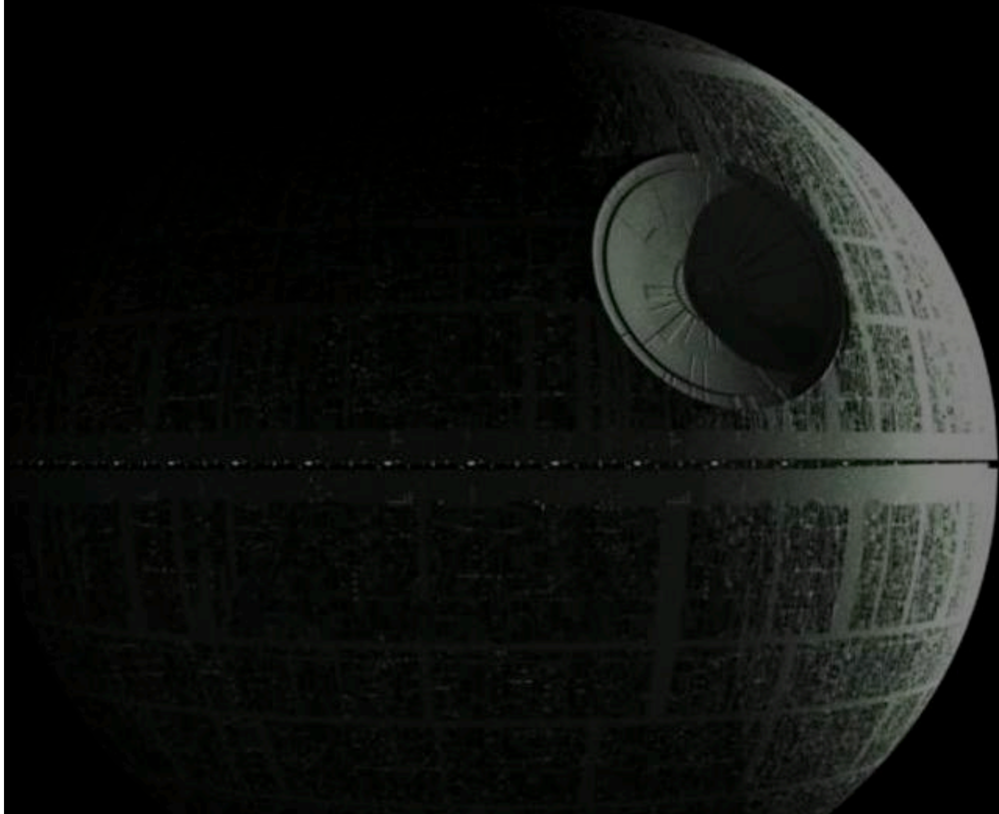


L'esperimento PADME alla BTF di Frascati

Paolo Valente

INFN Roma

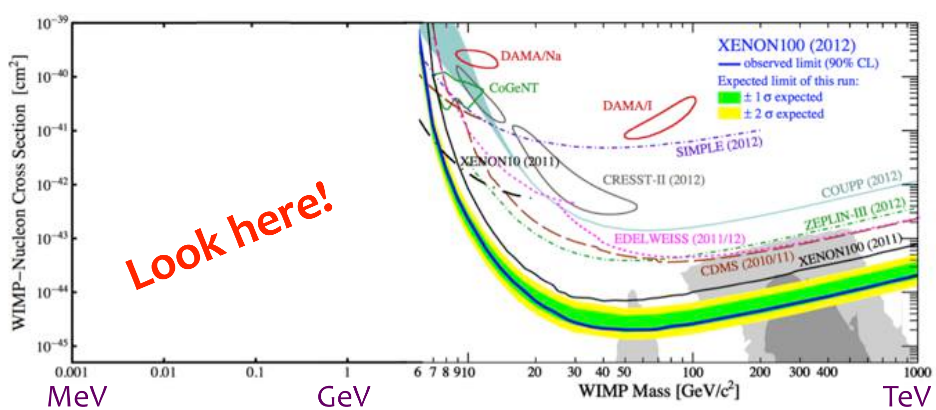
Outline

* Introduction: the dark photon model(s)
* Experimental panorama and existing constraints
  * Electron fixed-target experiments (beam dumps)
  * Proton beam dump experiments
  * Experiments at e+e- colliders
* Planned and future experiments
  * Electron fixed target with thin targets
* The DAFNE linac and beam-test facility
* The PADME experiment(s)

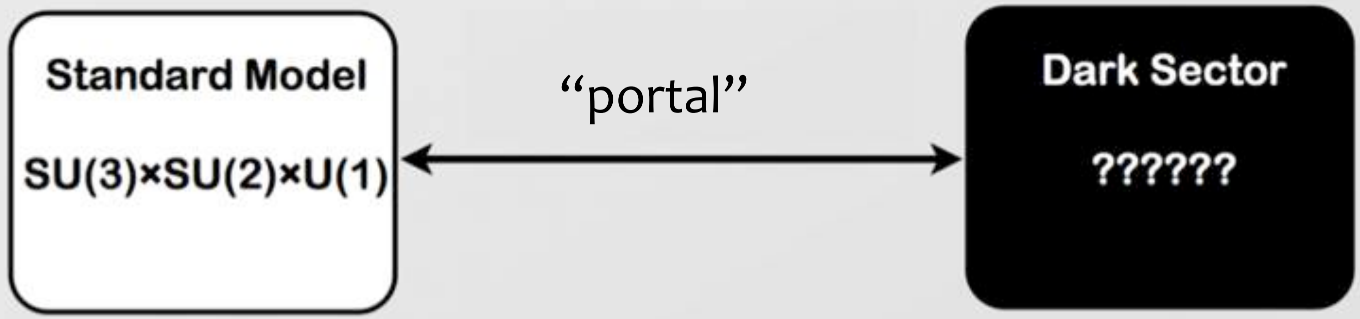
PADME

Secluded or hidden dark matter

- **Problem:** connect dark matter (e.g. WIMPs) to *SM* particles **while being compatible with direct measurements**:
  - Low elastic cross section on nuclei
  - Low production rates at colliders
- **Solution**: DM **not directly connected** to the *SM*, but only through mediator particles: **portals**
  - Hidden or secluded or dark sectors often present in string theories and super-symmetry
  - Simple model: add additional U(1)’ gauge group, but a **vector boson not the only possible mediator**
  - The mediator could be not the lightest dark particle and thus it is not itself a DM candidate



Portals to secluded dark sector

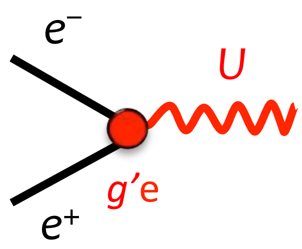


vector	$\frac{1}{2}\epsilon F^{Y}_{\mu\nu}F'^{\mu\nu}$	dark photon
Higgs	$\epsilon_h \lvert h\rvert^2 \lvert\phi\rvert^2$	dark scalar
neutrino	$\epsilon_\nu (hL)\psi$	sterile neutrino
axion	$\frac{1}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$	ALPs

The simplest dark photon model

* The simplest hidden sector model just introduces **one extra U(1) gauge symmetry** and a corresponding gauge boson: the so-called **dark photon** or ***U* boson**.
* **Two types of interactions with SM particles** should be considered:

1. **QED-like interactions**, with coupling g' and charges q_f:
   * $\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$
   * **Not all** the SM particles need to be **charged** under this new symmetry
   * In the most general case q_f is different between **leptons** and **quarks** and can even be 0 for quarks. (P. Fayet, Phys. Lett. B 675, 267 (2009).)



Holdom, Phys. Lett. B166, 1986

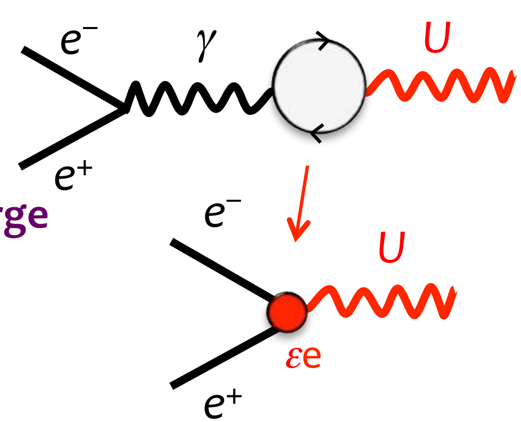
e^+

The simplest dark photon model

- The simplest hidden sector model just introduces **one extra U(1) gauge symmetry** and a corresponding gauge boson: the so-called **dark photon** or ***U* boson**.
- **Two types of interactions with SM particles** should be considered:

2. **Effective coupling** generated through the **kinetic mixing** between the QED photon and the new U(1) gauge boson:
   - $\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$; $F^{\mu\nu}_{dark} = \partial^{\mu} U'^{\nu}$
   - In this case the coupling is just **proportional to the electric charge** and thus it's the same for quarks and leptons:
   - $A_{\mu} \to A_{\mu} + \varepsilon\, a_{\mu}$; $\alpha' = \varepsilon^2 \alpha$

Holdom, Phys. Lett. B166, 1986



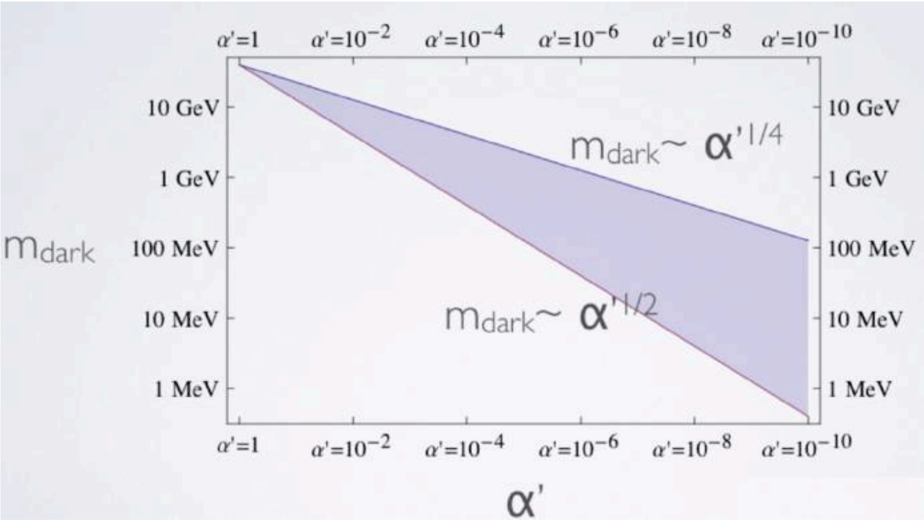
No direct coupling to SM, by far the most used model

U boson mass and couplings

* 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:
  * $m_U/m_W \sim \varepsilon - \varepsilon^{1/2}$

  leading to a MeV-GeV mass scale

N. Wiener

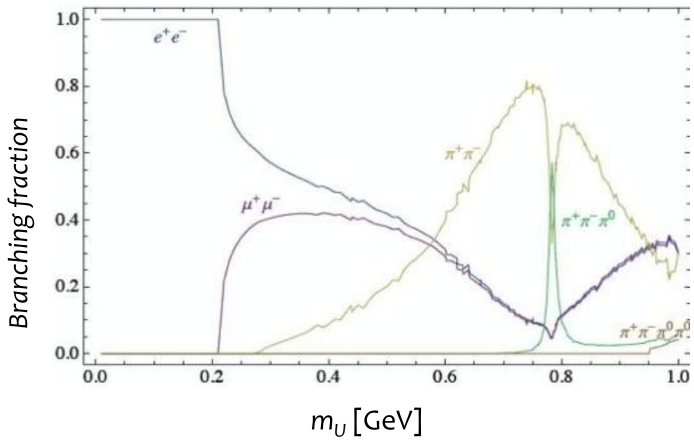


U boson decays to SM particles

Decay to "visibles"

If no lighter states exists in the dark sector with $m_\chi < m_U/2$, U decays **only to SM particles**

- If dark photon couples to SM particles **through kinetic mixing only** same coupling εq:
  - For $m_U < 2m_\mu$ it only decays to $e^+ e^-$
  - For $m_U < 2m_\mu$, take BR from $R(e^+e^- \rightarrow had./e^+e^- \rightarrow \mu^+\mu^-)$

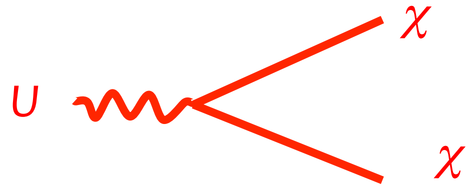


U boson decays to DM particles

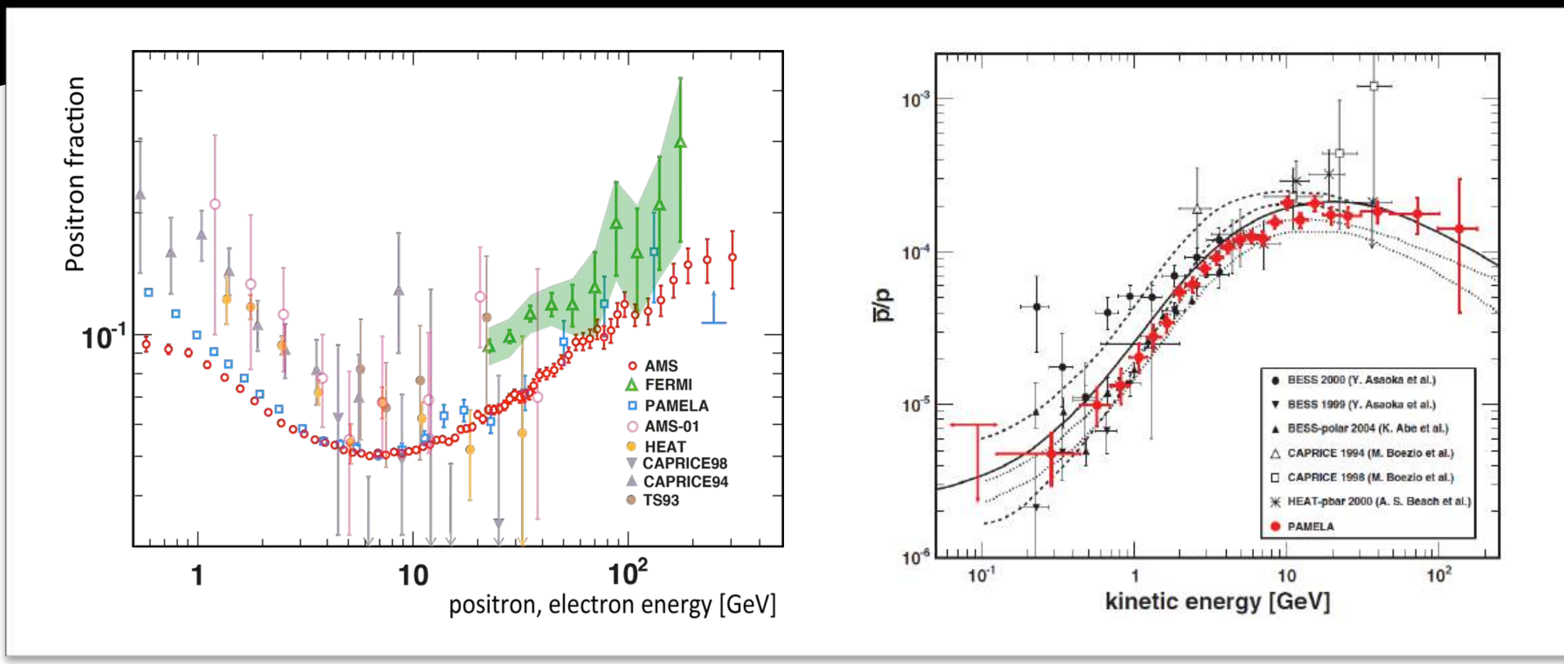
Decay to "invisibles"

If – instead – additional **lighter** states do **exist** in the dark sector with $m_\chi < m_U/2$

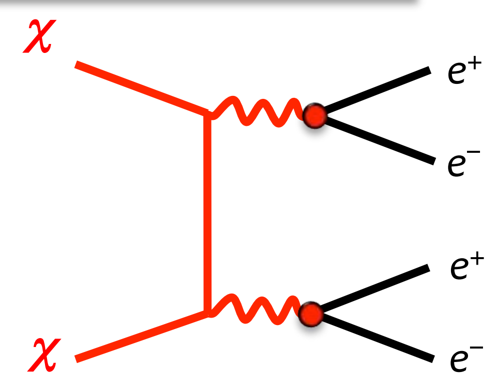
* Dark photon decays to SM particles will be **suppressed** by ε^2
* $U \to \chi\chi \approx 1$



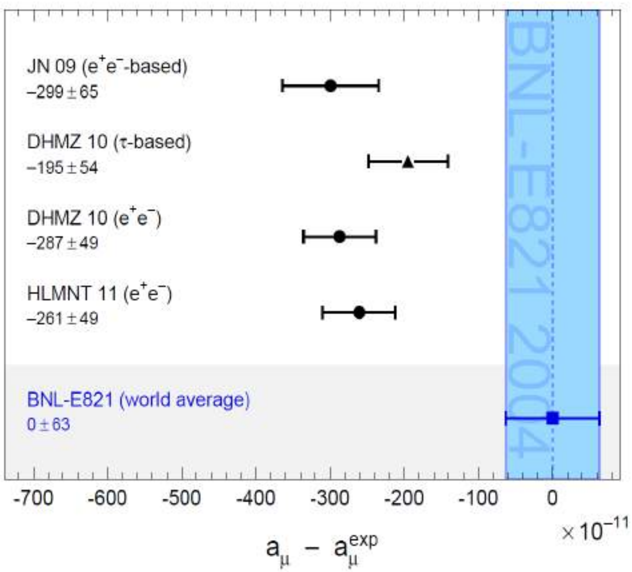
Particle astrophysics: PAMELA, AMS

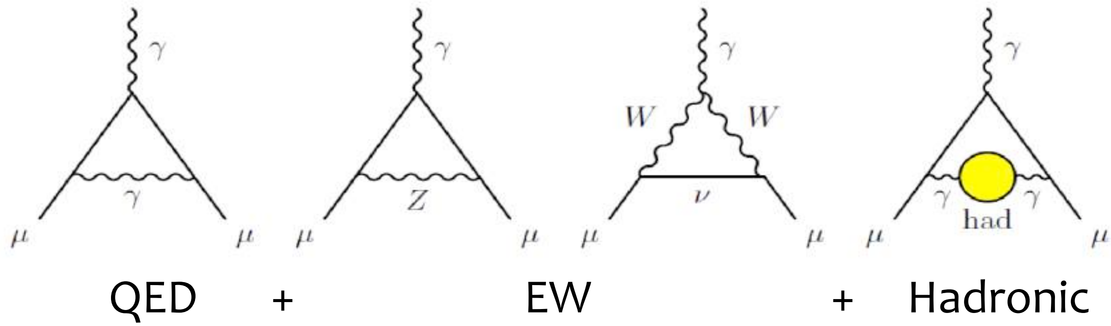


* Positron eccess: PAMELA, FERMI, AMS-02
* No significant excess in antiprotons
  * Consistent with pure secondary production
* Leptofilic dark matter annihilation?
* If DM is the explanation, the **mediator should be light**, < $2m_{proton}$



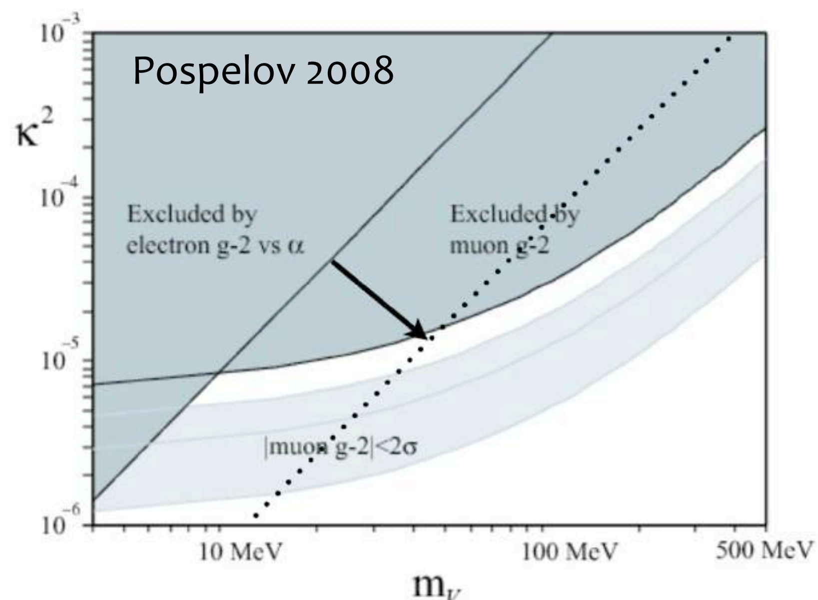
Muon g−2 SM discrepancy



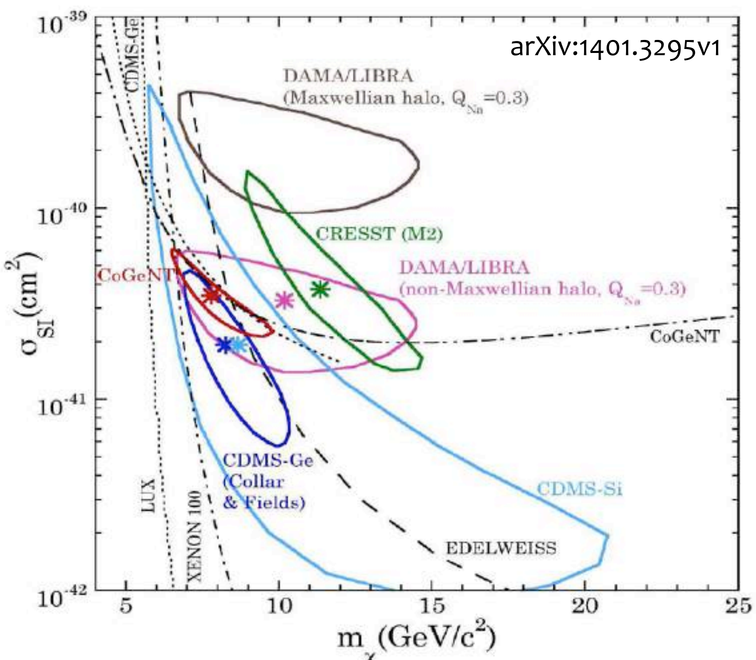


About **3σ** discrepancy between theory and experiment

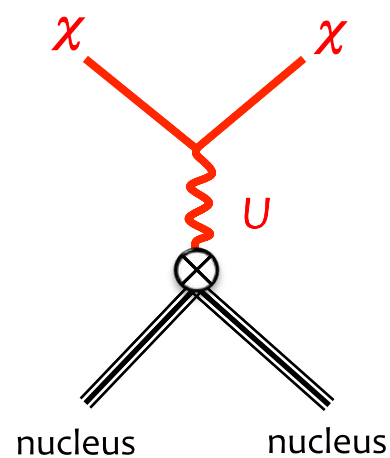
(**3.6σ**, if taking into account only $e^+e^- \rightarrow$ hadrons)

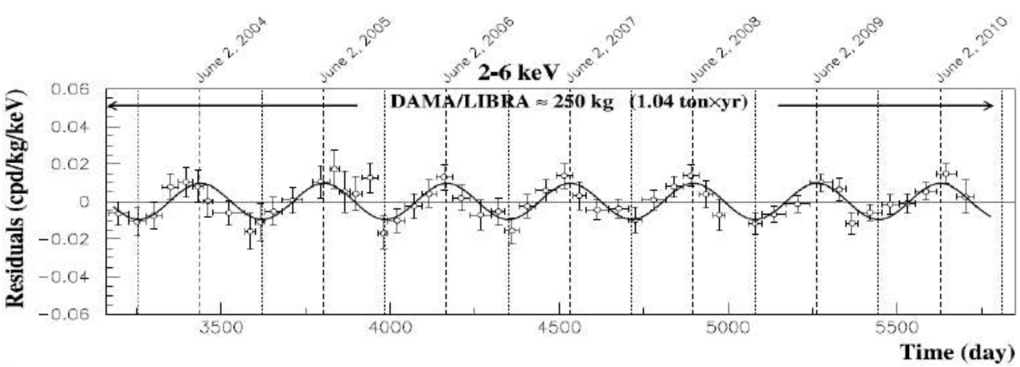


The DAMA-Libra effect



Radio-pure NaI (Tl)

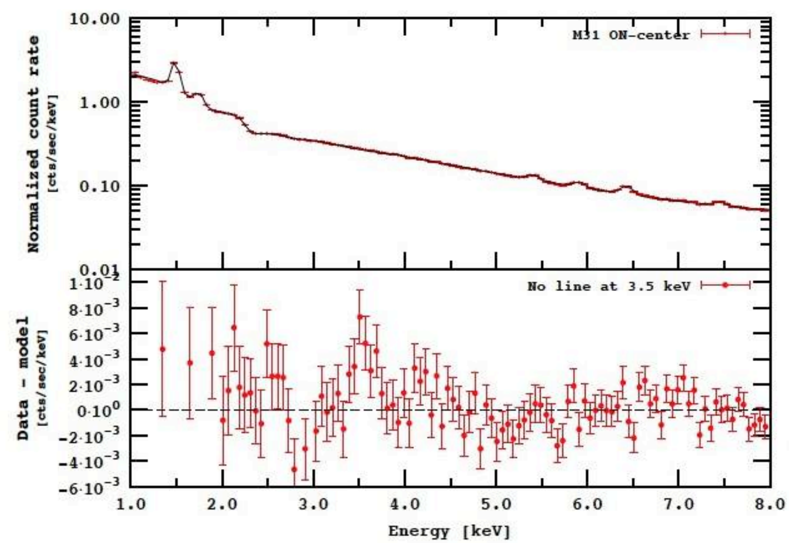




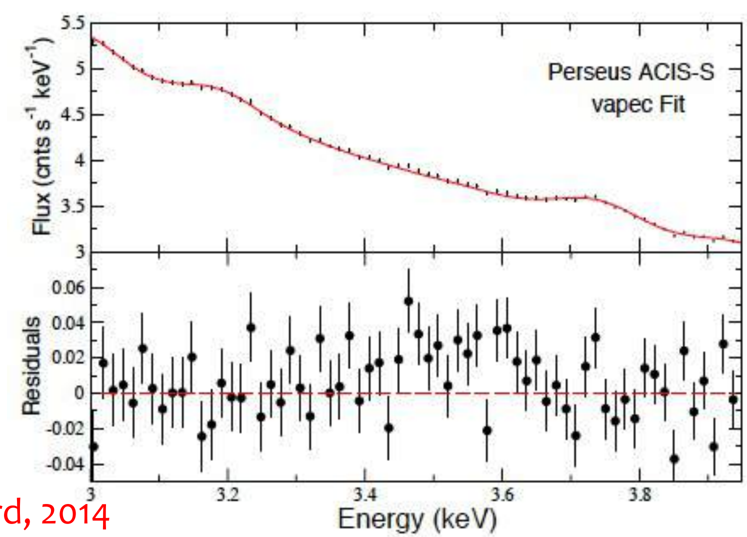
- Nuclear recoil by the exchange of a dark photon
- Independent of χ mass value

Observation of 3.5KeV X-ray line

* Recently a 3.55 KeV X-ray line (~3σ) has been reported in the stacks analysis of 73 galaxy clusters from the XMM-Newton telescope. **arXiv:1402.2301v1**



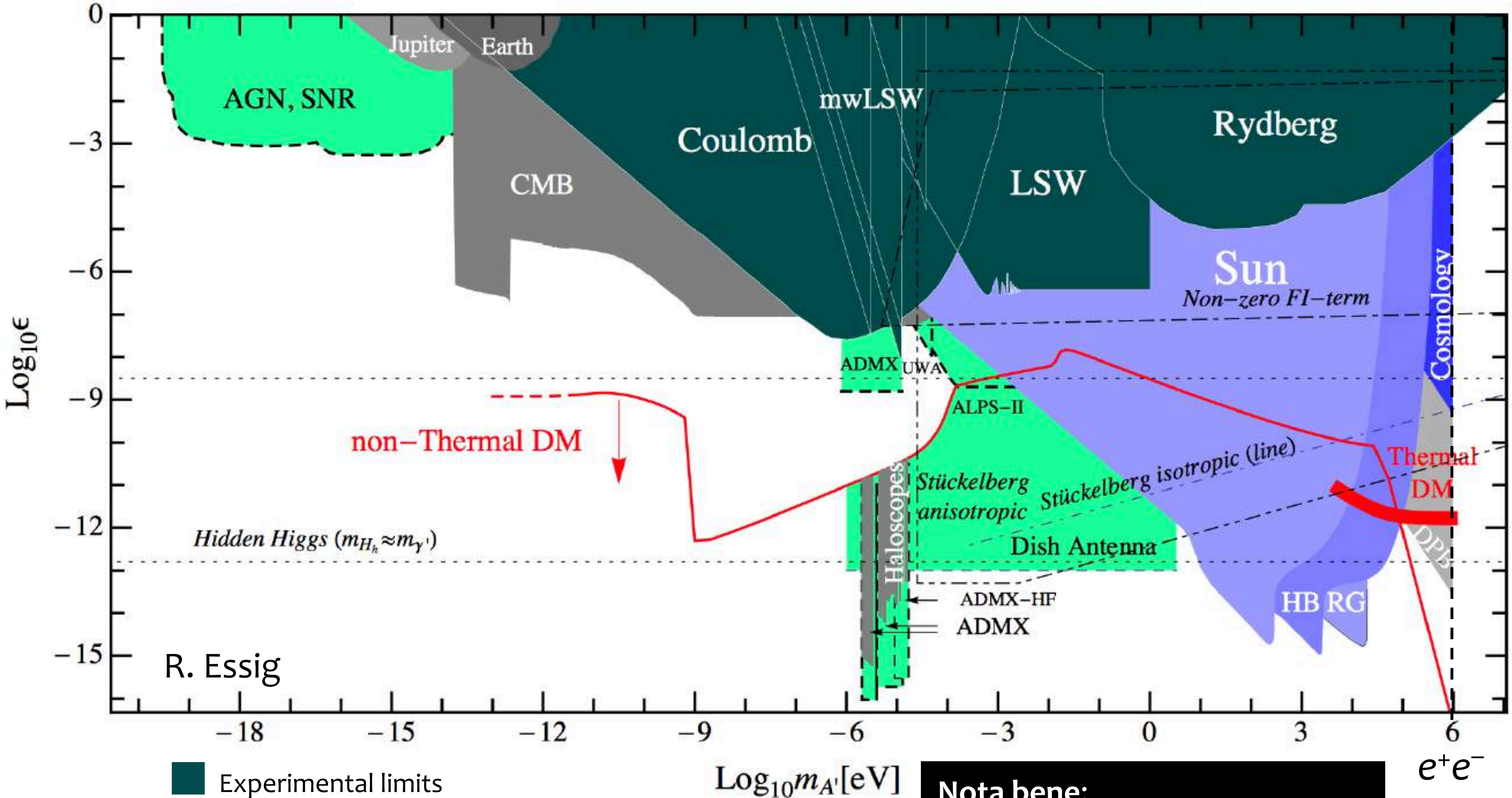
* A similar analysis finds an evidence at the 4.4σ level for a 3.52 KeV line from the analysis of the X-ray spectrum of the Andromeda galaxy (M31) and the Perseus Cluster. **arXiv:1402.4119**



3.5 KeV line explained through *U* boson

* Many models have been developed to explain such a line, based on sterile neutrinos
* A possible explanation of such a line in term of the U(1) gauge theory with an Higgs mechanism is proposed in **arXiv:1404.2220v1**
  * A **single new scalar dark matter field** ϕ of mass 7.1 KeV is introduced
  * ϕ couples to SM Higgs through *U* boson
  * Due to very small mass, ϕ can only decay into $\gamma\gamma$ (or $\nu\nu$), giving the X line at 3.5 KeV
  * After spontaneous symmetry breaking of U(1) symmetry, *U* boson becomes massive
  * Due to constraints coming from the relic abundance, a mass interval has been identified: 7KeV < m_U < 10MeV

Parameter space for *hidden photons*



- Experimental limits
- Planned experiments
- Astronomy and astrophysical observations
- Astrophysics and cosmology constraints
- All dark matter accounted for

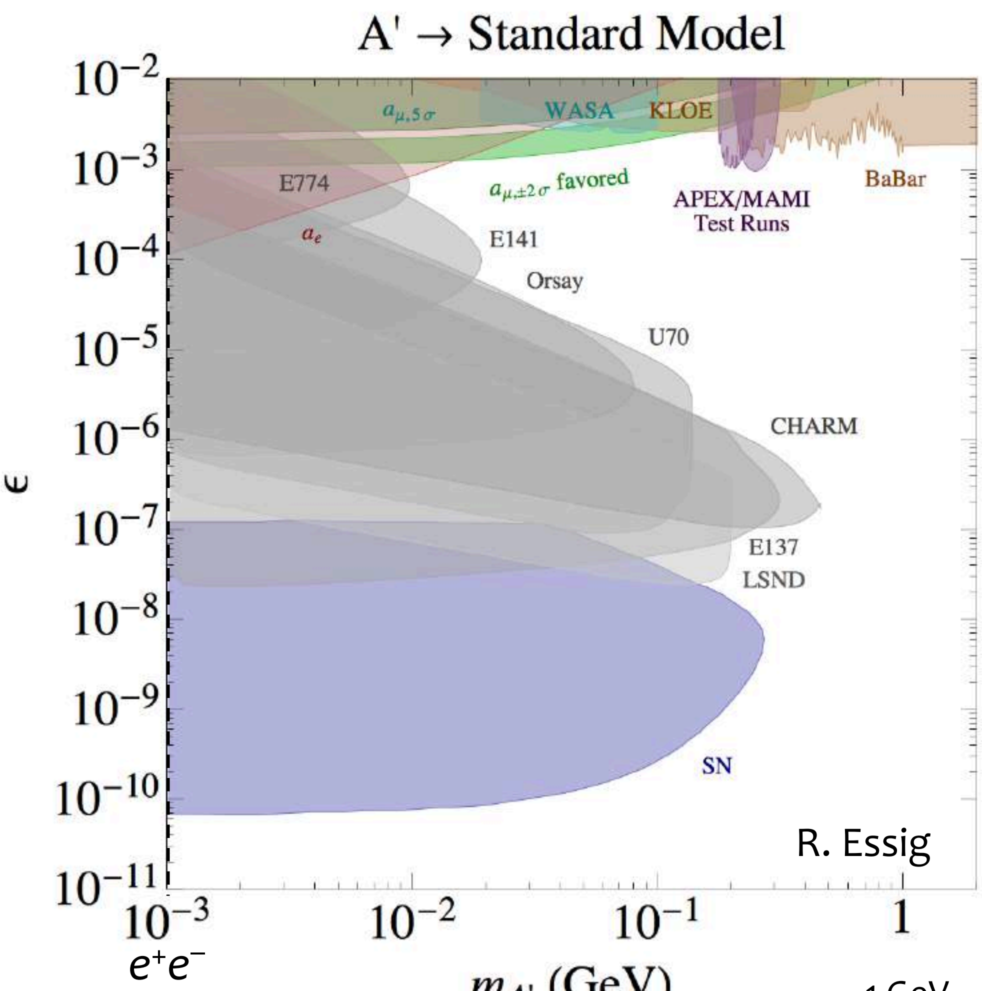
e^+e^- threshold

Nota bene:

Different naming in literature:

$U = \gamma' = A'$, sometimes V

Parameter space for *hidden photons*

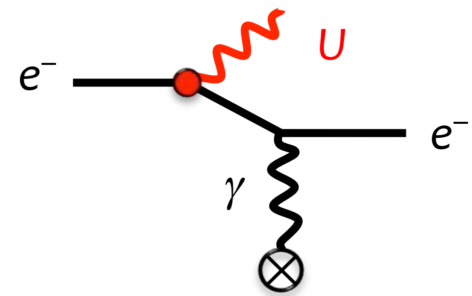


e^+e^- threshold

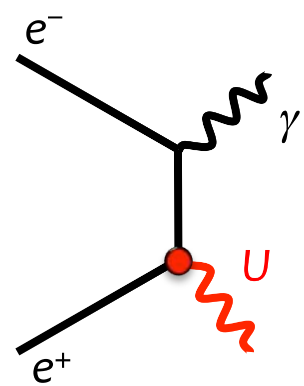
1 GeV

U boson production

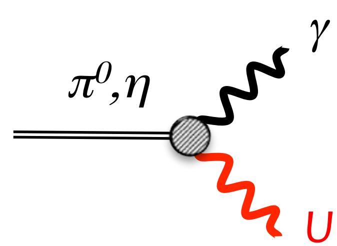
- *U* boson can be produced in **electron** collisions on target nuclei by the **Bremsstrahlung** process:
  - $e\,N \rightarrow e\,N\,U$



- *U* boson can be produced by **annihilation** of positrons on target electrons:
  - $e^+ e^- \rightarrow \gamma\,U$



- U bosons can also be produced in **meson** decays:



Fixed target vs. collider

$$\sigma_{\gamma'}^{\text{ft}} \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m_{\gamma'}^2}$$

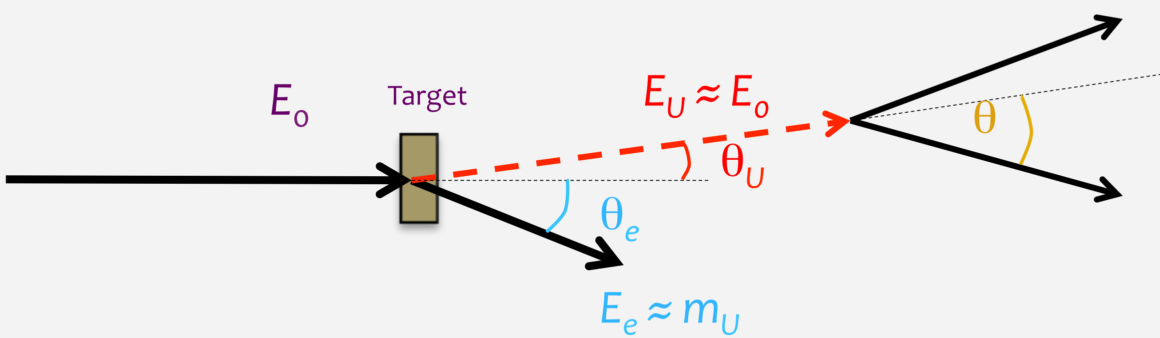
$$\sigma_{\gamma'}^{\text{coll}} \sim \frac{\alpha^2 \varepsilon^2}{E^2}$$

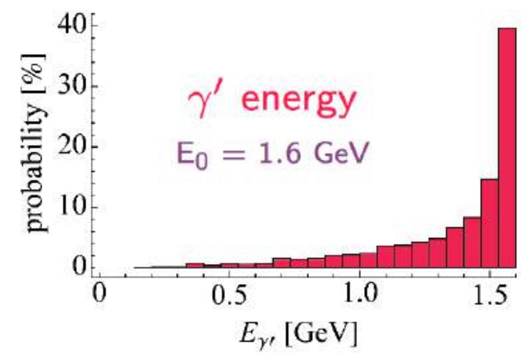
$$\sigma_{\gamma'} \sim 100 \text{ pb} \left(\frac{\varepsilon}{10^{-4}}\right)^2 \left(\frac{100 \text{ MeV}}{m_{\gamma'}}\right)^2$$

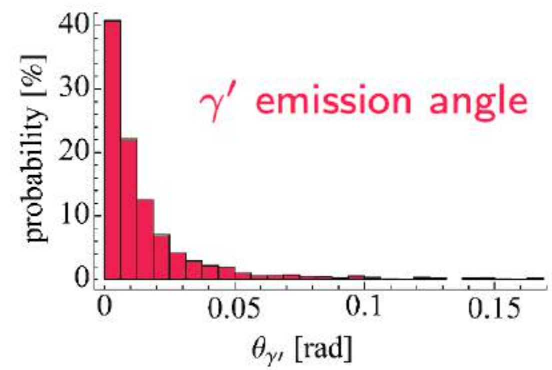
Electron fixed target experiments

Kinematics:

* *U* takes nearly all the beam energy (sharply peaked at $x \approx 1$)
  * Electron takes a small energy $\approx m_U$
* *U* emission almost collinear to the beam, narrow distribution around $\theta_U \approx (m_U/E_0)^{3/2}$
* Electron angle, wide distribution: $\theta_e \approx (m_U/E_0)^{1/2}$
* *U* decay products open by $\theta \approx m_U/E_0$



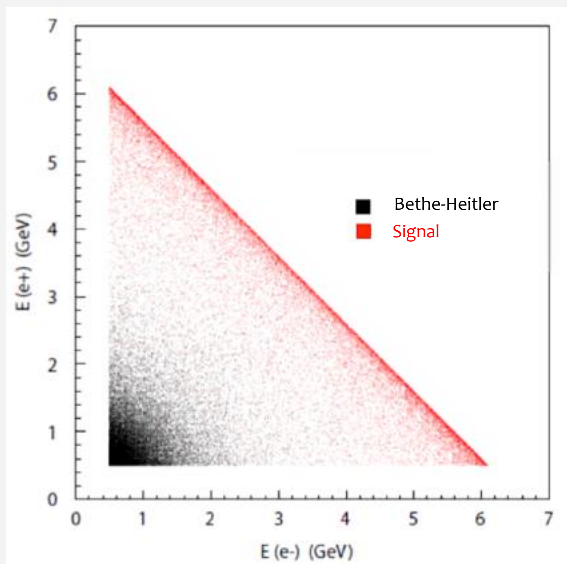


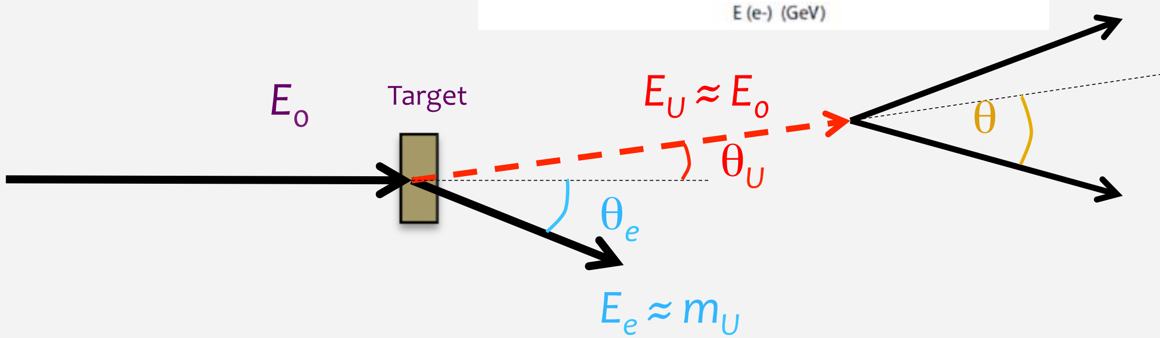


Electron fixed target experiments

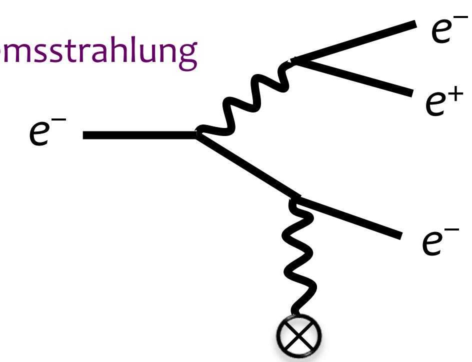
Main backgrounds:

* SM Bremsstrahlung
* Bethe-Heitler

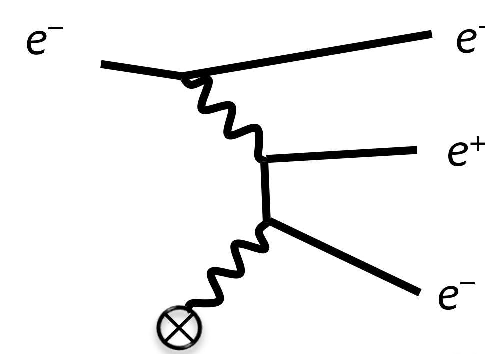




Bremsstrahlung

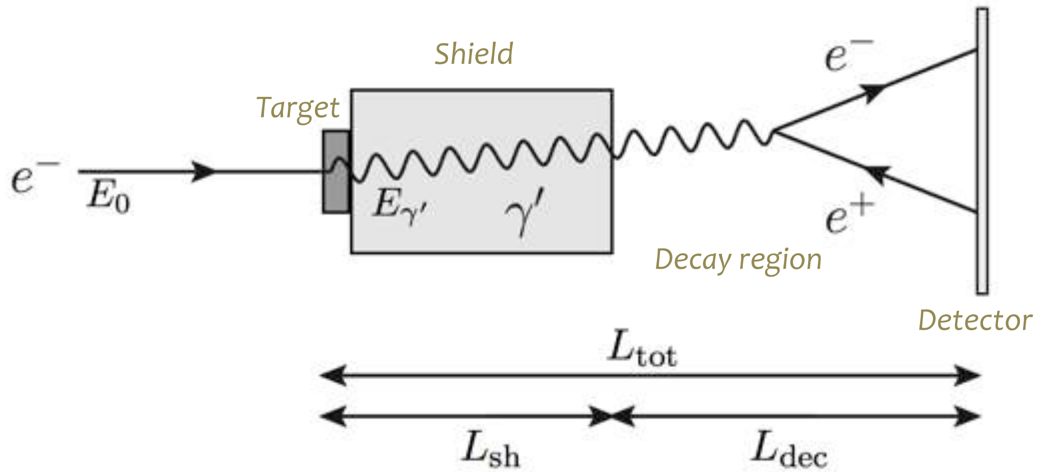


Bethe-Heitler



"Classical" beam-dump experiments

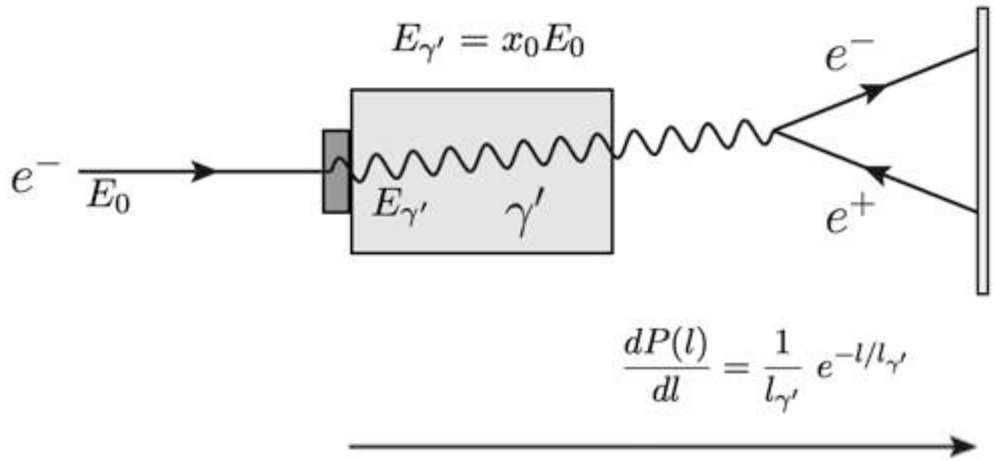
$$l_{\gamma'} \sim 10\text{cm}\,\frac{E_{\gamma'}}{1\text{GeV}}\left(\frac{10^{-4}}{\chi}\right)^2\left(\frac{10\text{MeV}}{m_{\gamma'}}\right)^2$$



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

At colliders: $\mathcal{L}^{\rm coll} \simeq \frac{N_e^2}{A_b}$ → Beam section

In addition to cross section advantage



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

Electron energy distribution due to the interaction in target+shield

Decay probability of γ'
after shield

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

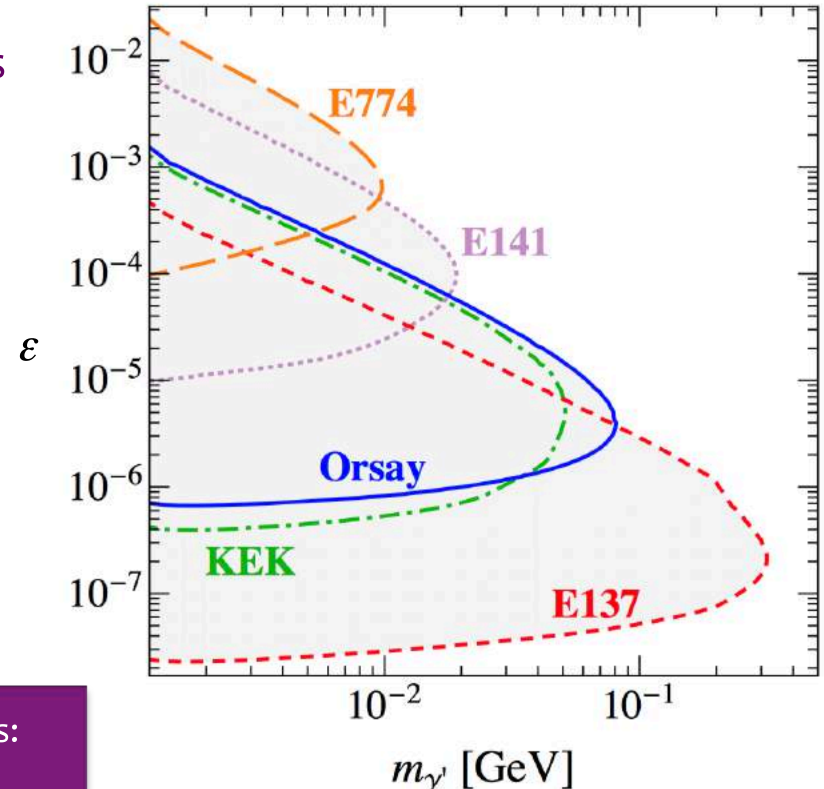
$$T_{sh} \equiv \rho_{sh} L_{sh} / X_0$$

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

Limits from electron beam-dump experiments

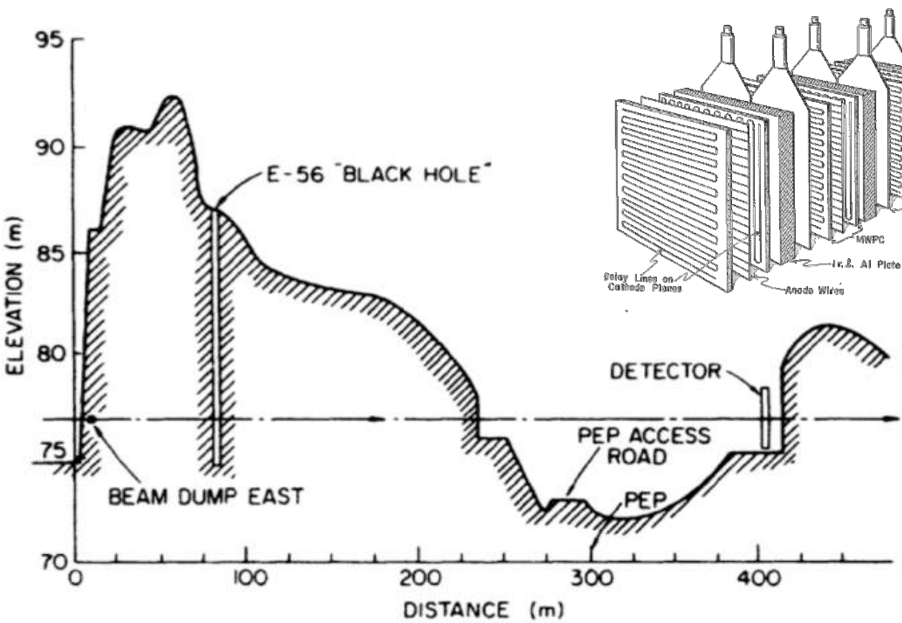
$$N_{events} \sim \int dE_{\gamma'} \int dE_e \int dl \; \frac{d\sigma_{\gamma'}}{dE_{\gamma'}} \; e^{-L_{sh}/l_{\gamma'}} \left(1 - e^{-L_{dec}/l_{\gamma'}}\right) \; N_e \; I_e(E_0, E_e, l) \; BR_{e^+e^-} \; A_{exp}$$

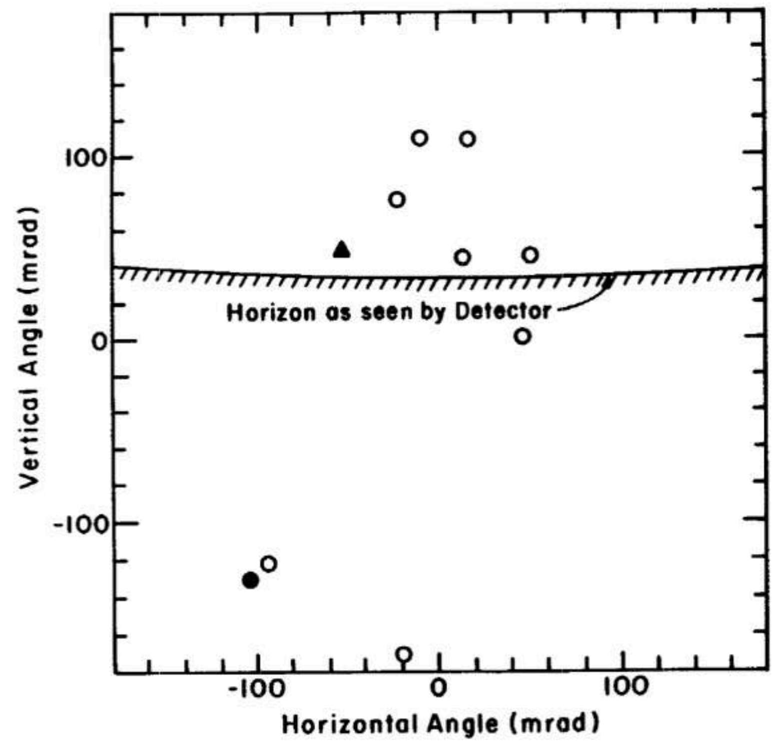
- Experiments looking for decay products of "rare penetrating particles" behind a **stopped electron beam**
- SLAC **E137** (1988)
  - 30 C, 20 GeV, 179 m + 204 m
- SLAC **E141** (1987)
  - 0.3 mC, 9 GeV, 10 cm, 35 m
- Fermilab **E774** (1991)
  - 0.8 nC, 275 GeV, 30 cm, 7 m



Model dependent limits:
⌘ Kinetic mixing
⌘ $BR(U \to e^+ e^-)=1$

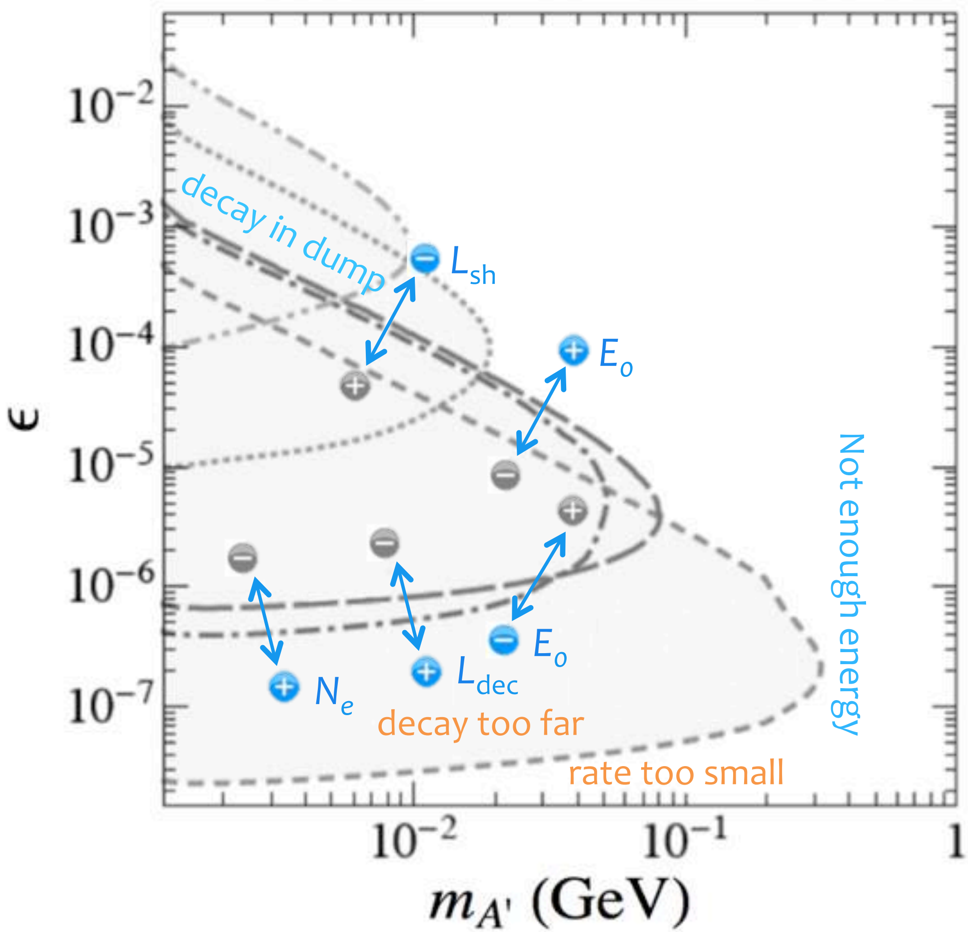
E-137 at SLAC



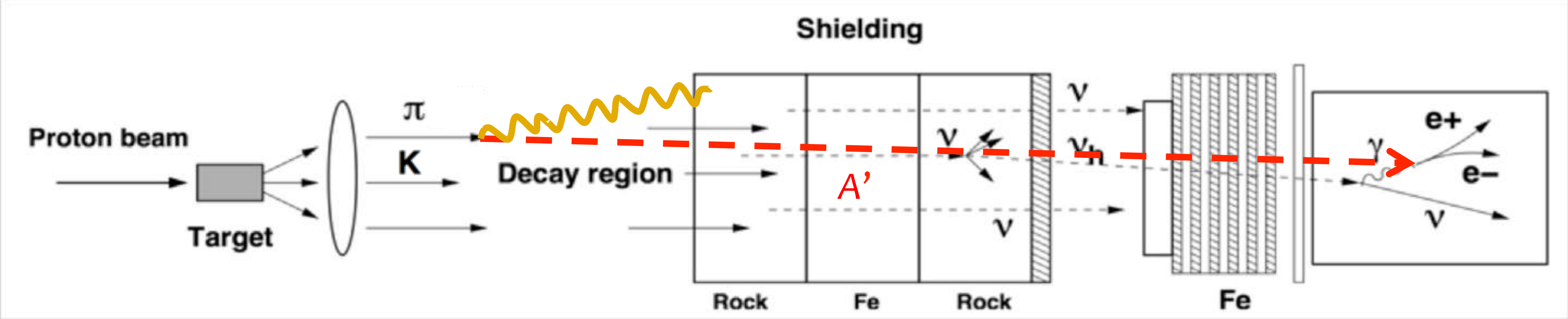


Scatter plot of the angular distribution of candidate events. Only the bold-faced point has energy >3 GeV; the triangular point has energy >2 GeV, but unambiguously does not point toward the dump. The three points apparently emergent from below the horizon are actually cosmic rays entering the detector from the rear.

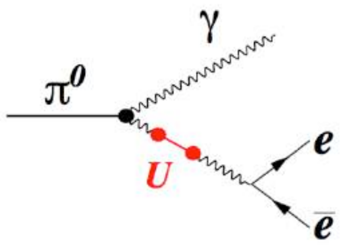
Limits from electron beam-dump experiments



Limits from proton beam dump experiments



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



Limits from past experiments: proton beam dump

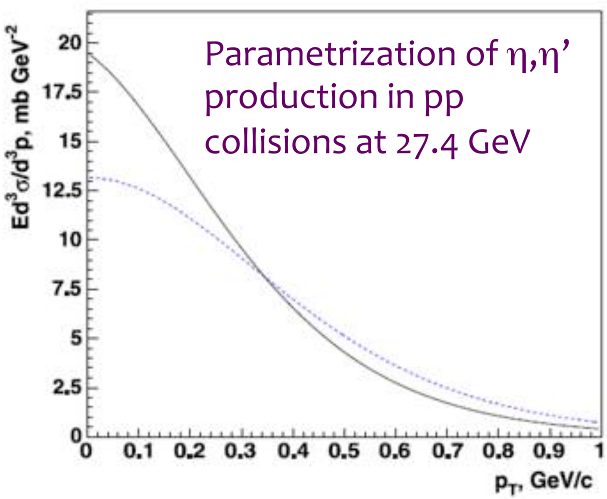
CHARM: $\nu_H \rightarrow \nu e^+e^-$ from π,K, D decays
$2.4\cdot10^{18}$ POT
Look for $\eta,\eta' \rightarrow \gamma A'$

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

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

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

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)

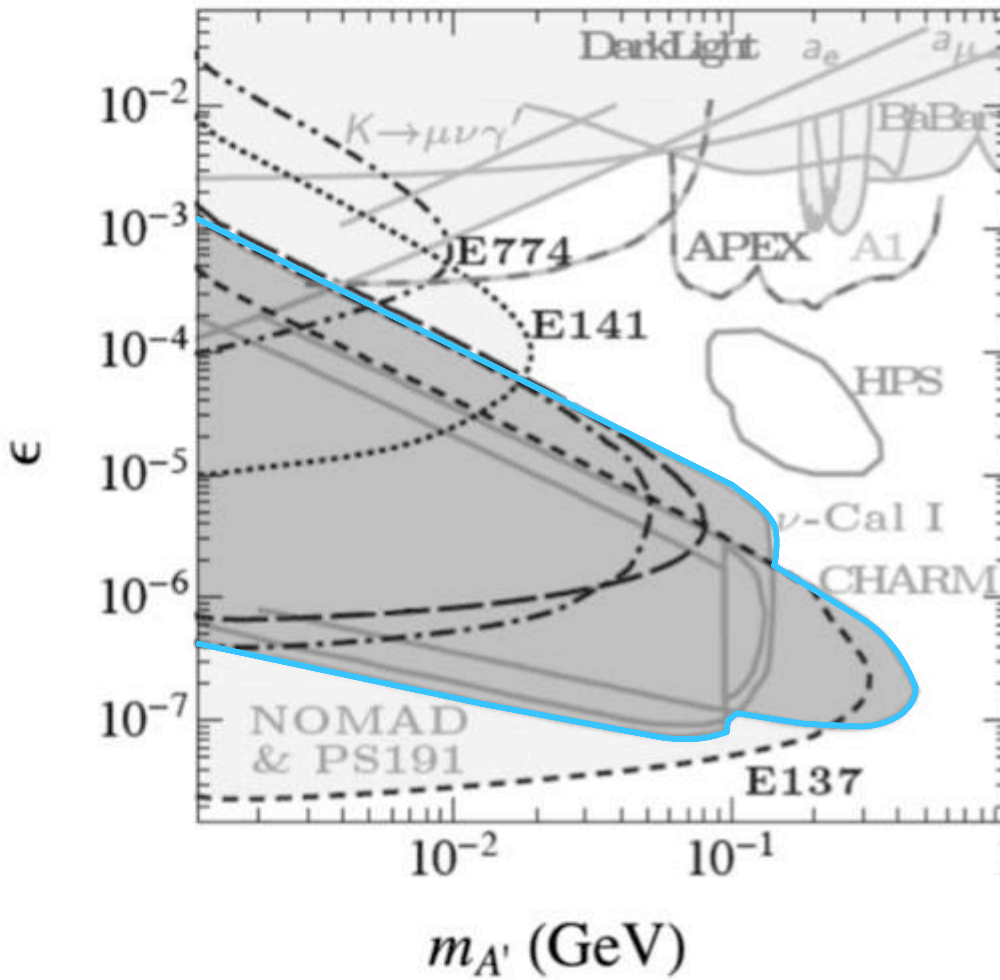
INFN

Limits from past experiments: proton beam dump

NOMAD and PS191 looked for heavy neutrino $\nu_H \to \nu e^+e^-$
Look for $\pi^0 \to \gamma A'$

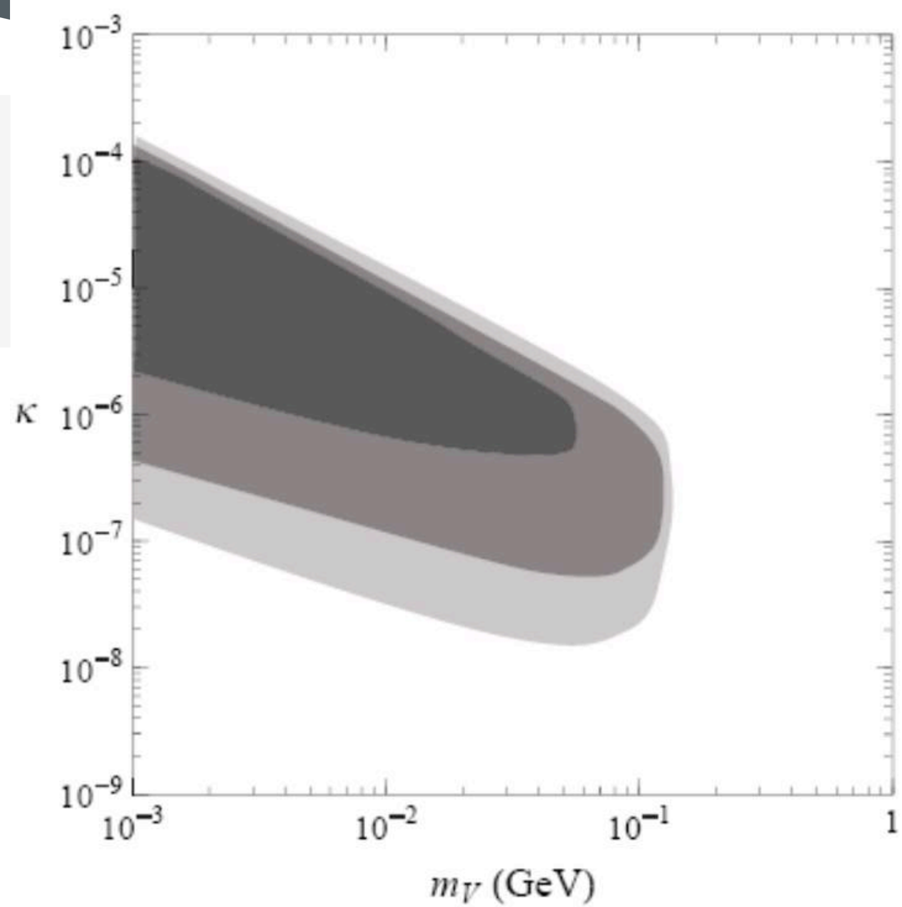
NOMAD: **$4.1 \cdot 10^{19}$ POT**
E>4 GeV, m_{ee}<95 MeV
PS191: **$0.89 \cdot 10^{19}$ POT**

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



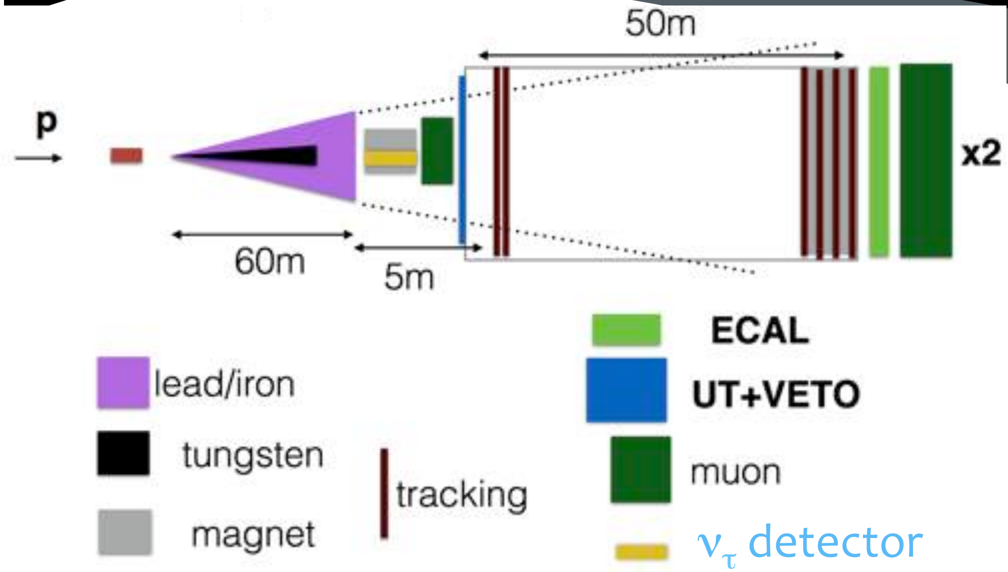
Limits from past experiments: proton beam dump

LSND: looked for heavy neutrino $\nu_H \rightarrow \nu e^+e^-$
Look for $\pi^0 \rightarrow \gamma V \rightarrow \gamma e^+e^-$
Energy ~ 800 MeV
10^{23} POT, 10^{21} π^0



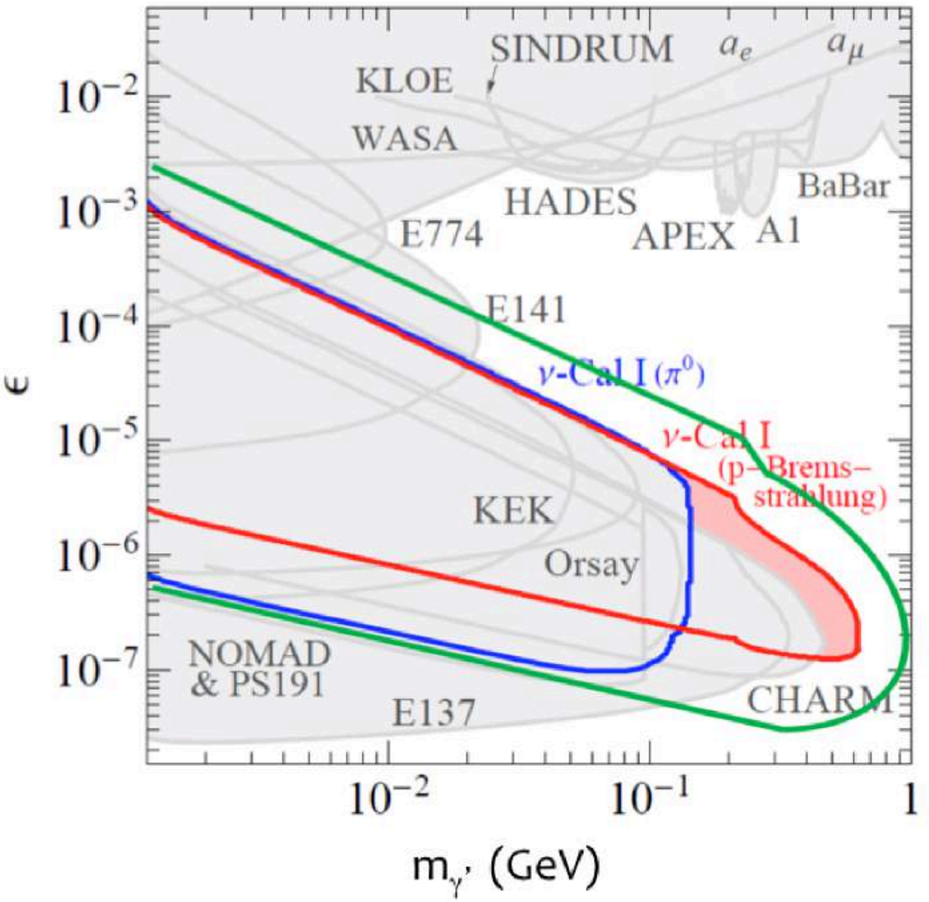
Nota bene:
Different naming in literature:
$\varepsilon = \kappa = \alpha'/\alpha$, sometimes χ
$\alpha = \varepsilon^2/4\pi$

Possible future proton beam dumps: SHIP at SPS

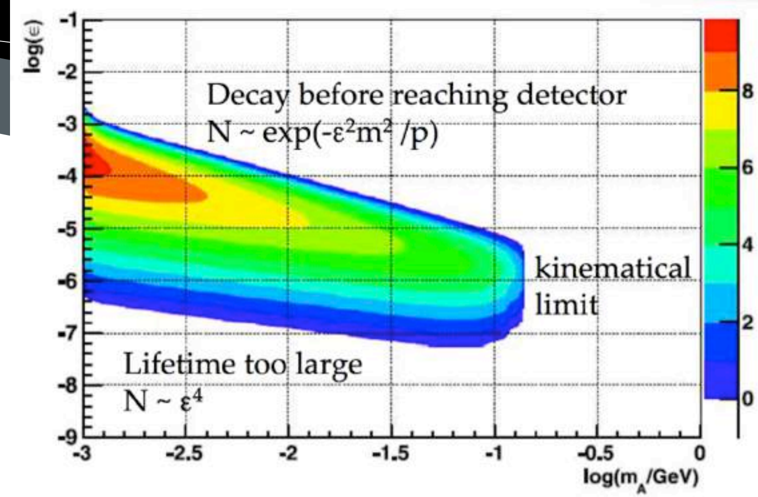


	Charm	PS191	NOMAD	NuCal	SHIP
BeamEnery	400 GeV	19.2 GeV	450 GeV	70 GeV	400 GeV
p.o.t.	$2.4\ 10^{18}$	$8.6\ 10^{18}$	$4.1\ 10^{19}$	$1.7\ 10^{18}$	$2.0\ 10^{20}$
Distance	480m	128m	835m	64m	60m
Detector	35m	12m	7.5m	23m	160m
Radius	1.5m	1.5m (?)	1.8	1.3m	2.5m

Possible future proton beam dumps: SHIP at SPS

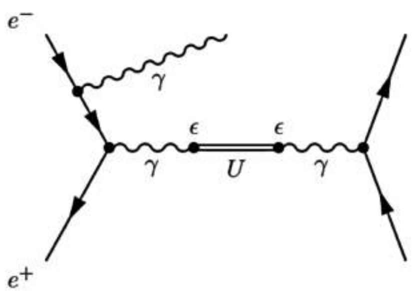


10 signal events

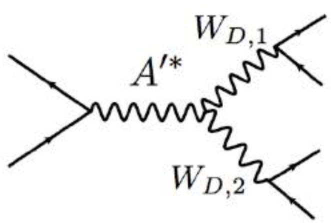


J. Brunner

Limits from e^+e^- colliders

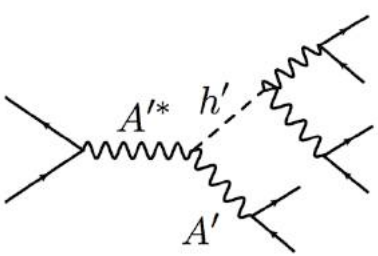


Dark photon decaying to lepton pair
At KLOE, also $\Phi \rightarrow \eta\gamma^* \rightarrow \eta U \rightarrow \eta\gamma^* \rightarrow \eta\ l^+l^-$



$4e, 4\mu, 2e + 2\mu$

Non-Abelian hidden sectors
(many gauge bosons)



$2\ell, 6\ell$

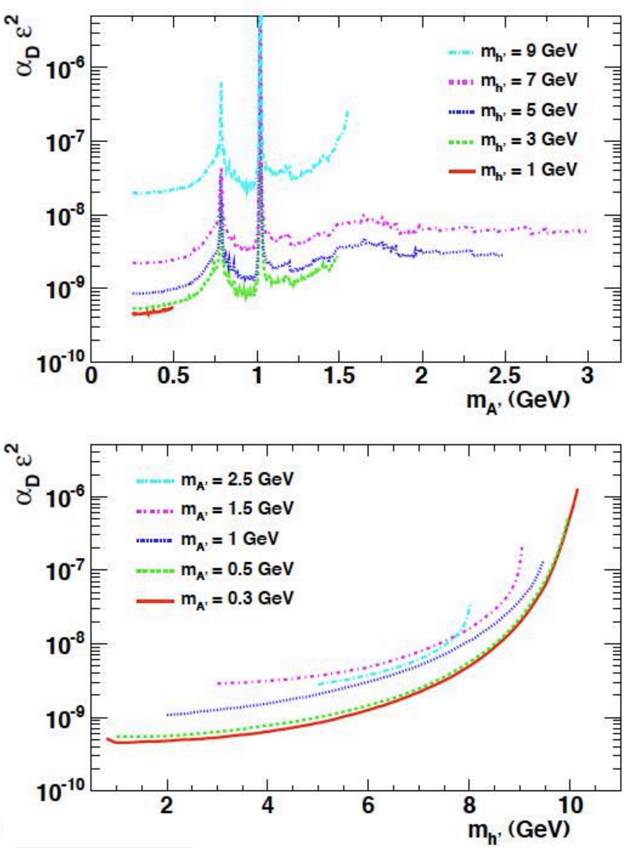
Light hidden-sector Higgs boson

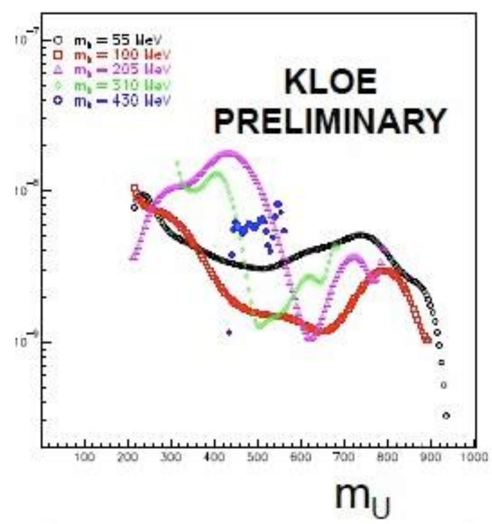
Dark sector with dark Higgs

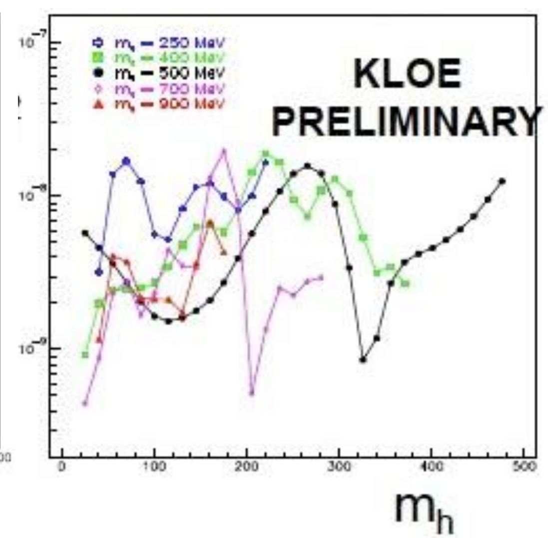
* Model assumes the existence of an elementary dark Higgs *h'* boson, which spontaneously breaks the U(1) symmetry. **PRD 79, 115008 (2009)**
* U boson can be produced together with a dark Higgs *h'* through a Higgs-strahlung $e^+e^- \to Uh'$
  * Cross section =20 fb × $(\alpha/\alpha_{dark})(\varepsilon^2/10^{-4})(10\text{GeV})^2/s$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

Experimental status U(1) + dark Higgs

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

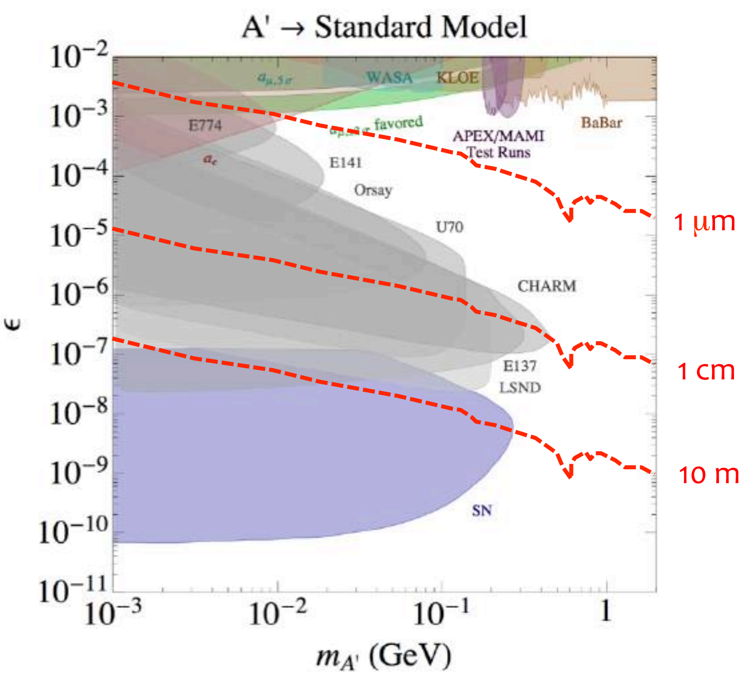




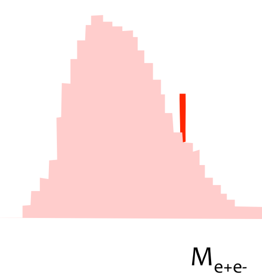


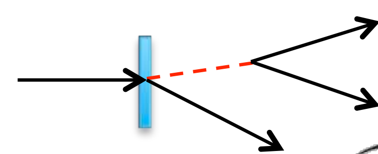
* No data available below 200 MeV in m_U
* PADME can provide sensitivity in unexplored parameter region.

From beam dump to thin target

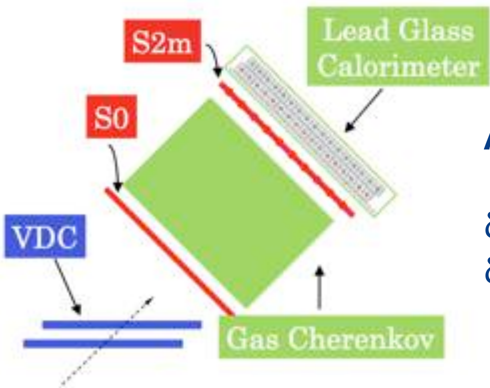


- Unexplored regions in parameter space correspond to **shorter *U* lifetimes**
- Experiments need to use a **thin target** and **close detectors**
  - huge SM background!
- Two possible techniques:
  - Bump hunting
  - Displaced vertex



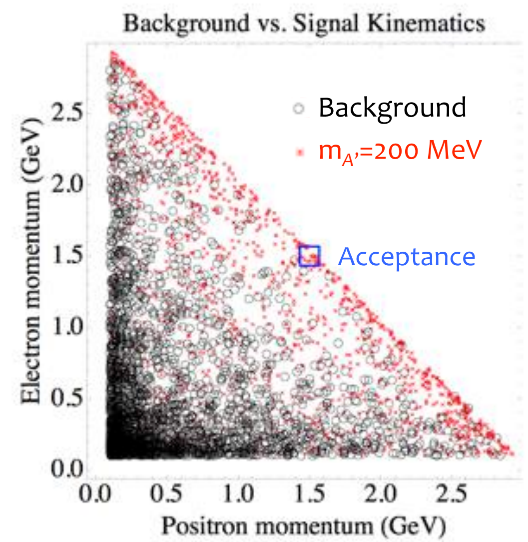


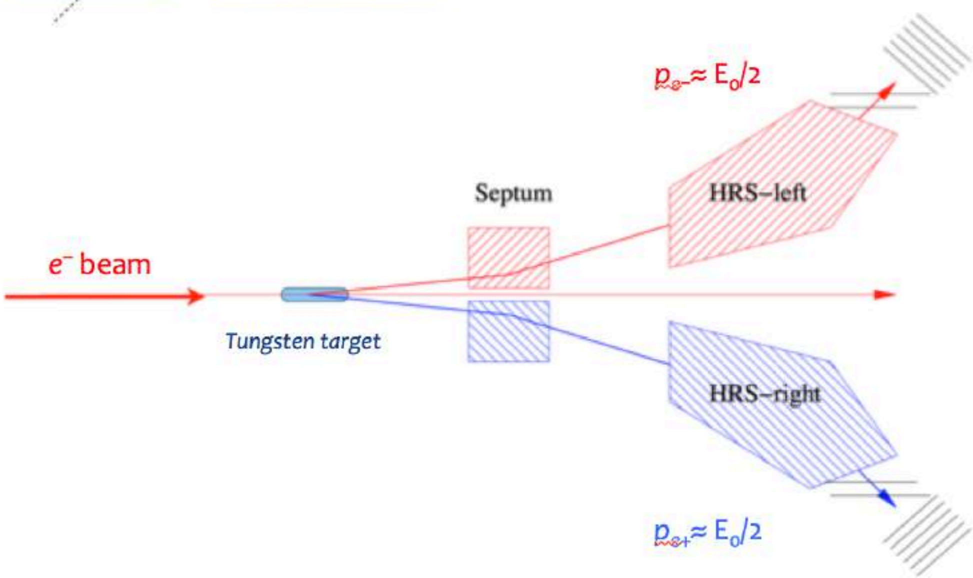
First generation thin target experiment: APEX at JLAB

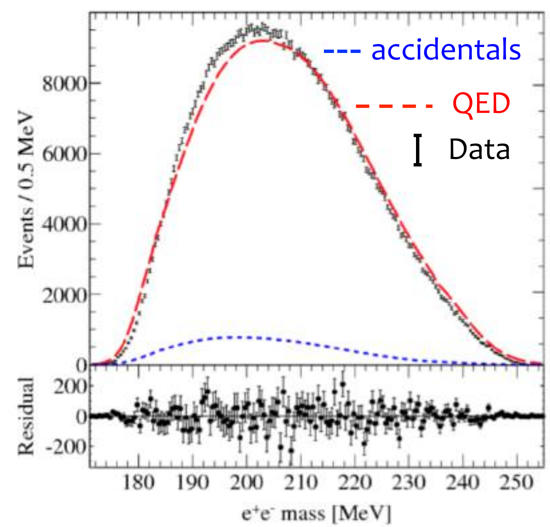


Acceptance=4.5 msr

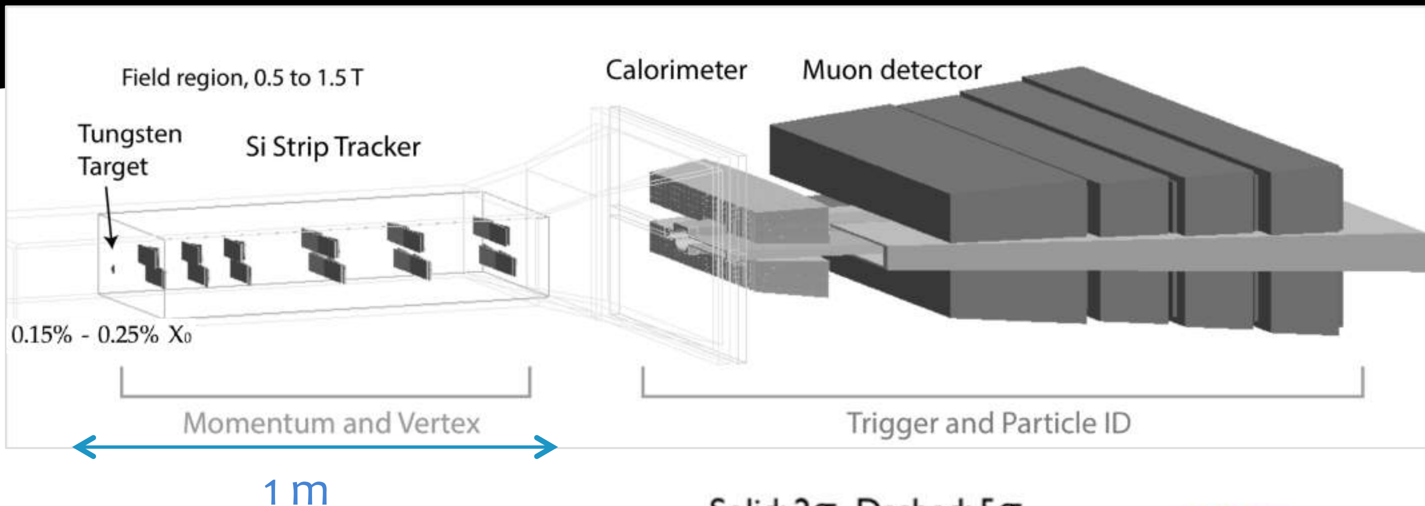
$\delta p/p < 2\times10^{-4}$
$\delta\phi$=0.5 mrad, $\delta\theta$=1 mrad



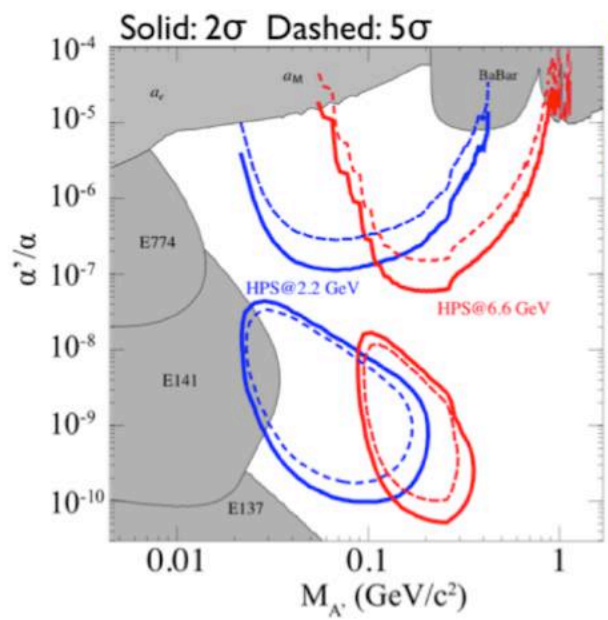




Thin target experiments: HPS at JLAB



* High rate
* High acceptance
* Excellent mass & vertex resolution
* Use Jefferson Lab e⁻ beam in Hall B.
* Commissioning in 2014
* Ready to get data in 2015



Thin target experiments

Bremsstrahlung conversion in target $\approx T^2$
$\langle\theta\rangle_{MS} \approx T^{1/2} E_0$
$N_{\gamma'} \approx T$

Running or coming soon:

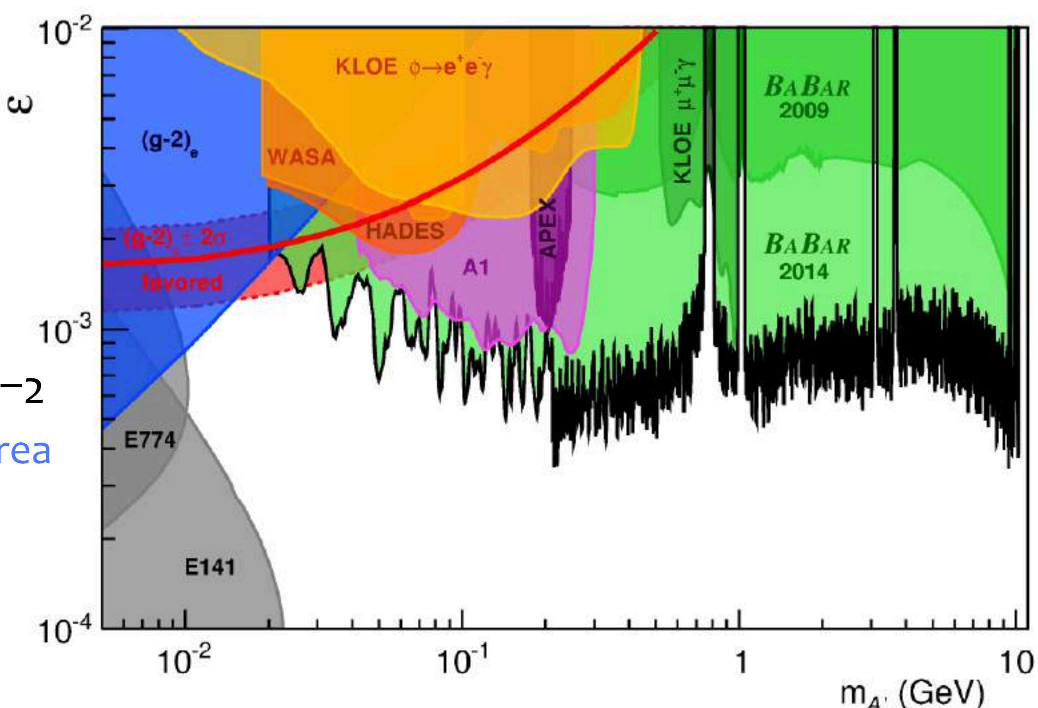
* APEX at JLAB Hall-A, test run done, full run coming
* A1 at MAMI
* HPS at JLAB Hall-B, test run done, full run coming

Proposed:

* DarkLight at JLAB FEL (electron on gas jet target)
* P-348 at CERN SPS (thin-thick)
* VEPP3 (electron on gas jet target)
* PADME

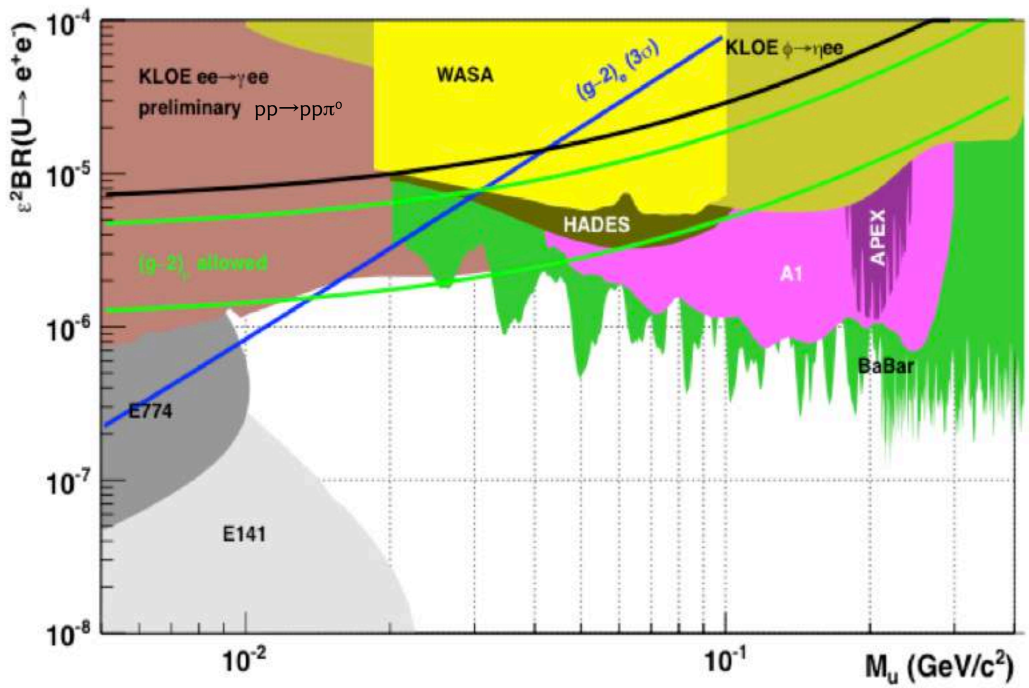
Summary of existing contraints on *U*

* Favored parameters values explaining g−2
  * U-boson light: 10-100 MeV
* Dark photon experiments
  * Beam dump experiments (grey)
  * Fixed target (thin)
    * Peak search in BG
  * Mesons decays
    * Peaks in M(e+e-) or M(μ+μ−)
* Indirect exclusion from g_e-2, $g_\mu-2$
  * Recent tight limit in blue filled area

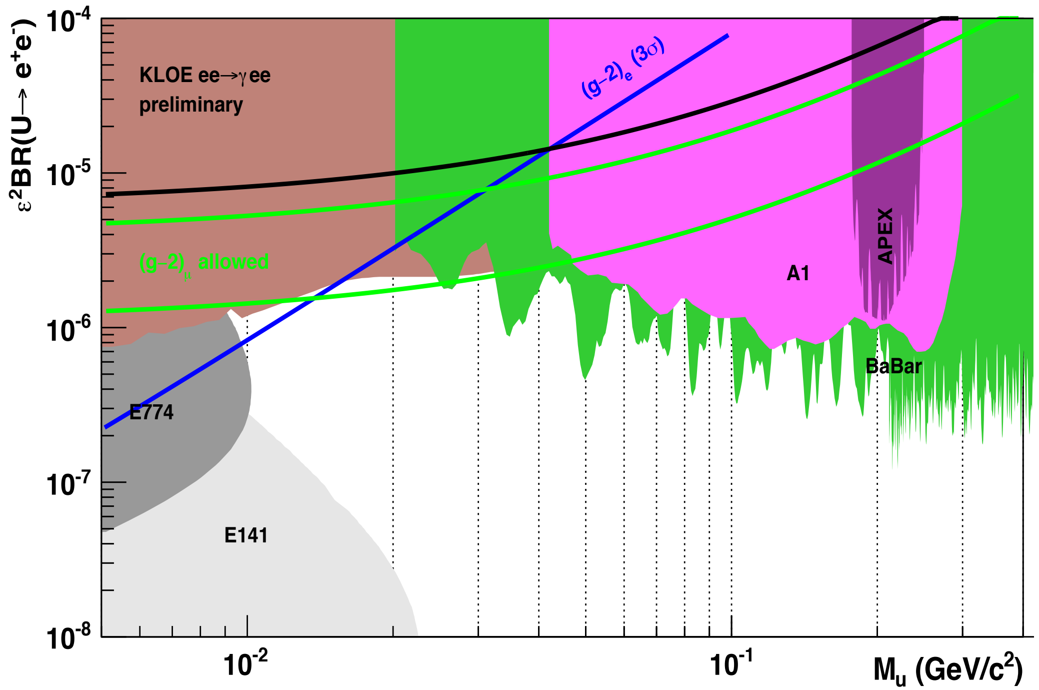


Many different techniques, assumptions on dark photon interaction models

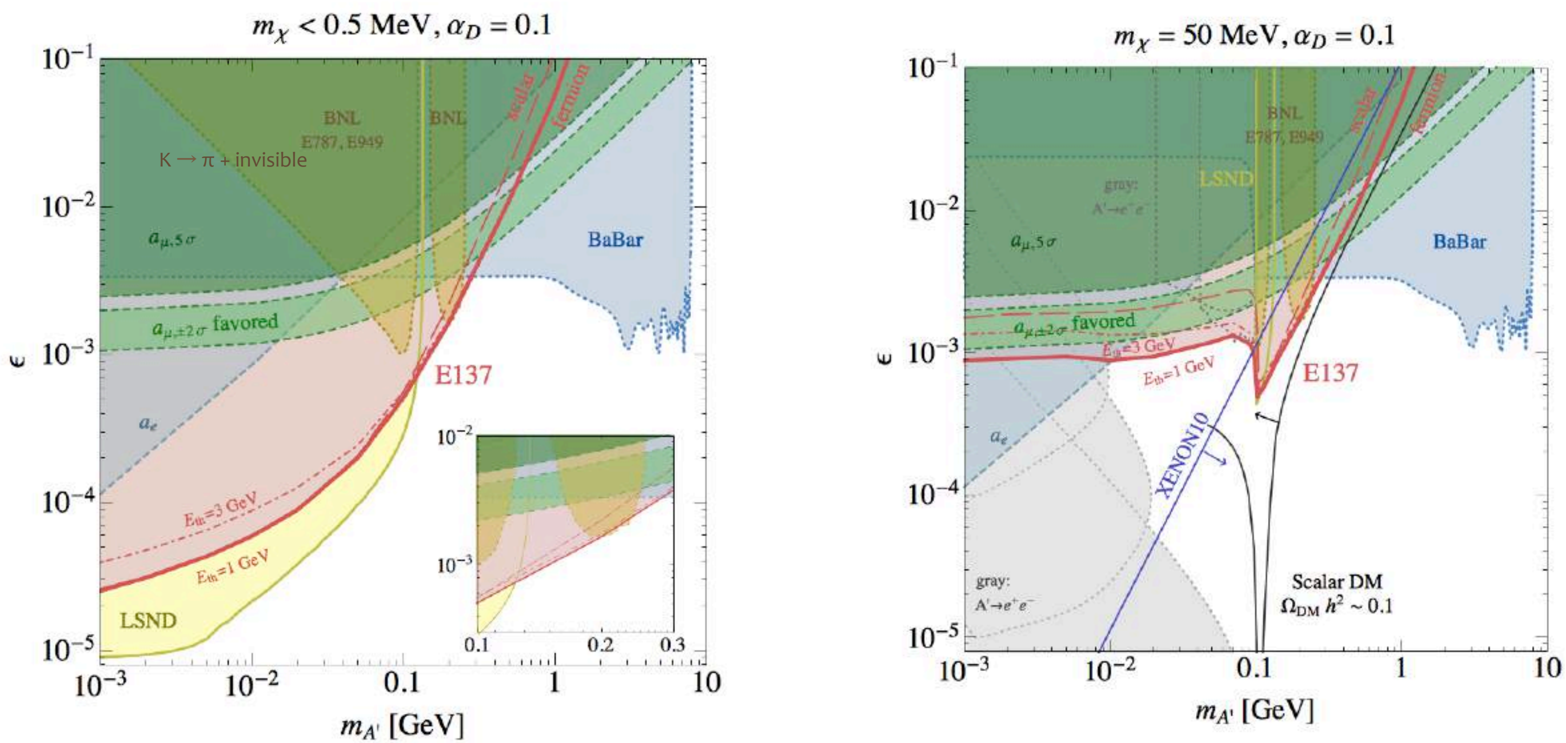
$\varepsilon_q \neq 0$ and $U \rightarrow e^+e^-$



$\varepsilon_q=0$ and $U \rightarrow e^+e^-$

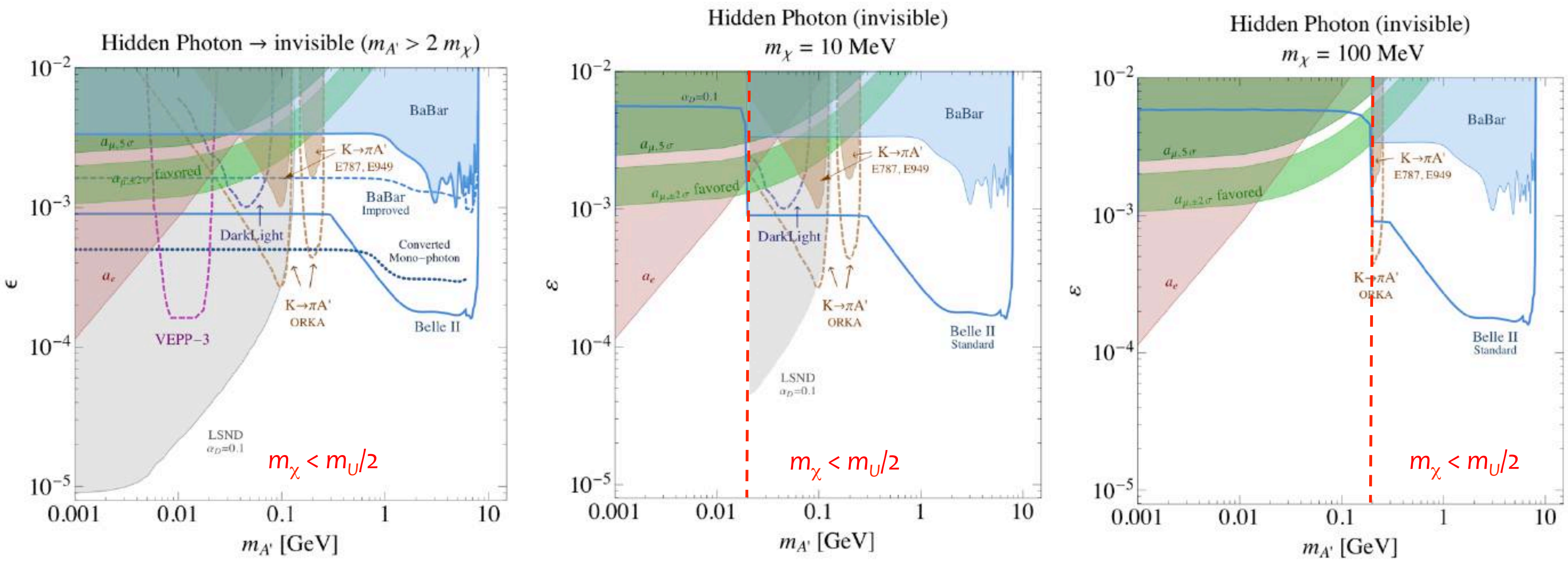


Visible decays suppressed by U→ χχ

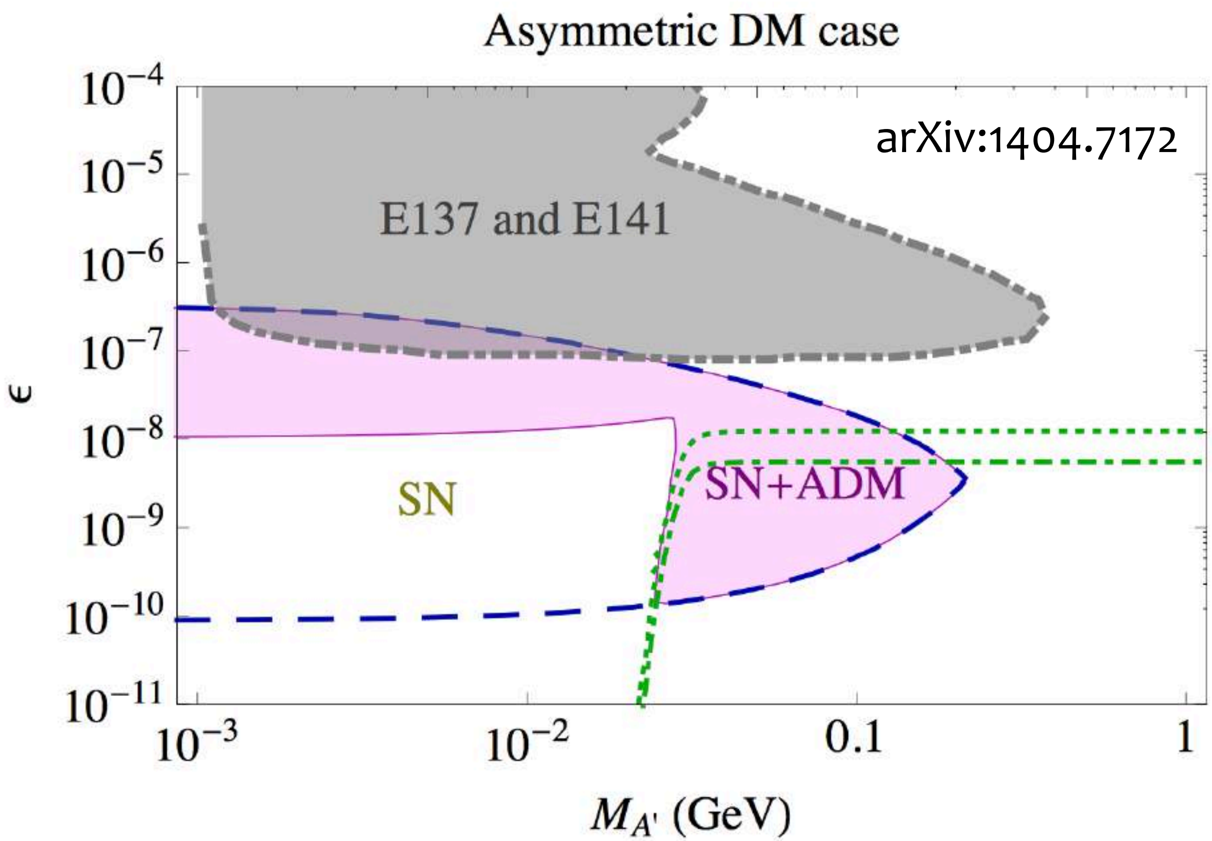


arXiv:1406.2698v1

Visible decays suppressed by U→ χχ

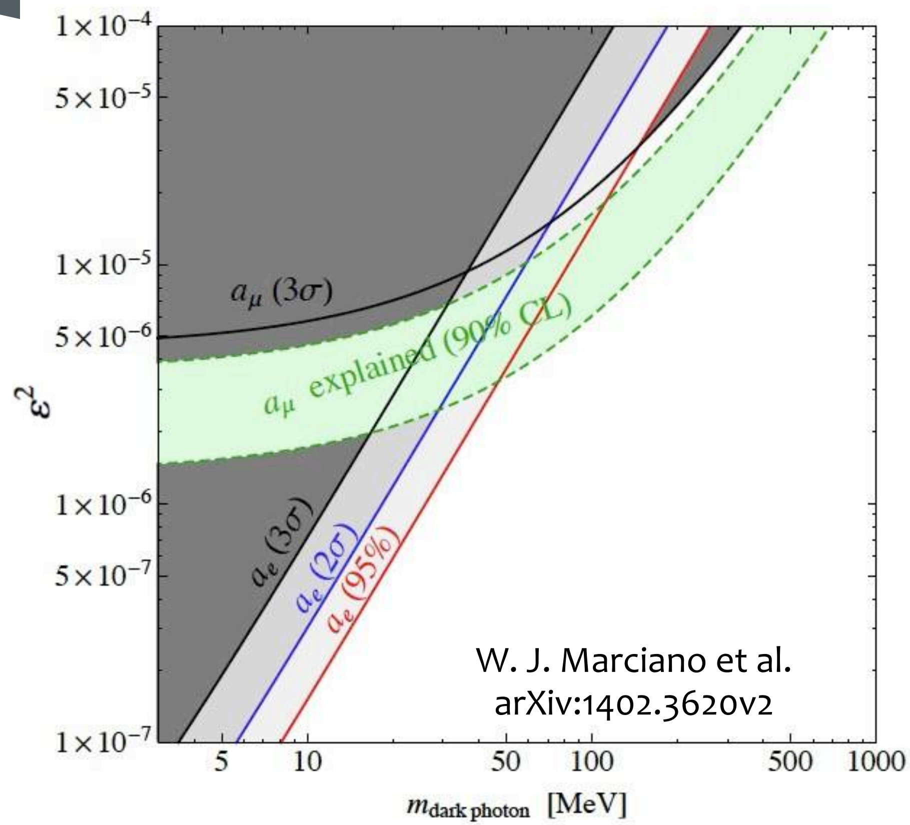


SN limits suppressed by DM



Dark photon invisible decays

- In this scenario U boson keeps the characteristics to explain positron excess, g−2
- The invisible search technique remove **any assumption** except **coupling to leptons**
- U boson increase its capability of having escaped detection so far
- Practically no data in the minimal assumptions

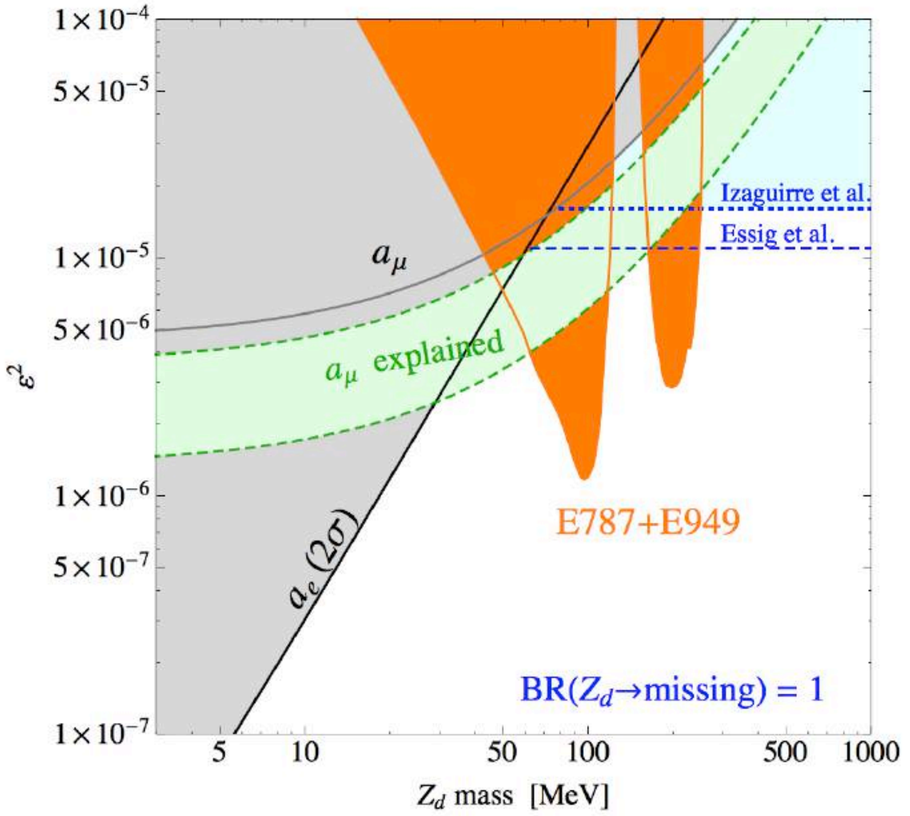


W. J. Marciano et al.
arXiv:1402.3620v2

PADME

Dark photon invisible decays

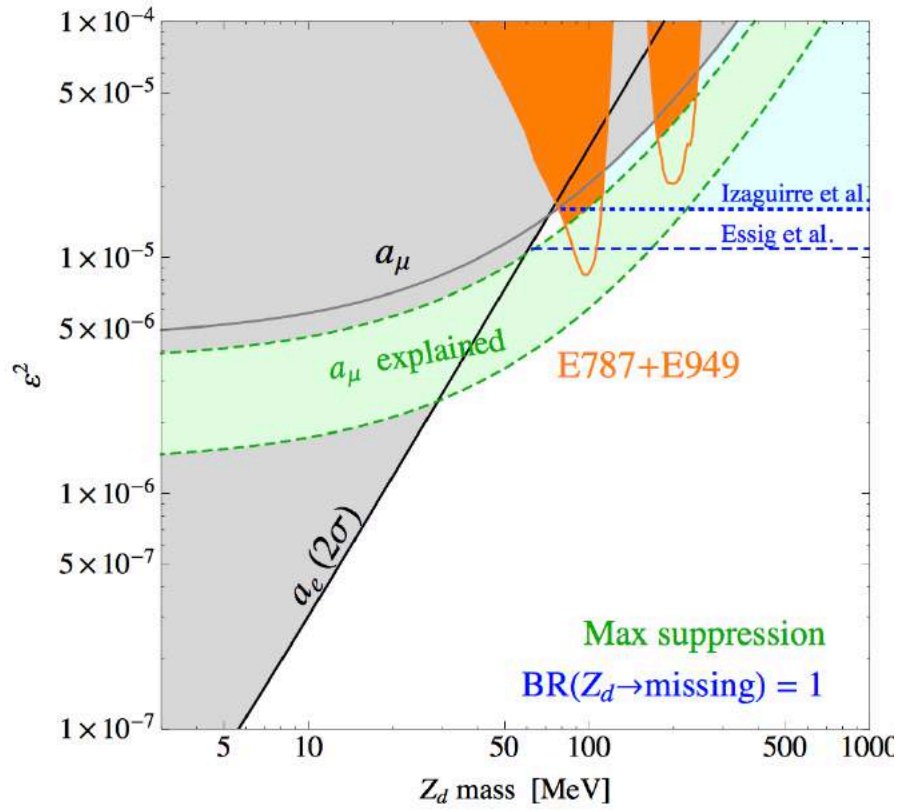
- At present there are very few experimental limits for the *U* invisible decays:
  - **arXiv 0808.0017:** Babar '08 (unpublished) with very limited sensitivity on ε^2 ($\Upsilon_{3S} \rightarrow \gamma U$ **assumes coupling to quarks**)
  - **arXiv:1309.5084v1:** Indirect limit fromE787+E949 $K^+ \rightarrow \pi^+ \nu\nu$ (**assumes coupling to quarks**)



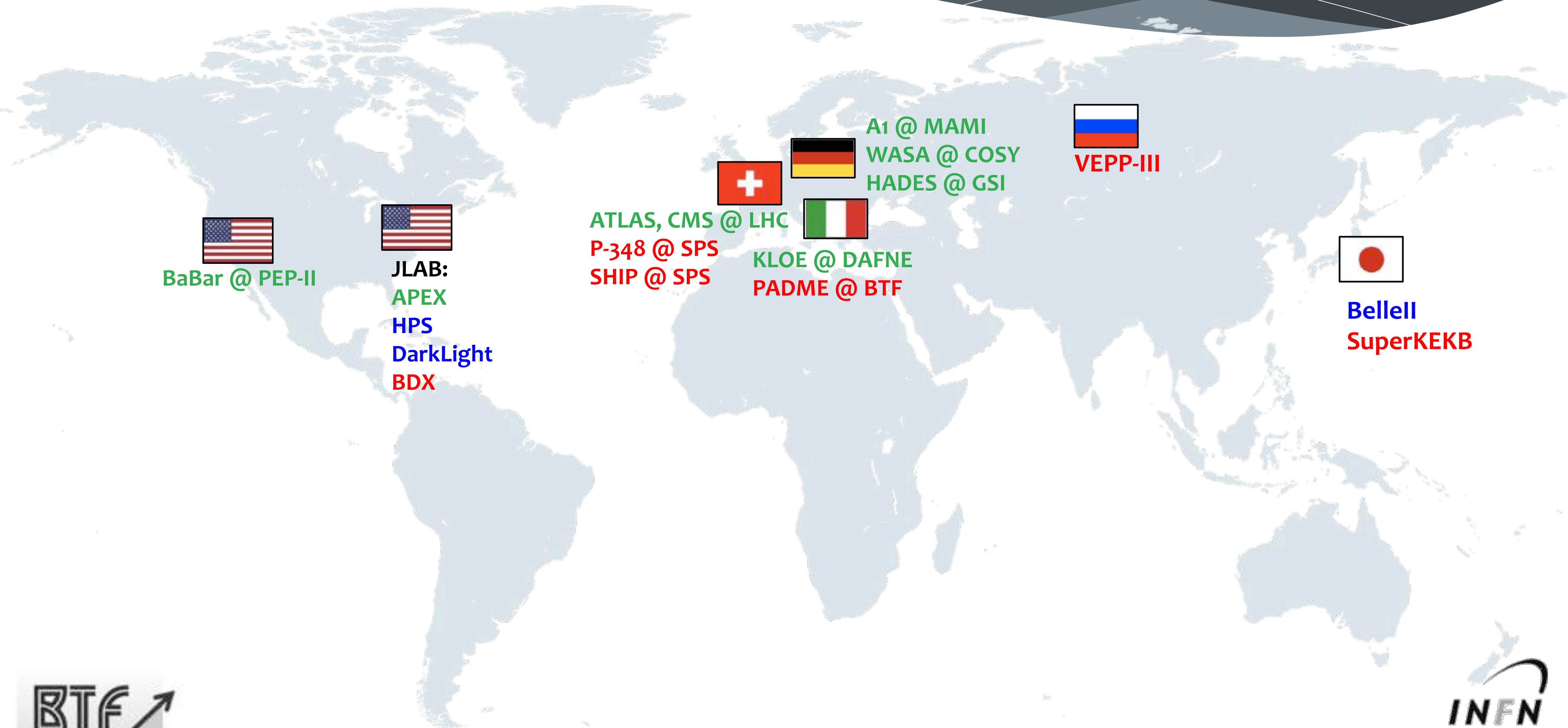
Dark photon invisible decays

* If we complicate the simple *U* boson model, these limits get even weaker, e.g. adding a dark Z

arXiv:1402.3620v2



Map of *hidden photon searches*

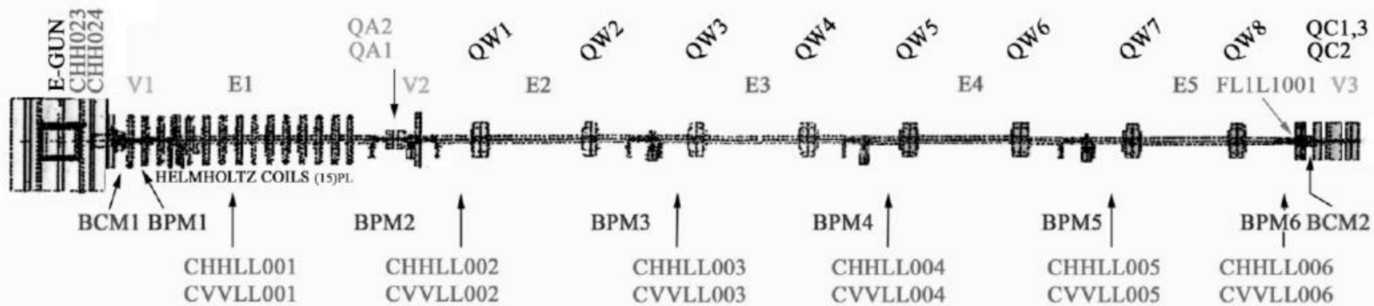


Status: publishing, approved, proposals

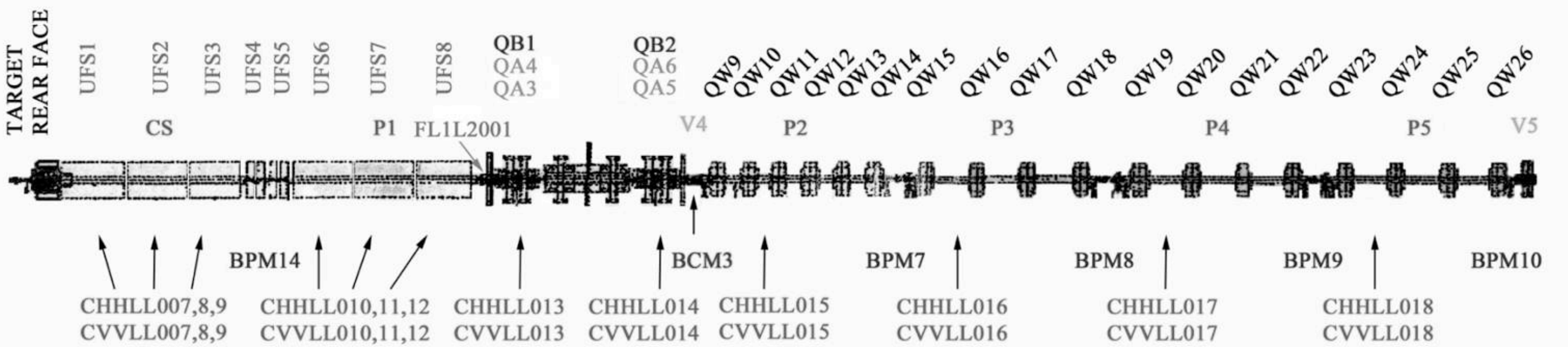
DAFNE linac and beam-test facility

PADME

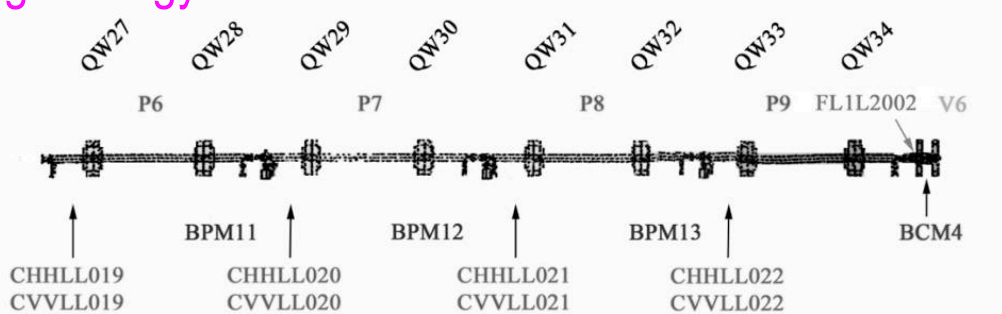
DAFNE linac



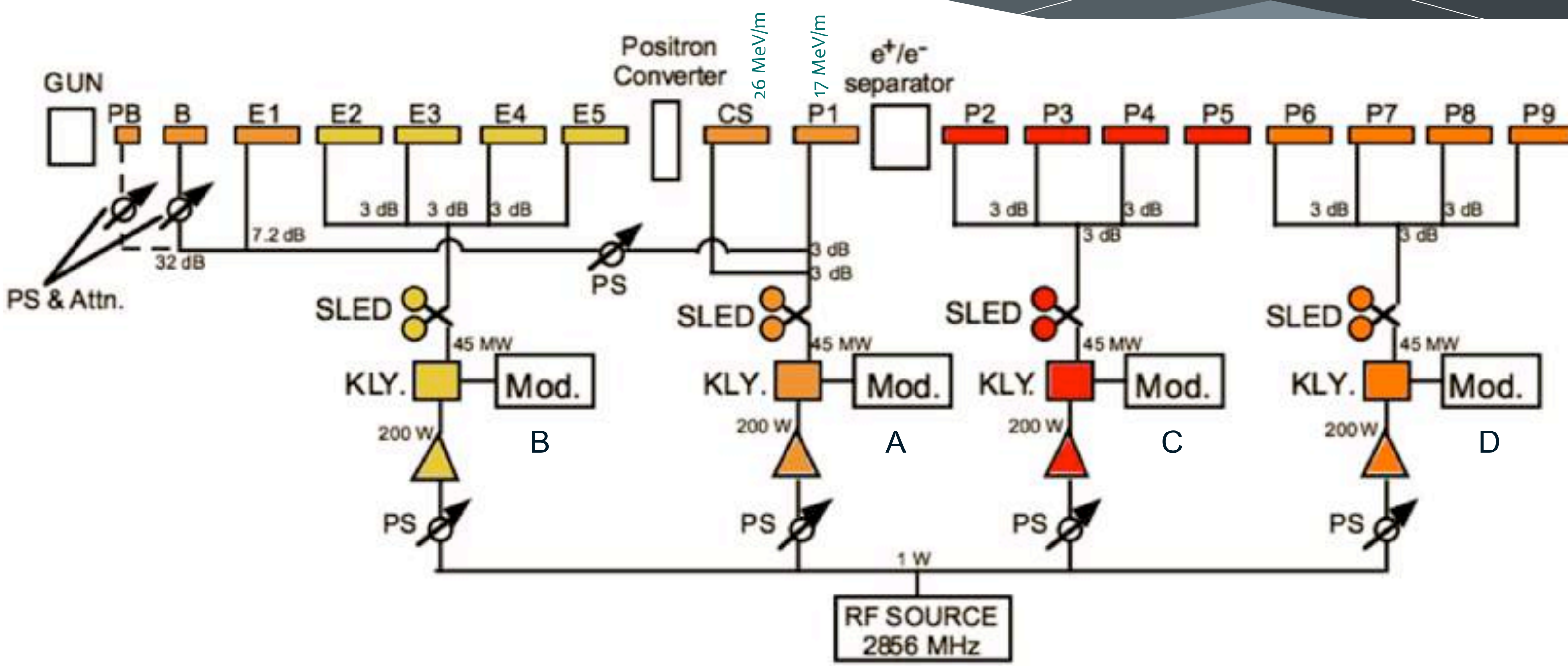
High current



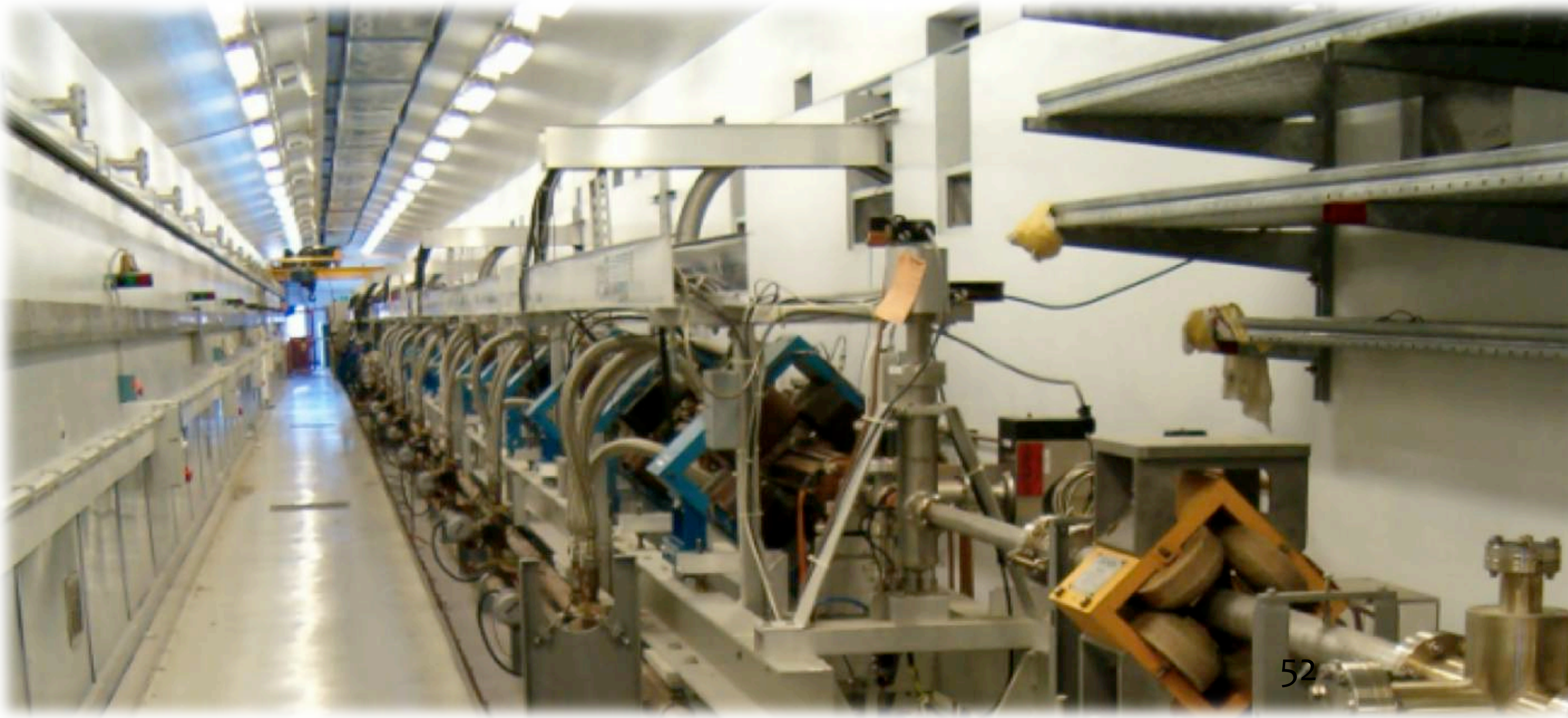
High energy



RF layout



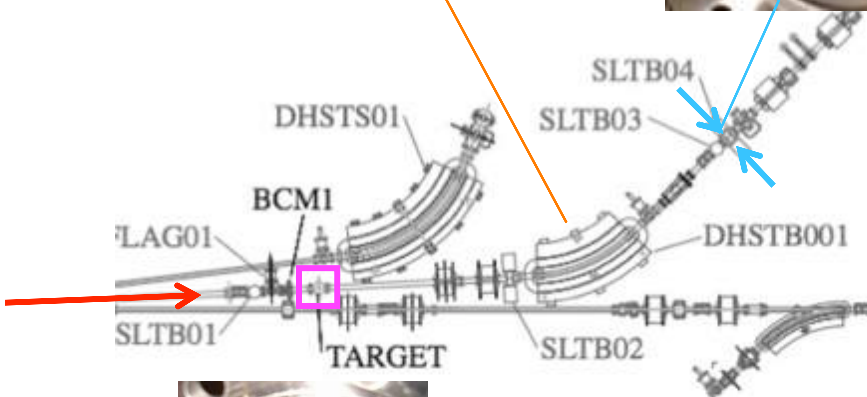
RF frequency	2856 MHz
Accelerating structure	SLAC-type, CG, 2π/3
RF source	4×45 MWp SLED-ed klystrons TH2128C

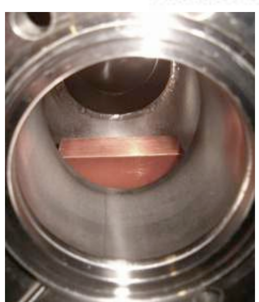


BTF beam attenuation and energy selection

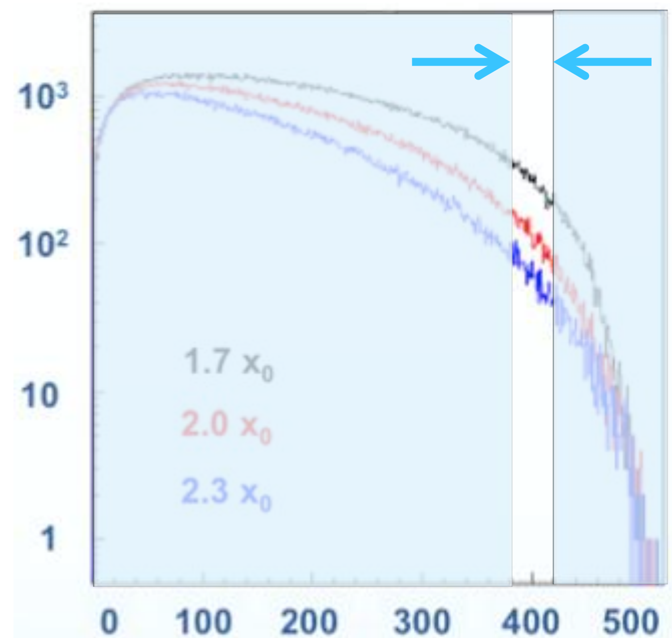
42° momentum selection dipole

Tungsten collimators



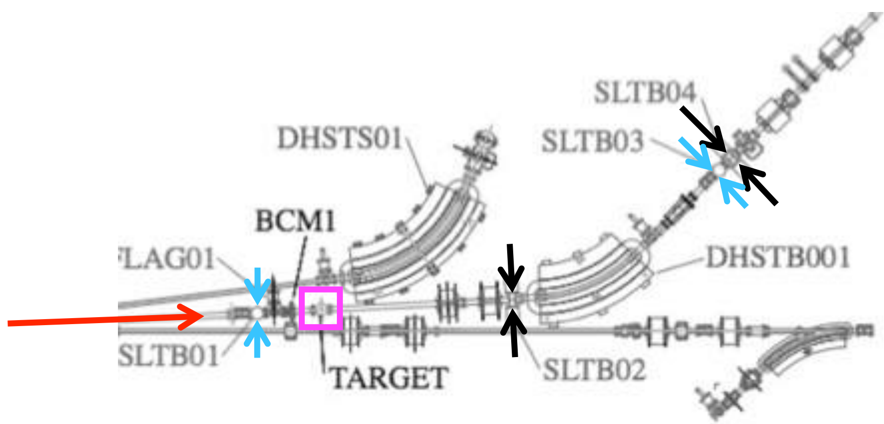


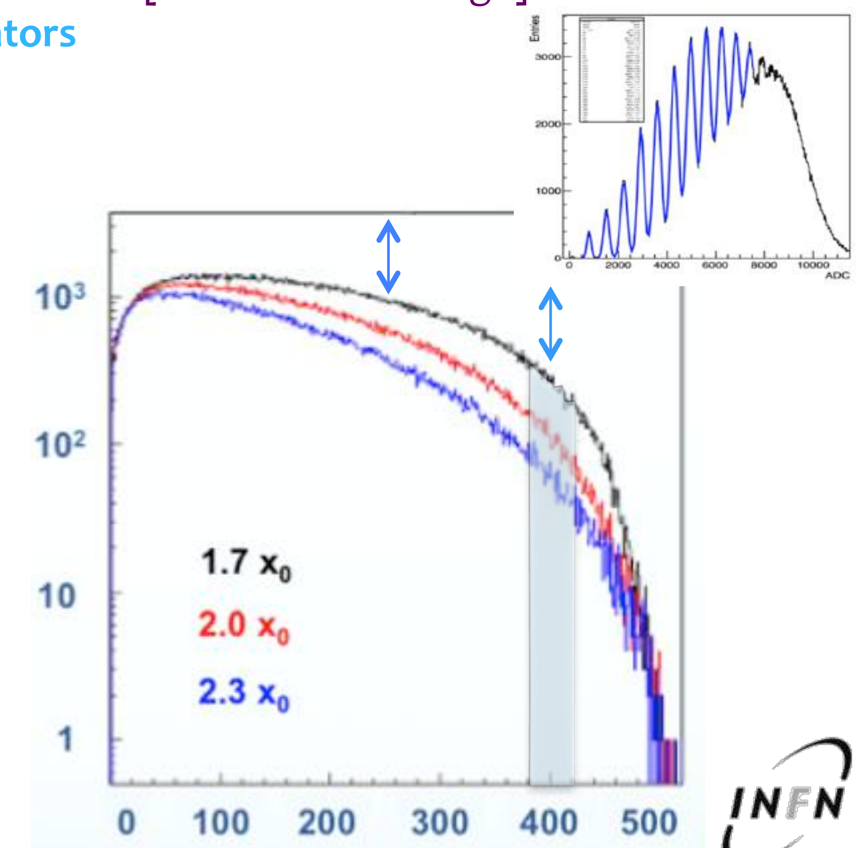
Variable depth
copper target



Adjustment of the number of particles can be achieved:

- Without changing the momentum resolution:
  - **Modulating** the linac **current** [not possible in 'parasitic mode', very rough]
    - Act on gun parameters, transport optics or modulators power/phase
  - Choosing another **target depth** [step change but reproducible]
  - Closing/Opening the **down-stream vertical collimators** [fine but small range]
  - Closing/Opening the **up-stream vertical collimators**
- Also changing the momentum resolution:
  - Closing/Opening the **horizontal collimators**





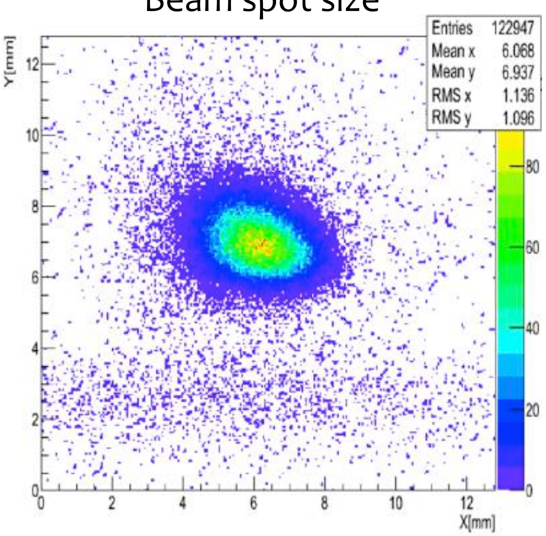
BTF operating modes

- Starting from 10^7-10^{10}(10^9) electrons (positrons) from the DAFNE LINAC, with E_{max}=550/750 MeV and Δt=1.5-40 ns, it operates mainly in **two different intensity regimes**:
  - **High intensity:** primary beam driven to the experimental hall, between 250 MeV and E_{max}, tuned with collimators
  - **Single particle/bunch** (Poisson distribution) between few tens of MeV and E_{max}, created intercepting the beam with a variable depth copper target, **selecting the energy** and **collimating**.
- **Intermediate** intensity (<10^5 particles/bunch) is possible
- Primary beam fixed to E=**510 MeV** and Δt=**10 ns** during operations of DAFNE collider

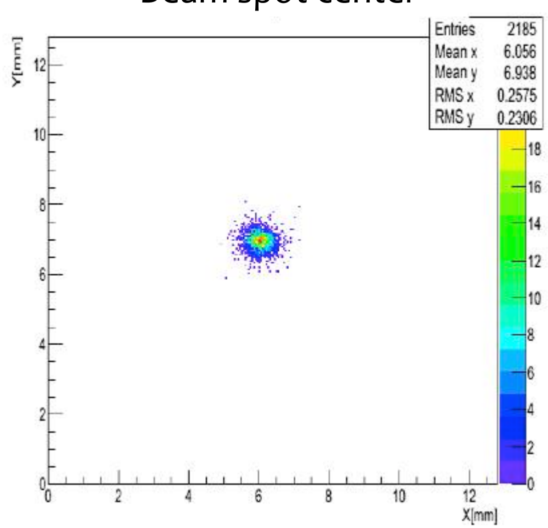
BTF beam

- 10^4 positrons of energy 550 MeV per bunch in 49 pulses/s
- Total e^+ on target per year: $50*10^4*3.15\ 10^7 = 1.6\ 10^{13}$ (we use 10^{13})
- Beam energy spread ~1% (linac and BTF can do better)
- RMS of beam spot 1 – 2 mm and emittance 1mm*mrad
- Beam position RMS 0.3 mm
- Bunch duration 10 ns (can already go up to 40ns)

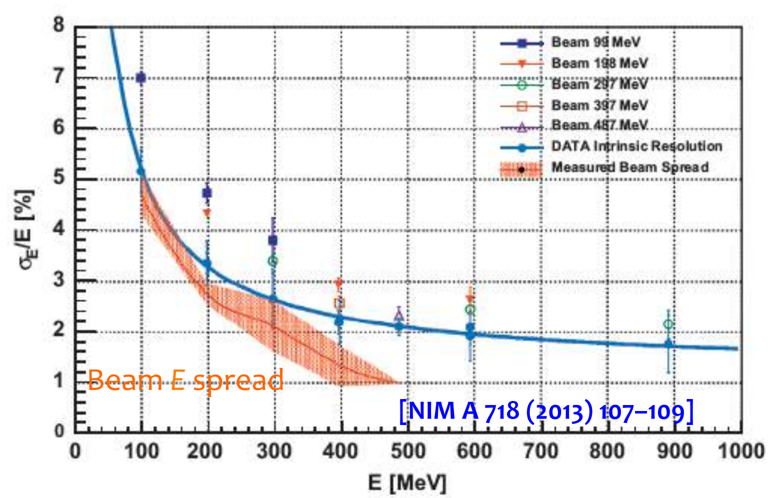
Beam spot size



Beam spot center



Measurement of the beam *E* spread

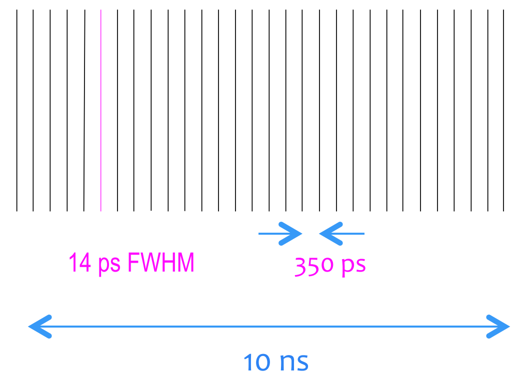


Linac pulse

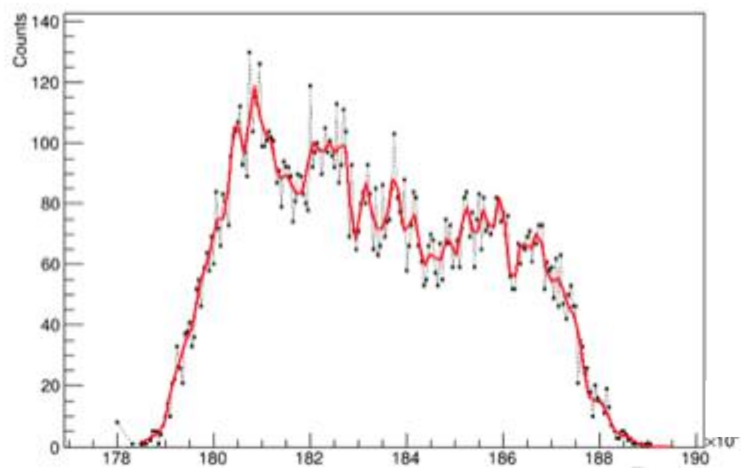
0.5 nC = 50 mA average current
(can be pushed a lot…)
10^8 electrons × about **30 micro-bunches**

25 Hz typical repetition rate
50 Hz maximum

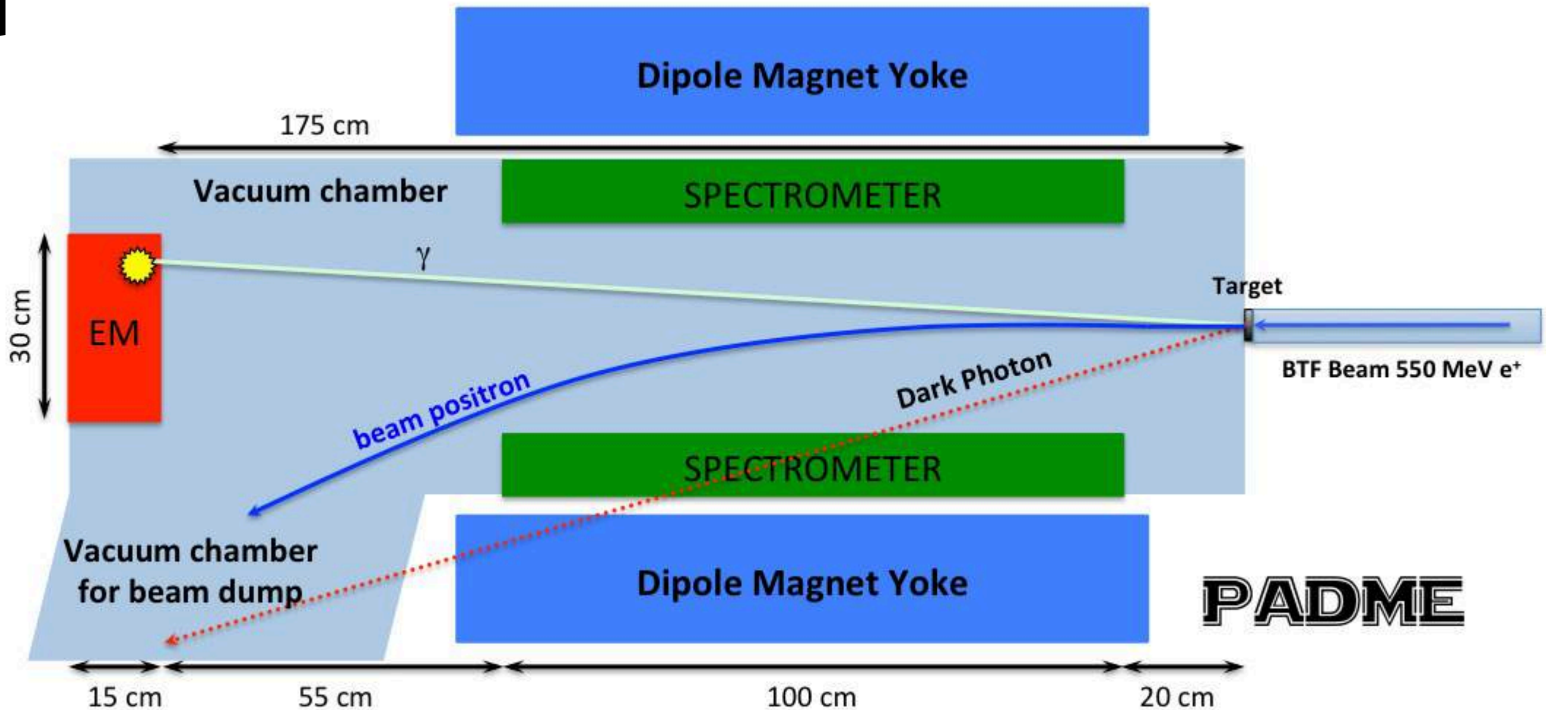
1 pulse/s sent to a **spectrometer** line
for energy monitoring
(45° dipole + metallic strip detector)



Real time structure of pulse
(diamond detector: micro-bunch structure convoluted with detector resolution, trigger jitter…)

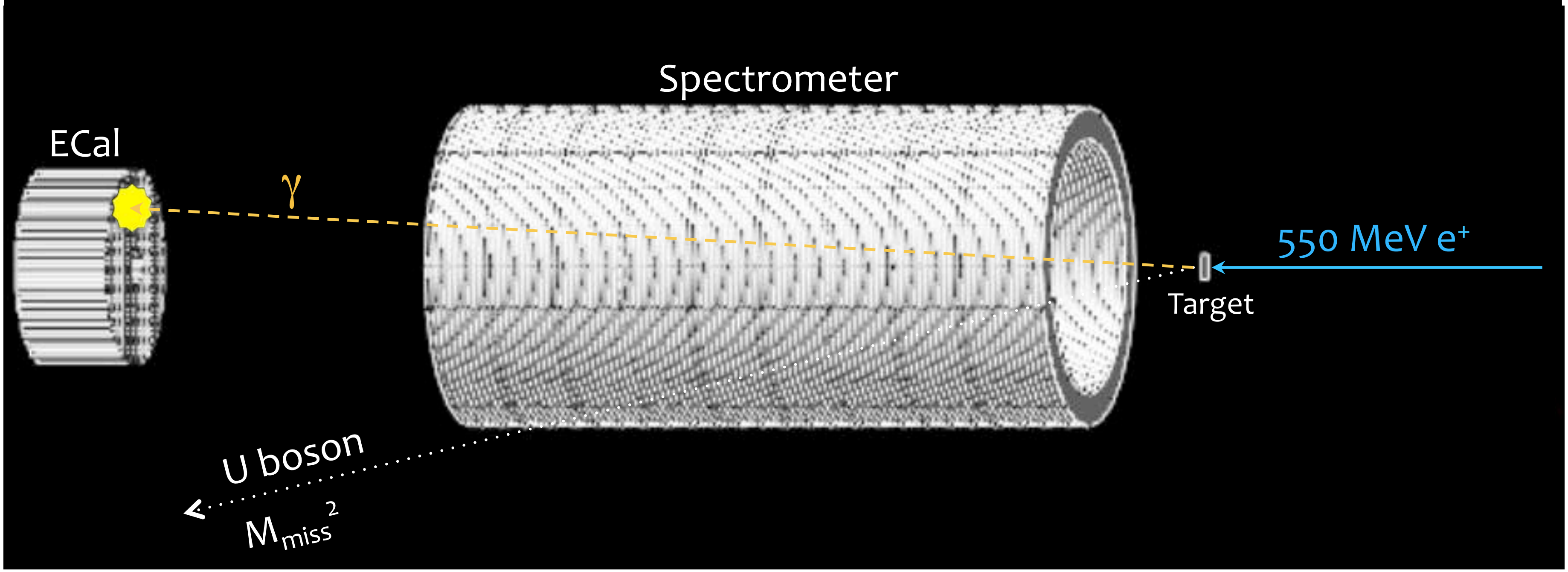


PADME setup concept



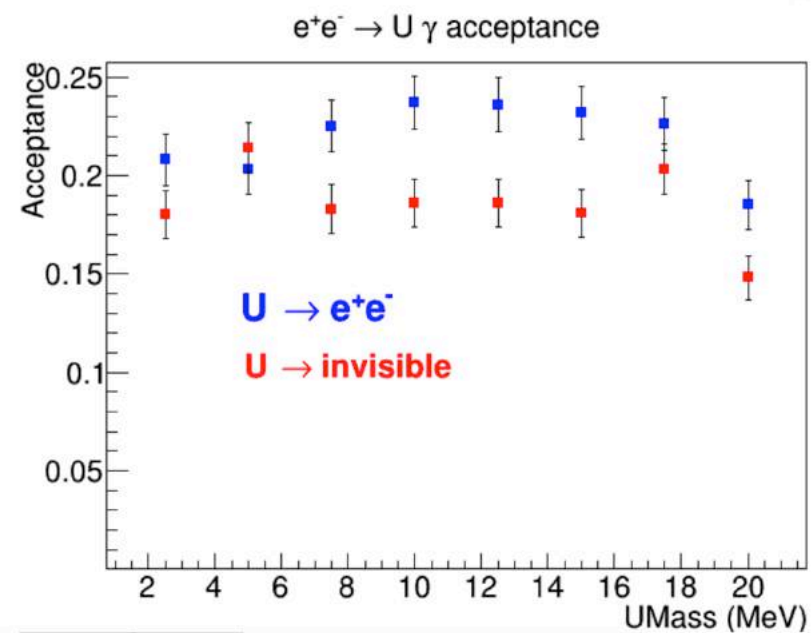
* Active 50μm diamond target (T=2.5 10^{-4})
* Magnetic spectrometer ~1m length
* Conventional 0.6T magnet
* 15 cm radius pseudo cylindrical LYSO calorimeter with 1x1x15 cm crystals

Search in annihilation production



* Search for the process: $e^+e^- \rightarrow \gamma U$
* 550 MeV positron beam on a 50 μm diamond target
* Measure in the ECal the E_γ and θ_γ angle wrt to beam direction
* Compute the $M_{miss}^2 = (P4_{e-} + P4_{beam} - P4_\gamma)^2$
    * $P4_{e-} = (0,0,0,m_e)$ and $P4_{beam} = (0,0,550,\mathrm{sqrt}(550^2 + m_e^2))$

Signal selection

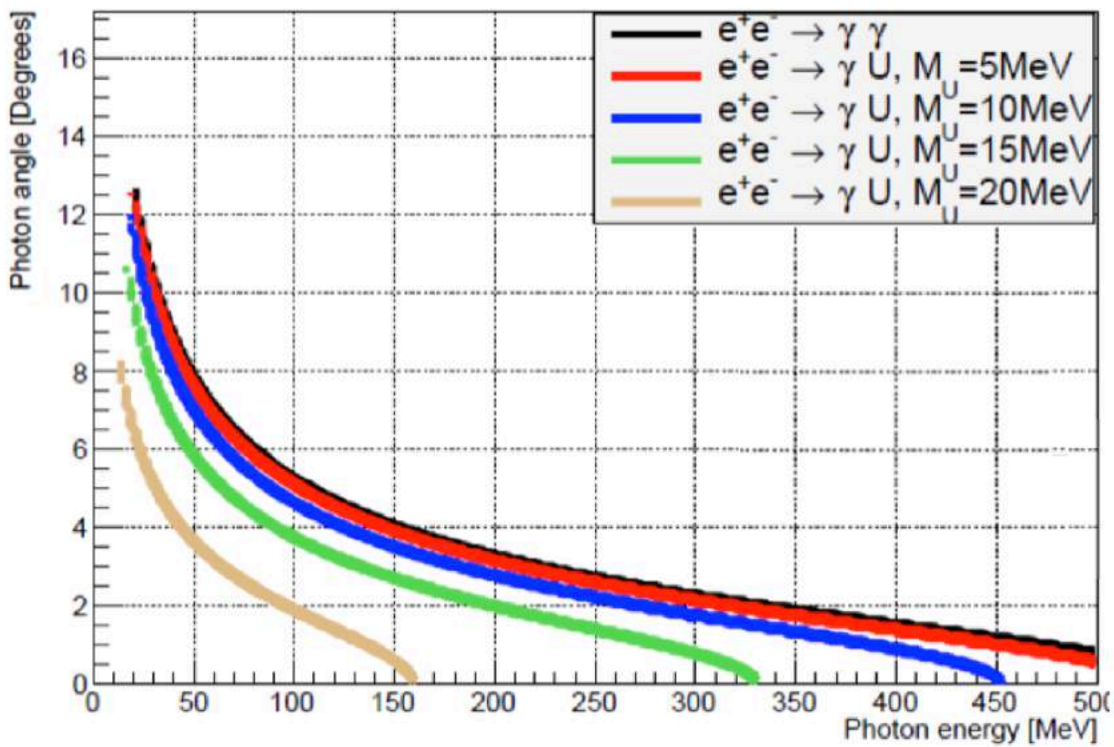


Selection cuts (all decay modes)

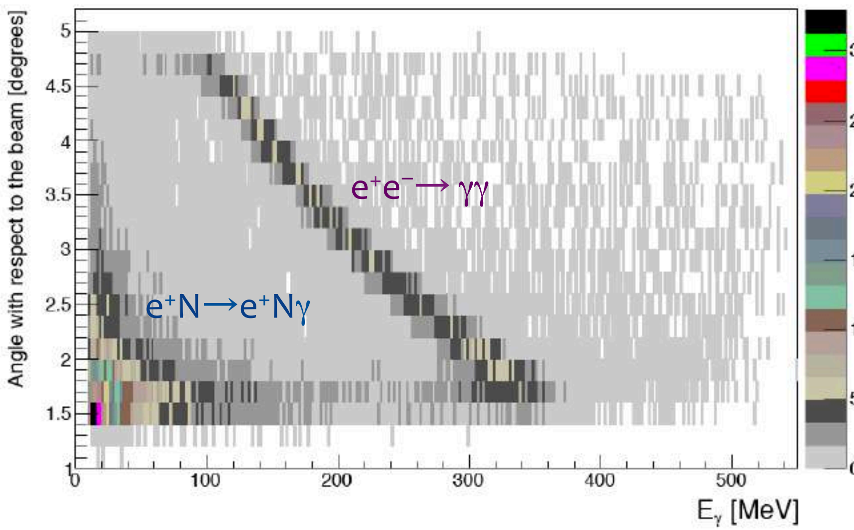
- Only one cluster in EM calo
  - Rejects γγ final state
- 5 cm < R_{Cl} < 13 cm
  - Improve shower containment
- Cluster energy within: $E_{min}(M_U) < E_{Cl} < 400$ MeV
  - Removes low energy bremsstrahlung photons and pile up clusters
- Positron veto in the spectrometer
  - $E_{e+} < 500$ MeV then $(E_{beam} - E_{e+} - E_{cl}) > 50$ MeV
  - Reject BG from bremsstrahlung identifying primary positrons
- Missing mass the region: $M_{miss}{}^2{}_U \pm \sigma(M_{miss}{}^2{}_U)$

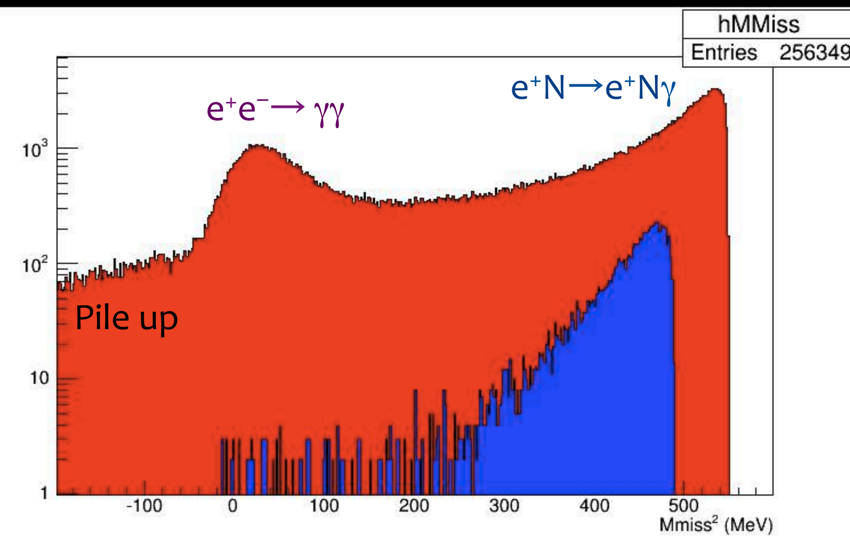
Photons in calorimeter

Energy-angle relation of the photons



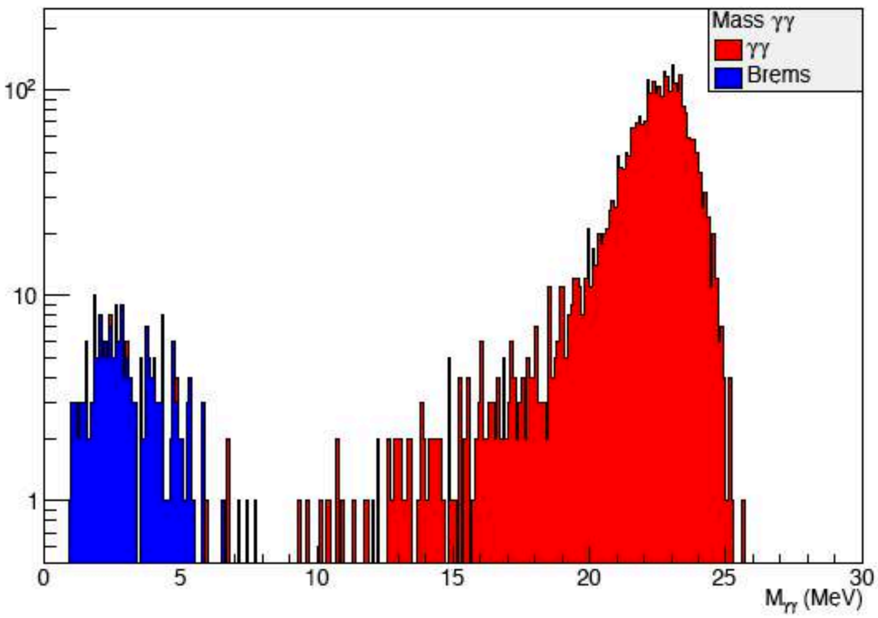
Background estimates





- Even with 10^4 e^+ per bunch kinematics is preserved
- Pile up contribution is important but rejected by the maximum cluster energy cut and M_{miss}^2.
- Veto inefficiency at high missing mass ($E(e^+) \simeq E(e^+)_{beam}$)
  - New Veto detector introduced to reject residual BG
  - New sensitivity estimate ongoing

The γγ normalization selection



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

* Number of calorimeter clusters = 2
* Cluster energy: 100MeV< E_{cl} <400 MeV
* Cluster radial position 5 cm < R_{Cl} < 13 cm
* γγ invariant mass 20 MeV < $M_{\gamma\gamma}$ < 26 MeV

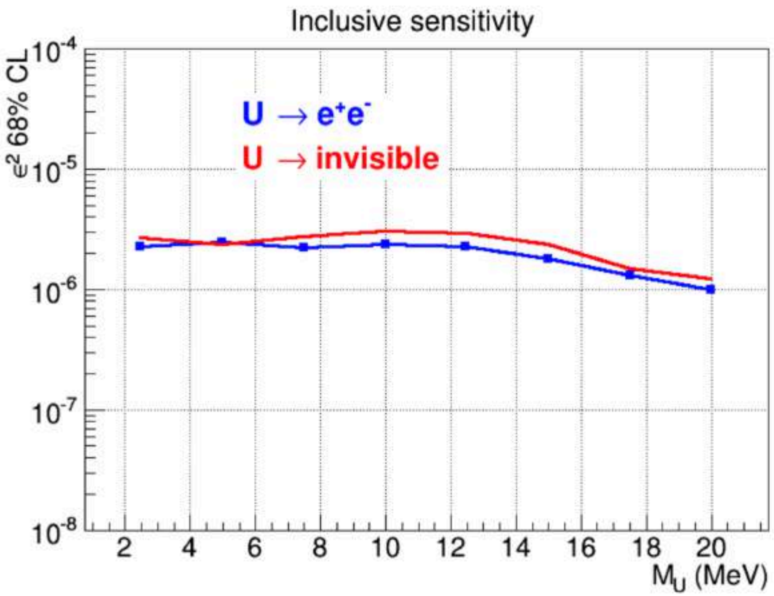
$$M_{\gamma\gamma} = \frac{\sqrt{[(X_{\gamma 1} - X_{\gamma 2}) + (Y_{\gamma 1} - Y_{\gamma 2})] E_{\gamma 2} E_{\gamma 2}}}{Z_{EMcal} - Z_{Target}}$$

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

PADME sensitivity estimate

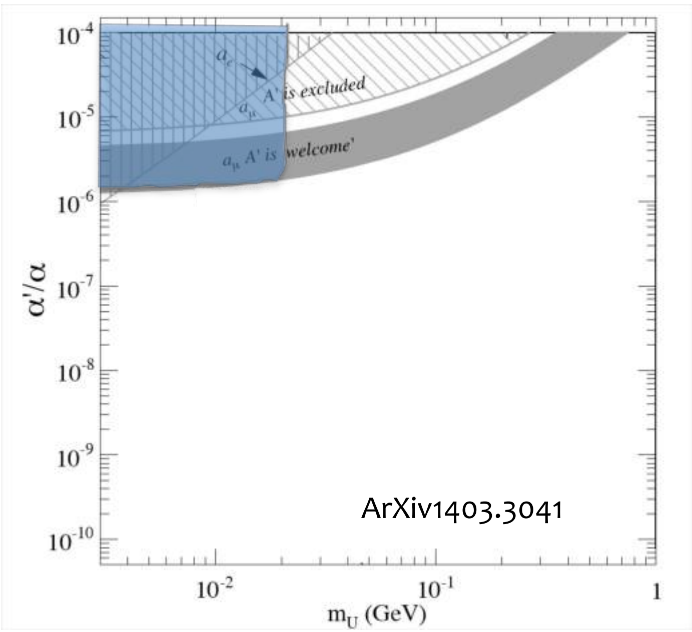
- Based on 10^{11} fully GEANT4 simulated e^+ on target events
- Number of background events is extrapolated to 10^{13}
  - Using $N(U\gamma)=\sigma(N_{BG})$
  - δ enhancement factor $\delta(M_U) = \sigma(U)/\sigma(\gamma\gamma)$ with $\varepsilon=1$

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



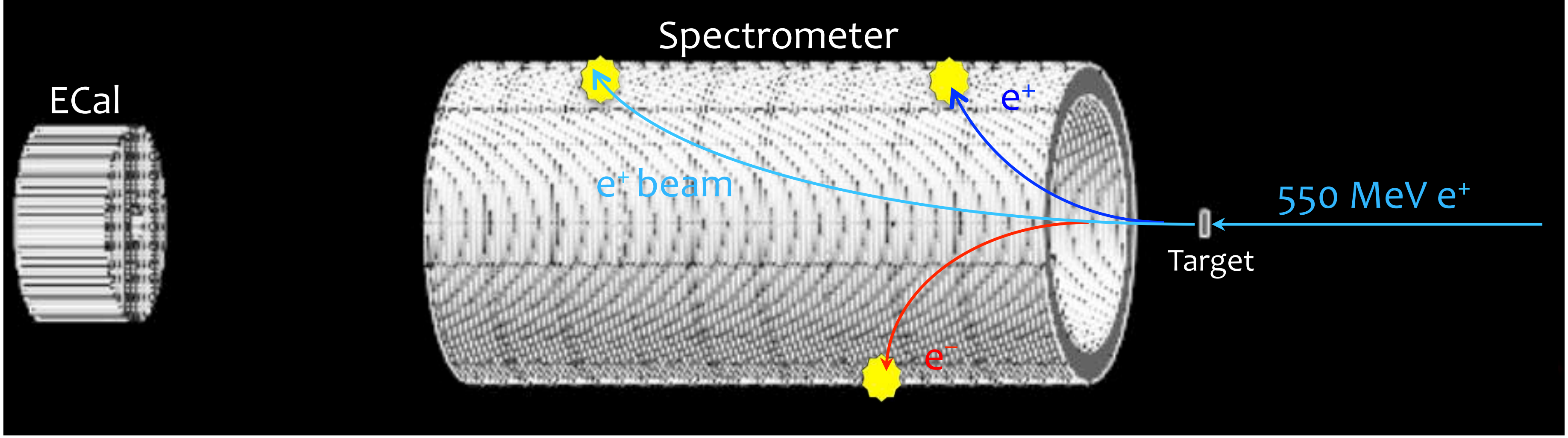
M. Raggi and V. Kozhuharov, Adv. In HEP, Vol. 2014 ID 959802

PADME invisible sensitivity



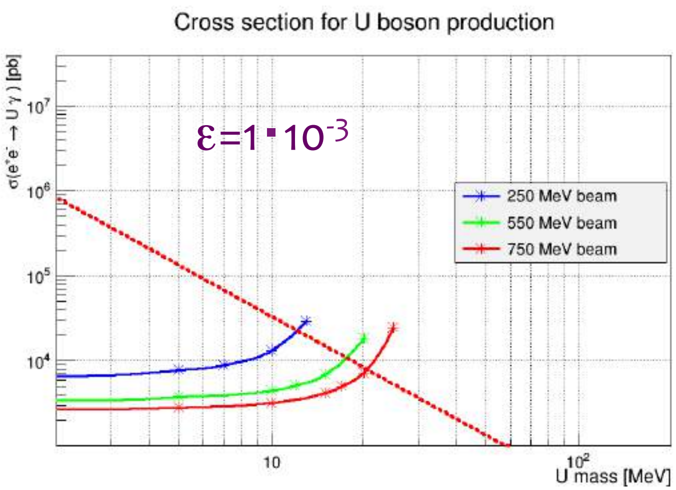
PADME

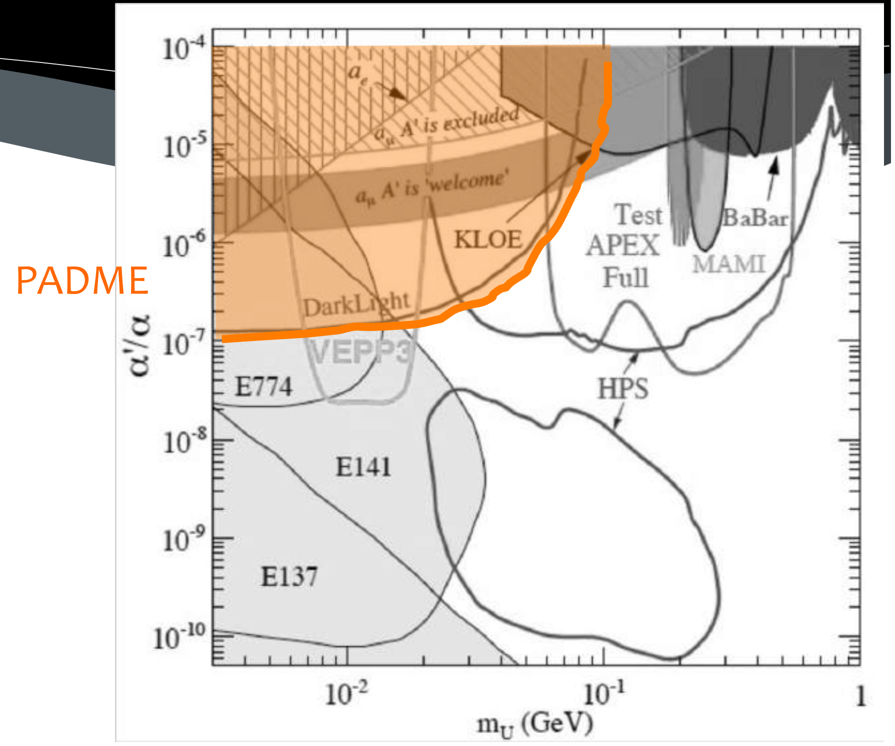
Search in bremsstrahlung production



- Search for the process: $e^+N \to Ne^+U \to Ne^+e^+e^-$
- 550 MeV positron beam on a 50 μm diamond target
- Measure in the spectrometer the P^4_{e-} P^4_{e+}
- Compute the $M_U^2 = (P^4_{e-} + P^4_{e+})^2$

Indication on visible decay sensitivity

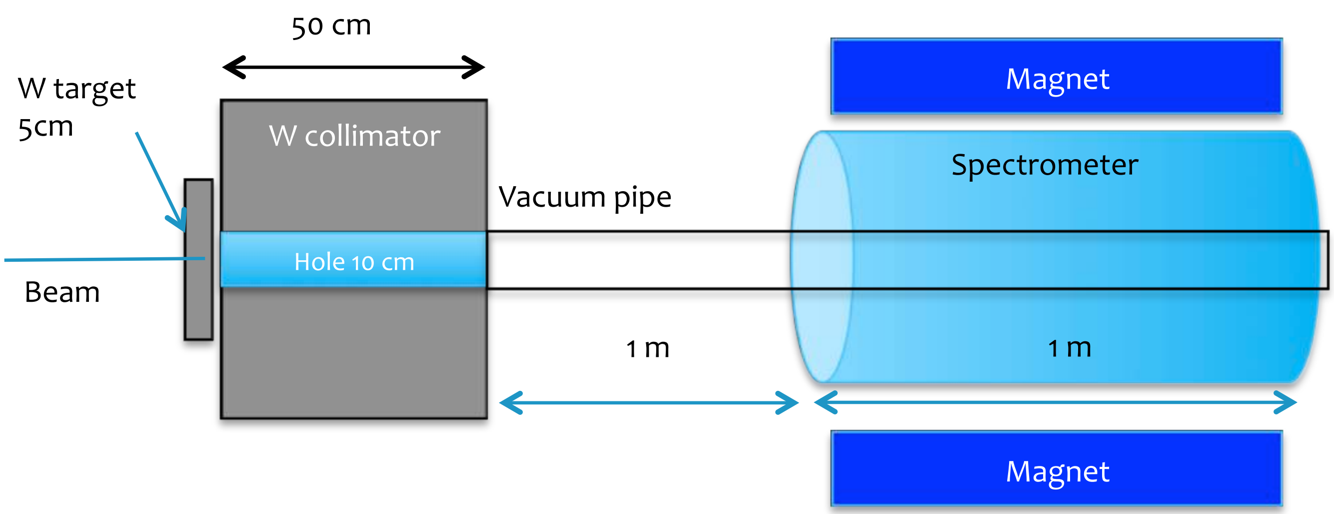




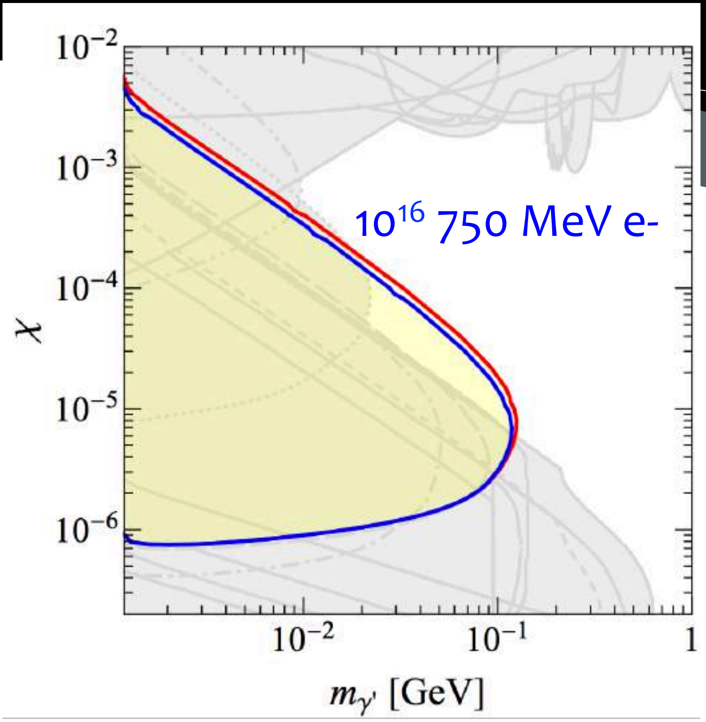
- Ratio of bremsstrahlung wrt to annihilation at 1MeV ~ 400
- Scaling low of the U-strahlung is $1/M_U^2$
- Final state is more constrained by invariant mass of the e^+e^- pair
- Naively a limit for $\varepsilon^2 < 10^{-5}$ is expected up to 100 MeV

Visible decay: dump experiment

* Same detectors as thin target measurements
  * Change the target with 5-7.5 cm W one
  * Build a W collimator
  * Remove the EM calorimeter



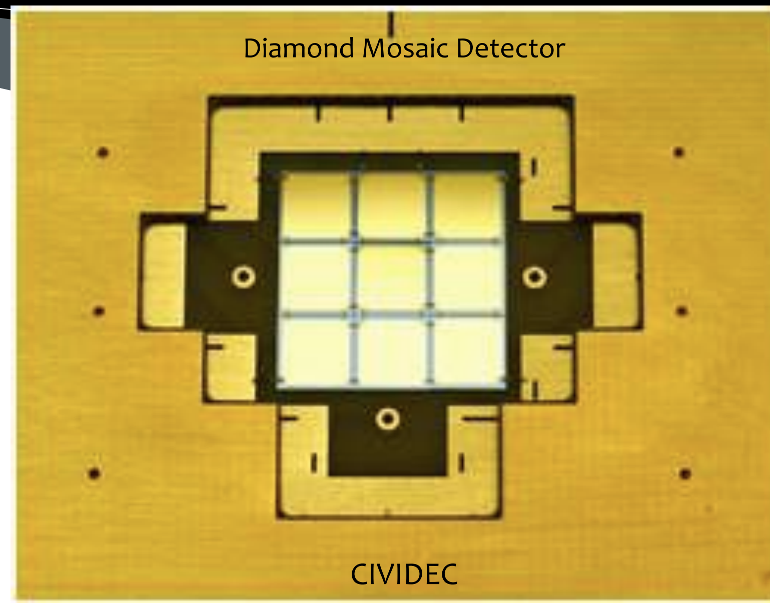
Visible decay: dump experiment



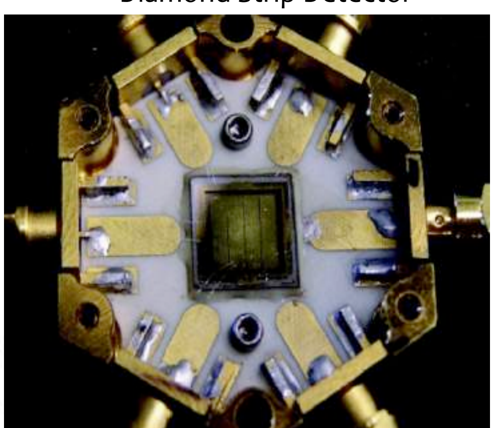
- Early study for a beam dump experiment (Sarah Andreas)
  - 10^7 electrons of energy 750 MeV per bunch in 50 bunch/s over 1 year
  - Total e^- on target being: $50*10^7*3.15\ 10^7 = 1.6\ 10^{16}$ (we use 1E16)
  - Study based on 0 events observed after the dump. (not easy to achieve)
  - Much better sensitivity can be achieved using 10^{10} e^-/bunch (total 10^{19})

PADME active target

* Diamond 50μm thick target
  * Most probably strip detector
* Active area 2x2cm²
* Position resolution ~2mm in both X and Y
* Sensitive from few particle to 10^9 particle
* Real time beam imaging
* Time resolution below 1ns
* Readout with QDC.
* R&D can start from CIVIDEC diamond mosaic detector



Diamond Strip Detector



Features:

Active area:	13 mm x 13 mm
Energy resolution:	35 keV FWHM
Particle rate:	1 MHz

NEW

Detector:

Type:	sCVD Diamond Mosaic-Detector
Diamond substrates:	4.5 mm x 4.5 mm
Thickness:	140 μm
Electrode structure:	3x3 mosaic structure
Metallization:	Au electrodes

BTF

Target termal load and out gassing

* The total energy deposit into the target will be
  * $E_{tot}=E_{mip} \cdot \rho \cdot T \cdot N_e \cdot N_{Pulses}=2MeV \cdot 2.62 \cdot 0.005 \cdot N_e \cdot 49=13$ GeV/s
  * Converting to joule gives $P=20 \cdot 10^{-10}$ W
  * The total mass of the target will be $M_{tar} = 2 \cdot 2 \cdot 0.005 \cdot 2.62 = 0.05$ g
  * $\Delta T/dt = P/(M_{target} \cdot c) = 5.6x10^{-8}$ °C/s
* Outgassing of the target is very low
* In the dump case the total power will be in the range 40 to 900 W (allowed intensity $3 \cdot 10^{10}$ e/s to maximum achievable linac current)
  * Study needed here…

PADME spectrometer & Magnet

First studies:

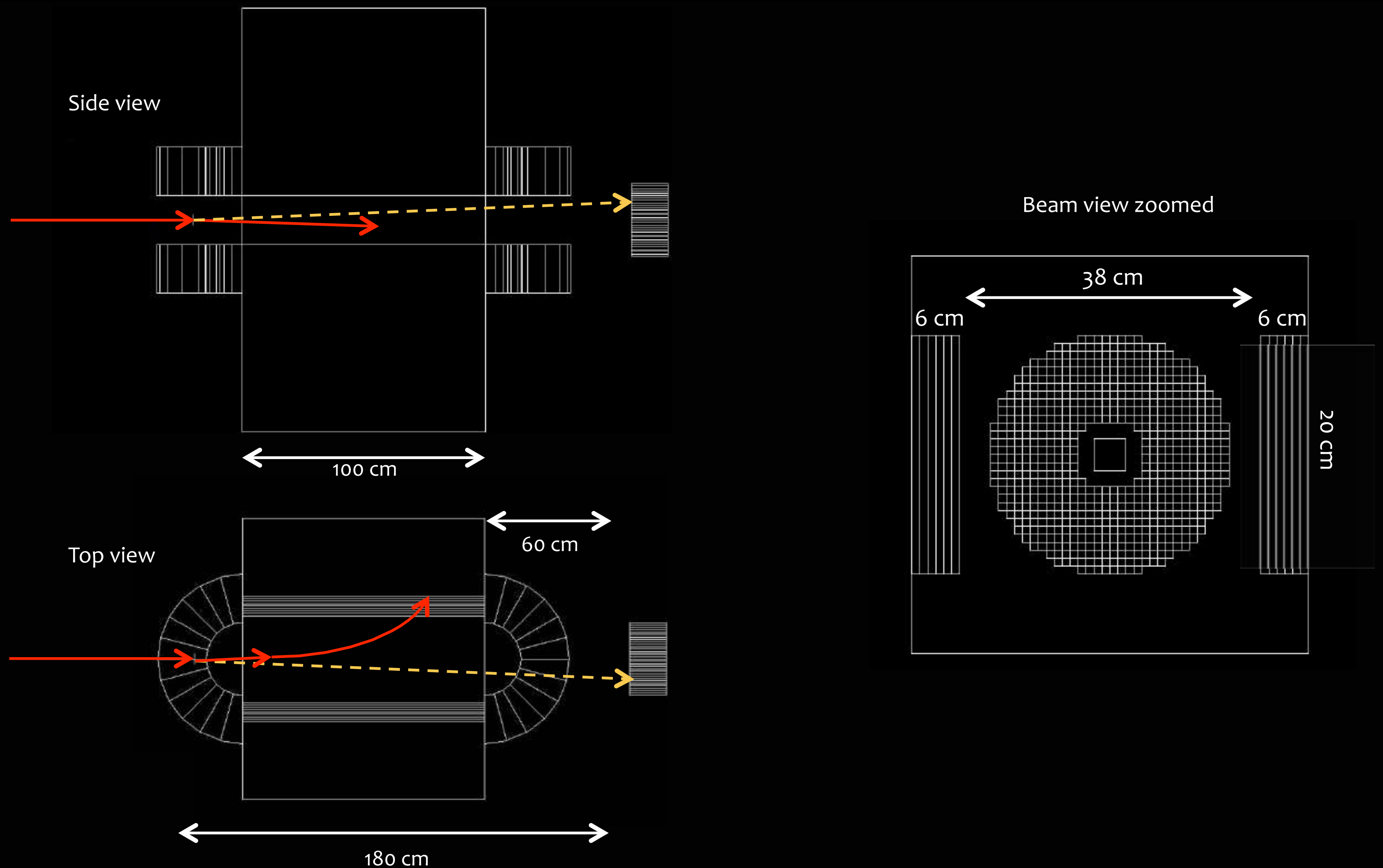
* Conventional dipole magnet with B=0.6 Tesla
* Generic cylindrical tracking chamber filled with gas
  * Inner radius 20 cm outer radius 25 cm length 100 cm
  * 5 cylindrical layers of 1cm each
* Expected to measure track crossing position with 300μm resolution
* Used in the experiment to veto positron and to reconstruct mass of lepton pairs

Quite **large gap** dipole needed >25 cm, long magnetic field (1 m)

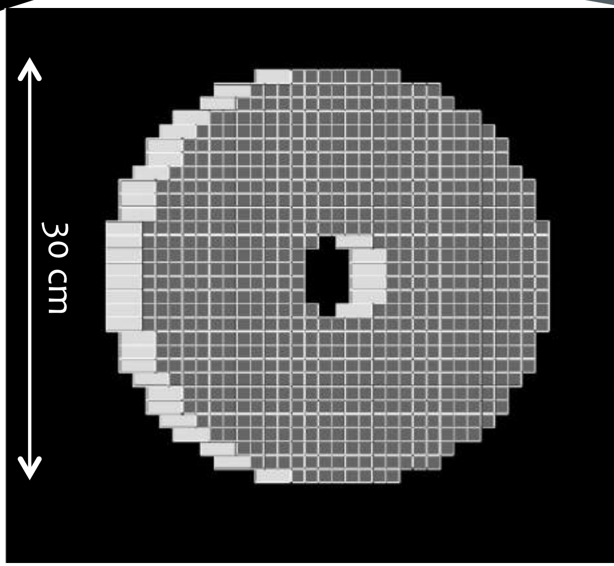
Available at CERN

Aperture width	**520.0 mm**
Aperture height	**110.0 – 200.0 mm**
Iron Length	**1000.0 mm**
Total Length	1700.0 mm
Total Width	1160.0 mm
Total Height	1740.0 mm
Weight	15000 Kg
Peak I (cycled)	675.0 A
RMS current	675.0 A
Resistance 20°C	195.0 mΩ
Inductance	663.0 mH
Total n of turns/pole	180
Power	**93.0 KW**
Delta P nominal	5.0 bar
Nominal flow	65.0 l/min
Dipole peak field	**1.64 T – 0.8 T**

New version of magnet + spectrometer



The electromagnetic 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	300^s	1.50	36^s	no	-1.9^s
							0.9^f	220^f		4.1^f		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	420^s	1.95	3.6^s	slight	−1.4
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.3^s	no	−2.5
							10^f	420^f		0.077^f		
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

* Cylindrical shape: radius 15 cm, depth of 15-20 cm
  * Inner hole 4 cm radius
  * Active volume 9840 cm^3 total of 656 crystals 1x1x15-20 cm^3
* Material LSO(Ce): high LY, high ρ, small X_0 and R_M, short τ_{decay}
* Expected performance:
  * $\sigma(E)/E = 1.1\%/\sqrt{E} \oplus 0.4\%/E \oplus 1.2\%$ superB calorimeter test at BTF [NIM A 718 (2013) 107–109]
  * $\sigma(\theta)$ = 3 mm/1.75 m < 2 mrad
  * Angular acceptance 1.5-5 degrees

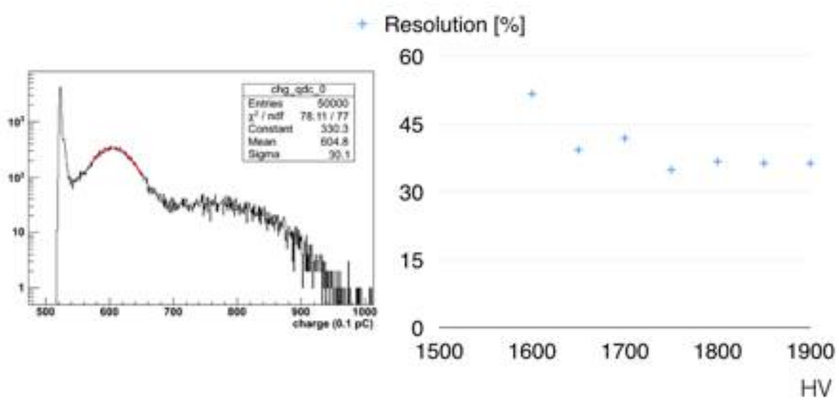
PADME

Calorimeter: a low-cost alternative?

From M. Marafini

BGO: matrice B

^{22}Na source: 0.511 MeV, 1.275 MeV γ's



THE L3 BGO ELECTROMAGNETIC CALORIMETER AT LEP

Fernando FERRONI

CERN and Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Roma, Italy

L3 experiment is operating since August 1989 at LEP in CERN. It contains a unique electromagnetic calorimeter consisting of bismuth germanate (BGO) crystals. The performances of the BGO calorimeter are discussed in this paper.

1. INTRODUCTION

L3 experiment[1] is one of the large detectors designed for the LEP electron-positron colliders. It is a detector that concentrates its efforts on measuring electron, photons and muons with high precision. The electromagnetic calorimeter makes use of a new type of crystals which allow the measurement of the energies of electrons and photons with an accuracy of 5% at 100 MeV and better than 1% at high energy. Muon momenta are measured by a set of large drift chambers with a precision of 2% at 50 GeV. Hadron jets are measured in a hadron calorimeter, made of depleted uranium plates with proportional wire readout, with a resolution of $(55/\sqrt{E}+5)\%$. A central detector based on the principle of *time expansion* is used to track charged particles. All the detectors are installed within a 7800t magnet providing a 0.5T field. The L3 detector is now running since one year.

The performances of the BGO electromagnetic calorimeter are discussed in this paper. We first discuss the electromagnetic calorimeter design, we then review its performance as measured in a test beam and finally we give some result on its behaviour obtained at LEP.

sic elements are $B_4Ge_3O_{12}$ (bismuth germanate)[3] scintillating crystals. This high density, high Z material was chosen mainly for its very short radiation length $X_0 = 1.12$ cm. Some properties of BGO are listed in table 1.

Table 1: BGO properties

Density	(g/cm^3)	7.13
Hardness	(Mho)	5
Melting point	(^{0}C)	1050
Radiation length	(cm)	1.13
Absorbtion length	(cm)	22
Critical energy	(MeV)	8.8
Moliere radius	(cm)	2.7
(dE/dx)	(MeV/cm)	9.2
$< \lambda_{scint} >$	(nm)	480
Decay constant at 20^{0}C	(ns)	300
Photons/MeV		10^4
Temperature gradient	(%/^{0}C)	-1.55
Index of refraction		2.19

- 24 cm length = 22 x_0
- Different shapes
- Excellent energy resolution

BGO from L3 calorimeter: time resolution

From M. Marafini

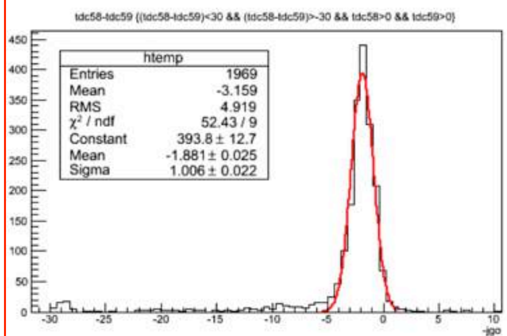
Matrici di BGO: B, G, O. Cosmici!

Dal jitter di due matrici (ex.G,O) si ottiene:

$$\sigma^2_{G-O} = \sigma G^2_{True} + \sigma O^2_{True} = 2 \cdot \sigma B^2_{True}$$

$$\sigma_{G-O} = \sqrt{2} \cdot \sigma_{BTrue}$$

$$\rightarrow \sigma_{BTrue} = 1/\sqrt{2} \cdot \sigma_{G-O}$$

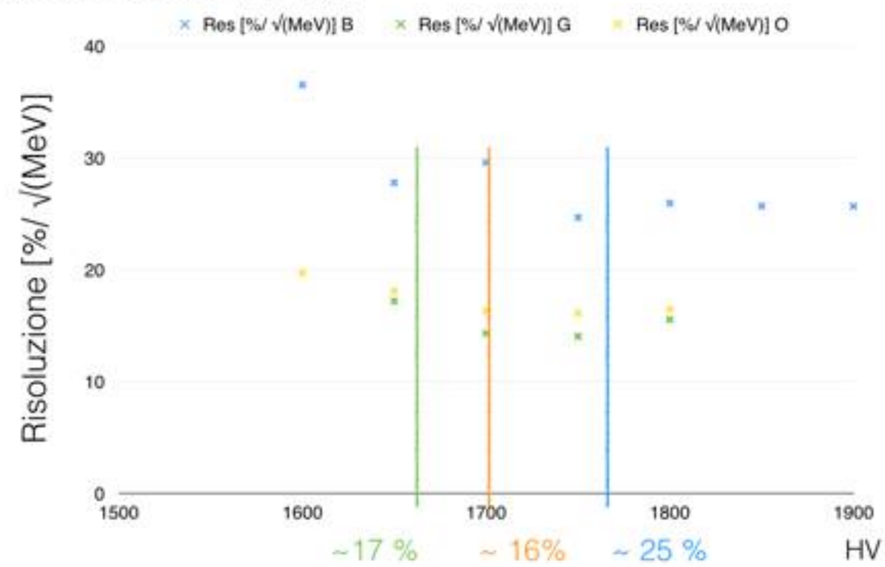


Risoluzione
BGO ~ 0.7 ns

$$\sigma_B = \sqrt{\sigma B^2_{True} + \sigma STS1^2_{True}}$$ => Risoluzione STS1~0.25 ns

11

Matrici di BGO: B, G, O



About 100 crystals available in Rome

Possible to cut precisely crystals

Possible BTF upgrades

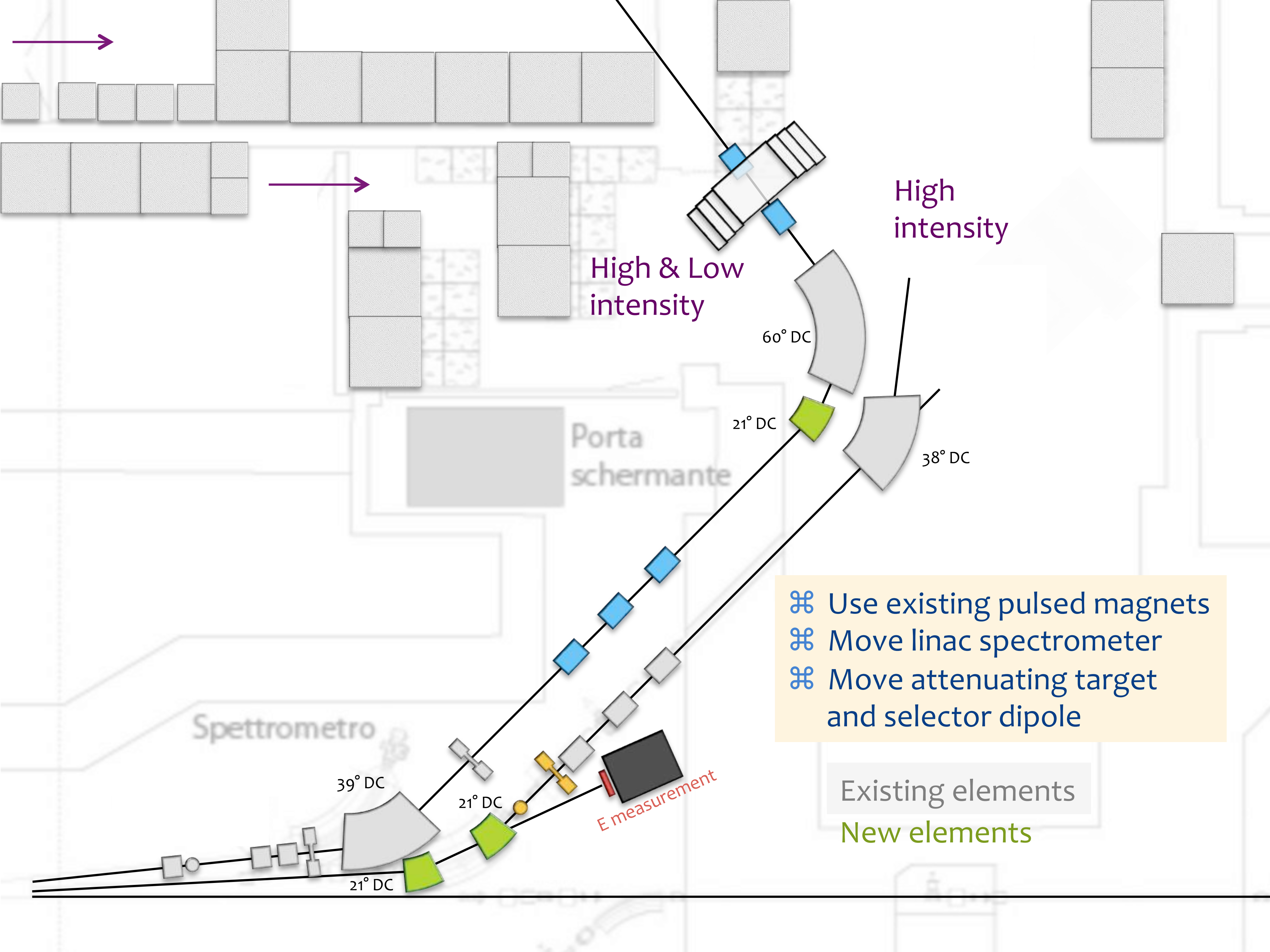
* **Beam-line splitting**
* **Energy upgrades**
  * Up to 1.1 – 1.2 GeV electrons
  * 800 – 850 MeV energy for positrons (see V. Buonomo BTF user workshop)
* **Longer pulses**
  * Standard BTF duty cycle = 50*10 ns = 5×10^{-7} s
  * Already obtained upgrade 50*40ns= 20×10^{-7} s
  * Aim at 100 – 200 ns range
* Increase of **beam charge**
* **Collimation system**
  * Assure better beam definition for positrons beam
* Maximum current in BTF hall
  * Limited by radio protection to 6.2×10^{8} per bunch for long term operation
  * Can reach $>3\times10^{10}$ particle per second after proper screening

See recent BTF user workshop for details at:
https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=7359
Coming next week:
"What Next LNF", **10/11 November 2014**

BTF beam-line doubling: main elements

A new, dedicated, high-intensity line, independent from medium-low intensity line for particle detectors testing

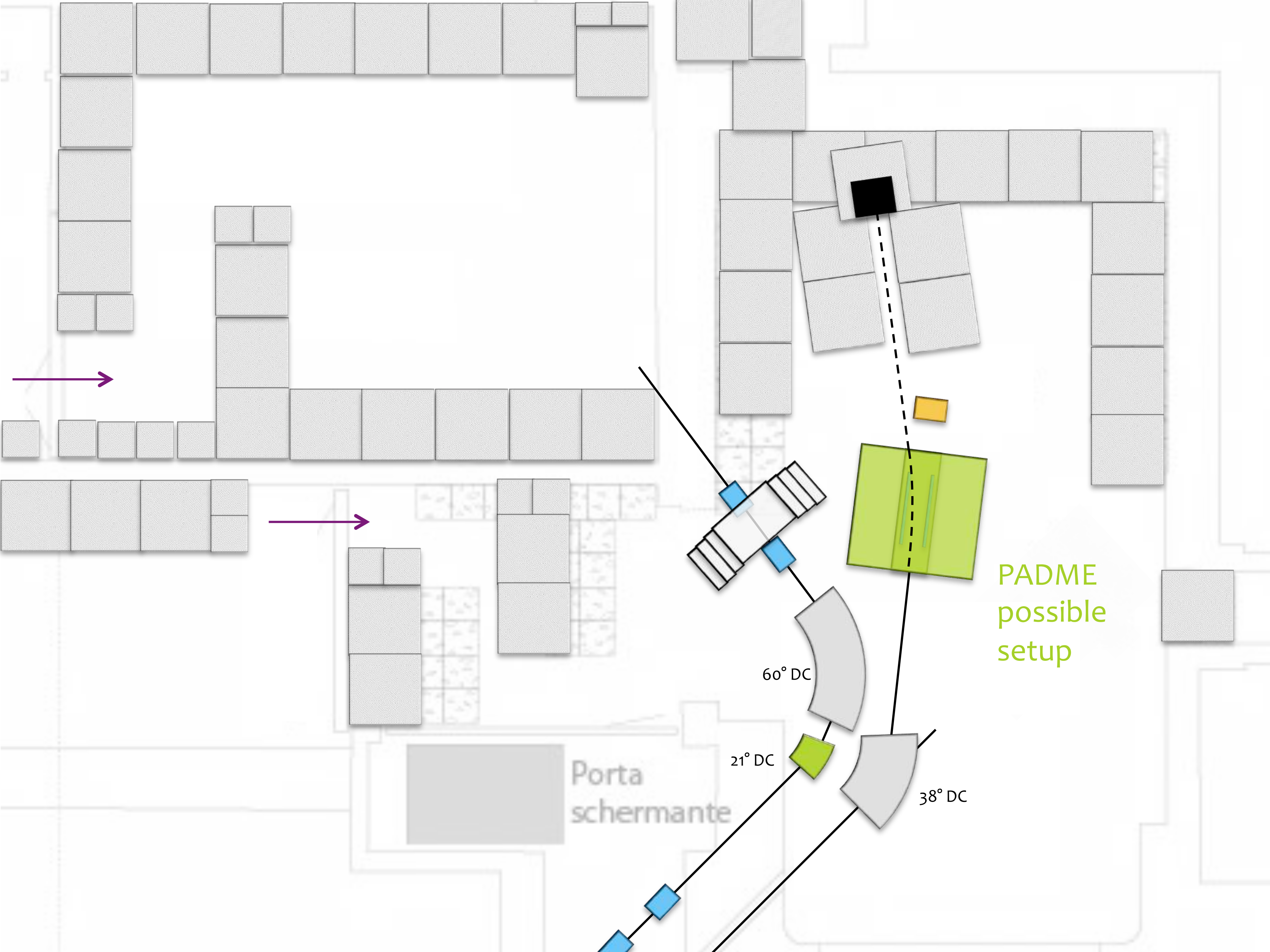
* Move the control room upstairs
* Shield the present control room to be used as second experimental hall
* Move DAFNE control racks upstairs ("vetrina")
* In order to re-use the linac spectrometer dipole:
  * Measure beam energy in the the BTF line



- ⌘ Use existing pulsed magnets
- ⌘ Move linac spectrometer
- ⌘ Move attenuating target and selector dipole

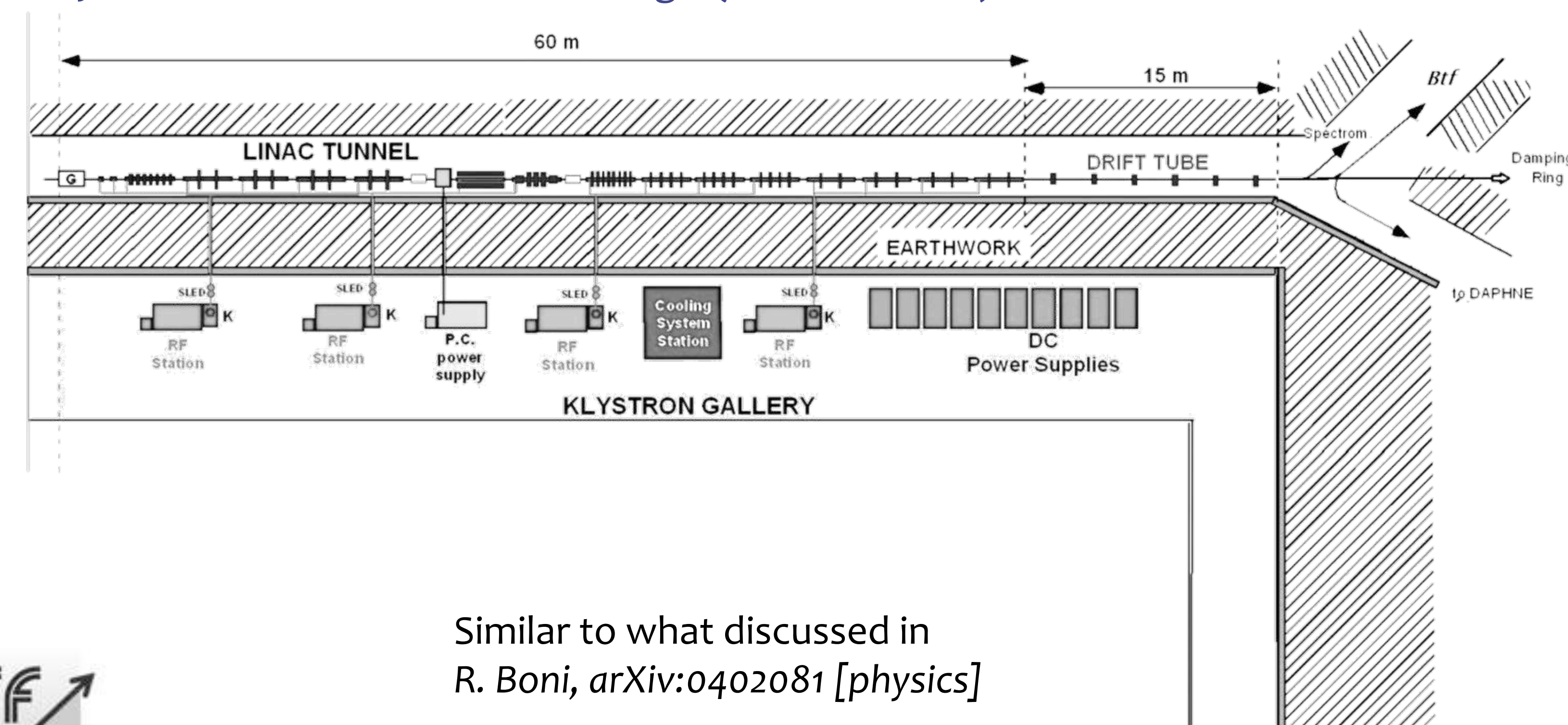
Existing elements

New elements


PADME
possible
setup
60° DC
21° DC
38° DC
Porta
schermante

LINAC energy upgrade/1

- 15 m in the final part of the LINAC
- Add 4 more accelerating sections (3 m) fed by 2 modulators + 2 SLED-ed klystrons to reach the 1 **GeV** range (for electrons)

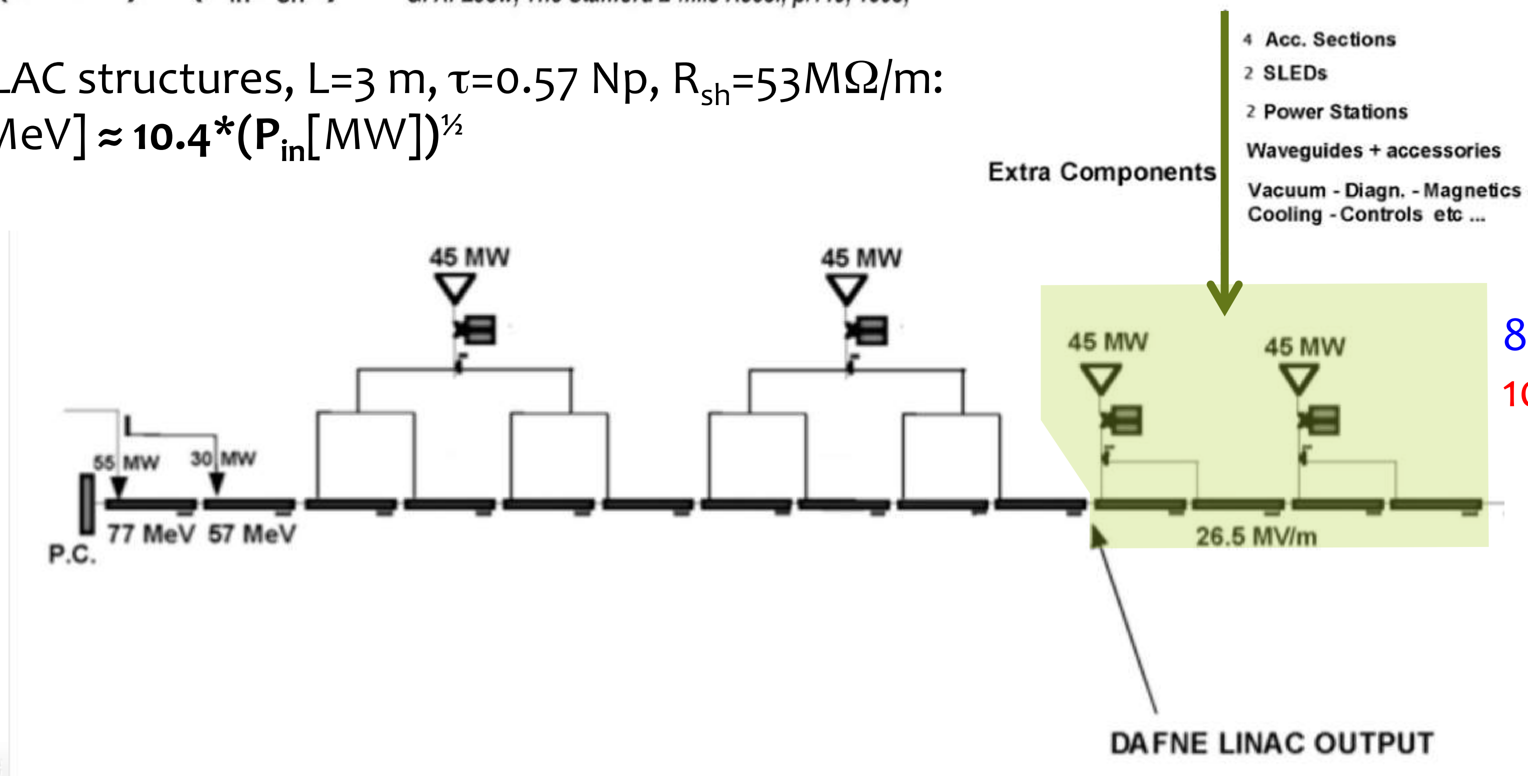


Similar to what discussed in
R. Boni, arXiv:0402081 [physics]

LINAC energy upgrade/2

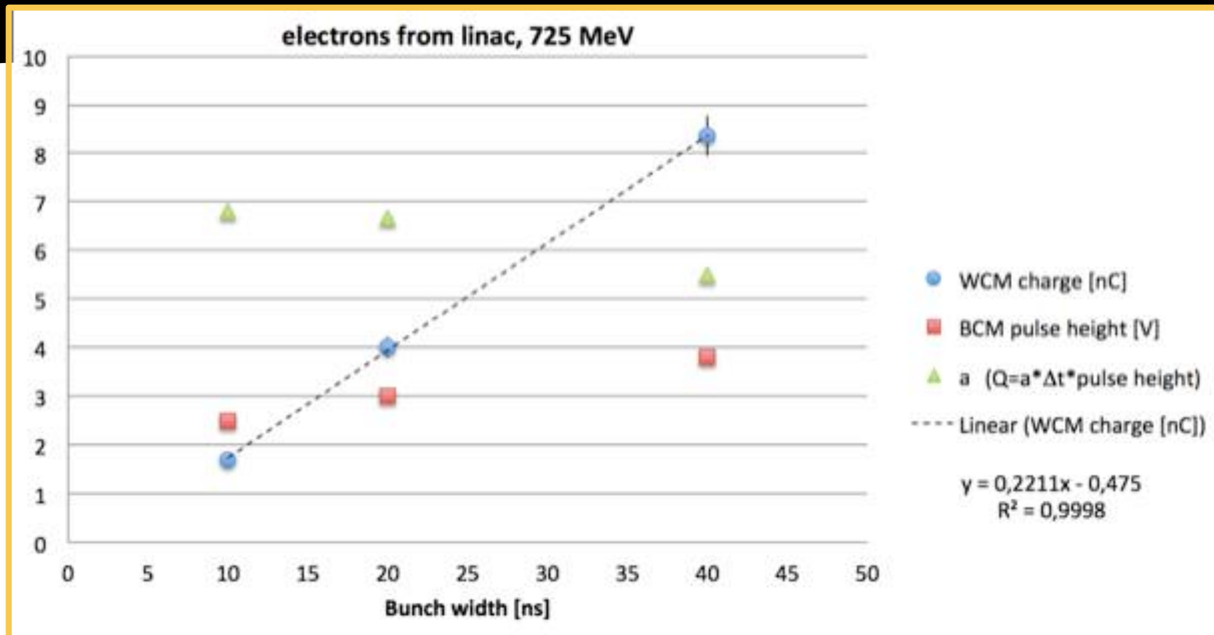
$U_0 = (1 - e^{-2\tau})^{1/2} (P_{in} R_{sh} L)^{1/2}$ *G. A. Loew, The Stanford 2-mile Accel, p.116, 1968,*

In SLAC structures, L=3 m, τ=0.57 Np, R_{sh}=53MΩ/m:
U_0[MeV] ≈ 10.4*(P_{in}[MW])^{½}



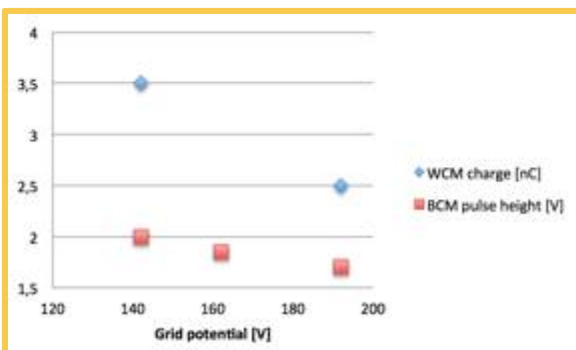
830 MeV e+
1070 MeV e−

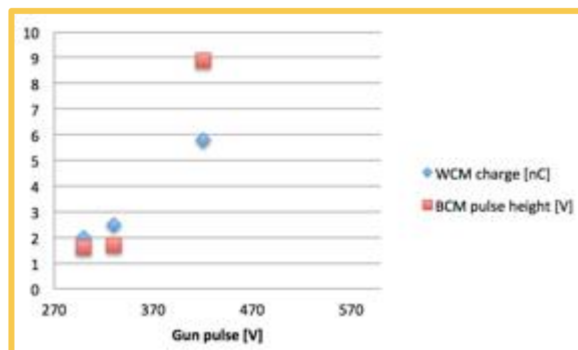
Linac bunch charge vs. length



×4 increasing pulse length

+30%
Decreasing grid stopping potential





×3 - ×5
Increasing gun pulse height

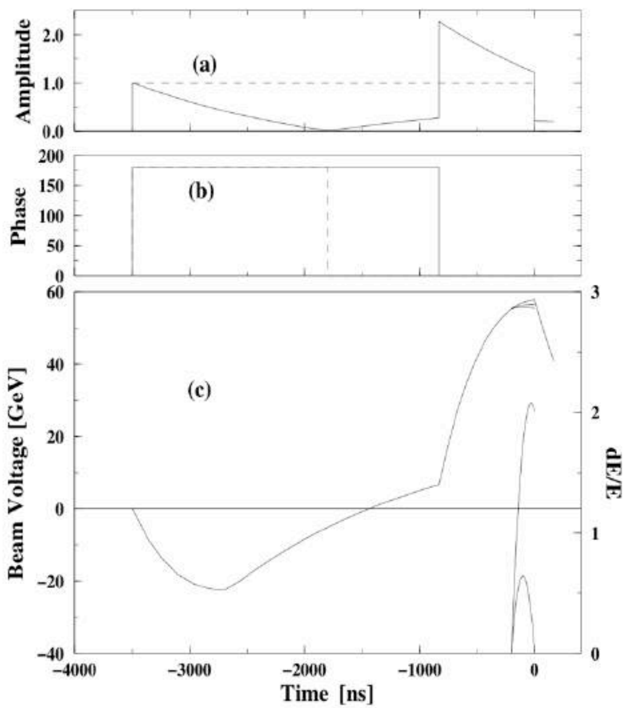
Extending the pulse length

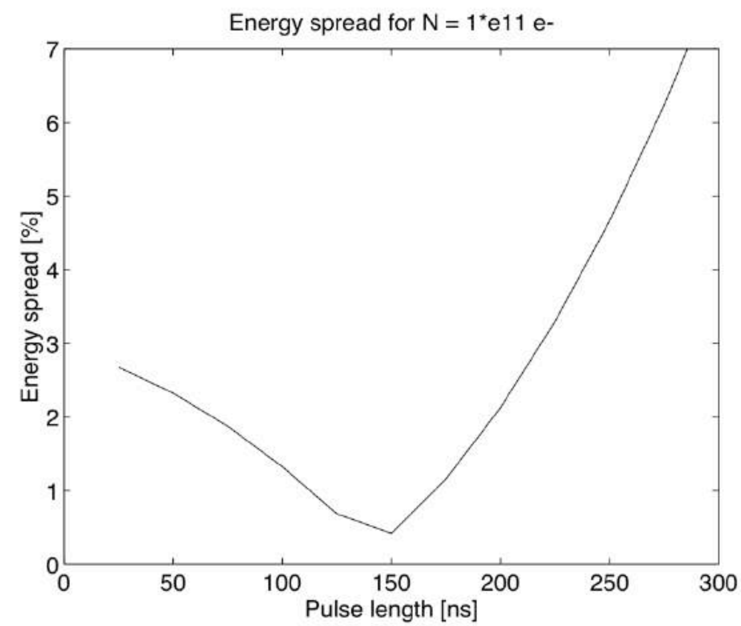
SLAC–PUB–7214
June 1996

Reducing Energy Spread for Long Bunch Train at SLAC*

F.-J. Decker, D. Farkas, L. Rinolfi[1], J. Truher
Stanford Linear Accelerator Center, Stanford CA 94309, USA

SLED



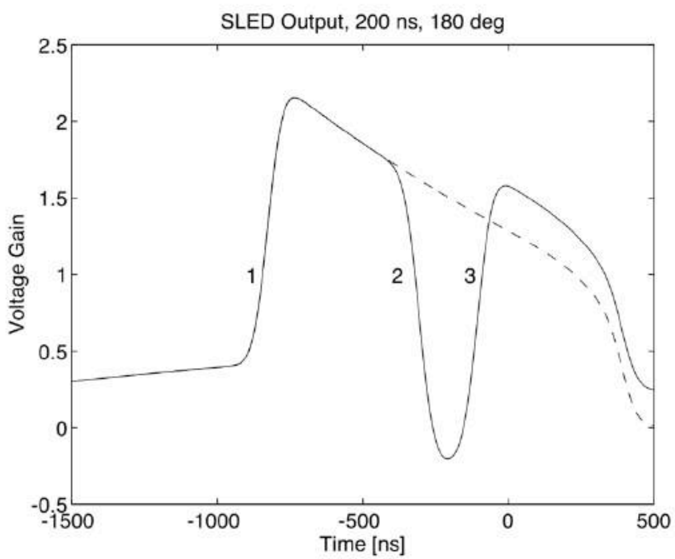


Extending more the pulse length

SLAC–PUB–7214
June 1996

Reducing Energy Spread for Long Bunch Train at SLAC*

F.-J. Decker, D. Farkas, L. Rinolfi[1], J. Truher
Stanford Linear Accelerator Center, Stanford CA 94309, USA

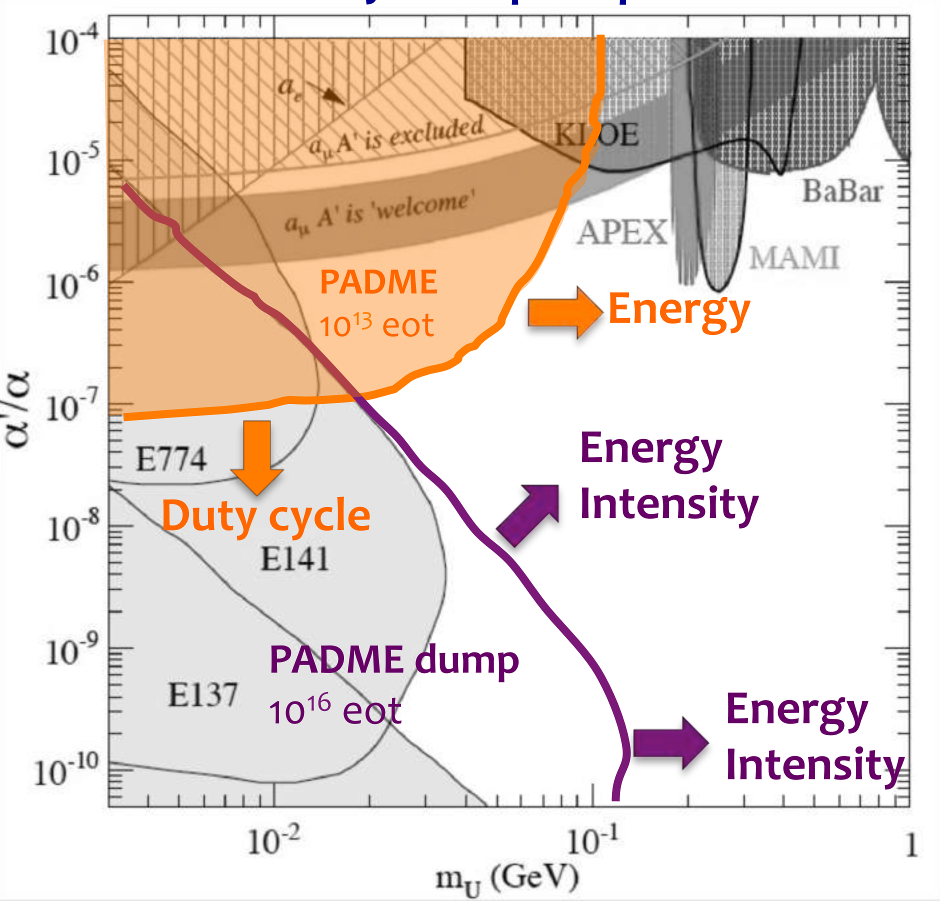


Add two more 180° phase inversions

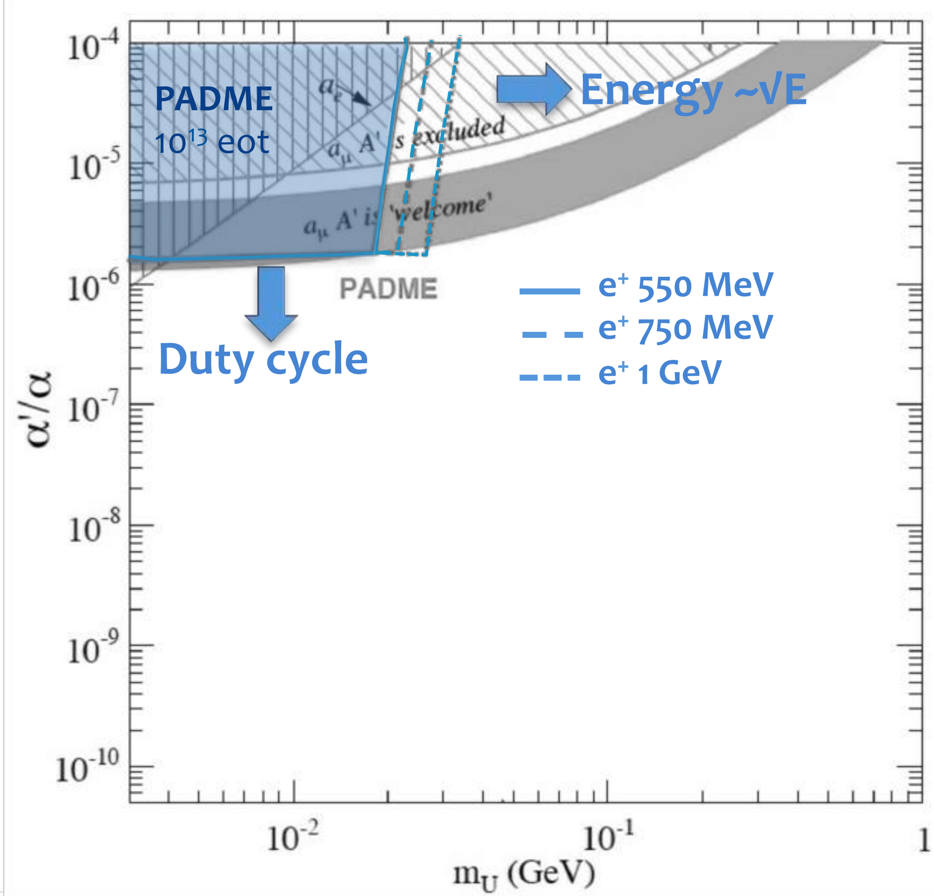
240 ns with <0.5% energy spread achieved at SLAC for E-154 experiment

Improvements on PADME from BTF upgrades

Decays to lepton pairs



Decays to invisible



Possible parameters for electron dump experiments

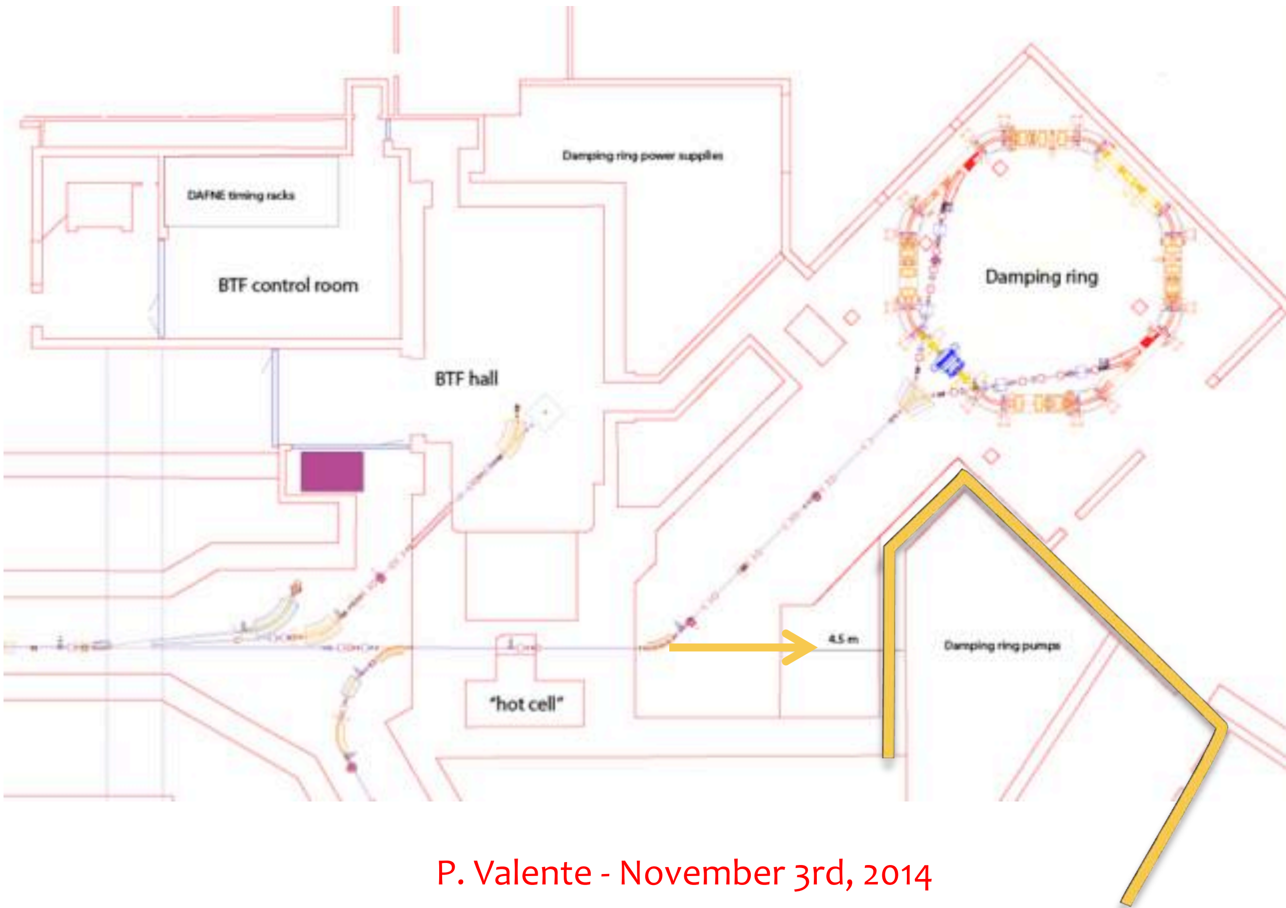
* E = 725 MeV
* Q = 25 nC
* $N_e = 0.784 \cdot 10^{13}$ e/s
  (Design intensity on positron converter: $1.44 \cdot 10^{13}$ e/s)
* **P = 0.9 kW**
* $1.6 \cdot 10^{11}$ e/bunch × 49 Hz × $\mathbf{3 \cdot 10^7}$ **s** = $2.4 \cdot 10^{20}$ eot
* Further increase (×2 at least) by enlarging the pulse time width up to >**100 ns**

The limitation will come from radio-protection issues

BTF radio-protection issues

* Present authorization: average **3.125 10^{10} electrons/s** at 800 MeV
  * 5 nC/s = 10 mA × 10 ns × 50 Hz
  * Translates to <**10^{18} electrons/year**
* Calculated for 1 m of concrete + 15 cm of lead around scattering target
* Dump experiments aim to two order of magnitudes more charge (available from the linac)

Use existing ADONE linac dump




Pumps
Racks
Racks
Pumps
Pumps

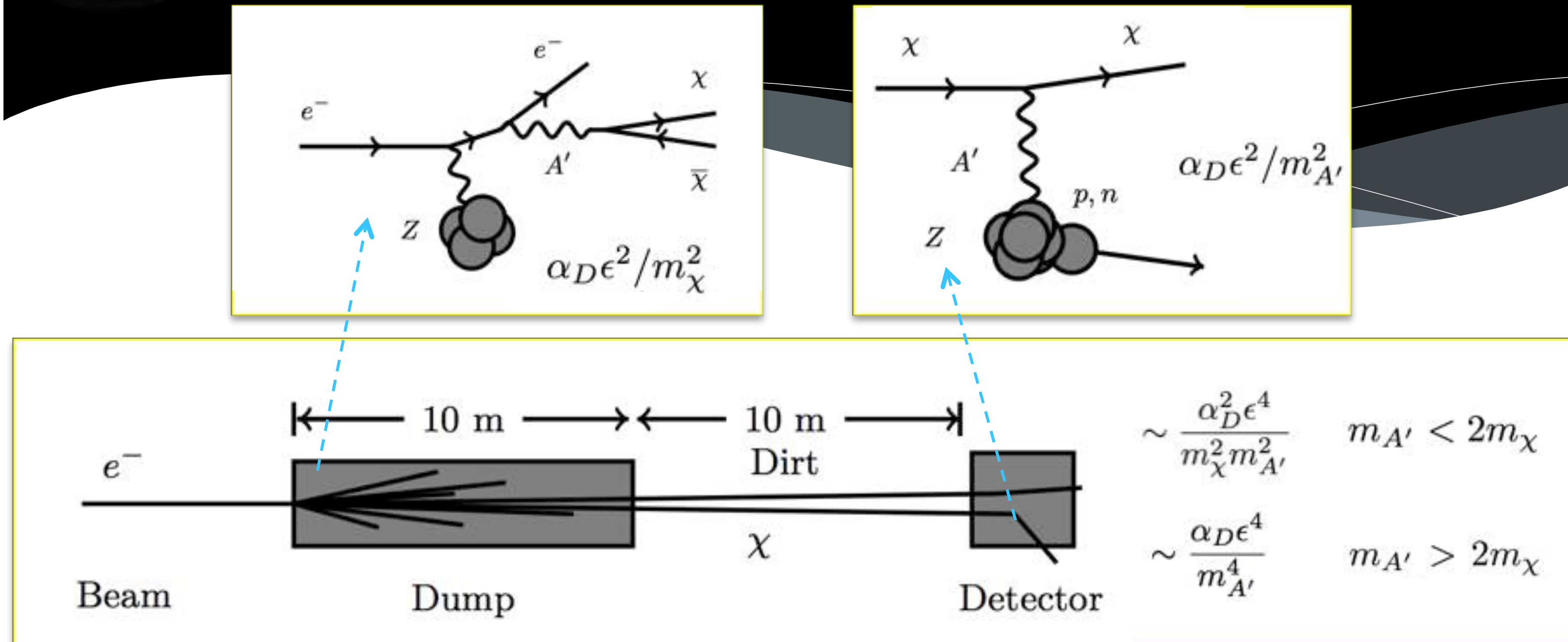
Use existing ADONE linac dump

- A number of issues to be tackled, e.g. how to extract the full beam: thin vacuum chamber inside pulsed magnet delicate and difficult to modify (design a chicane?)
- Real layout of ADONE dump
- Activation/radio-protection in the pump hall to be re-used for experimental setup
- …

PADME

DR pumps hall

New ideas for dump experiment: BDX at JLAB



Backgrounds:

- Neutrino production
- Cosmogenic muons and neutrons

LOI presented to PAC

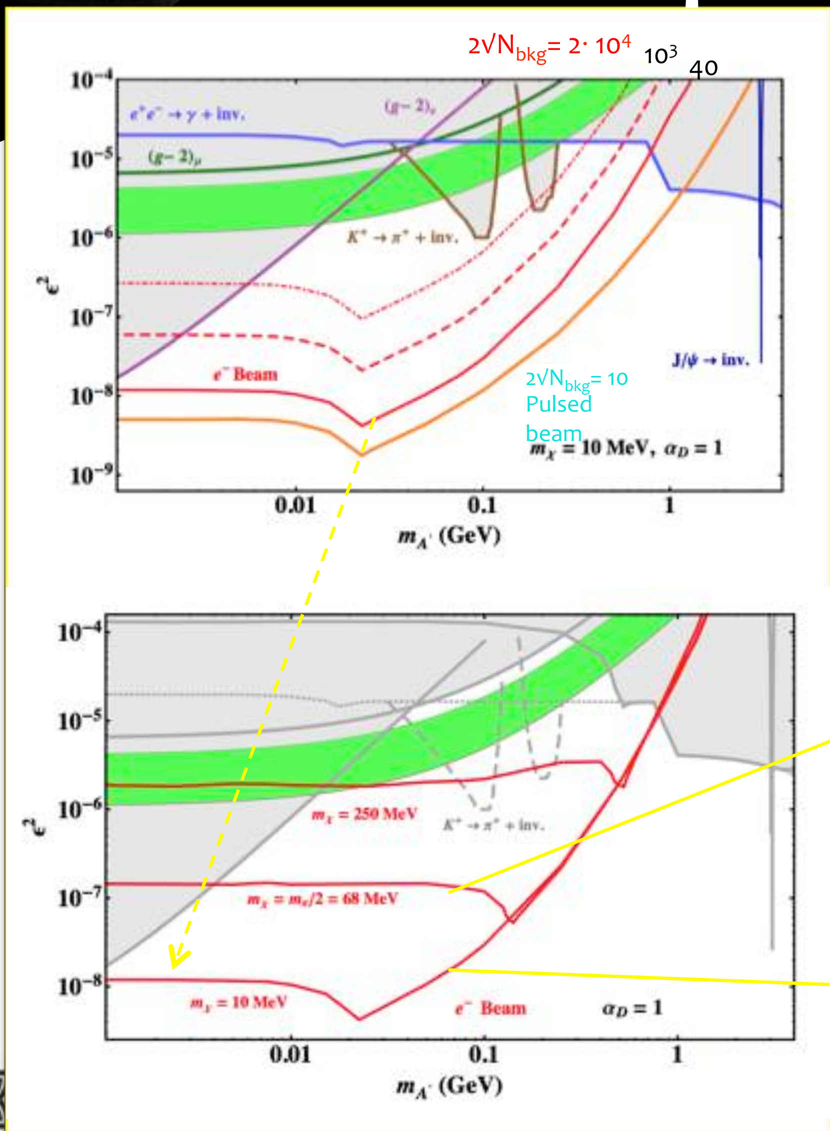
Scintillator 1 m^3

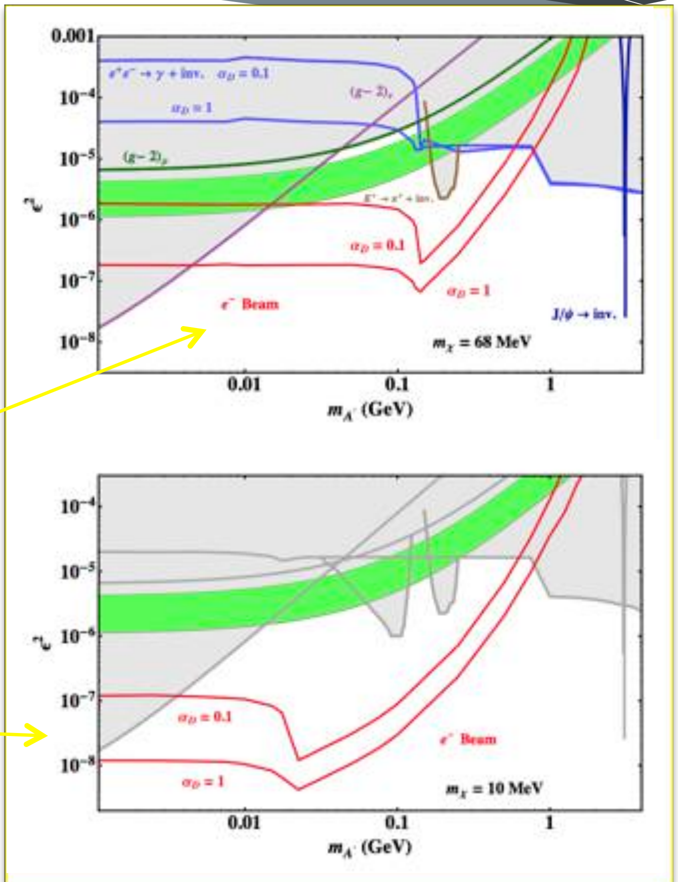
1 MeV/10 MeV e^+e^- detection threshold

Or crystal calorimeter

BDX experiment (Hall-A)

10^{22} EOT = 1 beam-year at Hall-A
3 beam-years at Hall-C?
arXiv:1307.6554





BDX at Frascati?

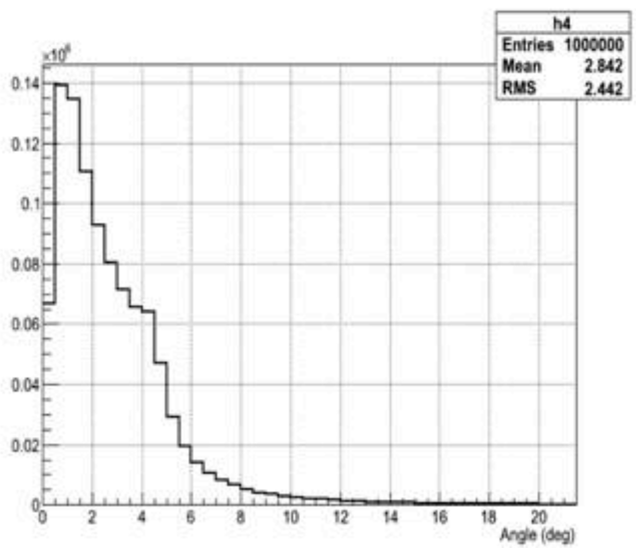
PADME

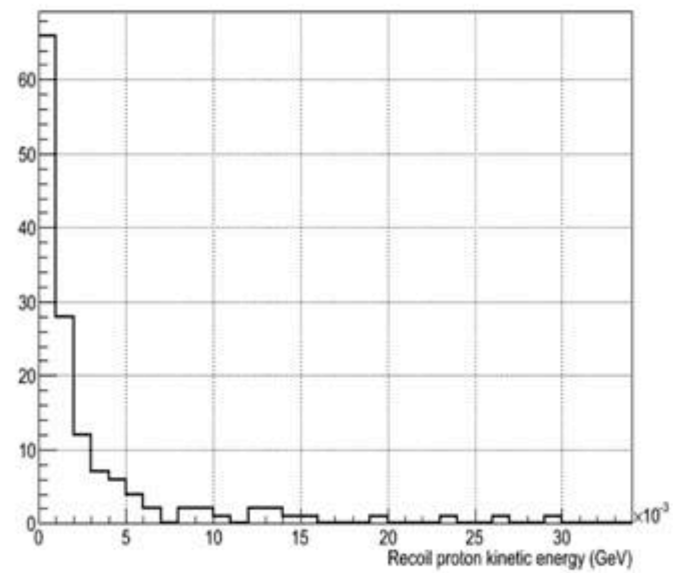
χ production and detection

- 1.5 GeV electron beam
- 7 10^{19} EOT/year
- 1 year run (50% efficiency)
- Repetition rate: 50 Hz, (0.7A in 10 ns bunch)
- **Negligible cosmogenic BG with timing cut**
- Expected ~20 counts in $1m^3$ plastic scintillator detector (1 MeVee threshold)
- **Significant sensitivity to low mass (A'/χ) region**

Parameters:

M_A' = 50 MeV
M_Chi = 10 MeV
Alpha_dark = 0.1
Epsilon = 10^-3

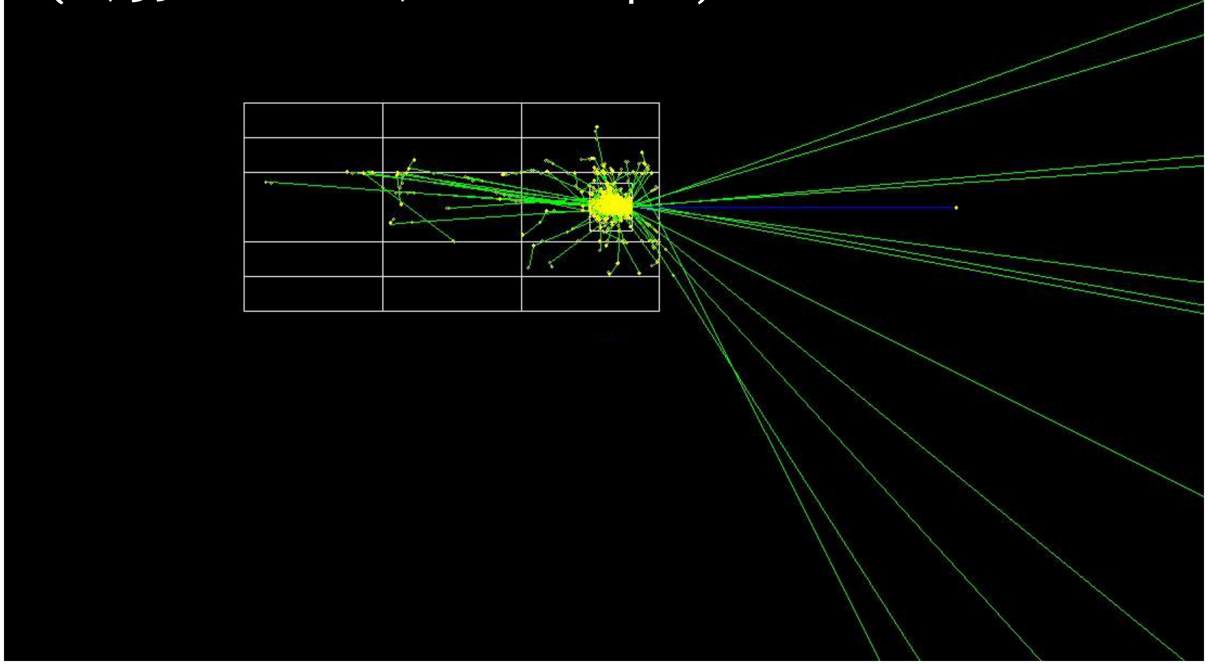




Very preliminary study. Results look very promising and should be investigated further.

BDX @ LNF and PADME dump background

Geant 4 simulation of BTF neutron target
(W, 35 mm radius, 60 mm depth)



PADME

In BDX @ LNF use the 40 ns pulse length, 50 Hz repetition:
duty cycle= 2 10^{-6}

So the total beam unrelated background goes to 3.4 10^{-8} Hz which leads to a total ~1 event/year

At LNF we can get a beam related background dominated experiment.

At 10^{20} EOT we will have a zero background experiment! Potential gain of factor 1000 in the sensitivity

	Rate $_{Thr=1\text{MeV}}$ (Hz/μA))	Rate $_{Thr=10\text{MeV}}$ (Hz/μA))
χ detection - S.I	$1.0\ 10^{-5}$	$1.2\ 10^{-6}$
χ detection - S.II	$2.0\ 10^{-7}$	$0.7\ 10^{-7}$
B-rel ν	$2.0\ 10^{-9}$	$2.0\ 10^{-10}$
B-rel neutron	0	0

	Rate $_{Thr=1\text{MeV}}$ (Hz)	Rate $_{Thr=10\text{MeV}}$ (Hz)
B-unrel ν	$2.0\ 10^{-6}$	$2.0\ 10^{-7}$
B-unrel neutron	$2.7\ 10^{-3}$	$0.6\ 10^{-3}$
Crossing muons	$3.3\ 10^{-3}$	$3.5\ 10^{-3}$
Captured μ^+	$1.4\ 10^{-3}$	$2.4\ 10^{-3}$
Decaying μ^- (CORM)	$2.9\ 10^{-3}$	$4.8\ 10^{-3}$
Stopped μ in lead	$7.0\ 10^{-3}$	$4.3\ 10^{-3}$
μ^- rare decay	$2.0\ 10^{-5}$	$8.0\ 10^{-6}$
Total Beam-unrelated bg	$1.7\ 10^{-2}$	$1.5\ 10^{-2}$

BDX background with 10^{22} EOT

	Counts $_{Thr=1\text{MeV}}$	Counts $_{Thr=10\text{MeV}}$
χ detection - S.I	$0.5\ 10^{6} \pm 700$	$5.7\ 10^{4} \pm 240$
χ detection - S.II	$1.0\ 10^{4} \pm 100$	$3.3\ 10^{3} \pm 60$
Beam-rel bg	100 ± 10	10 ± 3
Beam-unrel bg	$1.6\ 10^{6} \pm 1300$	$1.4\ 10^{6} \pm 1200$

PADME experiment(s)

Thin target

Low intensity

1. **PADME invisible**
   * Use a **positron** beam and **annihilation** diagram on target electrons: $e^+ e^- \to \gamma U$
   * Detect *U* decays **in any channel** by looking at the **missing mass**:
     * Measure the momentum of incoming e^+: use a thin target
     * Measure the momentum of the emitted γ: calorimetry

High intensity

2. **PADME visible**
   * Use a electron/positron beam and the **Bremsstrahlung** diagram on target nuclei: $e N \to e N U$
   * Look for *U* boson decays to $e^+ e^-$ pairs
   * Look for bump in $e^+ e^-$ invariant mass distribution
   * Look for a $e^+ e^-$ vertex displaced from the target

Thick target
Maximum intensity

3. **PADME dump**
   * Use the full electron beam of the linac, maximum energy and maximum intensity, and completely dump it on a thick target
   * Look for $e^+ e^-$ pairs behind dump + shield, from *U* **Bremsstrahlung** production in the target and subsequent decay
4. **BDX @ BTF**
   * Like PADME dump, but look for $U \to \chi\chi$ decays and subsequent χ interaction with nuclei in a recoil detector

Plans/1

- **PADME invisible**
  - Test of diamond target
  - Test of LYSO calorimeter prototype matrix
  - Tests of BGO crystals
  - Finalize details on vacuum pipe, target, dump, positron veto, etc.
  - **Write a technical proposal for the invisible**

- **PADME dump**
  - Perform study in more realistic intensity scenarios from **10^{18} to 10^{20} eot** and beyond
  - Further investigation on ADONE dump
  - **Simulate a realistic setup**
  - Study radio-protection issues

Plans/2

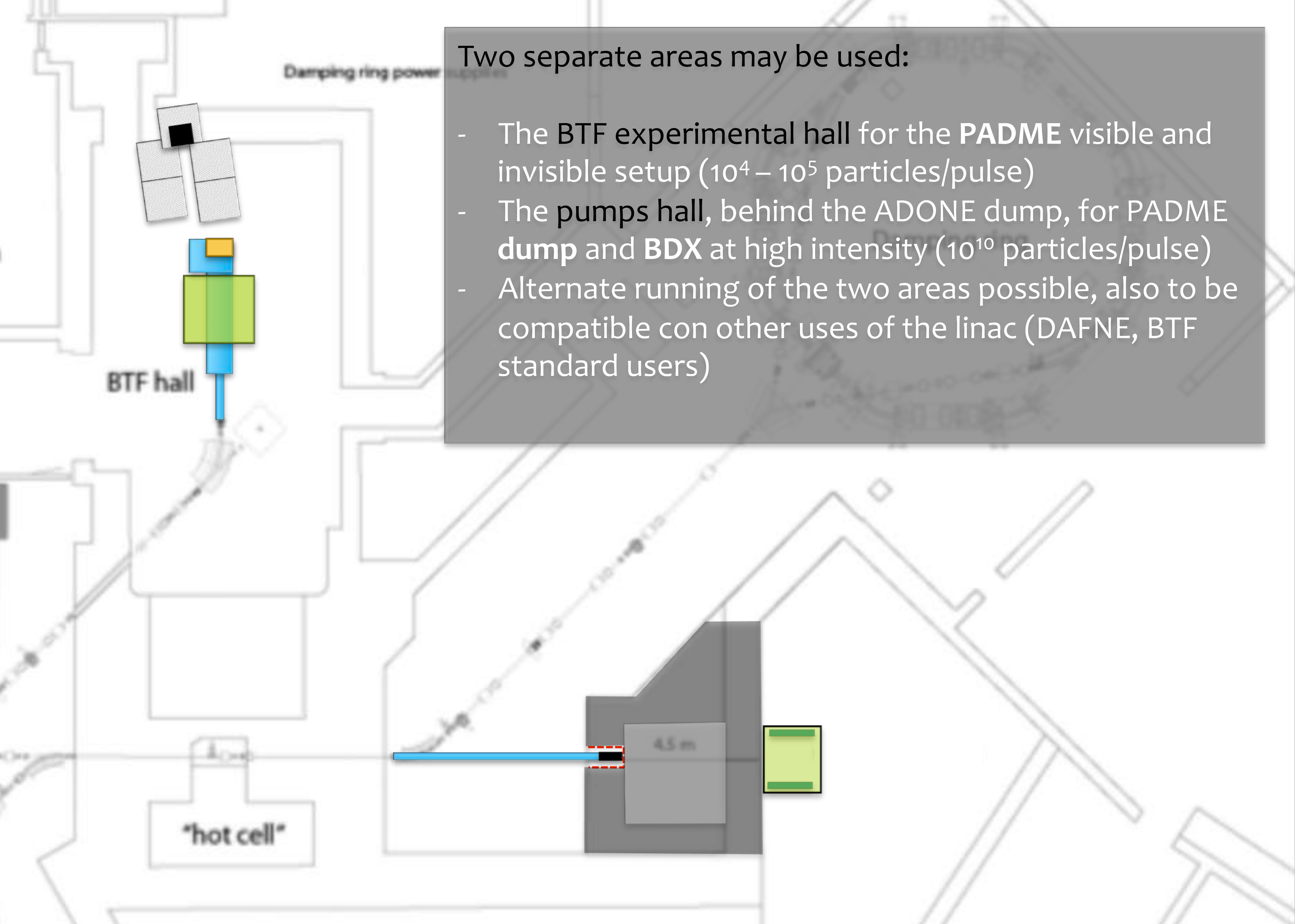
- **PADME visible**
  - **Refine study with realistic spectrometer**
  - Test of possible trackers

- **BDX @ BTF**
  - **Perform study up to 10^{20} eot and beyond**

- **BTF upgrades**
  - Study improved shielding
  - Refine studies for beam-line splitting
  - Plan modifications to the gun pulser
  - Improve design and planning for the energy upgrade

Two separate areas may be used:

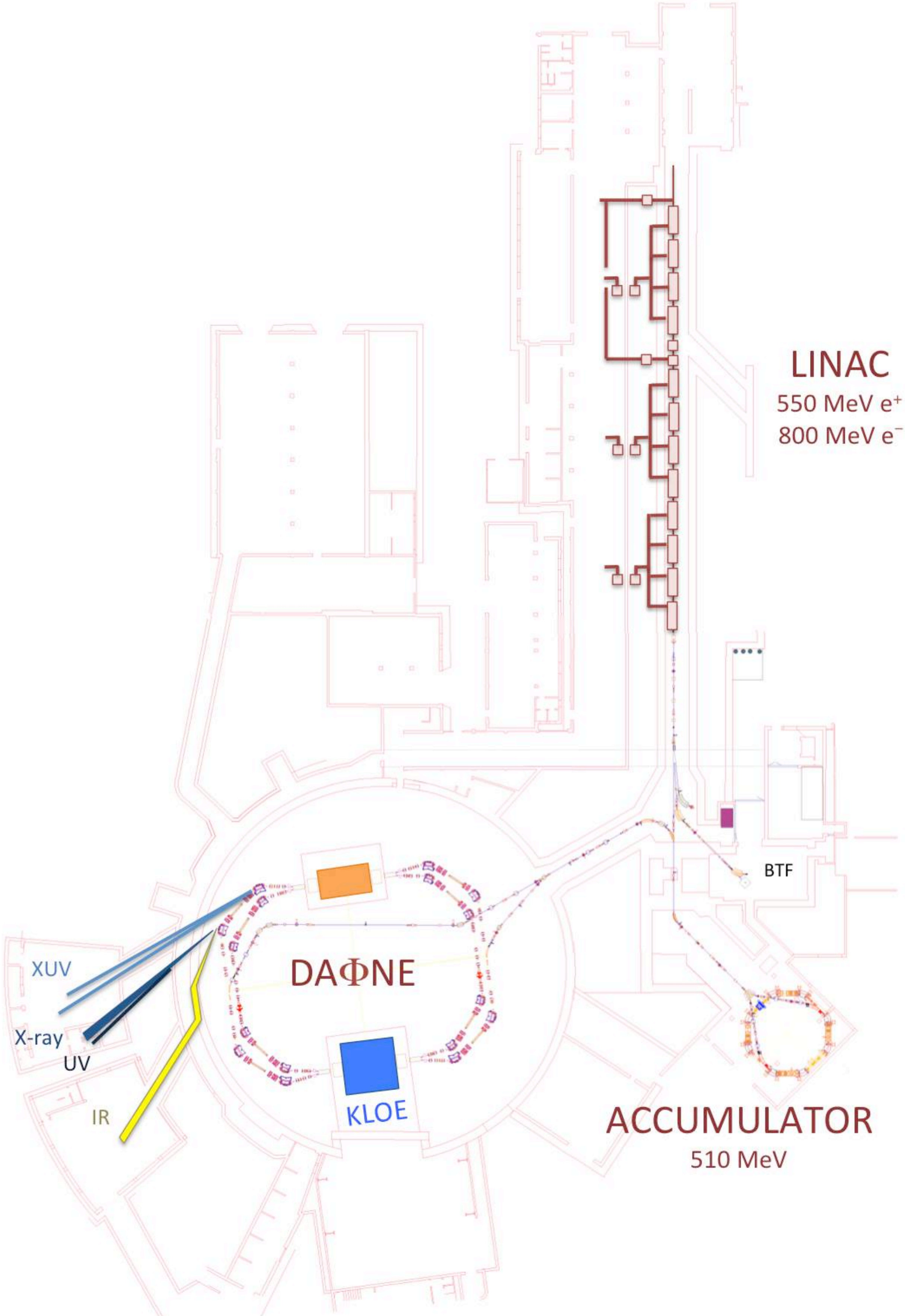
- The BTF experimental hall for the **PADME** visible and invisible setup ($10^4 – 10^5$ particles/pulse)
- The pumps hall, behind the ADONE dump, for PADME **dump** and **BDX** at high intensity (10^{10} particles/pulse)
- Alternate running of the two areas possible, also to be compatible con other uses of the linac (DAFNE, BTF standard users)

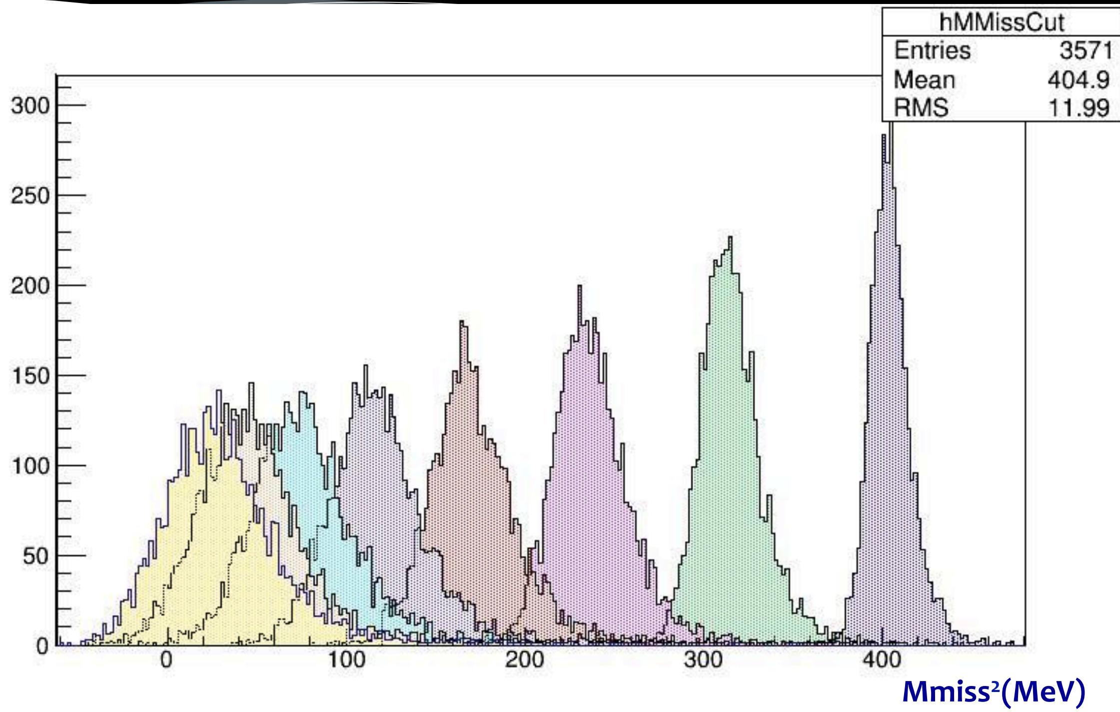


PADME

The **Dark** Side **is Calling** You

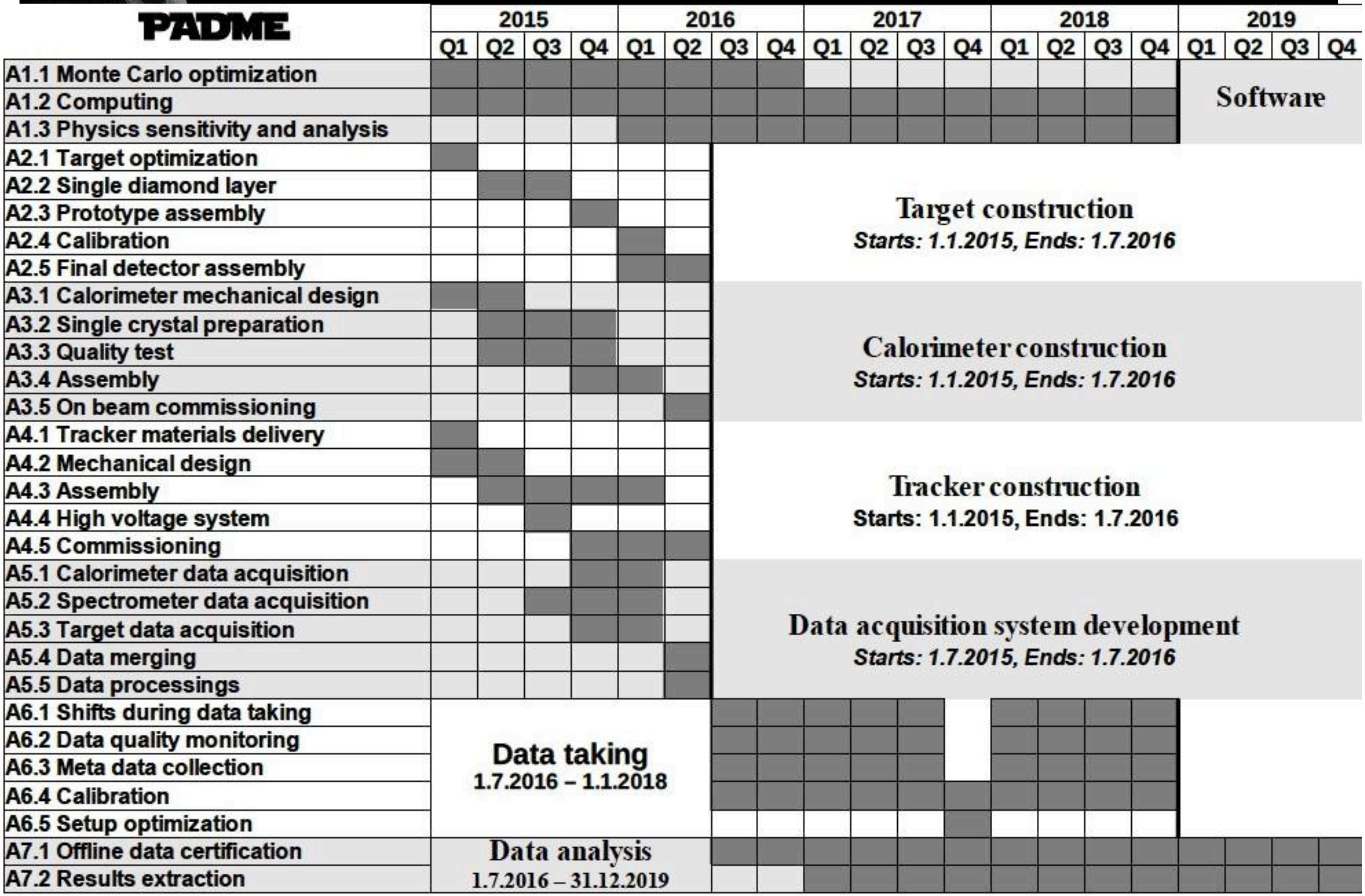
P. Valente - November 3rd, 2014


LINAC
550 MeV e+
800 MeV e−
BTF
XUV
X-ray
UV
IR
DAΦNE
KLOE
ACCUMULATOR
510 MeV



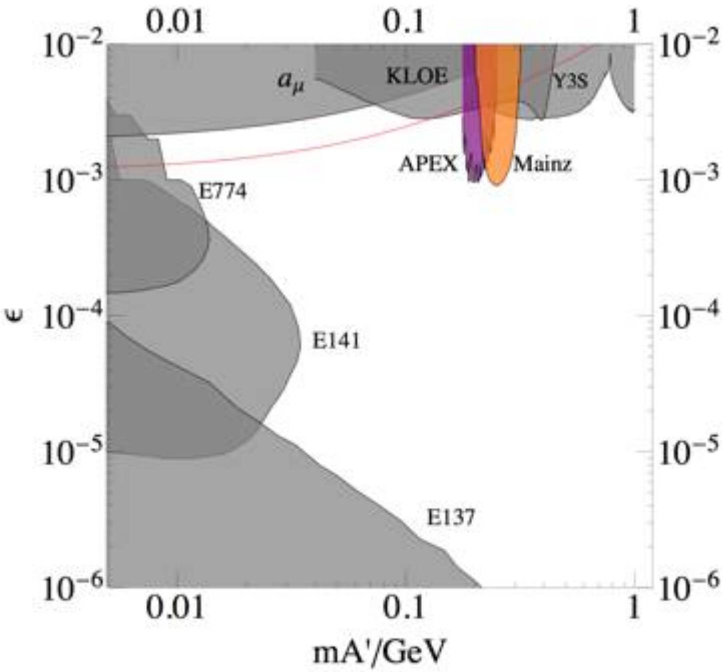
* Missing mass resolution in agreement with toy MC using
  * σ(E)/E =1.1%/√E ⊕ 0.4%/E ⊕1.2% [NIM A 718 (2013) 107–109]
  * Differences are ~ 10%
* Resolution is the result of combination of angular resolution energy resolution and angle energy correlation due to production

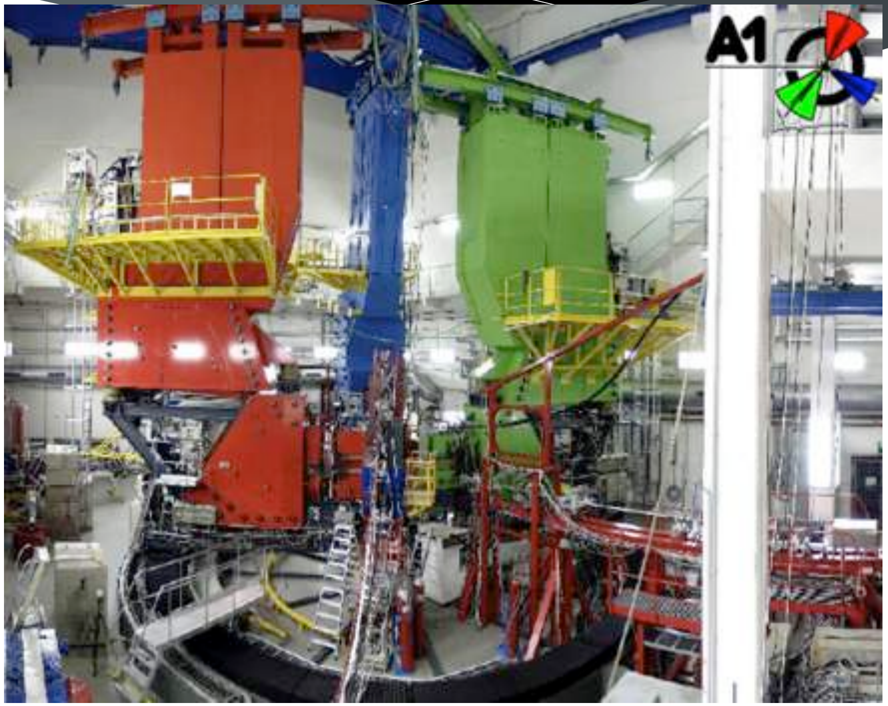
PADME


PADME
2015
2016
2017
2018
2019
Q1
Q2
Q3
Q4
A1.1 Monte Carlo optimization
A1.2 Computing
A1.3 Physics sensitivity and analysis
Software
A2.1 Target optimization
A2.2 Single diamond layer
A2.3 Prototype assembly
A2.4 Calibration
A2.5 Final detector assembly
Target construction
Starts: 1.1.2015, Ends: 1.7.2016
A3.1 Calorimeter mechanical design
A3.2 Single crystal preparation
A3.3 Quality test
A3.4 Assembly
A3.5 On beam commissioning
Calorimeter construction
Starts: 1.1.2015, Ends: 1.7.2016
A4.1 Tracker materials delivery
A4.2 Mechanical design
A4.3 Assembly
A4.4 High voltage system
A4.5 Commissioning
Tracker construction
Starts: 1.1.2015, Ends: 1.7.2016
A5.1 Calorimeter data acquisition
A5.2 Spectrometer data acquisition
A5.3 Target data acquisition
A5.4 Data merging
A5.5 Data processings
Data acquisition system development
Starts: 1.7.2015, Ends: 1.7.2016
A6.1 Shifts during data taking
A6.2 Data quality monitoring
A6.3 Meta data collection
A6.4 Calibration
A6.5 Setup optimization
Data taking
1.7.2016 – 1.1.2018
A7.1 Offline data certification
A7.2 Results extraction
Data analysis
1.7.2016 – 31.12.2019

Cost Category			Total in Euro
Direct Costs	**Personnel**	PI (5y)	225000
		Senior Staff	91000
		Postdocs	277000
		Students	
		Other	
	i. Total Direct costs for Personnel (in Euro)		593000
	Travel		80000
	Equipment		885000
	Other goods and services	Consumables	30000
		Publications (including Open Access fees), etc.	0
		Other (Audit)	10000
	ii. Total Other Direct Costs (in Euro)		1005000
A – Total Direct Costs (i + ii) (in Euro)			1598000
B – Indirect Costs (overheads) 25% of Direct Costs (in Euro)			399500
C1 – Subcontracting Costs (no overheads) (in Euro)			
C2 – Other Direct Costs with no overheads (in Euro)			
Total Estimated Eligible Costs (A + B + C) (in Euro)			**1997500**
Total Requested EU Contribution (in Euro)			1997500

MAMI A1



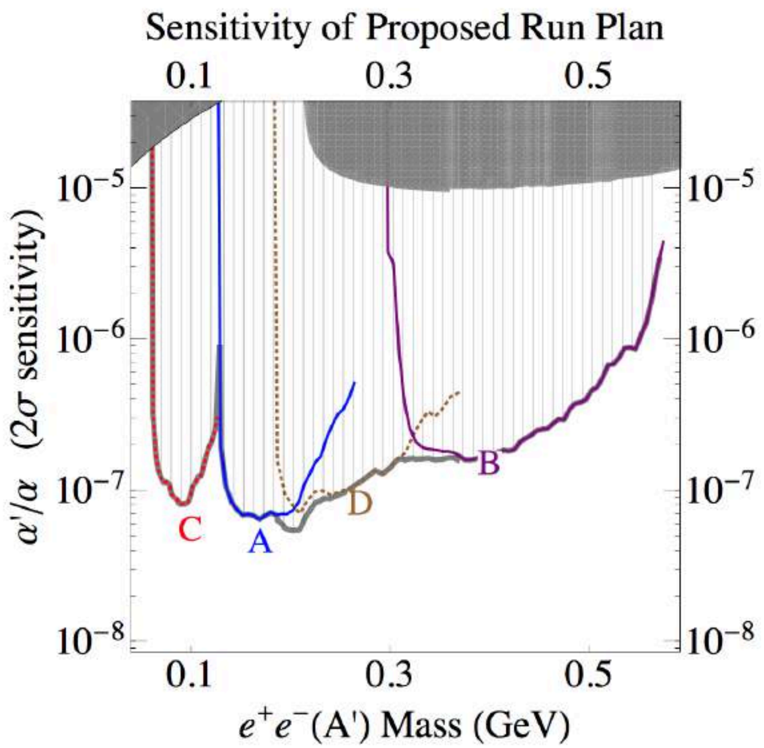


JLAB Hall-A APEX
n×1.1 GeV, continuous, 200 μA beam

MAMI A1
855 MeV, continuous, 90 μA beam

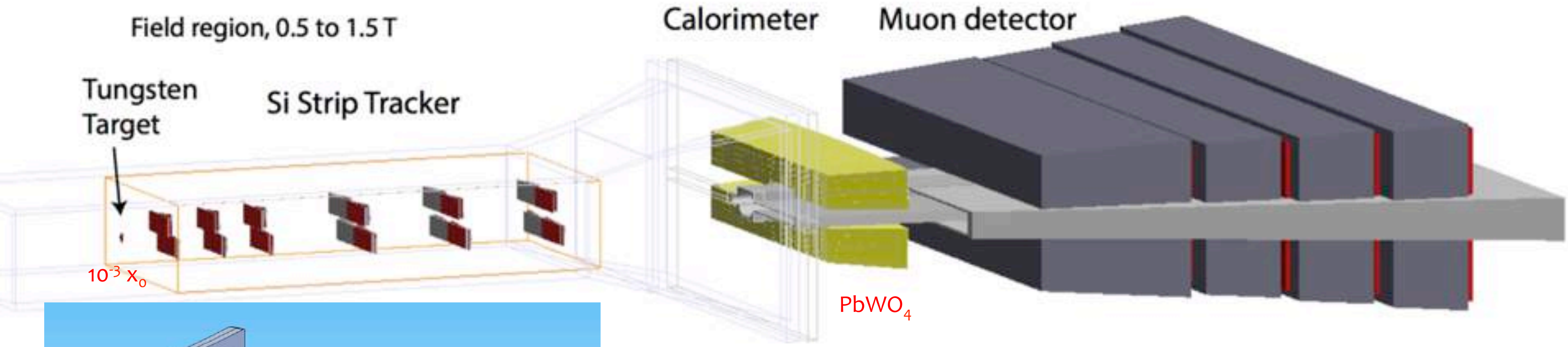
APEX

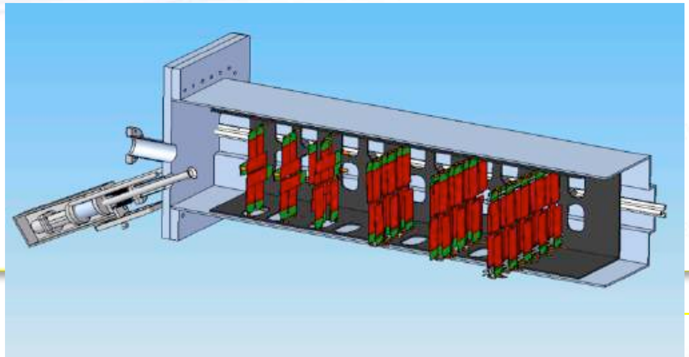
Settings	A	B	C	D
Beam energy (GeV)	2.302	4.482	1.1	3.3
Central angle	5.0°	5.5°	5.0°	5.0°
Effective angles	(4.5,5.5)	(5.25,6.0)	(4.5,5.5)	(4.5,5.5)
Target T/X_0 (ratio[a])	4.25% (1:1)	10% (1:1)	0.58% (1:3)	10% (1:1)
Beam current (μA)	80	80	80	80
Central momentum (GeV)	1.145	2.230	0.545	1.634
Singles (negative polarity)				
e^- (MHz)	4.5	0.7	6.	2.9
π^- (kHz)	640.	2200	36.	2500.
Singles (positive polarity)				
$\pi^+ + p$ (kHz)	640.	2200	36.	2500.
e^+ (kHz)	31.	3.6	24.	23.
Trigger/DAQ:				
Trigger[b] (kHz)	4.	0.4	3.2	3.4
Signal to background:				
Trident (Hz)	610	70	350	530
Two-step (Hz)	35	15	5	75
Background[c] (Hz)	70	1.3	70	35

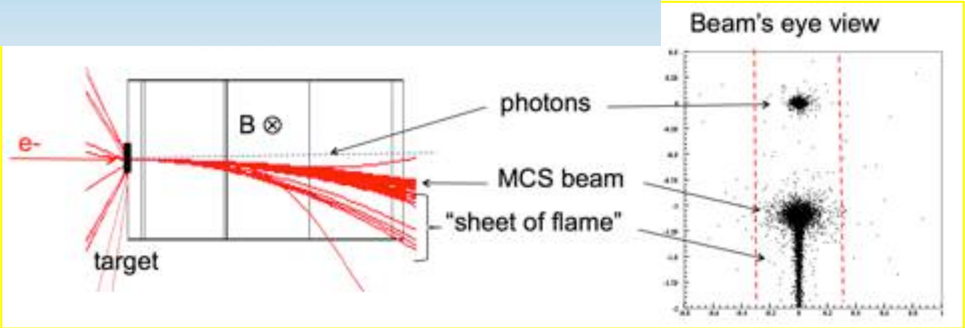


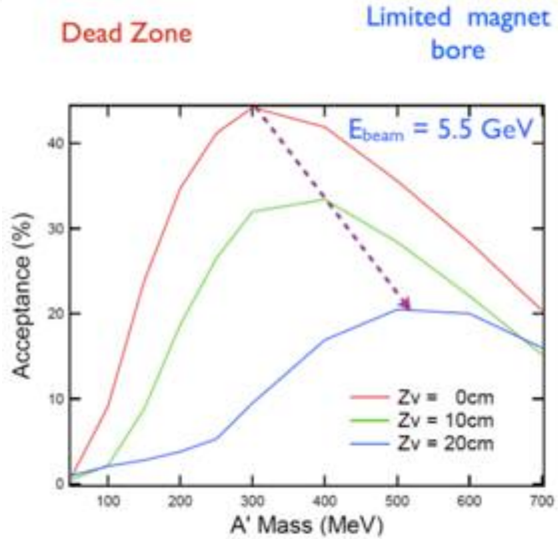
HPS

PADME









Detectors split in two halves to let the beam pass through

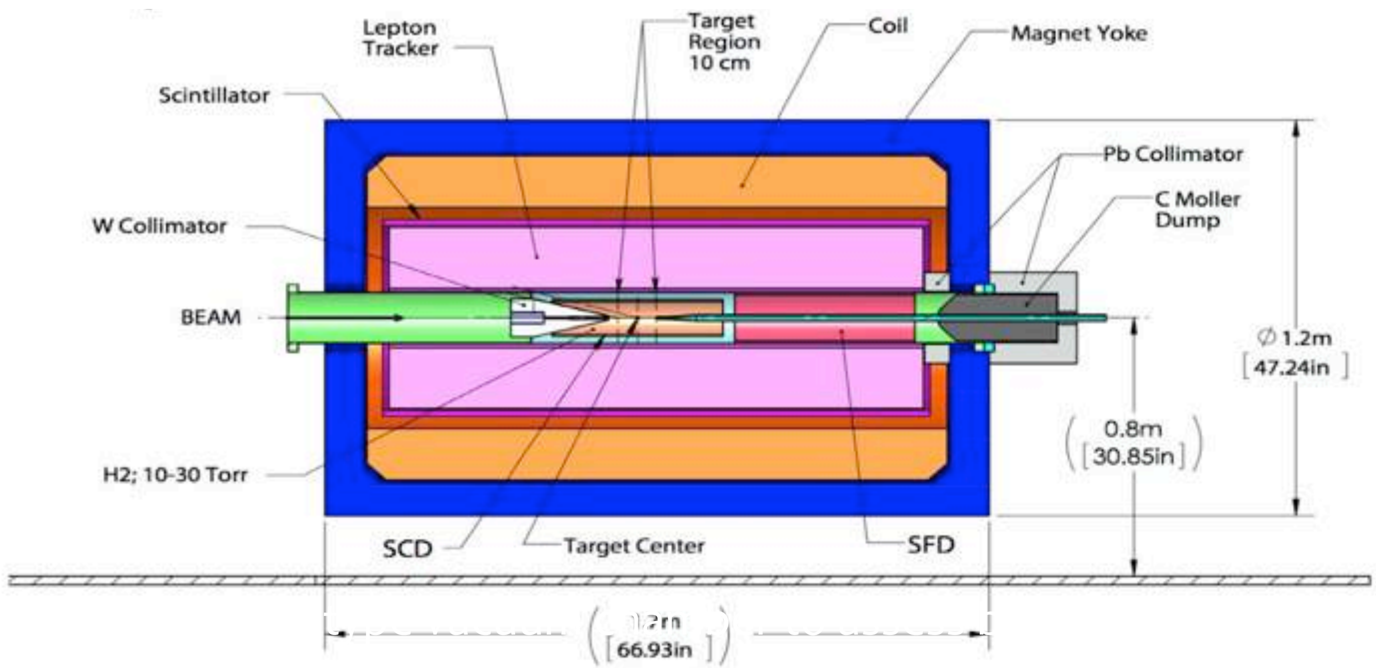
HPS beam

Parameter	Requirement/Expectation	Unit
E	2200 and 6600	MeV
$\delta p/p$	$< 10^{-4}$	
Current	> 100 and < 1000	nA
Current Instability	< 5	%
σ_x	< 30	μm
σ_y	< 30	μm
Position Stability	< 30	μm
Divergence	< 100	μrad
Beam Halo (> 5σ)	$< 10^{-5}$	

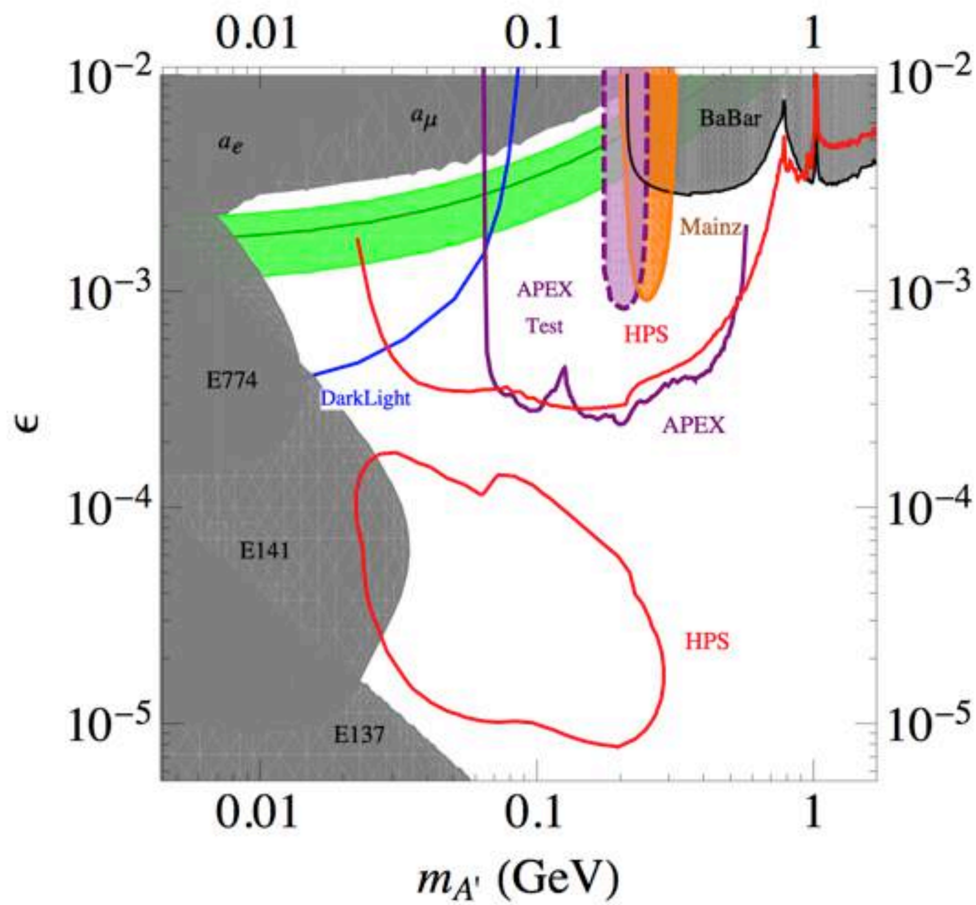
DarkLight

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

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

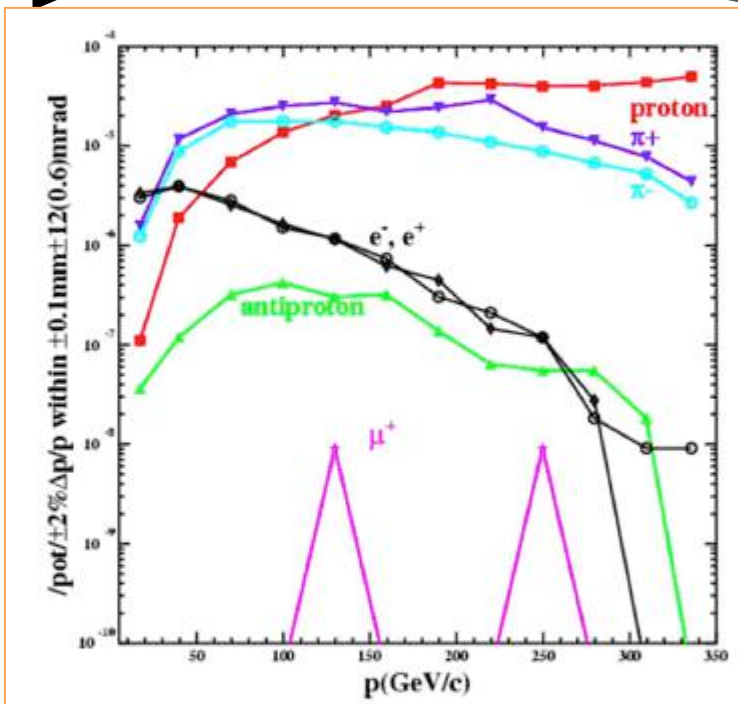


Dark photon at JLAB + MAinz



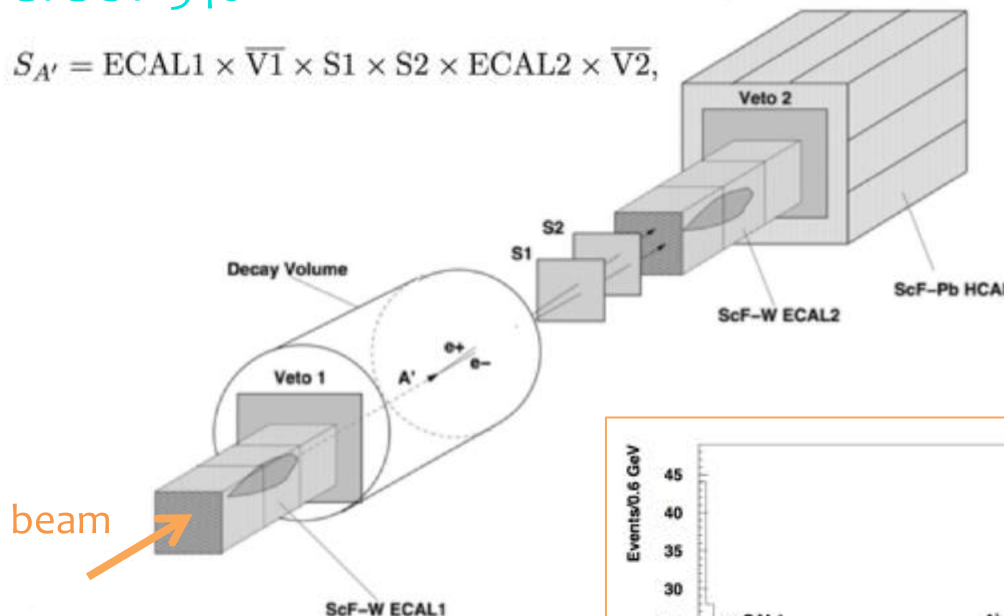
P-348 at CERN SPS

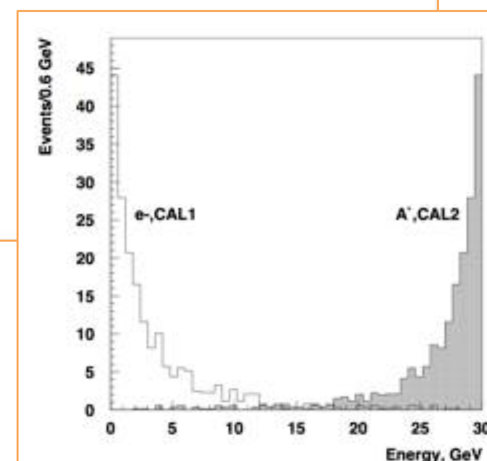
H4 high purity electron beam, <1% contamination required (tertiary, from γ conversions)



SPSC-P-348

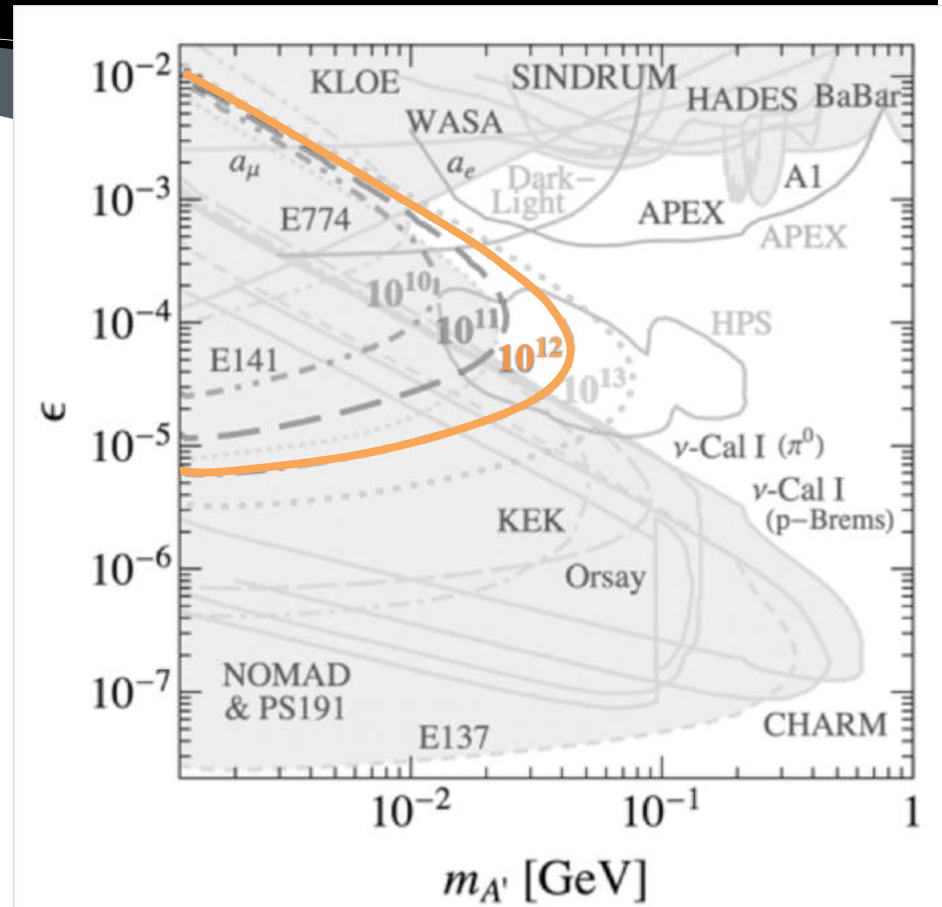
$$S_{A'} = \mathrm{ECAL1} \times \overline{\mathrm{V1}} \times \mathrm{S1} \times \mathrm{S2} \times \mathrm{ECAL2} \times \overline{\mathrm{V2}},$$





P-348 at CERN SPS

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

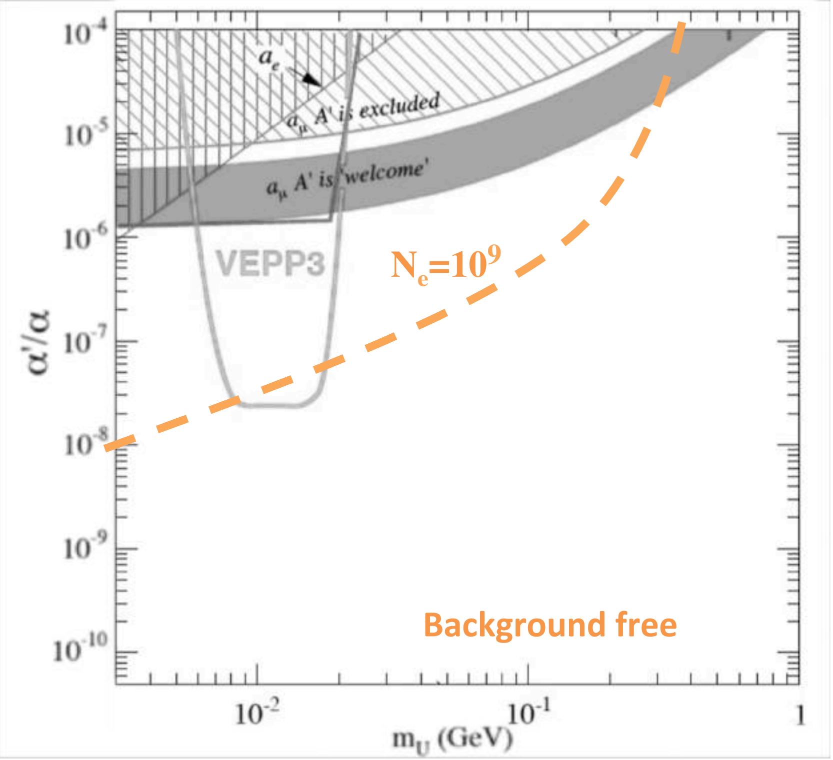


P-348 at CERN SPS

- Also proposal for A' →invisible search

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

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



Background assessment run requested for 2015, 10^{11} electrons

PADME missing mass resolution

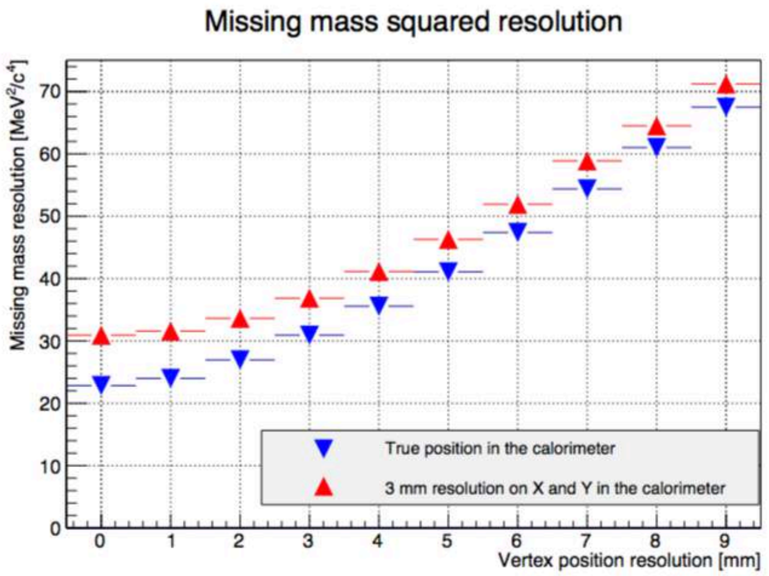


Figure 5: *Dependence of the missing mass squared resolution on the vertex position resolution. The mass of the U-boson is assumed to be 15 MeV.*

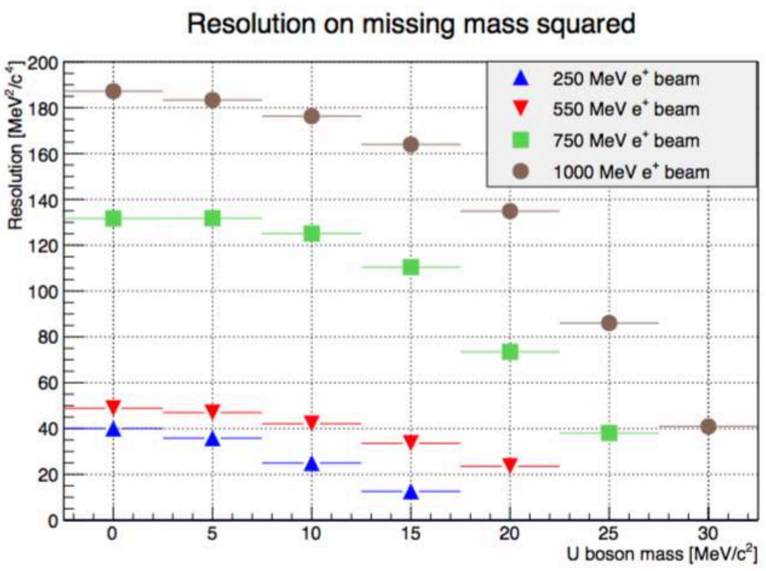
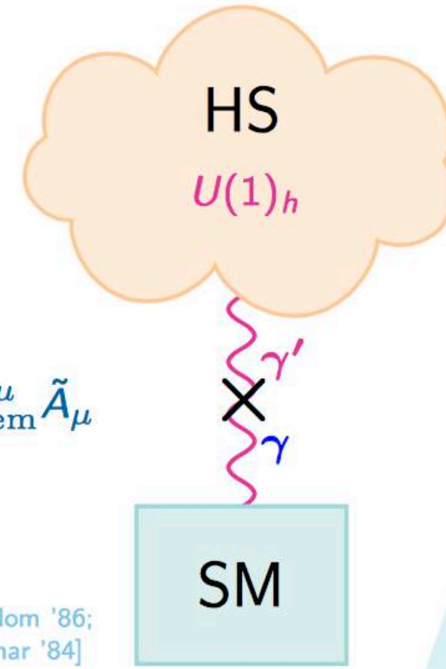


Figure 6: *Missing mass resolution as a function of the U-boson mass for four different energies of the impinging positron beam*

Dark/Hidden Photon and Kinetic Mixing



- gauge boson of extra $U(1)$ symmetry
- low energy effective Lagrangian

$$\mathcal{L}_{\rm eff} \supset -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{\chi}{2}\tilde{X}_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\tilde{m}^2_{\gamma'}\tilde{X}_\mu\tilde{X}^\mu + e j^\mu_{\rm em}\tilde{A}_\mu$$

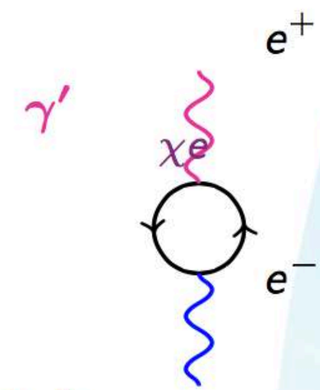
- dominant interaction: kinetic mixing of hidden & visible $U(1)$

  e.g. from integrating out heavy particles charged under both $U(1)$s [Okun '82; Holdom '86; Galison, Manohar '84]

  estimate for kinetic mixing parameter χ: $\chi \sim 10^{-3} - 10^{-4}$

- e.g. broken by Higgs mechanism

  γ' can be light with $m_{\gamma'} \sim$ MeV − GeV



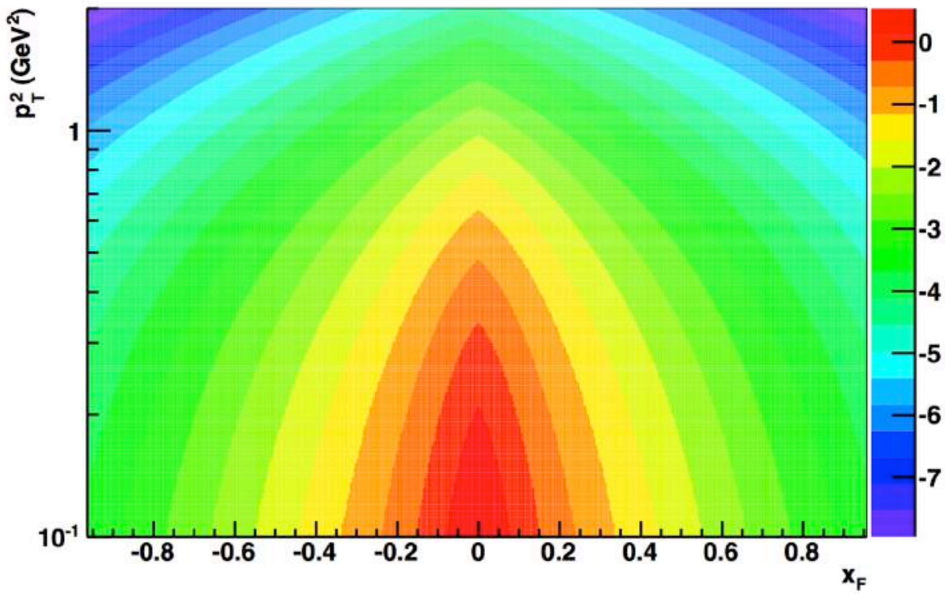
- diagonalize kinetic terms:

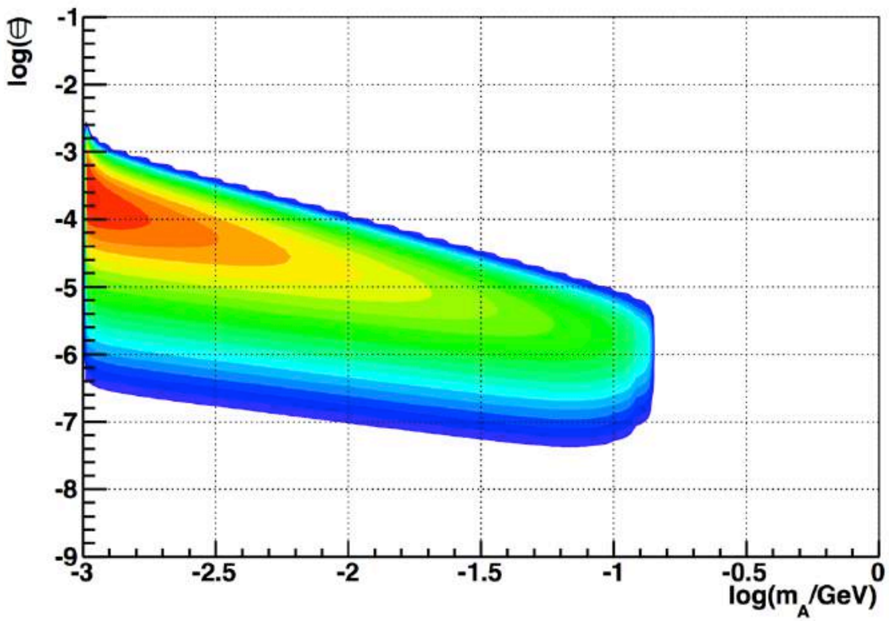
$$\mathcal{L}_{\rm eff} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}X_\mu X^\mu + e j^\mu_{\rm em}A_\mu + \boxed{e\chi j^\mu_{\rm em}X_\mu} + \mathcal{O}(\chi^2)$$

$\Rightarrow$ γ' couples to SM particles with strength $\chi \times$ electric charge

$$\frac{d\sigma}{dx_e} = 4\,\alpha^3 \epsilon^2\,\chi\,\sqrt{1-\frac{m_x^2}{E_e^2}}\;\frac{1 - x_e + \frac{1}{3}x_e^2}{m_x^2 \frac{1-x_e}{x_e} + m_e^2 x_e}\,.$$

Experiment	Target	E_0	N_e	L_{sh}	L_{dec}	E_{thr}	r_{Acc}	$N_{95\%}$
E137	Al	20	1.87×10^{20}	179	204	2	1.5	3
E141	W	9	2×10^{15}	0.12	35	4.5	0.0375	3419
E774	W	275	5.2×10^{9}	0.3	2	27.5	0.1	18
KEK	W	2.5	1.69×10^{17}	2.4	2.2	0.1	0.047	3
Orsay	W	1.6	2×10^{16}	1	2	0.75	0.15	3
JLab	Al	12	10^{20}	10			1	


p_T^2 (GeV^2)
1
10^{-1}
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
x_F
0
-1
-2
-3
-4
-5
-6
-7


log(∈)
-1
-2
-3
-4
-5
-6
-7
-8
-9
-3
-2.5
-2
-1.5
-1
-0.5
0
log(m_A/GeV)