A Beam Dump eXperiment (BDX) at LNF

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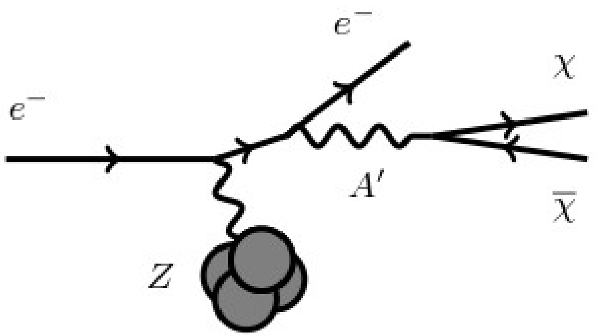
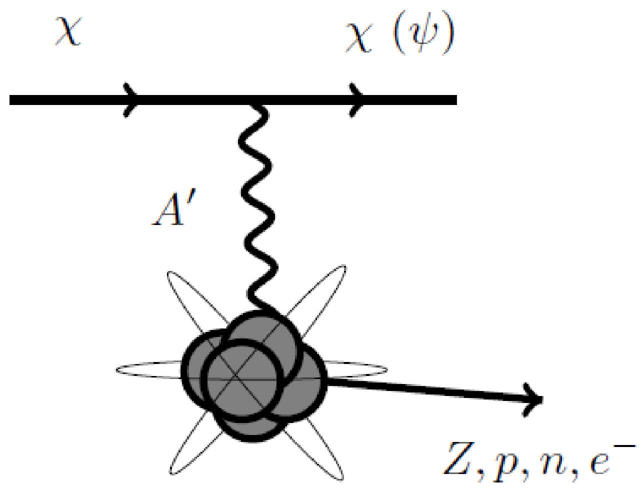
INFN - Genova

Beam dump experiments with e⁻ beam

How to access the A' invisible decay: direct detection in a two-step process.



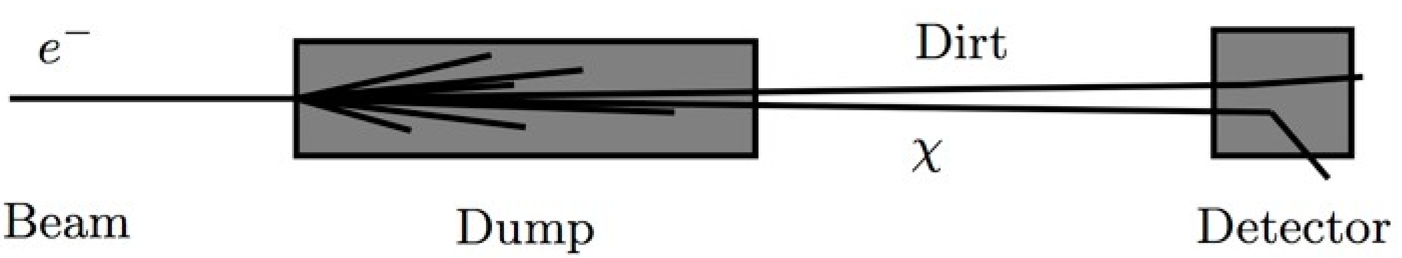
- **Fixed-target:** A' produced in the dump, decays promptly to invisible χ
- **Detector:** Neutral-current scattering of χ trough A' exchange, detect recoil. Different signals depending on the interaction (e⁻ scattering, coherent nuclear, quasi-elastic,..)



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



[arXiv:1307.6554]

Accelerator requirements

- **Beam current: critical.** The experimental sensitivity scales linearly with this parameter*.

* Assuming 0 beam-related background (see later)

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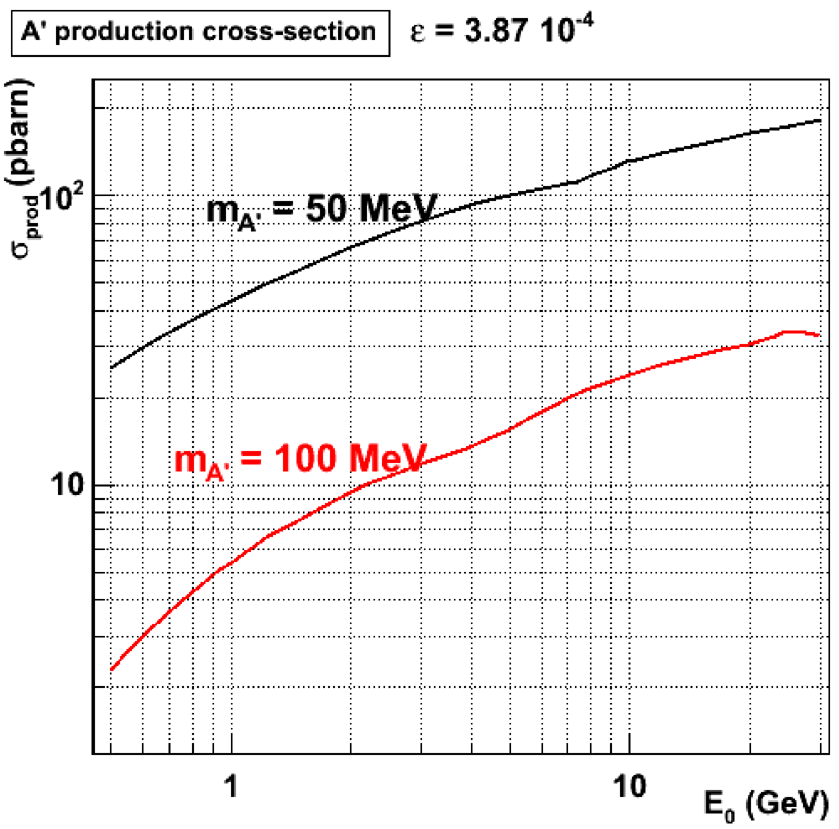
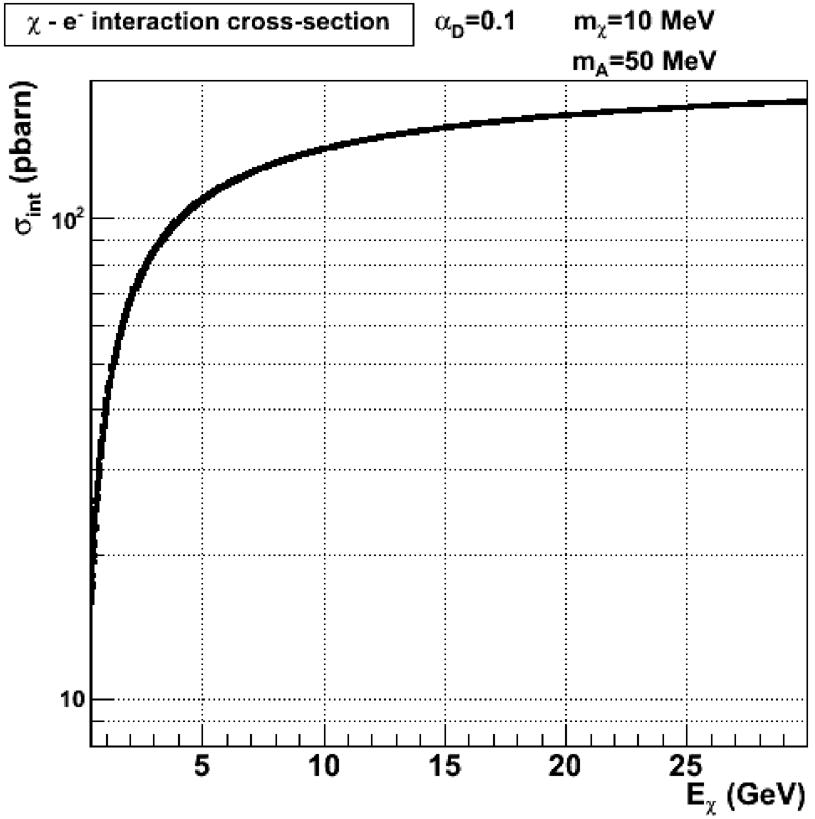
- **Beam energy:**

  - A' production and χ – matter interaction cross-sections increase smoothly with the beam energy.
  - At low energy ($E_0 \sim m_A$), there is a further signal enhancement with E_0 due to increased detector acceptance (χ beam more focused forward).





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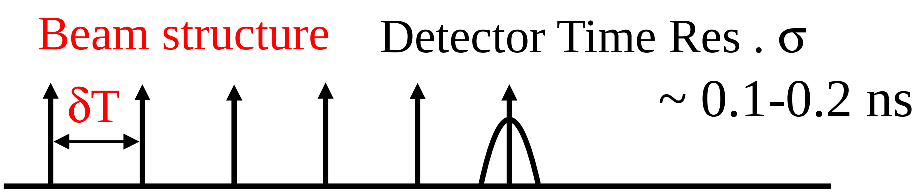
- **Beam structure:**

  - A pulsed beam permits to reject uncorrelated backgrounds by making a time coincidence between the beam RF signal and an hit in the detector

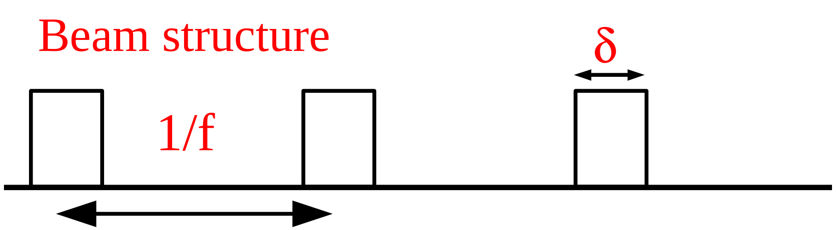
Continuous beam: detector time resolution is a mandatory requirement.

$$R \simeq \frac{\delta T}{3\sigma} <\simeq 100$$



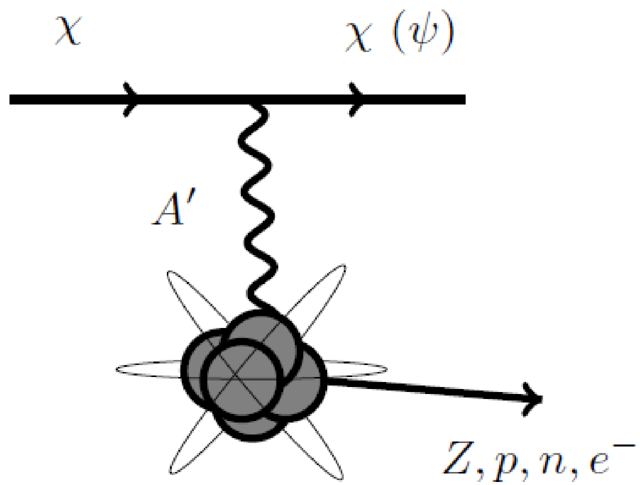
Pulsed beam: detector time resolution is not critical, if smaller than the bunch length.

$$R = \frac{1}{f \cdot \delta} = 2 \cdot 10^5 \ @ \ 50\,Hz, 100\,ns$$



χ - matter interaction

1) Elastic scattering on nucleons

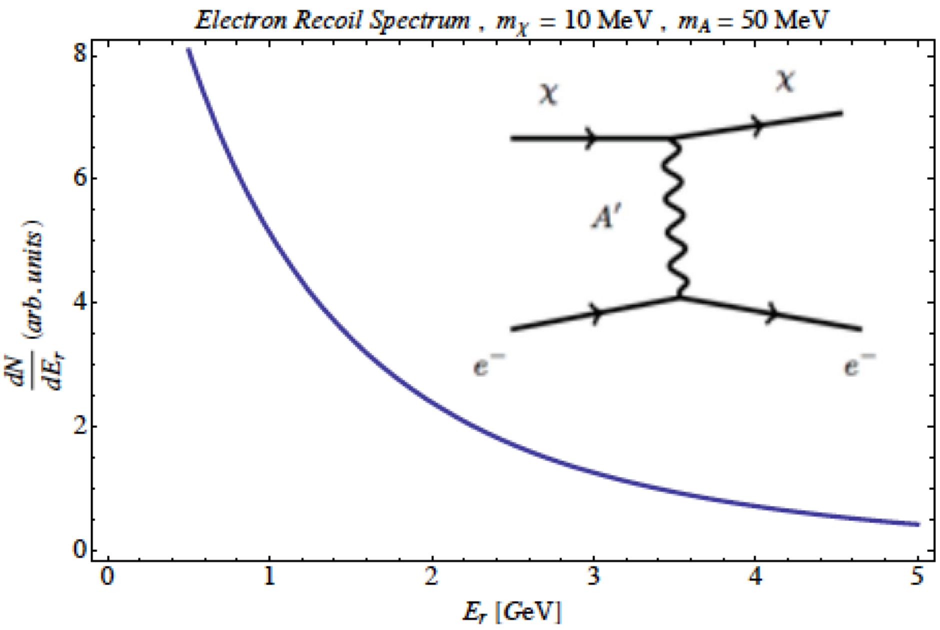


The χ scatters elastically on a nucleon (p) in the detector producing a visible recoil (~ MeV)

Experimental requirements:

- Sensitivity to ~ MeV nucleon recoil (low detection thresholds)
- Low energy backgrounds rejection capability

2) Elastic scattering on electrons



The χ scatters elastically on an electron in the detector producing a well visible recoil (~ GeV)

Experimental requirements:

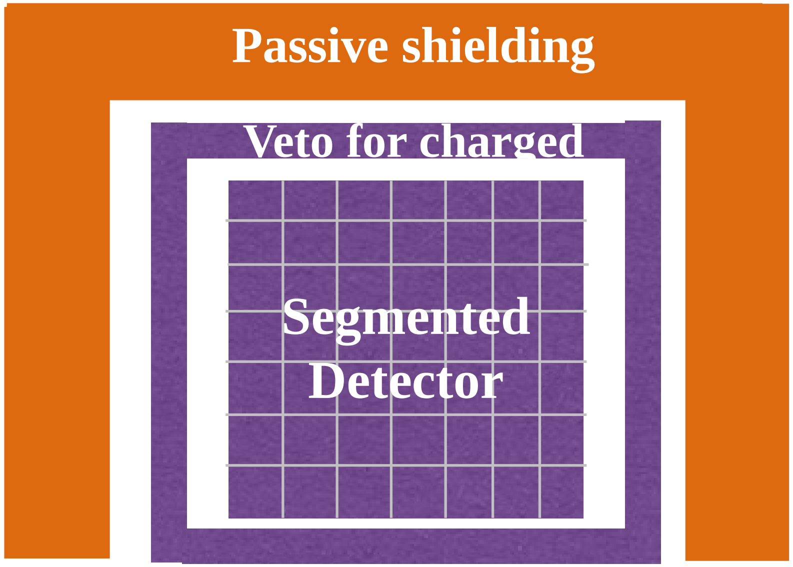
- Sensitivity to ~GeV electrons (EM showers) → Easy background rejection

Detector design and requirements

Signal detection:

- High density
- Low threshold for nucleon recoil detection (~ MeV)
- EM showers detection capability

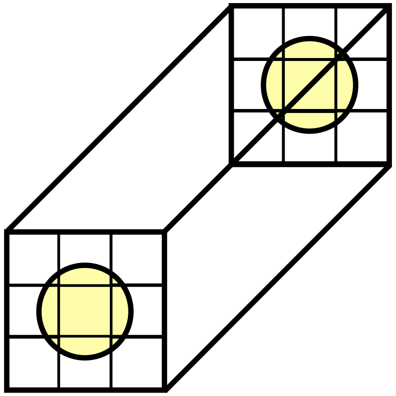
→ **Scintillation-based detector**



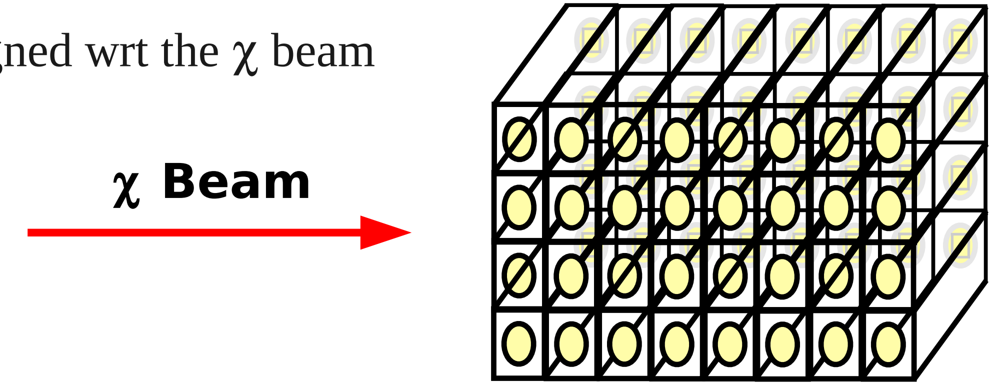
Background rejection / suppression:

- Segmentation
- Active veto
- Passive shielding
- Good time resolution (for continuous beams only)

Inner detector:



- Single optical module (possibly made of multiple opt. channels with single readout)
- Matrix of modules aligned wrt the χ beam

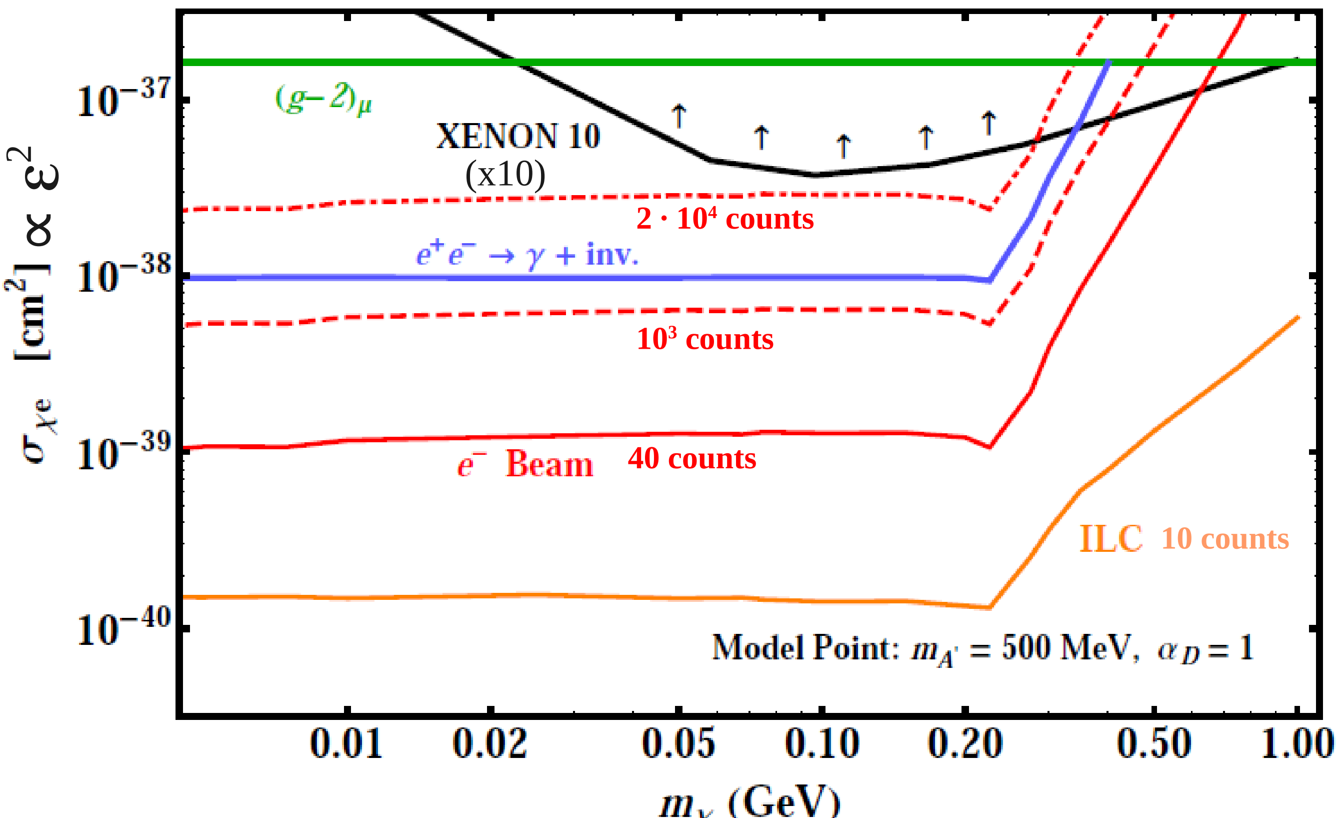


Possible reach

Reach for a "benchmark" beam-dump experiment at an electron machine:

- 10^{22} EOT, 12 GeV / 125 GeV (ILC)
- 1 year of run
- 1 m^3 detector, ρ=1 g/cm^3, placed 20 m from the beam dump

In the low-mass region (m_χ < 1 GeV), the reach of a beam-dump like experiment is O(100-1000) better than a traditional direct-search experiment.



For XENON10,
$\rho_{DM} = \rho_\chi$ = 0.4 GeV/cm^3

[arXiv:1206.2644, 1307.6554]

A beam-dump experiment at LNF

Accelerator parameters:

- **EOT (1 full year):**
  - **Today:** $5 \cdot 10^{19}$ (10 ns/bunch, 5 nC/bunch, 50 Hz), although legal regulations impose < ~ 10^{18}
  - **“Reasonable” upgrade:** $2.5 \cdot 10^{20}$, to be tested (larger bunch length / higher gun pulse height)
  - **“Optimistic” scenario:** ~ $1 \cdot 10^{21}$ (if all the possible upgrades are performed)

- **Beam energy:**
  - **Today:** 750 MeV
  - **“Reasonable”** upgrade: 1.1 GeV (12 m new accelerating sections @ 21 MeV/m, pushing existing sections)

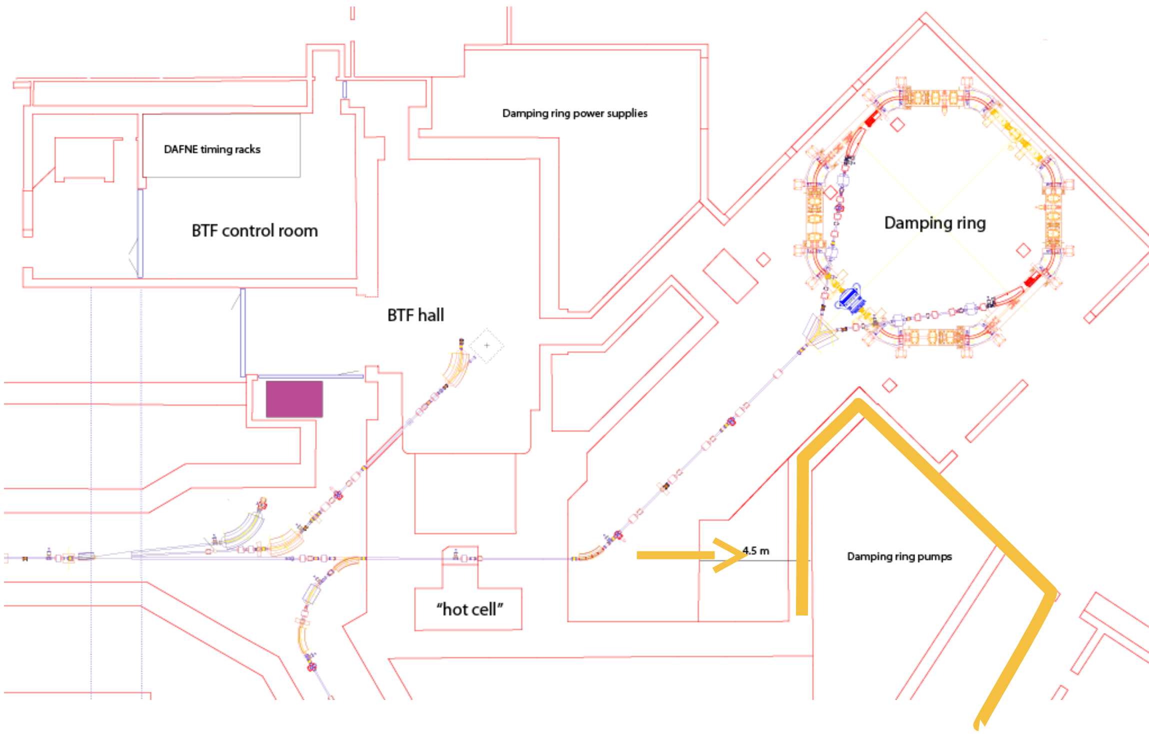
- **Beam structure:**
  - **Today:** 50 Hz @ 10 ns → Background rejection factor $2 \cdot 10^{6}$
  - **“Reasonable” upgrade:** 50 Hz @ 100 ns → Background rejection factor $2 \cdot 10^{5}$

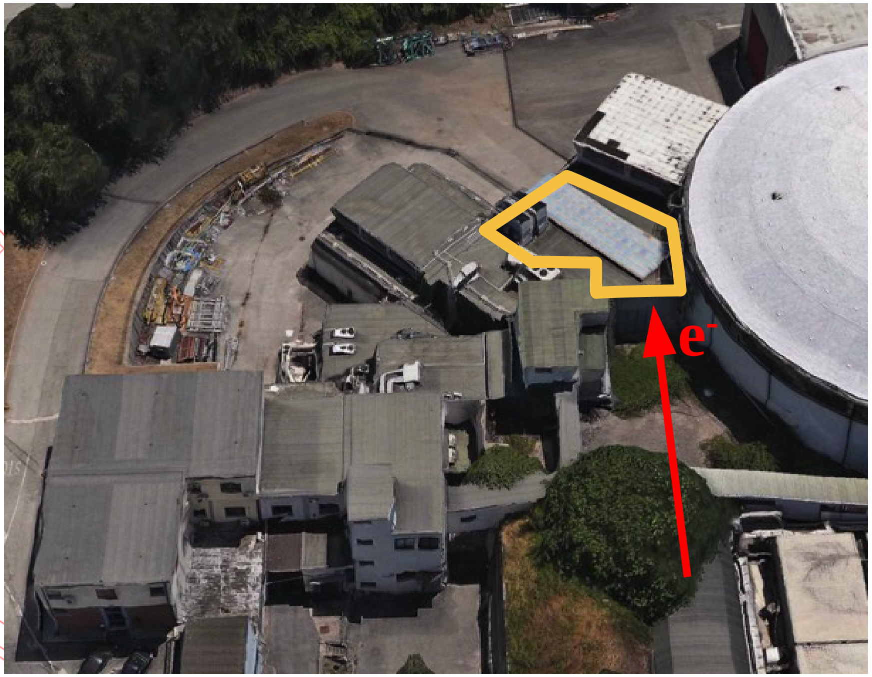
[P. Valente]

Experimental setup: detector location

Use the existing ADONE beam-dump and install the detector in the DAΦNE service room

- O(m) distance between the beam-dump and the detector: increased detector acceptance.
- Available space can fit a detector up to 5 m long.
- Minor engineering work required to prepare the hall for the detector installation (see P. Valente's talk)





[P. Valente, J. Esposito]

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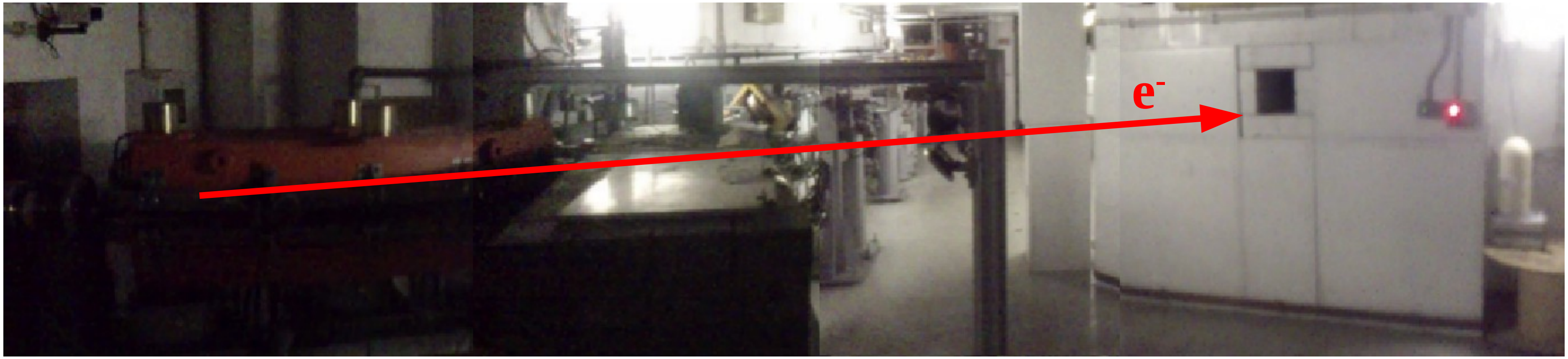
- **Existing dump needs to be re-enginereed.**

ADONE beam-dump (today): 4.5 m long, ~ 3 m ground + ~ 1.5 m concrete

New design requirements:

- **Dissipated power:** ~ 200 W today → < 10 kW for the best upgrade scenario
- **Beam-related backgrounds shielding:** ~2 m iron + ~ 2 m concrete to reduce beam-related backgrounds (γ/n) to less than few counts / year



[P. Valente, J. Esposito]

Detector design

Different solutions are possible for the inner detector.

Comparison of main properties, considering a ~ 1 ton detector.

Technology	Density	Optical module size	N. of channels	Cost
Plastic scintillator	~1 g/cm^3	15x15x30 cm^3	280	2 M€
BSO Crystals	6.8 g/cm^3	10x10x15 cm^3	90	2.6 M€

Crystal solution seems the most promising option:

- Higher density $\rightarrow$ compact detector
- Easy EM shower detection.
- Comparable cost to plastic.

Open issues to be addressed:

- Is the χ scattering on a free N equivalent to a quasi-free scattering on heavy nuclei?
- Light quenching?
- Minimum proton momentum detectable?

→ Dedicated measurement campaign required
(see M. De Napoli talk)

Detector design

Realistic option: build the detector using CsI crystals from a dismissed calorimeter

- Reduced costs: existing crystals, already equipped with readout and FE-electronics.
- Compact time-line: detector can be assembled and ready for measurement in O(1 year).

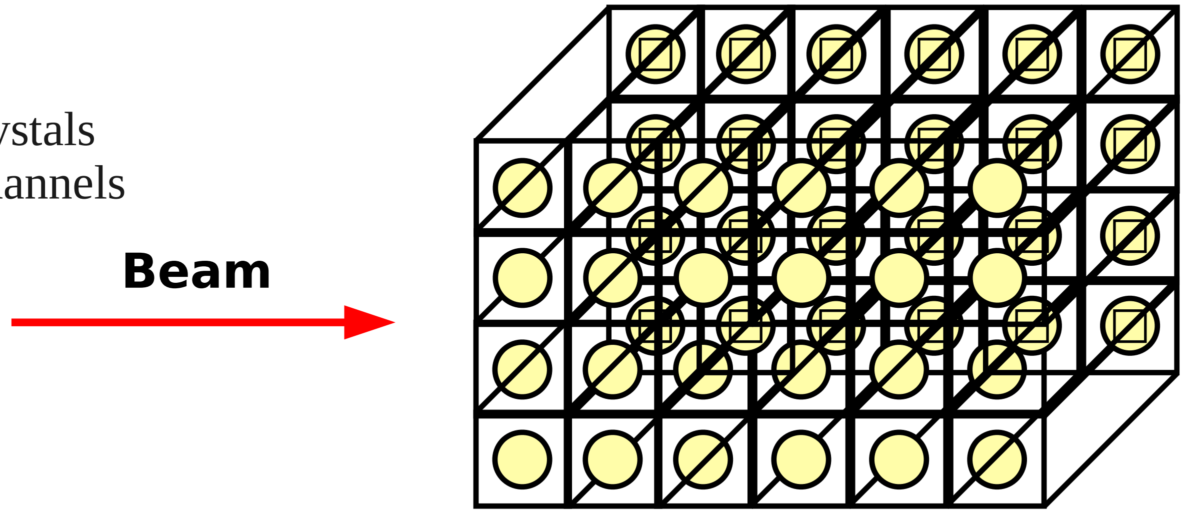
Hypothesis under investigation: **BaBar**, L3, CLEO
From preliminary contacts, **the BaBar option seems the most promising one.**

Technology	Density	Crystal-size	N. of channels	Cost
CsI Crystals	4.5 g/cm^3	5x5x30 cm^3	120	0.5 M€

(Possible) setup:

- 1 crystal: 5(6) x 5(6) x 30 cm^3
  - Tapered geometry is not an issue.
- 2 crystals align face-to-face
- Matrix of 12x45 modules: ~ 1080 crystals
  - If re-using BaBar readout, 1080 channels
  - If using PMTs, ~ 120 channels
- Detector: ~ 60 x 60 x 225 cm^3

This solution is equivalent to a plastic-based detector,
10 m long (with the same front-face)



Reuse of BaBar crystals

Design:

- 6580 CsI(Tl) ~ 5(6) x 5(6) x 30 cm^3 crystals (tapered geometry)
- 820 end cup + 5760 barrel crystals
- 2x Hamamatsu S2744-08 silicon diodes readout, thermalized
- 18-bit effective readout (dual-range output from FEE)

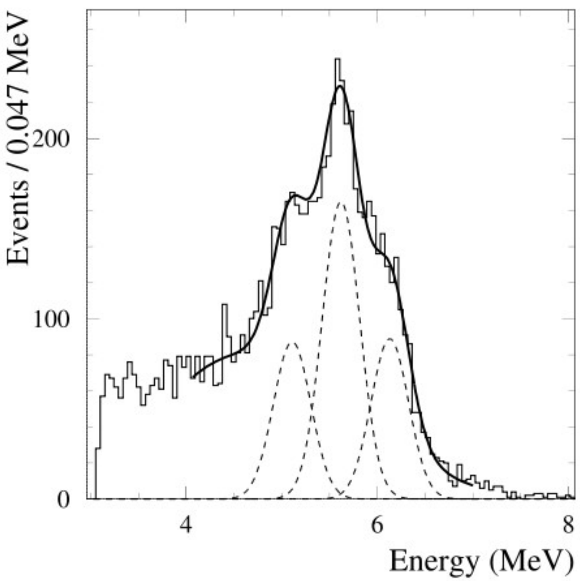
Properties:

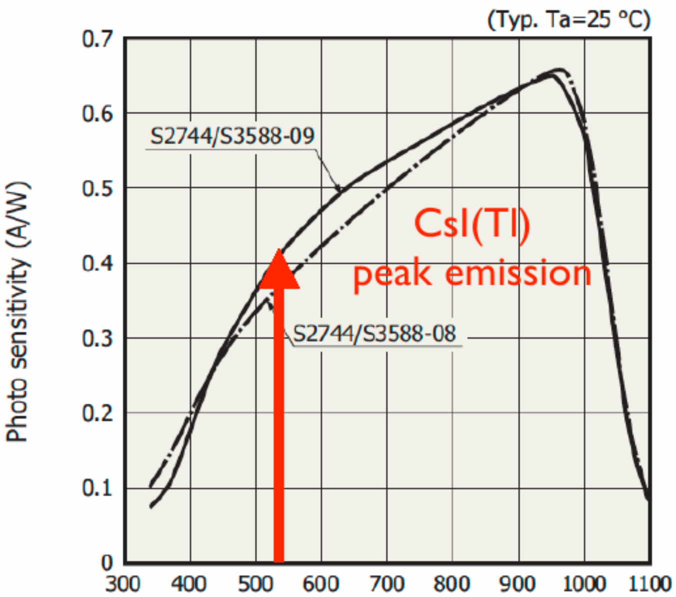
- ~ 7300 phe / MeV
- Low-energy calibration point for each crystal @ 6.13 MeV
- 250 keV ENE.

Low-energy calibration system:

$$^{19}\mathrm{F} + n \rightarrow ^{16}\mathrm{N} + \alpha$$

$$^{16}\mathrm{N} \rightarrow ^{16}\mathrm{O}^* \rightarrow ^{16}\mathrm{O} + 6.13\,\mathrm{MeV}\gamma$$





[arXiv:0105.5044]

Backgrounds

Beam-related backgrounds (R. De Vita's talk):

1) Prompt backgrounds (γ/fast n):

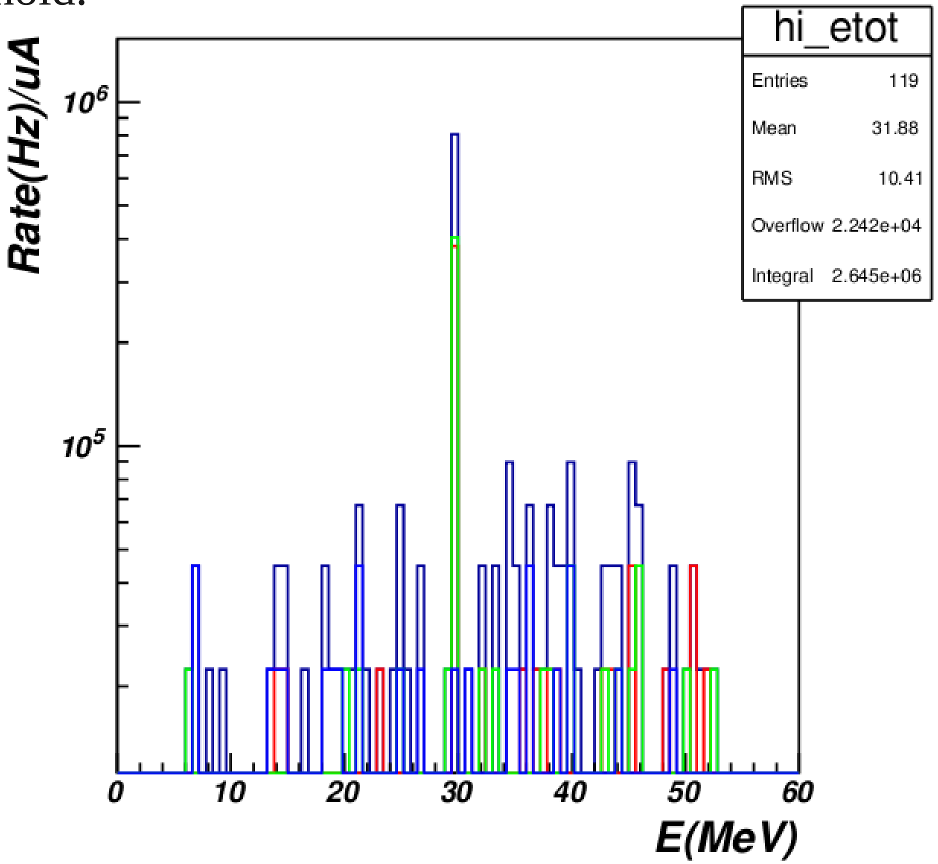
- Can't be reject with the detector-beam RF time coincidence
- Shielding is required to reduce γ/fast n rate on the detector
  - From preliminary simulations, 2 m iron + 2 m concrete are enough to reduce contribution to less than O(1 particle / year) @ 10 uA

2) Low energy / thermal n: not an issue

- Can apply detector-beam RF time coincidence
- Very low energy hits in the detector: cut with threshold.

3) Neutrinos:

- Neutrino flux on the detector:
  $\Phi \sim 1.16\ 10^{-7}\ \nu$ / EOT, $E_\nu < 50$ MeV
  (isotropic, from at-rest processes)
- Cross-section:
  $\sigma \sim 10^{-40}\ cm^2$
- Interactions (for 2.5 10^{20} EOT):
  N ~ 60
- Further suppression:
  - Energy threshold (~50% efficieny @ 1 MeV thr)
  - Beam RF-detector signal coincidence (not all processes are prompt)



Backgrounds

Beam-unrelated backgrounds (M. De Napoli's talk): all reduced by the beam RF – detector time coincidence

1) Cosmic neutrinos

- Considering flux, interaction cross-sections, and thresholds the contribution is negligible.

2) Cosmic muons

- Different background contributions (crossing/stopping/decaying/..).
- Reduced trough shielding + VETO around the detector + threshold + signal topology (different from χ-p and χ-e interactions).
- From preliminary estimates, 30 cm of iron around the detector, equipped with 2 VETO layers (5% inefficiency), are enough to reduce the contribution to O(counts)/year.

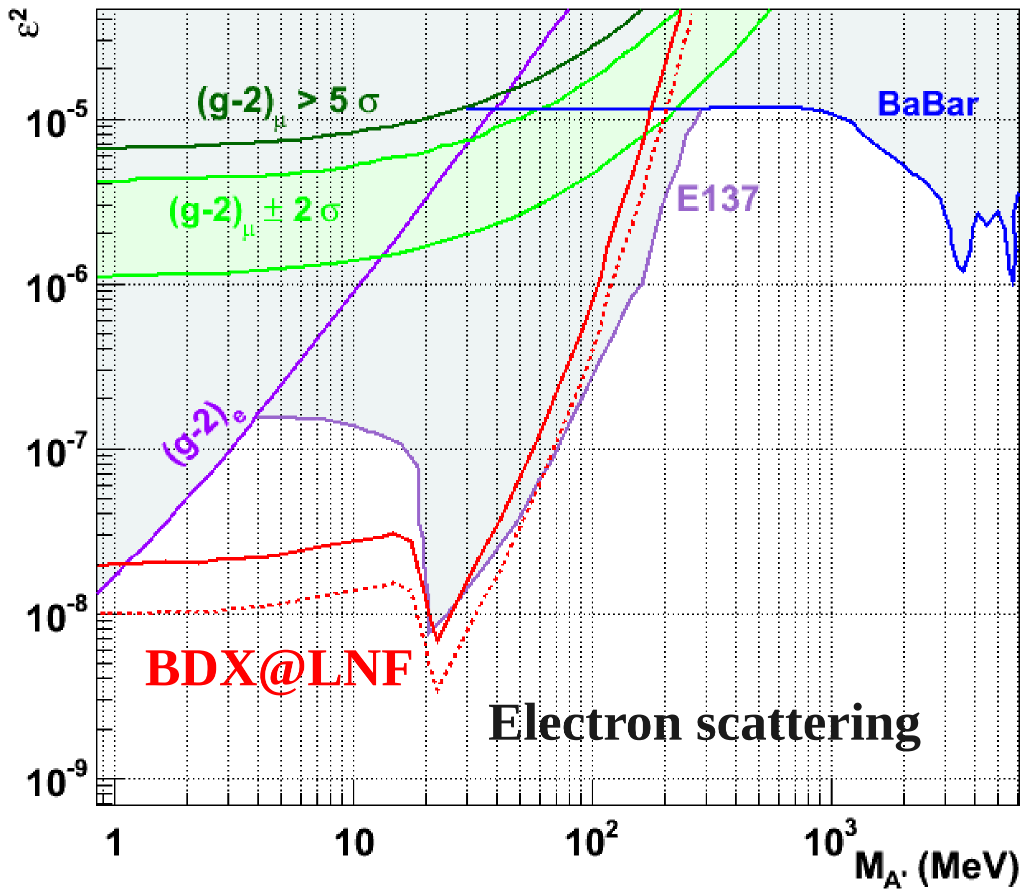
3) Cosmic neutrons

- High-energy neutrons can penetrate the shielding and interact inside the detector, mimicking a χ-N interaction.
- Reduced trough shielding + VETO around the detector + threshold.
- From preliminary estimates, 30 cm of iron around the detector, equipped with 2 VETO layers (5% inefficiency), are enough to reduce the contribution to O(counts)/year.

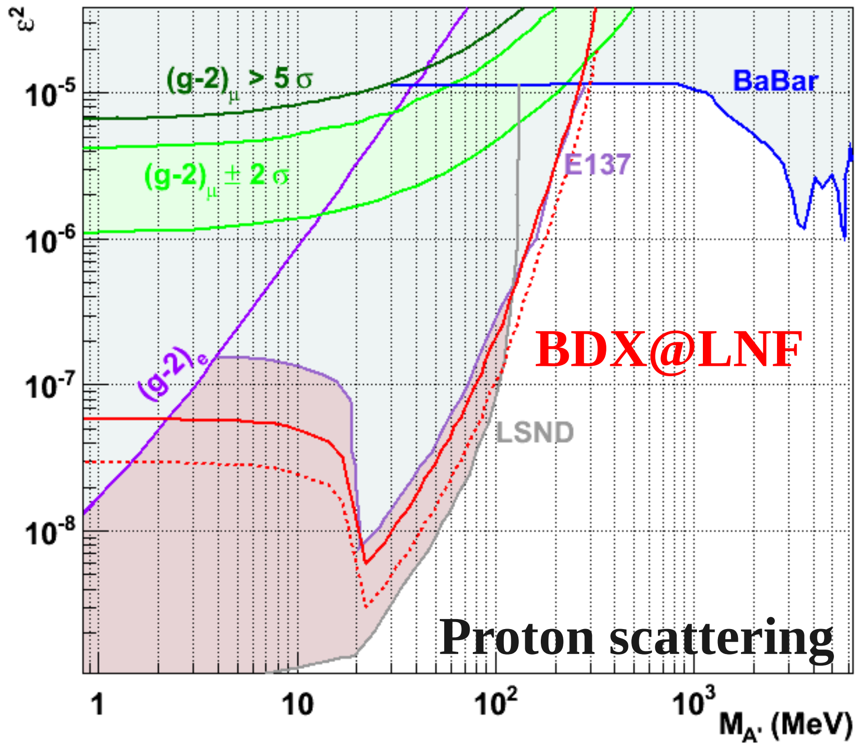
→ The BDX@LNF reach is evaluated with $N_s=3$, $N_b=0$

Experimental reach

Experimental reach for BDX@LNF, evaluated at m_χ=10 MeV, α_D=.1



- **Solid line:** $2.5 \cdot 10^{20}$ EOT
- **Dashed line:** 10^{21} EOT



Conclusions

- **The dark sector may be more complex than originally expected**
  - Extensive search for low mass DM
  - Natural extension of the heavy photon model to include light DM via invisible A' decay

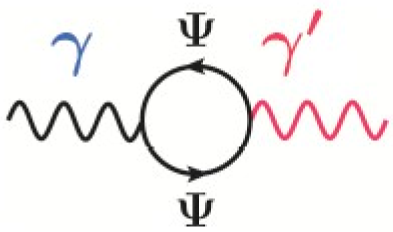
- **Beam dump experiments with electron beams are the “ideal” way to probe low-mass (< 1 GeV) dark-matter**
  - “Benchmark” scenario: 12 GeV beam, 10^{22} EOT, 1 m^3 detector (ρ=1)
  - Sensitivity is O(100-1000) better than “conventional” direct-search experiments.

- **Opportunity to run a beam-dump experiment at INFN-LNF**
  - Short time-scale, O(1-2 years)
  - Reduced costs:
    - Only “reasonable” Linac upgrade are required
    - Build the detector with existing BaBar CsI crystals
  - Foreseen reach: cover the low A' mass region ~ 1-20 MeV, down to $\varepsilon^2 \sim 10^{-8}$

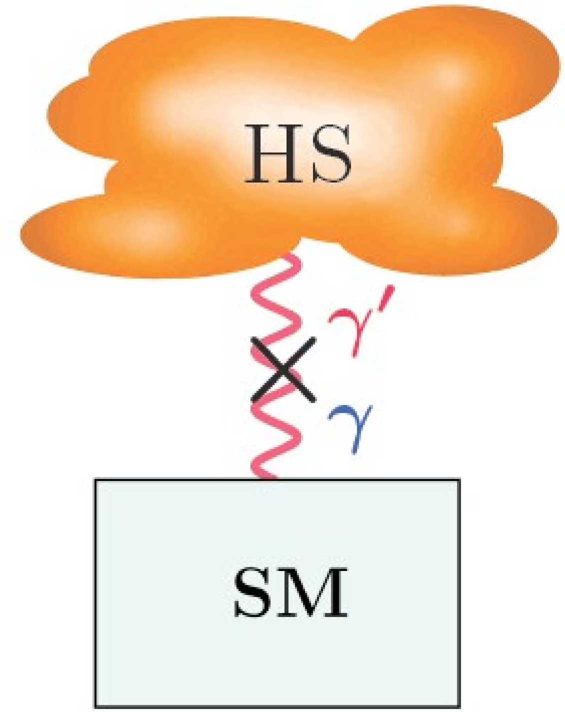
Back up

Dark Photons

- Consider an additional U(1) hidden symmetry in nature: this leads to a kinetic mixing between the photon and the new gauge boson A'



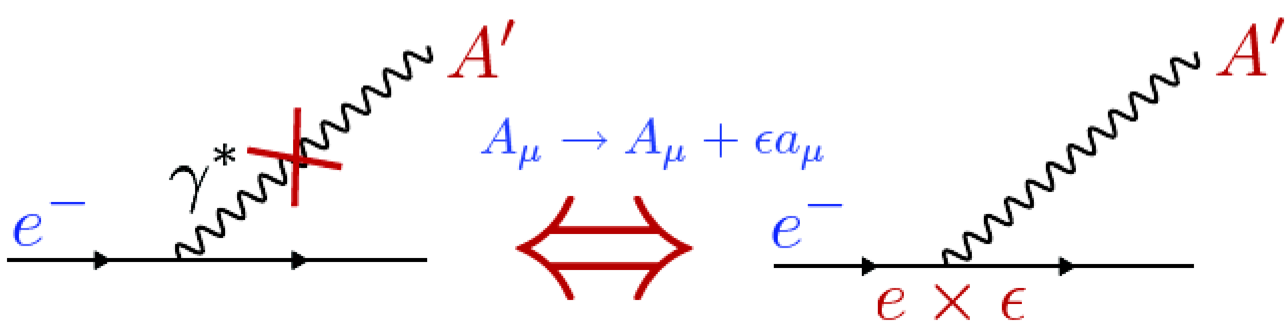
Ψ is a huge mass scale particle (M~1EeV) coupling to both SM and HS



- General hypothesis to incorporate new physics in the SM: the A' acts as a “portal” between the SM and the new sector

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + m_A^2 A'^{\mu} A'_{\mu}$$

- Under A' interaction, ordinary charged matter acquires a new charge **εe:**



New interaction term:

$$\varepsilon A'_{\mu} J^{\mu}_{EM}$$

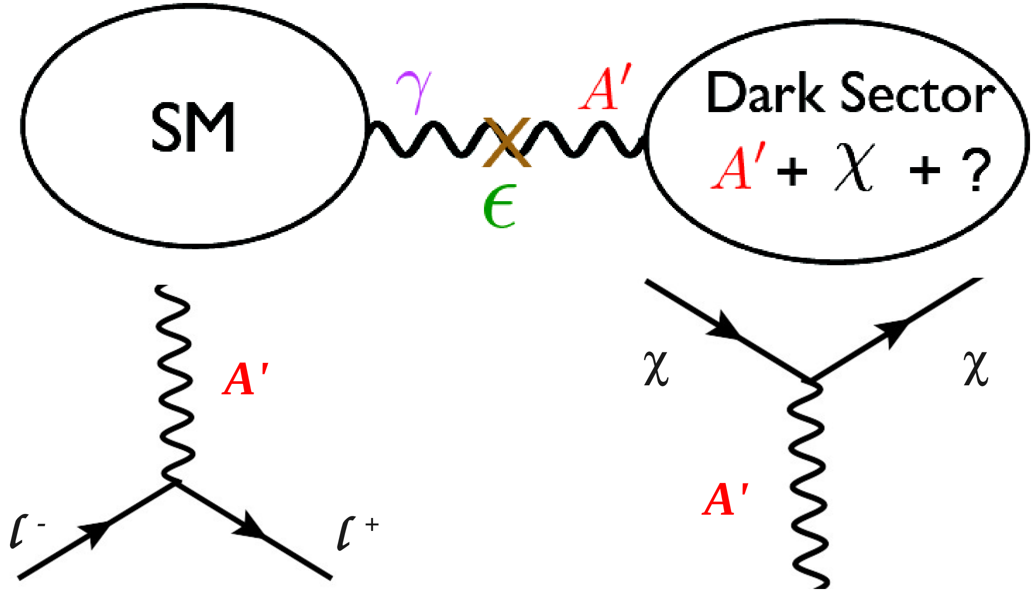
Boldom, Phys. Lett. B166, 1986

Dark photons and dark sector

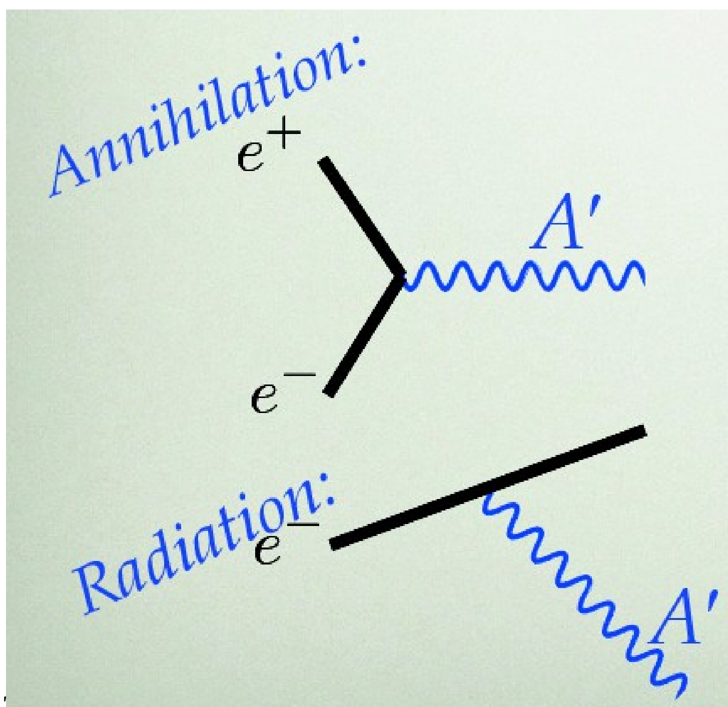
Model:

- A' interacts with γ trough kinetic mixing
- Dark sector particle χ interacts with A'

4 parameters: $M_{A'},\ M_{\chi},\ \varepsilon,\ g_d$

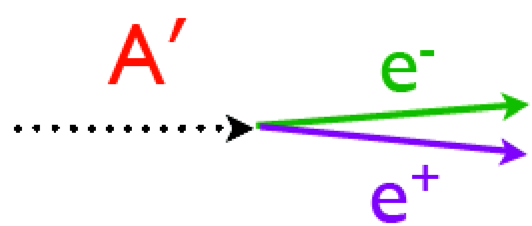


A' production: $\sigma \propto \varepsilon^2$



A' decay:

First scenario: only SM decays



- Minimal scenario
- $BR(A' \rightarrow SM) = 1$
- $\Gamma_{Tot} \propto \varepsilon^2$

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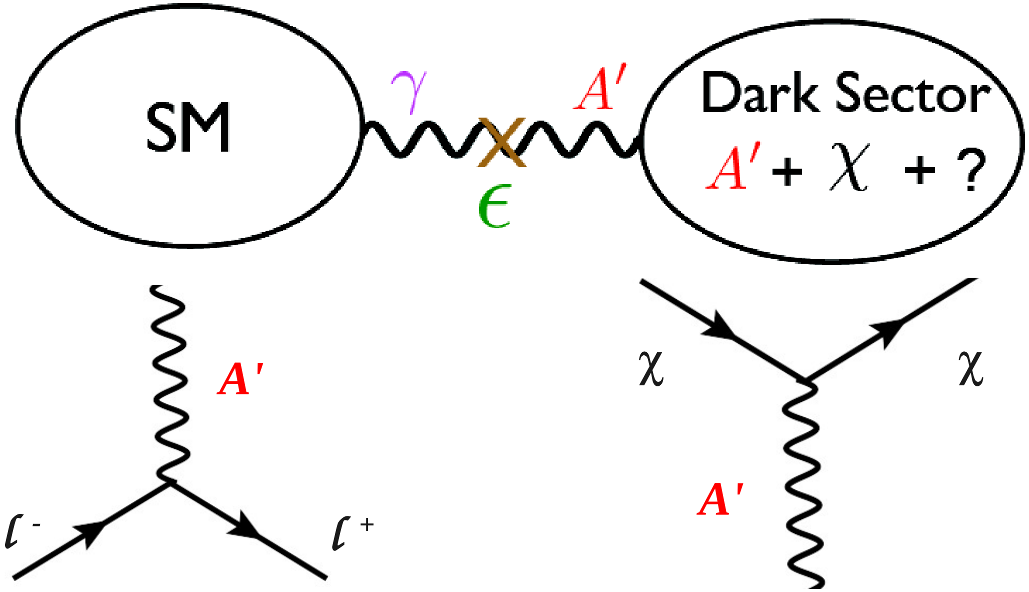

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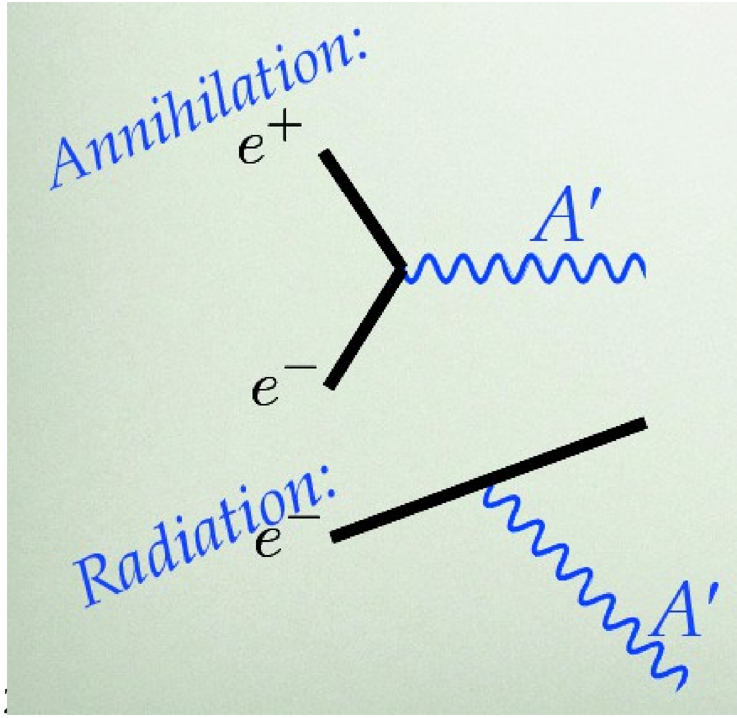
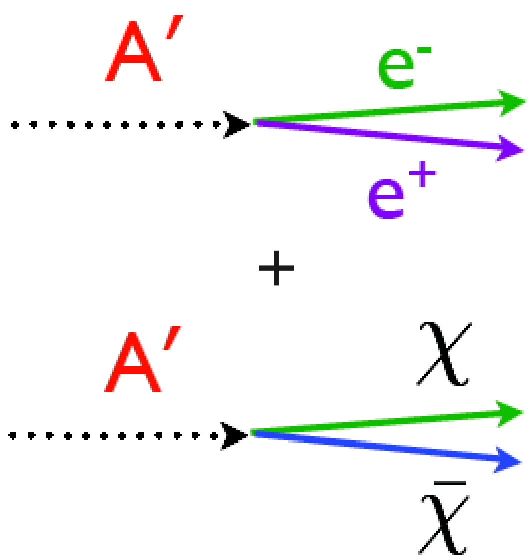


A' decay:

Second scenario: SM + hidden decays

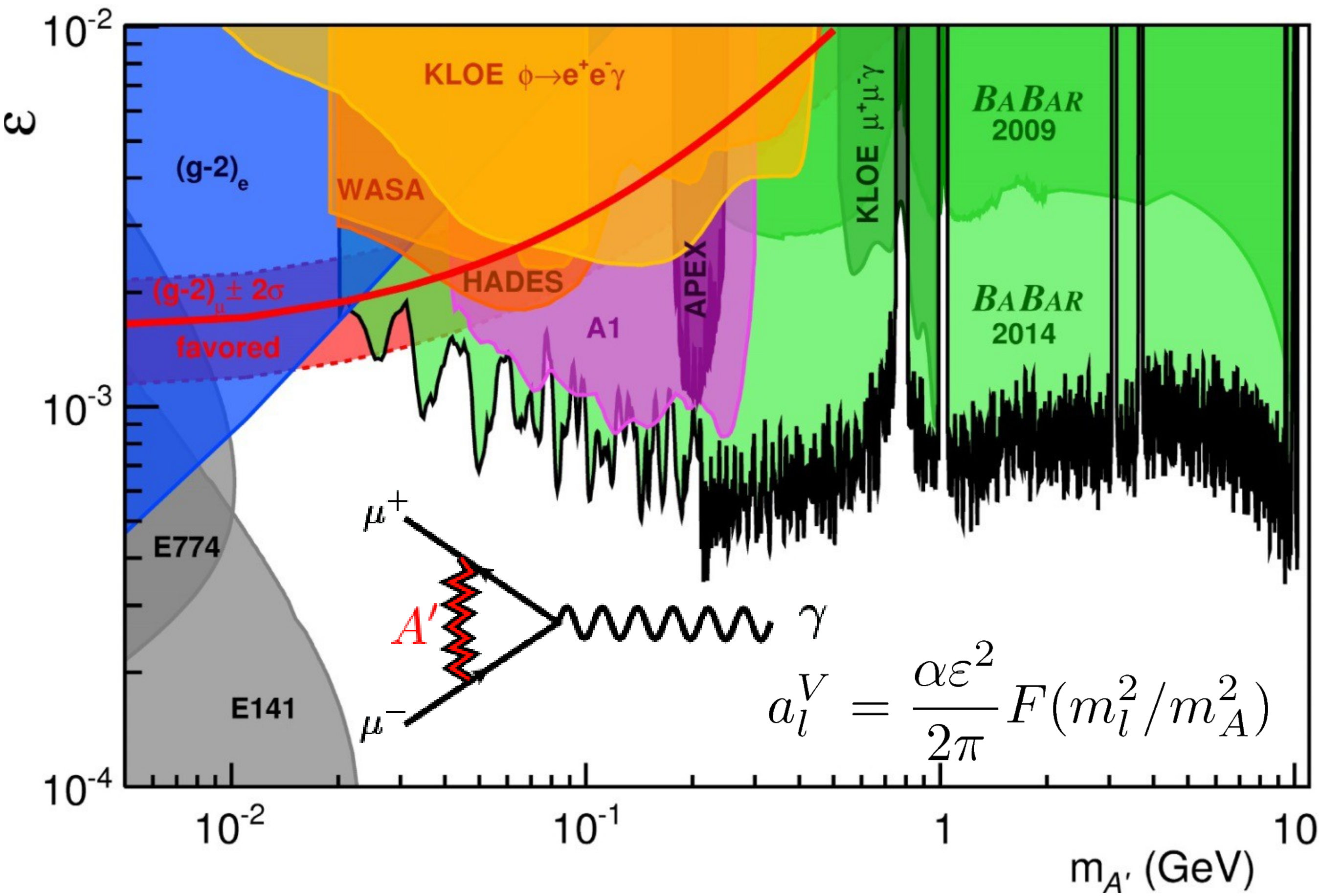


- Kinematically allowed only if $M_{A'} > 2\, M_{\chi}$
- $BR(A' \rightarrow SM) \propto \varepsilon^2$
- $\Gamma_{SM} \propto \varepsilon^2$
- $\Gamma_{\chi\chi} \simeq 1$

Dark photons invisible decay and g-2

- **Muon g-2 anomaly:** “traditional” motivation for A' search
  - New results (Phenix,Babar, KLOE) seem to exclude the g-2 preferred region in the $\varepsilon - M_A$ plane
  - This conclusion is model-dependent, based on BR(A' → SM) = 1
    If the invisible decay is included in the model, old limits do not hold!

Muon g-2 anomaly has to be investigated considering visible AND invisible decay modes



[arXiv:1406.2980]

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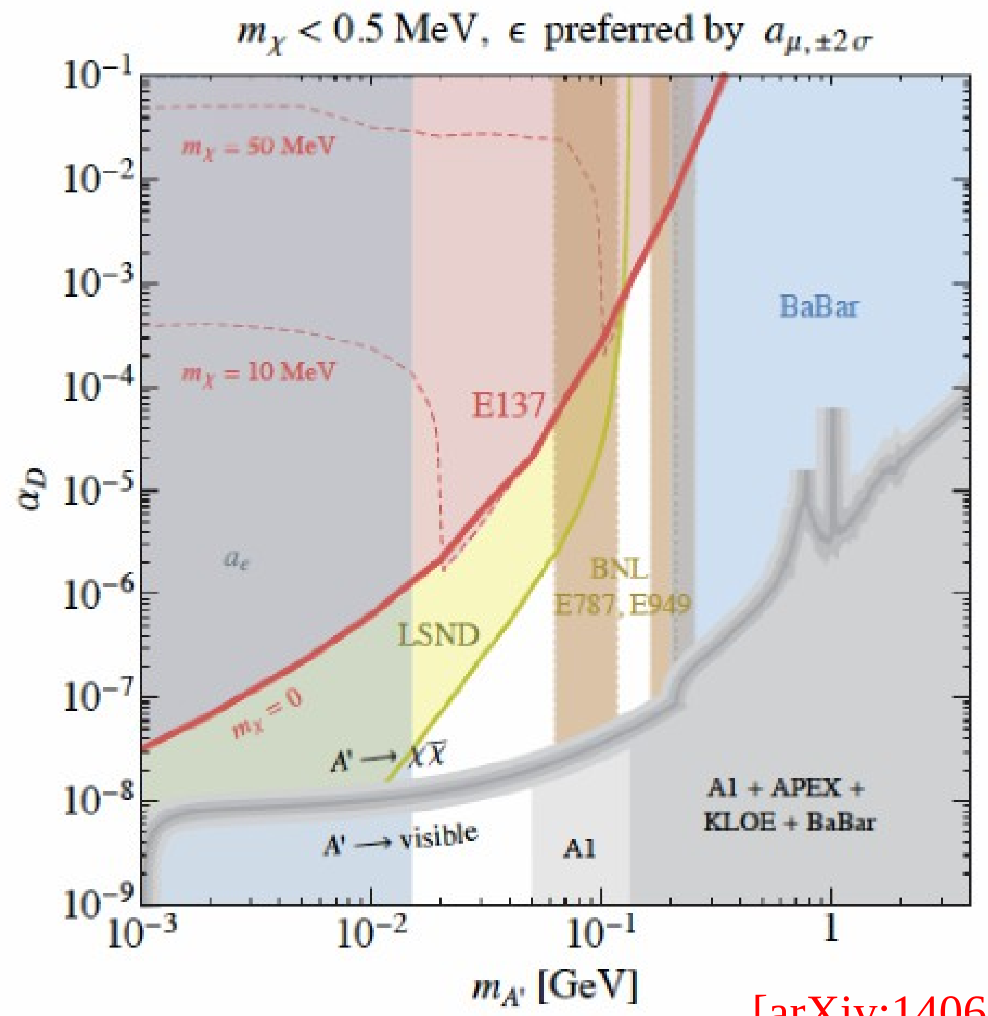
Muon g-2 anomaly has to be investigated considering visible AND invisible decay modes

A new approach:

- For a given M_A, fix ε to explain g-2
- Exclusion plot: $\alpha_D - M_A$ plane
- Depending on $\varepsilon(M_A)$ and α_D the decay can be visible or invisible

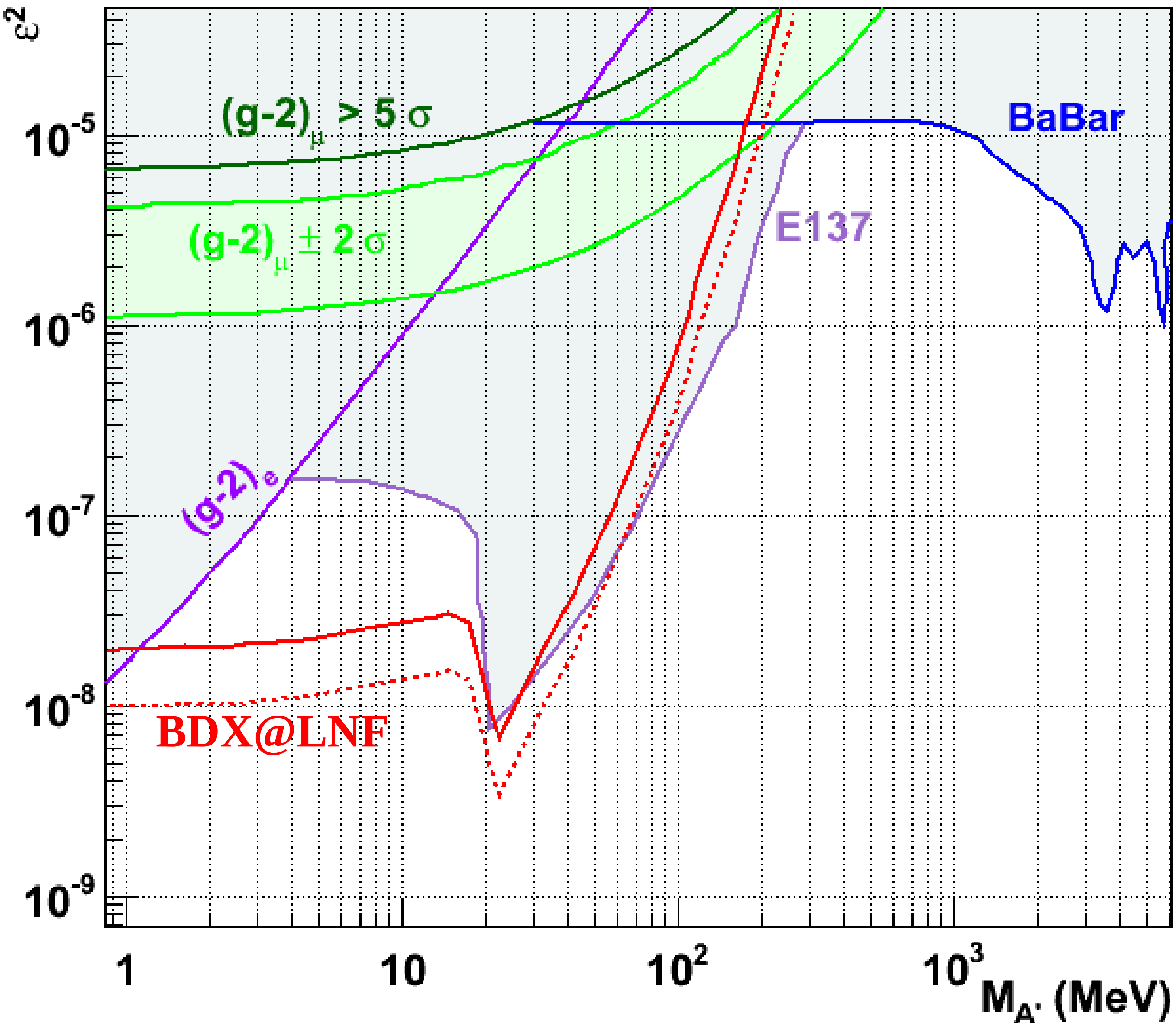
Both decay modes, visible and invisible, are considered to constrain the muon g-2



[arXiv:1406.2698]

Experimental reach: electron scattering

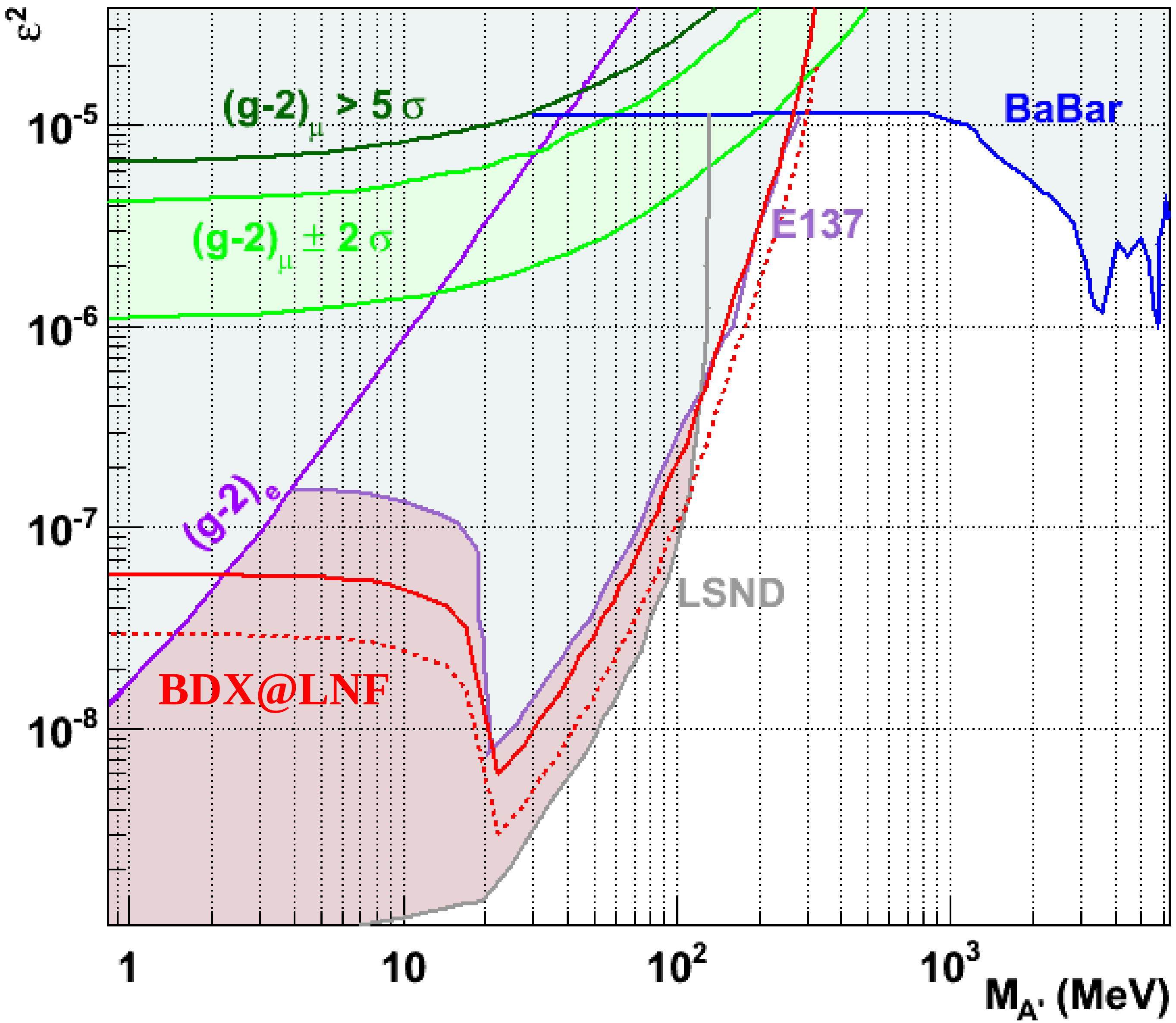
Experimental reach for BDX@LNF, evaluated at m_χ=10 MeV, α_D=.1



- **Solid line:** $2.5 \cdot 10^{20}$ EOT
- **Dashed line:** 10^{21} EOT

Experimental reach: proton scattering

Experimental reach for BDX@LNF, evaluated at m_χ=10 MeV, α_D=.1



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