New Accelerator Experiments to Search for Dark Matter and New Forces

Philip Schuster
Perimeter Institute

TRIUMF Colloquium &
Cosmology at Colliders Workshop
December 10, 2013

Overview

- Intro: Discovering the Laws of Nature
- New Forces & Matter
- Ongoing Experimental Efforts
- Fresh Opportunities to Search for Dark Matter using Electron Beams

The Big Questions Driving Particle Physics

The Big Questions Driving Particle Physics

What are we?

The Big Questions Driving Particle Physics

What are we?

Where did we come from?

The Big Questions Driving Particle Physics

What are we?

Where did we come from?

Are we alone?

What Are We?

Matter particles:

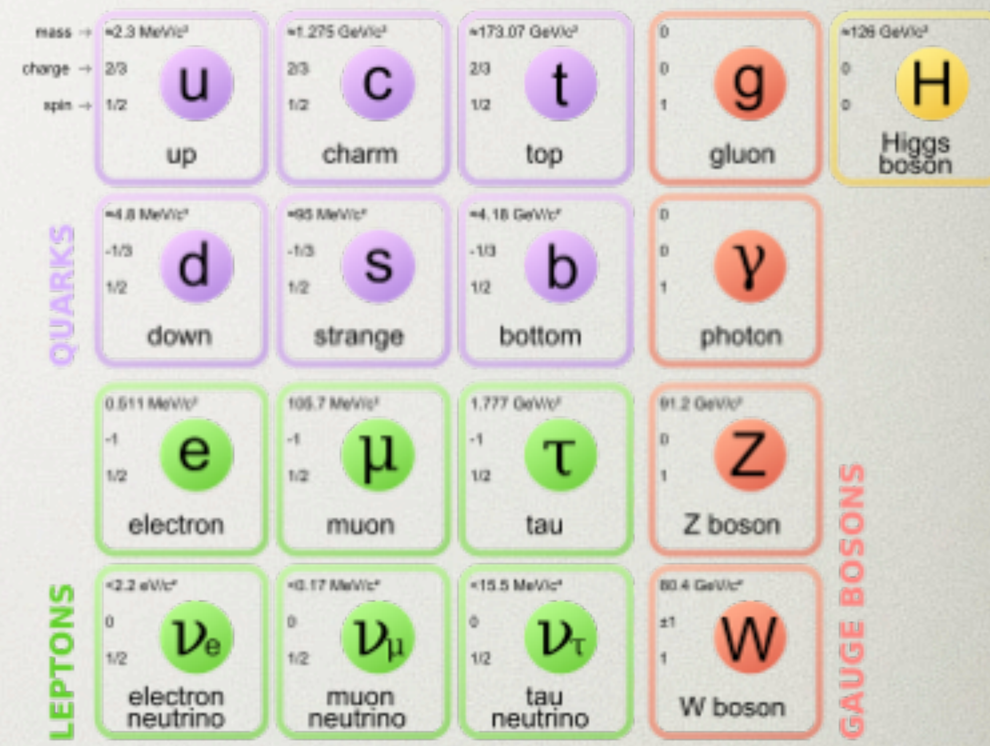
quarks, leptons...baryons, mesons...etc

Force particles:

photon (EM), gluons (strong), W&Z (weak), higgs, graviton

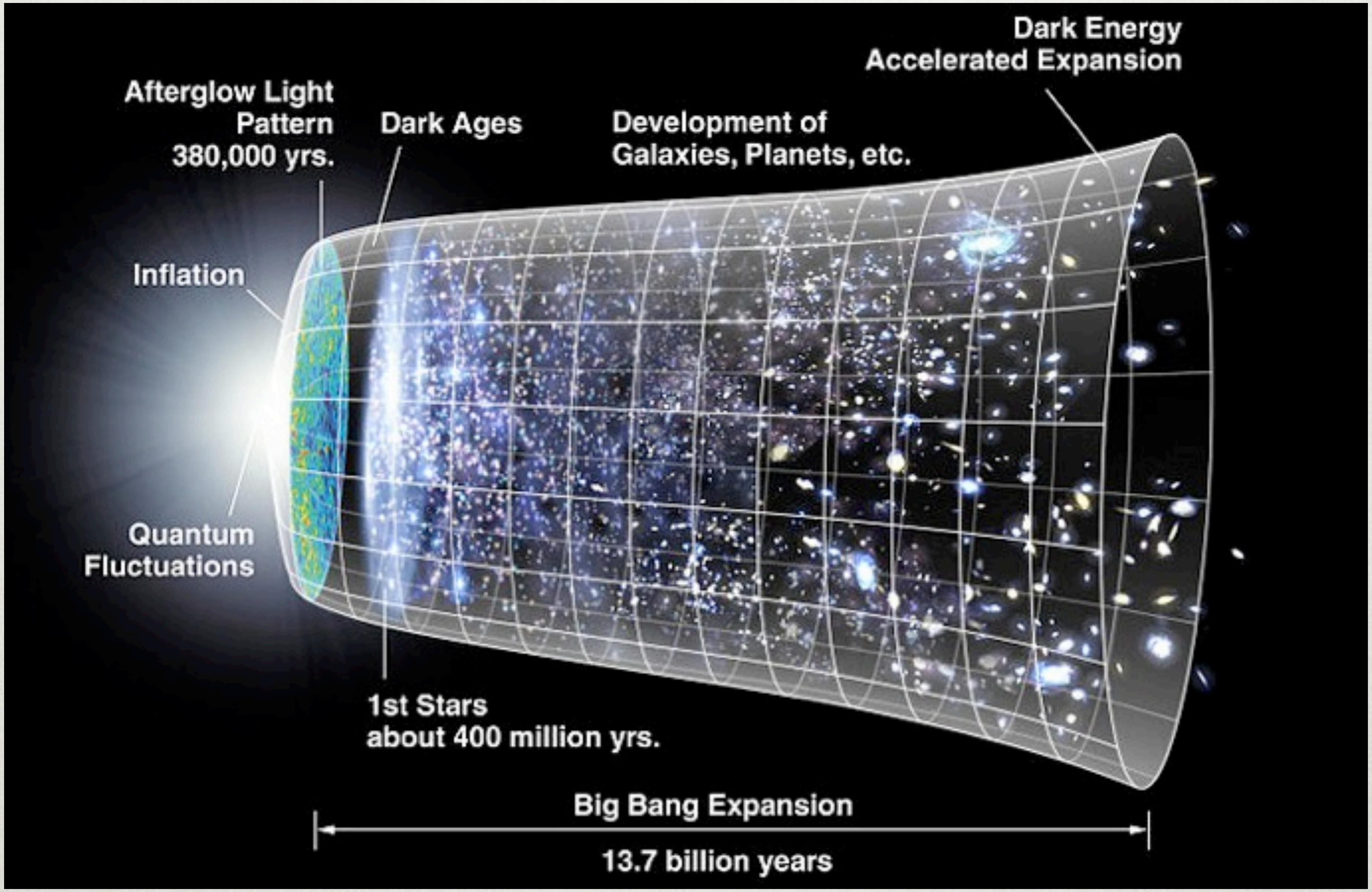
Fundamental Principles:

quantum mechanics & relativity



...The Standard Model

Where Did We Come From?



...The Lambda-Cold Dark Matter Model

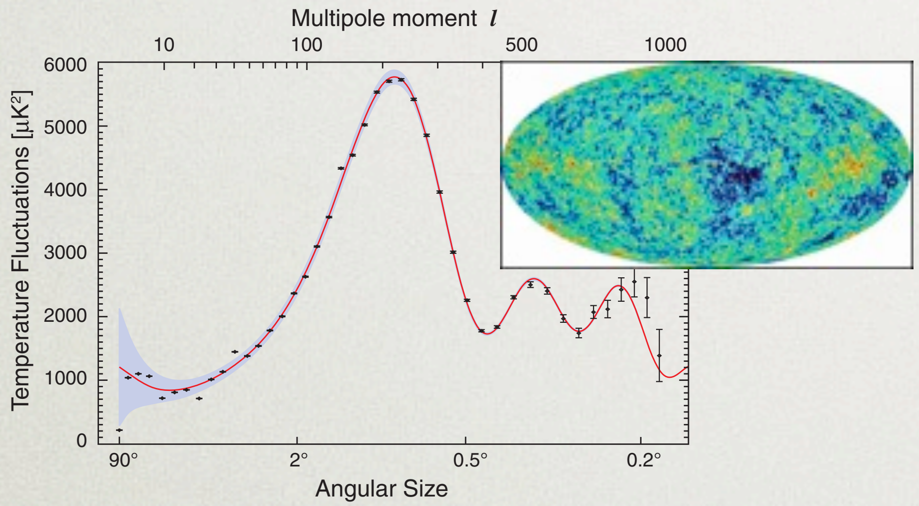
Are We Alone?

Almost certainly not!

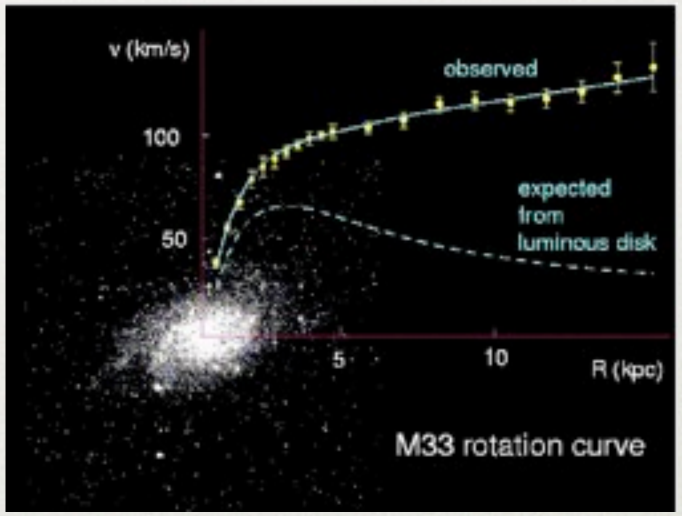
Just Look Up!

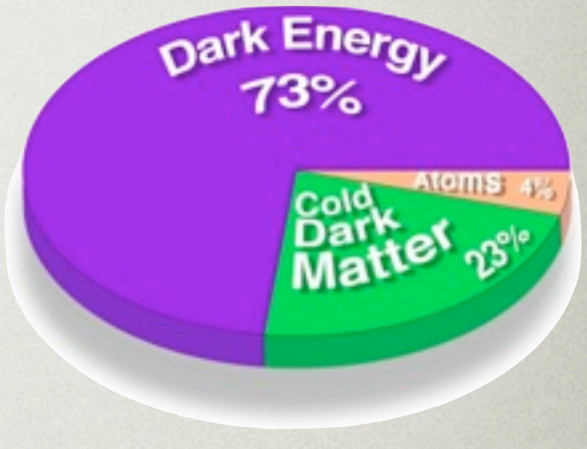
A wealth of evidence for dark matter

Cosmological



Galactic Data





5x more abundant than the matter we understand

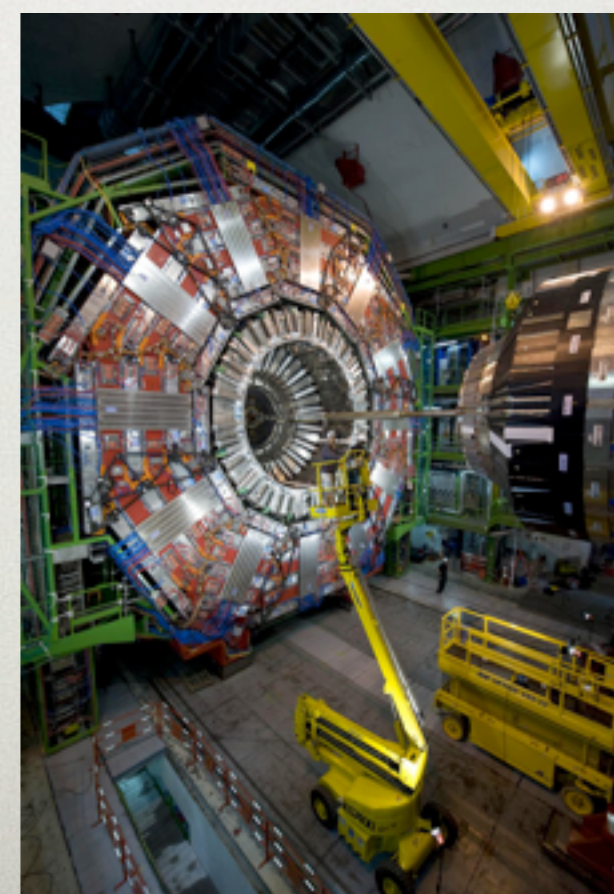
...but we don't yet know what it is, how it got here, or how it interacts (if at all).

What Else Is there?

Known matter interacts through three gauge forces (strong, weak, and electromagnetic)

If new matter is *interacting through the same forces*, we would see it unless it is heavy

Search at high energy with the Large Hadron Collider!



What Else Is there?

...but what about **matter that is not charged under known forces?**

Quantum mechanics and relativity ***severely*** *restrict possible interactions* of such matter with us

→ New matter, even with proton mass or smaller, would not be visible unless we ***search correctly***!

We Are Not Alone...

$$U(1)_D \times \ldots$$

New matter & new forces?

$$U(1)_Y \times SU(2)_W \times SU(3)_s$$

EM weak strong

Dark matter may be a sector of matter like our own (but more abundant), with gauge forces, matter...etc

...a "Dark" Sector

We Are Not Alone...

$U(1)_D \times ...$

New matter & new forces?

$U(1)_Y \times SU(2)_W \times SU(3)_s$

EM weak strong

Dark sector gauge forces provide a simple explanation for long-lived dark matter

(1) the dark matter carries a "dark charge" $\rightarrow$ stability
(2) we are not "dark charged", so we don't interact with it

We Are Not Alone...

$U(1)_D \times \ldots$

New matter & new forces?

$U(1)_Y \times SU(2)_W \times SU(3)_s$

EM weak strong

We can study this scenario by searching for residual interactions allowed by symmetry, and by searching for dark matter more broadly!

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New Forces?

Forces / Matter	EM	Weak	Strong
Electron	✓	✓	—
Neutrino	—	✓	—
Quarks	✓	✓	✓

New Forces?

Forces / Matter	EM	Weak	Strong
Electron	✓	✓	—
Neutrino	—	✓	—
Quarks	✓	✓	✓

New force?
—
—
—

New Forces?

Forces / Matter	EM	Weak	Strong	New force?
Electron	✓	✓	—	—
Neutrino	—	✓	—	—
Quarks	✓	✓	✓	—
Dark Matter?	—	—	—	✓

New Forces?

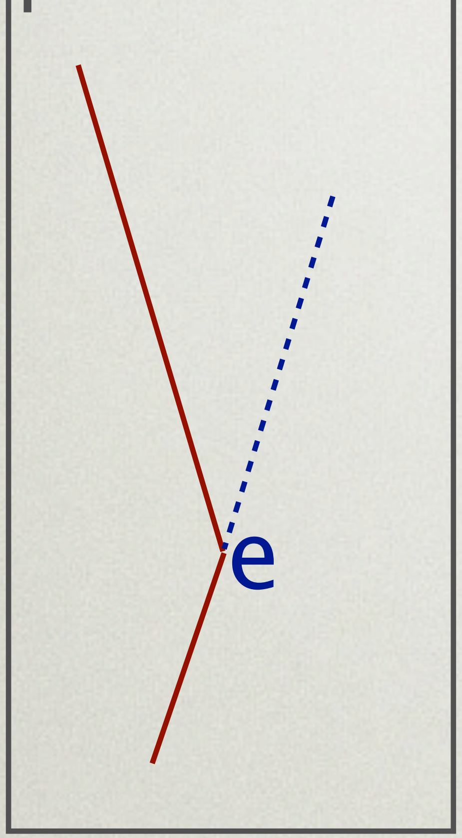
Forces / Matter	EM	Weak	Strong	New force?
Electron	✓	✓	—	—
Neutrino	—	✓	—	—
Quarks	✓	✓	✓	—
Dark Matter?	—	—	—	✓
The X	✓	?	?	✓

The X might be so heavy that humans never produce it. It's reasonable to think that there are many particles with very high masses, and some might talk to both EM and new forces.

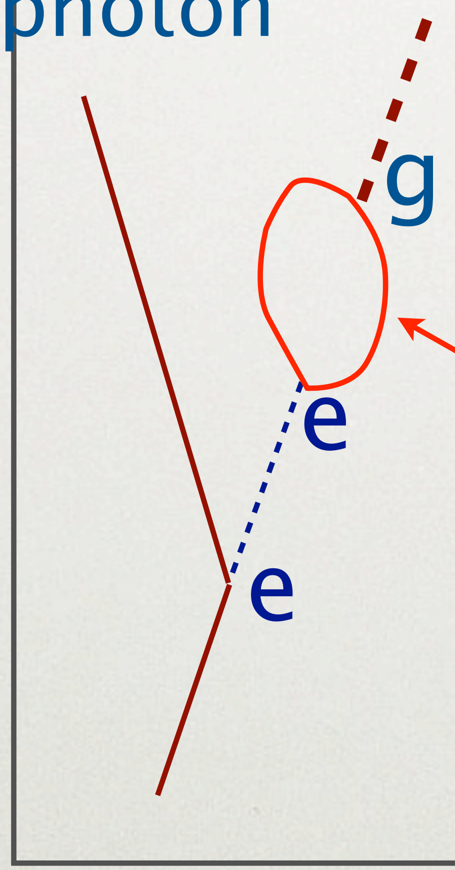
That Which is not Forbidden is Mandatory

time

An electron can emit photons...



Photons talk to the X which talks to dark photon



⇒ Electron can emit dark photons [Bob Holdom, 1986]

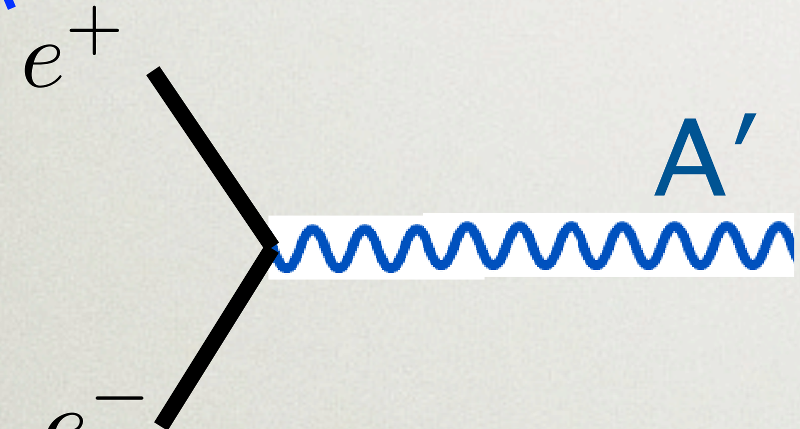
Quantum mechanics: states you don't have energy to produce still affect dynamics in calculable way.

Suppression: $\epsilon \sim \frac{e\, g_D}{16\pi^2} \log \frac{m_\psi}{M_*} \sim 10^{-2} - 10^{-4}$

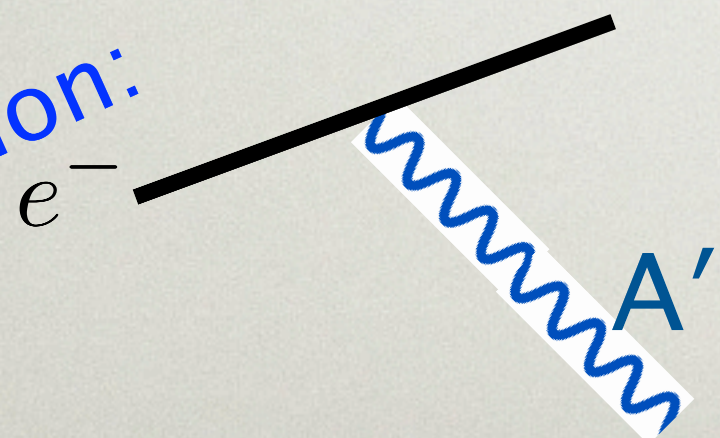
Basic Picture

Production
(like ordinary radiation of light, but suppressed by ε)

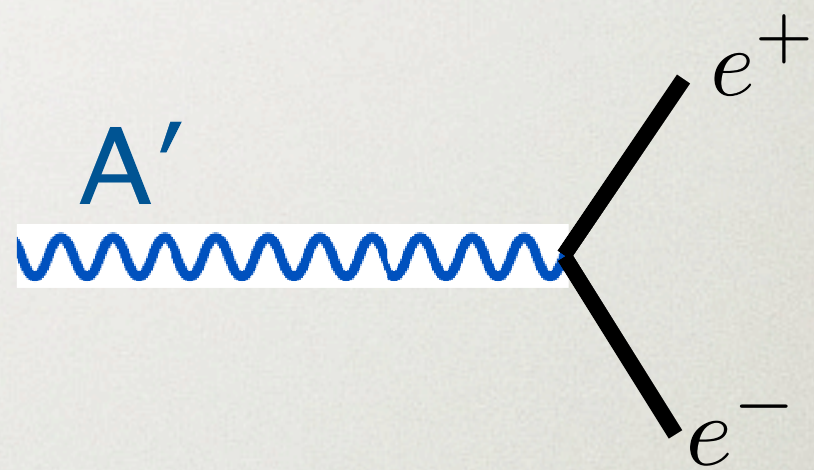
Annihilation:



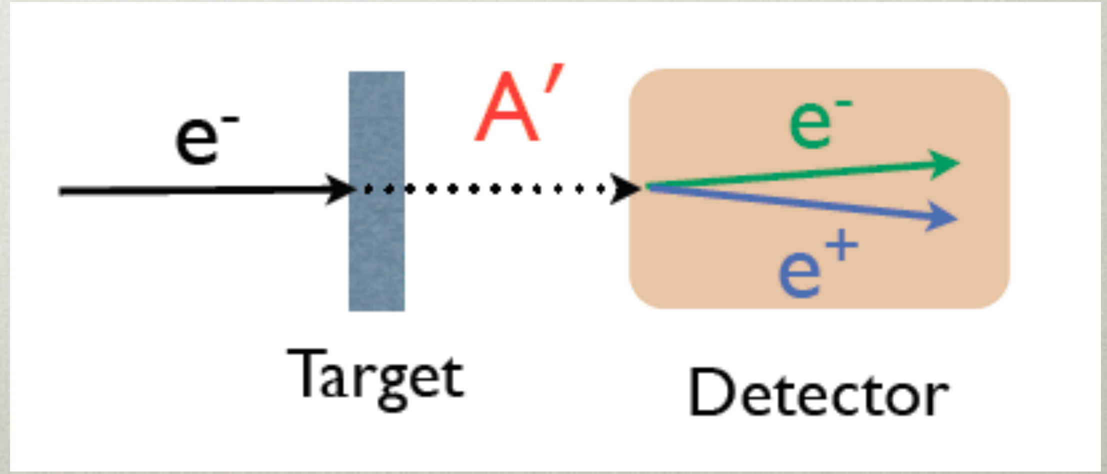
Radiation:



Decay



Put it together:

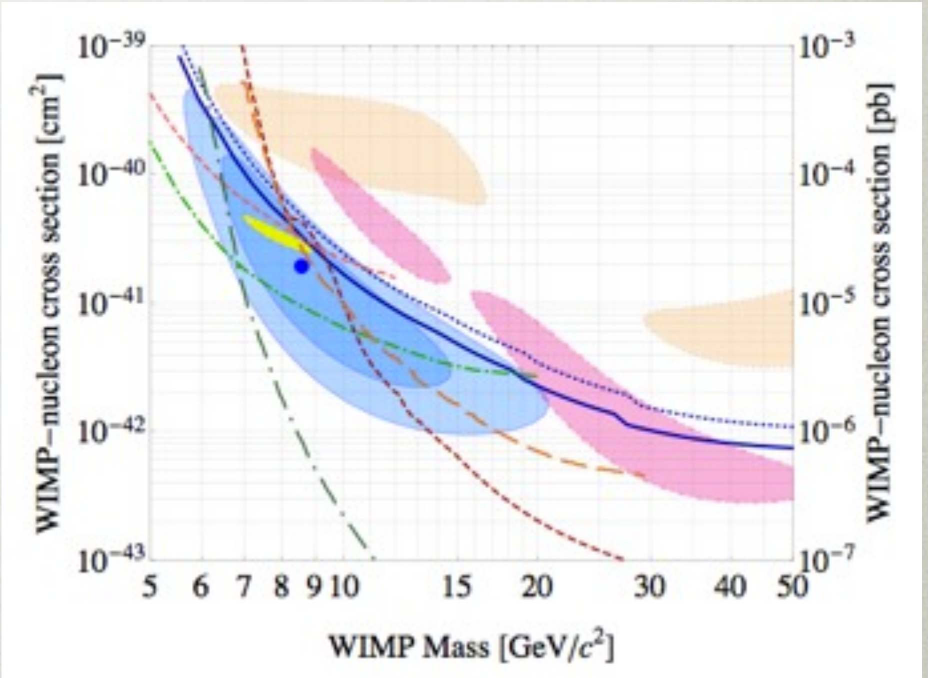


New Dark Matter Scenarios

New dark sector forces also open up a broad class of dark matter scenarios where the mass is sub-GeV

Direct detection experiments can search **above** a few GeV. Below a few GeV, there is **much less** sensitivity (too low recoil energy)

sub-GeV?

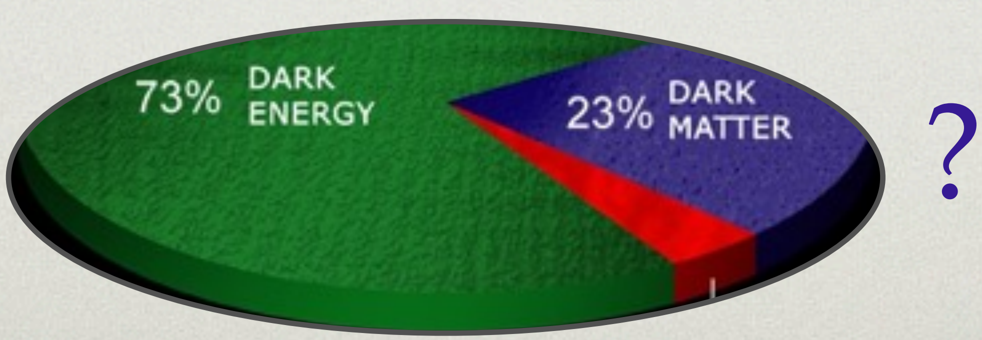


High intensity accelerator experiments can explore the sub-GeV scenarios!

The GeV-Scale Frontier

Tremendous opportunity to explore GeV-Scale dark matter and weakly coupled physics with novel small-scale experiments!

What will we find?



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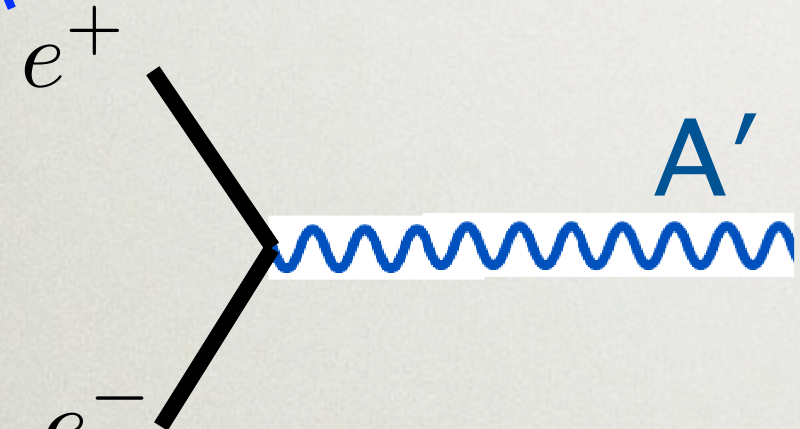
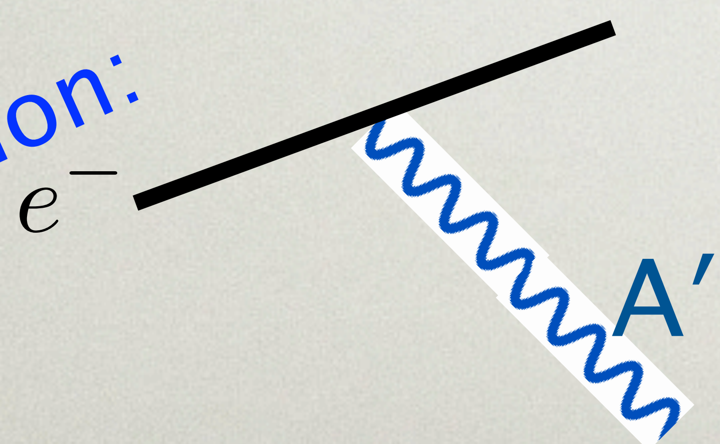
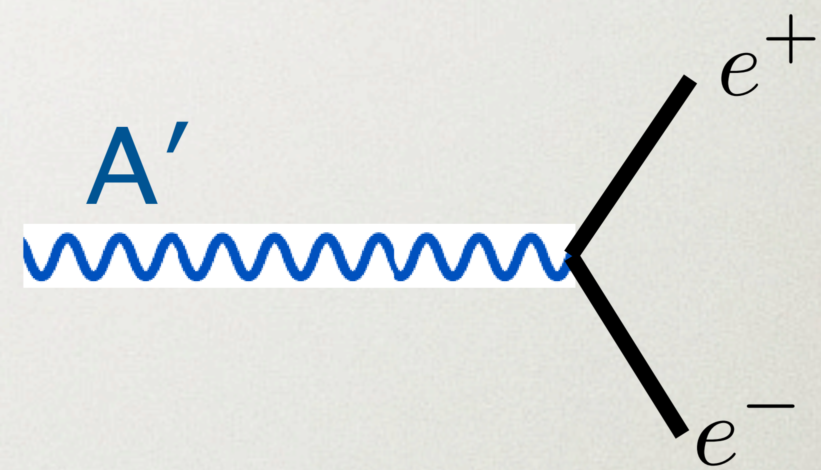


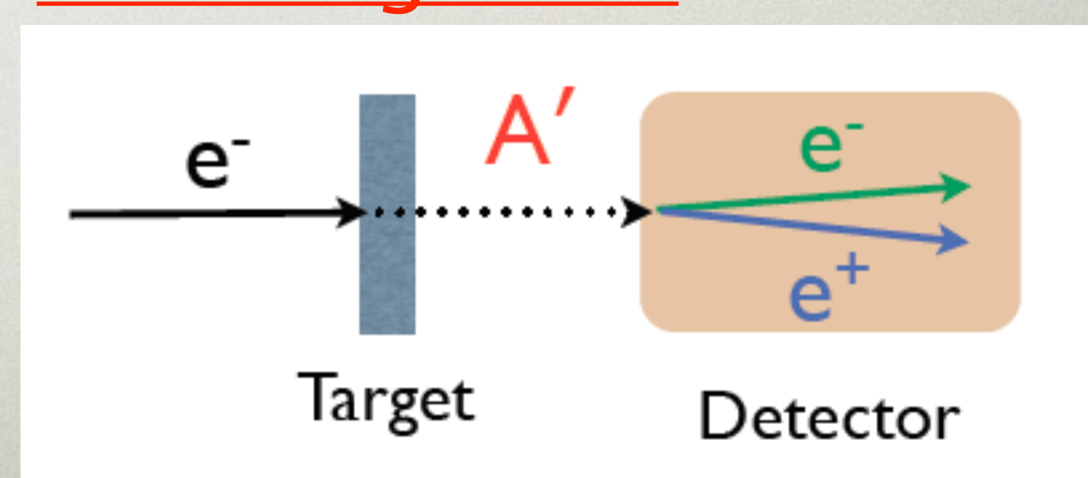
Radiation:



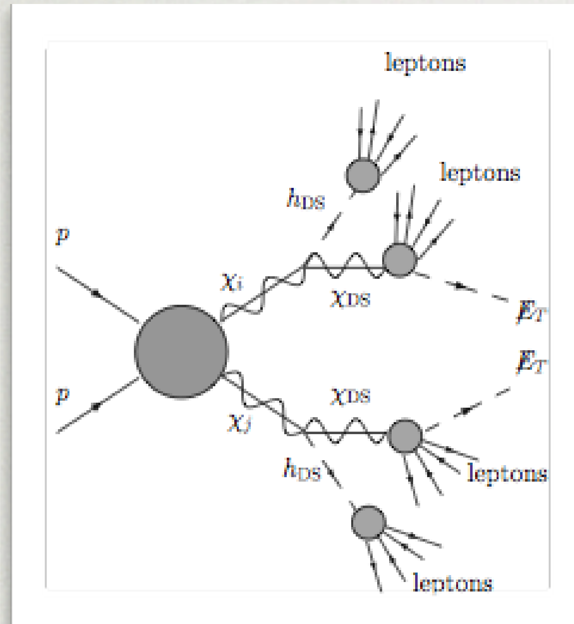
Decay



Put it together:

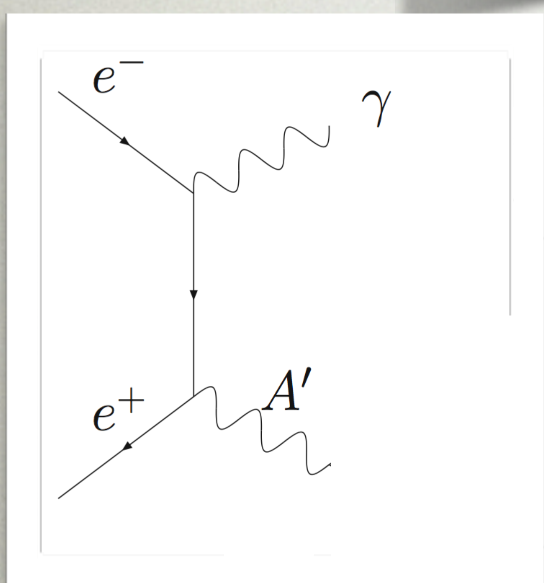


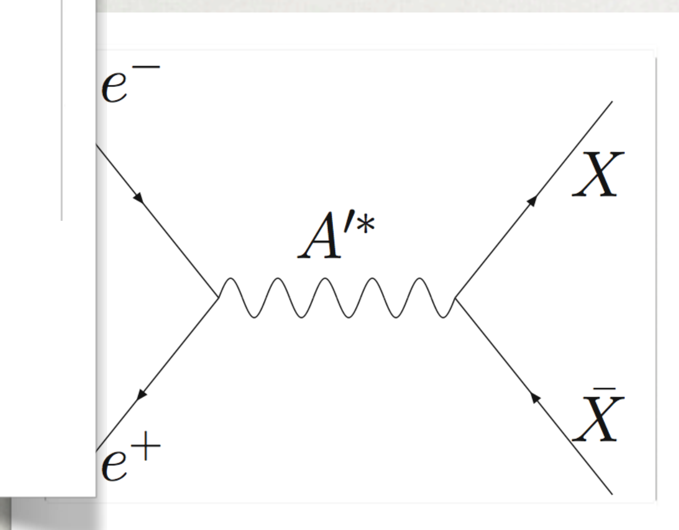
Broad Array of Searches! (done, ongoing, planned)



High Energy Hadron Colliders (indirect) – New heavy particles can decay into dark sector “lepton jets”

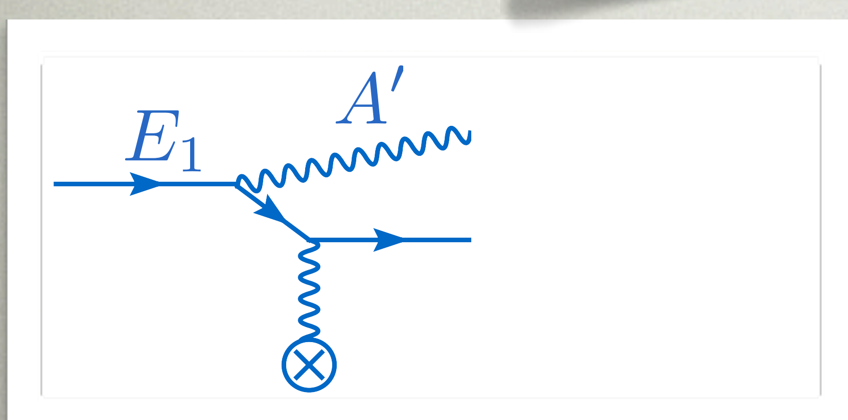
(ATLAS, CMS, CDF & D0)





Colliding e+e-: On- or Off- shell A′, X=dark sector or leptons & pions

(BaBar, BELLE, BES-III, CLEO, KLOE)



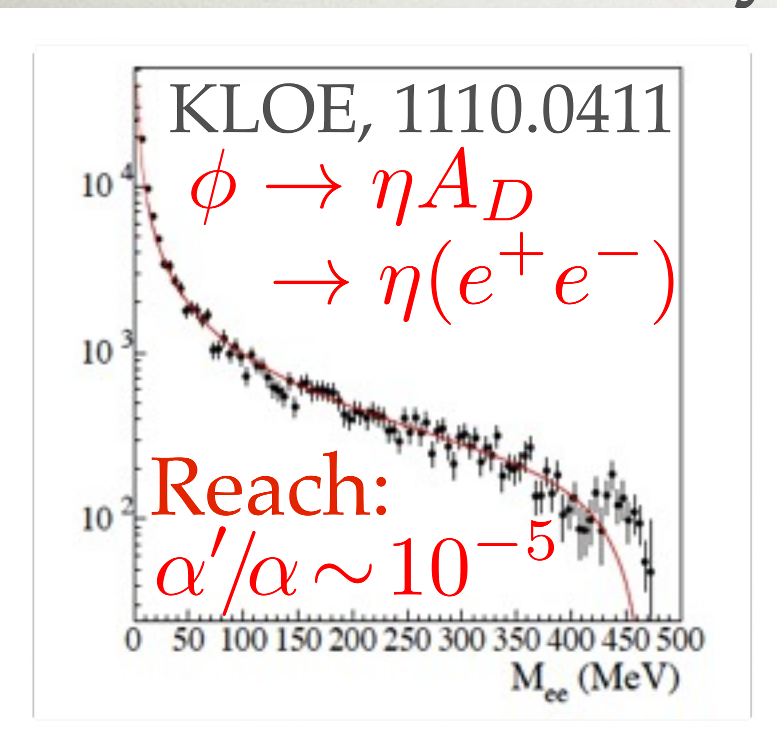
Fixed-Target: Electron or Proton collisions, A′ decays to di-lepton, pions, invisible

(FNAL, JLAB (Hall A & B & FEL), MAMI (Mainz), WASA@COSY ...)

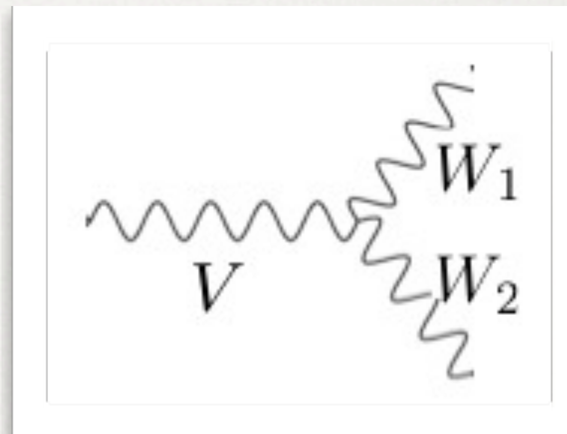
Wide Breadth of Searches

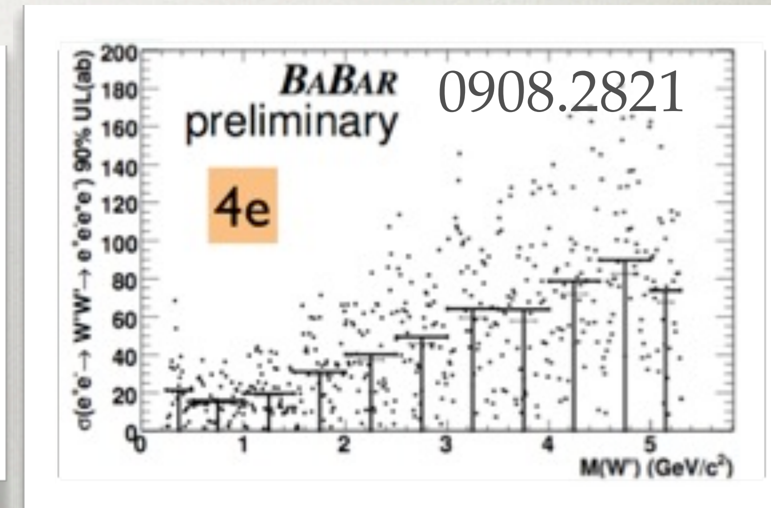
(just a few representative examples)

Minimal Decay

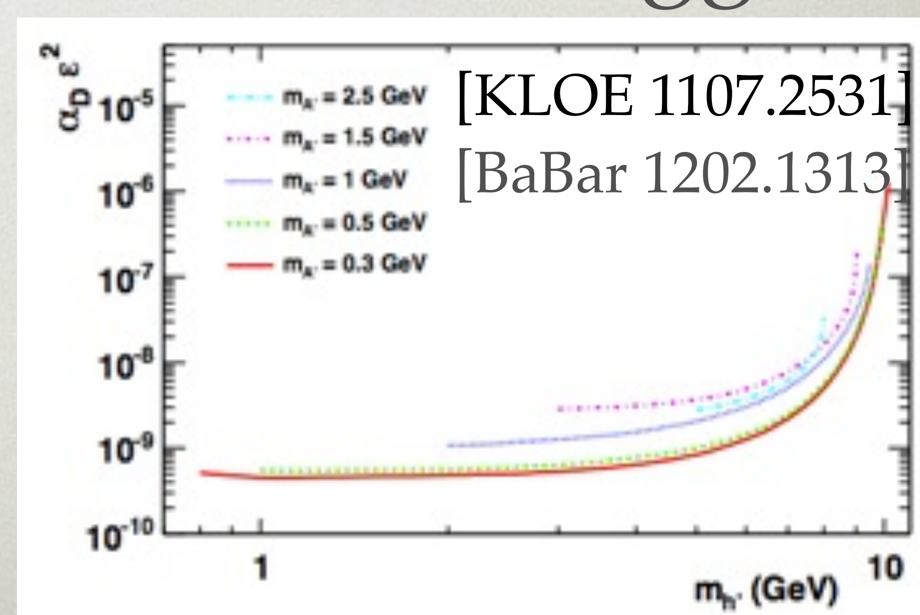


Non-Abelian Dark Sector

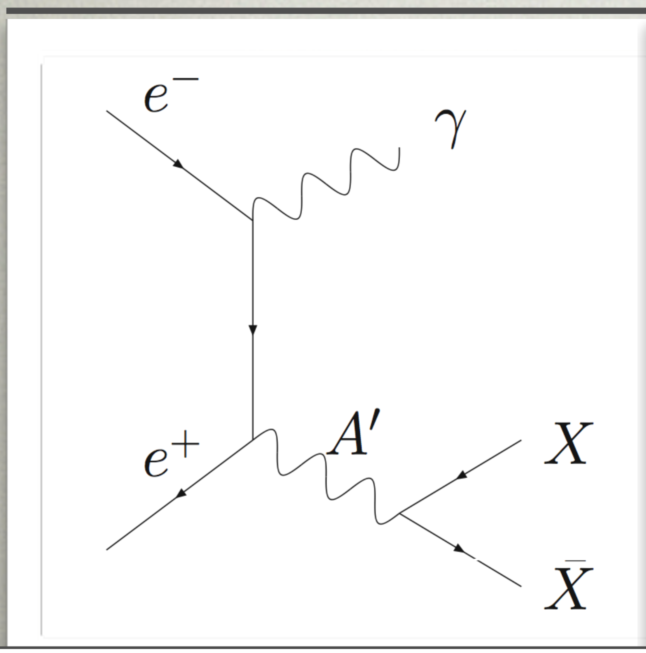


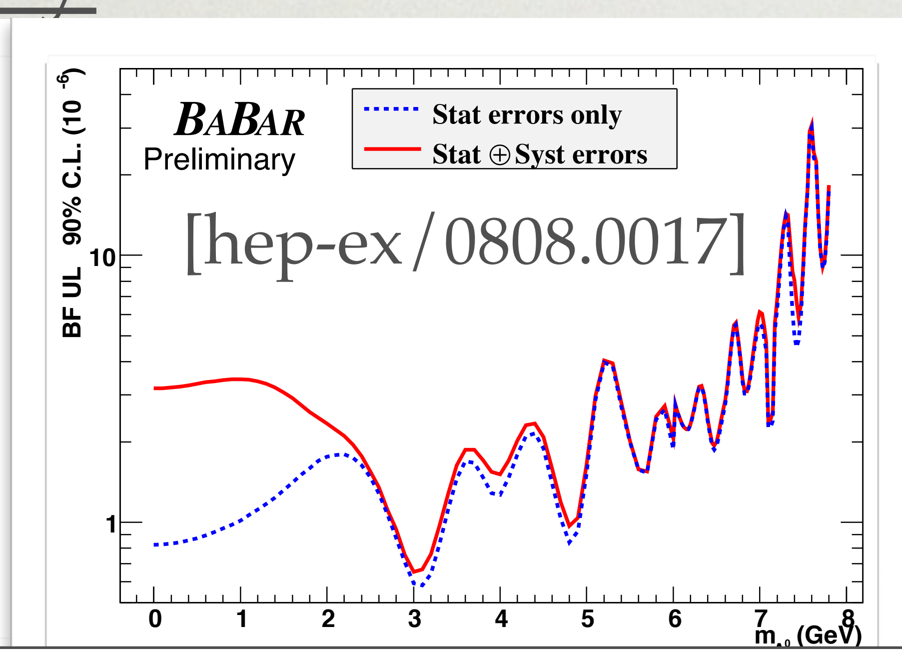


Vector + Higgs:

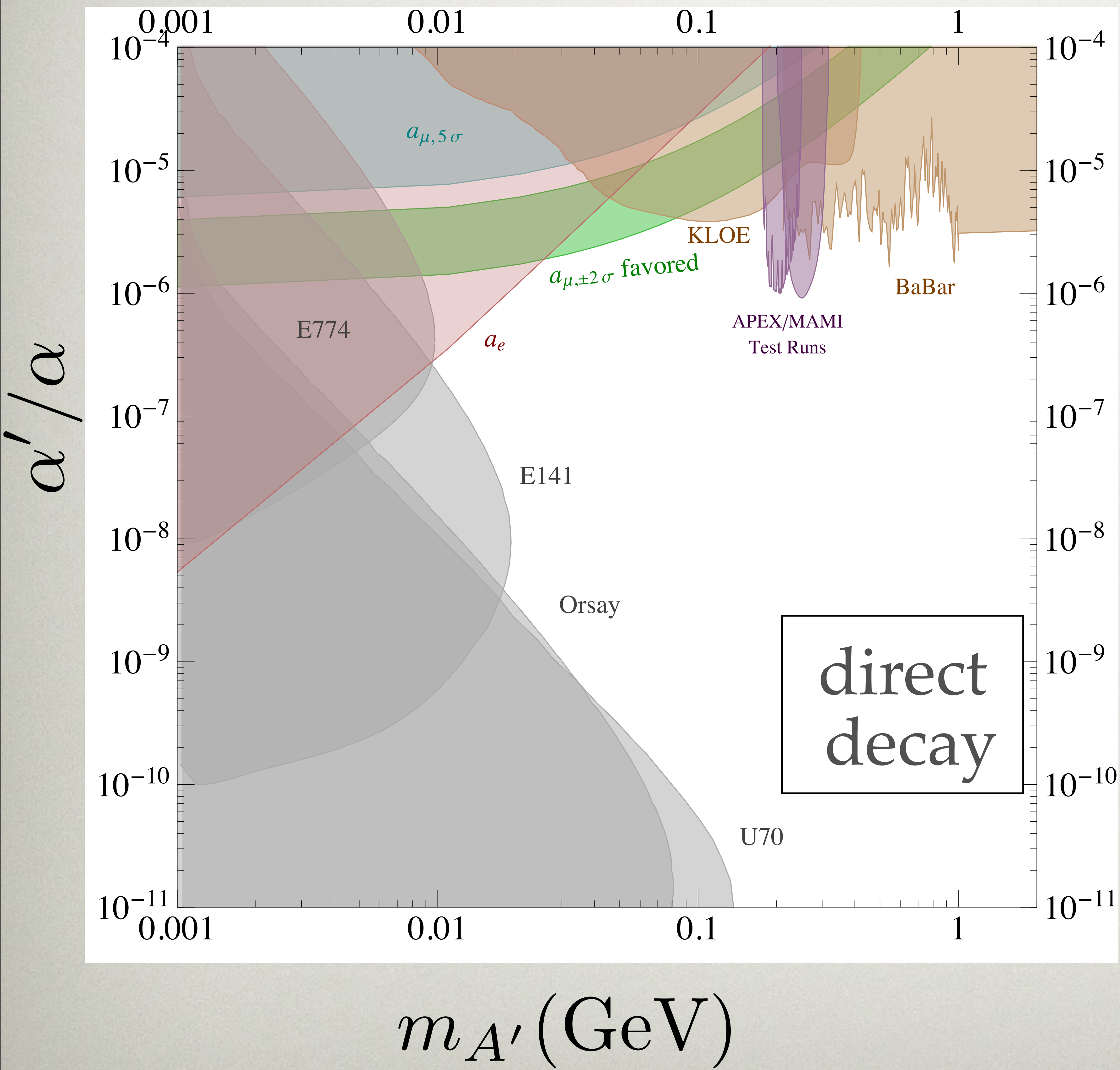


Invisible Decay





"Minimal" visible decay (l^+l^-)

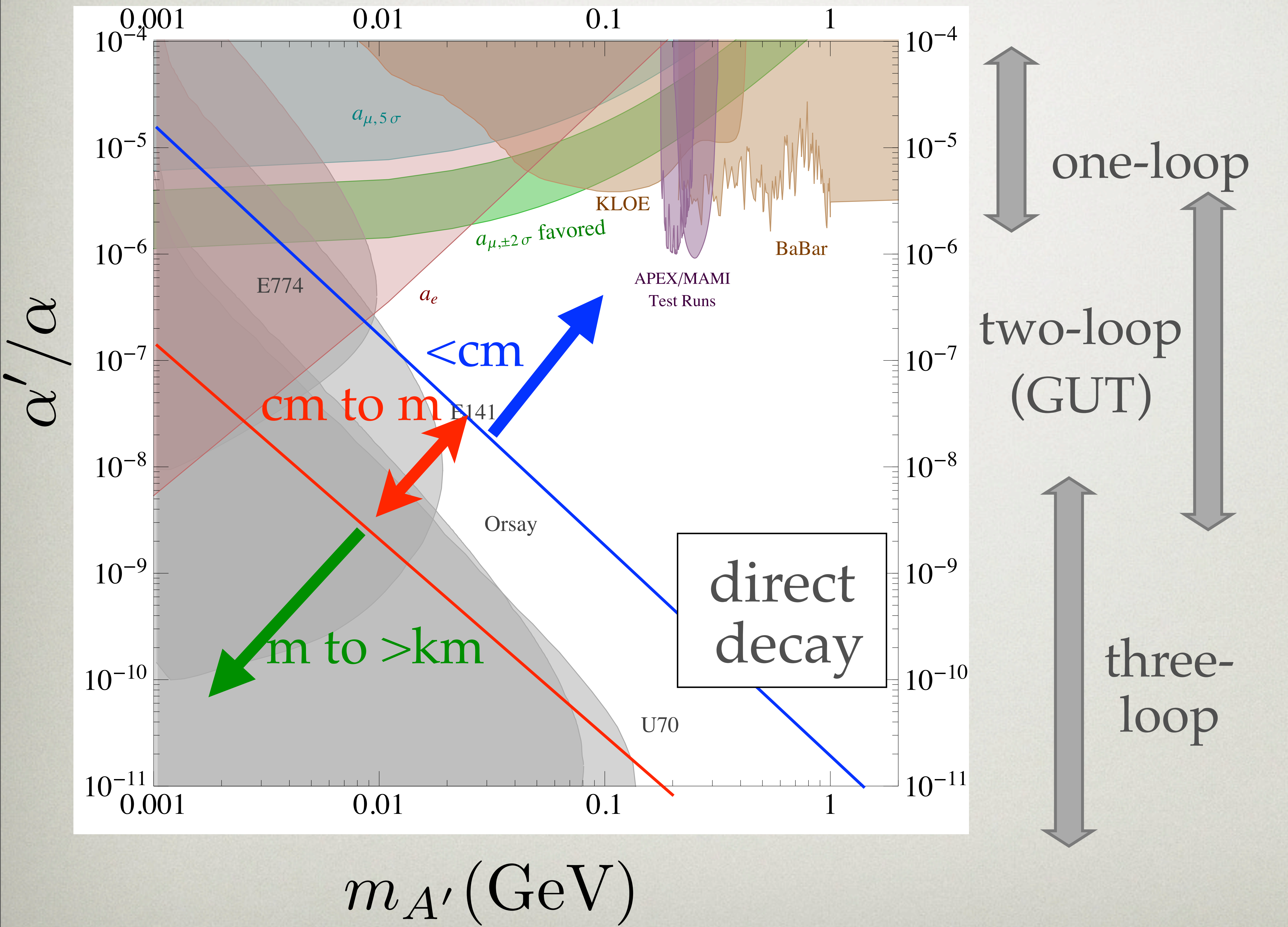


one-loop

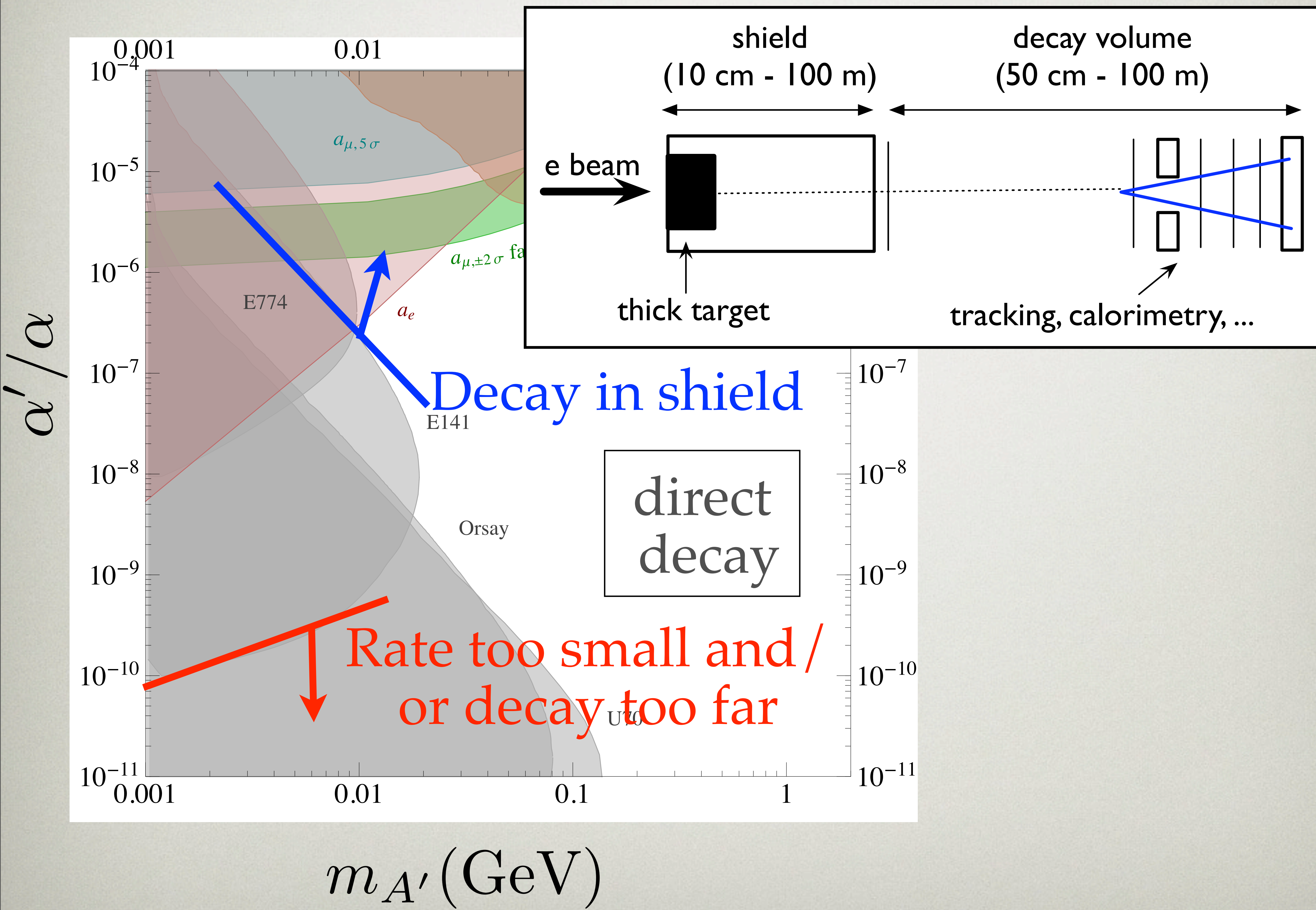
two-loop
(GUT)

three-
loop

"Minimal" visible decay (l^+l^-)



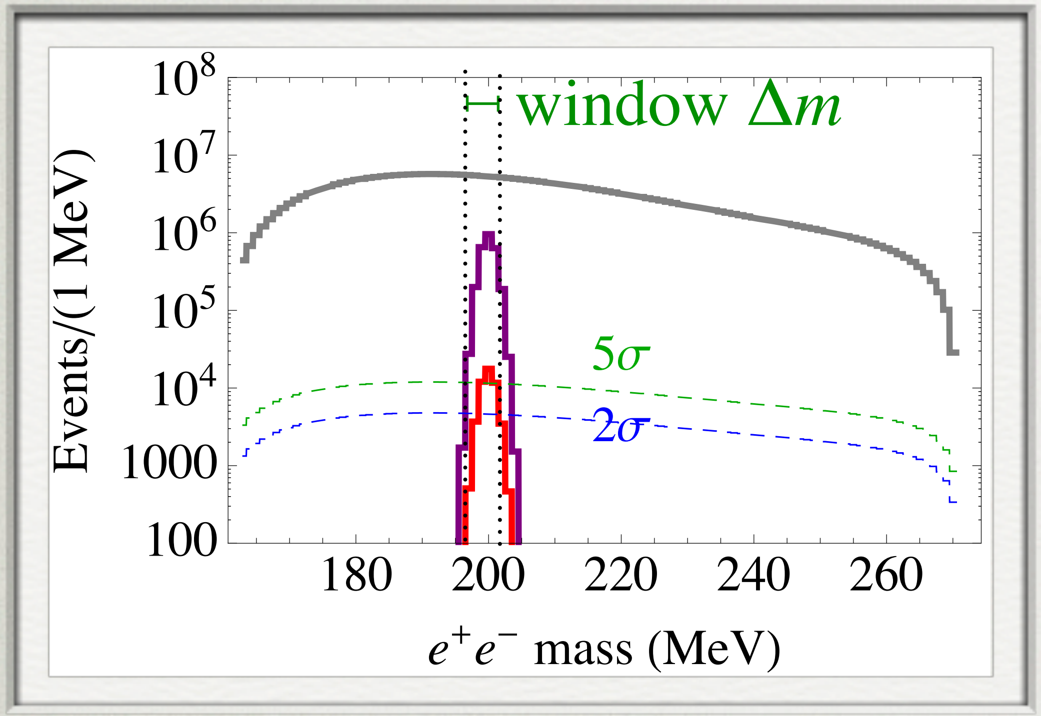
Beam-Dump Limits



Two Search Strategies

High-Statistics Resonance Search

(MAMI, APEX, HPS, DarkLight)

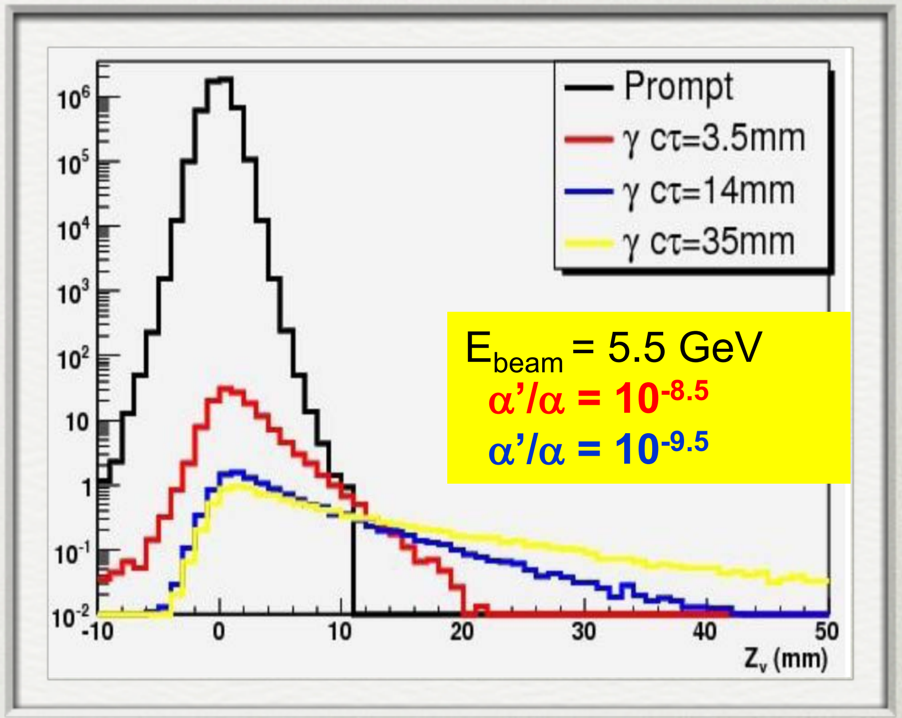


Demands high data-taking rate, background suppression and excellent mass resolution

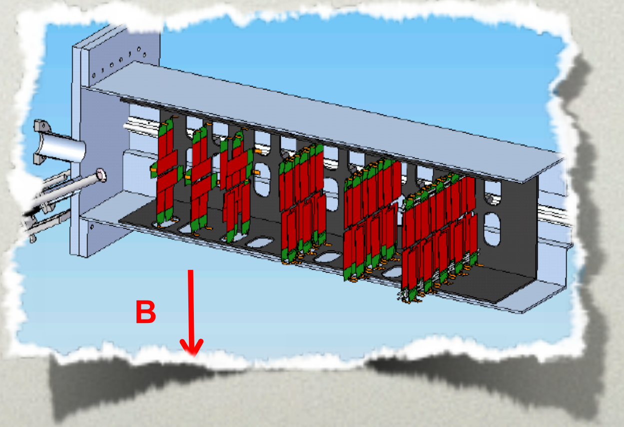
Demonstrated in test runs: Mainz (1101.4091) and APEX (1108.2750)

Long-lived particle search

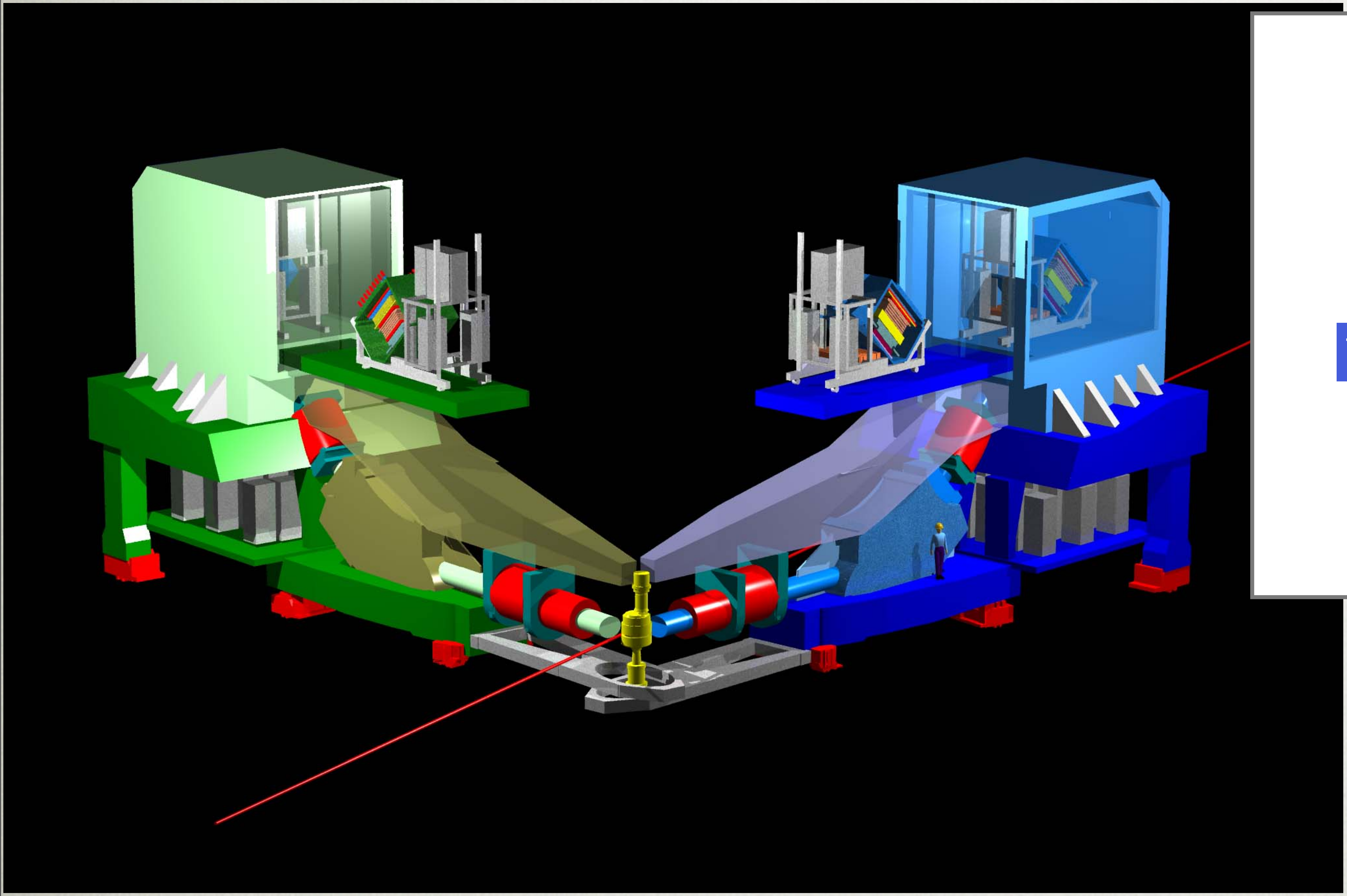
(HPS)

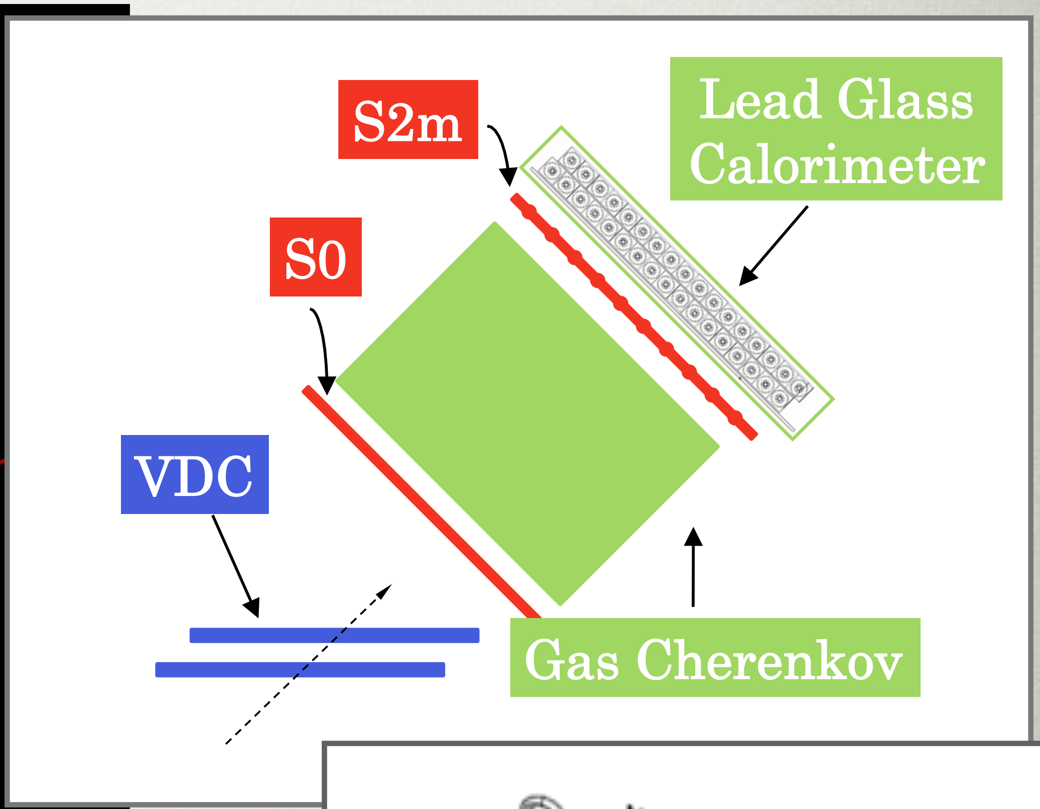


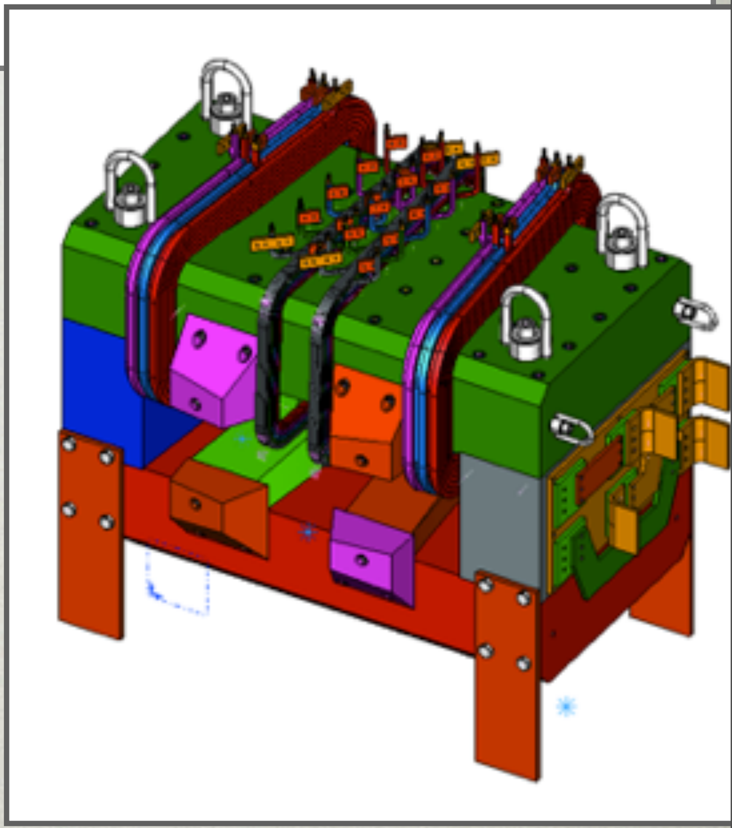
...and forward vertex resolution (well-controlled tails)



APEX $A' \rightarrow e^+e^-$ resonance search using Hall A high-resolution spectrometers and septa magnet







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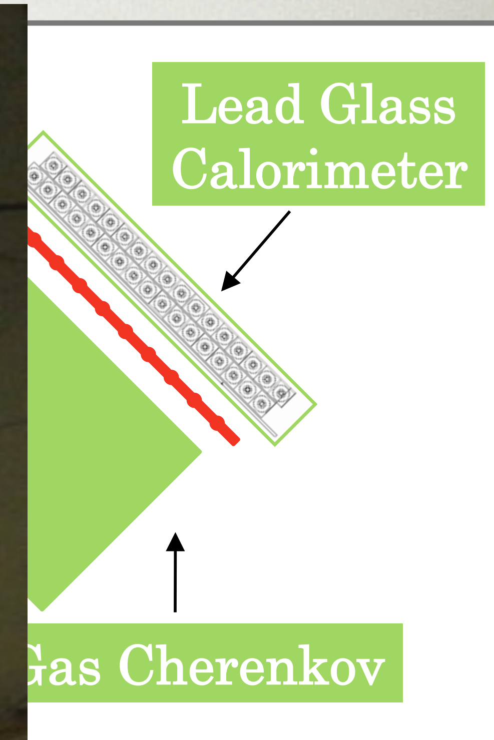

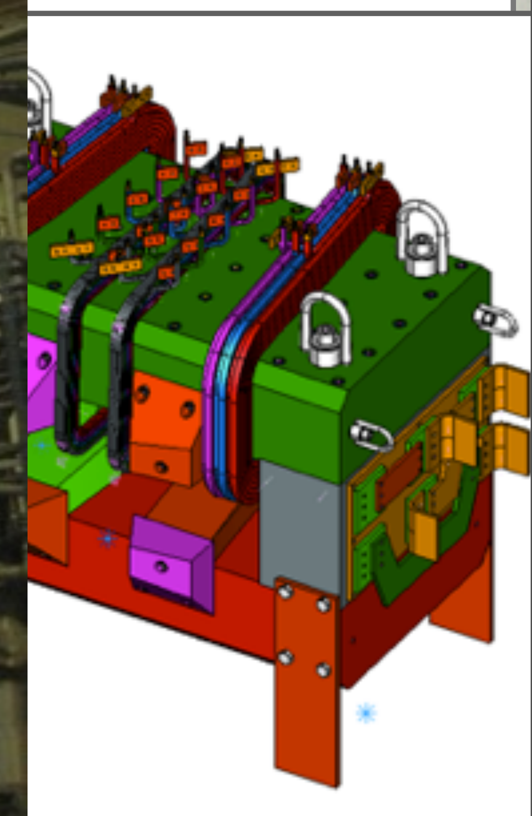

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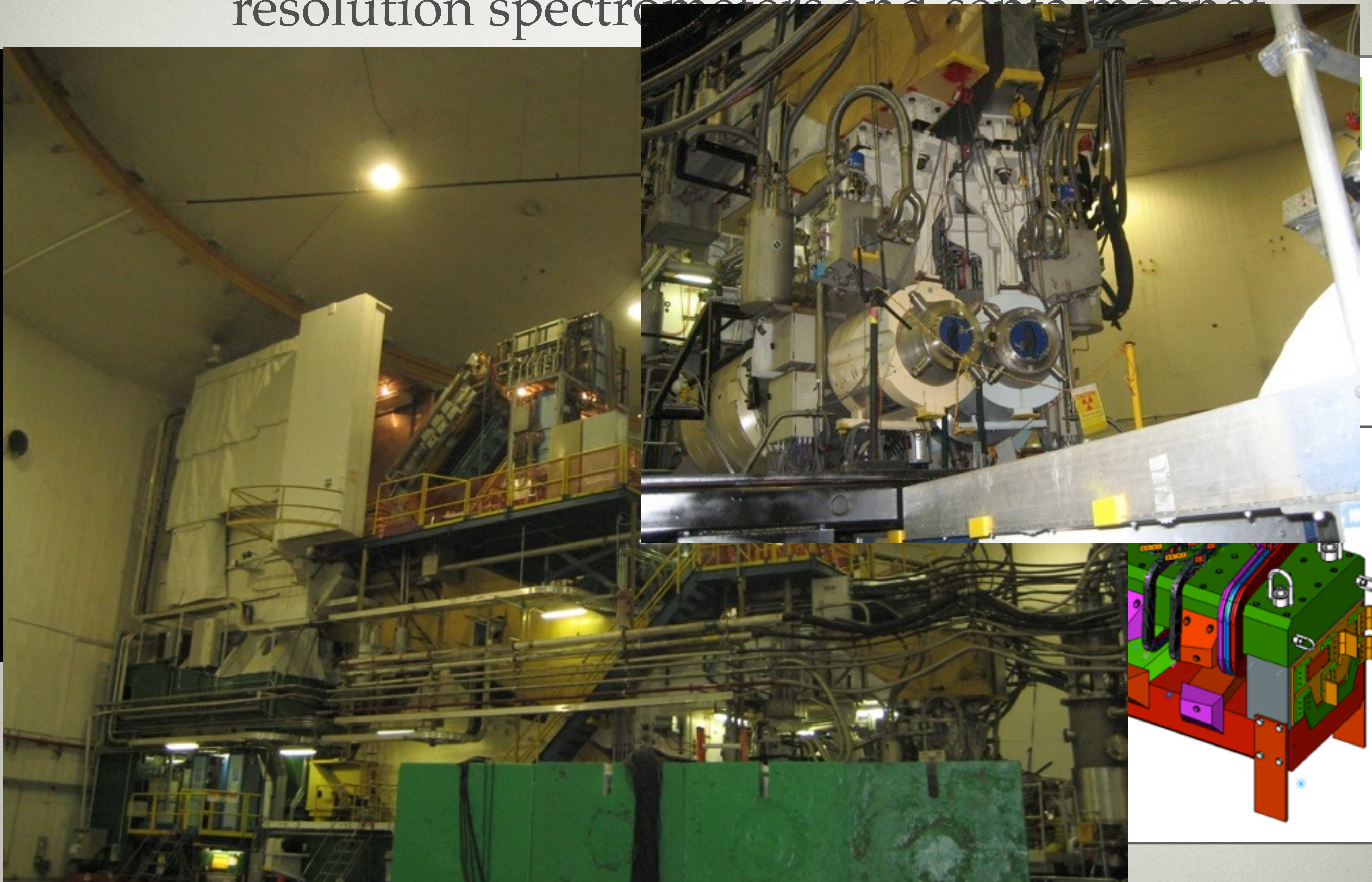

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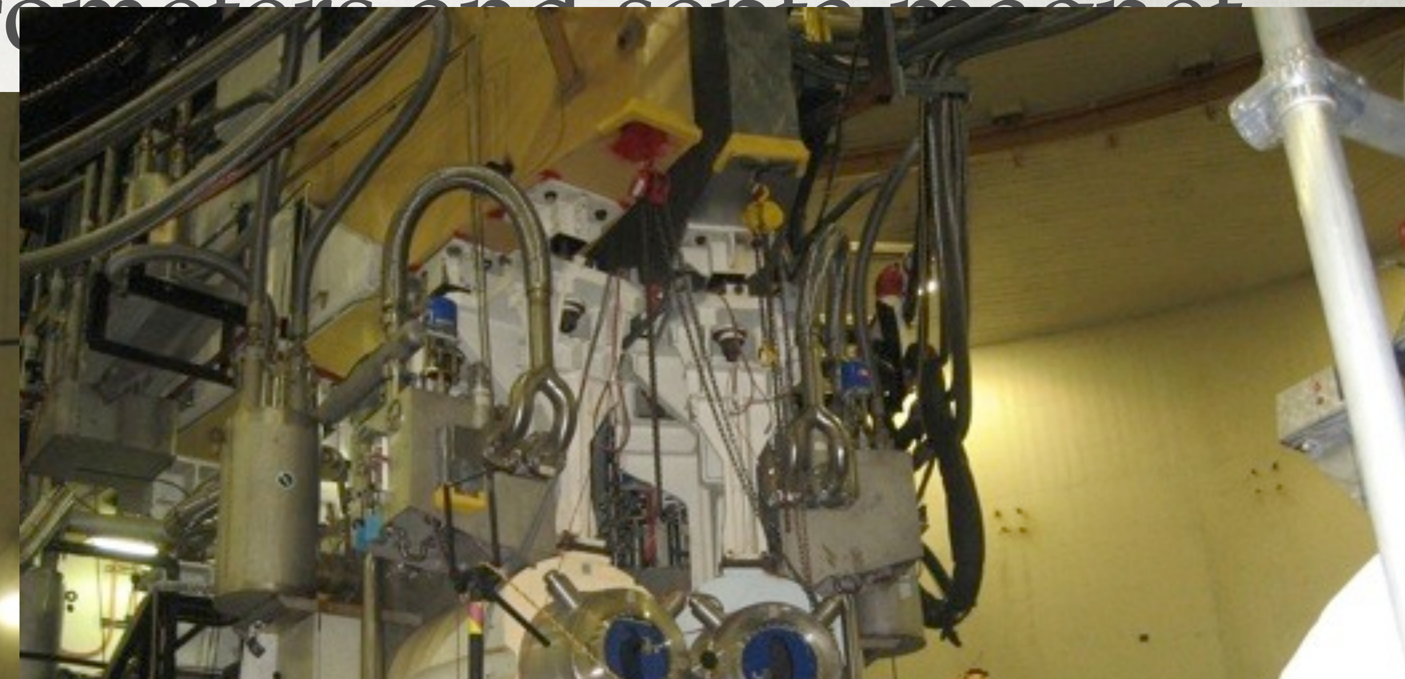
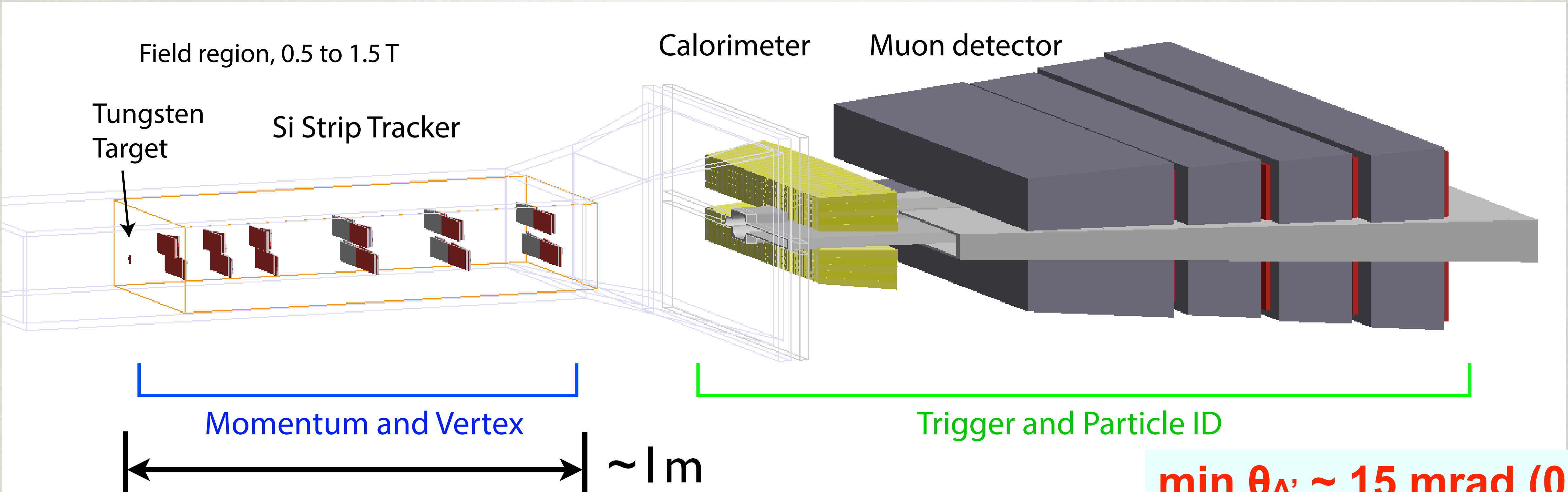


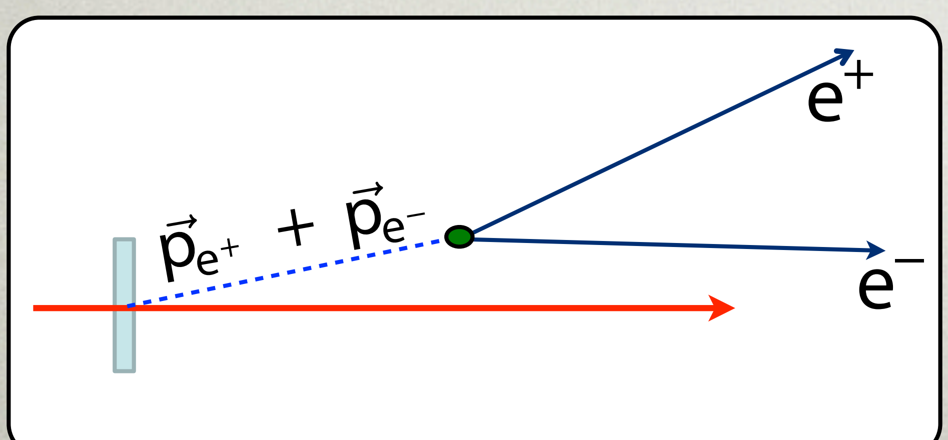
APEX $A' \rightarrow e^+e^-$ resonance search using Hall A high-resolution spectr

HPS: Resonance + Vertex Searches

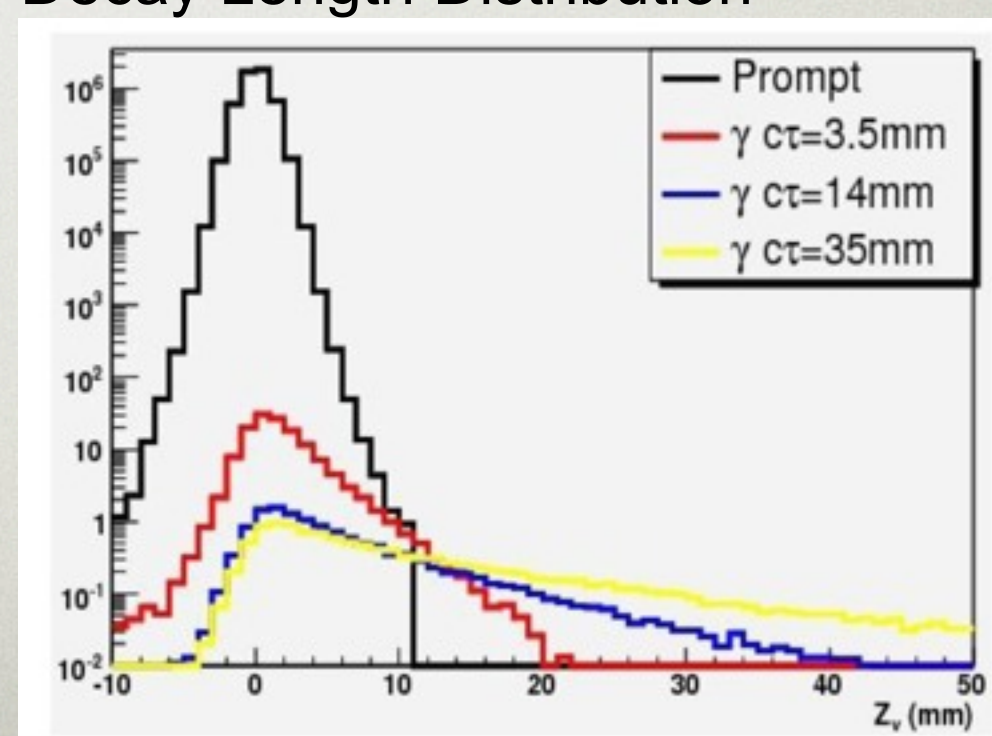


min $\theta_{A'}$ ~ 15 mrad (0.85°)
$\Delta m/m$ ~ 1% (bump hunt)
Δz ~ 1mm (vertexing)

Vertexing allows sensitivity to weakly coupled A′ that produce only ~25 events!



Decay Length Distribution



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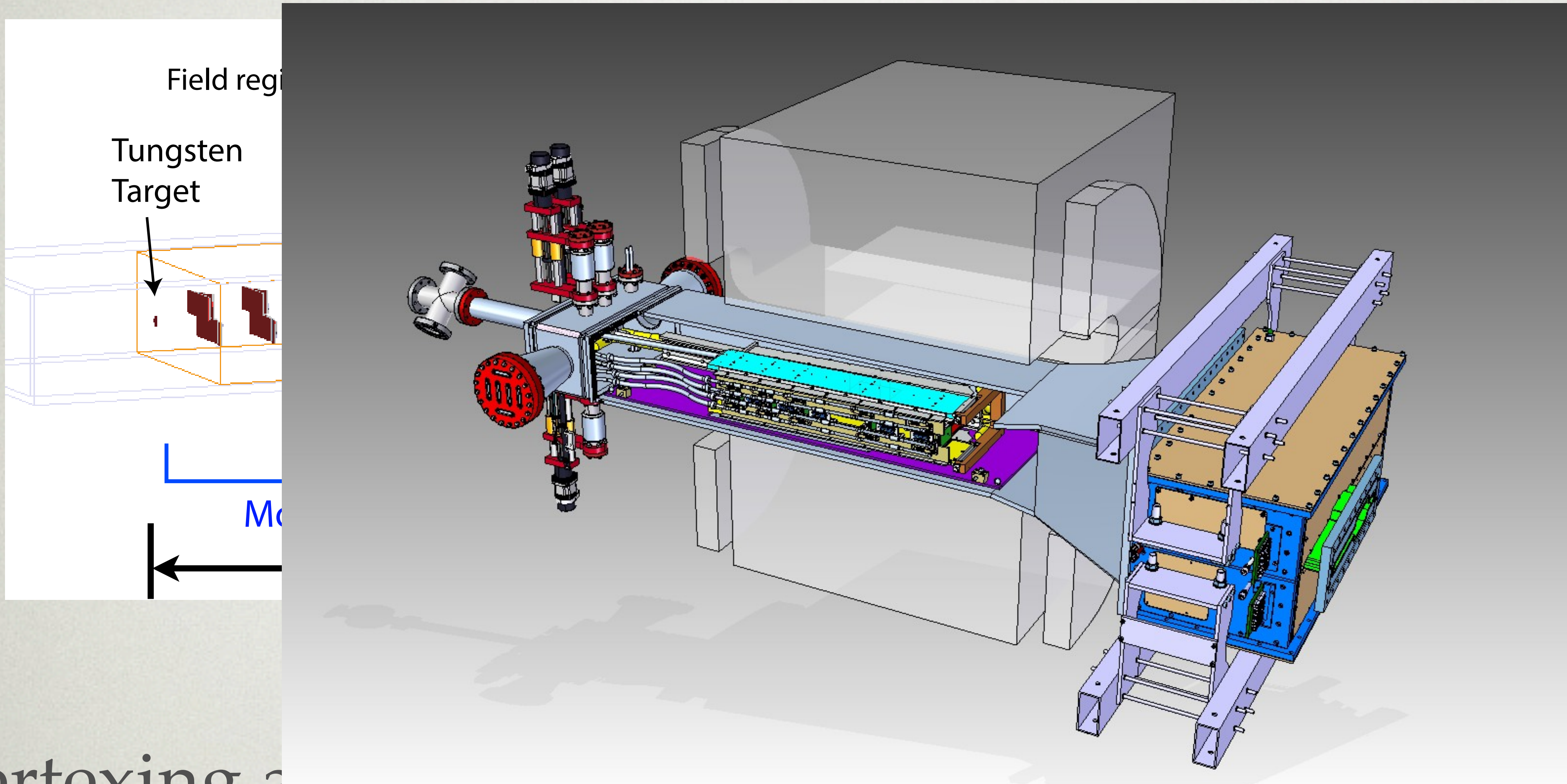
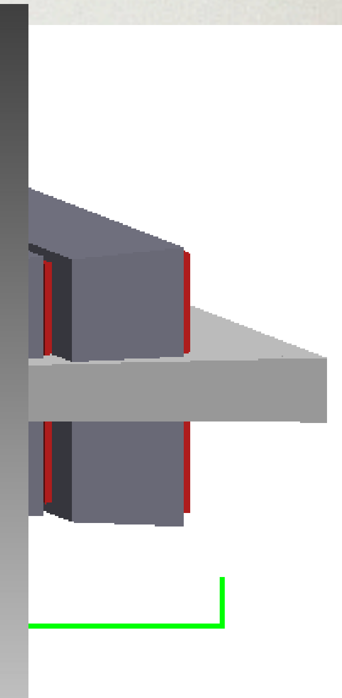
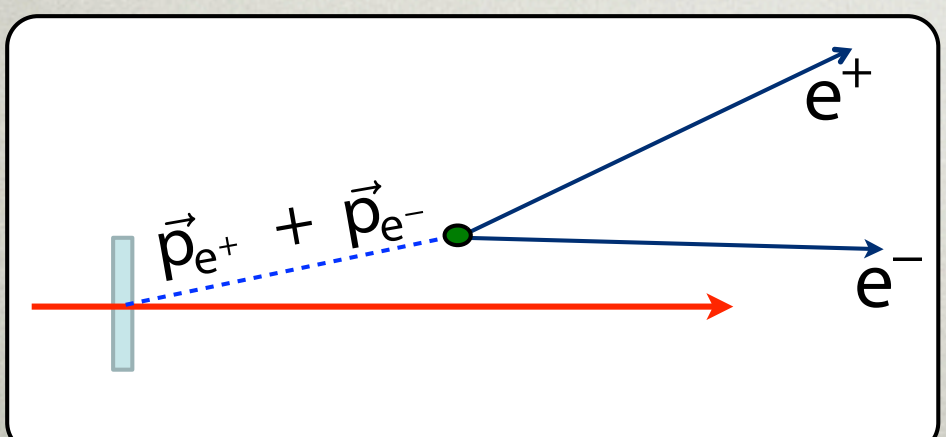




15 mrad (0.85°)
% (bump hunt)
n (vertexing)

Vertexing allows sensitivity to weakly coupled A′ that produce only ~25 events!



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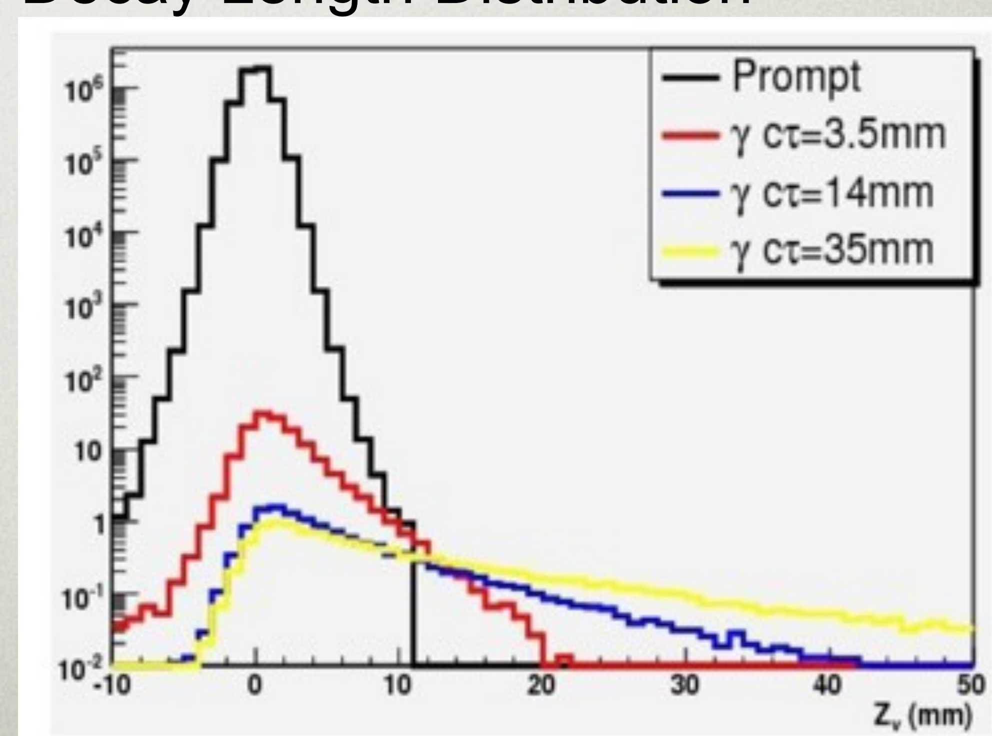

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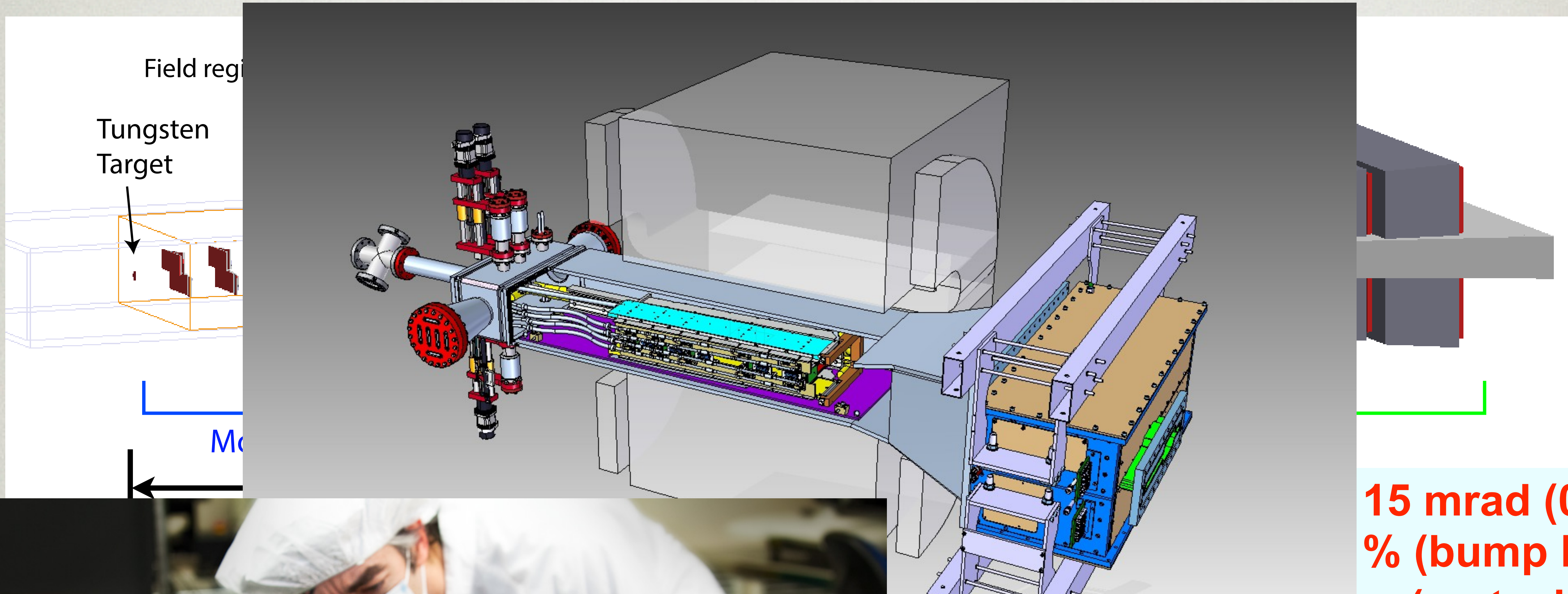

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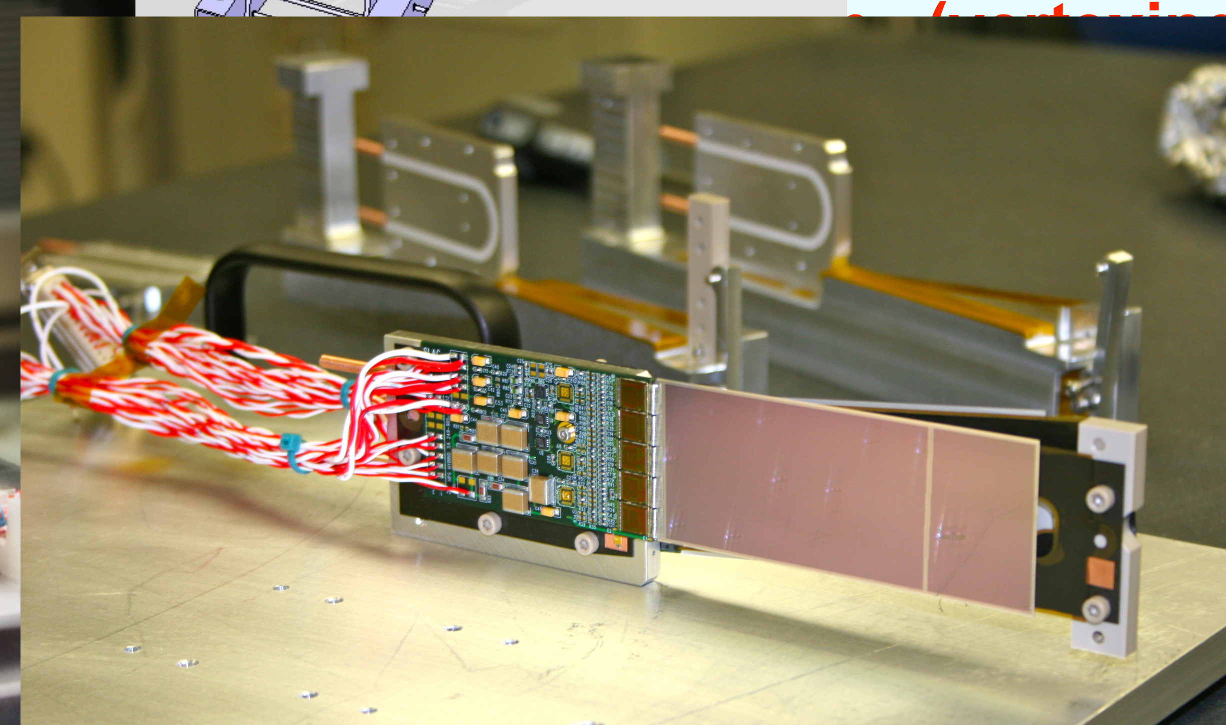
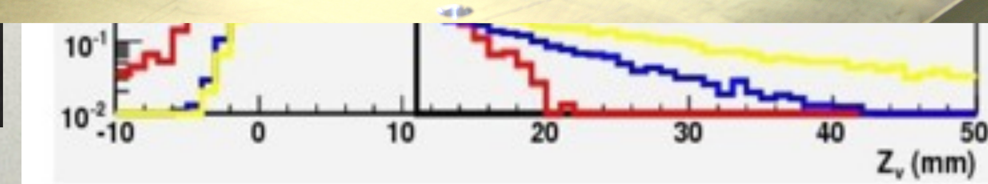
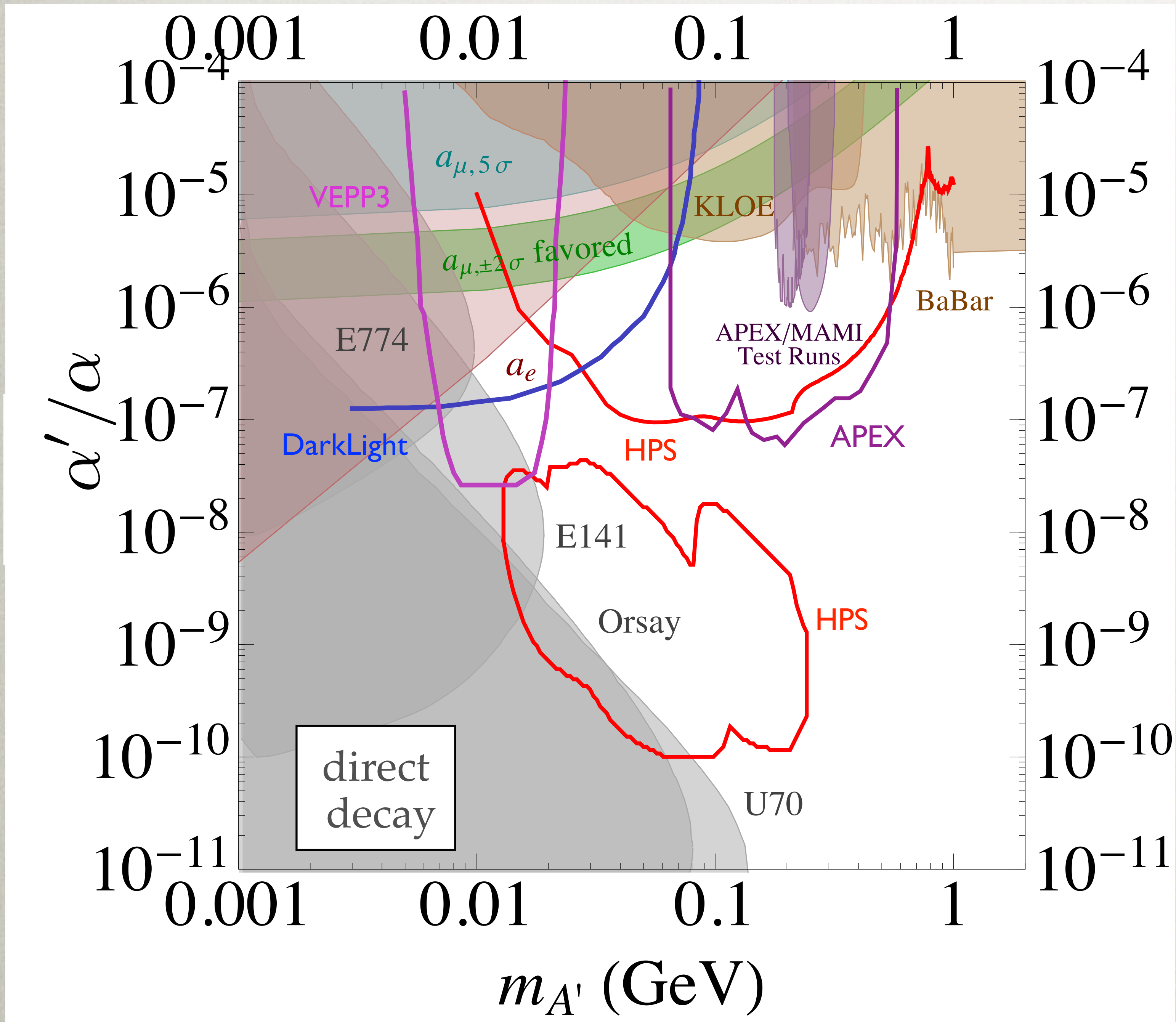




Electron Beam Sensitivity

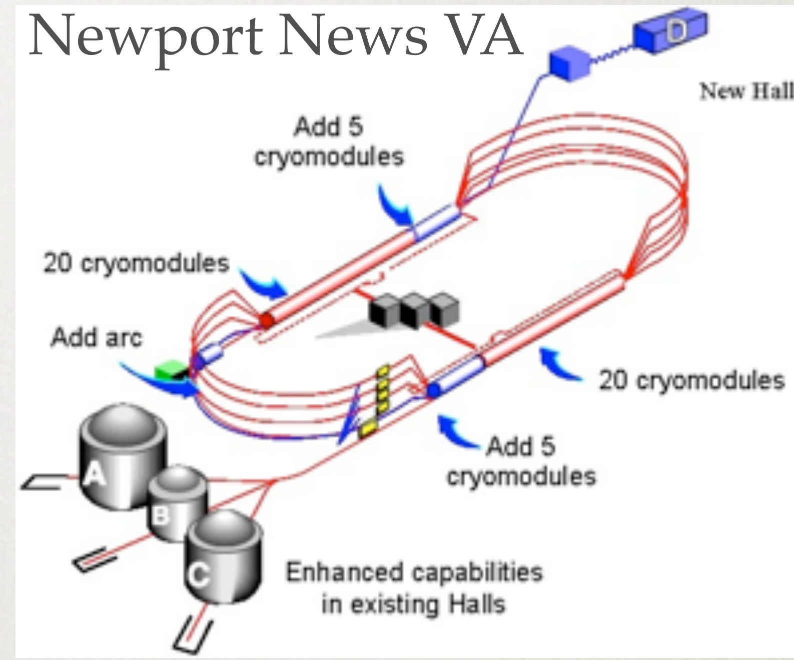
Approved and funded experiments will explore much of the parameter space below 300 MeV in next few years



APEX, HPS, Mainz strategies following scenarios discussed in Phys.Rev. D80 (2009) 075018 (Bjorken, Essig, Schuster, NT)

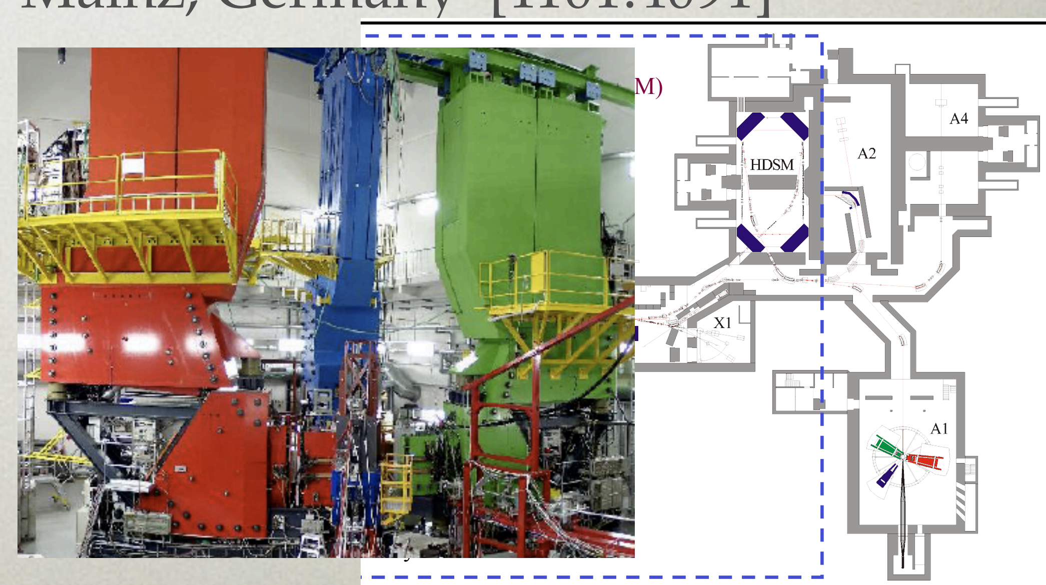
JLAB CEBAF

Newport News VA



MAMI/A1 (sensitivity not shown)

Mainz, Germany [1101.4091]



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  [with Eder Izaguirre, Gordan Krnjaic & Natalia Toro]

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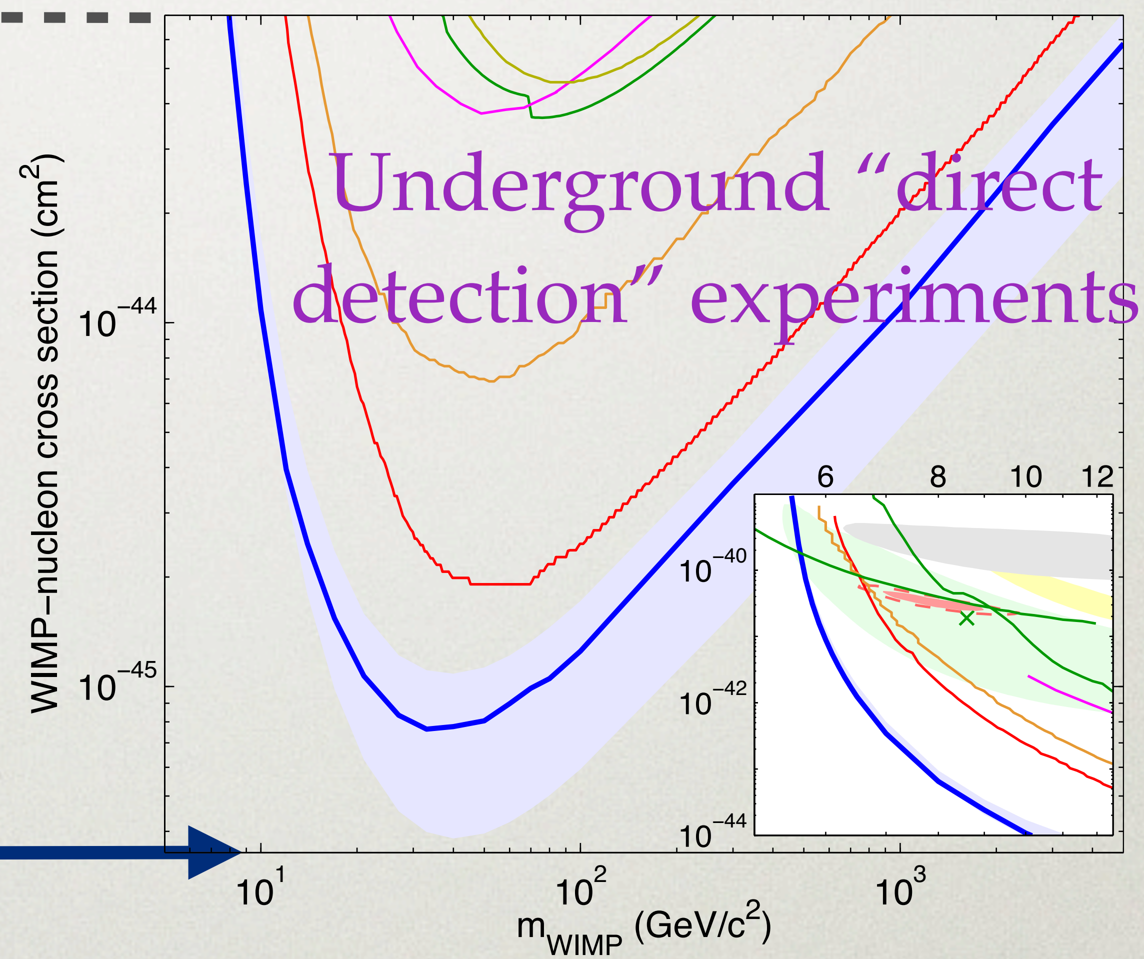
sub-GeV?

Not well explored!



High intensity accelerator experiments can explore the sub-GeV scenarios!

Accelerator Searches for Dark Matter

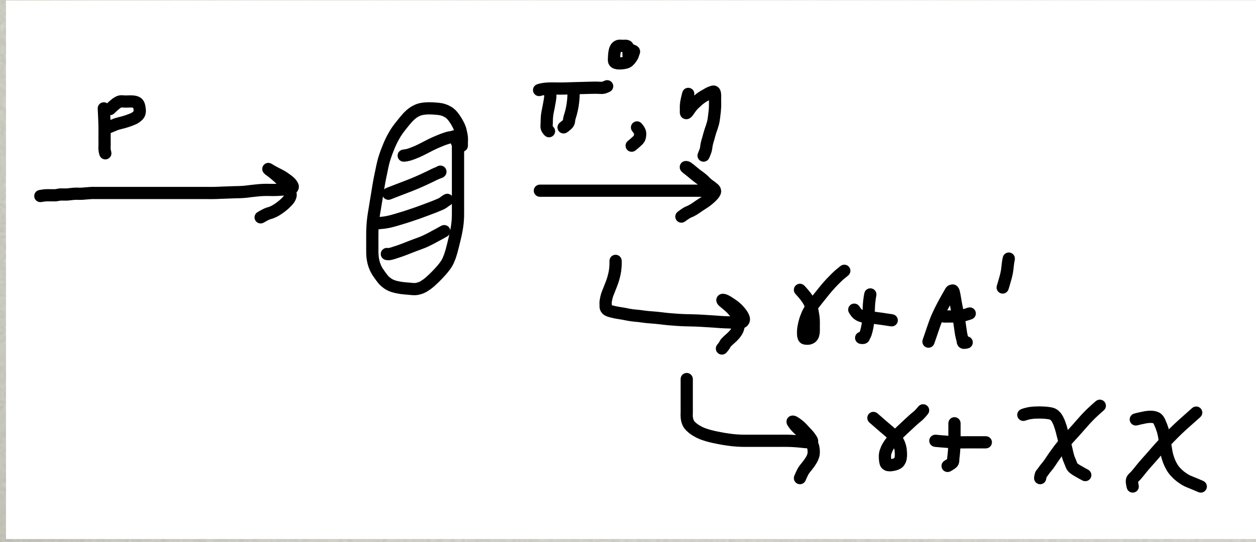
- The basic strategy
  - Proton & Electron beams
- Anatomy of electron beam dump searches
  - Discovery potential
  - Backgrounds
- Future prospects

Fixed-Target Dark Matter Searches

Proton beams and large scale neutrino detectors have been considered for fixed-target dark matter searches

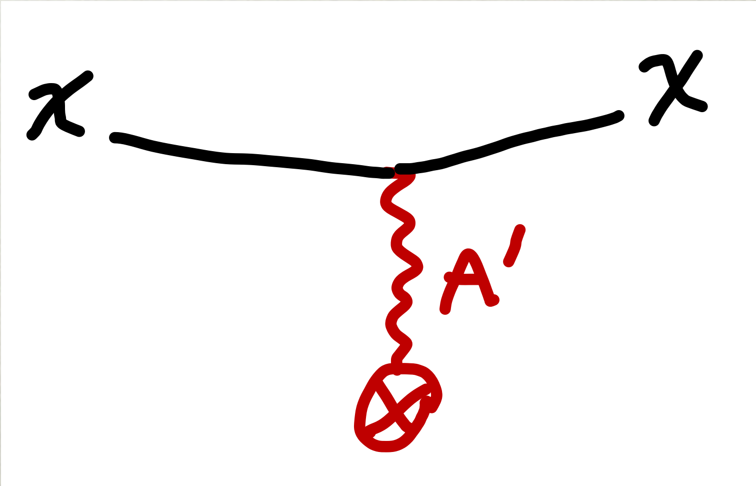
[Recently pioneered by B. Batell, P. deNiverville, D. McKeen, M. Pospelov, A. Ritz]

Production of Dark Matter:
Initiated by meson production, followed by A′ decay



+

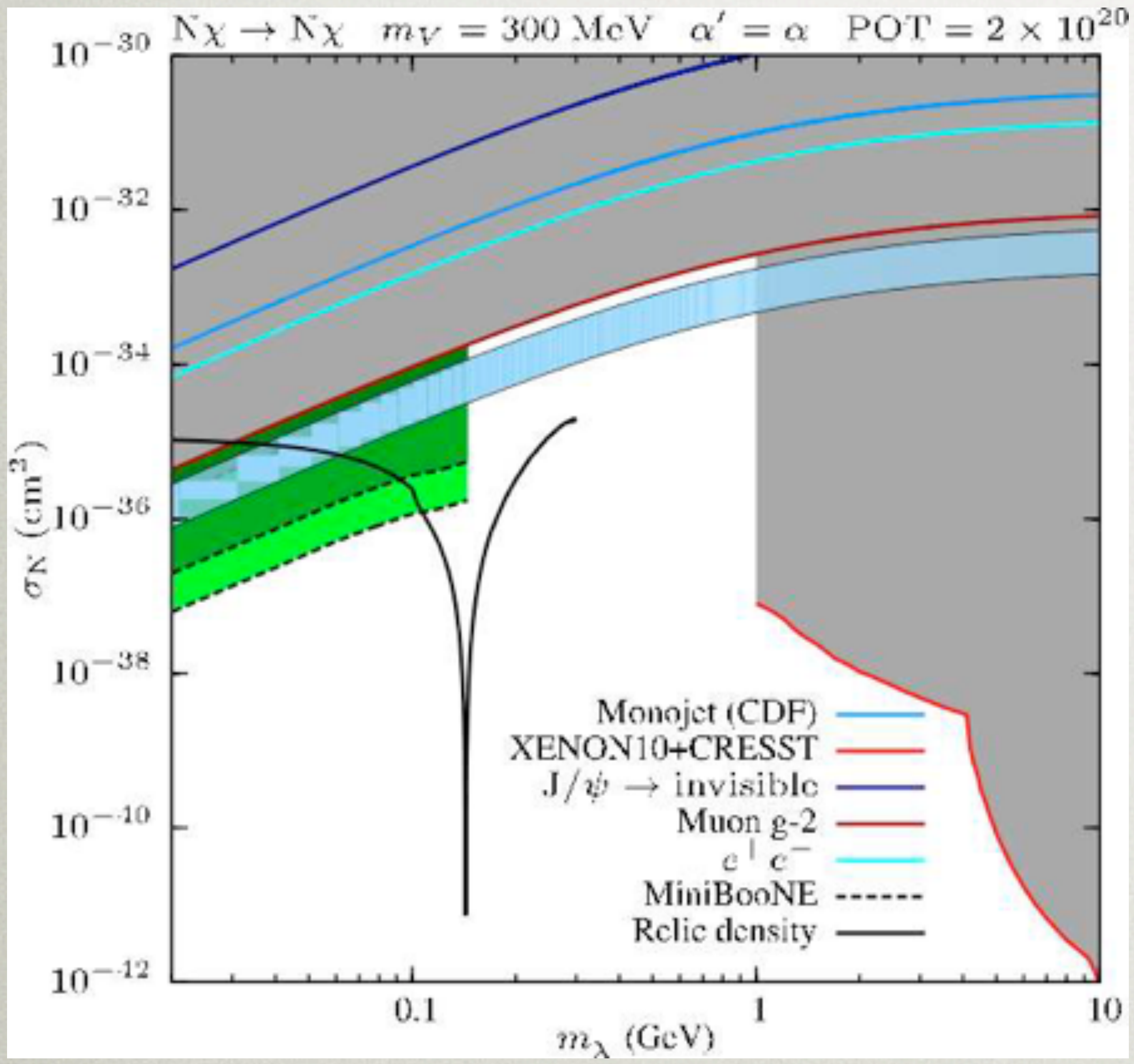
Look for neutral current scattering

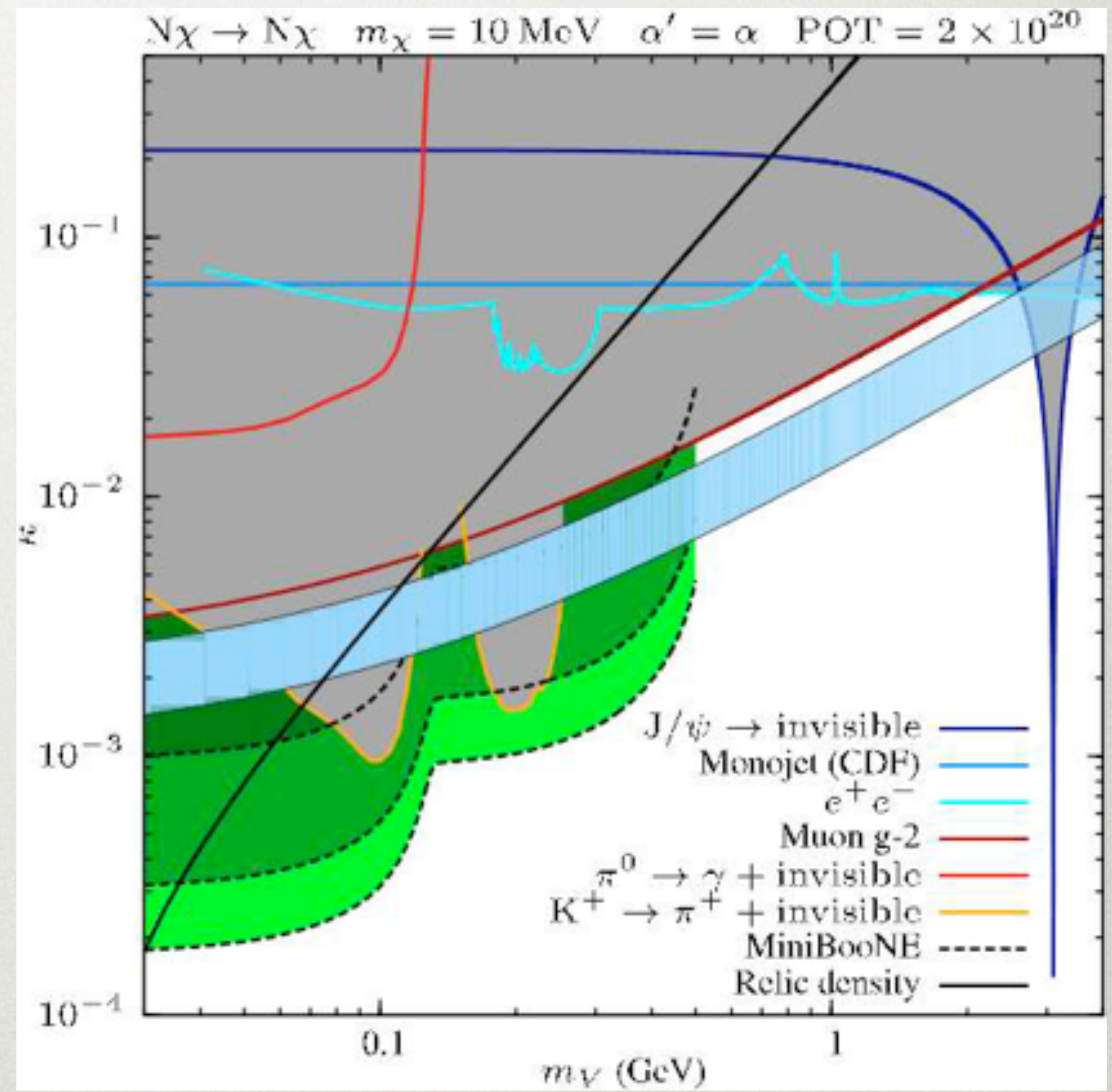


Proton Beams

sub- 500 MeV WIMP search using MiniBooNE

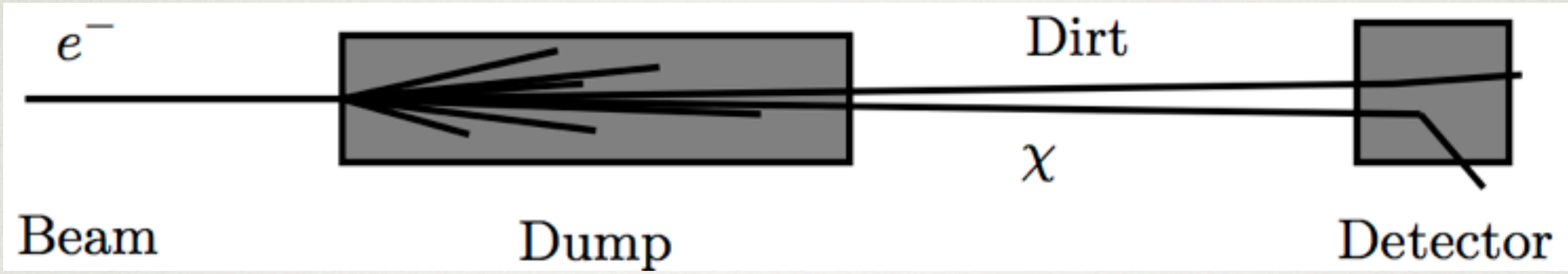
Fix m_V, vary m_χ	Fix m_χ, vary m_V





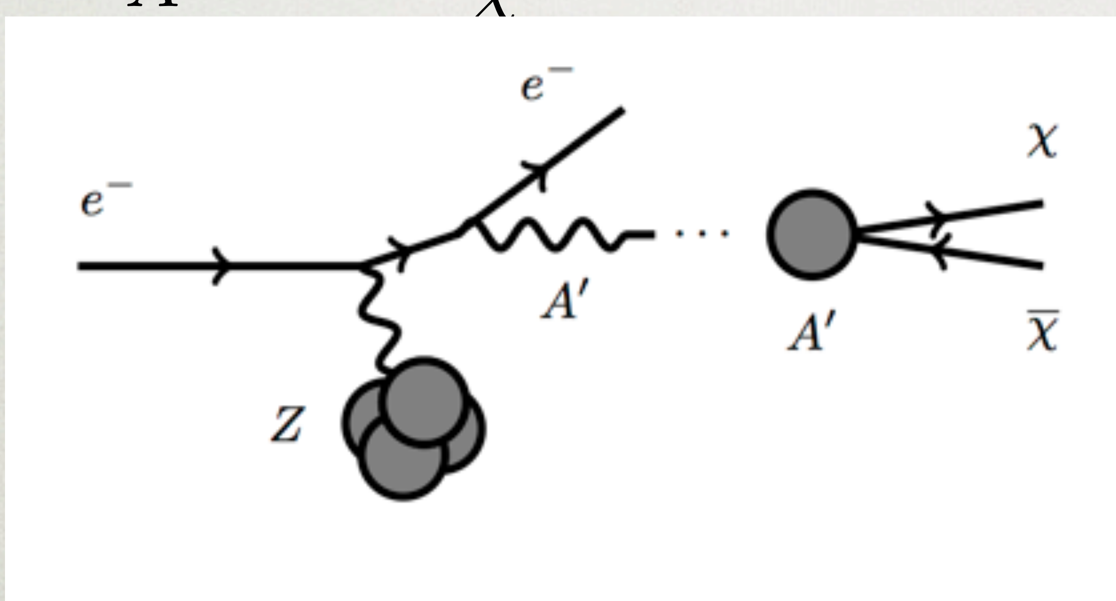
(see: arXiv:1211.2258 for proposal)

An Electron Beam-Dump Experiment



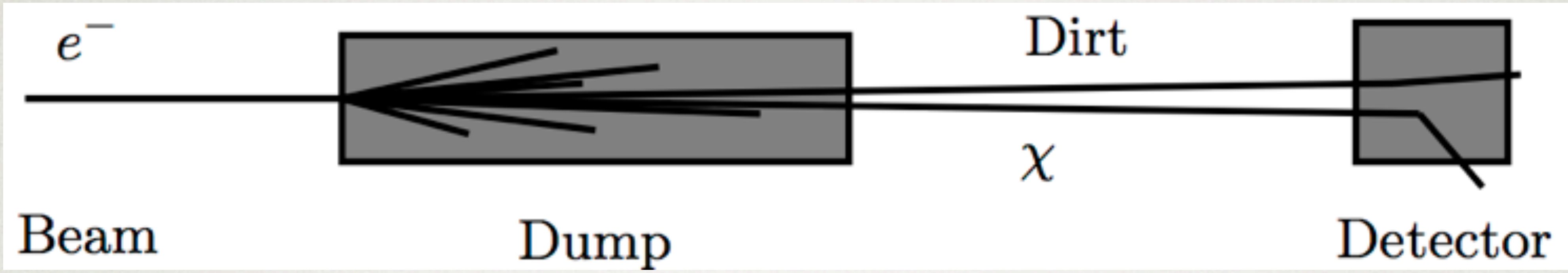
Production:

$$m_{A'} > 2m_\chi \implies \text{on-shell A'-strahlung}$$



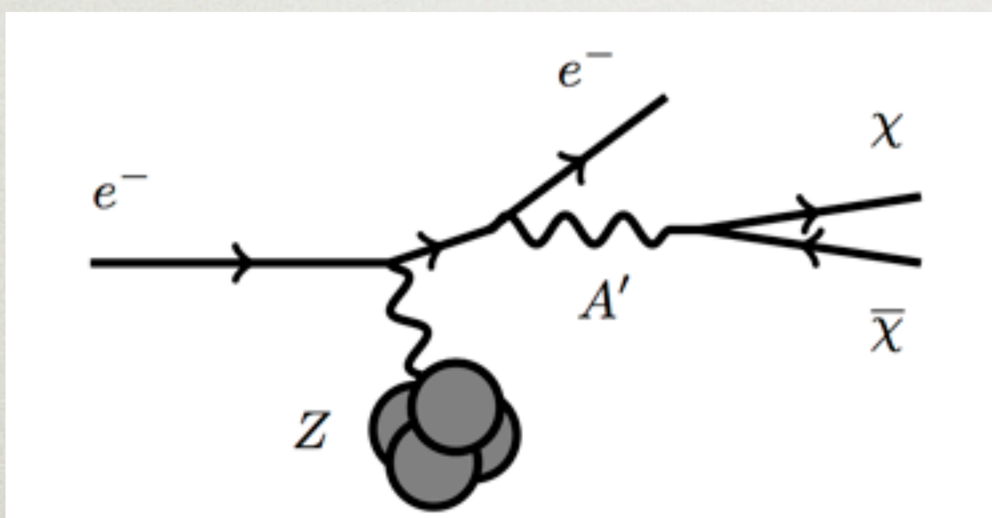
$$\sigma \sim \frac{\epsilon^2}{m_{A'}^2}$$

An Electron Beam-Dump Experiment



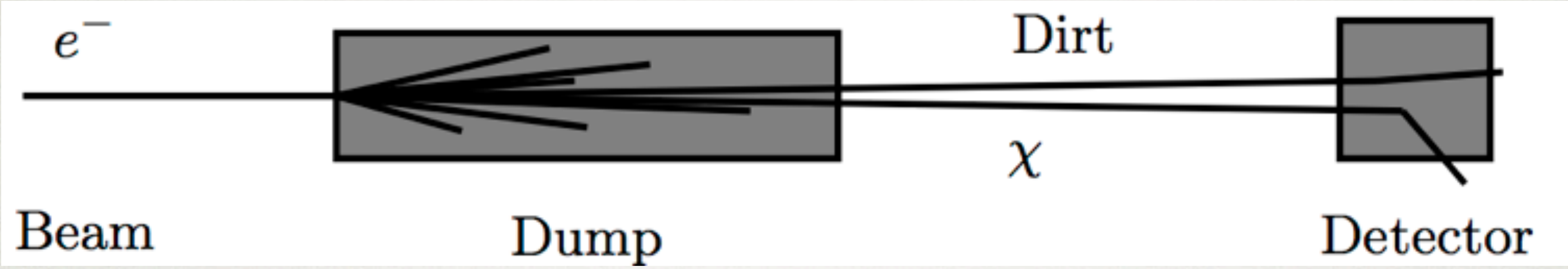
Production:

$$m_{A'} < 2m_\chi \implies \text{off-shell radiative}$$



$$\sigma \sim \frac{\alpha_D \epsilon^2}{m_\chi^2}$$

An Electron Beam-Dump Experiment



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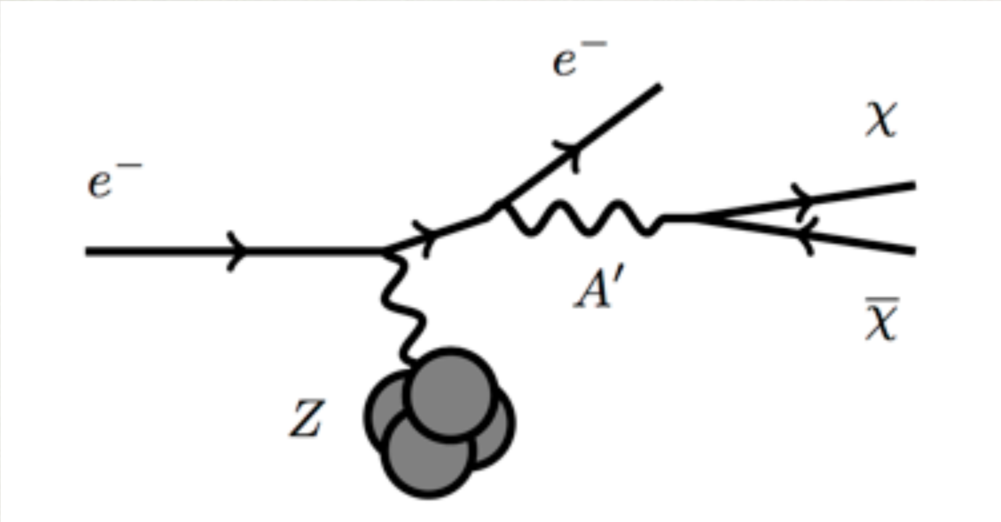
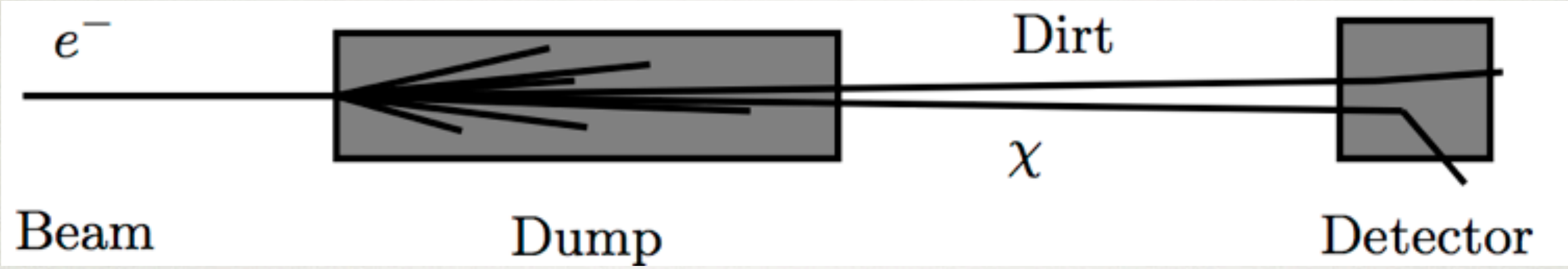


$$\sigma \sim \frac{\alpha_D \epsilon^2}{m_\chi^2}$$

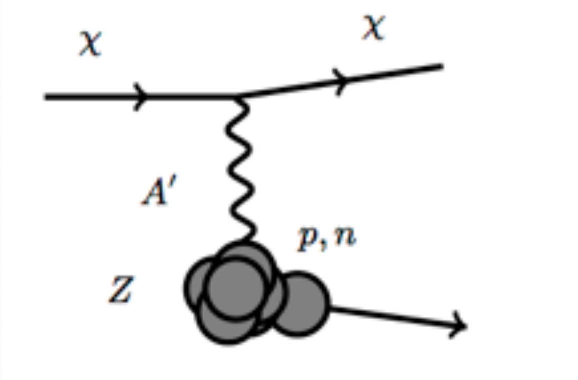
Yields forward peaked DM beam with nearly the full beam energy!

An Electron Beam-Dump Experiment

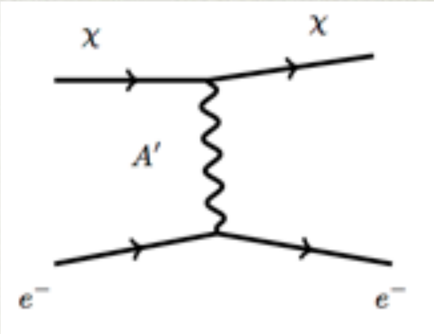


Detection:

Quasi-elastic Nucleon
Higher recoil energies > 10s MeV,
$\sigma \sim \alpha_D \epsilon^2 / m_{A'}^2$



Electron Scattering
Low recoil energies, light mediator



Familiar to neutrino physicists, but with different kinematics.
Several other potential signals...

Existing Electron Beams

Two types: "continuous" (CEBAF) and low duty cycle "pulsed" beams

Jefferson Lab and SLAC have **high energy**

JLab

$$E = 12\ \text{GeV} \qquad \text{EOT} = 10^{22}/\text{year}$$

SLAC's FACET facility

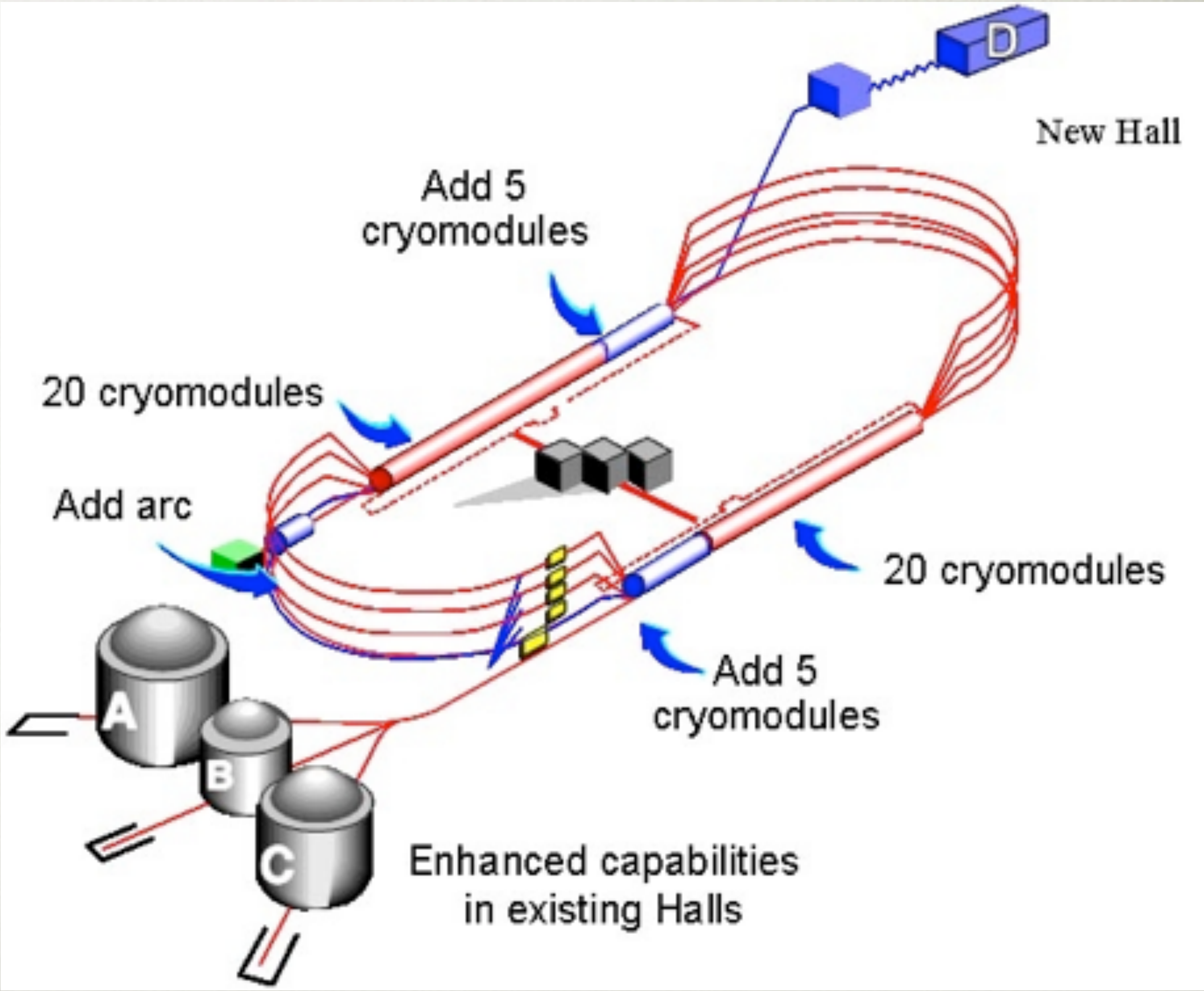
$$E = 20\ \text{GeV} \qquad \text{EOT} = 10^{20}/\text{year}$$

Example: Continuous Electron Beam Accelerator Facility

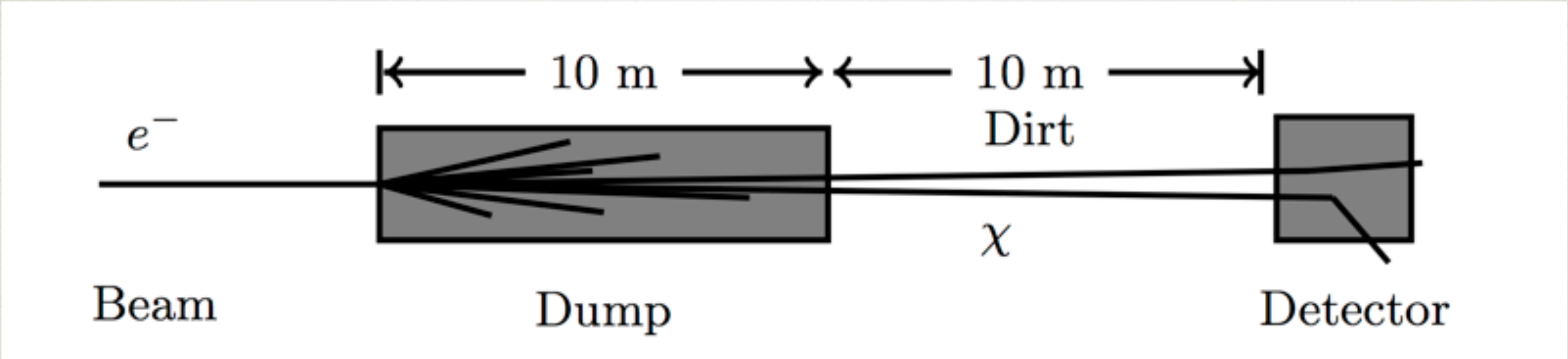
- Will deliver beam up to 11 GeV to 4 experimental halls

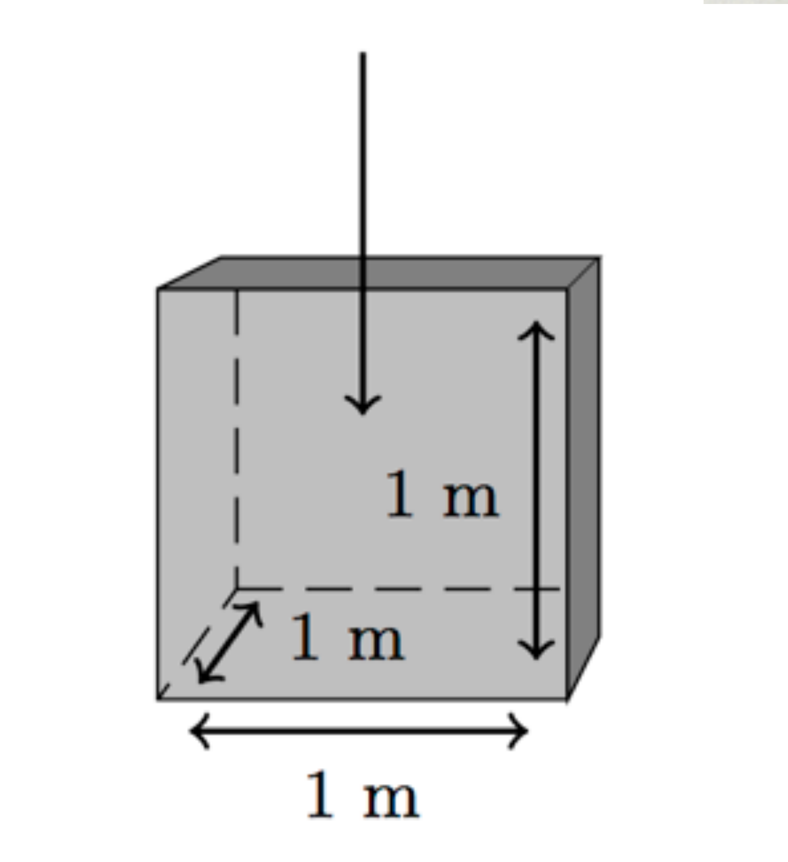
Halls A,C up to 100 μA
Hall B: 1 μA

- 1.5 GHz RF ⇒ each hall gets bunch every 2(4) ns
- upgrade complete in 2014



Possible Set-Up





Aluminum dump ~ 10 GeV beam

Average current ~ $80\mu A$

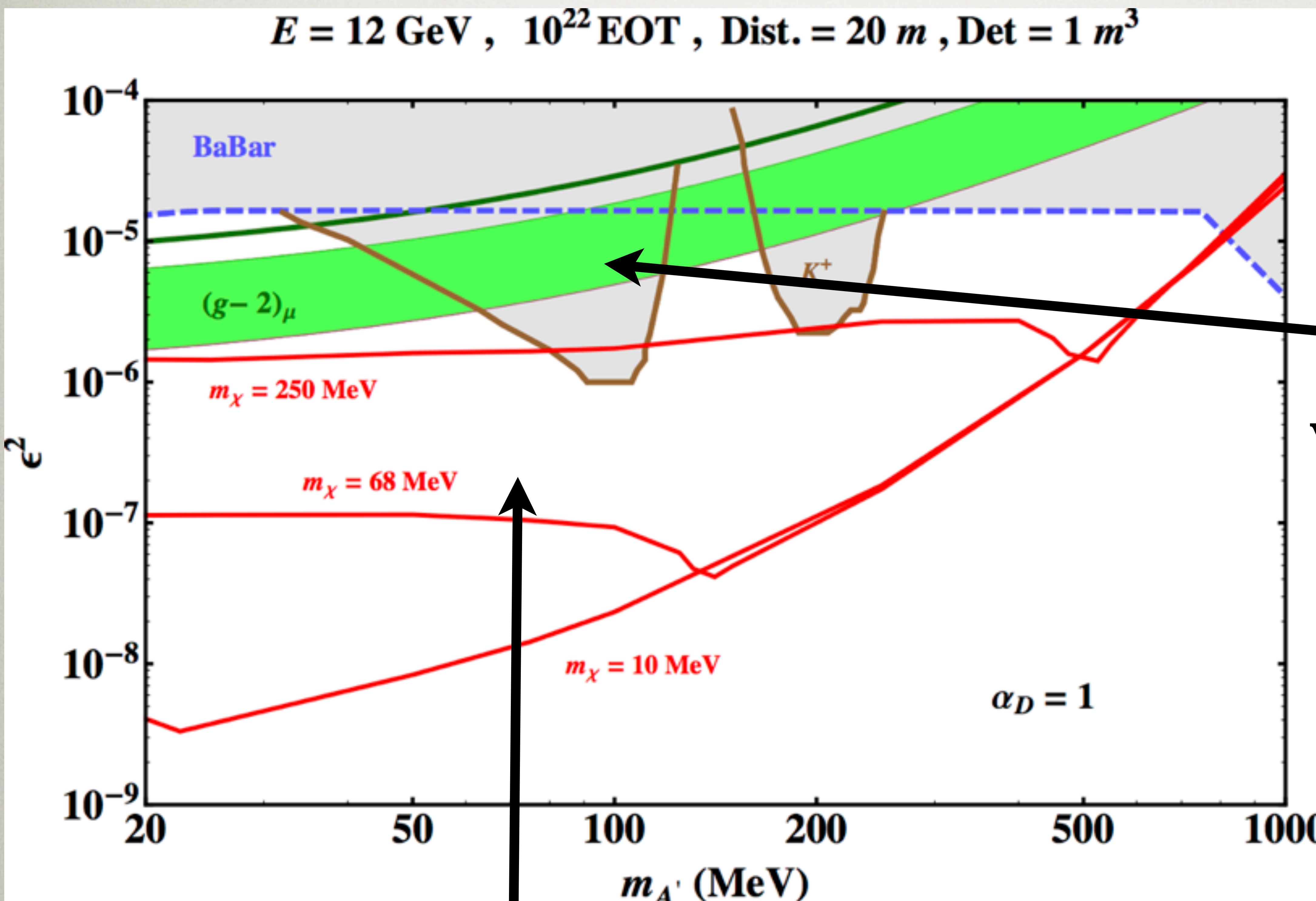
10^{22} EOT (~ year operation)

Duty cycle ~ 10^{-4} , live-time ~ 10^3s
and/or aggressive bkg rejection

Fiducial volume $= 1\text{m}^3$

Oil or plastic based detector
Depth = 15 m.w.e.

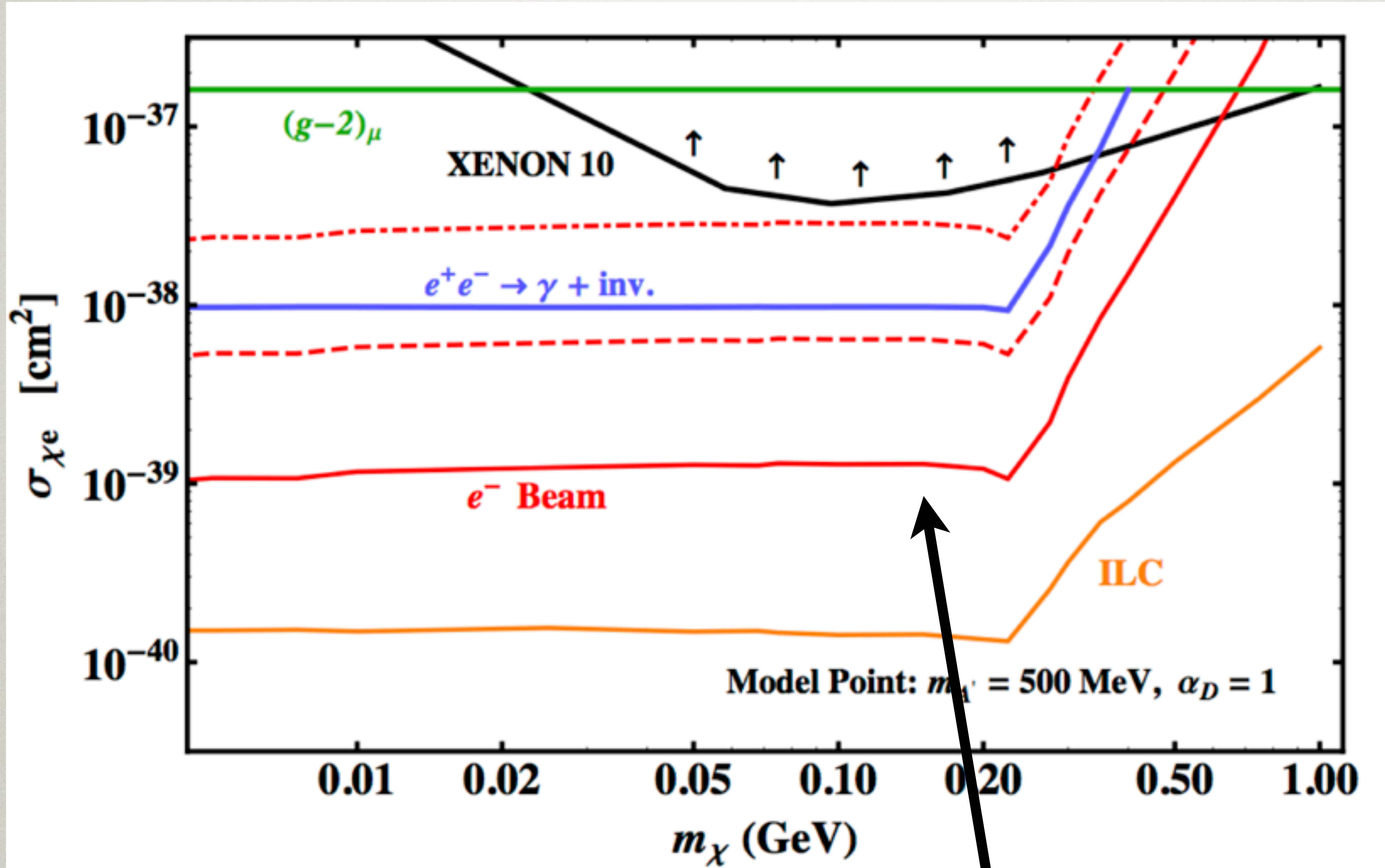
Possible Sensitivity



Covers g-2 anomaly region for wide range of masses

Probes one-loop mixing with new forces

Direct Detection and Fixed Target



$$\sigma_{\chi e} = \frac{16\pi\alpha\alpha_D\epsilon^2 m_e^2}{m_{A'}^4}$$

Probes dark sector - matter interactions beyond direct detection sensitivity

Backgrounds

Beam backgrounds can be negligible for electron beams

1. Neutrinos from beam π/μ

Nuclear recoil cut $E_{recoil} > 10$ MeV

$< (0.1 - 1)$ BG event per $10^{22}\, e^-$

Consistent with SLAC mQ rates

2. "Skyshine"

Source of "Fast" neutrons (observed by mQ at SLAC)

$E_n < 10\,\text{MeV}$, below cuts, and time delayed

Backgrounds

Beam-unrelated backgrounds more important

1. Cosmic muons

Decays in flight ~ 0.005 Hz (veto)

Stopped decays ~ 100 μs cut (veto)

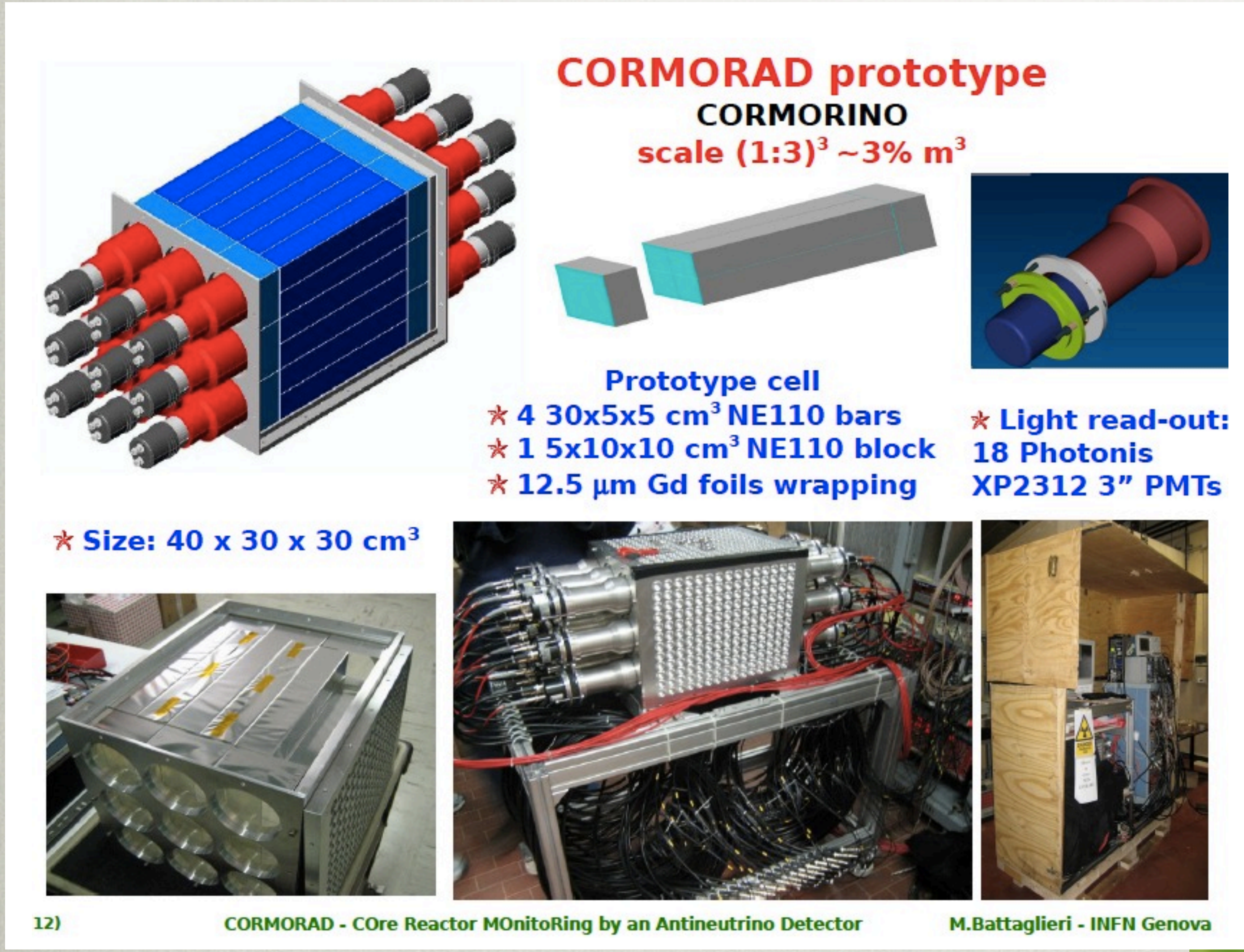
2. Cosmic neutrons

$$\Phi(E > 10 \text{ MeV}) \approx 2 \times 10^{-2} \text{m}^{-2} \text{s}^{-1}$$

Consistent with CDMS-SUF (~ 10 m.w.e)

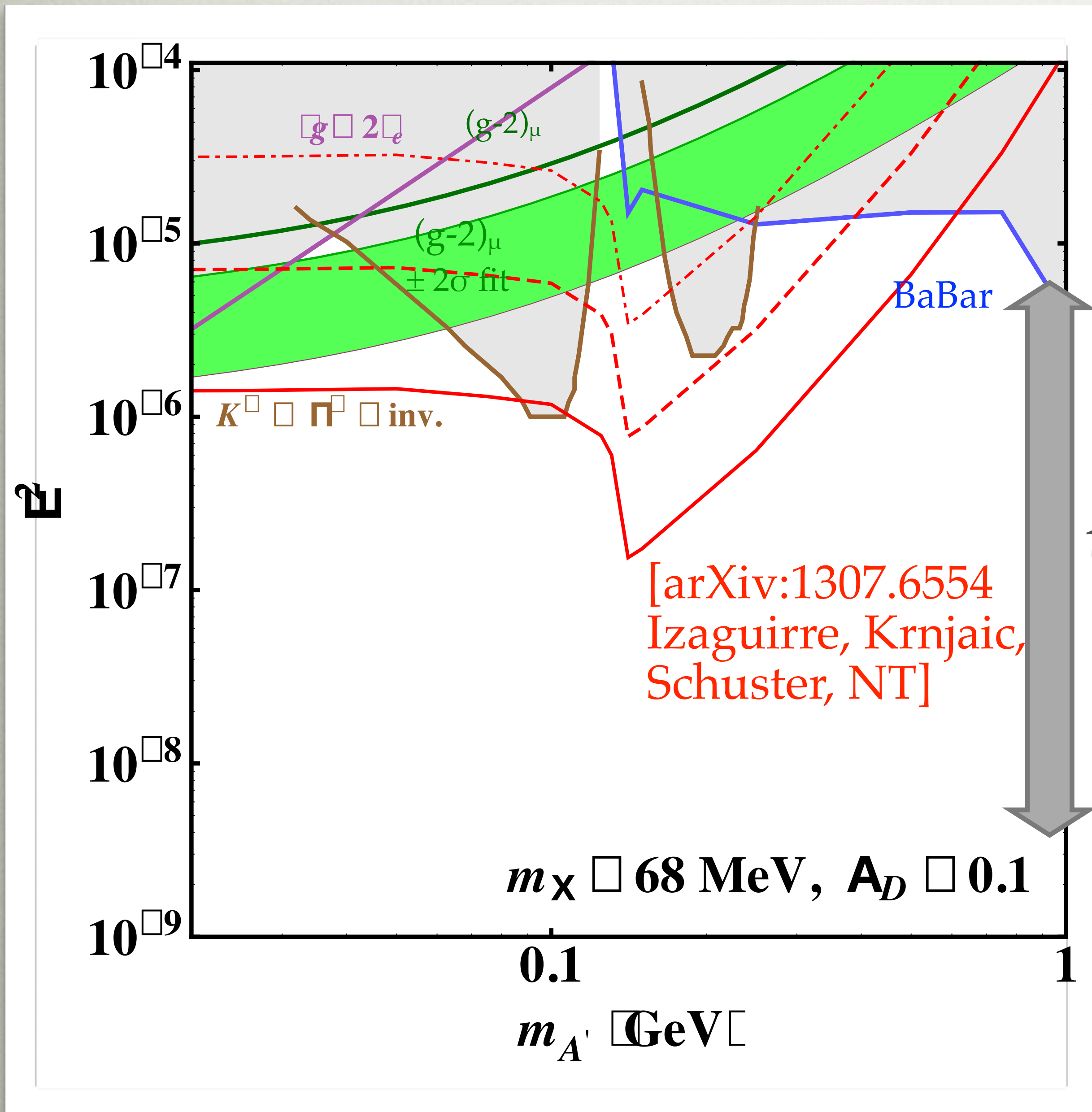
Current Efforts

Jefferson Lab test run to measure backgrounds and study performance requirements… aiming for 2014/15



Use existing detector behind Hall D (or A) dump

STATUS AND PROSPECTS



one-loop

two-loop (GUT)

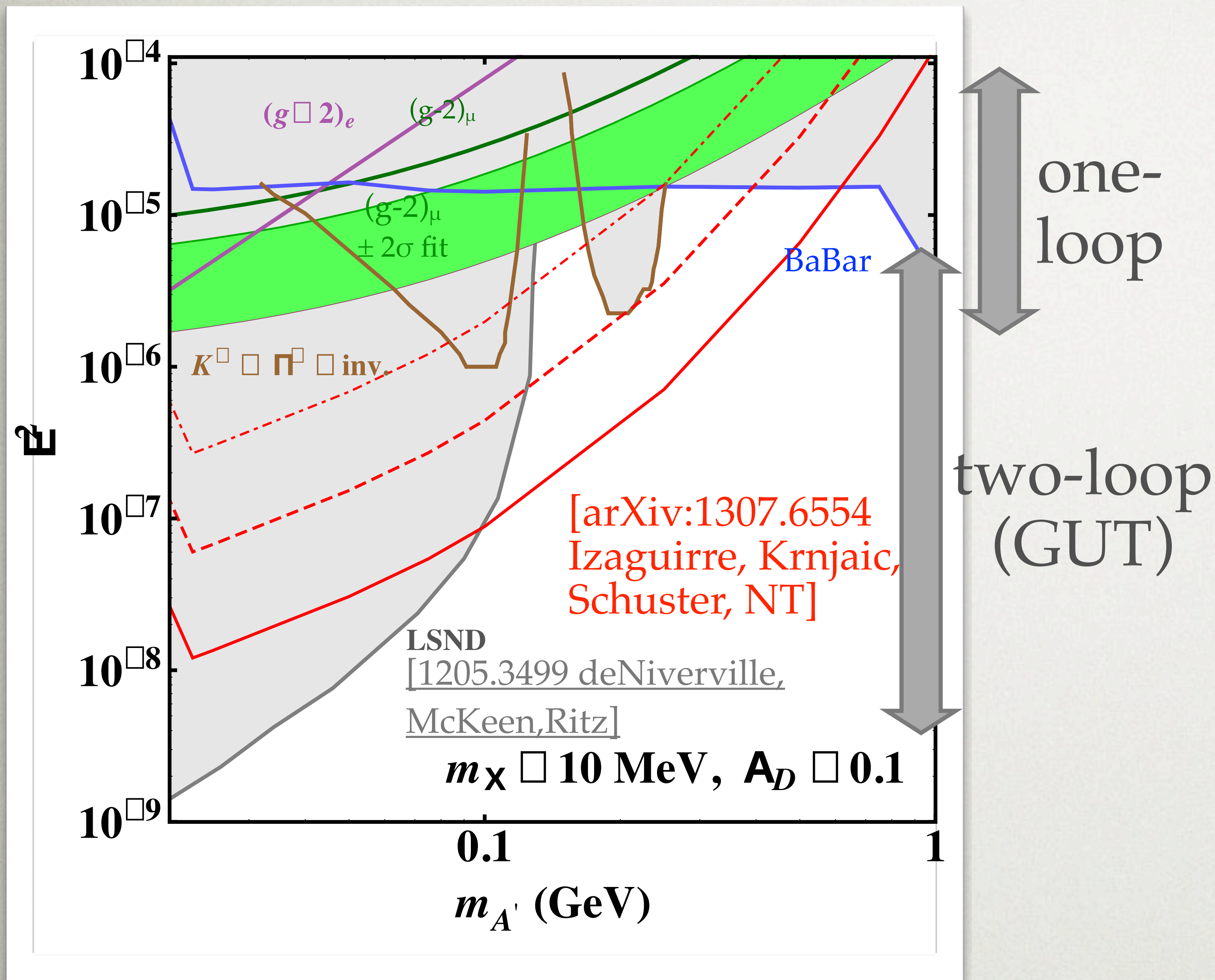
Important parameter range:

- $(g\text{-}2)_\mu$ preferred region
- motivated ε^2 range
- generic possibility of light dark-sector matter
- χ dark matter not constrained by direct detection or LHC

Red lines = quasi-elastic scattering behind JLab-like beam dump, with (top to bottom) no neutron bg rejection, **1/20 rejection**, 10^{-3} rejection

Dedicated MiniBoone run sensitivity comparable to middle line [arXiv:1211.2258]; see also [arXiv:1309.5084 Essig et al] for impact of aggressive analysis with new triggers at Belle 2

Status and Prospects



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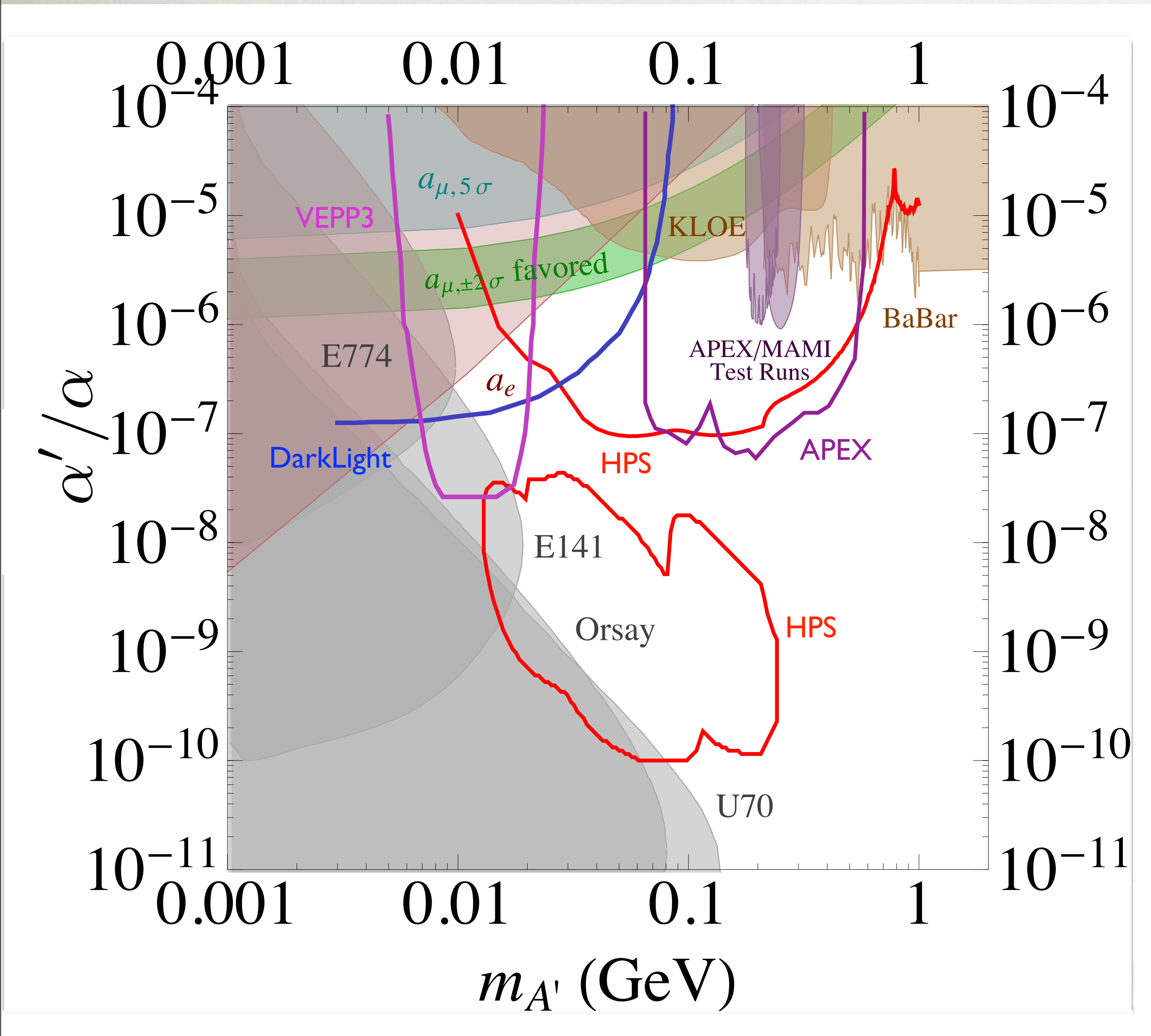
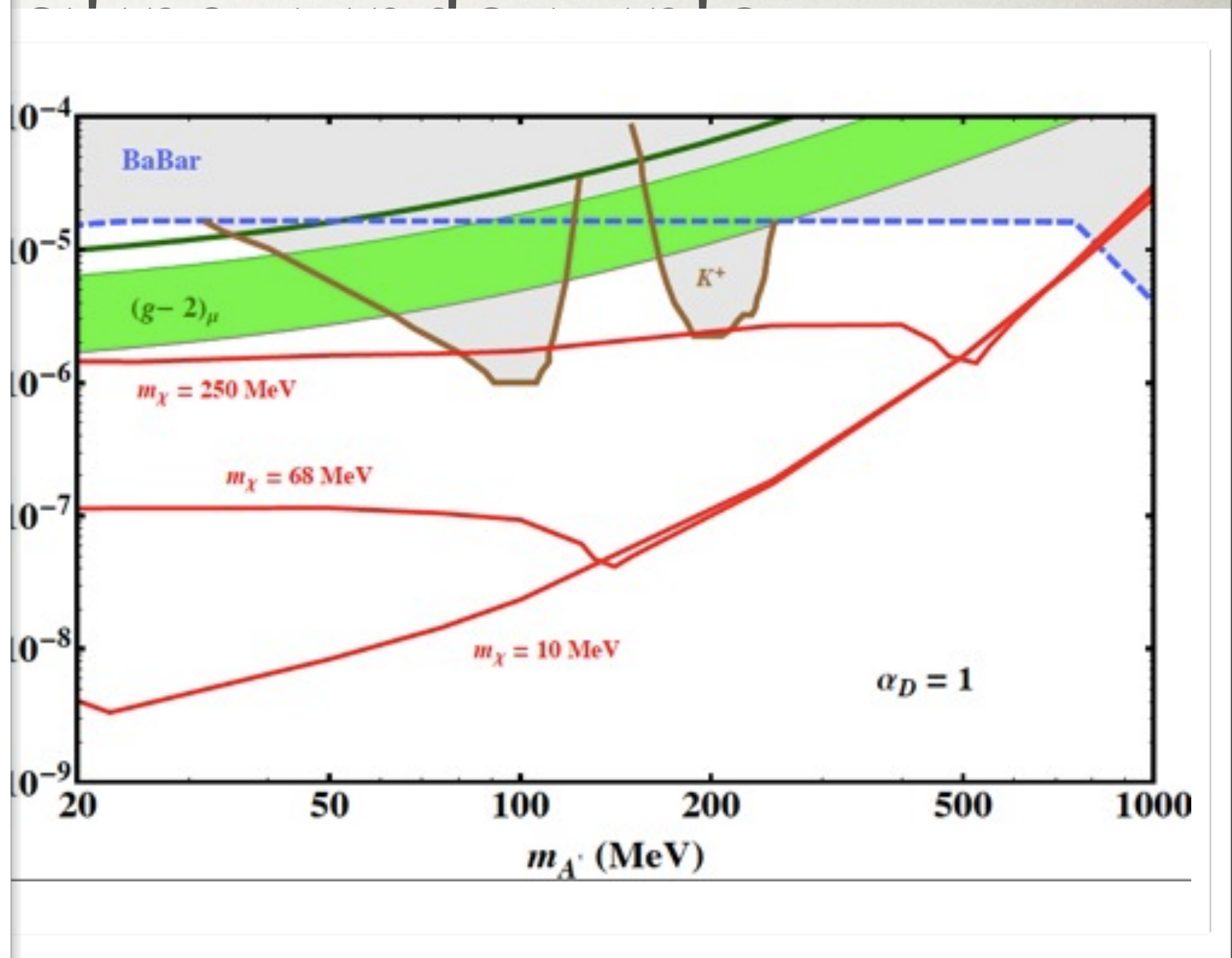
Conclusions

- Dark Forces are an exciting window into physics far beyond the Standard Model
  - Possible connections to dark matter and physics at very high scales
- Excellent Prospects for New Beam-Dump Searches
  - Ongoing proton beam searches (MiniBooNE)
  - Extend coverage with small, low background & parasitic electron beam experiment
  - Unique sensitivity to broad range of dark matter scenarios and long-lived weakly coupled particles

Conclusions





ed weakly coupled particles

We are not alone – we're trying hard to make first contact!

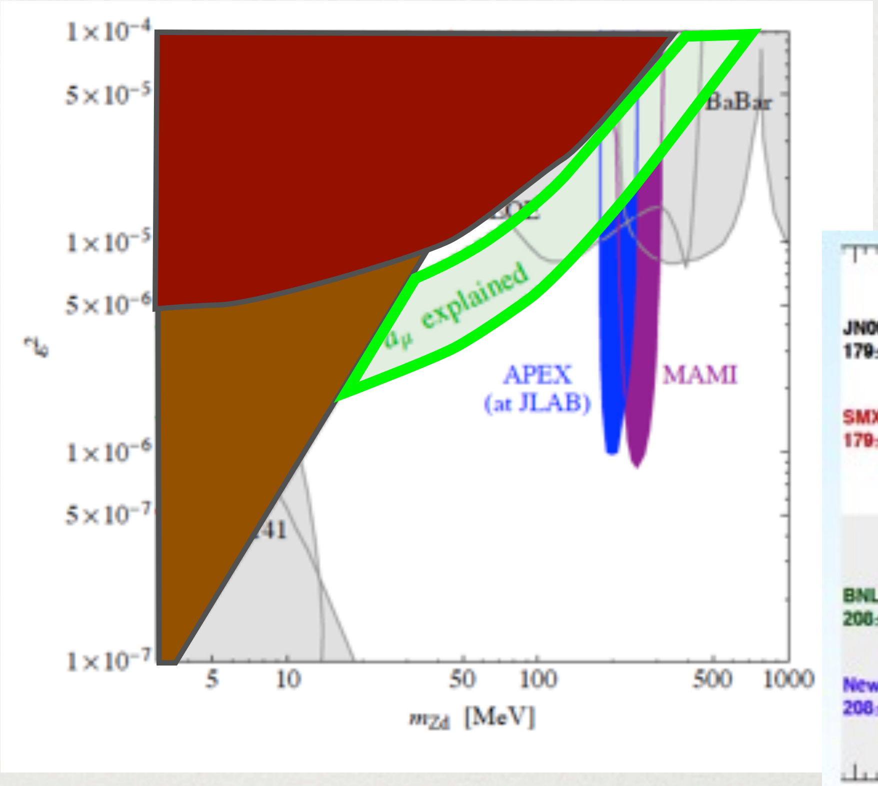
Thanks!

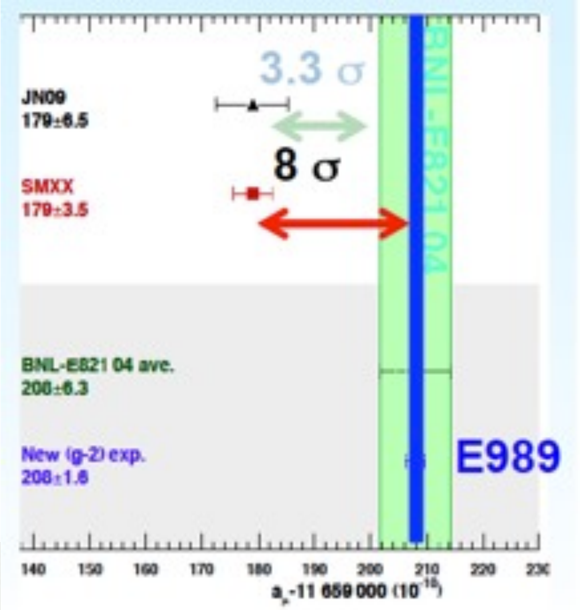
Backup Slides

Target of Interest? Precision Anomalies

Muon g-2

$U(1)_D$ coupling modifies $(g-2)_\mu$, *with correct sign.* ε~1-3 10^{-3} **can explain discrepancy with Standard Model**

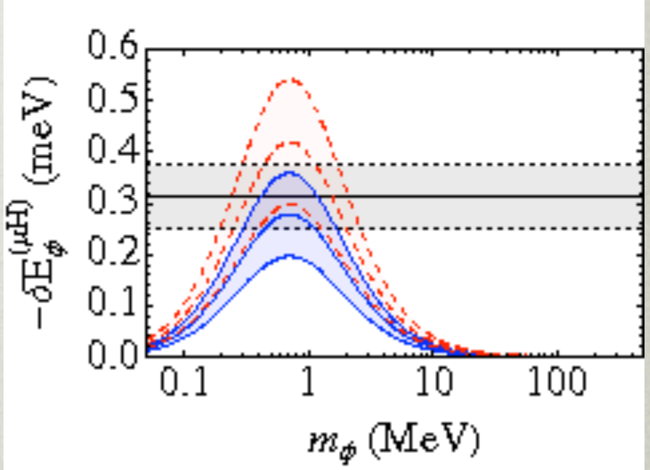




Muonic hydrogen

MeV-scale force carriers can explain the discrepancy between (μ^-,p) Lamb shift [Pohl et al. 2010] and other measurements of proton charge radius.

Requires couplings *beyond* kinetic mixing (lepton flavor-violating component)

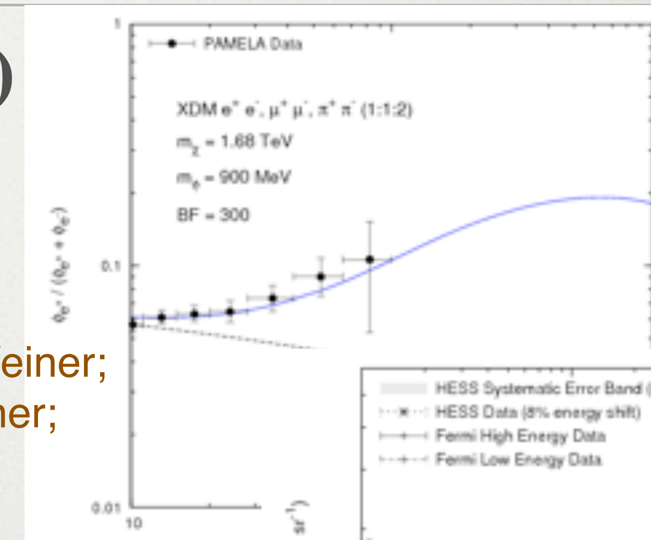


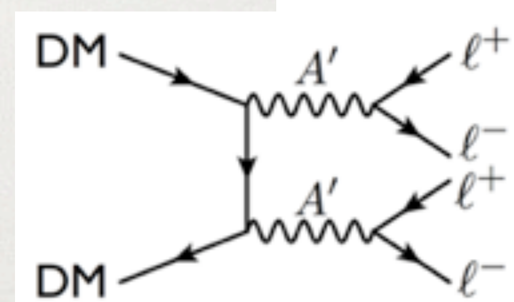
[Tucker-Smith & Yavin, 1011.4922]

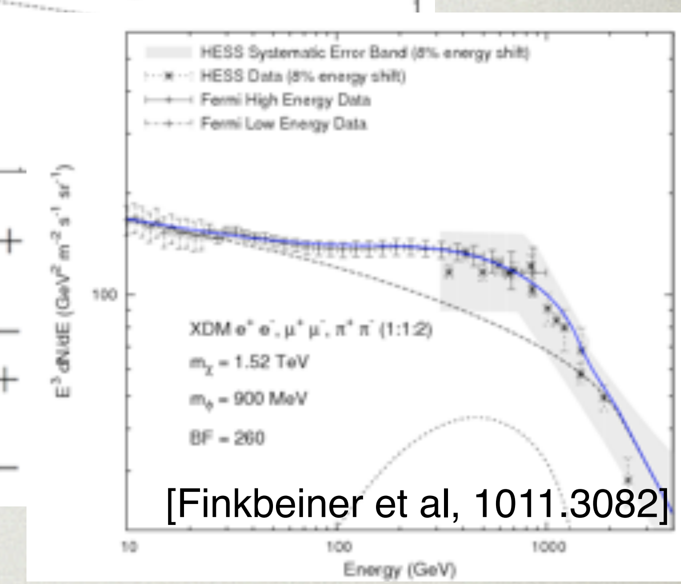
Target of Interest? Dark Matter Interactions

High-energy cosmic e^+/e^- (PAMELA, FERMI, AMS)

Thermal DM charged under $U(1)_D$ can have large local annihilation rate (Sommerfeld enhancement) and hard, lepton-rich decays [Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Cholis, Finkbeiner, Goodenough, Weiner; Pospelov & Ritz]







[Finkbeiner et al, 1011.3082]

No signals in other probes of DM annihilation

– constrained but not excluded

– interesting ways out of constraints

Light dark matter hints (DAMA, CoGeNT, CRESST, CDMS-Si)

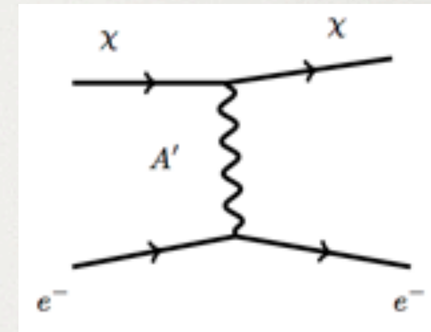
Strong tension with LUX

Many instrumental challenges & constraints…

A dark force easily reconciles ≲10 GeV DM with Standard-Model-like decays of Z and h

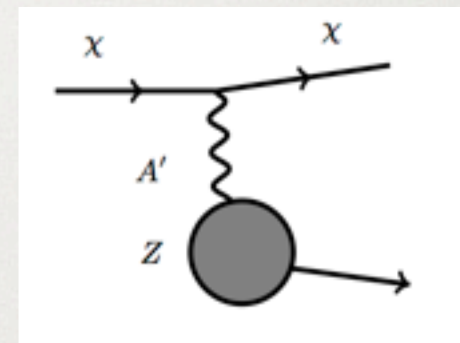
Detector Scattering

Electron Scattering
Low recoil energies, light mediator

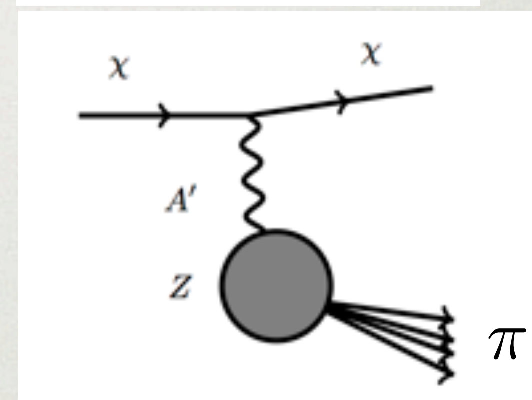


Coherent Nuclear

Low recoil energies, light mediator
Z^2 enhancement, form factor

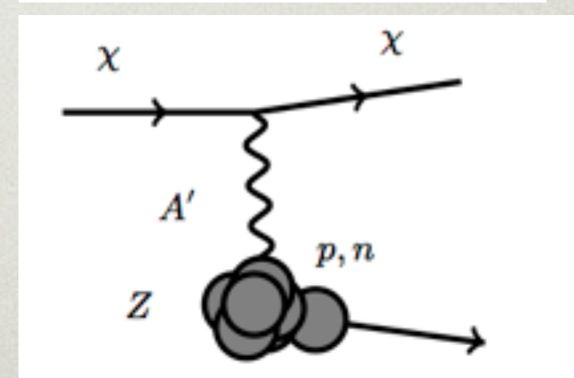


Inelastic hadro-production
High recoil energies



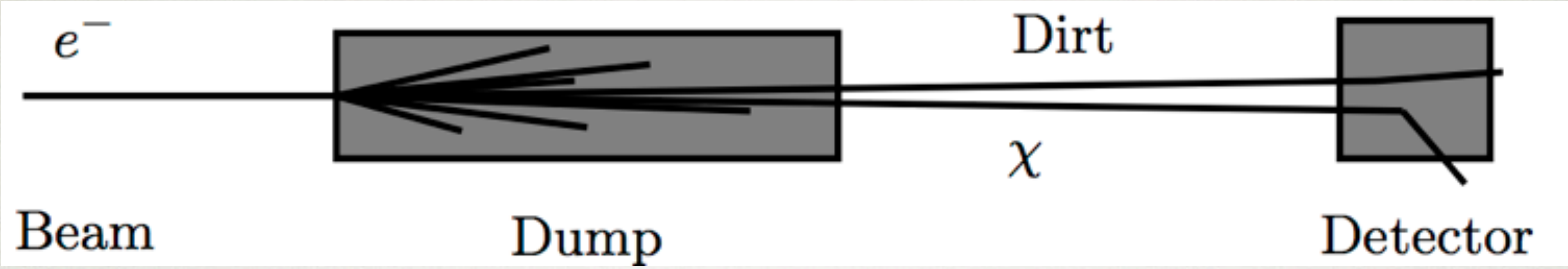
$\pi, \Delta, K \cdots$

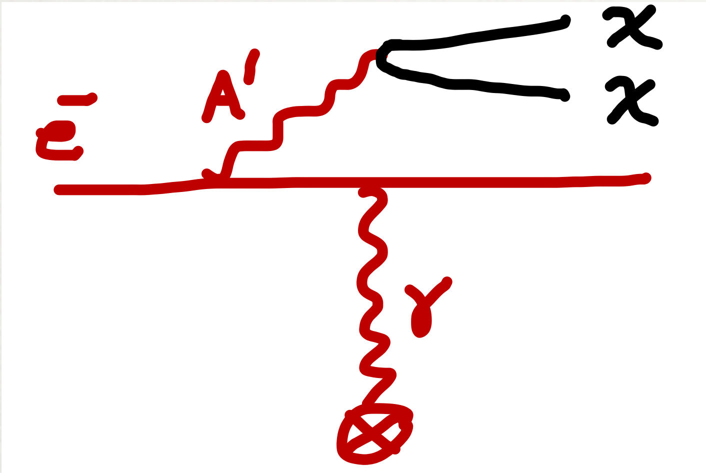
Quasi-elastic Nucleon
Higher recoil energies > 10s MeV,
$\sigma \sim \alpha_D \epsilon^2 / m_{A'}^2$

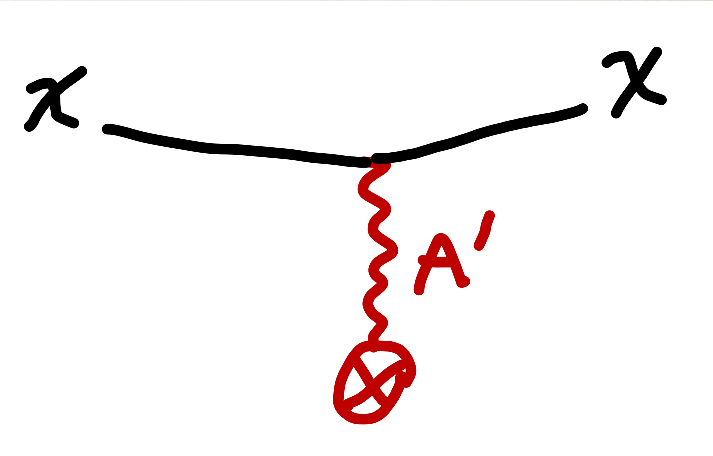


Familiar to neutrino physicists, but with different kinematics

Exploiting Nice Features







- Several nice features:
  - Negligible beam related background
  - Small (meter-scale or smaller) & completely parasitic
  - Efficient forward-peaked production over wide mass range
  - Excellent sensitivity prospects

Backgrounds

1. Neutrinos from beam π/μ

Biggest source of neutrinos is from pion electro-production through Delta resonance

$$\mathrm{EOT} = 10^{22} \qquad \sigma_{e+N\to e+\pi+X} = 2\ \mu\mathrm{b} \qquad L_{\mathrm{Al}} = 10^{25}/\mathrm{cm}^2$$

Assume every pion gives a neutrino with E > 100 MeV

Acceptance ~ 10^{-4}

$$N_\nu \sim 10^{17}$$

Backgrounds

1. Neutrinos from beam π/μ

Re-scattering

$$\sigma_{\nu+n\to\nu+n} \sim E_\nu^2 G_\mathrm{F}^2 \sim \mathrm{fb}$$

$$n_\mathrm{oil} = 3\times 10^{22}/\mathrm{cm}^3 \qquad A_\mathrm{oil} = 14 \qquad l_\mathrm{det} = 100\ \mathrm{cm}$$

Probability to scatter: 10^{-14}

$$N_\mathrm{events} \sim O(1)$$

Backgrounds

Beam-unrelated backgrounds more important

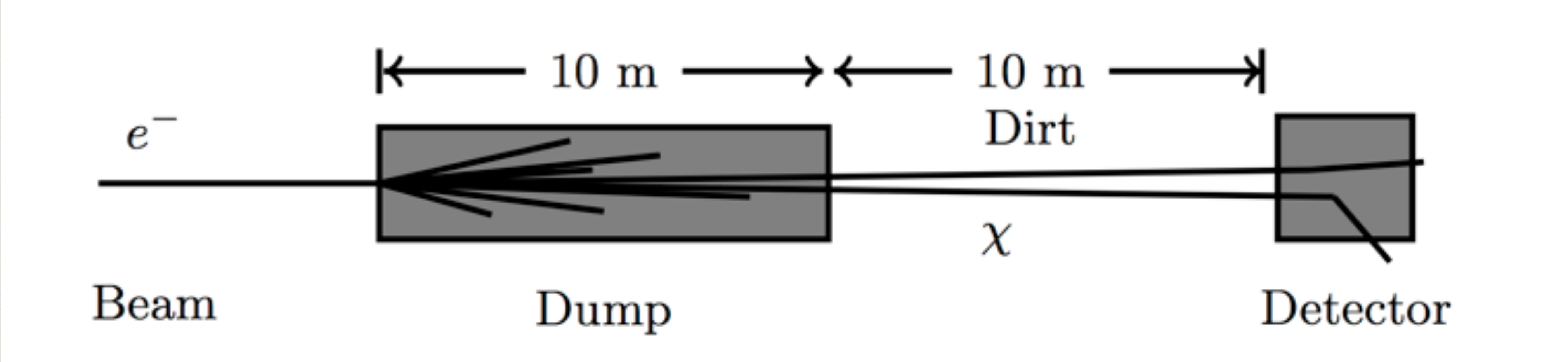
2. Cosmogenic neutrons

Pulsed beam: e.g. livetime $\sim 10^3$ seconds
O(10) cosmogenic neutron events in one year
Sensitivity to ~ 10 signal events

Continuous beam: e.g. livetime $\sim 10^7$ seconds
O(10^5) cosmogenic neutron events in one year
Sensitivity to ~ 10^4 signal events
Assuming no further rejection and ~few% Systematics

Some combination of timing and shielding/veto is required
to reduce cosmics by factor of 1000 to obtain ~10 event sensitivity

Background Rejection at CEBAF



Need combination of:

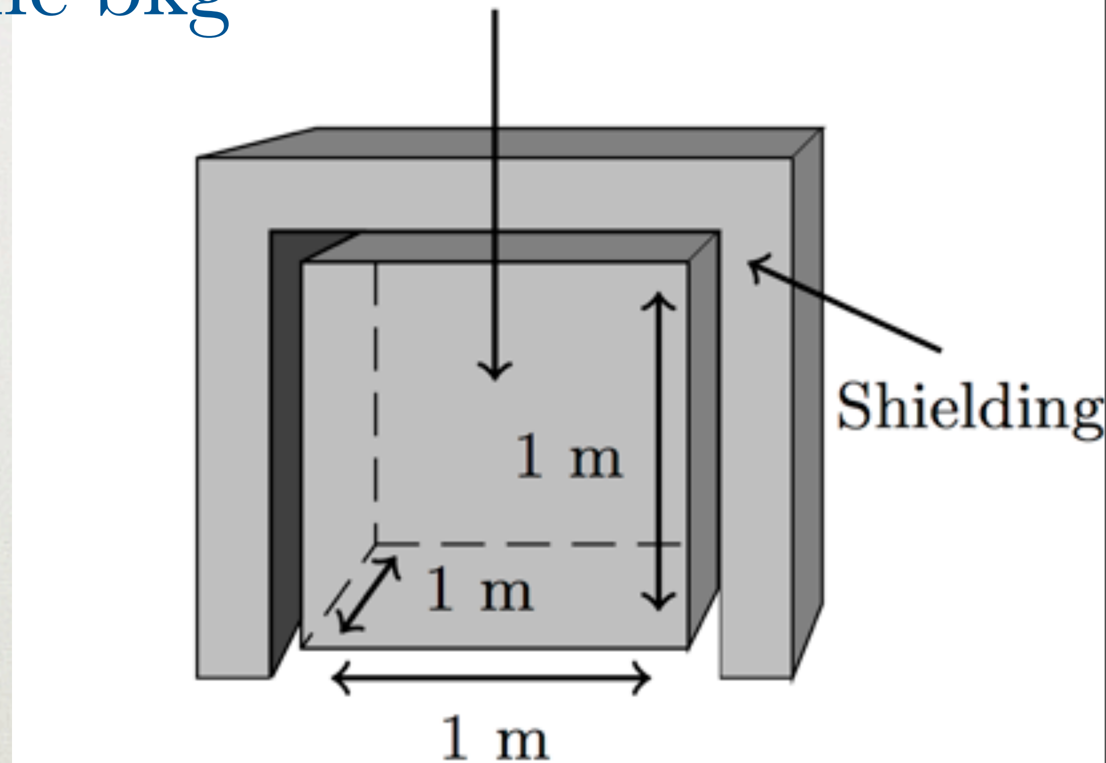
Aim for combined ~1000 reduction in cosmic bkg

Sub-ns timing

4ns bunch spacing with ~200 ps timing would provide ~20 rejection

Active neutron veto or shielding

factor of 10-20 reduction (e.g. CDMS-SUF)

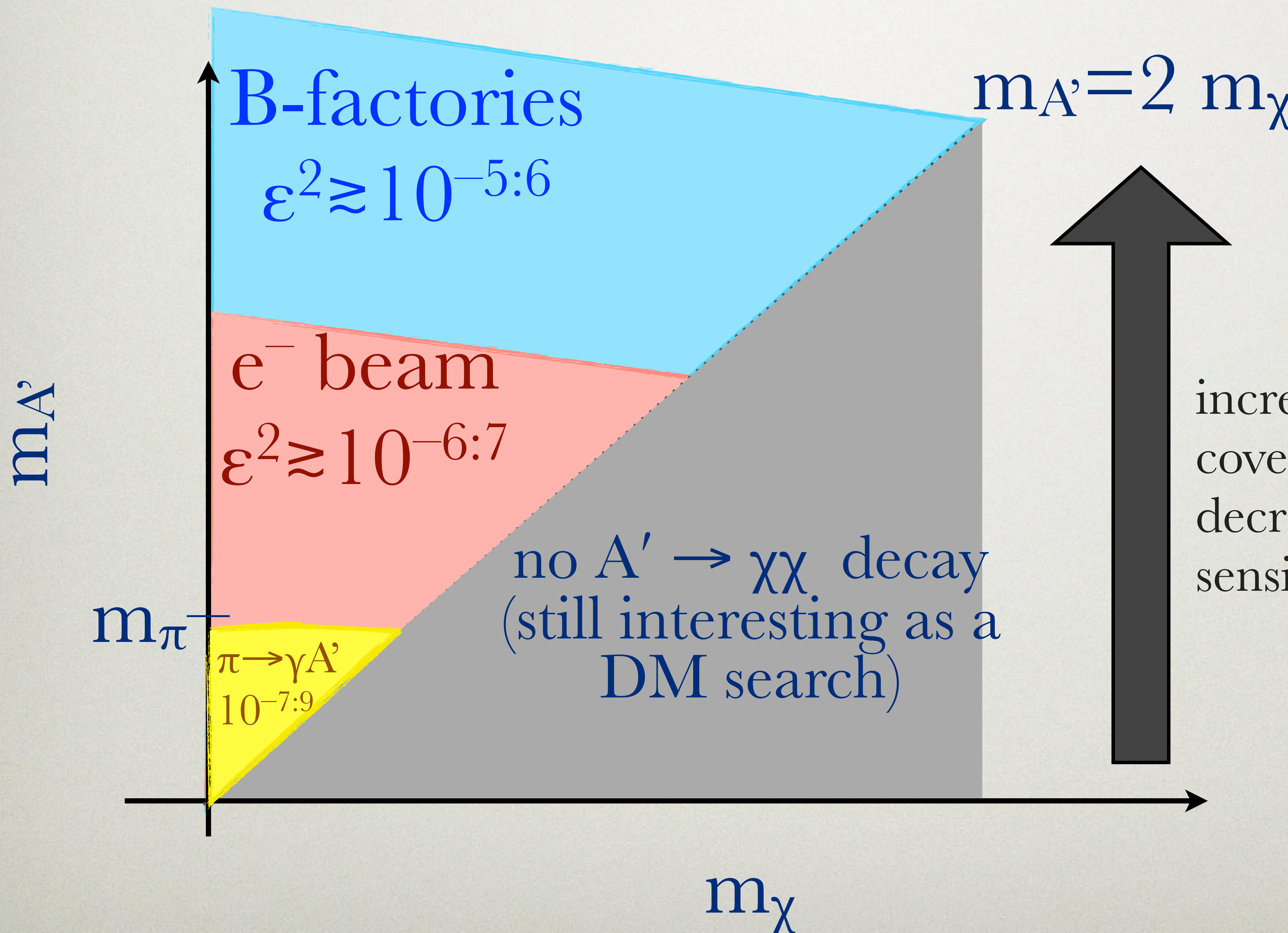


Depth ~15 m.w.e

Directional information

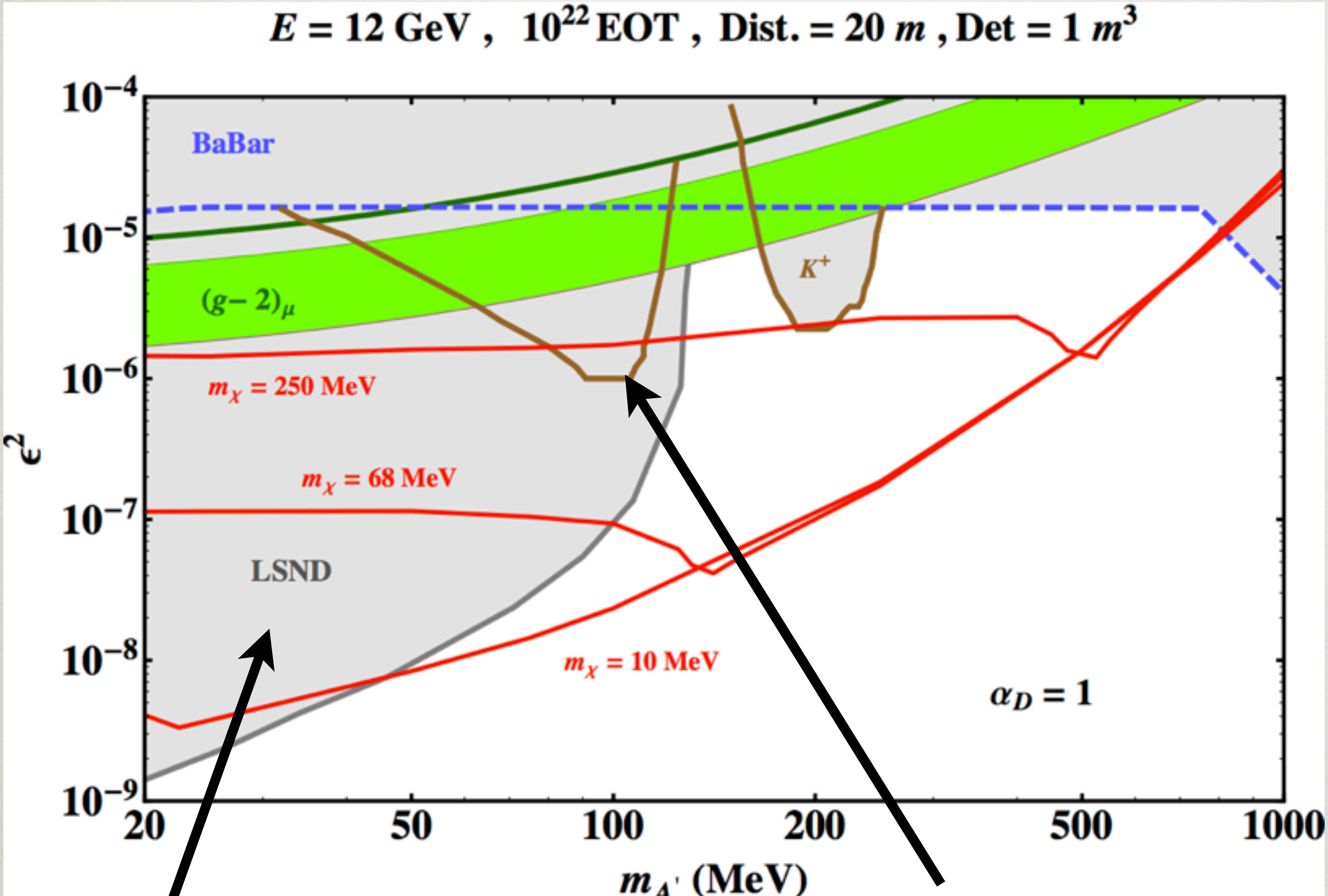
factor of 2?

The Parameter Space



increasing mass coverage but decreasing coupling sensitivity

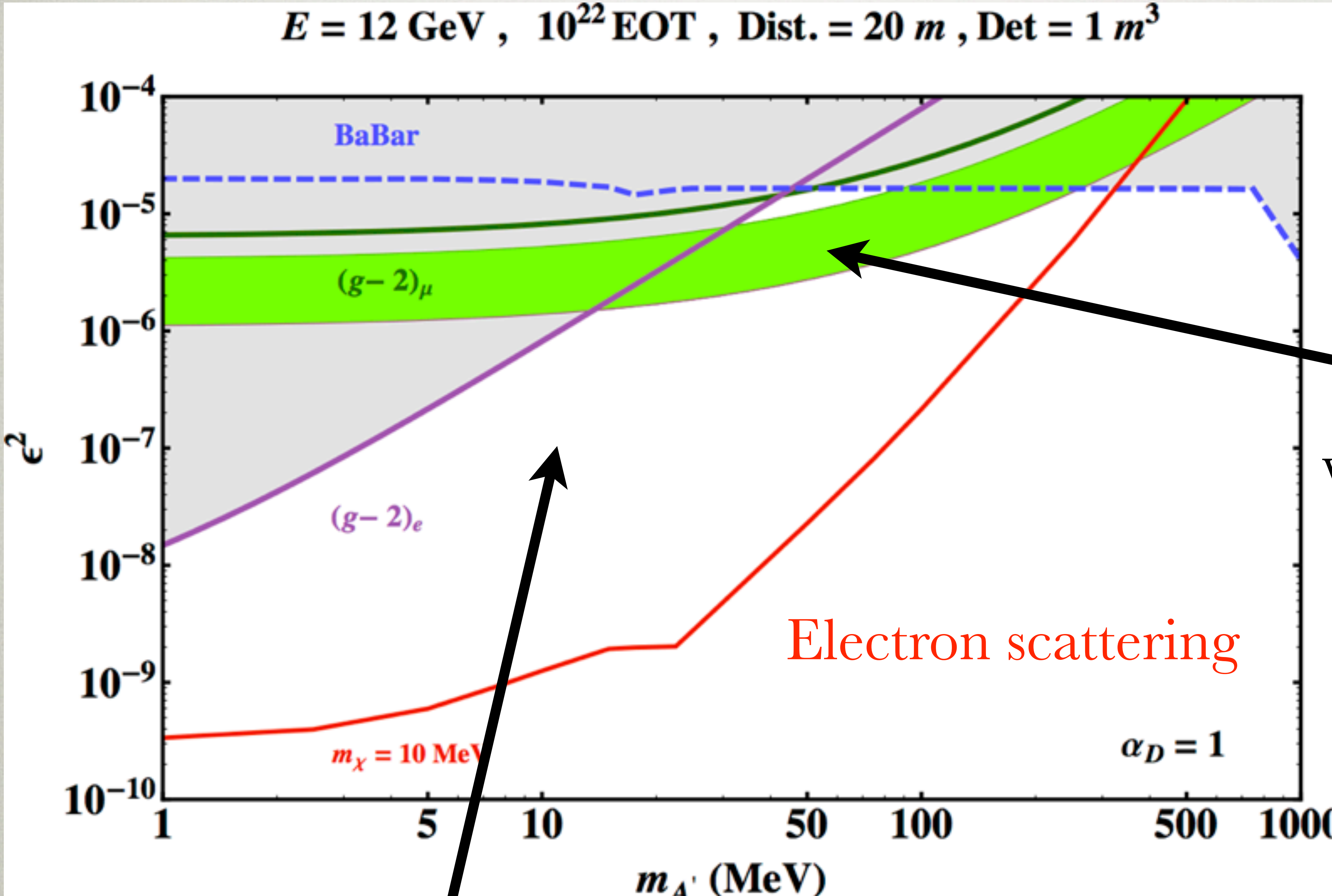
Possible Sensitivity



LSND only applies when A' decay products have mass less than ~60 MeV

Only applies when A' decay products less than ~50 MeV

Possible Sensitivity



Covers g-2 anomaly region for wide range of masses

Probes one-loop kinetic mixing region

Electron scattering, uses only coupling of A' to lepton current