Dark photon searches with PADME

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The long quest for dark matter

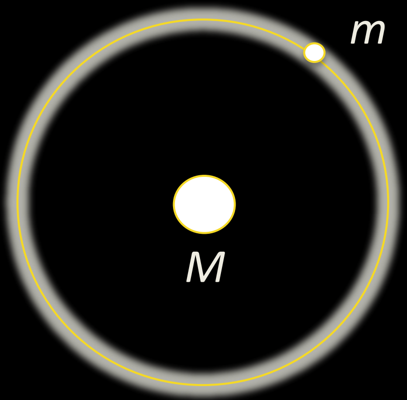
Zwicky, Coma cluster (1933)

$M/L \approx 660\ M_\odot/L_\odot$

Hubble Space Telescope (2007)
Cluster Cl 0024+17

Lensing of background galaxies

Virial theorem



$\frac{1}{2} mv^2 = GMm/R$

For a system of N particles, the moment of inertia and its derivatives are:

$$I = \tfrac{1}{2} \Sigma_i\, m_i \mathbf{r}_i \cdot \mathbf{r}_i$$

$$dI/dt = \Sigma_i\, m_i\, d\mathbf{r}_i/dt \cdot \mathbf{r}_i$$

$$d^2I/dt^2 = \Sigma_i\, m_i \left(d\mathbf{r}_i/dt \cdot d\mathbf{r}_i/dt\ + \mathbf{r}_i \cdot d^2\mathbf{r}_i/dt^2\right)$$

Equation of motion:

$$m_i\, d^2\mathbf{r}_i/dt^2 = -\Sigma_{j\neq i}\, Gm_im_j\, / \,|\mathbf{r}_i - \mathbf{r}_j|^3\ (\mathbf{r}_i - \mathbf{r}_j)$$

Kinetic energy;

$$2T = \Sigma_i\, m_i \left(d\mathbf{r}_i/dt \cdot d\mathbf{r}_i/dt\right)$$

$$d^2I/dt^2 - 2T = -\Sigma_i \Sigma_{j\neq i}\, Gm_im_j\, / \,|\mathbf{r}_i - \mathbf{r}_j|^3\ \mathbf{r}_i \cdot (\mathbf{r}_i - \mathbf{r}_j) = \dots$$

$$= \tfrac{1}{2}\, \Sigma_i \Sigma_j\, Gm_im_j\, / \,|\mathbf{r}_i - \mathbf{r}_j| = U$$

$$\boxed{d^2I/dt^2 = 2T + U}$$

Virial equilibrium: $2\langle T\rangle + \langle U\rangle = 0$

Estimate masses using velocities

$\Sigma_i m_i \langle v_i^2\rangle = \Sigma_i \Sigma_{j<i} G m_i m_j \; 1/\langle|\mathbf{r}_i - \mathbf{r}_j|\rangle$

$\langle v_{r,i}^2\rangle_\Omega = 1/3 \; v_i^2$

projected along radial direction, averaged over solid angle Ω

- We see only radial component of motion, $\langle v_i\rangle \approx \sqrt{3}\, v_r$
- We see projected radii: $r = \theta d$

$1/\langle|\mathbf{r}_i - \mathbf{r}_j|\rangle = 1/|\mathbf{r}_i - \mathbf{r}_j|\langle 1/\sin\theta_{ij}\rangle_\Omega$

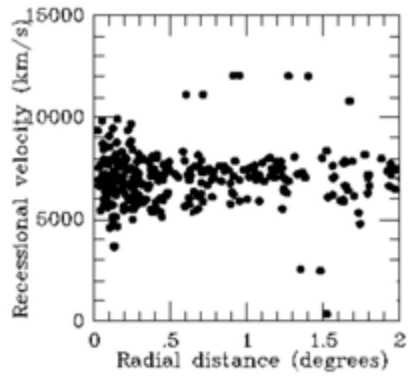
Assuming N equal masses $\Sigma_i m_i = N m$

$M_{VT} = 3/2\pi \; G^{-1} N \; \Sigma_i v_i^2 / \; \Sigma_{j<i} 1/r_{ij}$

Coma cluster (Zwicky):

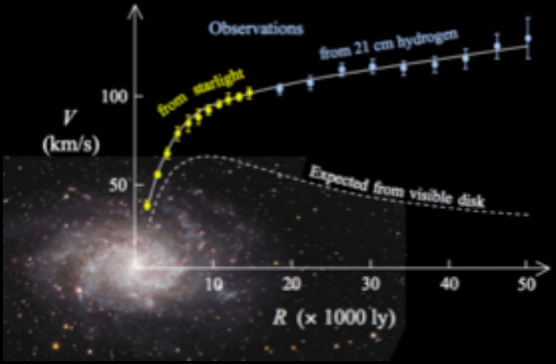
$\sigma \approx 1000\ km/s,\ R \approx 3 Mpc,\ M_{VT} = 3\ 10^{15}\ M_\odot$

$L = 5\ 10^{12}\ L_\odot$

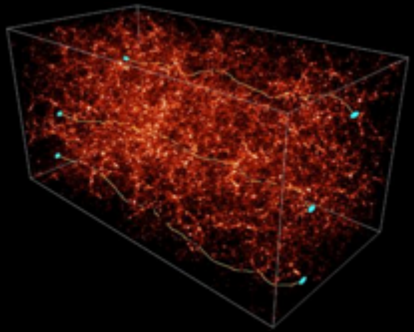


Many pieces of evidence for dark matter

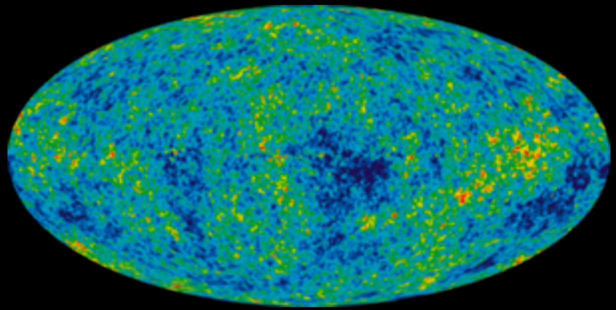
Rotation curves



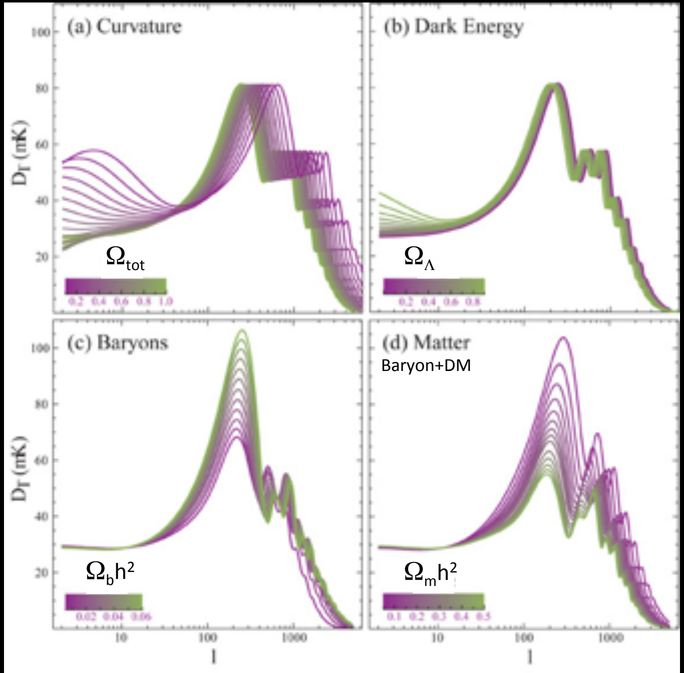
Large scale structures



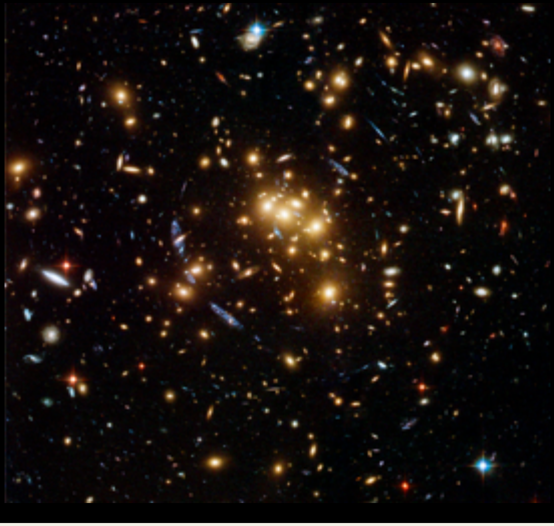
Cosmic Microwave Background



Λ-CDM model



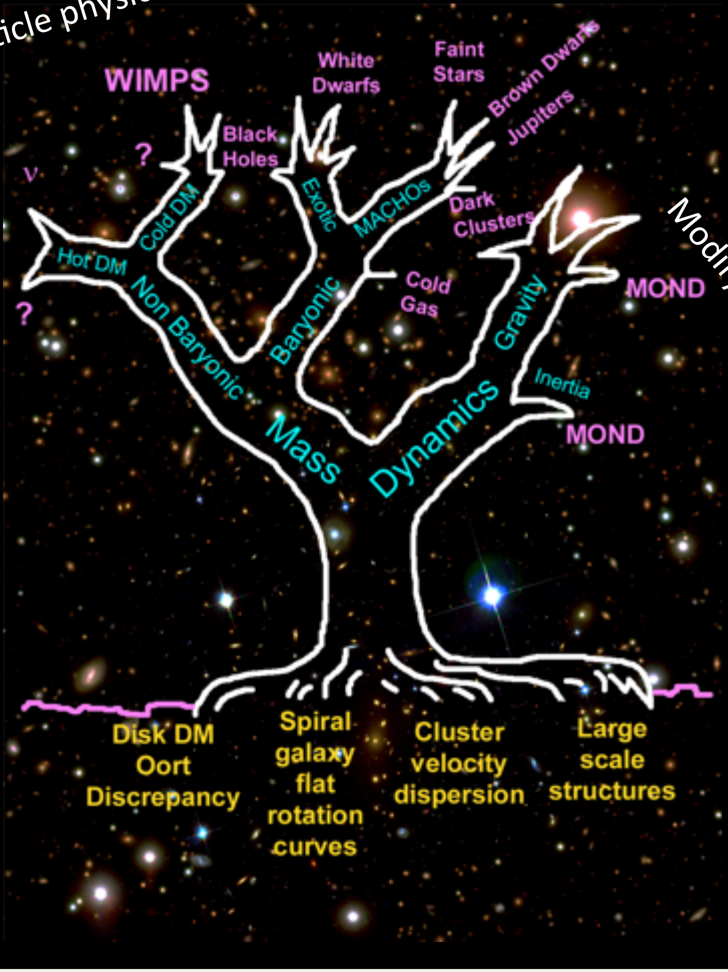
Lensing



Colliding clusters (Chandra)

The dark matter problem

Original drawing by Stacy McGaugh (1995)



Particle physics

Astrophysics

Modify gravity

Several hypothesized solutions

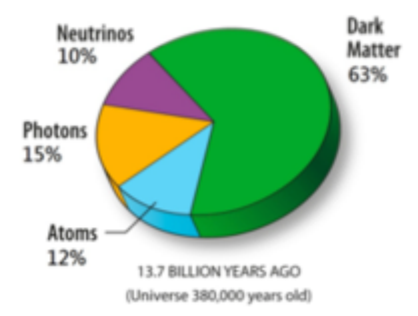
Roots are the empirical observations

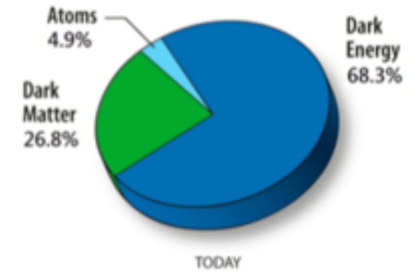
Particle physics is not the only possible solution

However…

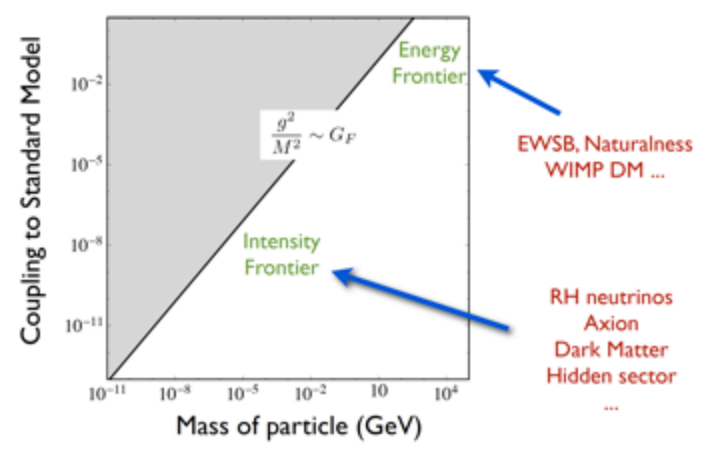
A new kind of matter?

Dark matter dominating in the early Universe





- Standard Model only includes <20% of the **matter** in the Universe
  - We only know dark matter interacts gravitationally
- Many open questions
  - What is dark matter made of?
  - How dark matter interact, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the dark sector spectrum?



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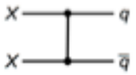
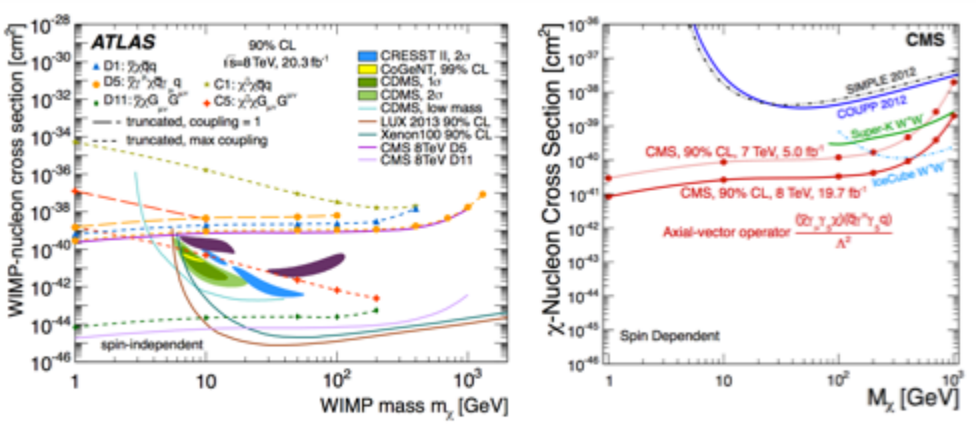
Where to search for dark matter

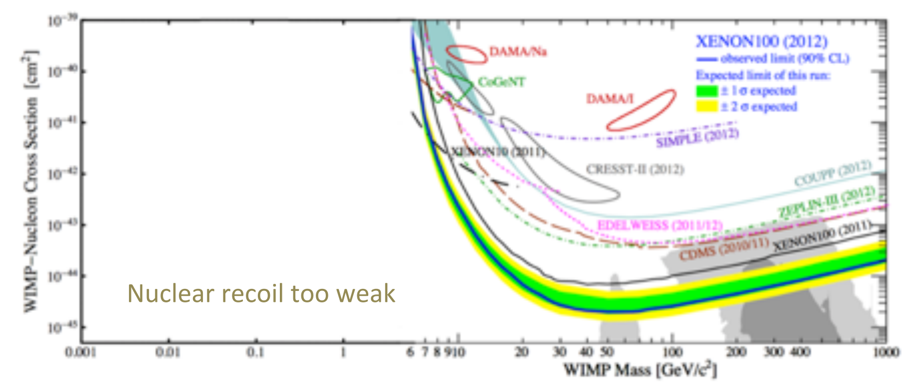
- **Without** modifying the SM structure: $U(1)_Y+SU(2)_L+SU(3)_C$
  - Dark matter can't be strong interacting (scattering cross section too high)
  - Cannot be electrically charged, otherwise it would not be dark!
  - It can be weakly interacting and massive!
- The WIMP has all the characteristics needed to solve the dark matter problem…
- But so far* more than 20 years of unsuccessful attempt to detect WIMPs
  - Strong constraints from the **LHC** and **direct searches** at masses up to 1TeV
  - *Some hints however…

$$\Omega_X \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_X^2}{g_X^4}$$



The WIMP "miracle": m_χ=100 GeV,g_χ=0.6, Ω_χ = 0.1



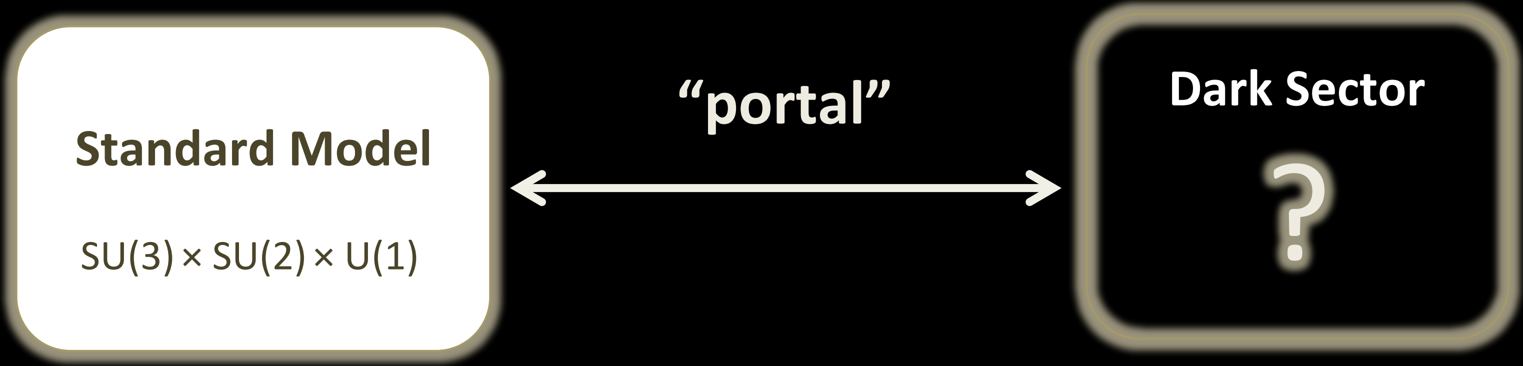


Nuclear recoil too weak

MeV GeV TeV

What about introducing a **new force**?

Portals to secluded sector



Standard Model

SU(3) × SU(2) × U(1)

“portal”

Dark Sector

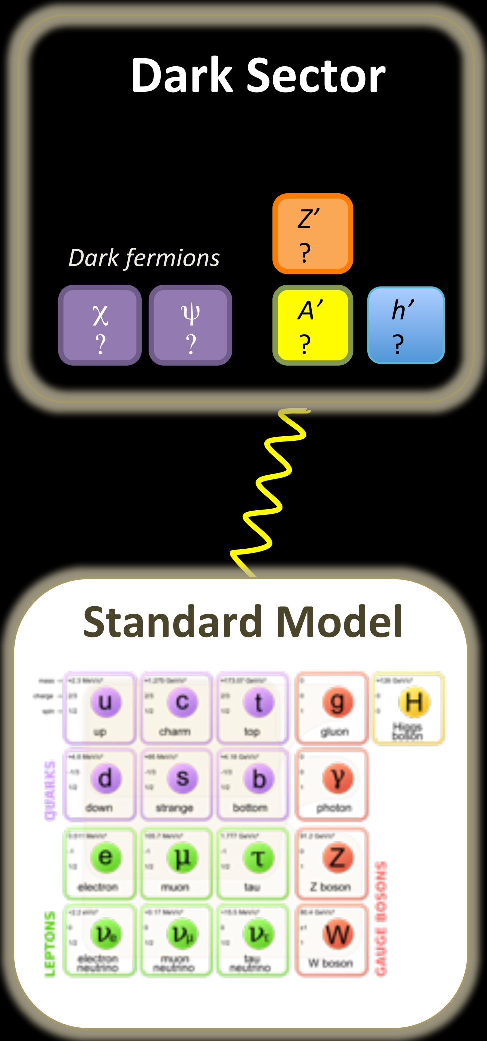
?

vector	$\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$	**dark photon**
Higgs	$\epsilon_h \lvert h\rvert^2 \lvert\phi\rvert^2$	dark scalar
neutrino	$\epsilon_\nu (hL)\psi$	sterile neutrino
axion	$\frac{1}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$	ALPs

Dark photon

- The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the “dark photon" or U boson or heavy photon (γ' or A')

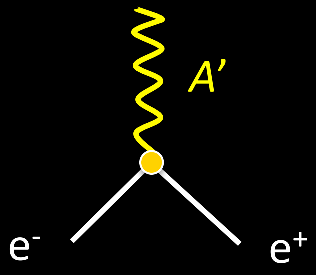
- An extra U(1) symmetry implied in many Standard Model extensions, some classes of string theory, etc.



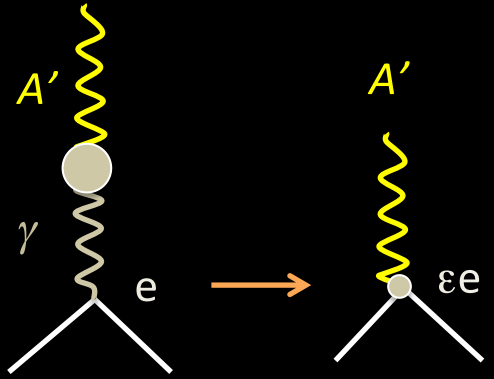
Dark photon

- Two types of interactions with SM particles should be considered
  - As in QED, generates interactions of the type:

$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

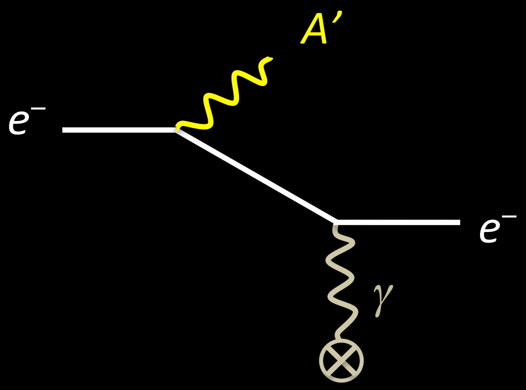


    - Not all the SM particles need to be charged under this new symmetry
    - In the most general case q_f is different in between leptons and quarks and can even be 0 for quarks. (P. Fayet, Phys. Lett. B 675, 267 (2009).)
  - Couples to *SM* hypercharge through kinetic mixing operator:
    - $\varepsilon/2\, F^Y_{\mu\nu} F'^{\mu\nu}$, where $F'^{\mu\nu} = \partial_\mu A'_\nu$
    - $A_\mu \rightarrow A_\mu + \varepsilon a_\mu$; $\alpha' = \varepsilon^2 \alpha$
    - The dark photon acquires a (small) SM charge

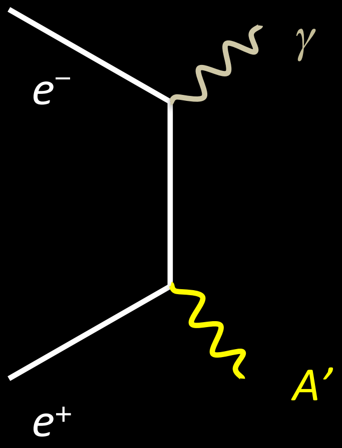


Dark photon production

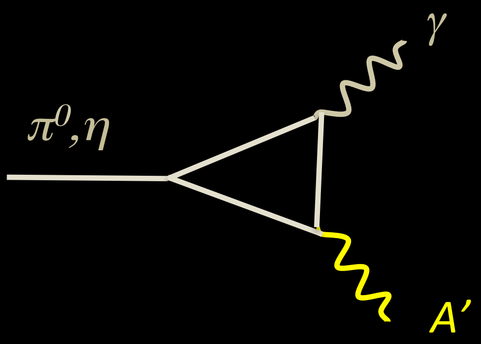
Bremsstrahlung



Annihilation



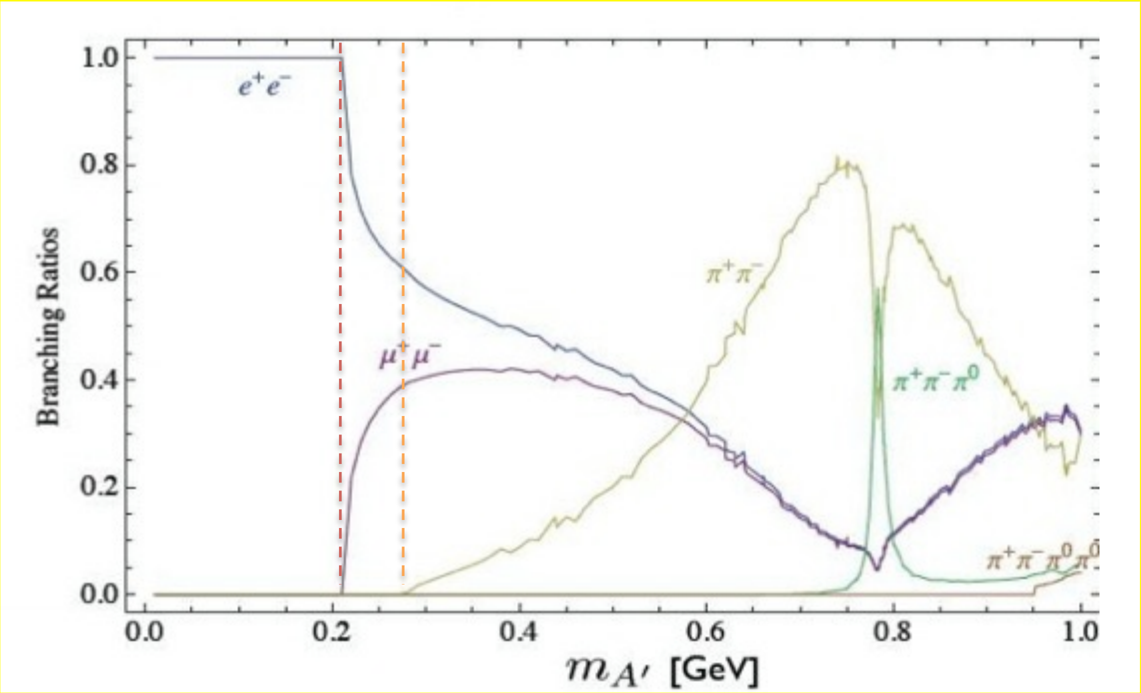
Meson decay



- *A′* can be produced in electron collision on target by:
  - Bremsstrahlung: e N → e N *A′*
  - Annihilation: $e^+ e^- \rightarrow \gamma$ *A′*
  - Meson decays

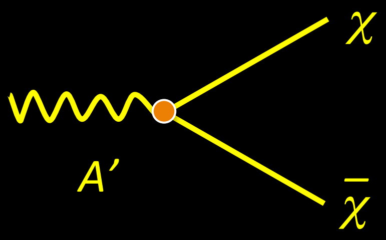
Dark photon visible decays

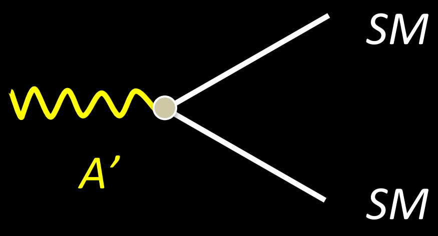
- Assume that no additional **lighter** states exists in the dark sector with $m_\chi < m_{A'}/2$
- Dark photon couples to SM particles through kinetic mixing only (with same coupling εq)
- For $m_{A'} < 2\, m_\mu$ only decays to e^+e^-



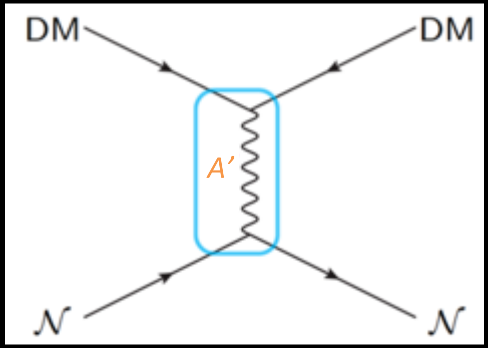
Dark photon invisible decays

- If χ state with U(1) charge q_U and coupling constant g_U exists in the dark sector with $m_\chi < m_{A'}/2$, the coupling to the *A'* will be: $q_U g_U$
- $A' \rightarrow \bar{\chi}\chi$ will be dominant wrt to visible decays for $\alpha_D > \alpha$, i.e. $|q_U g_U| > \varepsilon e$

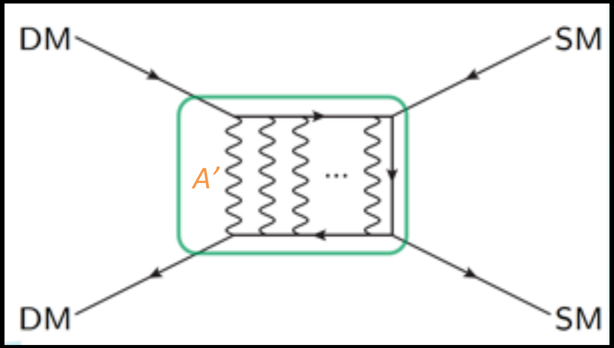




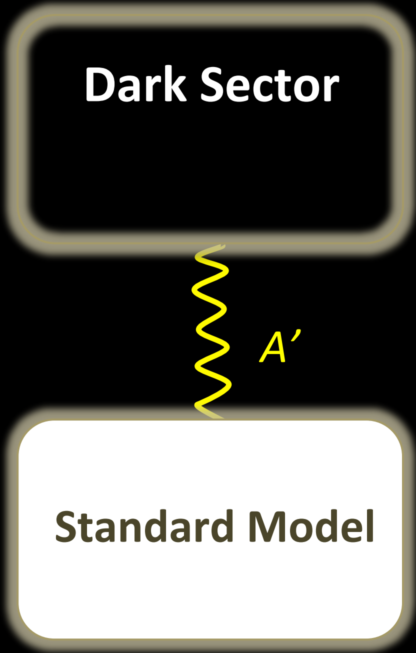
A dark matter "messenger"



Dark Matter scattering on nuclei



Dark Matter annihilation…

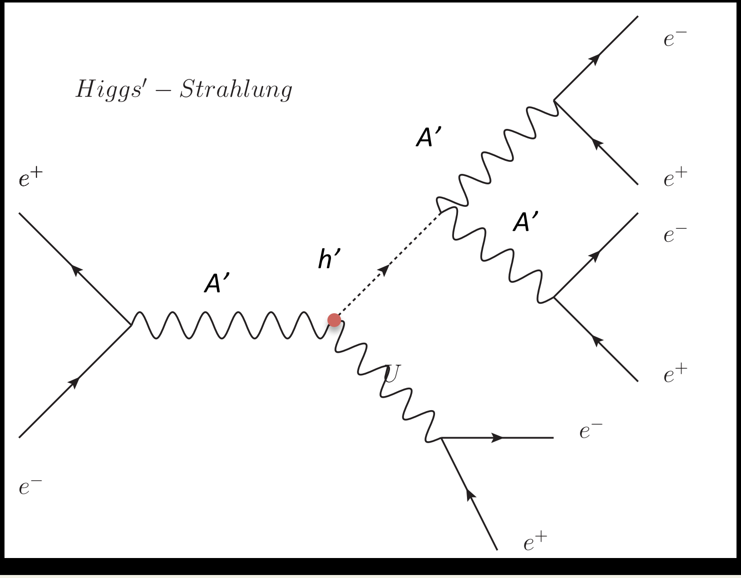


Dark Sector

Standard Model

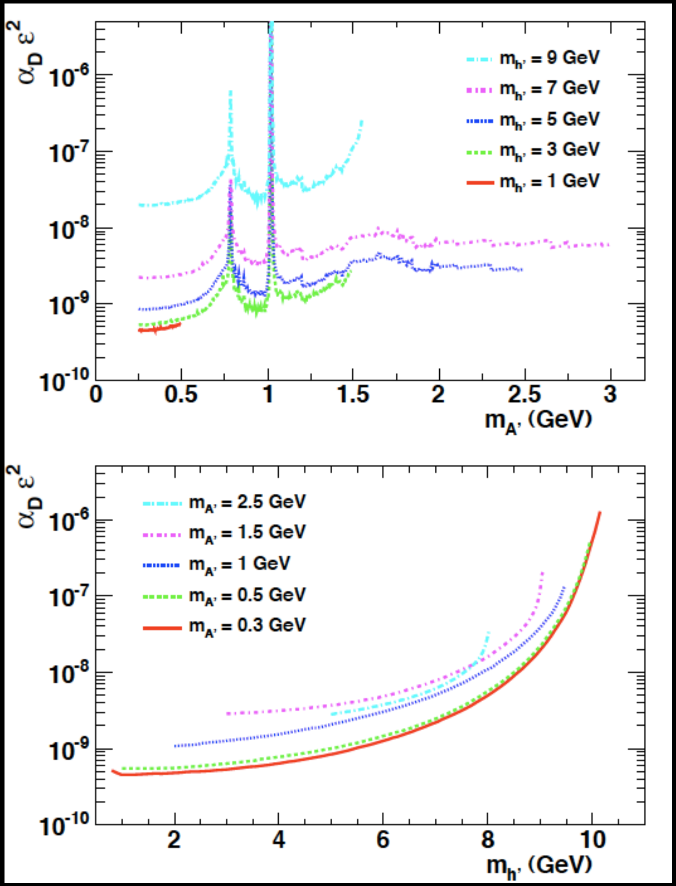
Dark sector with dark Higgs

- Model assumes the existence of an elementary dark Higgs boson *h'*, which spontaneously breaks the U(1) symmetry.
  PRD 79, 115008 (2009)
- *A'* boson produced together with a dark Higgs *h'* through a Higgs-strahlung $e^+e^- \to A' h'$
  - Cross section $=20\text{fb}\times(\alpha/\alpha_D)(\varepsilon^2/10^{-4})(10\text{GeV})^2/s$
  - For light *h'* and *A'* ($M_{U,h'}<2M\mu$) final state with $3(e^+e^-$ pair) are predicted
  - Background events with 6 leptons are very rare at this low energies
  - Due to *A'*,*h'* being very narrow resonances strong kinematical constraints are available on lepton pair masses
- Experimental search by **BaBar** and **KLOE-2** for *A'* masses above 200 MeV

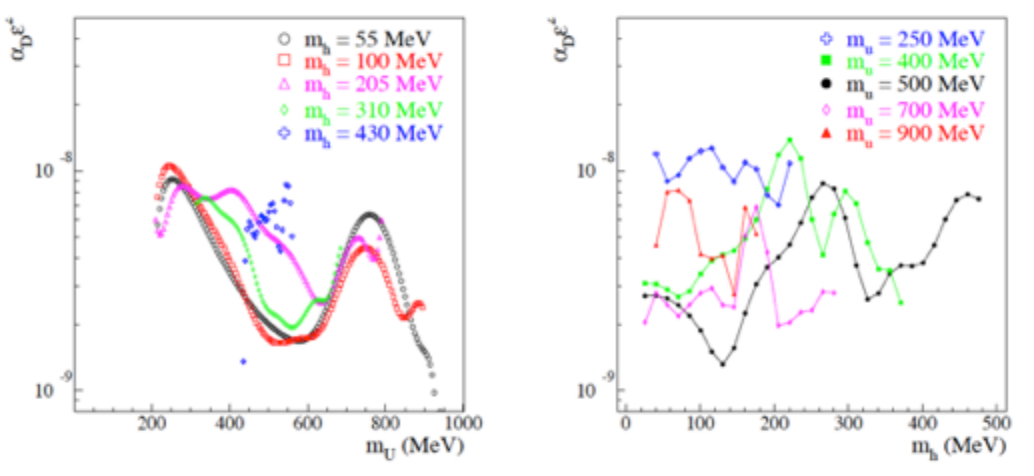


Dark photon + dark Higgs searches

BaBar Phys. Rev. Lett. 108, 211801 (2012)

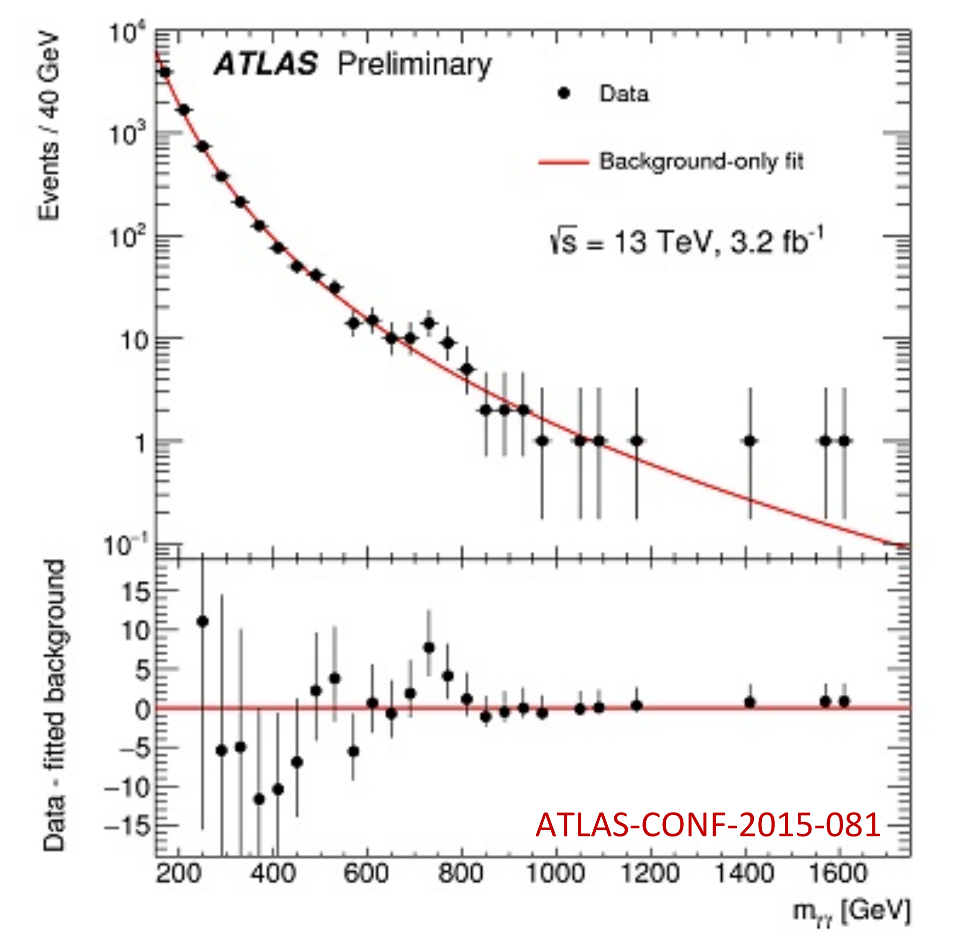


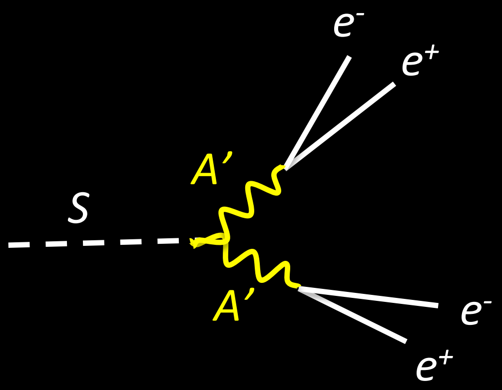
KLOE-2 arXiv:1501.06795



- **No data** available below 200 MeV in $M_{A'}$
- Production mechanism being Bremsstrahlung, PADME can reach $M_{A'}$>100MeV
- PADME can provide sensitivity in unexplored parameter region

and the ATLAS excess of course…

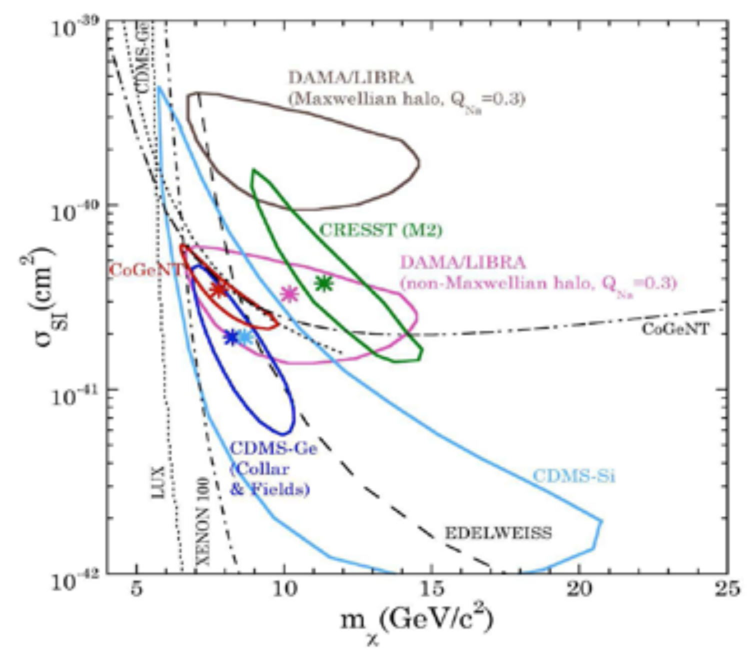


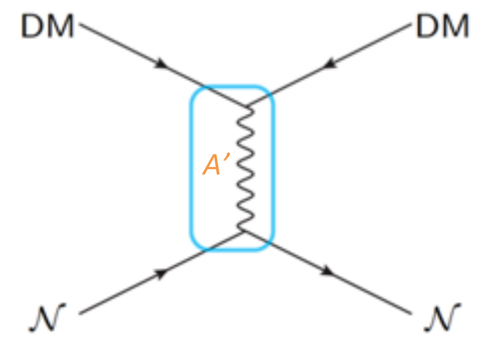


Photons, Photon Jets and Dark Photons at 750 GeV and Beyond, arXiv:1602.04692

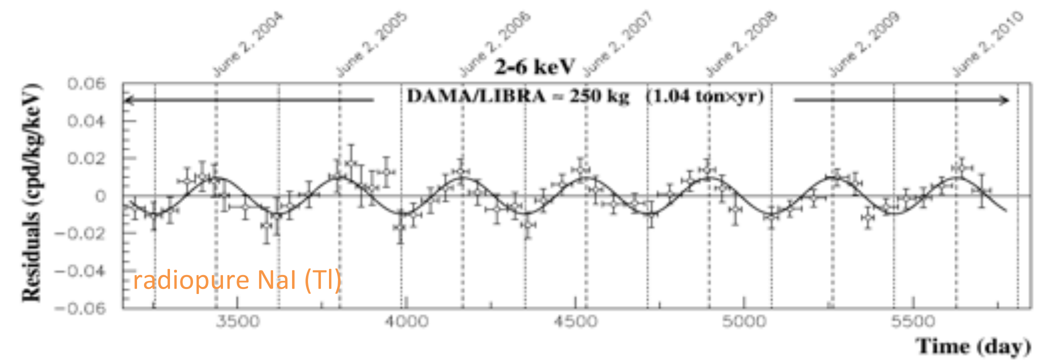
Dark sector shining through 750 GeV dark Higgs boson at the LHC, arXiv:1601.02490

The DAMA-Libra effect


arXiv:1401.3295v1

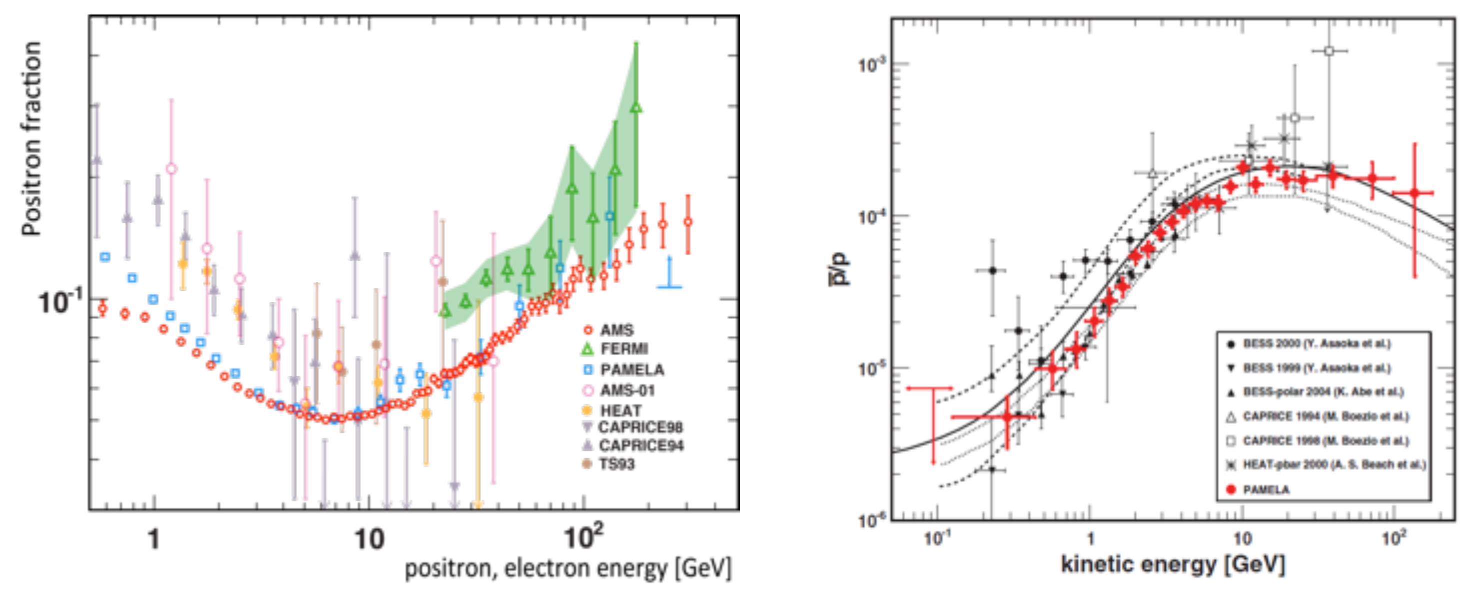


- Nuclear recoil by the exchange of a dark photon
- Independent of χ mass value

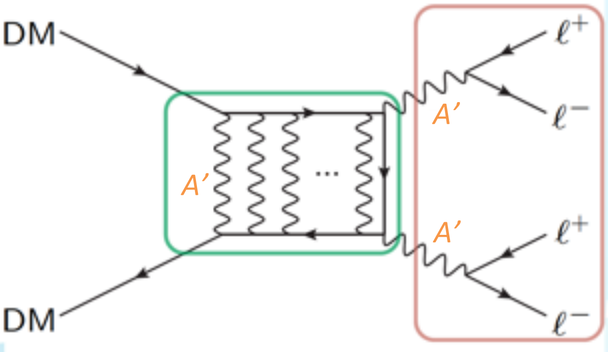


radiopure NaI (Tl)

Particle astrophysics: PAMELA, AMS

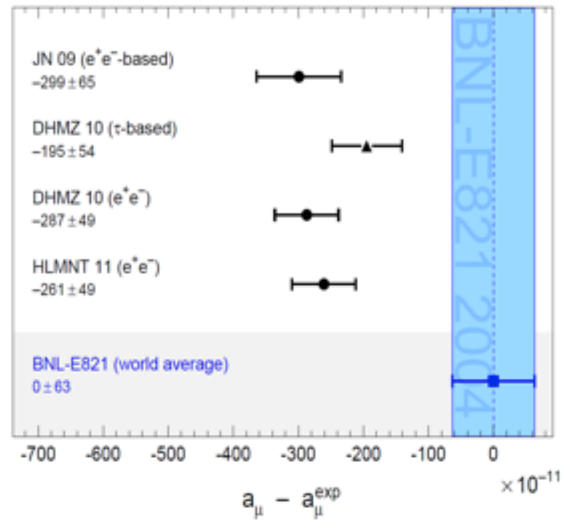


- Positron eccess: PAMELA, FERMI, AMS-02
- No significant excess in antiprotons
  - Consistent with pure secondary production
- Leptofilic dark matter annihilation?
- If DM is the explanation, the **mediator should be light**, < $2m_{\text{proton}}$

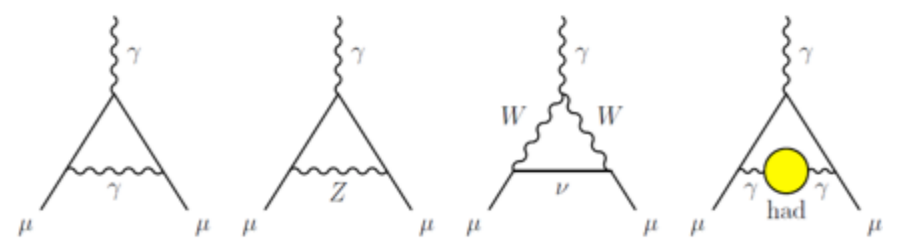


…naturally leptophilic

Muon g-2 SM discrepancy



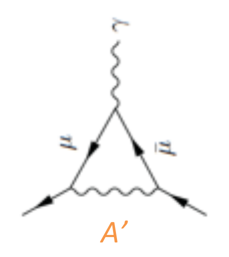
g-2 in the **Standard Model**



About 3σ discrepancy between theory and experiment (3.6σ, if taking into account only e+ e- → hadrons)

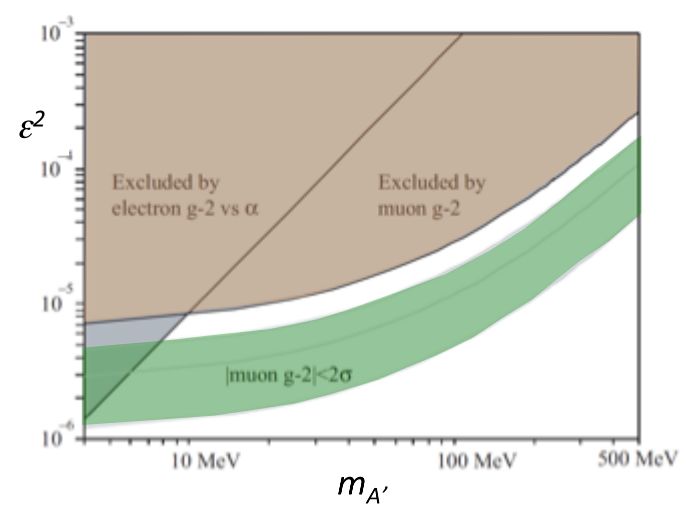
Additional diagram with dark photon exchange can fix the discrepancy (with sub GeV *A'* masses)

g-2 and ***A'***

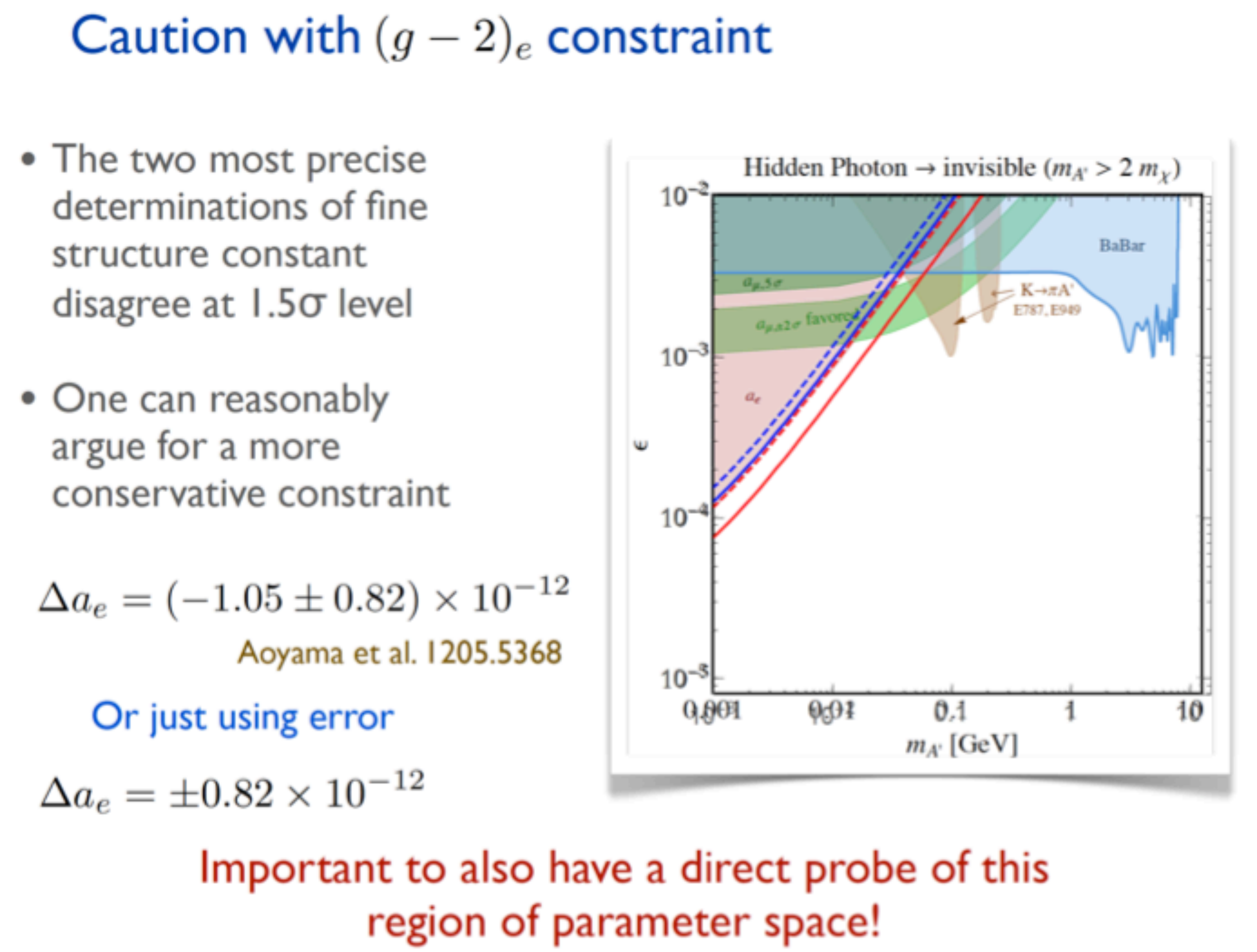


Contribution to **g-2** from **dark photon**

$$\Delta a_\mu = \frac{\varepsilon^2 \alpha}{2\pi} \times \begin{cases} 1 & \text{for} \quad m_\mu \ll m_{A'} \\ \frac{2m_\mu^2}{3m_{A'}^2} & \text{for} \quad m_\mu \ll m_{A'} \end{cases}$$



g-2 electron



Caution with $(g-2)_e$ constraint

- The two most precise determinations of fine structure constant disagree at 1.5σ level
- One can reasonably argue for a more conservative constraint

$$\Delta a_e = (-1.05 \pm 0.82) \times 10^{-12}$$

Aoyama et al. 1205.5368

Or just using error

$$\Delta a_e = \pm 0.82 \times 10^{-12}$$

Important to also have a direct probe of this region of parameter space!

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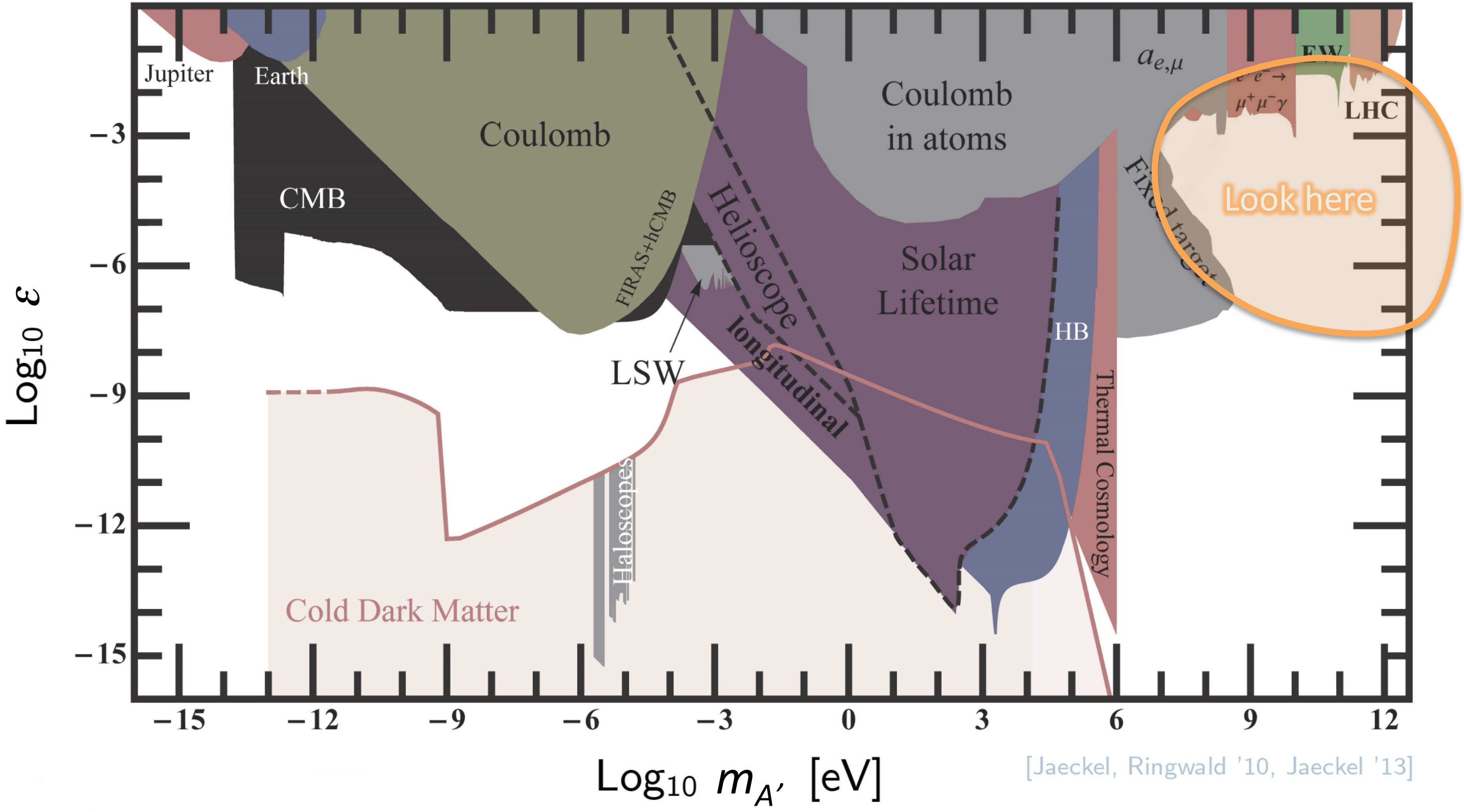
Where to look for dark photons?



Look here

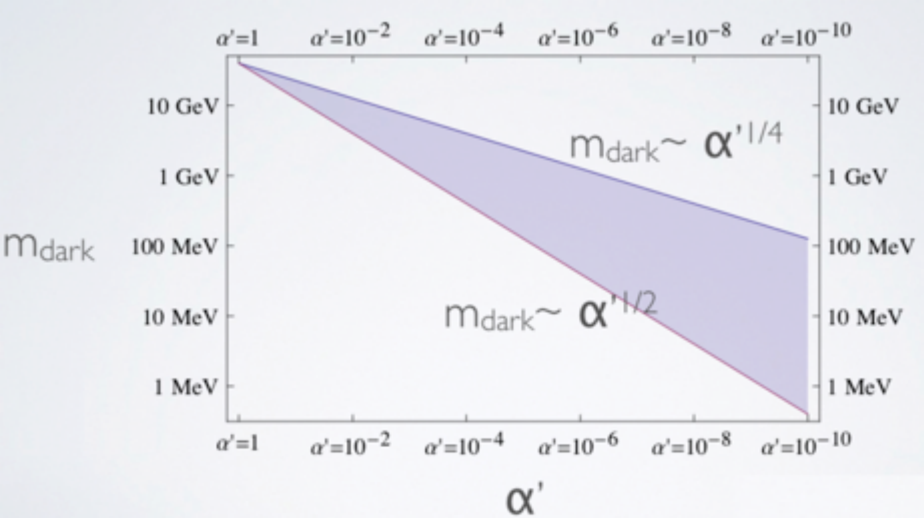
[Jaeckel, Ringwald '10, Jaeckel '13]

Where to look for dark photons?

- Coupling expected in the range $\varepsilon \sim 10^{-2}$ - 10^{-3} but can be further suppressed by an enhanced symmetry
- Depending on the model, mass scales like:
  - $m_{A'}/m_W \sim \varepsilon - \varepsilon^{1/2}$

leading to a MeV-GeV mass scale

N. Wiener

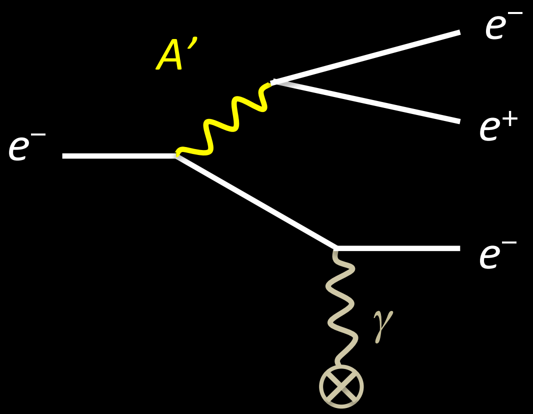


Dark photon experiments

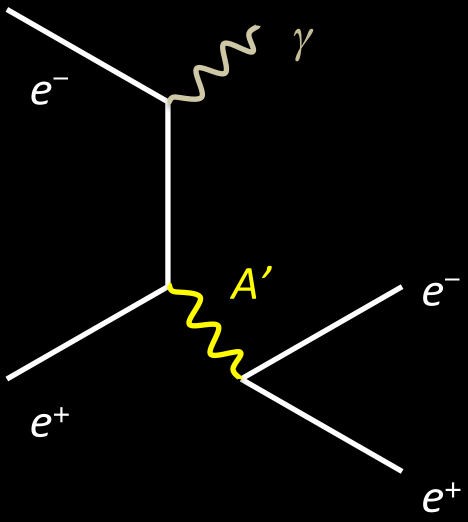
- Thick target (beam-dump)
  - Absorb all SM backgrounds
  - Look for visible decays (e+ e−, μ+ μ−, …)
- Thin target + decay of dark photon:
  - Decay to visible particles (e+ e−, μ+ μ−, …)
    - "Bump hunting", looking for a peak in the invariant mass
    - Displaced vertices, looking for long-lived particles
  - Decay to invisible particles
    - Look for missing mass
    - DM particles recoil
- Meson decays
- Dark particles scattering

Why fixed target?

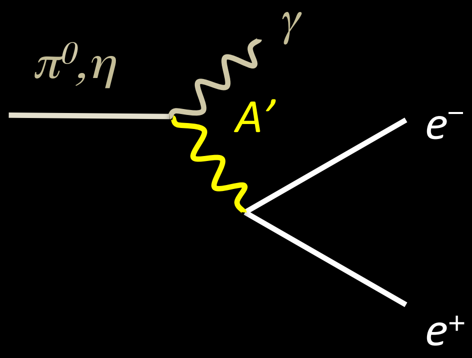
Bremsstrahlung



Annihilation



Meson decay



$$\sigma^{\mathrm{ft}}_{\gamma'} \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m^2_{A'}}$$

O(pb)

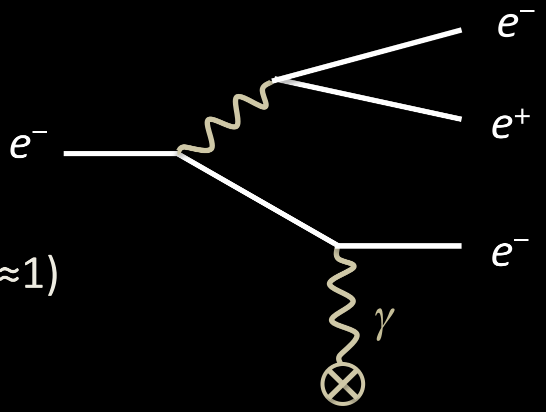
$$\sigma^{\mathrm{coll}}_{A'} \sim \frac{\alpha^2 \varepsilon^2}{E^2}$$

O(fb)

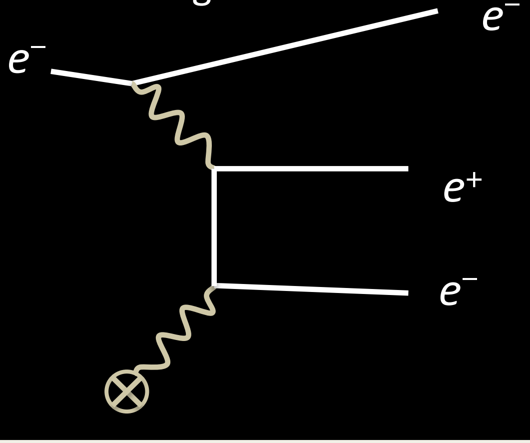
Fixed target experiments

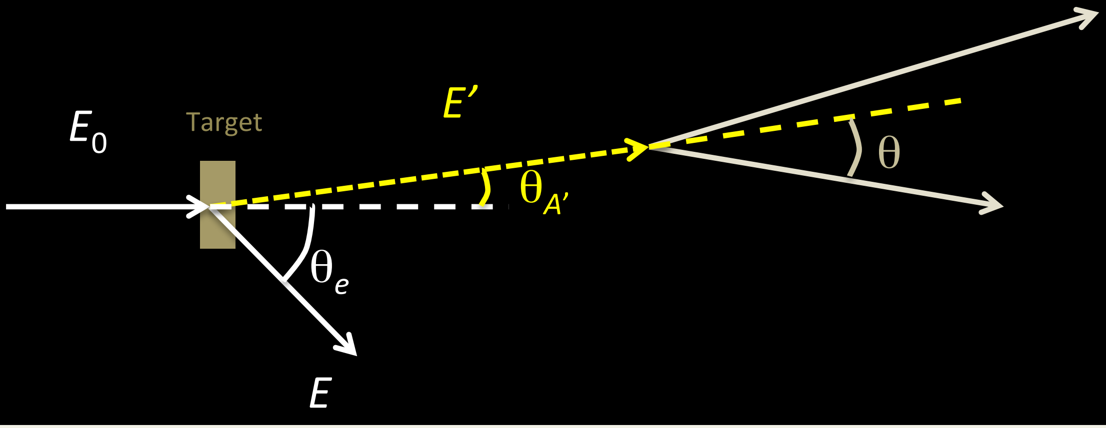
- Main backgrounds: SM Bremsstrahlung + Bethe-Heitler
- Kinematics:
  - A' takes nearly all the beam energy E_0 (sharply peaked at $x \approx 1$)
  - Electron takes a small energy $\approx m_{A'}$
  - A' emission almost collinear to the beam: $\theta_{A'} = (m_{A'}/E_0)^{3/2}$
  - Electron going at "wide" angle: $\theta_e = (m_{A'}/E_0)^{1/2}$
  - A' decay products open by $\theta \approx m_{A'}/E_0$

Radiative background

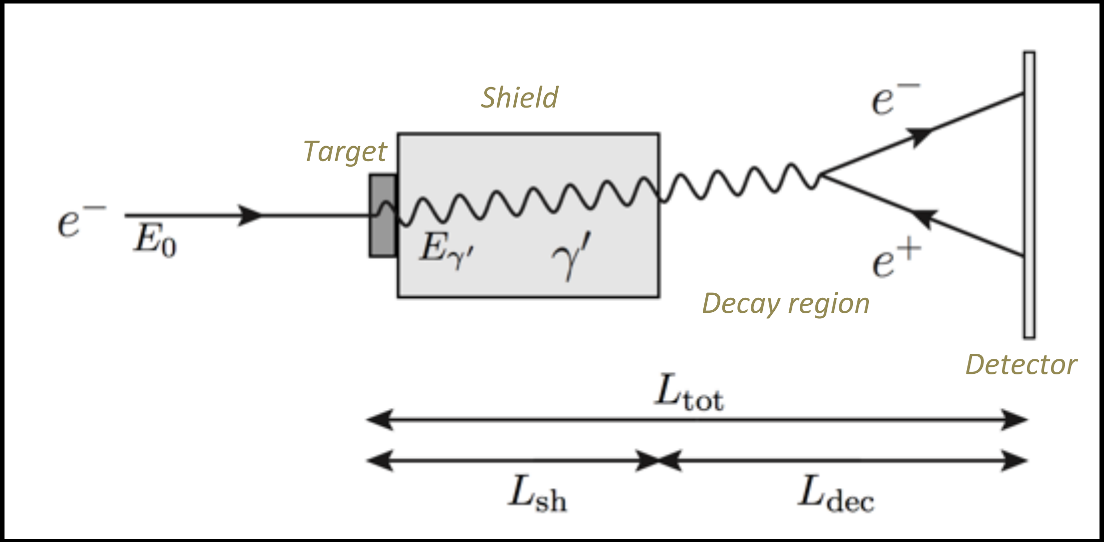


Bethe-Heitler background





Electron beam-dump experiments



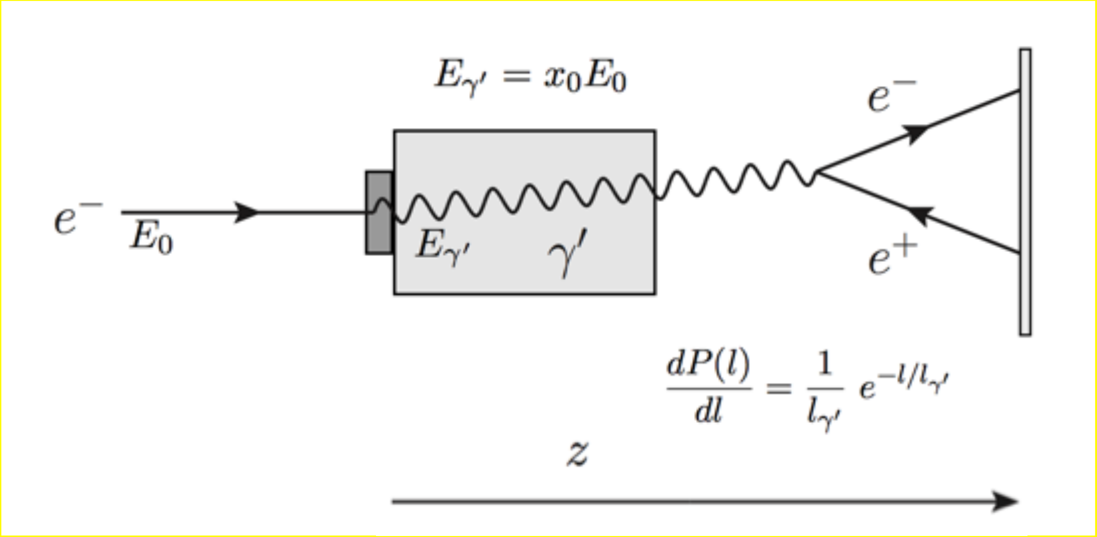
Luminosity: $$\mathcal{L}^{\rm ft} \simeq N_{\rm e}\frac{N_0\rho_{\rm sh}l_{\rm sh}}{A}$$

At colliders: $$\mathcal{L}^{\rm coll} \simeq \frac{N_{\rm e}^2}{\mathcal{A}_{\rm b}}$$

→ Beam section

In addition to cross section advantage

Electron beam-dump experiments



$$N_{\gamma'} = \sigma_{\gamma'} N_e \frac{N_0}{A} \rho_{\rm sh} L_{\rm sh}$$

Electron energy distribution due to the interaction in target+shield

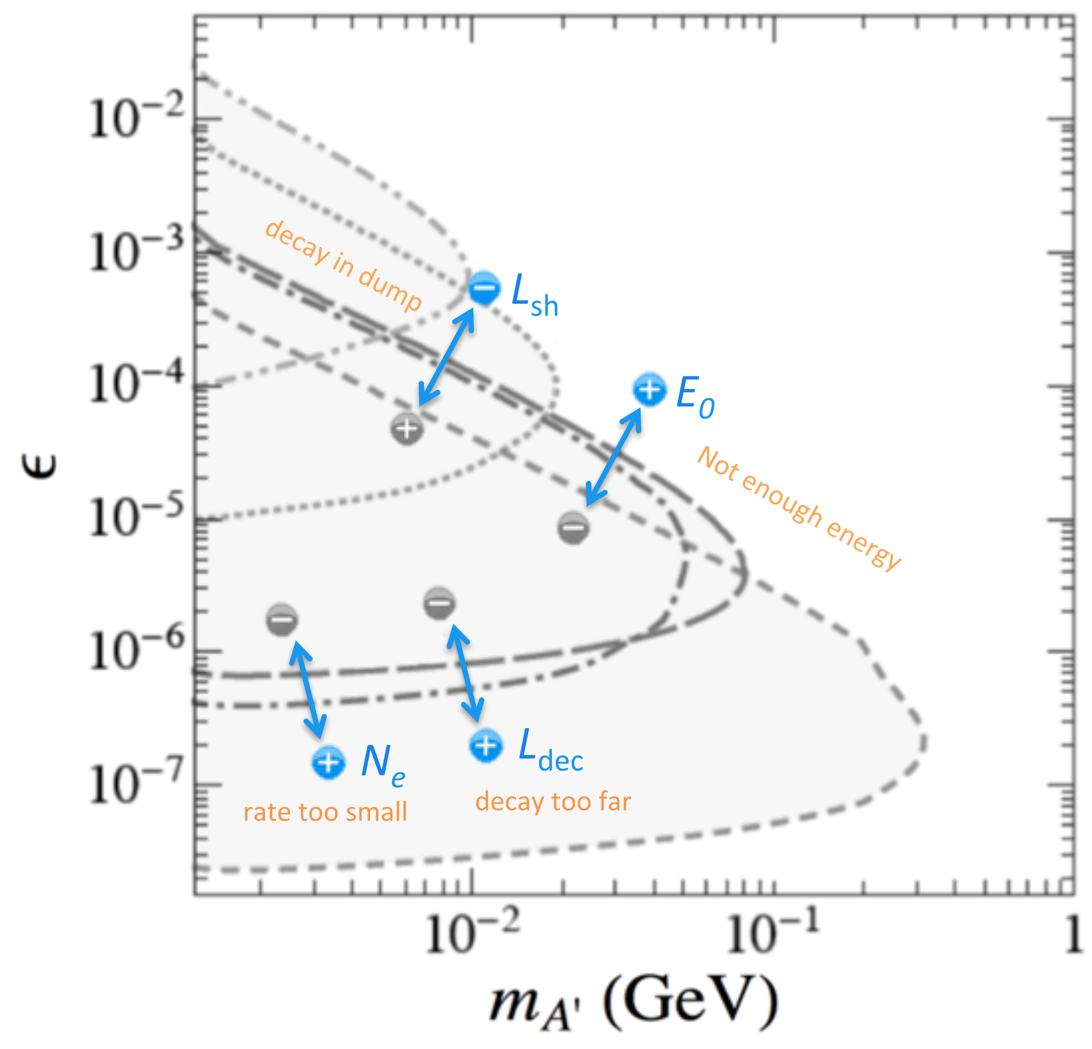
Decay probability of γ ’ after shield

$$\frac{dN_{\gamma'}}{dx_0\, dz} = N_e \frac{N_0 X_0}{A} \int_{E_{\gamma'}+m_e}^{E_0} dE_e \int_0^{T_{\rm sh}} dt_{\rm sh} \left[I_e(E_0, E_e, t_{\rm sh}) \, \frac{E_0}{E_e} \, \frac{d\sigma}{dx_e}\bigg|_{x_e = \frac{E_{\gamma'}}{E_e}} \frac{dP(z - \frac{X_0}{\rho_{\rm sh}} t_{\rm sh})}{dz} \right]$$

$$T_{\rm sh} \equiv \rho_{\rm sh} L_{\rm sh} / X_0$$

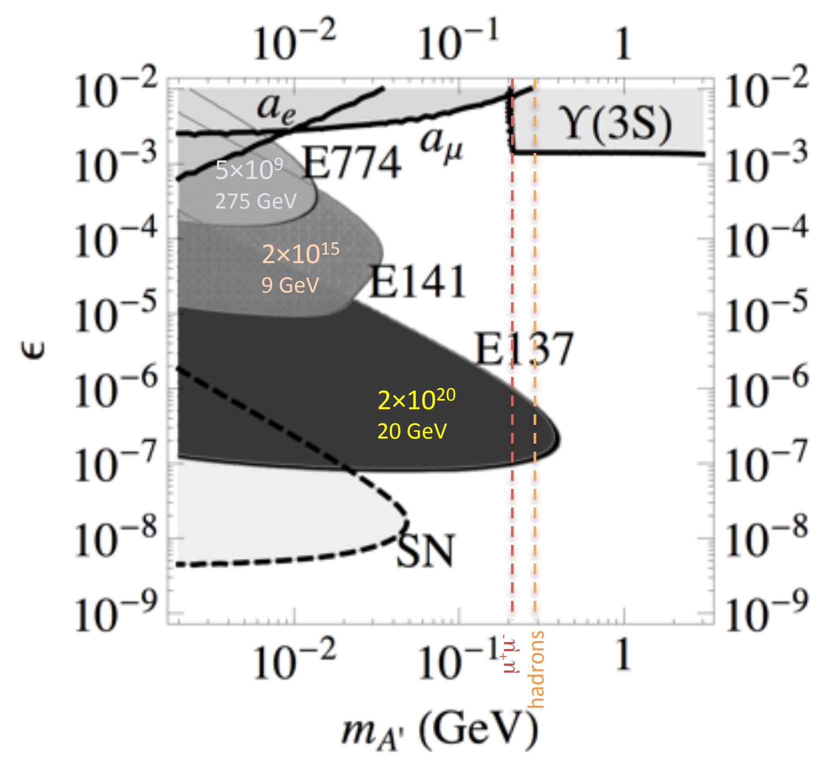
dσ/dx for γ ’ production by Bremsstrahlung

Limits from electron beam-dump experiments



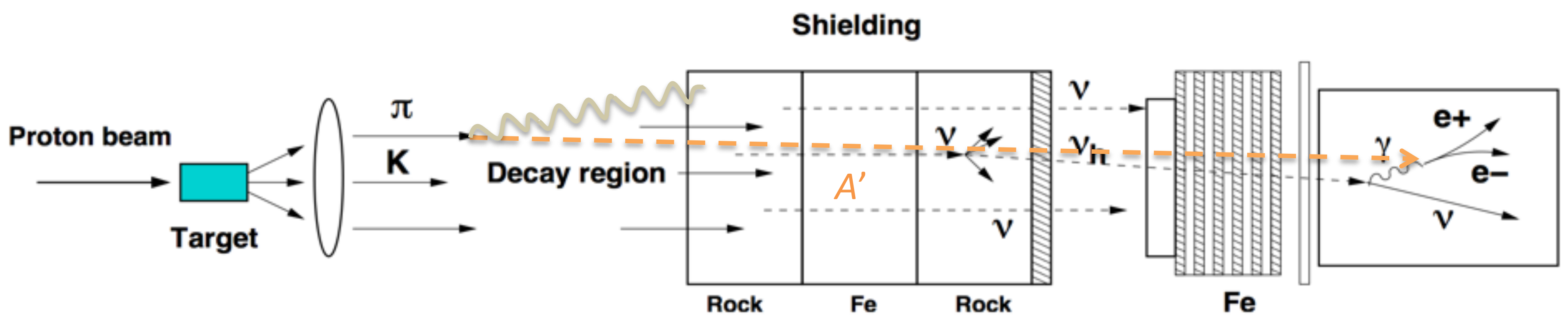
Limits from electron beam-dump experiments

- Beam-dump experiments: looking for decay products of "rare penetrating particles" behind a **stopped electron beam**
- SLAC **E141** (1987) and SLAC **E137** (1988), Fermilab **E774** (1991)



Proton beam dump experiments

Use data of the search of $\nu_H \to \nu e^+ e^-$ for looking for $P \to \gamma A'$
Pseudoscalar decaying to spin 0 or ½ particles negligibly small



Limits from past experiments: proton beam dump

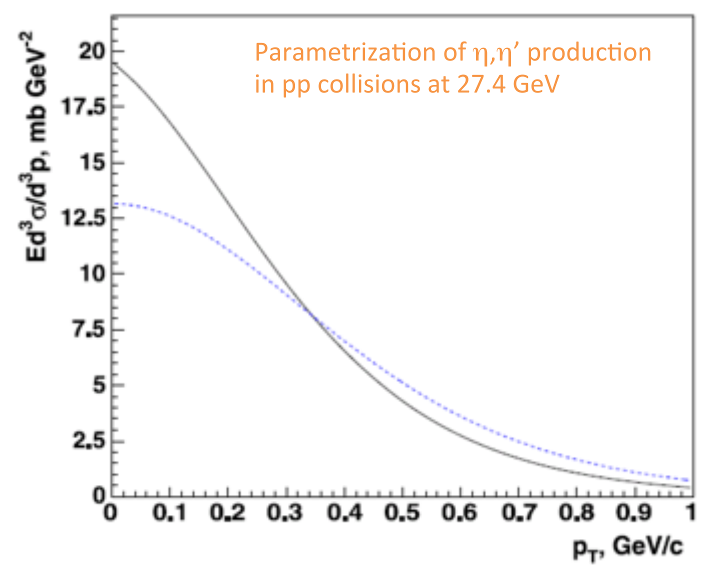
CHARM: $\nu_H \to \nu e^+ e^-$ from π,K, D decays
$2.4 \cdot 10^{18}$ POT
Look for $\eta,\eta' \to \gamma A'$

$$\mathrm{Br}(\eta \to \gamma A') = 2\epsilon^2 \mathrm{Br}(\eta \to \gamma\gamma)\left(1 - \frac{M_{A'}^2}{M_\eta^2}\right)^3$$

$$N_{A' \to e^+e^-} = \mathrm{Br}(\eta(\eta') \to \gamma A')\mathrm{Br}(A' \to e^+e^-) \int \frac{d\Phi}{dE_{A'}} \cdot \exp\left(-\frac{L' M_{A'}}{P_{A'} \tau_{A'}}\right)\left[1 - \exp\left(-\frac{L M_{A'}}{P_{A'} \tau_{A'}}\right)\right] \zeta A \, dE_{A'}$$

$$\Phi(A') \propto N_{pot} \int \frac{d^3\sigma(p + N \to \eta(\eta') + X)}{d^3 p_{\eta(\eta')}} \times \epsilon^2 \mathrm{Br}(\eta(\eta') \to \gamma\gamma) f \, d^3 p_{\eta(\eta')}$$

e^+e^- reconstruction efficiency


Parametrization of η,η' production in pp collisions at 27.4 GeV

Bourquin-Gaillard parametrization for the invariant cross section of hadron production in high energy hadronic collisions over the phase-space

$\pi^0:\eta:\eta'$ yield=1 : 0.078 : 0.024

Phys. Rev. D85, 055027 (2012), Phys. Lett. B713, 244 (2012)

Limits from past experiments: proton beam dump

NOMAD and PS191 looked for decay of and heavy neutrino $\nu_H \rightarrow \nu e^+e^-$

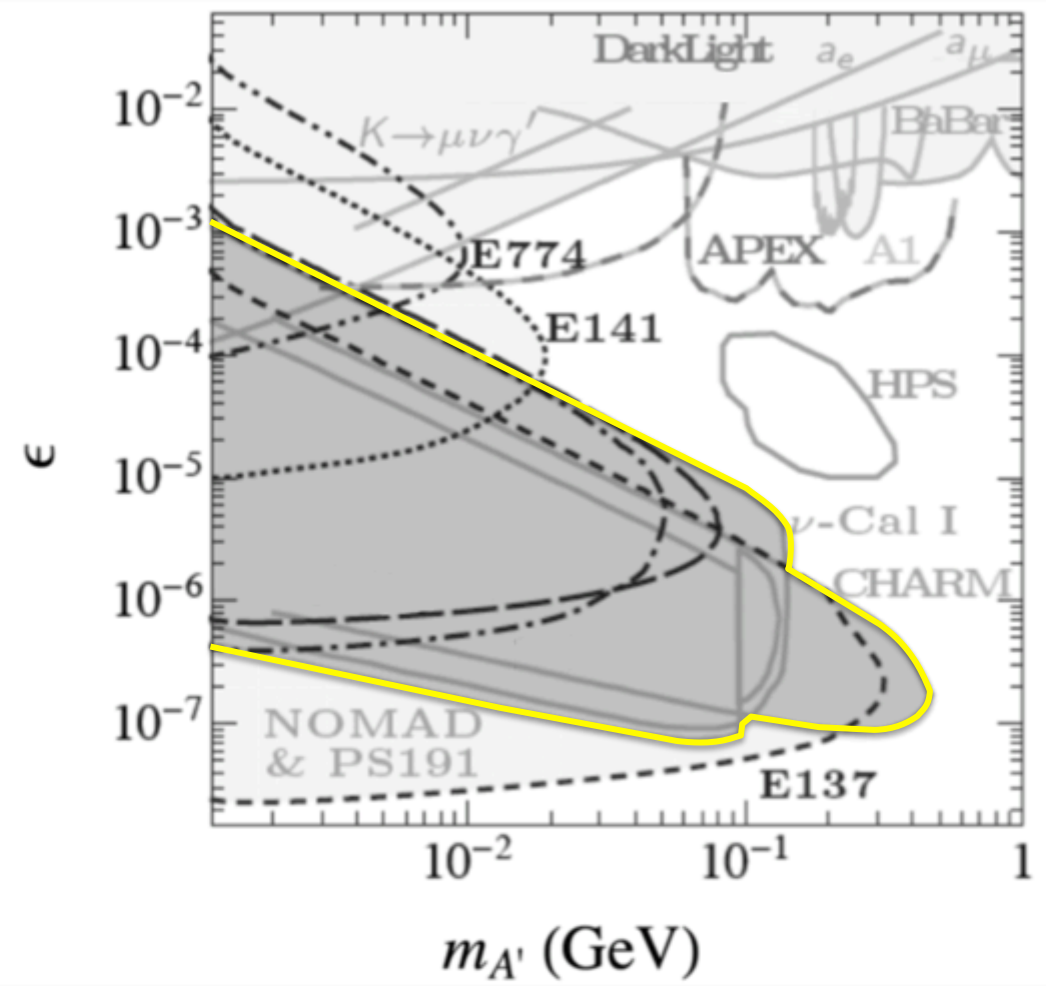
Look for $\pi^0 \rightarrow \gamma A'$

NOMAD: $4.1 \cdot 10^{19}$ POT

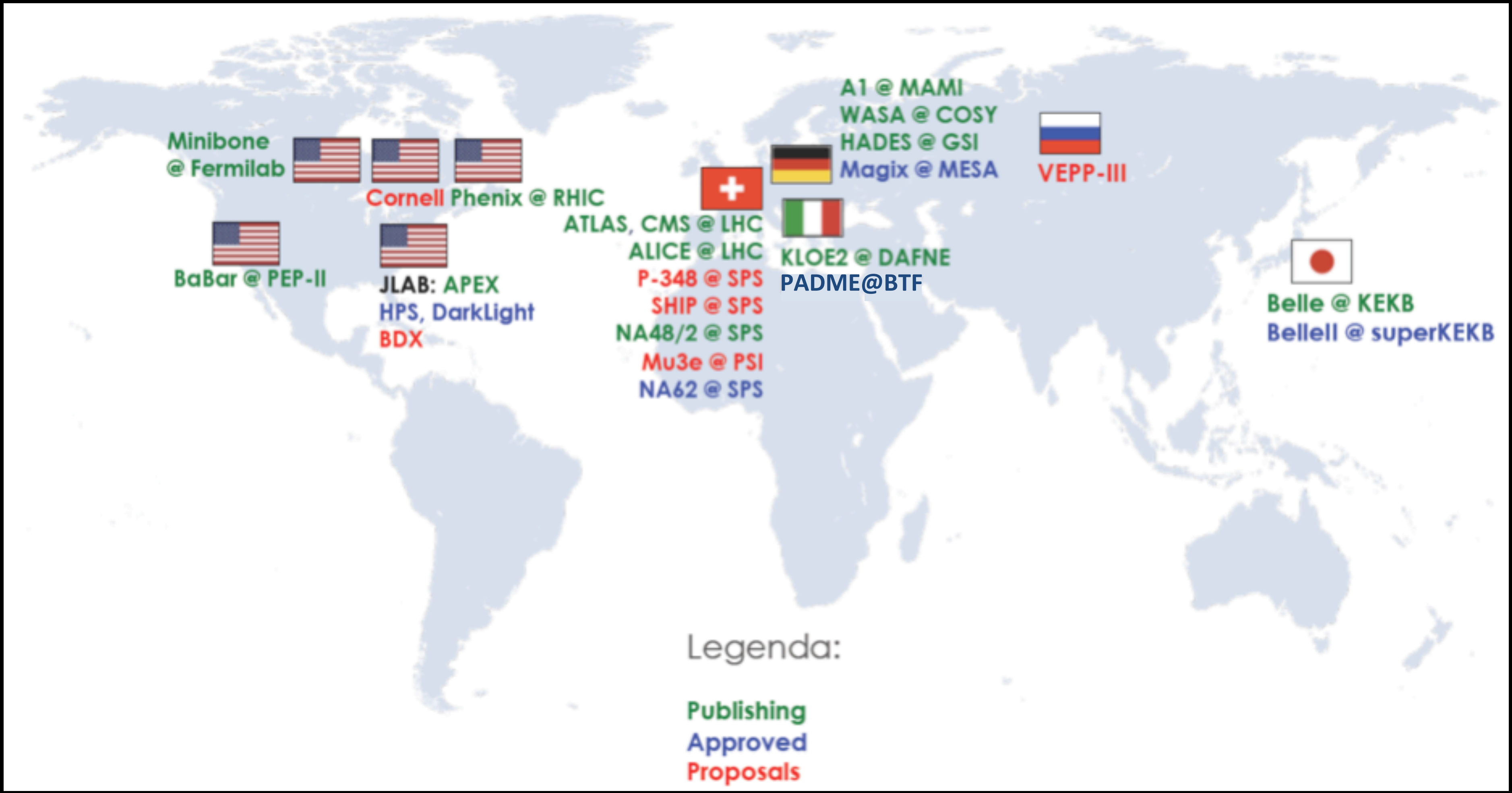
E>4 GeV, m_{ee}<95 MeV

PS191: $0.89 \cdot 10^{19}$ POT

$$Br(\pi^0 \to \gamma A') = 2\epsilon^2 Br(\pi^0 \to \gamma\gamma)\left(1 - \frac{M_{A'}^2}{M_{\pi^0}^2}\right)^3$$



Dark photon experiments map



Thin target experiments

Running:

- APEX at JLAB Hall-A, test run done, full run coming
- A1 at MAMI
- HPS at JLAB Hall-B, first run done in 2015

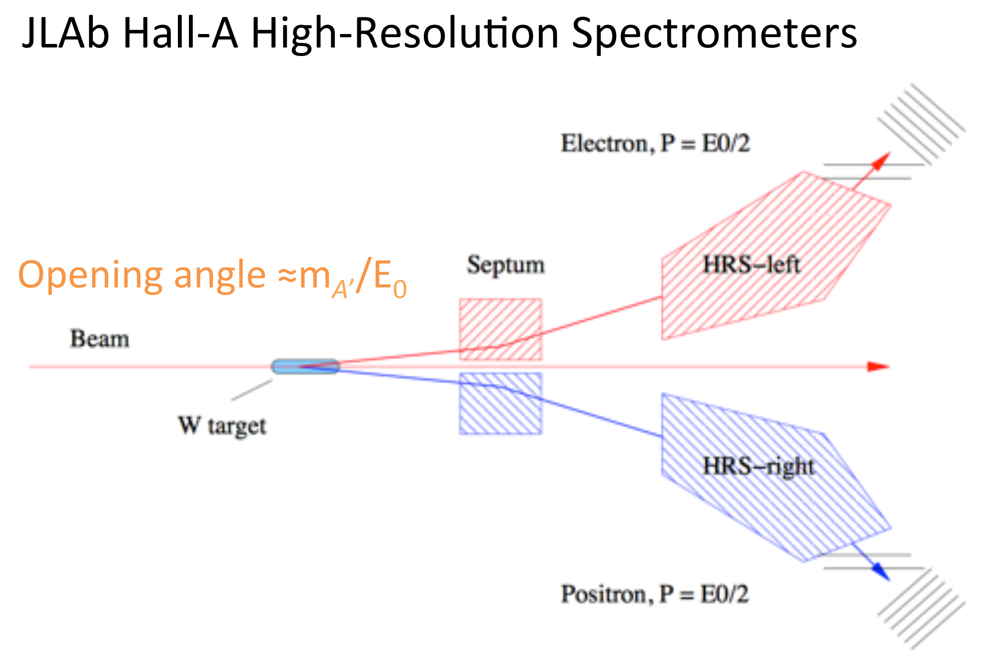
Coming soon:

- PADME at Frascati (approved)

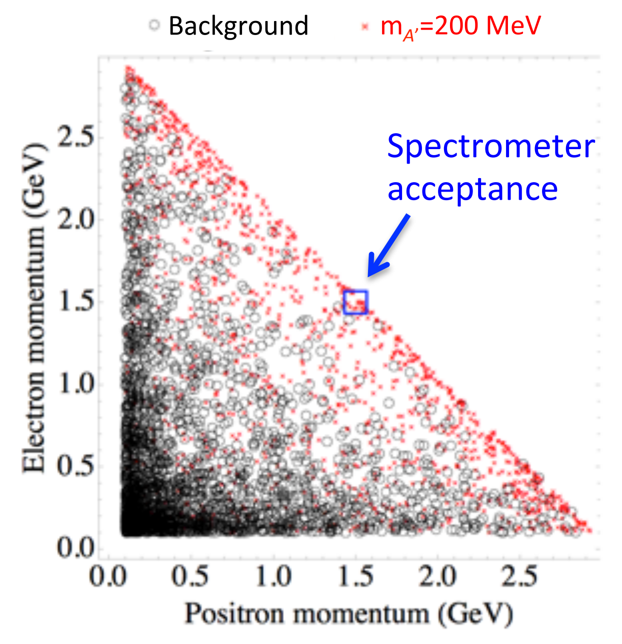
Proposed:

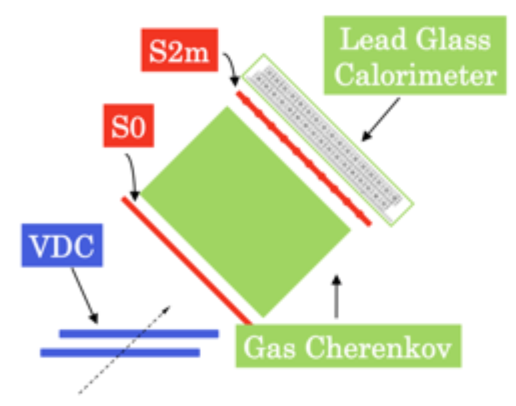
- DarkLight at JLAB FEL (electron on gas jet target)
- VEPP3 (electron on gas jet target)
- Cornell (positron extracted from CESR on H_2 target)

APEX


JLAb Hall-A High-Resolution Spectrometers

Opening angle ≈$m_{A'}/E_0$


Spectrometer acceptance



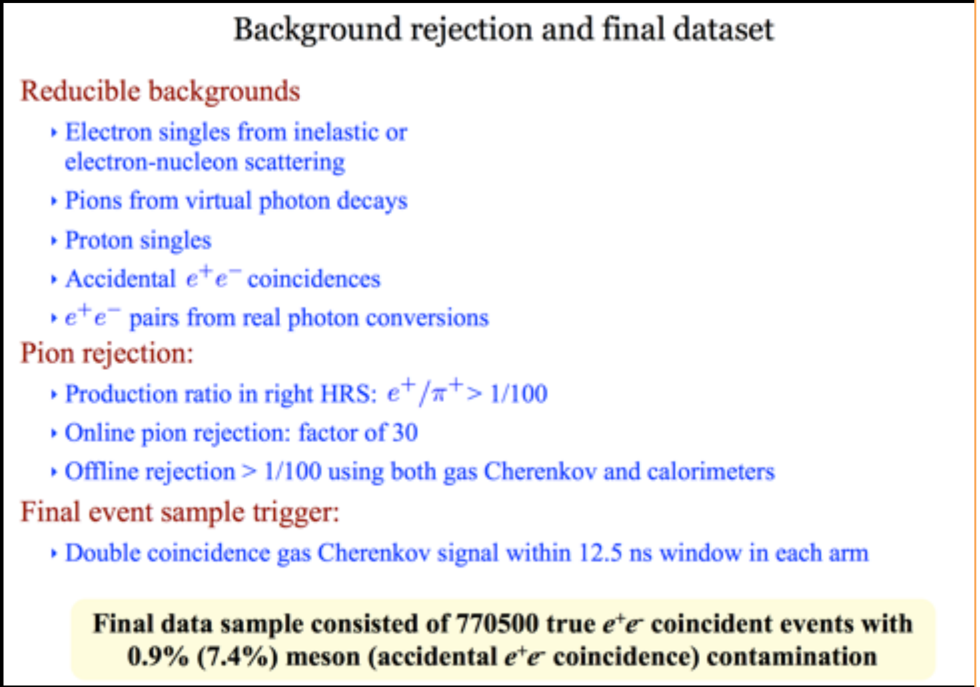
$0.3<p<4.0$ GeV, $\theta_0=5°$

Acceptance=4.5 msr

$\delta p/p < 2\times10^{-4}$

$\delta\phi=0.5$ mrad, $\delta\theta=1$ mrad

APEX test



Background rejection and final dataset

Reducible backgrounds

- Electron singles from inelastic or electron-nucleon scattering
- Pions from virtual photon decays
- Proton singles
- Accidental e^+e^- coincidences
- e^+e^- pairs from real photon conversions

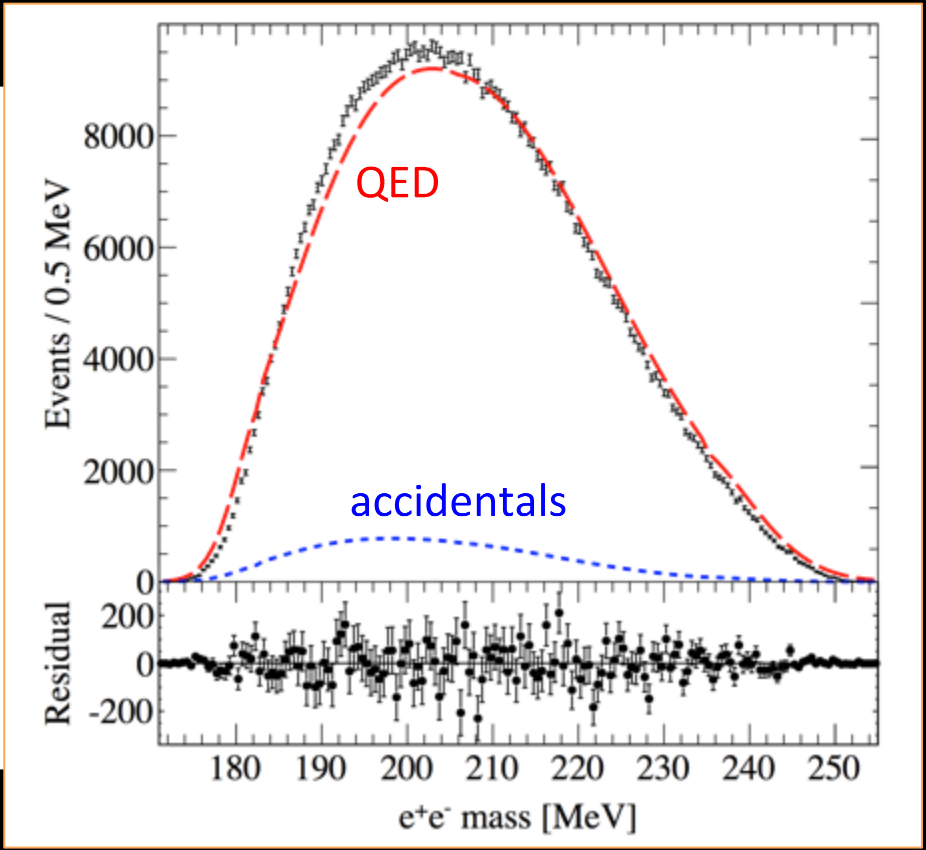
Pion rejection:

- Production ratio in right HRS: $e^+/\pi^+ > 1/100$
- Online pion rejection: factor of 30
- Offline rejection > 1/100 using both gas Cherenkov and calorimeters

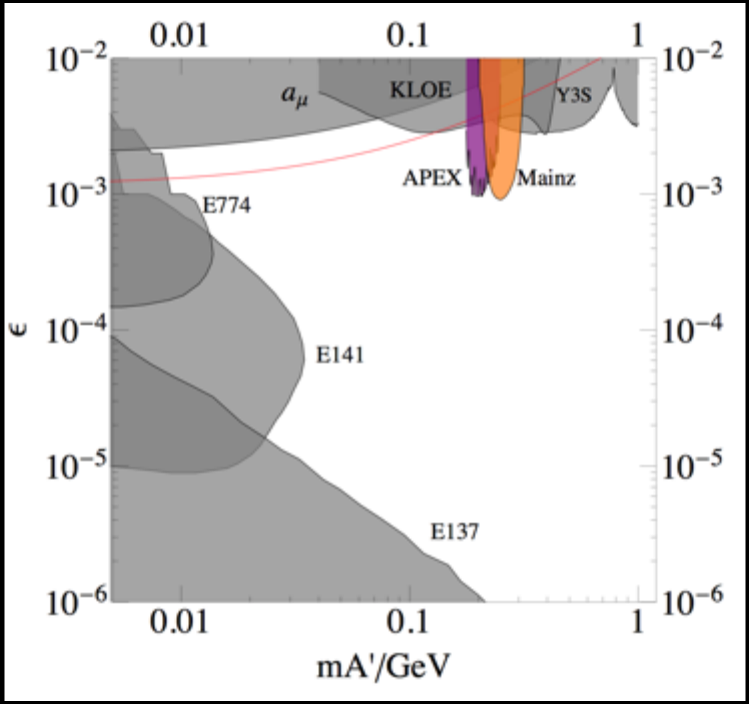
Final event sample trigger:

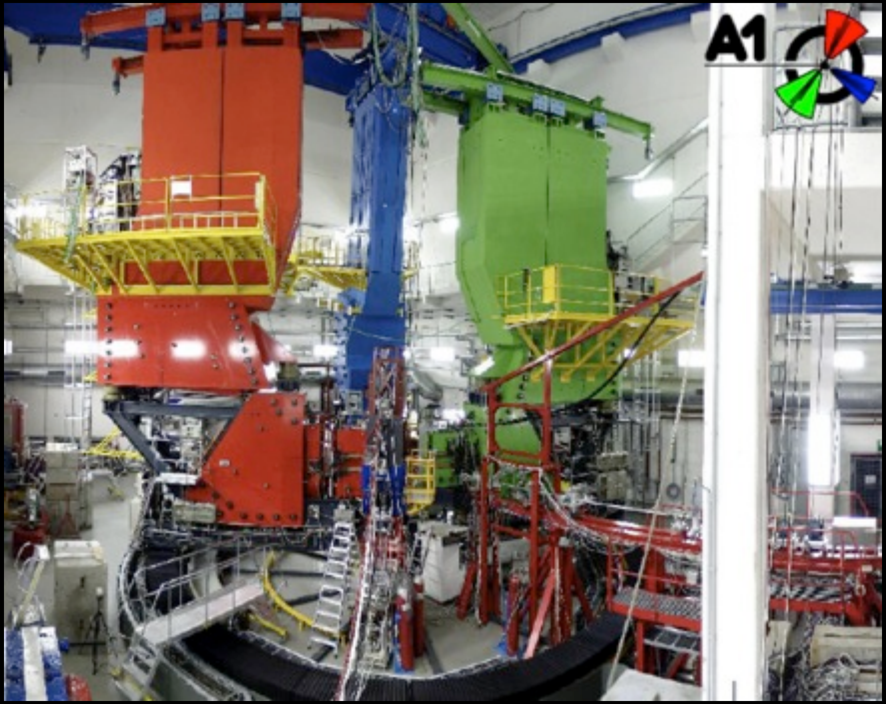
- Double coincidence gas Cherenkov signal within 12.5 ns window in each arm

Final data sample consisted of 770500 true e^+e^- coincident events with 0.9% (7.4%) meson (accidental e^+e^- coincidence) contamination



MAMI A1





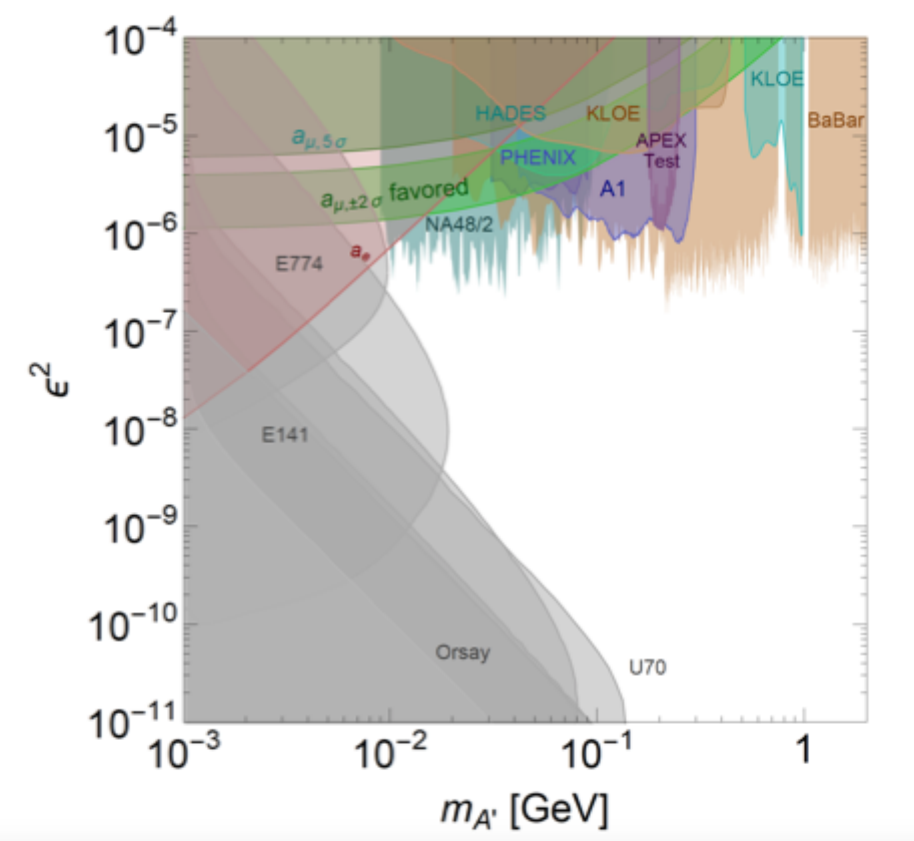
JLAB Hall-A APEX
n×1.1 GeV, continuous, 200 μA beam

MAMI A1
855 MeV, continuous, 90 μA beam

Summary of limits from visible decays

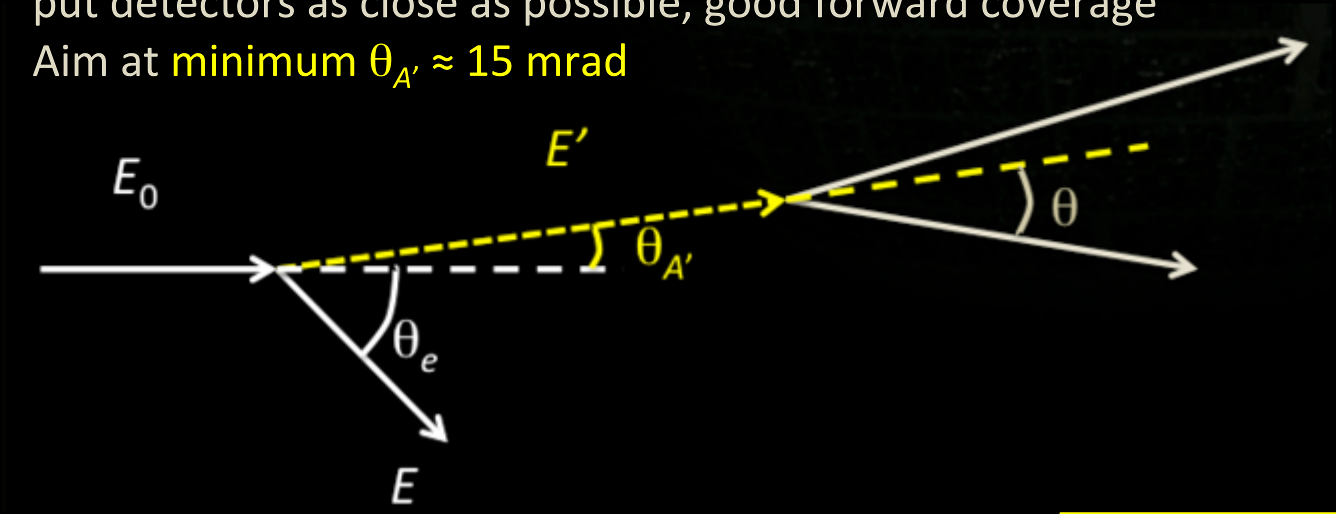
Practically, all the $(g\text{-}2)_\mu$ favored band already excluded

But still large interest for excluding the uncovered parameter space

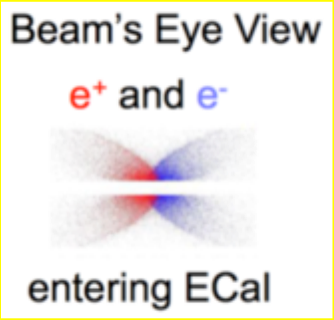


HPS

- Increase acceptance wrt double arm spectrometer
- Look for displaced vertex
- θ of the decay is small:
  - put detectors as close as possible, good forward coverage
  - Aim at minimum $\theta_{A'} \approx 15$ mrad

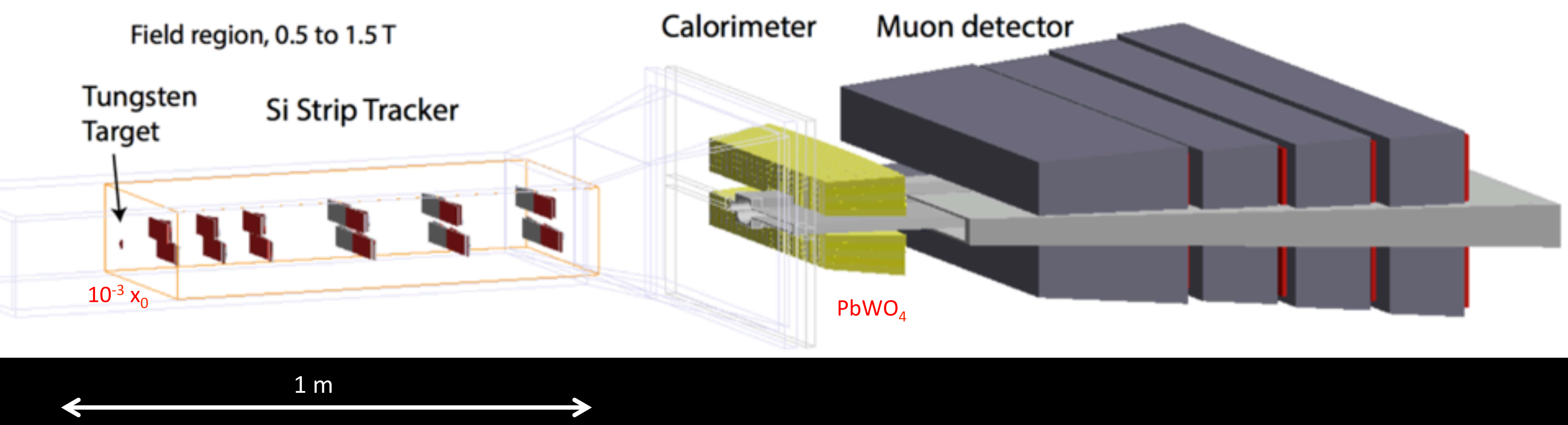


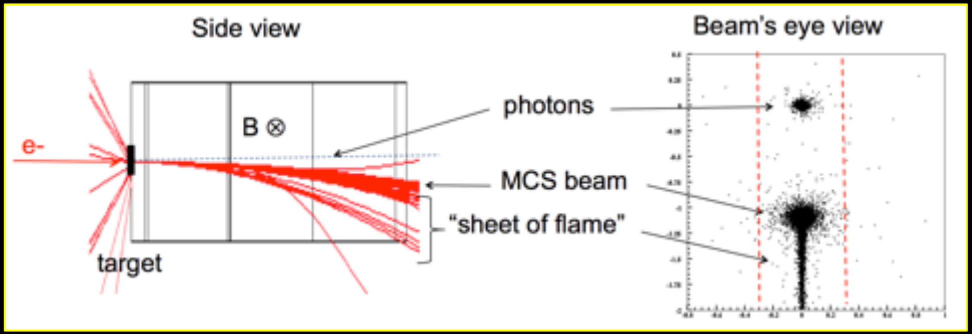
- Bump hunting needs good momentum/mass resolution
- Good tracking and analyzing magnet
- Aim at $\Delta m/m \approx 1\%$ and $\Delta z \approx 1$ mm



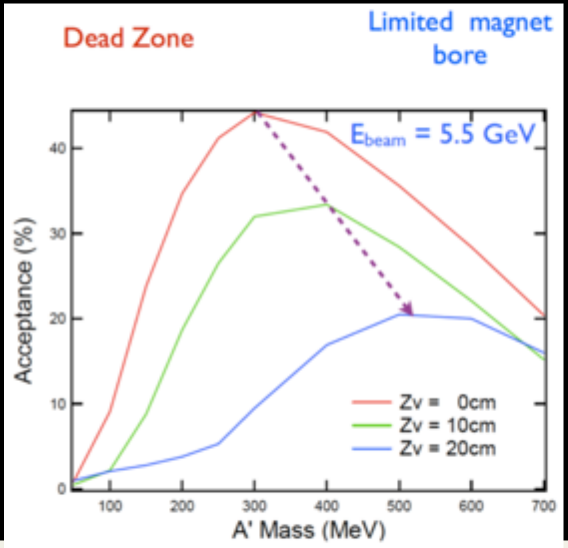
- Trigger with a high rate calorimter
- Magnet+calorimeter to select e^+ and e^-
- Magnet+muon detector to select μ^+ and μ^-

HPS

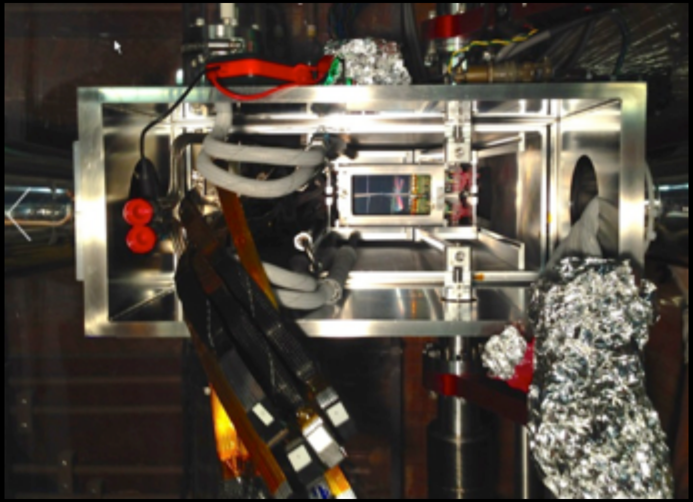


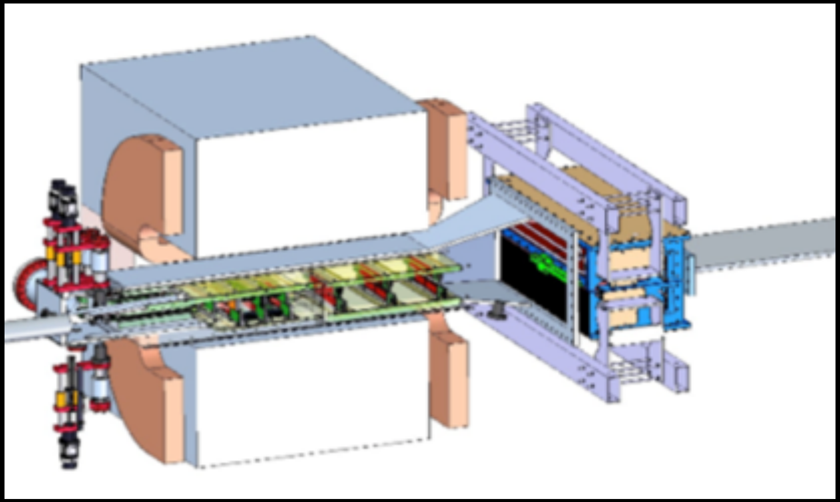


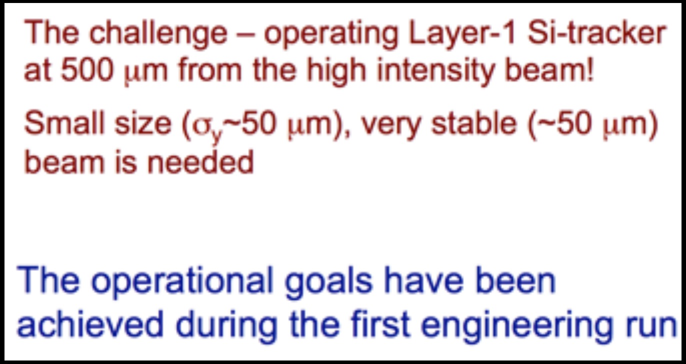
Detectors split in two halves to let the beam pass through



HPS







The challenge – operating Layer-1 Si-tracker at 500 μm from the high intensity beam!

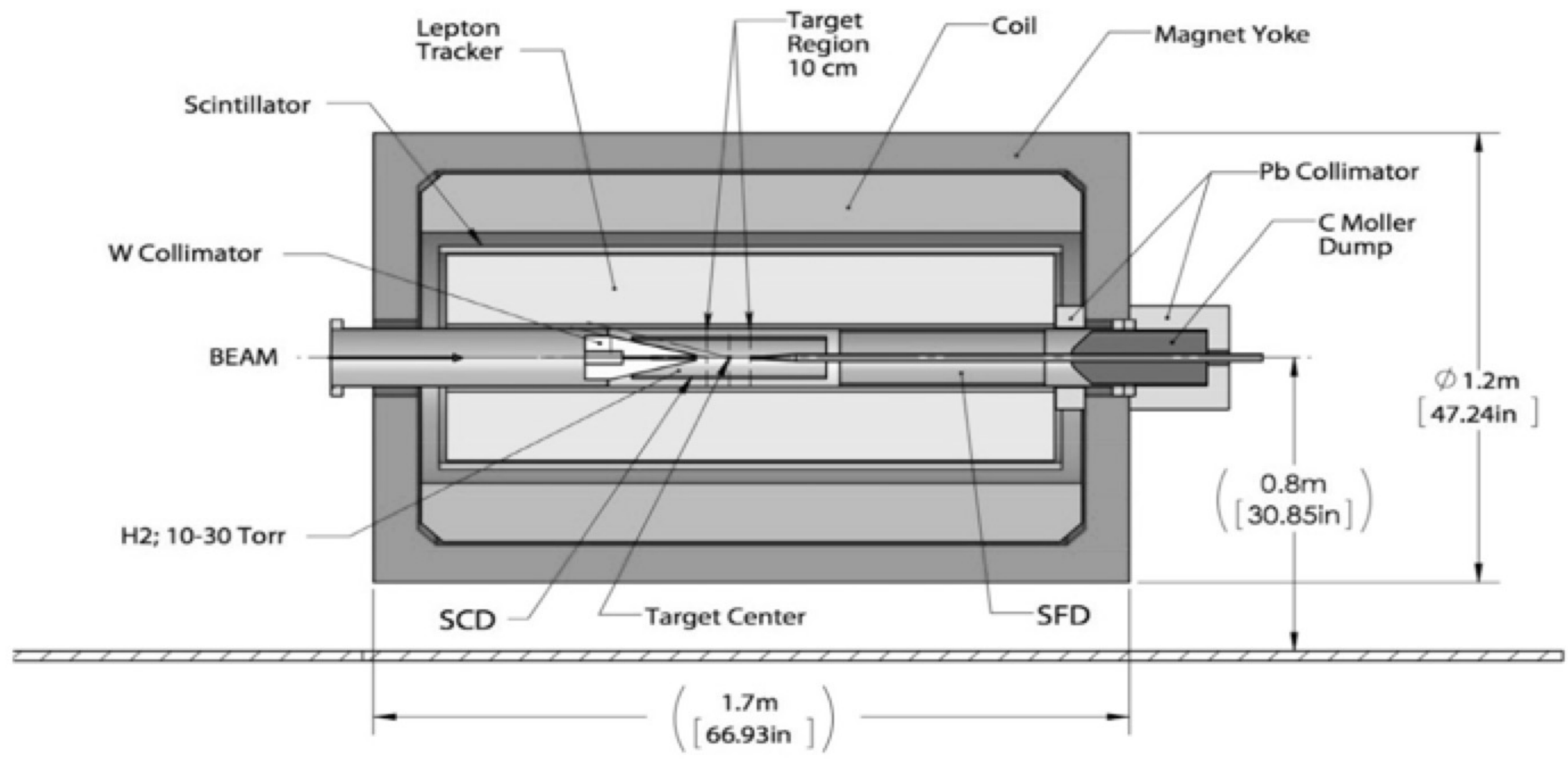
Small size (σ_y~50 μm), very stable (~50 μm) beam is needed

The operational goals have been achieved during the first engineering run

DarkLight

FEL electron beam, 100 MeV, continuous, 10 mA, onto 10^{19} H_2/cm^2 gas jet target

- Proton recoil detector. Full reconstruction of event for background rejection
- Vertexing and low momentum lepton tracker: TPC
- Outer trackers

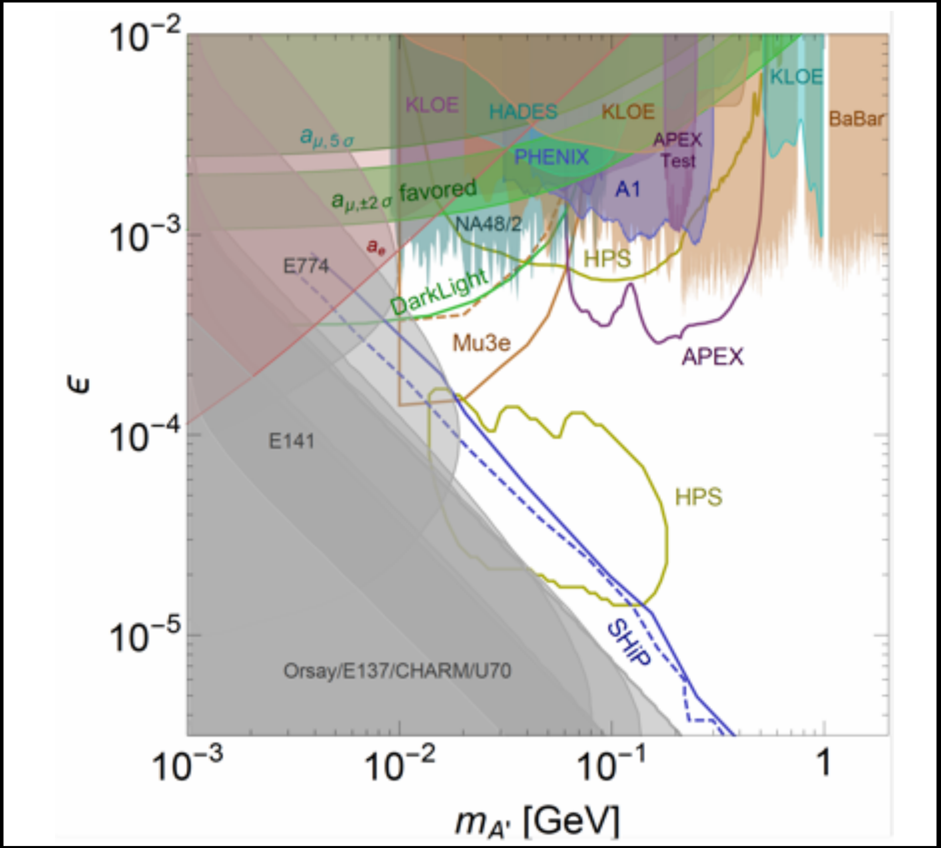


Test performed on prototype vacuum chamber to assess beam transport feasibility

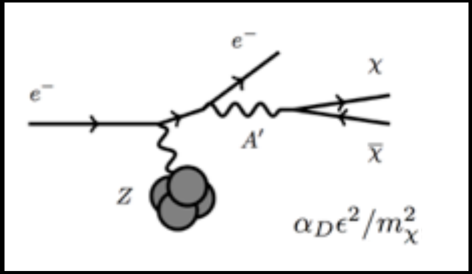
Summary of limits from visible decays

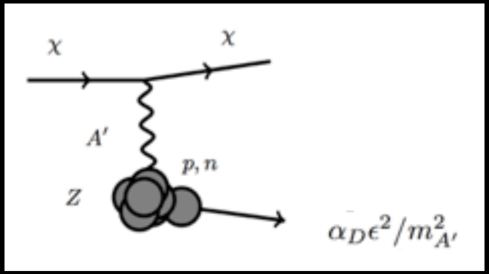
Practically, all the $(g\text{-}2)_{\mu}$ favored band already excluded

Still large interest for excluding the uncovered parameter space

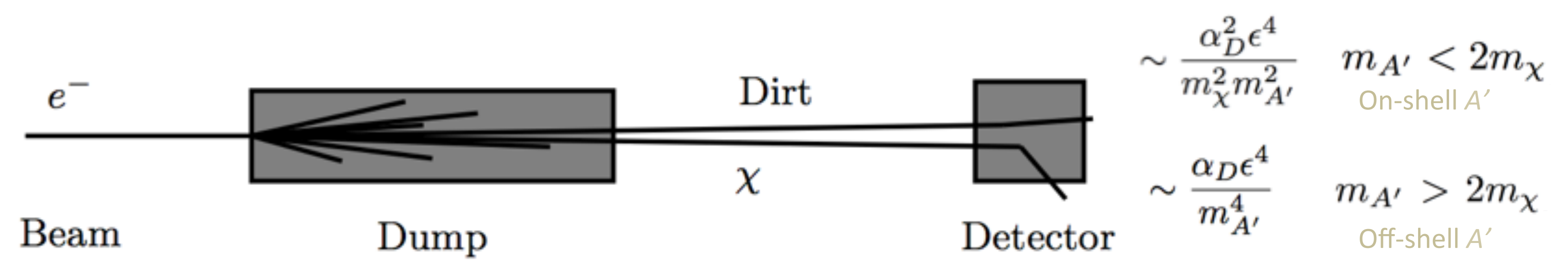


Invisible decays: a dark matter beam





Scattering on nuclei

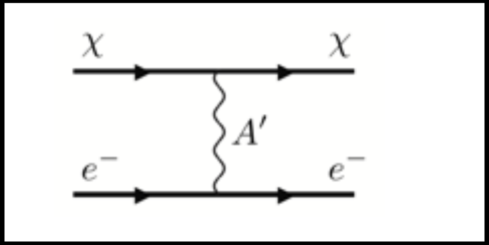


$\sim \frac{\alpha_D^2\epsilon^4}{m_\chi^2 m_{A'}^2}$ $m_{A'} < 2m_\chi$

On-shell *A′*

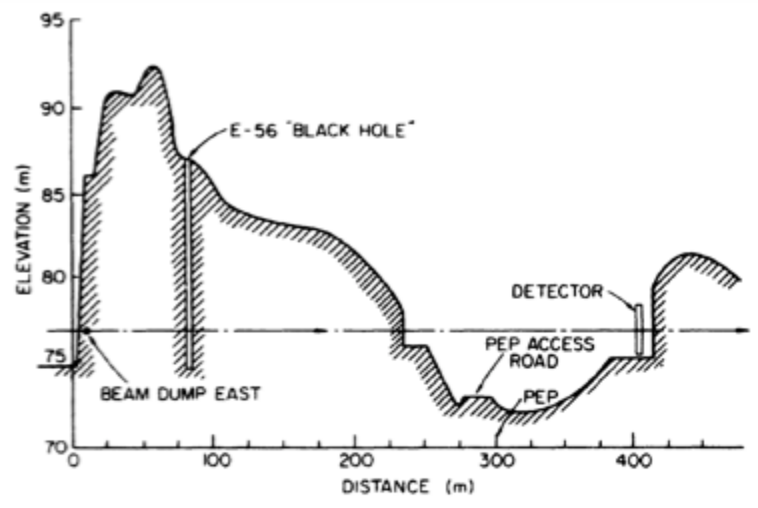
$\sim \frac{\alpha_D\epsilon^4}{m_{A'}^4}$ $m_{A'} > 2m_\chi$

Off-shell *A′*



Elastic scattering on electrons

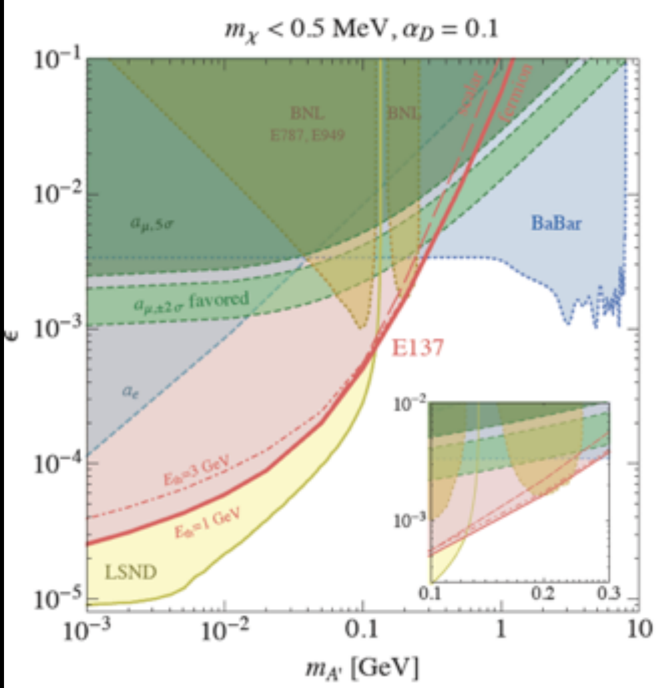
Back to past experiments



SLAC E-137
20 GeV electron beam
30 C dumped on Aluminum target
Shower calorimeter, 400 m distance
Re-analysis (Batell, Essig, Surujon) constrains
$m_{A'}$ vs ε, **dependent on** α_D and m_χ

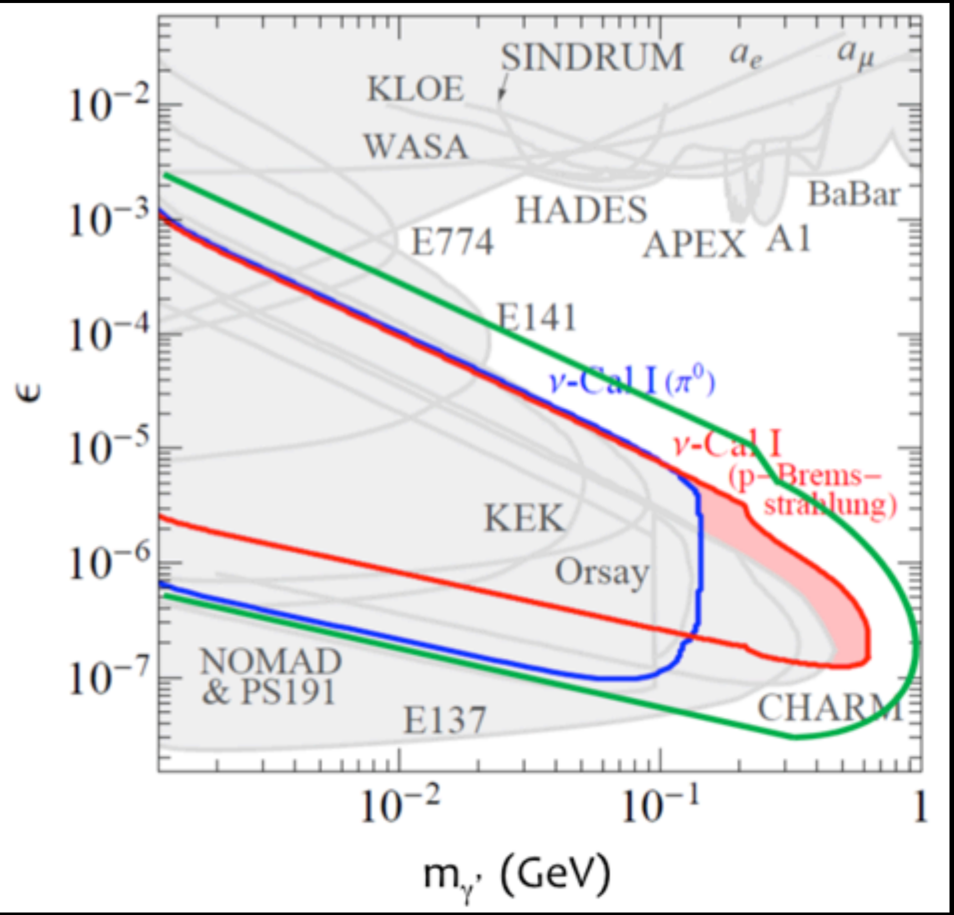
χe elastic scattering

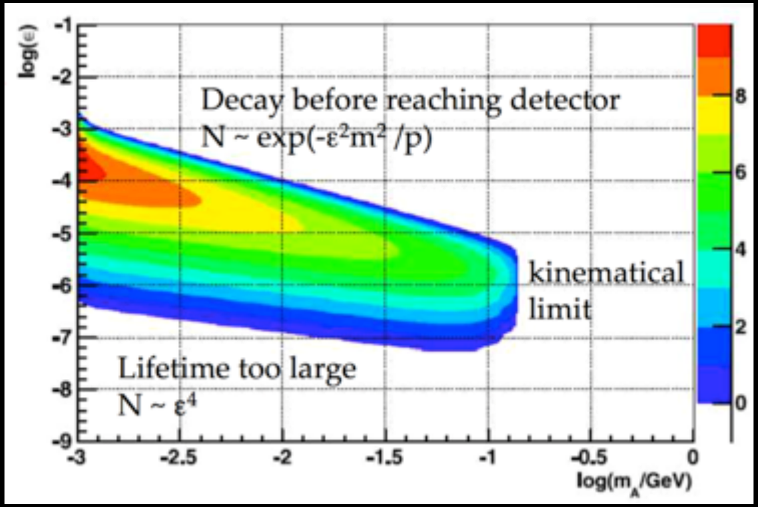
arXiv:1406.2698v1



LSND
π^0 decays to $\gamma A'$ from LAMPF 800 MeV protons
10^{23} POT
30 m off-axis detector, 170 ton mineral oil

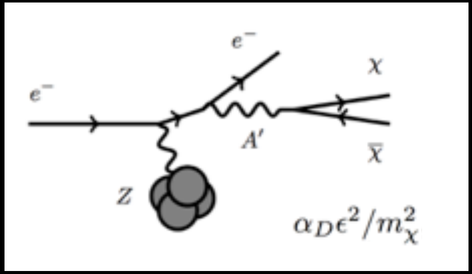
Possible future proton beam dumps: SHIP at SPS

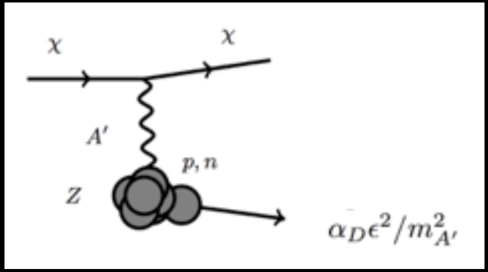




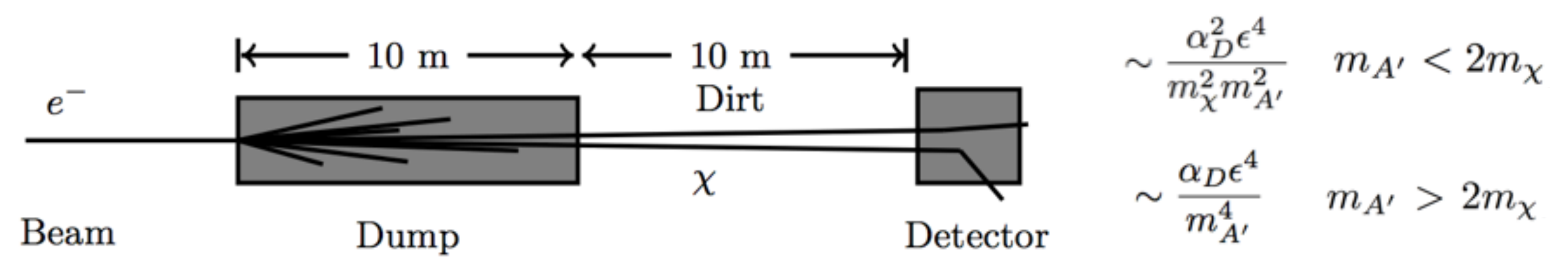
10 signal events

A new scattering experiment: BDX at JLAB





Scattering on nuclei



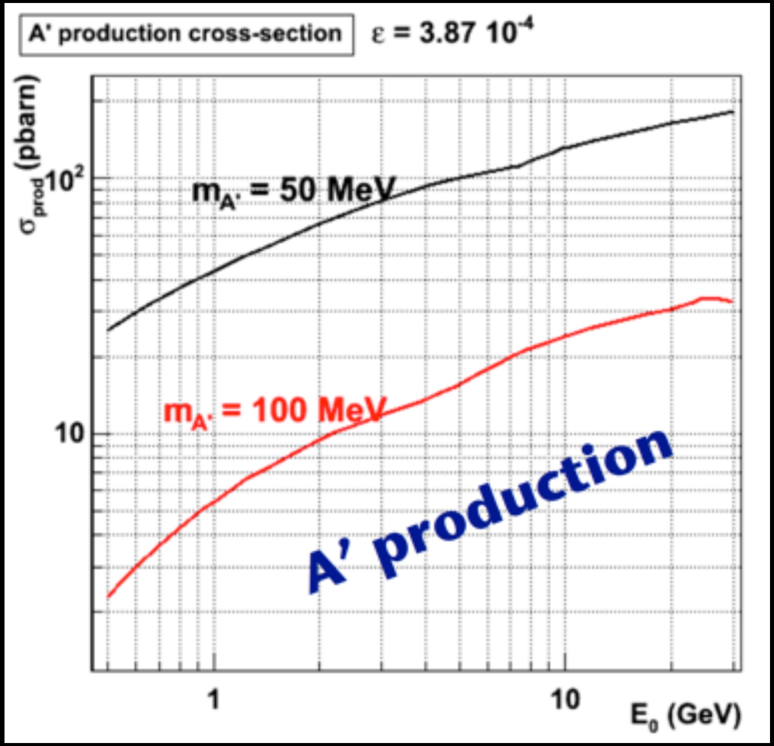
Backgrounds:
- Neutrino production
- Cosmogenic muons and neutrons

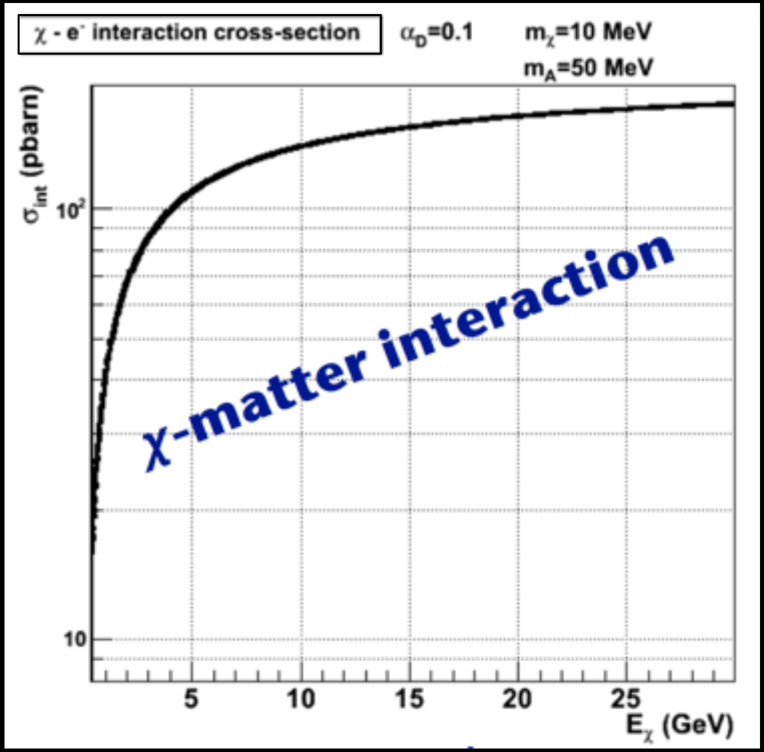
Scintillator 1 m^3
1 MeV/10 MeV e^+e^- detection threshold

LOI presented to JLAB PAC

Scattering experiment: BDX at JLAB

High energy beam advantages:
- Higher cross sections
- χ beam boosted, larger acceptance

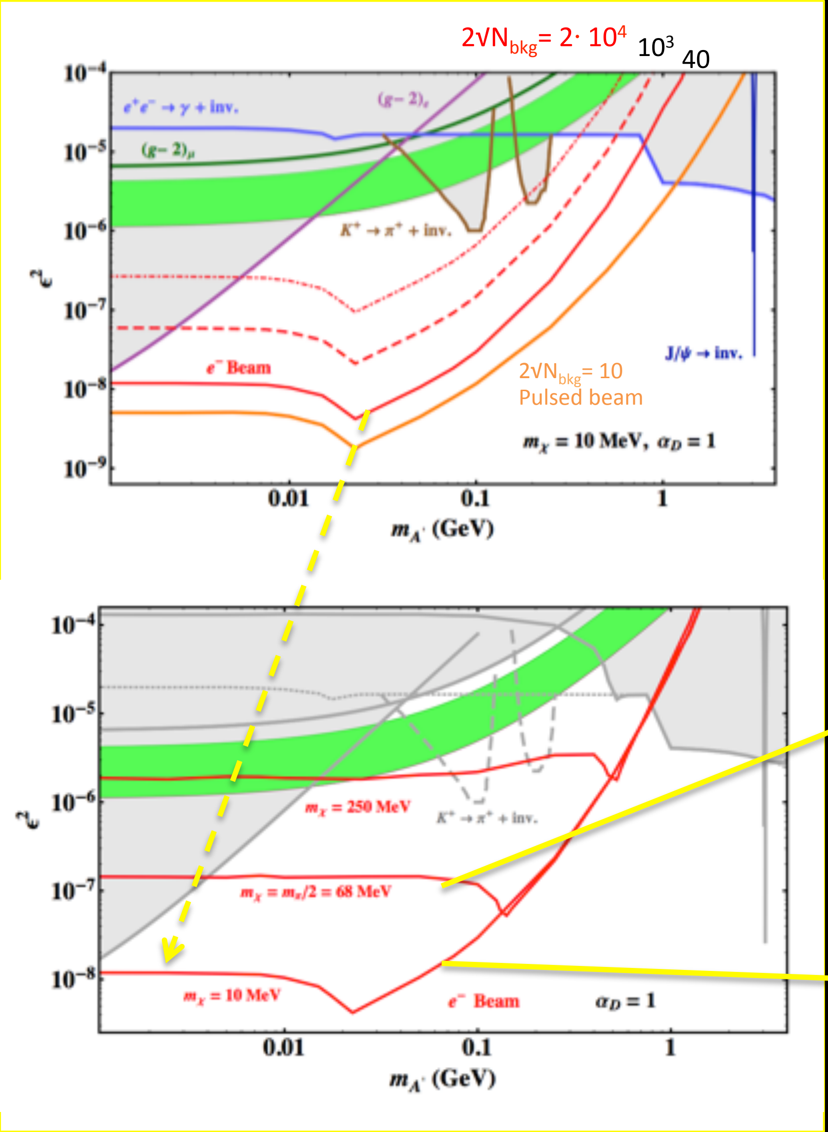




Cross section dependence from *A'* mass

Cross section dependence from *A'* mass, χ mass, coupling constant

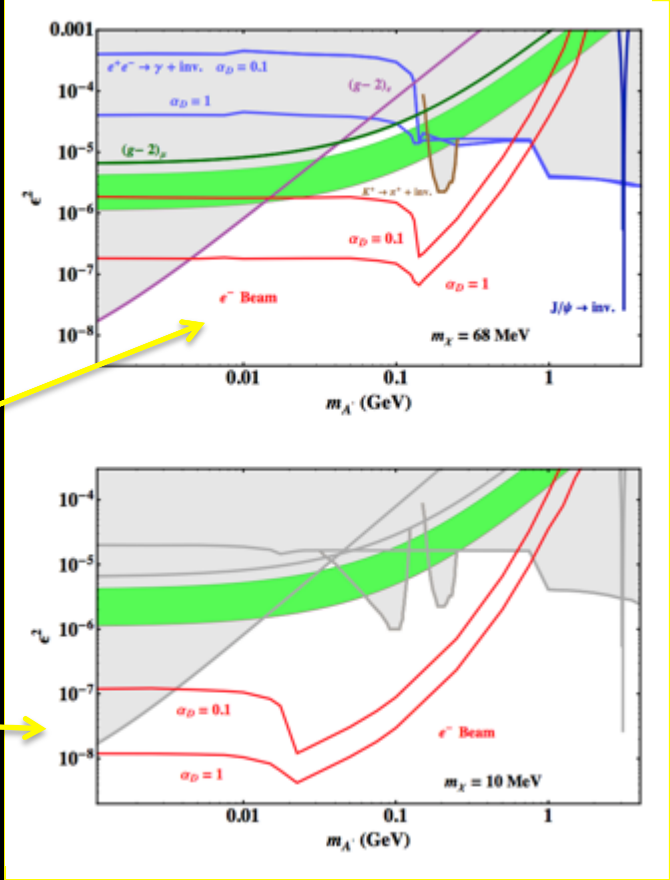
BDX experiment (Hall-A)



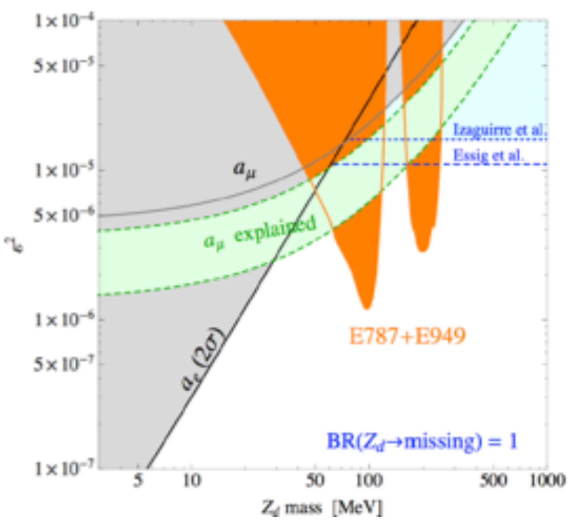
10^{22} EOT = 1 beam-year at Hall-A

3 beam-years at Hall-C?

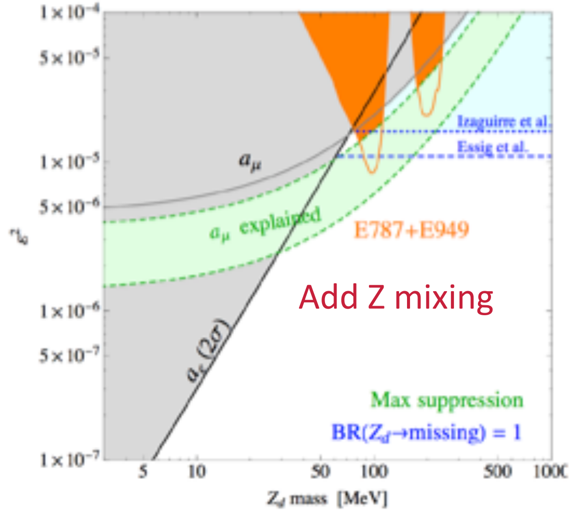
arXiv:1307.6554



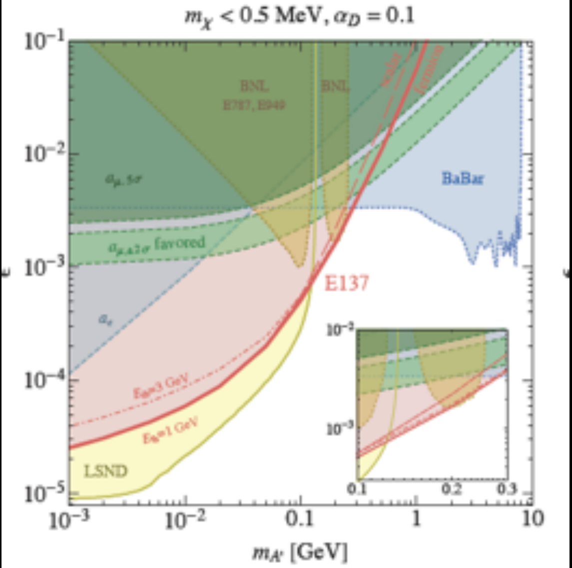
Invisible decays, model dependence of limits

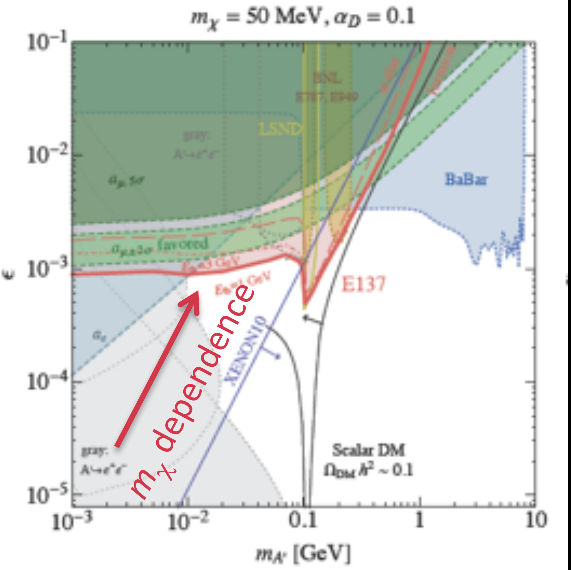


$K^\pm \to \pi^\pm \nu\nu$ used to constrain $K^\pm \to \pi^\pm A'$ assuming kinetic mixing and coupling to quarks ≠ 0



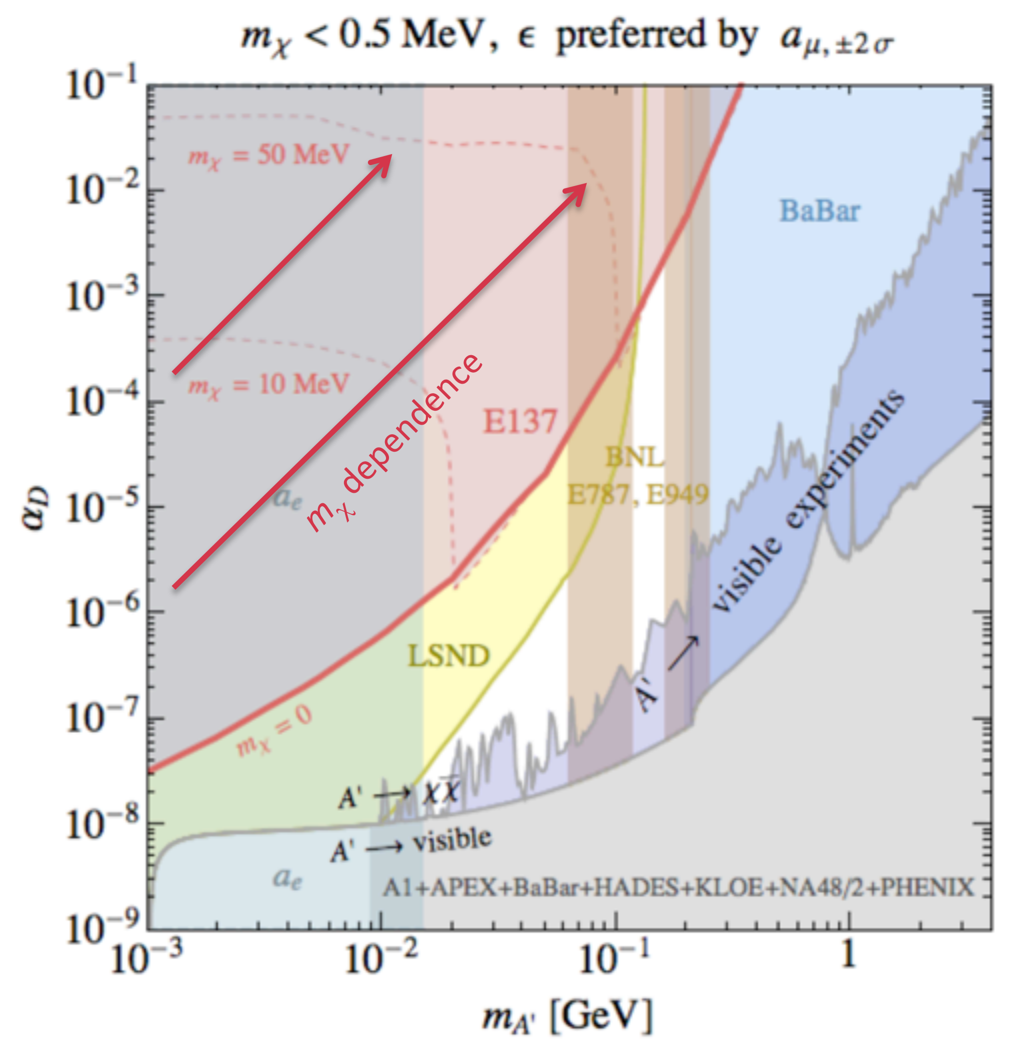
Add Z mixing



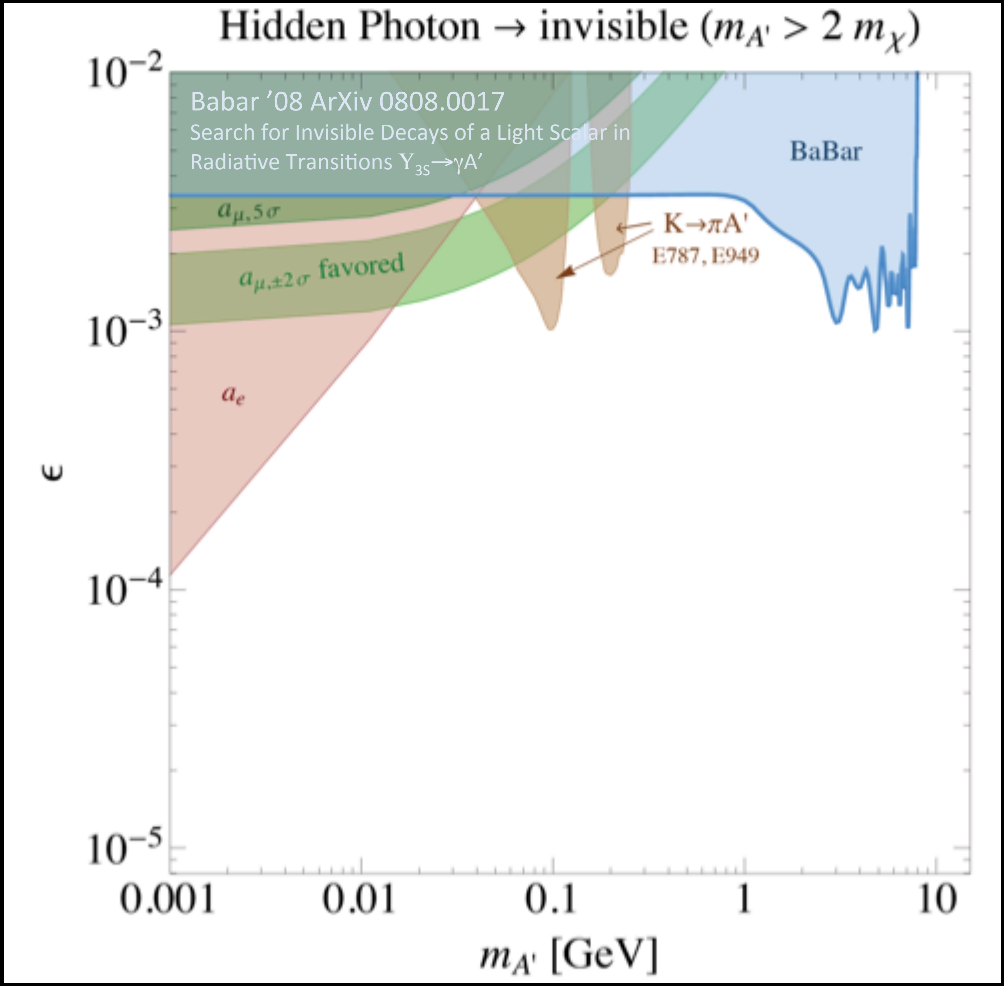


m_χ dependence

Combine visible and invisible decays



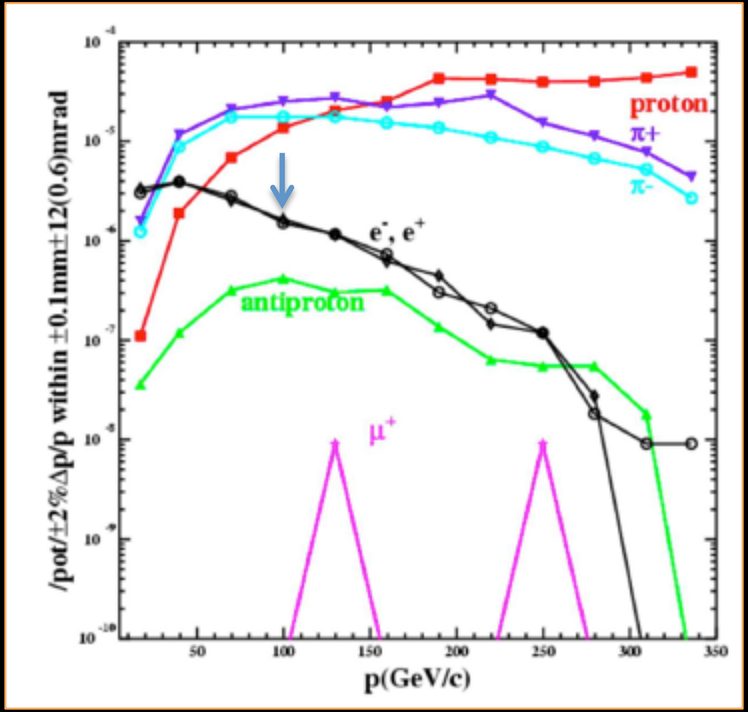
Model independent limits from invisible decays

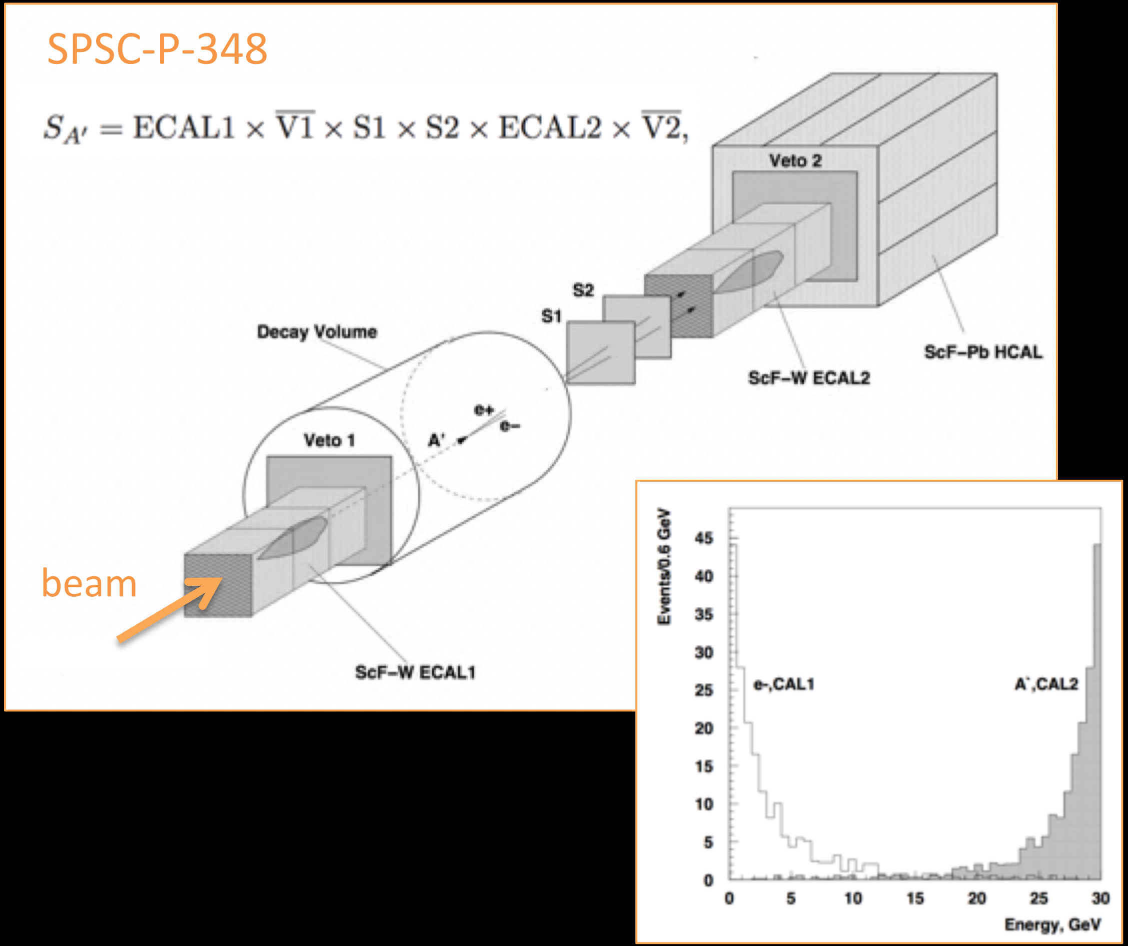


- Direct searches for *A'* invisible decays only depend on ε^2 and $m_{A'}$
- **No assumptions on coupling to quarks** (Both Υ_{3S} and $K^{\pm}$ results rely on that)

P-348 at CERN SPS

H4 high purity electron beam, <1% contamination required
(tertiary, from γ conversions)
Use synchrotron radiation tagging



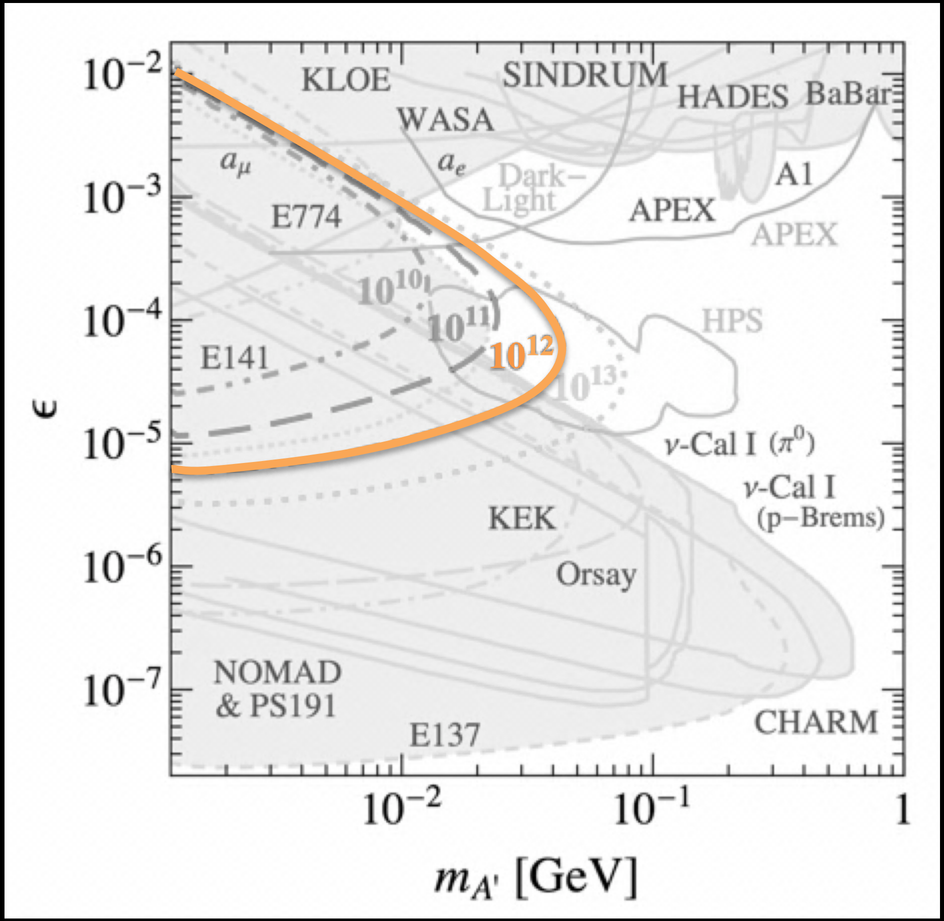


SPSC-P-348

$$S_{A'} = \mathrm{ECAL1} \times \overline{\mathrm{V1}} \times \mathrm{S1} \times \mathrm{S2} \times \mathrm{ECAL2} \times \overline{\mathrm{V2}},$$

P-348 at CERN SPS

- $N_e = 10^{12}$ requested (3 months run)
- Main backgrounds:
  - punch-through of primary energy into ECAL1
  - Beam-related background (mis-identified electrons): muon and hadronic events

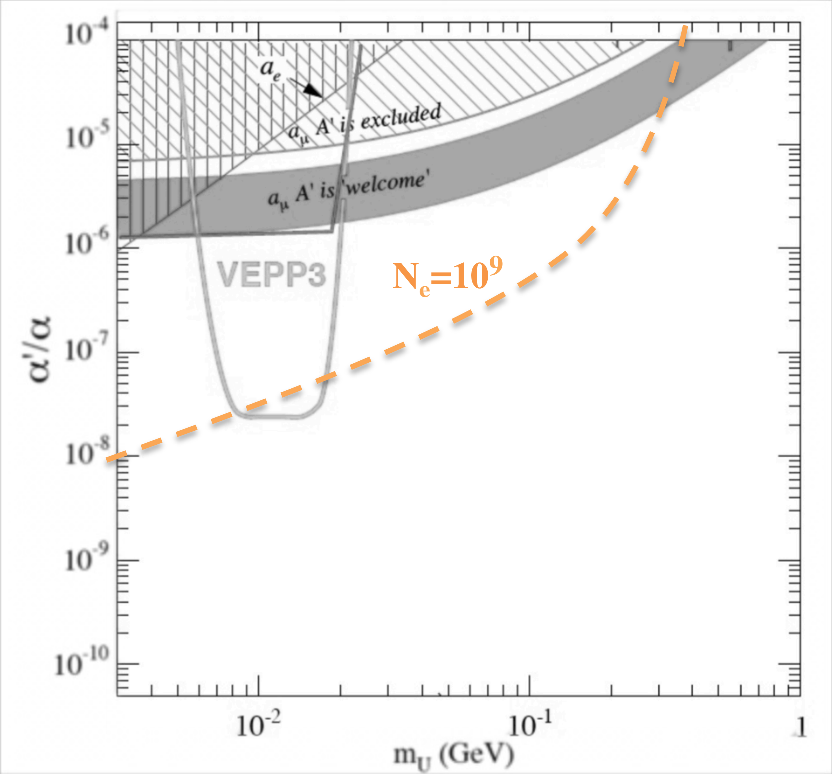


P-348 at CERN SPS

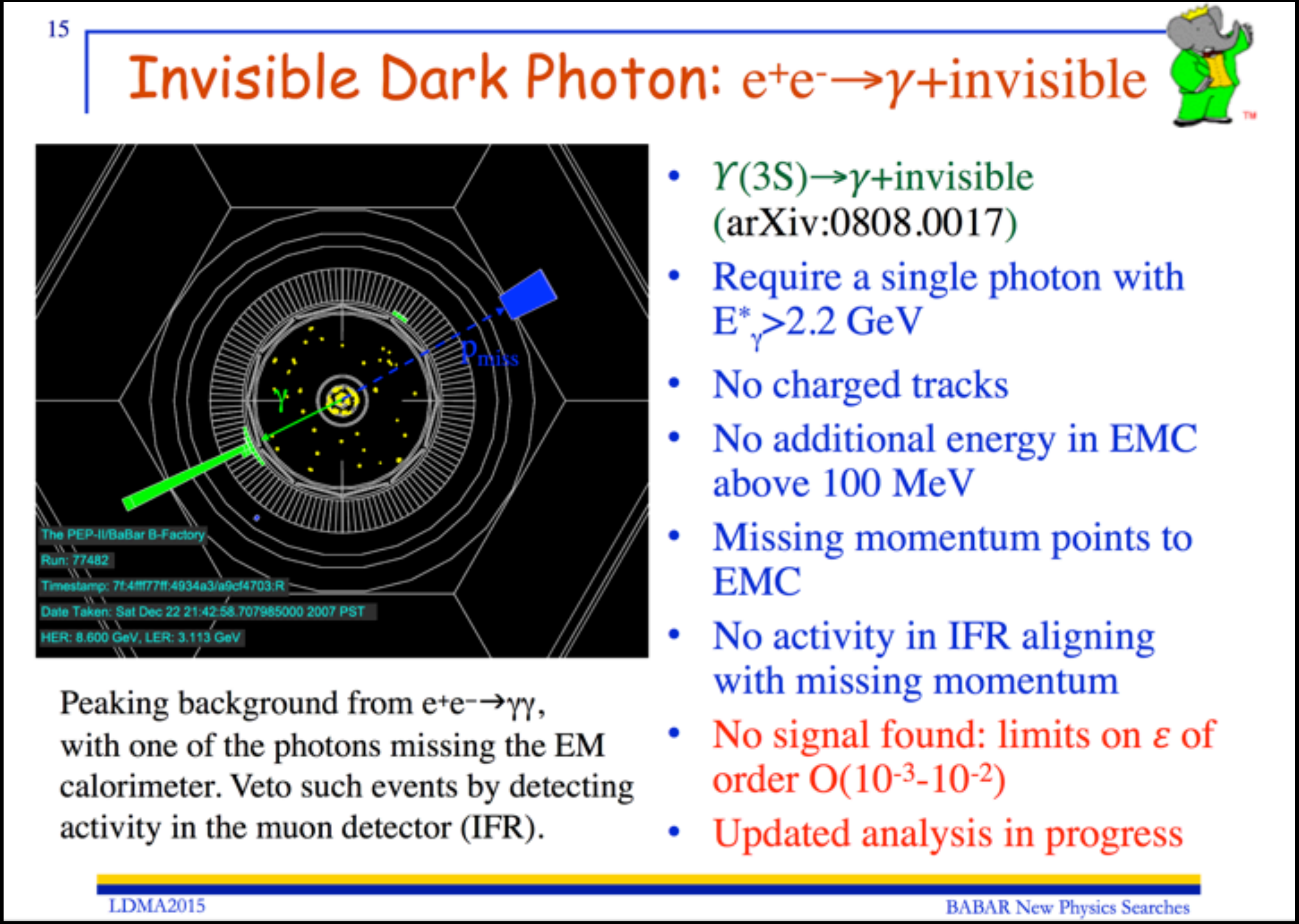
- Also proposal for A’ → invisible search

$$S_{A'} = \mathrm{ECAL1} \times \overline{\mathrm{V1} \times \mathrm{S1} \times \mathrm{S2} \times \mathrm{ECAL2} \times \mathrm{V2} \times \mathrm{HCAL}}$$

- Main backgrounds:
  - punch-through of e^- or γ
  - Non-hermeticity of HCAL
  - Low energy tail of e^- beam
  - e^- induced photo-nuclear reactions
  - Muon events



BaBar limit



15

Invisible Dark Photon: $e^+e^- \to \gamma$+invisible

Peaking background from $e^+e^- \to \gamma\gamma$, with one of the photons missing the EM calorimeter. Veto such events by detecting activity in the muon detector (IFR).

- $\Upsilon(3S) \to \gamma$+invisible (arXiv:0808.0017)
- Require a single photon with $E^*_\gamma > 2.2$ GeV
- No charged tracks
- No additional energy in EMC above 100 MeV
- Missing momentum points to EMC
- No activity in IFR aligning with missing momentum
- No signal found: limits on ε of order $O(10^{-3}\text{-}10^{-2})$
- Updated analysis in progress

LDMA2015

BABAR New Physics Searches

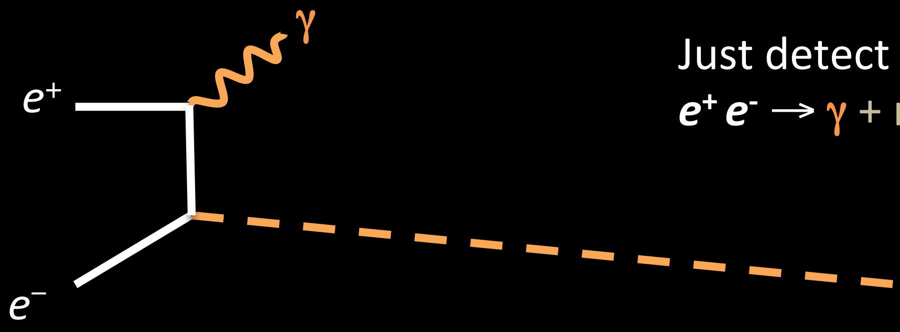
Alberto Lusiani

The PADME approach

- At present all experimental results rely on **at least one** of the following model dependent assumptions:
  - *A′* decays to e^+e^- (visible decay assumption BR($A' \to e^+e^- = 1$)
  - *A′* couples with the same strength to all fermions ($\varepsilon_q = \varepsilon_l$) (kinetic mixing)
- In the **most general** scenario
  - *A′* can decay to dark sector particles lighter than the A' BR($A' \to e^+e^- << 1$)
    - Dump and meson decay experiment only limit ε^2BR($A' \to e^+e^- << 1$)
  - *A′* can couple to quark with a coupling constant smaller ε_l or even 0
    - Suppressed or no production at hadronic machines and in mesons decays

- **PADME aims at detecting *A′* produced in e^+e^- annihilation and decaying into invisibles by searching for missing mass in $e^+e^- \to \gamma A'$, $A' \to XX$**
  - No assumption on the *A′* decays products and coupling to quarks
  - Only minimal assumption: *A′* bosons couples to leptons
  - PADME will limits the coupling of **any new light particle** produced in e^+e^- collision (scalars (H_d), vectors (*A′* and Z_d)

What we need: signal



Just detect one photon + missing energy:
$e^+ e^- \rightarrow \gamma$ + nothing

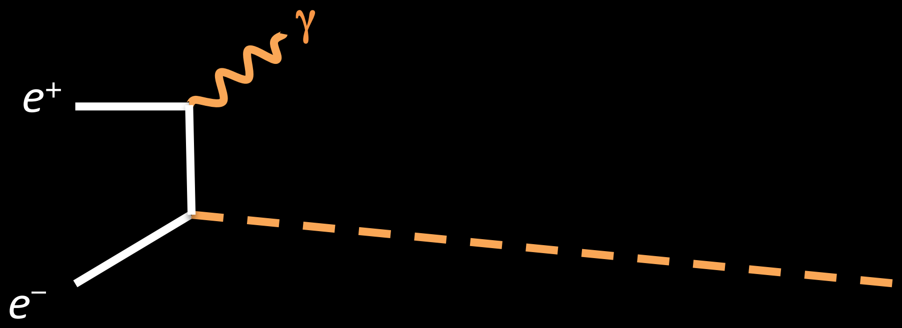
In order to compute $M^2_{\text{miss}} = (\underline{P}_\gamma - \underline{P}_{e+})^2$ we need:

a) A **positron** beam with a well defined four-momentum
  1. Small energy and angular spread
  2. Small transverse spot

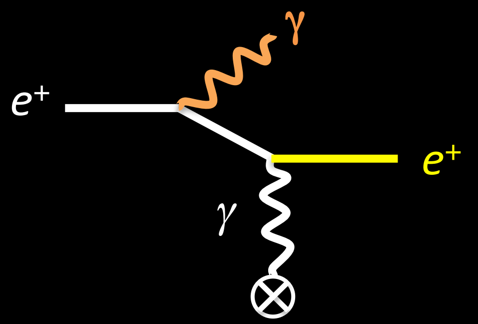
     1+2 = small emittance
  3. Tunable intensity (in order to optimize annihilation vs. Bremsstrahlung)

b) Measure precisely the photon (tri-)momentum (angle and energy)

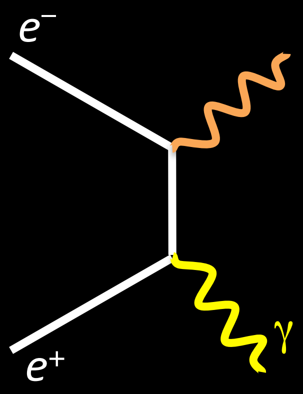
What do we need: background



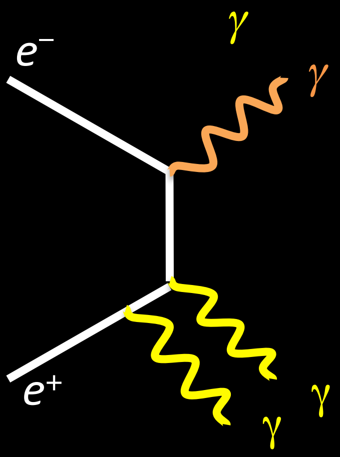
We need to fight the backgrounds
i.e. one photon + something else, eventually going undetected:



+1 electron
Bremsstrahlung process, ≈Z^2



+1 γ
$\gamma\gamma$ process, ≈Z



+2 γ
3γ process

DAΦNE complex in Frascati

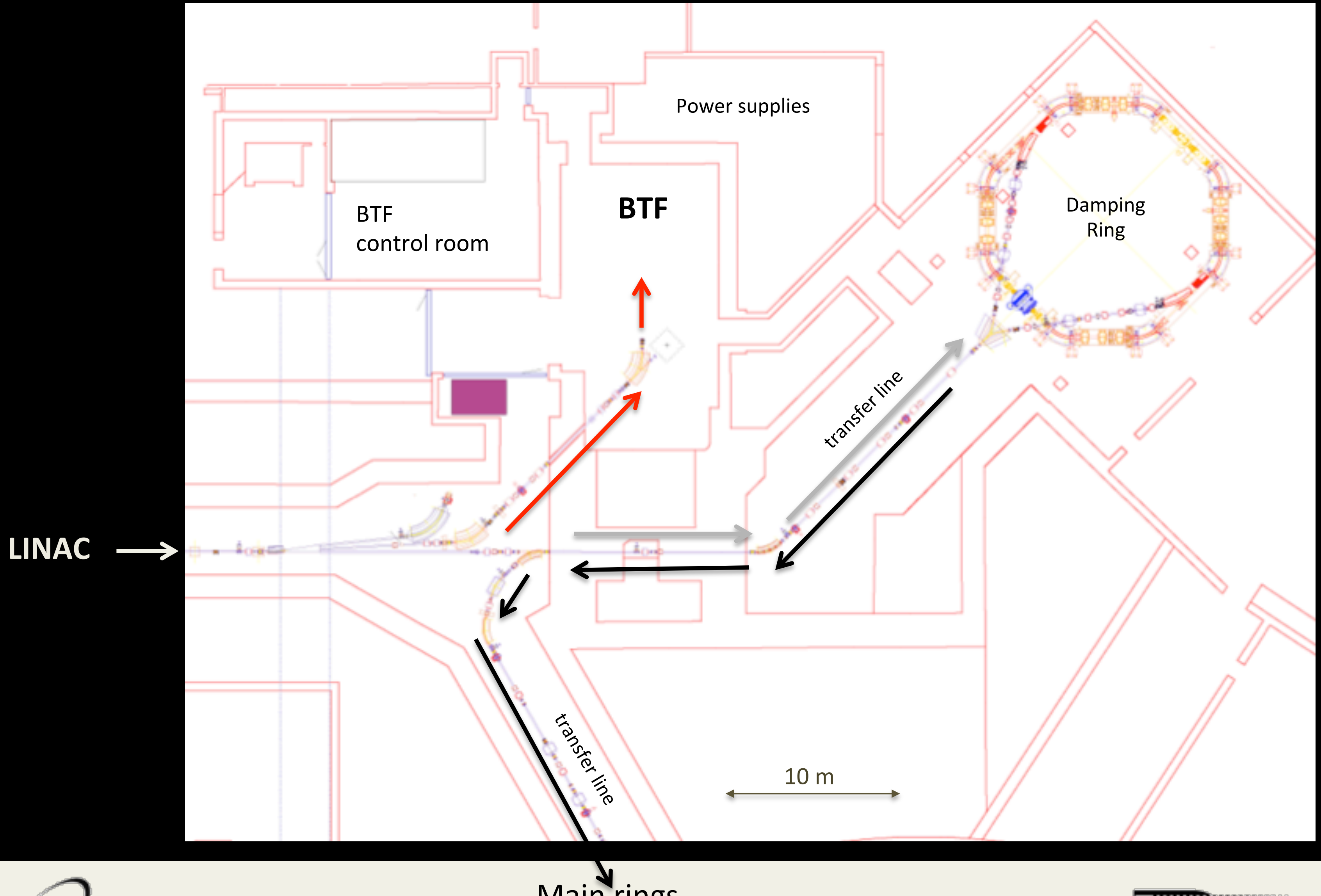
- DAΦNE, replacing ADONE (operational until 1993), has been running as e^+e^- collider at 1,02 GeV since 1999, for KLOE, DEAR, FINUDA, Siddharta, and now KLOE/2 …
- Synchrotron light source operational with 3 lines (X, UV, IR)
- **High current electron/positron linac** + damping ring + **test facility**

LINAC parameters

The “shotgun” of the system is of course the high-current linac

	Design	Operational
Electron beam final energy	800 MeV	510 MeV
Positron beam final energy	550 MeV	510 MeV
RF frequency	2856 MHz	
Positron conversion energy	250 MeV	220 MeV
Beam pulse rep. rate	1 to 50 Hz	1 to 50 Hz
Beam macropulse length	10 nsec	1 to 40 nsec
Gun current	8 A	8 A
Beam spot on positron converter	1 mm	1 mm
norm. Emittance (mm. mrad)	1 (electron) 10 (positron)	< 1.5
RMS energy spread	0.5% (electron) 1.0% (positron)	0.5% (electron) 1.0% (positron)
electron current on positron converter	5 A	5.2 A
Max output electron current	>150 mA	350 mA
Max output positron current	36 mA	100 mA max
Trasport efficiency from capture section to linac end	90%	90%
Accelerating structure	SLAC-type, CG, 2π/3	
RF source	4 x 45 MWp SLED-ed klystrons TH2128C	

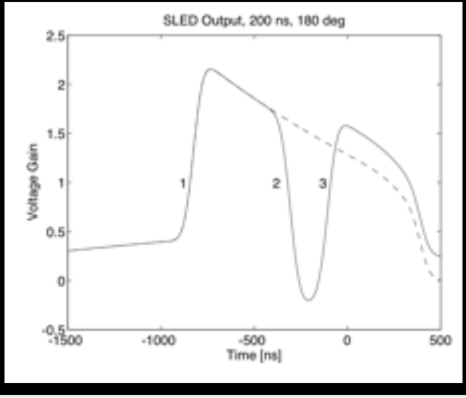
The beam test facility



DAΦNE Beam Test Facility (BTF)

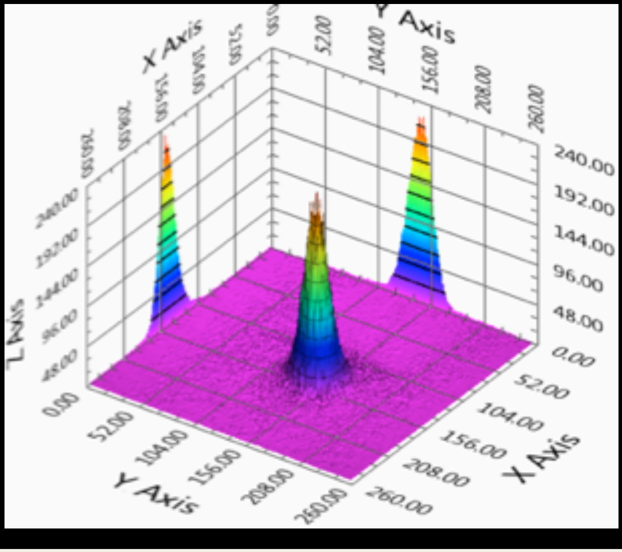
- Longer Duty Cycle
  - Standard BTF duty cycle = 50***10 ns** = 5x10^{-7} s
  - Already obtained upgrade 50***40ns**= 20x10^{-7} s
  - Work in progress to reach **150 ns** (new pulser) …
  - … Up to **250 ns** (double phase inversion at the SLED) …
  - … and beyond (no SLED, or SLED detuning), in principle up to 4 μs
- Energy upgrade planned in 2017.
  - Region from 0-22 MeV can be explored with a positron beam of **550 MeV**
    - The accessible $M_{A'}$ region is limited by beam energy
    - e.g. $M_{A'}$ up to **28 MeV** with 750 positron beam

240 ns, 0.5% energy spread achieved at SLAC (same LINAC) for E-154 experiment



BTF beam summary

- Energy spread **Δp/p ~1%**
- Beam spot: <**1 mm RMS**
- Divergence: **1 – 1.5 mrad**
  - Effect of **multiple scattering and Bremsstrahlung** on the Beryllium exit window and in air has to be considered
  - Both size and divergence depend on the **optics**
- Beam position: **0.25 mm RMS**
- Pulse duration: **1.5 – 40 ns**
  - 10 ns during collider operations

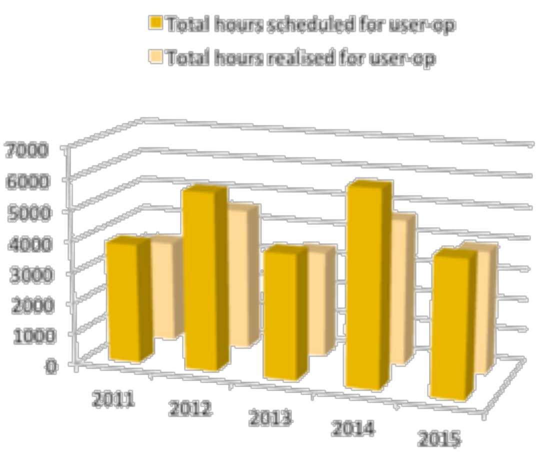

Beam spot size

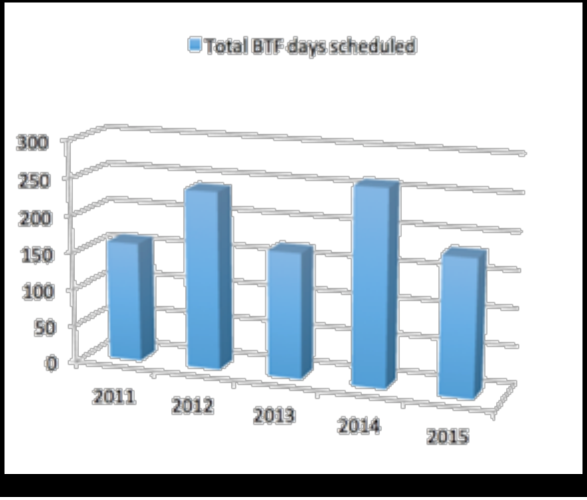
BTF experimental hall

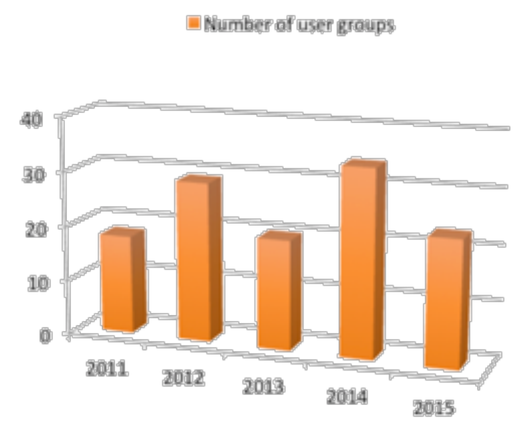
Approximately **<5.5 m total** length
(<3 m lateral width)

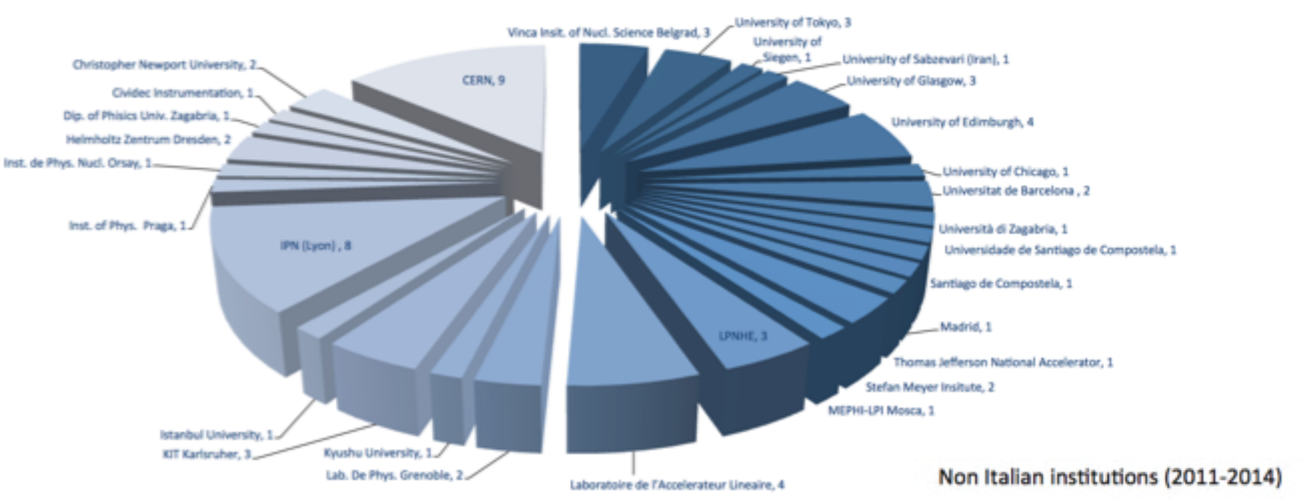
BTF users

Luckily enough, BTF is already extensively used by many experimental groups in HEP and astro-particles…

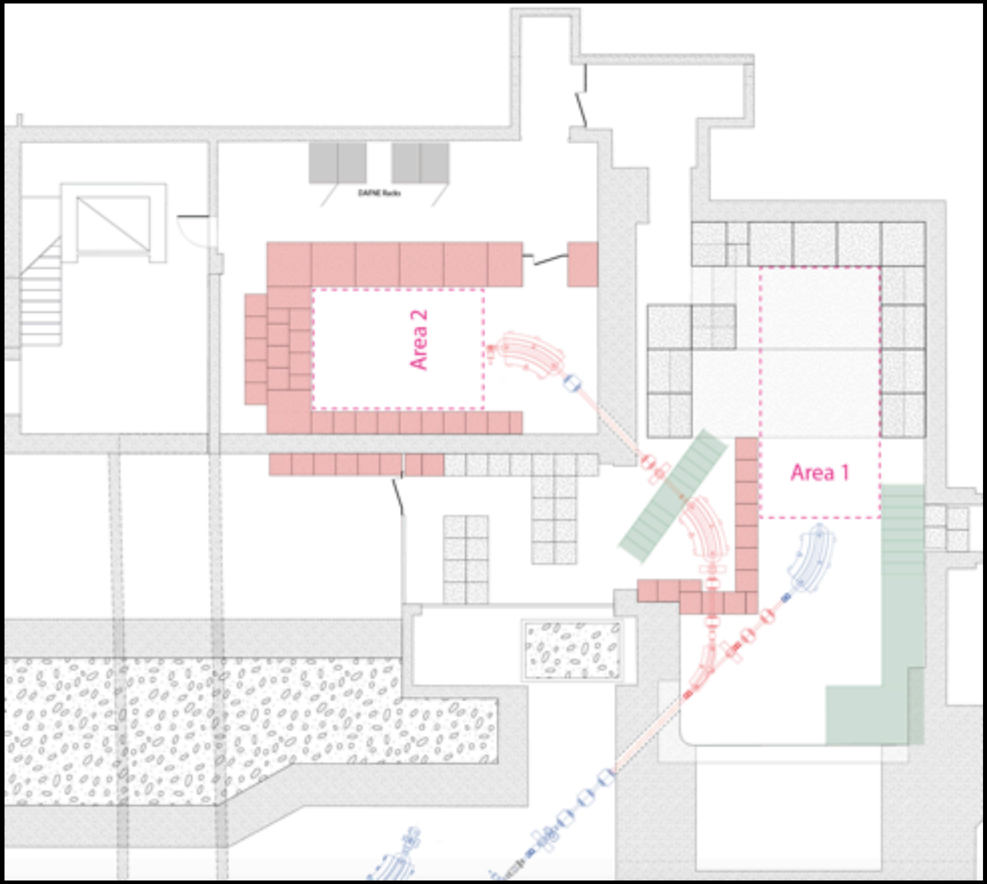




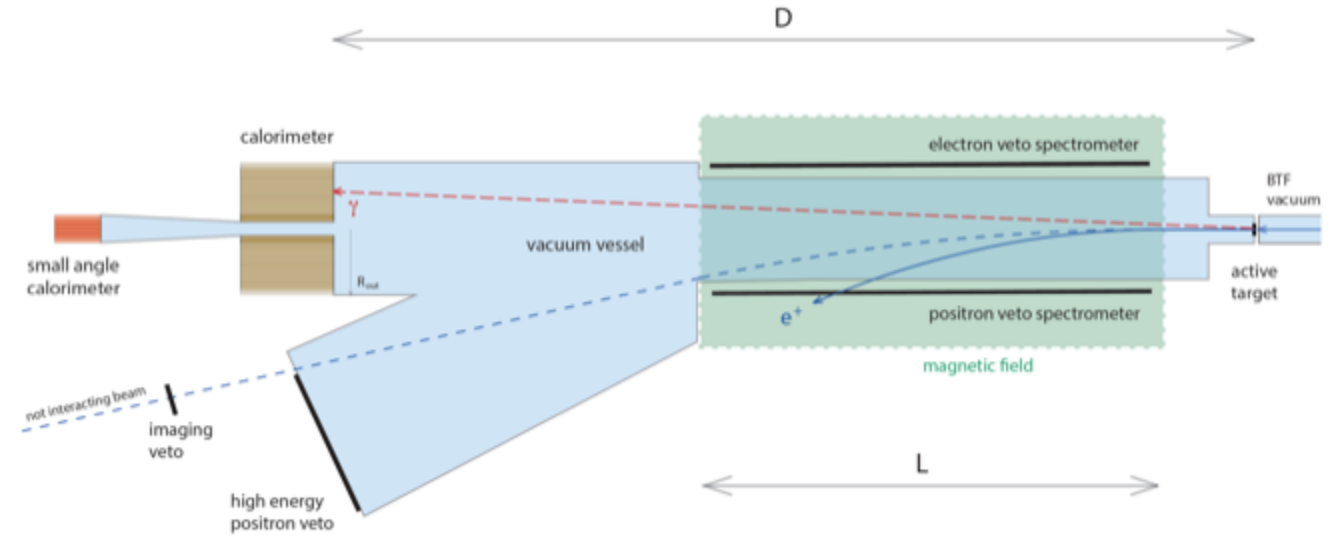




BTF beam-line upgrade

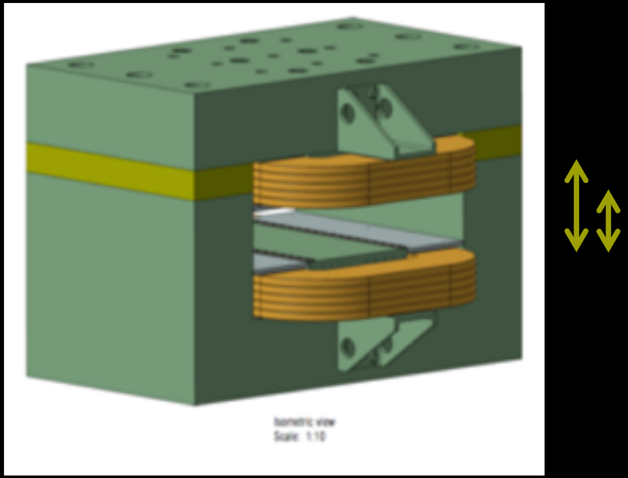


The PADME experiment



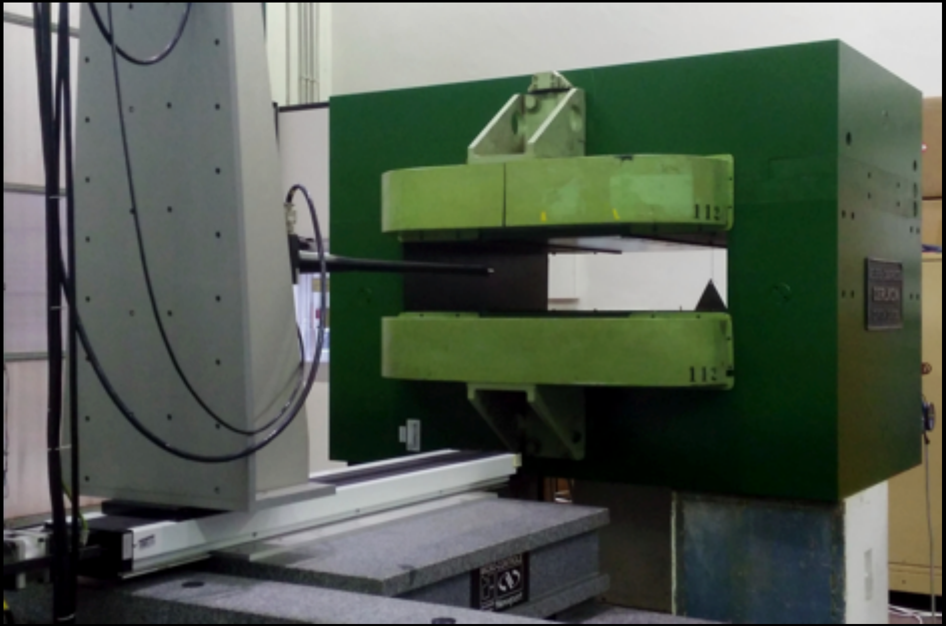
- 10^3-10^4 e^+ on target per bunch, at 50 bunches/s (10^{13}-10^{14} e^+/year), limited by pile-up, mainly due to Bremsstrahlung events
- Active target, **thin**: e.g. 50-100μm diamond with strips
  - Optimize by looking at **annihilation vs. Bremsstrahlung** cross section
- Magnetic spectrometer/veto ~ 1m length × 0.5 T for sweeping away 550 MeV beam
  - Conventional magnet with **large gap** for gaining **acceptance**
  - Possibility to increase field for energy upgrade to ~ 1 GeV
  - Available from CERN, spare of MBP dipoles of SPS transfer line
- Cylindrical crystal calorimeter
  - Optimize radius vs. distance by looking at **background rejection vs. acceptance**
  - In order to have an acceptable rate, central hole and
- Small angle detector for Bremsstrahlung veto
- Vacuum pipe

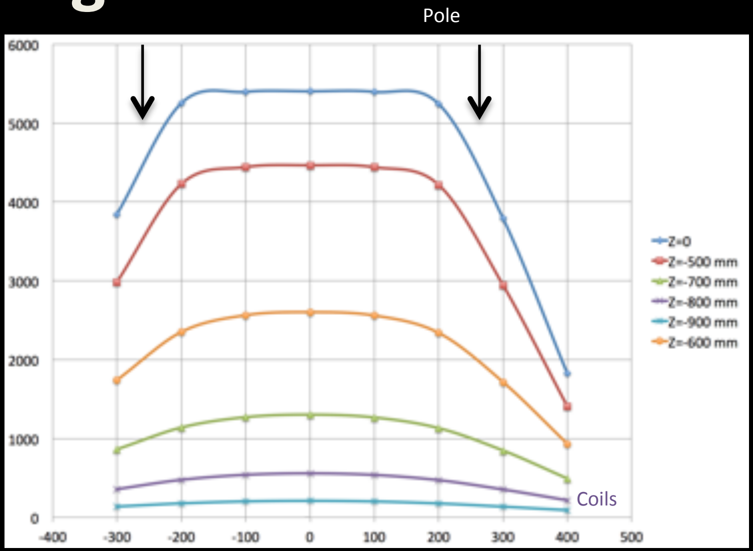
Starting from the magnet, build the layout around it

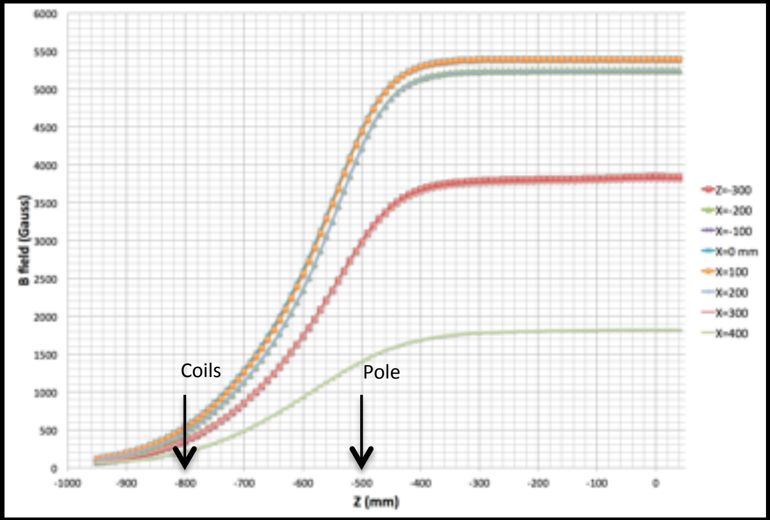


Adjustable gap by adding/removing iron insets

The PADME magnet

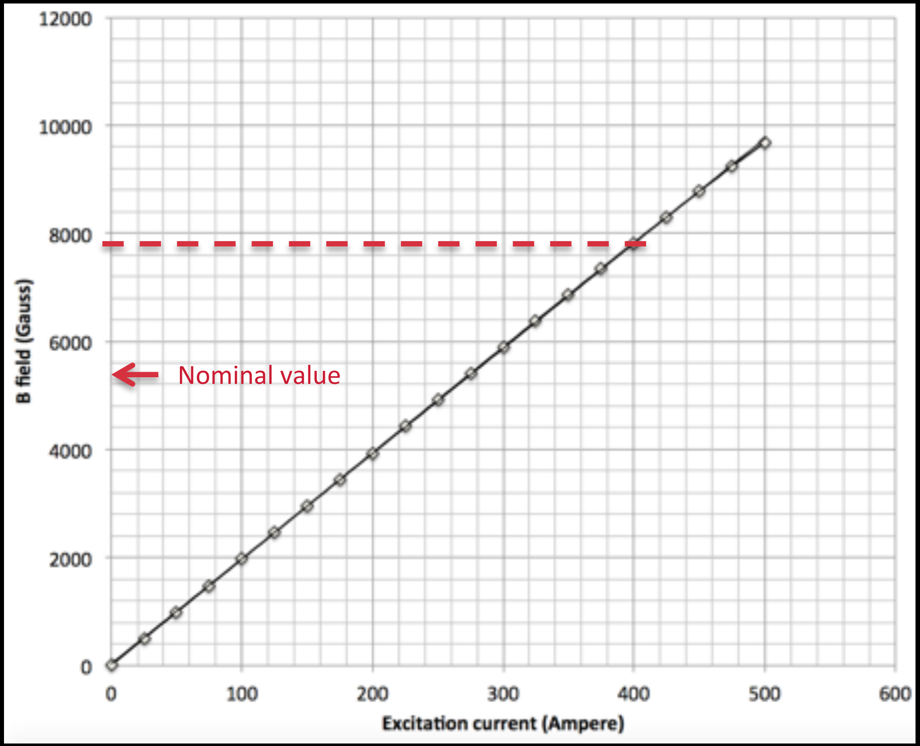






- MBP-S series, **on loan from CERN**
  - Many thanks to TE-MSC-MNC, R. Lopez, D. Tommasini
  - Shipped to Frascati in Dec. 2015
- Poles: 100 cm length, 52 cm width
- Variable gap 11 to 20 cm, we further extended to **23 cm** gap
- Preliminary field mapping:
  - Good B field quality
  - **Fringe field** not negligible, even outside the coils, relevant for beam control upstream of the active target

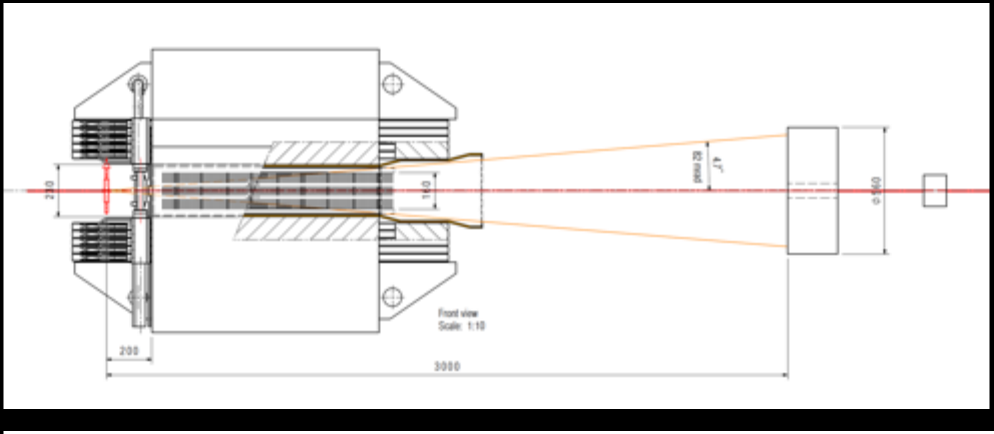
The PADME magnet



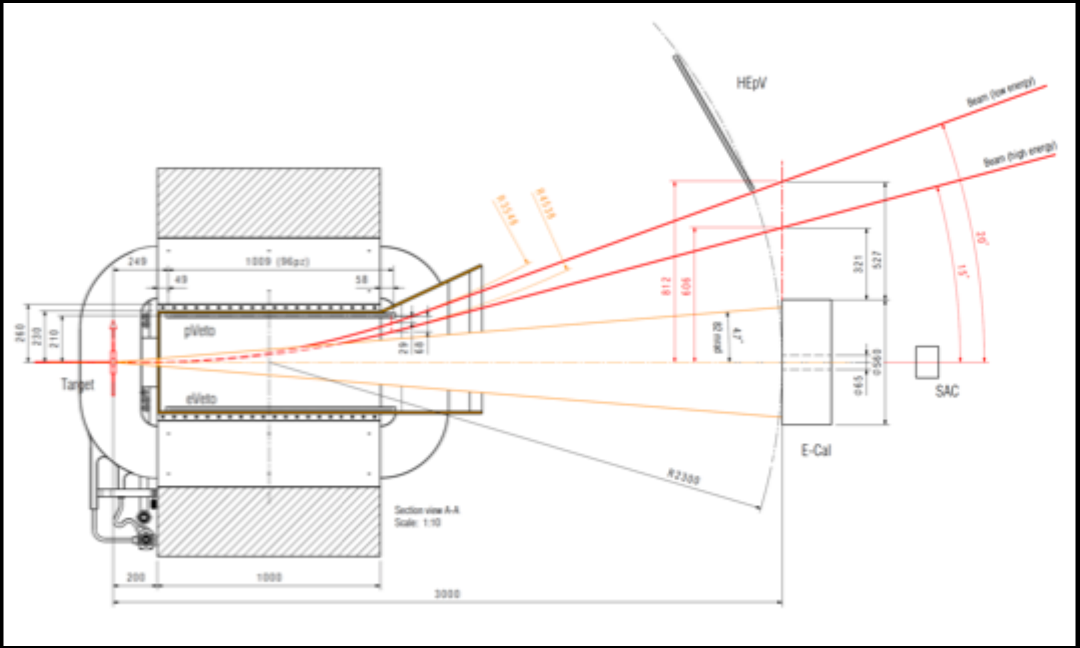
Fix 5500 G at 550 MeV (275 A)

Available power supply: 80 V/400 A

The PADME magnet



Magnet **gap** (– vacuum pipe depth)
Fixes the maximum (vertical) **acceptance**
together with the target position



Given the gap, the minimum magnetic field is given by **beam momentum** and **sweeping angle**

First task, measure the recoil photon

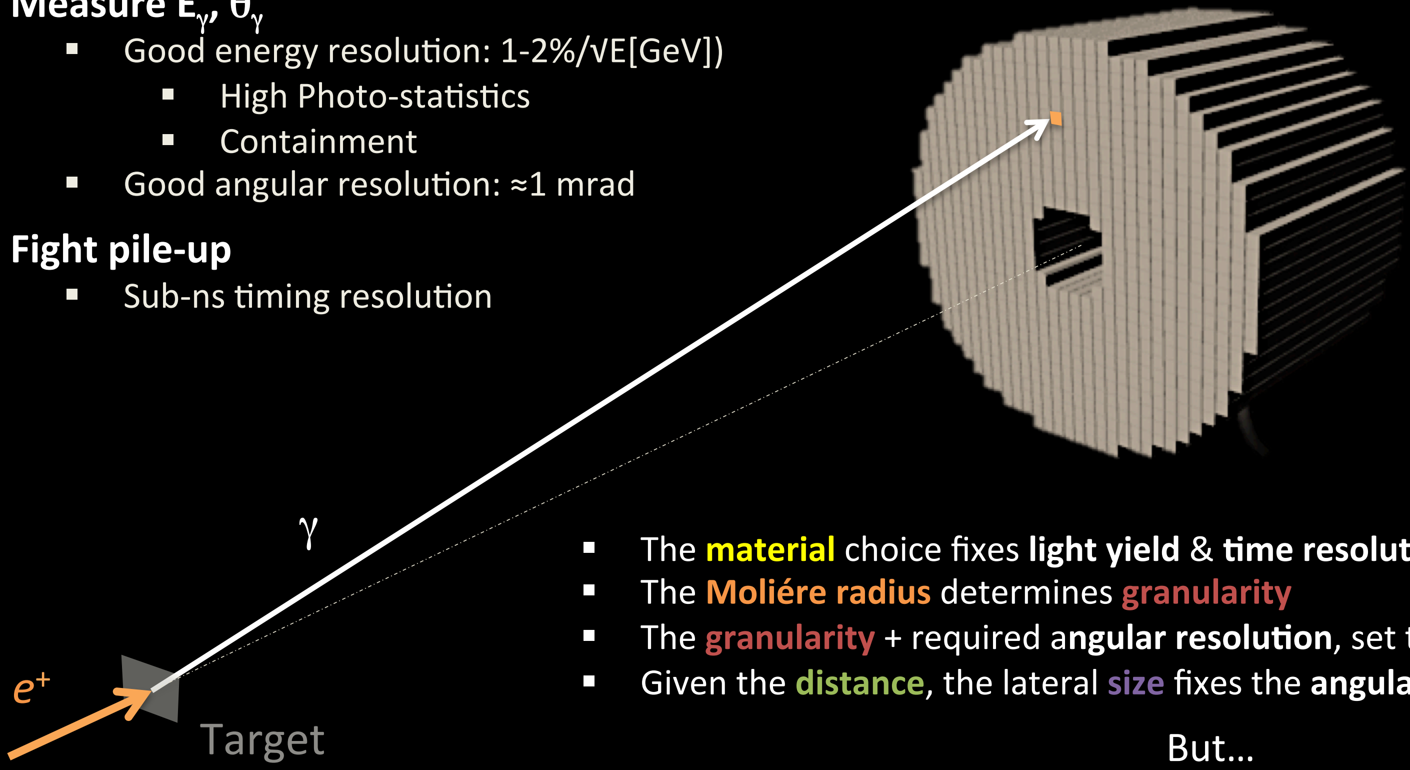
Our main detector is of course a calorimeter, with two basic requirements:

1. Measure E_γ, θ_γ

- Good energy resolution: 1-2%/√E[GeV])
  - High Photo-statistics
  - Containment
- Good angular resolution: ≈1 mrad

2. Fight pile-up

- Sub-ns timing resolution



- The **material** choice fixes **light yield** & **time resolution**, **Moliére radius** & X_0
- The **Moliére radius** determines **granularity**
- The **granularity** + required a**ngular resolution**, set the **distance** from the target
- Given the **distance**, the lateral **size** fixes the **angular coverage** (i.e. acceptance)

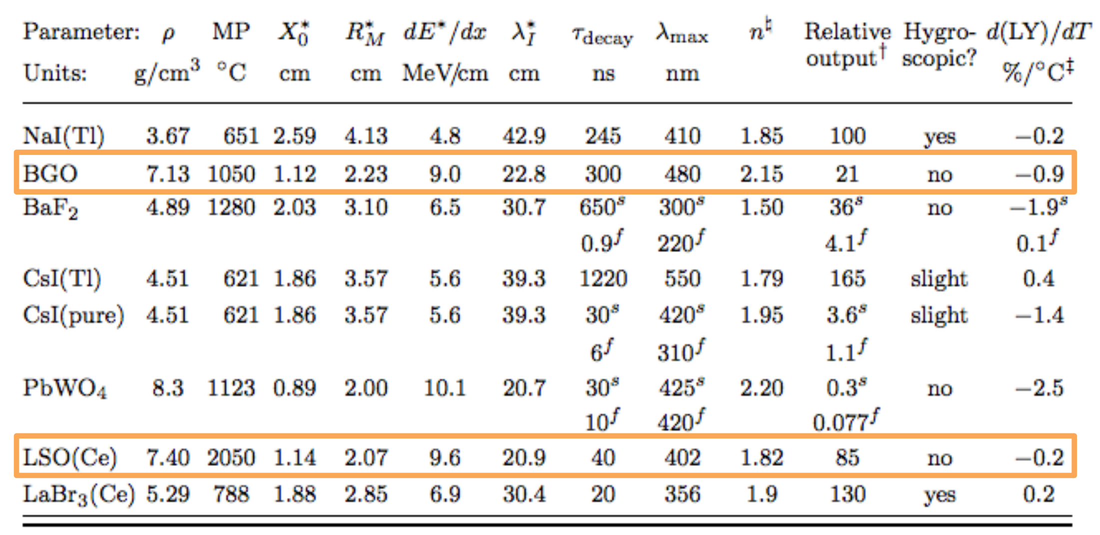
But…

…we have to take into account two important constraints:

- The **overall size** of the experiment is the hall length (<5 m)
- Another important bound is the **cost**, which is driven by the **material**, **size** and **granularity** (i.e. the number of channels)

So the message is "**keep it compact!**"

The calorimeter



Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygroscopic?	$d(LY)/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s 0.9^f	300^s 220^f	1.50	36^s 4.1^f	no	-1.9^s 0.1^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1220	550	1.79	165	slight	0.4
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	30^s 6^f	420^s 310^f	1.95	3.6^s 1.1^f	slight	−1.4
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s 10^f	425^s 420^f	2.20	0.3^s 0.077^f	no	−2.5
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	85	no	−0.2
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356	1.9	130	yes	0.2

LYSO(Ce): high LY, high ρ, small X_0 and small R_M, short τ_{decay}

- Performance:
  - $\sigma(E)/E = 1.1\%/\sqrt{E} \oplus 0.4\%/E \oplus 1.2\%$

BGO: high LY, high ρ, small X_0 and small R_M, long τ_{decay}

- Resolution also in 1-2%/√E range

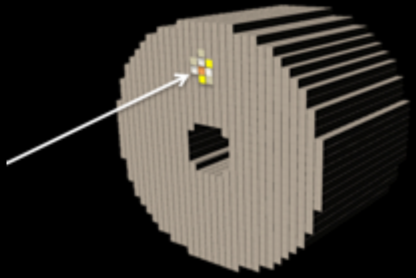
Small Moliére radius and high light yield:
LYSO and **BGO**

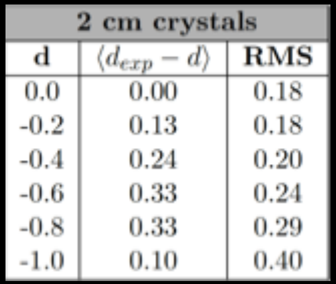
- **Granularity ≈R_M** → 2 cm
- a=2 cm → **point resolution**: 2 cm/√12=6 mm
- σ_{point}=6 mm → 1 mrad at 6 m **distance** → too much!

But…

...we have **clusters**!

- Center of gravity should have a better resolution
- Most of the energy will be in a single crystal, pulling the cog towards the center of the most energetic one)





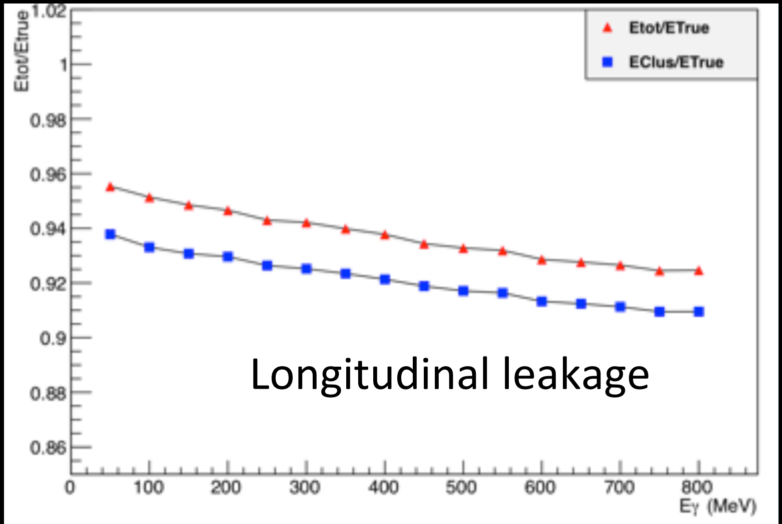
2 cm crystals		
d	$\langle d_{exp} - d \rangle$	RMS
0.0	0.00	0.18
-0.2	0.13	0.18
-0.4	0.24	0.20
-0.6	0.33	0.24
-0.8	0.33	0.29
-1.0	0.10	0.40

Results with a Geant4 "photon gun", E=500 MeV
$\sigma_{cluster}$≈4.5 mm (including the systematic shift), better than 6 mm

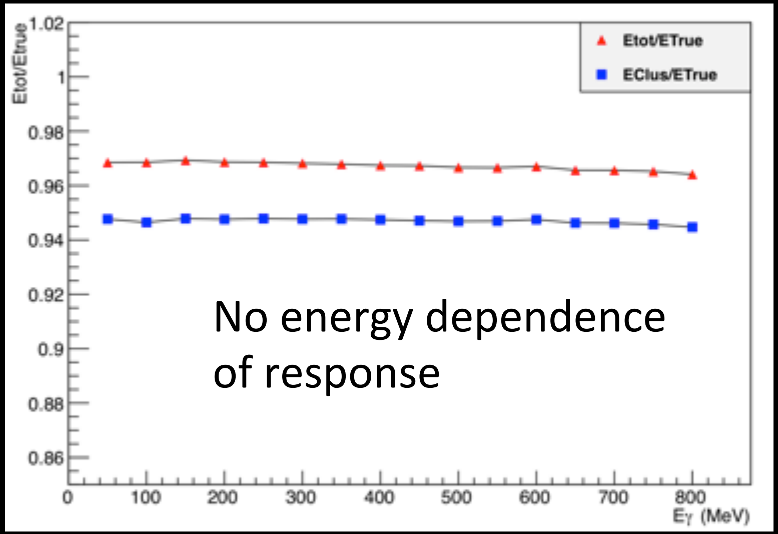
Longitudinal containment

15 cm long crystals (13.2 X_0)

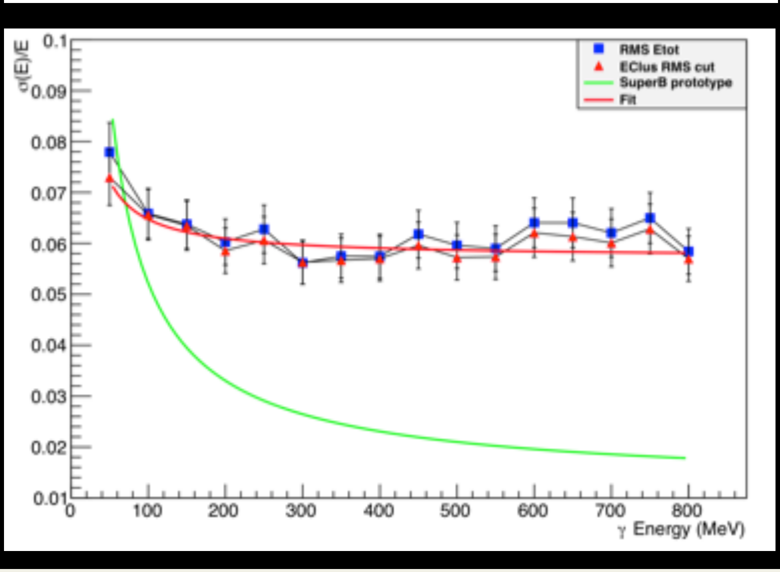
20 cm long crystals (17.5 X_0)

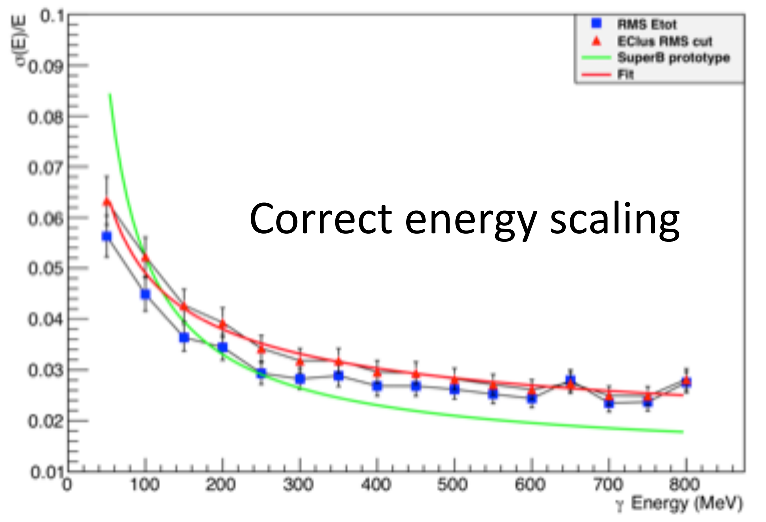


Longitudinal leakage



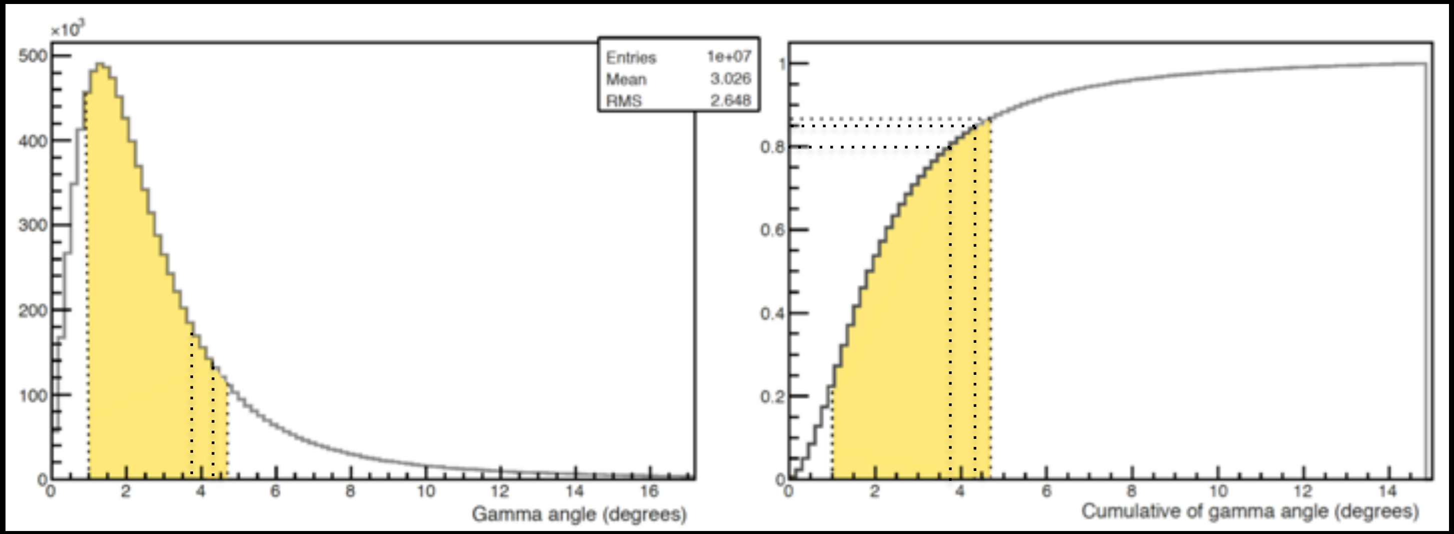
No energy dependence of response





Correct energy scaling

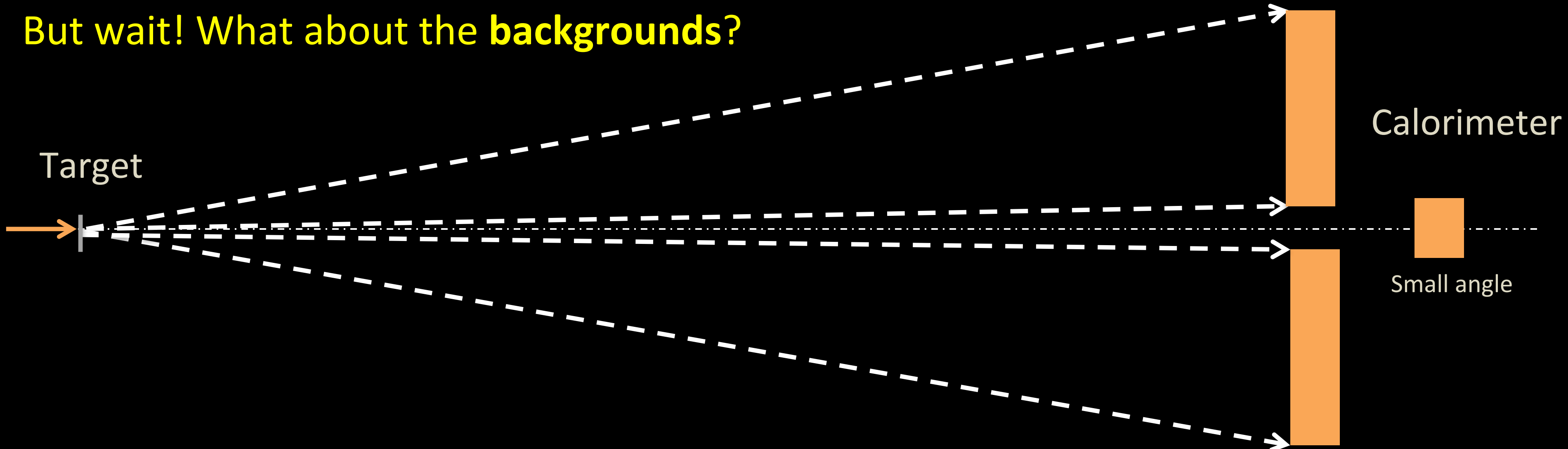
Signal acceptance in calorimeter



Calorimeter hole:
20 mrad

θ_{max}=65, 75, 83 mrad
from 58% to 65%
acceptance

But wait! What about the **backgrounds**?


Target

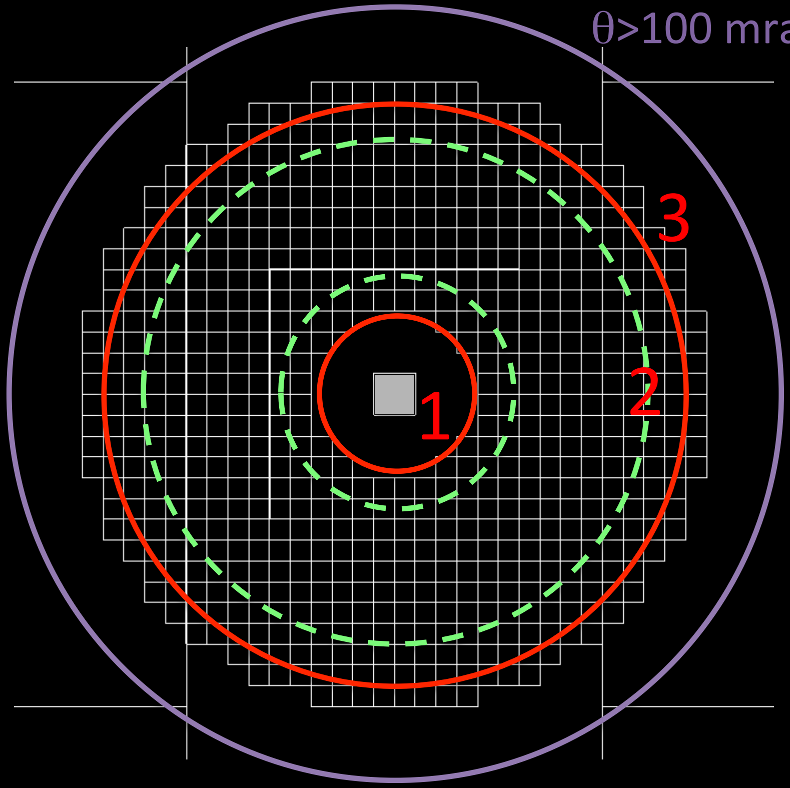
Calorimeter

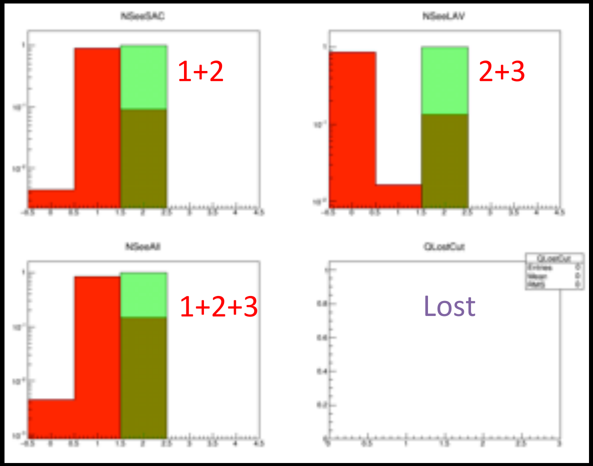
Small angle

Calorimeter 2γ and 3γ backgrounds

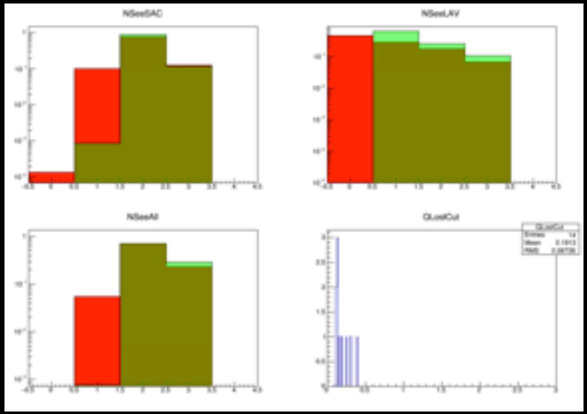
Region 1
<20 mrad

Region 3
θ>75 mrad





No 2γ events



Per-mil 3γ background

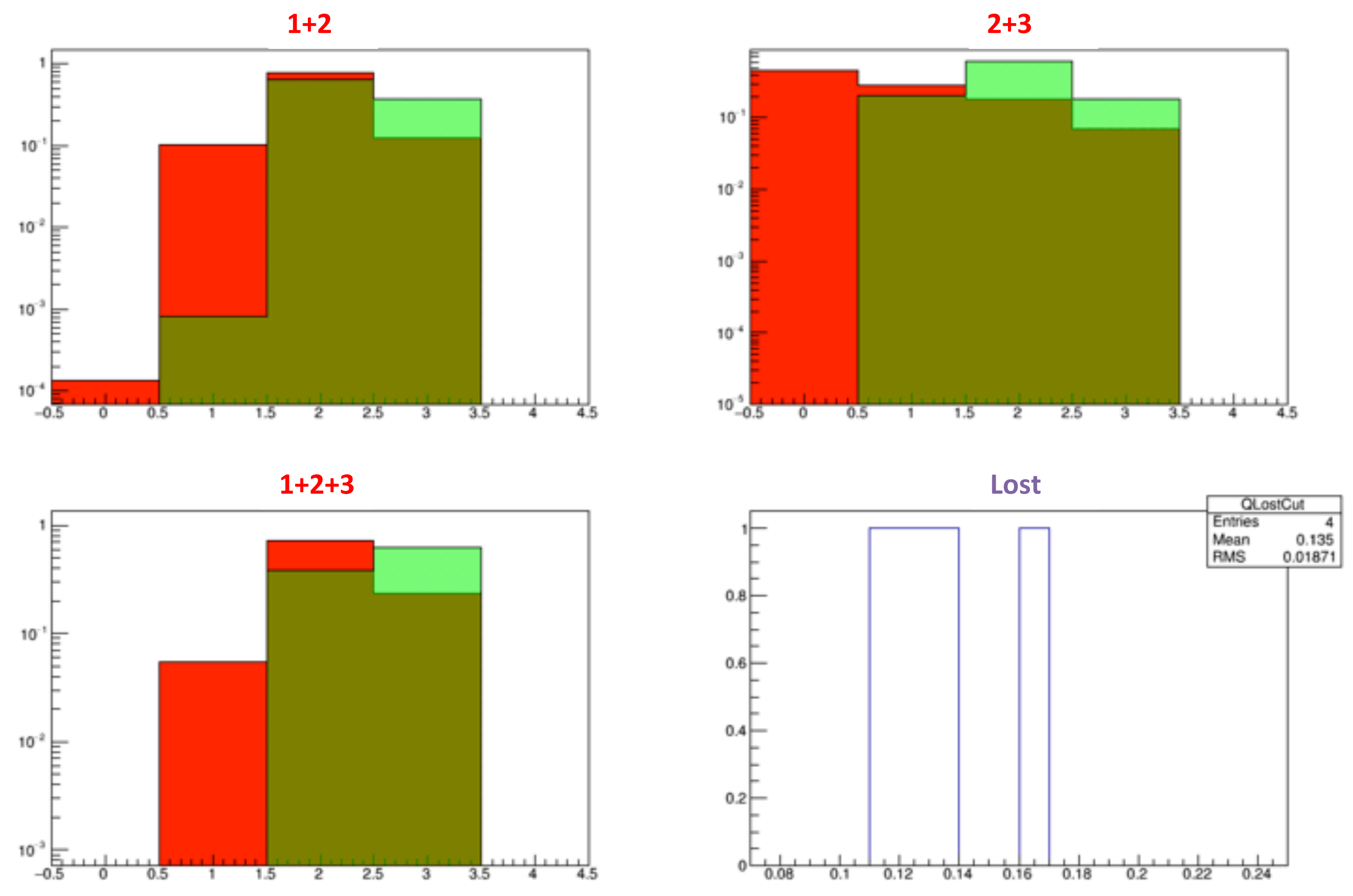
Recoil γ definition:

10 MeV < E < 400 MeV

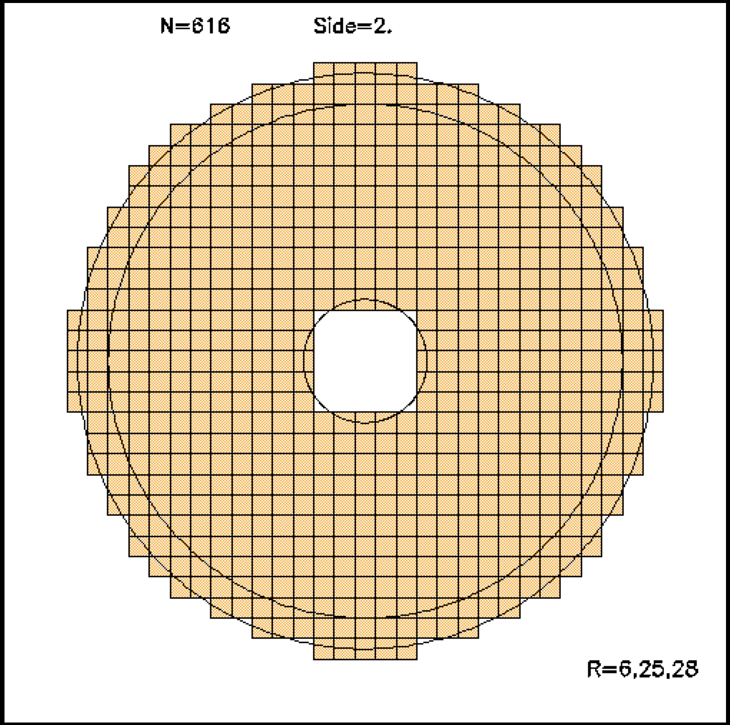
30 mrad < θ < 65 mrad

Residual background

Tighter signal definition: in fiducial region **and** 150 MeV < E < 450 MeV



Calorimeter layout

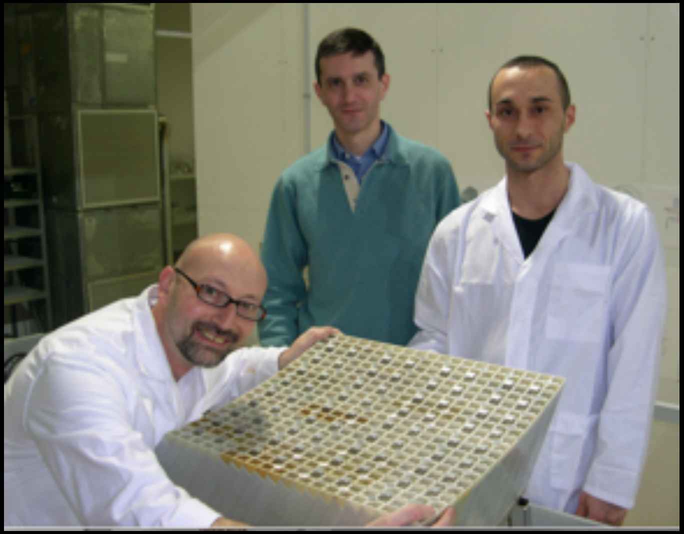


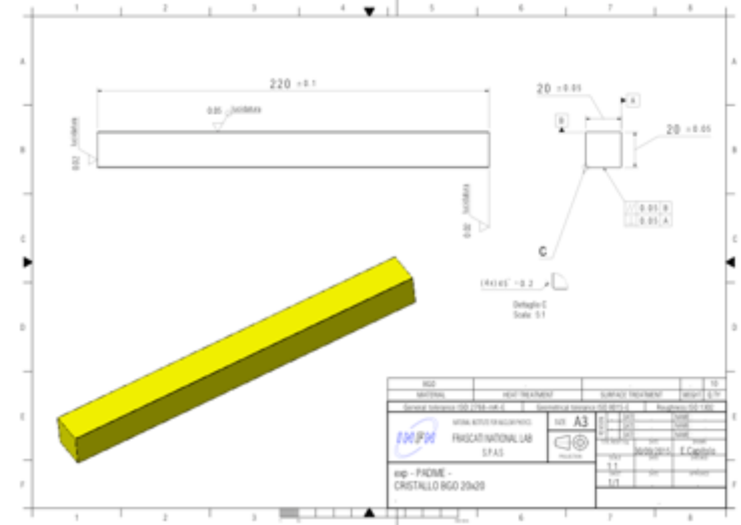
- Length >20 cm
- Cell side 2 cm
- Make simpler (square) hole, radius≈6 cm
- Fix outer radius at 28.5 cm, fiducial radius=25 cm
- Given 300 cm distance:
  - Fiducial acceptance 25/300=83 mrad
  - Angular resolution 4.5 mm/3 m≈1.5 mrad
- Total of **616 crystals**
- 616×20×2×2 = 50000 cm^3

Now…

... at 20€/cc such a calorimeter will cost 1 M€ only for buying the crystals
+ photosensors
+ readout

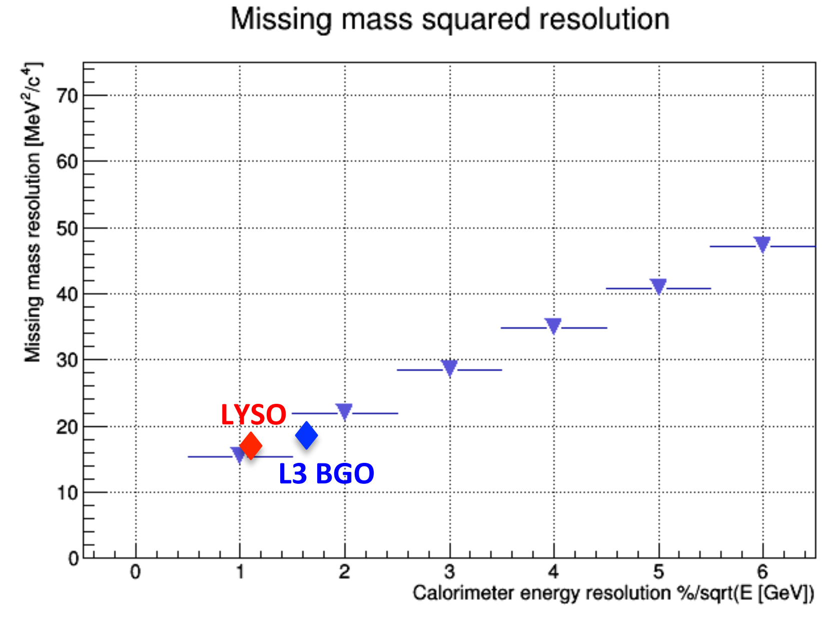
L3 BGO crystals

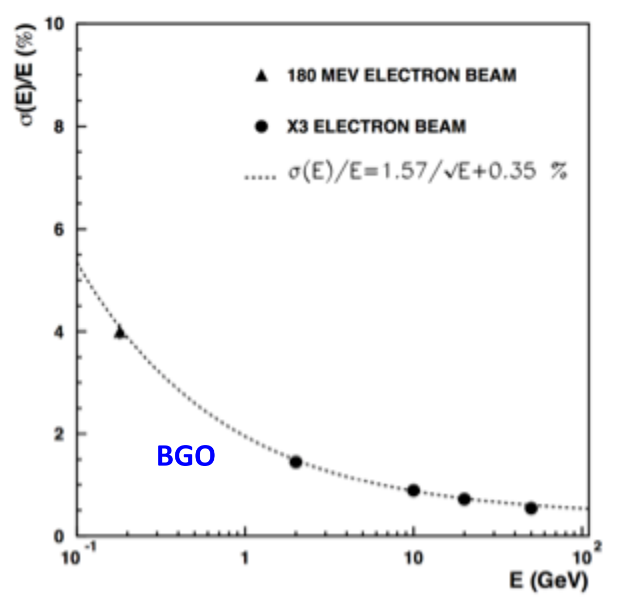




- 140 BGO crystals from former L3 electromagnetic calorimeter
- Asked **500 more** to the L3 collaboration
- Cut from trapezoidal prism shape to square section **20×20 mm^2**, **220 mm** long

Missing mass resolution

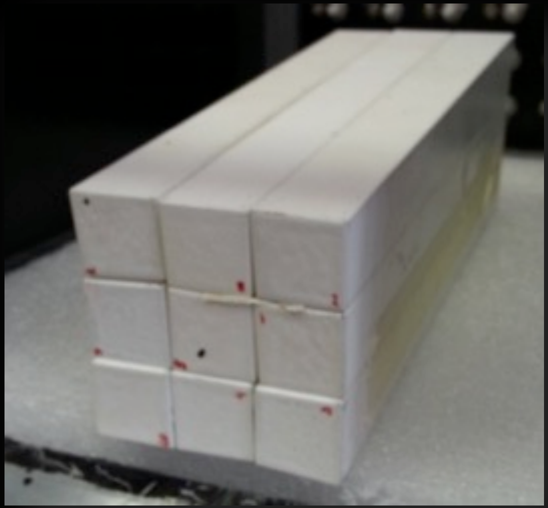




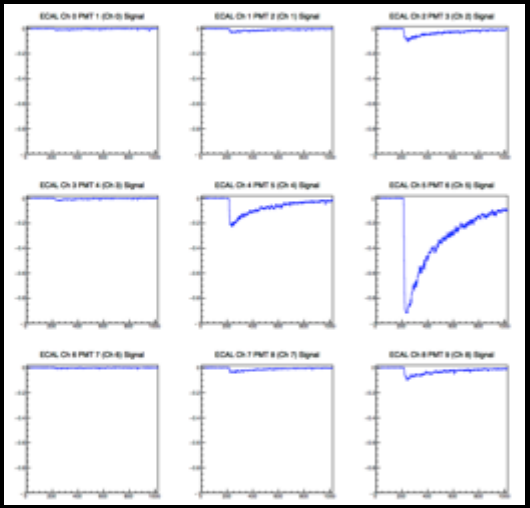
The minimum energy is also very important

BGO performance (electron beam)

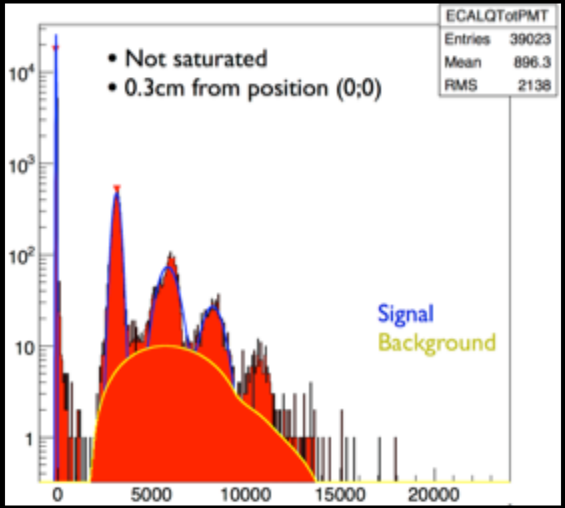
3×3 matrix

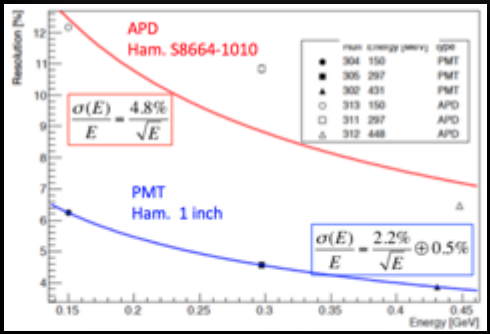


τ=300 ns light signal

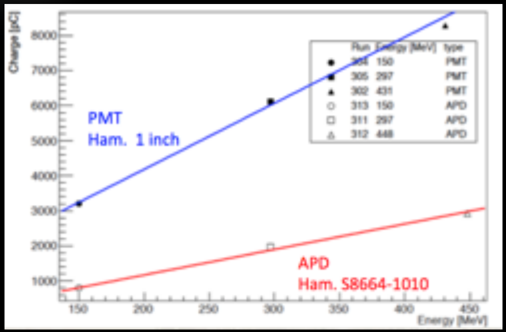


Total charge (150 MeV)

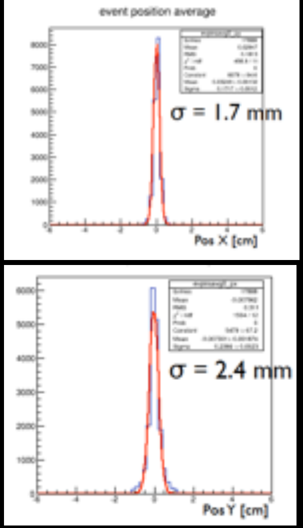




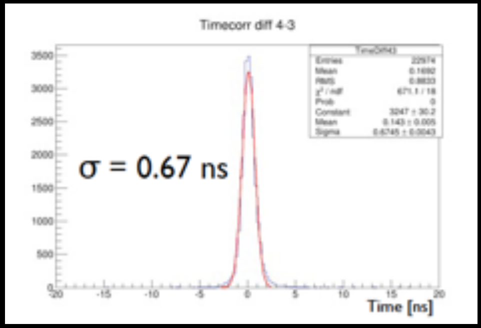
Energy resolution



Linearity

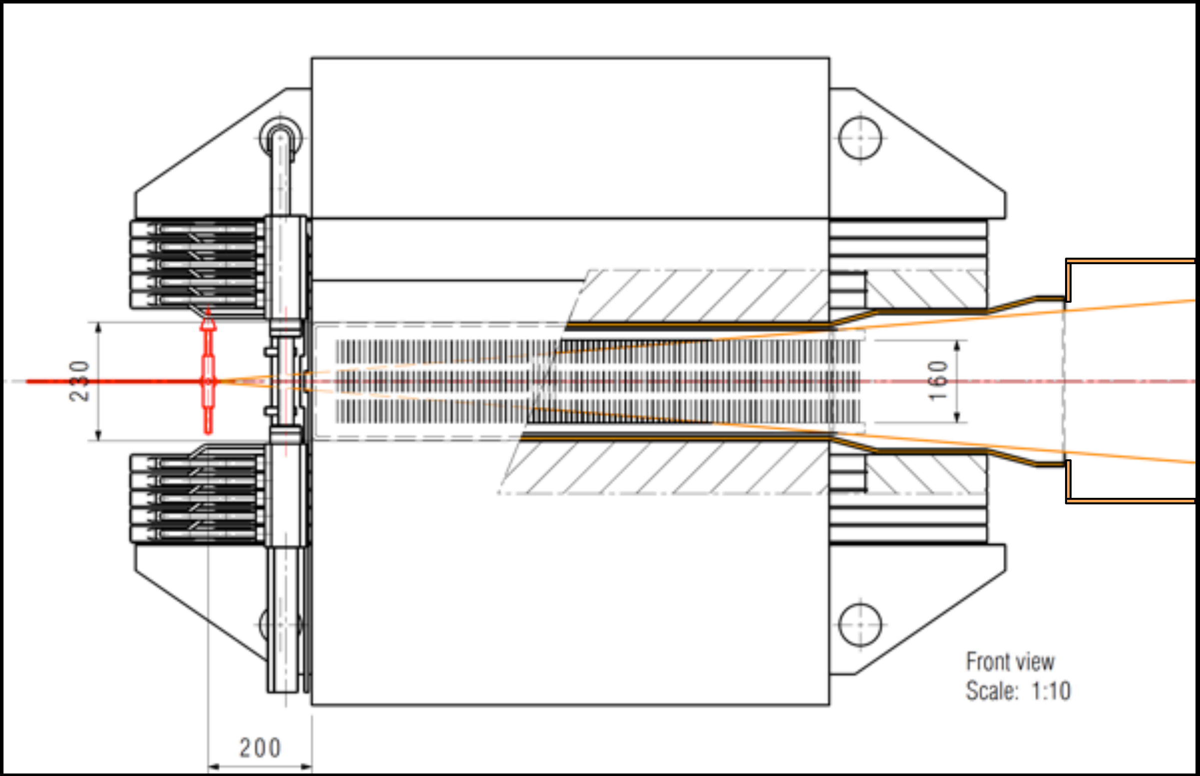


Cluster cog resolution



Time resolution

PADME vacuum vessel



Vacuum mandatory for **three purposes**:

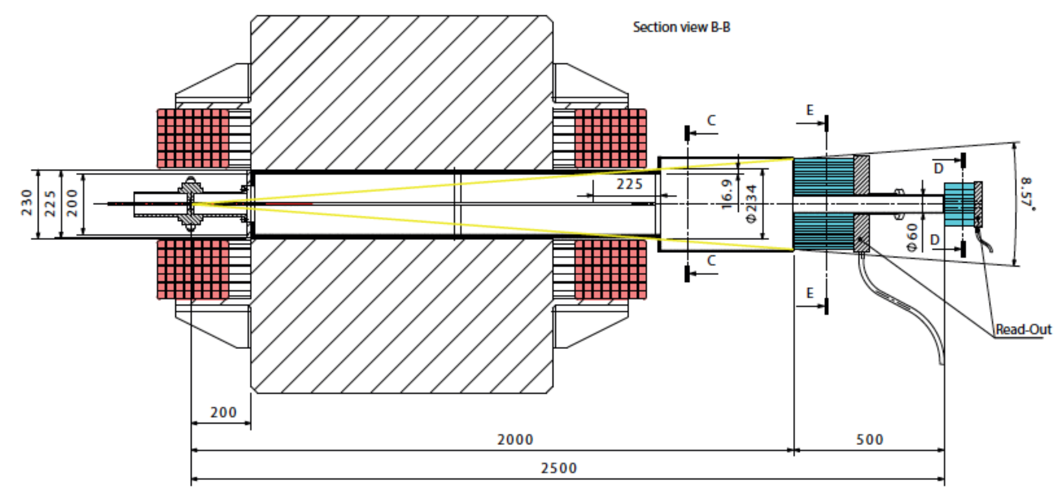
1. Not to spoil **beam quality** before hitting the target
2. To minimize **photon interactions** before reaching the calorimeter
3. To minimize **positron interactions** before hitting the veto detector (in particular showers!)

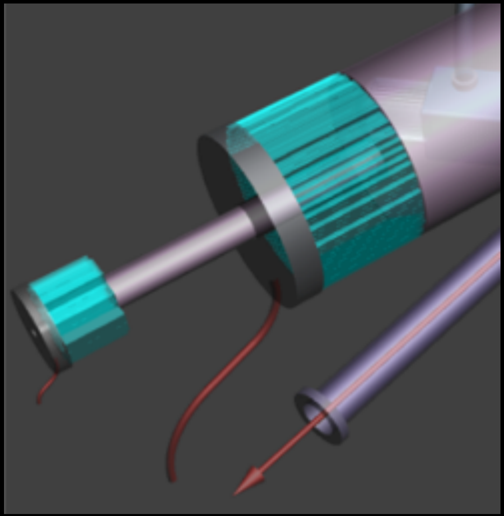
Different possibilities under study to minimize the material thickness, i.e. increase acceptance (given the magnet gap) for the vessel, with the following requirements:

- Hold the vacuum
- Host the scintillating bars for positron veto detectors
- Interface to target box (upstream) and straight section before calorimeter (downstream)

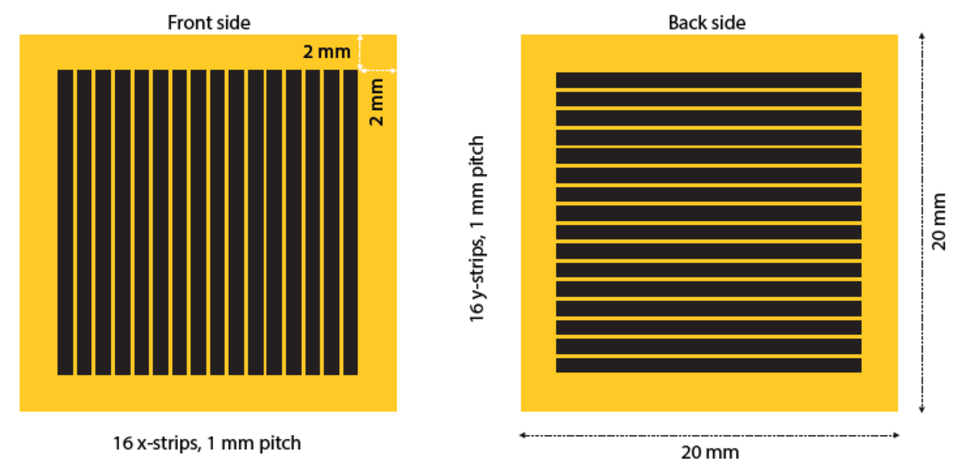
Small angle calorimeter

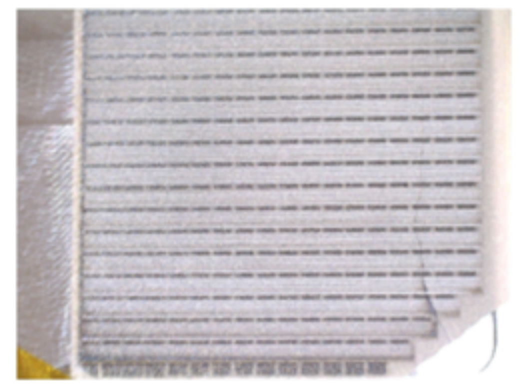
- BGO calorimeter cannot tolerate the Bremsstrahlung rate in the very central crystals
  - Inner hole 4-8 cm radius
- Small angle calorimeter aim to tolerate a rate of the order of 10 clusters (40 ns bunch length)
- The only fast enough inorganic crystal is BaF_2 with a fast PMT readout
- A possible alternative: Cherenkov detector



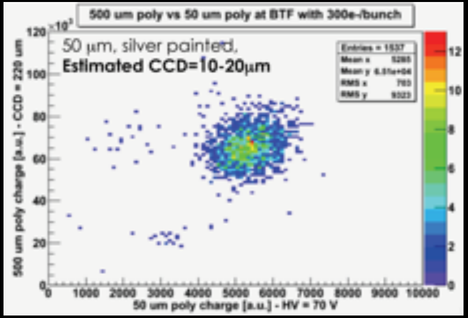


The diamond target

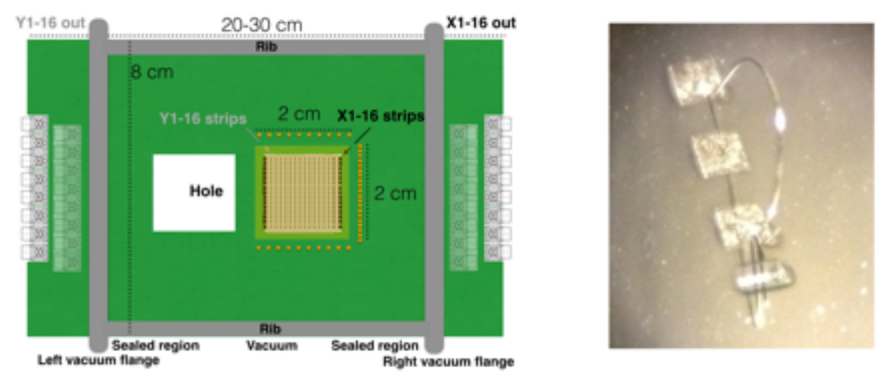




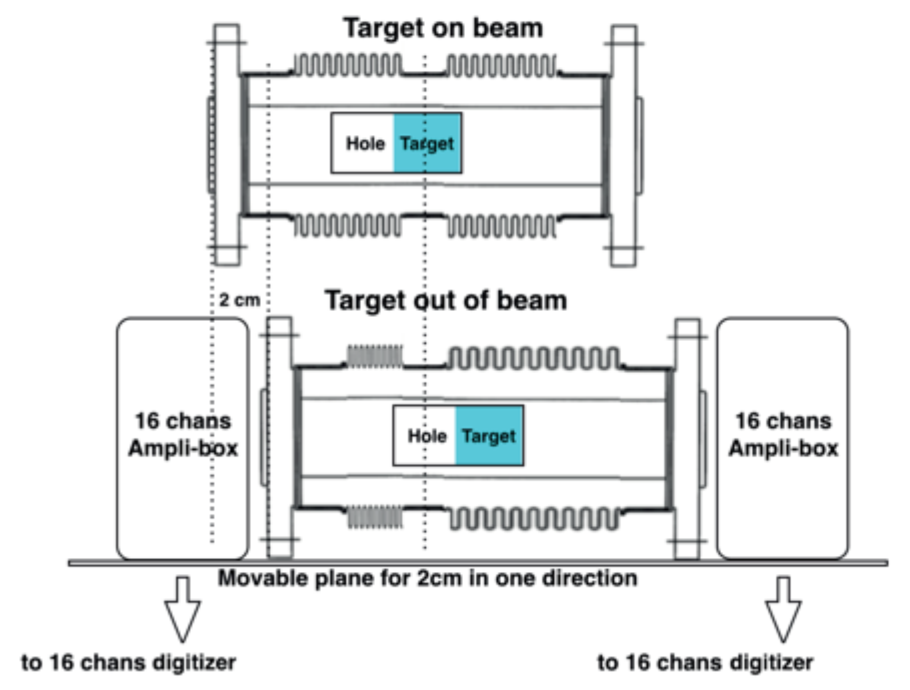
- Diamond is the **rigid** material with the best ee(γγ)/Bremsstrahlung ratio (Z=6)
- Measure charge and position of 5000-10000 positrons/bunch
    - **Below mm** precision in x-y coordinates
    - Better than 10% charge measurement
- Polycrystalline diamonds 50-100 mm thickness:
    - 16x1mm^2 strip and **x-y readout in a single detector**
    - Readout strips are **graphitized** by using a laser to avoid metallization
    - PADME prototype 50 μm thick, 20×20mm^2 sample produced and tested on beam



The diamond target

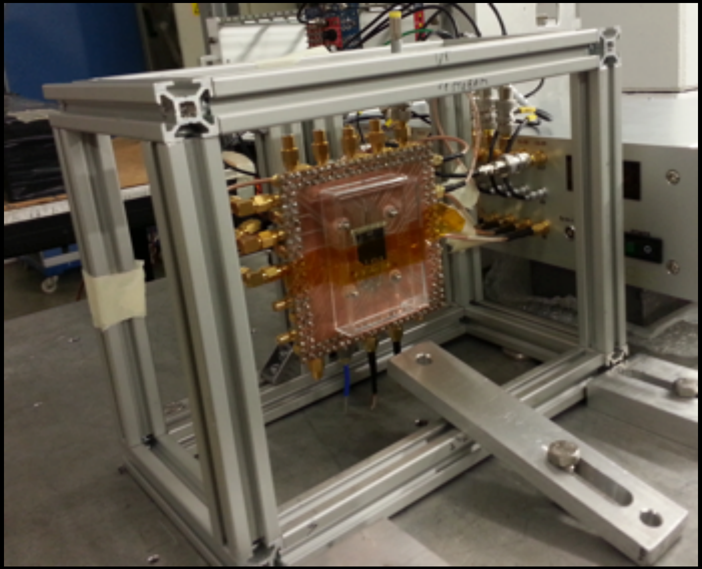


- Bonding to the readout board
- Connect to amplifier
- Digitize signal

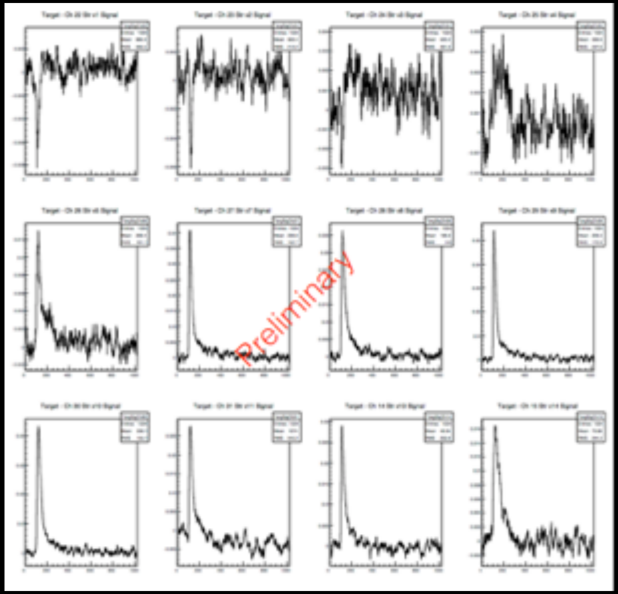


- Step motor to move target in and out of the beam
- Possibly, add a (thick) Silicon pixel detector in order to have a more accurate transverse image of the incoming positron beam

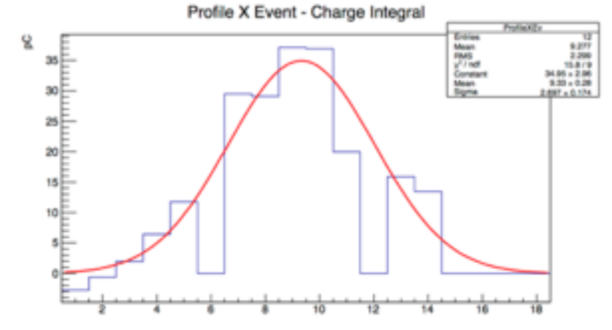
The diamond target



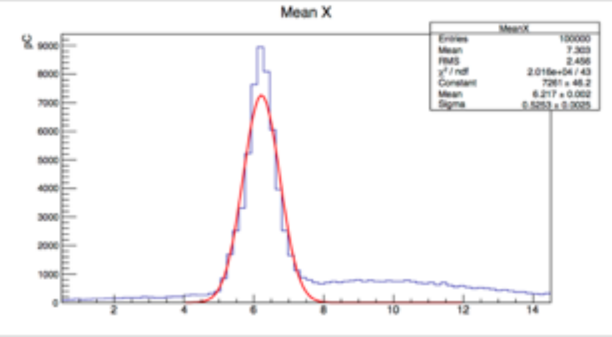
Beam-test, end of 2015



Digitized strips signals



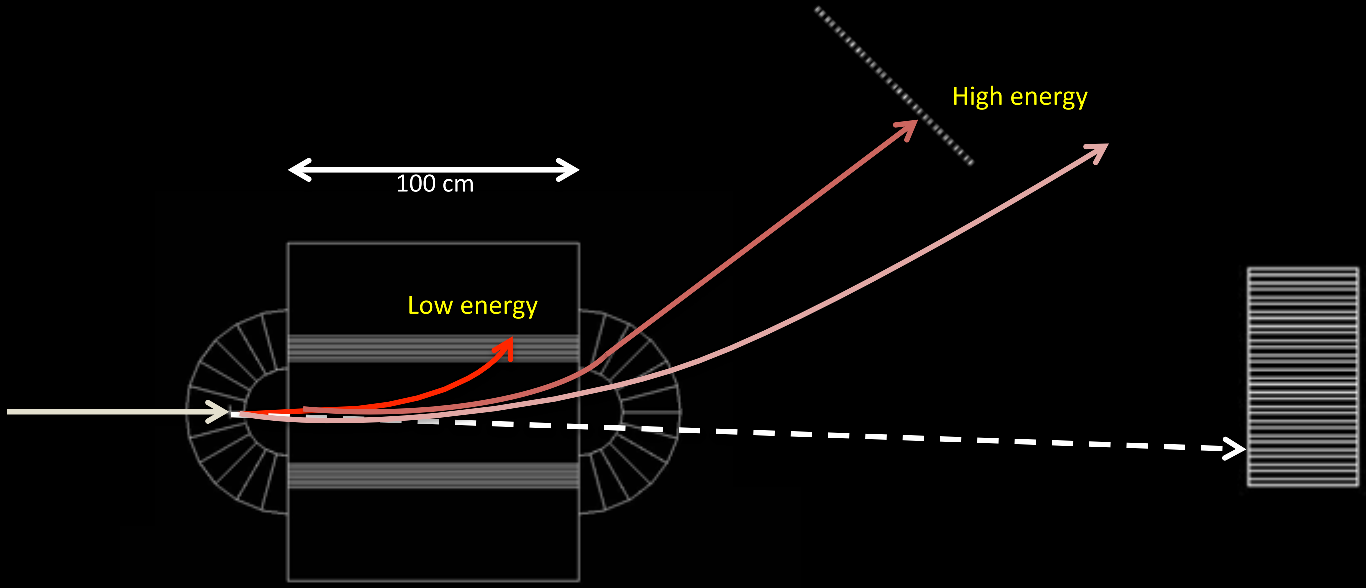
Center of gravity



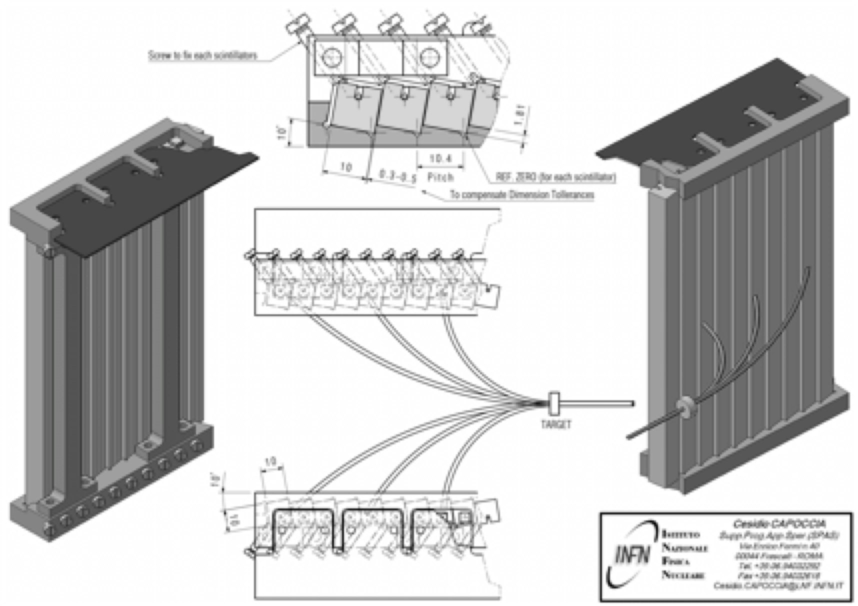
Average position

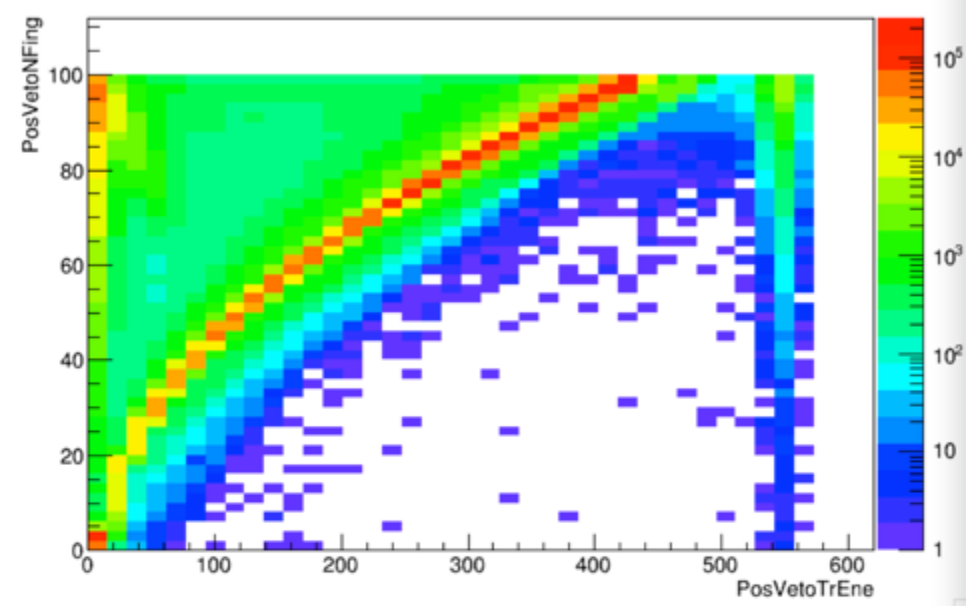
Positron veto

- Time resolution better than 500ps
- Momentum resolution of few % based on impact position
- Efficiency better than 99.5% for MIPs
- Low energy part inside the magnet gap
- High energy part close to not interacting beam



Positron veto





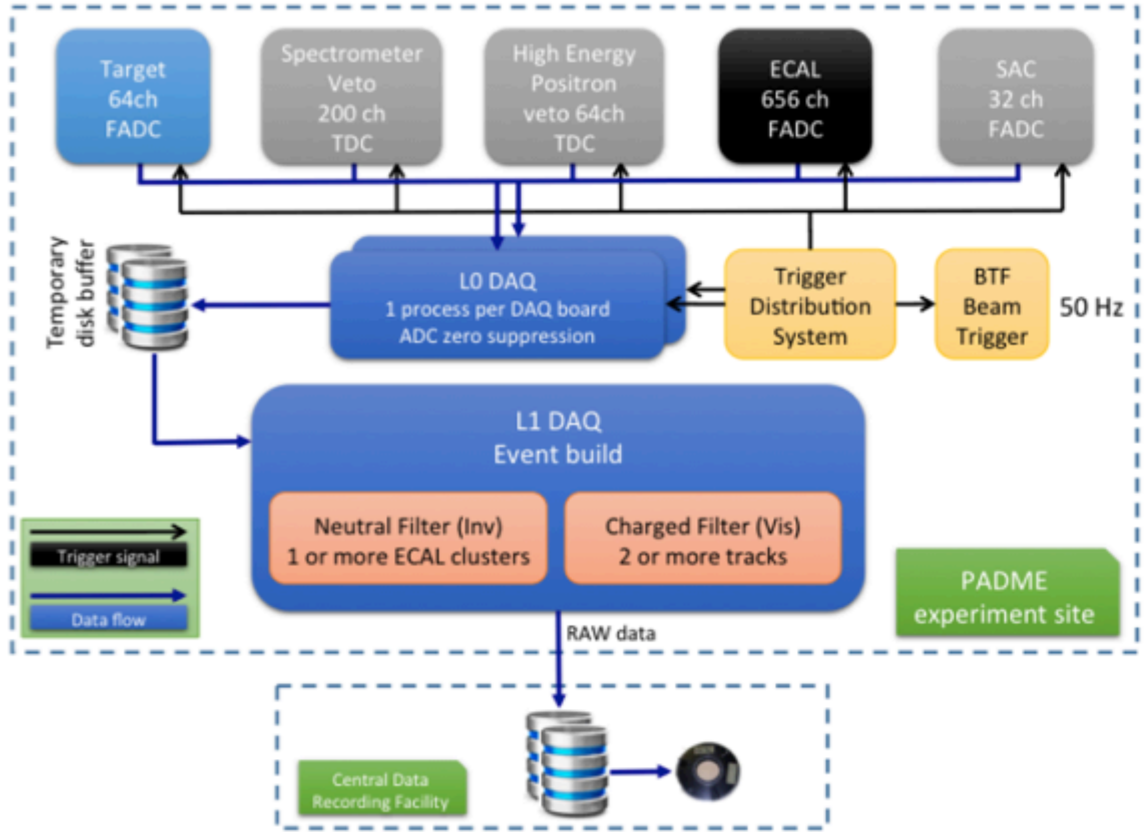
Low momentum losses are reduced for E_γ<400 MeV
Interesting positron energy starting at ~150 MeV

Which granularity?

- 1 cm scintillator bars, readout by SiPM
- Few % momentum resolution in a large part of the spectrum

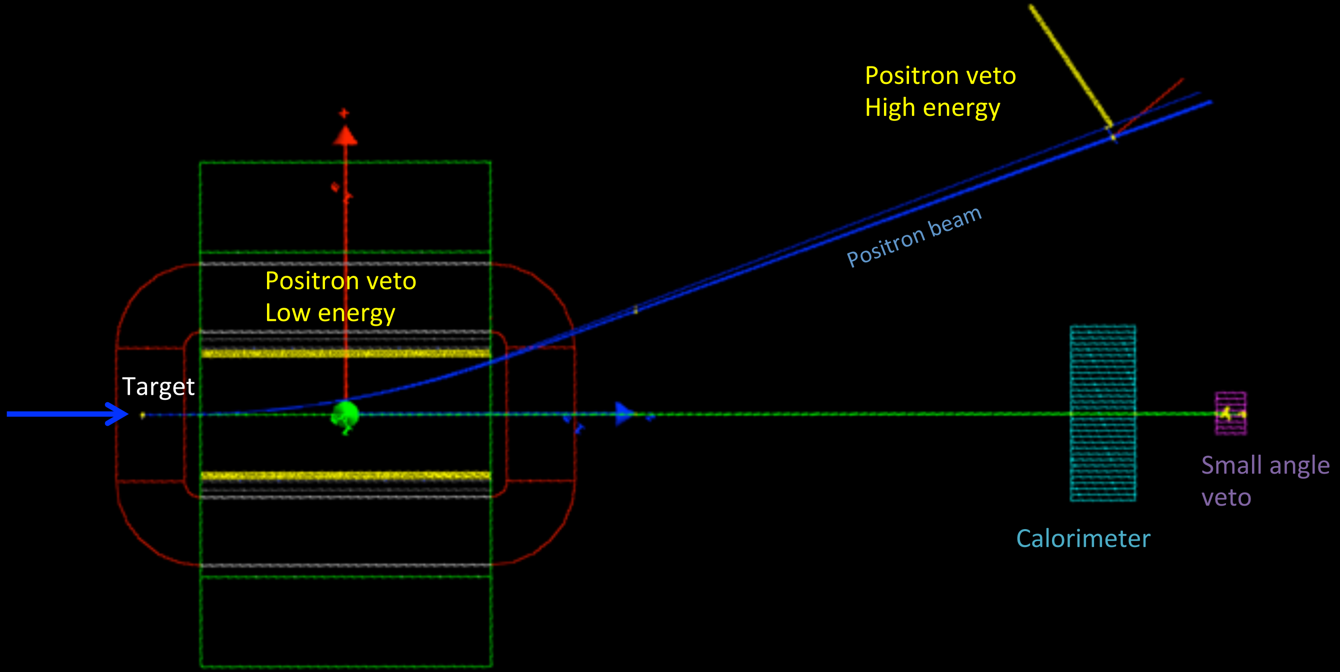
PADME TDAQ

- Readout based on digitizers CAEN V1742
- ~1000 channels
- ~33 FADC boards involved

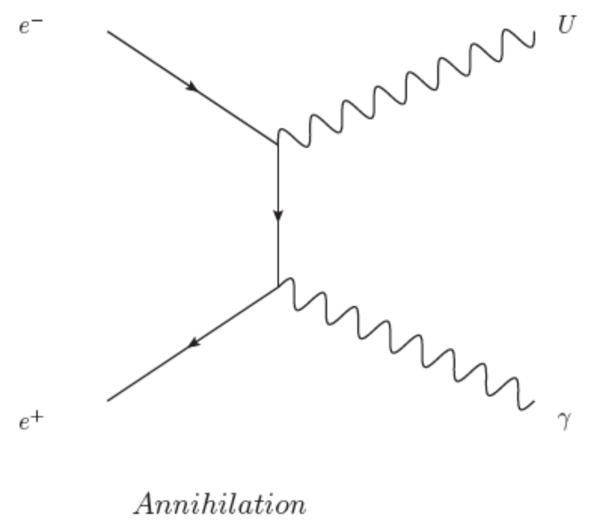


- Trigger and clock distribution to the 33 boards
- Online FADC zero suppression (L0)
- FADC boards synchronization to few 100ps needed

Monte Carlo simulation

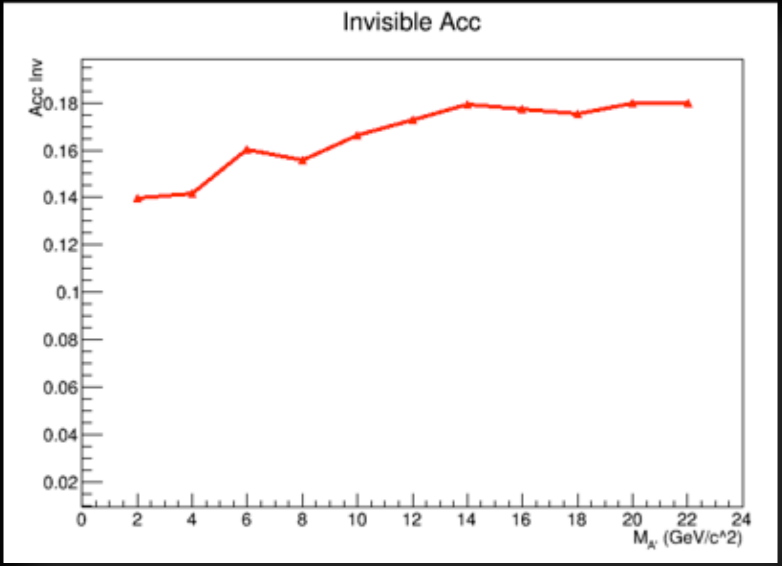


Search in annihilation production



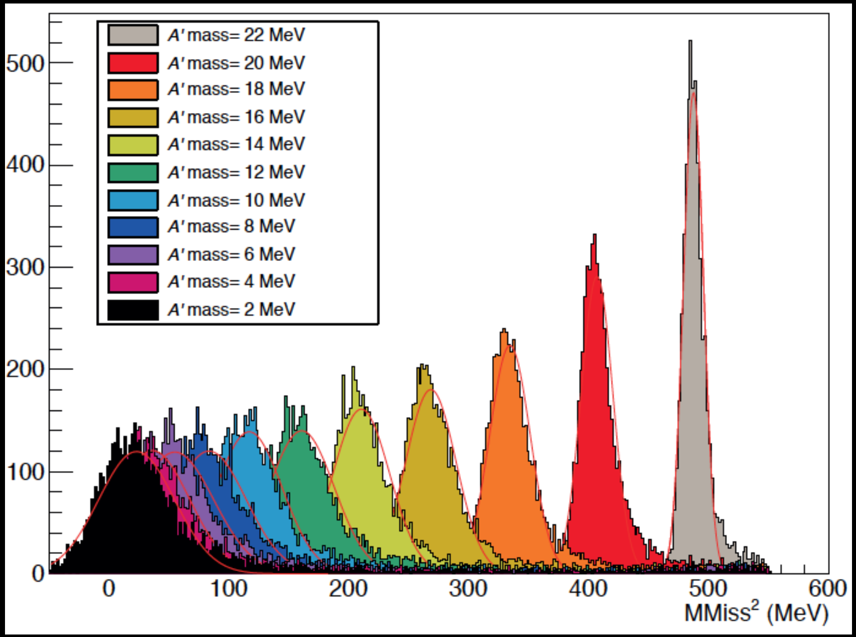
Decay to invisible signal selection

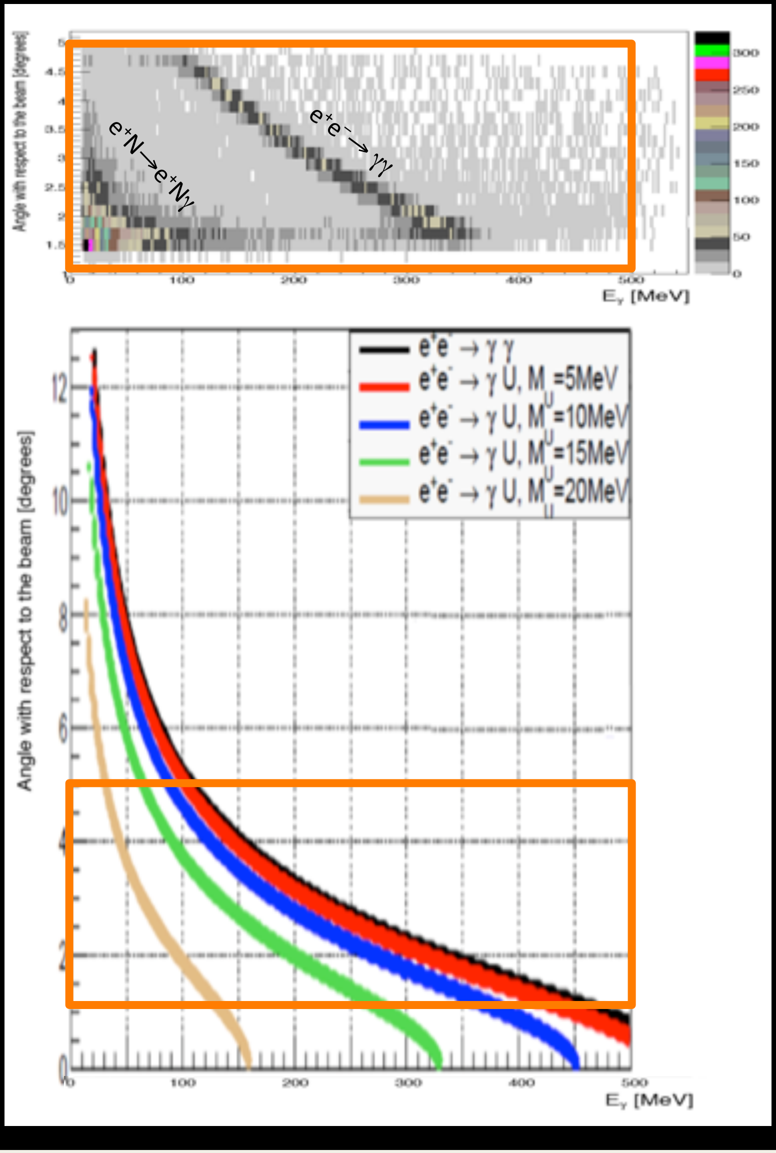
- Only one cluster in **calorimeter**…
  - Rejects $e+e^- \rightarrow \gamma\gamma$, $e+e^- \rightarrow \gamma\gamma(\gamma)$ final states
- … in the fiducial region 30 mrad < θ_{Cl} < 65 mrad
  - Ensure shower containment, $\sigma(E)/E$
- **Positron veto**: no tracks in ±2 ns
  - Reject background from Bremsstrahlung identifying primary positrons
- Photon veto: no γ with E_γ>50 MeV in time in ±1ns in the **small angle veto** (SAV), covering the hole acceptance



- **Cluster** energy within: $E_{min}(M_{A'}) < E_{Cluster} < E_{max}(M_{A'})$
  - Removes low energy bremsstrahlung photons and piled up clusters
- **Missing mass** in the region: $M^2_{miss} \pm \sigma(M^2_{miss})$

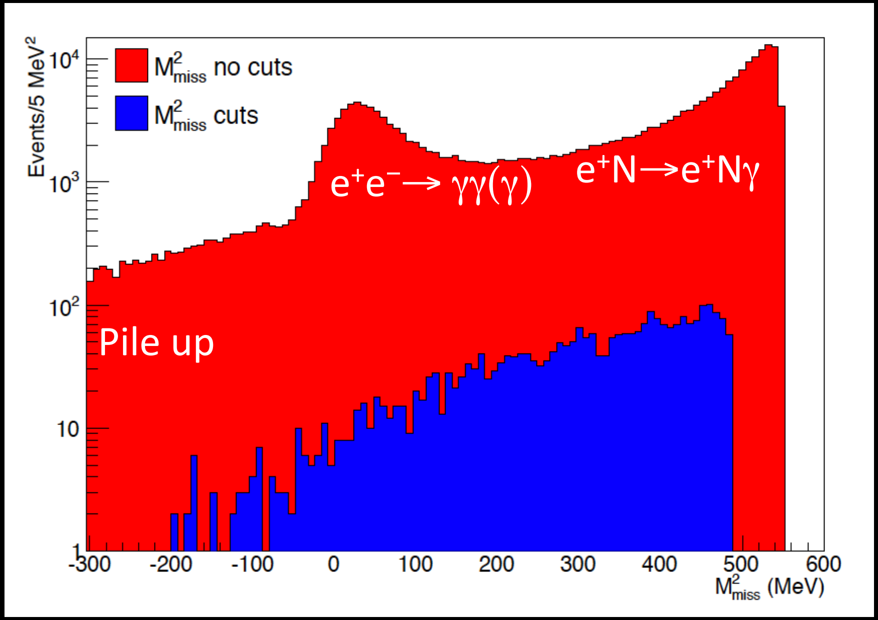
Signal vs. background

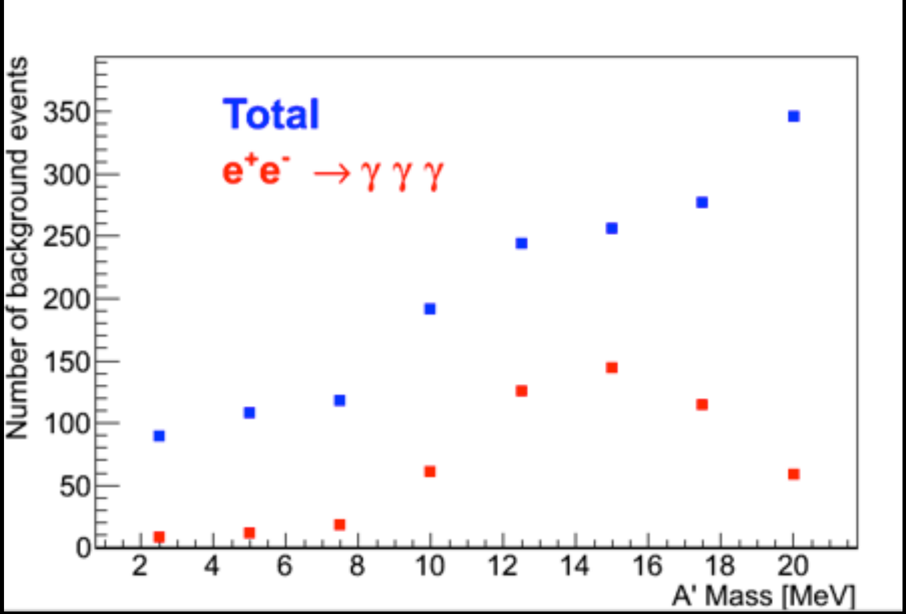




- Resolution is the result of combination of angular resolution, energy resolution and **angle-energy correlation** due to production

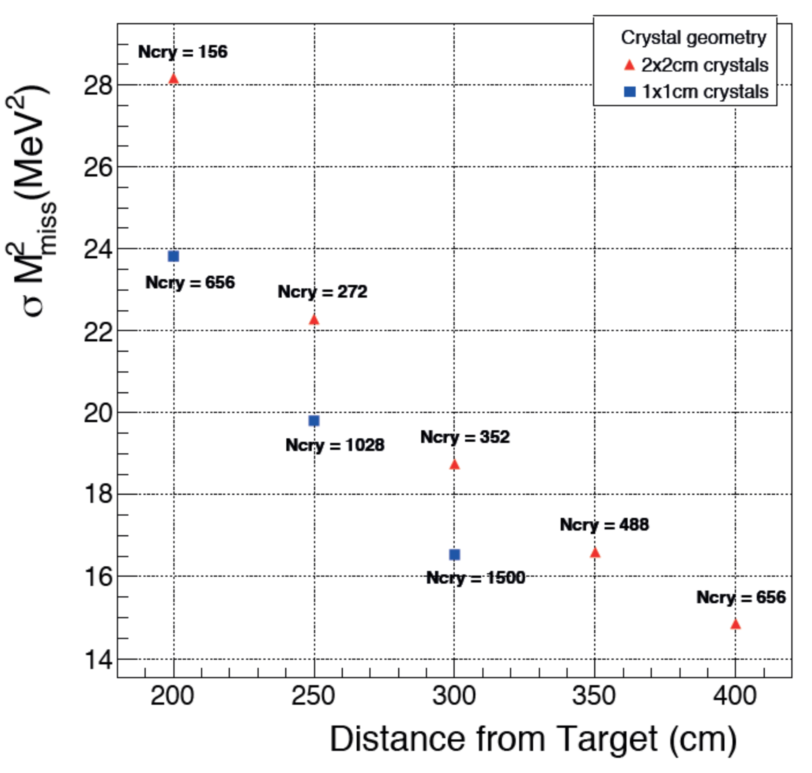
Background estimates

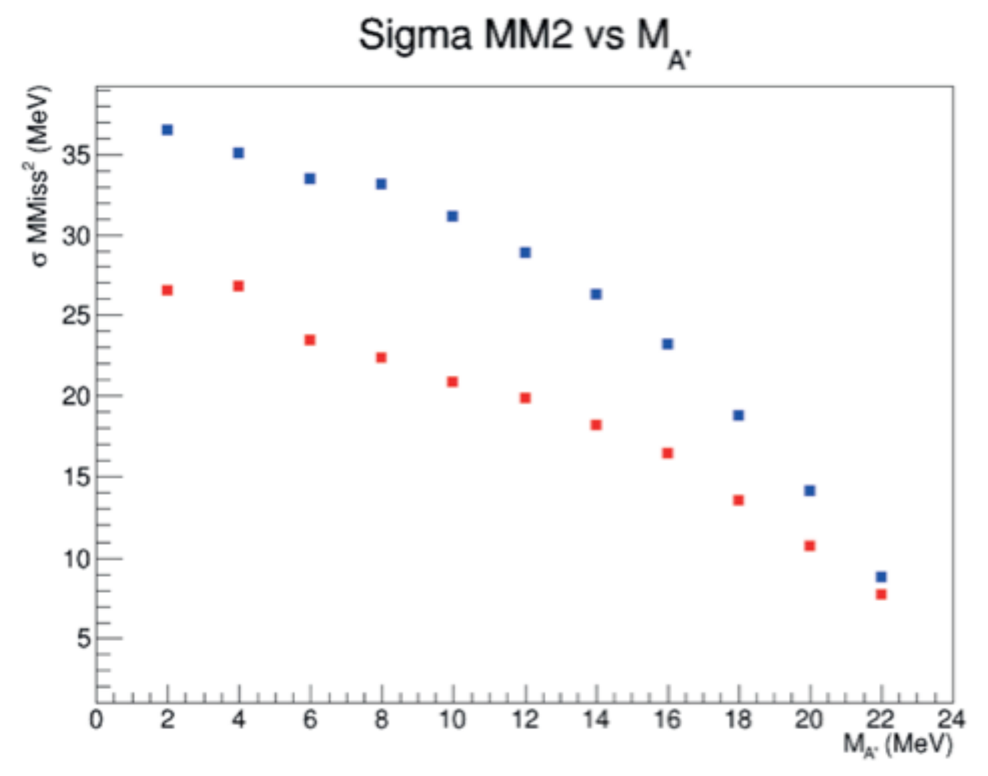




- Main background sources are: $e^+e^- \to \gamma\gamma$, e+e-→γγ(γ), e+N→e+Nγ, **Pile-up**
- **Pile-up** contribution is important but rejected by the maximum cluster energy cut and M^2_{miss}
- Veto inefficiency at high missing mass ($E_{e+} \simeq E_{beam}$)
  - Additional Veto detector introduced to reject residual background

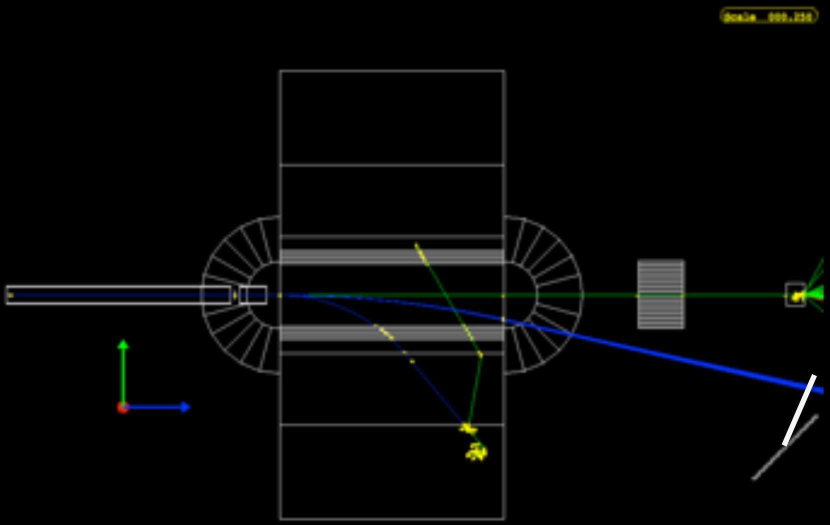
Missing mass resolution

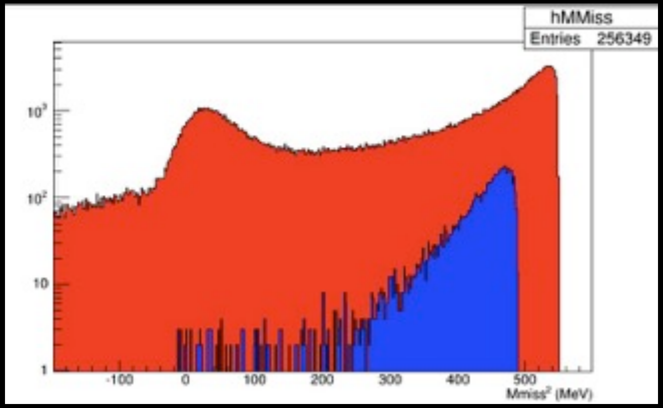


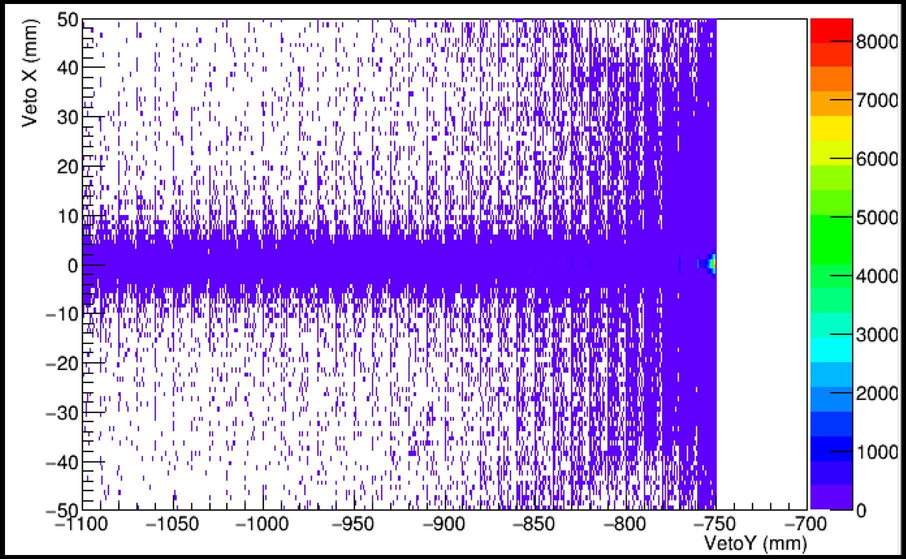


- Improvement mainly due to better angular resolution when the calorimeter distance increase
- Depending on dark photon mass angular resolution is no more the dominant contribution to the M^2_{miss} resolution and the improvement is reduced (smaller for higher dark photon masses, i.e. lower energy γ)
- Impact of beam angular divergence to be taken into account!

Improving BG rejection

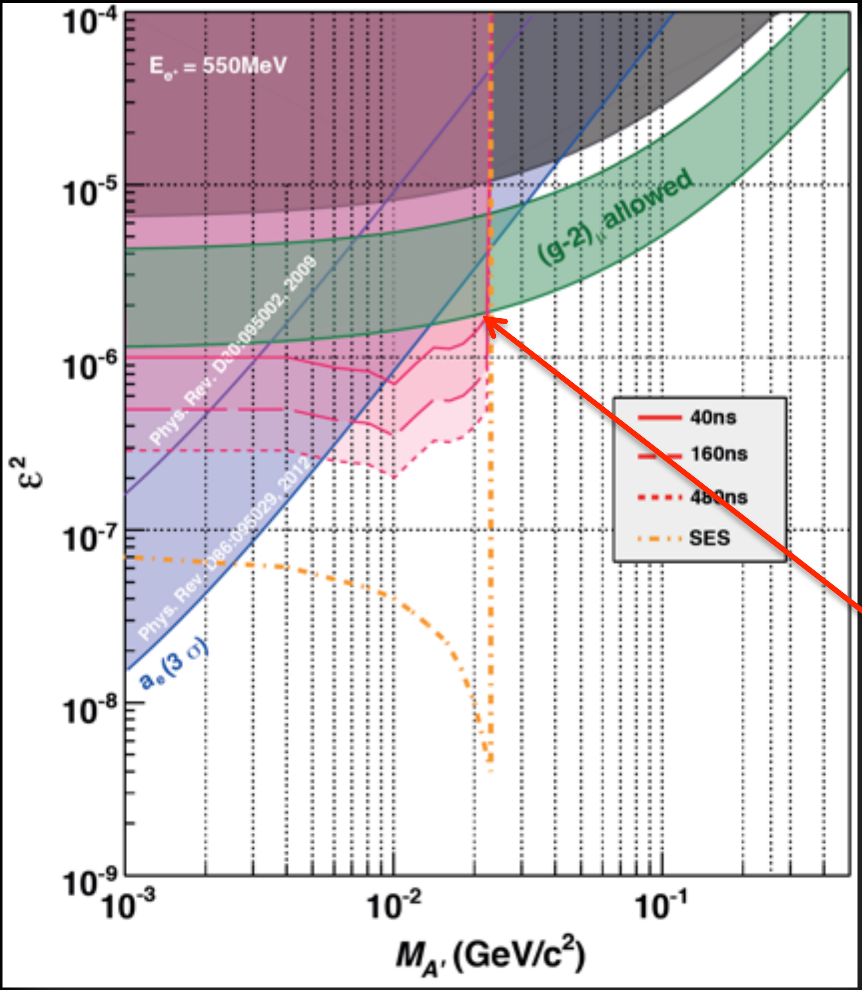






- Move the front veto detector inside the beam or add a new detector
- Thanks to the dispersion included by the dipole magnetic field, a high resolution front detector can enhance the background rejection for events with a positron emitting a soft photon

PADME-invisible decay sensitivity



- Based on 2.5×10^{10} fully GEANT4 simulated 550MeV e+ on target events
  - Number of BG events is extrapolated to 1×10^{13} electrons on target
- Using $N(A'\gamma)=s(N_{BG})$
- δ enhancement factor $\delta(M_{A'}) = \sigma(A'\gamma)/\sigma(\gamma\gamma)$ with $\varepsilon=1$

$$\frac{\Gamma(e^+e^- \to U\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \epsilon^2 * \delta$$

PADME 2 years of data taking at 50% efficiency with bunch length of 40 ns
10^{13} EOT = **6000 e$^+$/bunch × 3.1·10^{7}s · 49 Hz**

PADME can explore in a ***model-independent way the*** favourite by $(g\text{-}2)_\mu$ band up to $\boldsymbol{M^2_{A'} = 2m_eE_{e+}}$

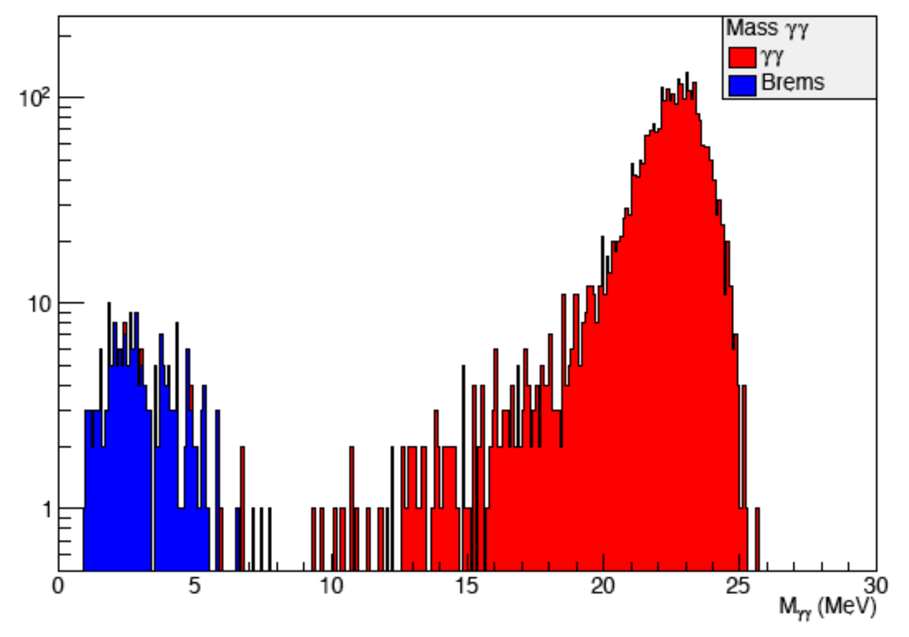
E_{e+}=550 MeV: $M_{A'} < 23.7$ MeV/c^2

E_{e+}=750 MeV: $M_{A'} < 27.7$ MeV/c^2

E_{e+}=1 GeV: $M_{A'} < 32$ MeV/c^2

The $\gamma\gamma$ normalization selection

$$N_{\gamma\gamma}^{tot} = \frac{N_{\gamma\gamma}}{Acc_{\gamma\gamma}} = Flux(e^{+}) \cdot \sigma_{\gamma\gamma}$$

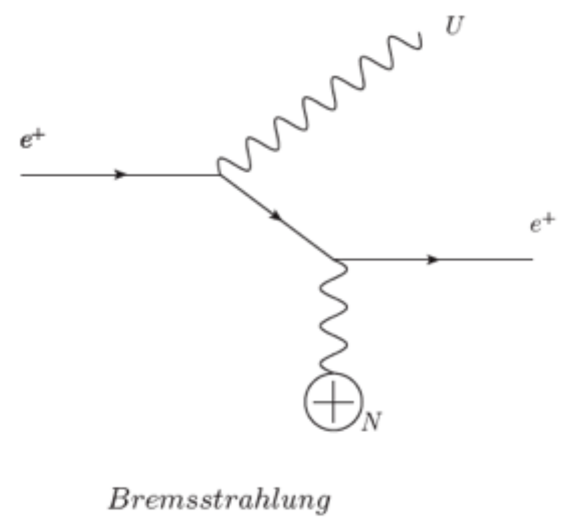


- Number of calorimeter clusters = 2
- Cluster energy: $100\,\text{MeV} < E_{cl} < 400\,\text{MeV}$
- Cluster radial position cut
- $\gamma\gamma$ invariant mass $20\,\text{MeV} < M_{\gamma\gamma} < 26\,\text{MeV}$

$$M_{\gamma\gamma} = \frac{\sqrt{[(X_{\gamma 1} - X_{\gamma 2}) + (Y_{\gamma 1} - Y_{\gamma 2})] E_{\gamma 2} E_{\gamma 2}}}{Z_{EMcal} - Z_{Target}}$$

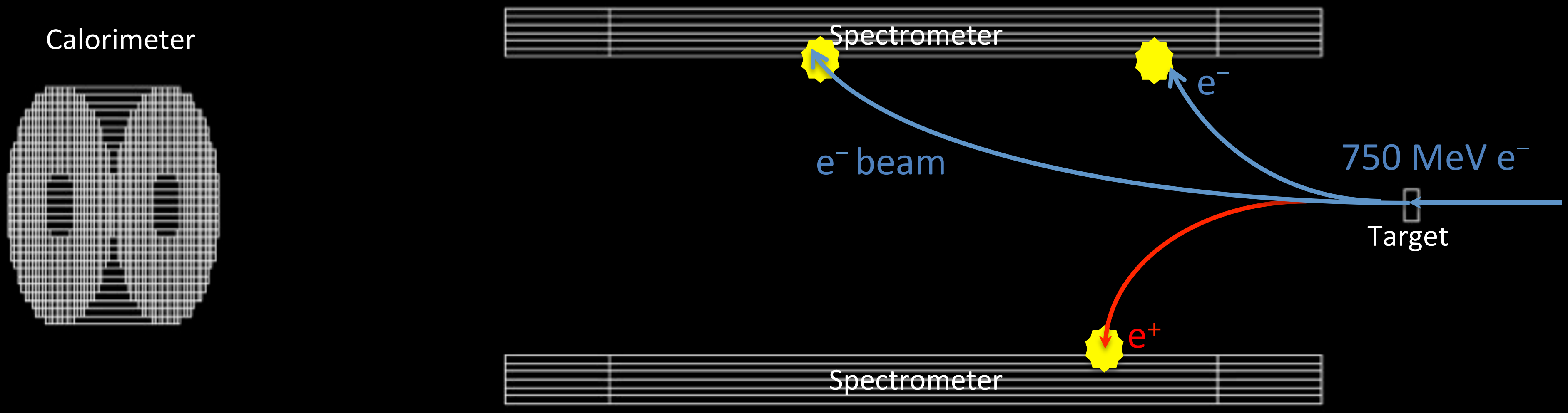
- $\text{Acceptance}_{\gamma\gamma} = 7\%$
- Contamination from Bremsstrahlung < 1‰

Search in bremsstrahlung production



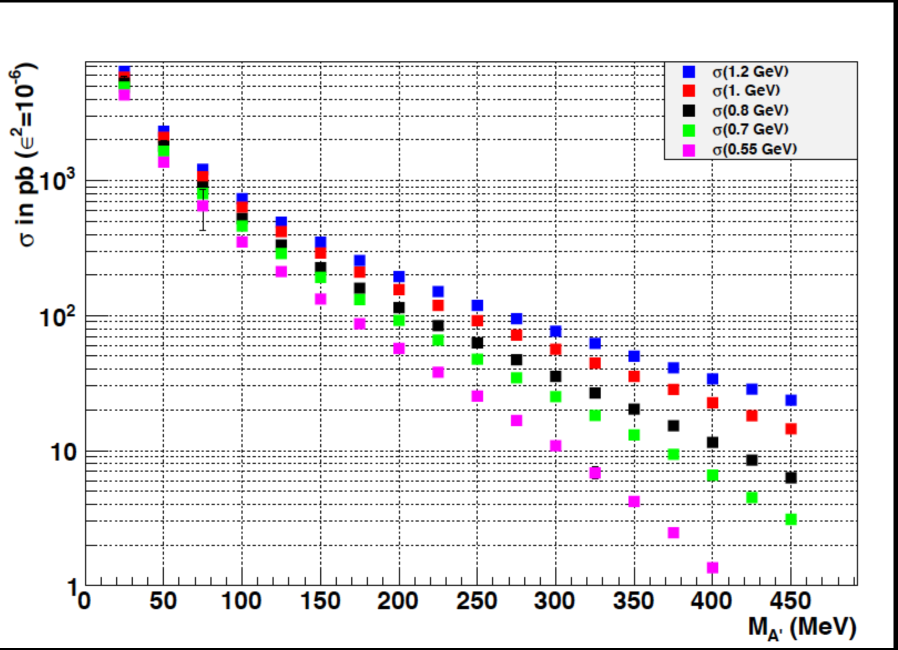
Bremsstrahlung

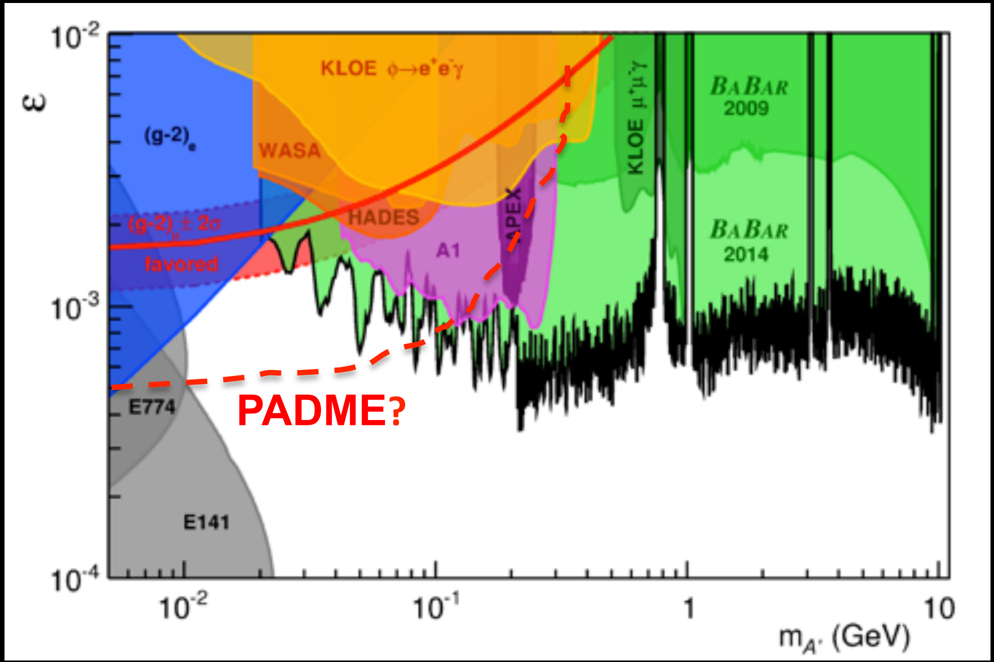
Visible search experiment



- Search for the process: **$e^- N \rightarrow N e^- A' \rightarrow N e^- e^- e^+$**
- 750 MeV electron beam on a ~0.5 mm tungsten target
- Measure in the **spectrometer** only the P^4_{e-} P^4_{e+}
- Compute the $M_{A'}^2 = (P^4_{e-} + P^4_{e+})^2$ and decay vertex position
  - Search for peaks in the e^+e^- invariant mass

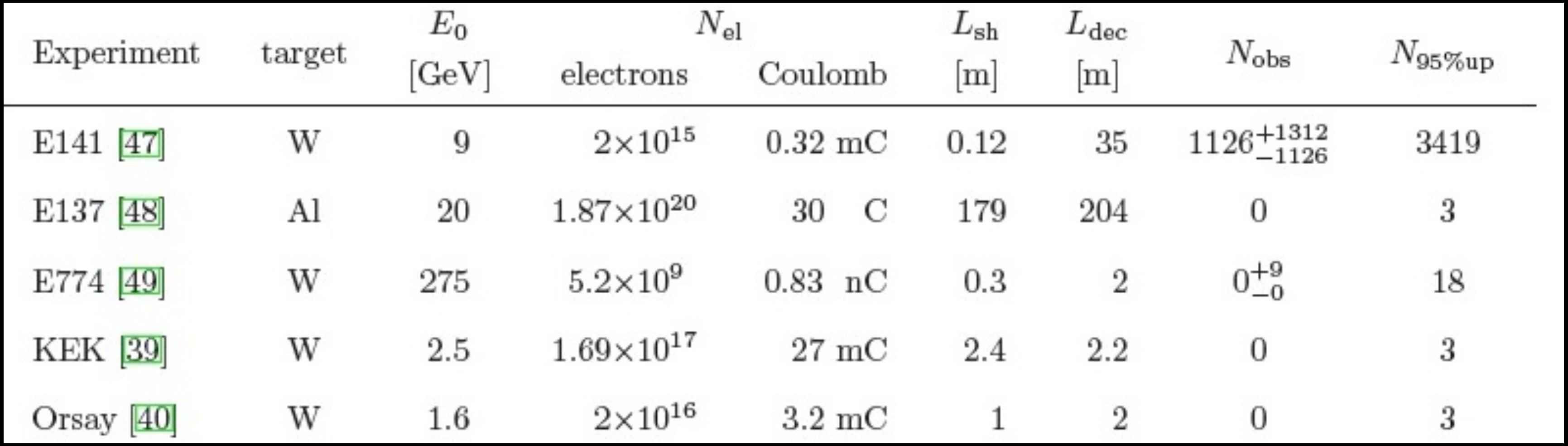
Indication on visible decay sensitivity



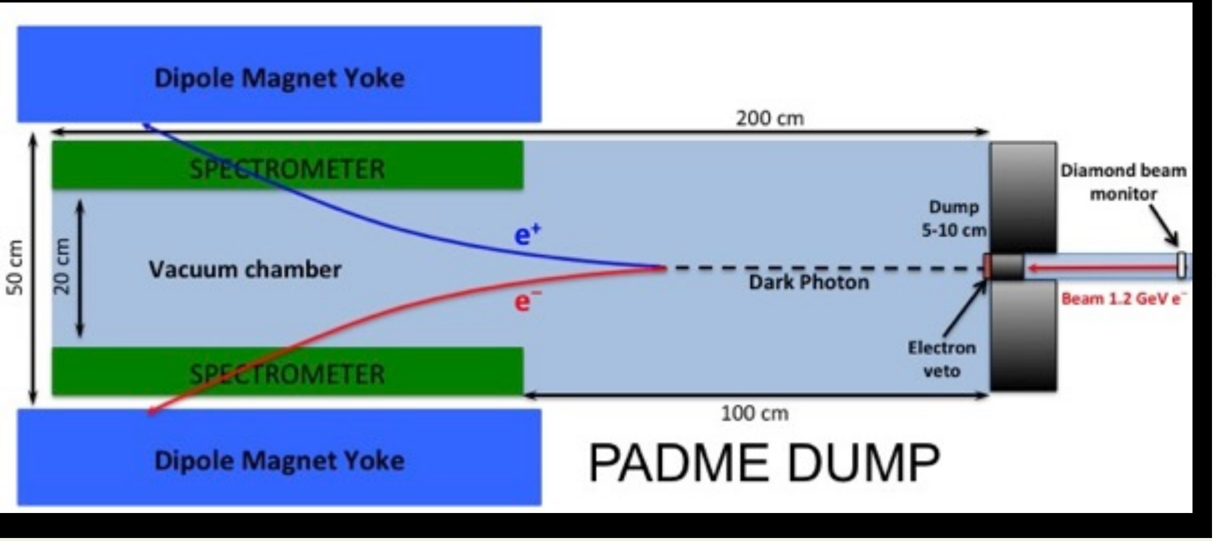


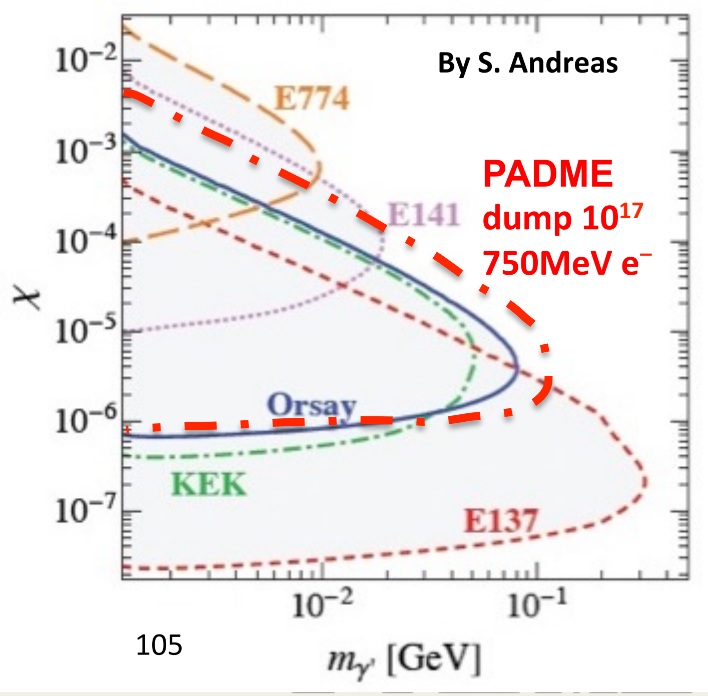
- Production cross section calculated with MADGraph code
- Final state is more constrained by invariant mass of the e^+e^- pair
- Indication of a limit down to $\epsilon^2 \sim 10^{-7}$ is expected at low masses
    - **Density of tracks in the spectrometer is the crucial point to be clarified**
    - **Design of the spectrometer not yet finalized**

Electron dumps experiments

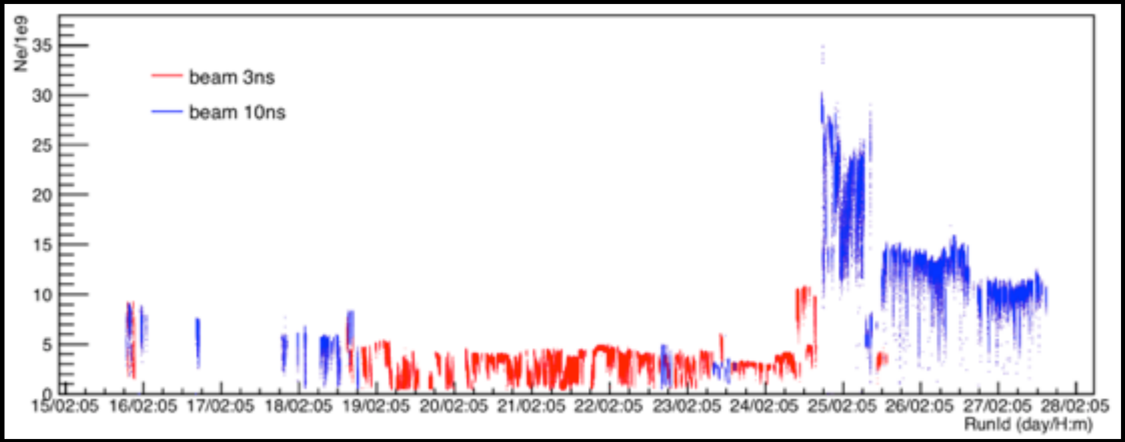


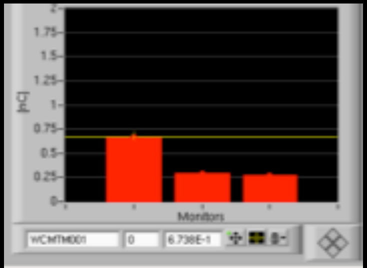
Experiment	target	E_0	N_{el}		L_{sh}	L_{dec}	N_{obs}	$N_{95\%up}$
		[GeV]	electrons	Coulomb	[m]	[m]		
E141 [47]	W	9	2×10^{15}	0.32 mC	0.12	35	1126^{+1312}_{-1126}	3419
E137 [48]	Al	20	1.87×10^{20}	30 C	179	204	0	3
E774 [49]	W	275	5.2×10^{9}	0.83 nC	0.3	2	0^{+9}_{-0}	18
KEK [39]	W	2.5	1.69×10^{17}	27 mC	2.4	2.2	0	3
Orsay [40]	W	1.6	2×10^{16}	3.2 mC	1	2	0	3
PADME dump	**W**	**1.2**	**$2\cdot10^{20}$**	**~30 C**	**~0.1**	**1**		



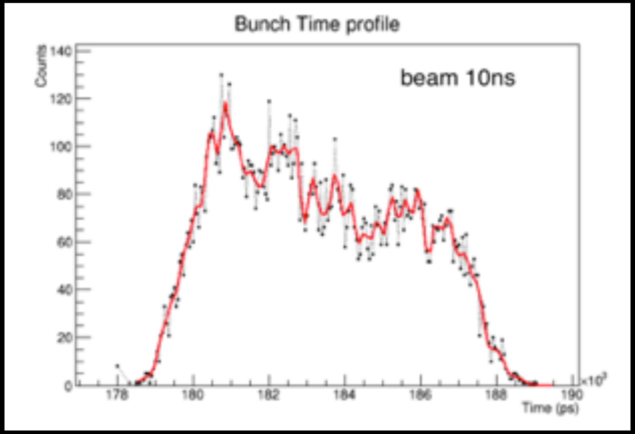

By S. Andreas

High intensity





WCMTM001 0 6.738E-1



Radioprotection limit:
<n> = **3.125×10^{10} particles/s**

Typical charge to damping ring:

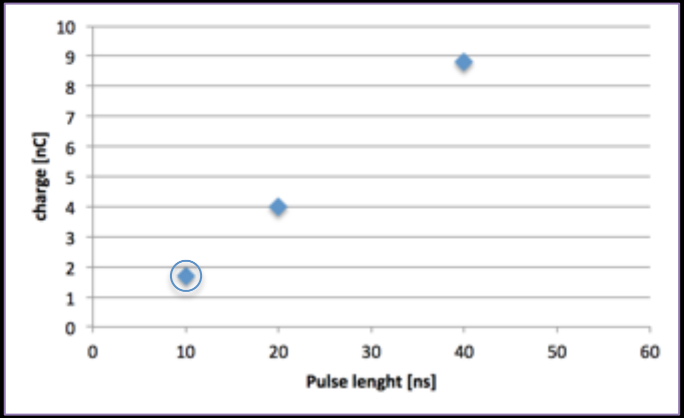
- ✧ **>1 nC/pulse** for **e^-**
- ✧ **0.7-0.8 nC/pulse** for **e^+**

But…

- ✧ Much higher charge on positron converter
- ✧ 8 A (12 A) from gun cathode

A few measurements on the maximum LINAC charge, driven by beam-dump experiments requirements

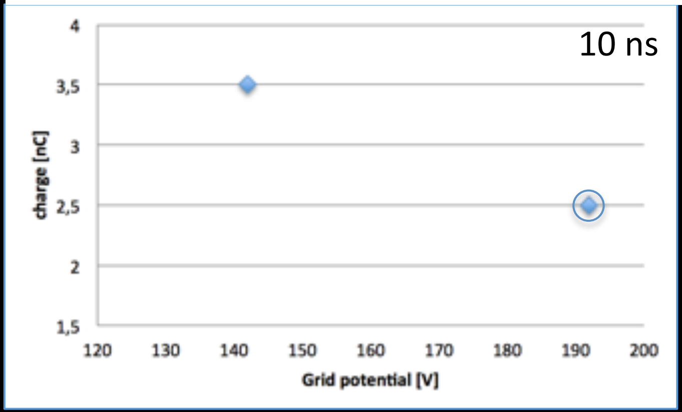
Bunch charge vs. length



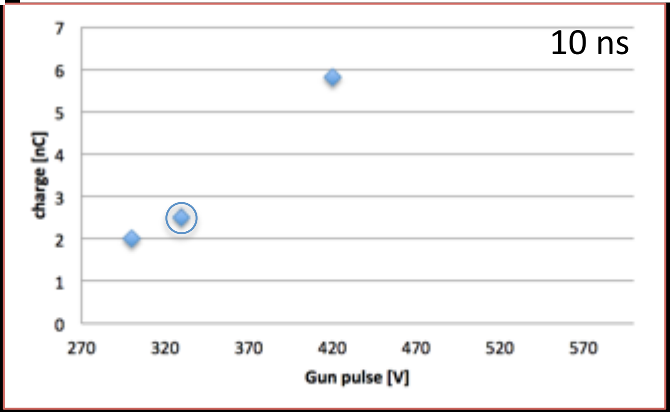
E = 725 MeV

×4 increasing pulse length

+30%
Decreasing grid stopping potential



×3 - ×5
Increasing gun pulse height



Trying to put all together: WCM readout saturated at 16 nC…

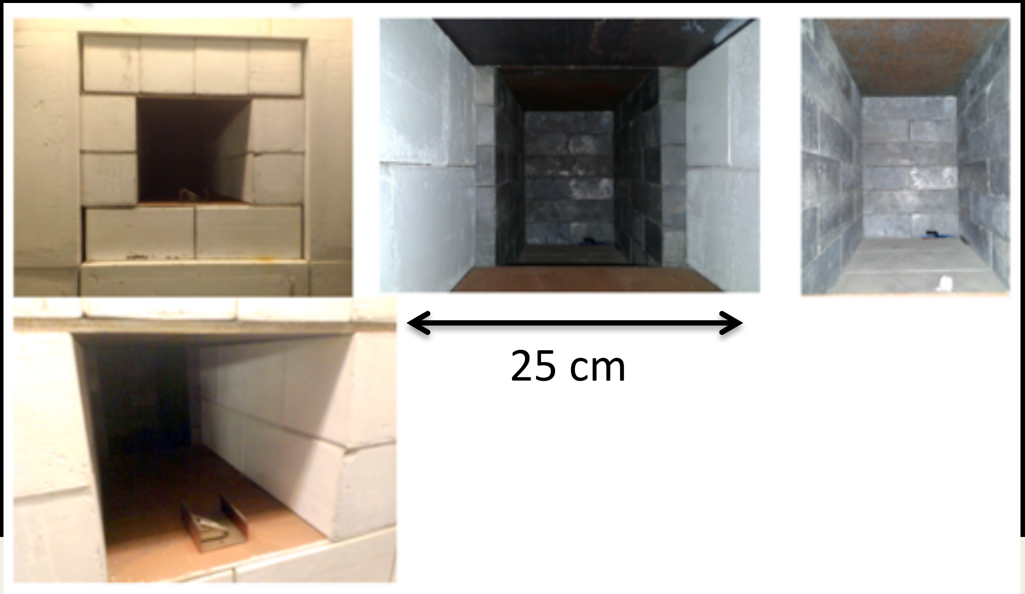
How many electrons on target?

- Let's compute how many **eot/y*** for **10 nC/pulse** so we can scale easily with the charge available from the LINAC
  - **10 nC** = $10^{-8}/1.6\times10^{-19}$ = **6.25×10^{10}**
  - At 49 Hz (1 pulse to spectrometer line) = 3×10^{12} e/s
    - 2 orders of magnitude more than present BTF authorization
    - Standard year = 1 y*= 120 days at 100% efficiency (10^7 s)
    - **3.175×10^{19} eot/y***
- **25 nC** translates in **0.8×10^{20} eot/y***
  - Considering measurements at 725 MeV, 40 ns, in the **present LINAC configuration** and quite conservative assumptions
  - Further extension of the pulse to 150 ns seems feasible with the present RF configuration, and should bring us to ≈100 nC, i.e. **3×10^{20} eot/y***

Where can we dump 3×10^{12} to 3×10^{13} e/s ?

LINAC beam dump

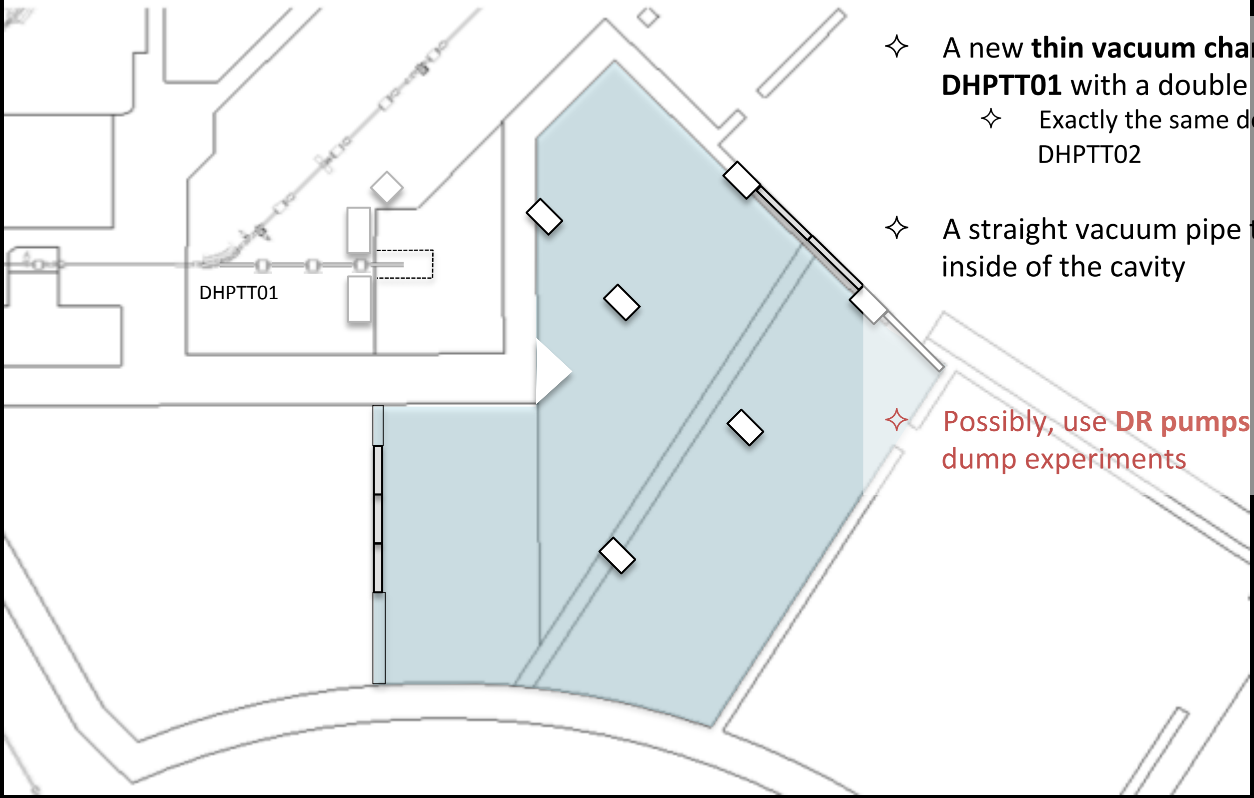
50 cm



30 cm

LINAC beam dump

DHPTT02



- A new **thin vacuum chamber** for **DHPTT01** with a double exit
  - Exactly the same design of DHPTT02
- A straight vacuum pipe to the inside of the cavity
- Possibly, use **DR pumps hall** for dump experiments

DR pumps hall

PADME dump toy Monte Carlo

- Try to evaluate driving design parameters for the PADME dump
- Toy MC includes:
  - Production cross section calculated by MADgraph

$$\frac{d\sigma_{\gamma'}}{dx_e\, d\cos\theta_{\gamma'}} = 8\alpha^3\chi^2 E_e^2 x_e\, \xi(E_e, m_{\gamma'}, Z, A)\sqrt{1-\frac{m_{\gamma'}^2}{E_e^2}} \left[\frac{1-x_e+\frac{x_e^2}{2}}{U^2}+\frac{(1-x_e)^2 m_{\gamma'}^4}{U^4}-\frac{(1-x_e)x_e m_{\gamma'}^2}{U^3}\right],$$

  - Evaluate the produced number of dark photons

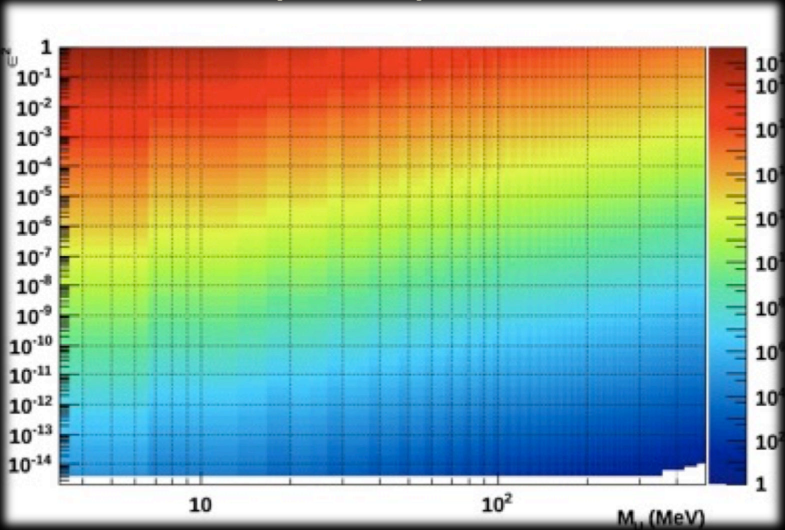
$$N_{\gamma'} = \sigma_{\gamma'}\, N_e\, n_{\text{sh}}\, L_{\text{sh}} = \sigma_{\gamma'}\, N_e\, \frac{N_0}{A}\, \rho_{\text{sh}}\, L_{\text{sh}}\,,$$

$$\frac{dP(l)}{dl} = \frac{1}{l_{\gamma'}}\, e^{-l/l_{\gamma'}}$$

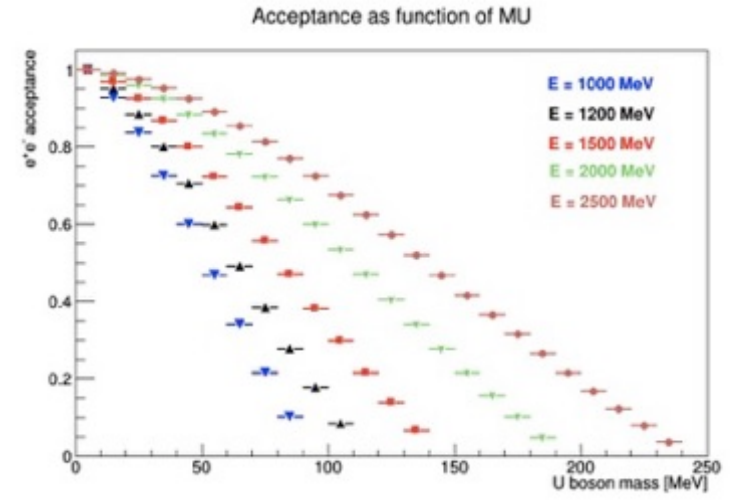
  - Scale by decay length acceptance
  - Scale by electron acceptance in the detector using kinematical distribution from a toy MC
    - Distribution have been compared with MADGraph for several $M_{A'}$
  - Not yet implemented in depth production of the *A'*

PADME dump main parameters

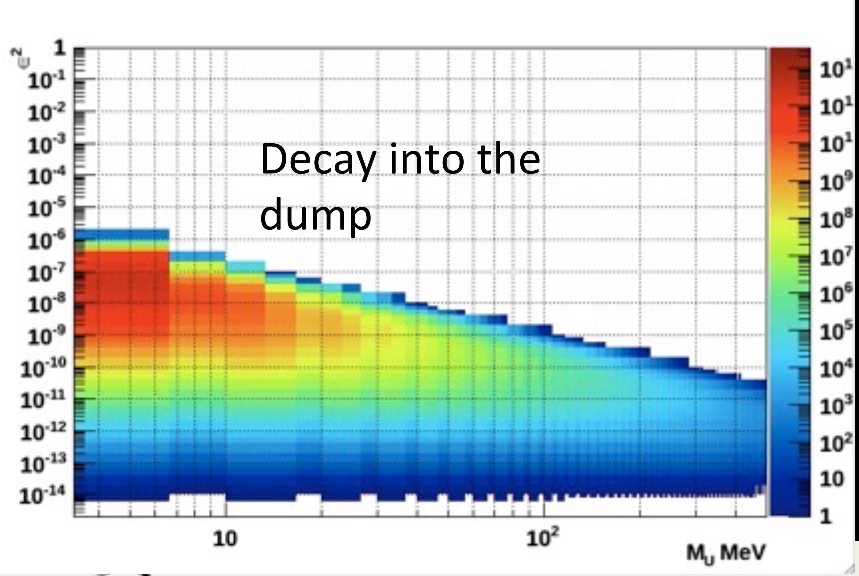
Dark photon production



±10 cm at 1m

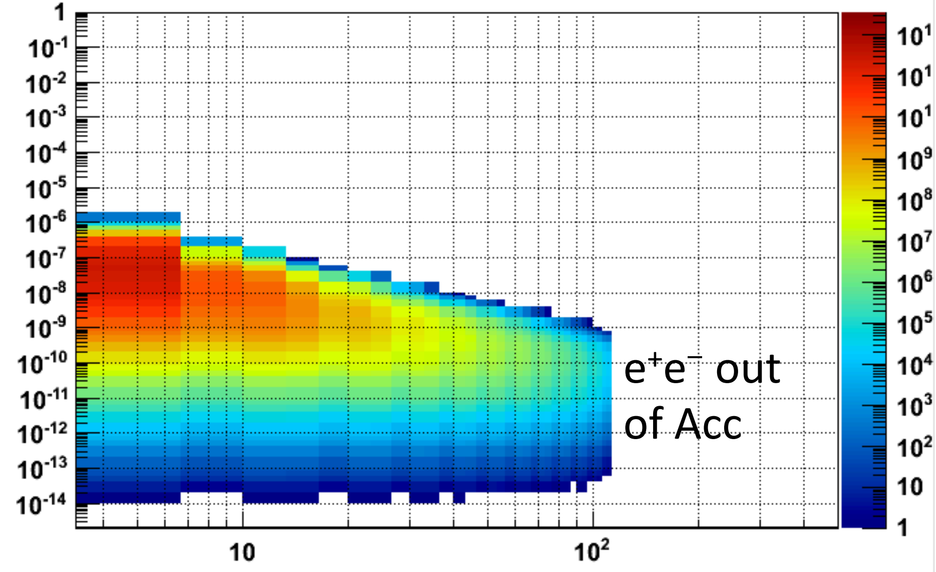


Decay length acceptance applied



Decay into the dump

Electron angular acceptance

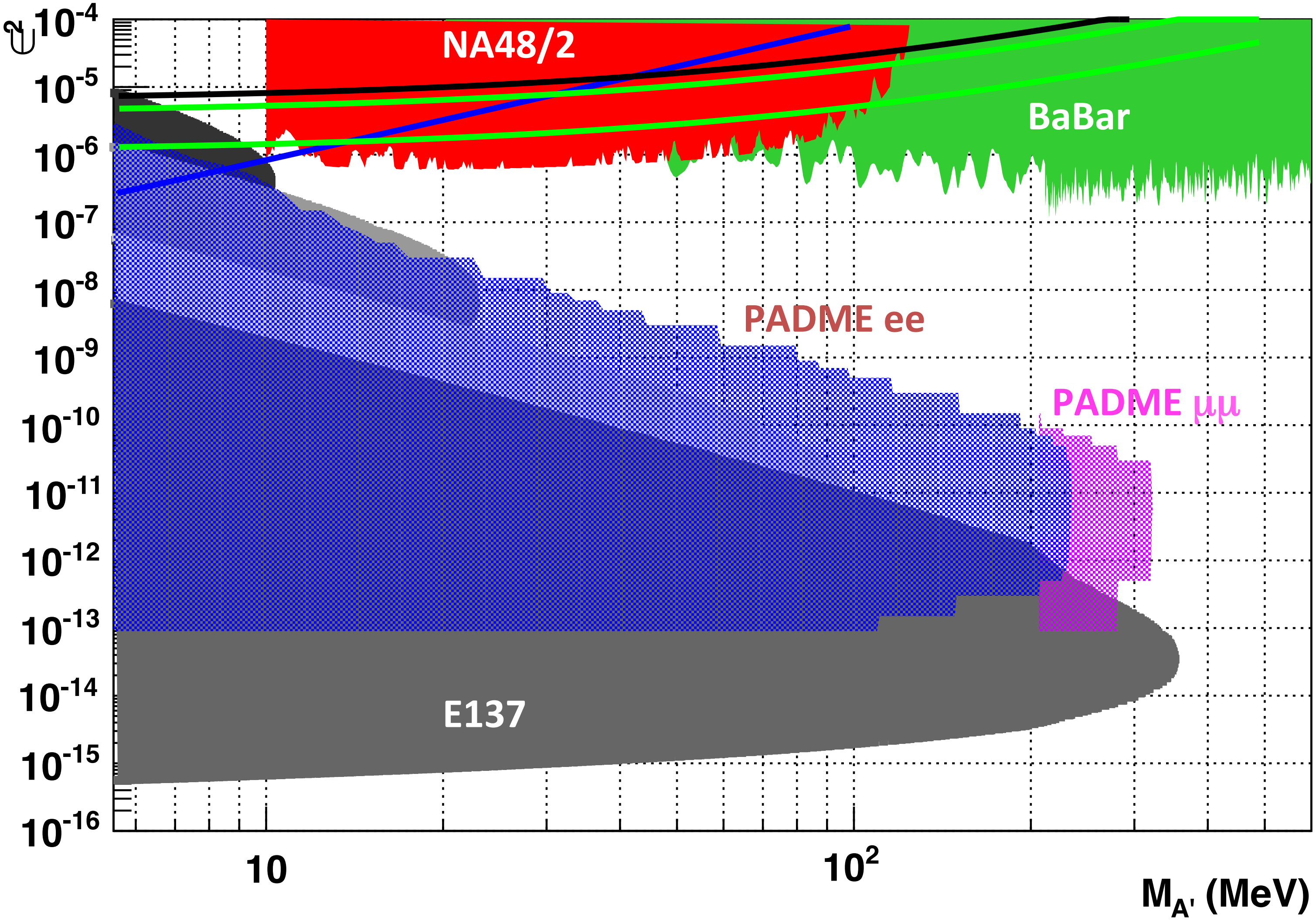


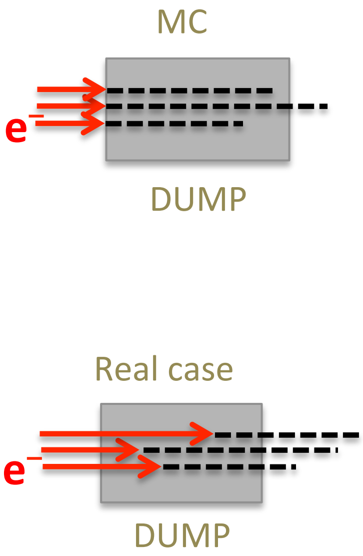
e^+e^- out of Acc

Dump comparison

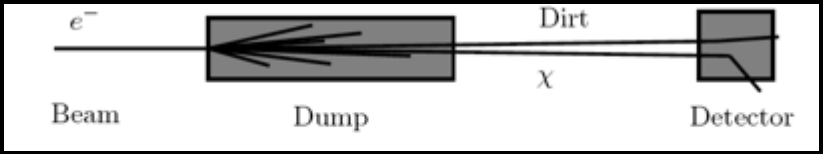
$1 \cdot 10^{20}$, 1.2 GeV electrons; 20 cm aperture at 50 cm from 8 cm W dump

Zero background hypothesis, in depth production to be refined, not yet a sensitivity plot

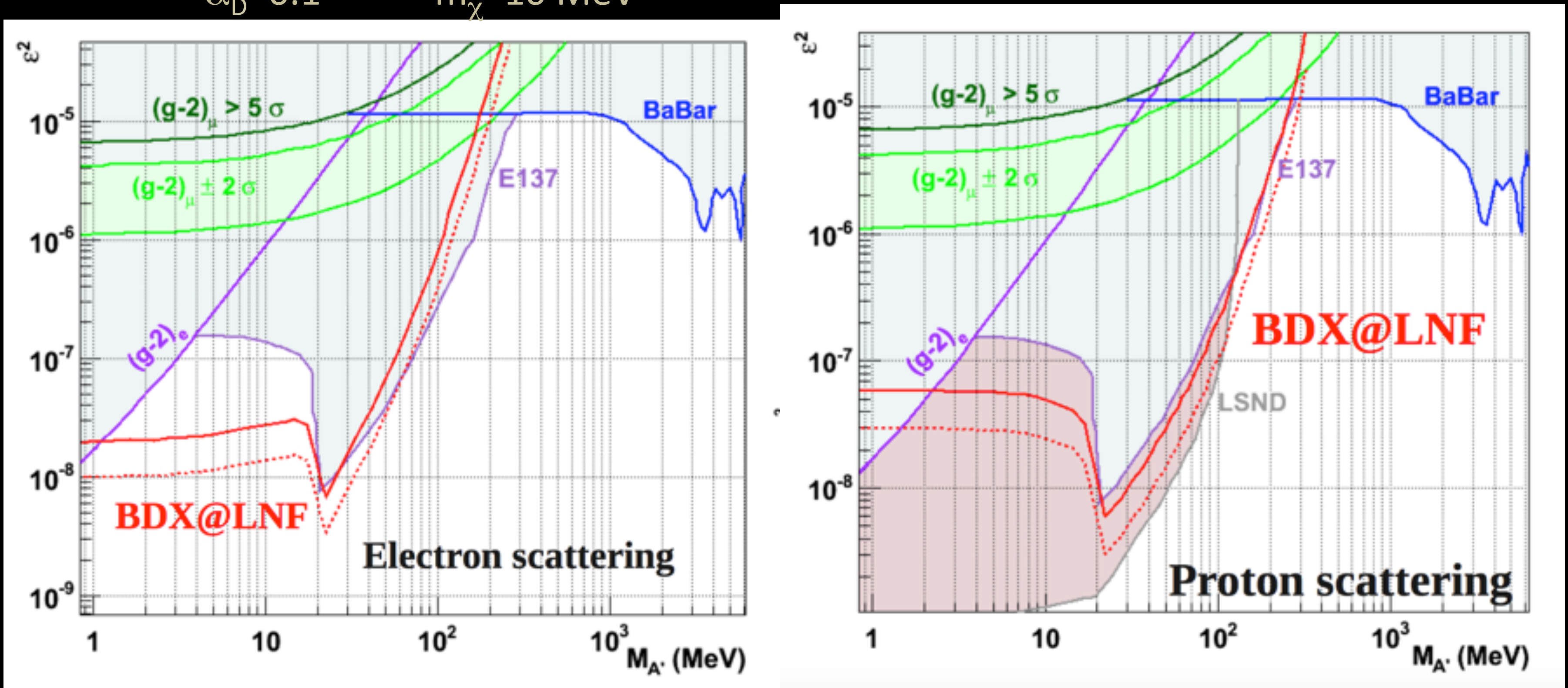




BDX @ LNF



α_D=0.1 m_χ=10 MeV

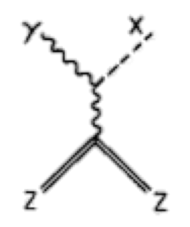


Beam energy **1.2 GeV** (e^-)

CsI detector 60×60×225 cm^3 built with crystals from dismounted BaBar ECal?

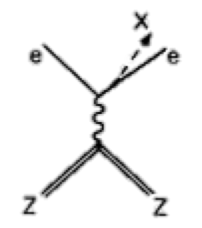
ALP physics at PADME

Primakoff



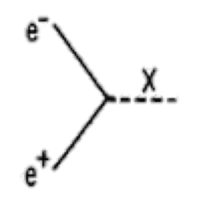
PADME can search for invisible decaying or long living ALP by searching for
$1\ \gamma + M^2_{miss}$ final states

Bremsstrahlung

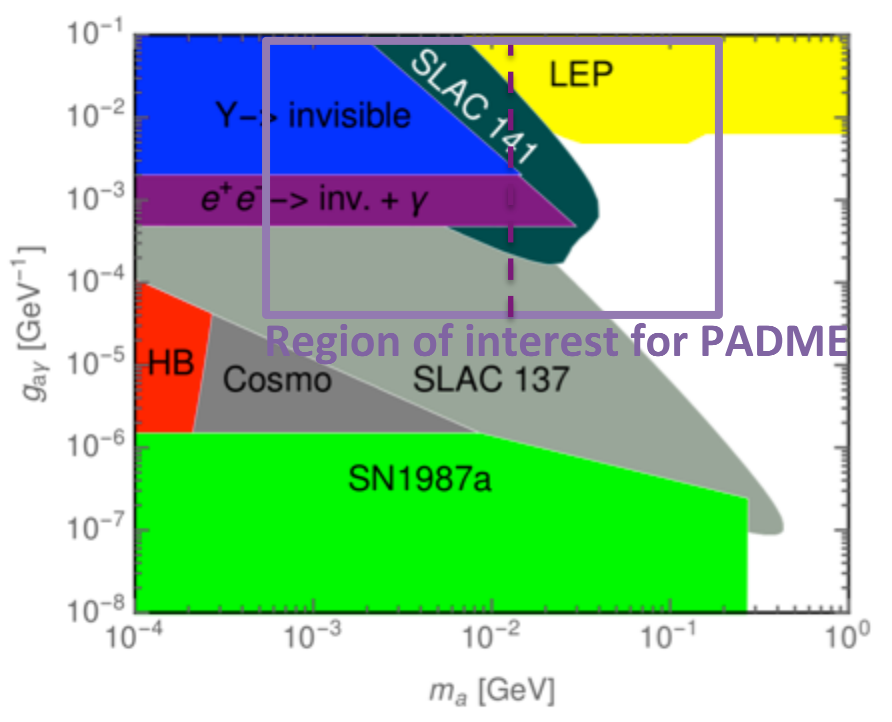


In the visible final state a->γγ all production mechanisms can be explored extending the mass range in the region of ~100MeV
The observables at PADME will be: eγγ or γγγ

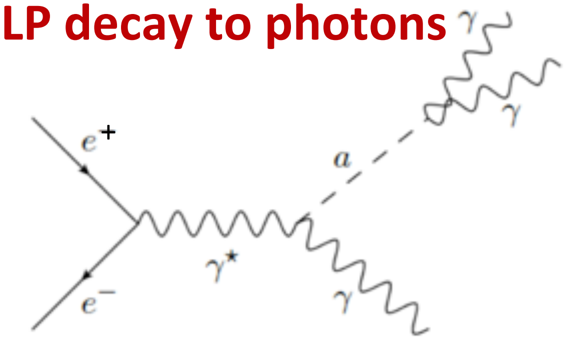
Annihilation



Limits on ALPs coupling to photons

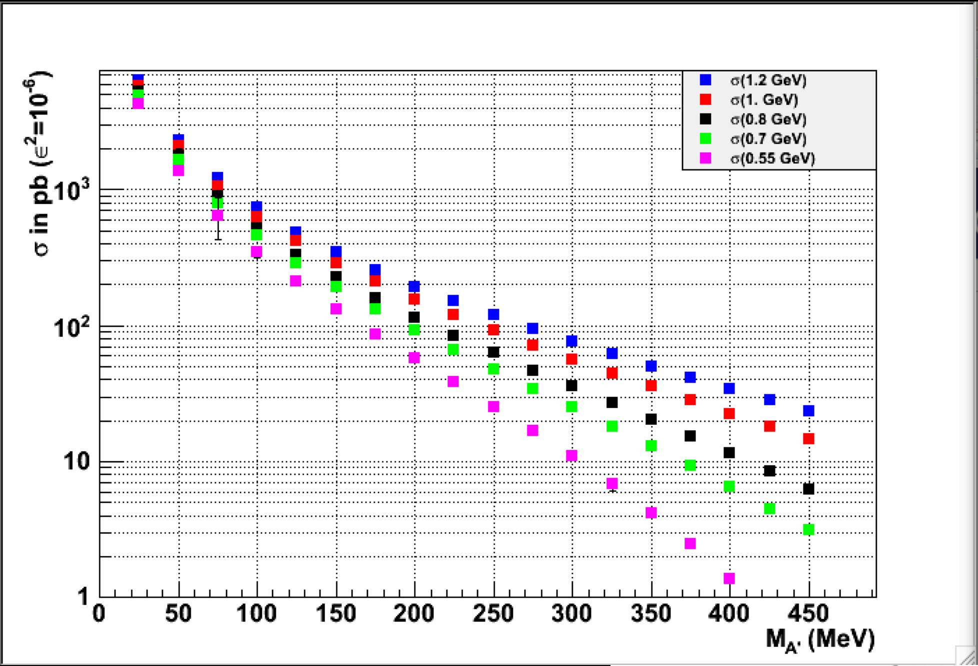


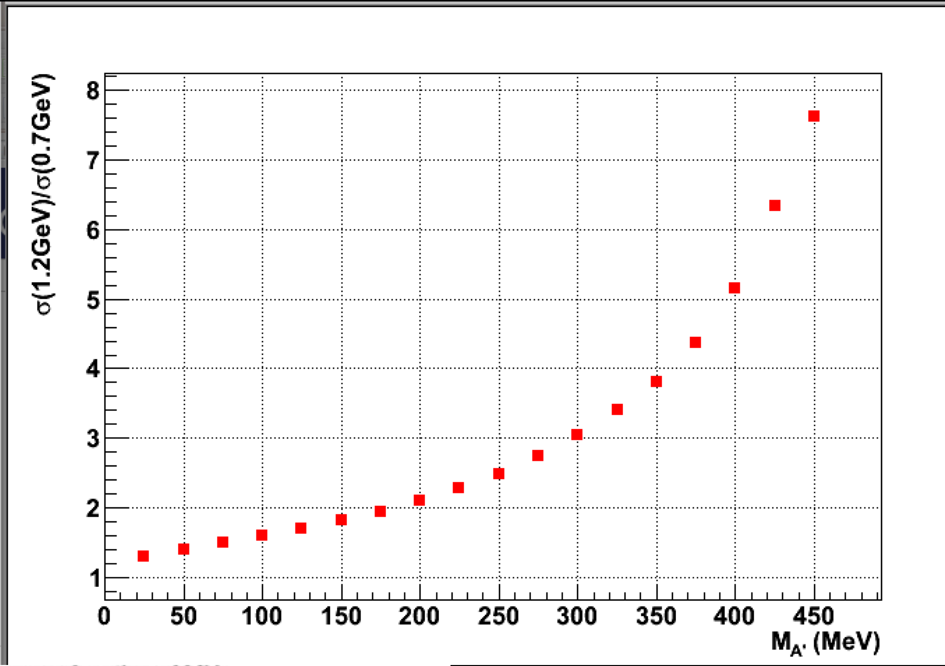
ALP decay to photons

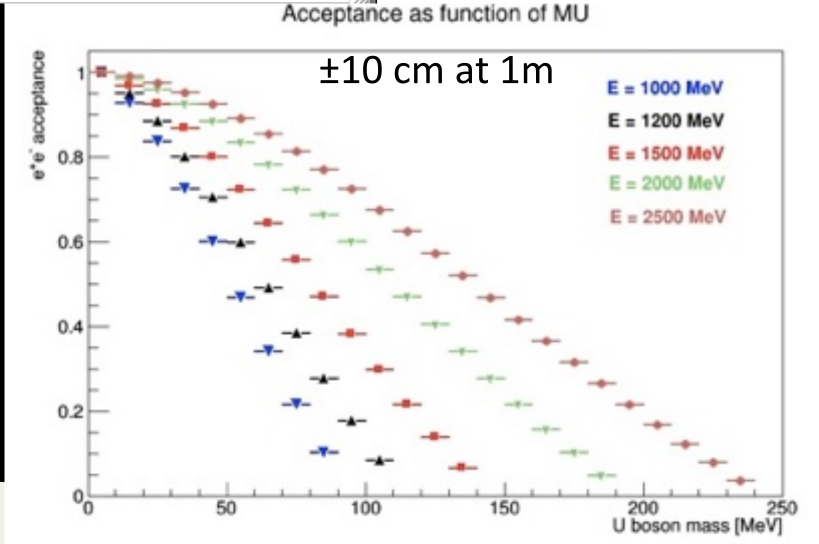


Phys rev D 38 11 1998

Energy upgrade



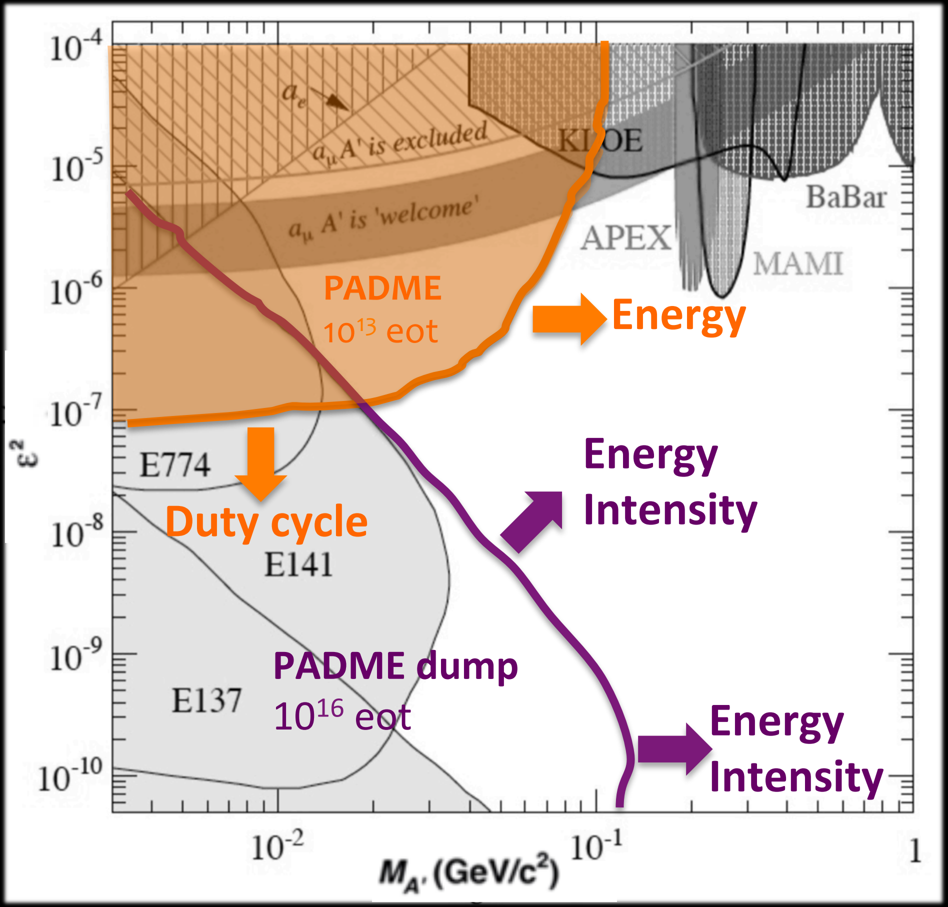




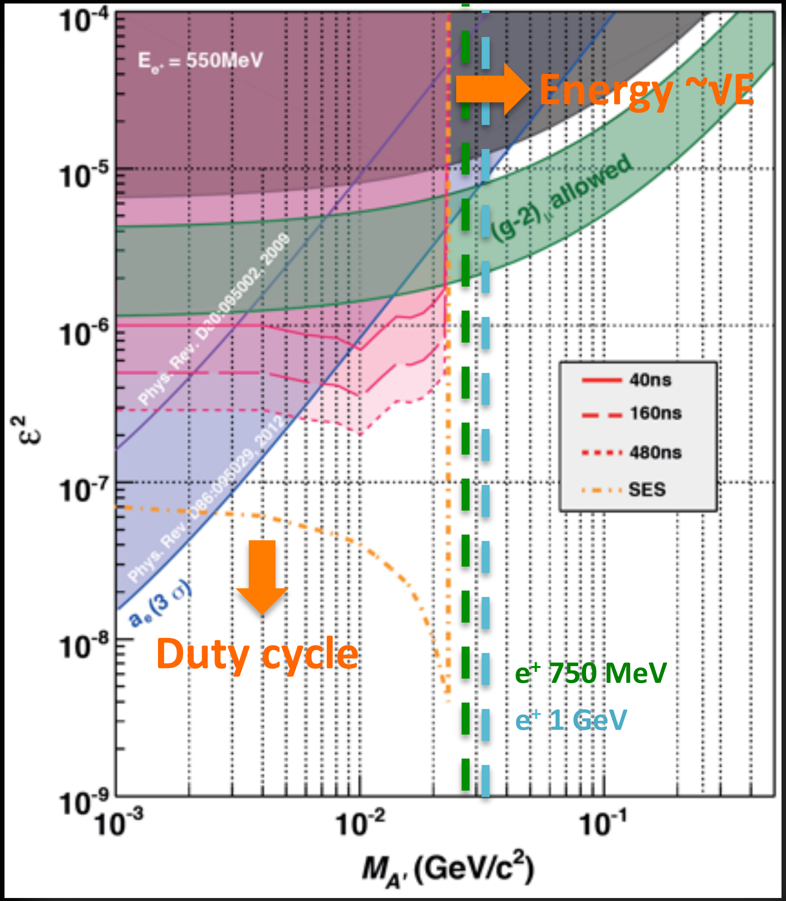
±10 cm at 1m

BTF upgrade

Decays to lepton pairs



Decays to invisible



15 m

Add 4 sections + 2 SLED-ed klystrons

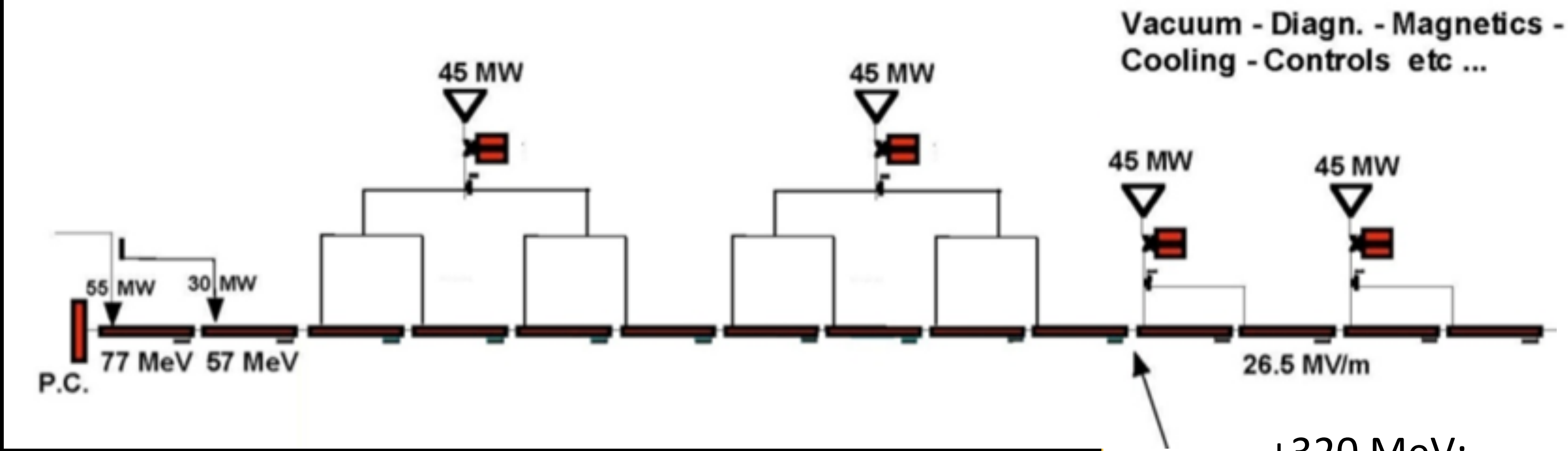
4 Acc. Sections

2 SLEDs

2 Power Stations

Waveguides + accessories

Vacuum - Diagn. - Magnetics - Cooling - Controls etc ...



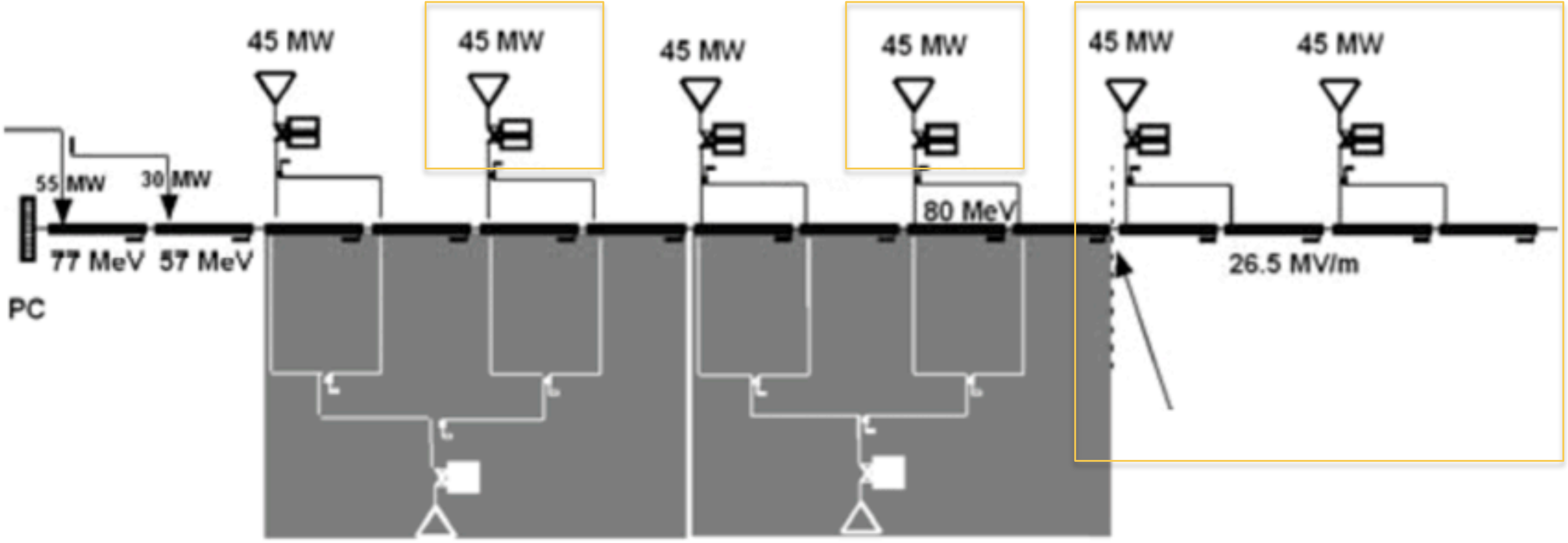
+320 MeV:

Reach:
1070 MeV electrons
870 MeV positrons

Add 4 sections + 4 SLED-ed klystrons

+180 MeV:

+320 MeV:



Reach:
1250 MeV electrons
1050 MeV positrons

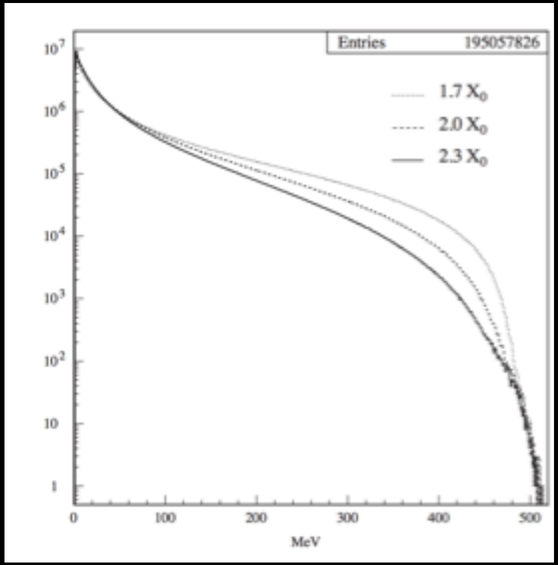
ORIGINAL RF LAYOUT

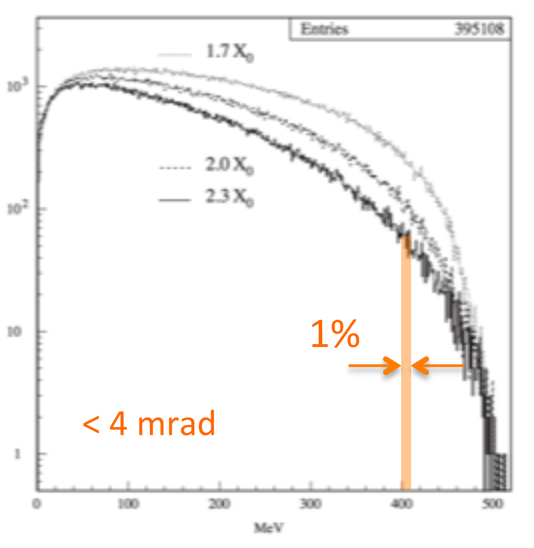
Add **two more SLED-ed klystrons** and split power only in two sections instead of four

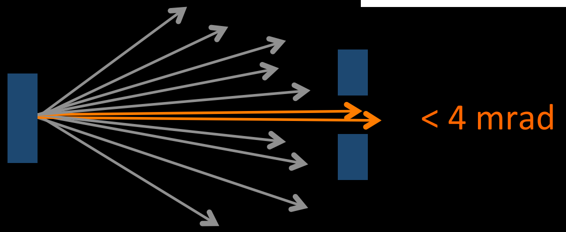
"Low cost" energy upgrade

$$w(E_o,\alpha,E) = \frac{1}{E_o}\,\frac{\left[\ln\left(\frac{E_o}{E}\right)\right]^{\frac{\alpha}{\ln 2}-1}}{\Gamma\left(\frac{\alpha}{\ln 2}\right)}$$

The shower development in the target follows the Rossi model quite well







The acceptance of the line and the collimators will select **forward** secondary particles, thus smoothing the energy distribution

The reduction factor depends on the energy selection: E and ΔE

Can we reach 10^4 e^+/40 ns with acceptable energy spread and spot size?

Test of positron beam

E_0=510 MeV electrons, Q=1 nC

E=447 MeV=88% E_0, N≈2000 positrons

10 ns bunch width

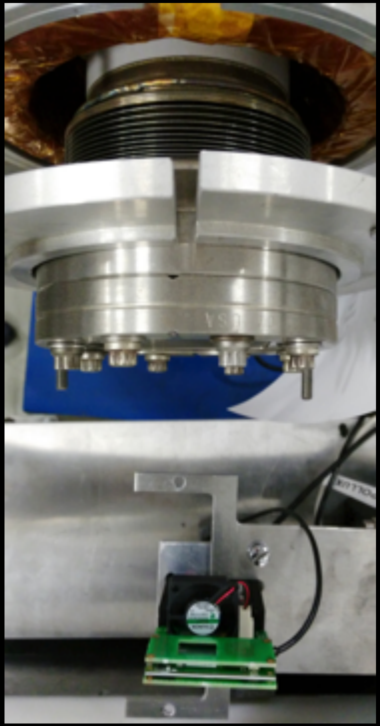
BTF target at 1.7 x_0

σ_y

- ≈0.8 mm (2 mm FWHM)
- Dominated by multiple scattering on 0.5 mm Be window + 20 cm of air
- Can be pushed down to 0.6-0.7 mm (with Be window)
- Can be further improved operating in vacuum

σ_x

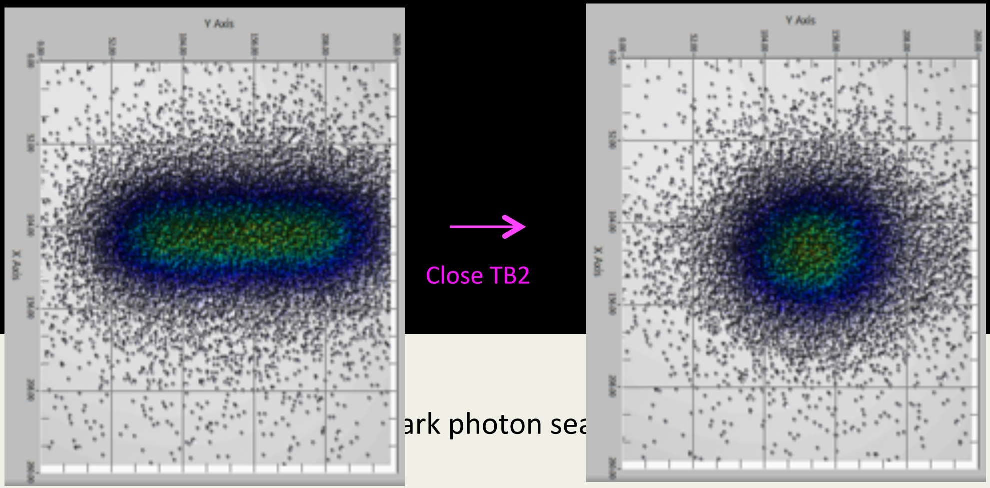
- Dominated by momentum spread, TB2 slits (before selecting dipole) + TB4 (after)
- Can be improved by using an optimized (thinner) target and by closing the slits
- A thinner target also allows to run closer to the primary energy



Finestra Berillio

FITPIX

15×15 mm^2



PADME status

- The PADME construction phase is just starting
    - Magnet delivered at LNF, being mapped
    - First diamond target tests (20x20mm^2 e 50um di spessore)
    - First calorimeter test beam with just 3x3 crystal matrix
- Approval status
    - Project has been endorsed by both LNF scientific committee and INFN CSN1
    - Crystals from L3 collaborations obtained
    - 2016 budget secured in INFN CSN1 by “What Next” program
- New physics cannels for PADME identified (ALP)
- Refinement of Monte Carlo and sensitivity estimates ongoing
- Additional dark sector searches identified waiting to be explored

A new hope

- Growing interest in the low mass dark matter/hidden sectors/portals
- Careful with assumptions and model-dependent limits!
- Lots of limits from old experiments re-analysis
- JLAB strong investment
- Opportunities with Frascati electron/positron beam
- PADME-invisible could start at the beginning of 2018