Dark photon: an experimental overview

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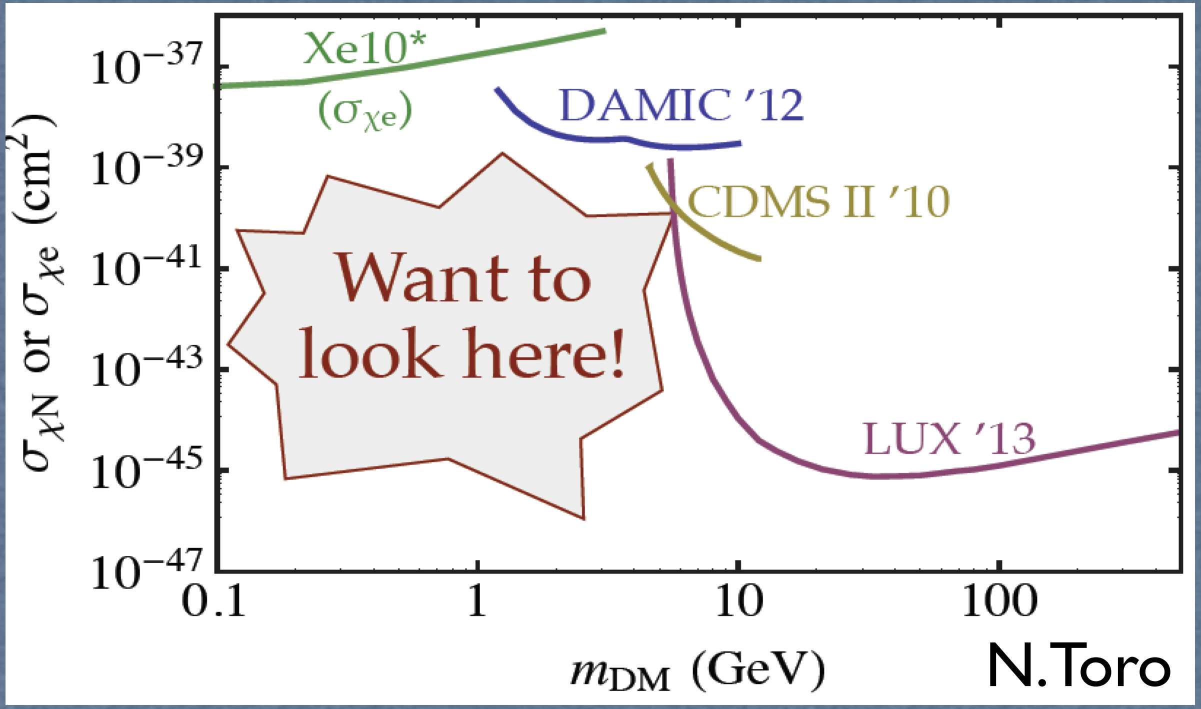
Accelerators-based DM search

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



Neutral doors (portals) to include DM into the SM

★ The new force should be weak
★ Different combination of DM and mediator masses are possible:

- heavy WIMPs / heavy mediators
- heavy WIMPs /light mediators
- light WIMPs / light mediators
- light WIMPs / heavy mediators

Accelerators-based DM search

covers an unexplored mass region extending the reach outside the classical DM hunting territory

- High intensity
- Low energy

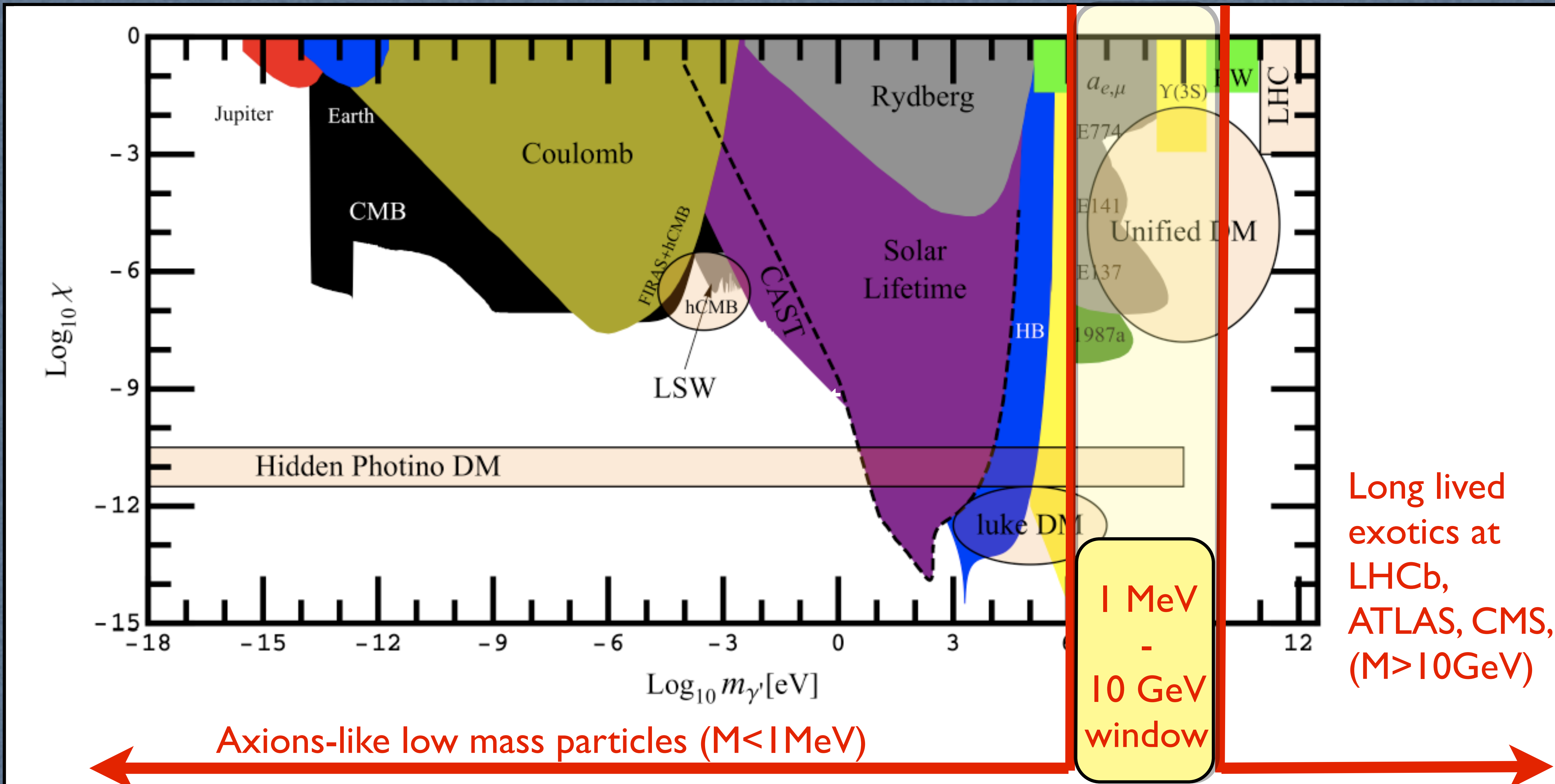
Many theoretical suggestions and experimental attempts to extend the search region to lower mass:

MiniBoone@FNAL, SPS@CERN, BDX@JLab, PADME@LNF

Unique features of accelerator-based (L)DM search

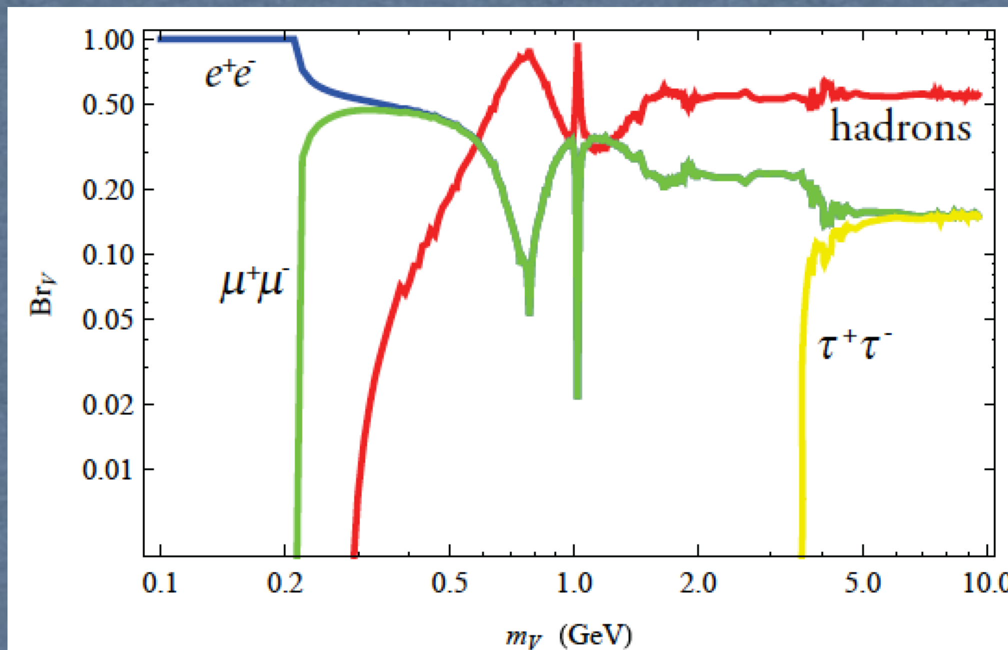
✳ Tagging wrt cosmic anomalies (clear way of distinguish DM from other effects)
✳ Unprecedented sensitivity in the keep-out zone for direct DM search
✳ High intensity electron beam available to play a significant role in LDM search

Where to look for?



3

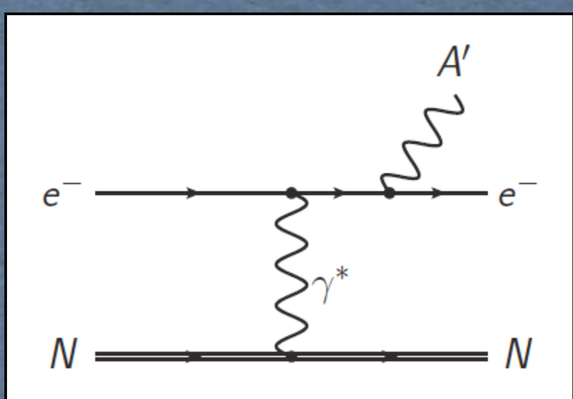
A’ searches: visible decays



Assumptions:
$M_{A'}$>1 MeV and no light dark fermions

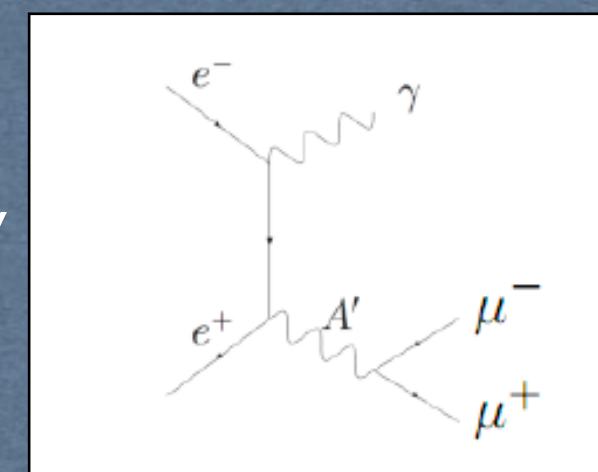
- γ’/A’ decay back to SM particles
- Prompt decay
- BF (A’→hadrons/A’→leptons) ~ M^2(A’)

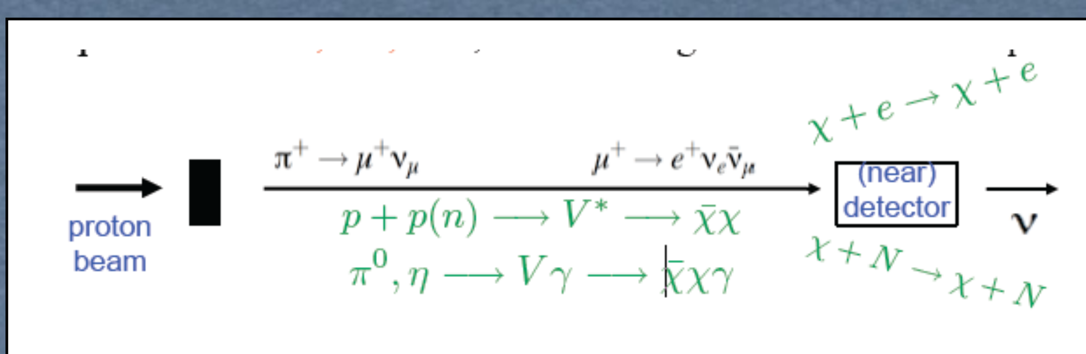
Below 1.2 GeV leptonic decays dominate



Fixed target:
e N →N γ’→ N Lepton Lepton+
→ **JLAB, MAINZ**

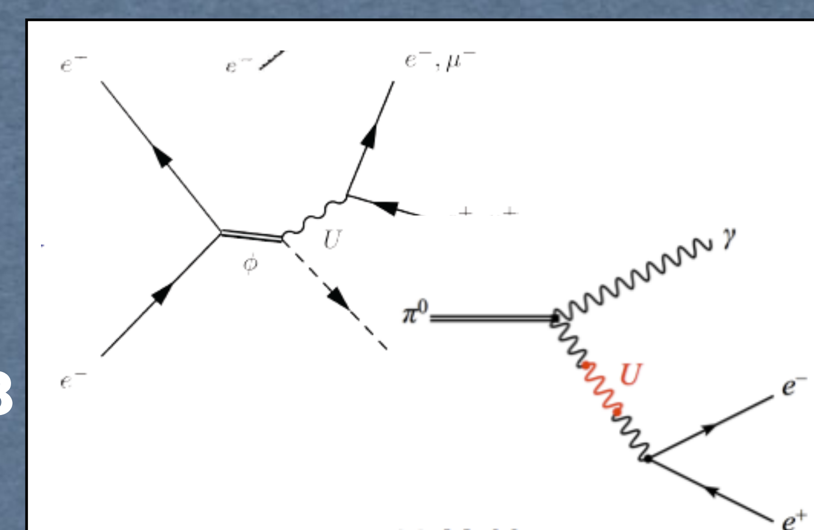
Annihilation:
e+e- → γ’ γ → μμ γ
→ **BABAR, BELLE, KLOE**





Fixed target:
p N →N γ’→ p Lepton Lepton+
→ **FERMILAB, SERPUKHOV**

Meson decays:
π^0, η, η’, ω,’ → γ’ γ (M)
→Lepton Lepton + γ (M)
→ **KLOE, BES3, NA48**
PHENIX, ALICE



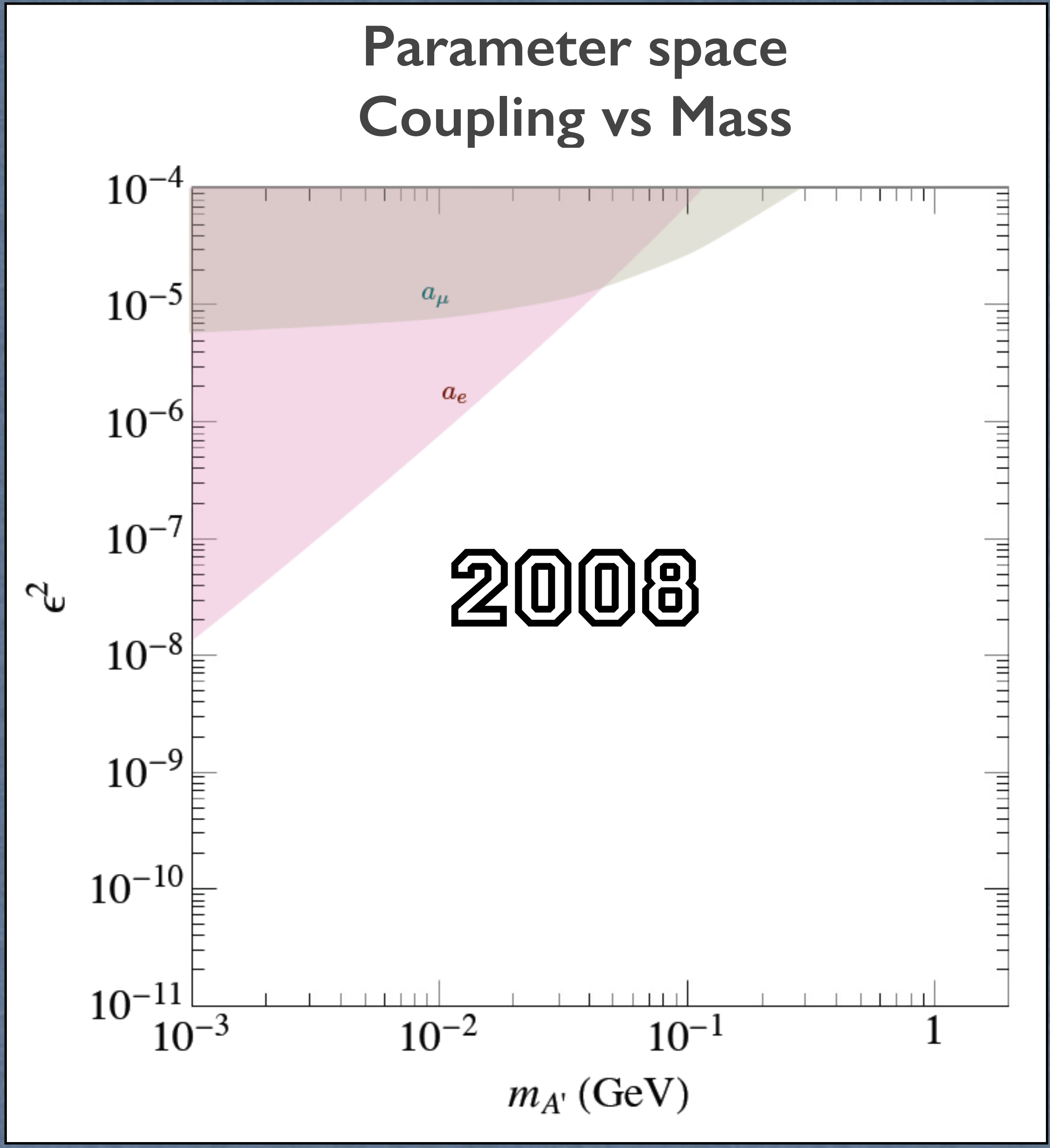
Particle physics search of A'

Fixed target: e N →N γ'→ N Lepton⁻ Lepton⁺
→ **JLAB, MAINZ**

Fixed target: p N →N γ'→ p Lepton⁻ Lepton⁺
→ **FERMILAB, SERPUKHOV**

Annihilation: e+e- → γ' γ → μμ γ
→ **BABAR,BELLE,KLOE**

Meson decays: π^0, η, η', ω,' → γ' γ → Lepton⁻ Lepton⁺ γ
→ **KLOE, BES3, NA48, HC**



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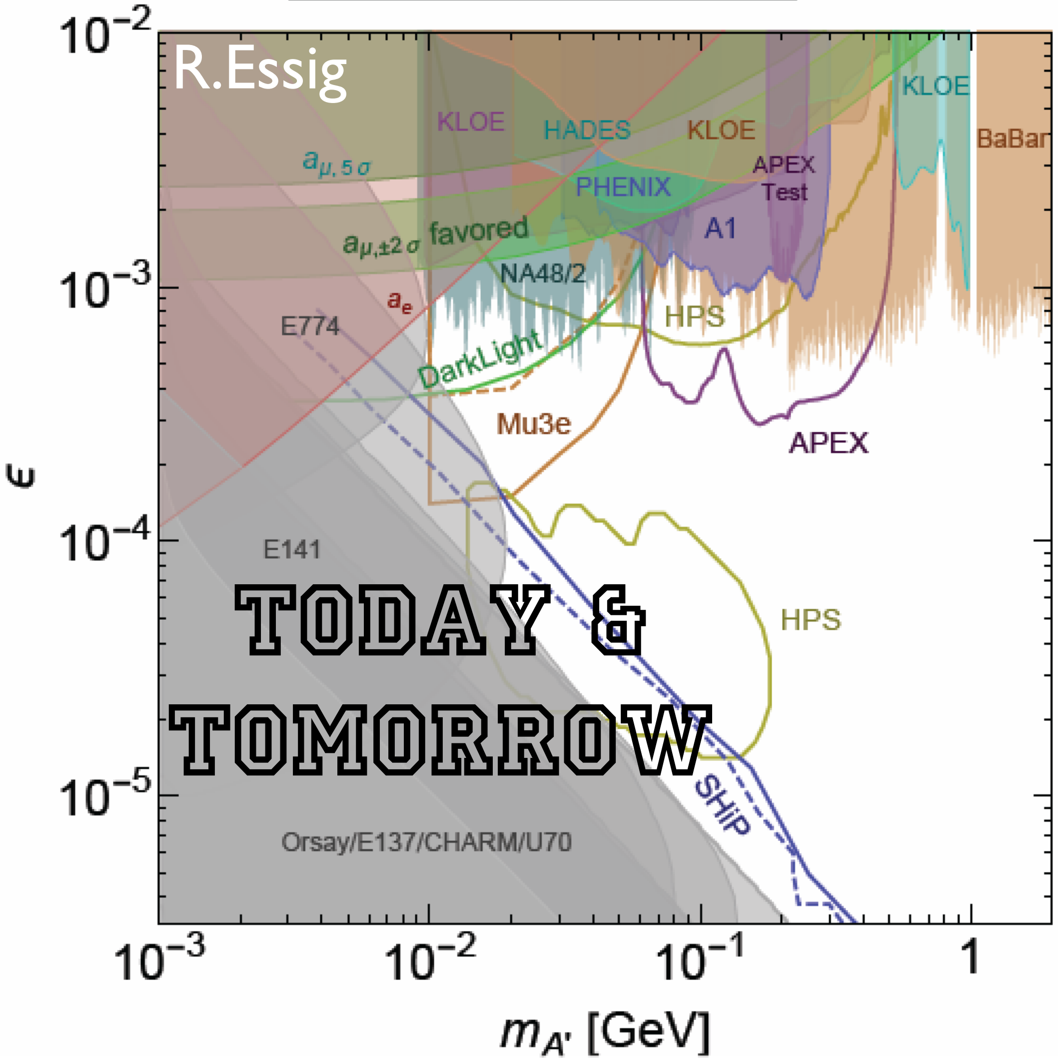
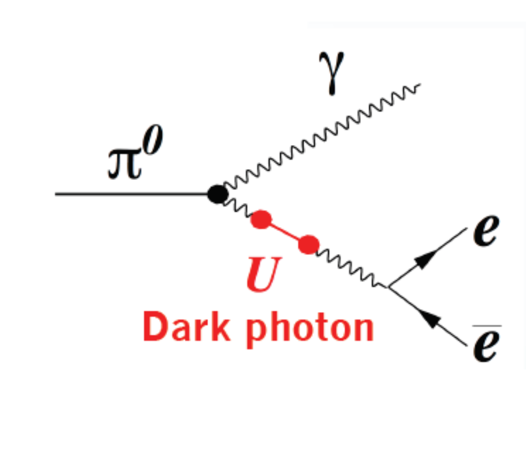
Meson decays: π^0, η, η', ω,' → γ' γ → Lepton⁻ Lepton⁺ γ
→ **KLOE, BES3, NA48, HC**

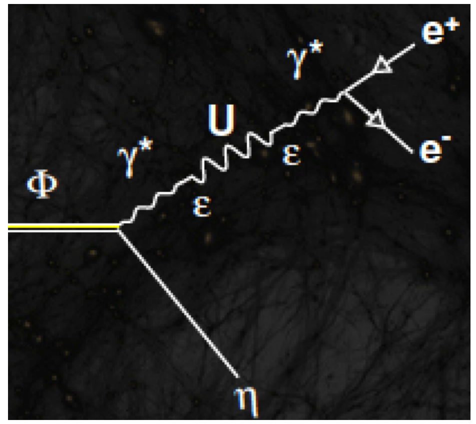
No positive signal (so far) but limits in parameter space coupling vs mass

Parameter space
Coupling vs Mass

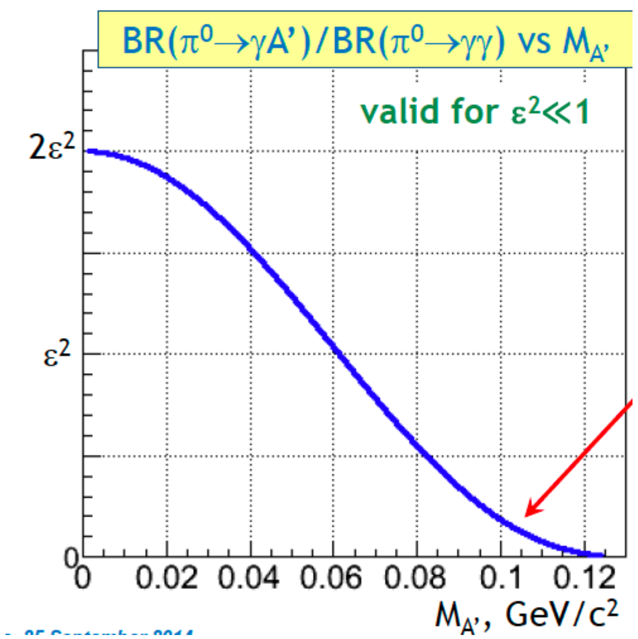


Meson Decay - The latest Results

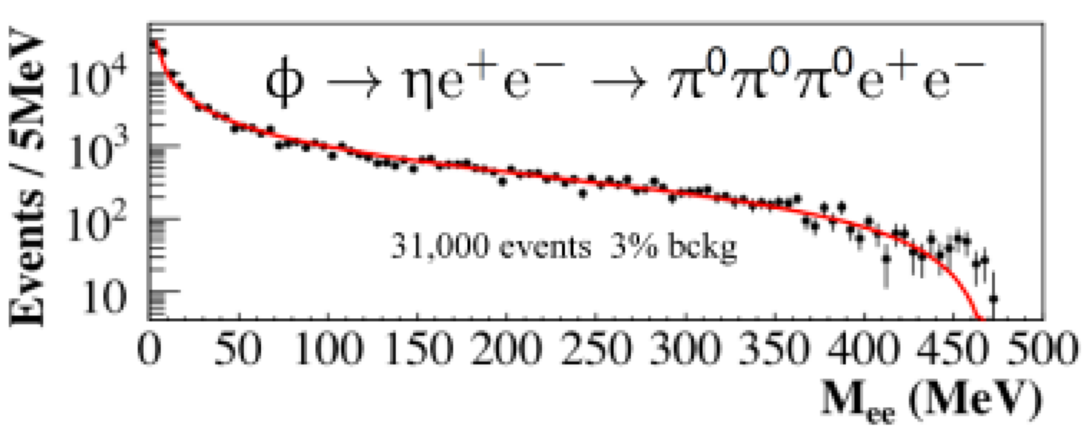


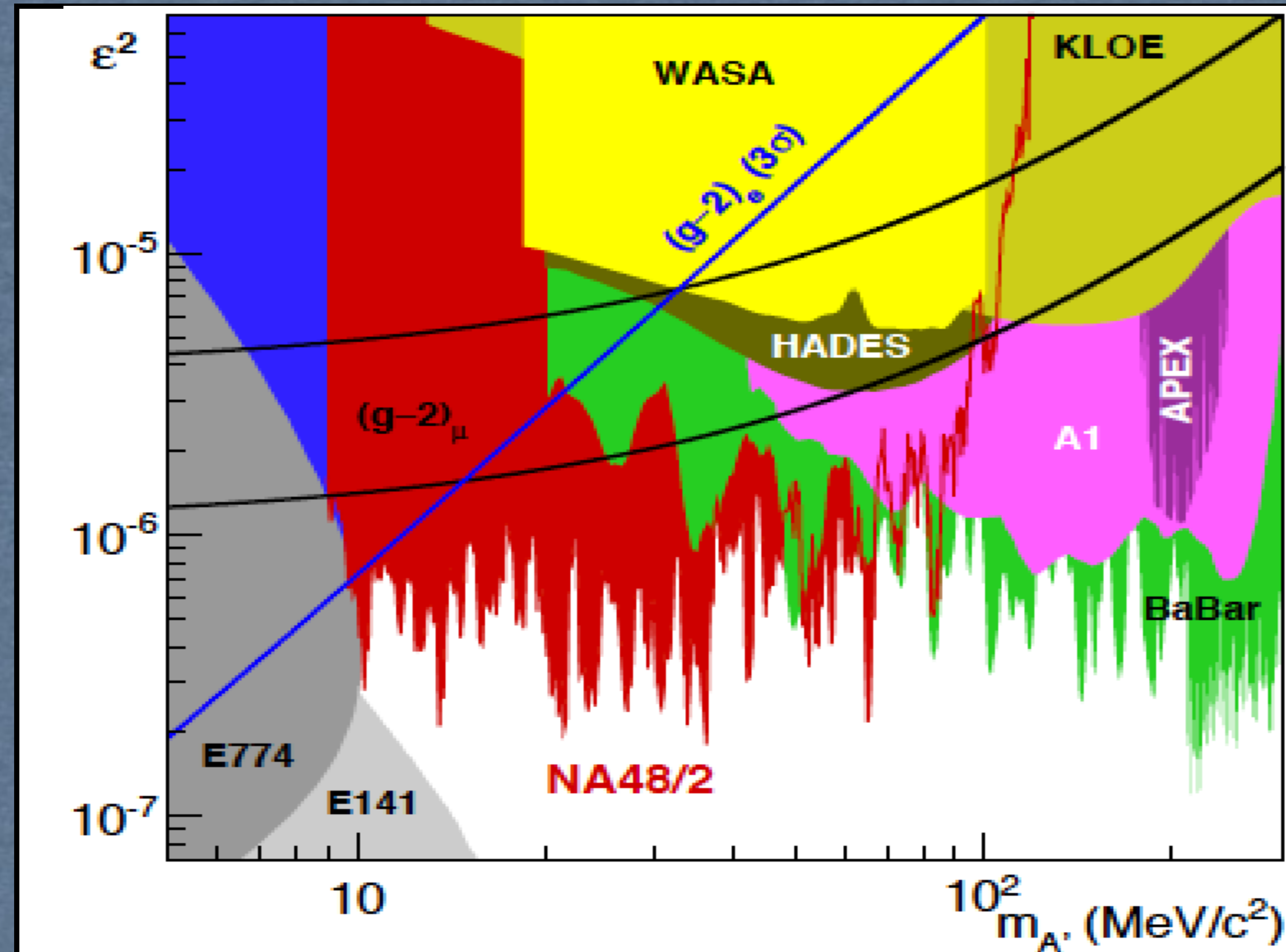


$K^\pm \to \pi^\pm \pi^0$, $\pi^0 \to \gamma A'$, $A' \to e^+e^-$



- 4×10^{10} π^0
- Acceptance ~ 2.5%
- δM ~ 1% Mee

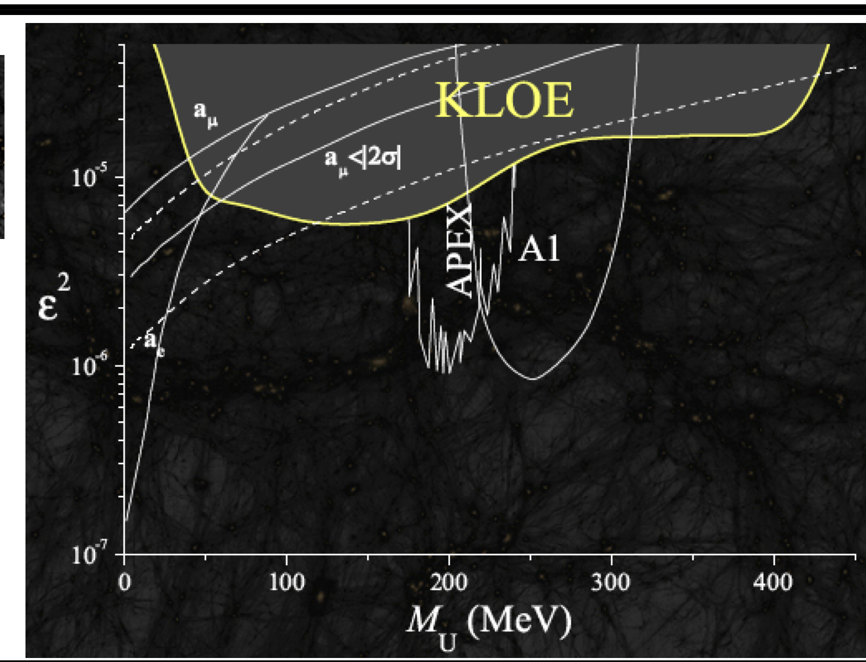




NA48/2

J.R.Batley et al.
Arxiv: 1504.00607

Phys. Lett. B 706 (2012) 251
Phys. Lett. B720 (2013) 111

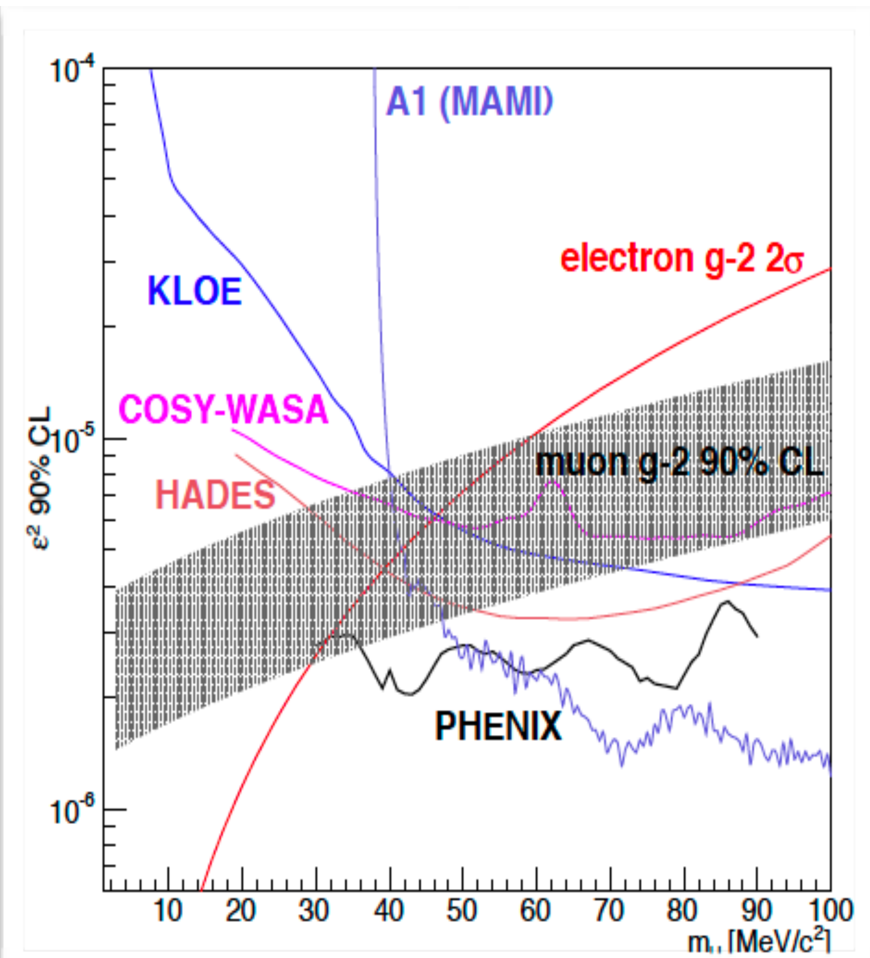


Meson decays at Hadron Colliders Present & Future Results

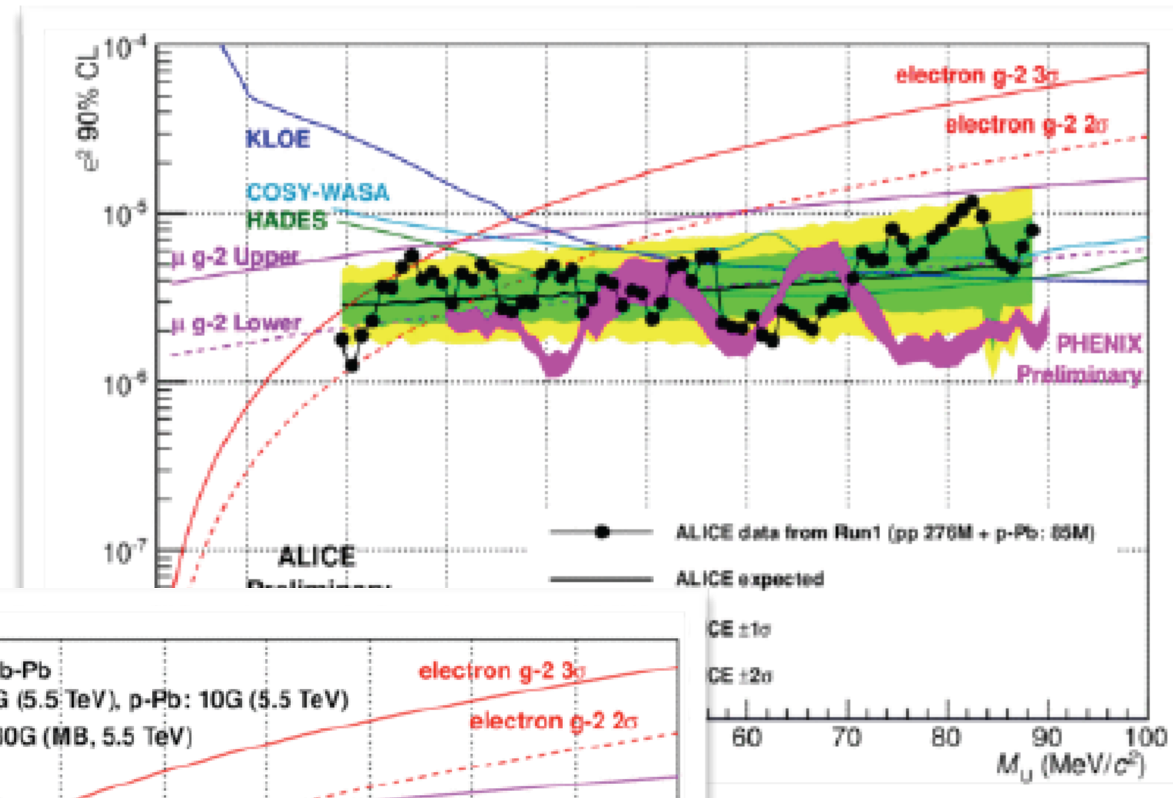
PHENIX

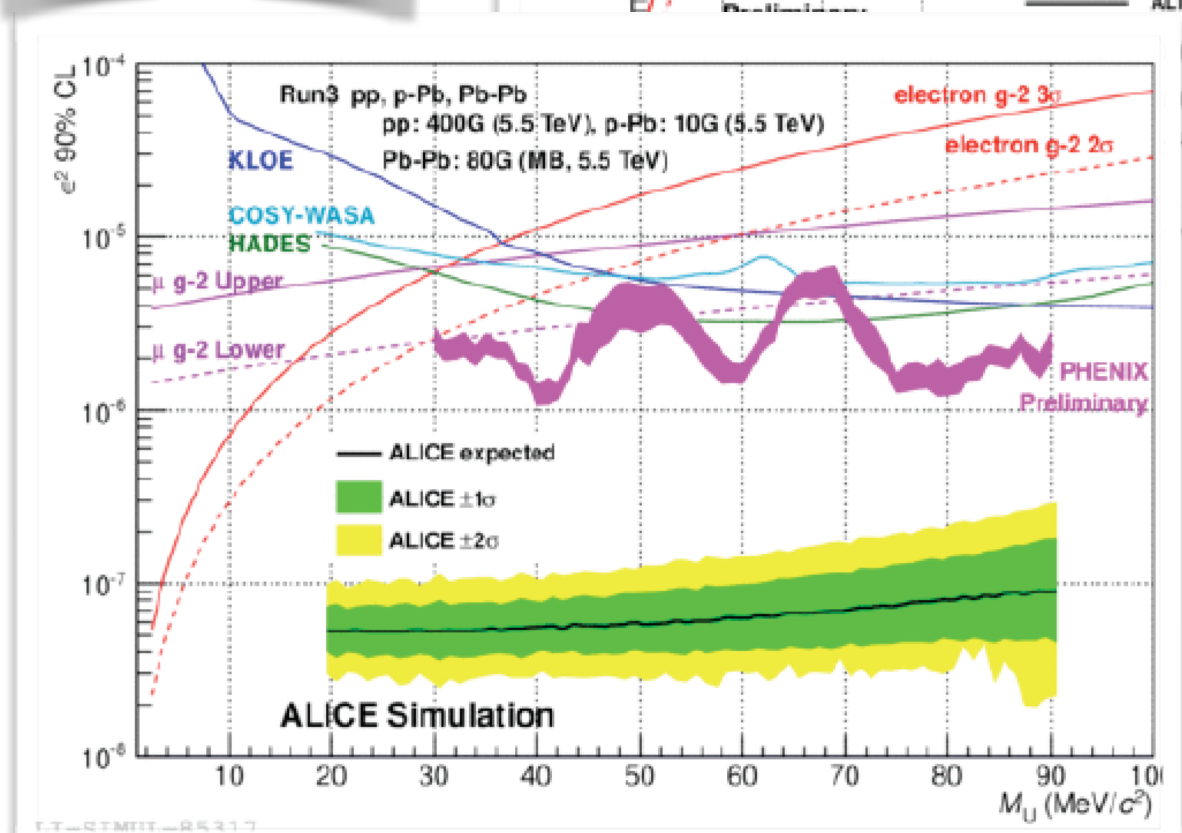
A. Atare et al. arXiv:1409.0851

- Events with e+e- detected
- 1.4M e+e- pairs (p+p and p+Au)
- Mass resolution: 2 MeV - 6 MeV



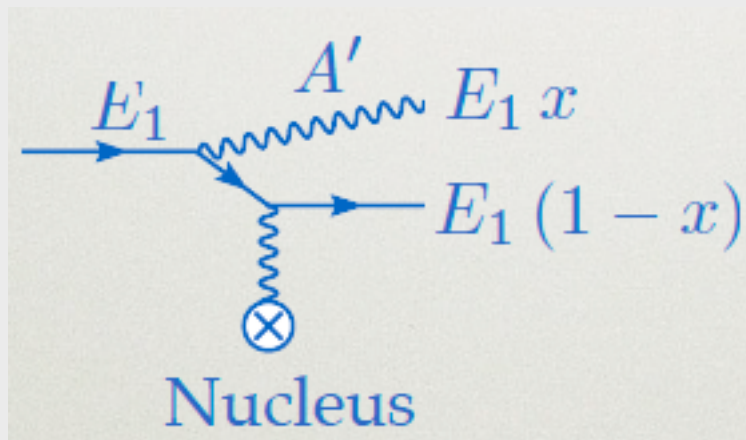
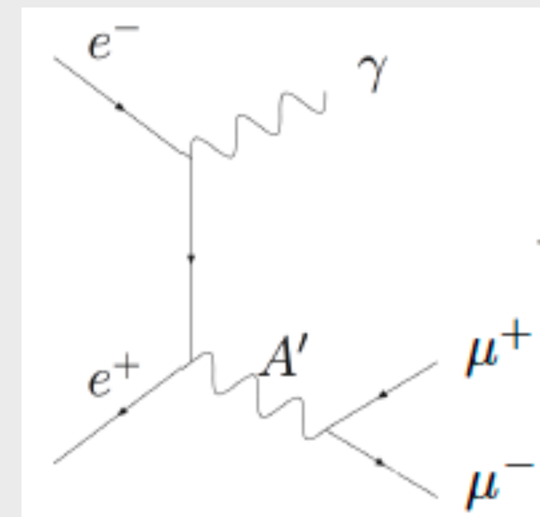
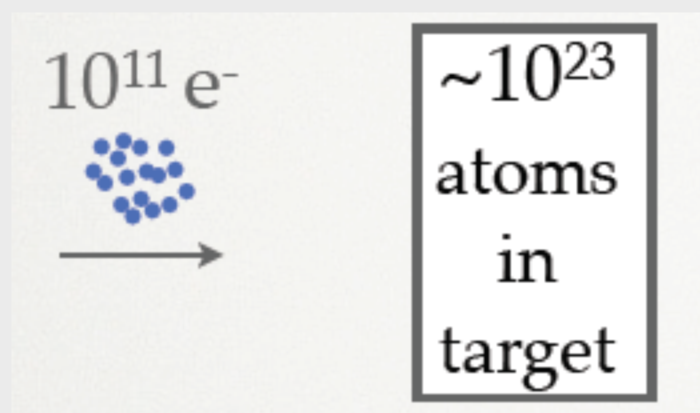
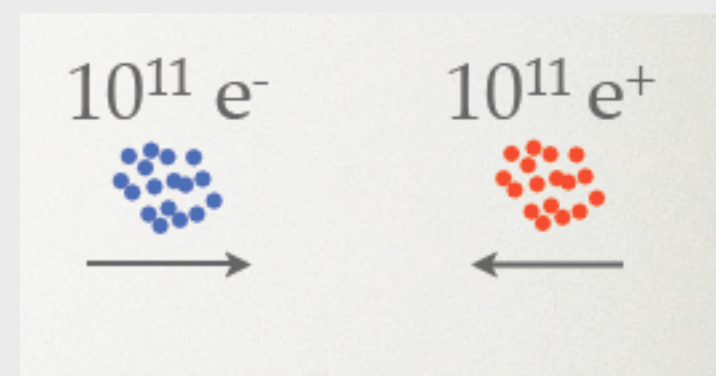
ALICE





- Events with e+e- detected
- ~300M e+e- pairs (p+p and p+Pb)
- Mass resolution: 1%

A' production: fixed target vs. collider

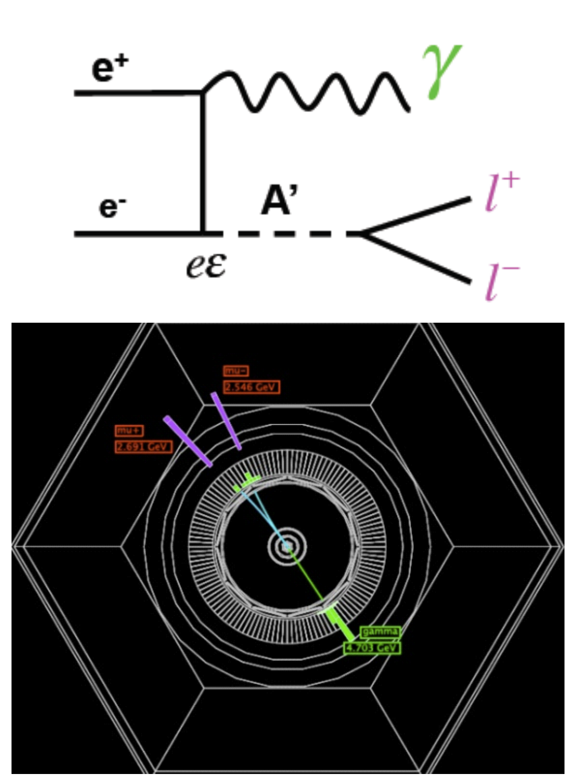
	Fixed Target	e+e- colliders
Process		
Luminosity		
Cross-Section	$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$	$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$

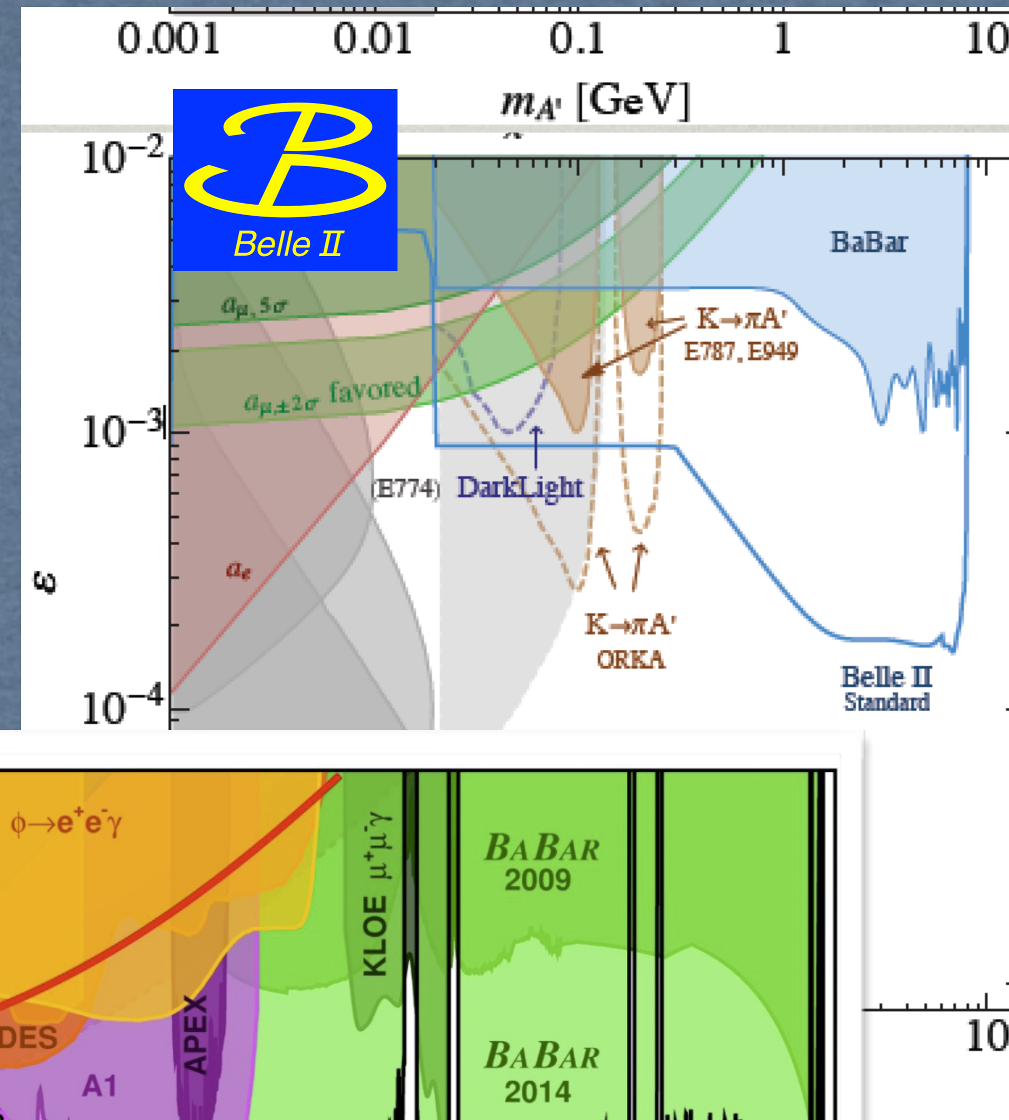
✳ $1/M_{A'}$ .vs. $1/E_{beam}$
✳ Coherent scattering from Nucleus (~Z^2)

Fixed Target:
- high backgrounds
- limited A' mass

e+e- colliders:
- low backgrounds
- higher A' mass

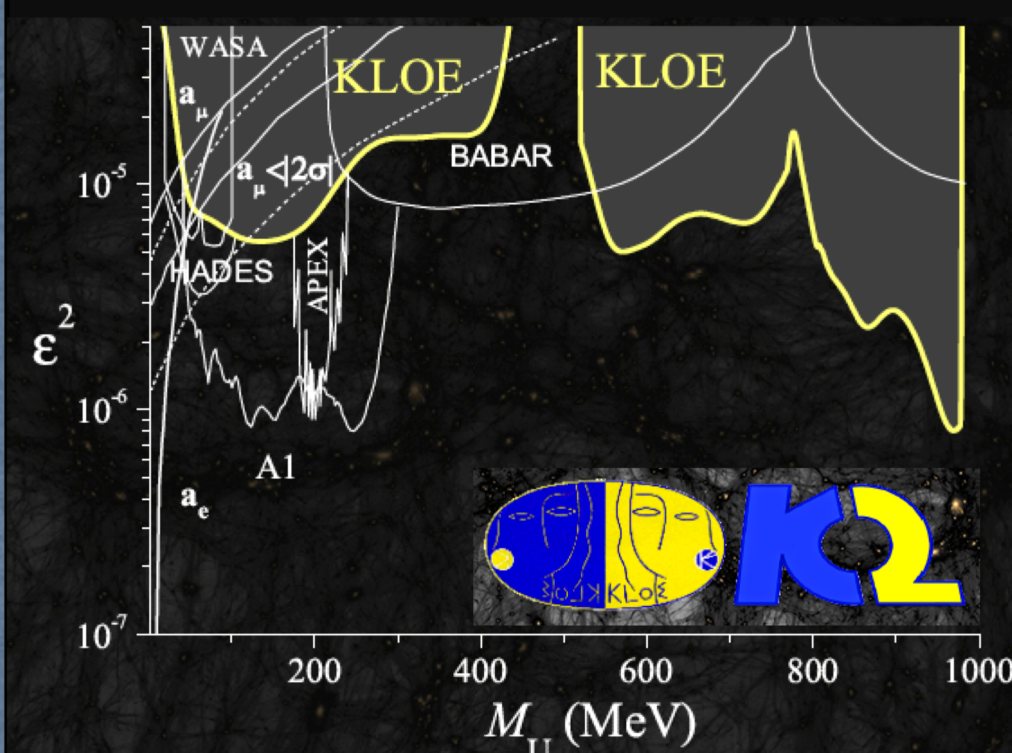
e+e- Colliders Recent & future results



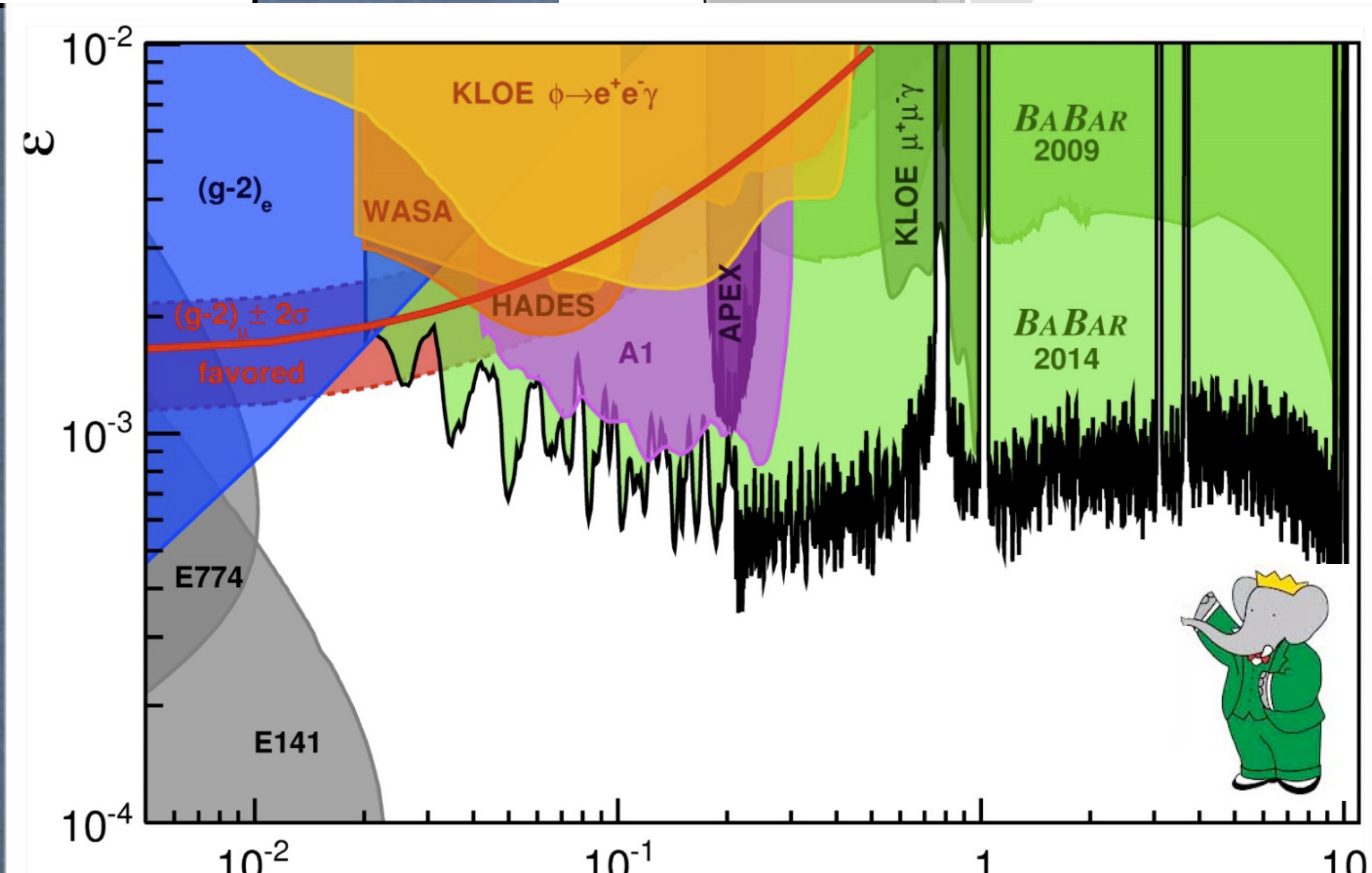


- 1gamma + 2 opposite leptons
- Di-lepton mass fit to a bg
- Mass resolution: 1.5 MeV - 8 MeV
- Int (L) = 514 fb^{-1}

Phys. Lett. B 736 (2014) 459



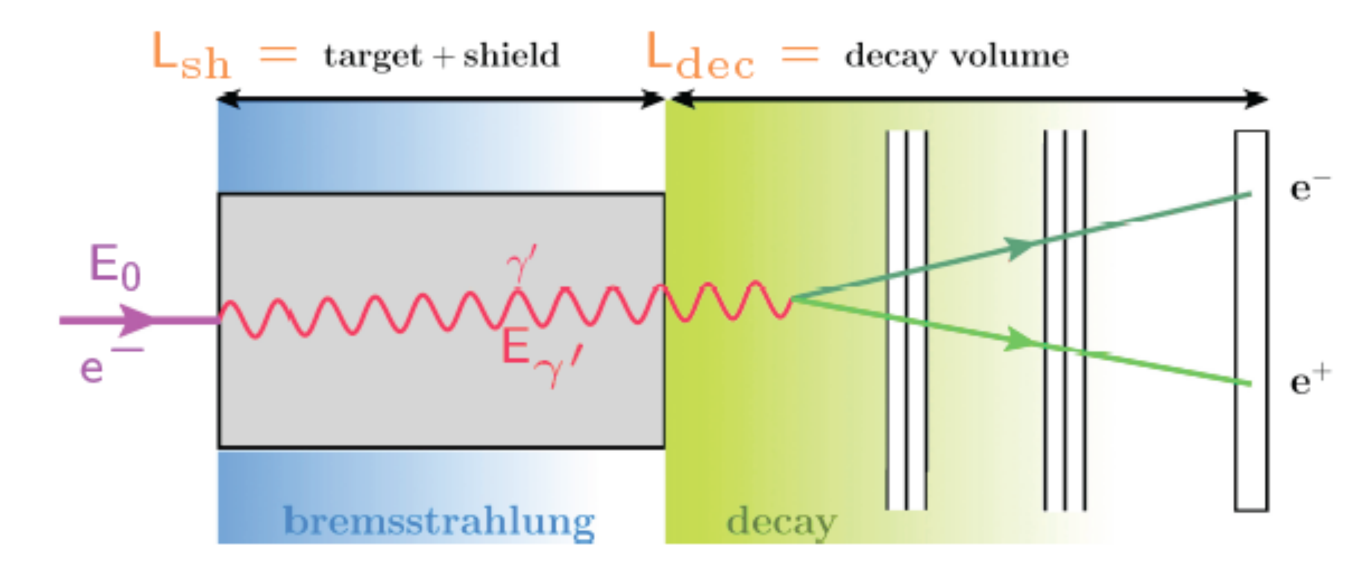
- Events with μ+μ- detected
- L~ 240 pb^{-1}



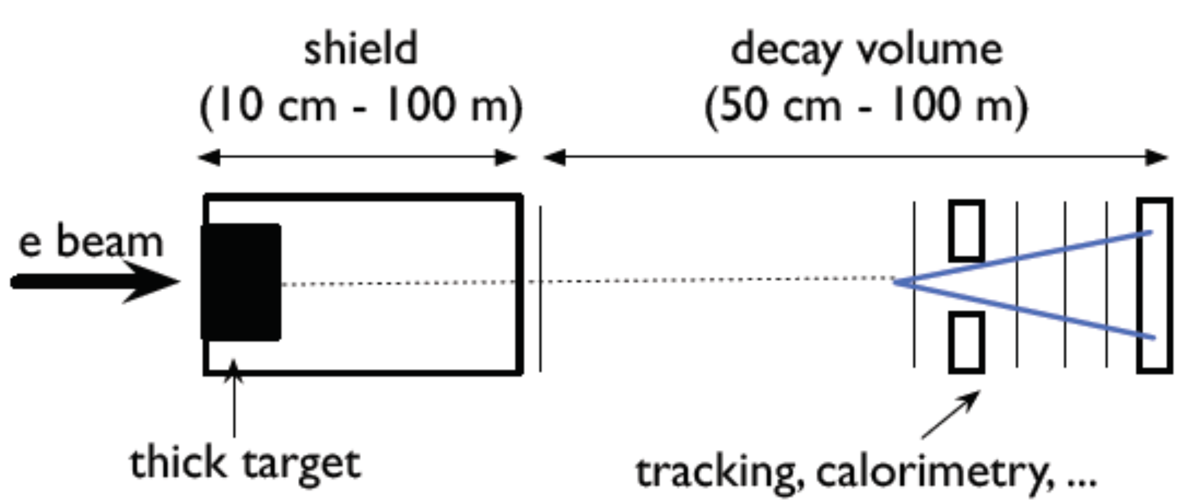
J.P. LEEs et al. arXiv:1406.2980

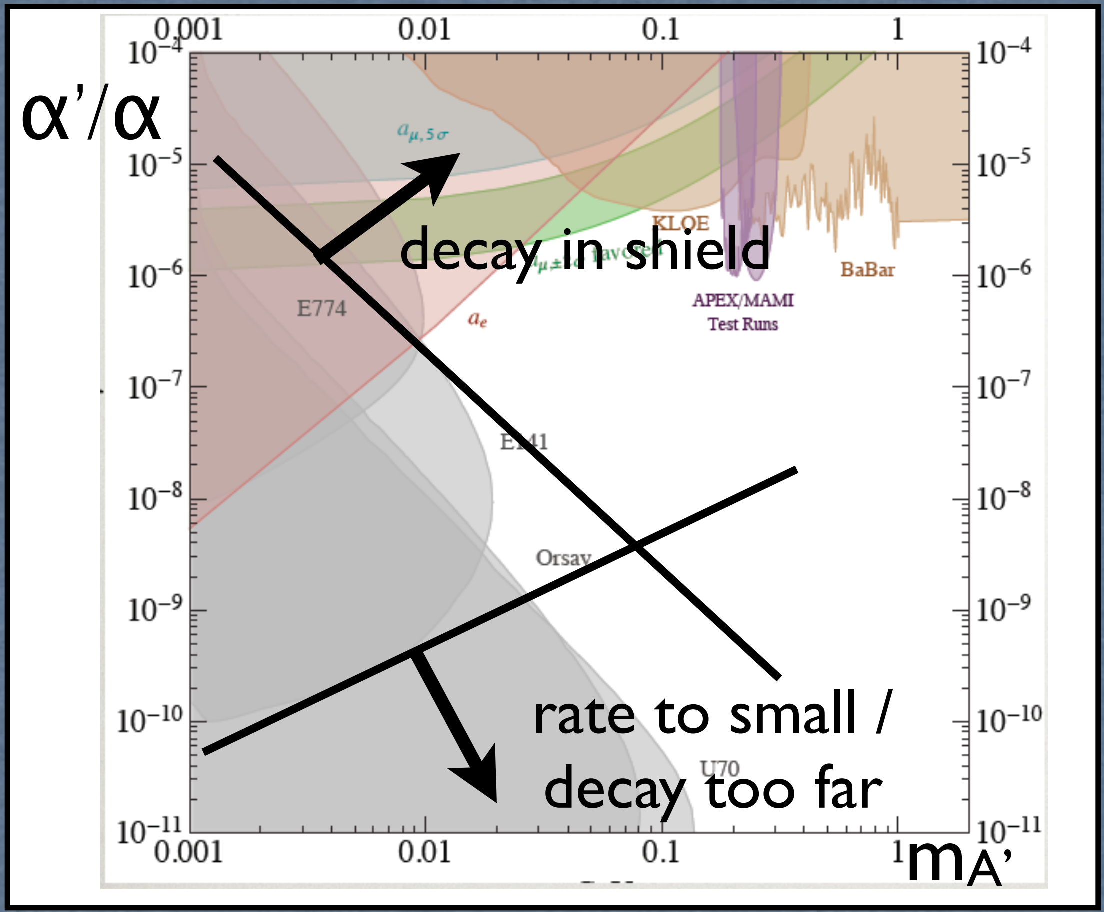
I[st] generation fixed target exp: beam dump

- e- beam incident on thick target
- A’ is produce in a process similar to ordinary Bremsstrahlung
- A’ carries most of the beam energy
- A’ emitted forward at small angle
- A’ decays before the detector



$$\gamma c\tau \approx 1\ \mathrm{mm}\,(\gamma/10)\,(10^{-8}\alpha/\alpha')$$
$$\times\,(100\ \mathrm{MeV}/m_{A'})$$



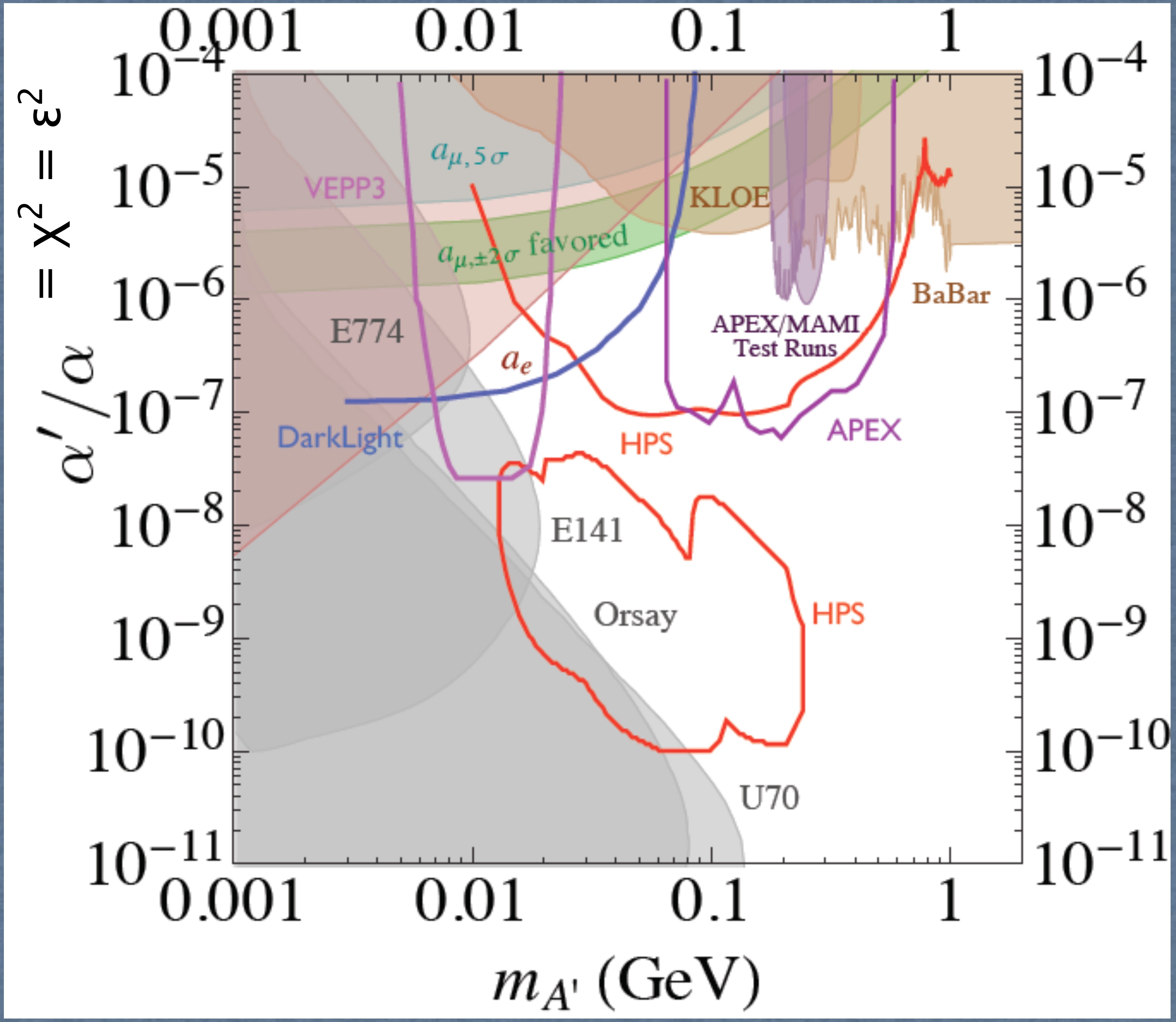


Current generation fixed target exp: thin target JLab and Mainz

JLab

- ✳ DARK LIGHT (FEL)
- ✳ APEX (Hall-A)
- ✳ HPS (Hall-B)

- Unconventional use of the CEBAF
- PAC approval (max rating conditioned to technical feasibility)
- Positive run-tests
- Experiments begin: 2015-16



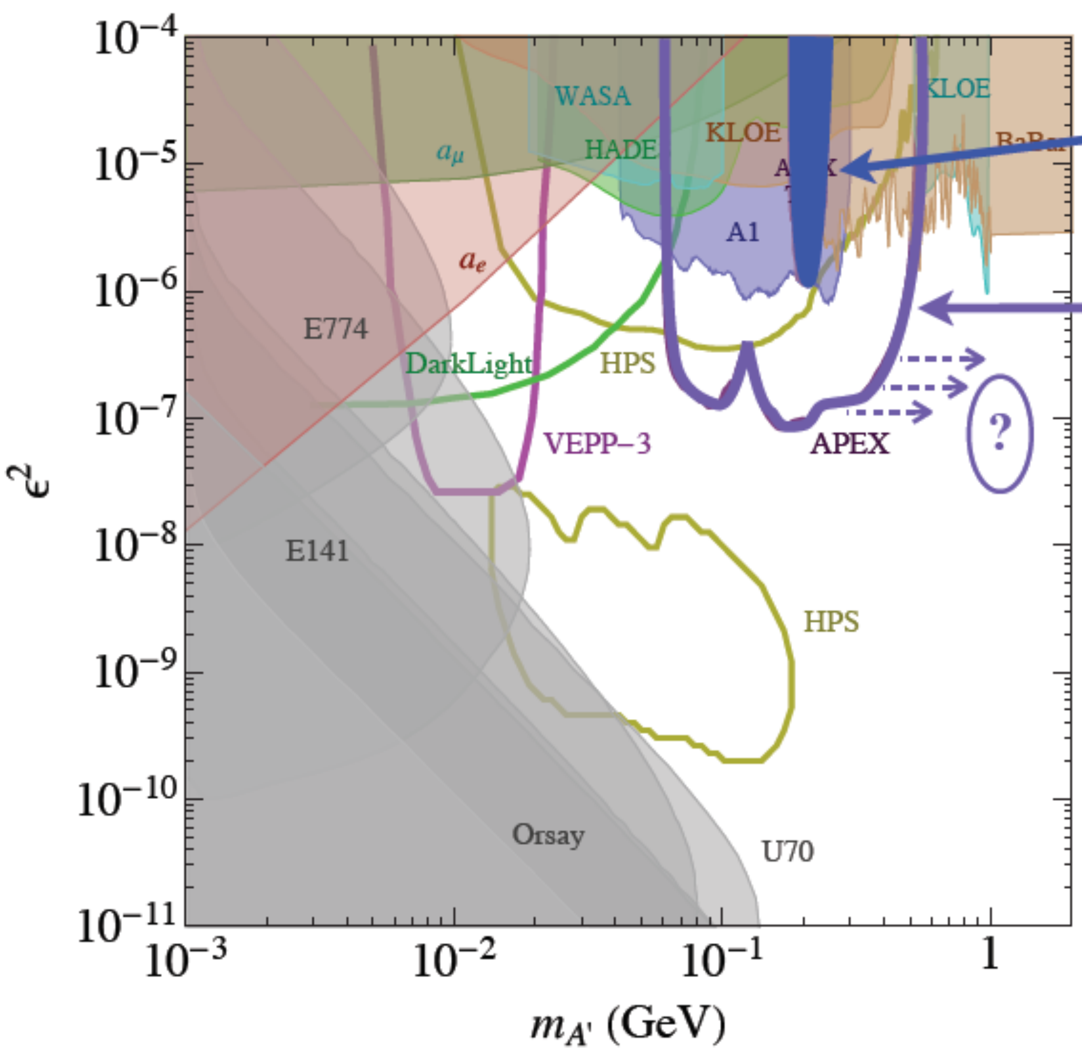
Mainz

- Magnetic spectrometers (A1)
- Pilot run in 2012
- Full analysis published in 2014
- Future plans

JLab experiments
APEX (A-Prime EXperiment)

- Dark photon search in fixed target experiment in Hall-A at Jefferson Lab
- Looking for a small, narrow bump on top of a smooth histogram of QED processes
- Excellent mass resolution required (~ 0.85 - 1.1MeV)

S.Abrahamayan et al.,
Phys. Rev. Lett. 107 (2011) 191804



APEX Test Run Results

Full Run Projected Sensitivity

APEX test run

Relevant Characteristics

- Beam current up to 150μA
- Target: Ta foil, 22 mg/cm2
- HRS Central momenta: 1.13 GeV
- Momentum acc: ± 4.5%
- Electron beam energy: 2.26 GeV
- Solid angle acceptance: ~2.8 msr

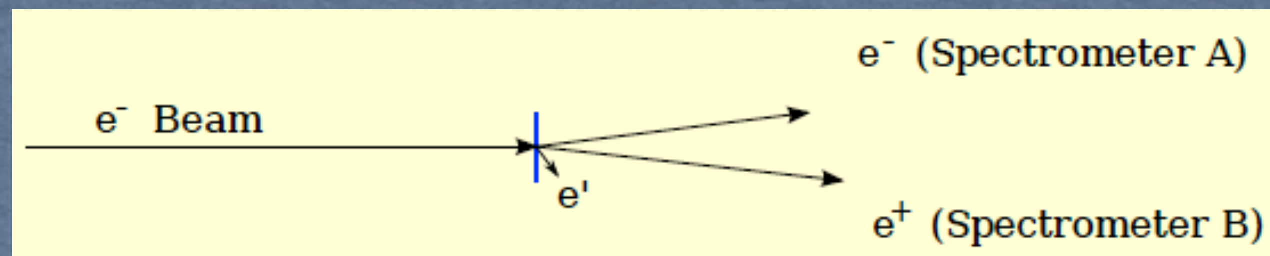
APEX full run

Projected sensitivity

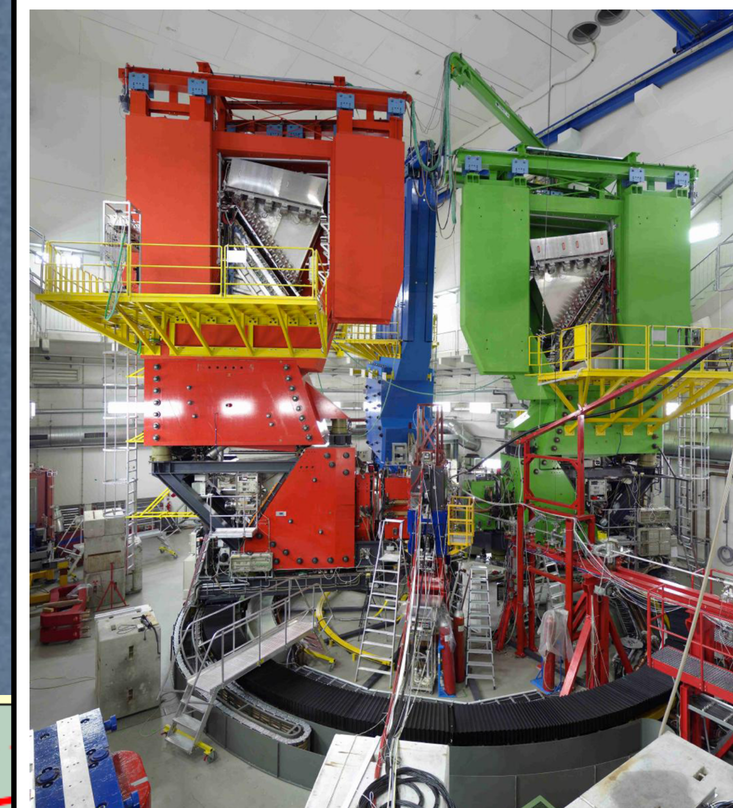
- e+e- statistics 200x
- a'/a 2 100x below current limits
- Beam E from 1.1 GeV to 4.4 GeV
- Beam current: 60-100 μA
- JLab - PAC41 High impact rate
- Ready to run in 2015

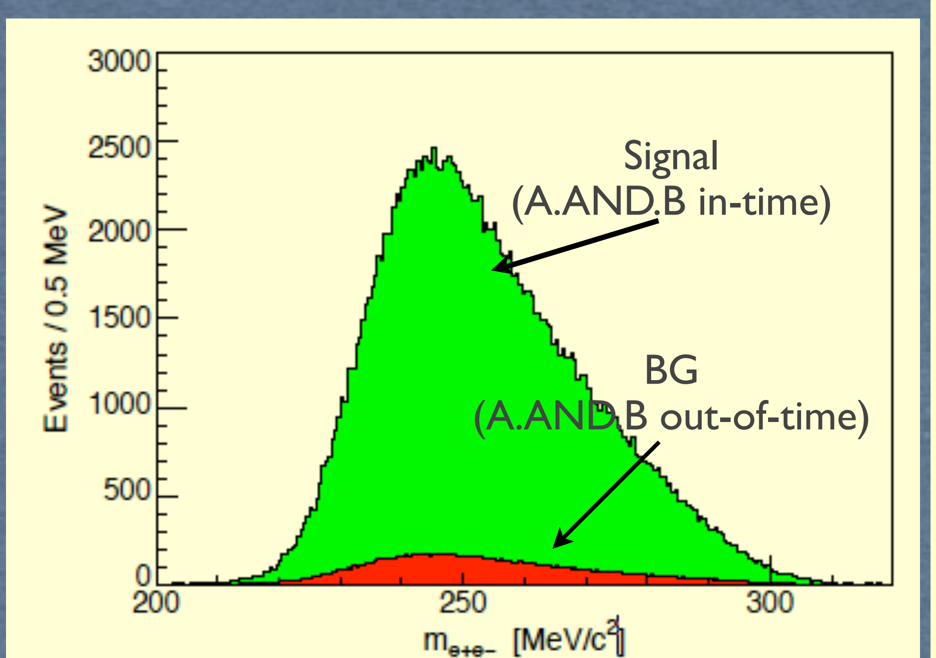
A' search at MAINZ
Full data analysis

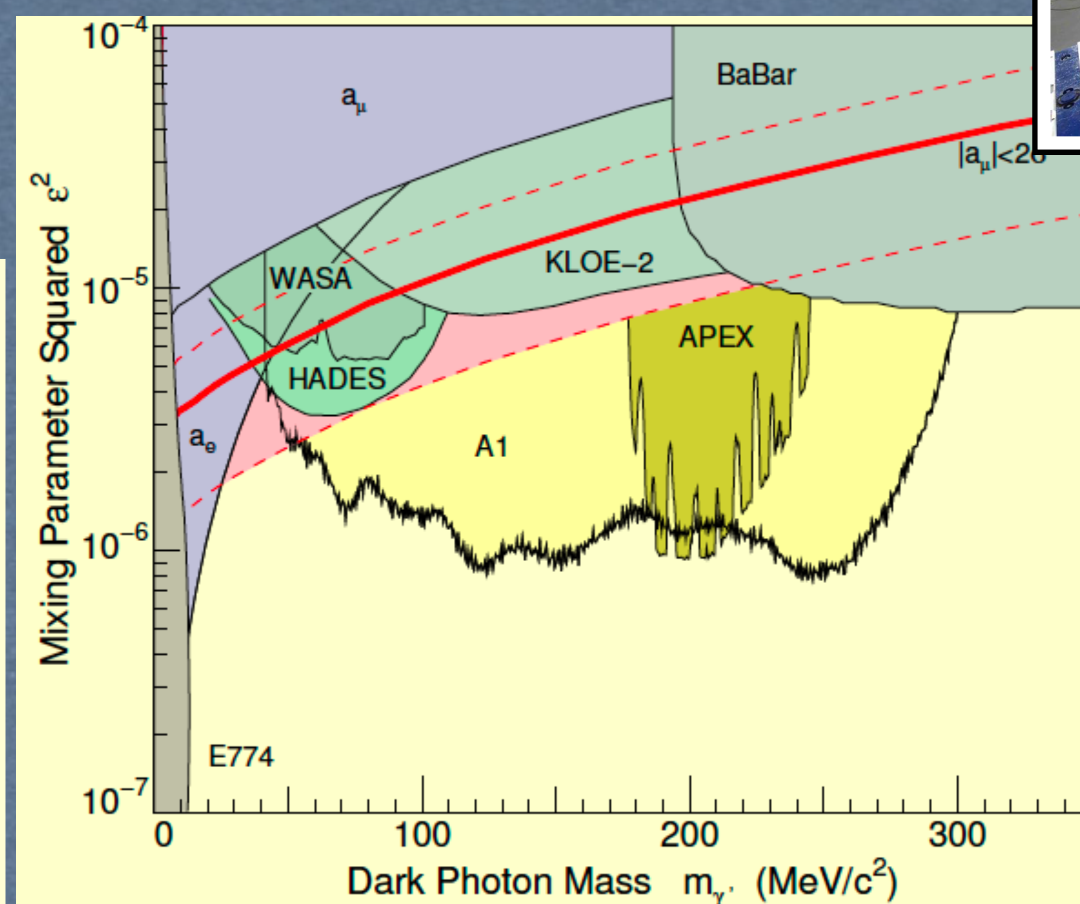
- E=855 MeV
- I=100uA
- Ta target
- Spectrometer A (red): p_{e-} 338 MeV/c $J_{e-}=22.8^{o}$
- Spectrometer B (blue): p_{e+} 470 MeV/c $J_{e+}=15.2^{o}$



A1 spectrometers @ MAMI

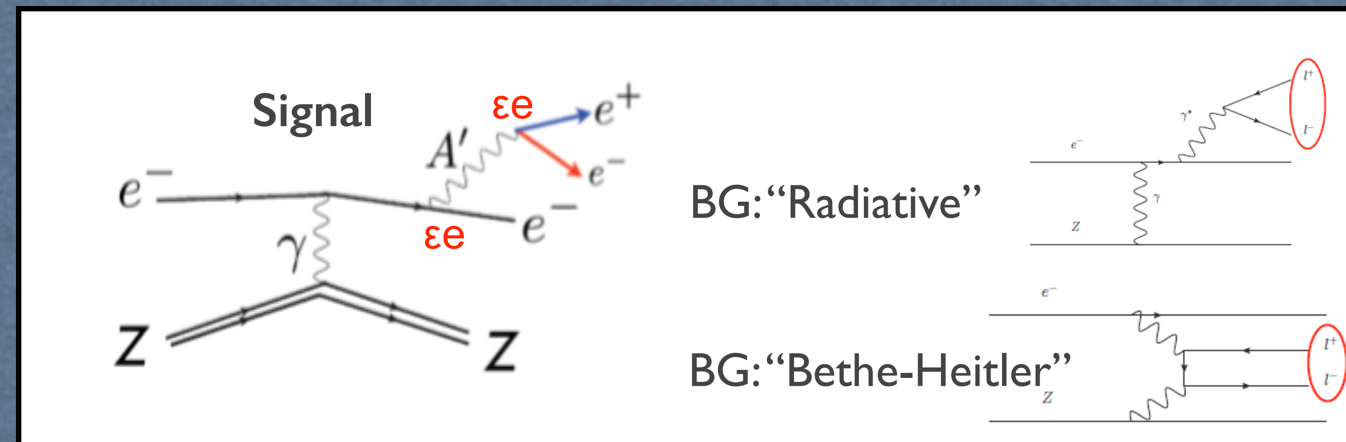


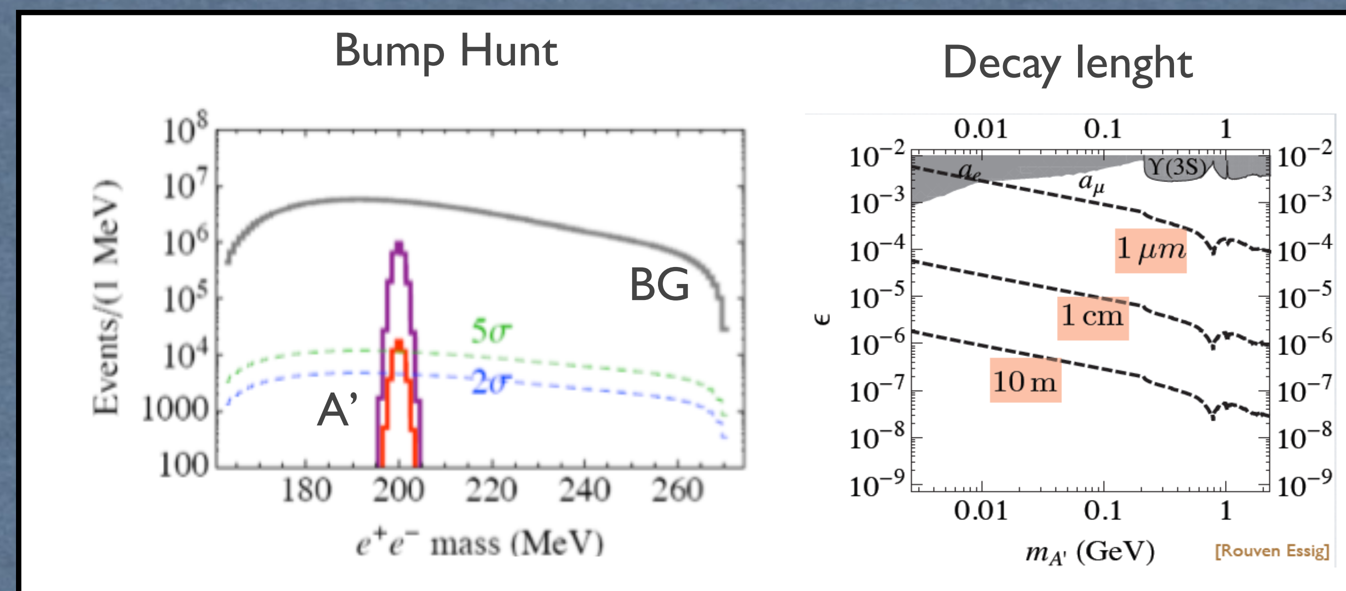




H. Merkel et al.,
Phys. Rev. Lett. 112 (2014) 015032

HPS@JLab
Heavy Photon Search





Heavy photon signatures in HPS

1) Bump Hunting (BH)

Narrow e+e-resonance over a QED background

➥ good mass resolution: $\sigma_{A'mass}$~1 MeV

2) Secondary decay vertex (vertexing)

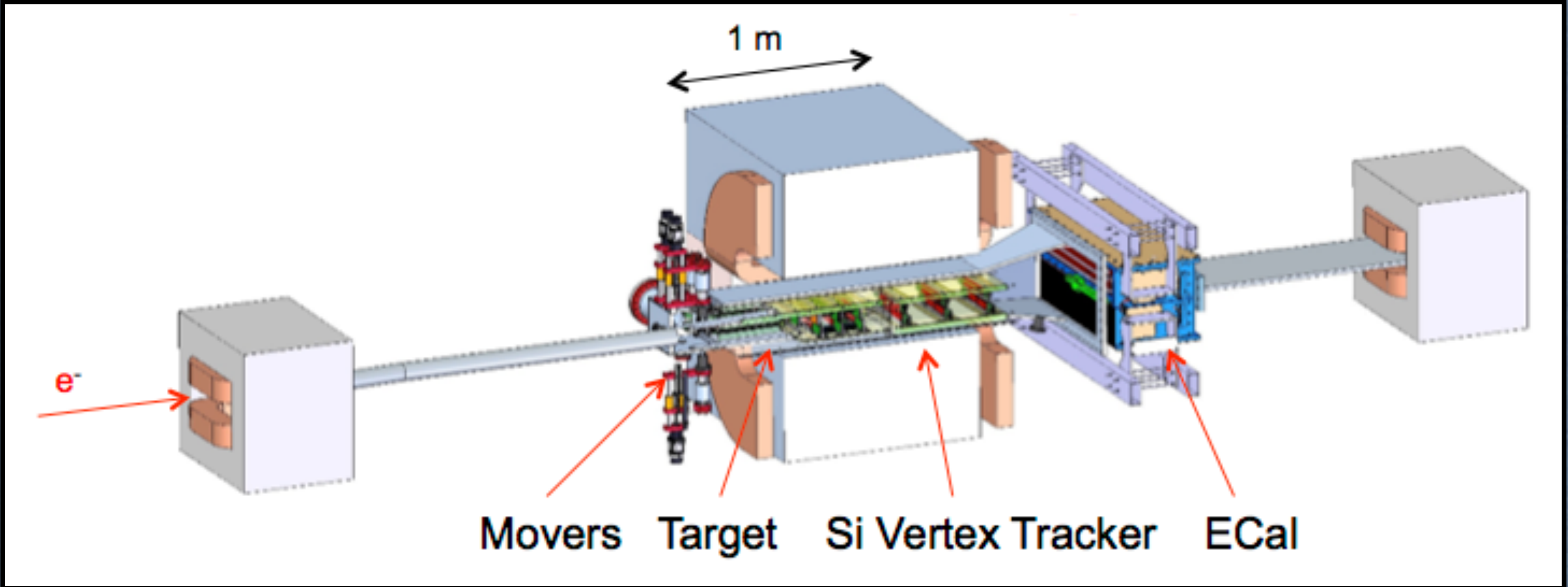
Detached vertex from few mm to tens cm

➥ good spacial resolution: σ_{vertex}~1mm

BH + Vertexing = enhanced experimental reach

$$l_{\gamma'} \sim \frac{E_{\gamma'}}{\alpha\chi^2 m_{\gamma'}^2} \sim 10\mathrm{cm}\ \frac{E_{\gamma'}}{1\mathrm{GeV}} \left(\frac{10^{-4}}{\chi}\right)^2 \left(\frac{10\mathrm{MeV}}{m_{\gamma'}}\right)^2 \sim \mathcal{O}(\mathrm{mm}-\mathrm{km})$$

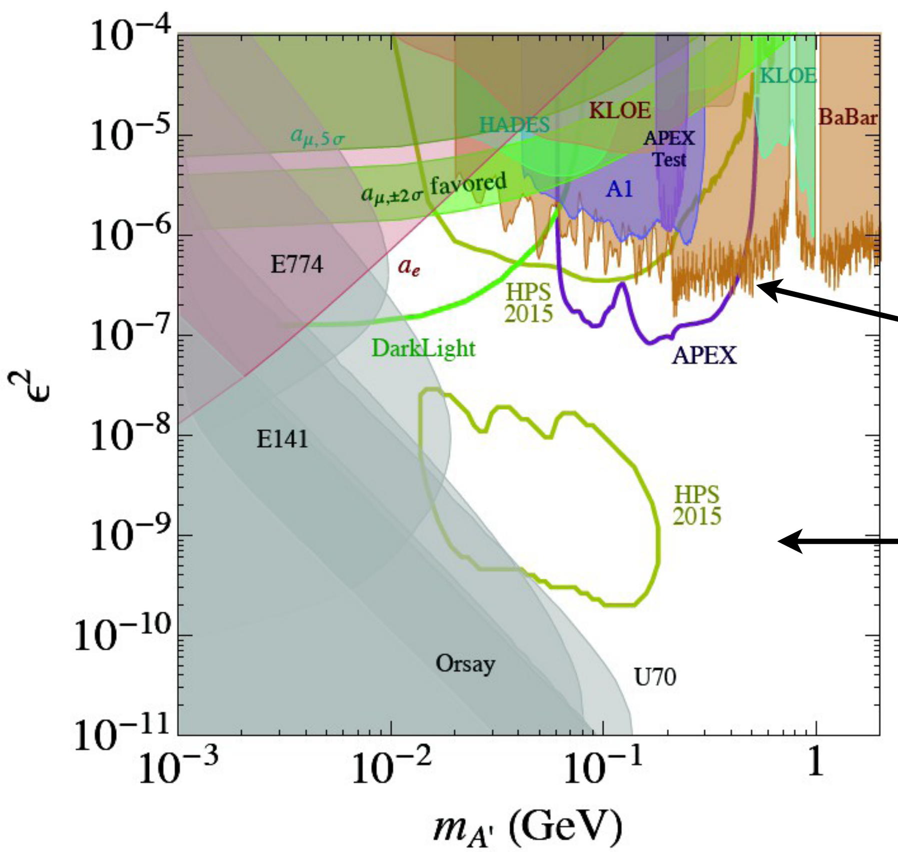
The HPS Experiment



Requirements:
- forward angles coverage
- good spacial resolution:
  $\sigma_{vertex} \sim 1$mm (vertexing)
- good mass resolution:
  $\sigma_{A'mass} \sim 1$ MeV (bump hunting)

Experimental set-up
- B field to bend e+/e- pairs
- Si TRCK for vertexing
- EM cal for triggering

Projected results



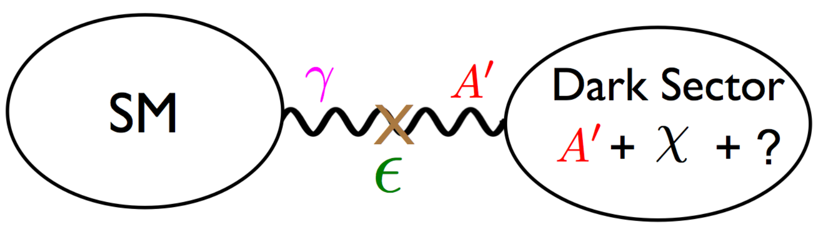
Bump hunting

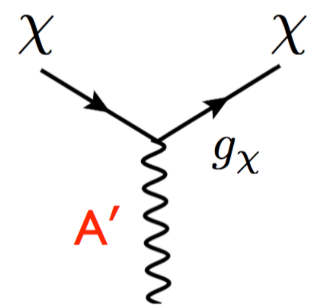
Bump hunting + vertexing

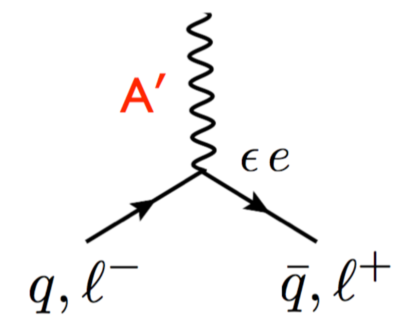
Running now!	1 week 1.1 GeV 1 week 2.2 GeV 2 weeks 4.4 GeV	Phase I 2015
	few months 2.2 GeV few months 4.4 GeV few months 6.6 GeV	Phase II 2017 -2019

JLab - PAC41 High impact rate

Dark forces and dark matter
(Light WIMPs - light mediators)



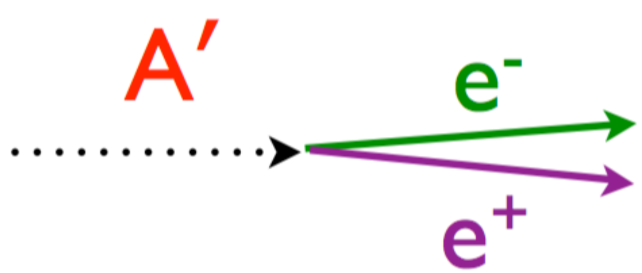




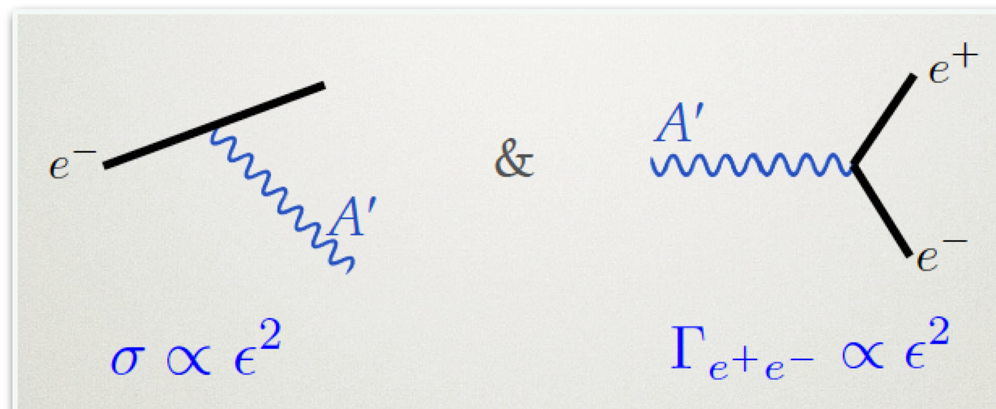
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

$m_\chi \sim m_{A'} \sim \mathrm{MeV} - 5\ \mathrm{GeV}$

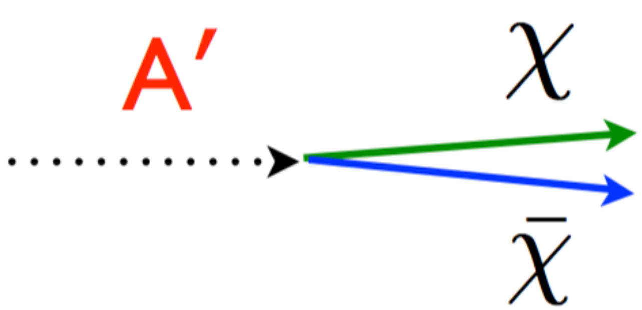
Visible



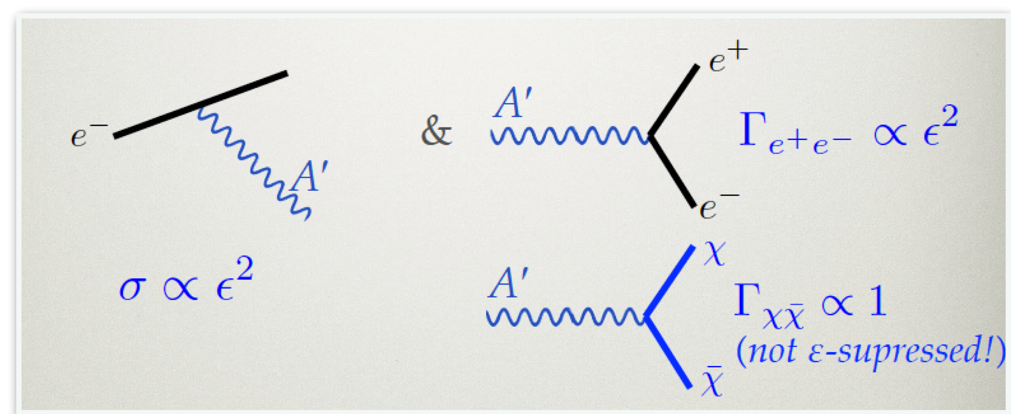
- *Minimal* decay
- Decay regulated by ε^2
- Independent on m_χ
- Requires $m_{A'} < 2m_\chi$



Invisible

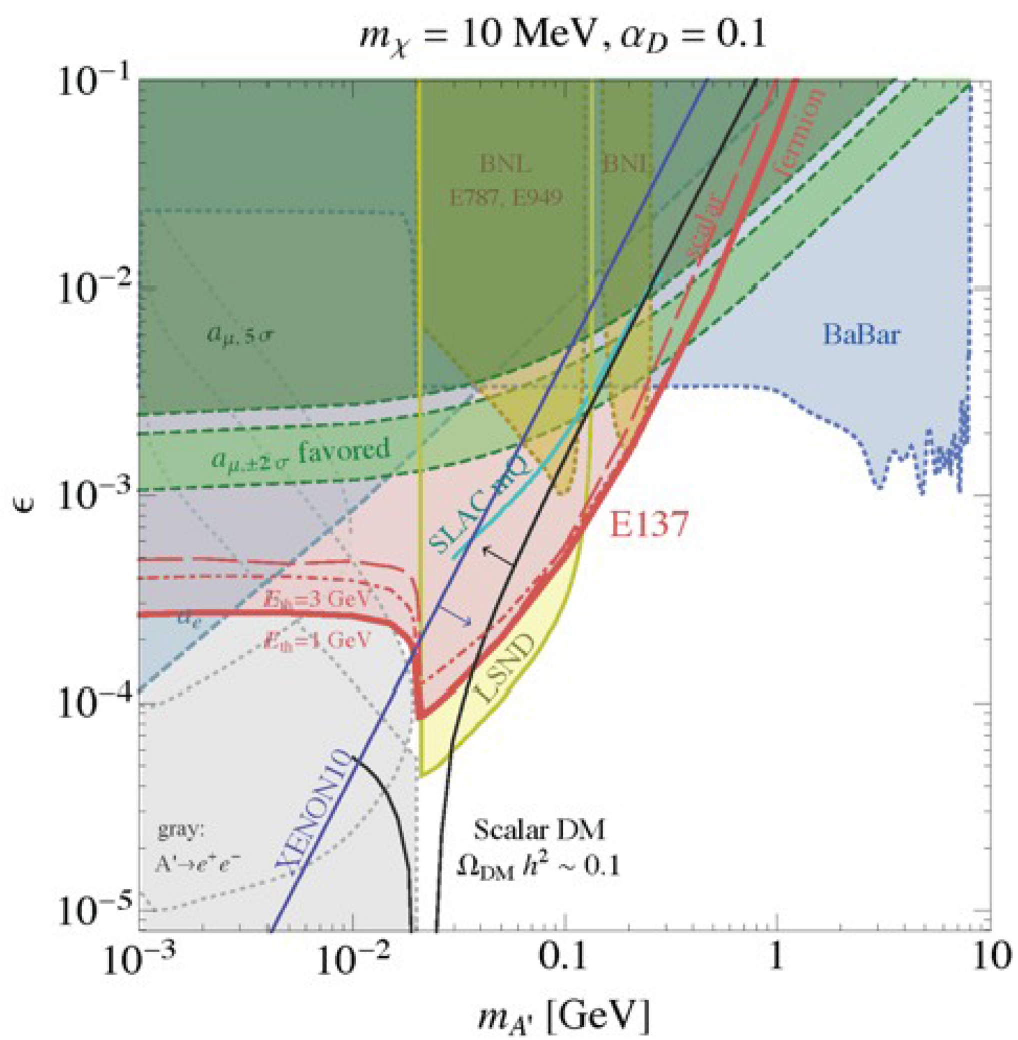


- $m_\chi < 2m_{A'}$
  - i) stable and invisible
  - ii) decays to SM particles
- Independent on ε

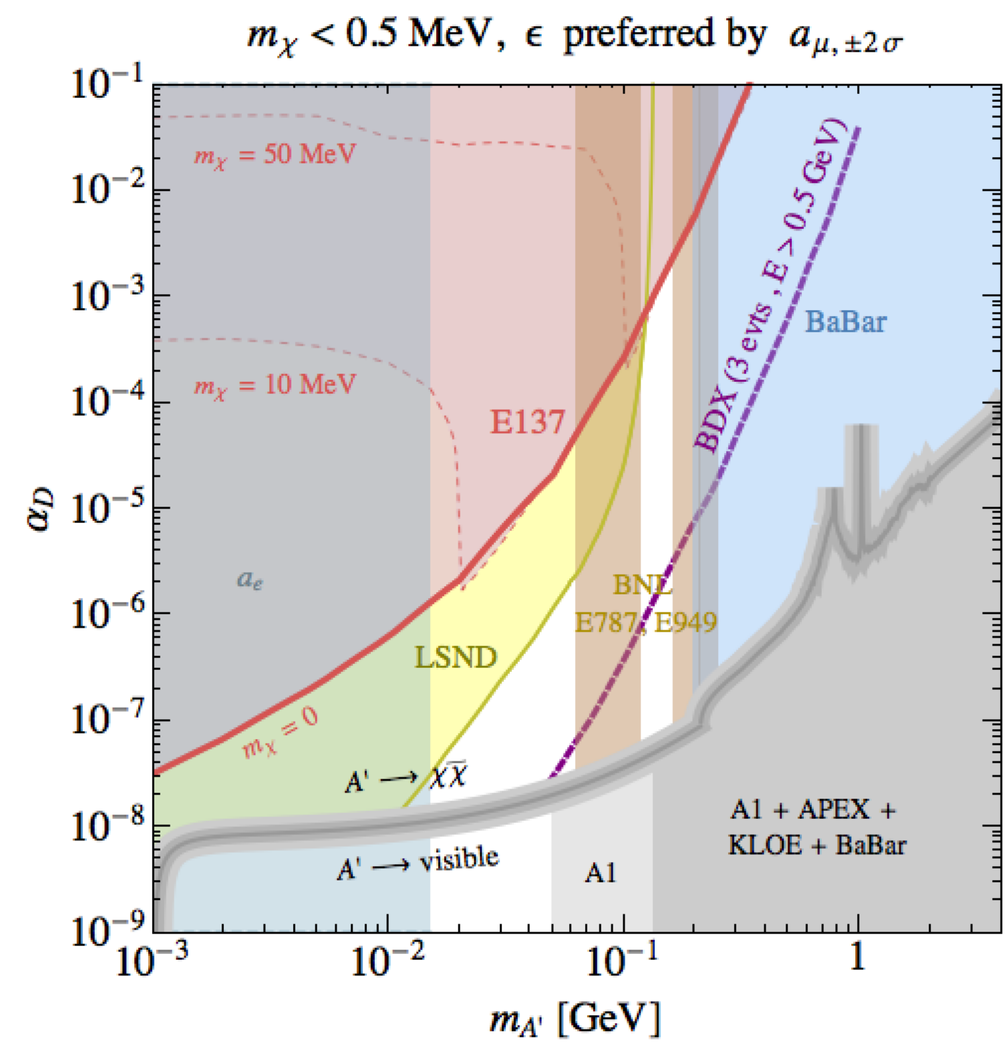


Visible vs Invisible: complementarity
$(g-2)_\mu$

Invisible only



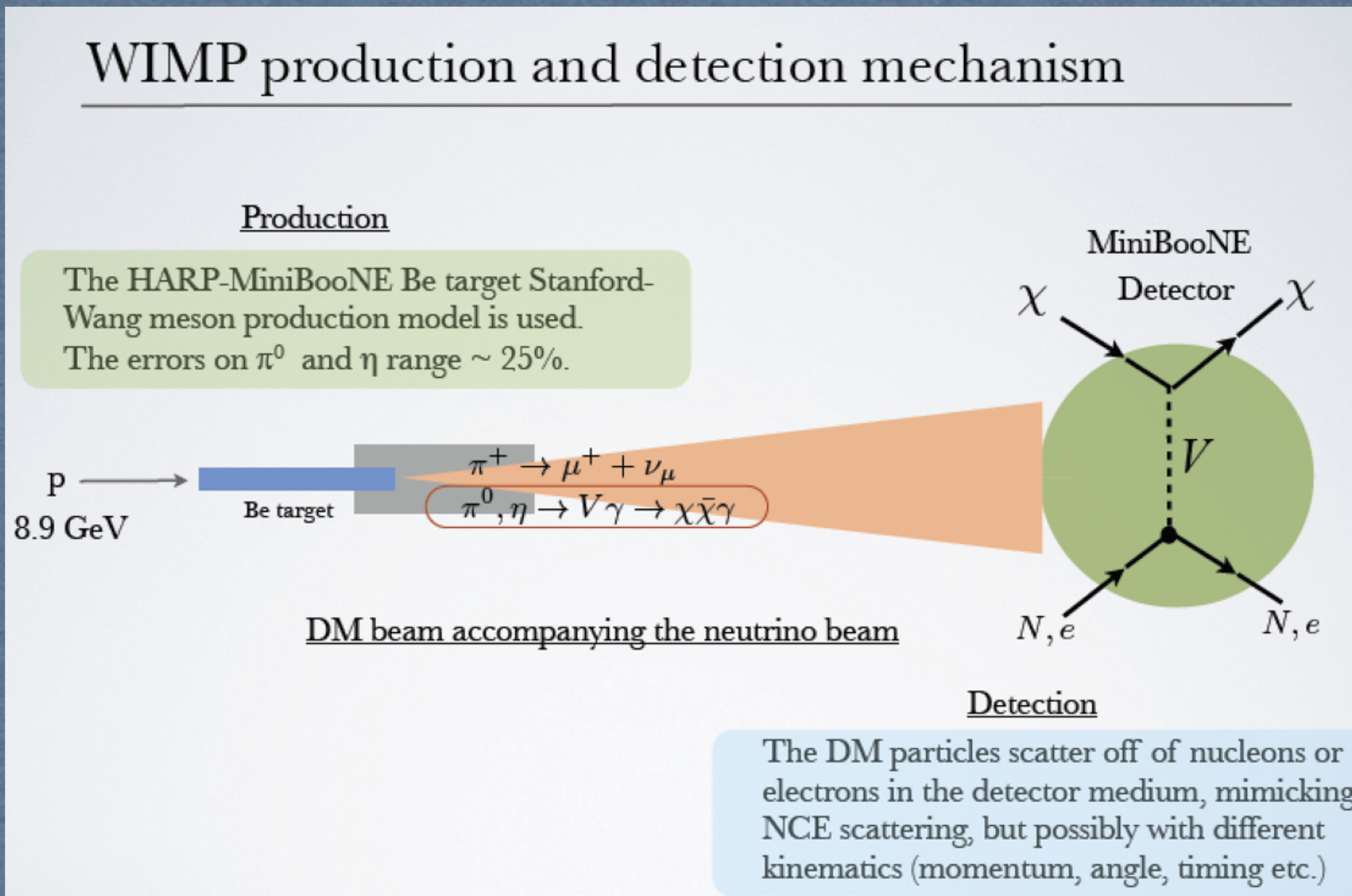
Visible + Invisible

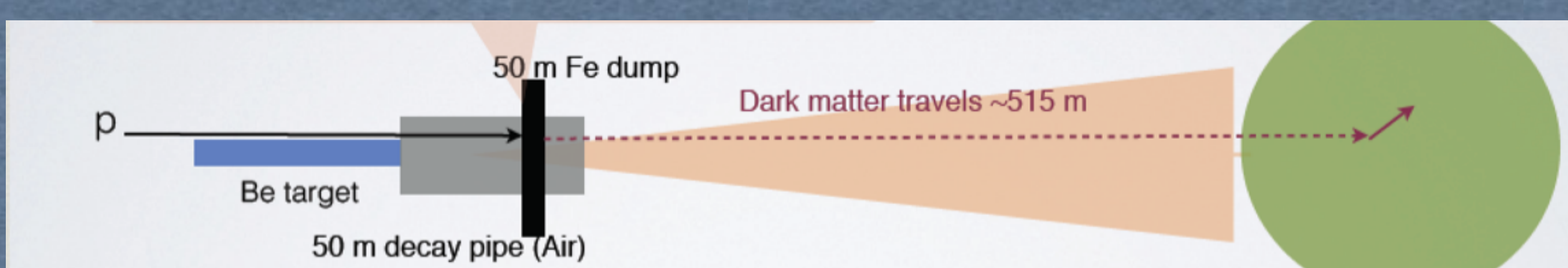


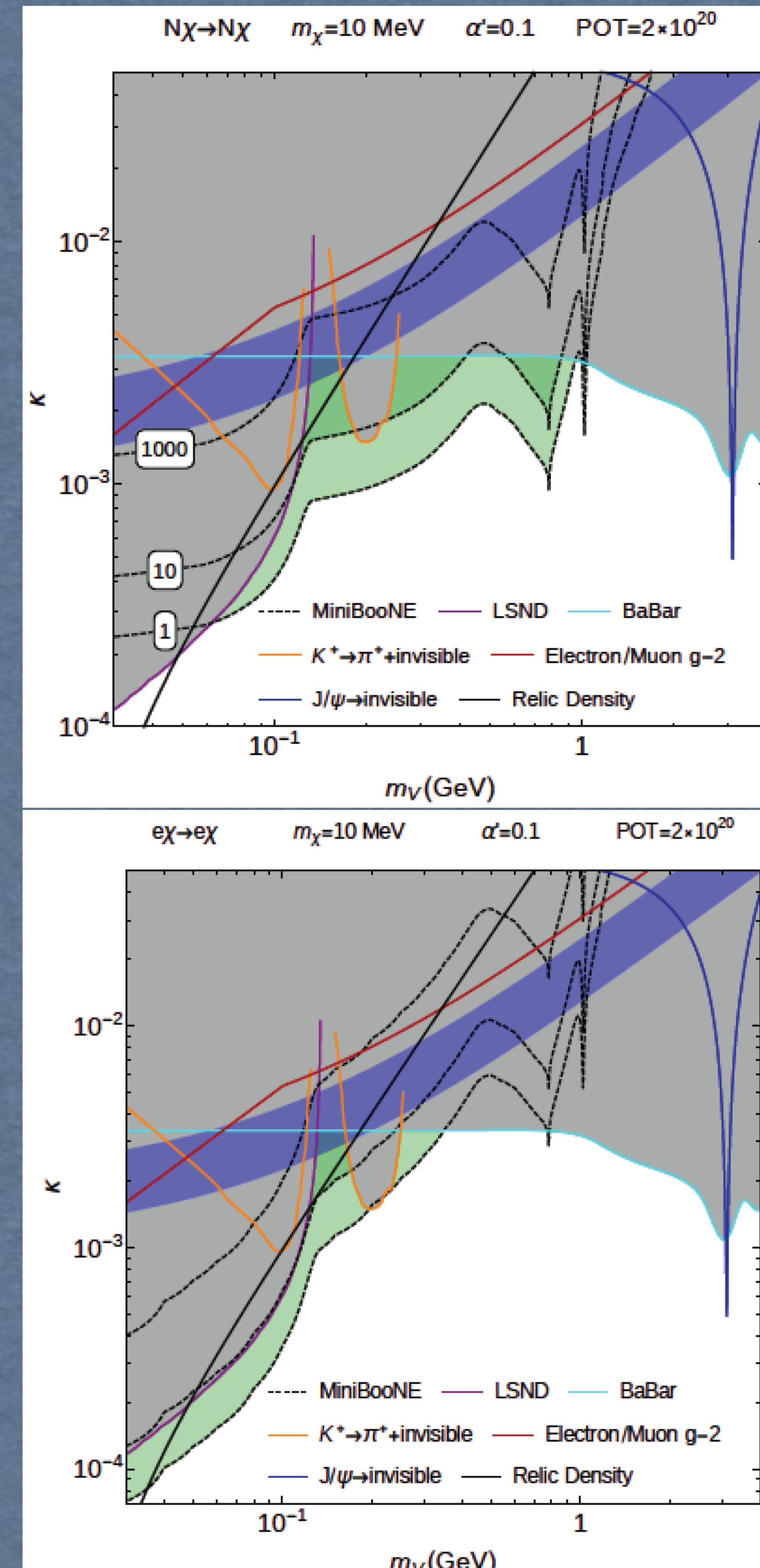
Strong Constraints on Sub-GeV Dark Matter from SLAC Beam Dump E137
PhysRevLett.113.171802 Brian Batell, Rouven Essig, Ze'ev Surujon

- Reinterpretation of existing data are ruling out *(g-2)*$_\mu$ favoured region
- Exclusion limits are model dependent: if invisible decay is included limits do not hold!

MiniBooNE@FERMILAB

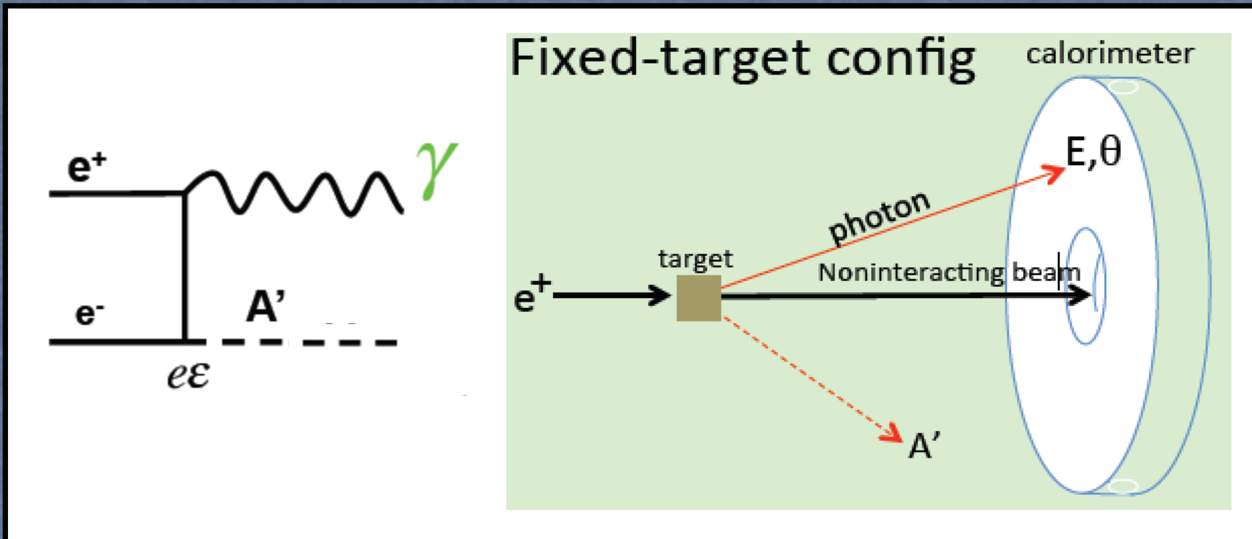






- Test run just ended
- Similar plans for T2K & ND280 (30 GeV p +50t near detector)

e^+ annihilation on fixed target: proposals

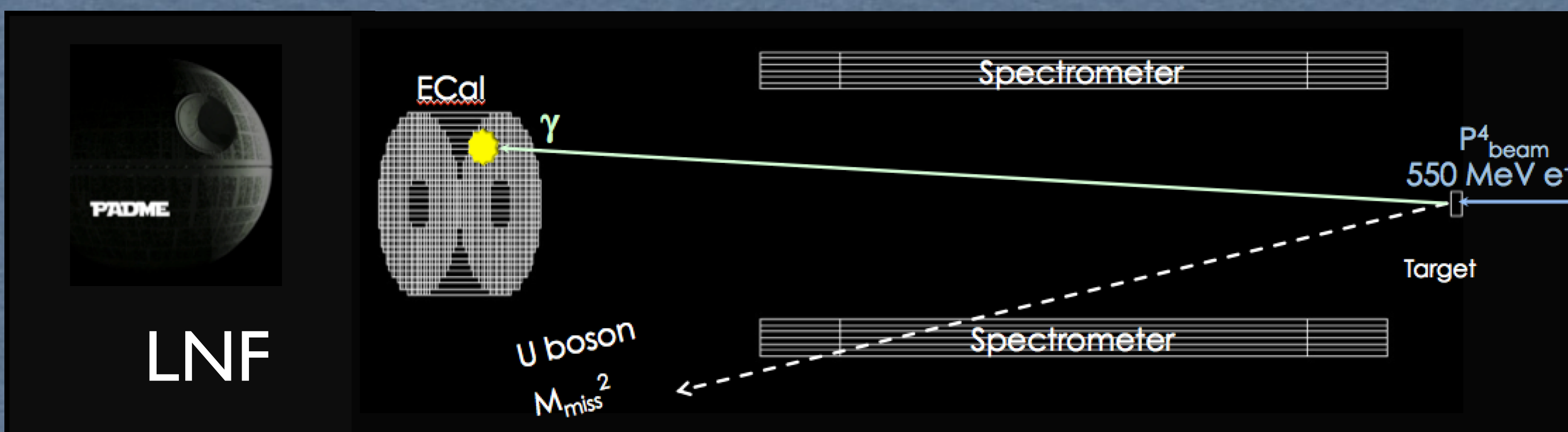


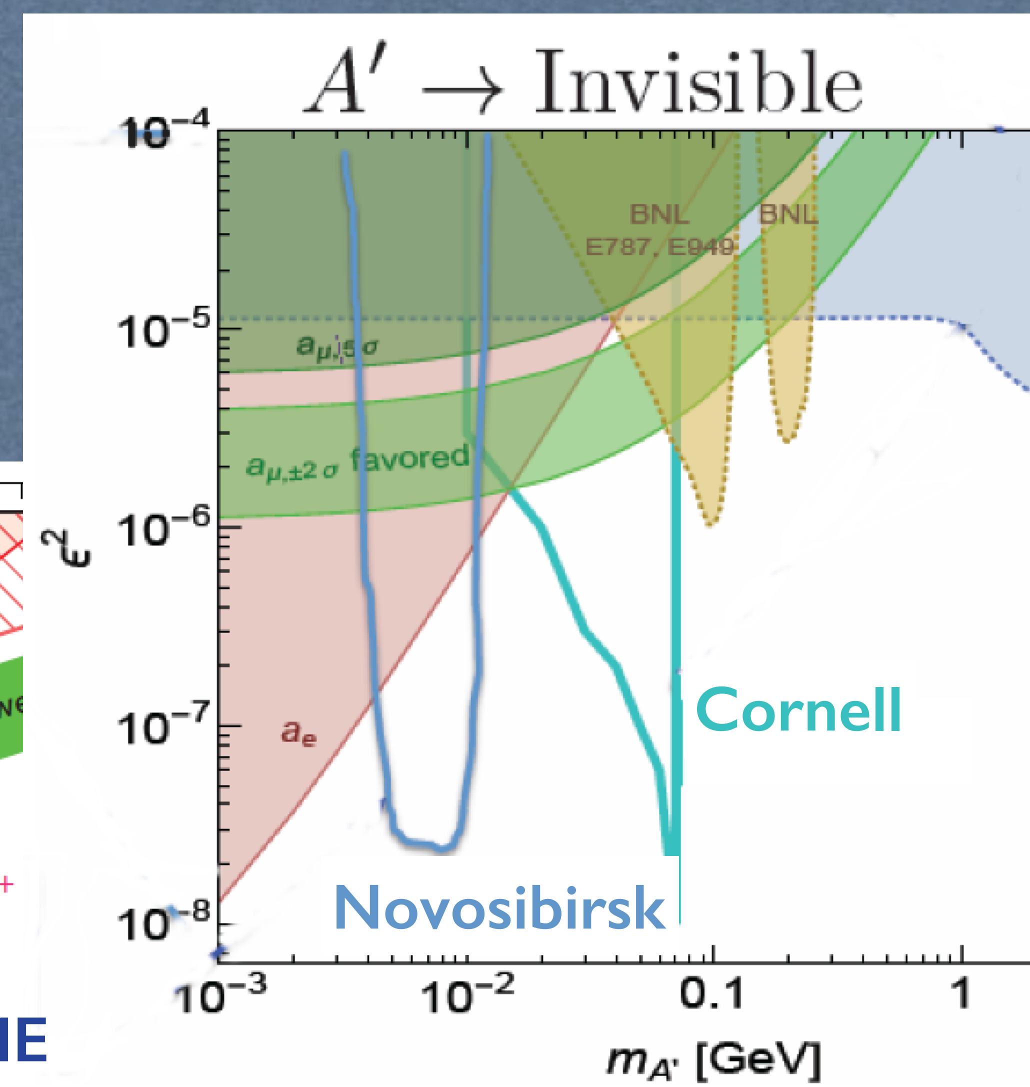
Missing mass search:

- Independent of A' decay mechanism
- Bump hunt (monophoton@collider)

- Need a positron beam
- Limited $M_{A'}$ accessible
  - 1 GeV beam: MA' < 31 MeV
  - 5 GeV beam: MA' < 71 MeV

- **Novosibirsk**
- **LNF**
- **Cornell**





VEPP3

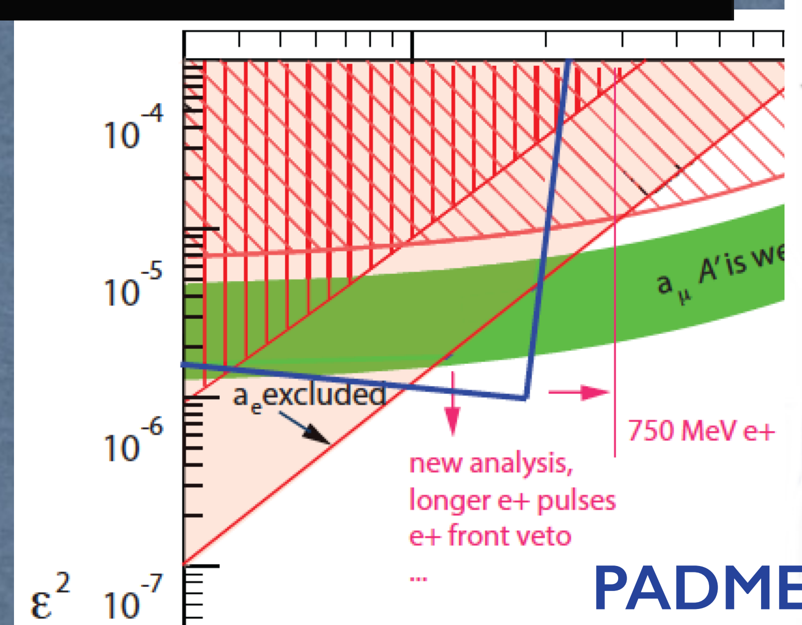
- E_{e+} = 500 MeV
- EOT ~ 10^{15} - 10^{16} year^{-1}

LNF

- E_{e+} = 550 MeV
- EOT ~ 10^{13} - 10^{14} year^{-1}

Cornell

- E_{e-} = 5.3 GeV
- EOT ~ 10^{17} - 10^{18} year^{-1}

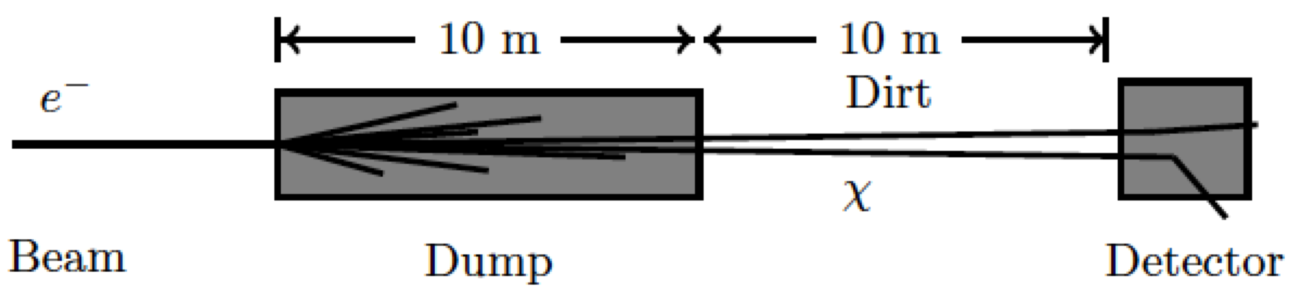


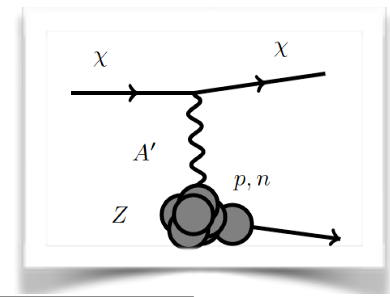
Fixed target DM production

Two steps process

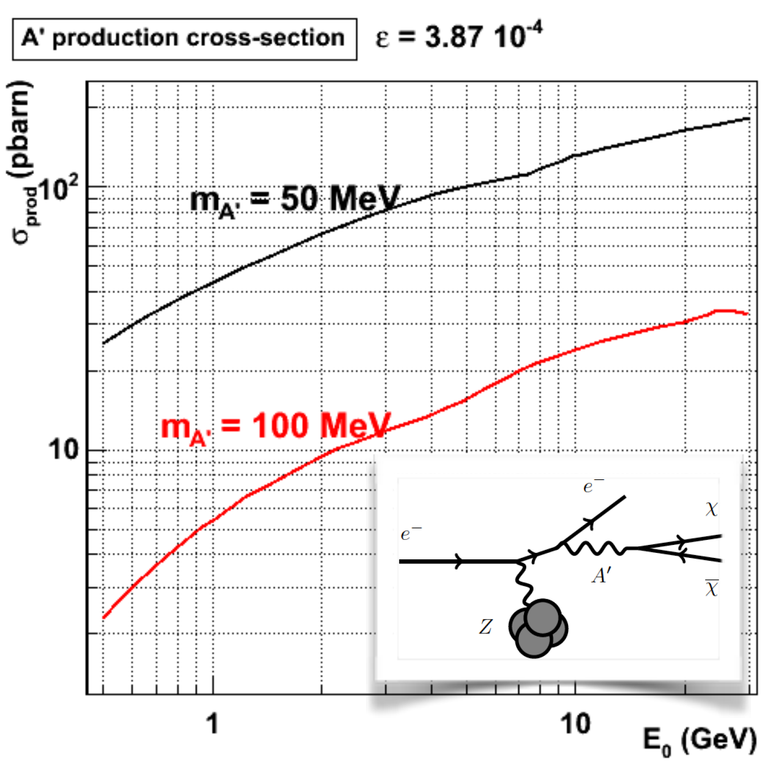
I) An electron irradiates an A' and the A' promptly decays to a χ (DM) pair

II) The χ (in-)elastically scatters on a e^-/nucleon in the detector producing a visible recoil (GeV/MeV)





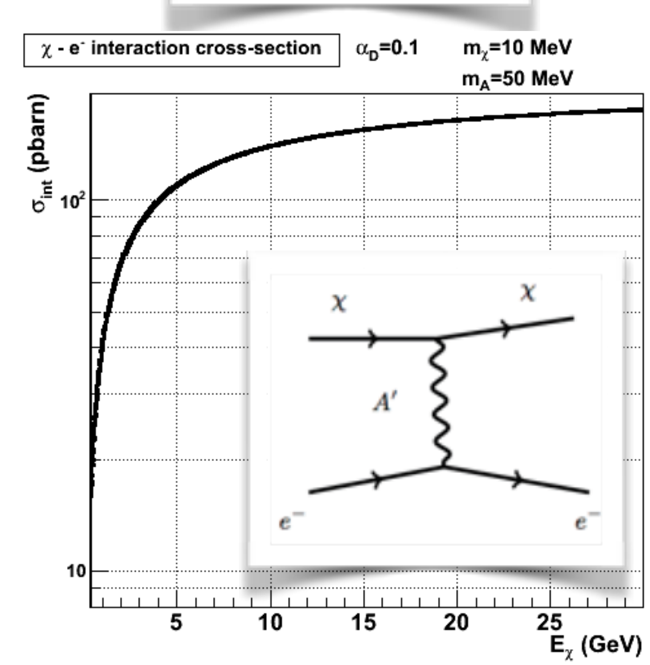
Elastic on nuclei



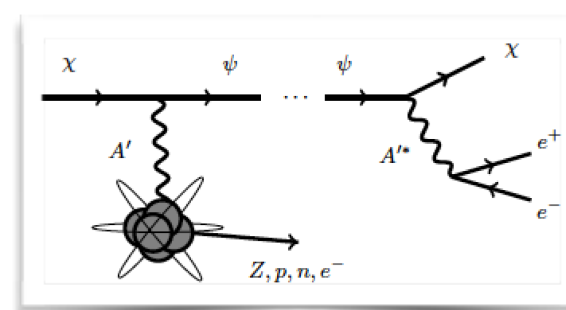
A' yield: $N_{A'} \propto \frac{\varepsilon^2}{m_{A'}^2}$

χ cross-section: $\sigma_{\chi e} \propto \frac{\alpha_D \varepsilon^2}{m_{A'}^2}$

Number of events: $N_\chi \propto \frac{\alpha_D \varepsilon^4}{m_{A'}^4}$



Elastic on electrons

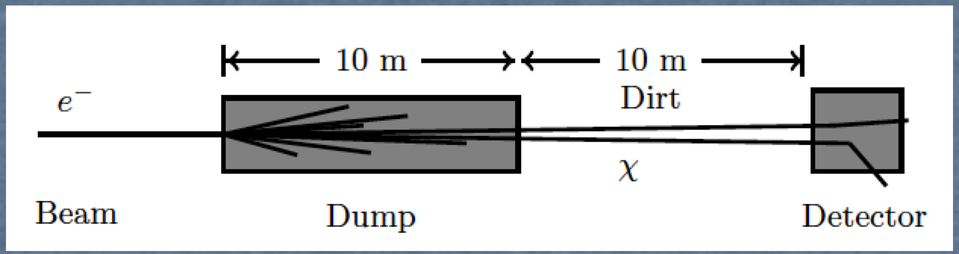


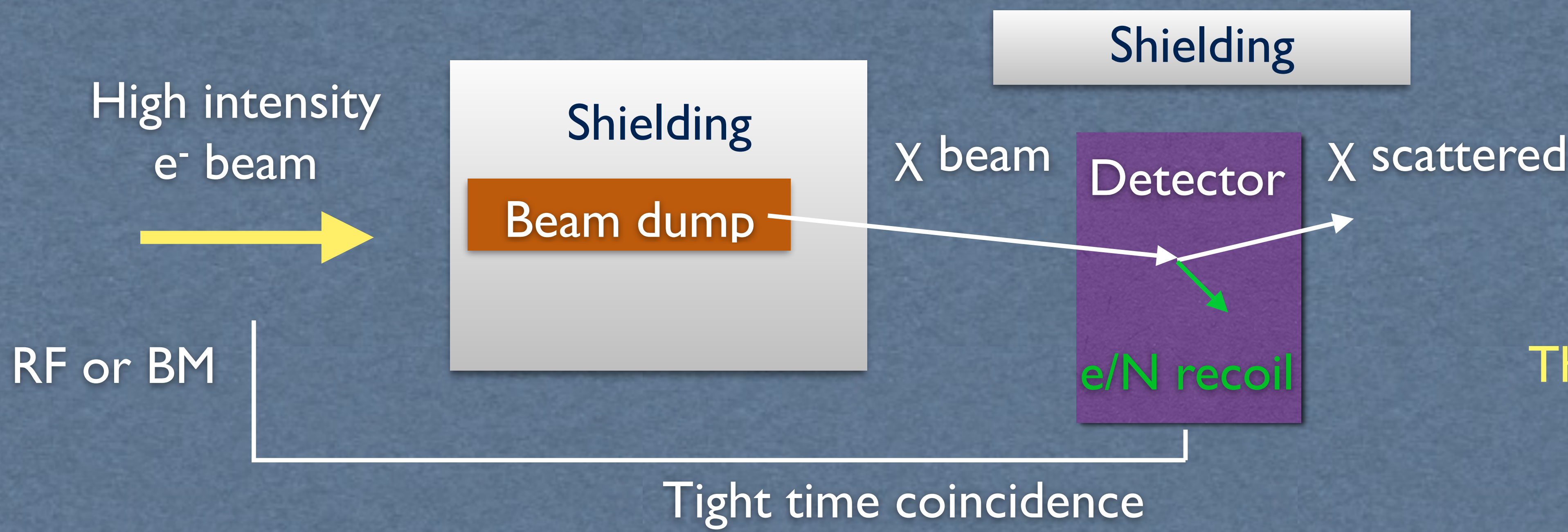
Inelastic on nuclei

- Weak Xsections dependence on E_{beam} for E>few GeV
- At low energy detector acceptance can be an issue

PhysRevD.88.114015 E.Izaguirre,G.Krnjaic, Gordan, P.Schuster, N.Toro

Experimental technique





Experimental signature:

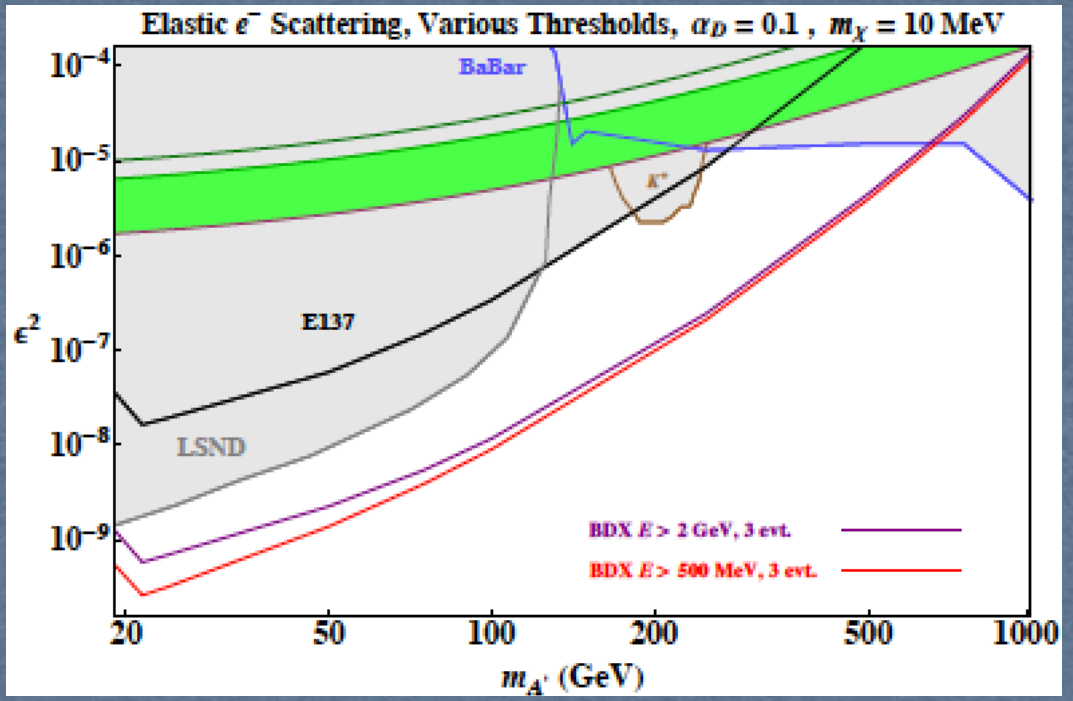
- proton (MeV)
- electron (GeV)

The simultaneous measurement of both provides a strong evidence of LDM existence

BDX@JLab reach

- 1ton detector (~2.5 m x 0.4x0.4 m2)
- 10^{22} EOT (100 uA for 6 months, full parasitic)
- realistic estimates of cosmogenic and beam-related background

At least, two orders of magnitudes better than any previous experiments

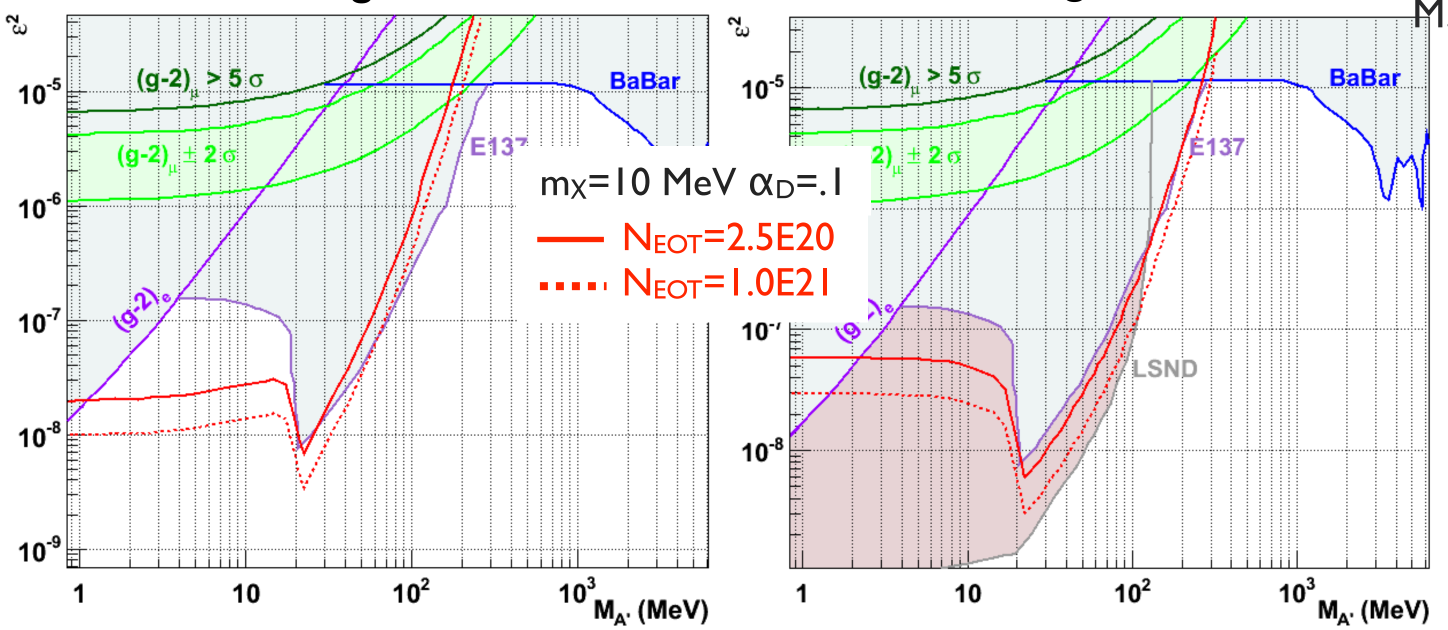


BDX runs at other facilities

BDX @ LNF

A.Celentano
M. De Napoli

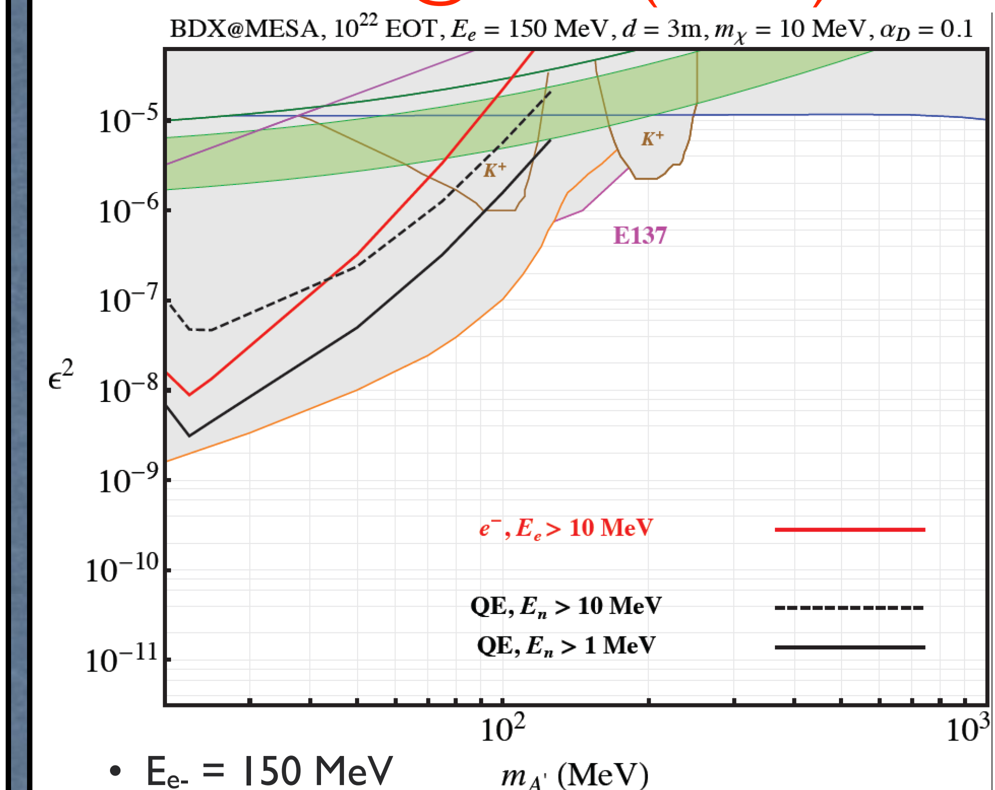
El scattering on electrons | El scattering on nucleon



- E_{e-} = 1.250 GeV (now 0.75GeV)
- EOT ~ 10^{20}-10^{21} year^{-1} (now 10^{19})
- Pulsed beam 50Hz
- Minimal infrastructure costs

- Re-use of BaBar crystals (~1080)
- Detector: 60x60x225 cm3 at 5m from the dump
- 1y run (within PADME Experiment)
- 2-3y from now

BDX@Mainz (MESA)



- E_{e-} = 150 MeV
- EOT ~ 10^{22}
- CW beam (3ns)
- Infrastructure costs limited
- Time line ?

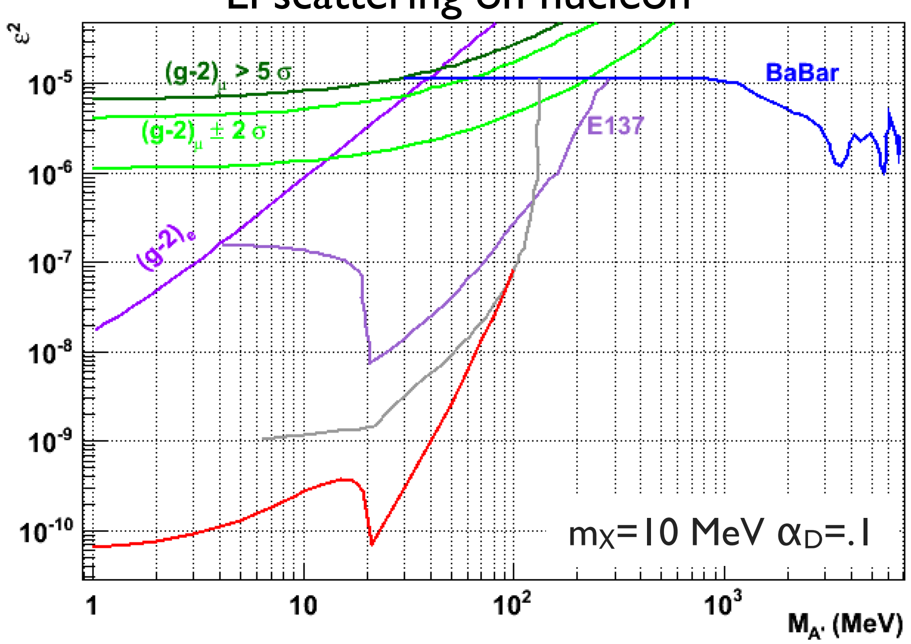
- Re-use of BaBar crystals (~1080)
- Detector: 60x60x225 cm3 at 3m from the dump
- 3y run (parasitic to PV exp)

- Proposal submitted

A.Denig

BDX@Cornell

El scattering on nucleon



- E_{e-} = 286 MeV
- EOT ~ 2.5 10^{24}
- CW beam
- Infrastructure costs ?
- Time line ?

- Re-use of BaBar or Cleo crystals (~1080)
- Detector: 60x60x225 cm3 at 5m from the dump

??? Not applicable for *energy recovery* beam ???

J.Alexander

BDX@SLAC

- E_{e-} = 20 GeV
- EOT ~ 10^{22}
- Pulsed beam 180Hz
- Infrastructure costs limited
- Time line ?

Putting LDM search into context

Report of the Particle Physics Project Prioritization Panel (P5) (May '14)

Premises

... **The dark matter may be composed of ultra-light (less than a GeV), very weakly interacting particles. Searches for such states can be carried out with high-intensity, low-energy beams available at Jefferson Lab or with neutrino beams aimed at large underground detectors.**

Recommendations

Dark Matter

The experimental challenge of discovery and characterization of dark matter interactions with ordinary matter requires a multi-generational suite of progressively more sensitive and ambitious direct detection experiments. This is a highly competitive, rapidly evolving field with excellent potential for discovery. **The second-generation direct detection experiments are ready to be designed and built, and should include the search for axions, and the search for low-mass (<10 GeV) and high-mass WIMPs.** Several experiments are needed using multiple target materials to search the available spin-independent and spin-dependent parameter space. This suite of experiments should have substantial cross-section reach, as well as the ability to confirm or refute current anomalous results. Investment at a level substantially larger than that called for in the 2012 joint agency announcement of opportunity will be required for a program of this breadth.

Recommendation 19: Proceed immediately with a broad second-generation (G2) dark matter direct detection program with capabilities described in the text. Invest in this program at a level significantly above that called for in the 2012 joint agency announcement of opportunity.

Conclusions

- ✳Existence of Dark Matter is a compelling reason to investigate new forces and matter over a broad range of masses
- ✳Strong physics motivation for the possible existence of MeV-GeV dark photon
- ✳Visible A' decay searches are excluding a significant part of parameters space
- ✳Invisible A' decay represents a straightforward extension of the minimal model
- ✳Light Dark Matter (coupled to A' invisible decay) could explain null results resetting experimental limits
- ✳Accelerator-based (Light)DM search provides unique feature of distinguish DM signal from any other cosmic anomalies or effects
- ✳Extensive experimental plans at high intensity e-facility: JLab, LNF, Cornell, Mainz
- ✳Discovery or decisive tests will possible in the next ~5-8 years!