Search for New Physics at Medium Energy

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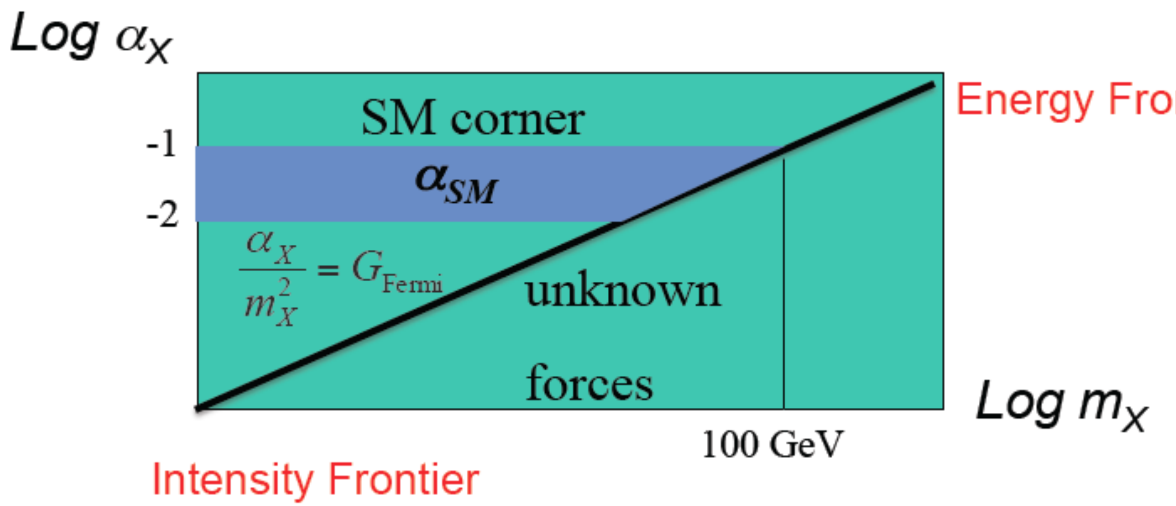
How to Search for New Physics



LHC regime: m_X~1TeV, a_X~a_{SM}

First results show no hints of new strongly-interacting states or new heavy EW bosons (other than Higgs)

What about if: m_X~1GeV, $a_X<10^{-6}$?

Search for new physics at medium energy

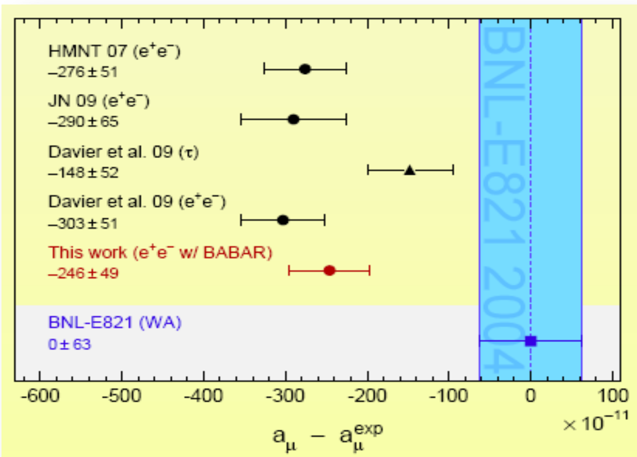
Small effects…high precision and high intensity

Precision experiments at low or medium energy!

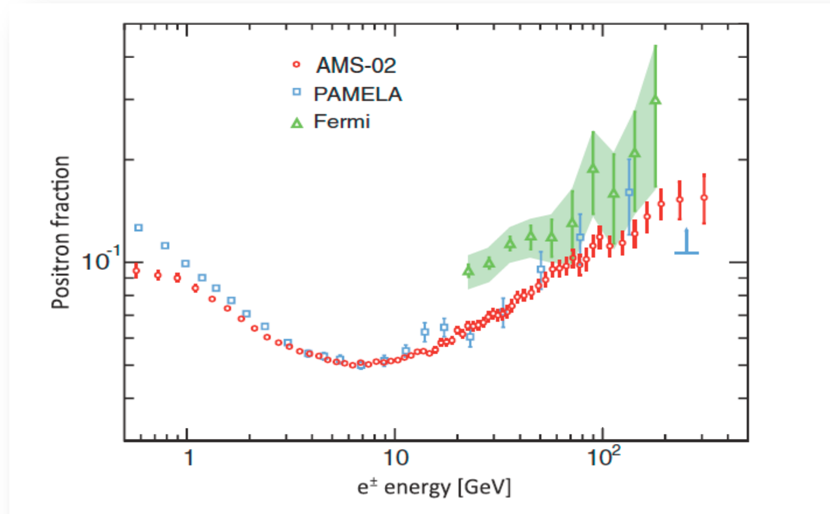
Hints of New Physics…

Indications for (potentially) new physics from anomalies…

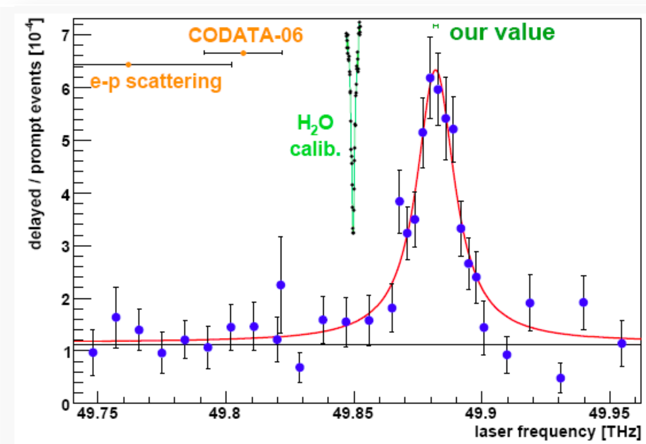
g-2 of muon



Positron and antiproton abundance



muonic hydrogen Lamb shift



$$\boxed{r_p = 0.84184(67)\ \text{fm} \qquad u_r^{th} = 8 \times 10^{-4}}$$

CODATA 2006: $r_p = (0.8768 \pm 0.0069)$ fm, from H

e-p scattering: $r_p = (0.895 \pm 0.018)$ fm (2%)

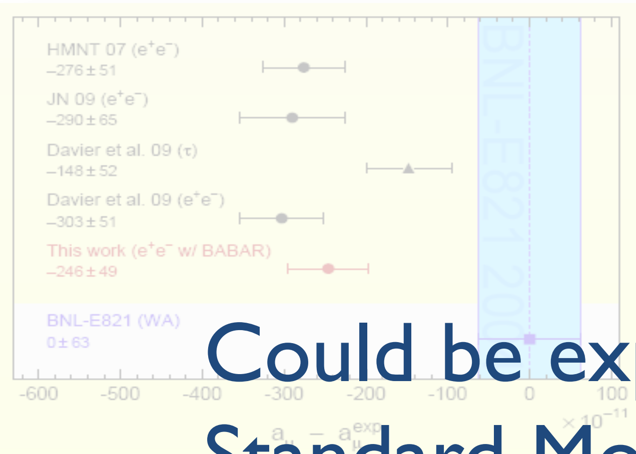
★ Muon 200 times closer to p (w.r.t. hydrogen)

★ New forces for muon?

Hints of New Physics…

Indications for (potentially) new physics from anomalies…

g-2 of muon



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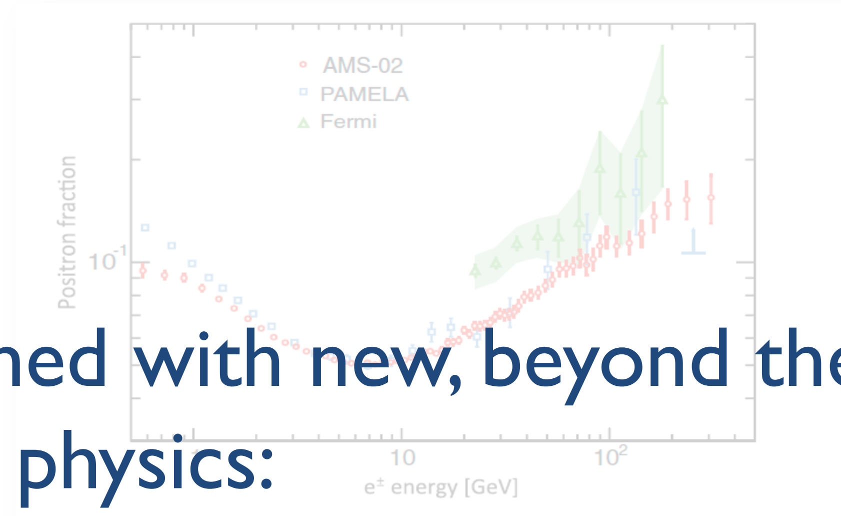
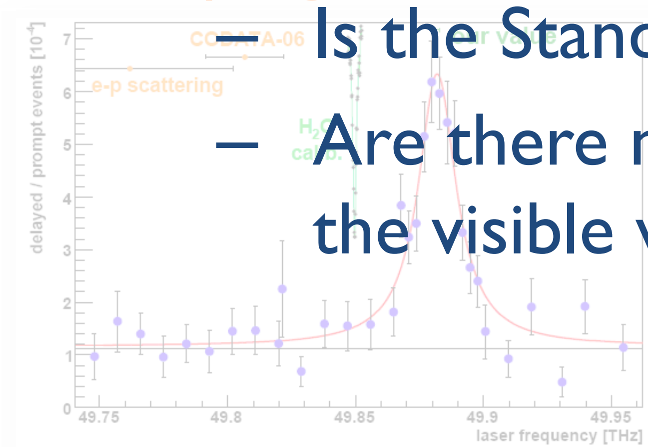


muonic hydrogen Lamb shift



★ Muon 200 times closer to p (w.r.t. hydrogen)

★ New forces for muon?

Could be explained with new, beyond the Standard Model, physics:

– Is the Standard Model correct?

– Are there new forces and particles that affect the visible world?

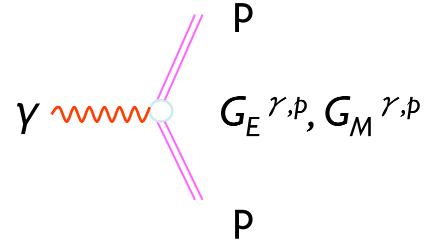
Electro-Weak Couplings and SM Tests

Electroweak charged fermion couplings

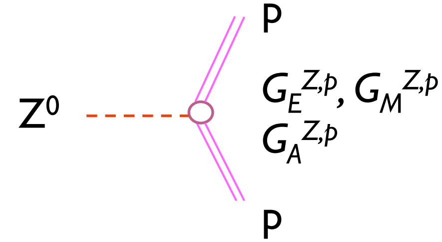
	q^γ	q^Z	a^Z
e	-1	$-(1-4\sin^2\theta_W)$	$+1$
u	$\frac{2}{3}$	$1-\frac{8}{3}\sin^2\theta_W$	-1
d	$-\frac{1}{3}$	$-1+\frac{4}{3}\sin^2\theta_W$	$+1$
s	$-\frac{1}{3}$	$-1+\frac{4}{3}\sin^2\theta_W$	$+1$

★ $Q_W^p = 1 - 4\sin^2 q_W$ ~ 0.071(SM)
★ $Q_W^n = -1$

Electromagnetic interaction



Neutral weak interaction



$$G_E^\gamma = \frac{2}{3}G_E^u - \frac{1}{3}G_E^d - \frac{1}{3}G_E^s$$

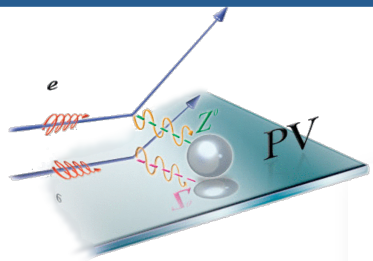
$$G_M^\gamma = \frac{2}{3}G_M^u - \frac{1}{3}G_M^d - \frac{1}{3}G_M^s$$

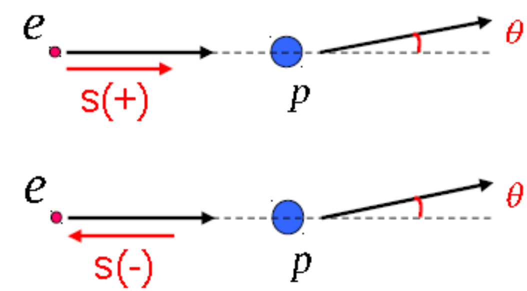
$$G_{E,M}^Z = (1-\frac{8}{3}\sin^2\theta_W)G_{E,M}^u + (-1+\frac{4}{3}\sin^2\theta_W)G_{E,M}^d + (-1+\frac{4}{3}\sin^2\theta_W)G_{E,M}^s$$

Access to rich physics:

- Novel Probes of Nucleon Structure
- Strange Quark Form Factors
- Neutron skin of a heavy nucleus
- Indirect Searches for New Interactions

Parity Violating Electron Scattering





Electromagnetic (PC) + Neutral-weak (PV)

Using Isospin symmetry ($p \leftrightharpoons n$) A_{PV} is expressed as a combination of strange-quark G^s_M and G^s_E only

Parity-Violating Asymmetry: $A_{PV} \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$

$$A_{PV}(p) = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\left[\frac{\epsilon G_E G_E^Z + \tau G_M G_M^Z - (1-4\sin^2\theta_W)\epsilon' G_M G_A^Z}{\epsilon (G_E)^2 + \tau (G_M)^2}\right]$$

Forward angles *Backward angles*

As $Q^2 \to 0$, $\theta \to 0$:

$$A_{PV}(p) \Rightarrow \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\left[Q_W^p + Q^2 B(Q^2)\right]$$

~230 ppb

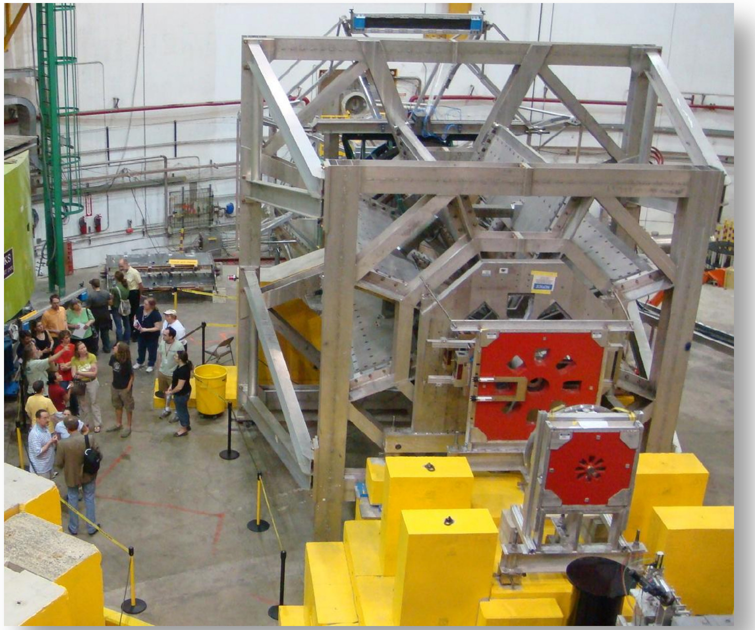
Leading order term: $Q_W^p\ (E)$

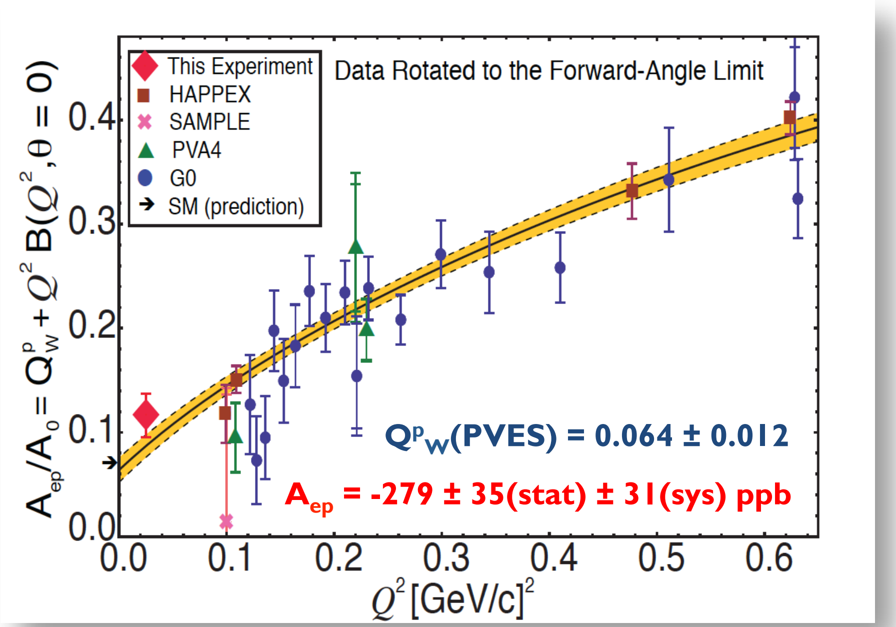
$B(Q^2)$: contains $G^{\gamma}_{E,M}$, $G^{Z}_{E,M}$ which are constrained by previous PC and PV form factor measurements

Qweak at Jefferson Lab

"A Search for New Physics at the TeV scale via a Measurement of the Proton's Weak Charge"

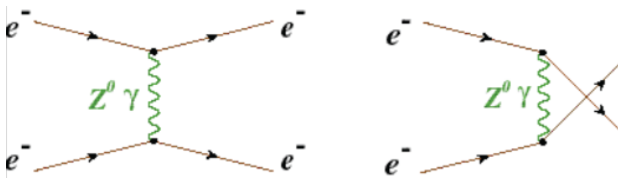
- Parity violating elastic electron-proton scattering at Jefferson Lab
- First direct measurement of the proton's weak charge Q^p_W and determination of $\sin^2\theta_W$ at low Q^2 (δ~5% goal)
- Analysis of commissioning run (4% of exp. statistics)





Future experiments at JLab: MOLLER

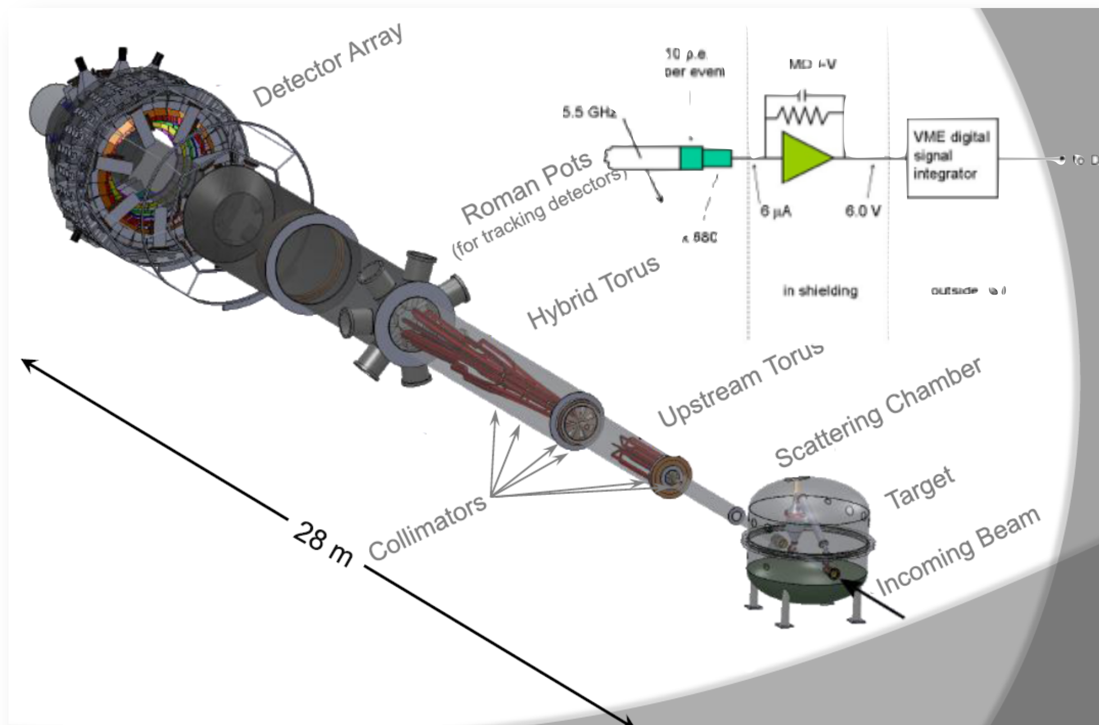
Measurement Of Lepton Lepton Elastic Reaction (Q^e_w measurement)



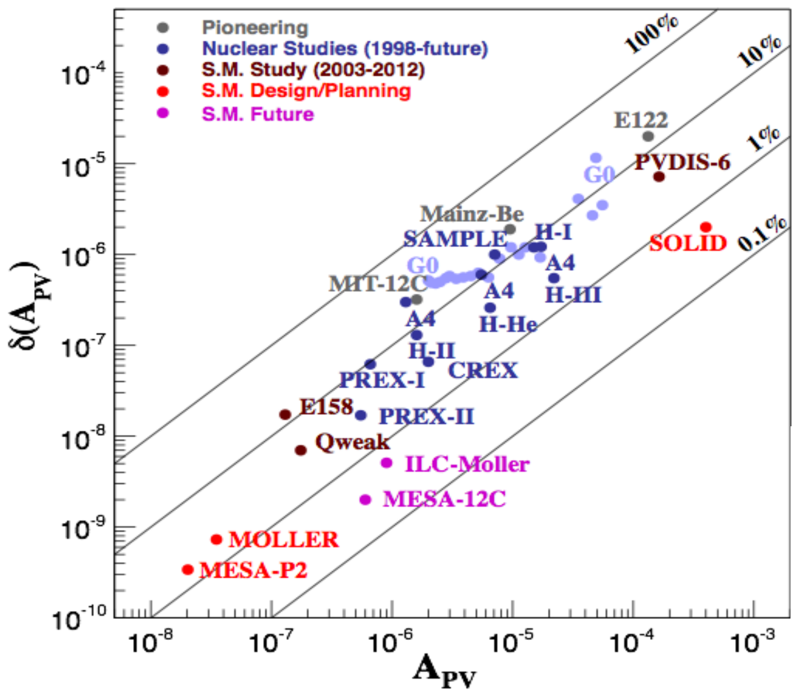
$Q^e_w=(1-4\sin^2\theta_W)$
+ 1-loop corrections

$$A_{PV} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\theta}{(3+\cos^2\theta)^2}Q^e_W$$ ~30 ppb

- Purely leptonic probe
- Unprecedented polarized luminosity and beam stability
- 11 GeV, 75 uA, P >85%
- Expected rate: ~150 GHz, <10% bg
- 5kW dissipated power on H2 target
- e-p elastic scattering bg suppression
- Goal: δA/A~2%

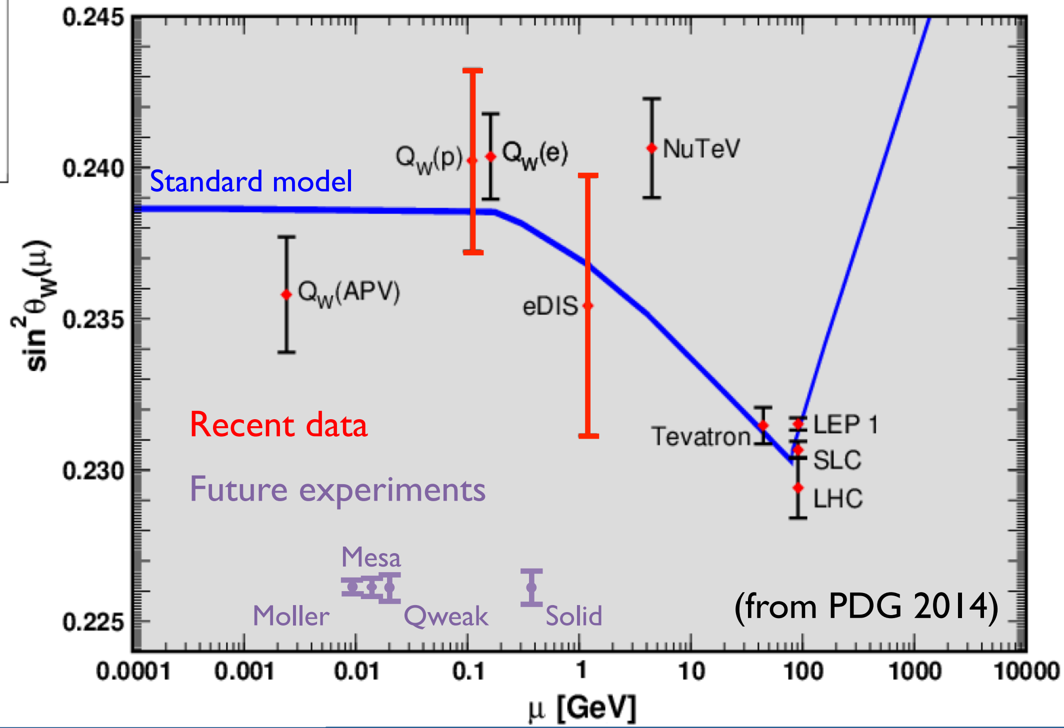


Testing the Standard Model



New experiments planned in near future will reach a precision of 1ppb in PV asymmetries

Measurements at GeV scale can be sensitive to new physics at the TeV scale

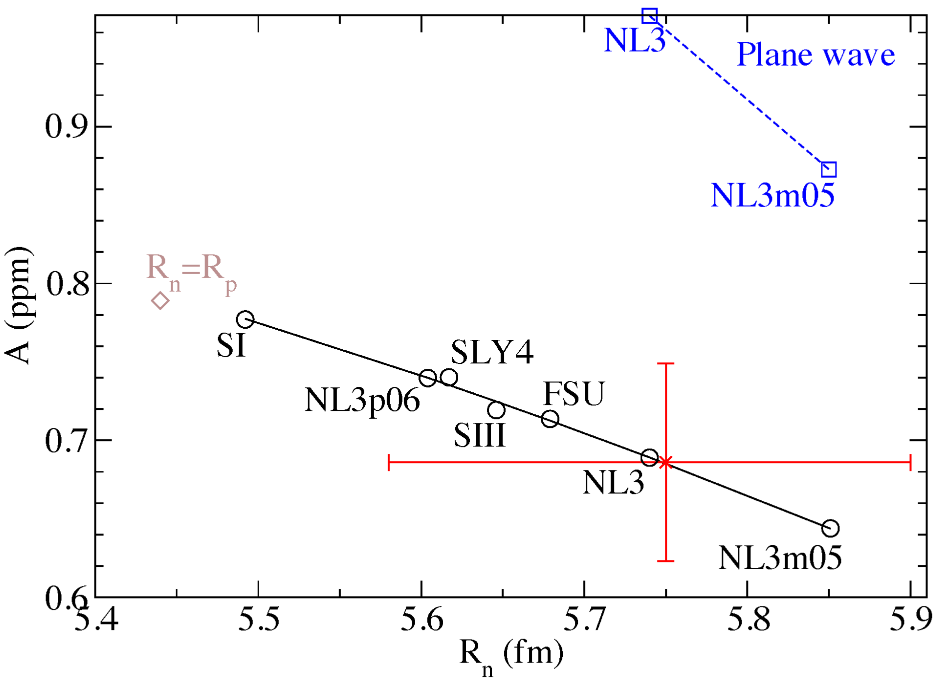


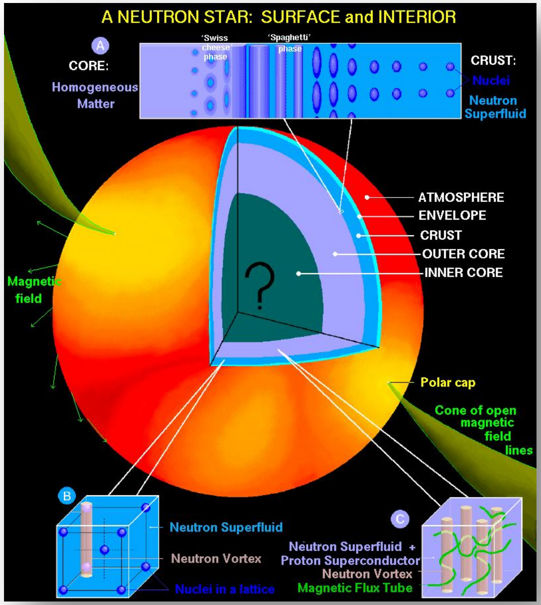
Lead (^{208}Pb) Radius Experiment: PREX

Parity Violating Electron Scattering from Nuclei
Exploit weak coupling of the neutron

First measurement:
clear indication of neutron skin

Future measurement:
constrain symmetry equation of state





A neutron skin of 0.2 fm or more has implications for our understanding of neutron stars and their ultimate fate.

^{48}Ca experiment also approved at Jlab
Parallel program at Mainz MESA facility

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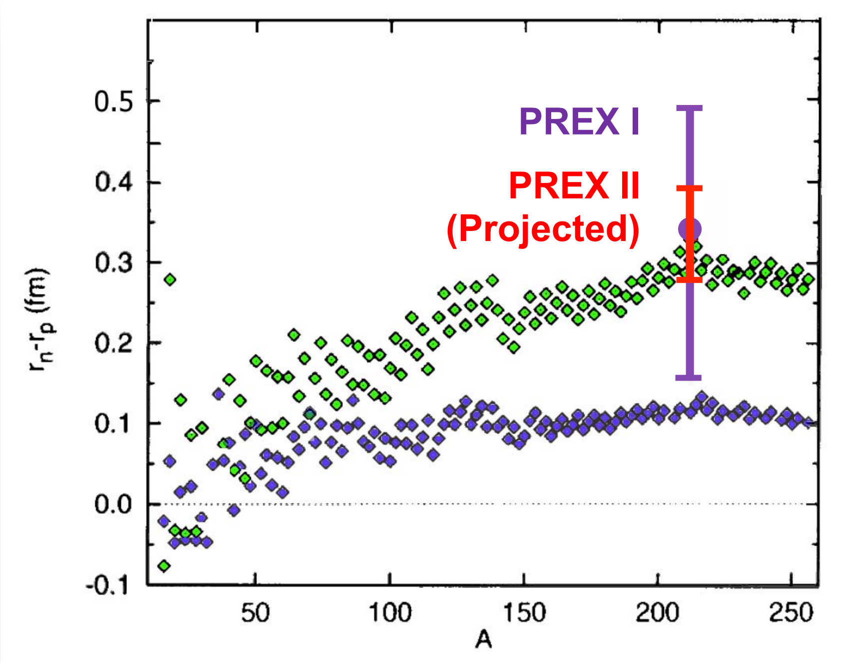
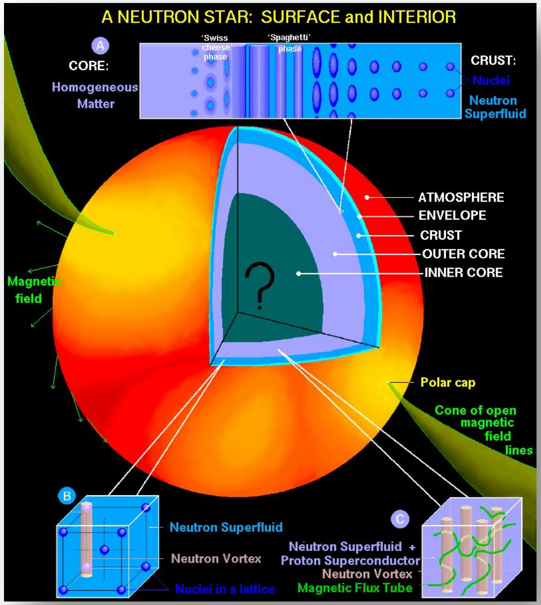


Relativistic mean field

Non-relativistic skyrme



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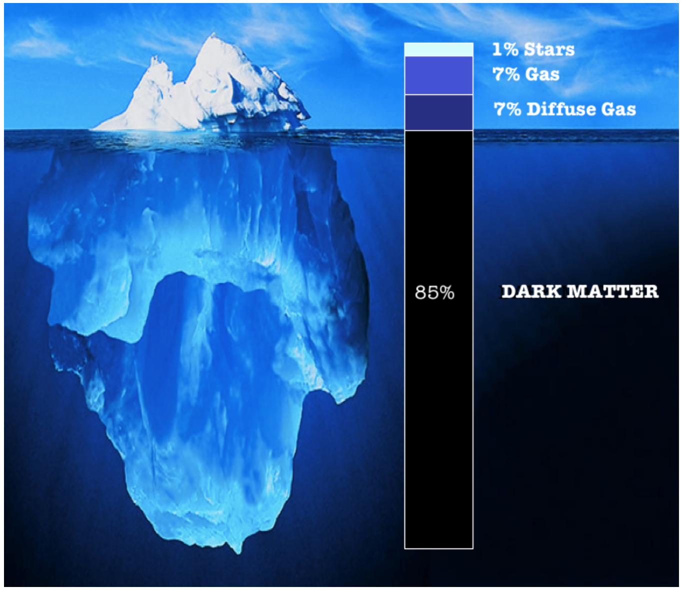
Parallel program at Mainz MESA facility

Dark Matter vs. Baryonic Matter

Compelling astrophysical indications about DM existence



★ Does DM participate to non-gravitational interactions?

★ Is DM a new particle?

- ★ Constraint on DM mass and interactions:
  - should be "dark" (no EM interaction)
  - should weekly interact with SM particles
  - should provide the correct relic abundance
  - should be compatible with CMB power spectrum

  … assuming that the gravity is not modified and DM undergoes to other interactions
- ★ We can use what we know about standard model particles to build a DM theory

Use the SM as a template: $SM = U(1)_{EM} \times SU(2)_{Weak} \times SU(3)_{Strong}$

Particles, interactions and symmetries

known particles & force-carriers

particles:
quarks, leptons

force-carriers:
gluons, γ, W, Z, graviton (?), Higgs, …

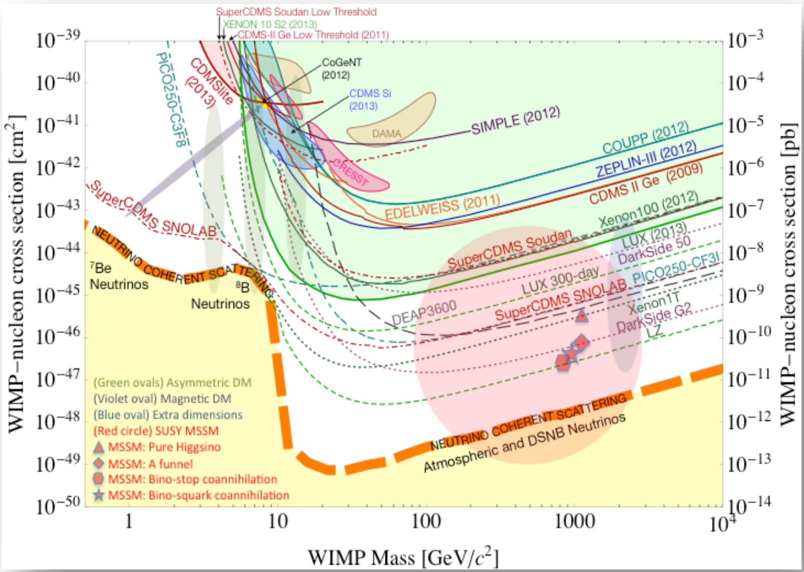
Two options:

★ New matter interacting through the same forces

★ New matter interacting through new forces

Weakly Interacting Massive Particles

Limits on DM_{Xsec} vs. DM_{Mass} from Direct Detection

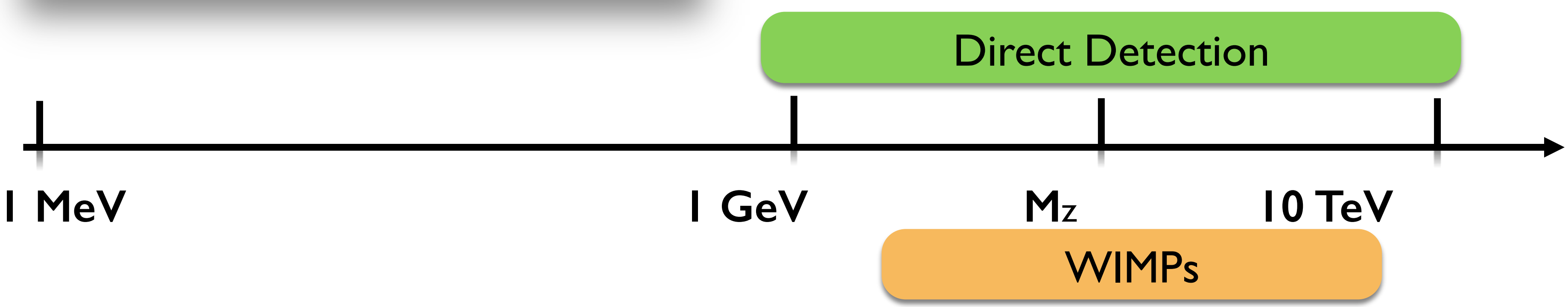


The WIMPs paradigm:

- slowly-moving cosmological Weakly Interacting Massive Particles interacting with the SM-Weak force
- DM detection by nuclear recoil
- Experiments optimized for heavy DM (M>10 GeV)

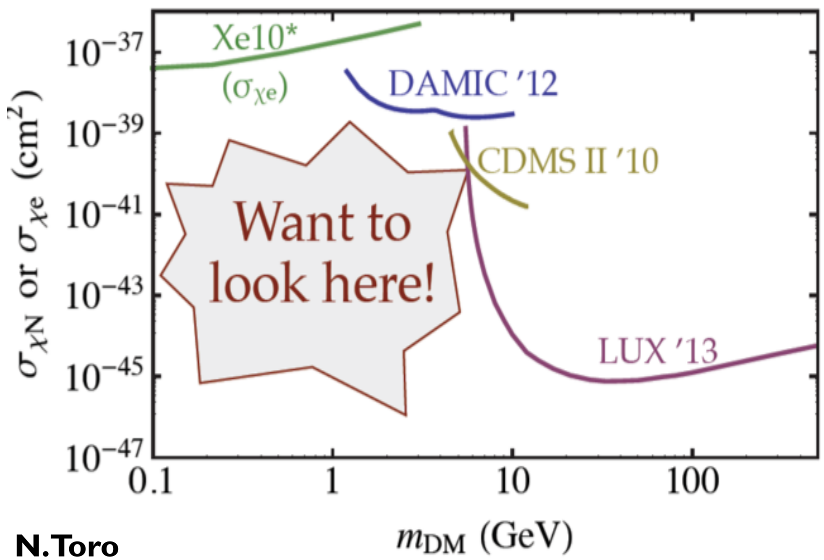
No (firm) evidence (so far):

- weak-interaction at tree level ruled-out
- exp. limits close to irreducible neutrino background



WIMPs paradigm is not the only theoretically well-motivated option
Light DM: extending the search to unconventional (and unexplored!) territory

Hunting for Dark Matter: light DM



N.Toro

Dark/Hidden Sector
Light Dark Matter couples to SM with a new force

- Light Dark Matter (χ) in 1-1000 MeV mass range
- New vector boson (A') responsible for DM-DM and DM-SM interaction
- (Traditional) Direct Detection is (almost) impossible

Accelerator-based DM search

- ★ High intensity
- ★ Medium energy

Unexplored territory | Direct Detection

1 MeV — 1 GeV — M_Z — 10 TeV

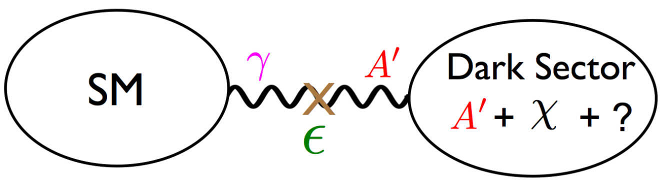
Light Dark Matter | WIMPs

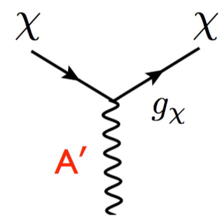
Dark Sector or Hidden Sector
DM not directly charged under SM interactions

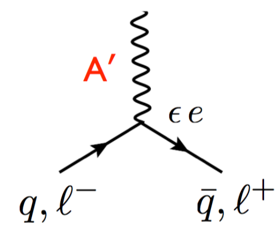
Can be explored at accelerators!

Dark Forces & Dark Matter

(Light DM - Light Mediators)



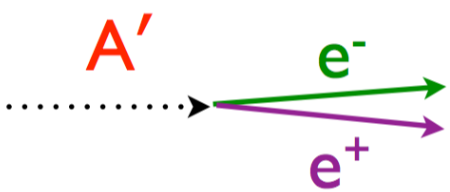




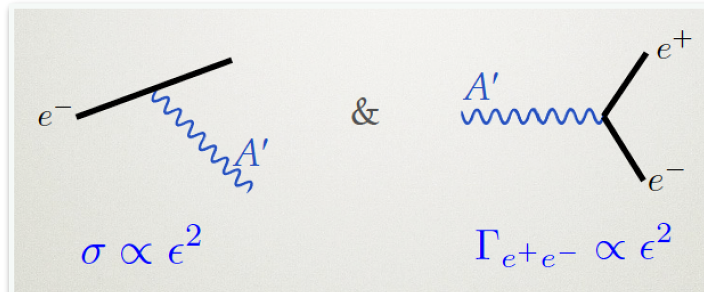
4 parameters:

- m_χ, $m_{A'}$, ε, α_D
- m_χ, $m_{A'}$: MeV - GeV

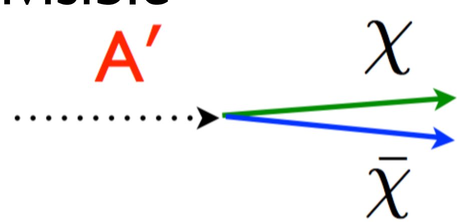
Visible



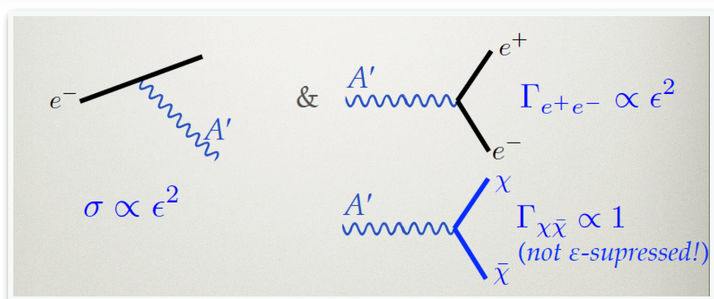
- *Minimal decay*
- Decay regulated by ε^2
- Independent of m_χ
- Requires $m_{A'} < 2m_\chi$ (on-shell)



Invisible



- Depends on 4 parameters
- $m_{A'} > 2m_\chi$ (on-shell)
- $\alpha_D = g^2_\chi/4\pi >> \varepsilon^2\alpha_{EM}$



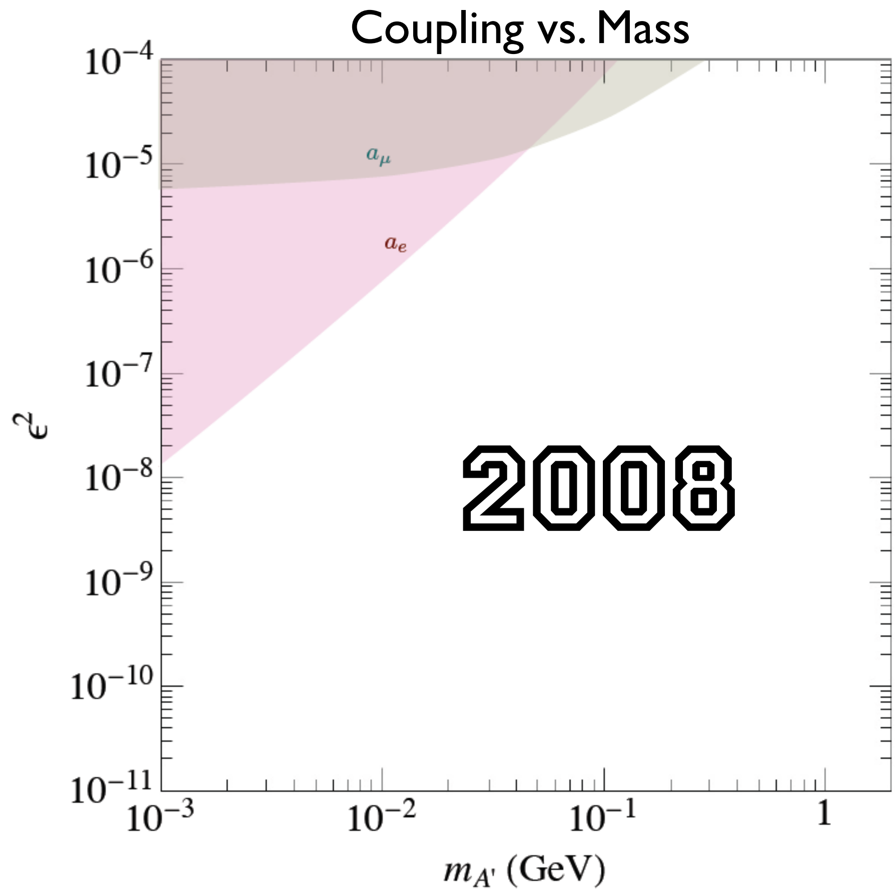
Hunting for the Dark Photon: visible decays

Fixed target: e N → e N A' → e N l^+l^-
→ **JLAB, MAINZ**

Fixed target: p N →N A'→ p l^+l^-
→ **FERMILAB, SERPUKHOV**

Annihilation: e^+e^- → A' γ → l^+l^- γ
→ **BABAR, BELLE, KLOE, CLEO**

Meson decays: π^0, η, η', ω, ϕ → A' γ (M)
→l^+l^- γ (M)
→**KLOE, BES3, WASA-COSY, PHENIX, NA48, LHCb**



Hunting for the Dark Photon: visible decays

Fixed target: $e\,N \rightarrow e\,N\,A' \rightarrow e\,N\,l^+l^-$

➔ **JLAB, MAINZ**

Fixed target: $p\,N \rightarrow N\,A' \rightarrow p\,l^+l^-$

➔ **FERMILAB, SERPUKHOV**

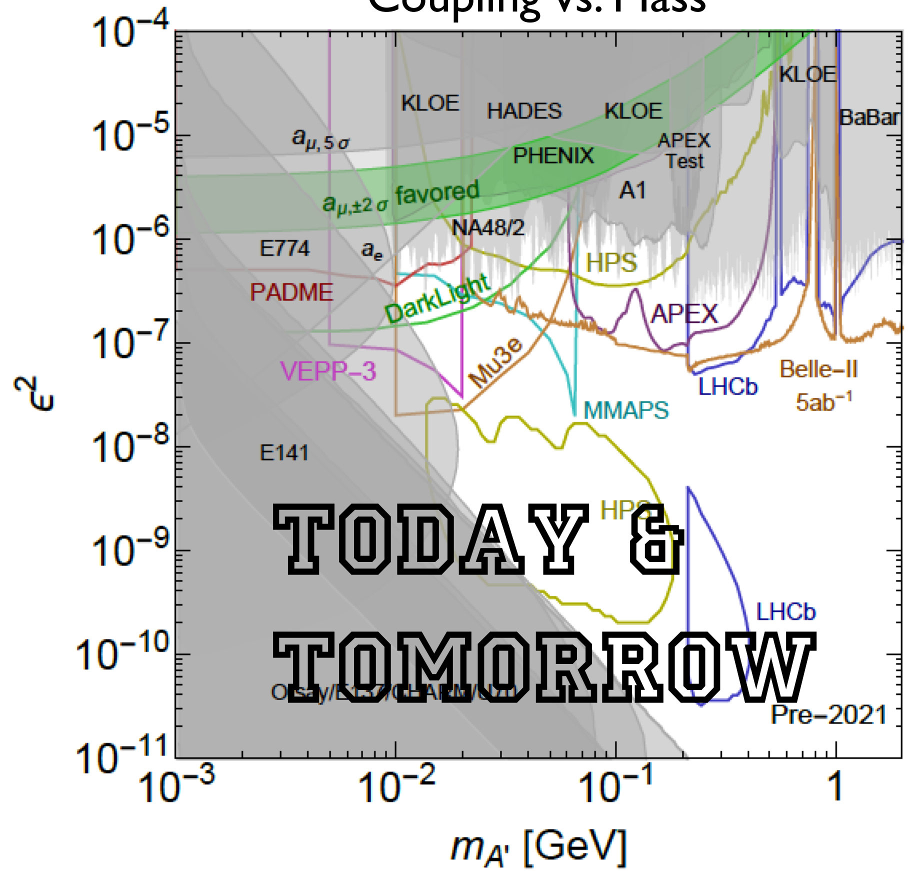
Annihilation: $e^+e^- \rightarrow A'\,\gamma \rightarrow l^+l^-\,\gamma$

➔ **BABAR, BELLE, KLOE, CLEO**

Meson decays: $\pi^0, \eta, \eta', \omega, \phi \rightarrow A'\,\gamma\,(M)$
$\rightarrow l^+l^-\,\gamma\,(M)$

➔**KLOE, BES3, WASA-COSY, PHENIX, NA48, LHCb**

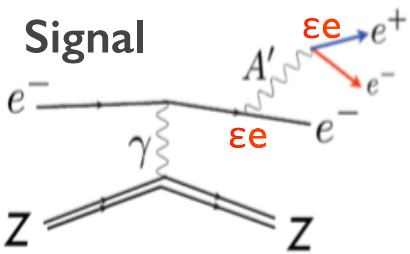
Coupling vs. Mass

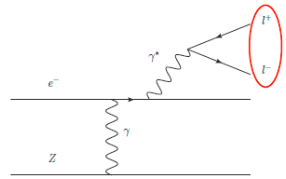


No positive signal (so far) but limits in coupling vs. mass parameter space

The Heavy Photon Search Experiment

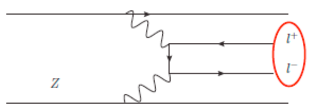
Signal

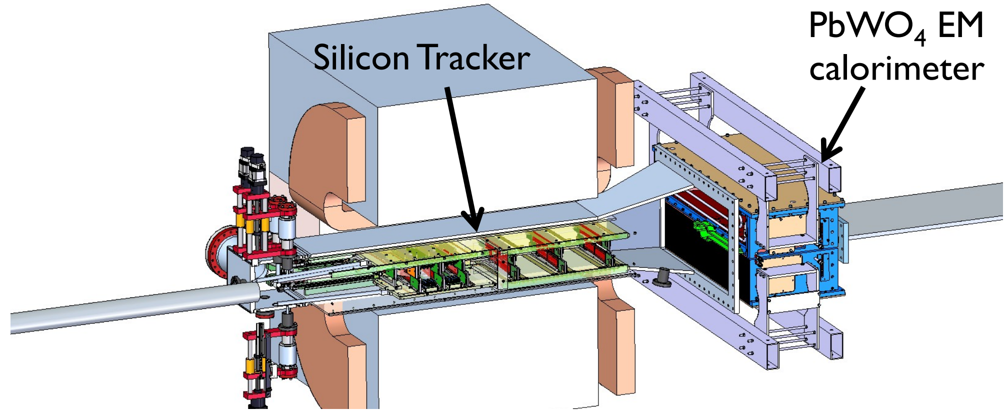


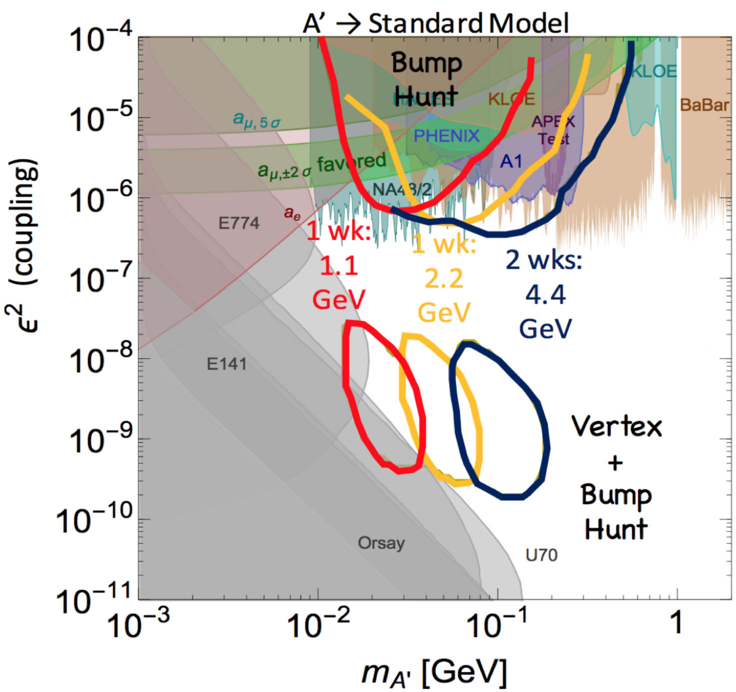


BG: "Radiative"

BG: "Bethe-Heitler"







HPS search strategy:

- *Bump hunt*: peak in the e^+e^- invariant mass spectrum (mass resolution 1 MeV)
- *Displaced vertex*: e^+e^- detached from primary vertex (target) for long-lived A'

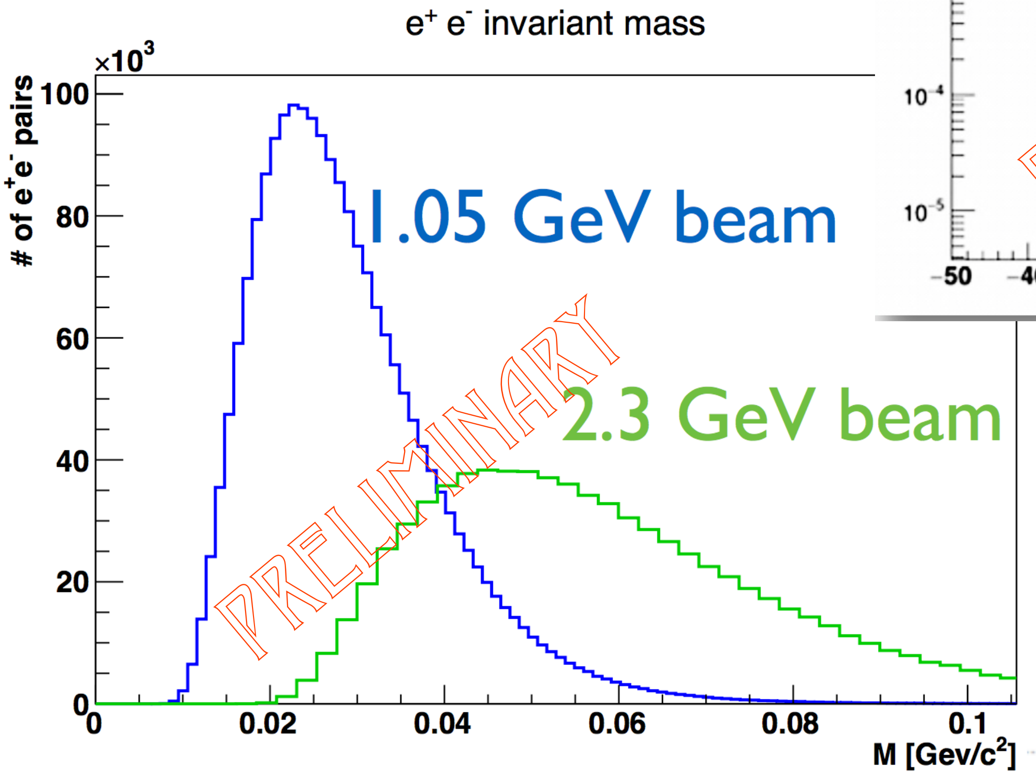
HPS Status:

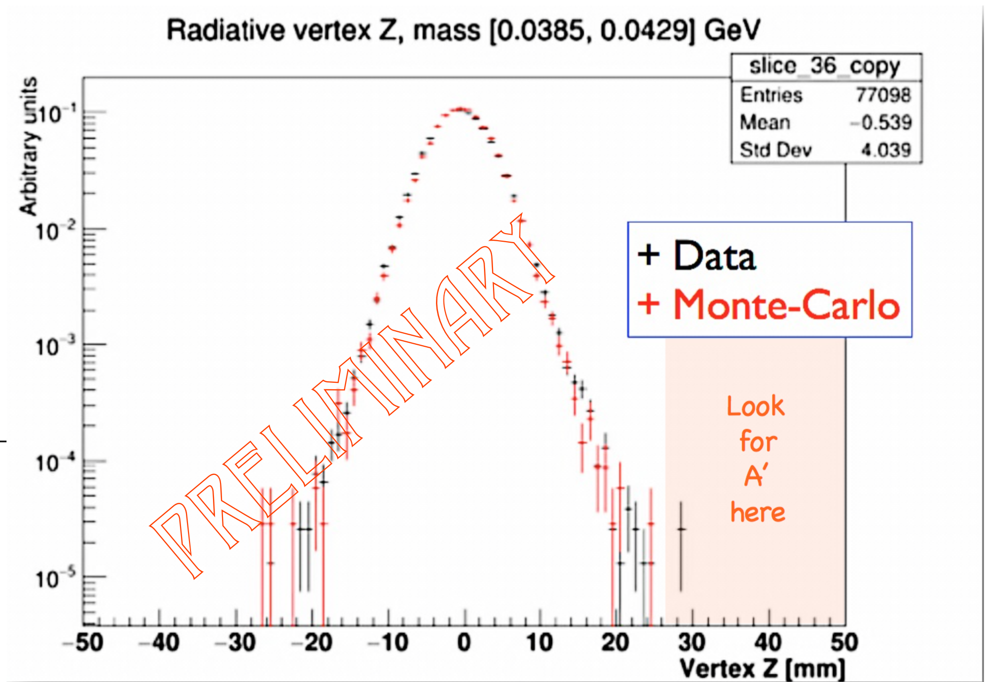
- 180 approved days at 1.1, 2.2 and 4.4 GeV in Hall B at JLab
- Commissioning run successfully completed in Spring 2015: SVT at 0.5 mm from the beam
- Opportunistic running in 2015-2016 at 1.05 and 2.3 GeV
- Data analysis in progress

The Heavy Photon Search Experiment

Searching for the Heavy Photon using a blinded analysis (10% of the data) for both bump hunting and vertexing

Unblind analysis (full statistics) after finalizing procedure and freezing cuts





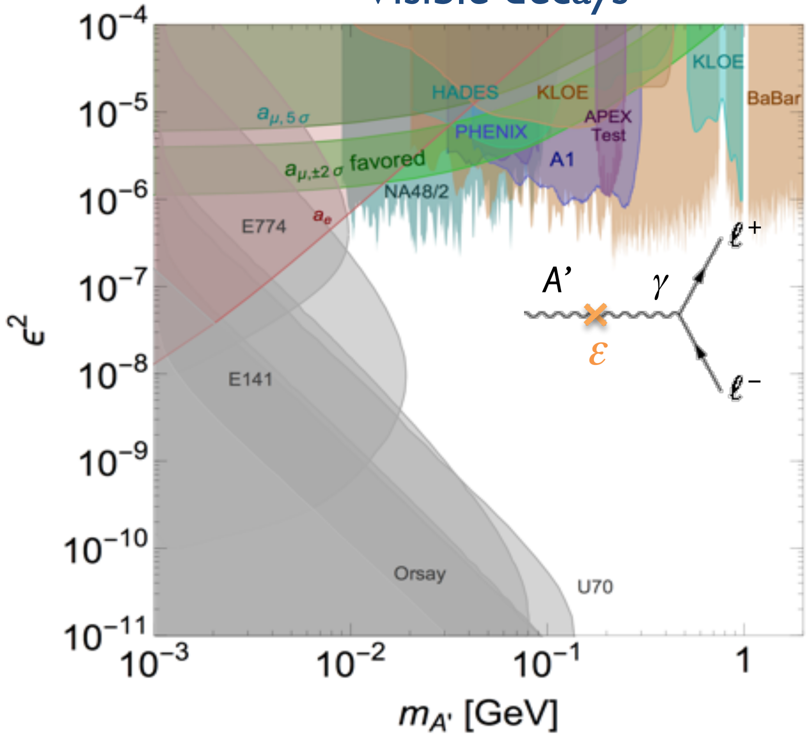
- Mass and vertex resolution in agreement with MC

- Results from 2015-2016 data in early 2017
- Detector upgrades to increase reach in progress
- Major data taking period in 2018

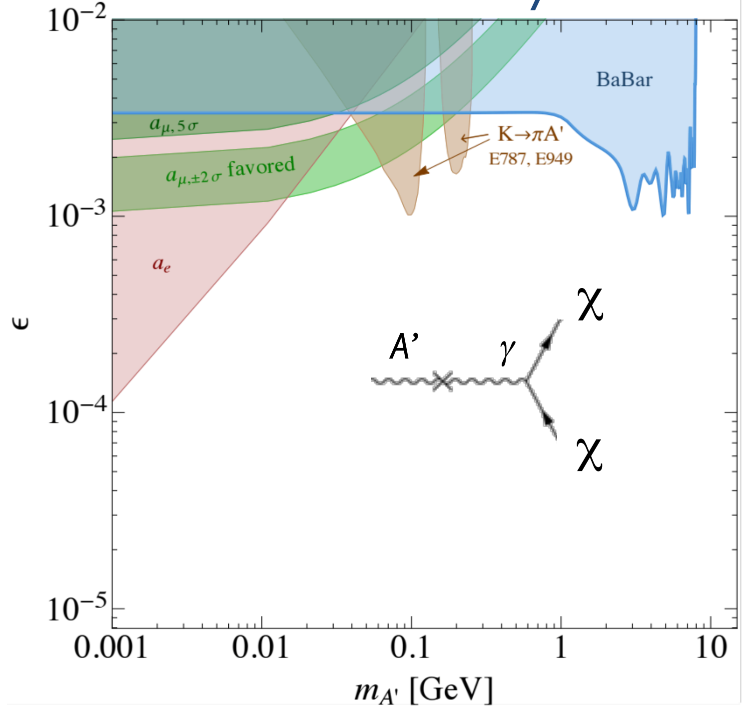
Dark Photon Invisible Decays

If any χ ($M_\chi < M_{A'}/2$) exists, A’ will decay into dark sector particles: very few model independent measurement are available in this scenario

Visible decays

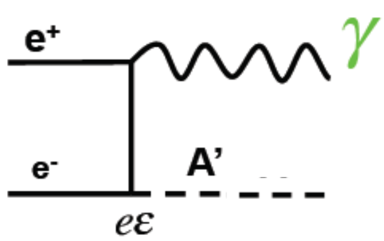


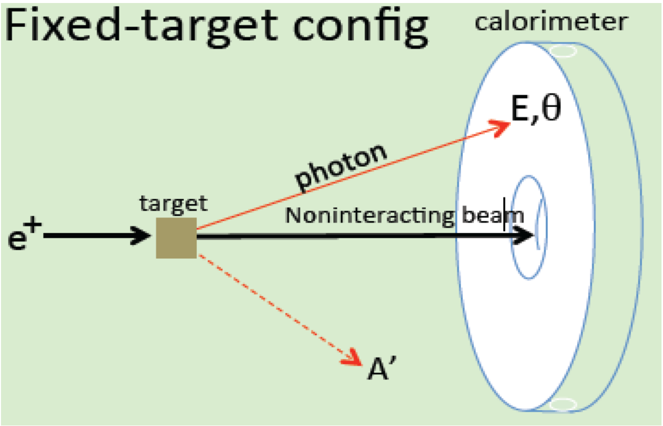
Invisible decays



Two experimental methods:
- missing mass A’ search
- dark matter χ scattering searches

Dark Photon Invisible Decays





Missing mass search:
- Independent of A' decay mechanism
- Bump hunt

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

VEPP3 @ Novosibirsk

E_{e+} = 500 MeV

EOT ~ 10^{15} - 10^{16} year^{-1}

PADME @ LNF

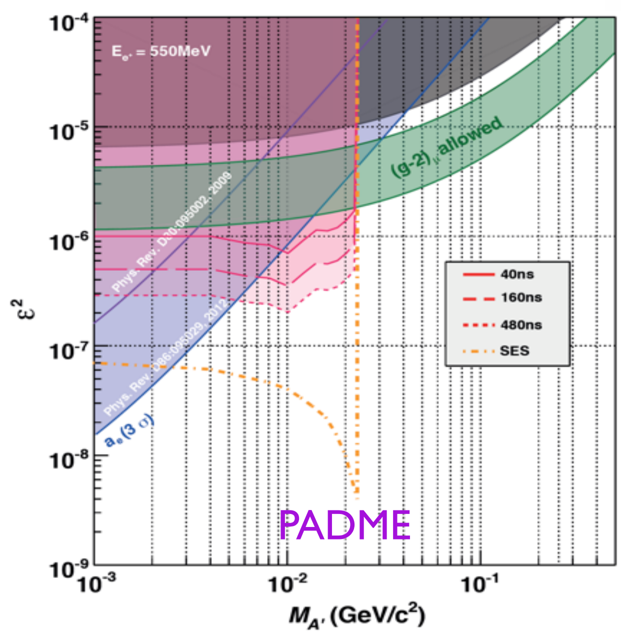
E_{e+} = 550 MeV

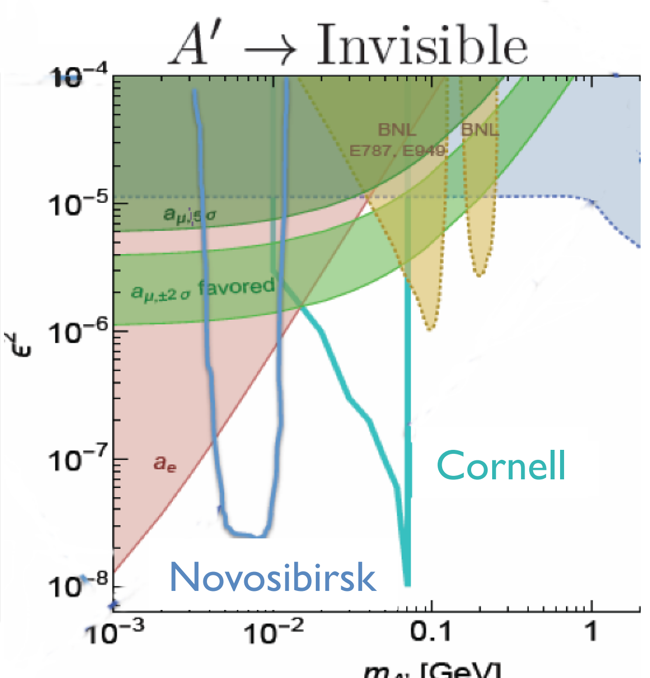
EOT ~ 10^{13} - 10^{14} year^{-1}

CORNELL

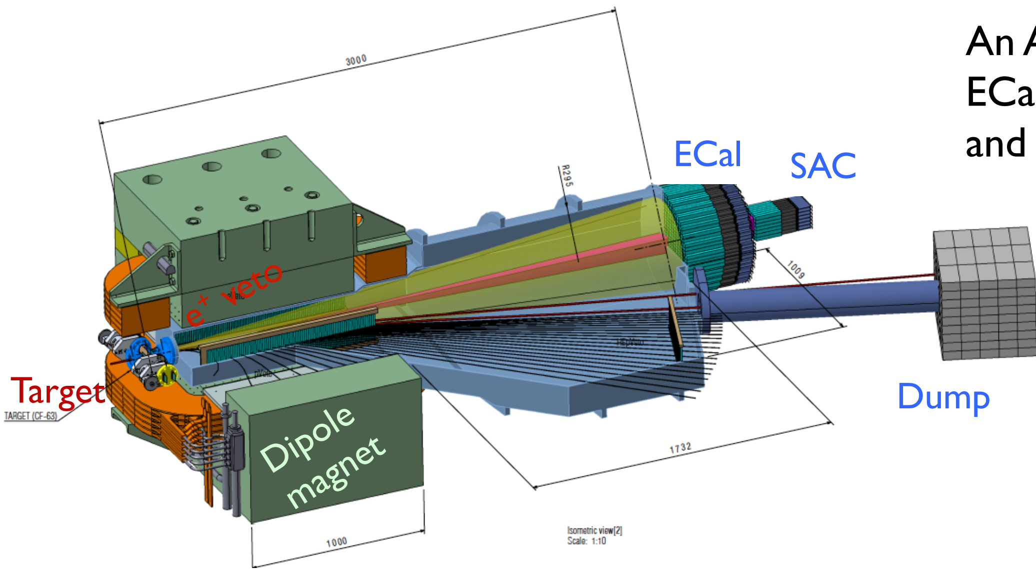
E_{e+} = 5.3 GeV

EOT ~ 10^{17} - 10^{18} year^{-1}





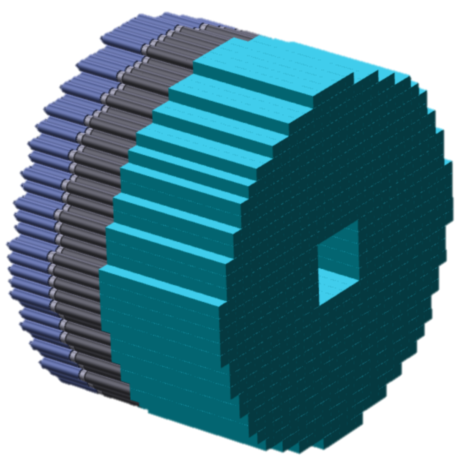
PADME @ LNF



An A' candidate in PADME is a single photon in the ECal having no charged particles in time in the veto and no photons in time in the SAC:

- Beam: ~ 5000 e^+ on target in 40 ns bunch, at 50 bunch/s (~10^{13} e^+/year)
- Measure: Energy, time and direction of photons
- Compute the $M_{miss}^2 = (P^4_{e-} + P^4_{beam} - P^4_{\gamma})^2$
- Veto any other particle outside the beam region

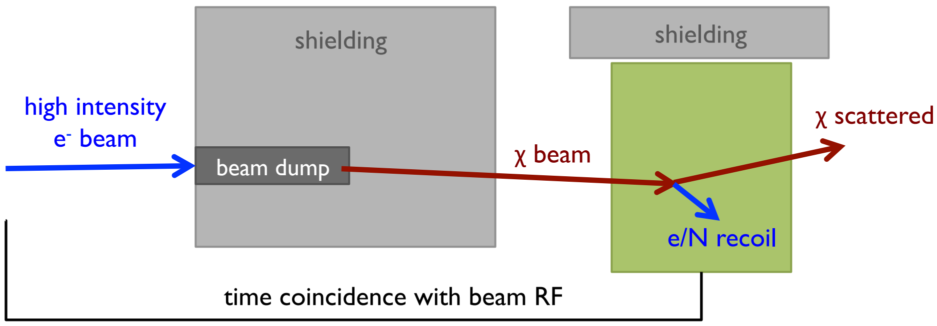
- The PADME experiment has been approved from INFN at the end of 2015
- The PADME experiment is financed by the "What Next" INFN program with 1.35M€ (2016-2018)
- Goal: completing the detector assembly by the end of 2017 and to accumulate 10^{13} e^+ on target by the end of 2018

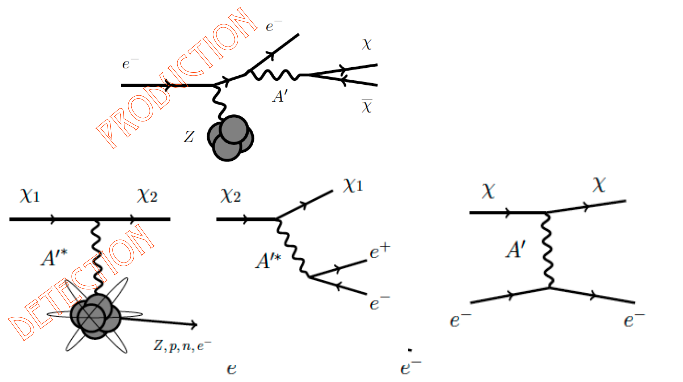


ECal:
- BGO calorimeter
- Cylindrical shape: radius 290 mm, depth of 230 mm, 616 crystals
- Expected performance:
  - $\sigma(E)/E = 1.57\%/\sqrt{E} \oplus 0.35\%$
  - 1.5 mrad angular resolution

Beam Dump eXperiment

A beam of DM particle can be produced by the interaction of a high intensity/high energy (electron) beam in a dump



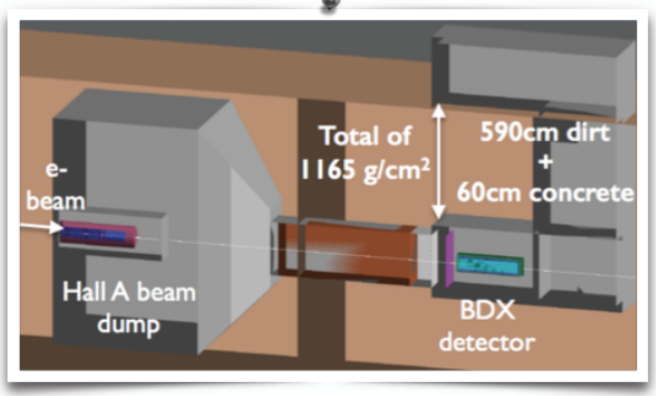


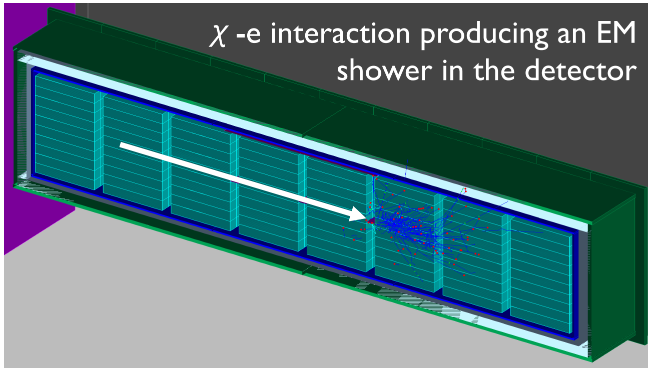
BDX @ JLab:

- New underground (~8m) hall downstream a high intensity dump
- Detector capable of measuring EM shower from electron recoil

BDX status:

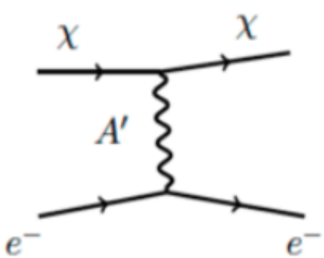
- Proposal approved by JLab PAC in July 2016 (arXiv:1607.01390)
  - 11 GeV electron beam, 10^{22} EOT (65 uA for 285 days)
  - ~800 CsI(Tl) crystals (ex BaBar EC) (~1 m^3 active volume) + plastic vetos

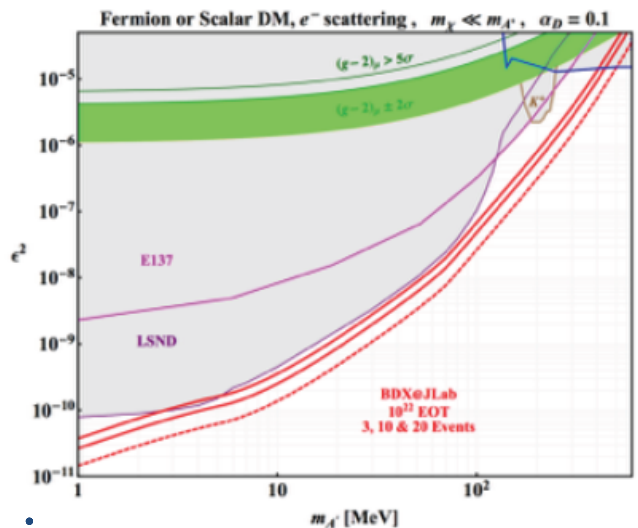


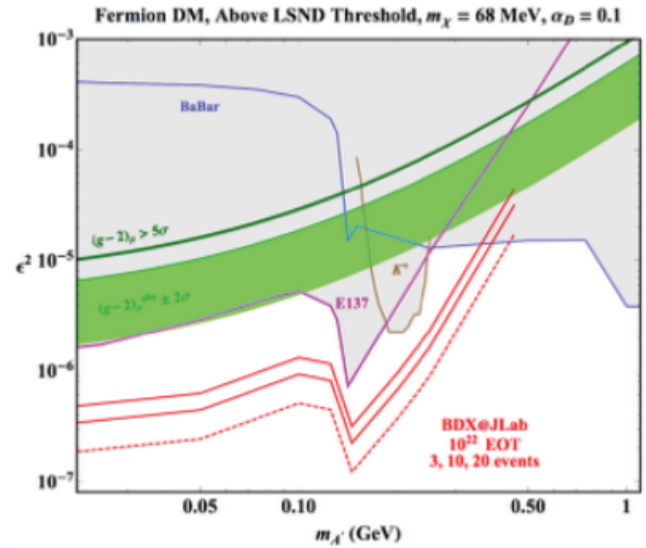


Beam Dump eXperiment

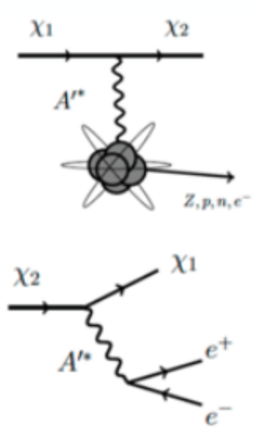
χ-e elastic scattering

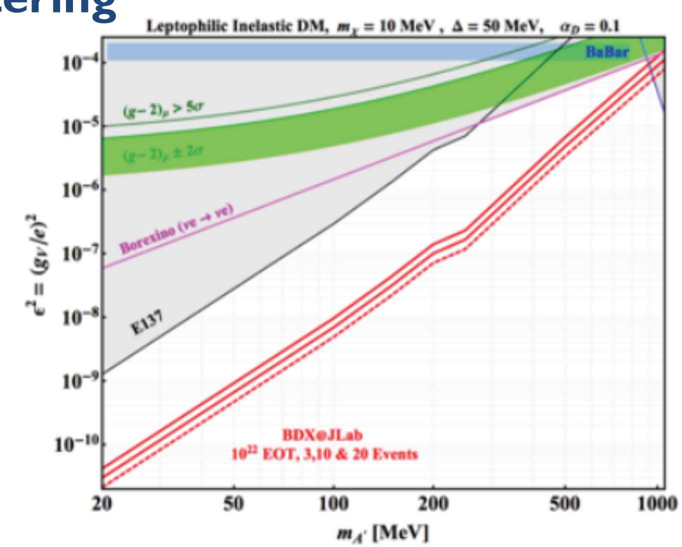






χ-e inelastic scattering





10-100 times more sensitive than previous experiments excluding a significant area of the parameter space

Summary

- Medium energy, high intensity experiments offers important opportunities for search for new physics at mass scale of ~ GeV
- Hints for new physics at this scale arise for various anomalous observations
- Ongoing searches explore different avenues:
  - Precision tests of the Standard Model
  - Search for light dark matter at accelerators
  - …
- A broad experimental program that involves several experiments and facilities that can reach unprecedented precision challenging the potentials of the energy frontier