L’esperimento PADME per la ricerca di dark mediators

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Anakin Skywalker and Padmé Amidala – © Lucasfilm Ltd.

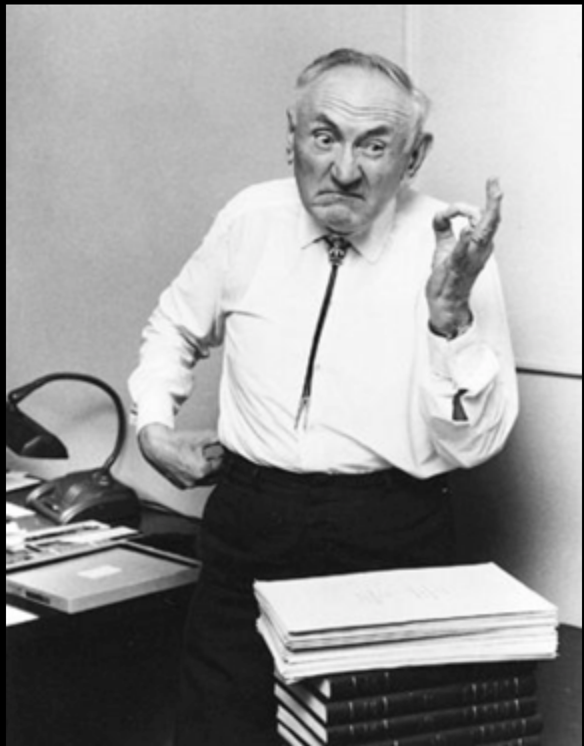
The long quest for dark matter

Zwicky, Coma galaxy cluster (1933)
$M/L \approx 660\ M_{\odot}/L_{\odot}$

Rubin, Andromeda galaxy rotating curves (1970's)

Hubble Space Telescope (2007)
Cluster Cl 0024+17
Lensing of background galaxies

The long quest for dark matter

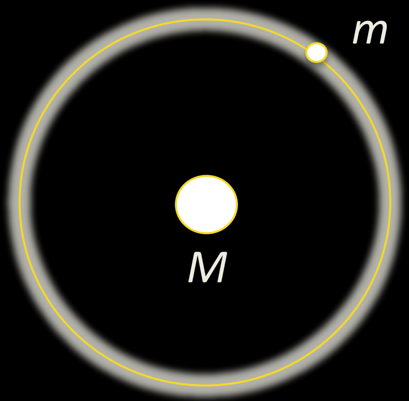


Fritz Zwicky

Vera Rubin

"A History of Dark Matter"
Gianfranco Bertone and Dan Hooper
https://arxiv.org/pdf/1605.04909v2.pdf

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:

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

Kinetic energy;

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

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

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

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

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, $\langle v_i \rangle \approx \surd 3 \; v_r$
- We see projected radii: $r = \theta d$

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

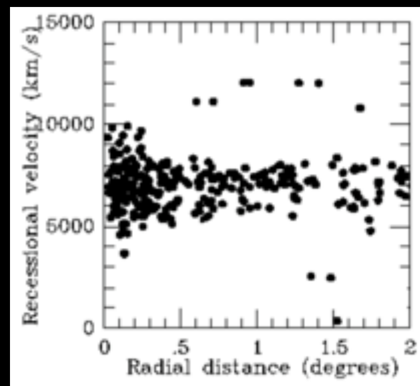
Assuming N equal masses $\Sigma_i m_i = N m$

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

Coma cluster (Zwicky):

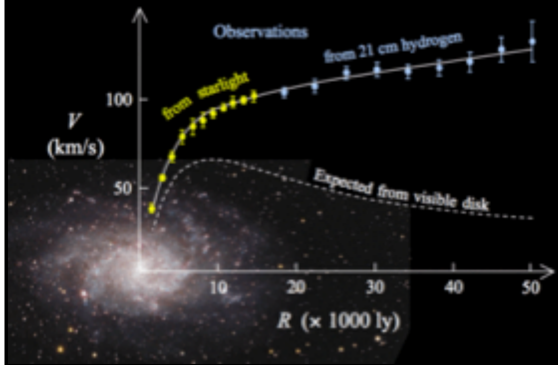
$\sigma \approx 1000$ km/s, $R \approx 3$Mpc, $M_{VT} = 3 \; 10^{15} \; M_\odot$

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

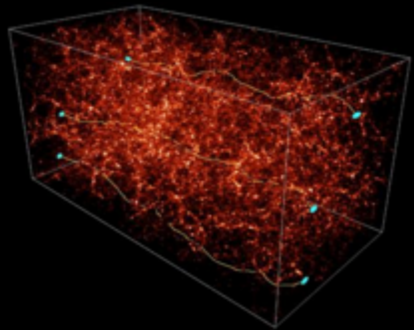


Many pieces of evidence for dark matter

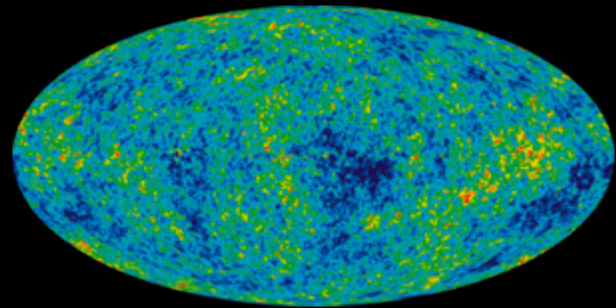
Rotation curves

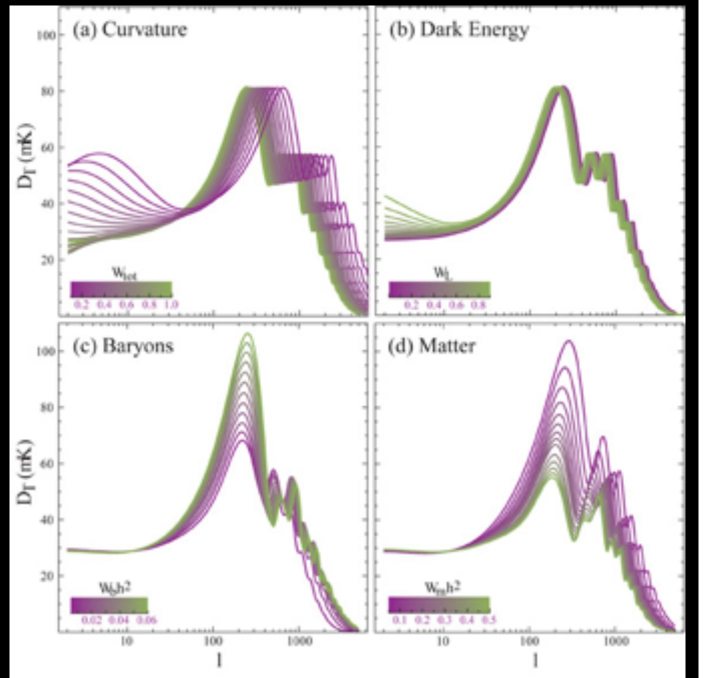


Large scale structures



Cosmic Microwave Background





Lensing

Colliding clusters (Chandra)

The dark matter problem

Original drawing by Stacy McGaugh (1995)

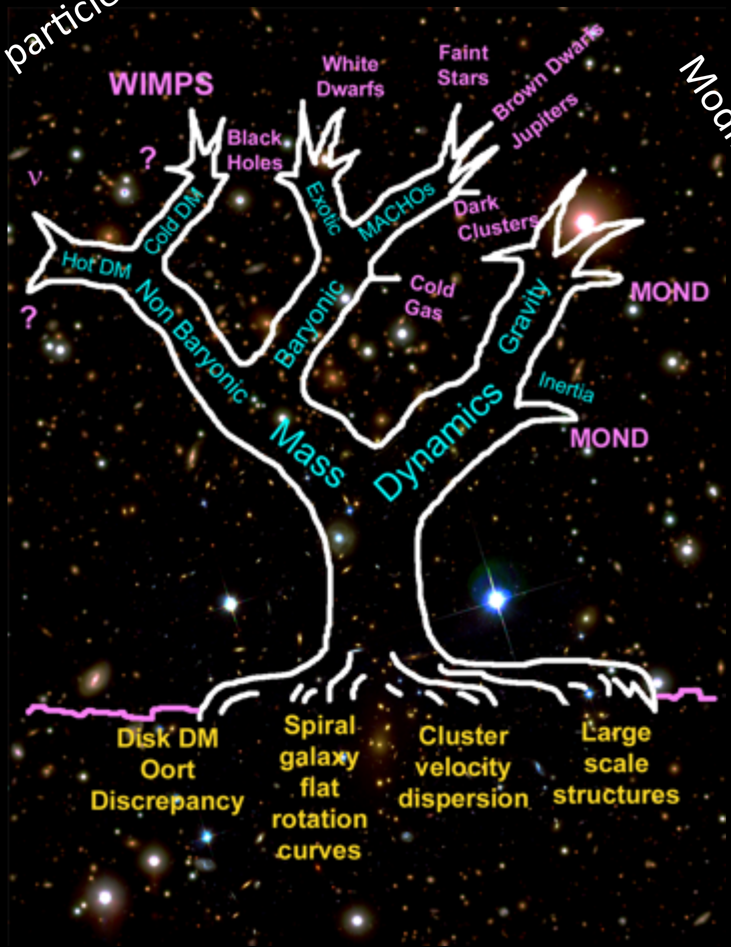
Several hypothesized solutions

Roots are the empirical observations

Astrophysics

New particles

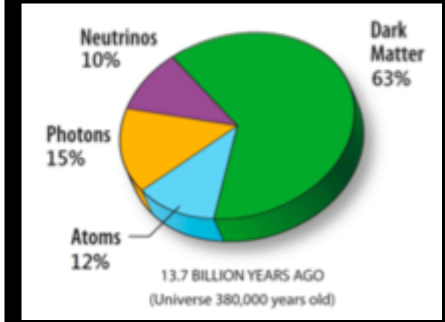
Modify gravity

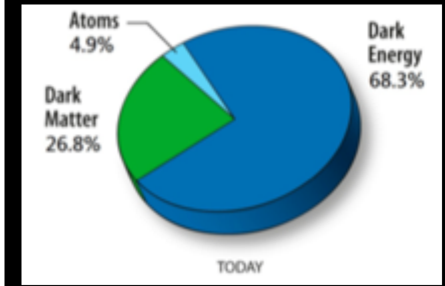


Particle physics is **only one** of the possible solutions…

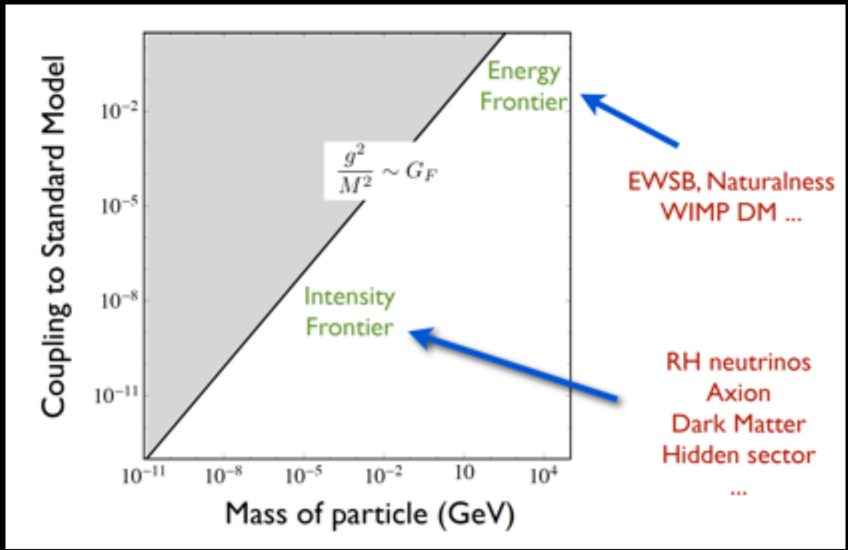
A new kind of matter?

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 a new dark force (or more) exist?
  - How complex is the dark sector spectrum?



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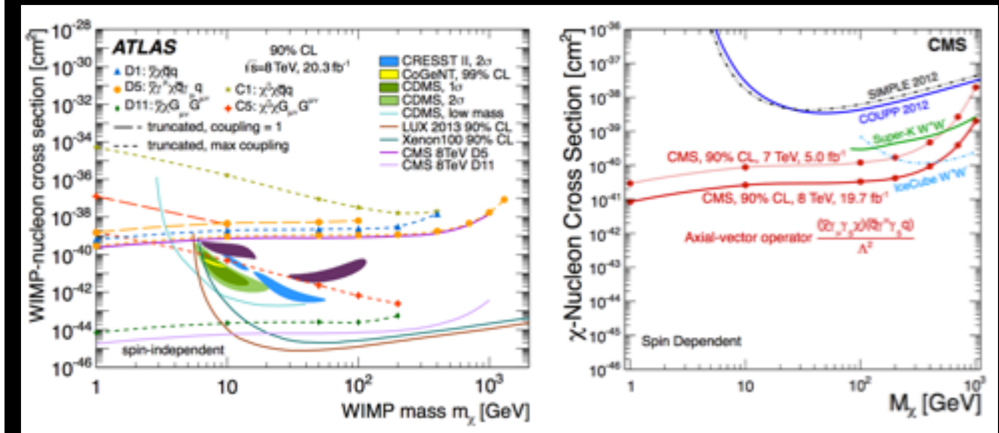
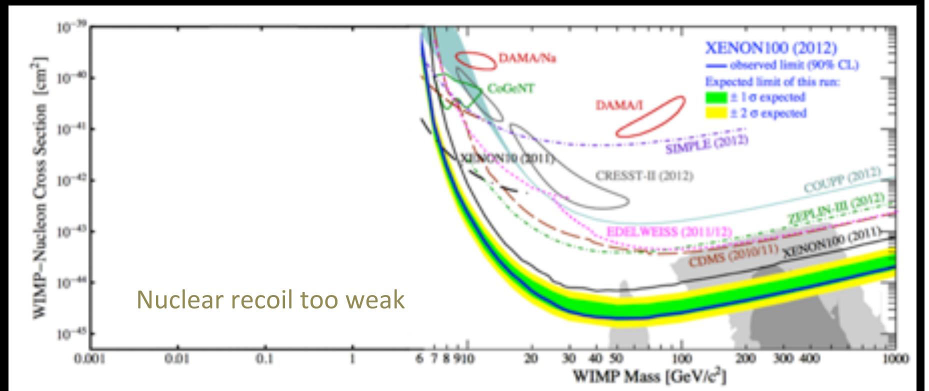
Where to search for dark matter

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! (**WIMP**)

- 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

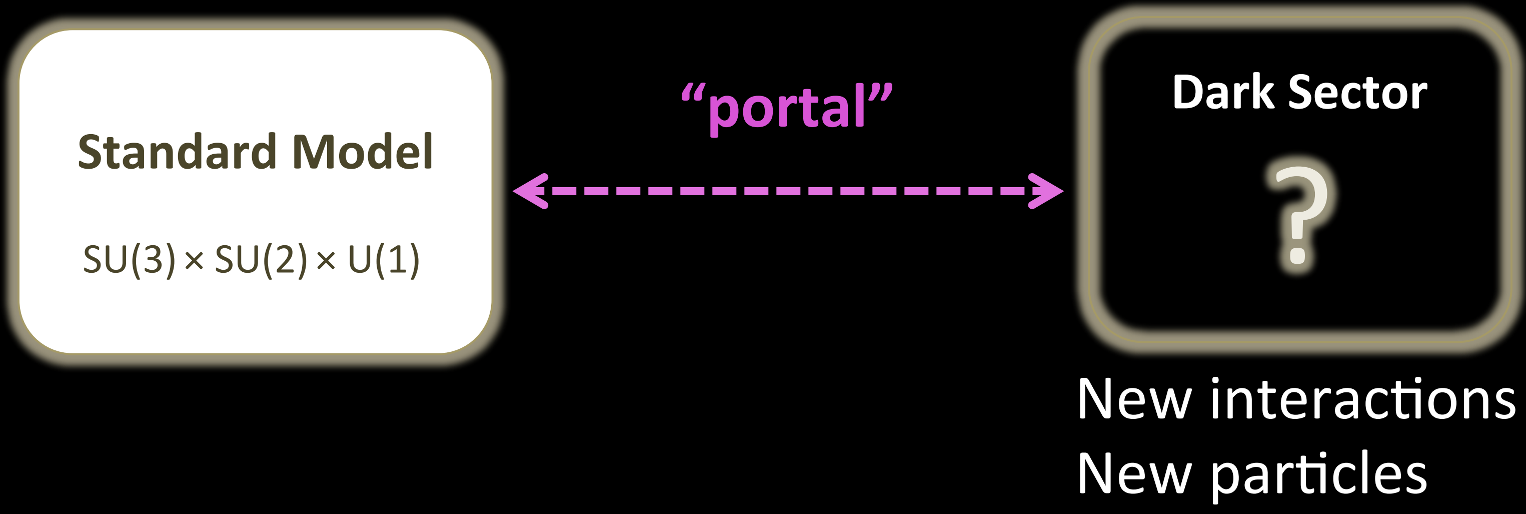




MeV GeV TeV

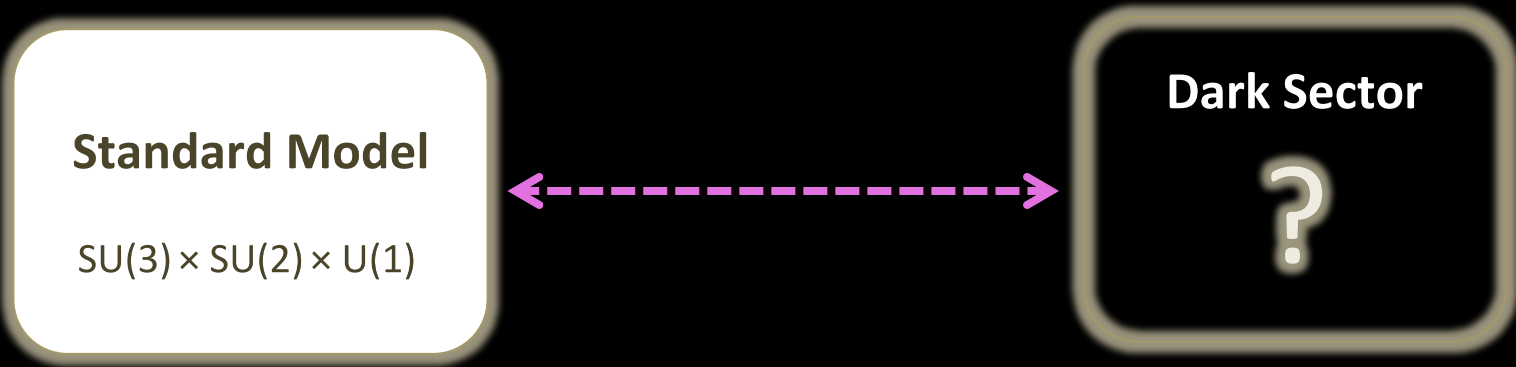
What about introducing a **new force**?

Secluded or hidder or dark sectors



- "Secluded" from the SM sector by a faint **interaction**
- Introduce it in a effective model

Portals to secluded sector

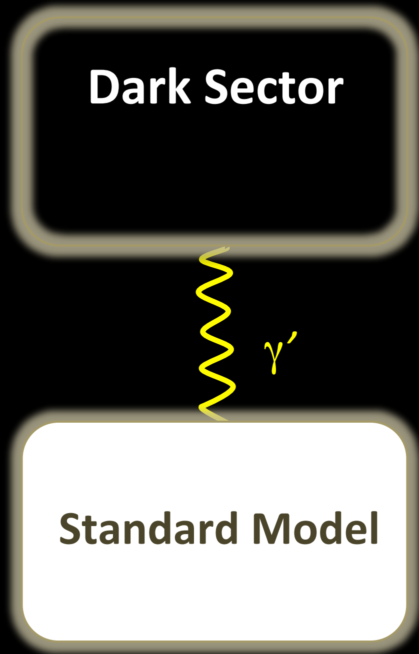


vector	$\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$	dark photon
Higgs	$\epsilon_h \lvert h\rvert^2 \lvert\phi\rvert^2$	dark scalar
neutrino	$\epsilon_\nu (hL)\psi$	sterile neutrino
axion	$\frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}$	ALPs

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')

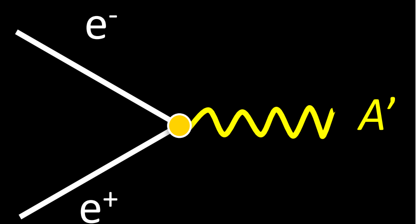
- An extra U(1) symmetry implied in many Standard Model extensions, some classes of string theory, etc.



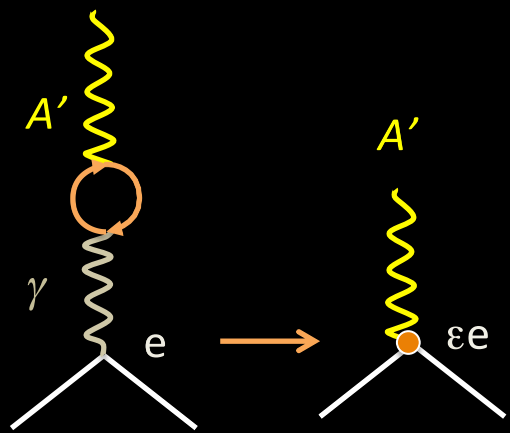
Dark photon

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

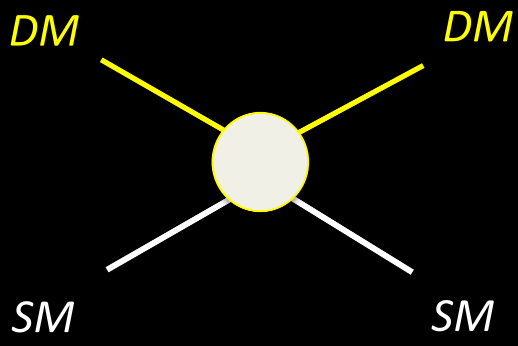
$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$



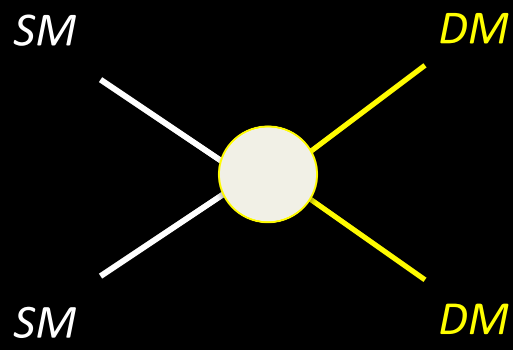
    - Not all the SM particles need to be charged under this new symmetry
    - In the most general case q_f is different in between leptons and quarks and can even be 0 for quarks. (P. Fayet, Phys. Lett. B 675, 267 (2009).)
  - Couples to *SM* hypercharge through kinetic mixing operator:
    - $\varepsilon/2\, F^Y_{\mu\nu} F'^{\mu\nu}$, 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



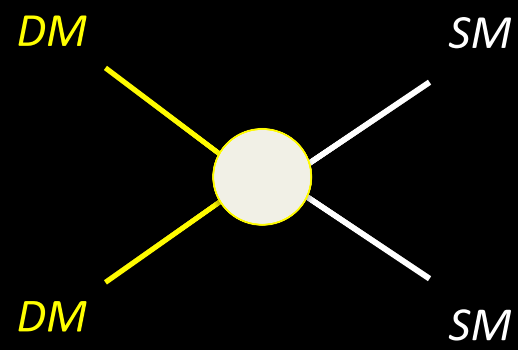
Esperimenti di ricerca di dark matter



Direct detection

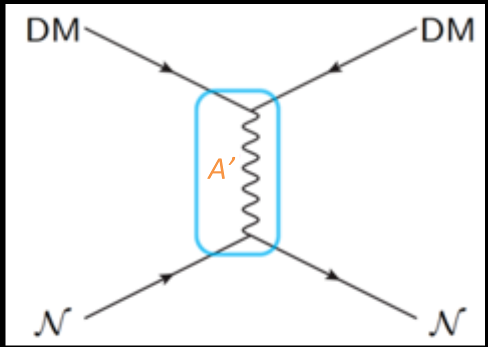


Production at accelerators

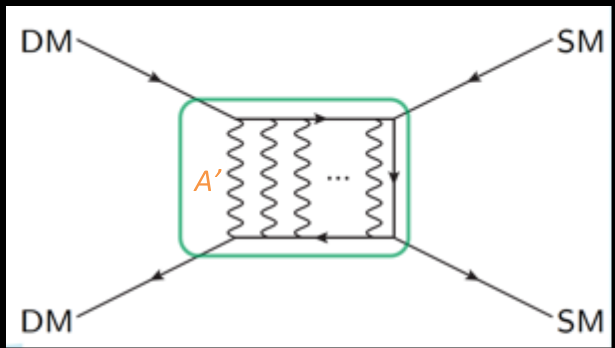


Indirect detection

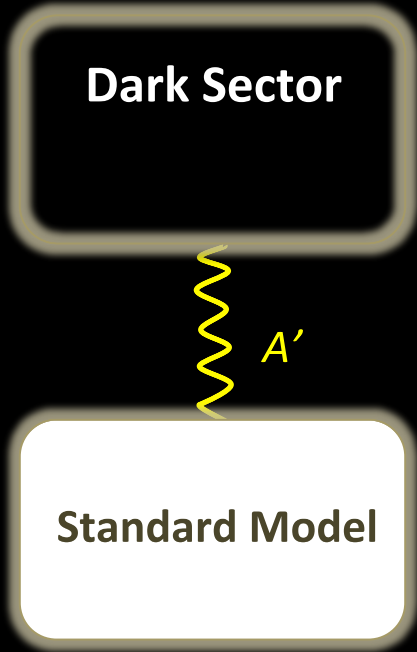
A dark matter "messenger"



Dark Matter scattering on nuclei

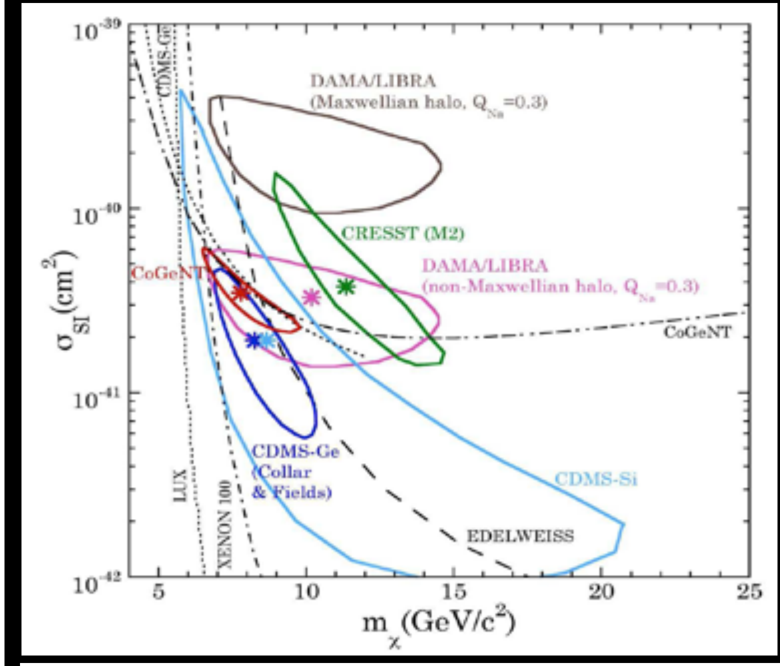


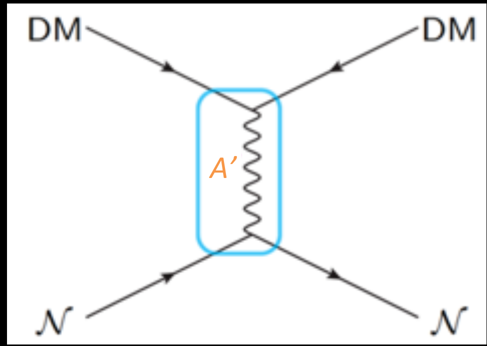
Dark Matter annihilation…



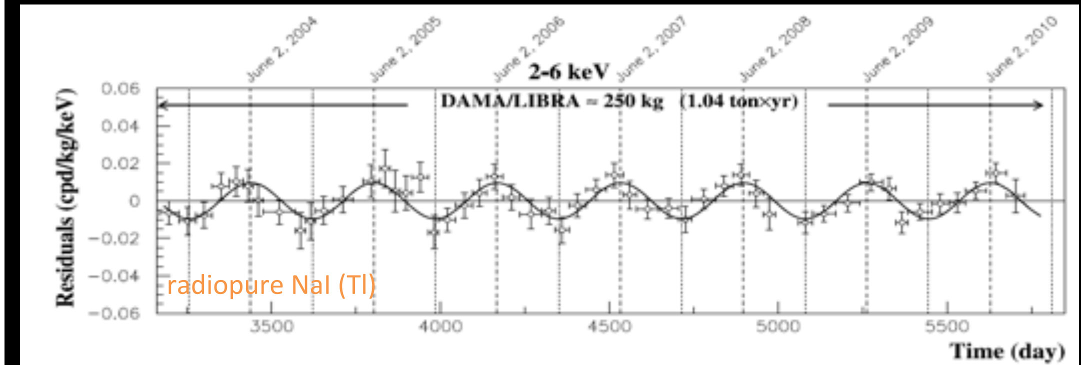
The DAMA-Libra effect

arXiv:1401.3295v1

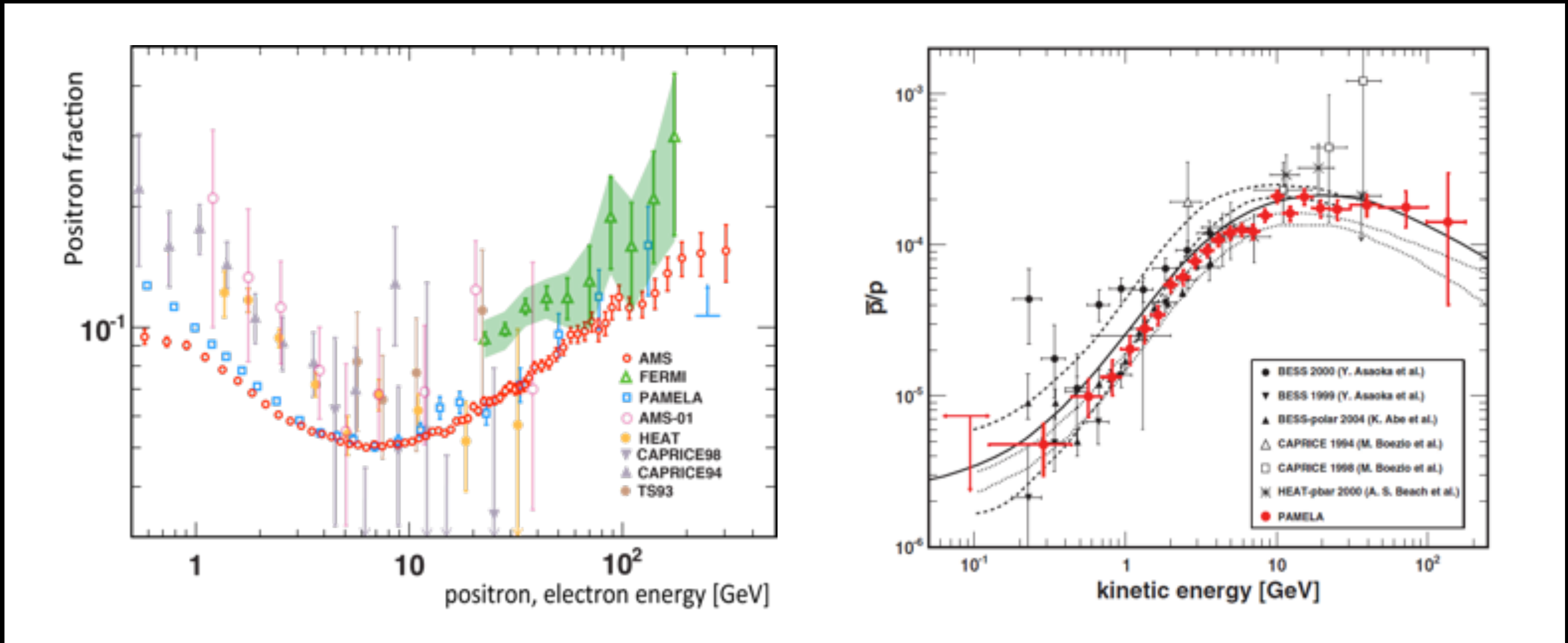




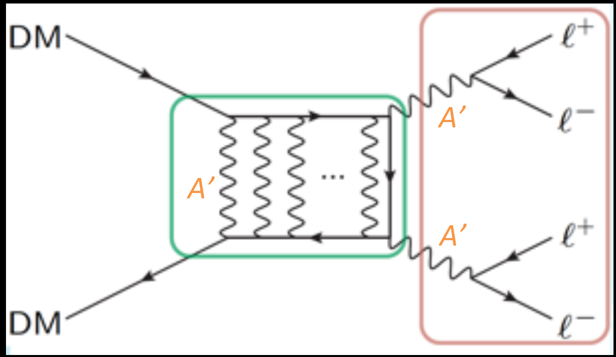
- Nuclear recoil by the exchange of a dark photon
- Independent of χ mass value



Particle astrophysics: PAMELA, AMS



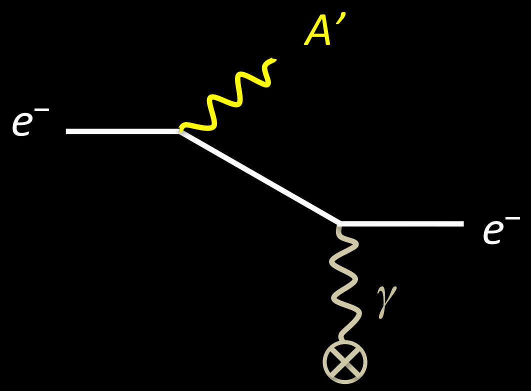
- Positron eccess: PAMELA, FERMI, AMS-02
- No significant excess in antiprotons
  - Consistent with pure secondary production
- Leptofilic dark matter annihilation?
- If DM is the explanation, the **mediator should be light**, < $2m_{\text{proton}}$



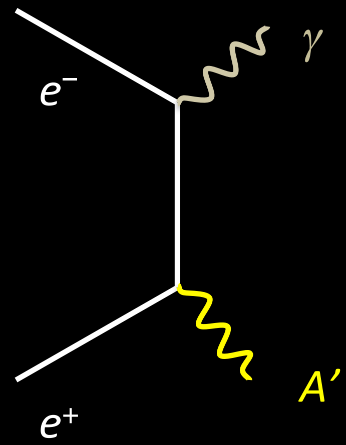
…naturally leptophilic

Dark photon production

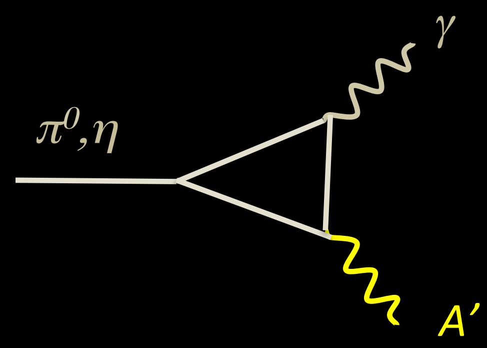
Bremsstrahlung



Annihilation



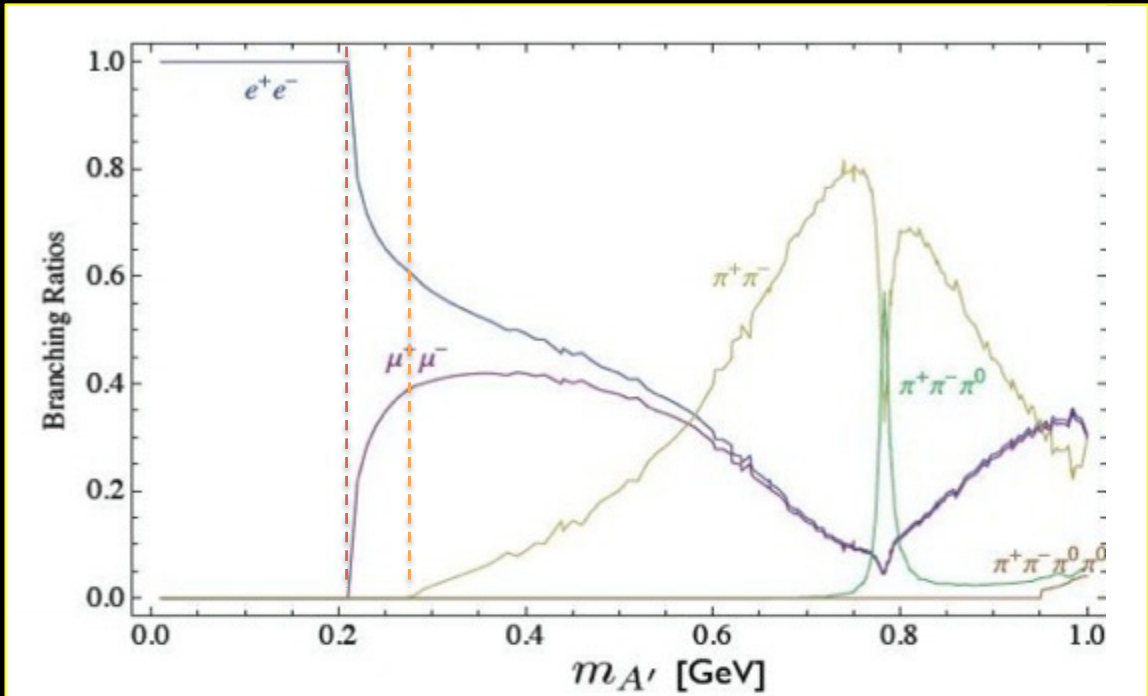
Meson decay



- *A'* can be produced in electron or positron collisions on target by:
  - Bremsstrahlung: e N $\rightarrow$ e N A'
  - Annihilation: $e^{+} e^{-} \rightarrow \gamma A'$
  - Meson decays

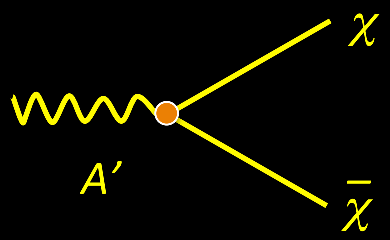
Dark photon visible decays

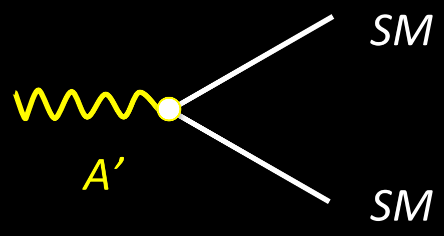
- Assume that no additional lighter states exists in the dark sector with $m_{\chi}<m_{A'}/2$
- Dark photon couples to SM particles through kinetic mixing only (with same coupling εq)
- For $m_{A'}<2\ m_{\mu}$ only decays to e^+e^-



Dark photon invisible decays

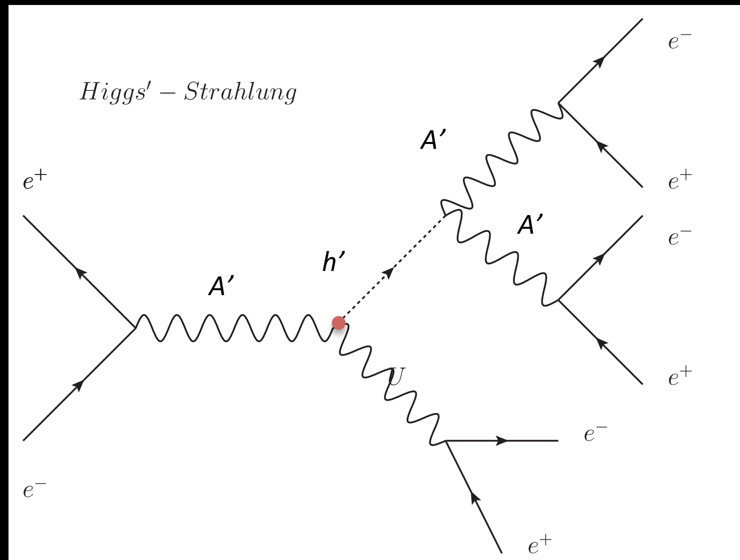
- If a χ state with U(1) charge q_U and coupling constant g_U exists in the dark sector with $m_\chi < m_{A'}/2$, the coupling to the *A'* will be: $q_U g_U$
- $A' \to \bar{\chi}\chi$ will be dominant wrt to visible decays for $\alpha_D > \alpha$, i.e. $|q_U g_U| > \varepsilon e$





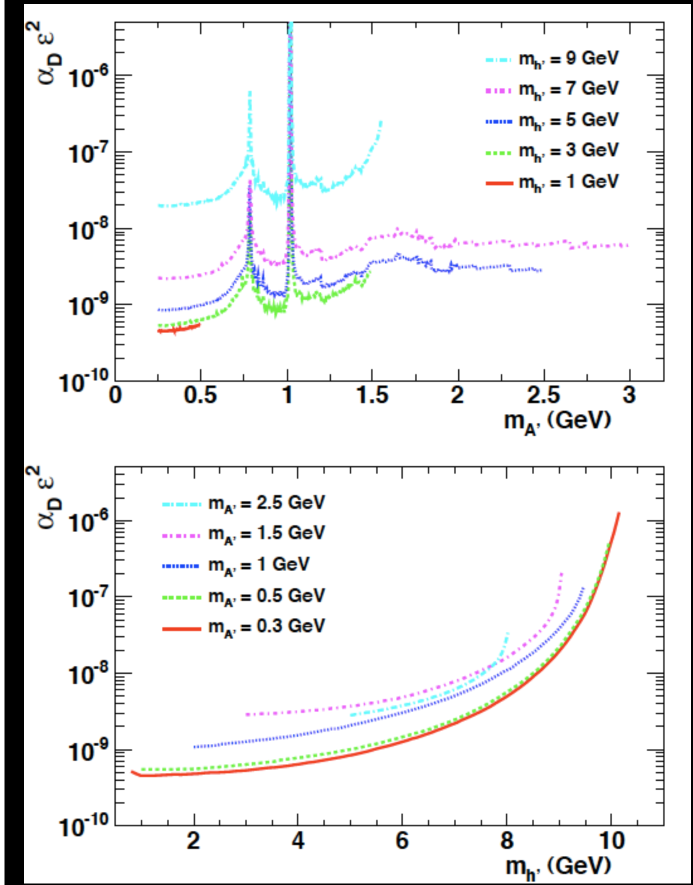
Dark sector with dark Higgs

- 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 $e^+e^- \rightarrow A' h'$
  - 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

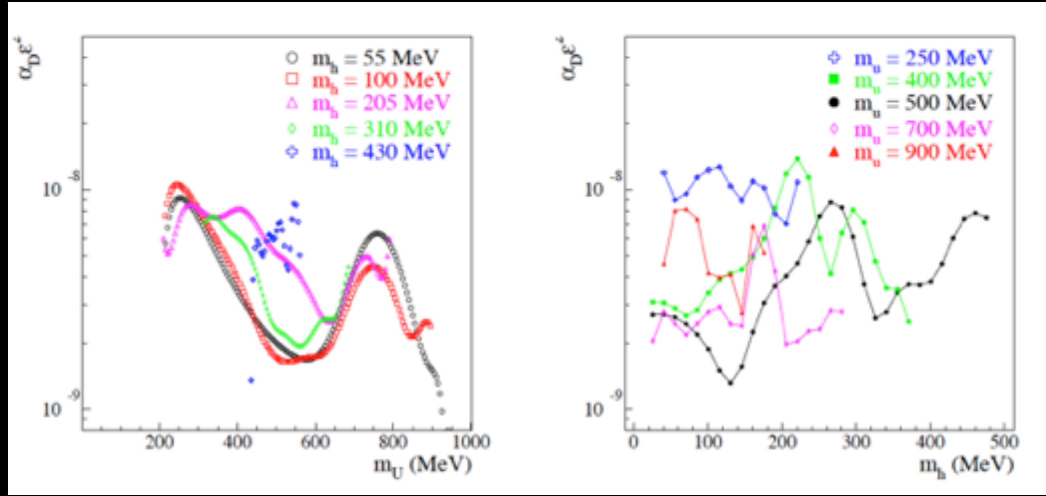


Dark photon + dark Higgs searches

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

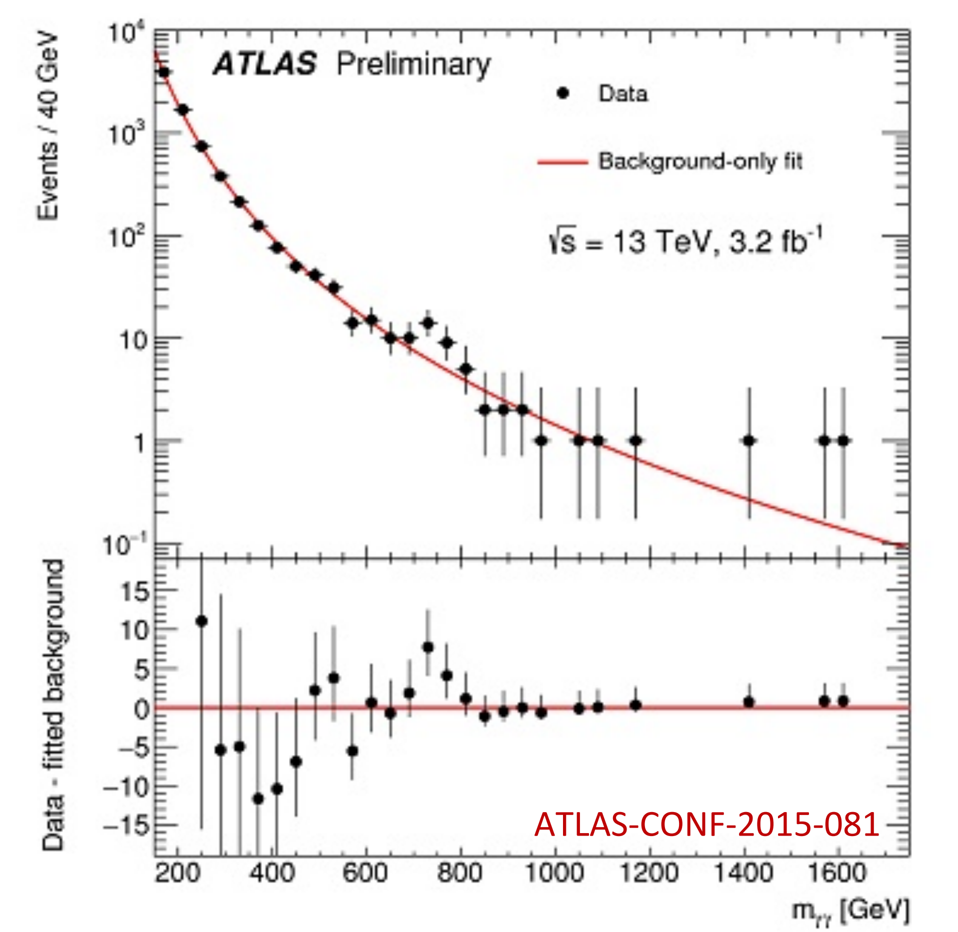


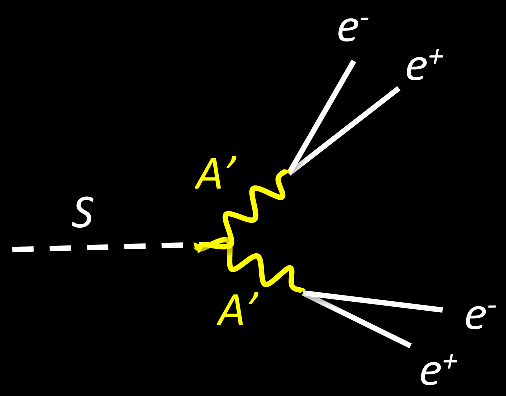
KLOE-2 arXiv:1501.06795



- **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…



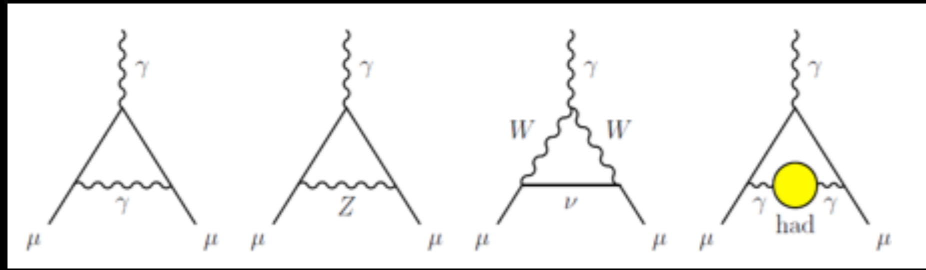


Photons, Photon Jets and Dark Photons at 750 GeV and Beyond, arXiv:1602.04692

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

Un motivo di particolare interesse

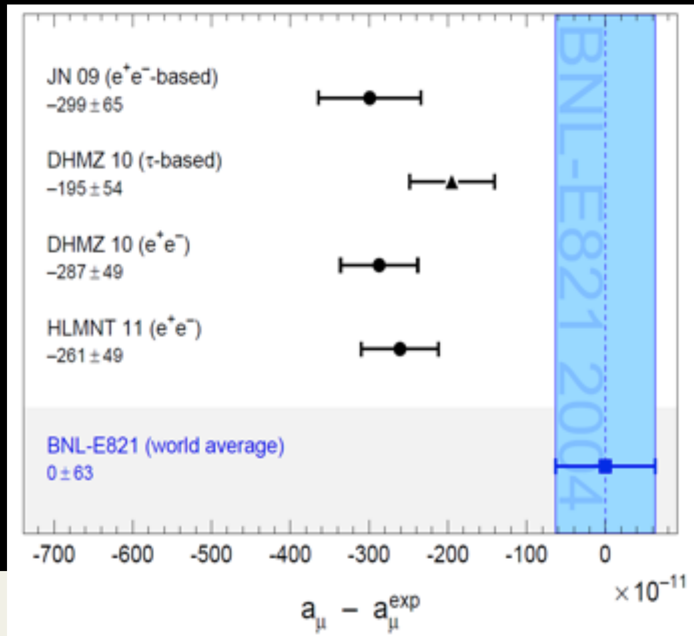
$(g\text{-}2)_\mu$ in the **Standard Model**

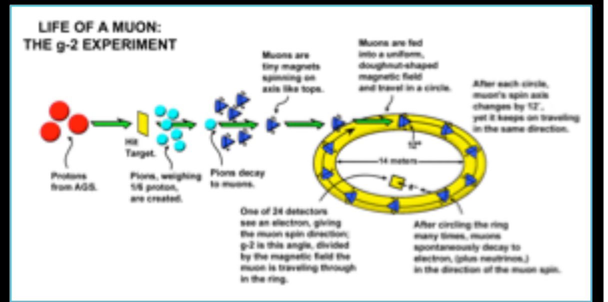


About **3σ discrepancy** between **theory** and **experiment**

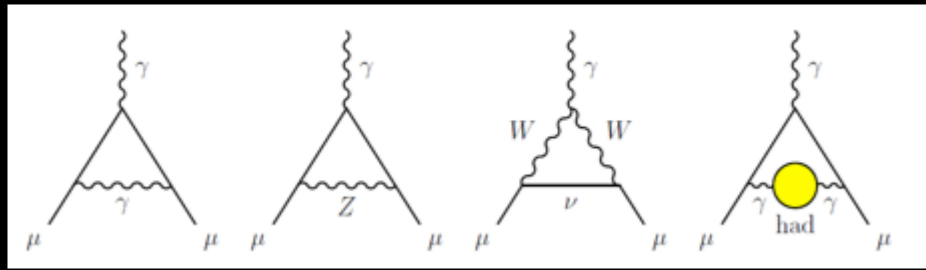
(3.6σ, if taking into account only $e^+e^- \rightarrow$ hadrons)

Additional diagram with dark photon exchange can fix the discrepancy…

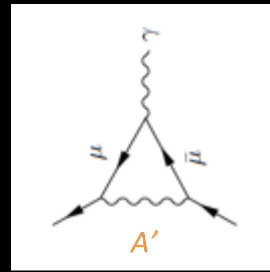




Muon g-2 SM discrepancy

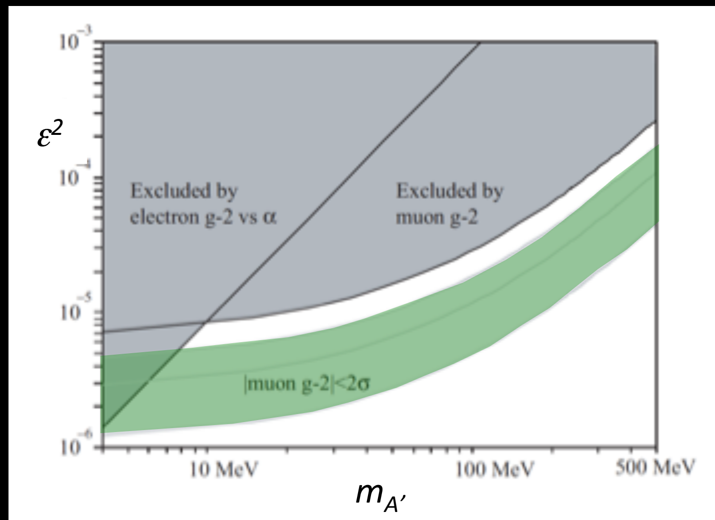


A' contribution



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

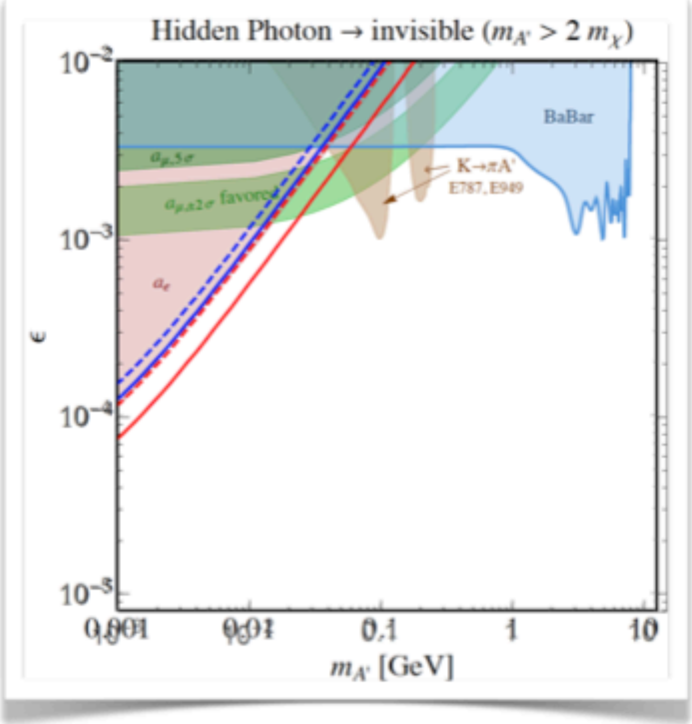
- The two most precise determinations of fine structure constant disagree at 1.5σ level
- One can reasonably argue for a more conservative constraint

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

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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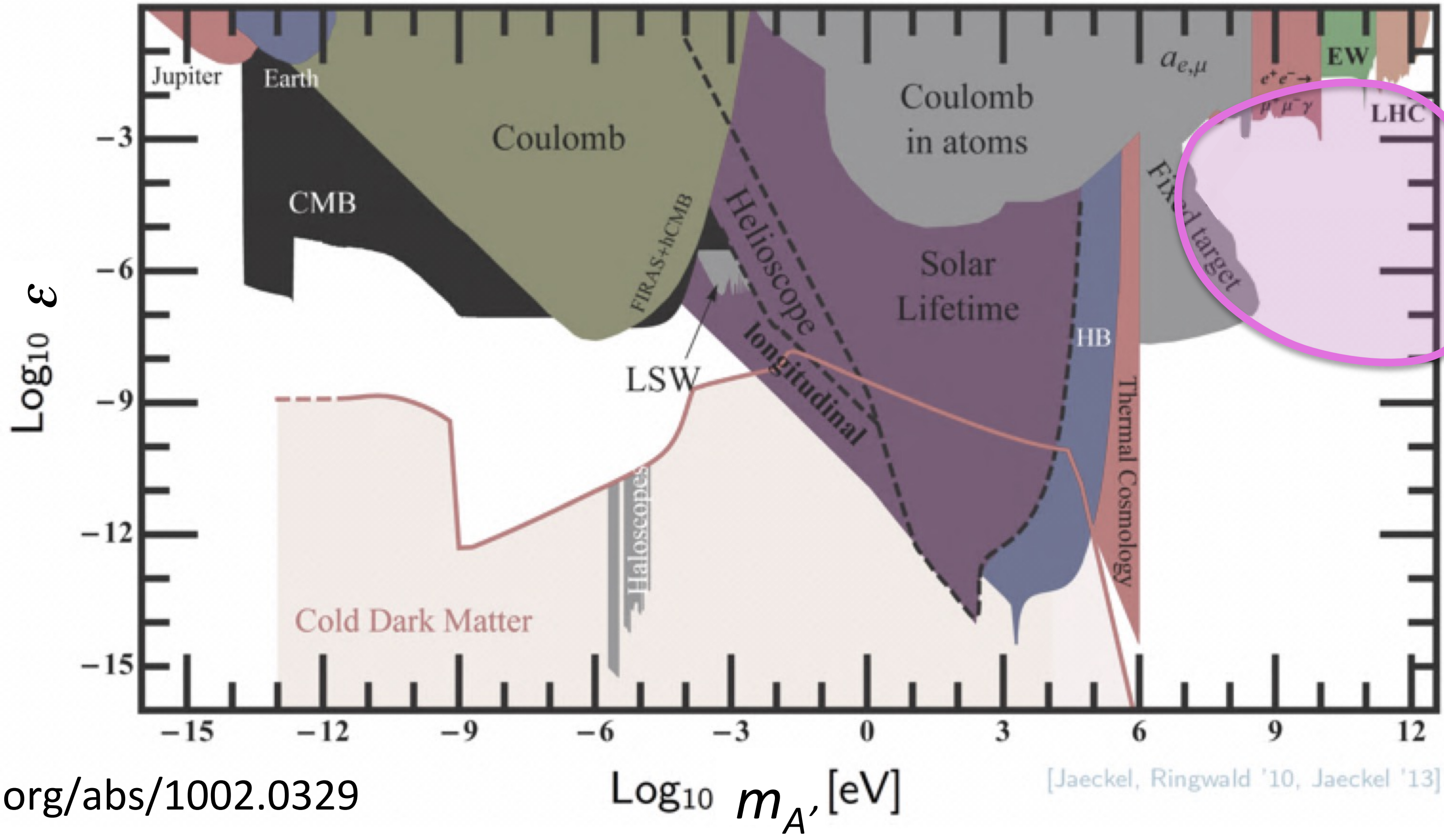
Where to look for dark photons?



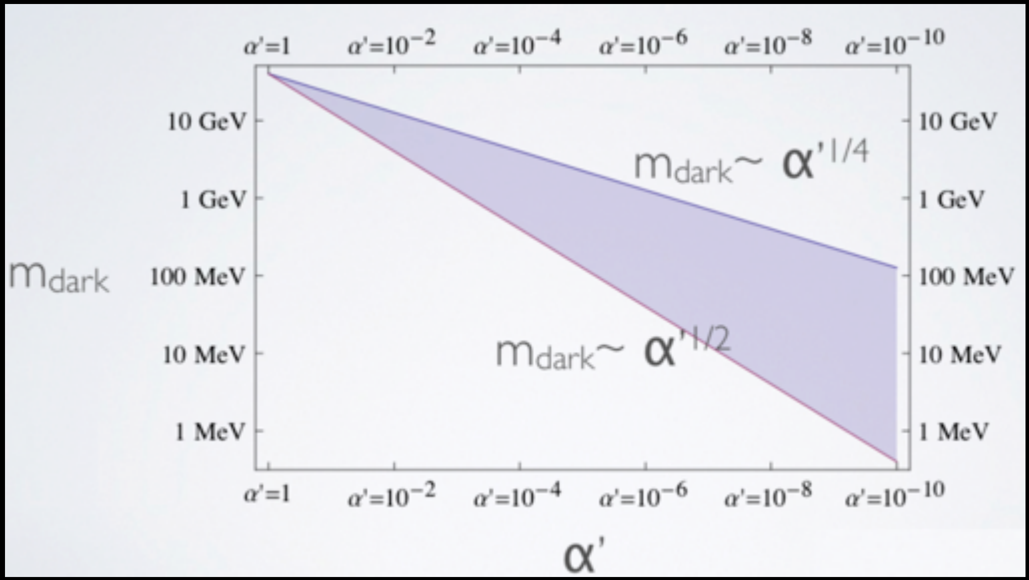
https://arxiv.org/abs/1002.0329

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 $m_{A'}/m_W \sim \varepsilon - \varepsilon^{1/2}$

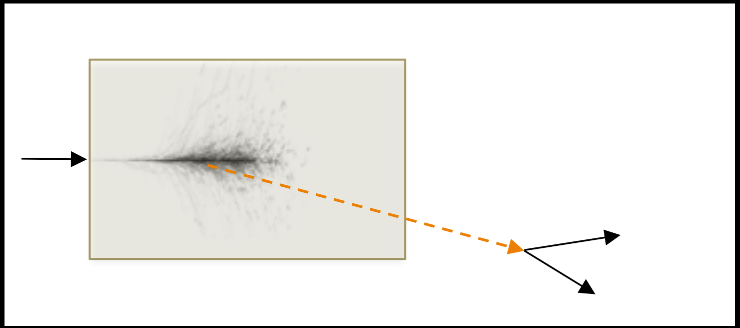
leading to a MeV-GeV mass scale

N. Wiener

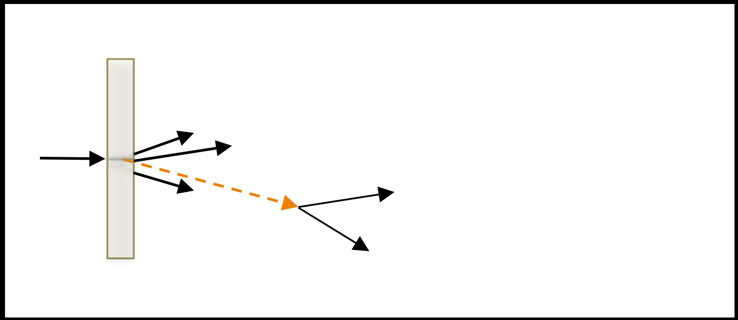


Dark photon experiments with accelerators

- Thick target (beam-dump)
  - Absorb all SM backgrounds
  - Look for visible decays (e+ e−, μ+ μ−, …)



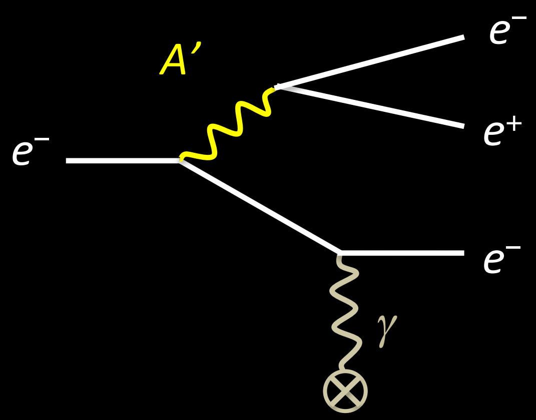
- Thin target + decay of dark photon:
  - Decay to visible particles (e+ e−, μ+ μ−, …)
    - "Bump hunting", looking for a peak in the invariant mass
    - Displaced vertices, looking for long-lived particles
  - Decay to invisible particles
    - Look for missing mass
    - DM particles recoil



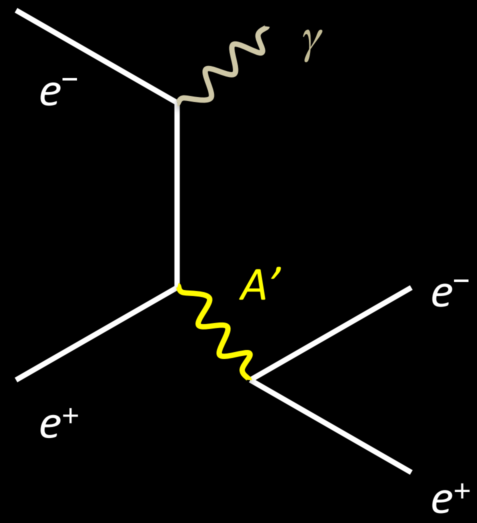
- Meson decays
- Dark particles scattering

Why fixed target?

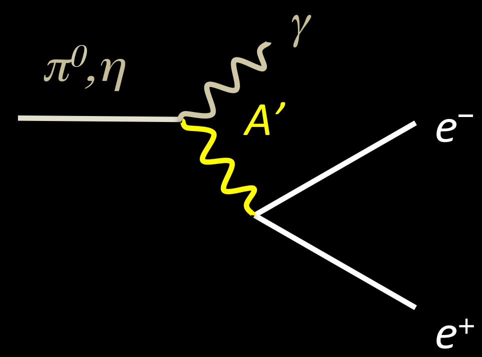
Bremsstrahlung



Annihilation



Meson decay



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

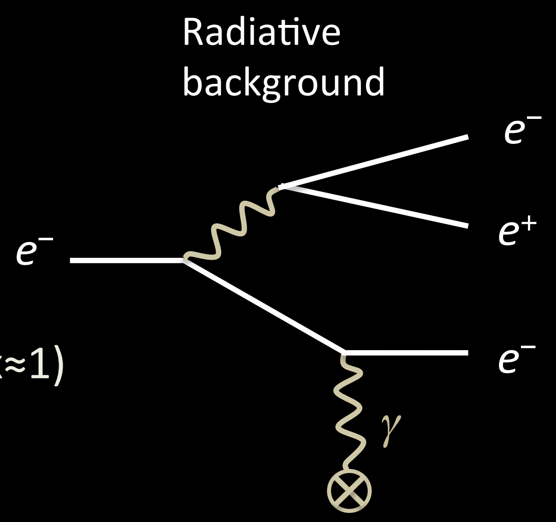
O(pb)

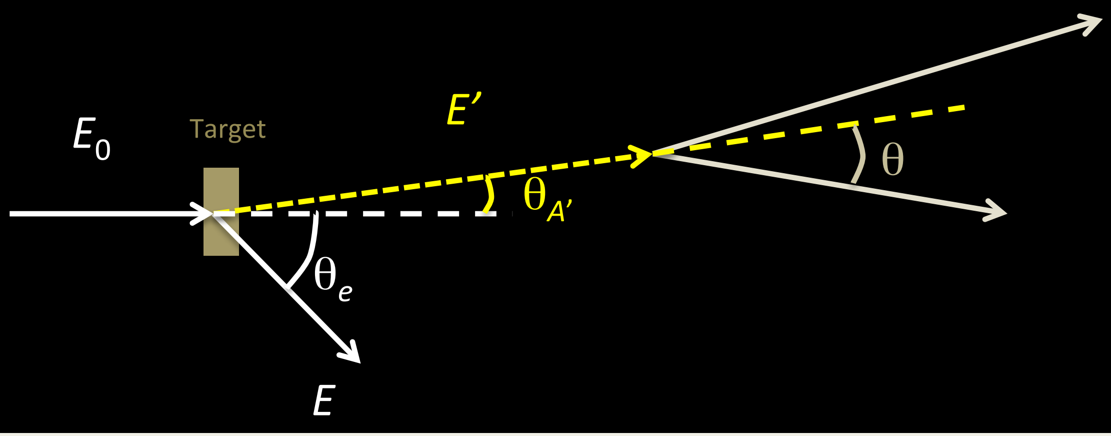
$$\sigma^{\mathrm{coll}}_{A'} \sim \frac{\alpha^2 \varepsilon^2}{E^2}$$

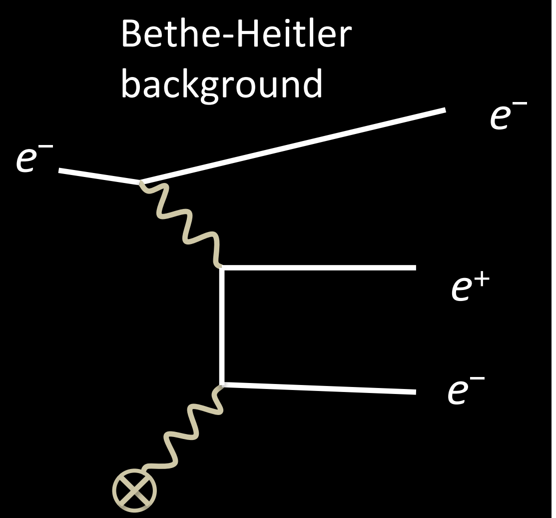
O(fb)

Fixed target experiments

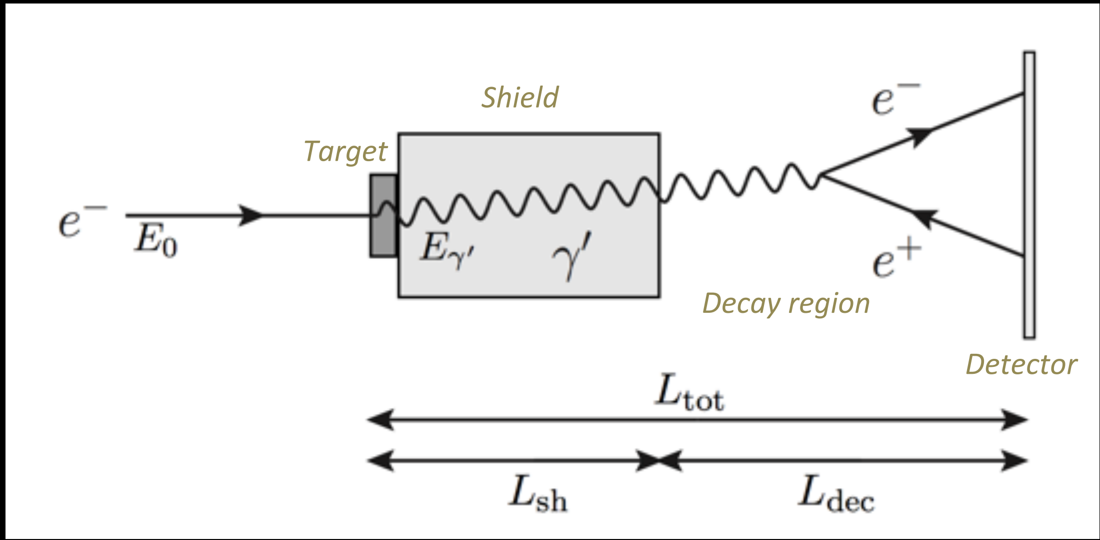
- Main backgrounds: SM Bremsstrahlung + Bethe-Heitler
- Kinematics:
  - *A'* takes nearly all the beam energy E_0 (sharply peaked at x≈1)
  - Electron takes a small energy ≈ $m_{A'}$
  - *A'* emission almost collinear to the beam: $\theta_{A'}=(m_{A'}/E_0)^{3/2}$
  - Electron going at "wide" angle: $\theta_e=(m_{A'}/E_0)^{1/2}$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







Electron beam-dump experiments

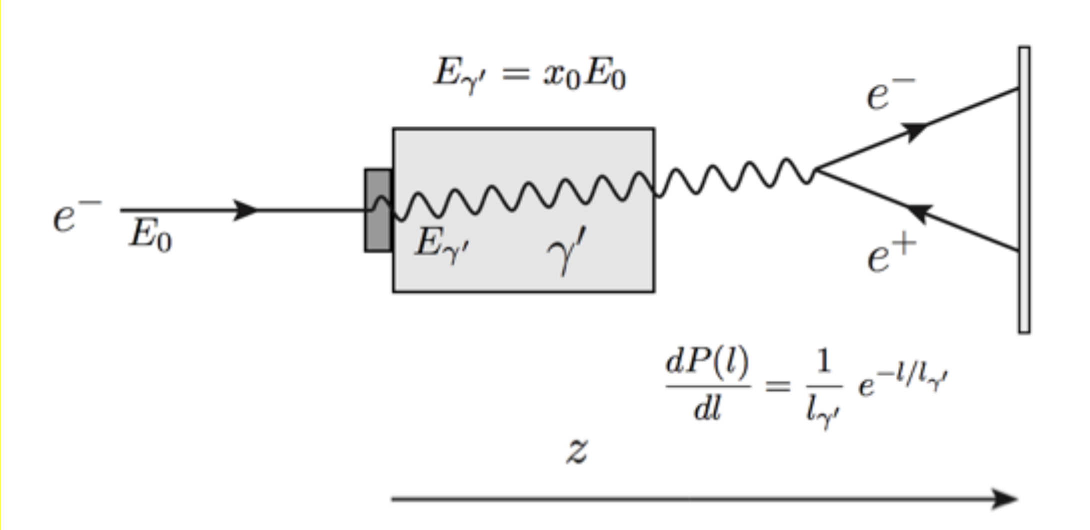


Luminosity: $\mathcal{L}^{\mathrm{ft}} \simeq N_e \frac{N_0 \rho_{\mathrm{sh}} l_{\mathrm{sh}}}{A}$

At colliders: $\mathcal{L}^{\mathrm{coll}} \simeq \frac{N_e^2}{\mathcal{A}_b}$ → Beam section

In addition to cross section advantage

Electron beam-dump experiments



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

Electron energy distribution due to the interaction in target+shield

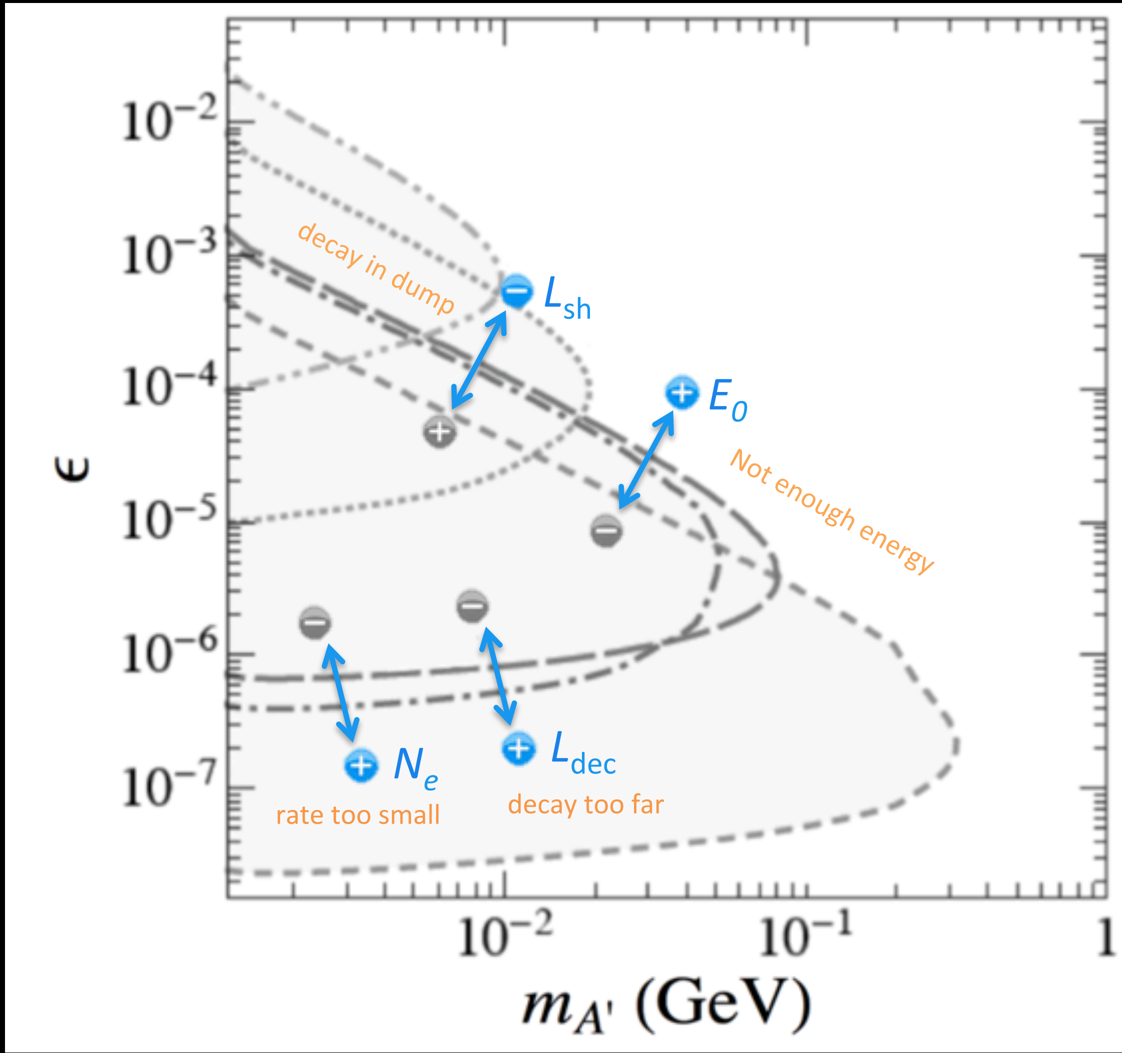
Decay probability of γ' after shield

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

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

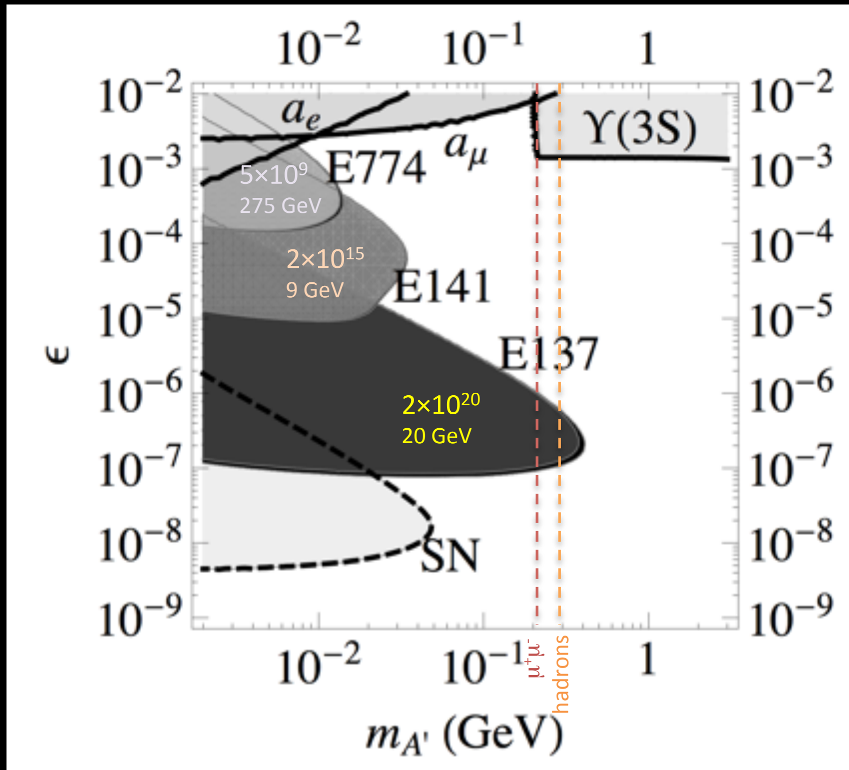
$d\sigma/dx$ for γ' production by Bremsstrahlung

Limits from electron beam-dump experiments



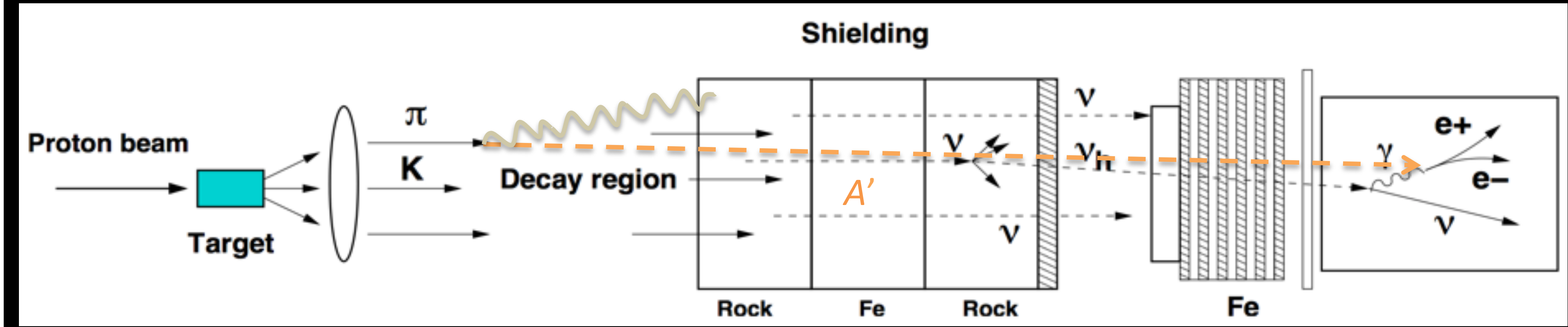
Limits from electron beam-dump experiments

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

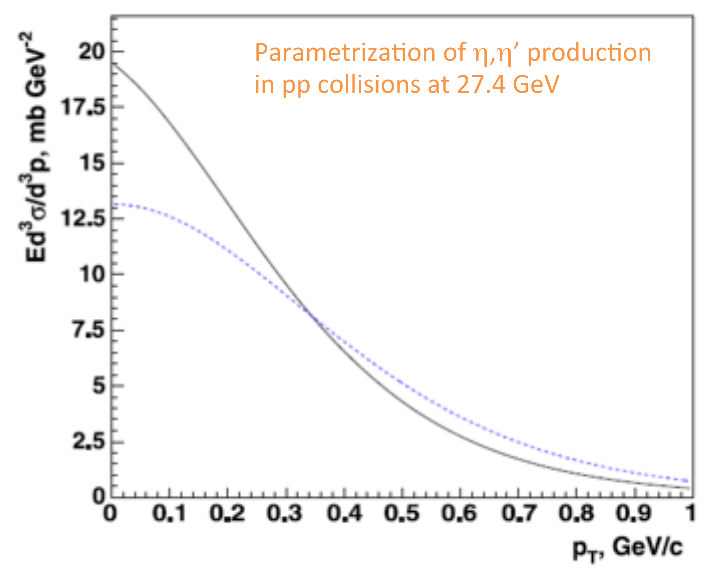


Limits from past experiments: proton beam dump

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

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 $\nu_H \rightarrow \nu e^+ e^-$

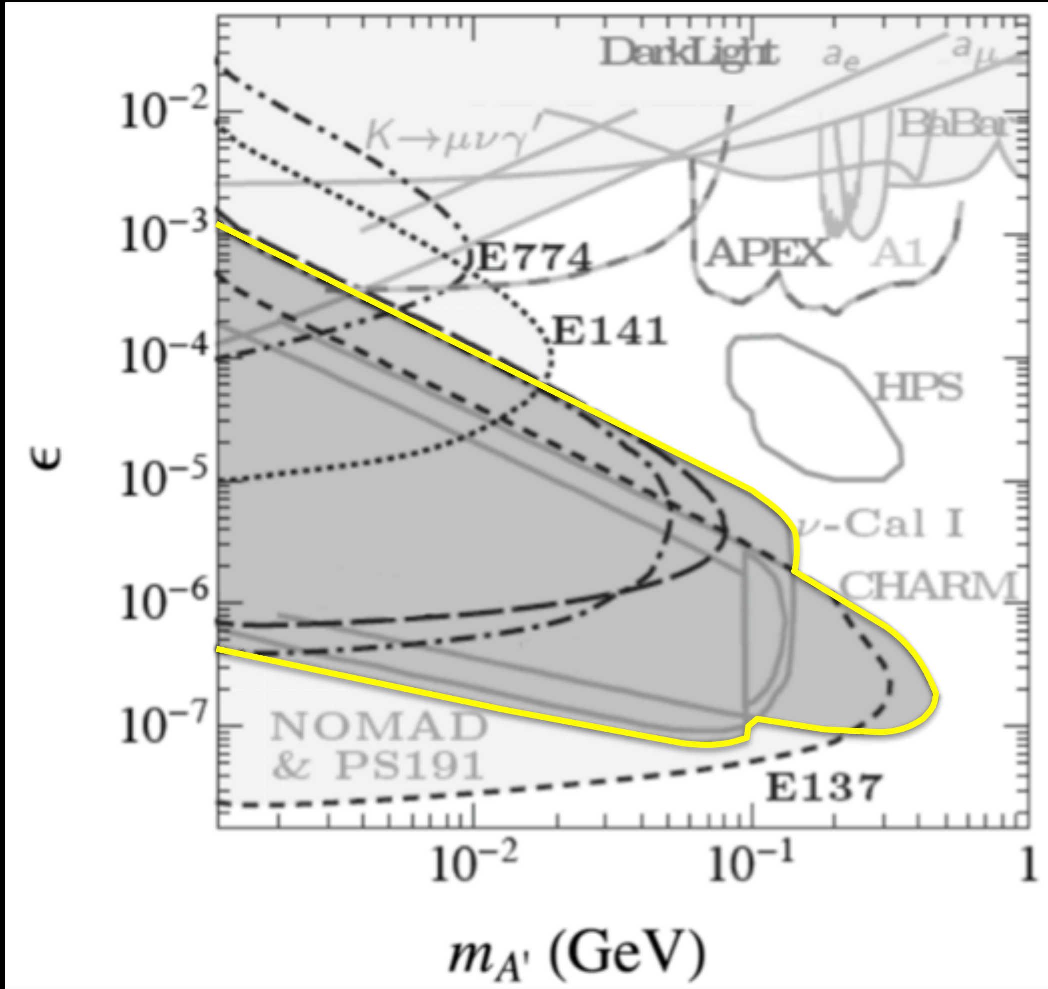
Look for $\pi^0 \rightarrow \gamma A'$

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

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

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

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



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

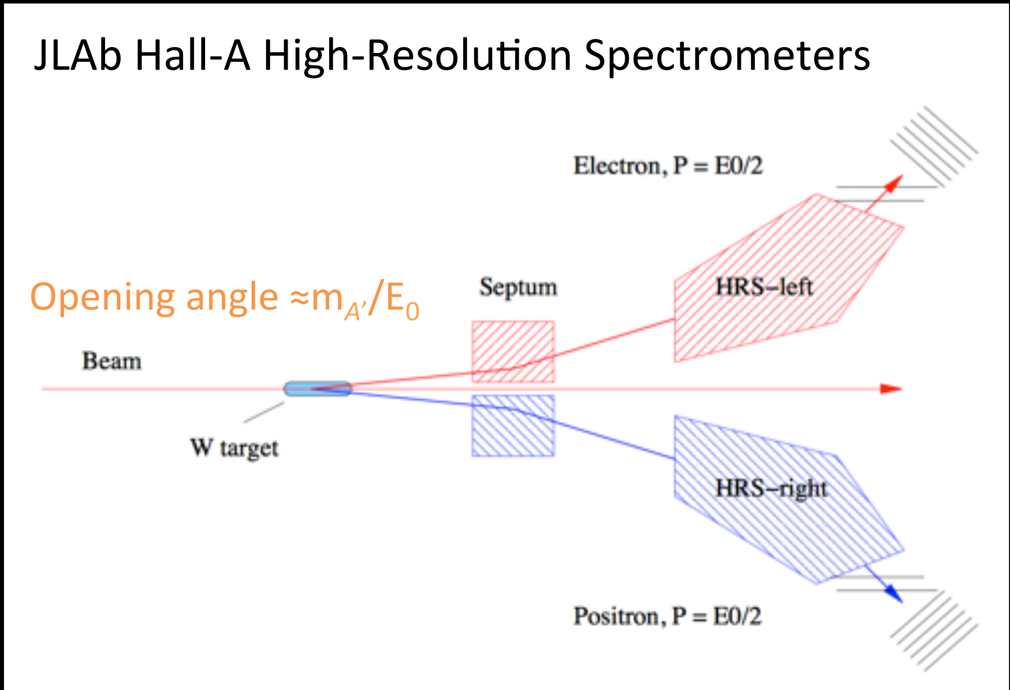
Coming soon:

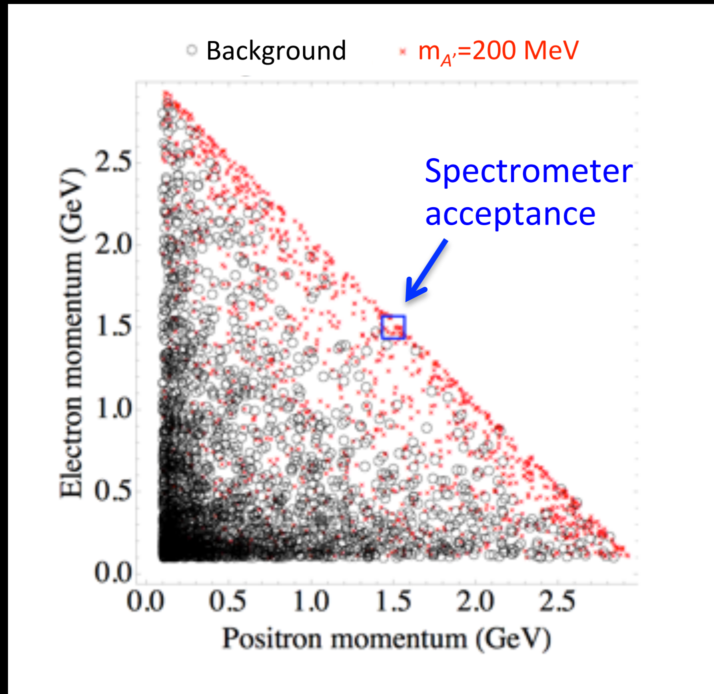
- PADME at Frascati

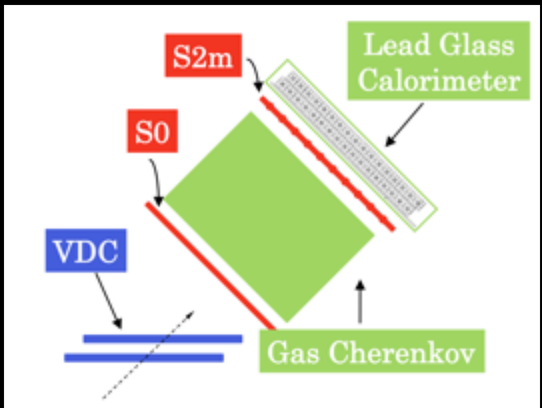
Proposed:

- 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







$0.3<p<4.0$ 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

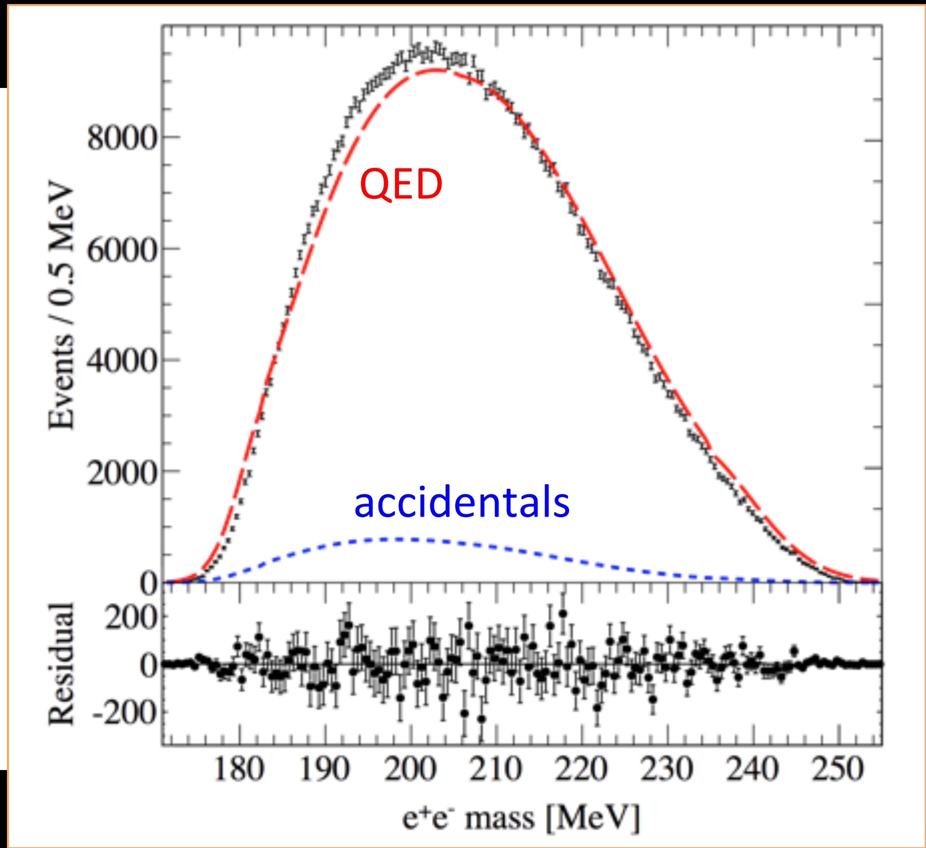
Pion rejection:

- 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

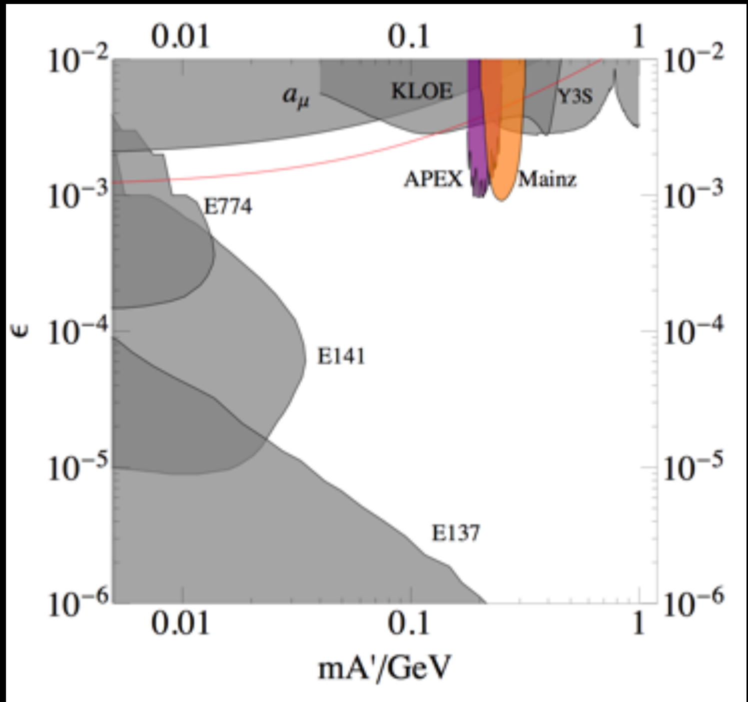
Final event sample trigger:

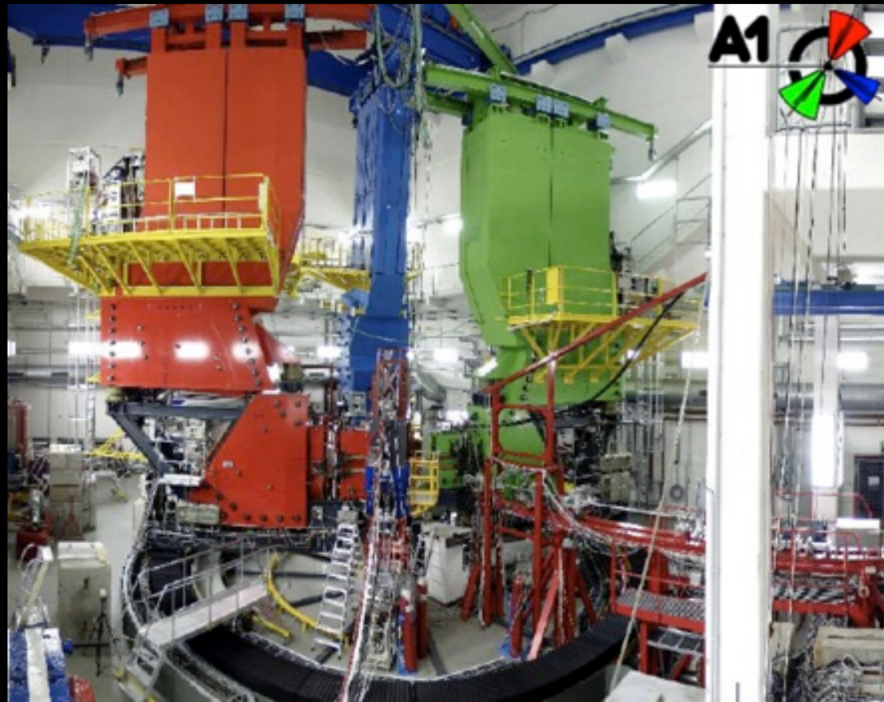
- Double coincidence gas Cherenkov signal within 12.5 ns window in each arm

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



MAMI A1



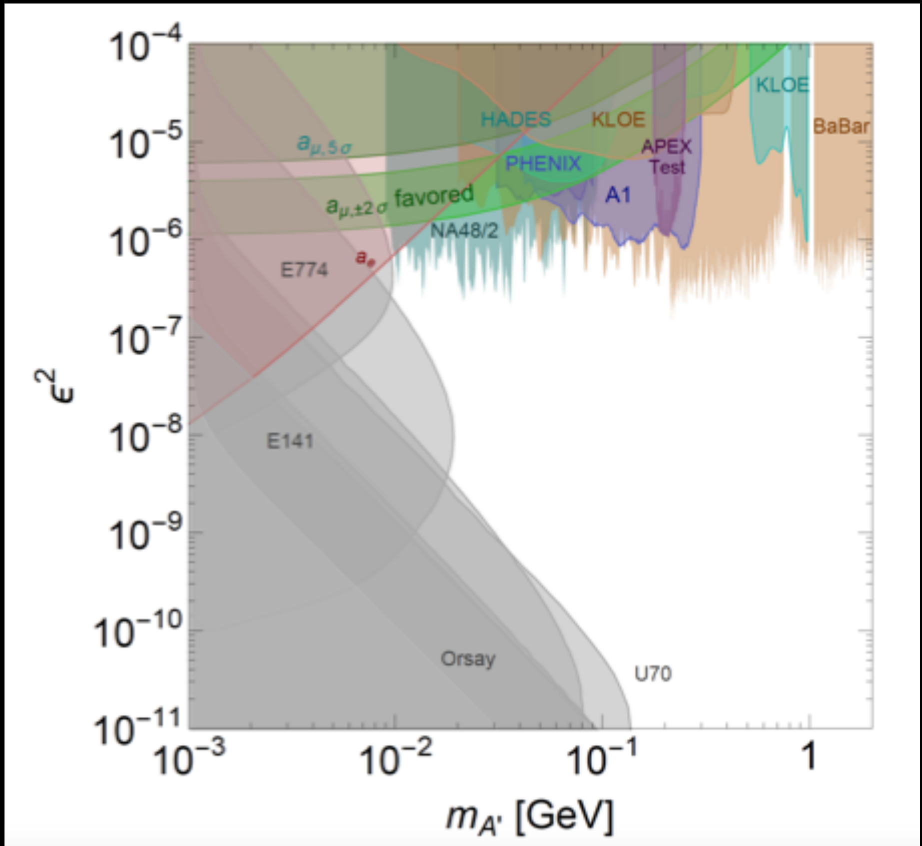


JLAB Hall-A APEX
n×1.1 GeV, continuous, 200 μA beam

MAMI A1
855 MeV, continuous, 90 μA beam

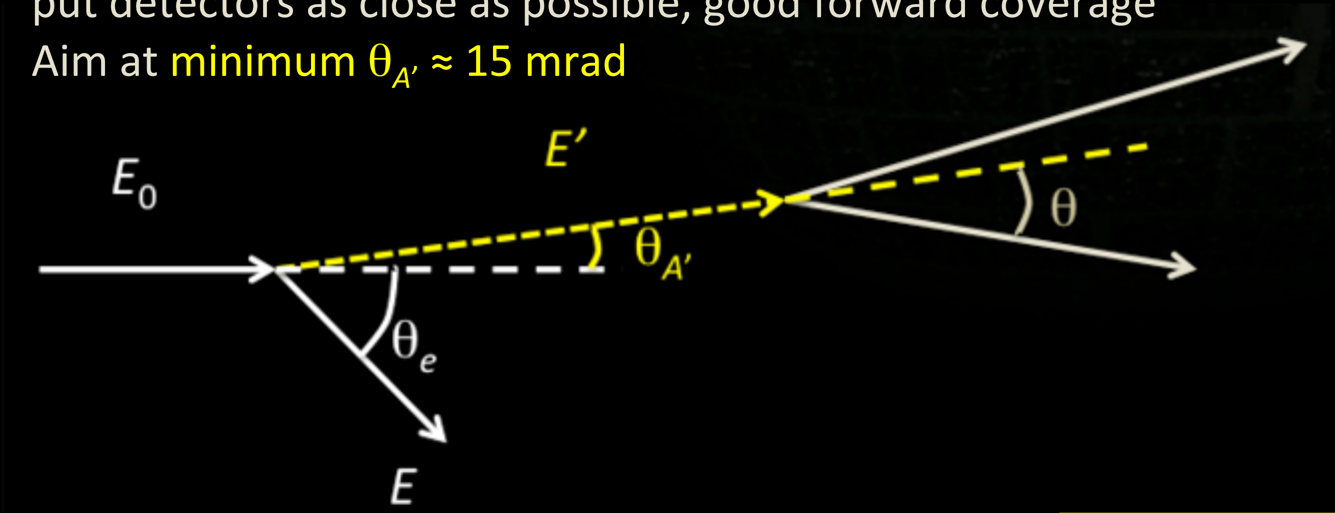
Summary of limits from visible decays

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

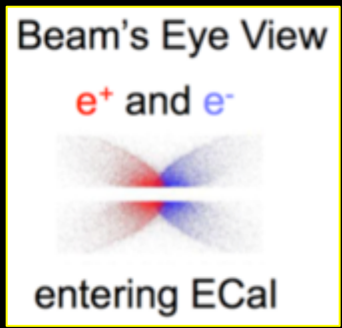


HPS

- 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

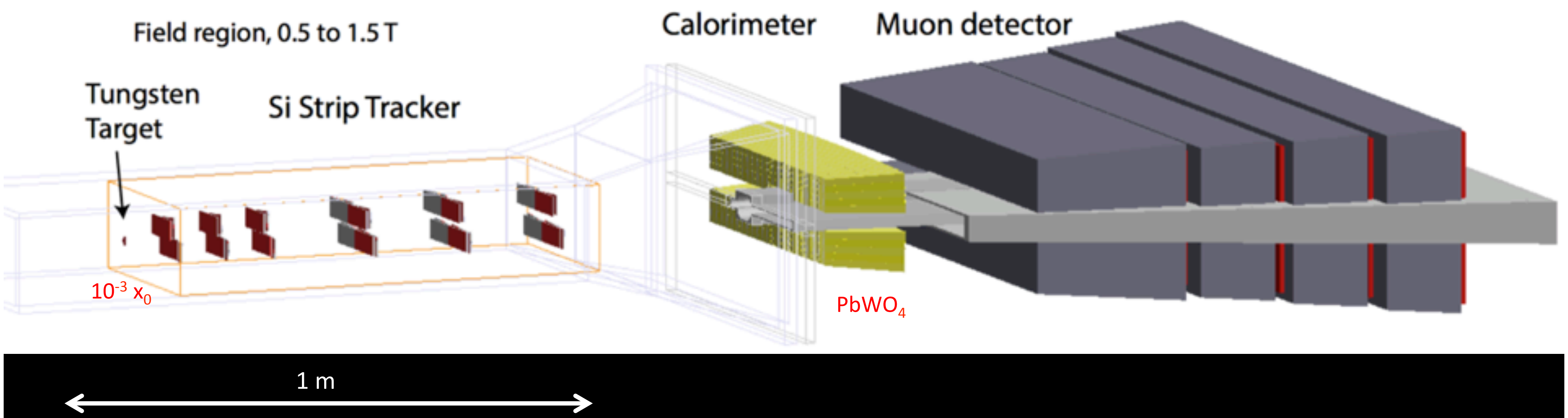


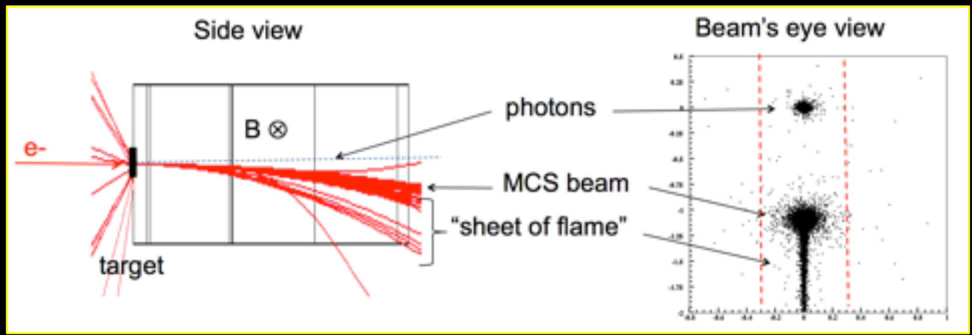
- Bump hunting needs good momentum/mass resolution
- Good tracking and analyzing magnet
- Aim at $\Delta m/m \approx 1\%$ and $\Delta z \approx 1$ mm

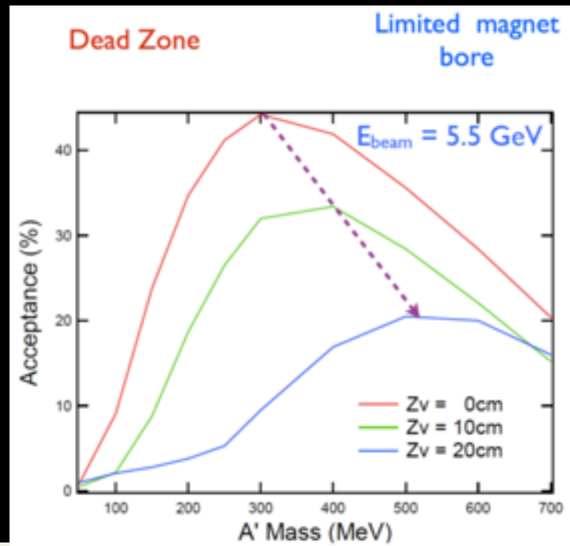


- Trigger with a high rate ECAL
- Magnet+ECAL to select e^+ and e^-
- Magnet+muon detector to select μ^+ and μ^-

HPS





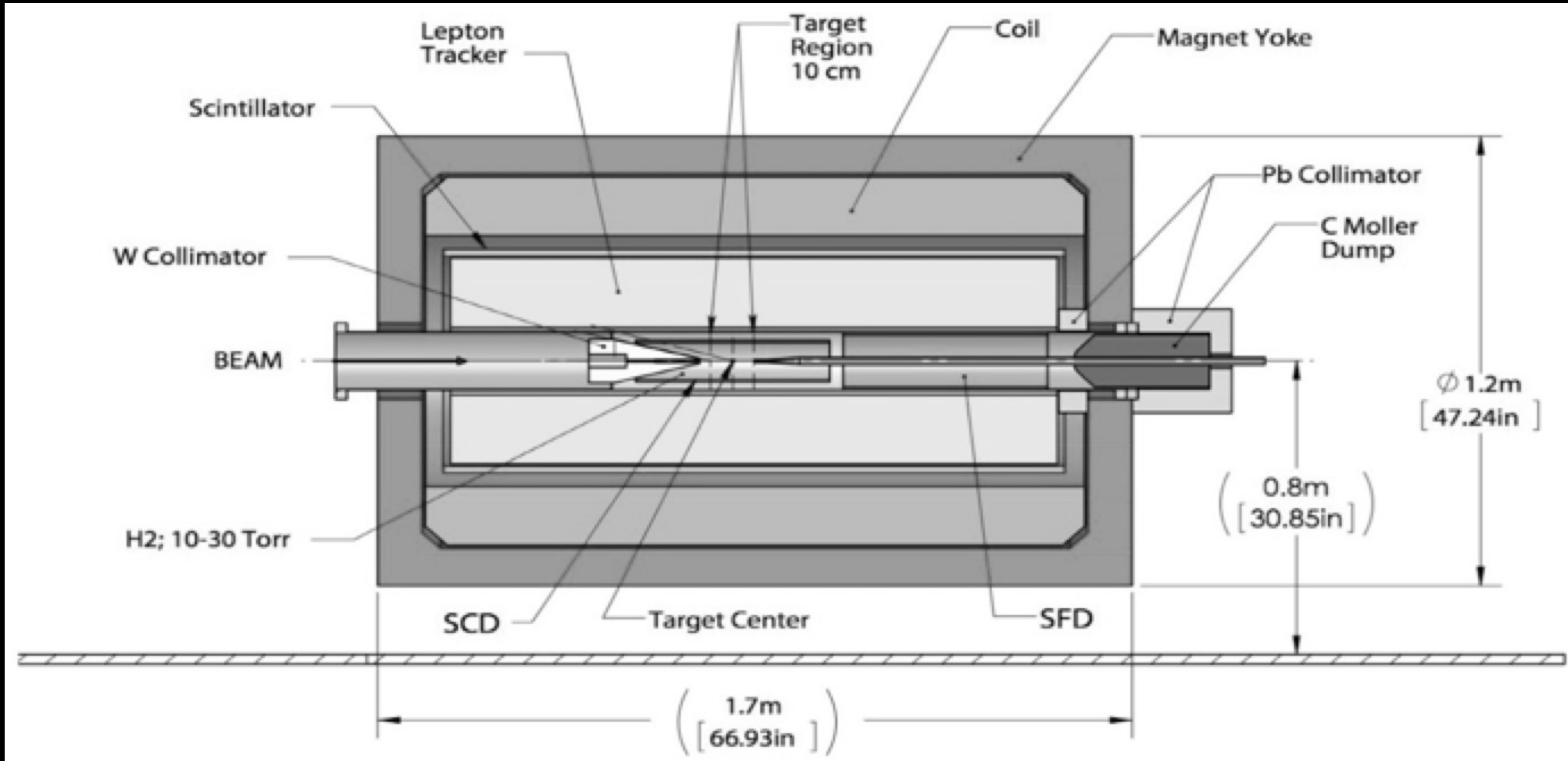


Detectors split in two halves to let the beam pass through

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

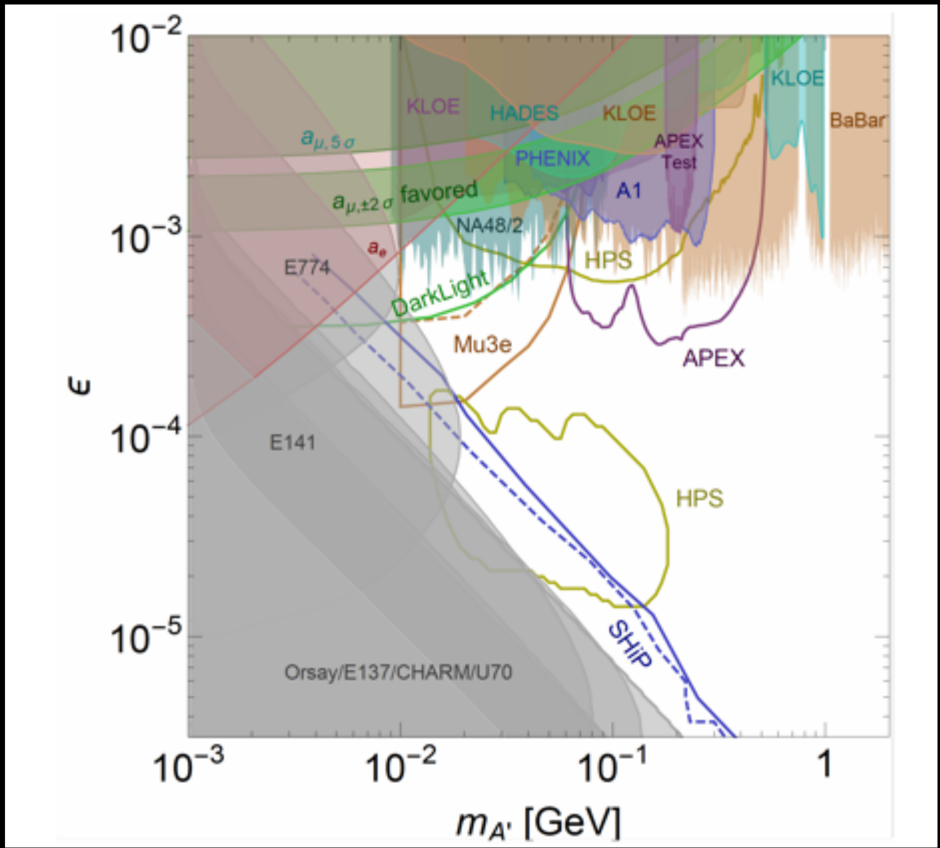


Test performed on prototype vacuum chamber to assess beam transport feasibility

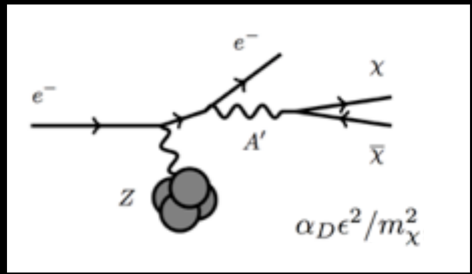
Summary of limits from visible decays

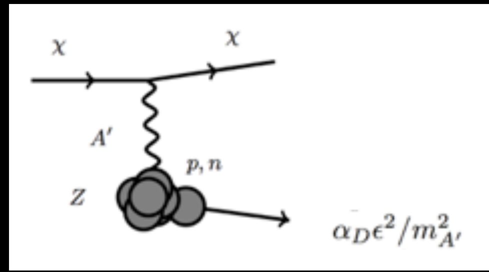
Practically, all the $(g\text{-}2)_\mu$ favored band already excluded

Still large interest for excluding the uncovered parameter space

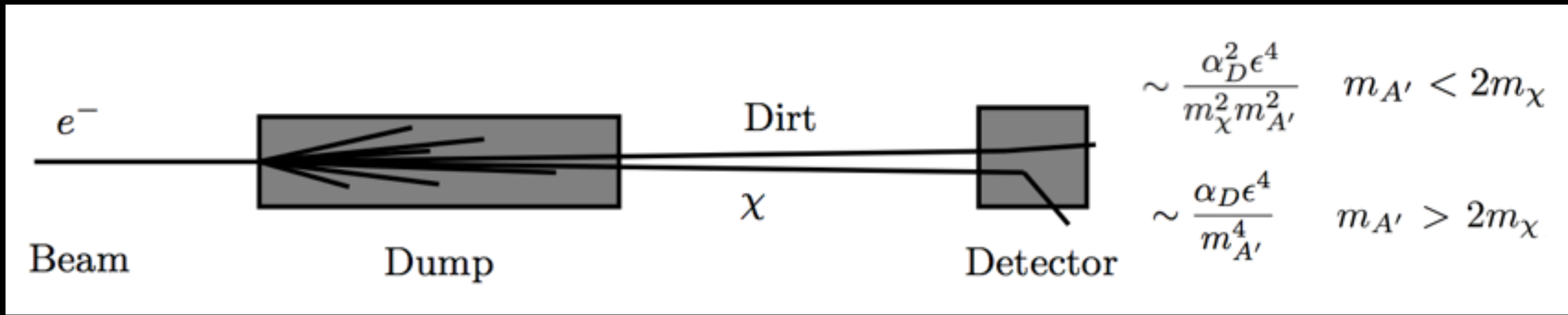


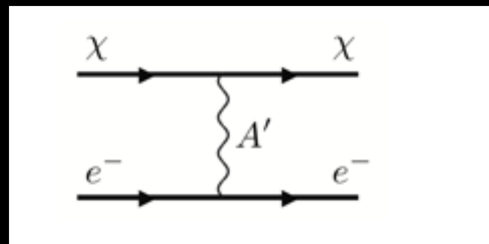
Invisible decays: a dark matter beam





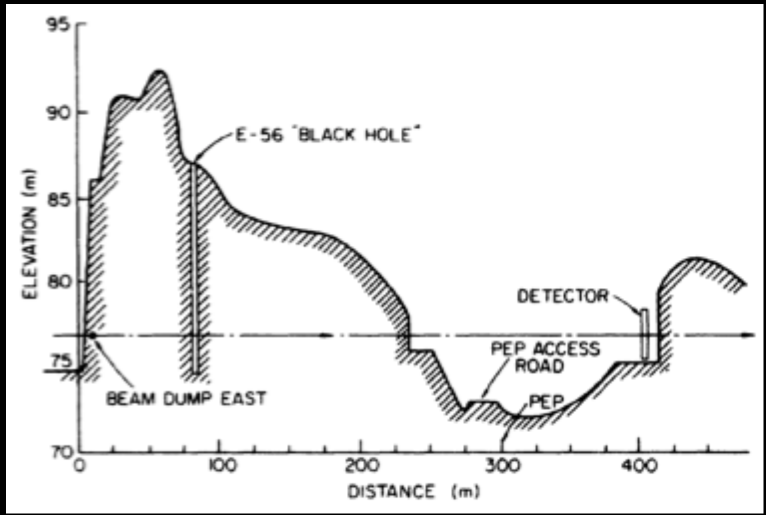
Scattering on nuclei





Elastic scattering on electrons

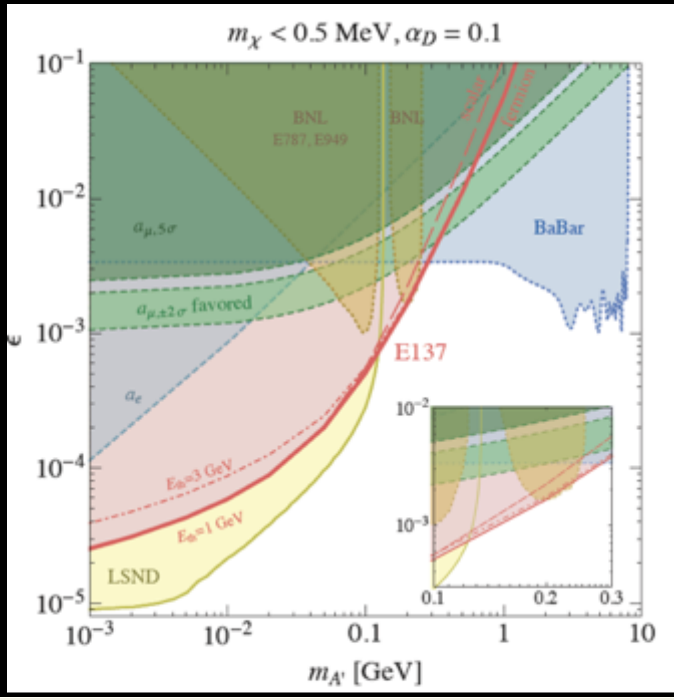
Back to past experiments



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

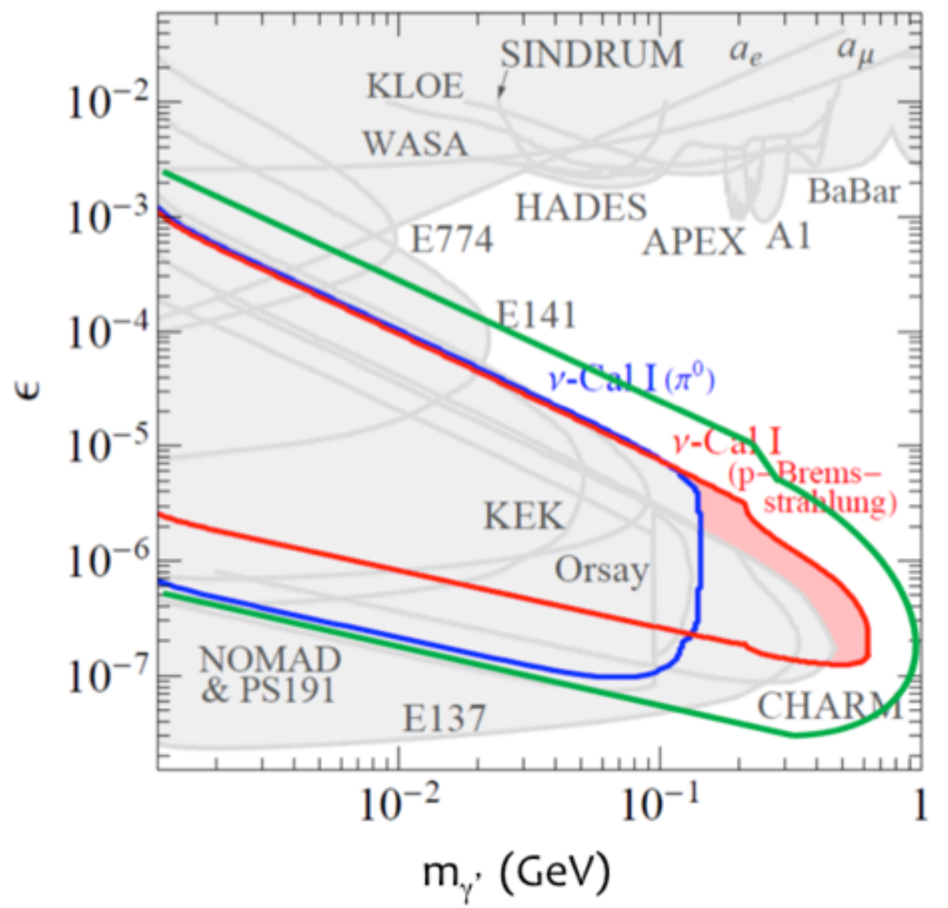
arXiv:1406.2698v1

χe elastic scattering

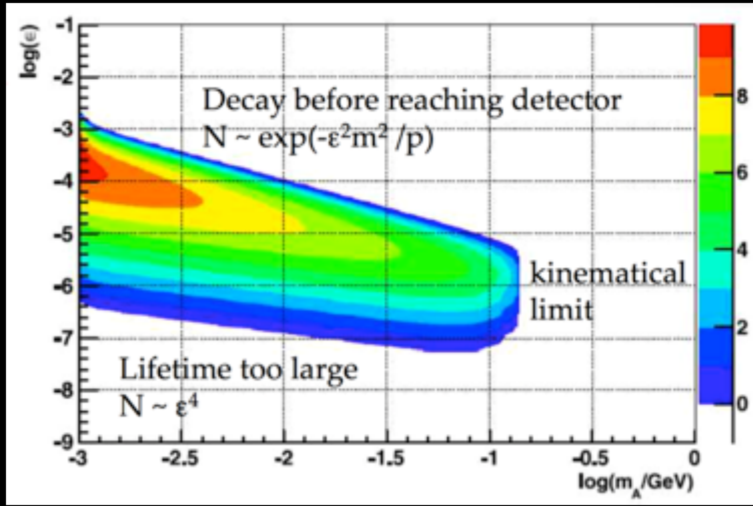


LSND
π^0 decays to $\gamma A'$ from LAMPF 800 MeV protons
10^{23} POT
30 m off-axis detector, 170 ton mineral oil

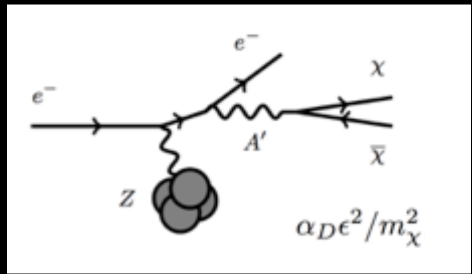
Possible future proton beam dumps: SHIP at SPS

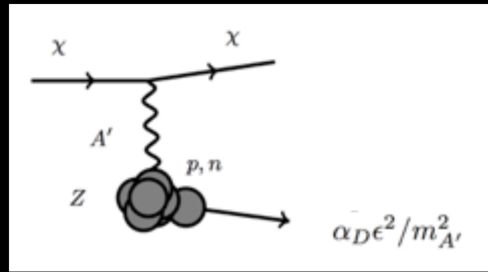


10 signal events

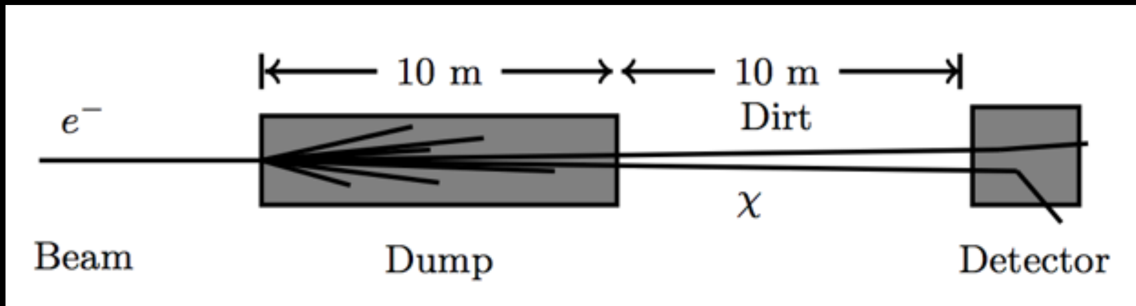


A new scattering experiment: BDX at JLAB





Scattering on nuclei



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

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

Backgrounds:

- Neutrino production
- Cosmogenic muons and neutrons

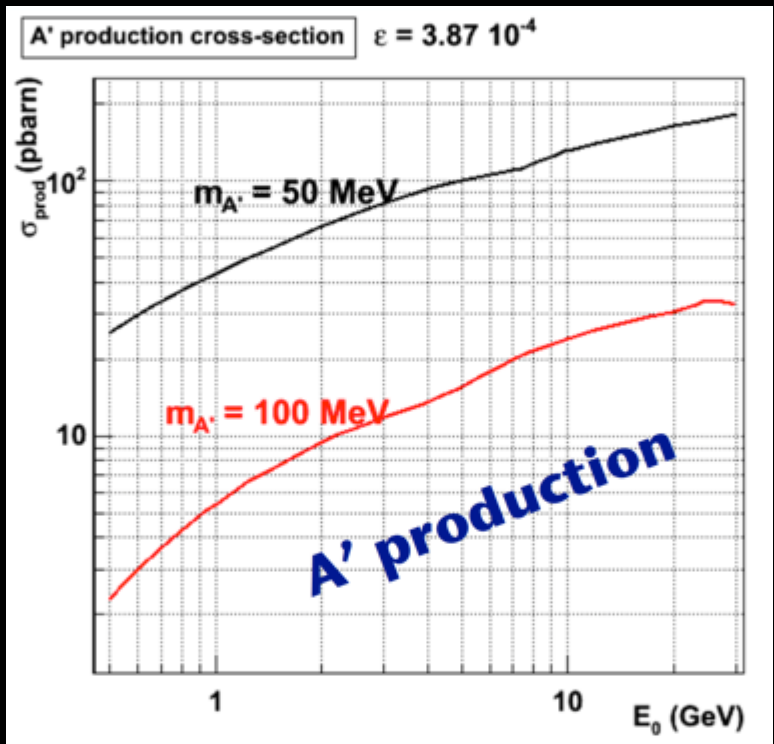
Scintillator 1 m^3

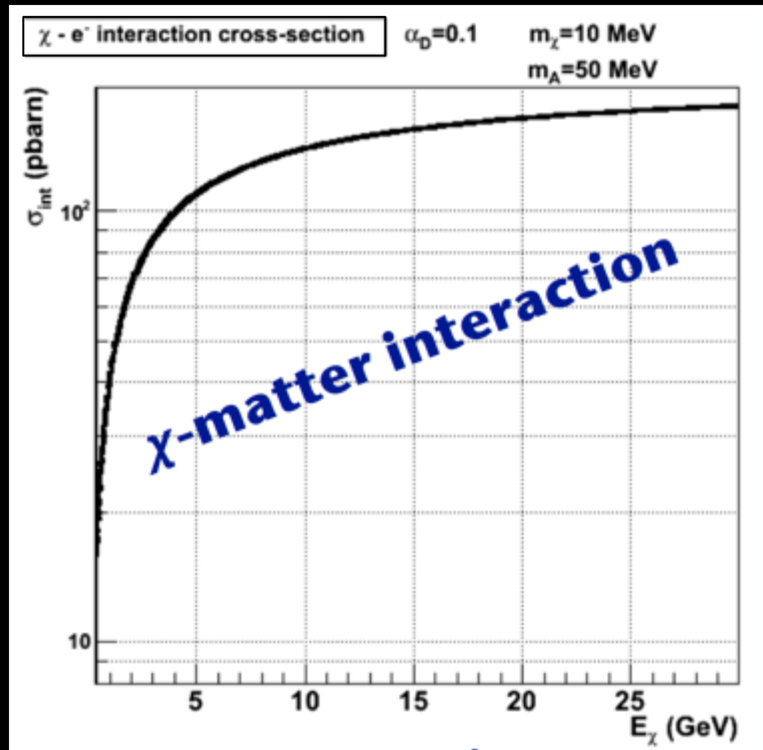
1 MeV/10 MeV e^+e^- detection threshold

LOI presented to JLAB PAC

Scattering experiment: BDX at JLAB

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

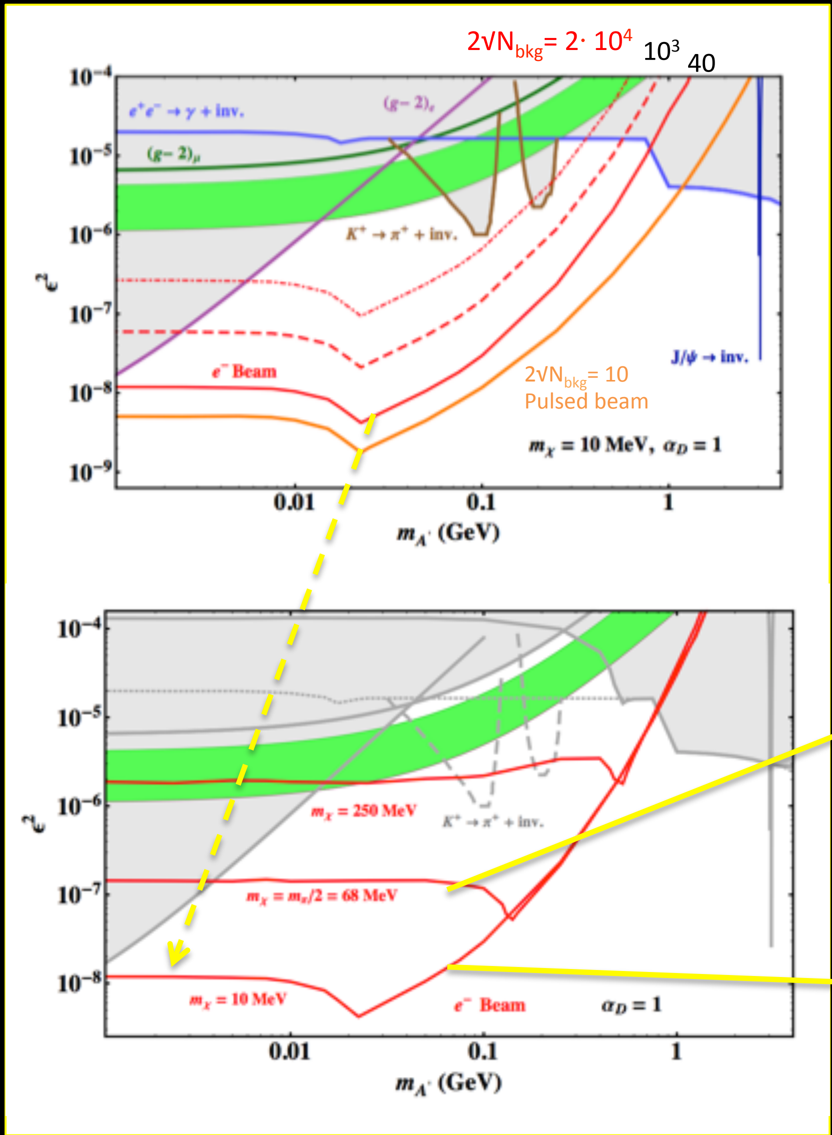




Cross section dependence from *A'* mass

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

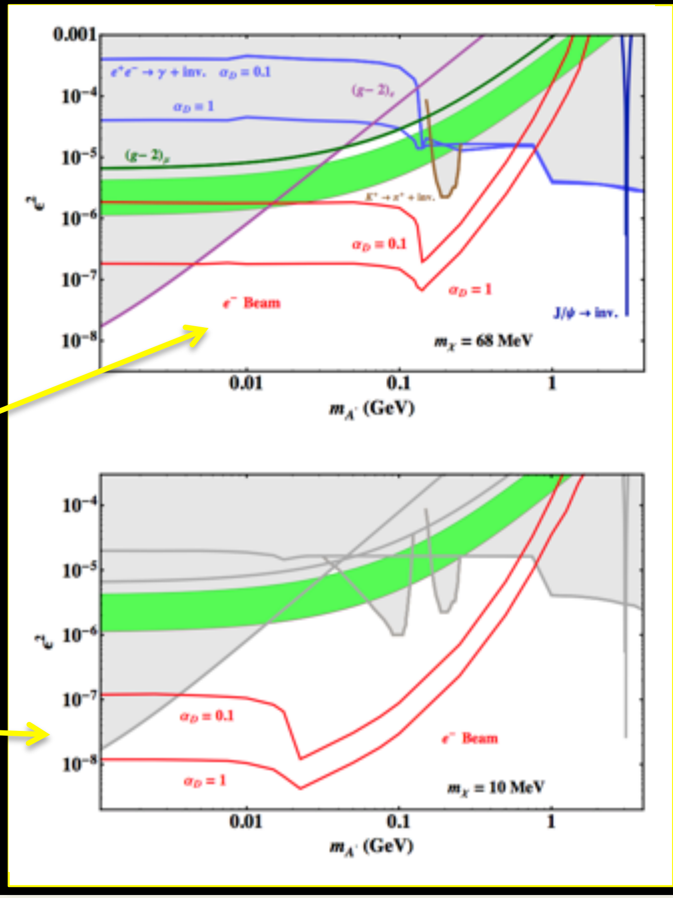
BDX experiment (Hall-A)



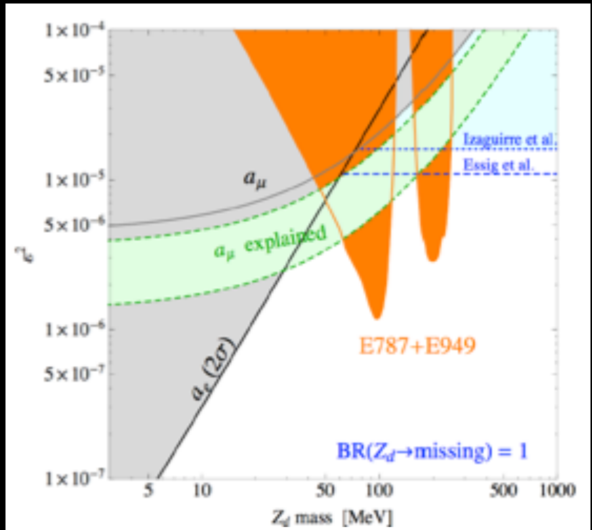
10^{22} EOT = 1 beam-year at Hall-A

3 beam-years at Hall-C?

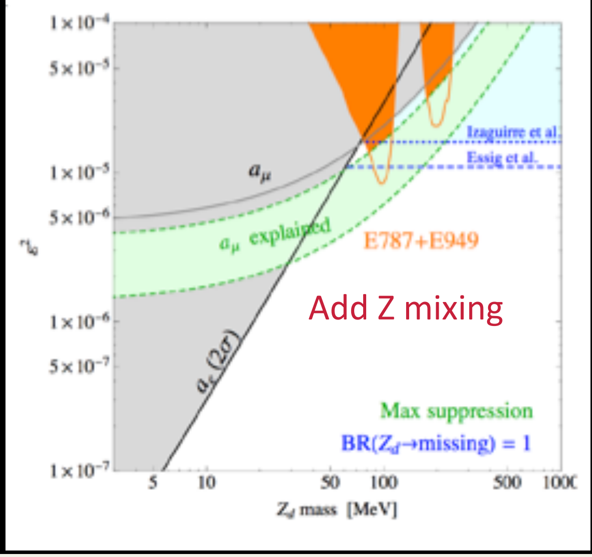
arXiv:1307.6554

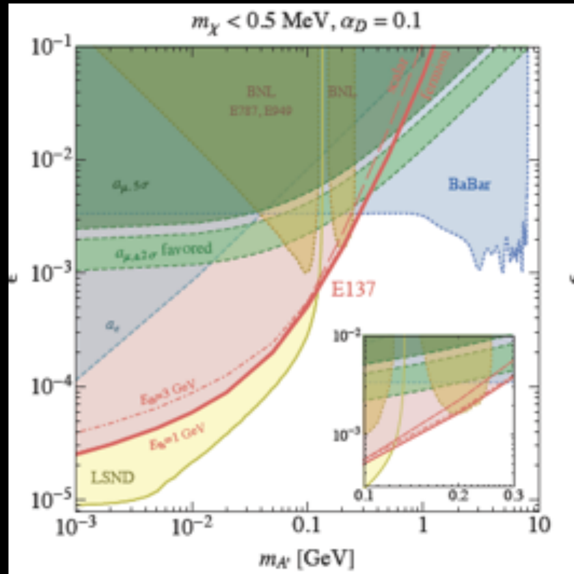


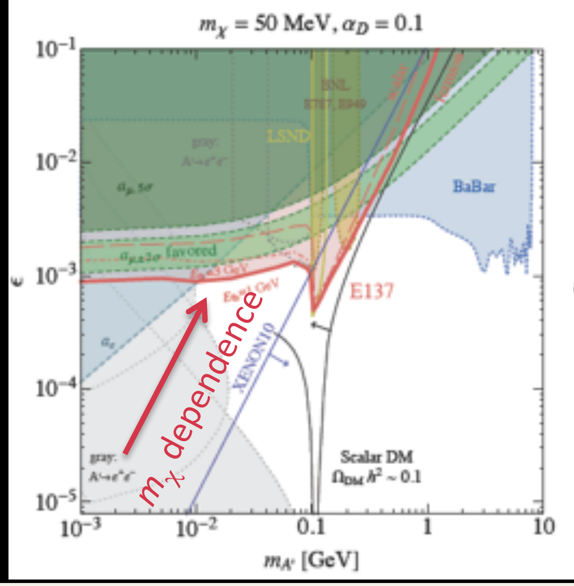
Invisible decays, model dependence of limits



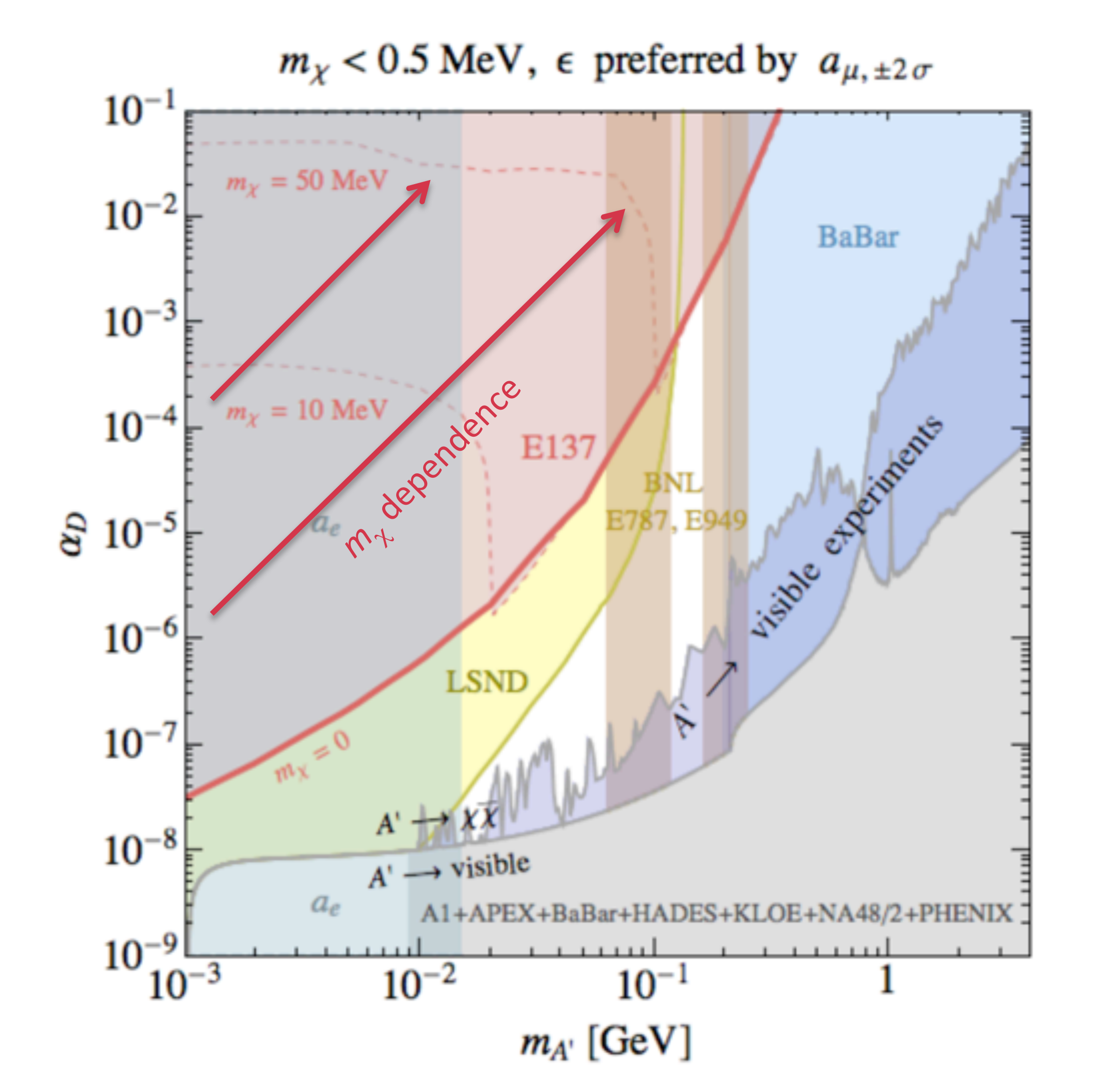
$K^{\pm}\to\pi^{\pm}\nu\nu$ used to constrain $K^{\pm}\to\pi^{\pm}A'$ assuming kinetic mixing and coupling to quarks ≠ 0



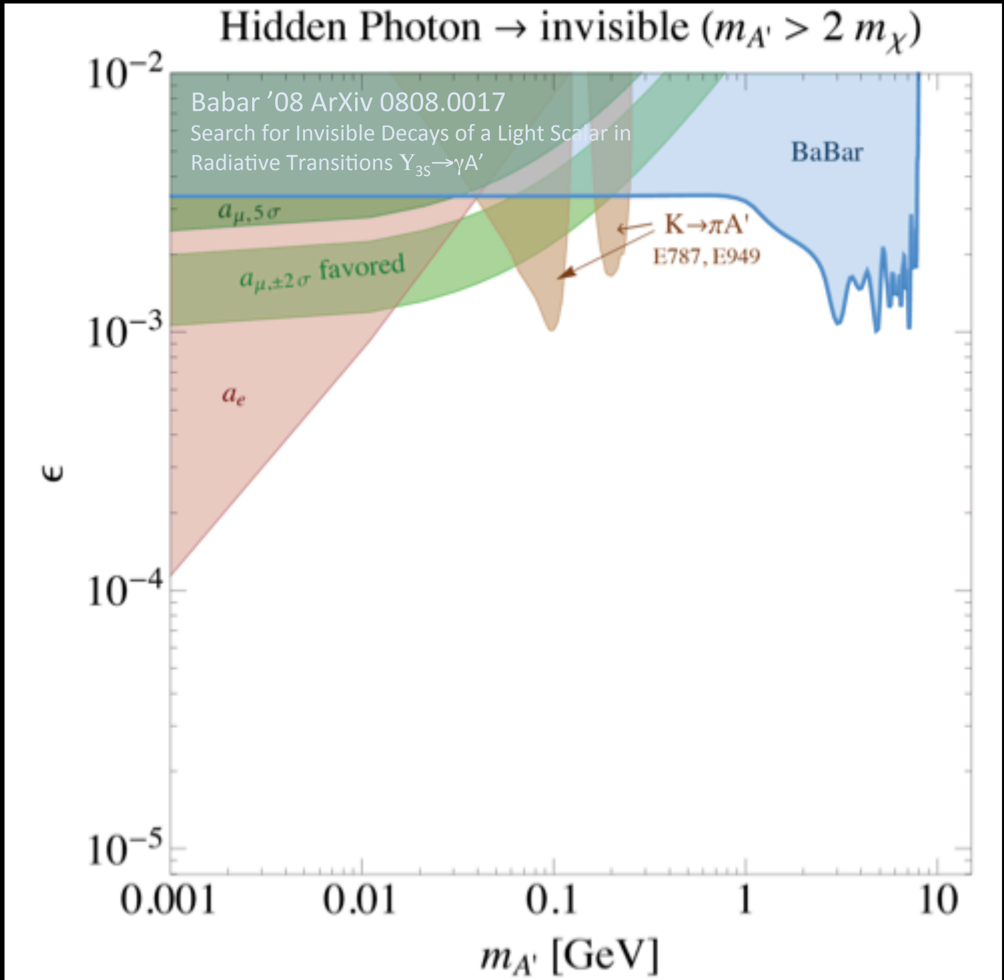




Combine visible and invisible decays

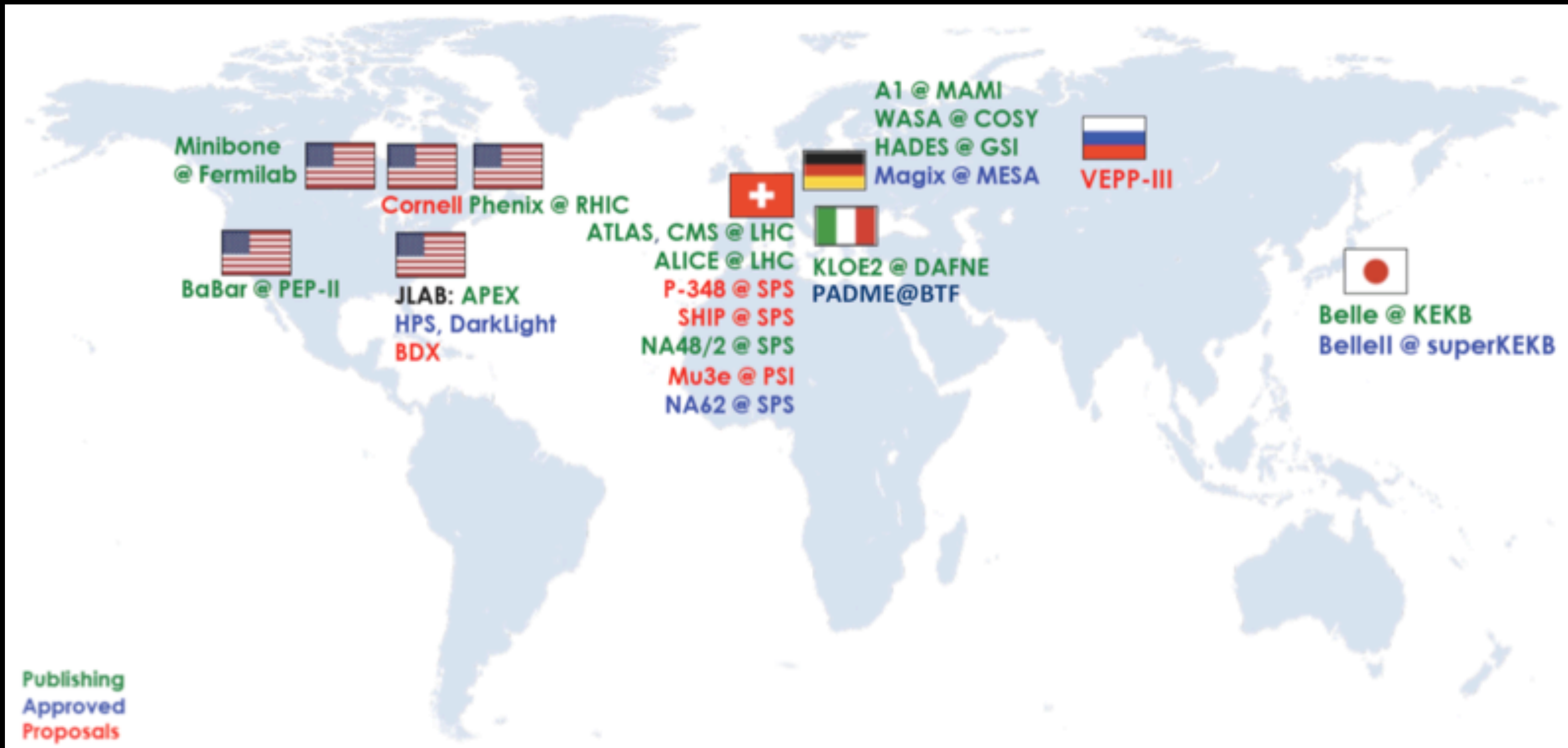


Model independent limits from invisible decays



- 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)

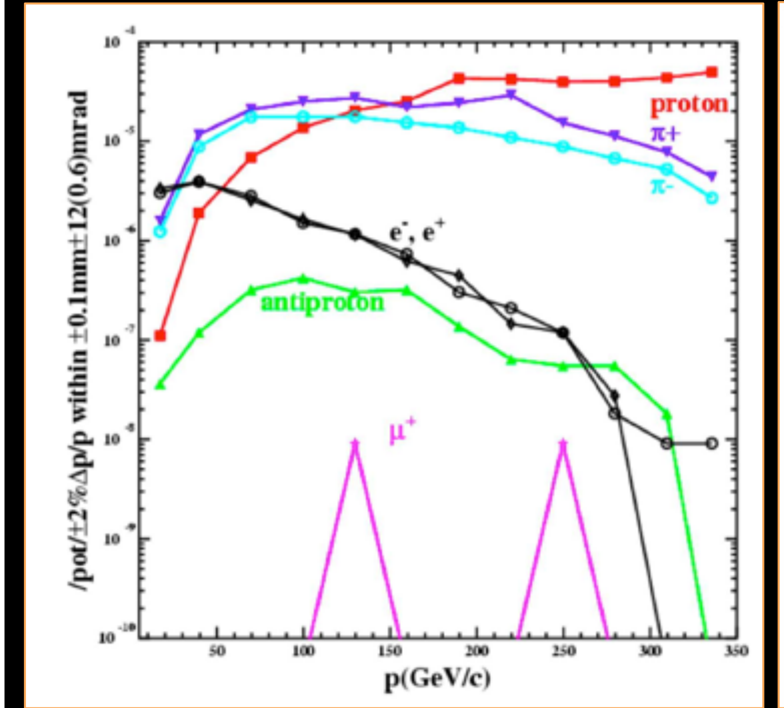
Dark photon map



J. Alexander *et al.*
"Dark Sectors 2016 Workshop: Community Report"
https://arxiv.org/pdf/1608.08632v1.pdf

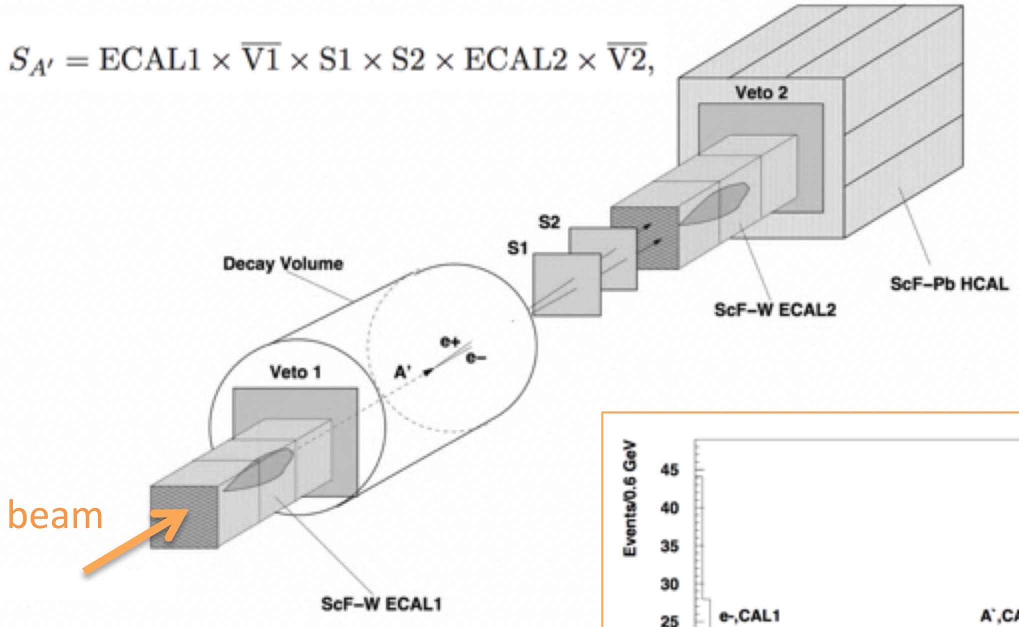
NA64 at CERN SPS

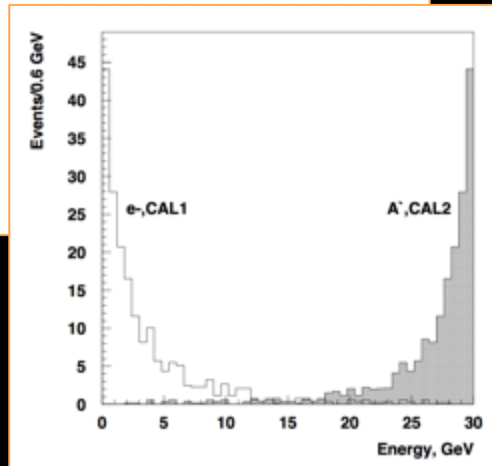
H4 high purity electron beam, <1% contamination required
(tertiary, from γ conversions)



SPSC-P-348

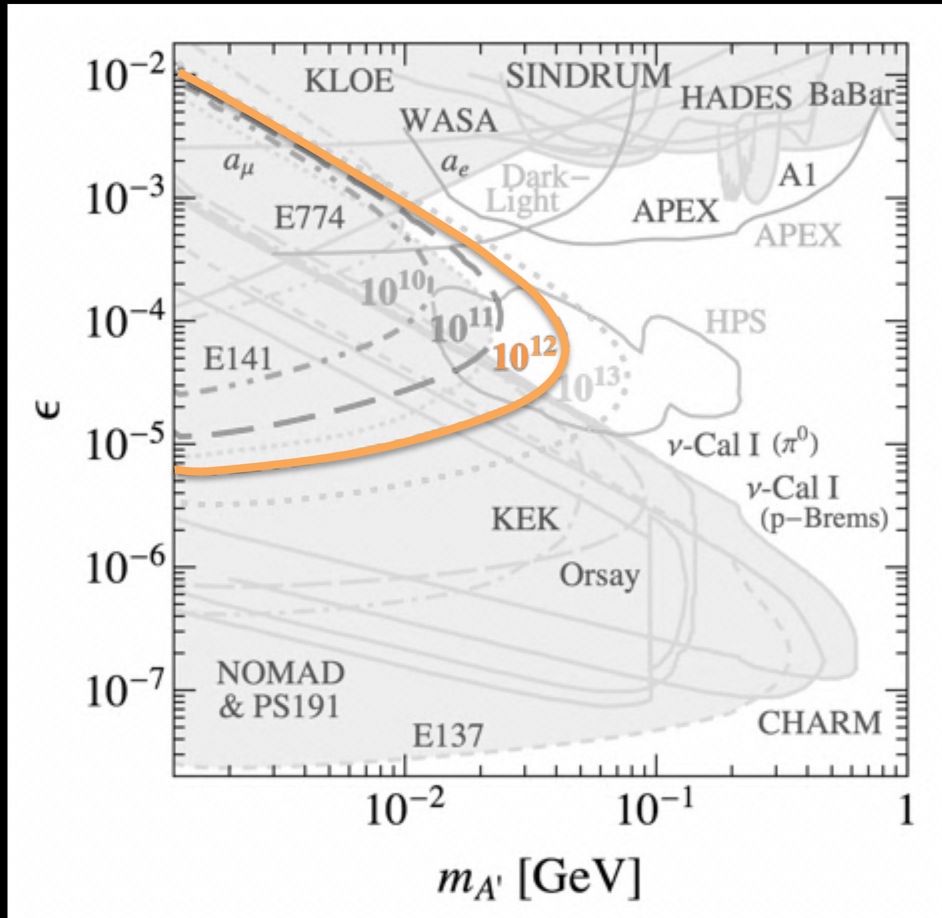
$$S_{A'} = \mathrm{ECAL1} \times \overline{\mathrm{V1}} \times \mathrm{S1} \times \mathrm{S2} \times \mathrm{ECAL2} \times \overline{\mathrm{V2}},$$





NA64 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

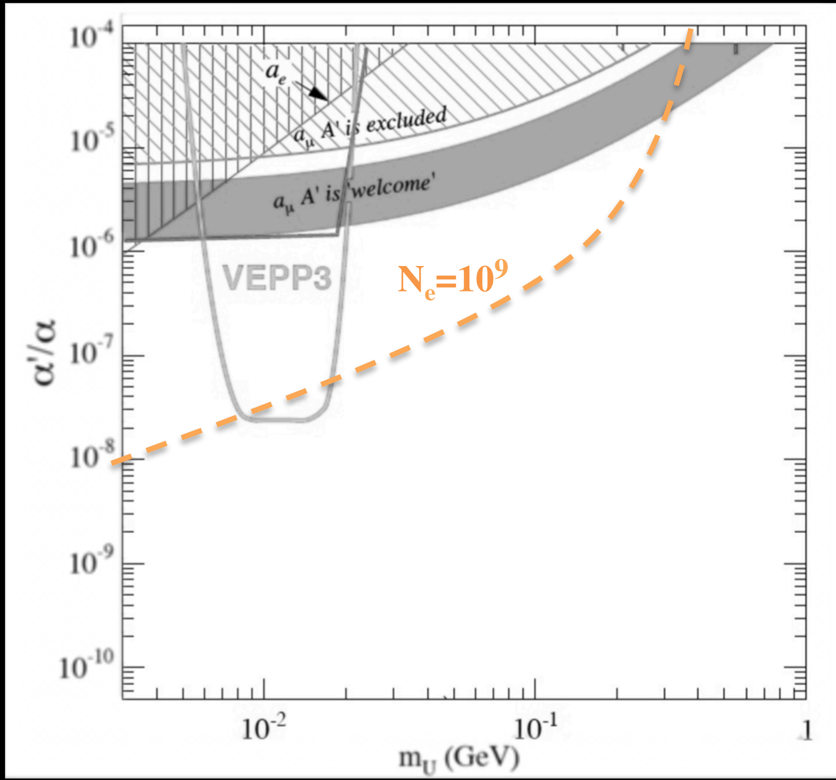


NA64 at CERN SPS

- Also proposal for A’ → invisible search

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

- 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



The PADME approach

At present **all** experimental results rely on **at least one** of the following **model-dependent** assumptions:

1. *A′* decays to e^+e^- (visible decay assumption): BR[$A' \to e^+e^-$] = 1
2. *A′* couples with the **same strength** to all fermions ($\varepsilon_q = \varepsilon_l$) (**kinetic mixing**)

In the **most general** scenario:

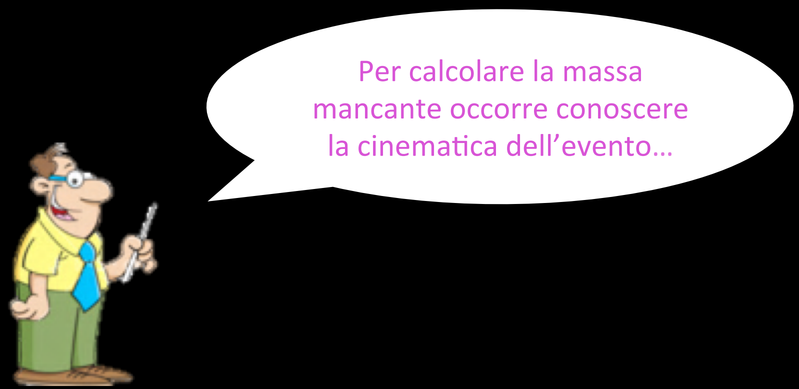
- *A′* can decay to dark sector particles also **lighter than the *A′***: in this case BR[$A' \to e^+e^-$] <<1
  - Dump and meson decay experiments only provide limits of the kind ε^2(BR[$A' \to e^+e^-$] <<1)
- *A′* can couple to quarks with a coupling <<ε_l (even 0)
  - Suppressed or no production at hadronic machines and in mesons decays

The PADME approach

PADME aims at detecting *A'* produced in e^+e^- annihilations and decaying into invisibles by searching for missing mass in events with only one photon:

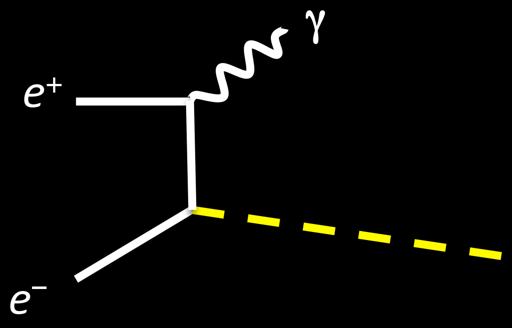
$$e^+e^- \rightarrow \gamma A' \; (A' \rightarrow XX)$$

- No assumption on the *A'* decays products and coupling to quarks
- Only minimal assumption: *A'* bosons couples to leptons
- Actually testing the coupling **of any new light particle** produced in e^+e^- collisions (scalars: H_d; vectors: *A'* and Z_d)

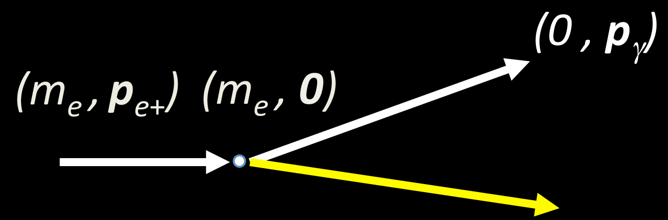


What we need: signal

- Just detect one photon + missing energy:



- We want to compute $M^2_{miss} = (\underline{P}_{e+} + \underline{P}_{e-} - \underline{P}_\gamma)^2$



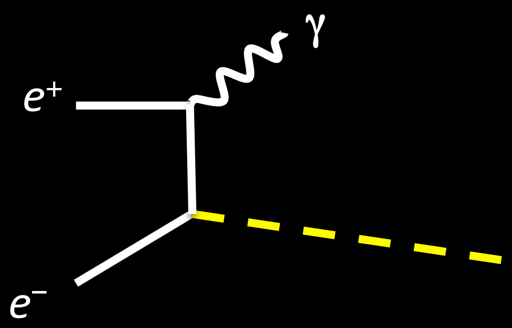
- We need:
  a) A **positron** beam with a well defined momentum
     1. Small energy and angular spread
     2. Small transverse spot

        1+2 = small emittance

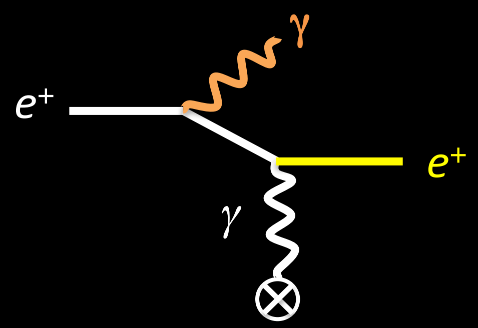
     3. Tunable intensity (in order to optimize annihilation vs. Bremsstrahlung)

  b) To measure precisely the photon momentum (angle and energy)

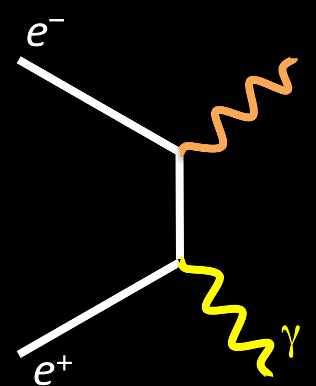
What do we need: backgrounds



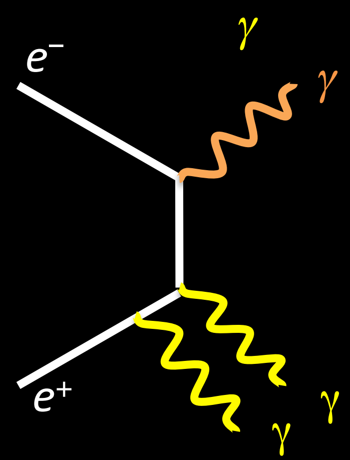
We need to fight the backgrounds
i.e. one photon + something else, eventually going undetected:



+1 electron
Bremsstrahlung process, ≈Z^2



+1 γ
γγ process, ≈Z



+2 γ
3γ process


Prima metà del
problema: il fascio
di positroni

DAΦNE complex in Frascati

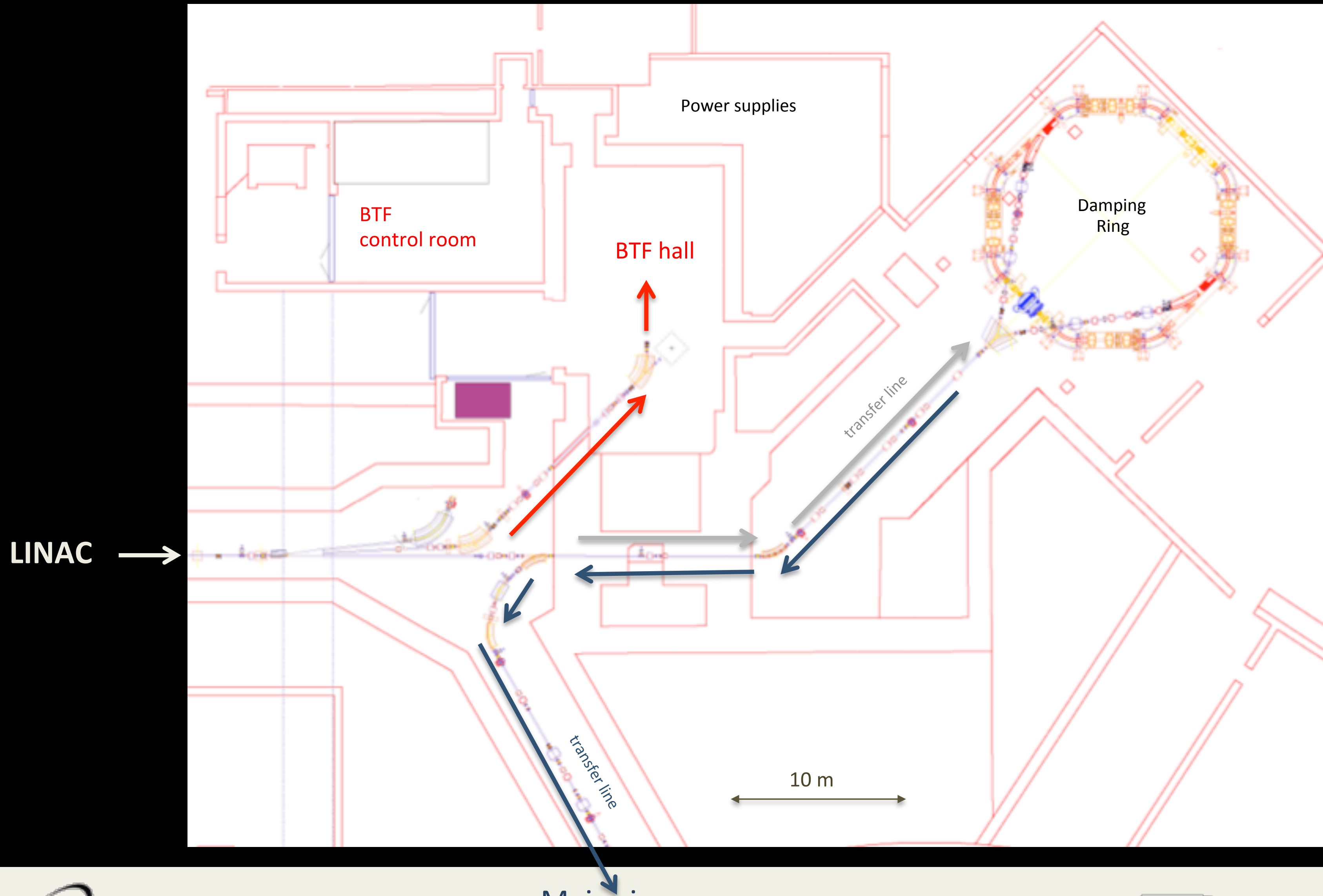
- DAΦNE, replacing ADONE (operational until 1993), has been running as e^+e^- collider at 1,02 GeV since 1999, for KLOE, DEAR, FINUDA, Siddharta, and now KLOE/2 …
- Synchrotron light source operational with 3 lines (X, UV, IR)
- **High current electron/positron linac** + damping ring + **test facility**

LINAC parameters

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



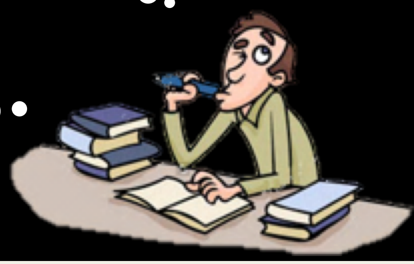
Beam parameters

- Duty Cycle
  - Standard DAΦNE duty cycle = 50***10 ns** = 5×10^{-7}
  - Already obtained upgrade 50***40 ns**= 2×10^{-6}
  - Work in progress to reach **250 ns** (new pulser) = 1.2×10^{-5}
  - … Up to **500 ns** (double phase inversion at the SLED) …
  - … and beyond (no SLED, or SLED detuning), in principle up to 4 μs
- Energy
  - Maximum positron beam of **550 MeV**
    - The accessible $M_{A'}$ region is limited to ≈**23 MeV**
    - e.g. $M_{A'}$ up to **28 MeV** with 750 positron beam

Il numero di eventi osservabili dipende linearmente (oltre che dalla sezione d'urto) dall'intensità del fascio

Ma occorre considerare l'effetto di eventi (tipicamente del fondo) sovrapposti (*pile-up*)

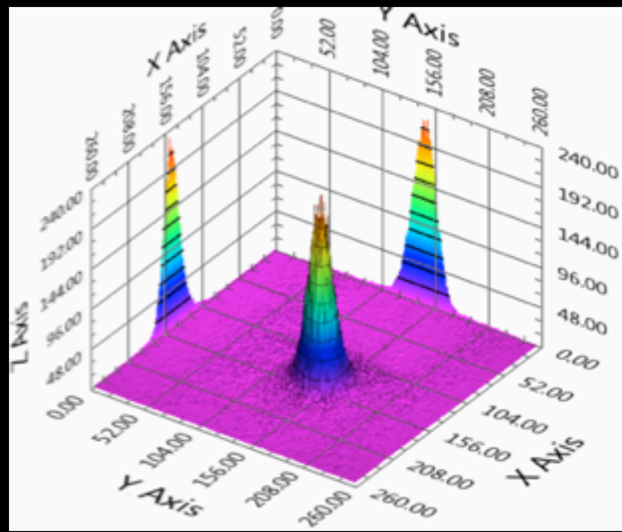
Diluire i positroni in un tempo più lungo è in generale vantaggioso: la situazione ideale sarebbe quella di un fascio continuo (duty cycle=1)



Beam parameters

- 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 (will not be there in PADME)
  - Both size and divergence depend on the **optics**
- Beam position: **0.25 mm RMS**

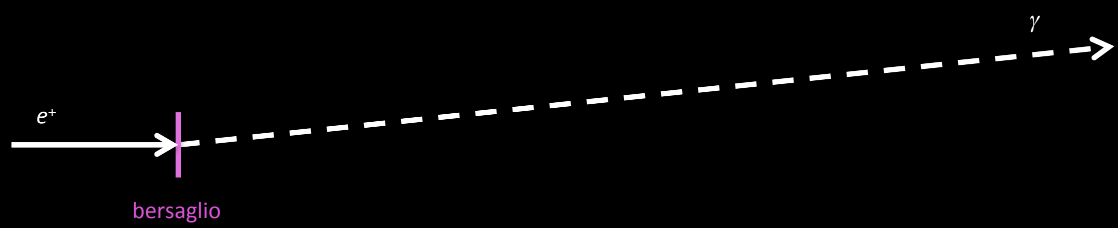
Beam spot size (450 MeV)



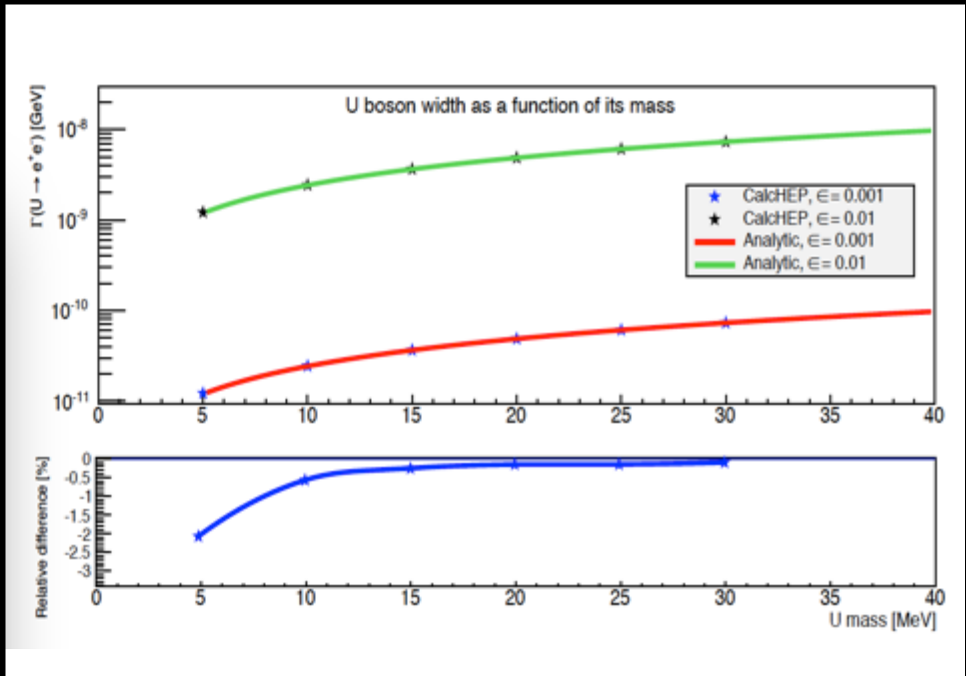
La seconda metà del problema è misurare l’**impulso del fotone**; al tempo stesso tenendo sotto controllo gli eventi di fondo

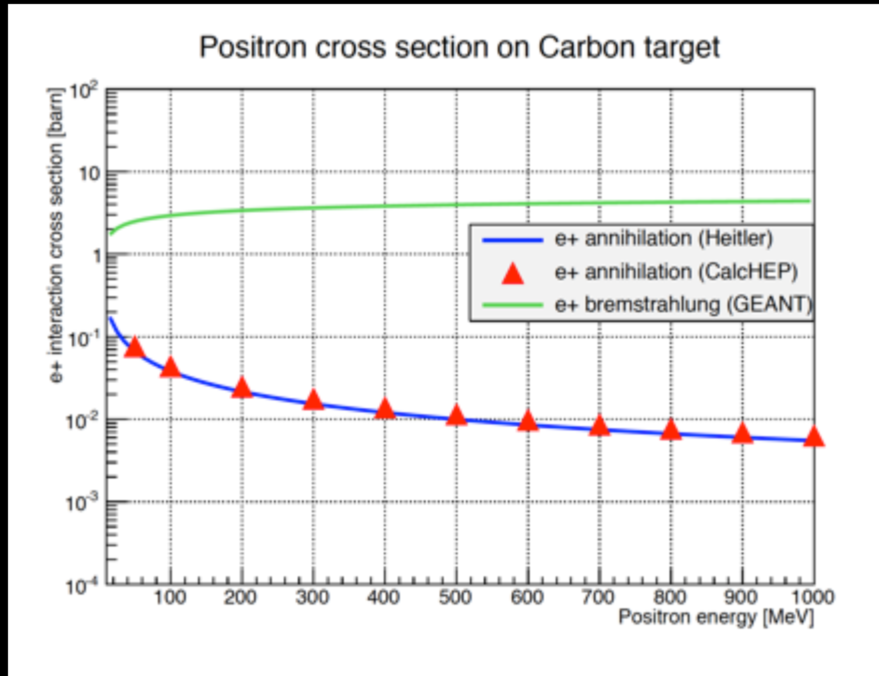
Un bersaglio sufficientemente sottile definisce la coordinata longitudinale dell’interazione, nel piano trasverso facciamo affidamento:

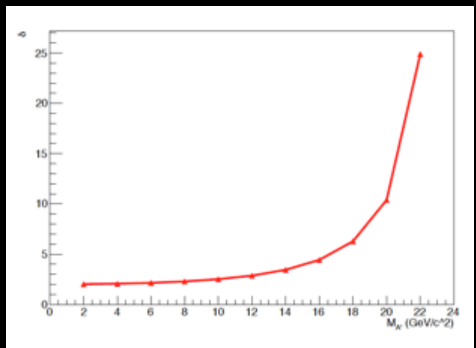
1. sulla conoscenza dell’impulso del fascio;
2. Su un bersaglio “attivo”



Dark photon cross section

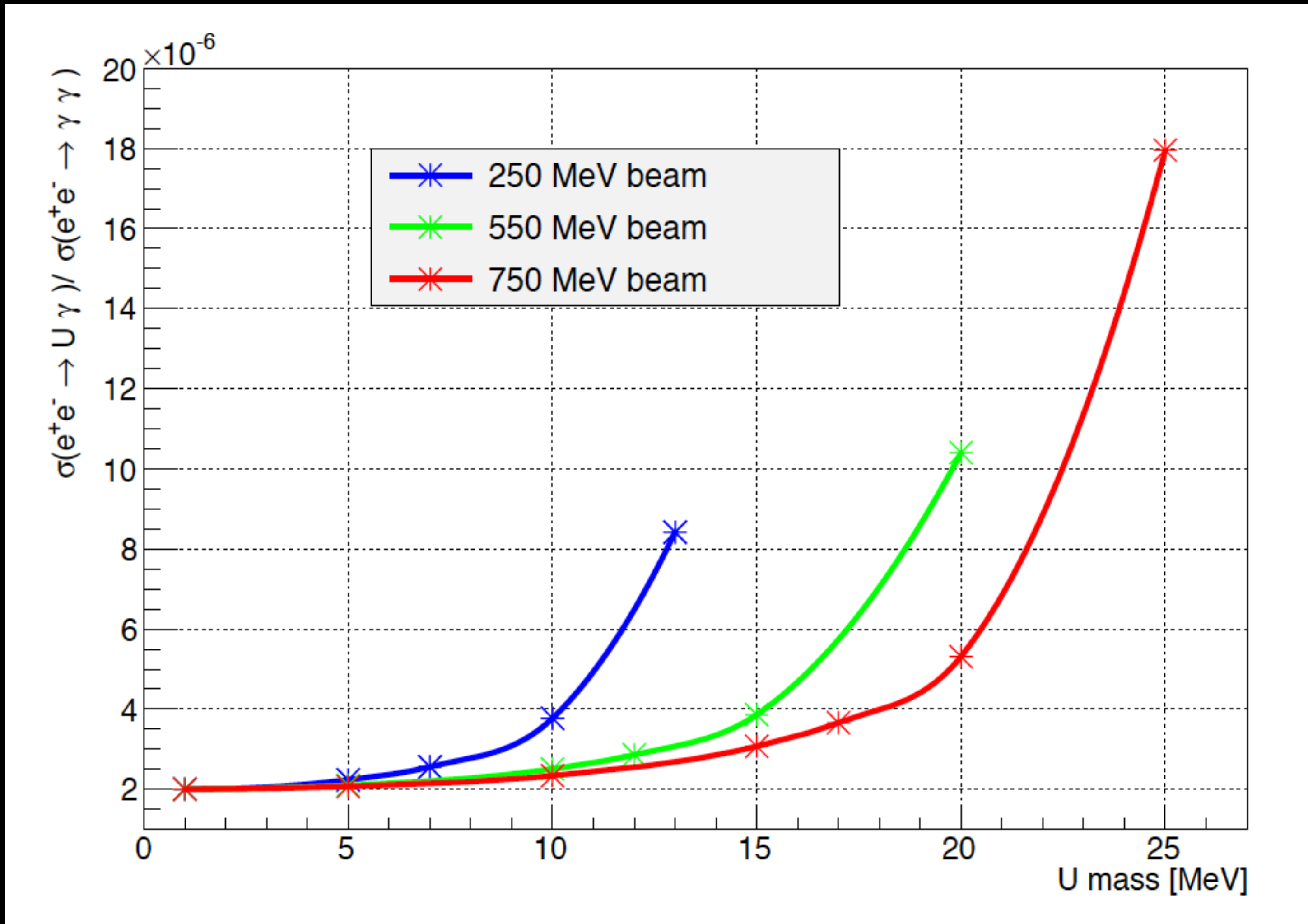




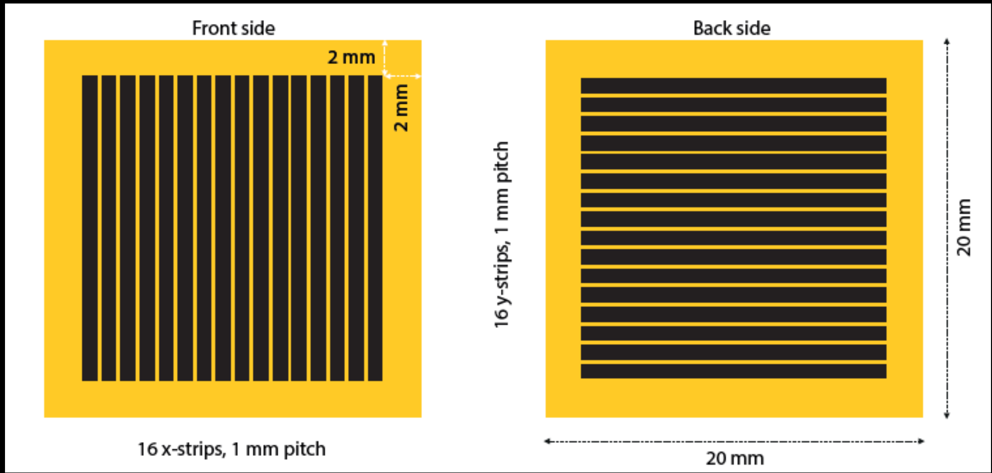


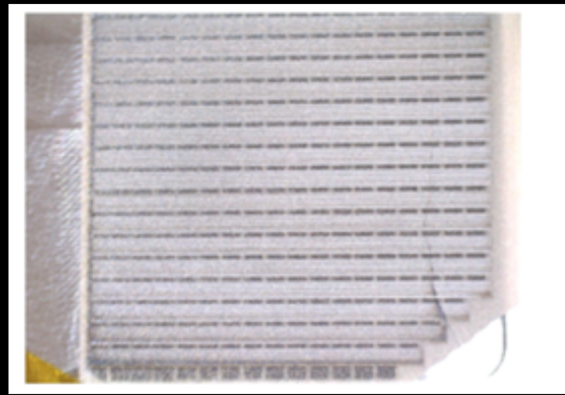
$$\frac{\sigma(e^+e^- \to A'\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \epsilon^2 * \delta,$$

Dark photon cross section

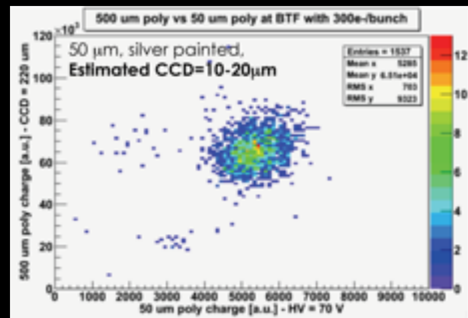


The diamond target

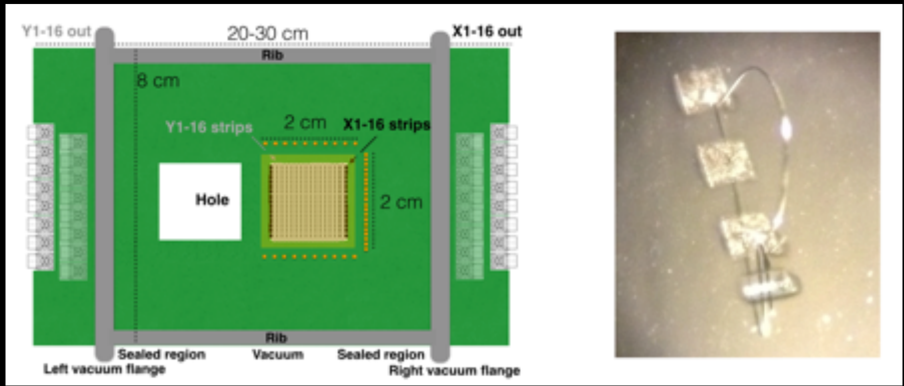




- Diamond is the **rigid** material with the best ee(γγ)/Bremsstrahlung ratio (Z=6)
- Measure charge and position of 5000-10000 positrons/bunch
  - **Below mm** precision in x-y coordinates
  - Better than 10% charge measurement
- Polycrystalline diamonds 50-100 mm thickness:
  - 16x1mm^2 strip and **x-y 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

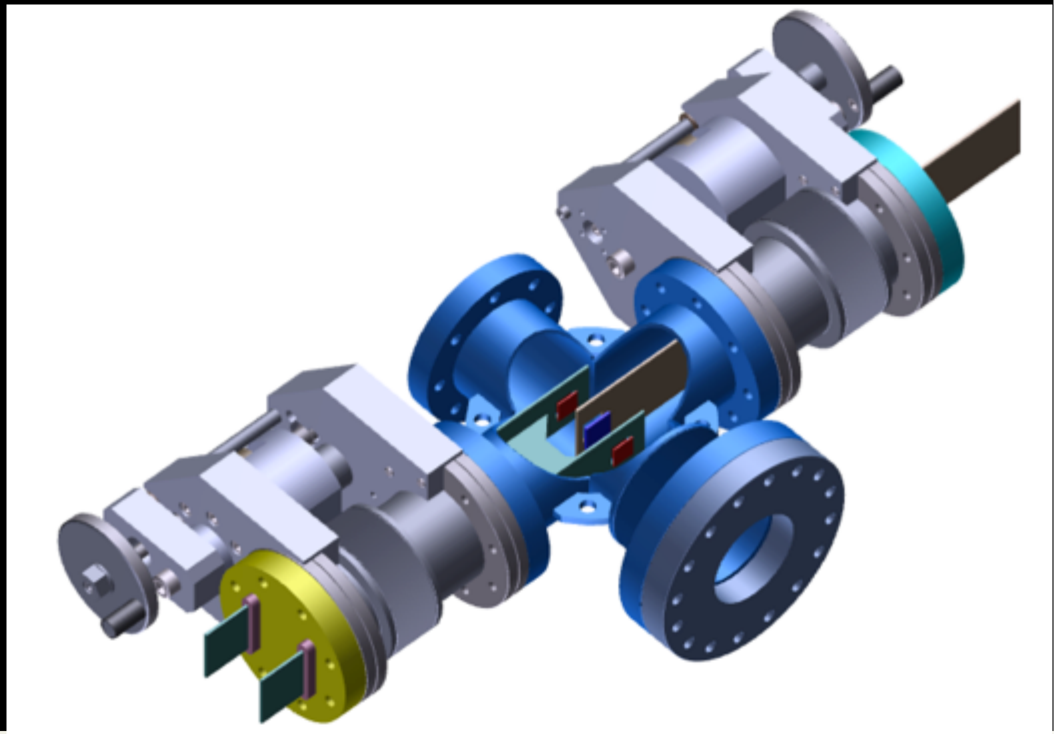


The diamond target

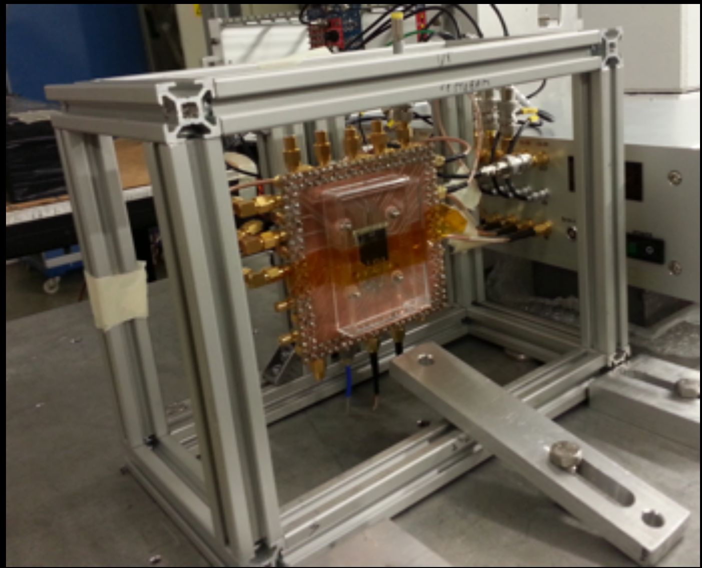


- Bonding to the readout board
- Connect to amplifier
- Digitize signal

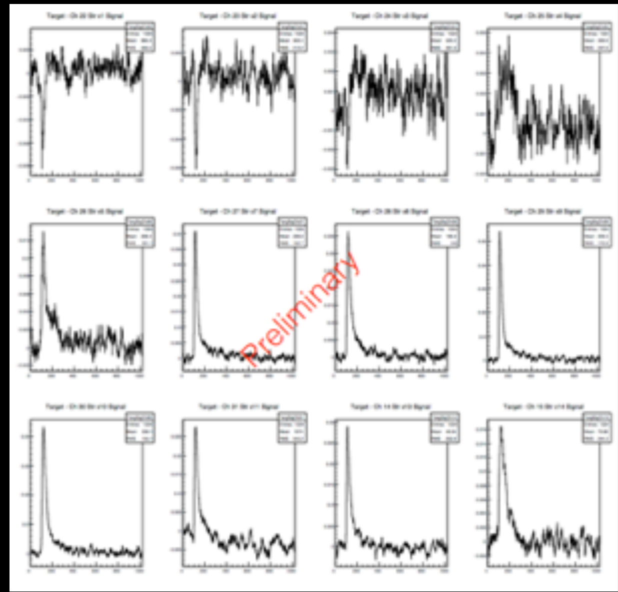
- Step motor for moving the target **in and out of the beam**
- Afd a (thick) **Silicon pixel tracker** in order to have a more accurate transverse image of the incoming positron beam



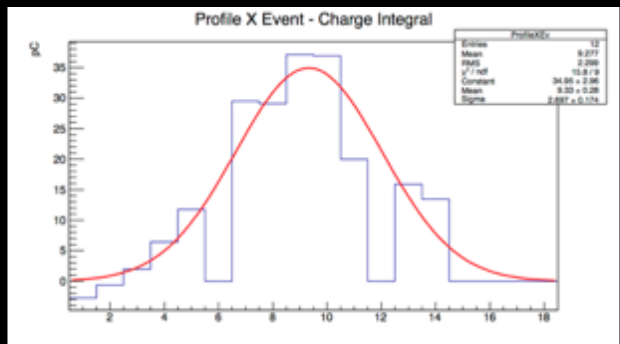
The diamond target



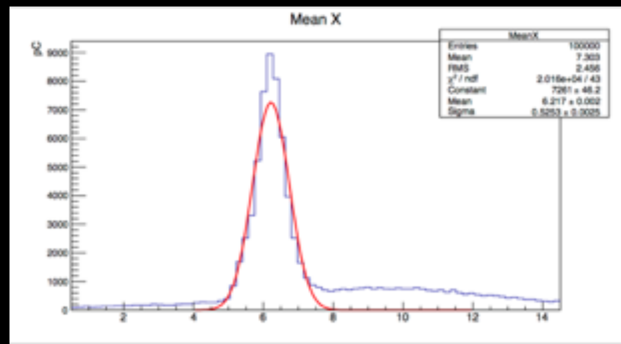
Beam-test, end of 2015



Digitized strips signals



Center of gravity

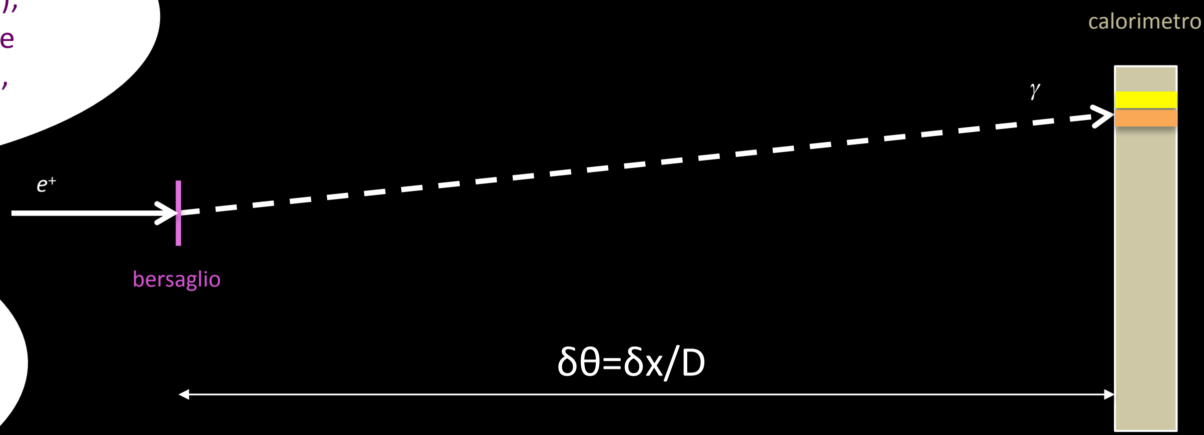


Average position

La seconda metà del problema è misurare l'**impulso del fotone**; al tempo stesso tenendo sotto controllo gli eventi di fondo

La misura della posizione e energia del fotone dipende naturalmente dalle caratteristiche del rivelatore (calorimetro); **Data la risoluzione spaziale**, la risoluzione angolare, e quindi sulla massa mancante, dipende dalla **distanza dal bersaglio**

La risoluzione in massa mancante è importante poiché determina la reiezione del fondo…



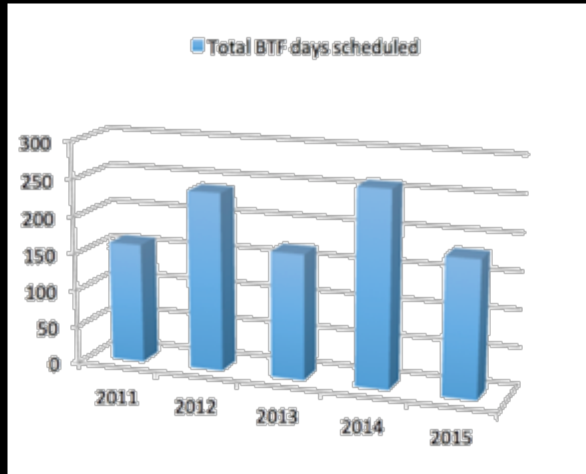
BTF experimental hall

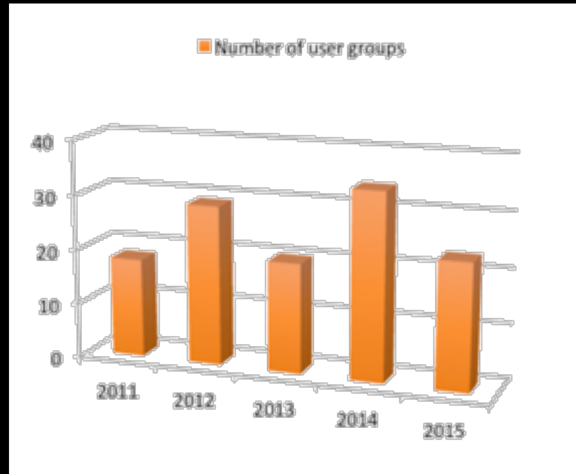
Approximately **<5.5 m total** length
(<3 m lateral width)

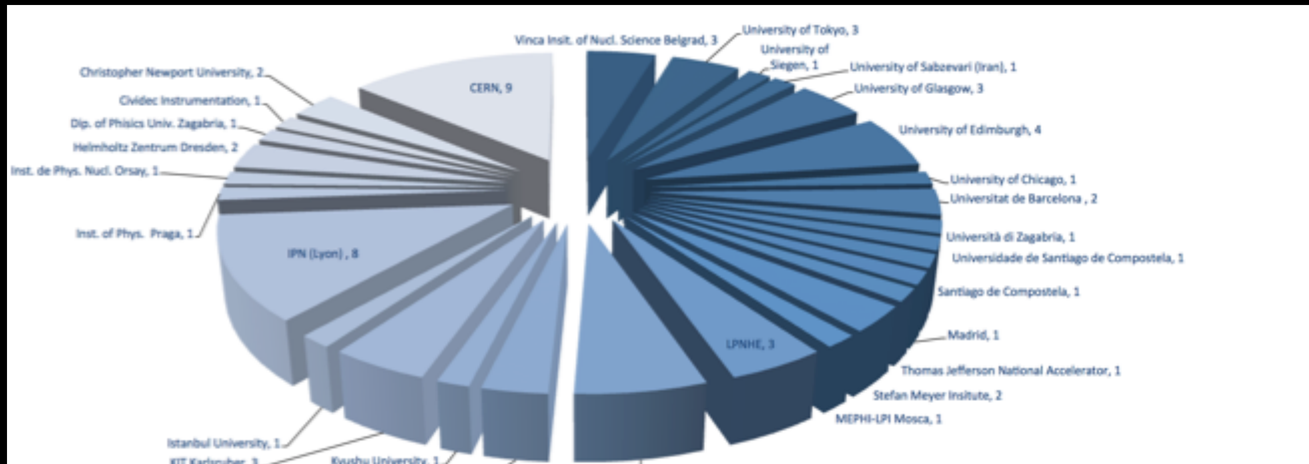
Una prima, **non banale** limitazione, è data dalle dimensioni della sala sperimentale disponibile

BTF users

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

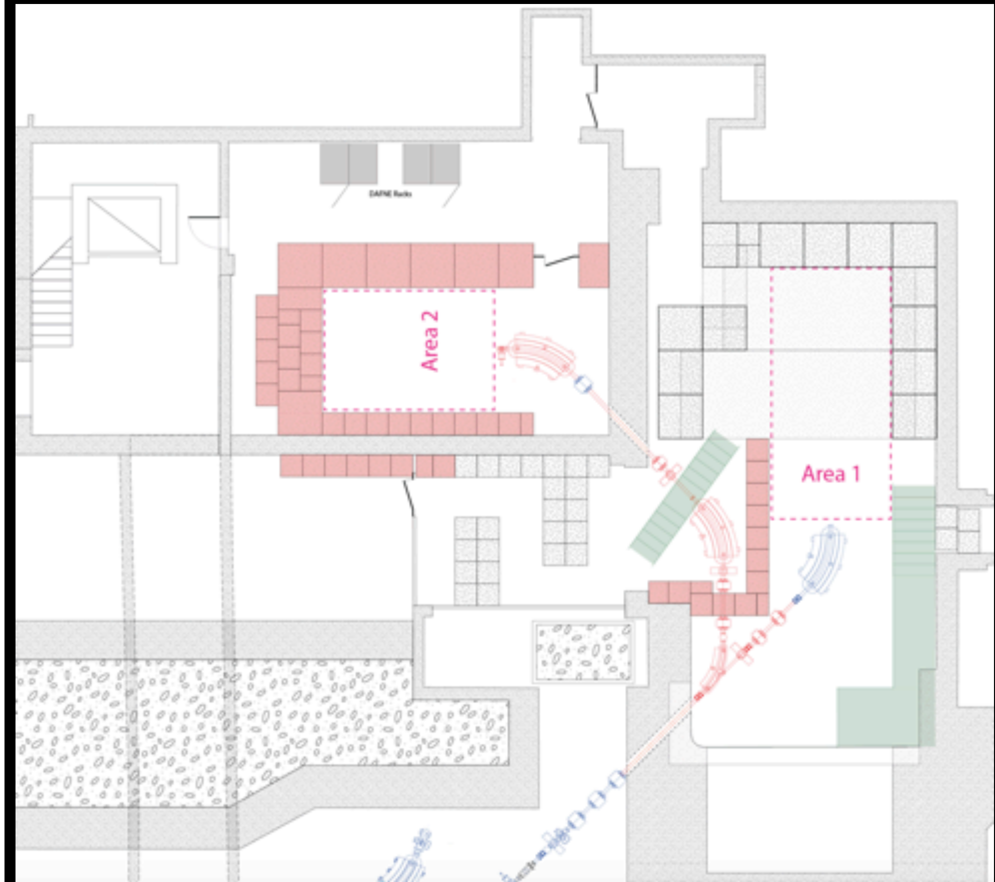


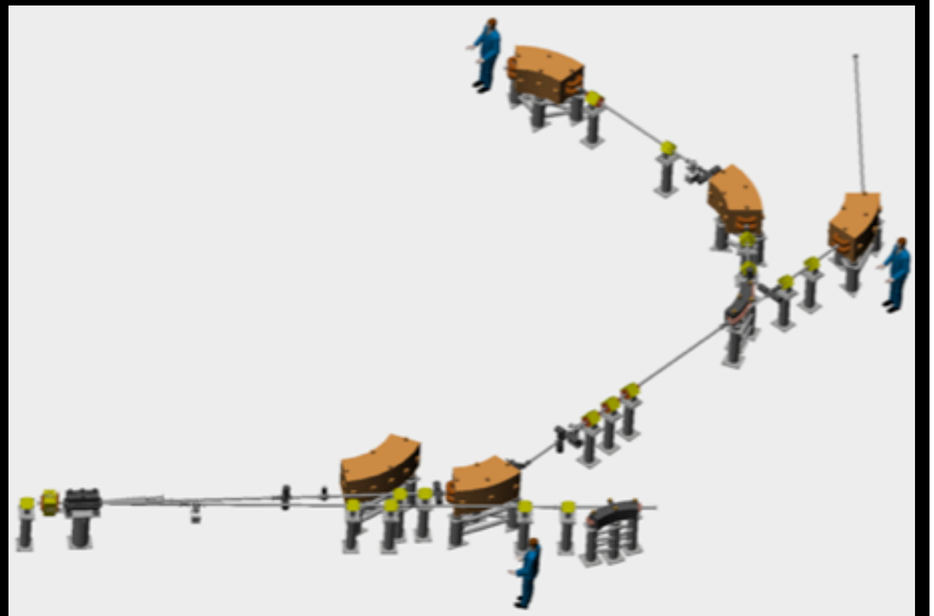


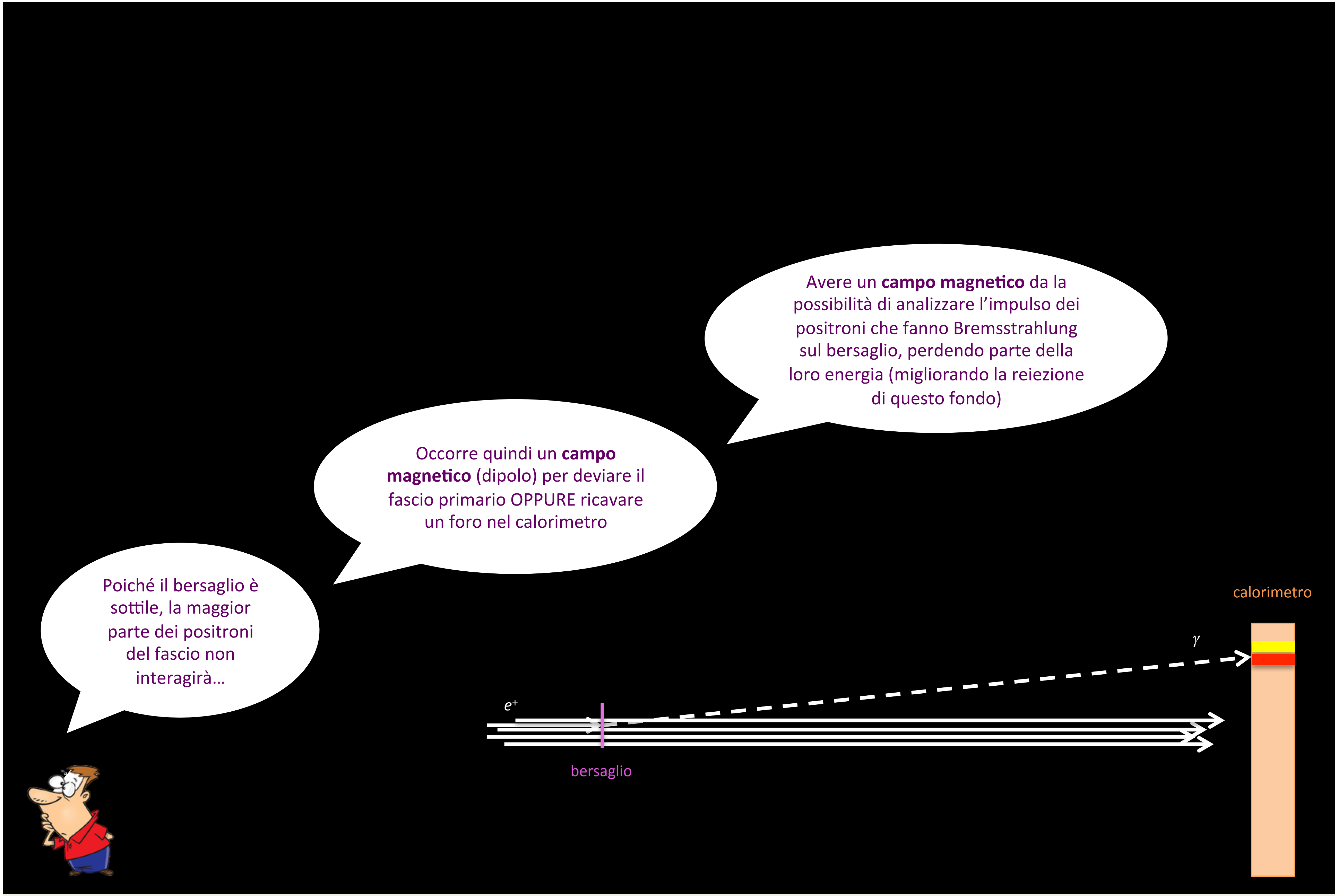


Non Italian institutions (2011-2014)

BTF beam-line upgrade







Poiché il bersaglio è sottile, la maggior parte dei positroni del fascio non interagirà…
Occorre quindi un **campo magnetico** (dipolo) per deviare il fascio primario OPPURE ricavare un foro nel calorimetro
Avere un **campo magnetico** da la possibilità di analizzare l'impulso dei positroni che fanno Bremsstrahlung sul bersaglio, perdendo parte della loro energia (migliorando la reiezione di questo fondo)
calorimetro
γ
e^+
bersaglio

$$\Delta\phi/2 = \arcsin L/2\rho$$

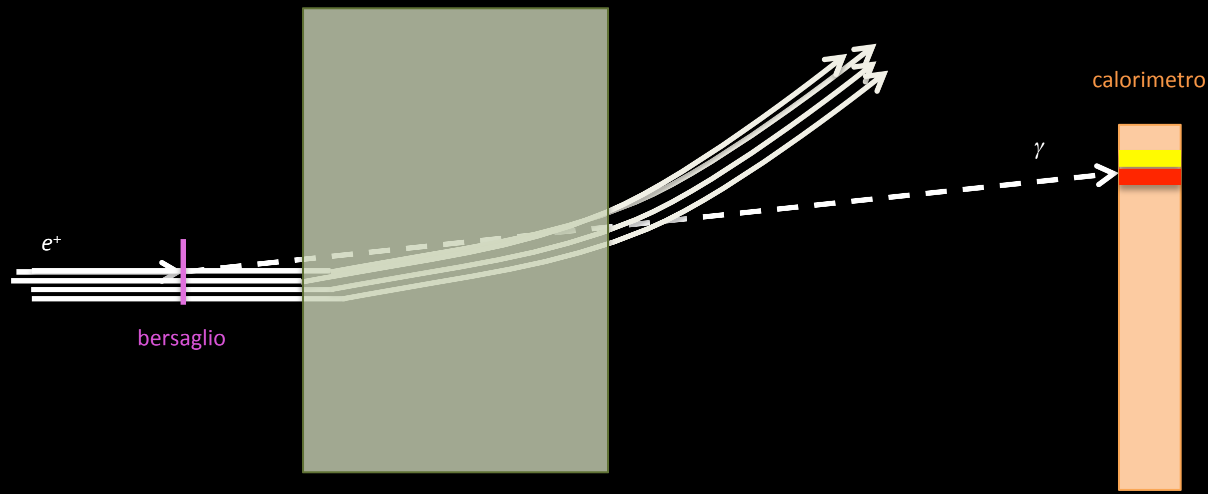
Small angles:

$$\Delta\phi \simeq \frac{L}{\rho}$$

$$(BL)_{min}\,[\mathrm{Tm}] \simeq \Delta\phi \cdot (B\rho)$$

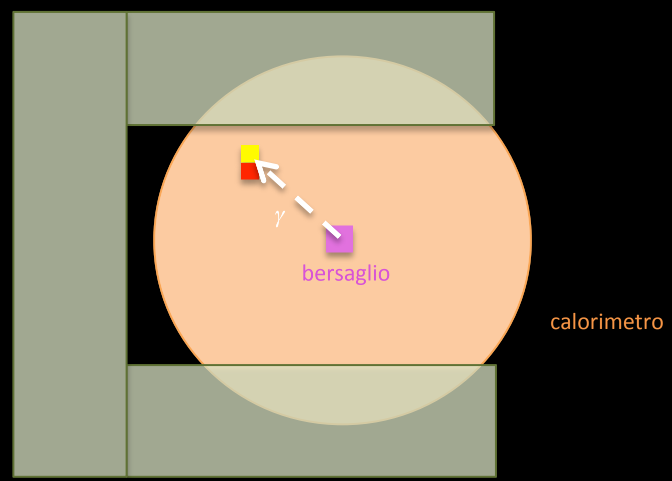
Le dimensioni trasverse del calorimetro determinano (data la distanza) l'**accettanza**. Se per es. consideriamo ≈100 mrad, anche considerando la possibilità di aumentare l'energia del fascio, è sufficiente un campo magnetico **relativamente moderato** (0.3 Tm)

Ma…



Data la massima distanza alla quale si può collocare il calorimetro

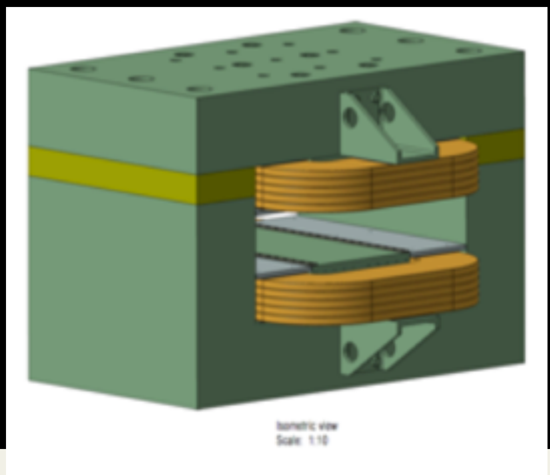
… la gap del dipolo non deve limitare essa stessa l'accettanza del calorimetro!



Starting from the magnet, build the layout around it

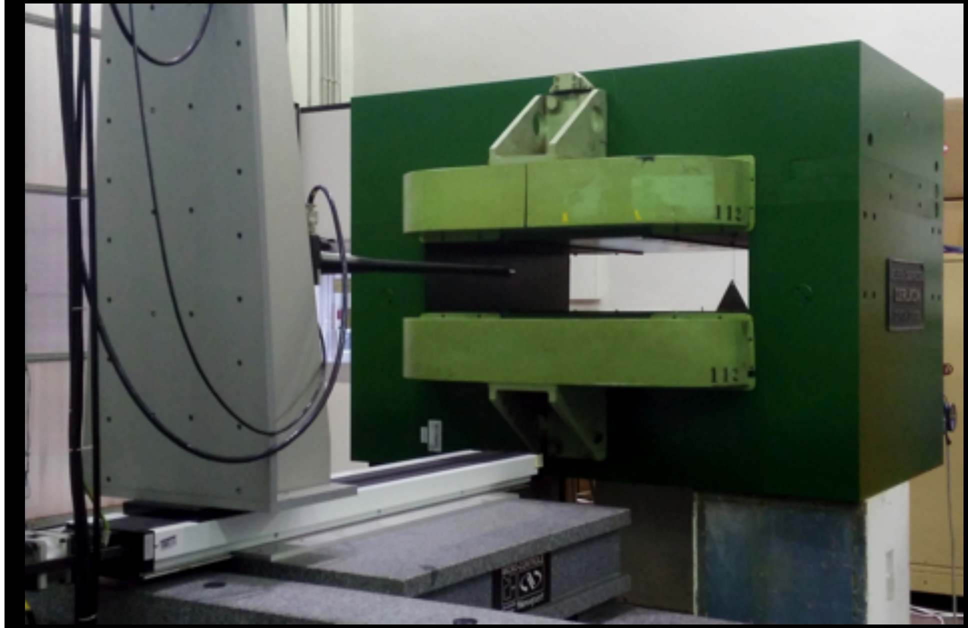
MBP-S series, **on loan from CERN**

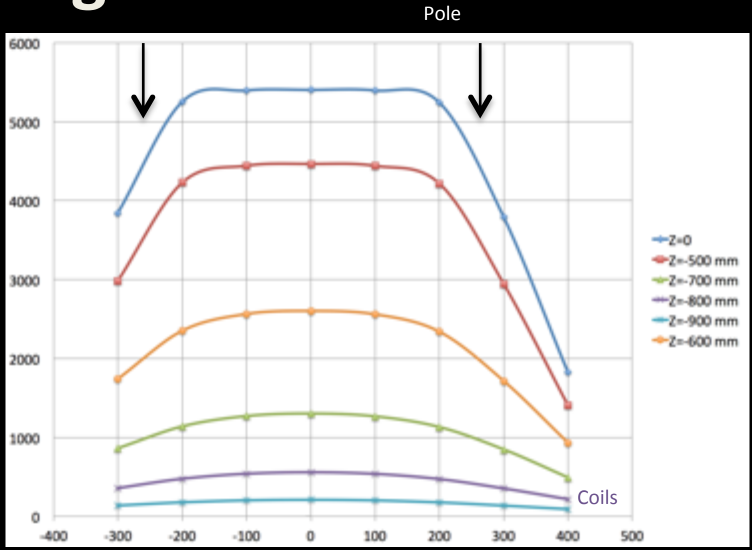
- Many thanks to TE-MSC-MNC, R. Lopez, D. Tommasini
- Shipped to Frascati in Dec. 2015

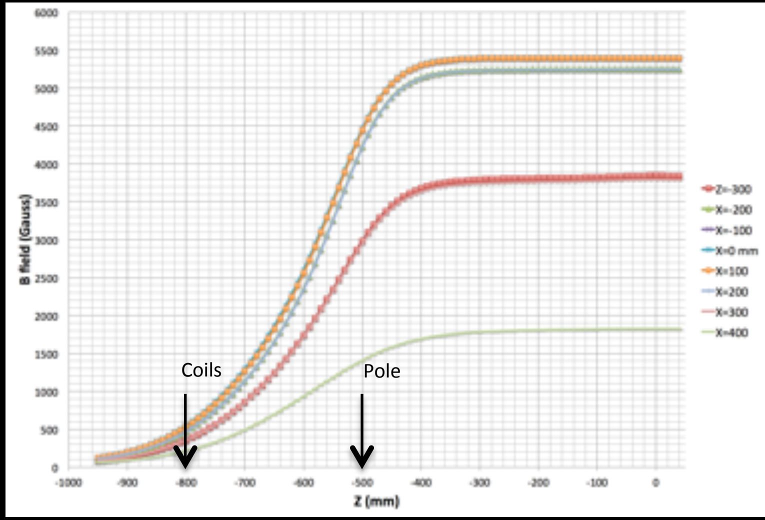


Adjustable gap by adding/removing iron insets

The PADME magnet



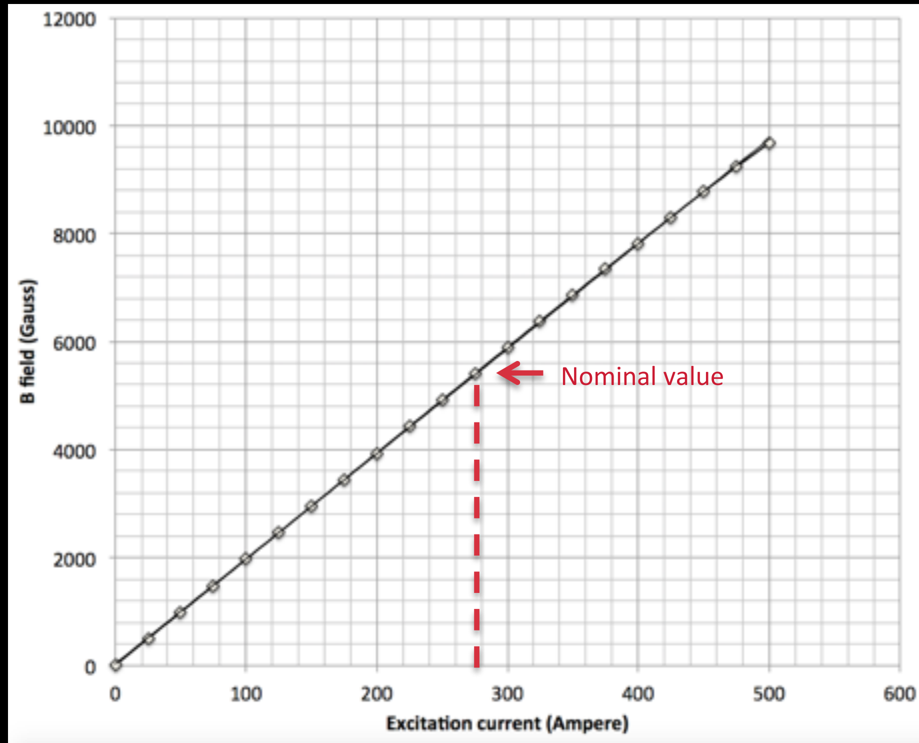




MBP-S series, **on loan from CERN**

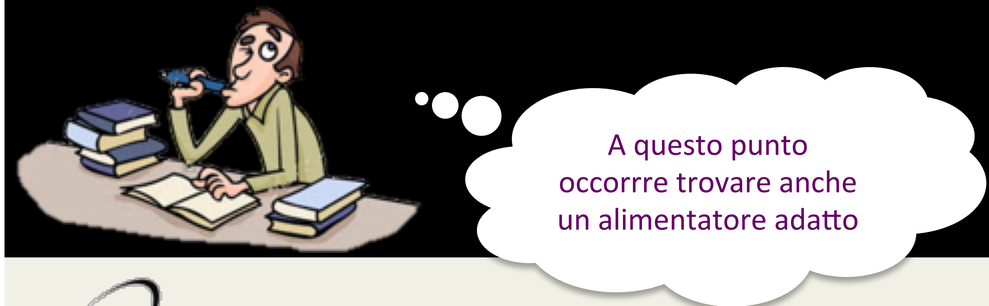
- Poles: 100 cm length, 52 cm width
- Variable gap 11 to 20 cm, we further extended to **23 cm** gap
- Preliminary field mapping:
  - Good B field quality
  - **Fringe field** not negligible, even outside the coils, relevant for beam control upstream of the active target

The PADME magnet

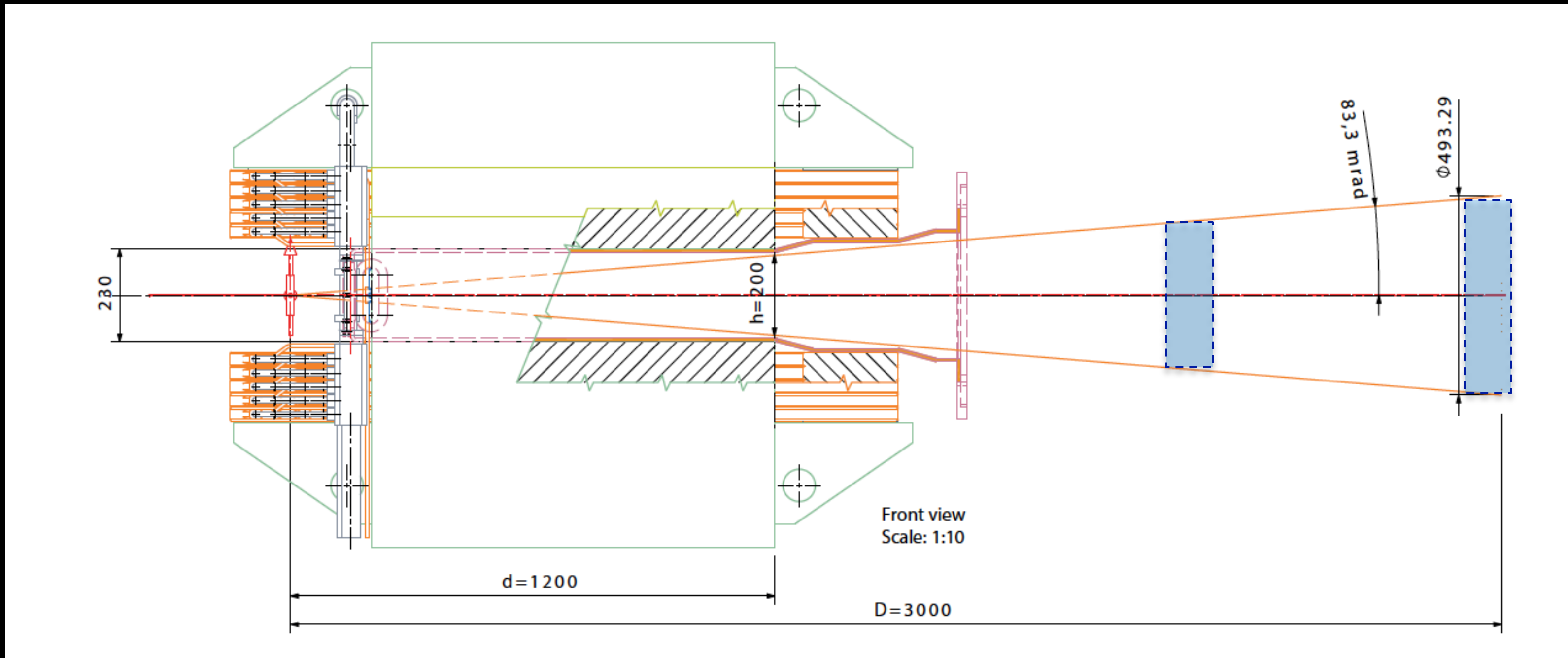


Available power supply: 80 V/400 A
(no longer used splitter magnets for DAFNE IR)

Fix 5500 G at 550 MeV (275 A)



The PADME magnet



- Target position determines **angular acceptance** given the **gap** (maximum 230 mm)
- Limited by fringe field in the coils region

- Calorimeter **granularity** and **lateral dimensions** can be adjusted by placing it at the appropriate distance

The calorimeter

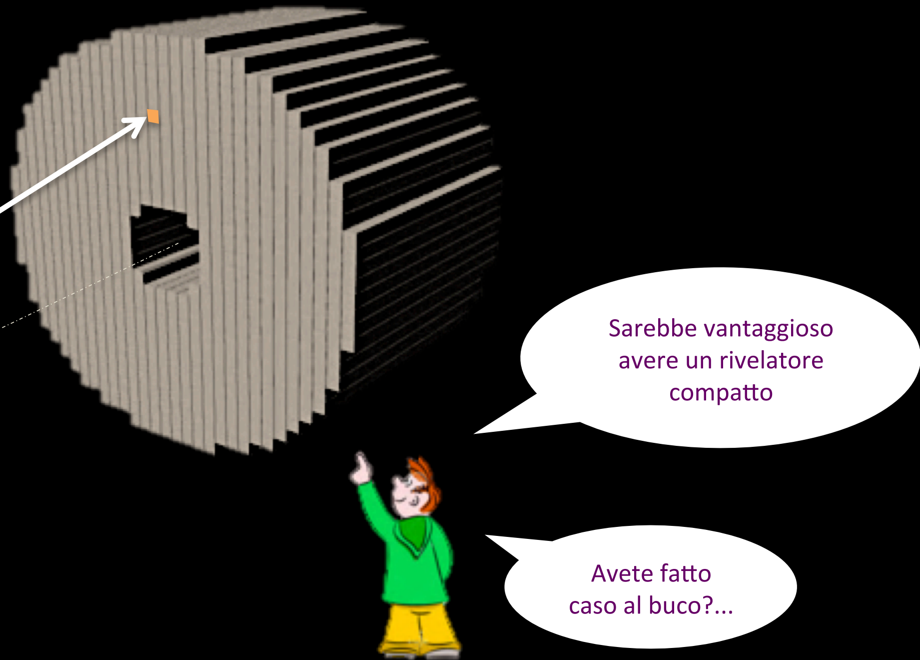
The two basic requirements of the calorimeter are:

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

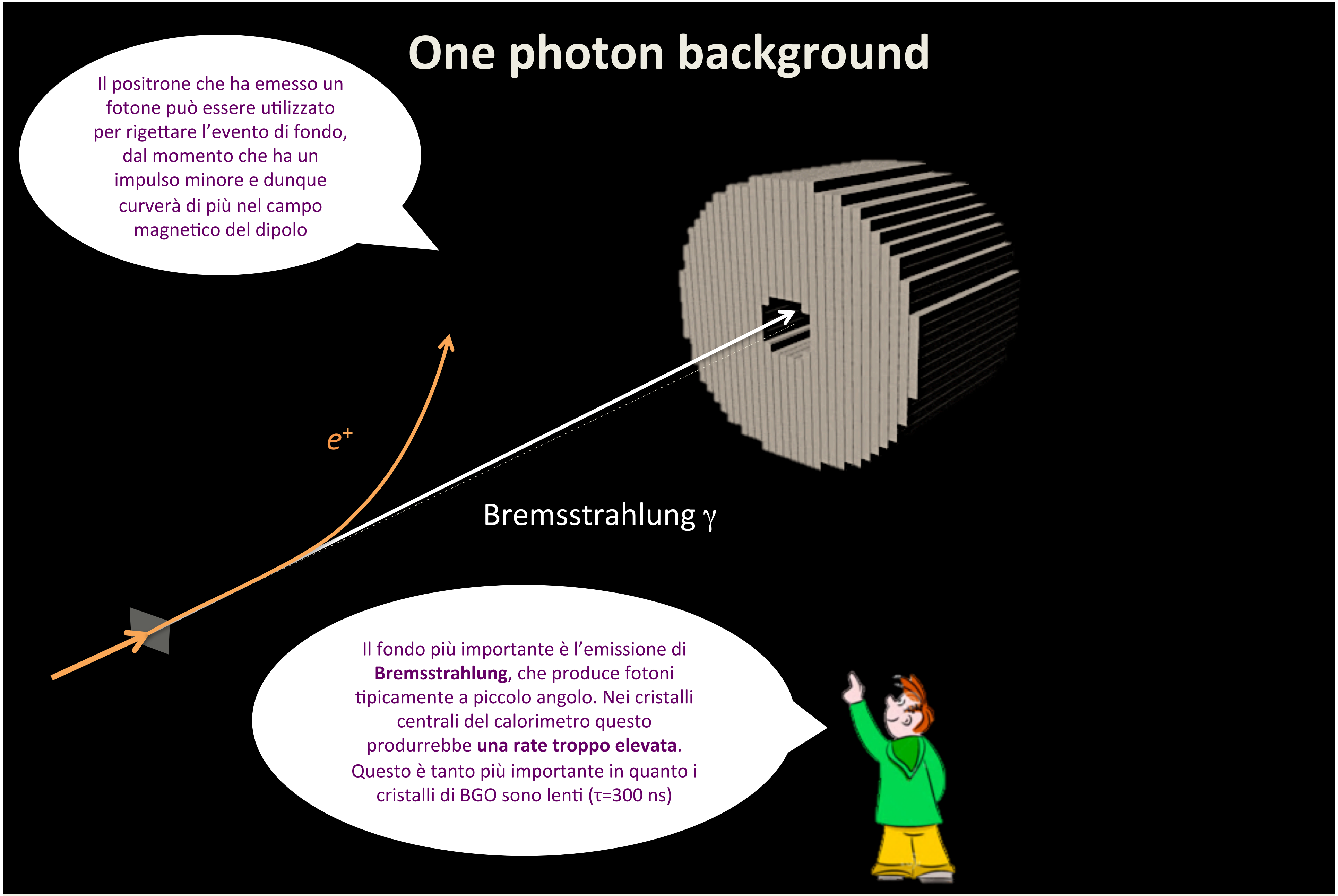
- Sub-ns timing resolution



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

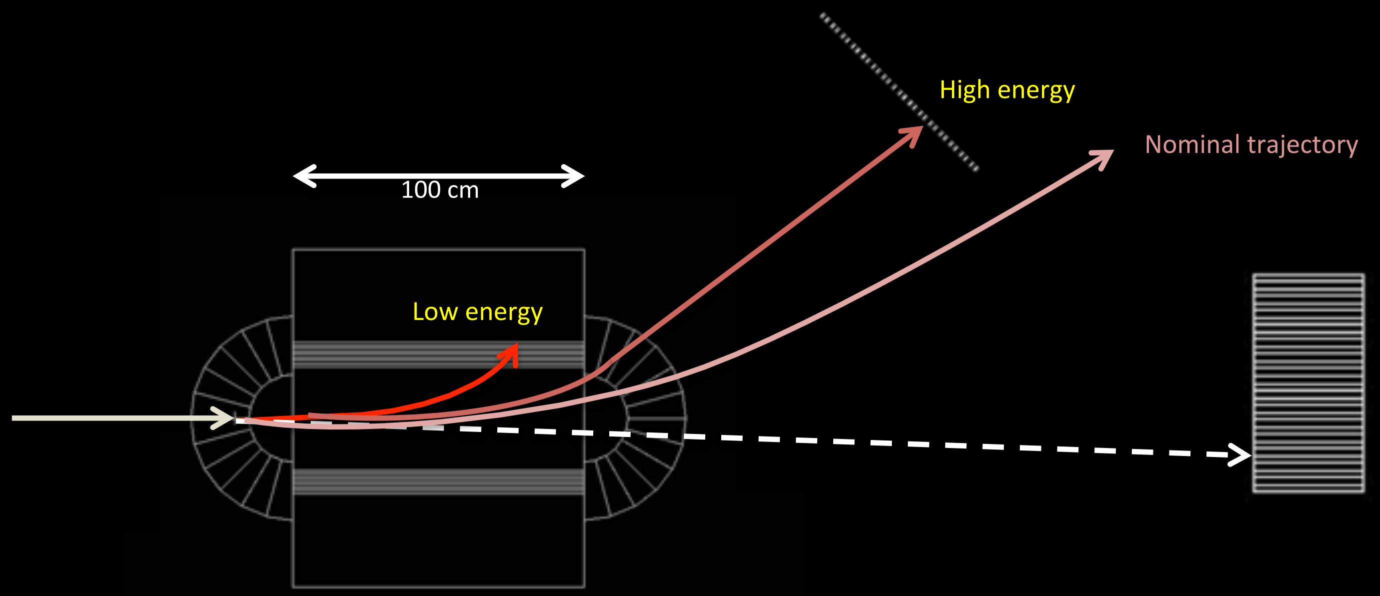
… and we have to take into account **another important constraint**:

- The **cost**, which is driven by the **material**, **size** and **granularity** (i.e. the number of channels)


One photon background
Il positrone che ha emesso un fotone può essere utilizzato per rigettare l'evento di fondo, dal momento che ha un impulso minore e dunque curverà di più nel campo magnetico del dipolo
e+
Bremsstrahlung γ
Il fondo più importante è l'emissione di Bremsstrahlung, che produce fotoni tipicamente a piccolo angolo. Nei cristalli centrali del calorimetro questo produrrebbe una rate troppo elevata. Questo è tanto più importante in quanto i cristalli di BGO sono lenti (τ=300 ns)

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



The calorimeter

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output[†]	Hygro-scopic?	$d(LY)/dT$
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}

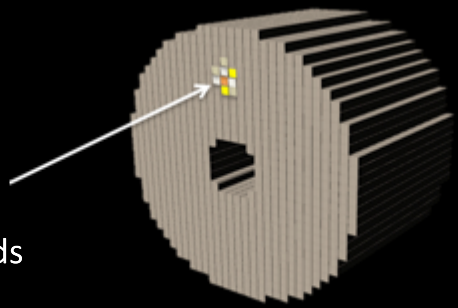
- Resolution also in 1-2%/√E range

Small Moliére radius and high light yield:
LYSO and **BGO** are both OK

- **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** → still too much

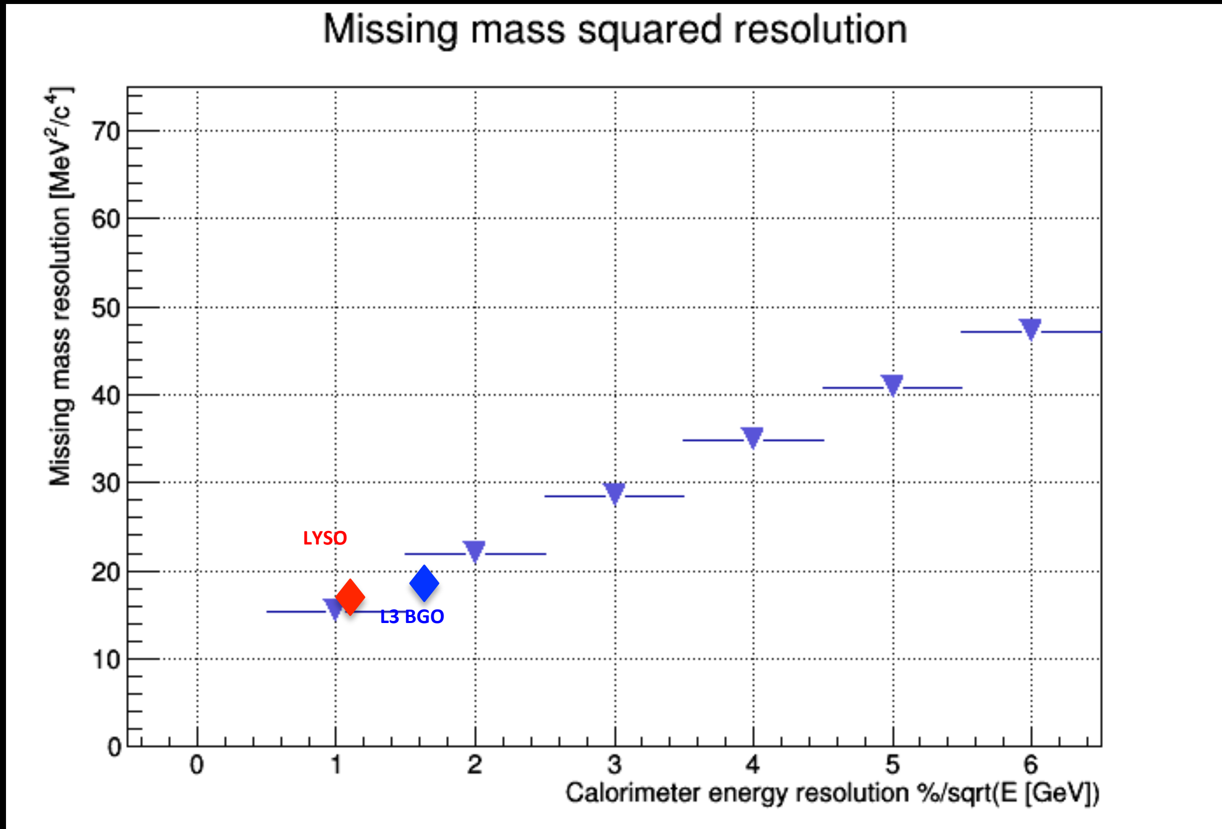
... But we have **clusters**!

- Center of gravity should have a better resolution
- Most of the energy will be in a single crystal, pulling the c.o.g. towards the center of the most energetic one
- Results with a Geant4 "photon gun", E=500 MeV:
  $\sigma_{cluster}$≈4.5 mm (including the systematic shift due to shower depth)



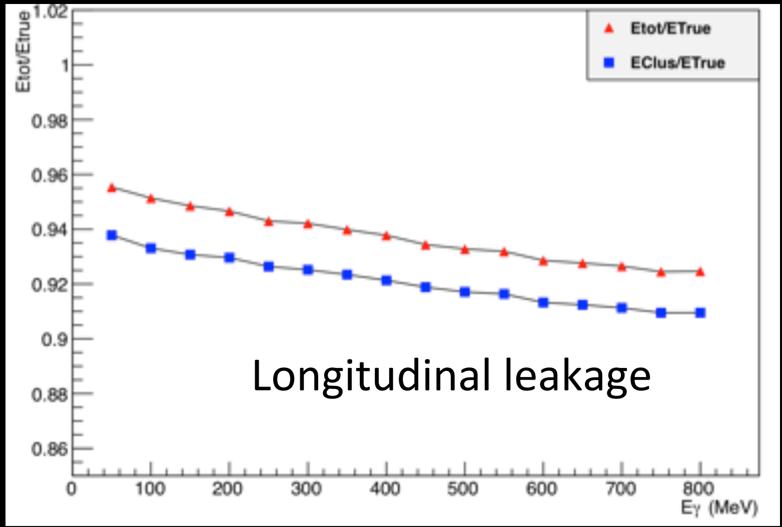
2 cm crystals		
d	$\langle d_{exp} - d \rangle$	RMS
0.0	0.00	0.18
-0.2	0.13	0.18
-0.4	0.24	0.20
-0.6	0.33	0.24
-0.8	0.33	0.29
-1.0	0.10	0.40

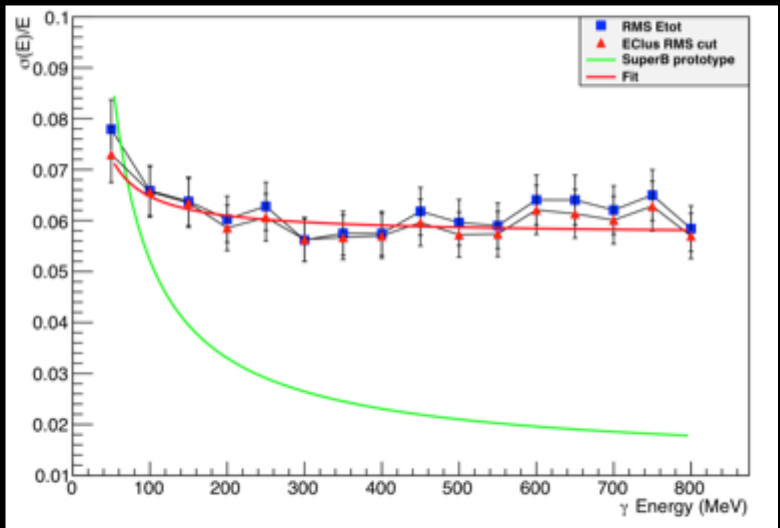
Missing mass resolution vs. calorimeter performance



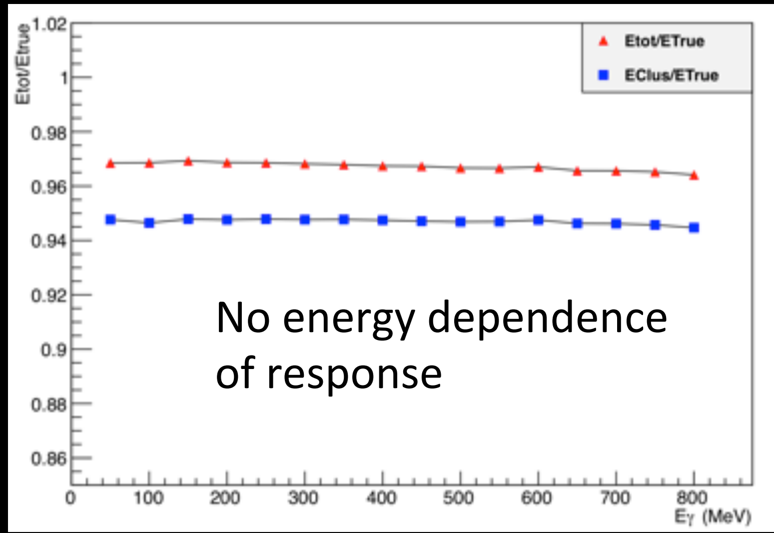
Longitudinal containment

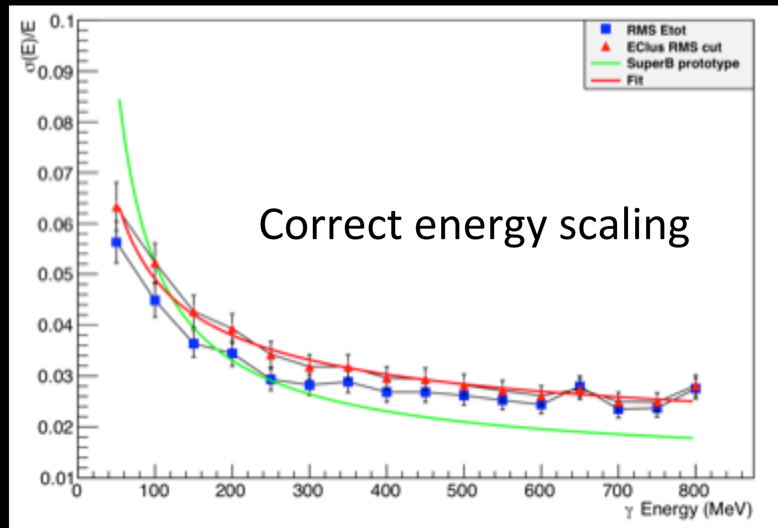
15 cm long crystals (13.2 X_0)



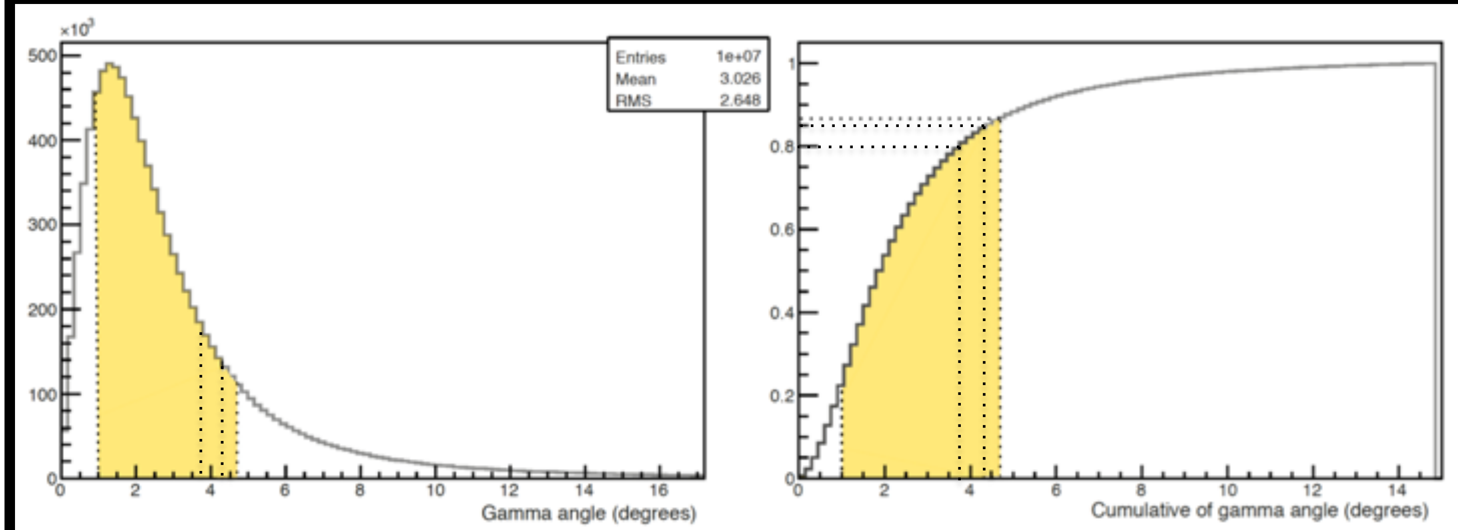


20 cm long crystals (17.5 X_0)





Signal acceptance in calorimeter



Central hole of 20 mrad (1°) ≈ 20% of acceptance

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

Acceptance increasing quite slowly

But wait! What about the **backgrounds** with **>1 photons**?

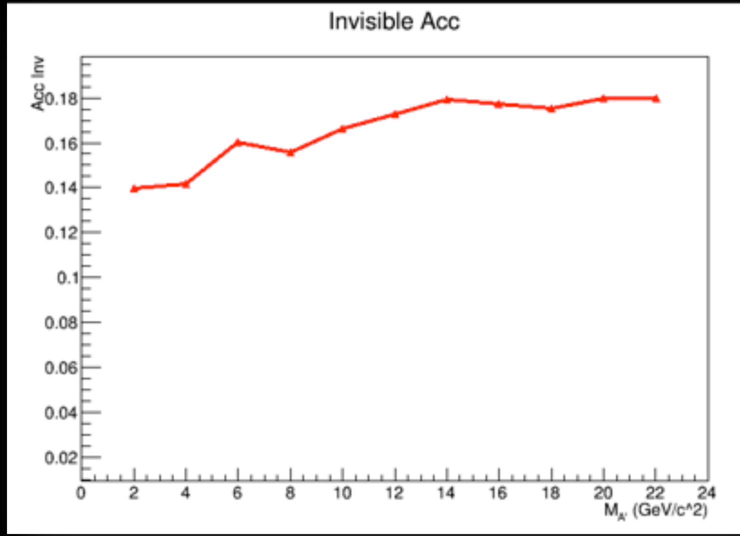
Occorre una selezione per gli eventi di segnale e verificare quanta contaminazione dei vari tipi di fondo comporta…

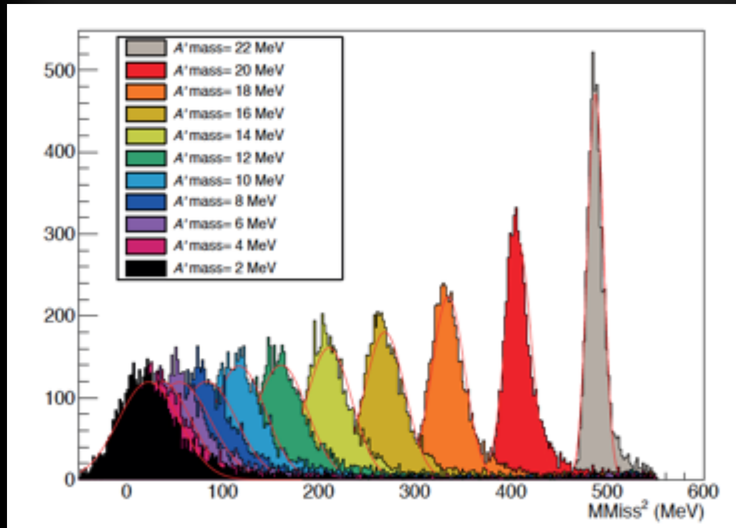
… questo può suggerire la necessità di ulteriori rivelatori per esempio nel "buco" del calorimetro

Signal selection

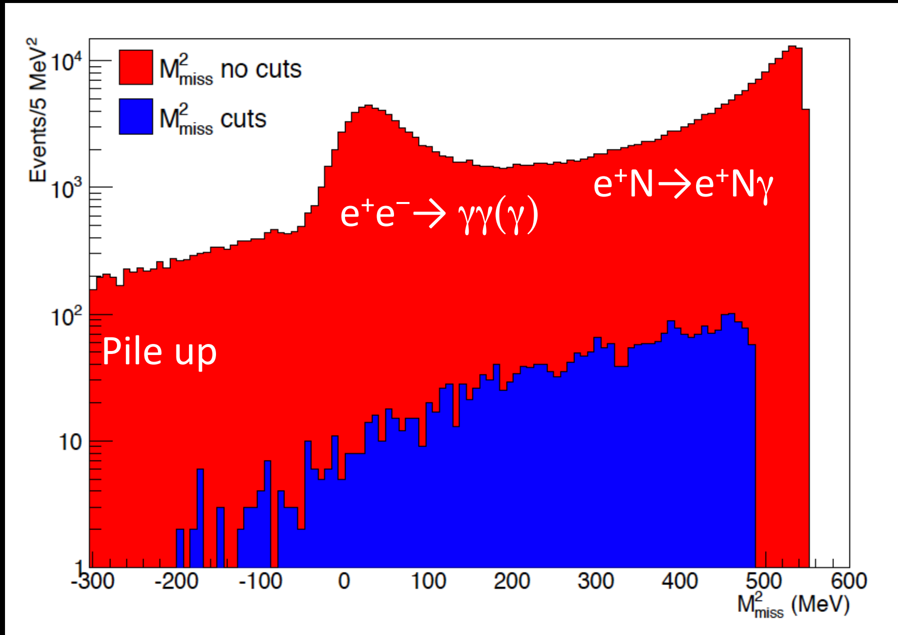
- Only one cluster in calorimeter
  - Rejects $e^+e^- \to \gamma\gamma$, $e^+e^- \to \gamma\gamma(\gamma)$ final states
- 30 mrad < θ_{Cl} < 65 mrad
  - Improve shower containment $\sigma(E)/E$
- Positron veto: no tracks in the spectrometer in ±2 ns
  - Reject Bremsstrahlung identifying primary positrons
- Photon veto: no γ with E_γ>50 MeV in time in ±1ns in the additional small angle veto (SAV), covering the hole acceptance
- Cluster energy within: $E_{min}(M_{A'}) < E_{Cl} < E_{max}(M_{A'})$ MeV
  - Removes low energy Bremsstrahlung and piled-up clusters
- Missing mass in the region: $M_{miss2} \pm \sigma(M_{miss2})$

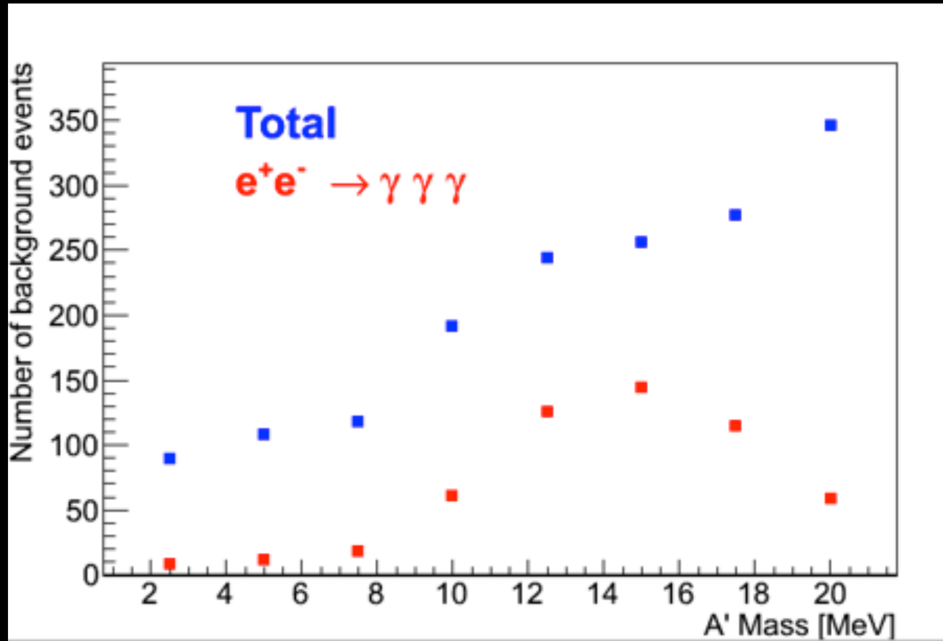
Resolution is the result of combination of angular resolution, energy resolution and angle-energy correlation due to production





Residual background estimate





- Pile up contribution is important but rejected by the maximum cluster energy cut and M^2_{Miss}.
- Veto inefficiency at high missing mass when $p_{e+} \simeq p_{e+beam}$
  - Additional positron veto detector can help rejecting residual background

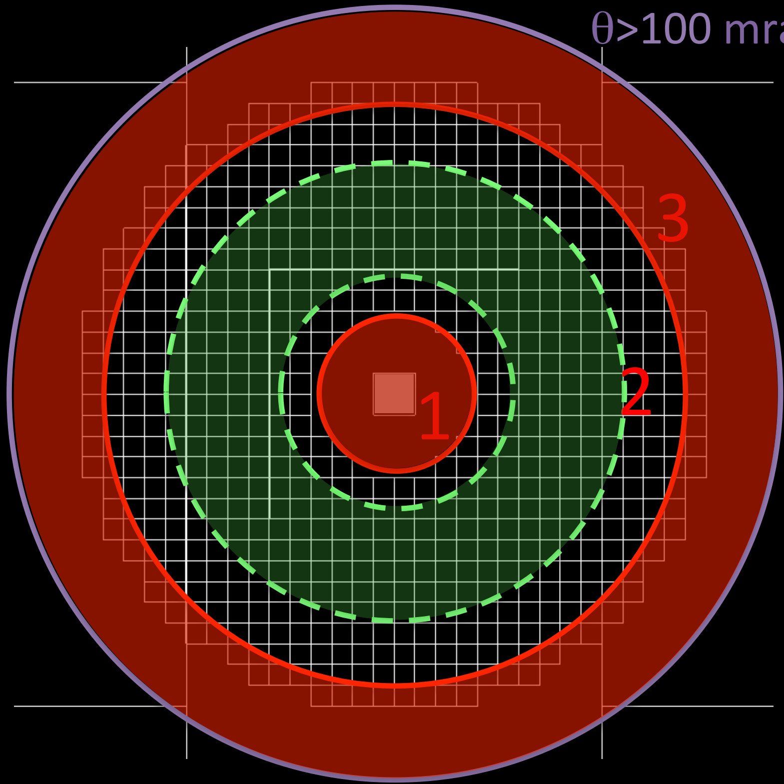
Rejection of 2 and 3 photons backgrounds depend on the cluster definition, on the topology cuts, and ultimately on the **calorimeter angular acceptance**

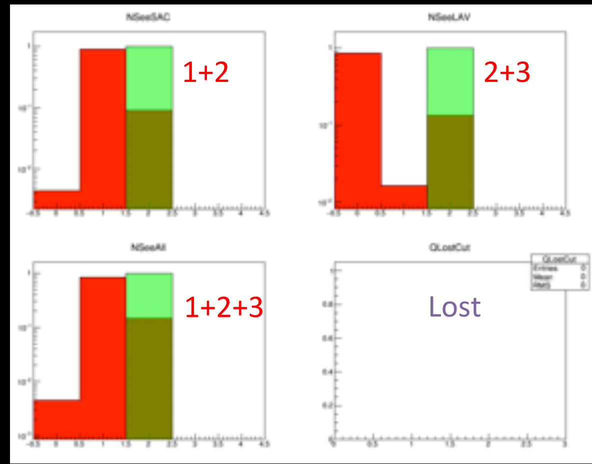
2γ and 3γ backgrounds in the calorimeter

Region 1
<20 mrad

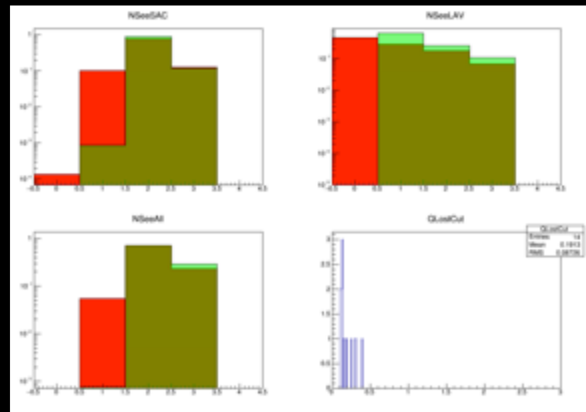
Region 3
θ>75 mrad

Lost
θ>100 mrad





No 2γ events



Per-mil 3γ background

Red: total number of hits in each region, without costraints

Green: total number of hits in each region, given the recoil γ request

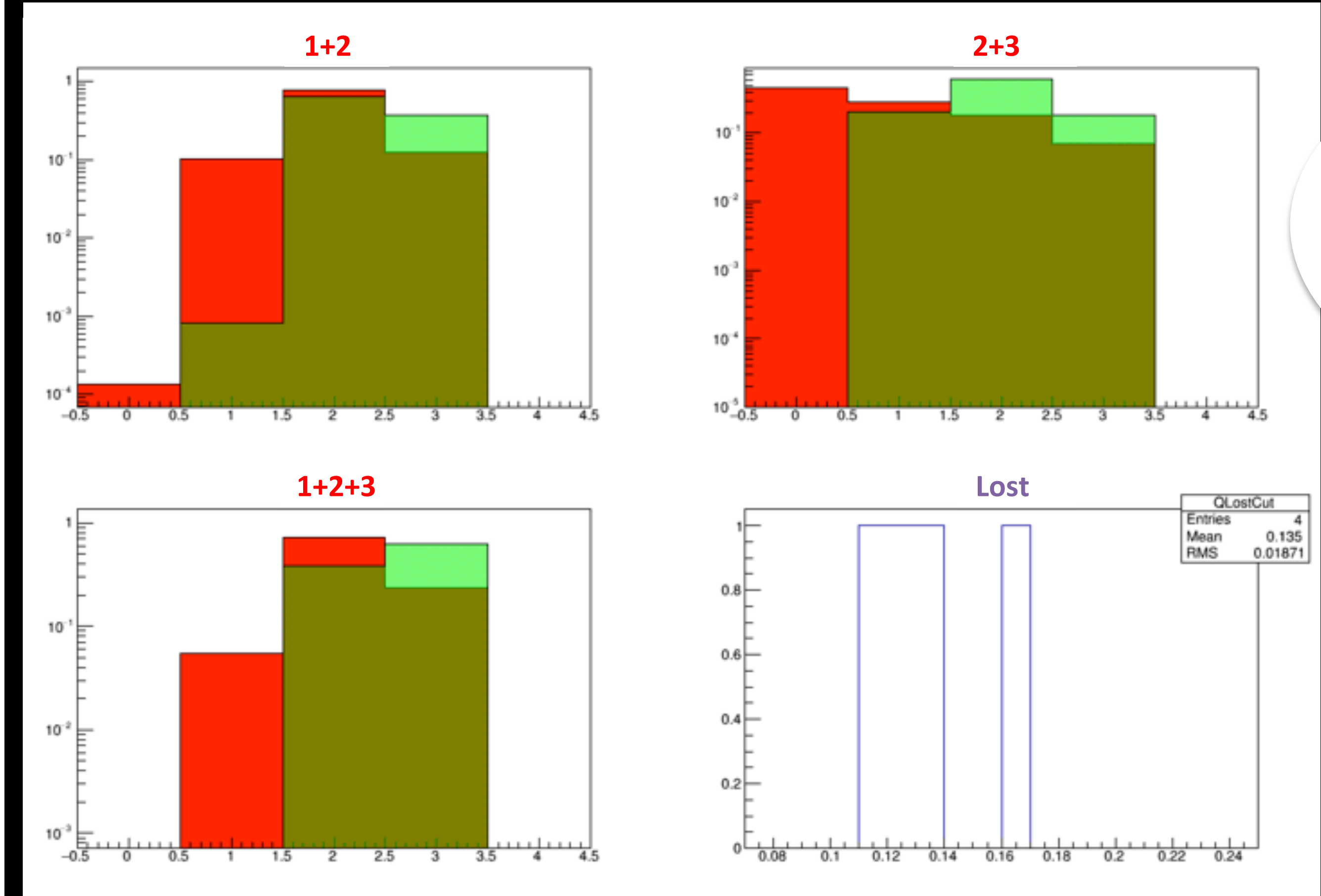
Recoil γ definition:

10 MeV < E < 400 MeV

30 mrad < θ < 65 mrad

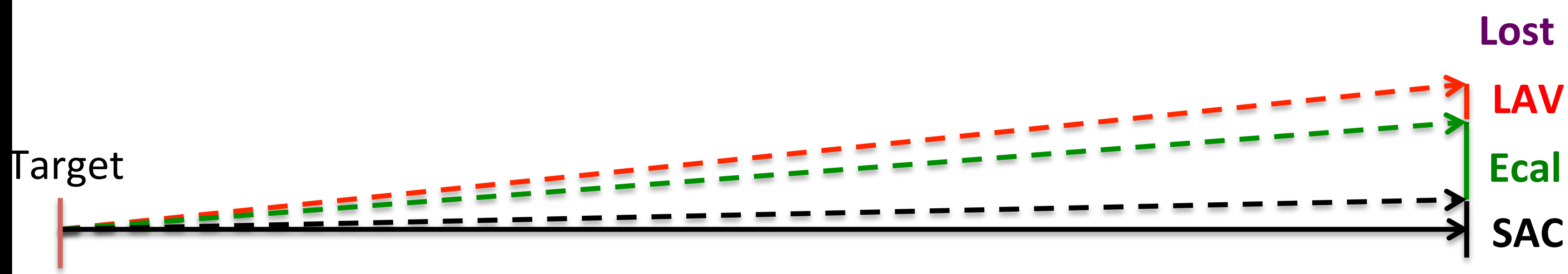
Residual background

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



Una frazione di eventi di fondo a 2 e 3 fotoni è nella zona “1”: è necessario un **rivelatore a piccolo angolo** che copra il “buco” del calorimetro

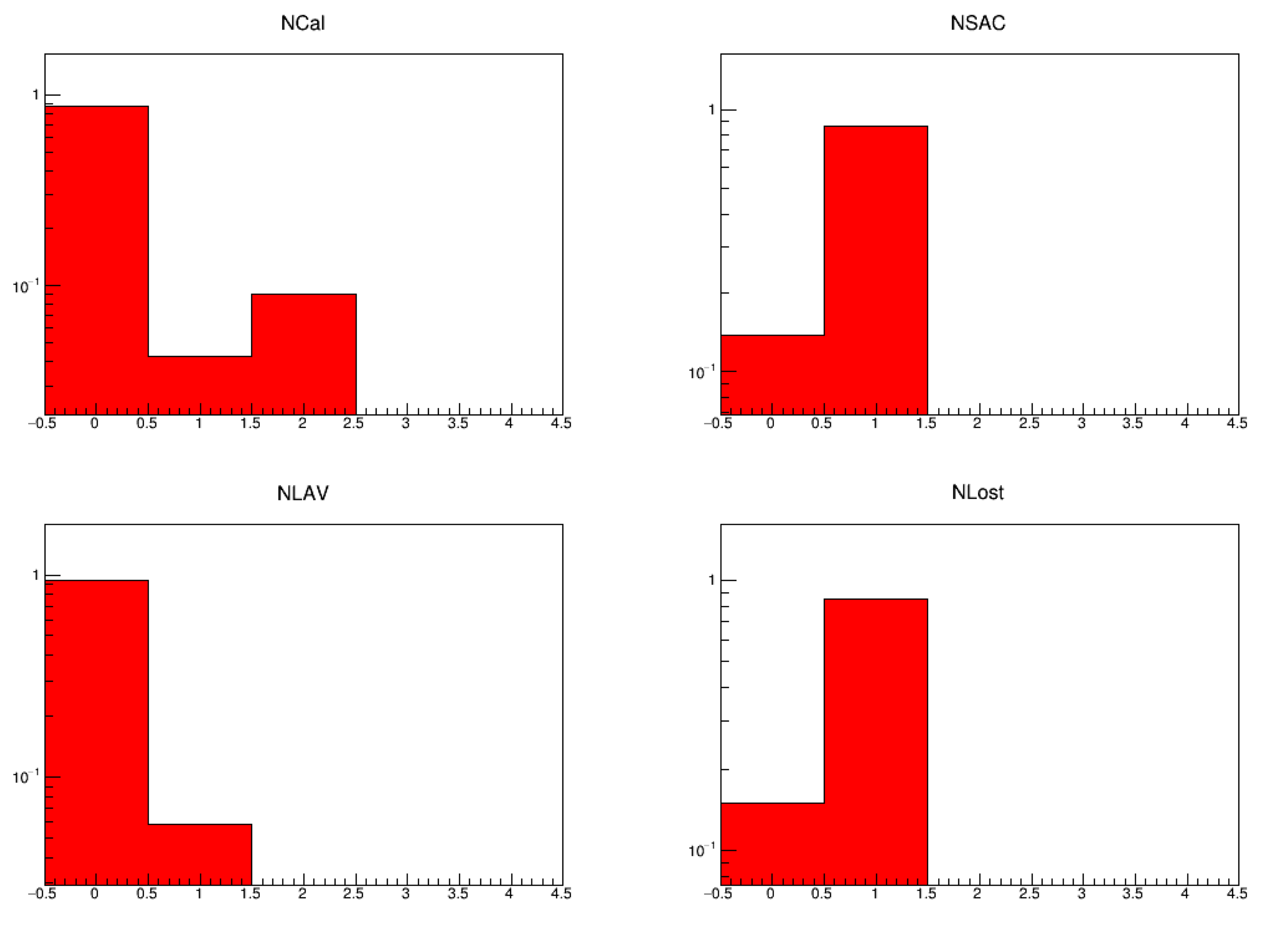
BG studies definitions



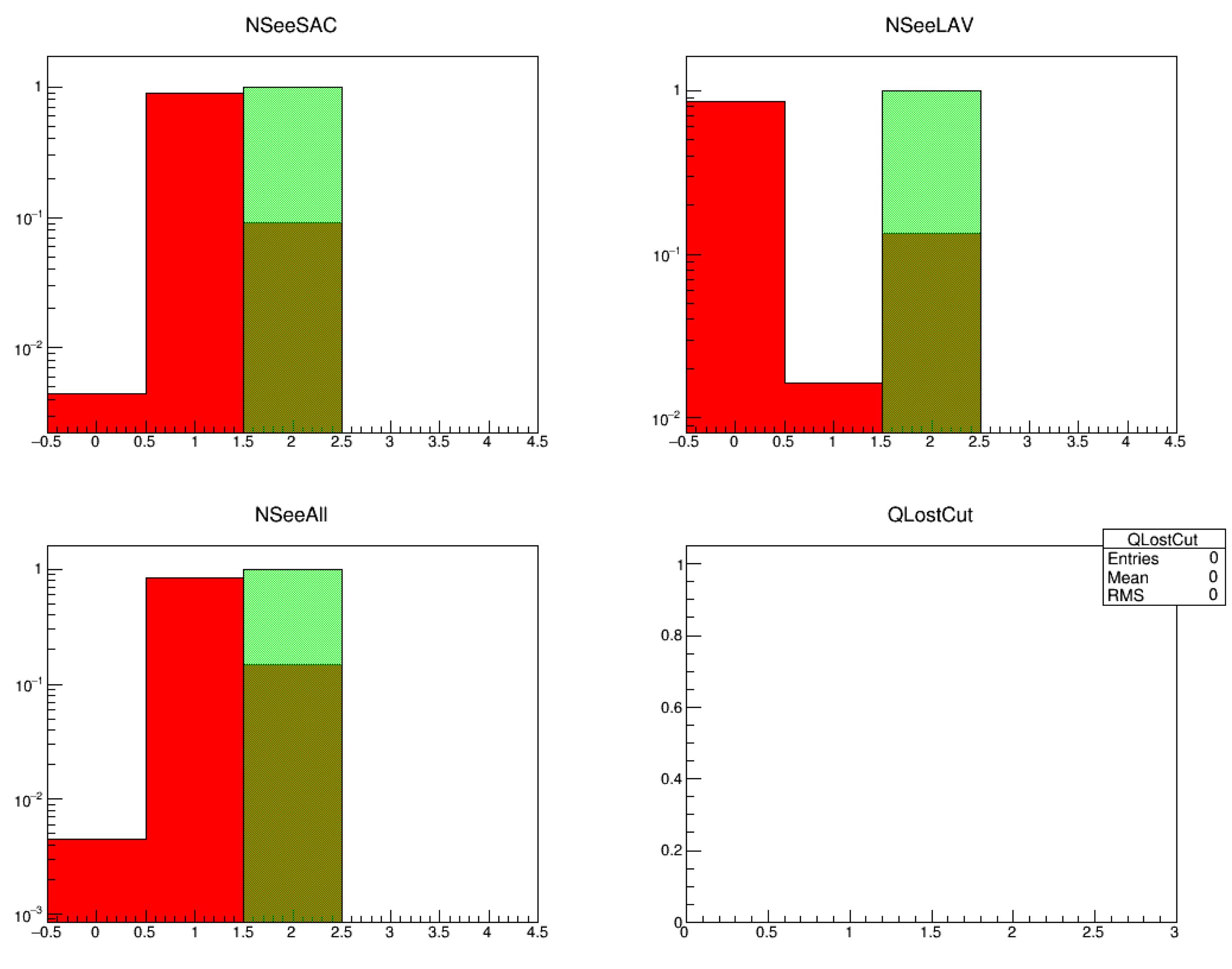
Detector	Angle	
Small angle Calo	0-20 mrad	NSAC
Electromagnetic Calo	20-75 mrad	NCal
Large angle Veto	75-100 mrad	NLAV
Lost	>100 mrad	Nlost

NseeSAC= NSAC+Ncal
NSeeLAV= NLAV+Ncal
NSeeALL= NLAV+NCal+NSAC

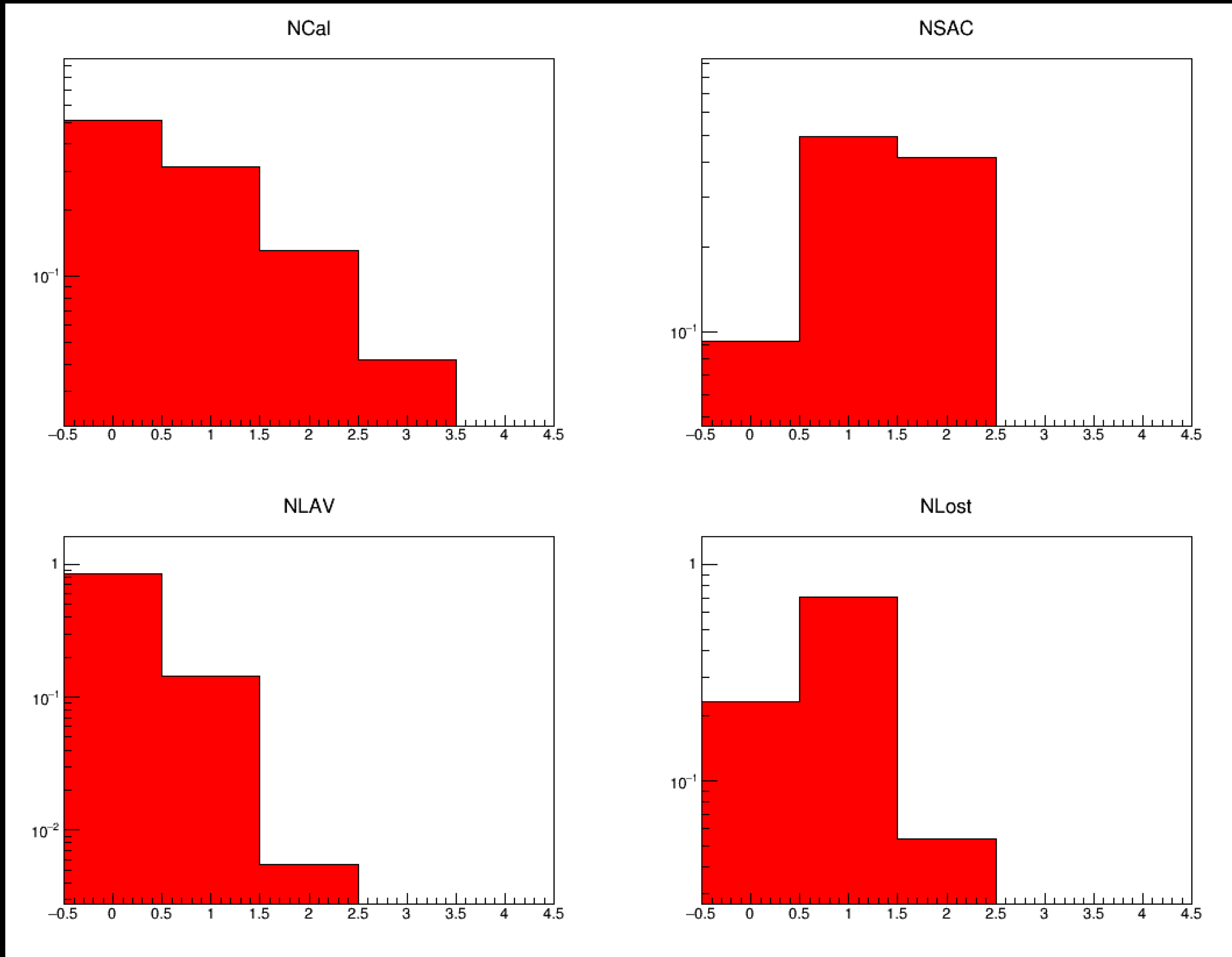
2γ distribution no cuts



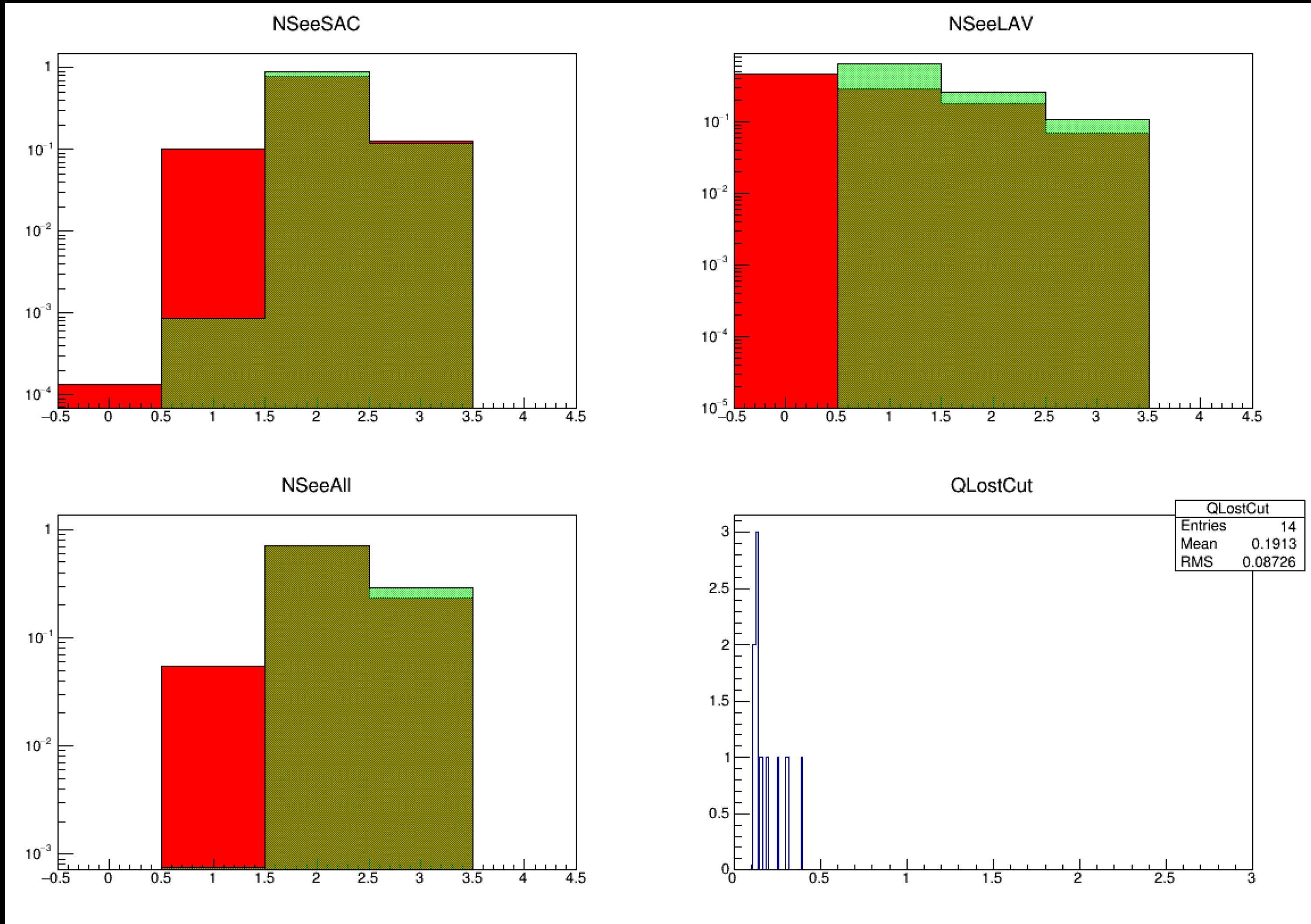
After applying the 1γ cut

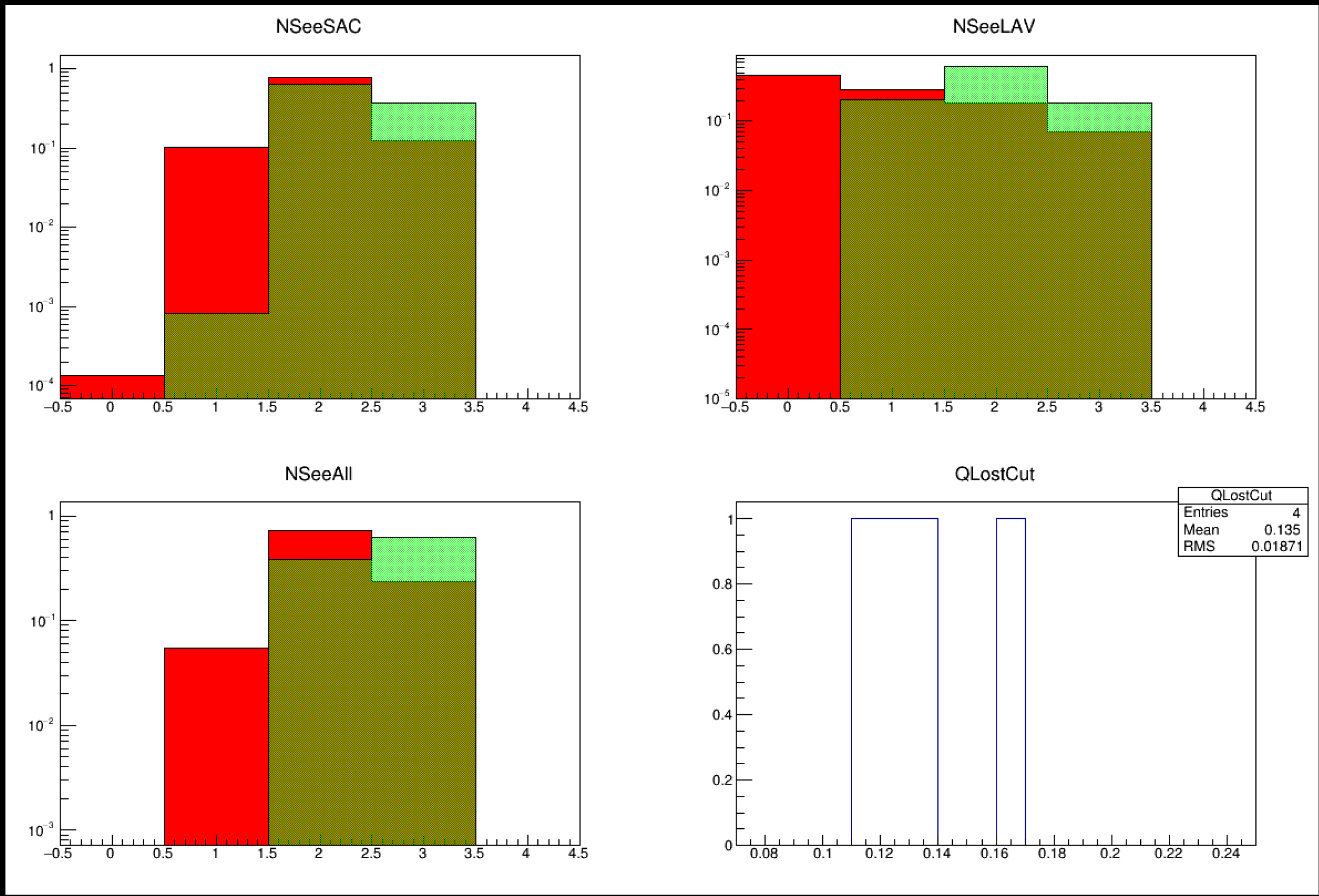


3g background distribution

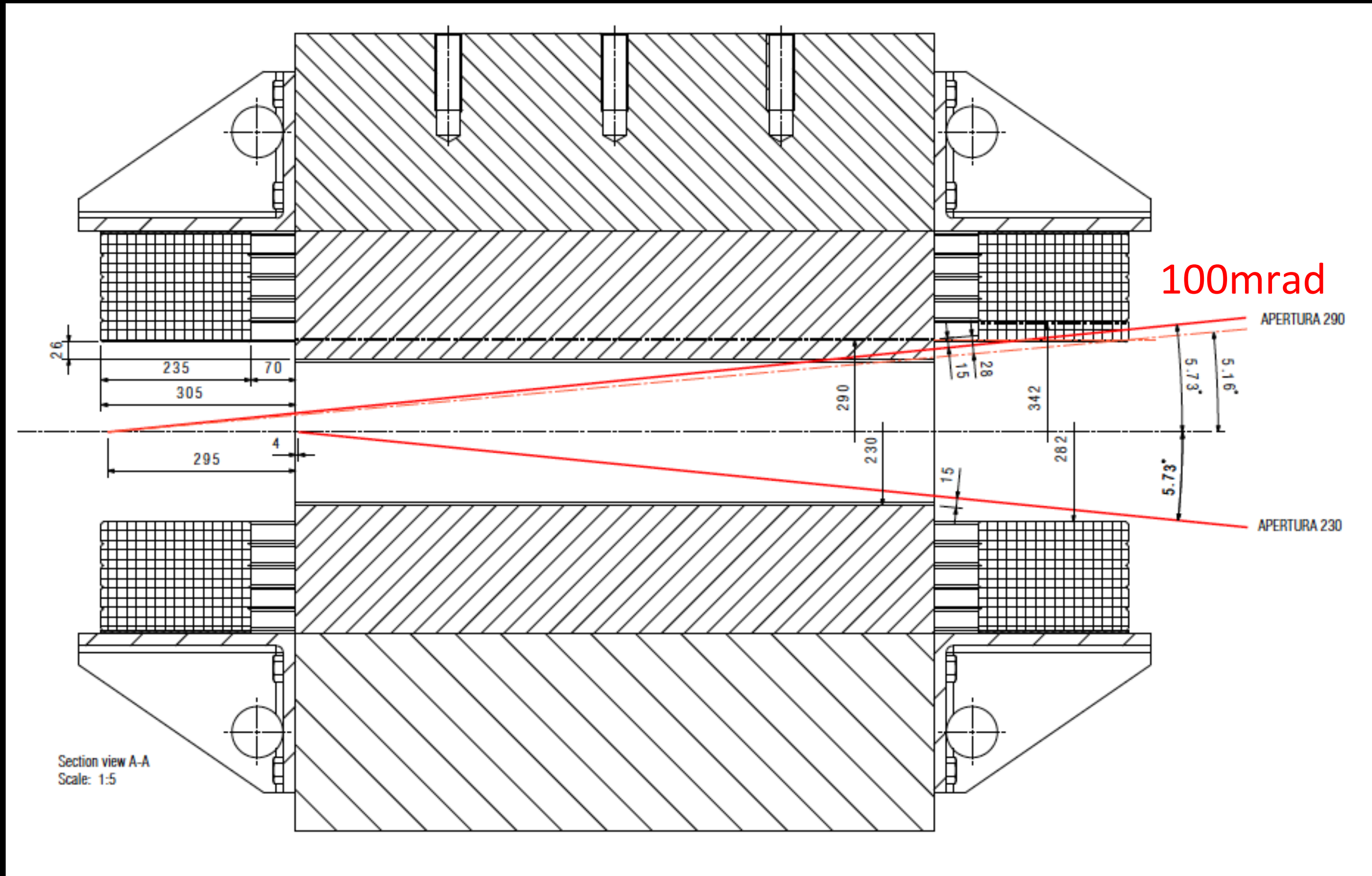


With standard 1γ definition



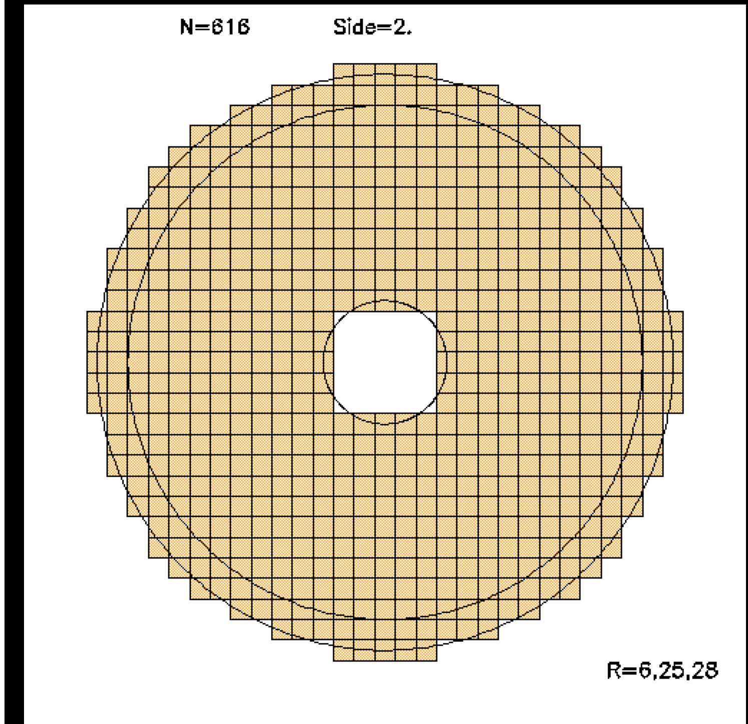


GammaEMin =150.; GammaQMin = 0.030;
GammaEMax =450.; GammaQMax = 0.065;



To keep the 100mrad acceptance for photons and the target out of the coils we need a gap of 290 mm. The parts needed for the extensions are available at CERN

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**
- $616 \times 20 \times 2 \times 2 = 50000\ cm^3$

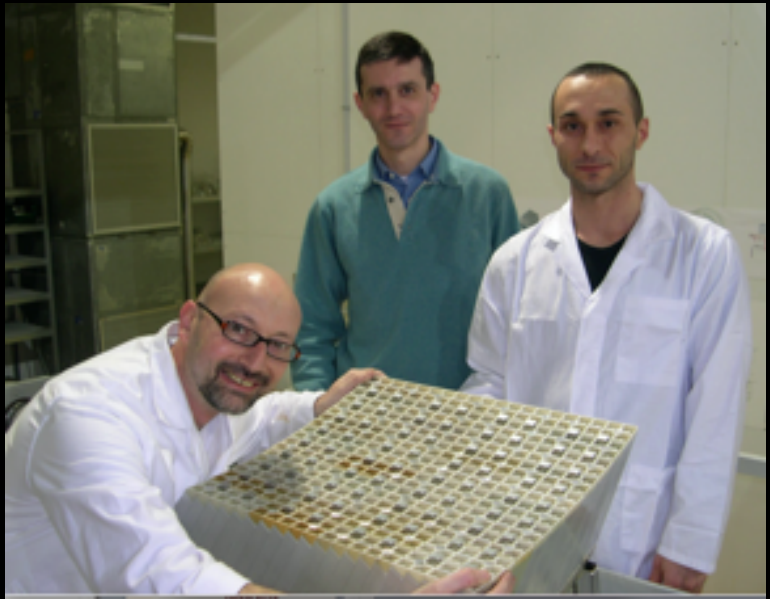
Now…

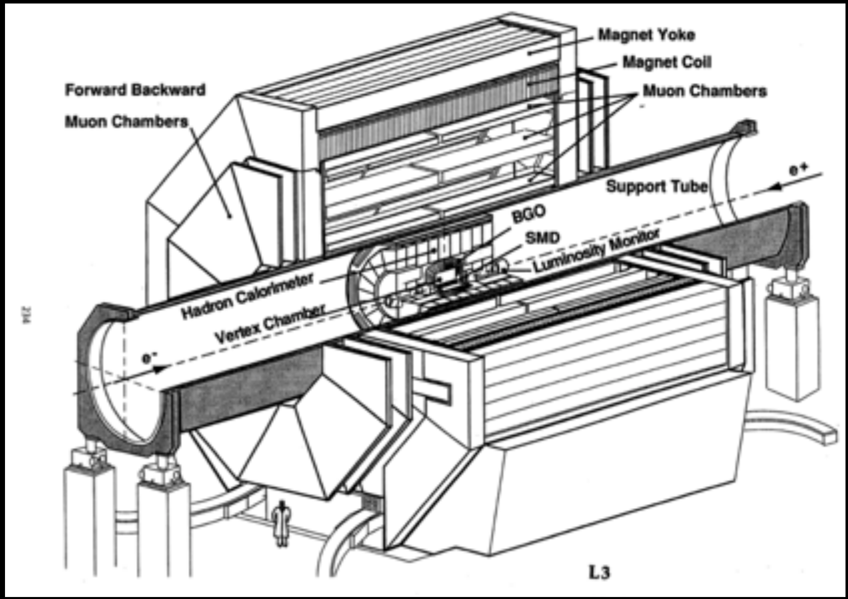
… at 20€/cc such a calorimeter will cost 1 M€ only for buying the crystals (probably **twice** in the case of LYSO…)
+ photosensors
+ readout

Sarebbe molto bello riuscire a trovare dei cristalli non più utilizzati da un vecchio esperimento!...

Non è che ci siano però tante possibilità: esperimenti del **LEP**, poi **BaBar**, **CLEO**…

L3 BGO crystals

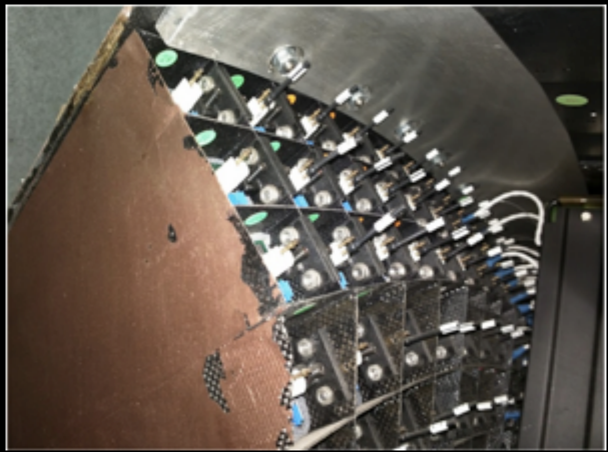


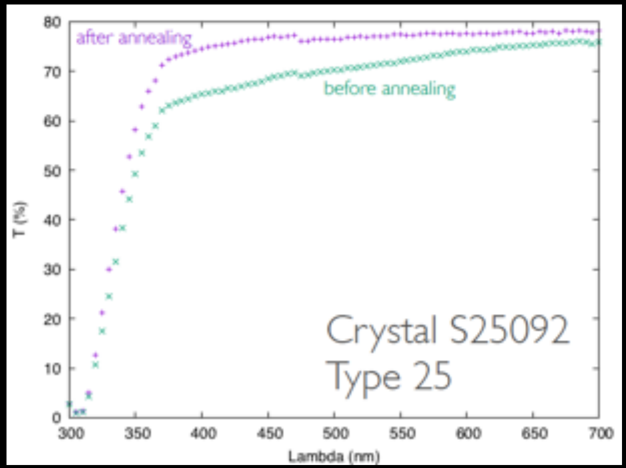


≈600 BGO crystals from former L3 experiment electromagnetic calorimeter

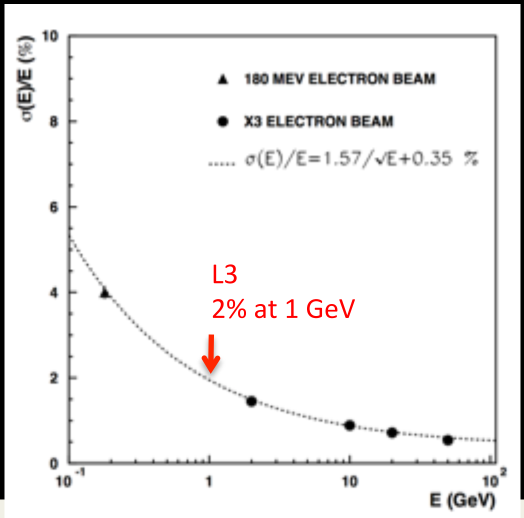
- **Many thanks to prof. S. Ting (L3 spokesperson) and INFN management**
- Cut from trapezoidal prism shape to square section **21×21 mm^2**, **230 mm** long

L3 em calorimeter endcap





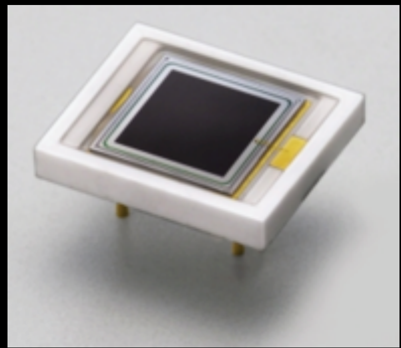
High-temperature **annealing** for recovering radiation damage (transparency loss)



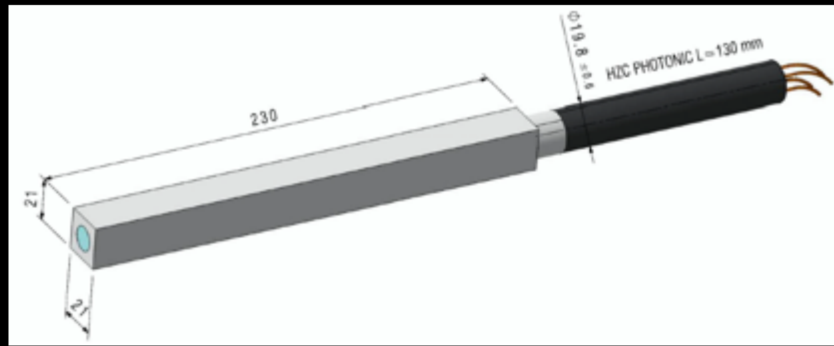
Next steps

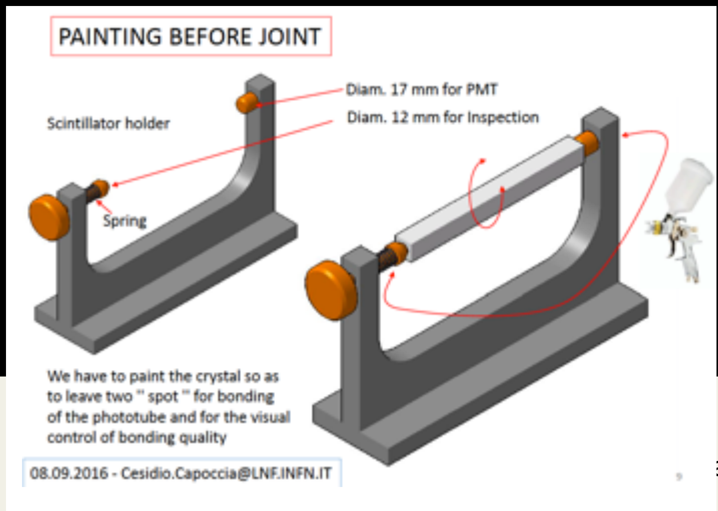
- Cut from trapezoidal prism shape to square section **21×21 mm²**, **230 mm** long
- Wrap and/or paint for light reflection/light tightness and protection
- **Choose photo-sensor**, how to couple (glue, grease…)
- Assembly procedure and mechanical structure
- Choose readout

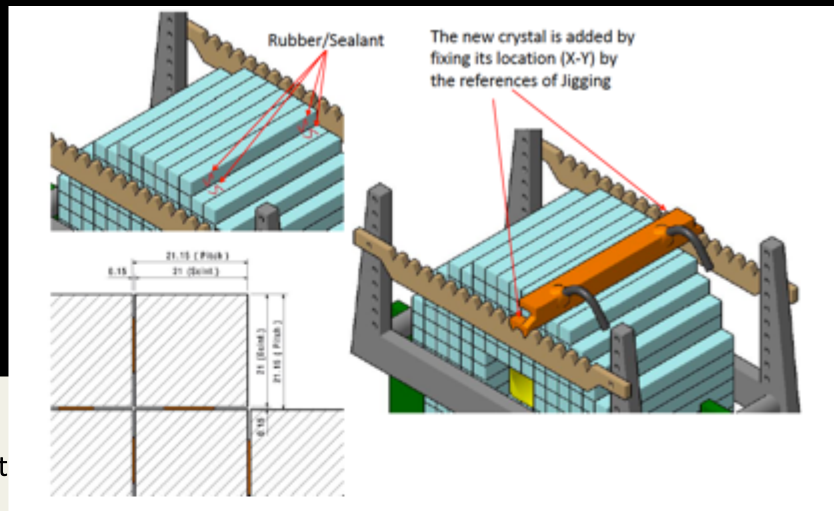
19 mm (3/4") photo-multiplier tube



10×10 mm² large area APD

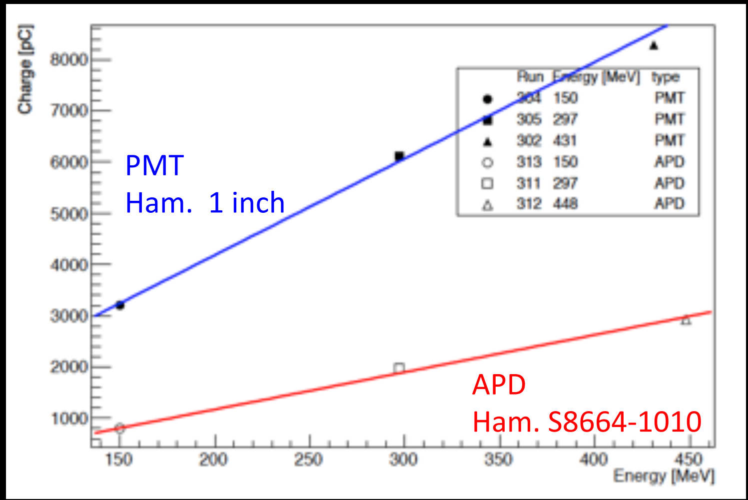


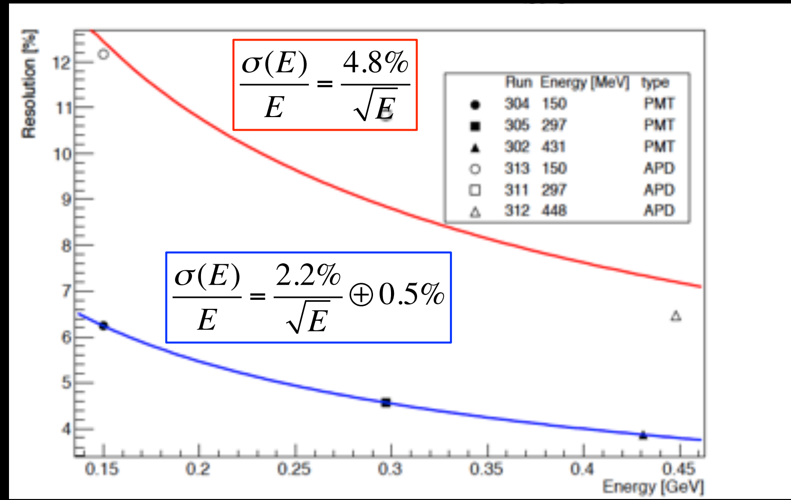


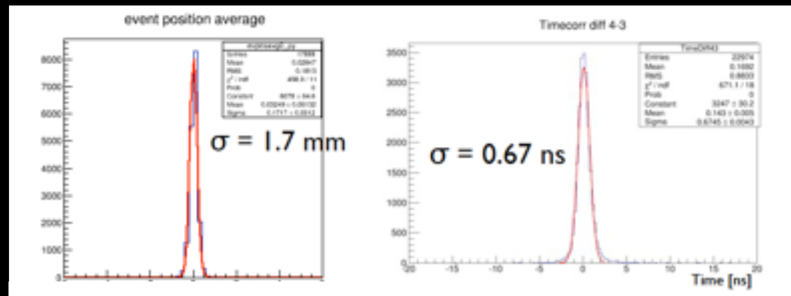


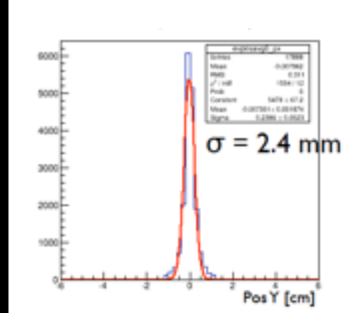
at

PMT vs LA-APD





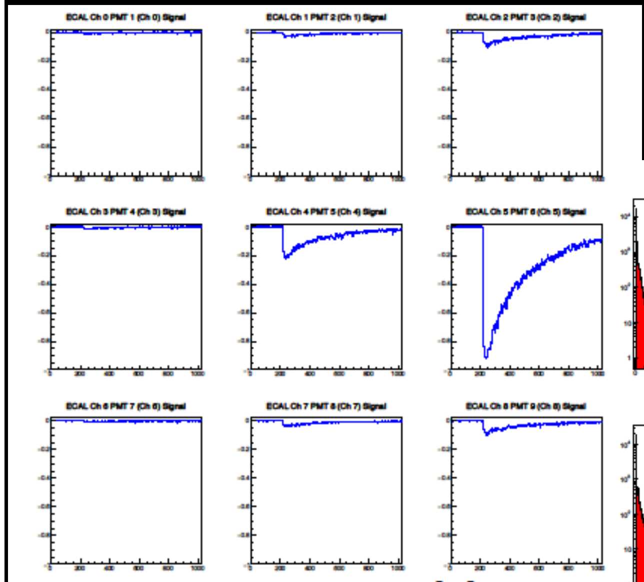




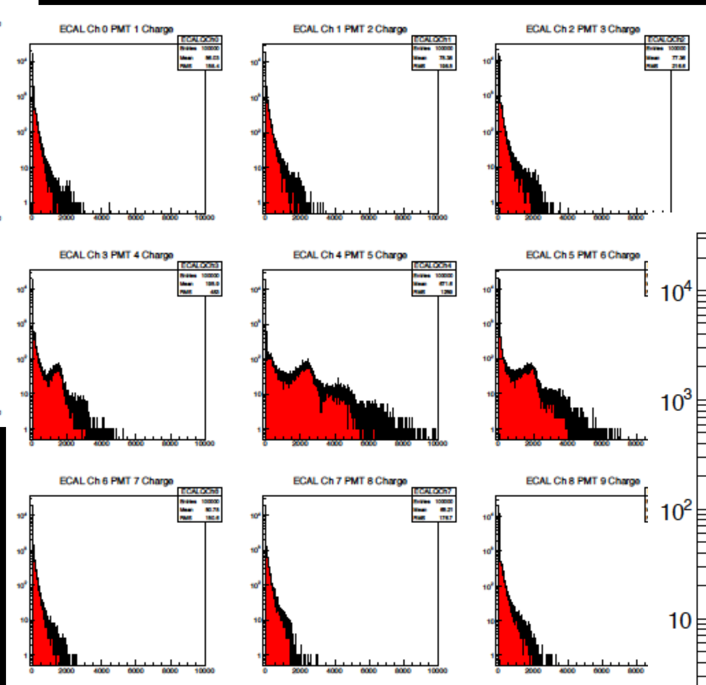
(Results on a first 3×3 prototype)

Readout

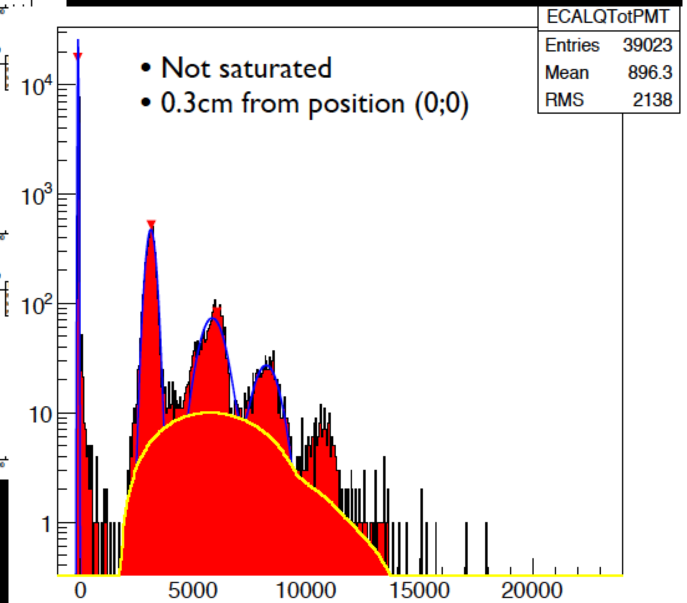
Digitized signal acquired with
CAEN V1742 (1 GS/s)



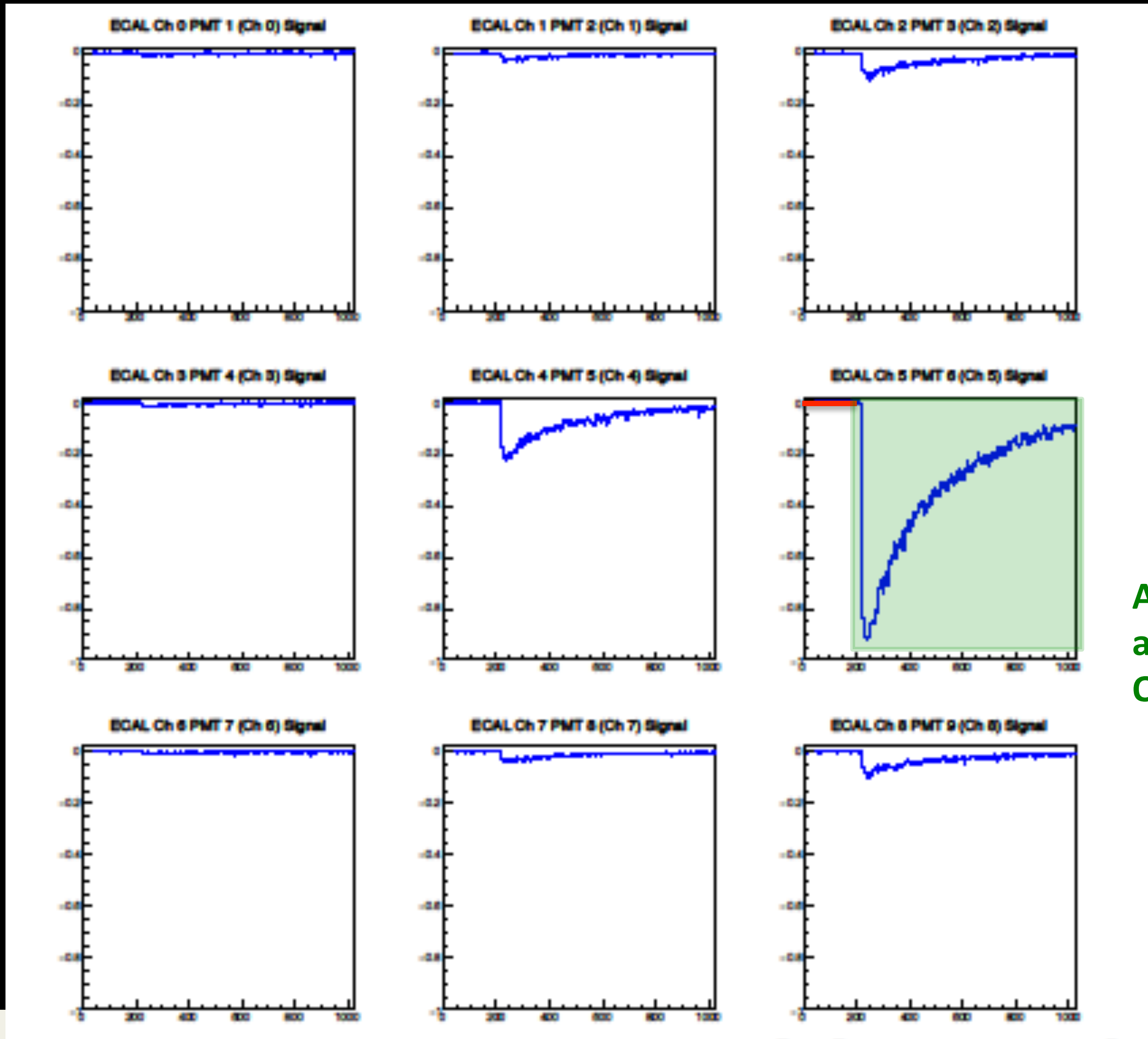
Raw signal converted into charge
integral in each crystal



Total charge spectrum obtained by
summing over all crystals



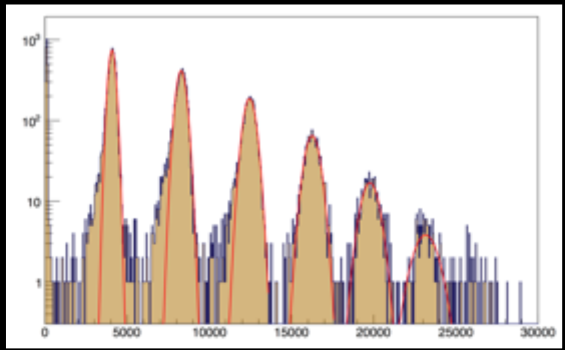
Reconstruction of charge

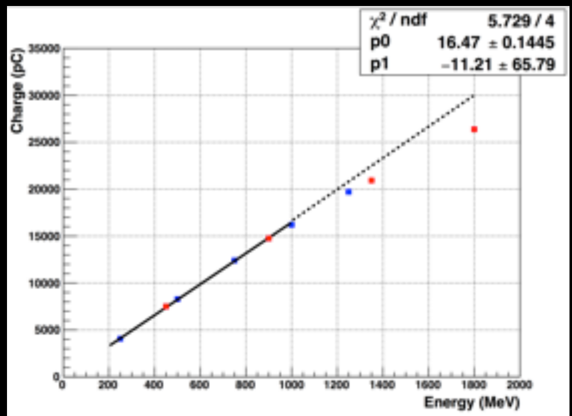


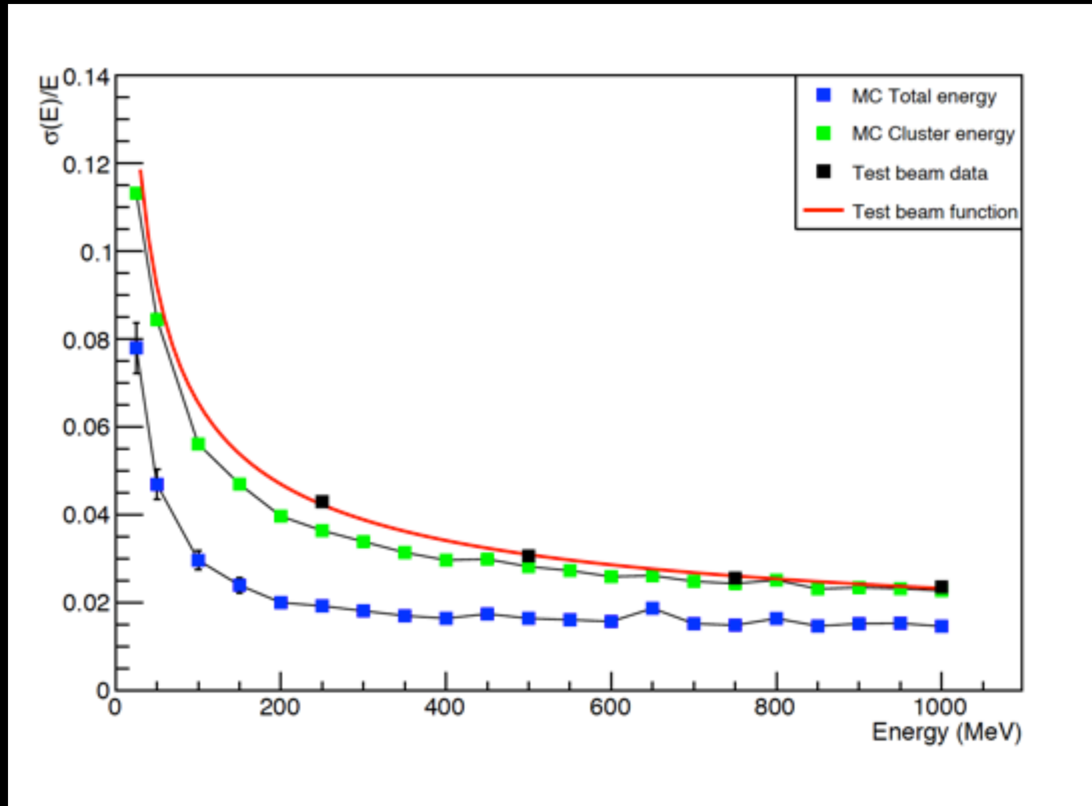
Pedestal measurement averaging first 100 samples

After reconstructing pedestal average:
Qch=Qch-Ped()

Resolution of 5×5 prototype

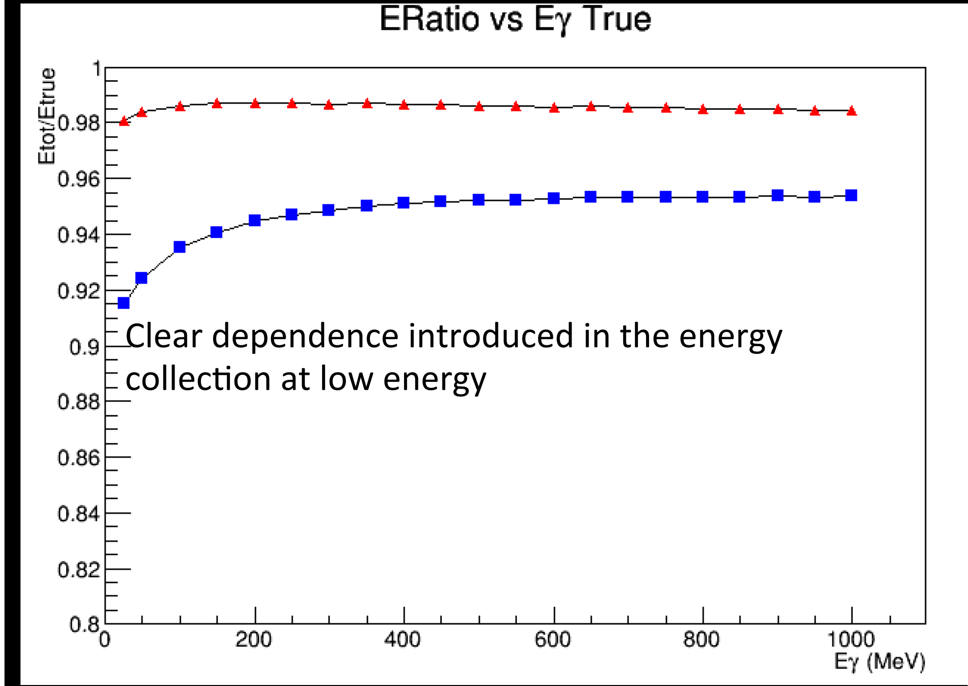


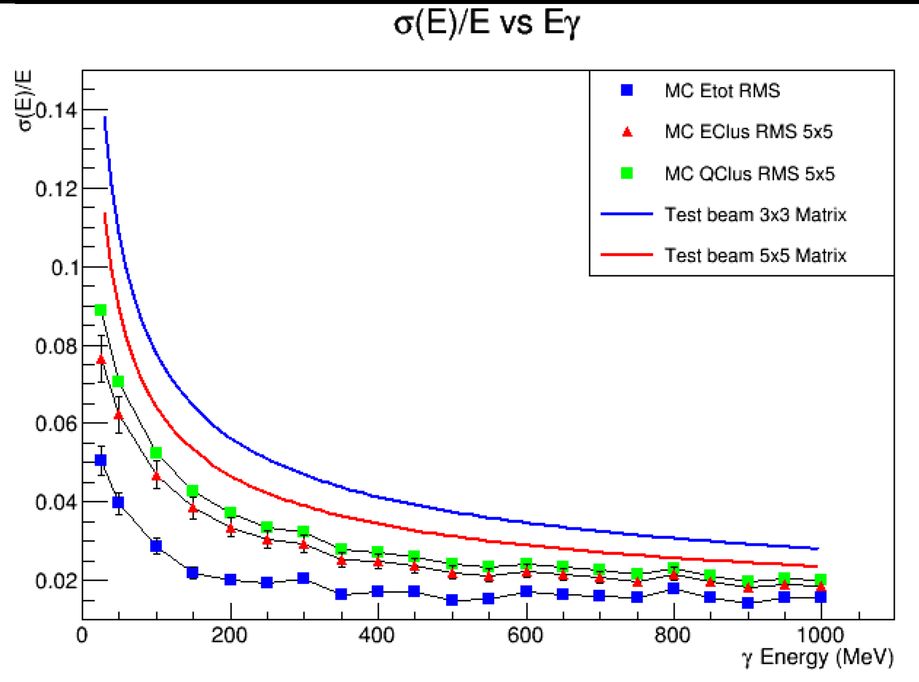




Results very similar to L3 one, even without optimal calibration

Data vs. MC



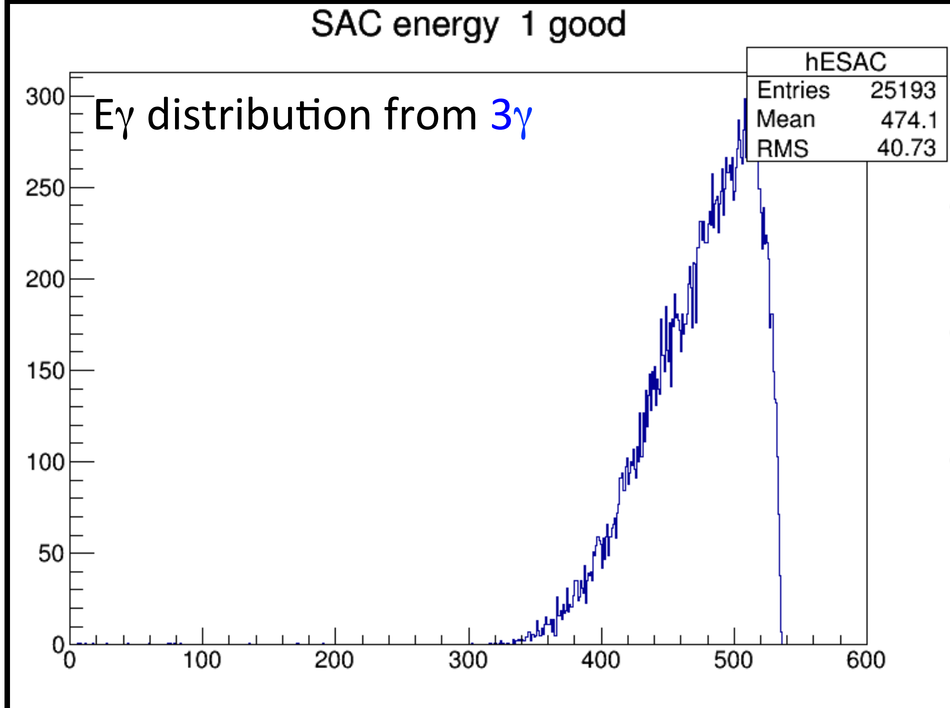


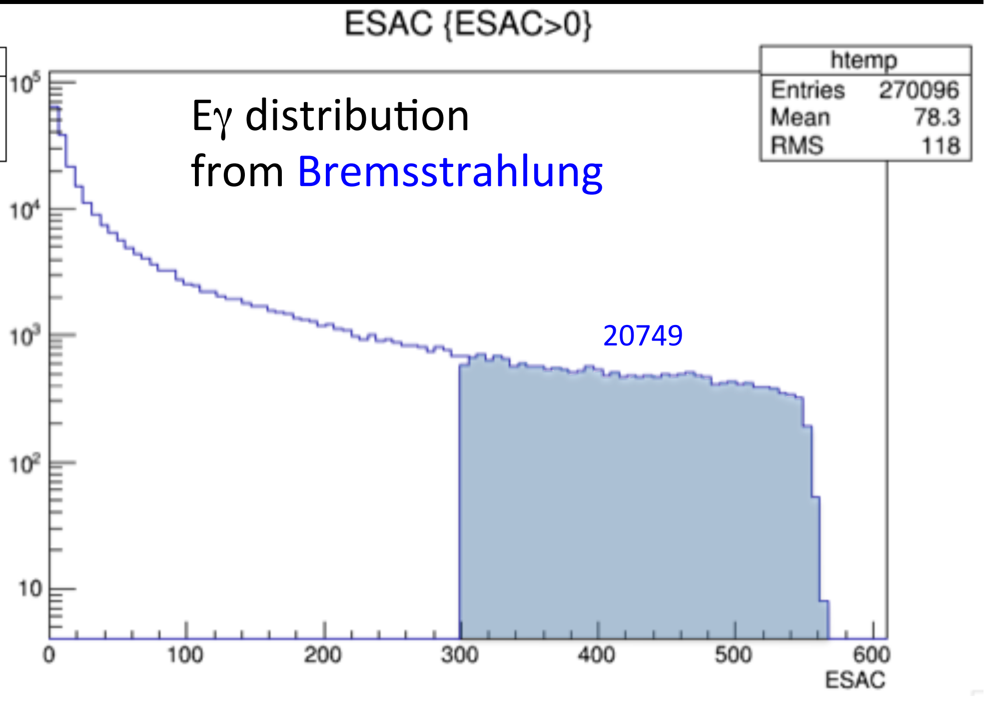
- Number of photo electrons: 100.
- Minimum of the zero suppression in MC: 1MeV
- Cell to Cell intercalibration errors: None

Torniamo al **rivelatore a piccolo angolo** che andrebbe a coprire il “buco” del calorimetro

Il suo ruolo è quello di “veto” per eventi con 2 o 3 fotoni.
Ma quali caratteristiche deve avere in termini di risoluzione, timing, efficienza…?

Small angle detector



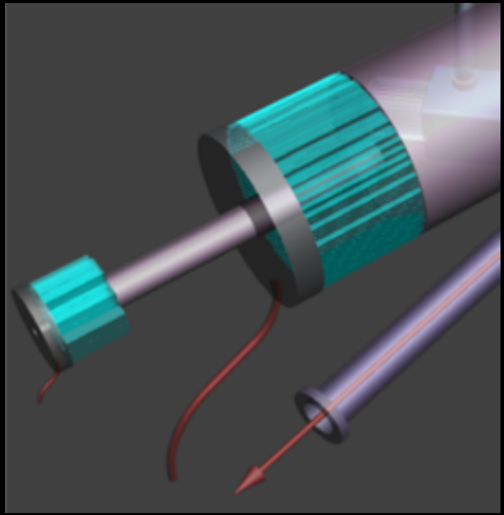


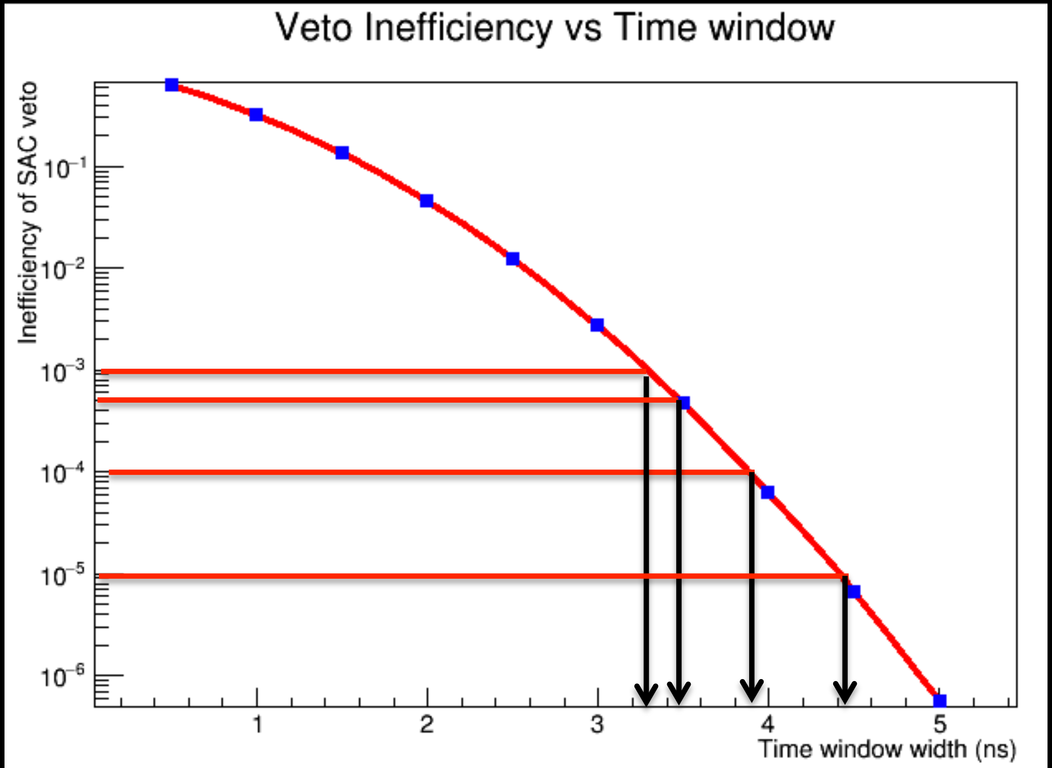
1 good cluster in calorimeter
<2 in small angle

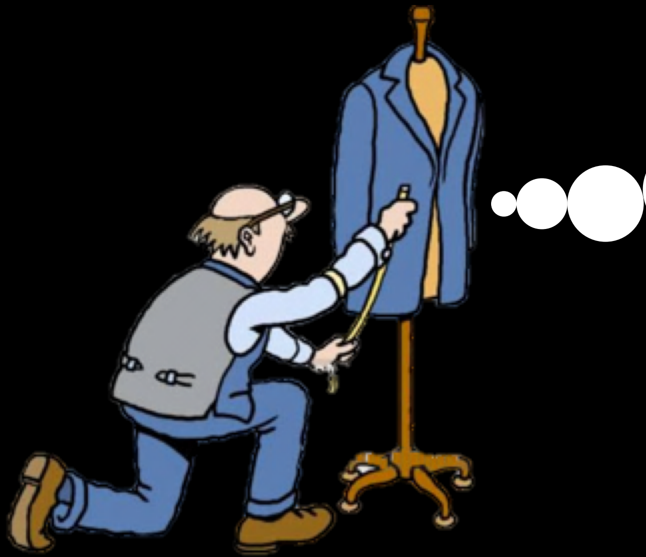
Only about 7.7% of the photons with **E>300MeV**
Need to be "blind" to photons below ≈100 MeV

Small angle detector

- BGO calorimeter cannot tolerate the Bremsstrahlung rate in the very central crystals
  - Inner hole 10×10 cm^2
- Small angle detector 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 like PbF_2 or SF57

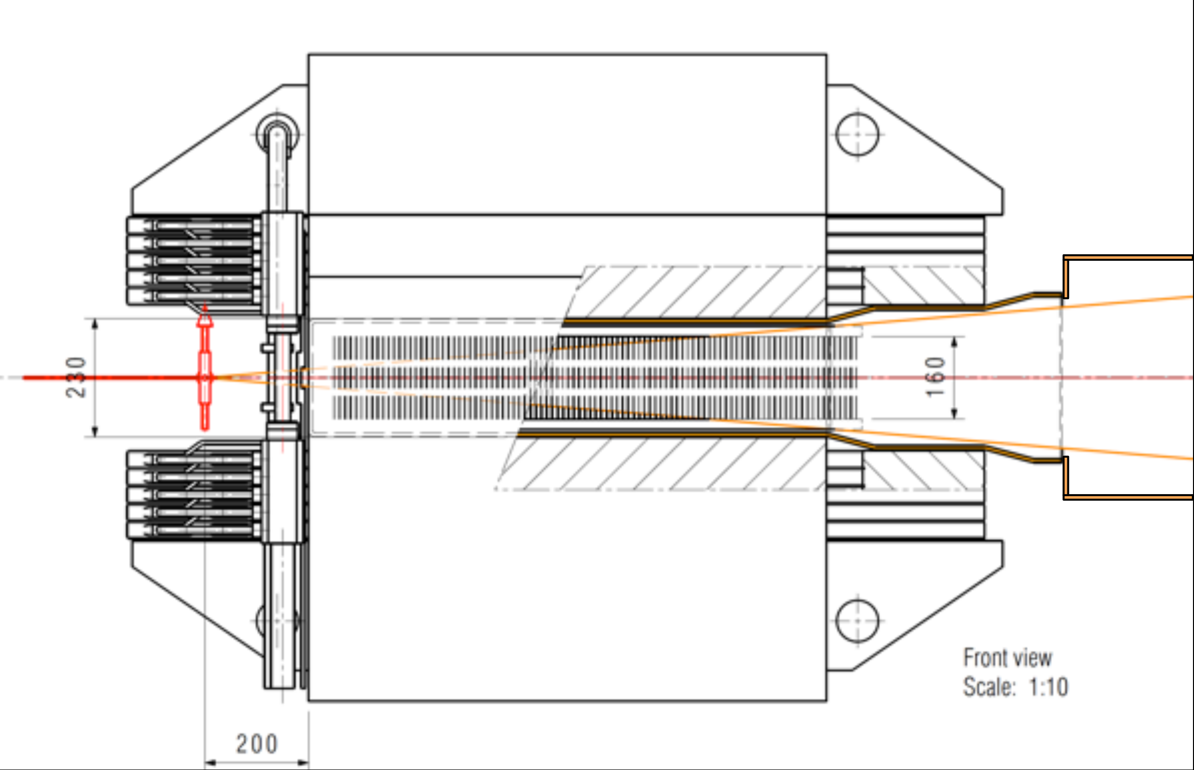






Tutti gli altri rivelatori e i dettagli dell'esperimento vanno quindi definiti tenendo conto del *layout* generale e dell'ottimizzazione dei principali elementi: magnete, calorimetro, bersaglio

Vacuum vessel



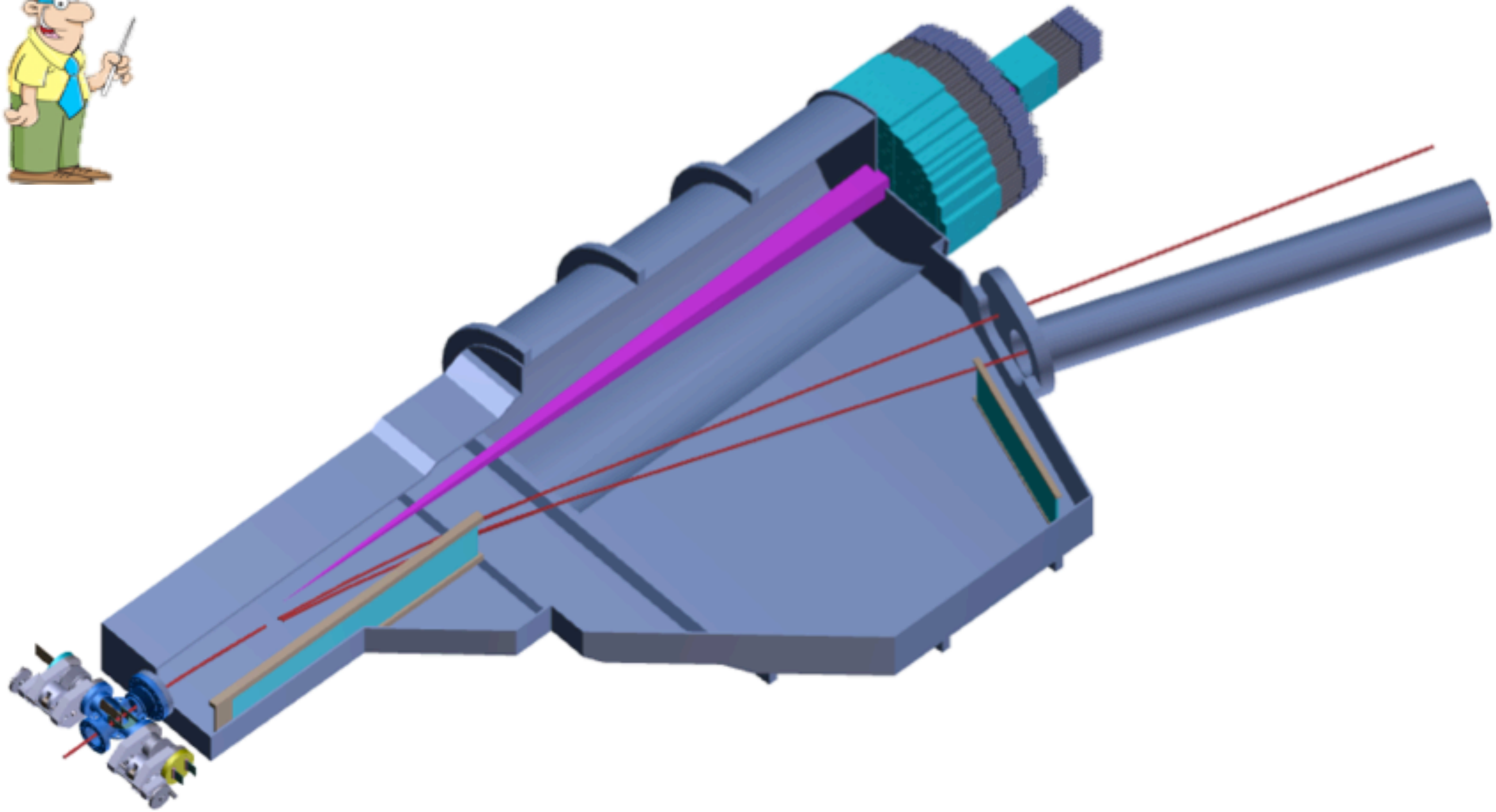
Vacuum mandatory for **three purposes**:

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!)

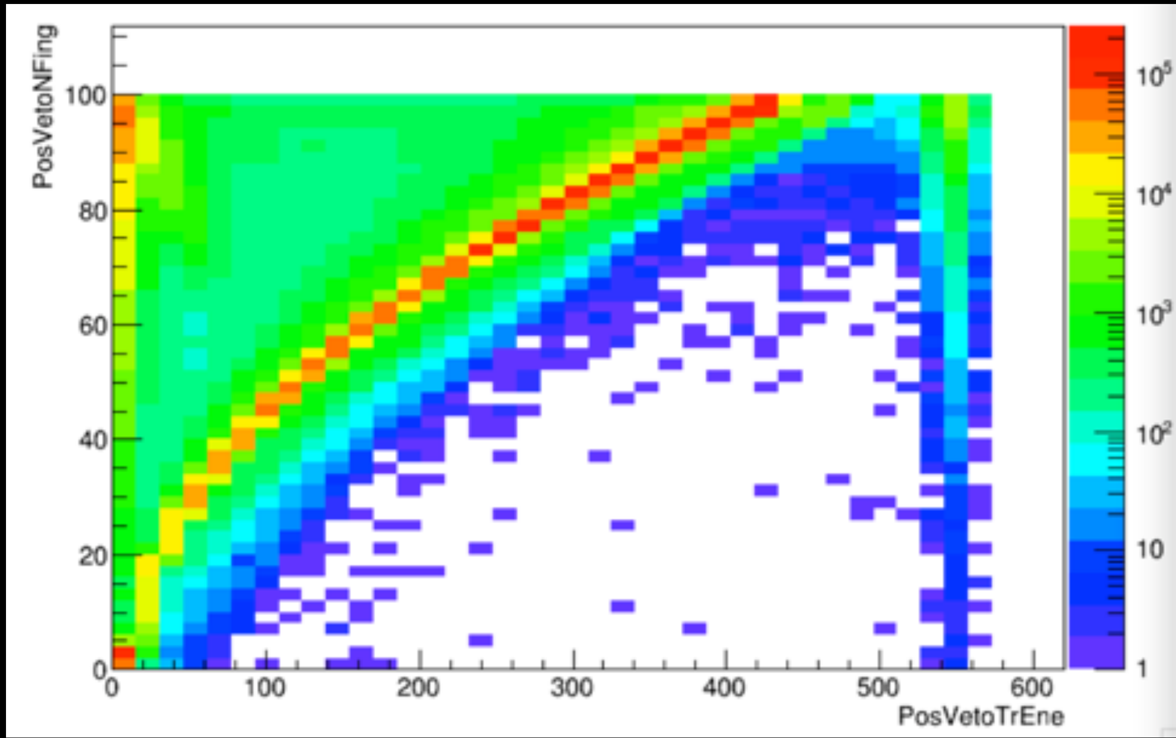
Different possibilities under study to minimize the material thickness, i.e. increase acceptance (given the magnet gap) for the vessel, with the following requirements:

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

Vacuum vessel



Positron veto

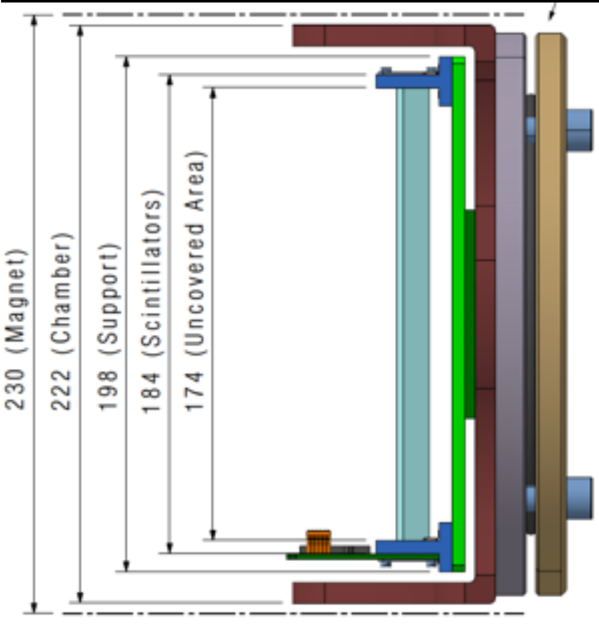


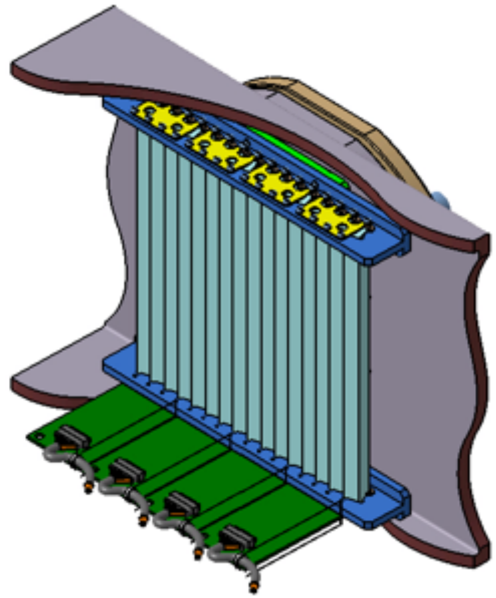
Low momentum losses are reduced for E_γ<400 MeV
Interesting positron energy starting at ~150 MeV

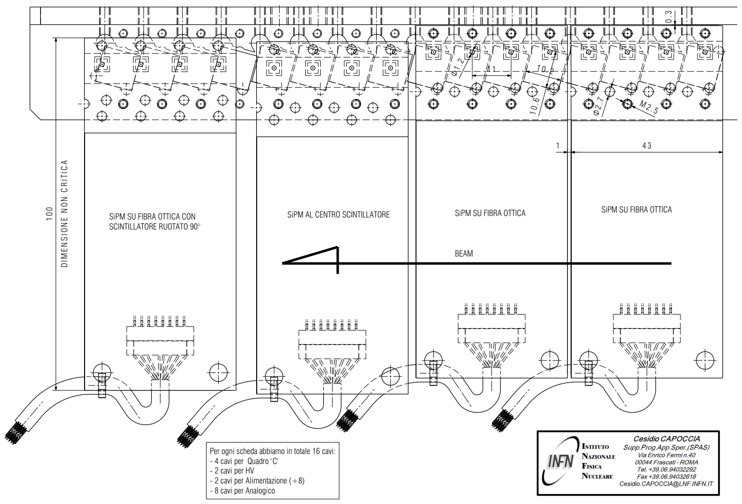
Which granularity?

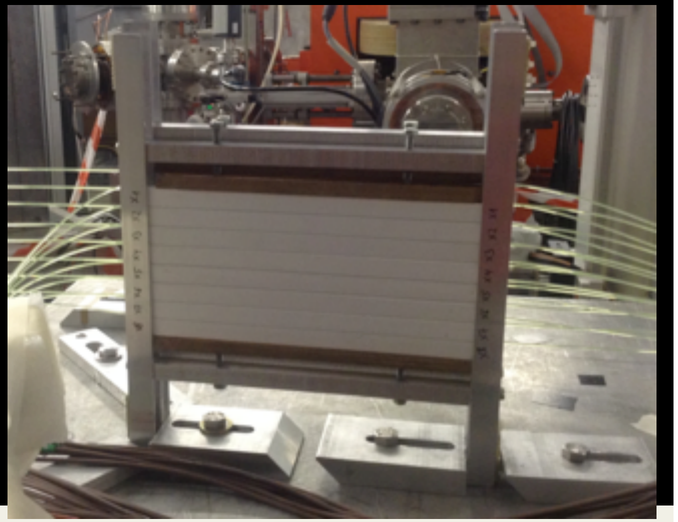
- 1 cm scintillator bars, readout by SiPM
- Few % momentum resolution in a large part of the spectrum

Optimized positron veto geometry

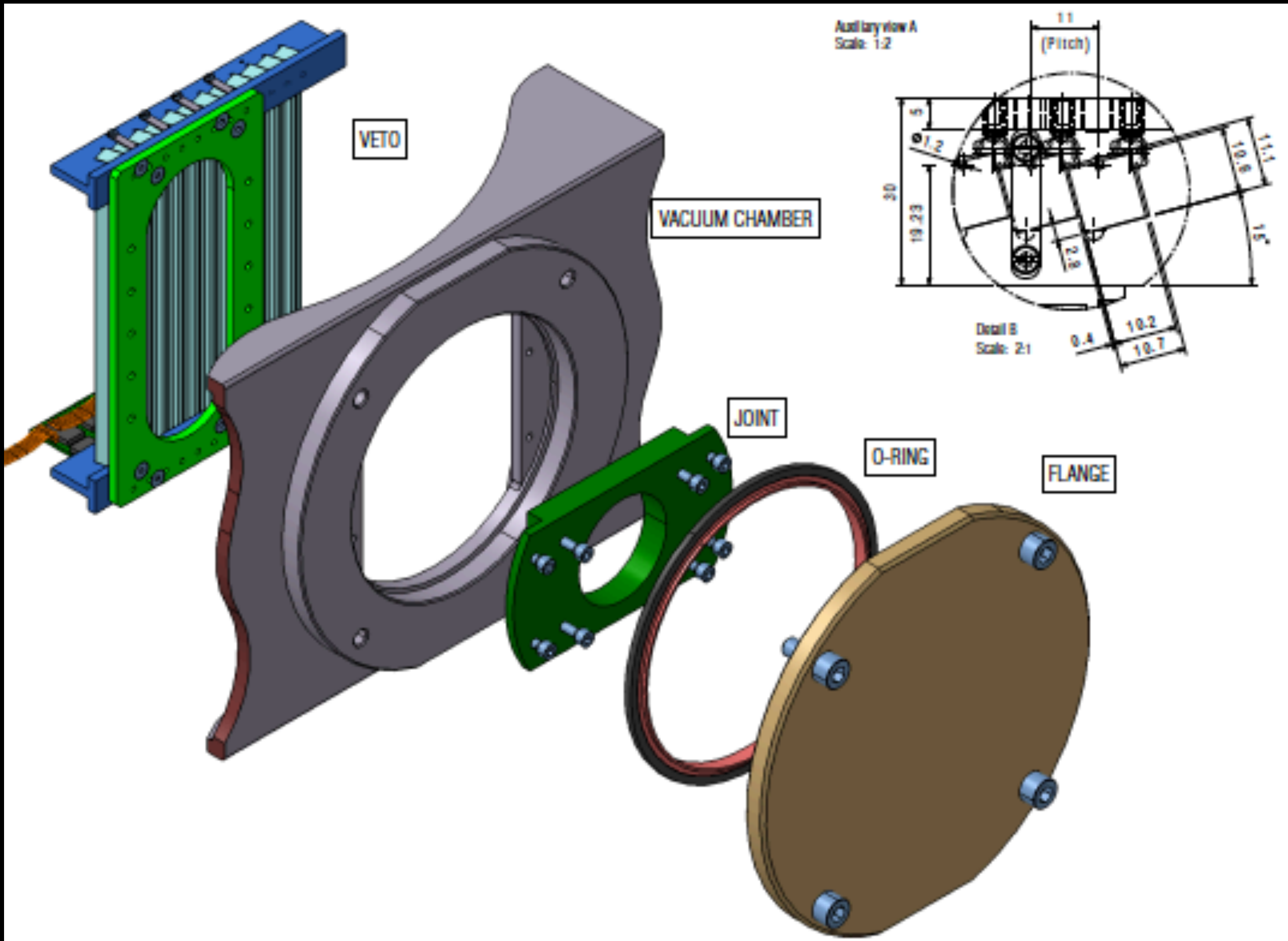






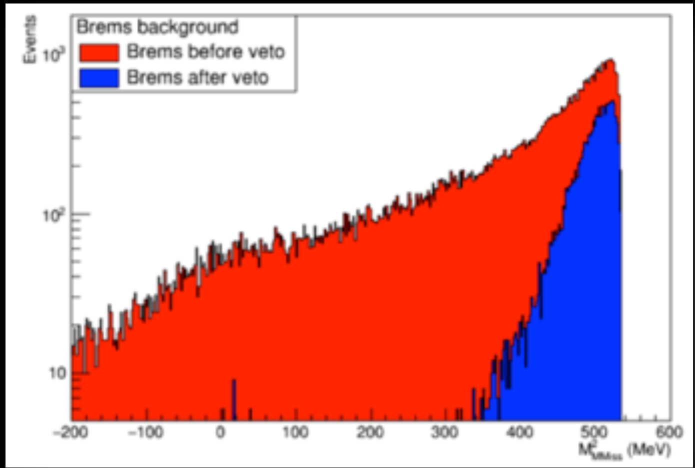


Study of the supports

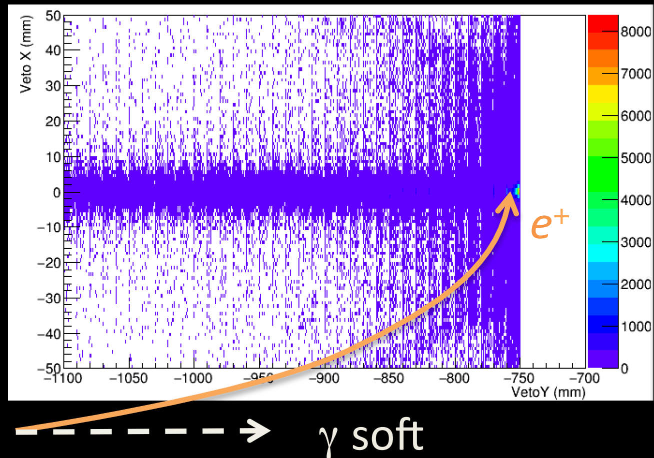


Residual background

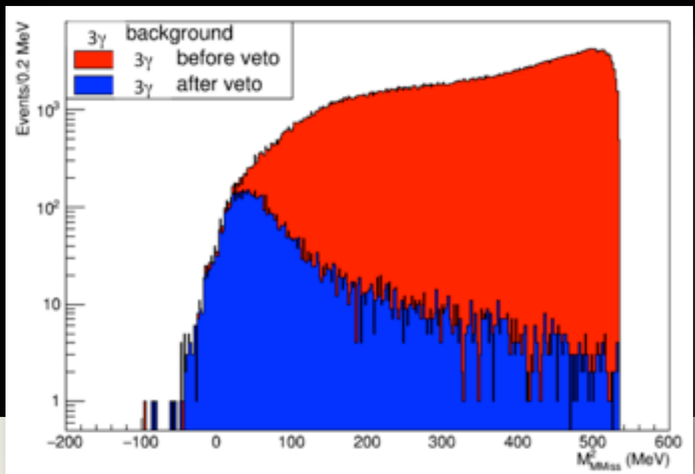
Bremsstrahlung



Difficult to veto positron with $E_{e+} \approx E_{beam}$ events

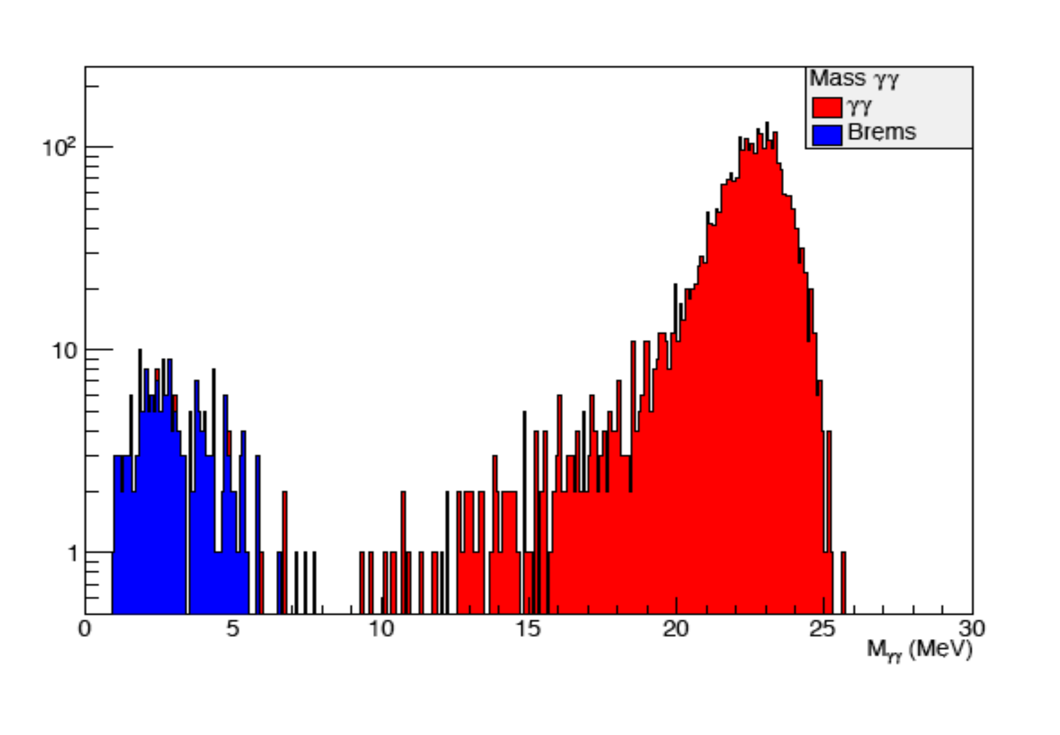


3 photons decay

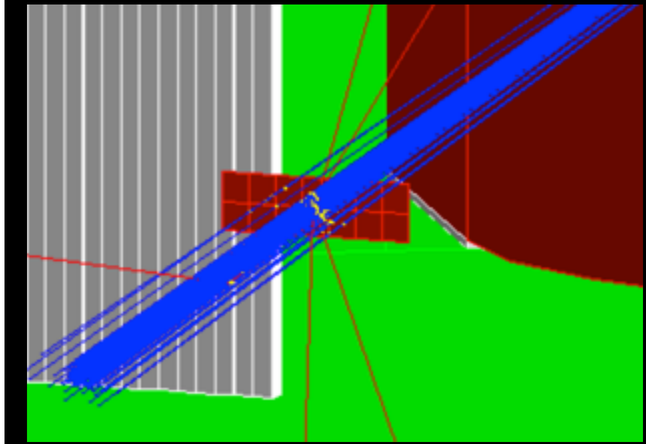


Difficult to veto low energy photons due to high Bremsstrahlung rate in the small angle detector

Design optimization ongoing to reduce residual background γγ events can be cleanly selected for measuring the **beam flux**, in addition to the diamond

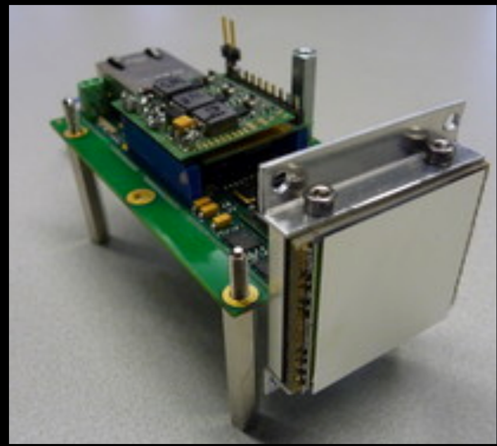


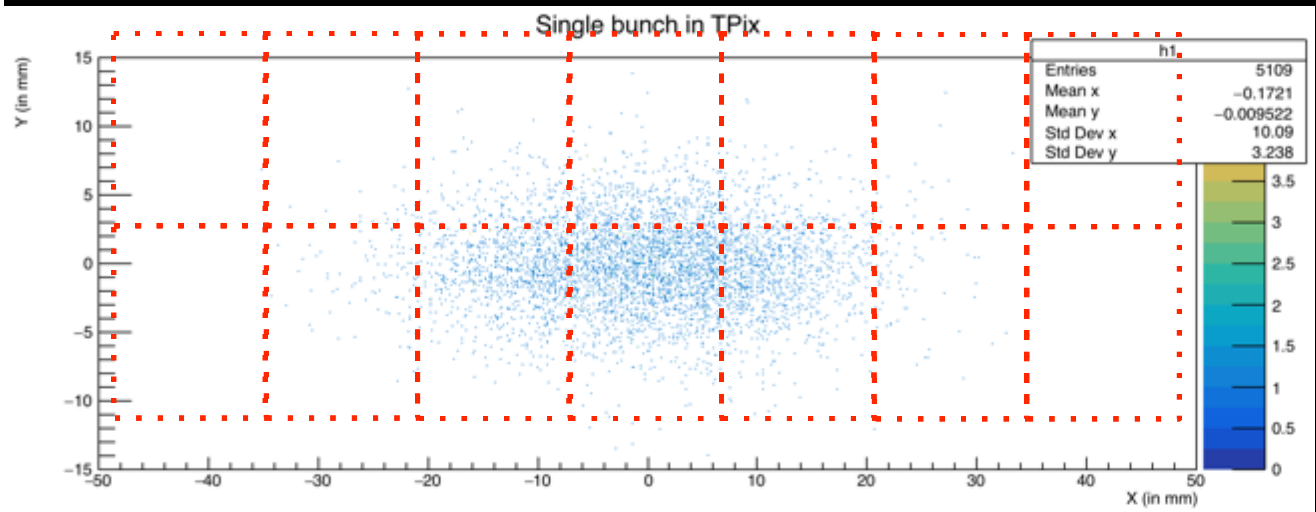
High energy positron veto



Monte Carlo simulation:

- 2x7 array of TimePix (Silicon pixel sensors+readout) in vacuum
- Directly placed in the beam (5000 particles in 40ns)

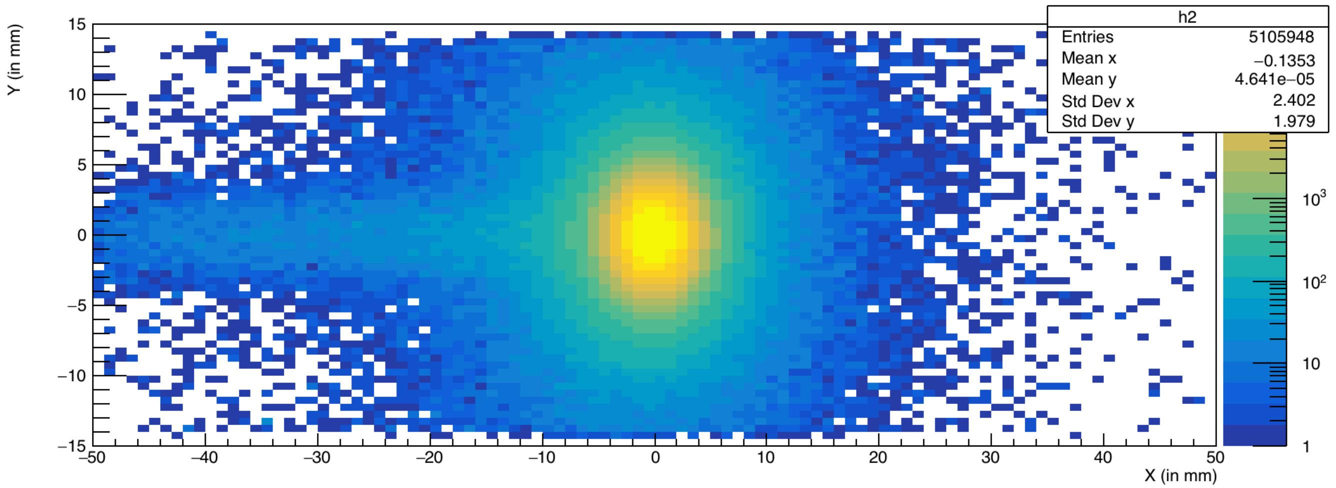




- Single bunch in TimePix array simulation
- Average 1 e^+/bunch/ fired pixel
  - Expect very precise measurement of N_{e+}

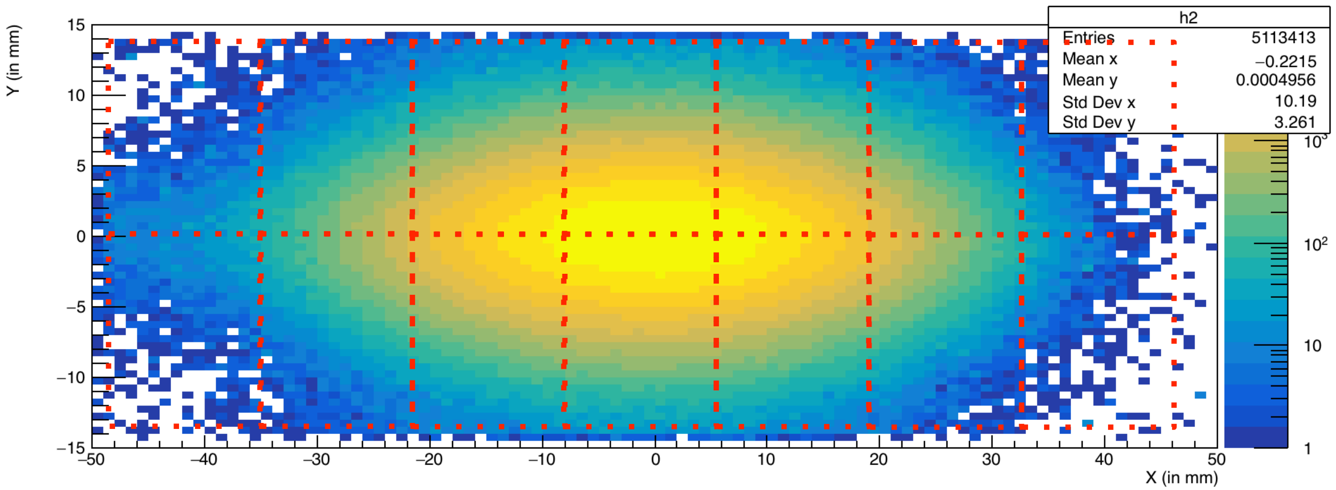
TimePix in PADME MC as veto

1000 bunch of 5000 e^+: no energy spread and no beam divergence



- The target produces radiative tails due to bremsstrahlung
- The scintillating veto system does'nt work for very soft bremsstrahlung
  - Too close to the beam spot
  - Too high rate per single bunch
  - Need much higher segmetation

1000 bunch of 5000 e^+: nominal beam conditions

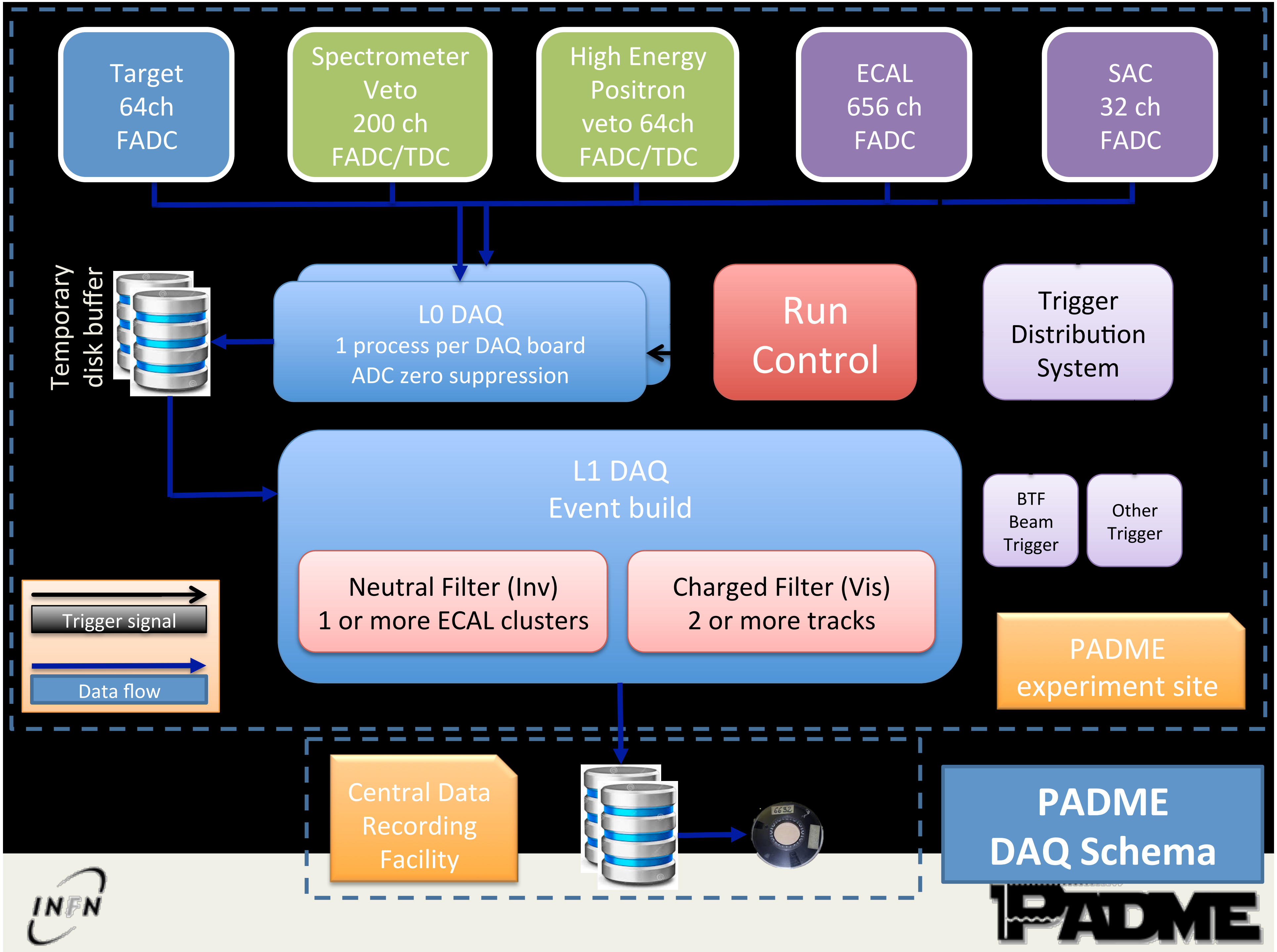


- Both the energy spread and beam divergence enlarge the spot
- TimePix able to cope with high rate providing timing and position useful to veto extra track out of the non radiative spot

PADME

PADME TDAQ

- Readout based on digitizers CAEN V1742
- ~1000 channels
- ~33 FADC boards involved (32 channels)
- Trigger and clock distribution to the 33 boards
- Online FADC zero suppression (L0)
- FADC boards synchronization to few 100ps needed


Target
64ch
FADC
Spectrometer
Veto
200 ch
FADC/TDC
High Energy
Positron
veto 64ch
FADC/TDC
ECAL
656 ch
FADC
SAC
32 ch
FADC
Temporary
disk buffer
L0 DAQ
1 process per DAQ board
ADC zero suppression
Run
Control
Trigger
Distribution
System
L1 DAQ
Event build
Neutral Filter (Inv)
1 or more ECAL clusters
Charged Filter (Vis)
2 or more tracks
BTF
Beam
Trigger
Other
Trigger
Trigger signal
Data flow
PADME
experiment site
Central Data
Recording
Facility
PADME
DAQ Schema

CAEN V1742

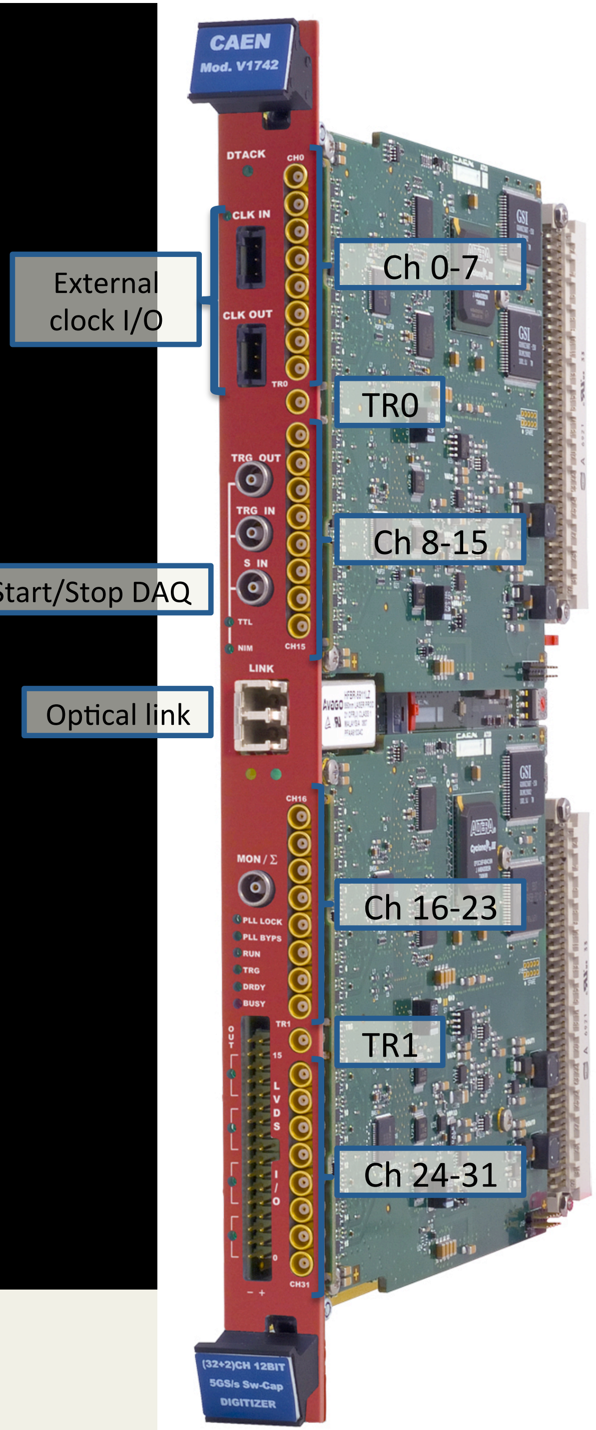
- Switched capacitor digitizer based on DSR4 chip
- 32 channels (+ 2x2 triggers)
- 1 Vpp on 12 bits
- 1024 samples @ 5-2.5-1 GHz
- 181 µs dead time
- 80 MB/s optical link to A2818/A3818 PCI controllers

Two V1742 boards (64 chns) and 1 A3818 controller (2 optical links) are currently available and will be used during the November test beam

To ensure multi-board synchronization:

- Centralized trigger signal distribution
- Control DAQ Start/Stop via S_IN
- Synchronous reset of trigger time tag
- Use an external clock source for all boards to avoid inter-board time drift O(1 ppm)

N.B. All this requires dedicated hardware interacting with the Run Control

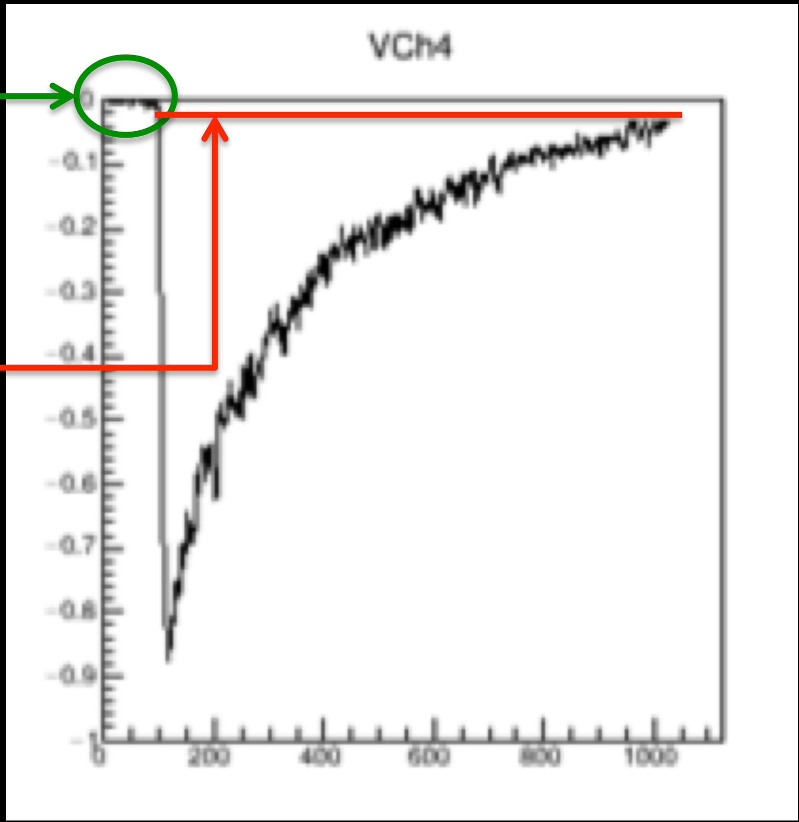


Zero Suppression

- ECAL expected occupancy: O(1 channel/event)+noise
- Most of the channels will be empty most of the times
- Zero-suppression will substantially reduce the amount of data saved to disk
- Expect a factor O(50) reduction

Algorithm

- Start ADC acquisition window ~100ns before start of spill
- Use first 80 ADC samples to compute Baseline and RMS
- Define threshold at Baseline-X*RMS
- Find largest set of consecutive samples below threshold
- If largest set contains more than N samples, channel is accepted
- X,N can be used to tune the algorithm



Note: zero-suppression can be applied on a per-board basis
E.g.: ON for ECAL and veto, OFF for Target and SAC

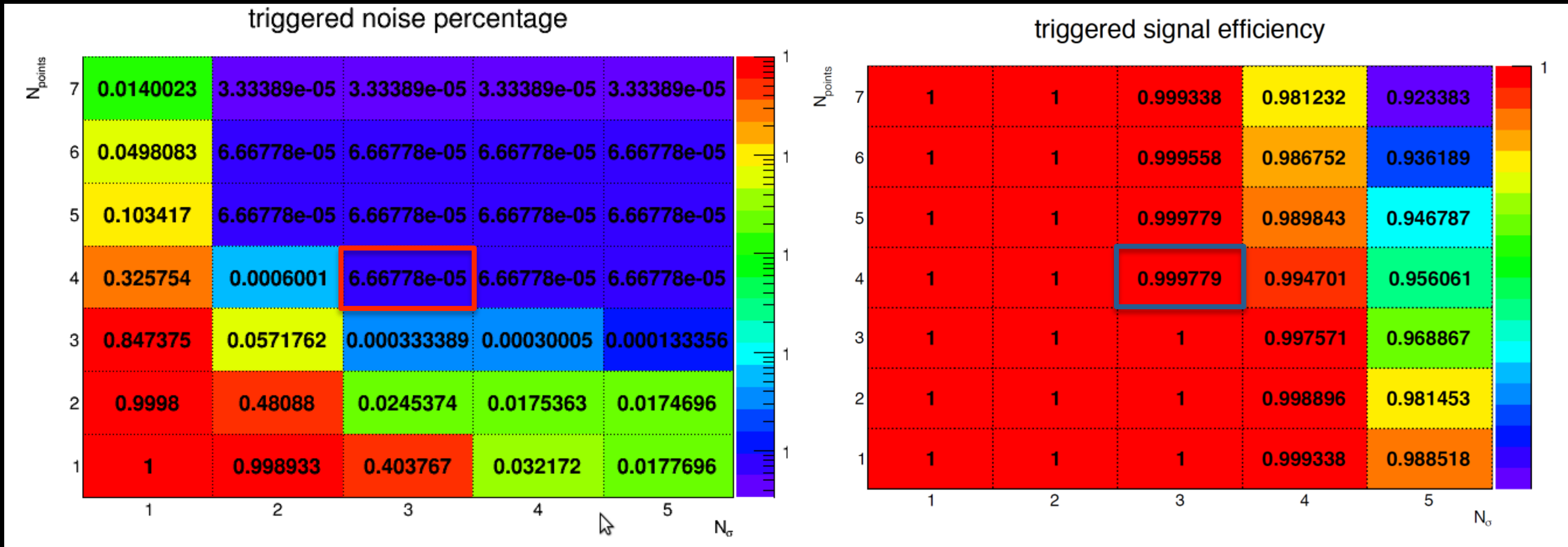
Preliminary test on 3x3-crystals detector.

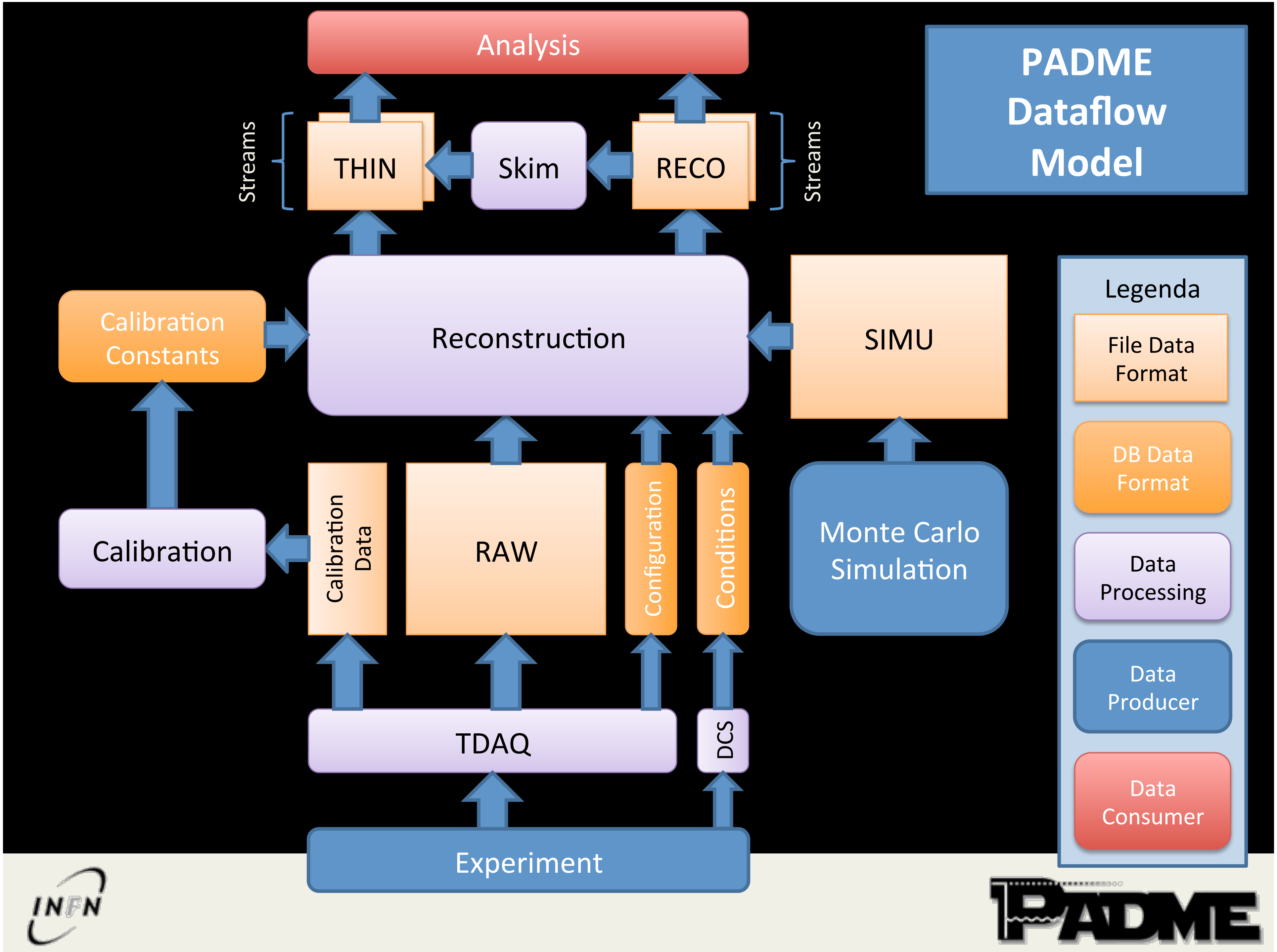
- Signal: test beam (500 MeV), ~4.5K events
- Noise: off-beam (i.e. empty + cosmic ray), ~30K events

Apply zero suppression with different values of X,N

X=3, N=4 ➔ ~15000 noise reduction factor, $<10^{-4}$ inefficiency

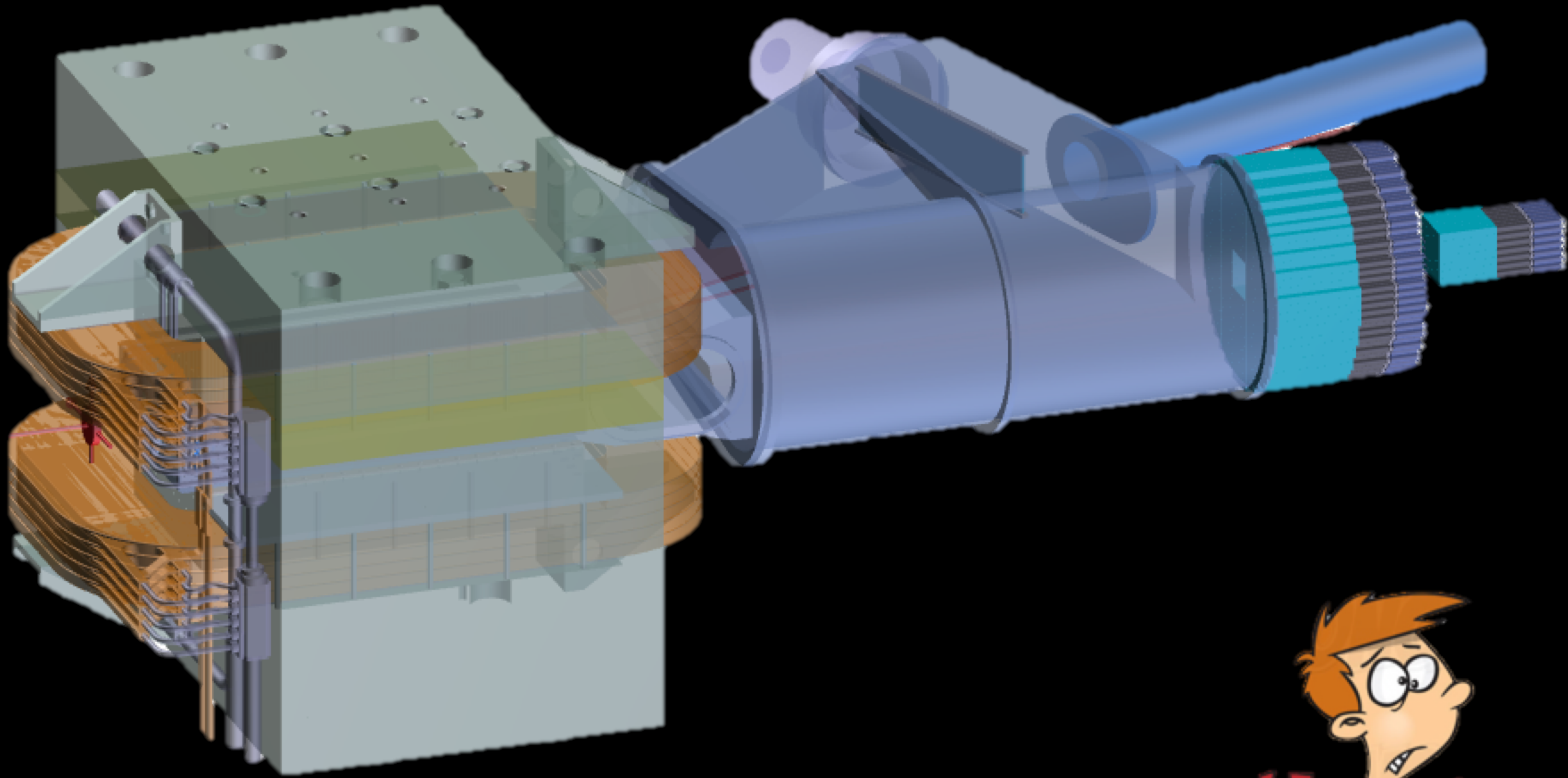
Need to study efficiency as a function of energy released in the crystal

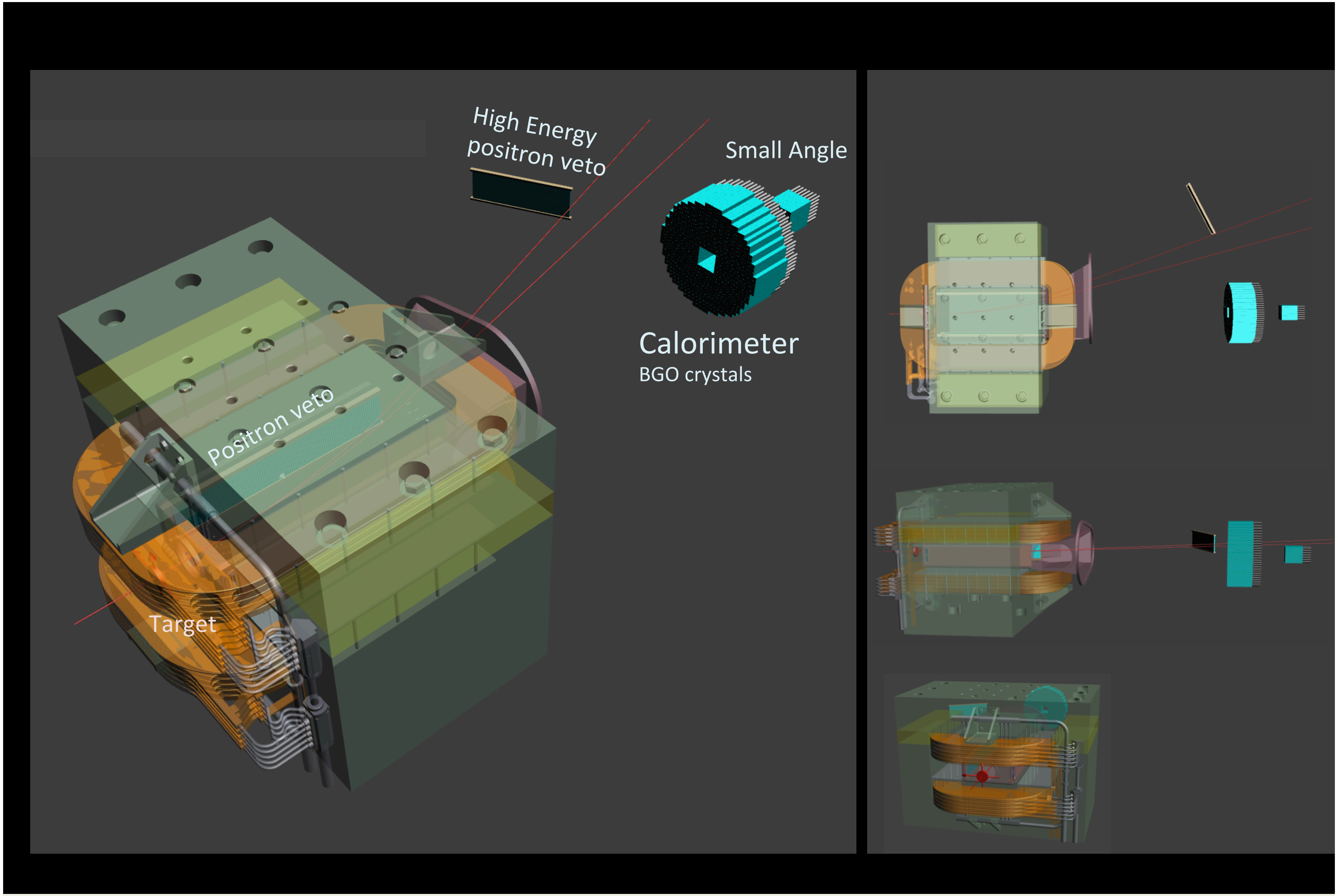



PADME Dataflow Model
Analysis
Streams
THIN
Skim
RECO
Streams
Calibration Constants
Reconstruction
SIMU
Calibration
Calibration Data
RAW
Configuration
Conditions
Monte Carlo Simulation
TDAQ
DCS
Experiment
Legenda
File Data Format
DB Data Format
Data Processing
Data Producer
Data Consumer
INFN
PADME

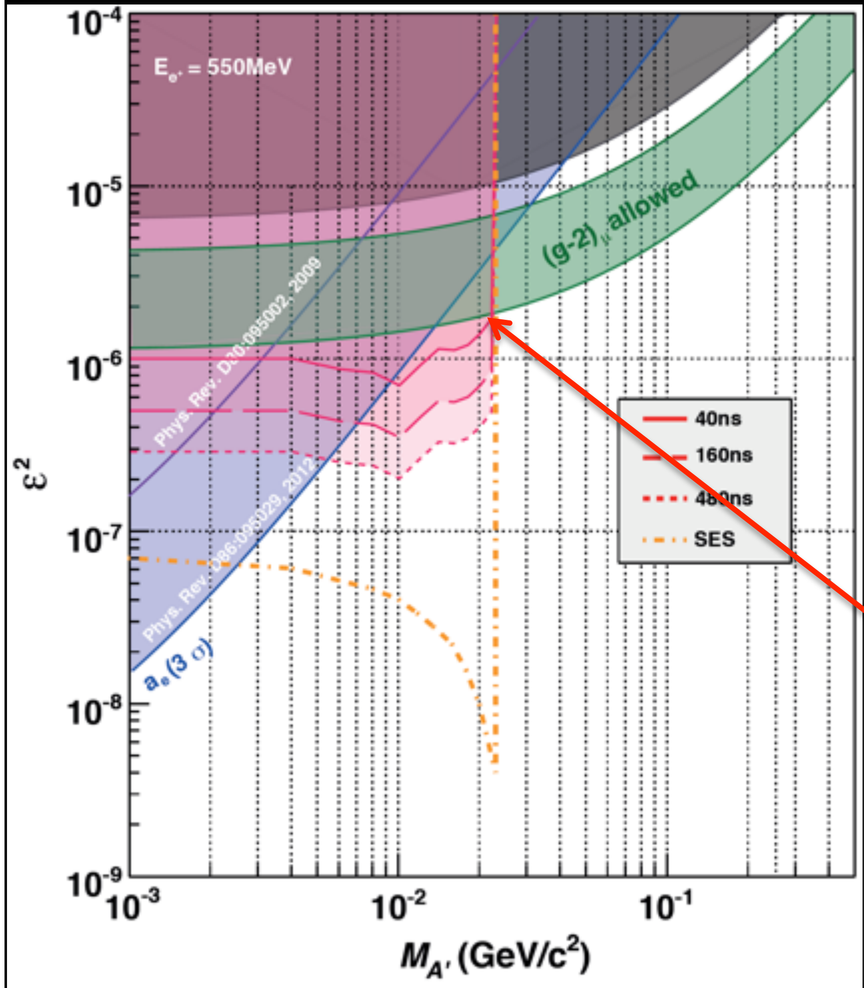
PADME experiment summary

- 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




High Energy
positron veto
Small Angle
Calorimeter
BGO crystals
Positron veto
Target

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**

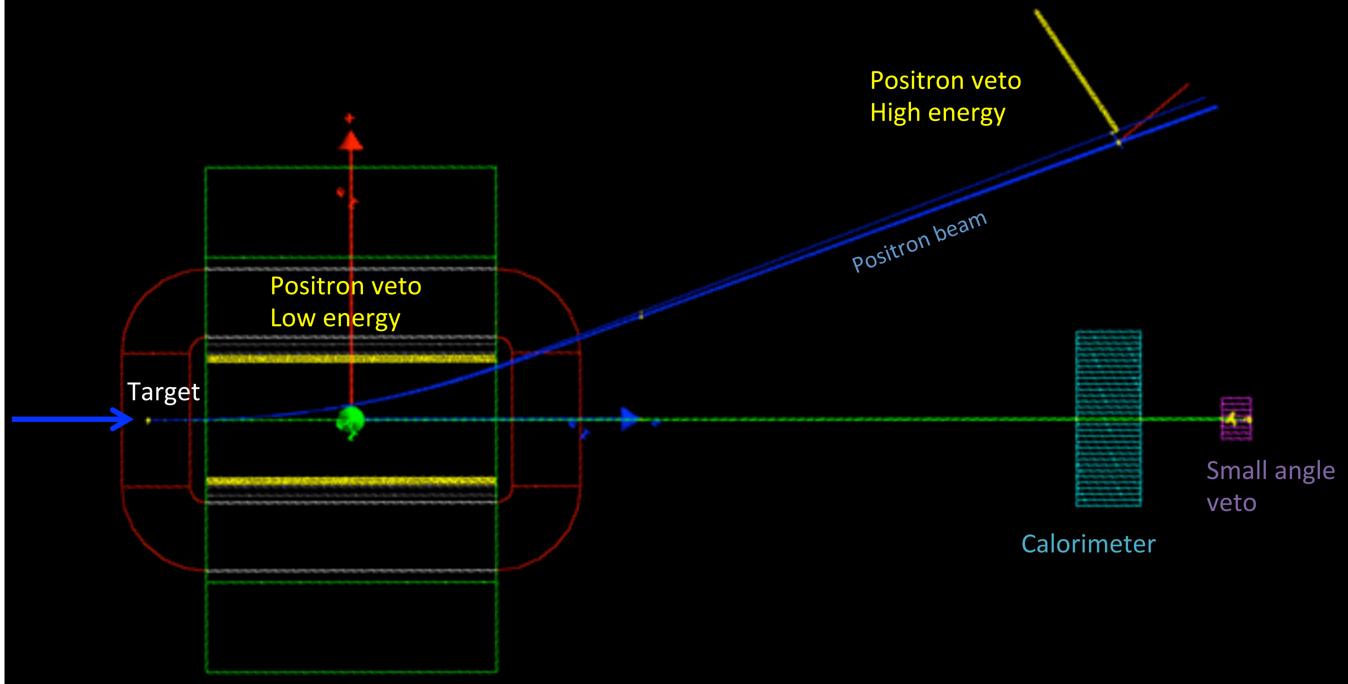
PADME can explore in a ***model-independent way the*** favourite by $(g\text{-}2)_\mu$ band up to $M^2_{A'} = 2m_eE_{e+}$

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

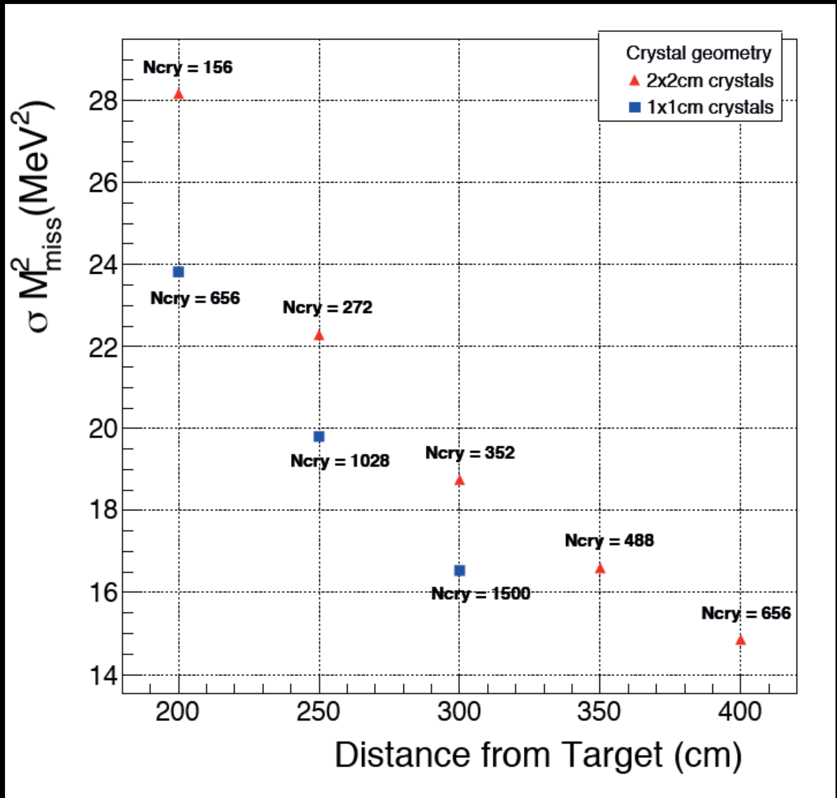
E_{e+}=750 MeV: $M_{A'} < 27.7$ MeV/c^2

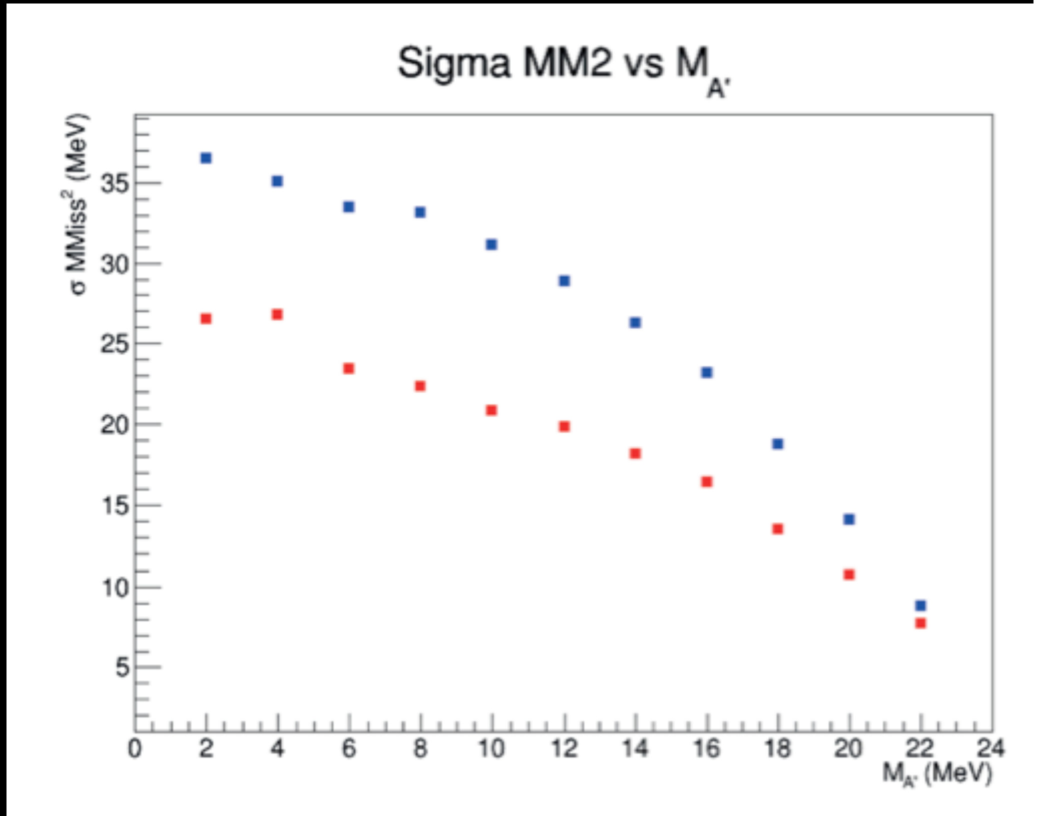
E_{e+}=1 GeV: $M_{A'} < 32$ MeV/c^2

Monte Carlo simulation



Missing mass resolution

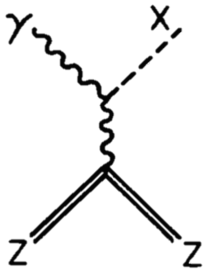




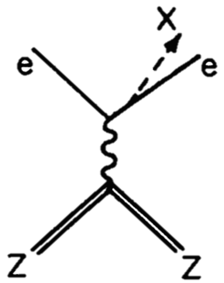
- Improvement mainly due to better angular resolution when the calorimeter distance increase
- Depending on dark photon mass angular resolution is no more the dominant contribution to the M^2_{miss} resolution and the improvement is reduced (smaller for higher dark photon masses, i.e. lower energy γ)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

ALP physics at PADME

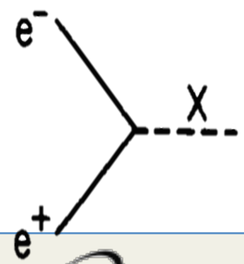
Primakoff



Bremsstrahlung



Annihilation

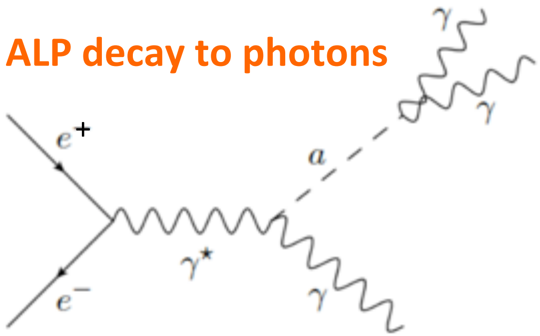


PADME can search for long living ALPs by looking for $1\,\gamma + M^2_{miss}$ final states

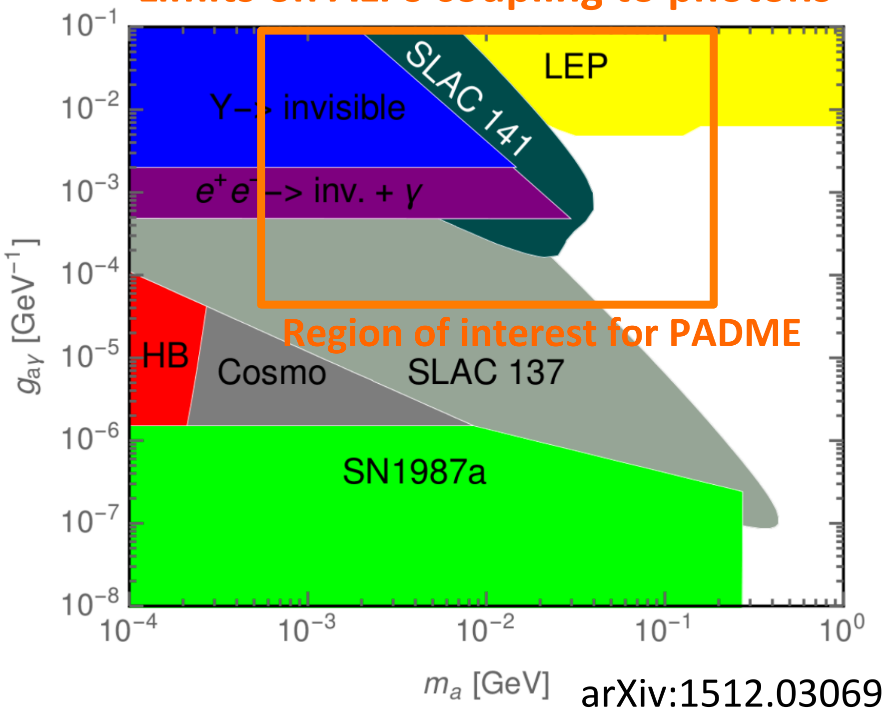
In the visible final state $a \to \gamma\gamma$ all production mechanisms can be explored extending the mass range in the region of ~100MeV

The observables at PADME will be: $e\gamma\gamma$ or $\gamma\gamma\gamma$

ALP decay to photons



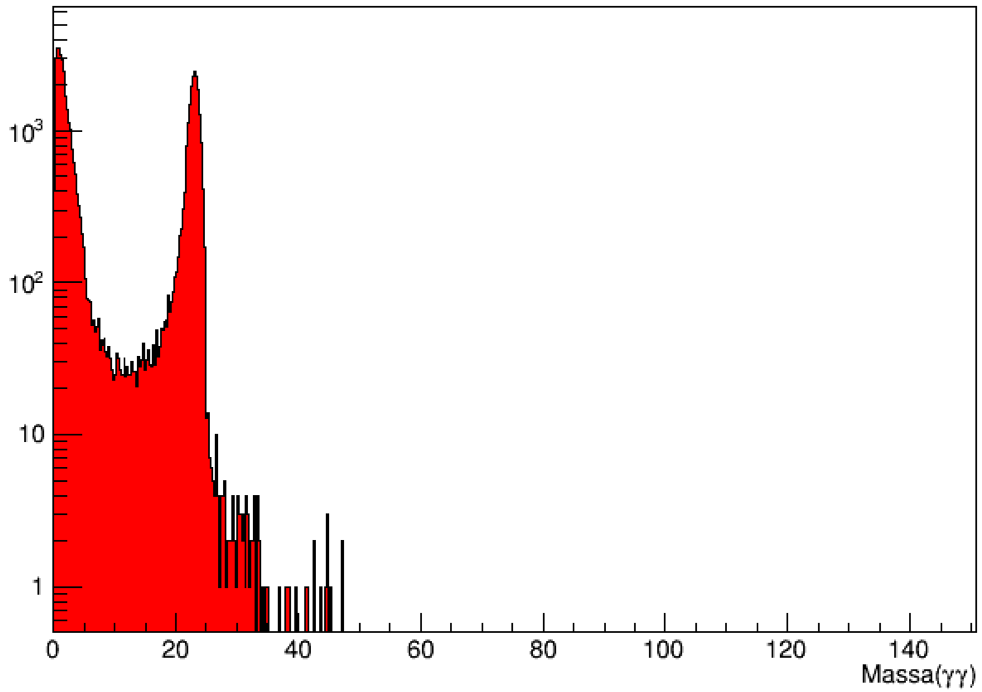
Limits on ALPs coupling to photons



arXiv:1512.03069

Phys rev D 38 11 1998

Background to ALPs searches



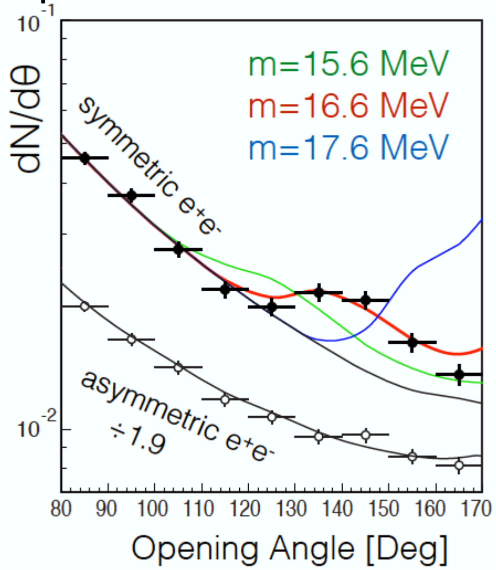
Invariant γγ mass for all events collected by Ecal (2×10^{10} POT) with two in time clusters

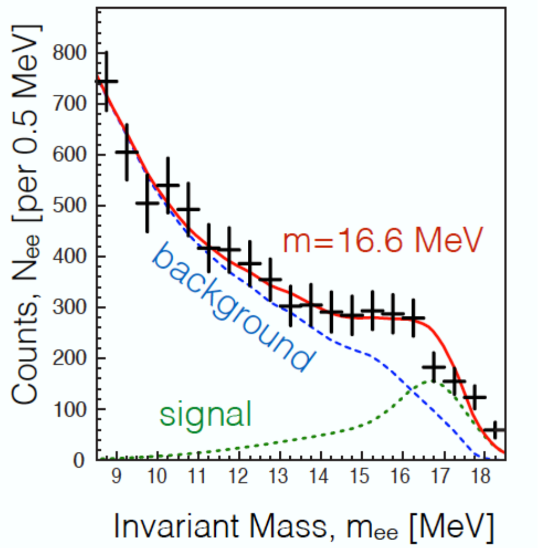
Even without any selection cut PADME will be background free for masses above 40-50MeV

- Main background $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow \gamma\gamma(\gamma)$ has a kinematic limit at $M_{\gamma\gamma}$ =24 MeV
- Il background at higer masses is due to overlapping photons from different bremsstrahlung interactions.
  - Can be suppressed by using the charged particle veto.

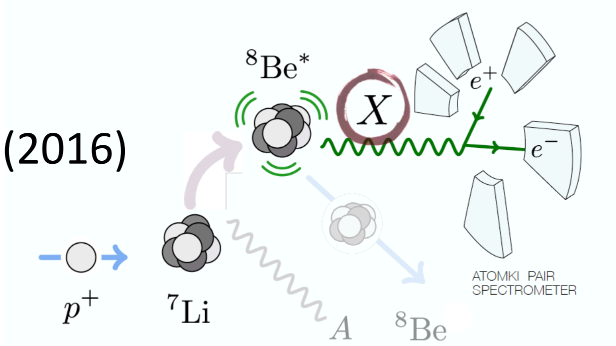
^{8}Be anomaly

Observation of Anomalous Internal Pair Creation in ^{8}Be
A possible indication of a light, neutral boson

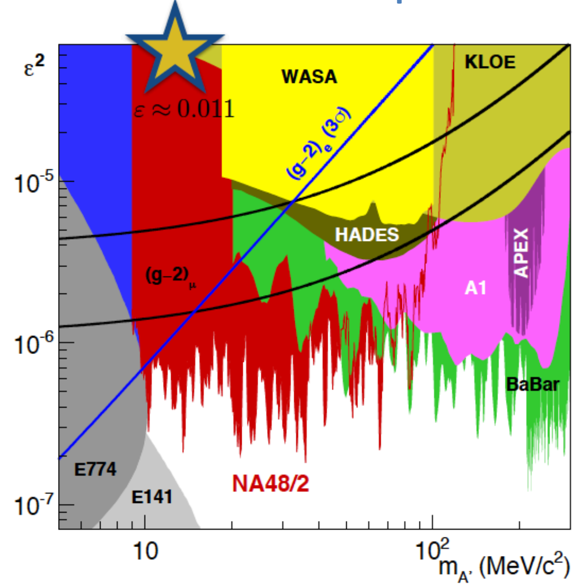




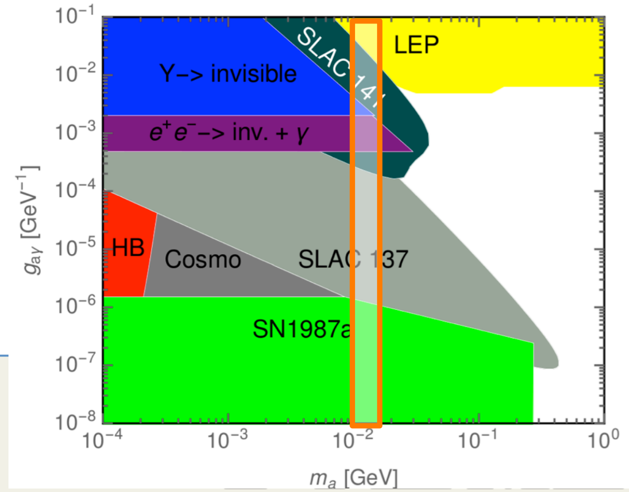
PRL 116, 042501 (2016)



Not a "trivial" dark photon



Not an ALP



Possible interpretation

"Evidence for a Protophobic Fifth Force from 8Be Nuclear Transitions"
J. L. Feng et al. arXiv:1604.07411

arXiv:1604.07411v1

π^0-phobia = p^+-phobia

To avoid NA48/2 prohibit π^0 decay to $X\gamma$

FROM QUARK CONTENT

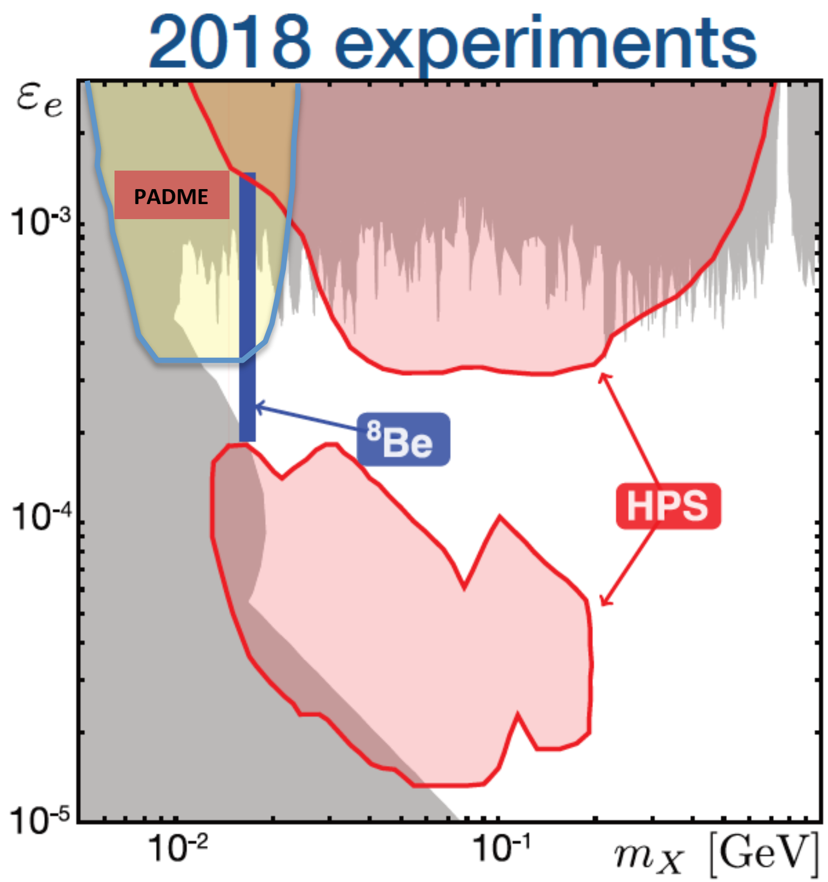
$$Q_u Q'_u - Q_d Q'_d = 0$$

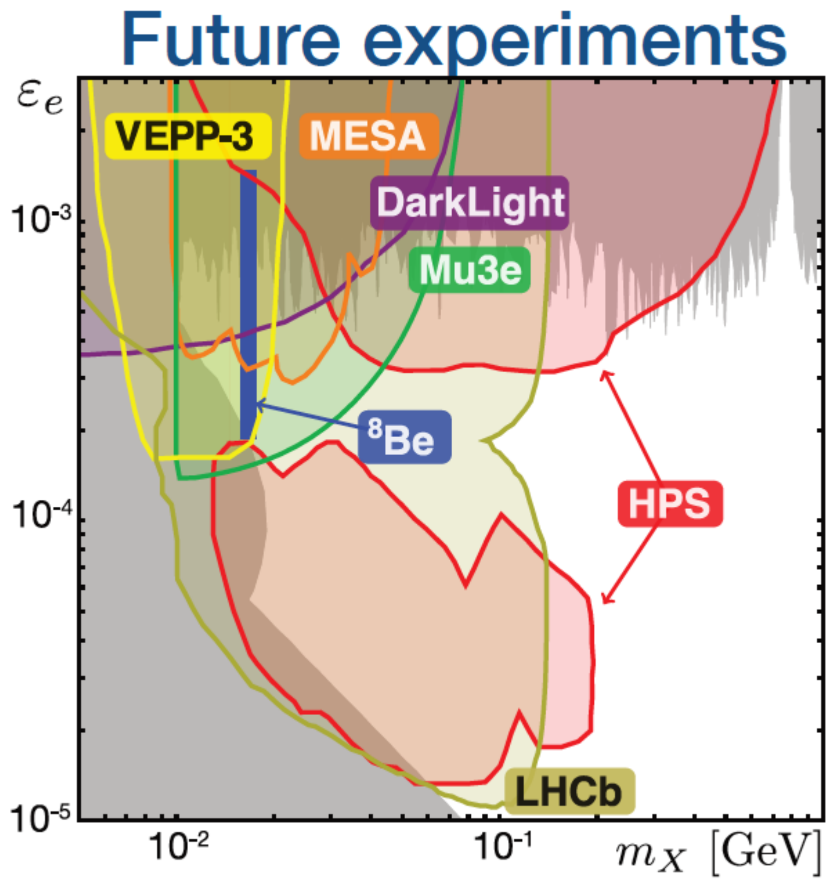
$$Q'_d = -2Q'_u$$

FROM CHIRAL PERT. THEORY

$$N = \begin{pmatrix} p \\ n \end{pmatrix}$$

^{8}Be anomaly a PADME?





- PADME has the unique chance of producing X in resonant mode BTF a 300 MeV
- Il problema del fondo γγ potrebbe essere risolto con scintillatori davanti al calorimetro
- Contatto con gli autori per stimare le sezioni d'urto

http://www.lnf.infn.it/acceleratori/padme/

POSITRON ANNIHILATION INTO DARK MEDIATOR EXPERIMENT

login: username password

Search

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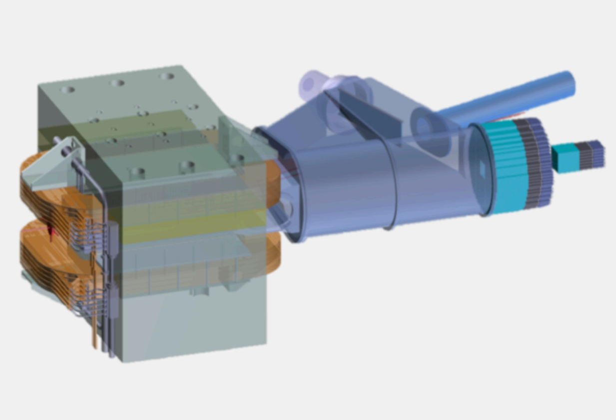
Searching for Dark Photon at Frascati

The PADME experiment at Laboratori Nazionali di Frascati of INFN aims to search for the "Dark Photon" using positron on target collision at the DAFNE **Beam Test Facility.**



The PADME Experiment

The long standing problem of reconciling the cosmological evidence of the existence of dark matter with the lack of any clear experimental observation of it, has recently revived the idea that the new particles are not directly connected with the Standard Model gauge fields, but only through mediator fields or “portals”, connecting our world with new “secluded” or “hidden” sectors. One of the simplest models just adds an additional U(1) symmetry, with its corresponding vector boson A'[1]. All SM particles will be neutral under this symmetry, while the new field will couple to the charged particles of the SM with an effective charge εe, so that this new particle is often called “dark photon”. Additional interest arises from the observation that A' in the mass range 1 MeV/ c 2 to 1 GeV/ c 2 and coupling ε~10−3, would justify the discrepancy between theory and observation for the muon anomalous magnetic moment, (g − 2)μ. This possibility has been recently disproved in the hypothesis that the A' decays to SM particles only, on the contrary if A'

Related links

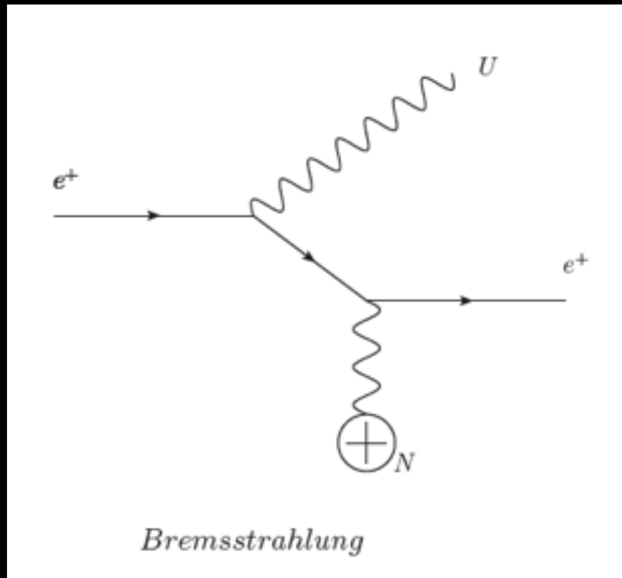
- INFN LNF
- DAFNE accelerator at LNF
- BTF at LNF
- Indico PADME
- PADME mailing list
- PADME calendar

. : PADME News

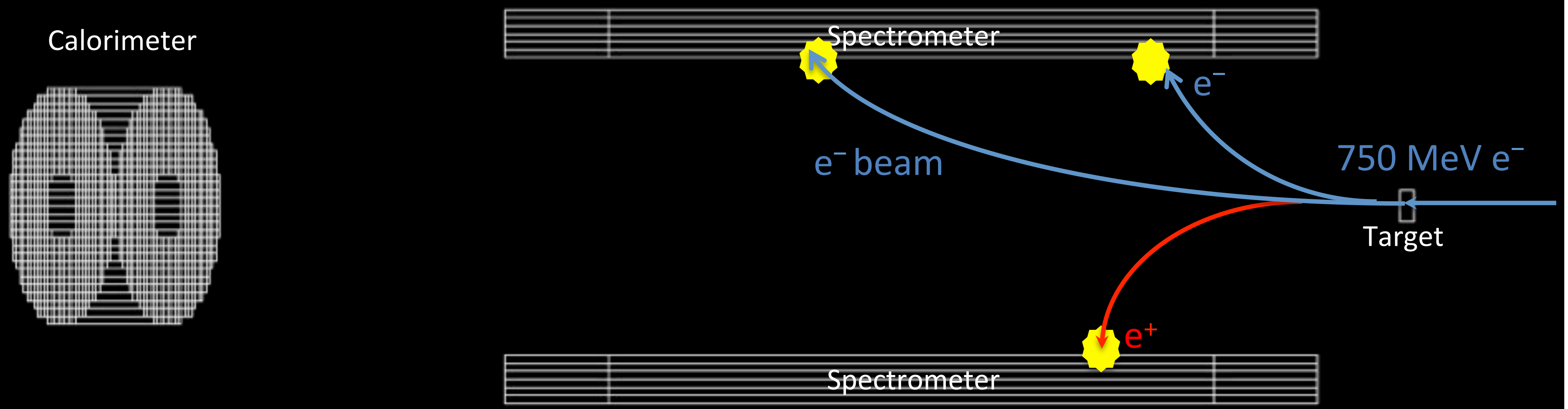
1-2 March 2016 at LNF
PADME CollaborationMeeting

April 4-11 2016
PADME test beam at BTF LNF

Search in bremsstrahlung production

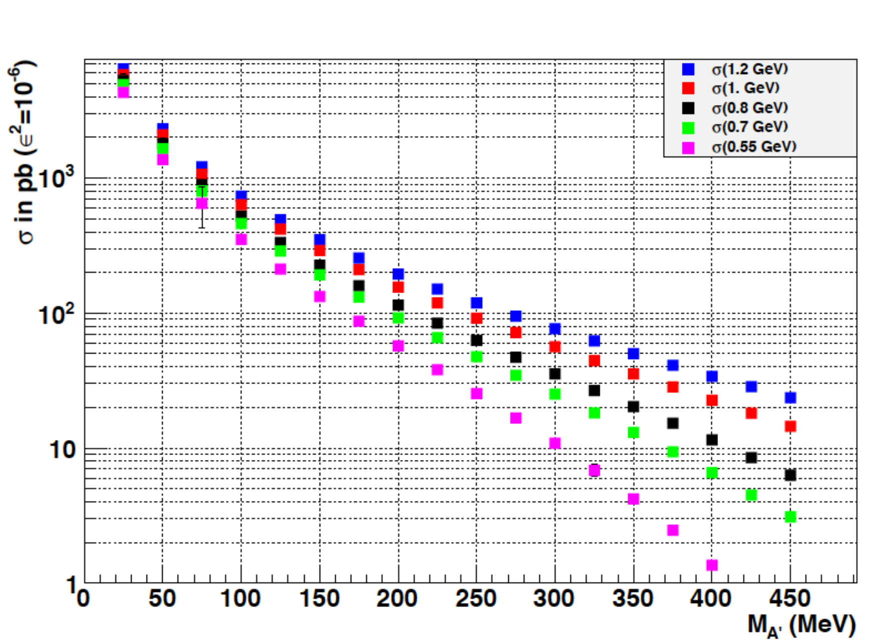


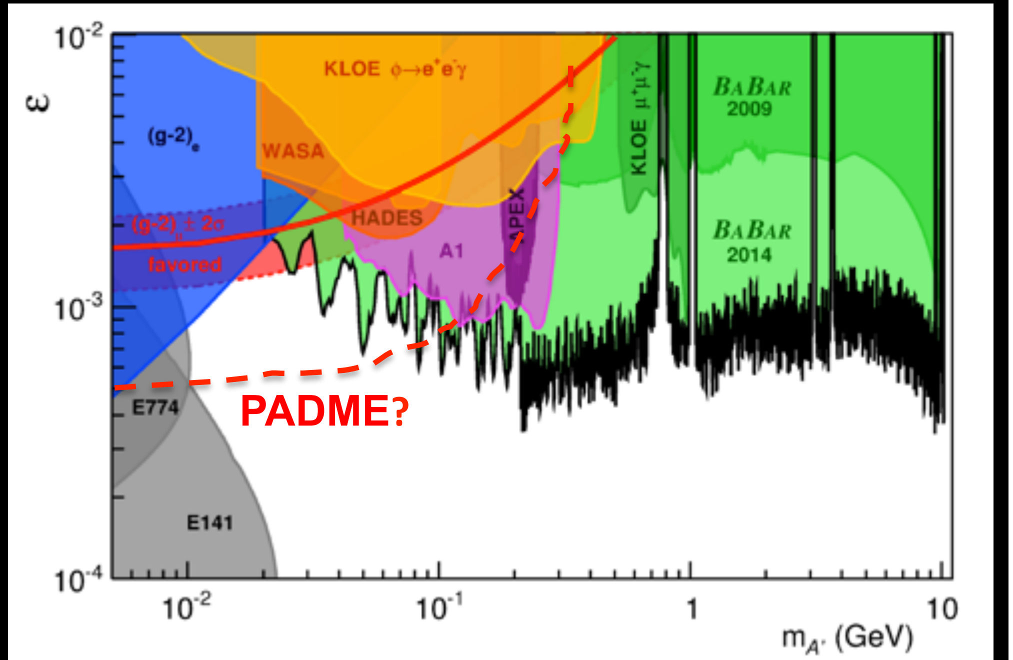
Visible search experiment



- Search for the process: **$e^-N \rightarrow Ne^-A' \rightarrow Ne^-e^-e^+$**
- 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

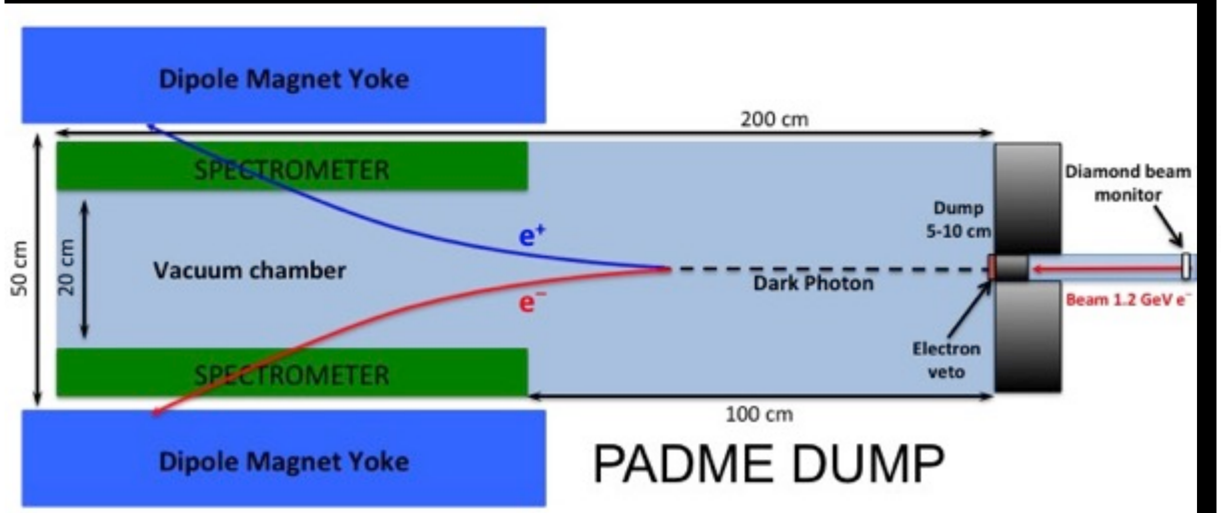


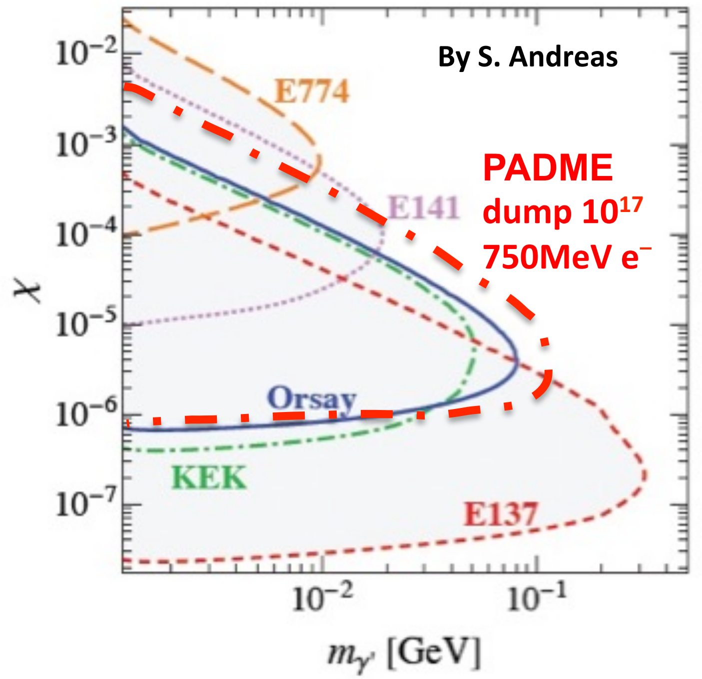


- Production cross section calculated with MADGraph code
- Final state is more constrained by invariant mass of the e^+e^- pair
- Indication of a limit down to $\varepsilon^2 \sim 10^{-7}$ is expected at low masses
  - **Density of tracks in the spectrometer is the crucial point to be clarified**
  -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

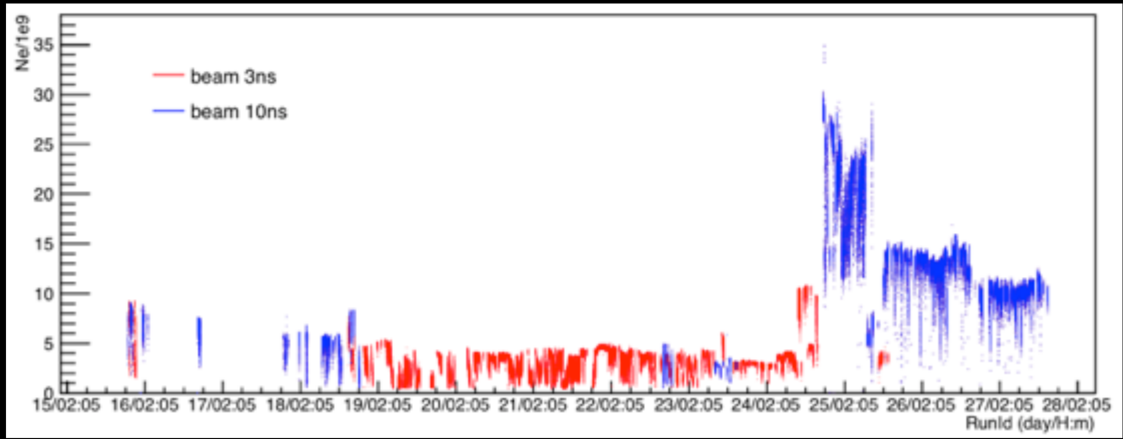
Electron dumps experiments

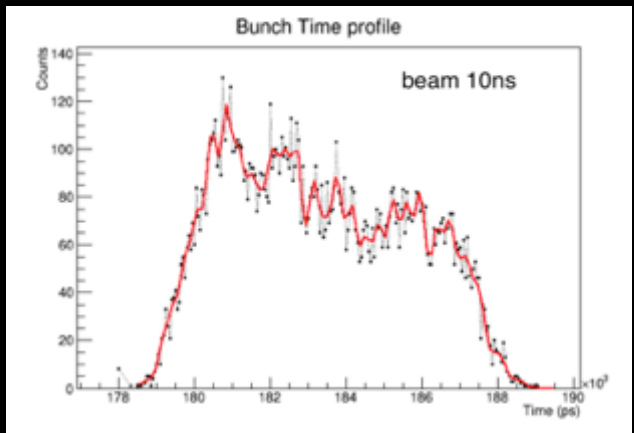
Experiment	target	E_0 [GeV]	N_{el} electrons	N_{el} Coulomb	L_{sh} [m]	L_{dec} [m]	N_{obs}	$N_{95\%up}$
E141 [47]	W	9	2×10^{15}	0.32 mC	0.12	35	1126^{+1312}_{-1126}	3419
E137 [48]	Al	20	1.87×10^{20}	30 C	179	204	0	3
E774 [49]	W	275	5.2×10^{9}	0.83 nC	0.3	2	0^{+9}_{-0}	18
KEK [39]	W	2.5	1.69×10^{17}	27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





High intensity





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

Typical charge to damping ring:

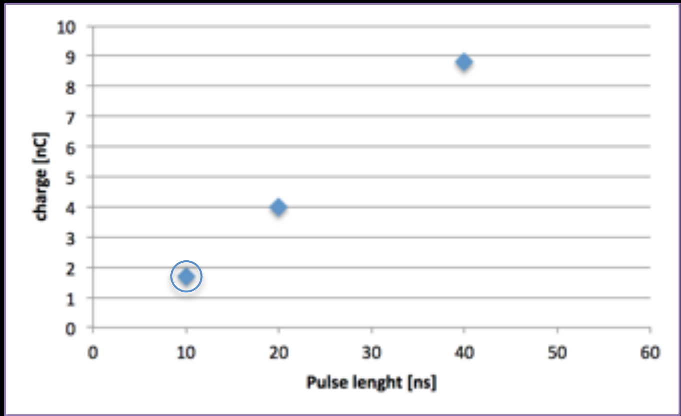
- **>1 nC/pulse** for **e^-**
- **0.7-0.8 nC/pulse** for **e^+**

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

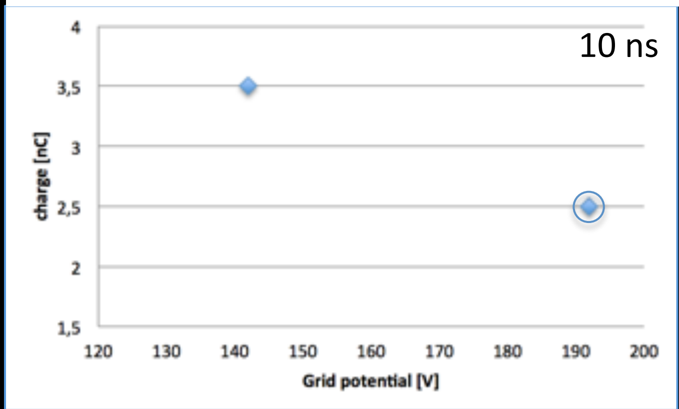
Bunch charge vs. length



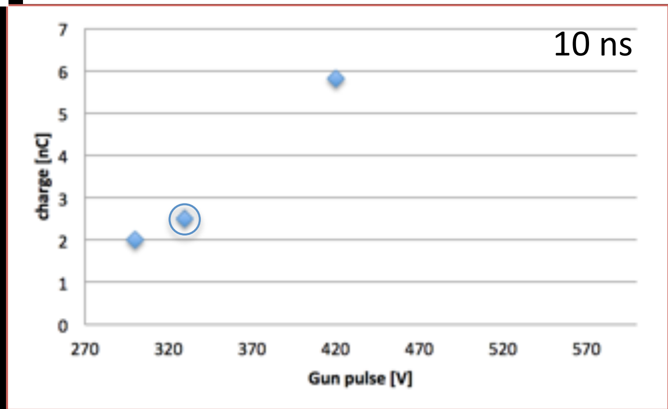
E = 725 MeV

×4 increasing pulse length

+30%
Decreasing grid stopping potential



×3 - ×5
Increasing gun pulse height



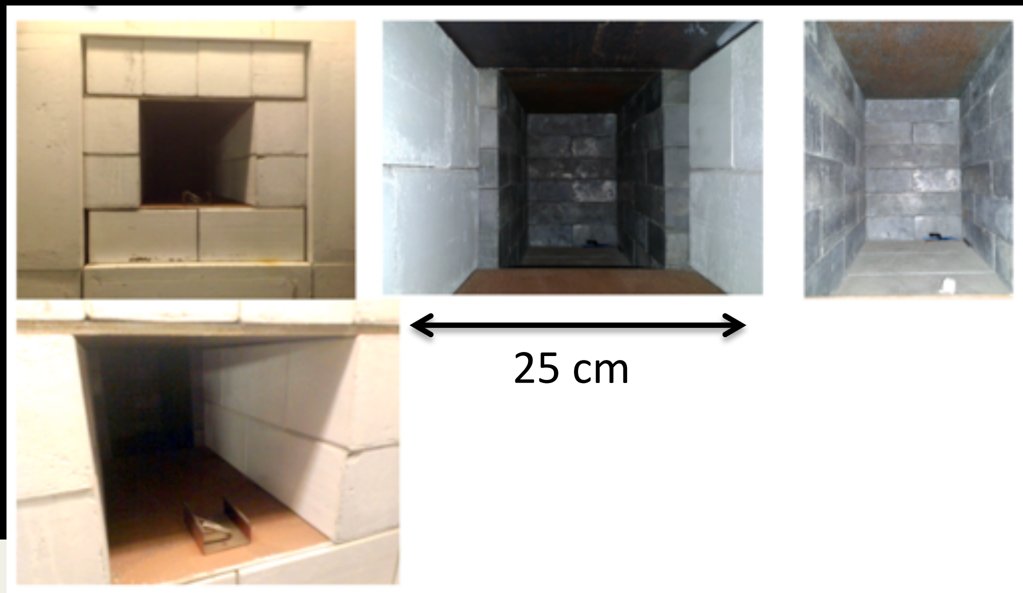
Trying to put all together: WCM readout saturated at 16 nC…

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^***

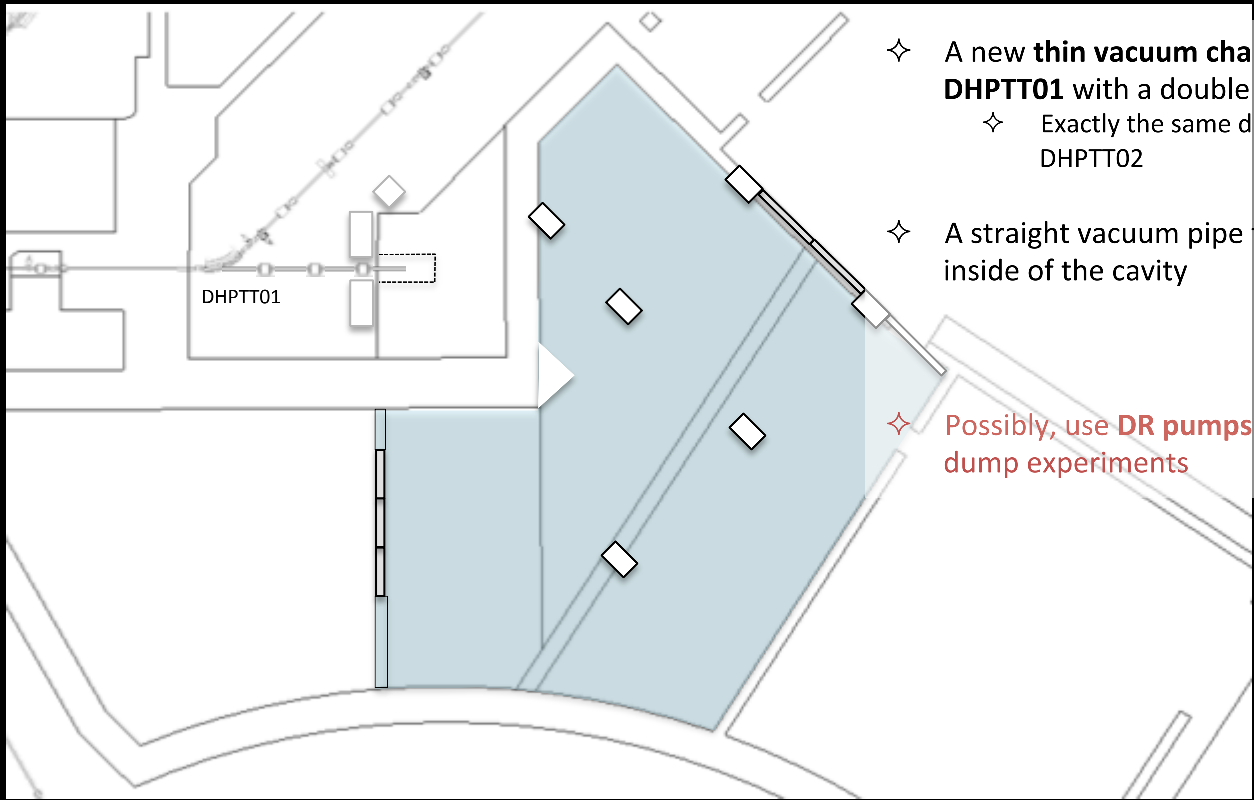
Where can we dump 3×10^{12} to 3×10^{13} e/s ?

LINAC beam dump



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

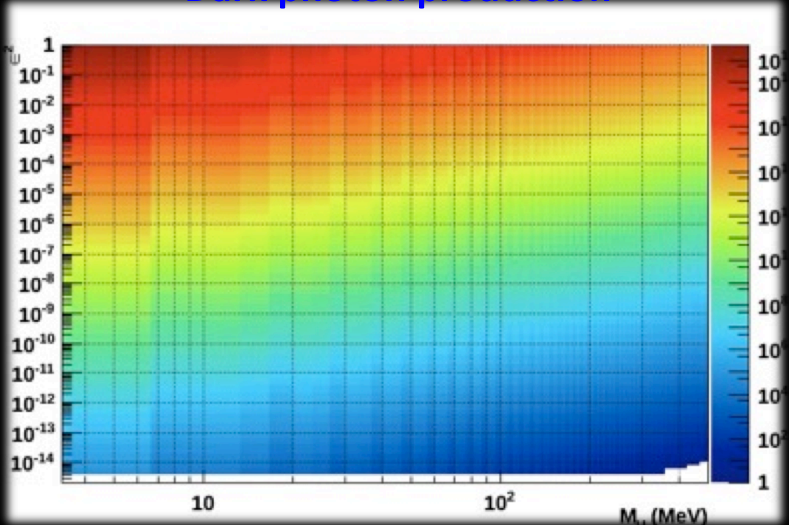
$$N_{\gamma'} = \sigma_{\gamma'}\, N_e\, n_{\text{sh}}\, L_{\text{sh}} = \sigma_{\gamma'}\, N_e\, \frac{N_0}{A}\, \rho_{\text{sh}}\, L_{\text{sh}}\,,$$

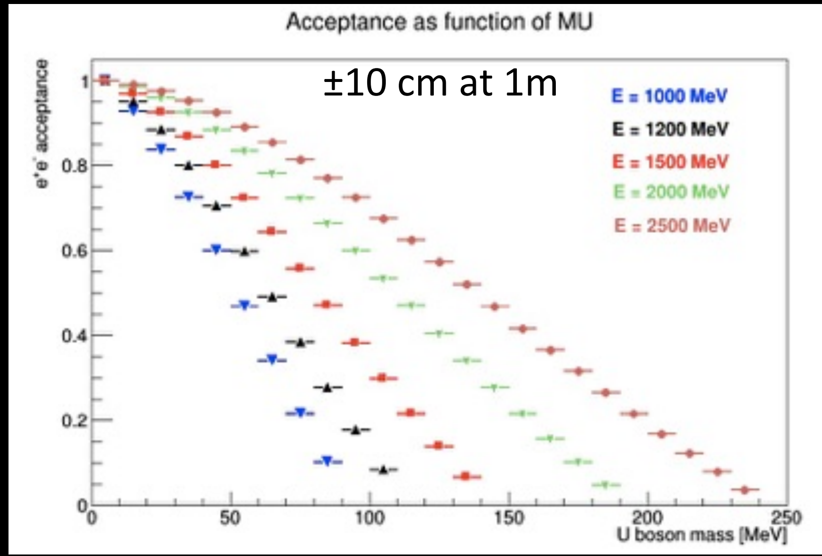
$$\frac{dP(l)}{dl} = \frac{1}{l_{\gamma'}}\, e^{-l/l_{\gamma'}}$$

  - 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_U
  - Not yet implemented in depth production of the A'
    - Next plot not to be considered exclusions still

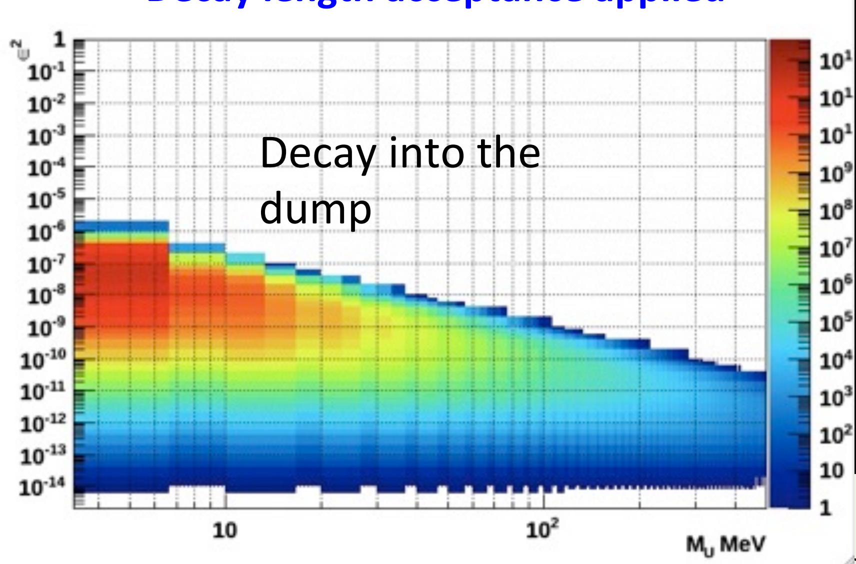
PADME dump main parameters

Dark photon production

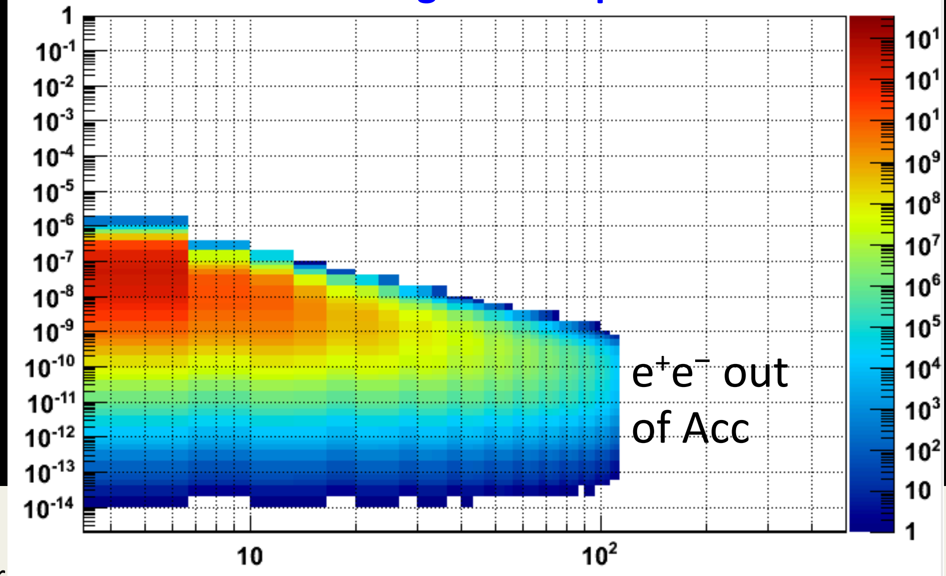




Decay length acceptance applied

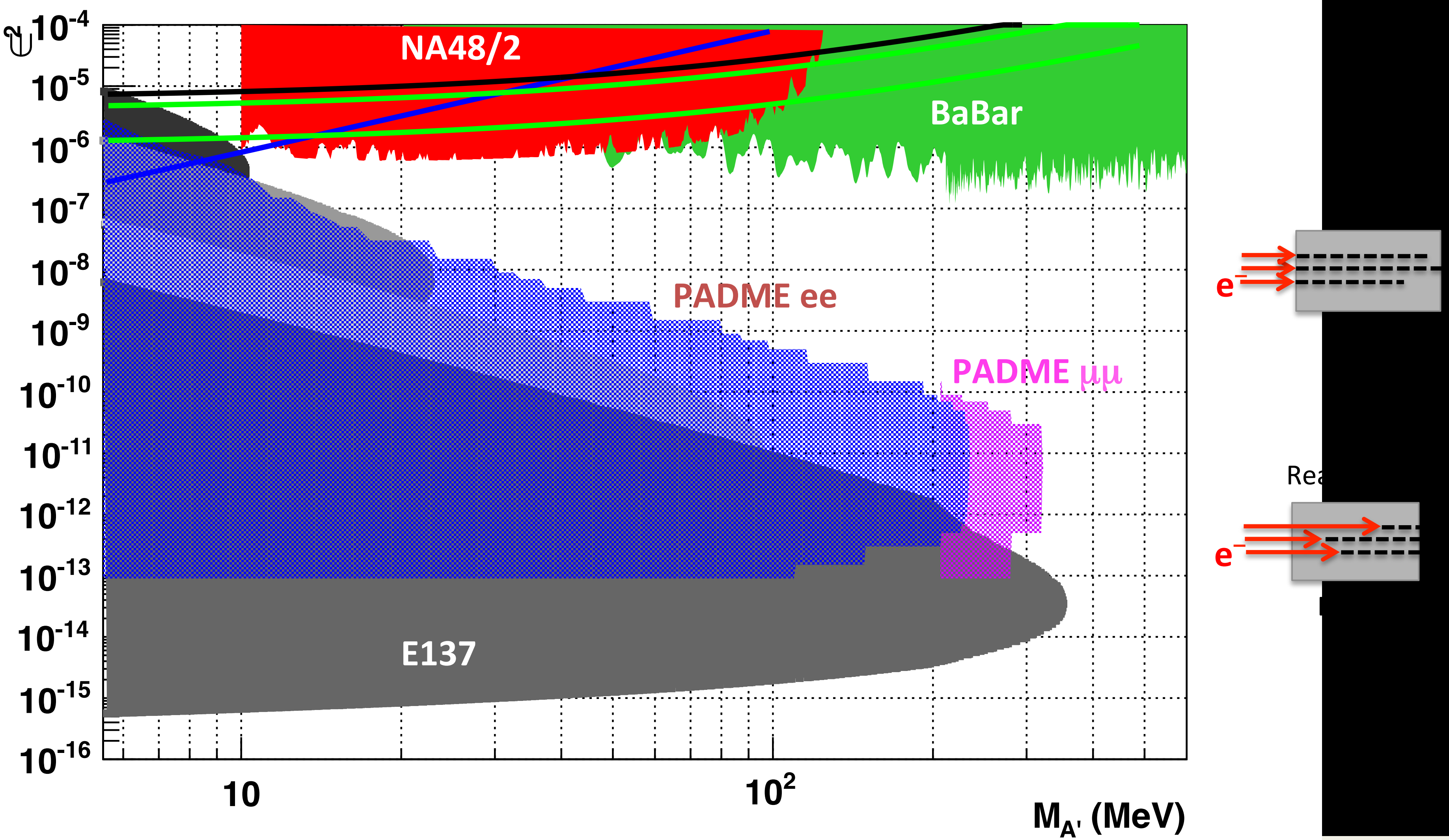


Electron angular acceptance



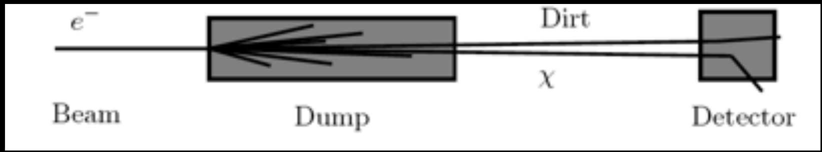
Dump comparison

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

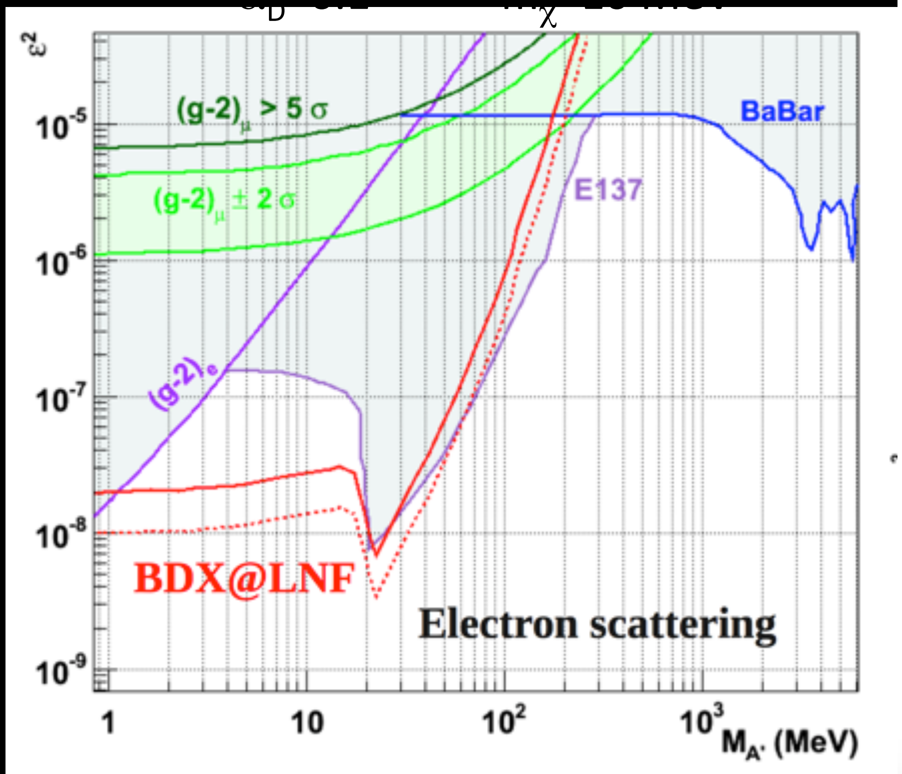


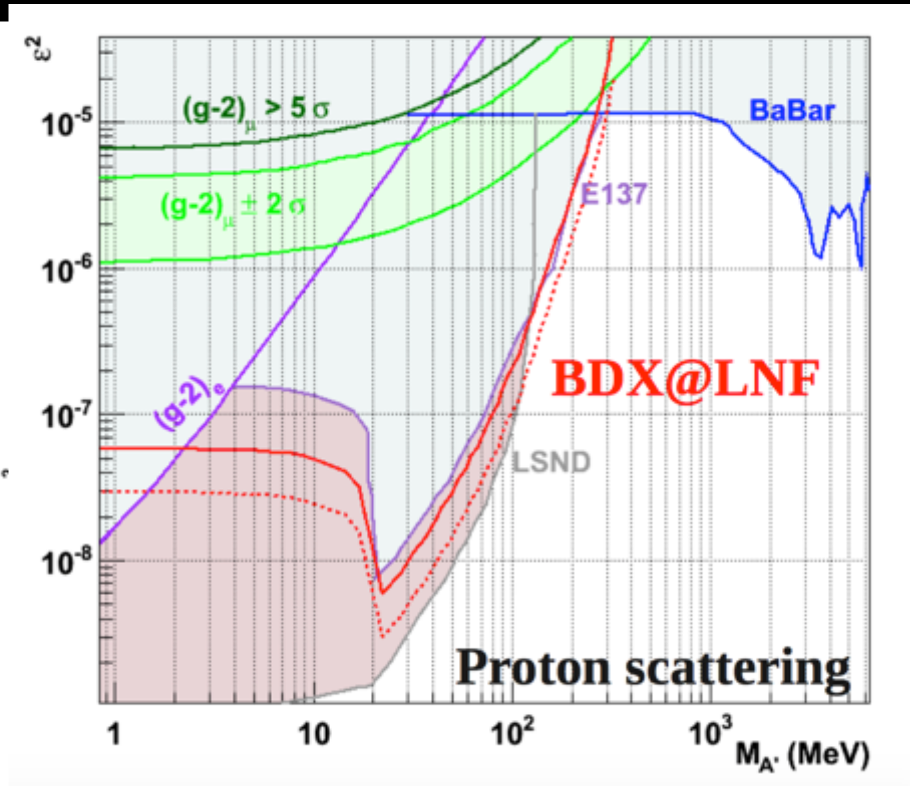
$1 \cdot 10^{20}$, 1.2 GeV electrons; 20 cm aperture at 50 cm from 8 cm W dump

BDX @ LNF



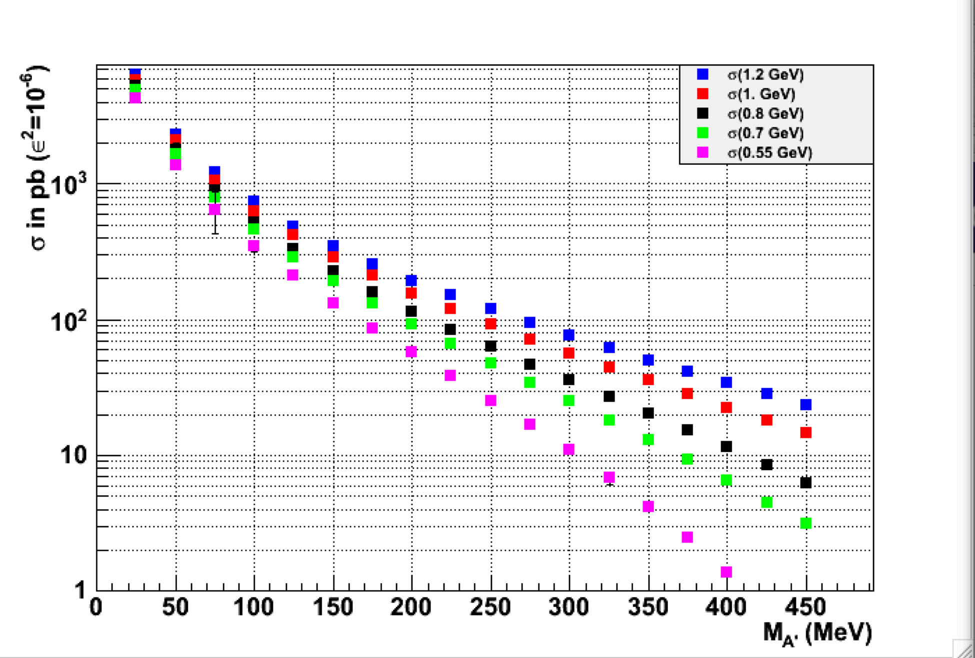
A. Celentano, talk at " What Next LNF"
Same acceptance limit at 100 MeV coming from low beam energy

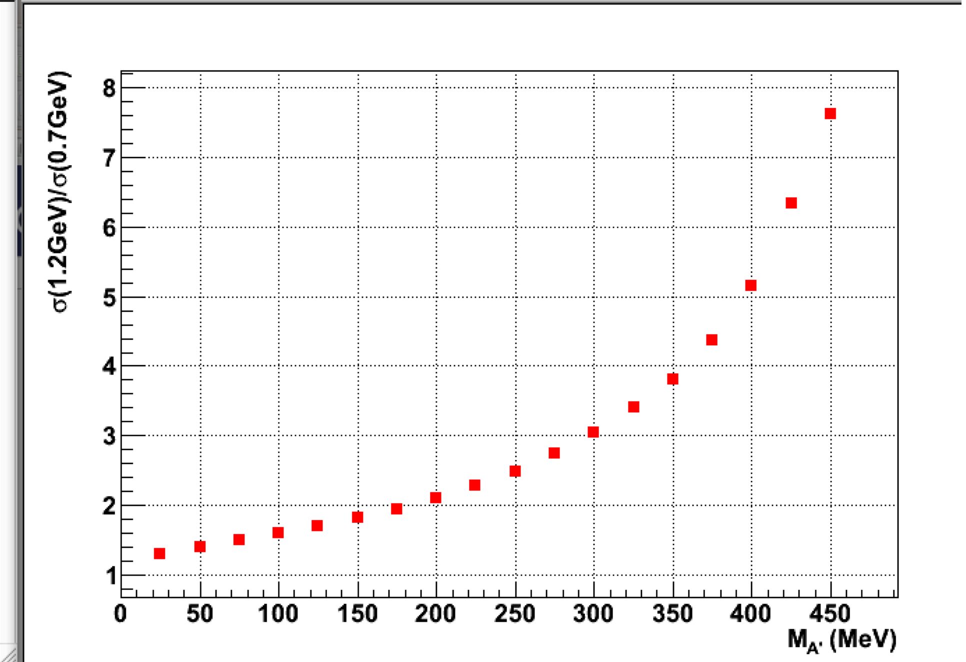


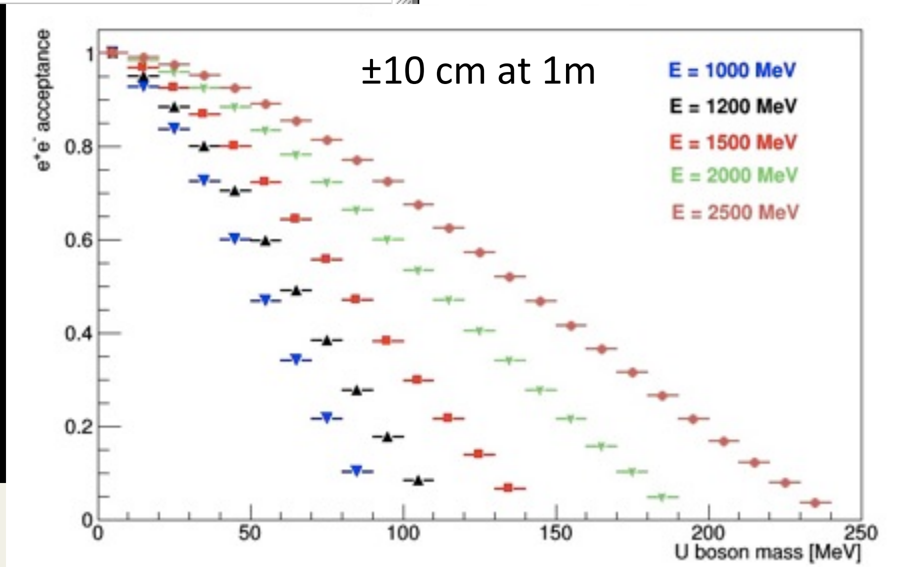


Beam energy **1.2 GeV** (e^-)
CsI detector 60×60×225 cm^3 built with crystals from dismounted BaBar ECal?

Energy upgrade

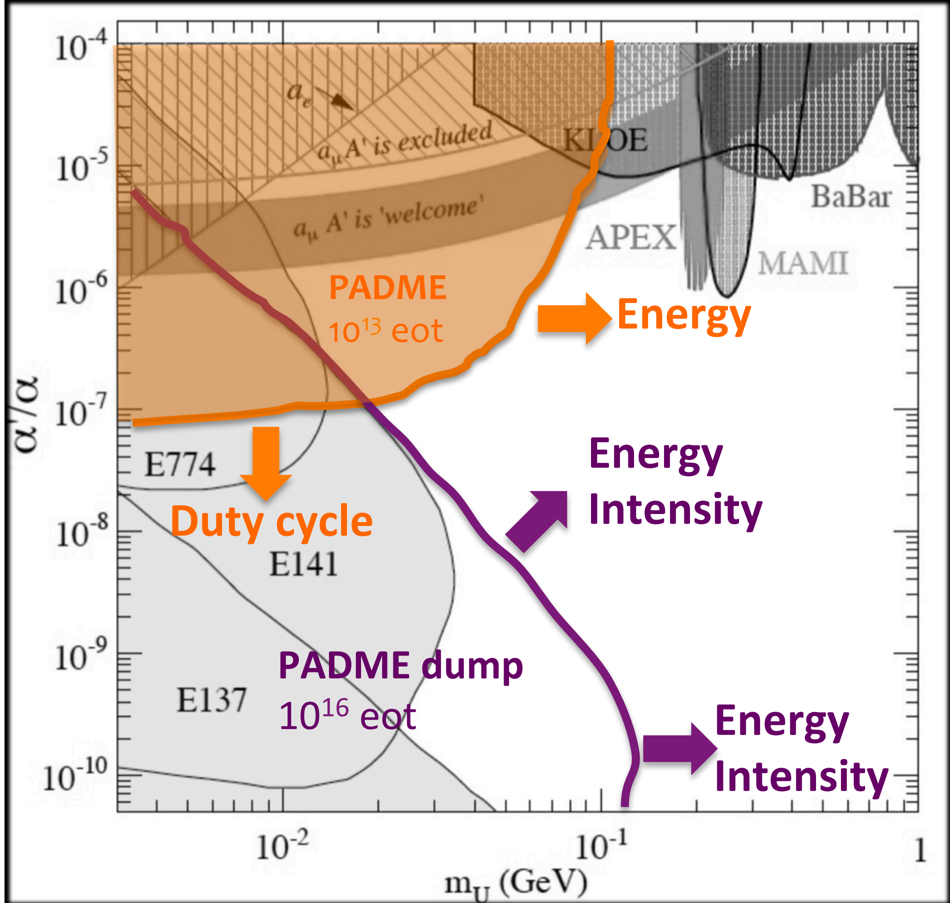




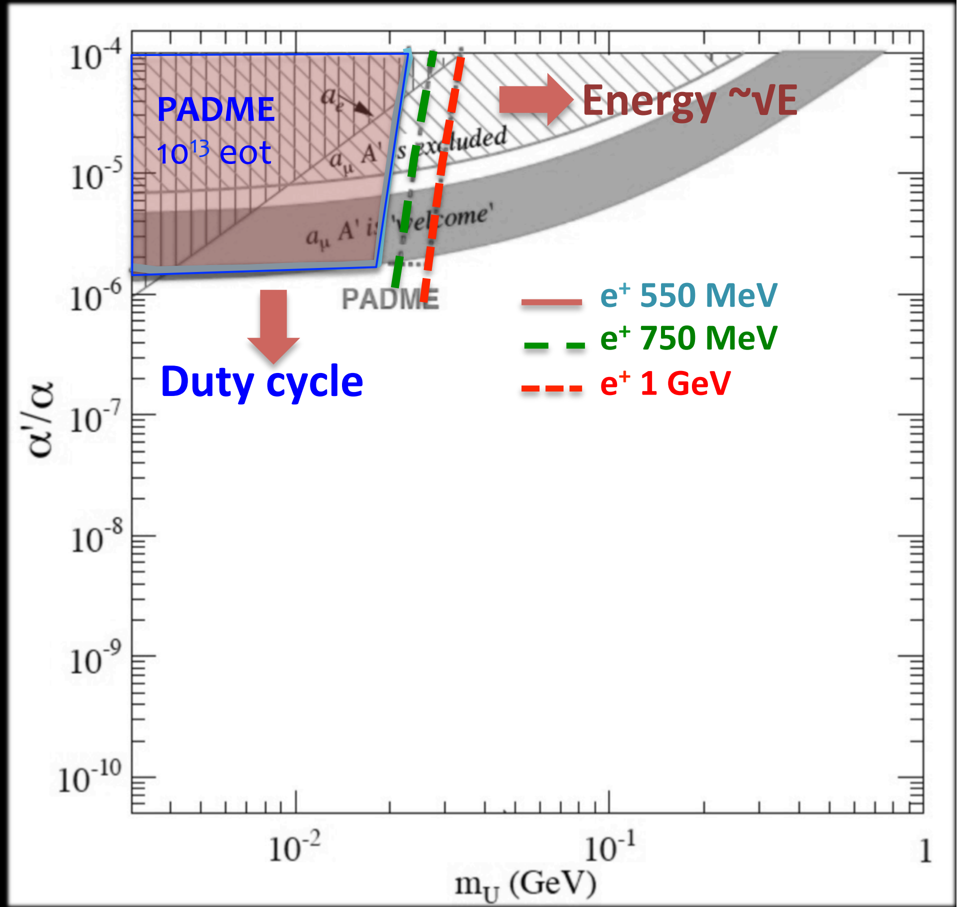


BTF upgrade

Decays to lepton pairs

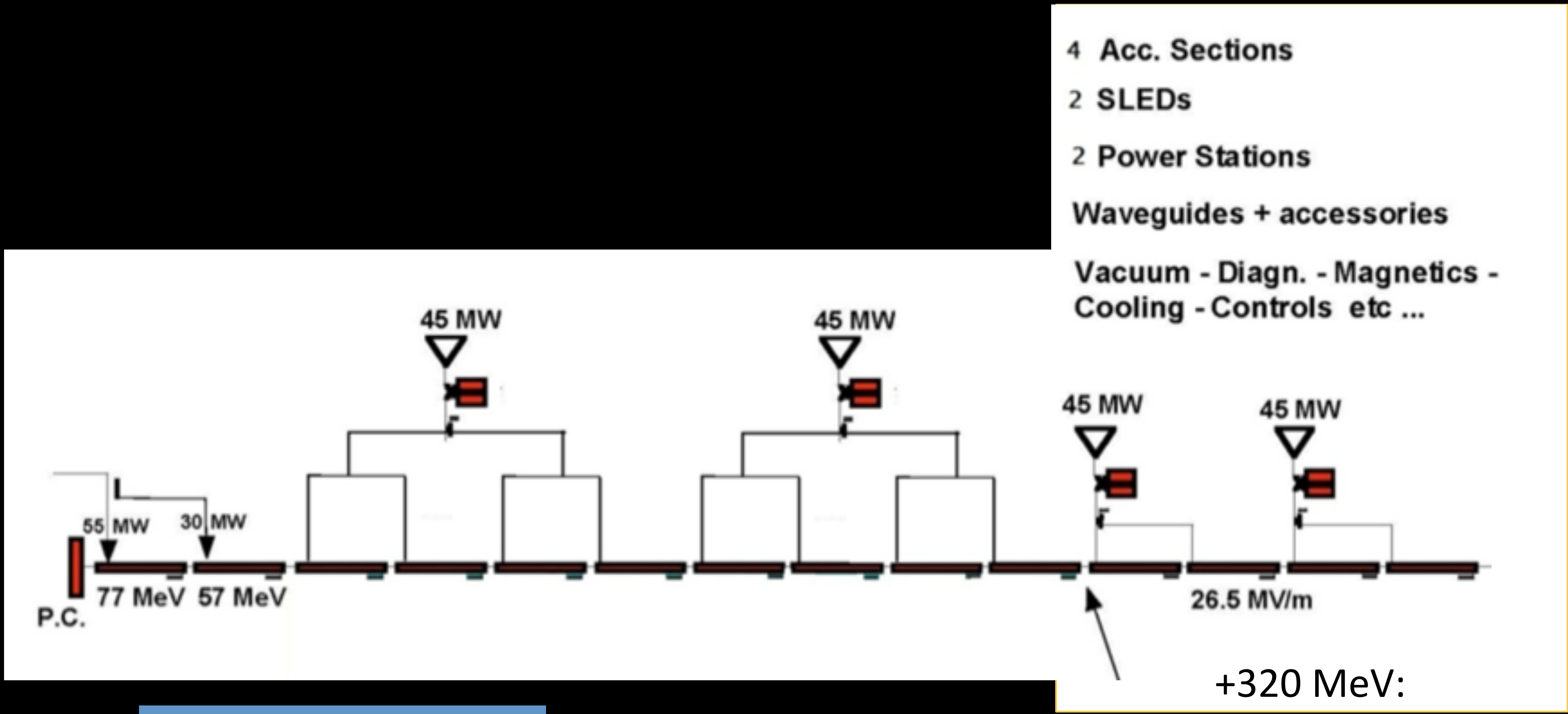


Decays to invisible



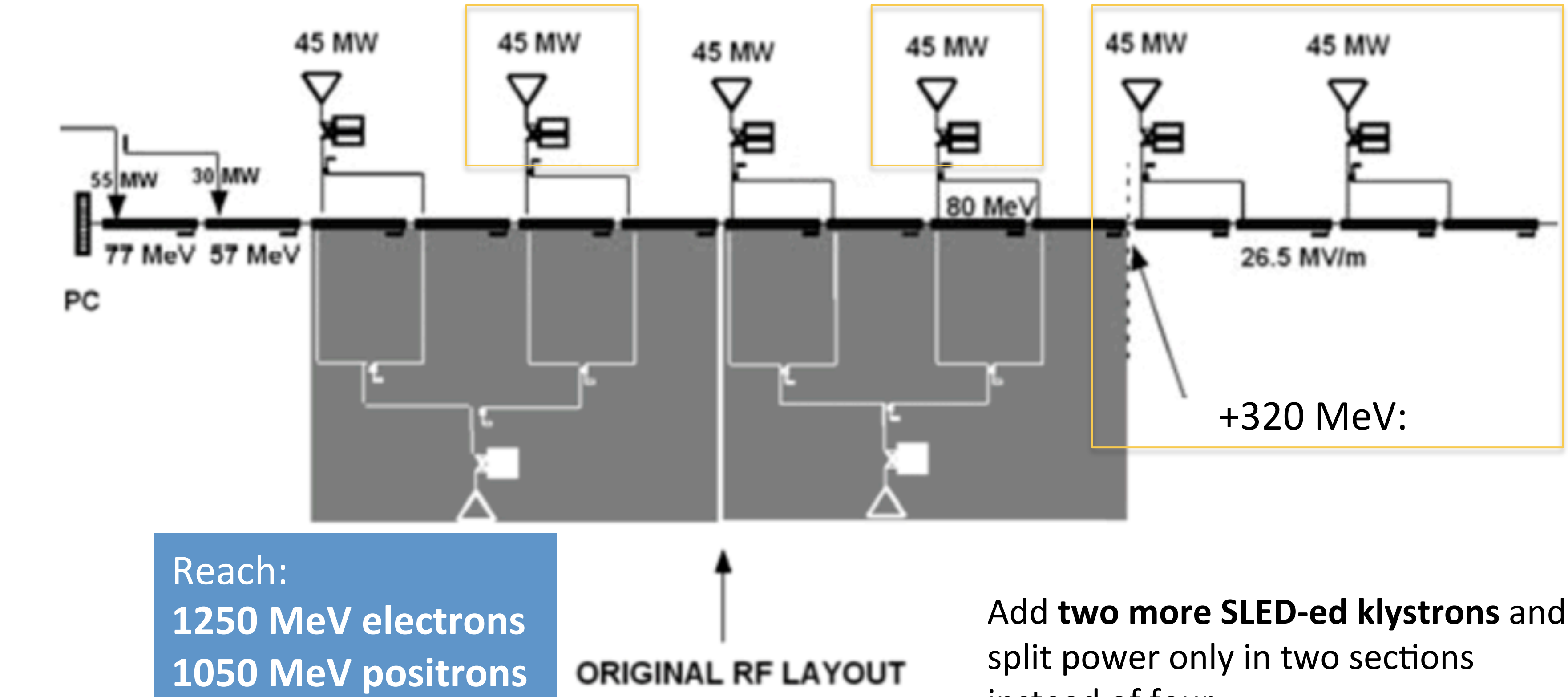

15 m

Add 4 sections + 2 SLED-ed klystrons



Reach:
1070 MeV electrons
870 MeV positrons

Add 4 sections + 4 SLED-ed klystrons



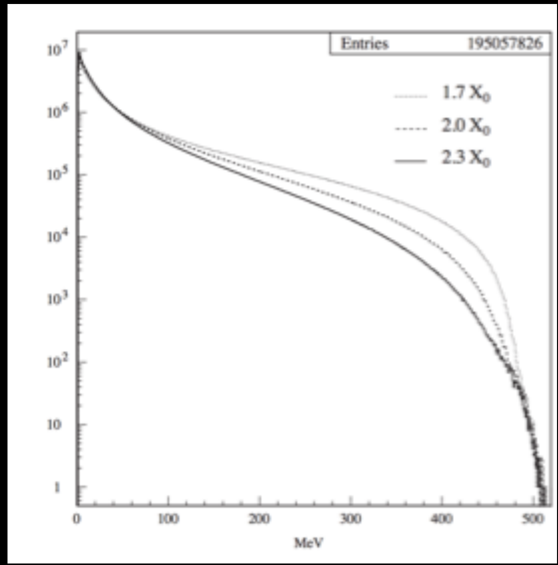
Reach:
1250 MeV electrons
1050 MeV positrons

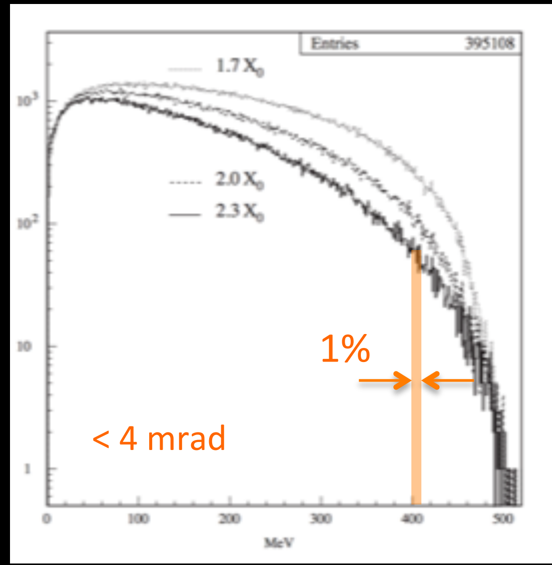
Add **two more SLED-ed klystrons** and split power only in two sections instead of four

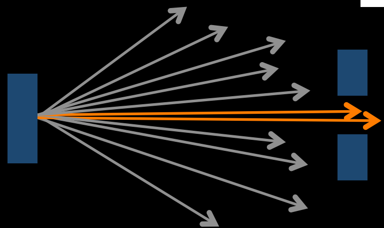
“Low cost” energy upgrade

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

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







< 4 mrad

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

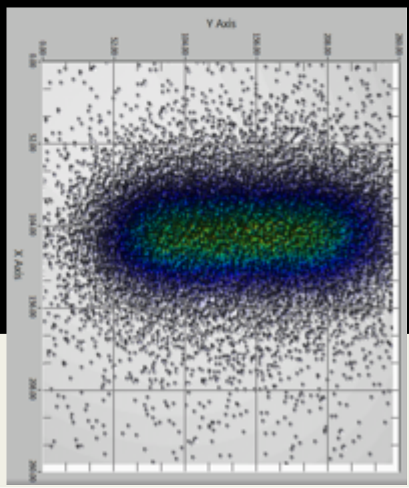
BTF target at 1.7 x_0

σ_y

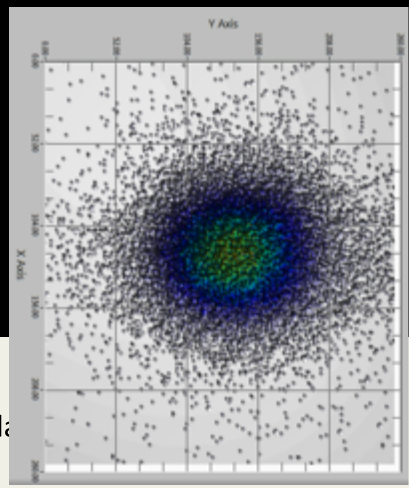
- ≈0.8 mm (2 mm FWHM)
- Dominated by multiple scattering on 0.5 mm Be window + 20 cm of air
- Can be pushed down to 0.6-0.7 mm (with Be window)
- Can be further improved operating in vacuum

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



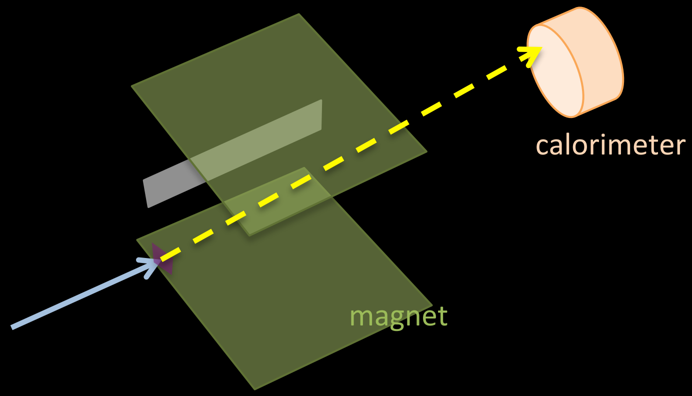
Close TB2



PADME project plans

- Project has been presented as a "What Next" Project in INFN CSN1
  - The project has received positive comments form CSN1 referees
  - Proposal for R&D financing will be discussed in the next CSN1 meeting
- Proto collaboration formed including
  - LNF, Rome1, Lecce and Sofia university
- **6 weeks** test beam time asked at **DAΦNE BTF in 2015**
  - Study the prototype of BGO calorimeter solution (L3 crystals)
  - Test diamond target prototypes
  - Study the maximum beam current per bunch and beam spot size
  - Optimize beam characteristics for PADME operation bunch length, number of particle per bunch, background, beam positioning stability
- Interesting synergy with BDX project identified (BDX at LNF?)
- Many item still to be covered! Search for more collaborators started

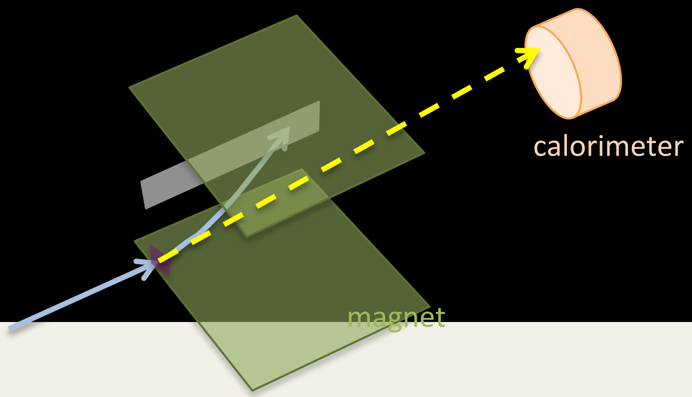
PADME Signal and backgrounds

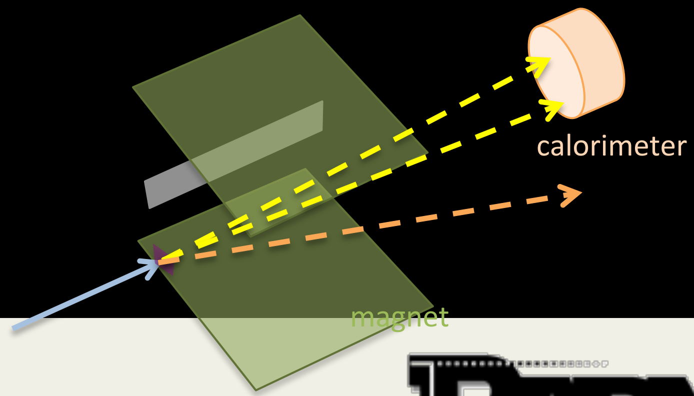


Our signal:

- One photon in the calorimeter
- No positron in the veto
- Kinematics matching a missing mass within defined constraints

We need to fight the backgrounds: one photon + something else, typically **one or more photons** going undetected





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