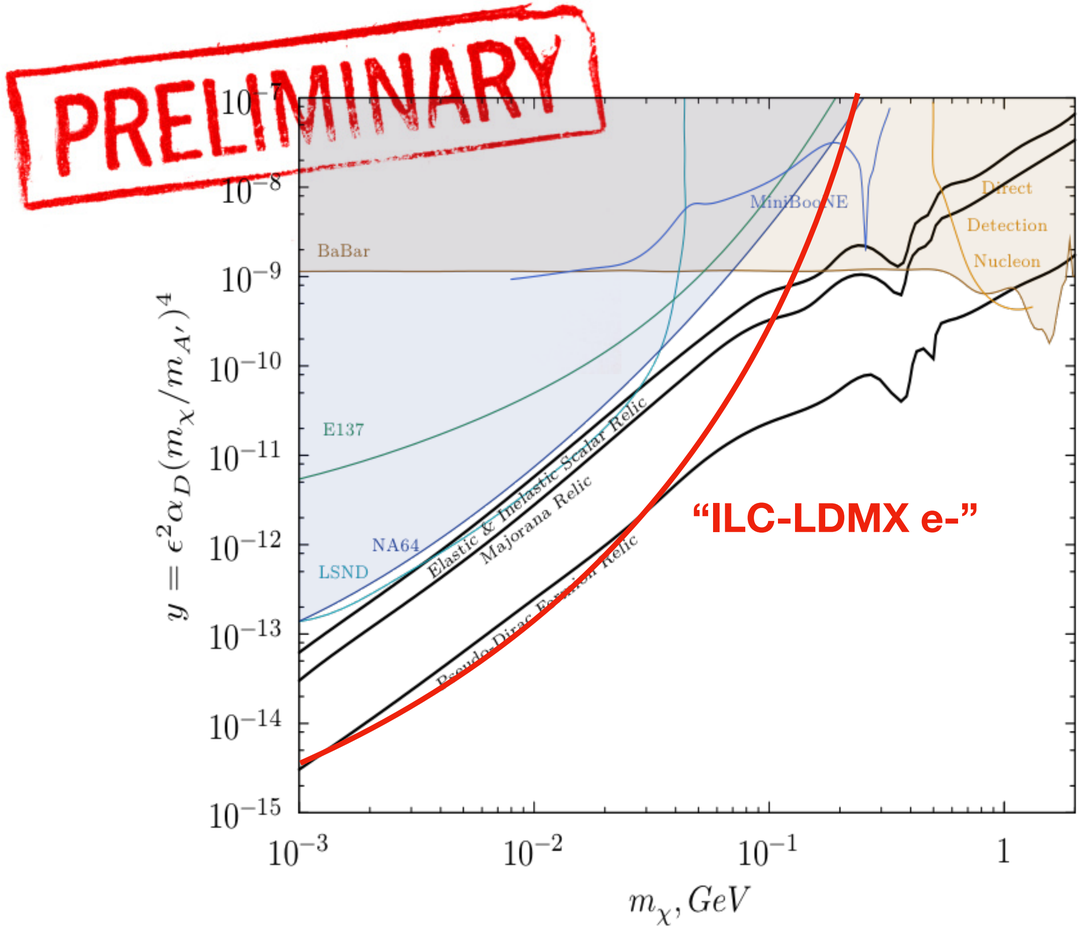
- Technique successfully used by NA64 experiment (100 GeV e- beam at CERN), planned LDMX at SLAC (4-8 GeV, higher luminosity)

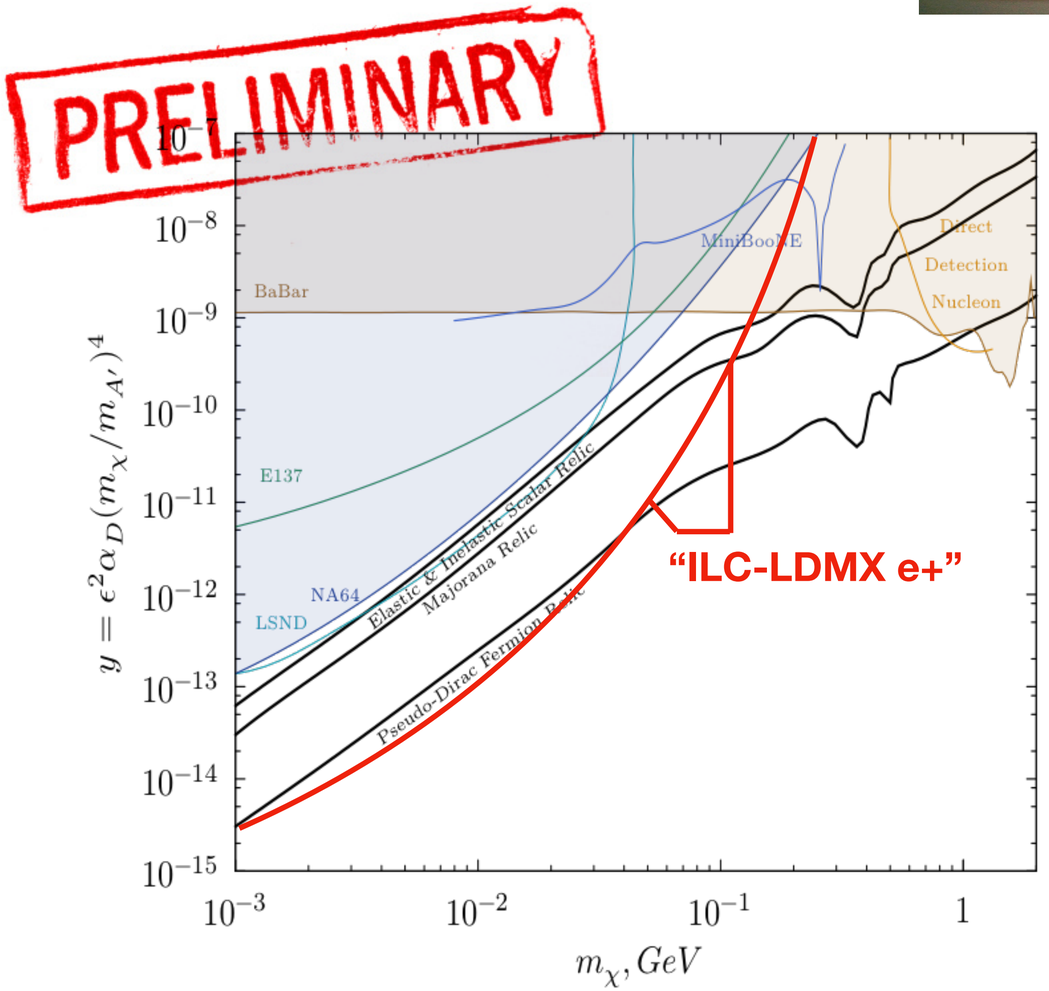
- Small bunch spacing (1-10 ns) required to collect interesting data set; O(1) particle per bunch is an interesting accelerator challenge

- If achieved, ~10^14 events/yr can be collected, similar to LDMX Phase I but at ~20x beam energy and potentially positrons

Extracted Beam Experiment: E-Miss







Scaling estimate based on LDMX projections
and Marsicano et.al., arXiv:1807.05884

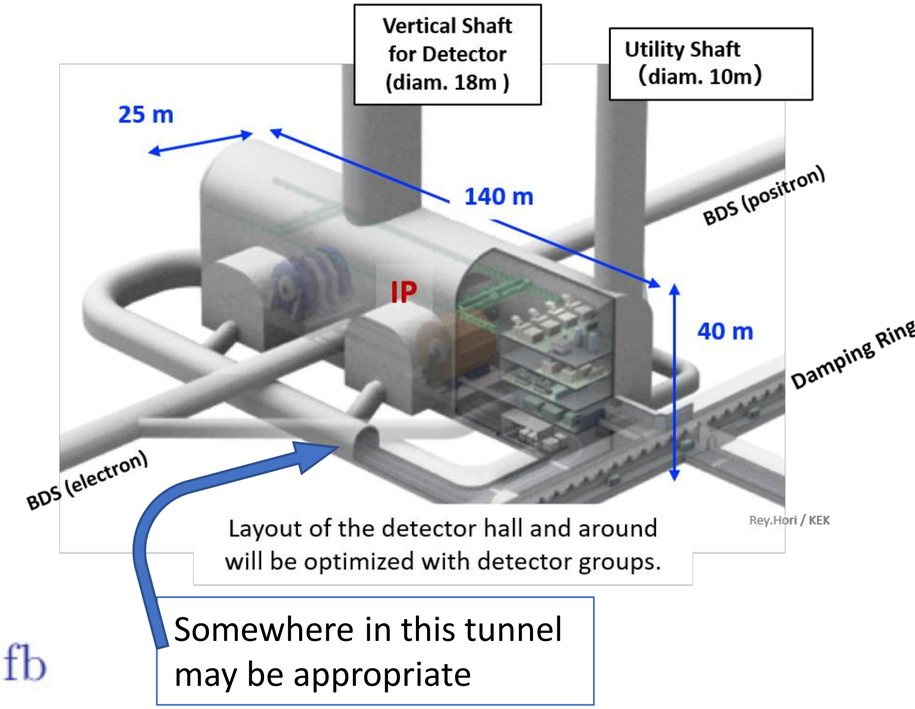
Long-Lived Particles from Main IP

- Related topic (though not fixed target) discussed in the SG is the possibility of a dedicated detector to search for visibly-decaying LLPs produced in main IP

- A ~(10 m)^3 detector situated underground ~100 m from the IP seems realistic

- An LLP with production cross section $\sigma_{\rm LLP} \sim 10 - 100$ fb and lifetime $\bar{b}c\tau \sim 100$ m can be detected

- If LLP decay is detected, specific event in the main detector can be associated with it (unlike LHC)



Conclusions

- Sub-GeV new particles feebly coupled to the SM are well motivated, e.g. as part of sector responsible for dark matter
- Fixed-target collider experiments are the primary means to search for such particles
- ILC offers new opportunities with main beam dumps and (possibly) extracted beams
- High-energy, high-luminosity positron beams are especially unique, have important advantages over electrons (e.g. new production channels)
- Simultaneous e- and e+ experiments may be useful, e.g. for model discrimination if a signal is discovered
- Additional opportunities to search for LLPs produced in the main IP
- Study of these subjects has just begun, now is a great time to get involved! Email me at mp325@cornell.edu to get on the Study Group mailing list.