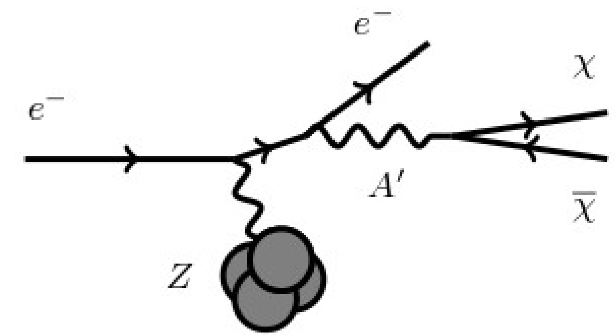
A Beam Dump eXperiment (BDX) at LNF

A. Celentano (for the BDX collaboration)

INFN - Genova

Beam dump experiments with e⁻ beam

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

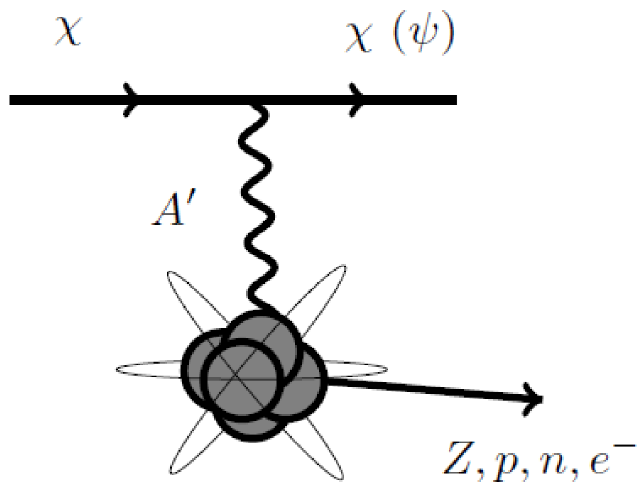


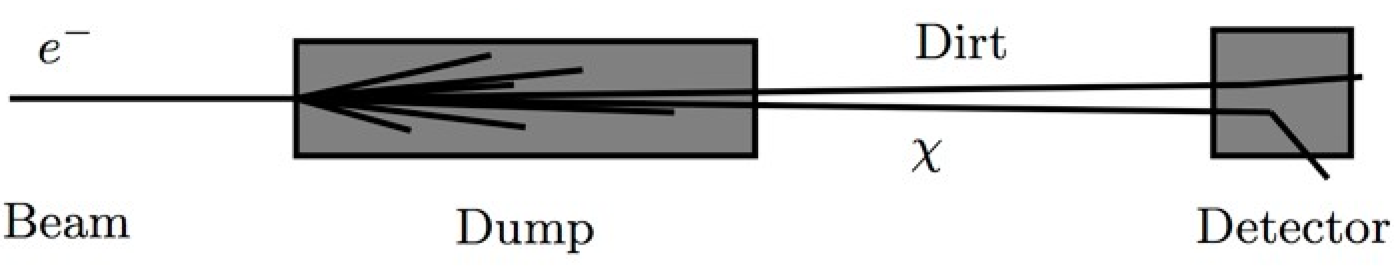
- **Fixed-target:** A' produced in the dump, decays promptly to invisible χ
- **Detector:** Neutral-current scattering of χ trough A' exchange, detect recoil. Different signals depending on the interaction (e^- scattering, coherent nuclear, quasi-elastic,..)

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*.

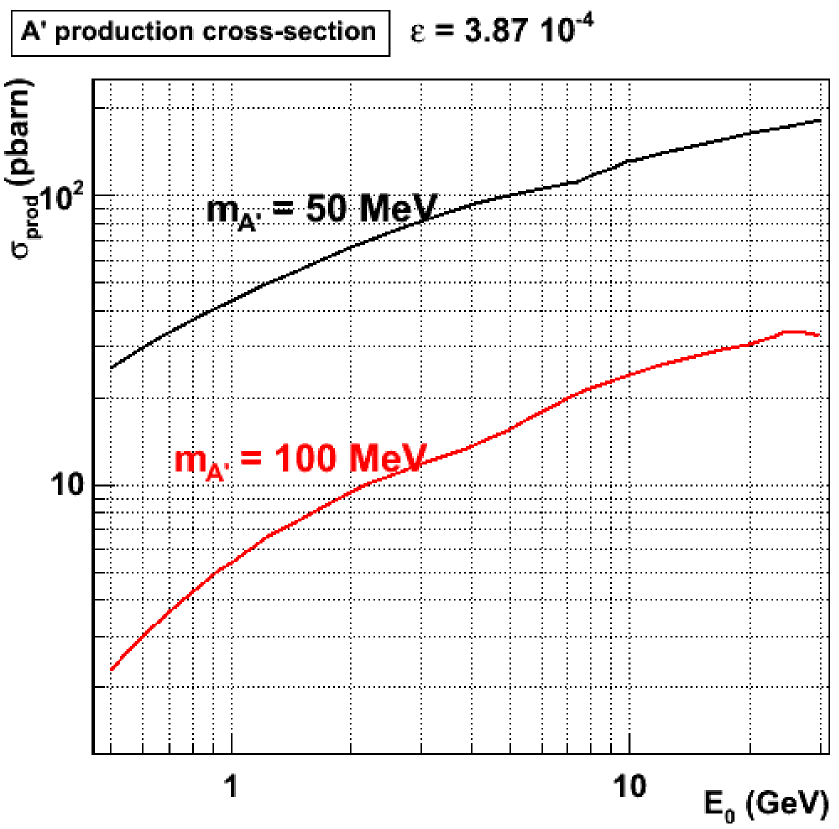
* Assuming 0 beam-related background (see later)

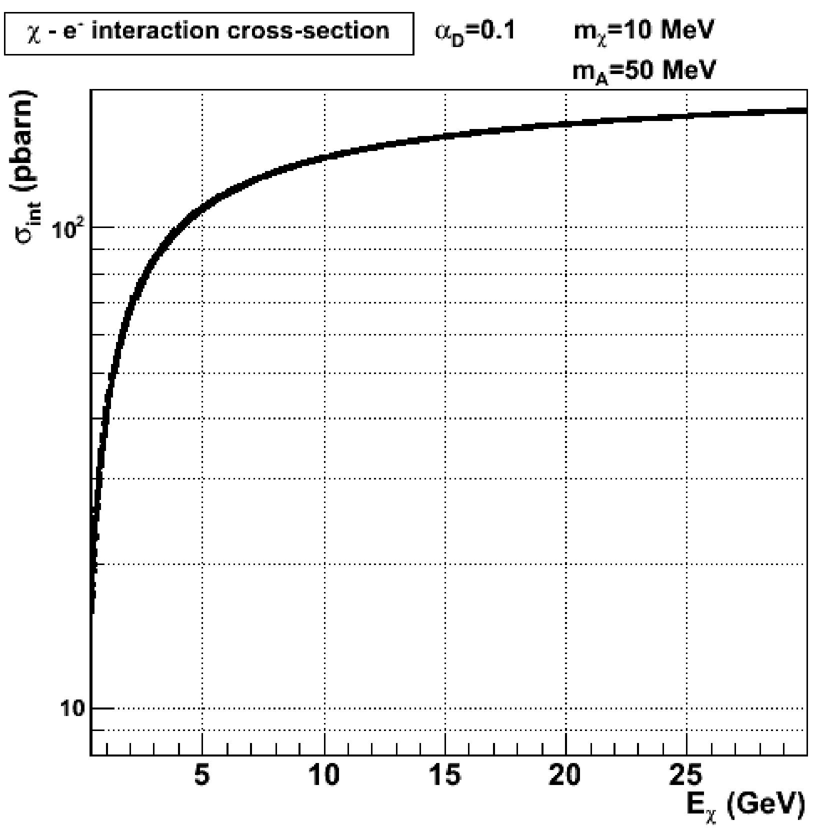
Accelerator requirements

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

- **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).





Accelerator requirements

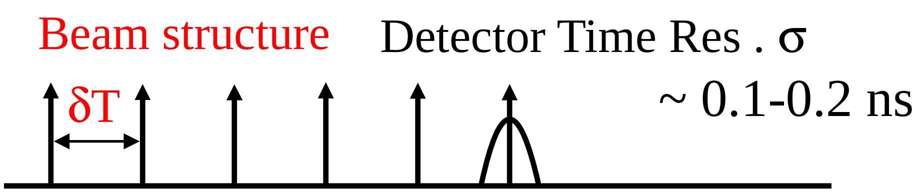
- **Beam current: critical.** The experimental sensitivity scales linearly with this parameter*.

- **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).

- **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

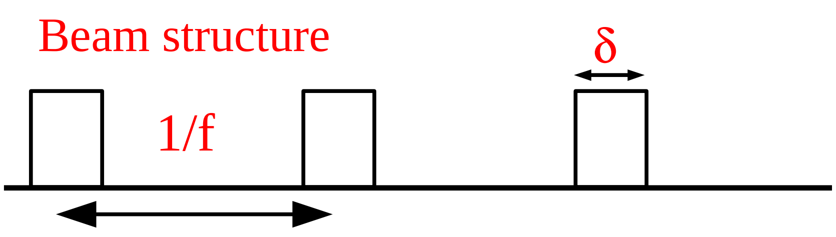
Continuous beam: detector time resolution is a mandatory requirement.

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



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

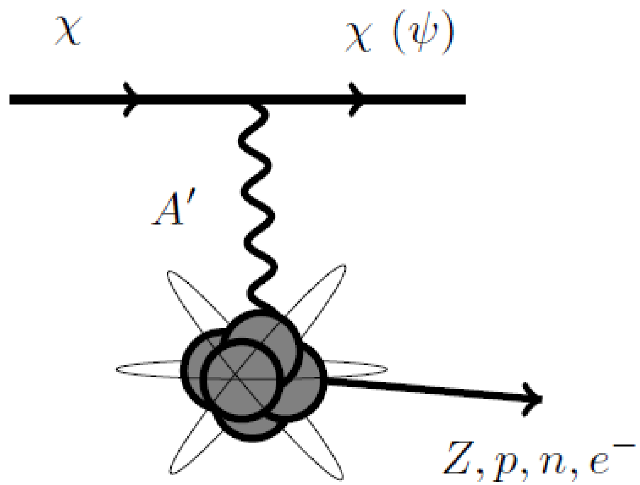
$$R = \frac{1}{f \cdot \delta} = 2 \cdot 10^5 \ @ \ 50\,Hz, 100\,ns$$



χ - matter interaction

1) Elastic scattering on nucleons

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

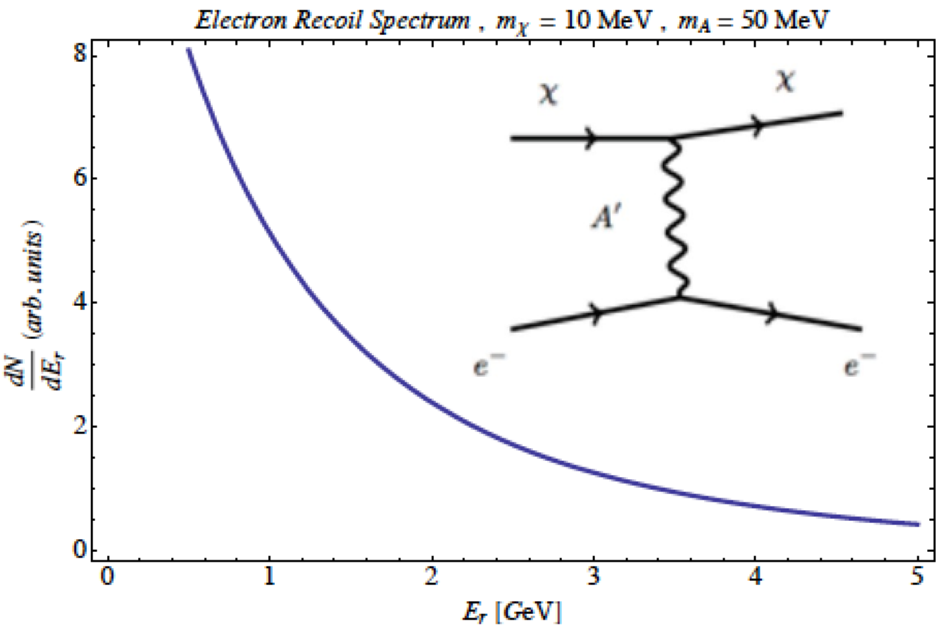


Experimental requirements:

- 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:

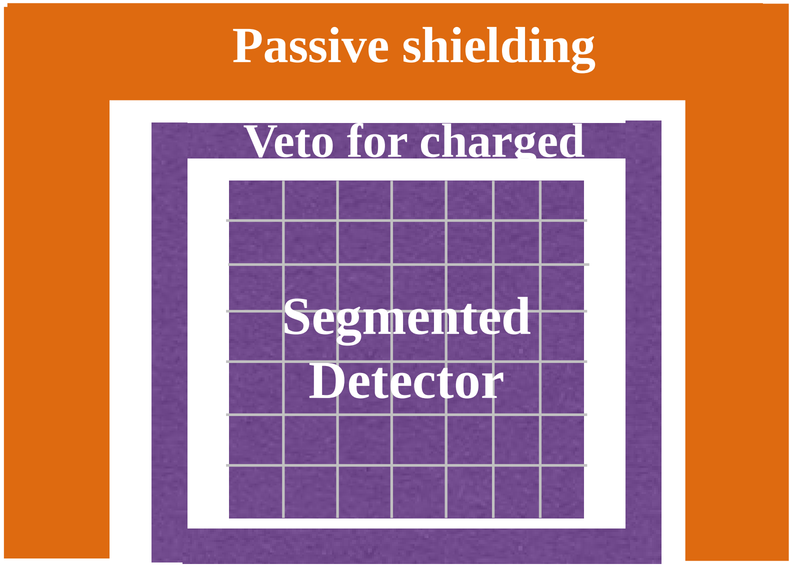
- Sensitivity to ~GeV electrons (EM showers) → Easy background rejection

Detector design and requirements

Signal detection:

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

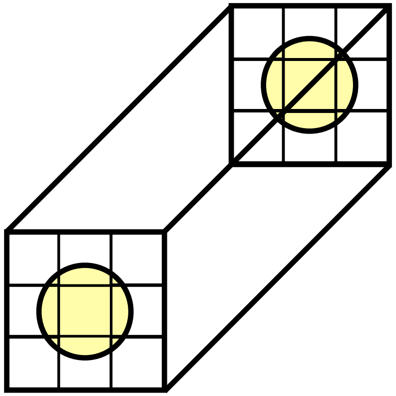
→ **Scintillation-based detector**



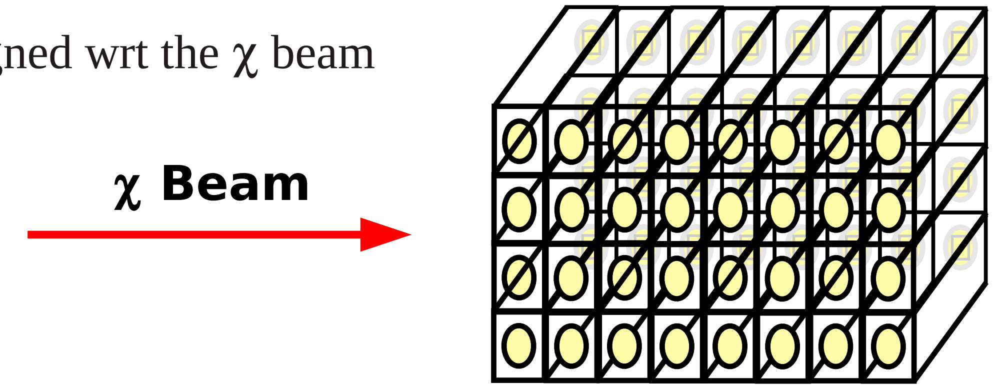
Background rejection / suppression:

- 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



[P. Valente]

A beam-dump experiment at LNF

Accelerator parameters:

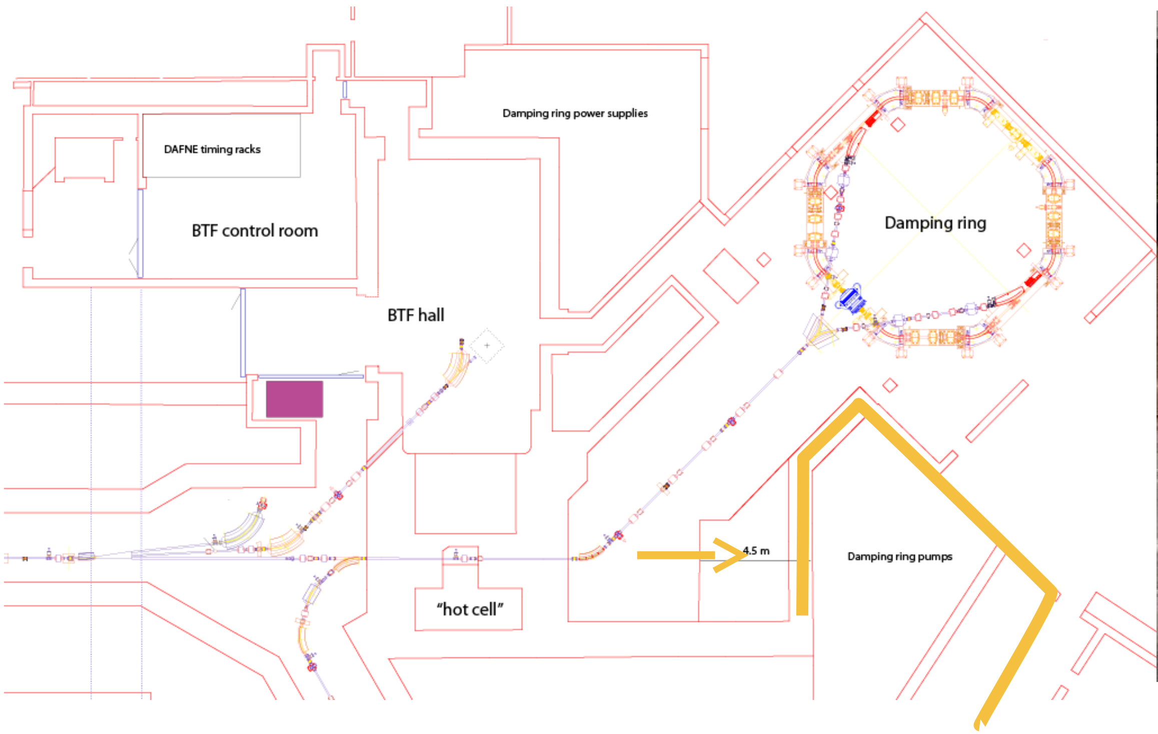
- **EOT (1 full year):**
  - **Today:** $5 \cdot 10^{19}$ (10 ns/bunch, 5 nC/bunch, 50 Hz), although legal regulations impose $< \sim 10^{18}$
  - **"Reasonable" upgrade:** $2.5 \cdot 10^{20}$, to be tested (larger bunch length / higher gun pulse height)
  - **"Optimistic" scenario:** $\sim 1 \cdot 10^{21}$ (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 $2 \cdot 10^{5}$

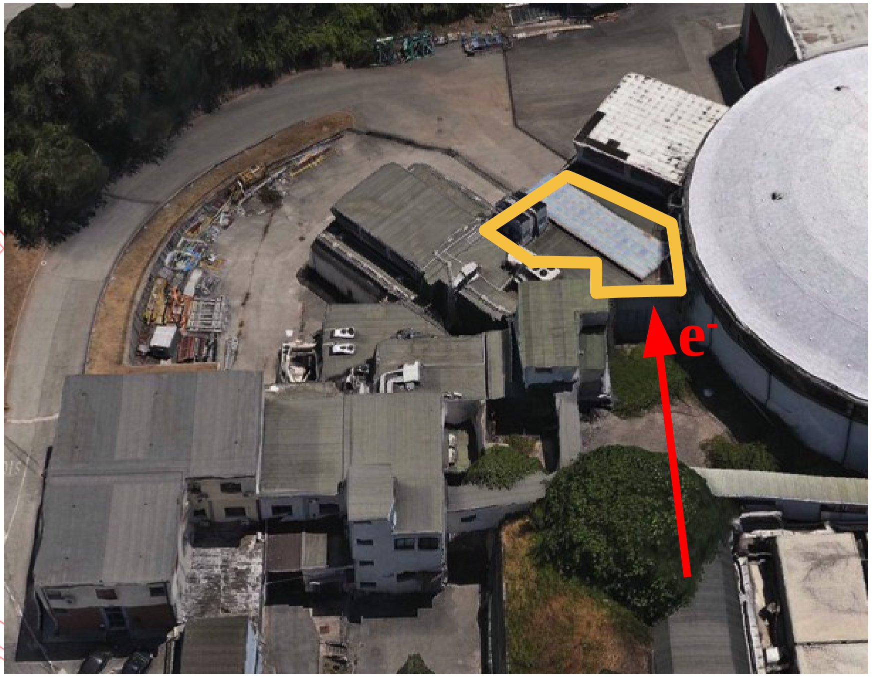
[P. Valente, J. Esposito]

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.





[P. Valente, J. Esposito]

Experimental setup: detector location

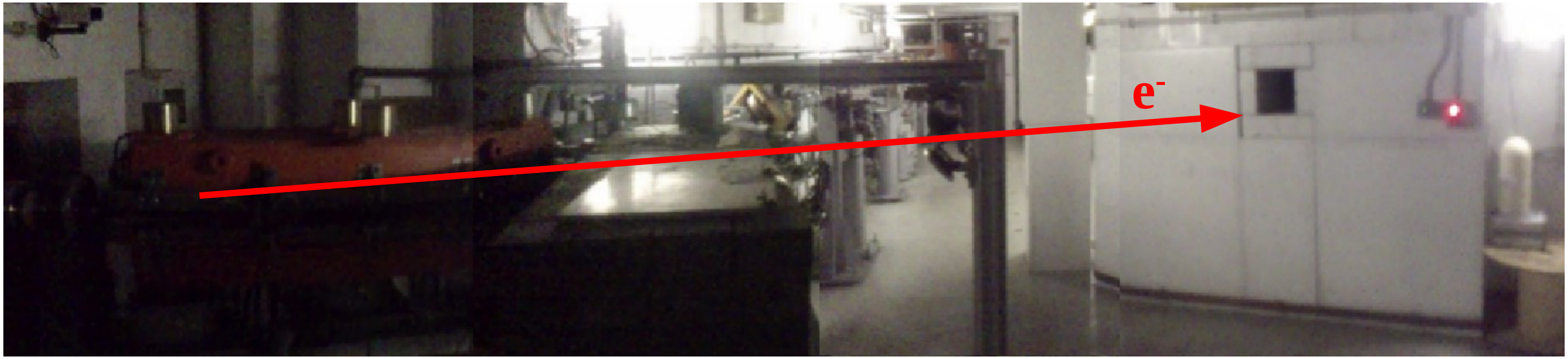
Use the existing ADONE beam-dump and install the detector in the DAΦNE service room

- 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
- **Existing dump needs to be re-engineered**

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



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 → 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)

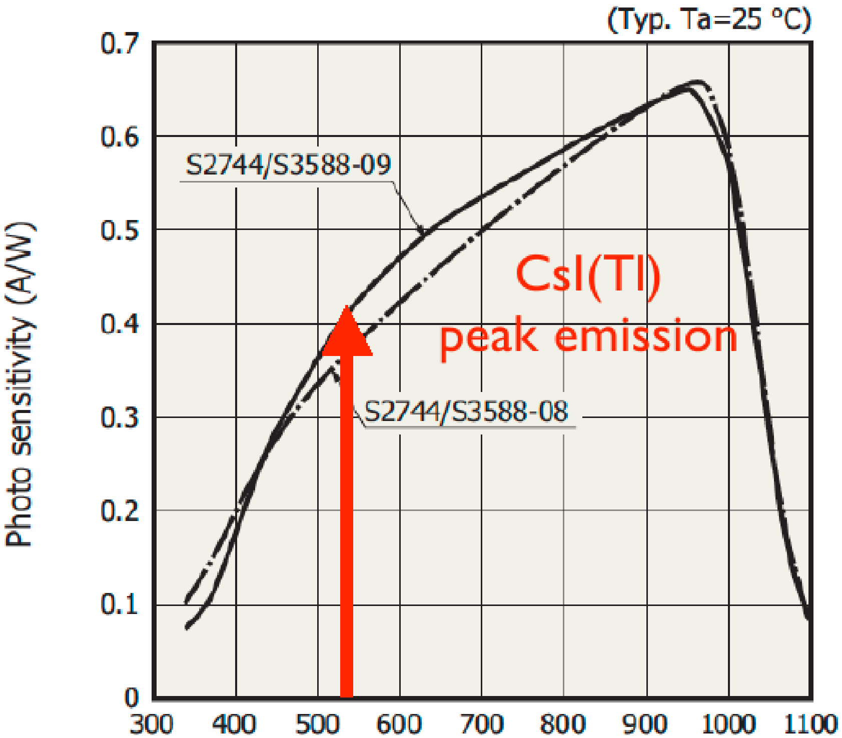
Detector design

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	~800	~ M€

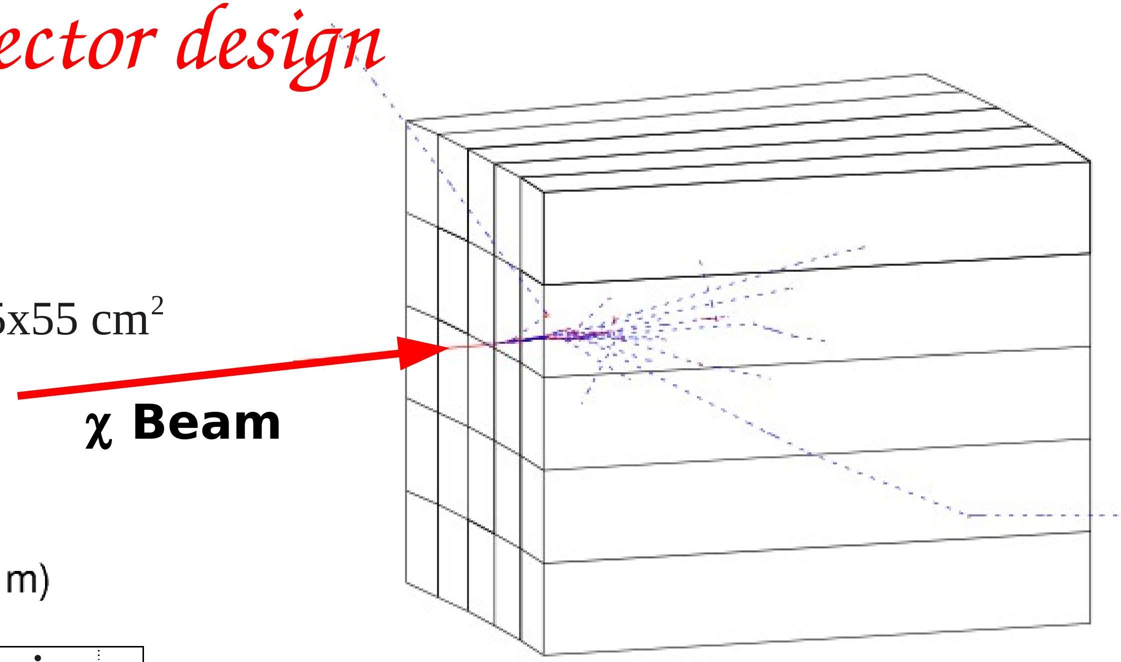


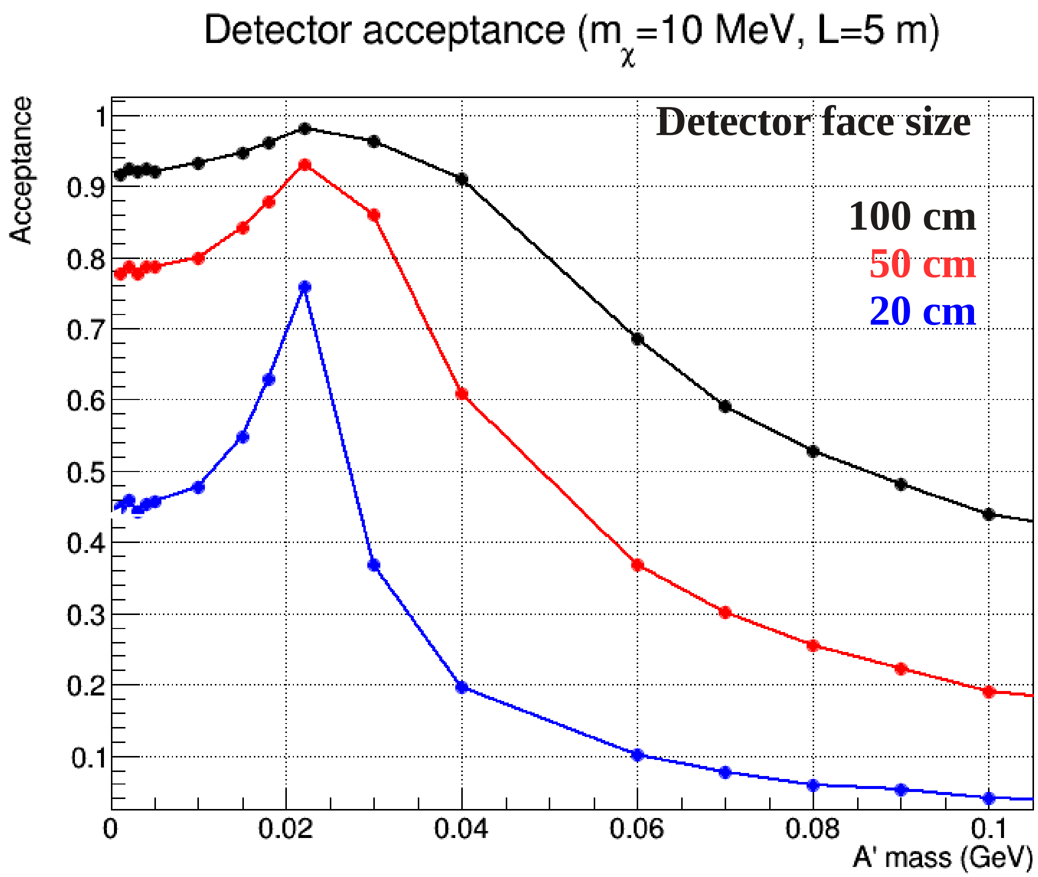
[arXiv:0105.5044]

Detector design

(Possible) setup: M. De Napoli talk

- 1 crystal: 5(6) x 5(6) x 30 cm^3
- 1 block of 11x11 crystals: front face ~ 55x55 cm^2
- 7 blocks: 210 cm length





Detector design has to be optimized according to the kinematics of the χ beam, in the parameters region the experiment is most sensitive to.

[R. De Vita]

Beam-related backgrounds simulation

Goal: estimate backgrounds created by beam interaction with the dump via MC simulations.

Conditions: 1 GeV e^- beam, $\sim 10^{20}$ EOT, 2 m iron + concrete absorber

Issues:

- **Computing limitations:** combination of very large number of incoming particles and very massive absorbers makes full-luminosity simulations prohibitive. **Extrapolation over several order of magnitudes needed.**
- **Physics issues:** accurate modeling of physics interaction from GeV to eV, including low energy nuclear reactions and neutron transport.

[R. De Vita]

Beam-related backgrounds simulation

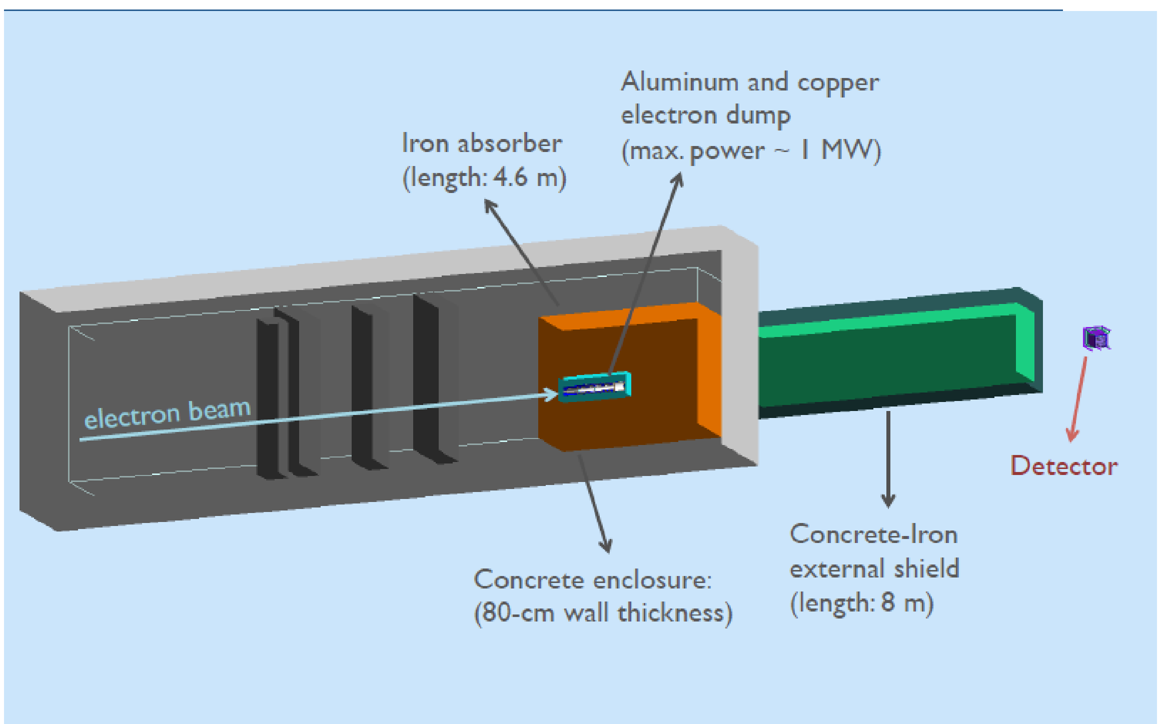
Brute-force approach: use GEANT4 to model the beam dump geometry and materials, and to simulate the interaction of the electrons. Determine fluxes of particles exiting from the dump and reaching the detector location.

Results from a "JLab-experiment" simulation (12 GeV e^-, 8 m iron/concrete shield):

- 1 event ~ 3 s computation time @ Intel Xeon (E5530) 2.4 GHz
- 1 month of simulation on 200 core farm: 2×10^9 EOT
- Extrapolate 12-13 orders of magnitude to reach the desired experiment luminosity:
  - Critical for neutrons and photons: zero rate obtained, only upper limit can be set

Although BDX @ LNF runs at lower energy, and less computation time is required, still the full 10^{20} EOT luminosity simulation is unfeasible.

A different approach is required

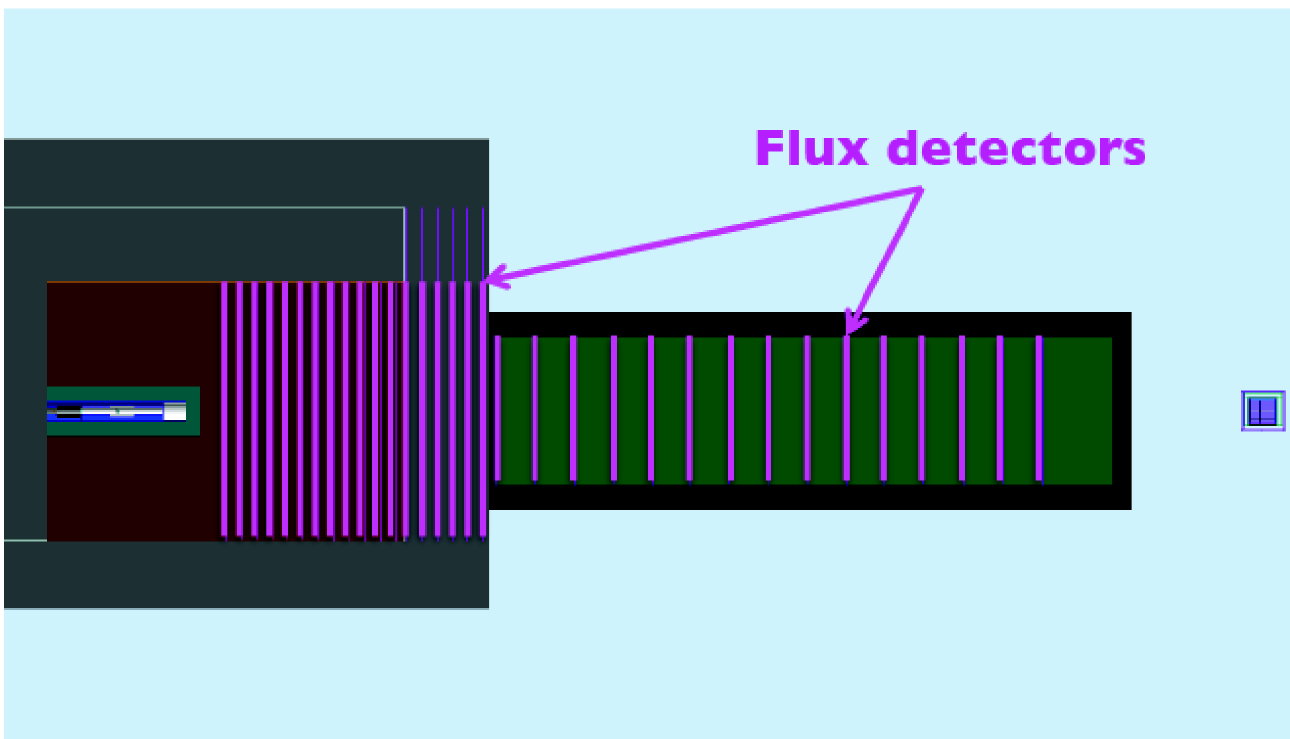


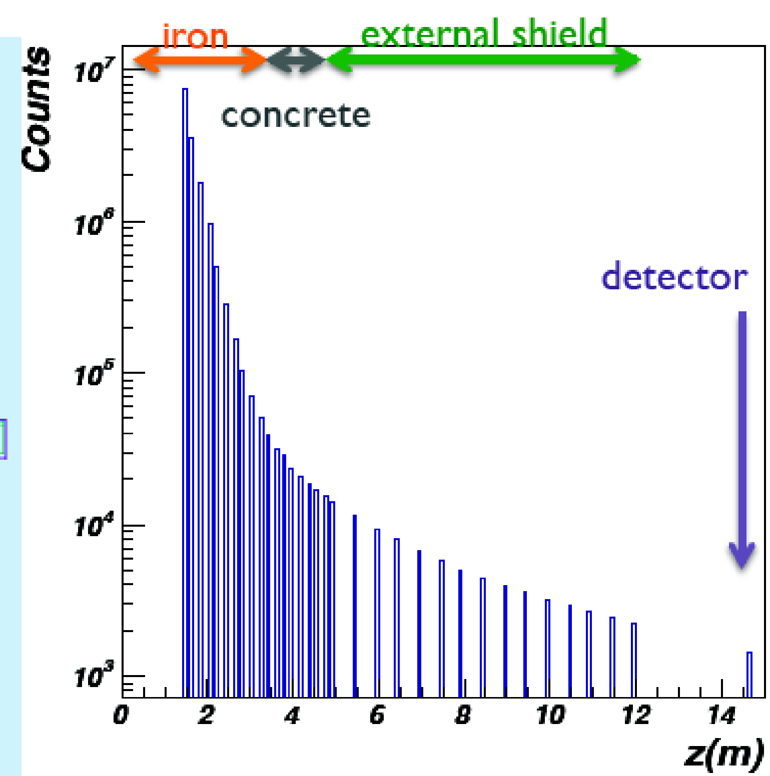
[R. De Vita]

Beam-related backgrounds simulation

Different approach:

- Use GEANT4 for treatment of high energy (GeV to MeV) interactions.
- Sample particle fluxes at different depths within the dump absorbers to study the flux profile and find non-zero values.
- Extrapolate non-zero fluxes to full luminosity based on flux profile
- Validate results for low energy neutrons/gamma with different simulation tools (MCNP) and using variance reduction techniques





Beam-related backgrounds: first preliminary results

1) Prompt backgrounds (γ/fast n):

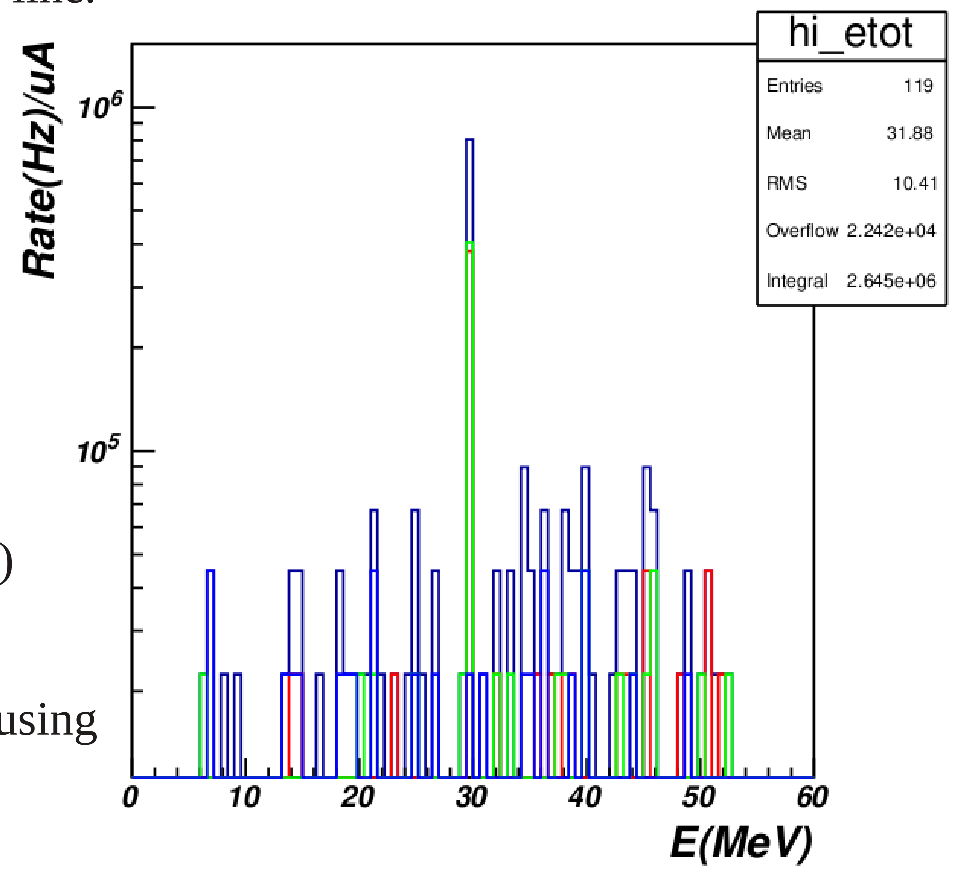
- Can't be reject with the detector-beam RF time coincidence
- Shielding is required to reduce γ/fast n rate on the detector
  - From preliminary simulations, 2 m iron + 2 m concrete are enough to reduce contribution to less than O(1 particle / year) @ 10 μA

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.
- This background contribution can be measured on-line.

3) Neutrinos:

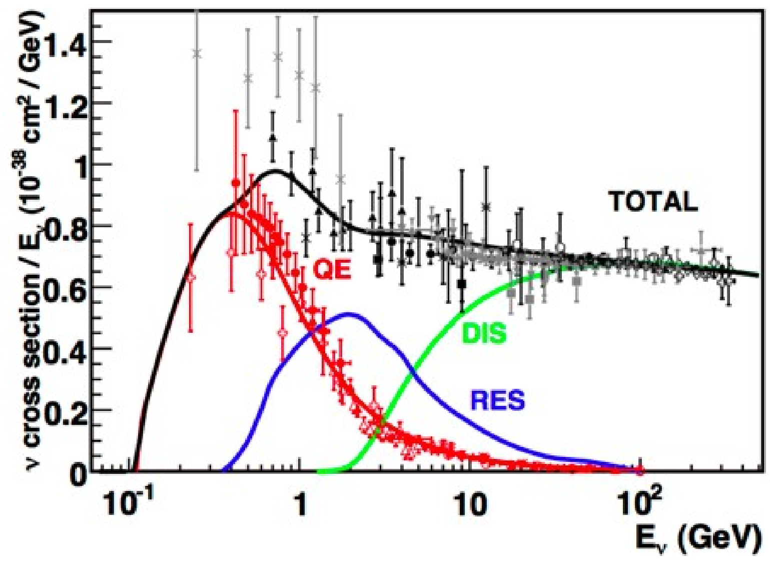
- Neutrino flux on the detector:
  $\Phi \sim 1.16\ 10^{-7}\ \nu$ / EOT, $E_\nu < 50$ MeV
  (isotropic, from at-rest processes)
- Cross-section:
  $\sigma \sim 10^{-40}\ \mathrm{cm}^2$
- Interactions (for $2.5\ 10^{20}$ EOT):
  N ~ 60
- Further suppression:
  - Energy threshold (~50% efficieny @ 1 MeV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



Cosmogenic backgrounds

1) Cosmic neutrinos

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



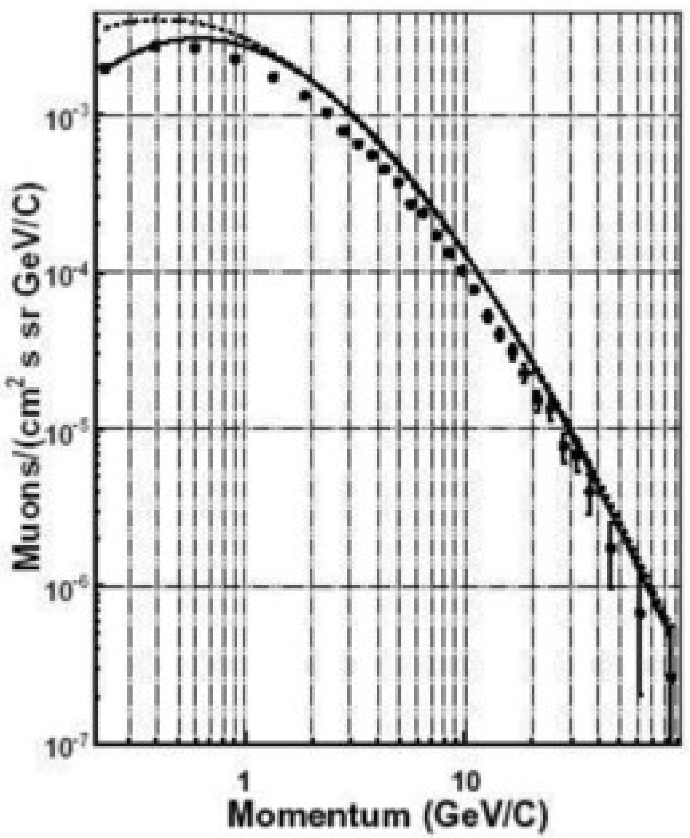
Cosmogenic backgrounds

1) Cosmic neutrinos

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

2) Cosmic muons: different background contributions

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



Cosmogenic backgrounds

1) Cosmic neutrinos

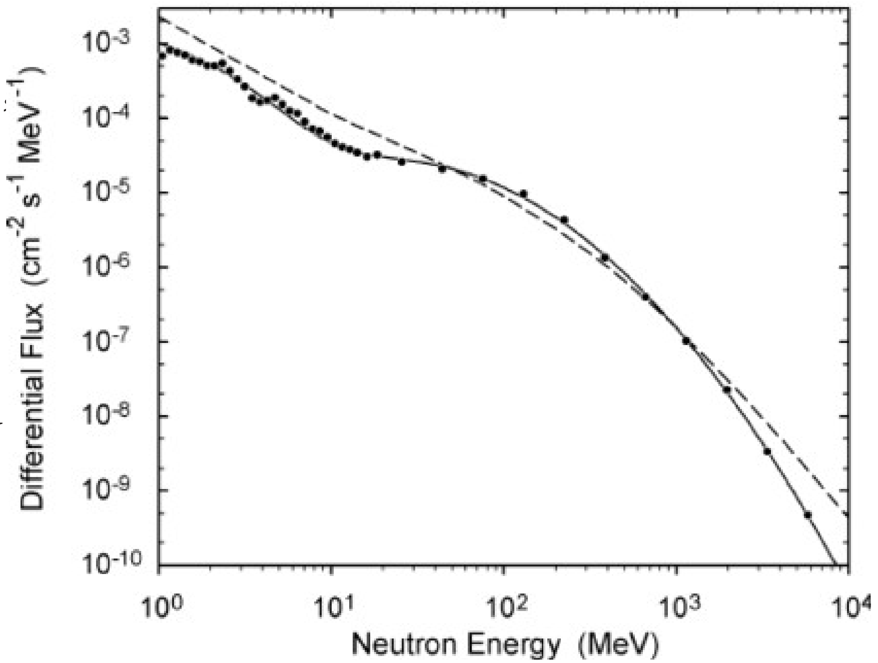
- Considering flux, interaction cross-sections, and thresholds the contribution is negligible

2) Cosmic muons: different background contributions

- Different background contributions (crossing/stopping/decaying/..).
- Reduced trough shielding + dual VETO around the detector + threshold + signal topology (different from χ-p and χ-e interactions).
- From preliminary estimates, 5 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
- 1 m iron shield + detection threshold introduce an energy cut-off on the primary spectrum ~ 50 MeV



Cosmogenic backgrounds

1) Cosmic neutrinos

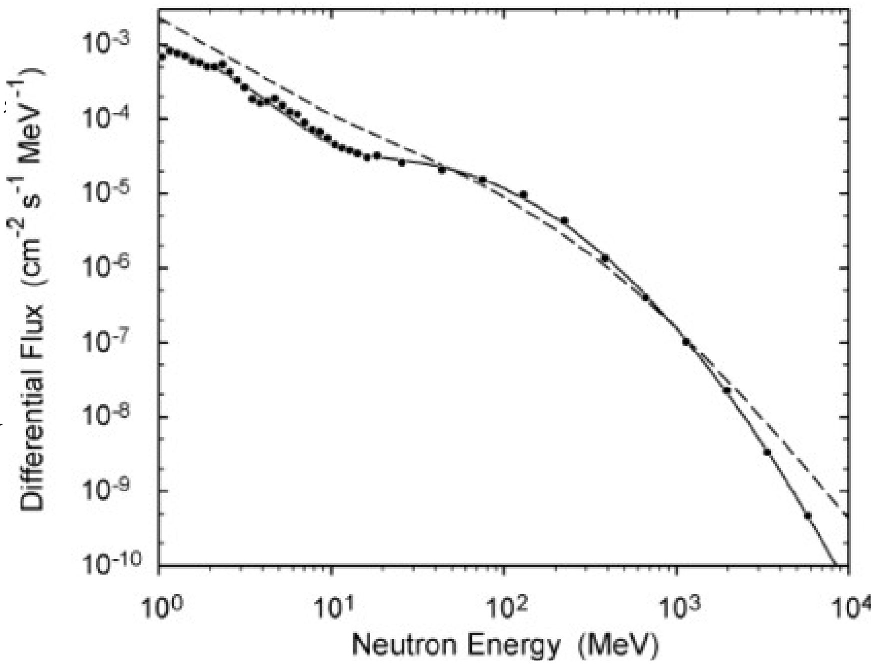
- Considering flux, interaction cross-sections, and thresholds the contribution is negligible

2) Cosmic muons: different background contributions

- Different background contributions (crossing/stopping/decaying/..).
- Reduced trough shielding + dual VETO around the detector + threshold + signal topology (different from χ-p and χ-e interactions).
- From preliminary estimates, 5 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

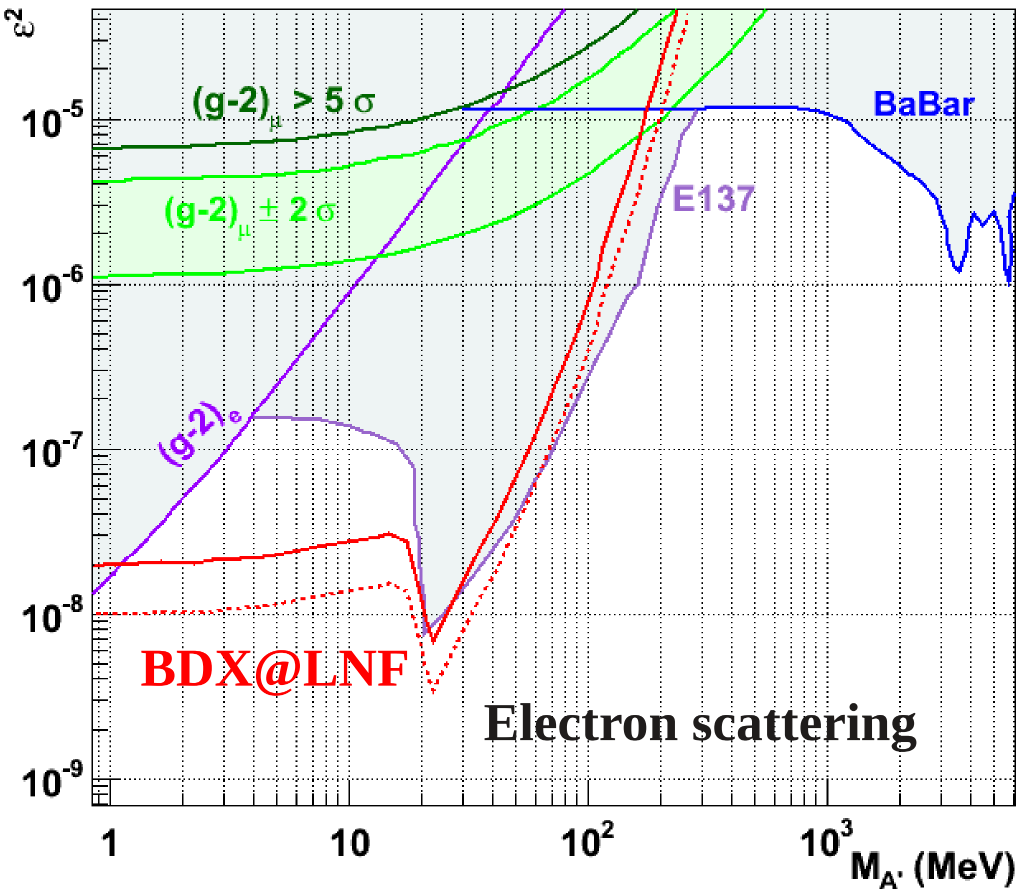
- High-energy neutrons can penetrate the shielding and interact inside the detector, mimicking a χ-N interaction
- 1 m iron shield + detection threshold introduce an energy cut-off on the primary spectrum ~ 50 MeV



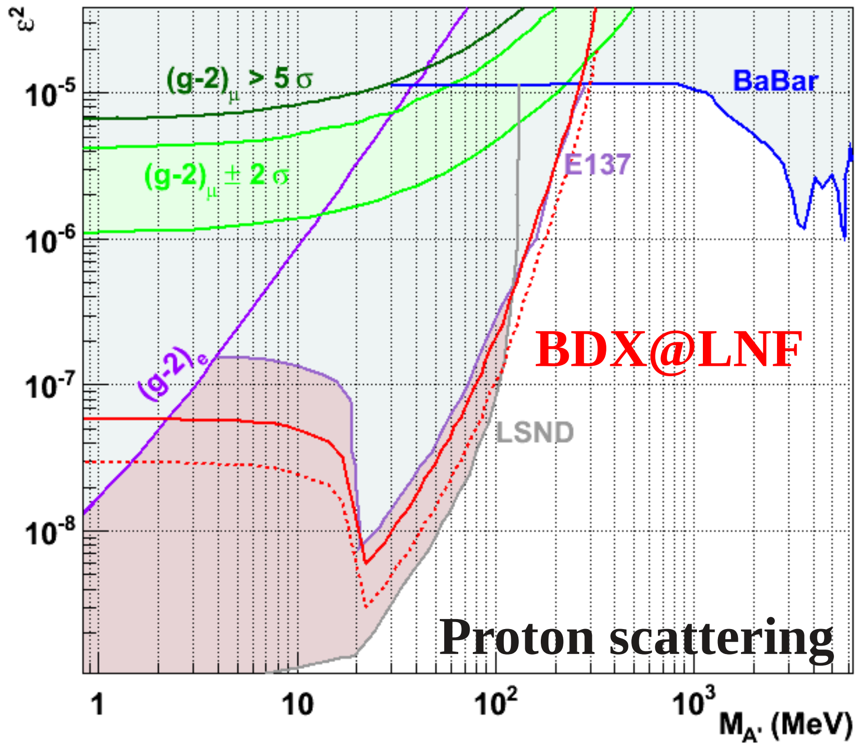
A dedicated measurement campaign is planned at LNS to measure these backgrounds and validate MC simulations

Experimental reach

Experimental reach for BDX@LNF, evaluated at m_χ=10 MeV, α_D=.1, assuming Ns=3, Nb=0.



- **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

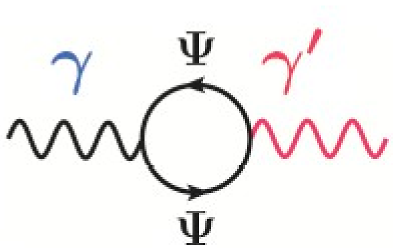
- **Beam dump experiments with electron beams are the “ideal” way to probe low-mass (< 1 GeV) dark-matter**

- **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 $\varepsilon^2 \sim 10^{-8}$
  - This will be the first experiment designed to measure both the electron and the nuclear recoil signals, for cross-check and for systematic effects evaluation

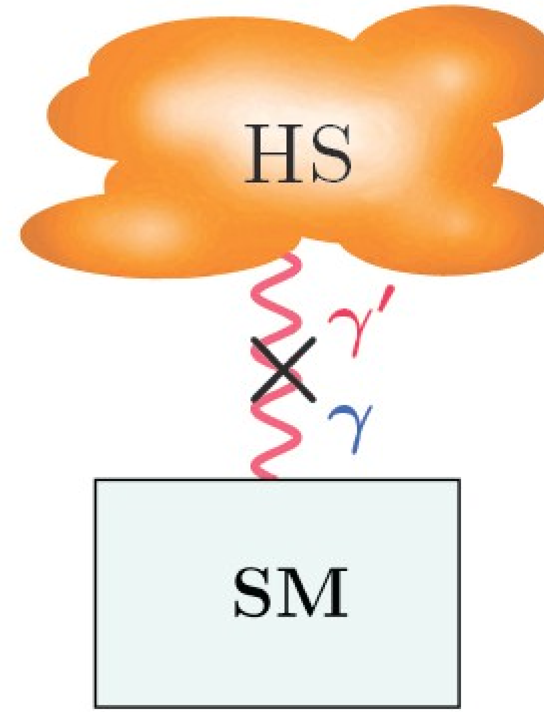
Back up

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'



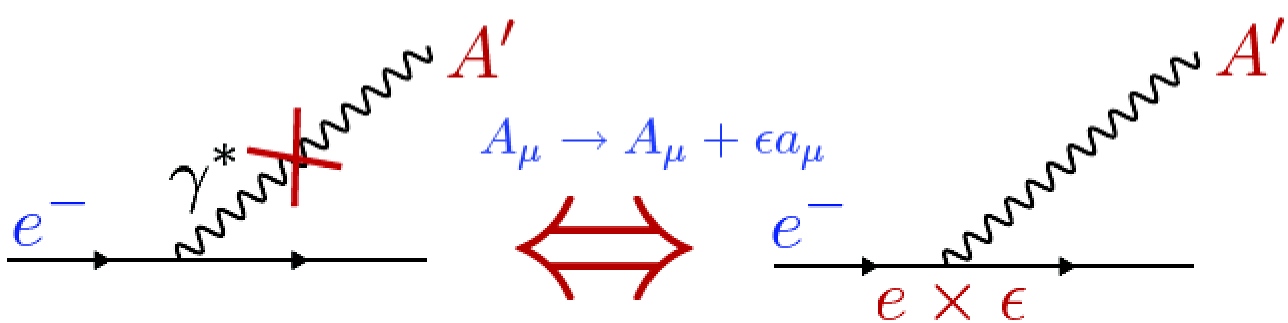
Ψ is a huge mass scale particle (M~1EeV) coupling to both SM and HS



- 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:

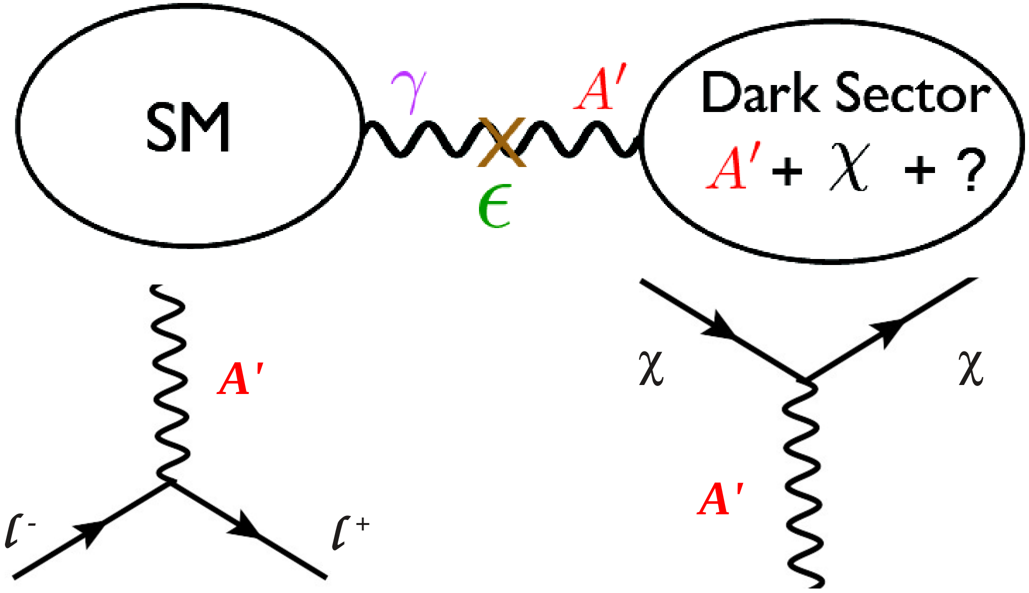
$$\varepsilon A'_\mu J^\mu_{EM}$$

Boldom, Phys. Lett. B166, 1986

Dark photons and dark sector

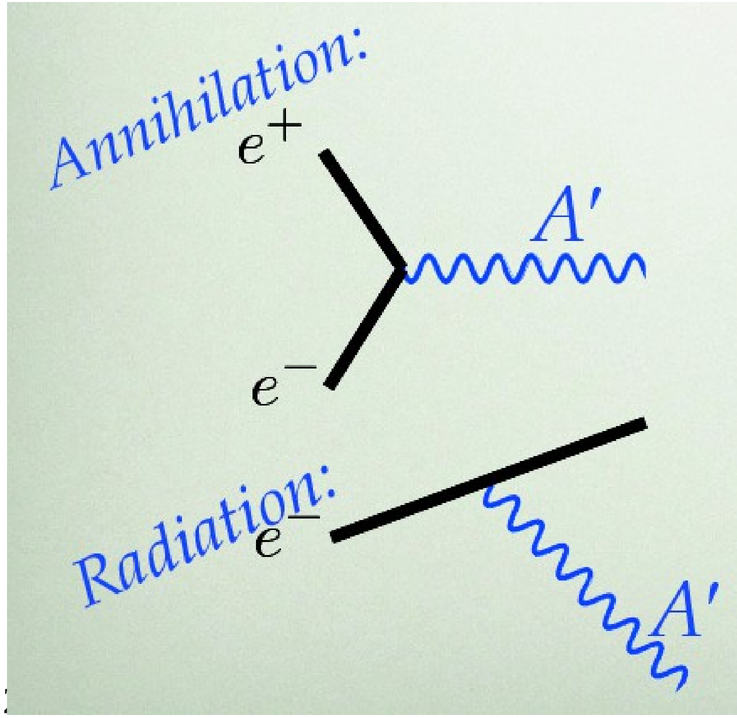
Model:

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



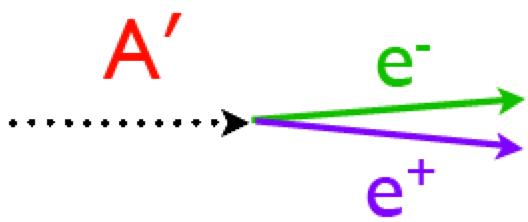
4 parameters: $M_{A'},\ M_{\chi},\ \varepsilon,\ g_d$

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



A' decay:

First scenario: only SM decays



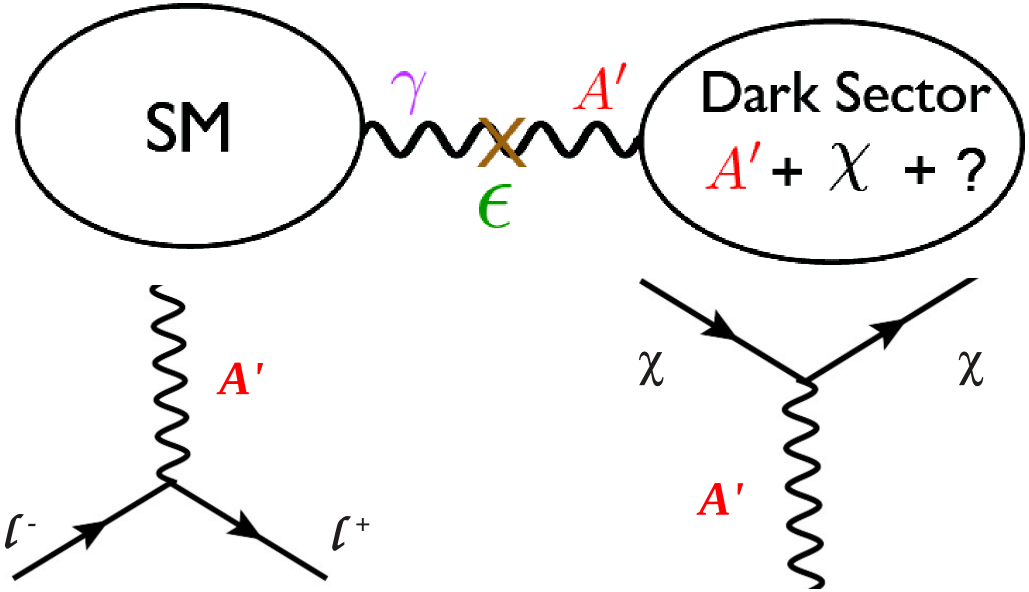
- Minimal scenario
- $BR(A' \to SM) = 1$
- $\Gamma_{Tot} \propto \varepsilon^2$

Dark photons and dark sector

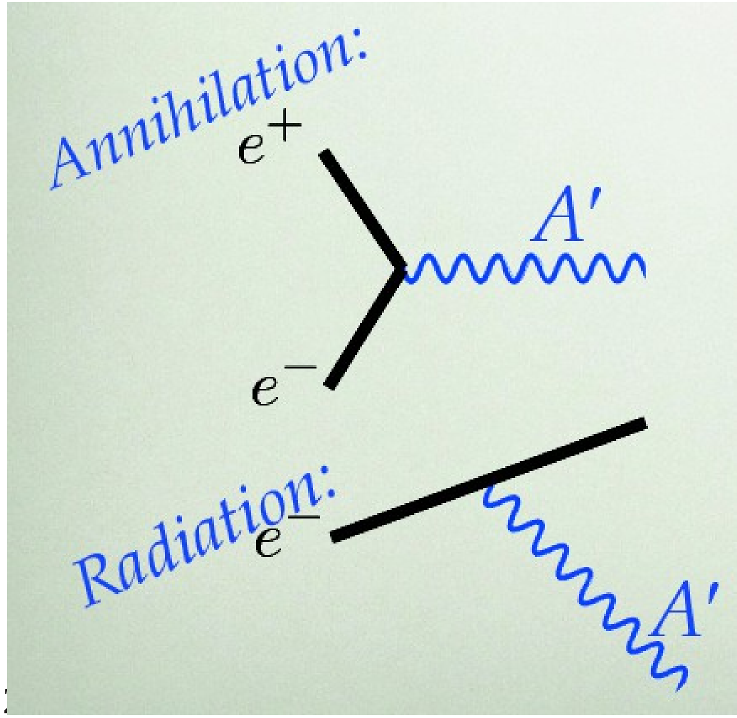
Model:

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

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

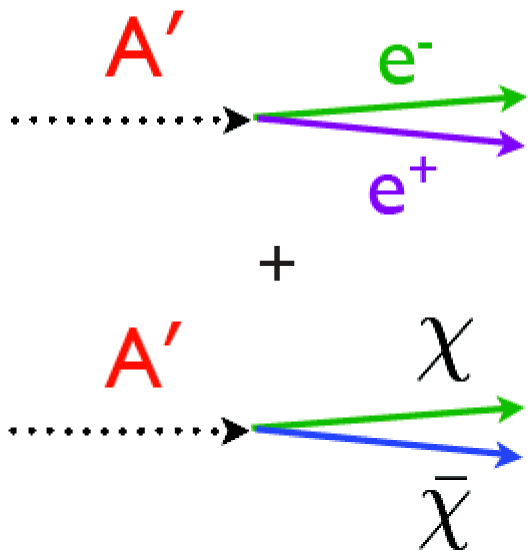


A' production: $\sigma \propto \varepsilon^2$



A' decay:

Second scenario: SM + hidden decays

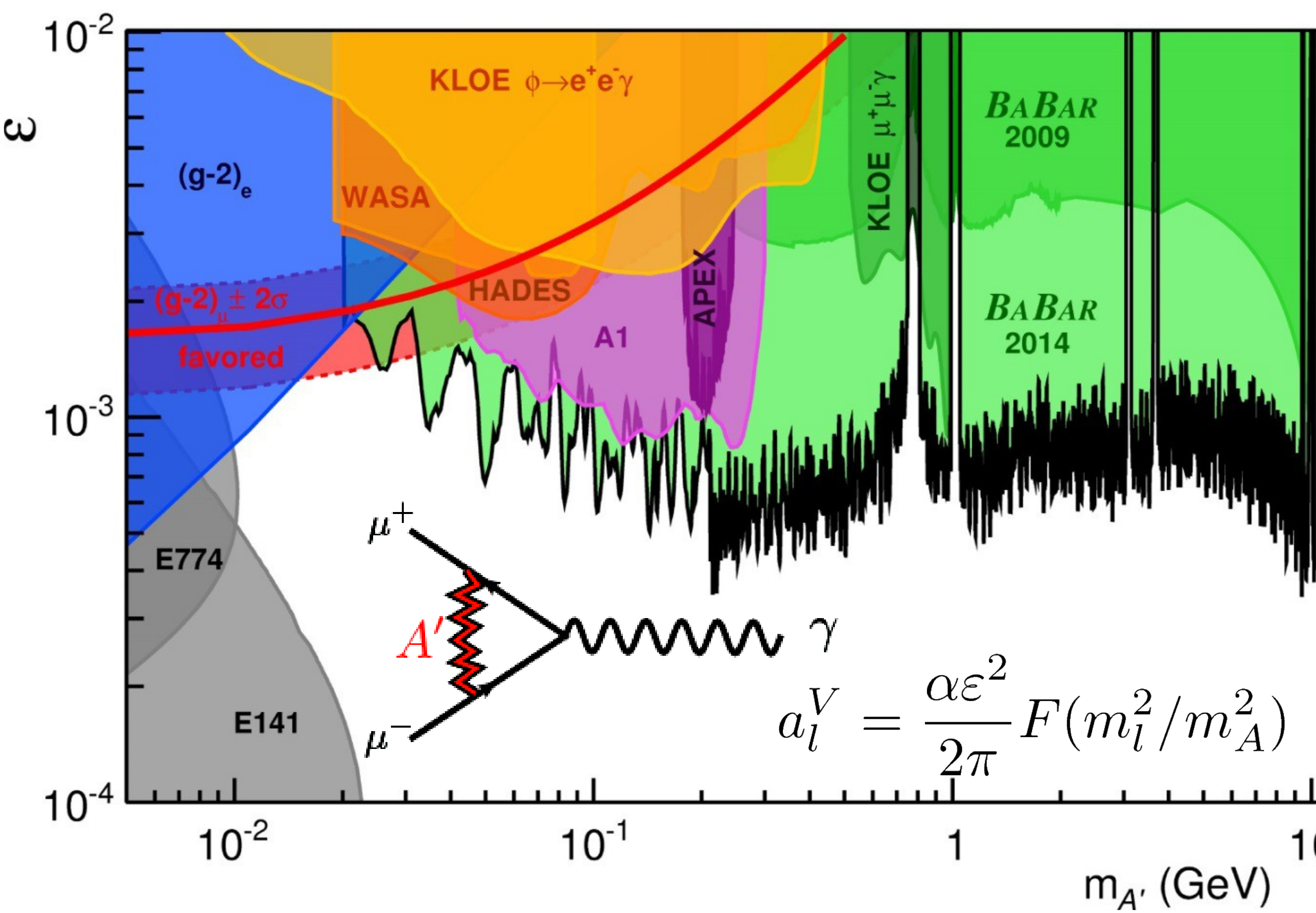


- Kinematically allowed only if $M_{A'} > 2\ M_{\chi}$
- $BR(A' \to SM) \propto \varepsilon^2$
- $\Gamma_{SM} \propto \varepsilon^2$
- $\Gamma_{\chi\chi} \simeq 1$

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]

Dark photons invisible decay and g-2

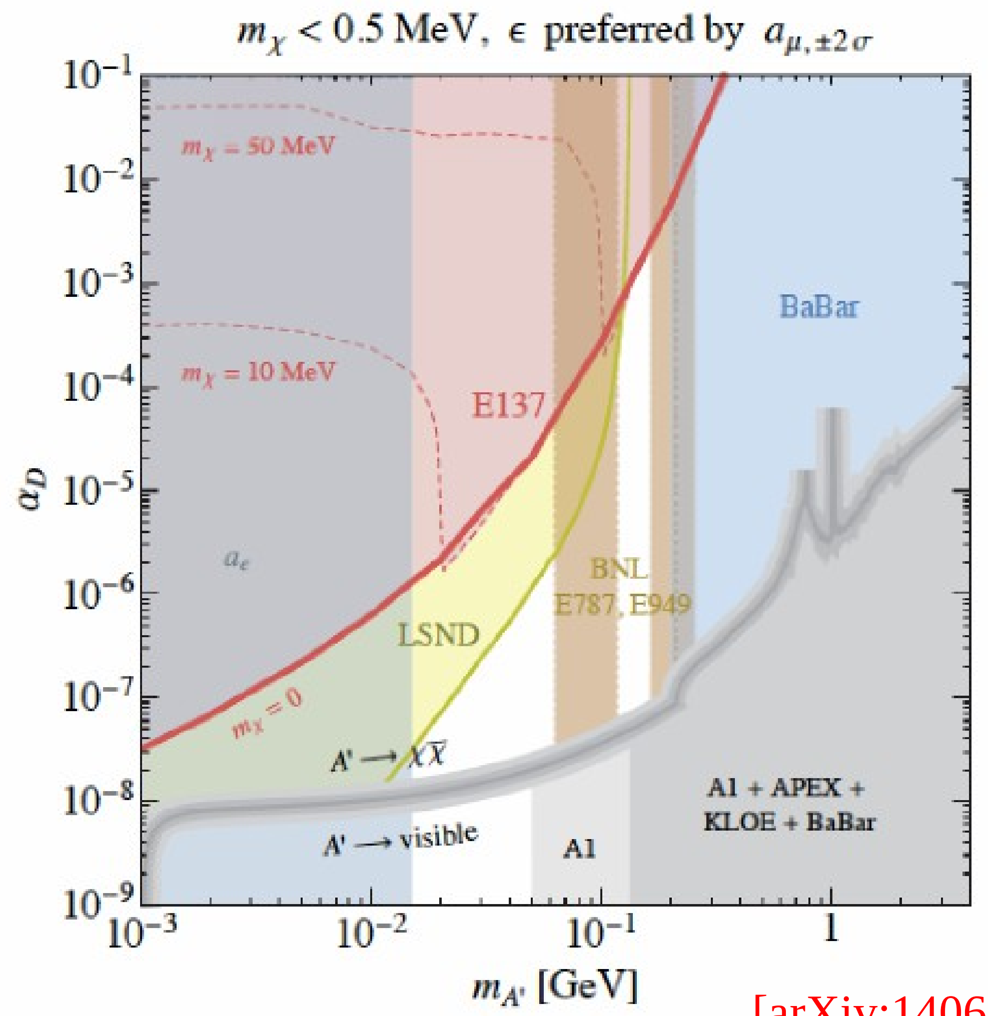
- **Muon g-2 anomaly:** "traditional" motivation for A' search
  - New results (Phenix,Babar, KLOE) seem to exclude the g-2 preferred region in the $\varepsilon - M_A$ plane
  - This conclusion is model-dependent, based on BR(A' → SM) = 1
    If the invisible decay is included in the model, old limits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

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

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



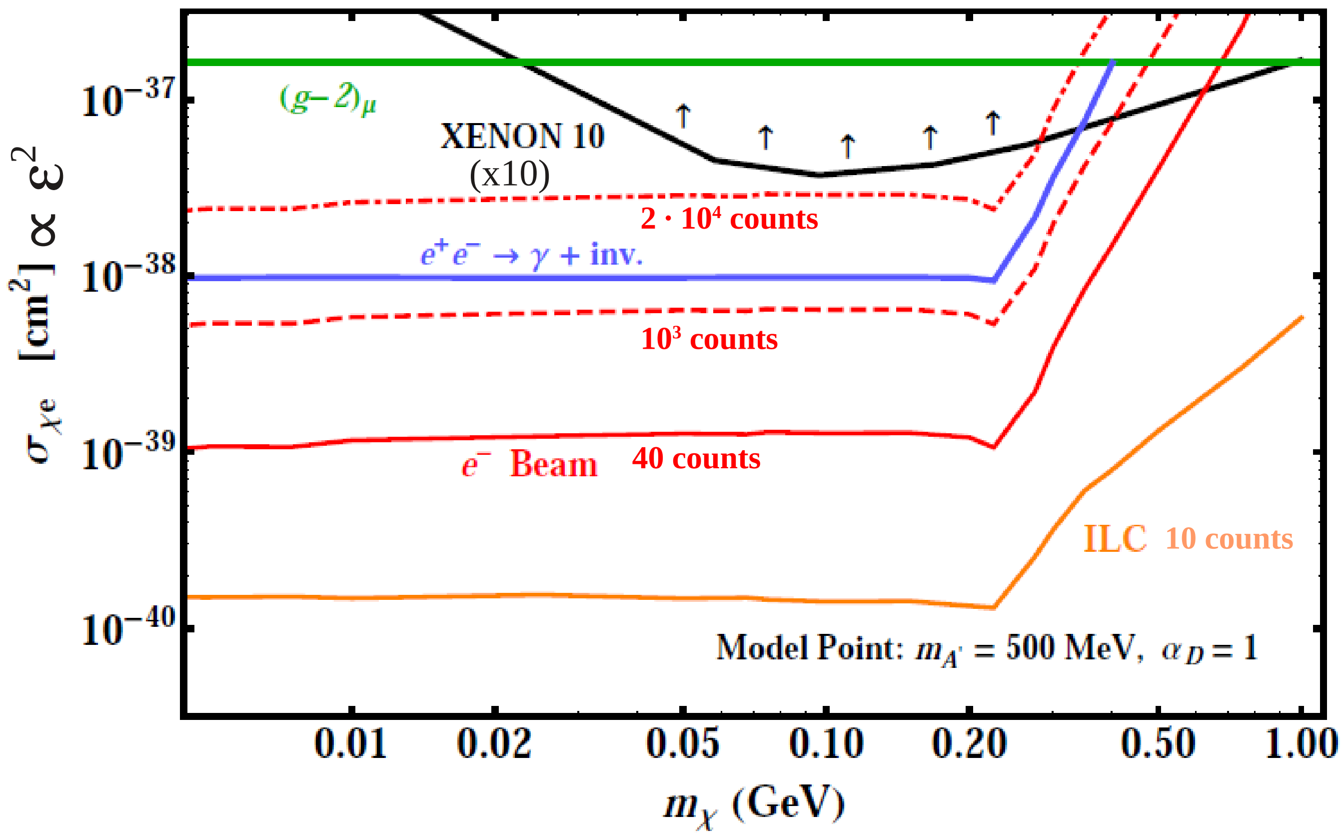
[arXiv:1406.2698]

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]

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)

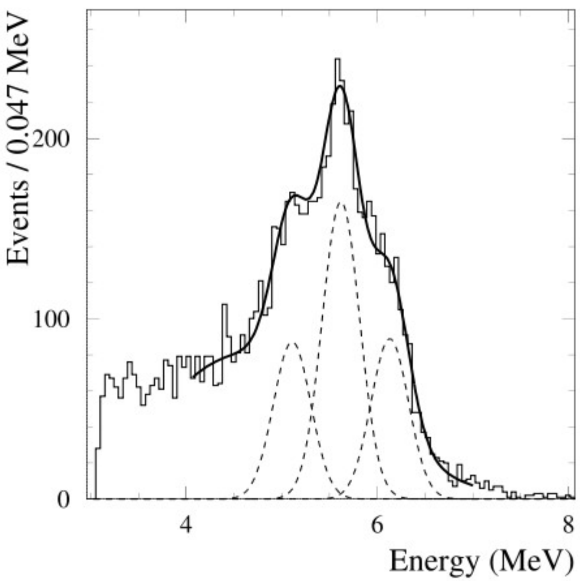
Properties:

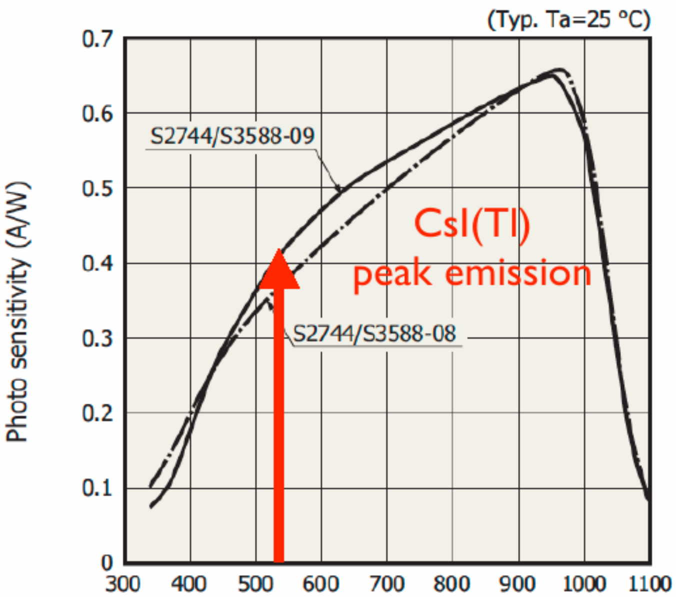
- ~ 7300 phe / MeV
- Low-energy calibration point for each crystal @ 6.13 MeV
- 250 keV ENE.

Low-energy calibration system:

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

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

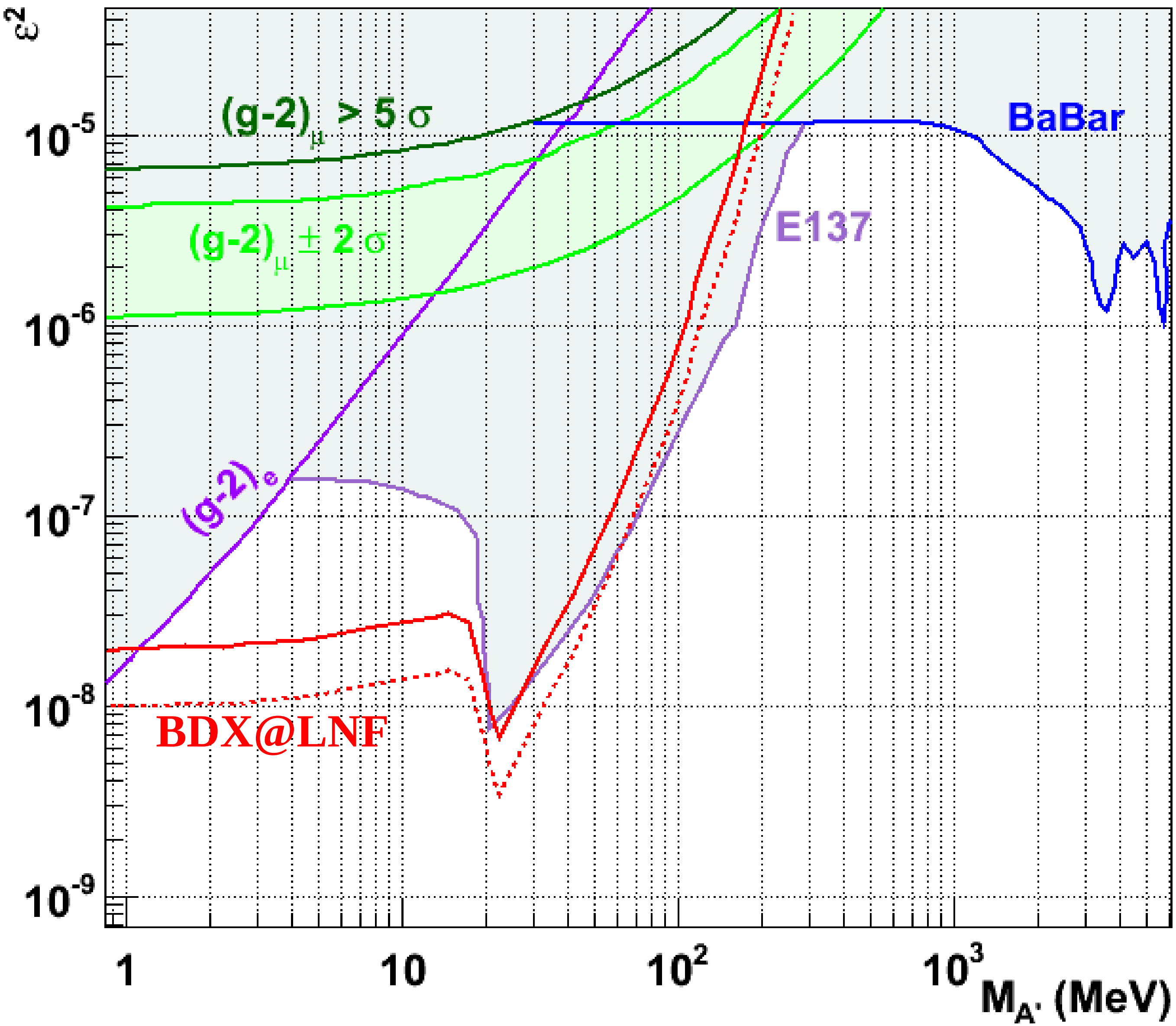




[arXiv:0105.5044]

Experimental reach: electron scattering

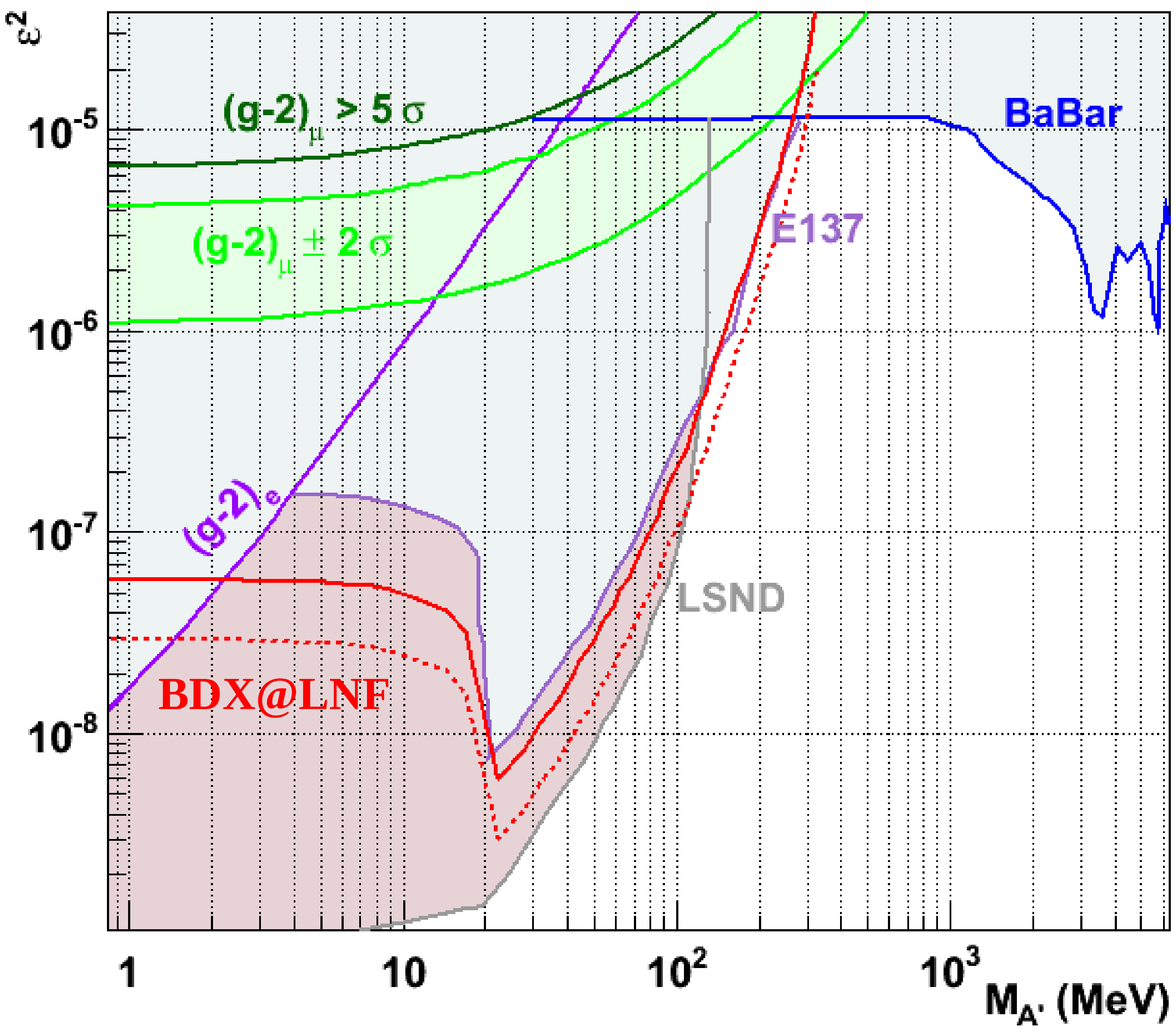
Experimental reach for BDX@LNF, evaluated at m_χ=10 MeV, α_D=.1



- **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



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