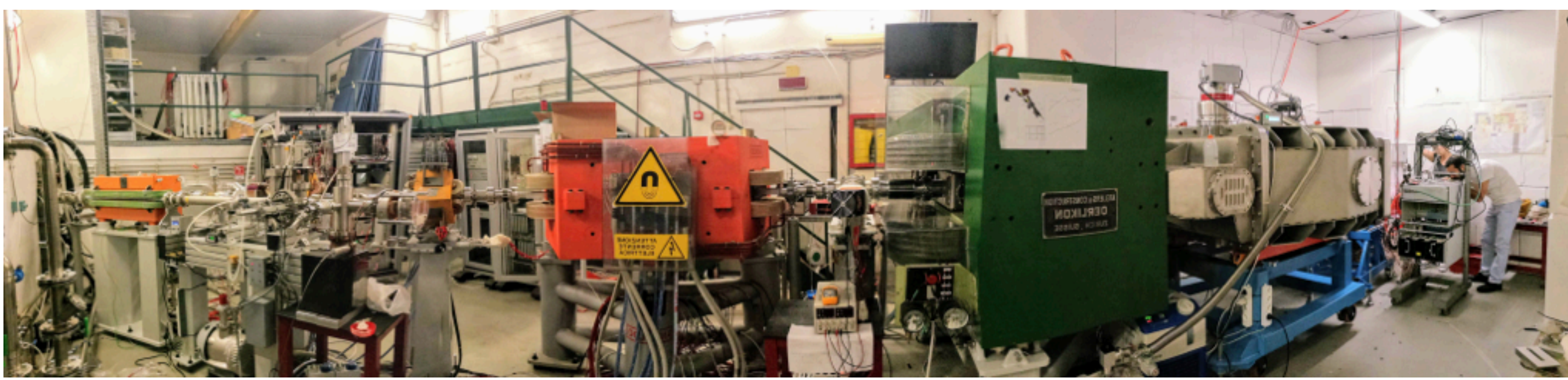
PADME experiment at the Beam Test Facility of Laboratori Nazionali di Frascati

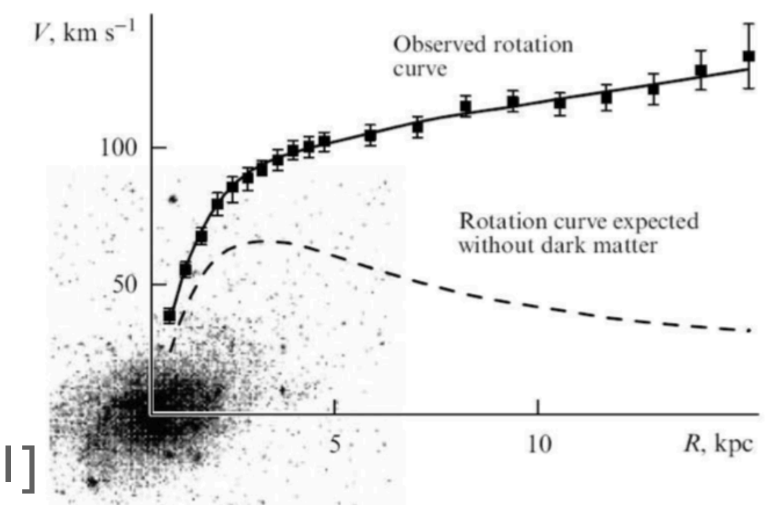
Isabella Oceano on behalf of PADME collaboration

9th Beam Telescopes & Test Beams Workshop

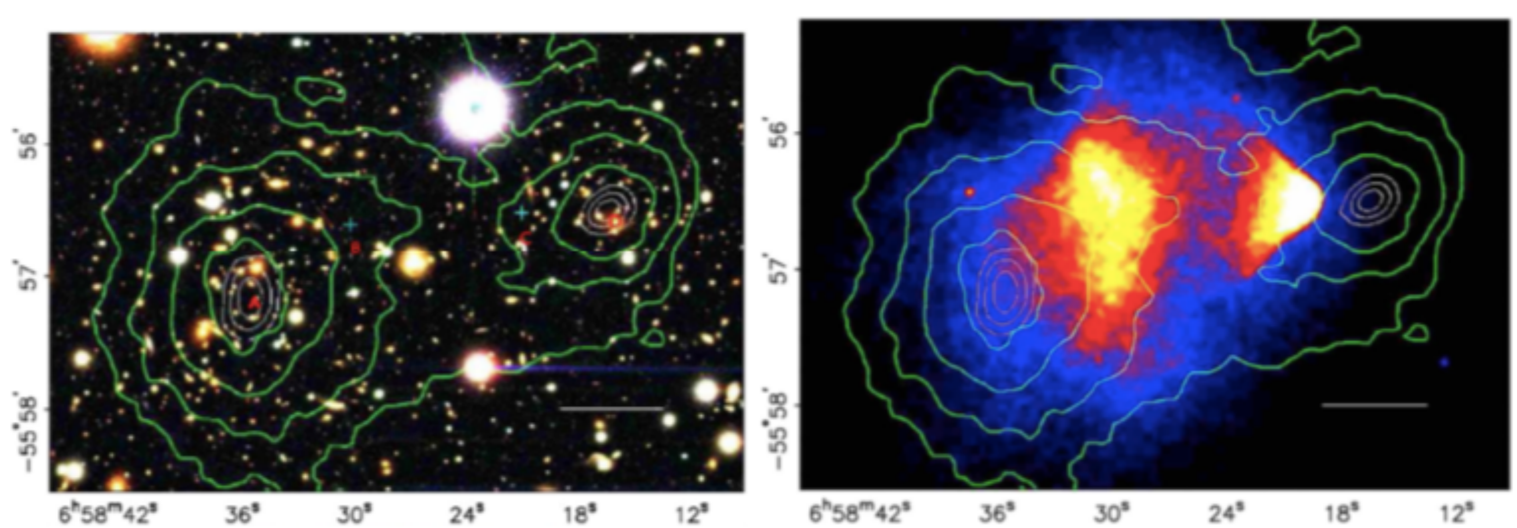


THE MYSTERY OF DARK MATTER

- The visible matter alone is not able to explain some astrophysical and cosmological phenomena
  - Rotation velocity of spiral galaxies
  - Gravitational lensing → Bullet Cluster
  - …



[1]



[2]

A NEW GAUGE BOSON

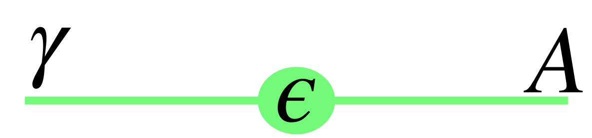
- The WIMP paradigm is challenged by LHC. A new idea introduces a hidden sector of particles interacting through a portal with the particles of the visible sector.

- A possible scenario: a New Gauge symmetry $U_D(1)$ in the hidden sector [1]

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

- Very weak interaction with the standard model particles via dark photon - photon mixing

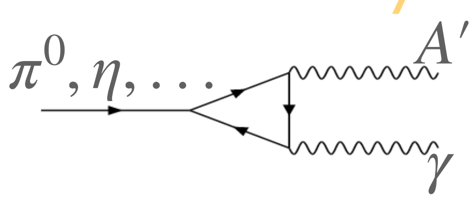
$$L_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$



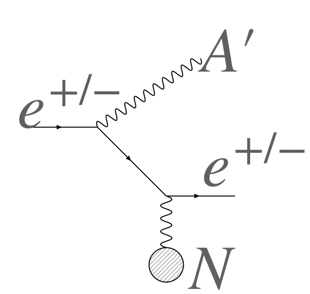
ϵ : kinetic mixing coefficient

Production mechanisms

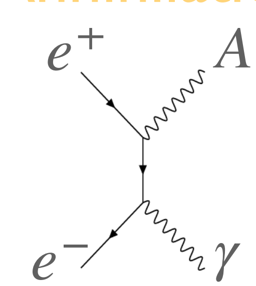
Meson decay



Bremsstrahlung

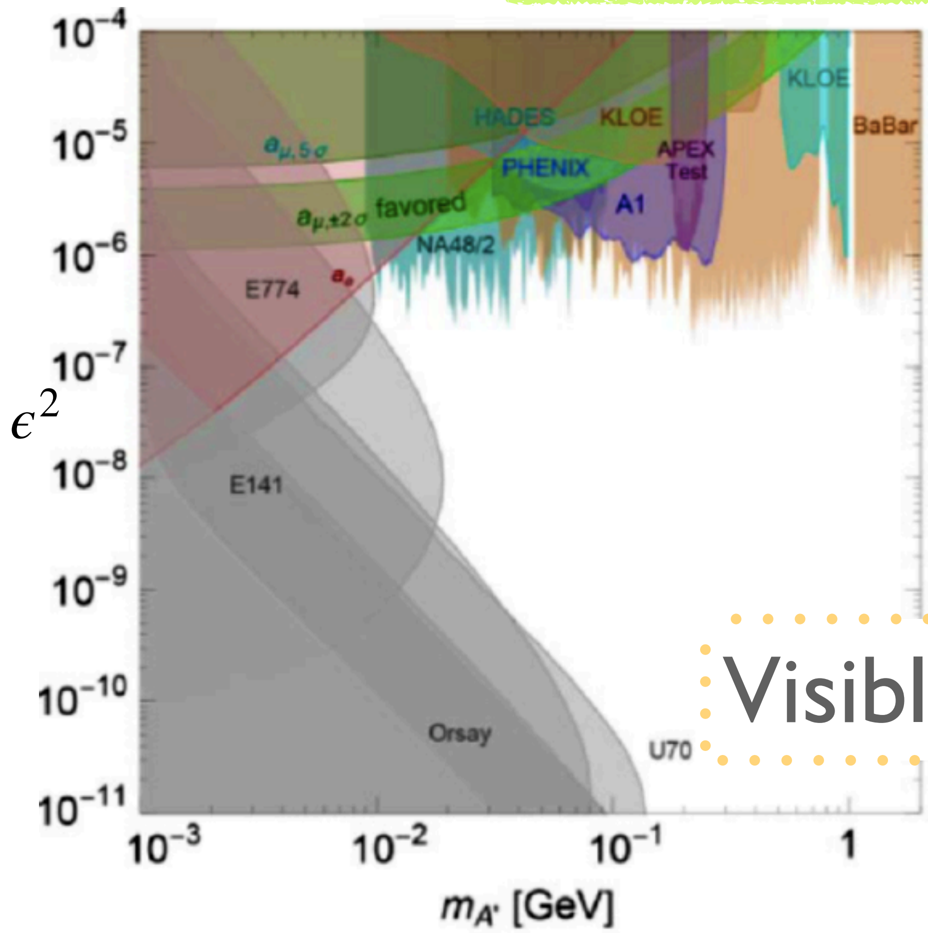


Annihilation

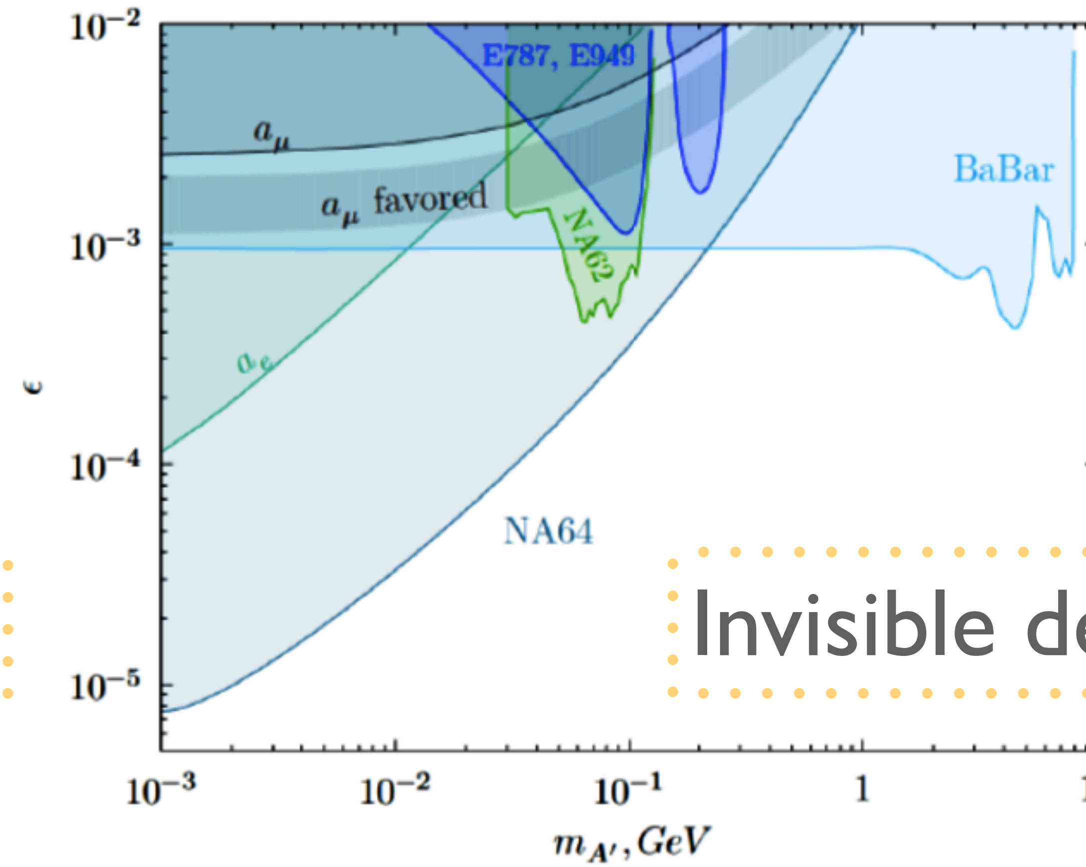


A' PARAMETER SPACE

Decays
– To SM model particles if $M_{DM} > M_{A'} > 2m_e$
– To DM (invisible) particles if $M_{DM} < M_{A'}$



Visible decay



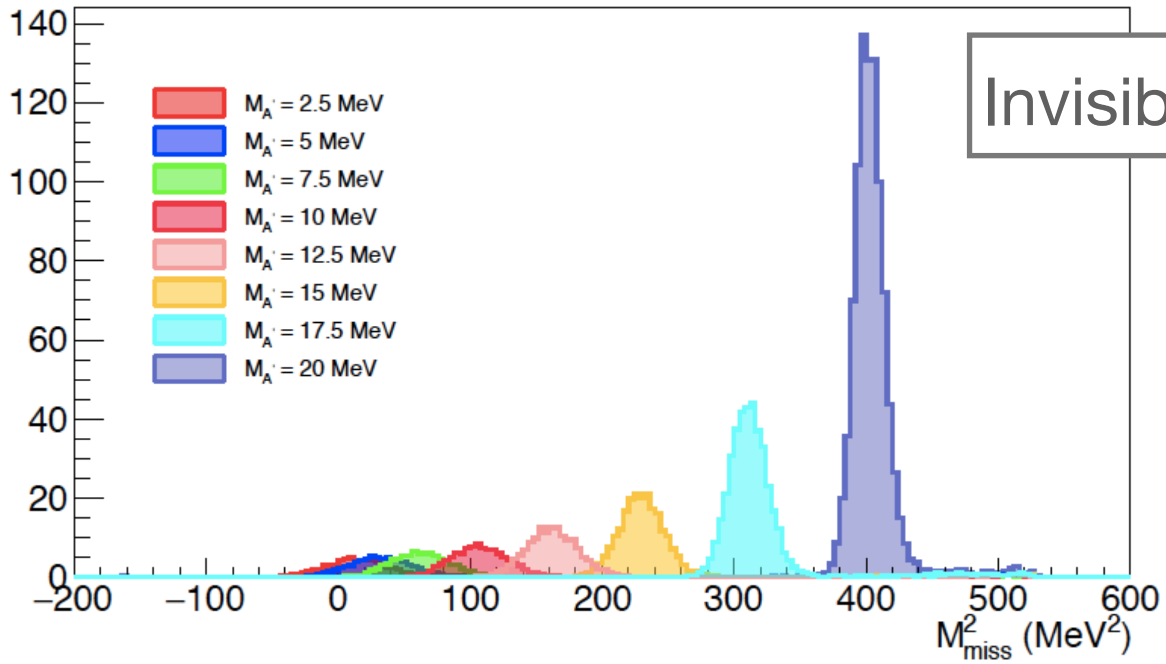
Invisible decay

- searches into visible decay modes
  - e+e- colliders
  - e- or p beam+dump / thick target
  - e- beam + thin target
  - LHC

- searches into invisible particles
  - indirect limits
  - model dependent bounds
  - e+ beam experiments: PADME concept and potential

THE APPROACH OF PADME

[1] (4×10^{13} Positron On Target POT)



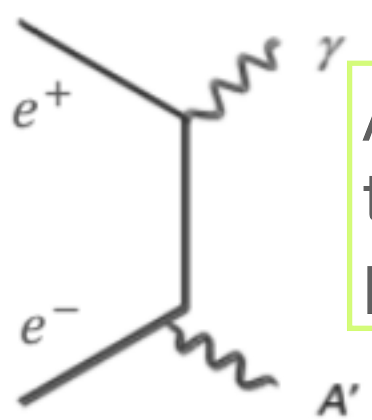
Invisible decay of A' → missing mass method

Possible A' production process

$$e^+e^- \to \gamma A'$$

Detection though the missing mass method

$$M^2_{miss} = (p_{e^-} + p_{beam} - p_\gamma)^2$$



A positron beam on a fixed target may produce a photon and a dark photon

$$\sigma(e^+e^- \to A'\gamma) \simeq 37\text{nb}$$

$$M_{A'} = 10 \text{ MeV}$$

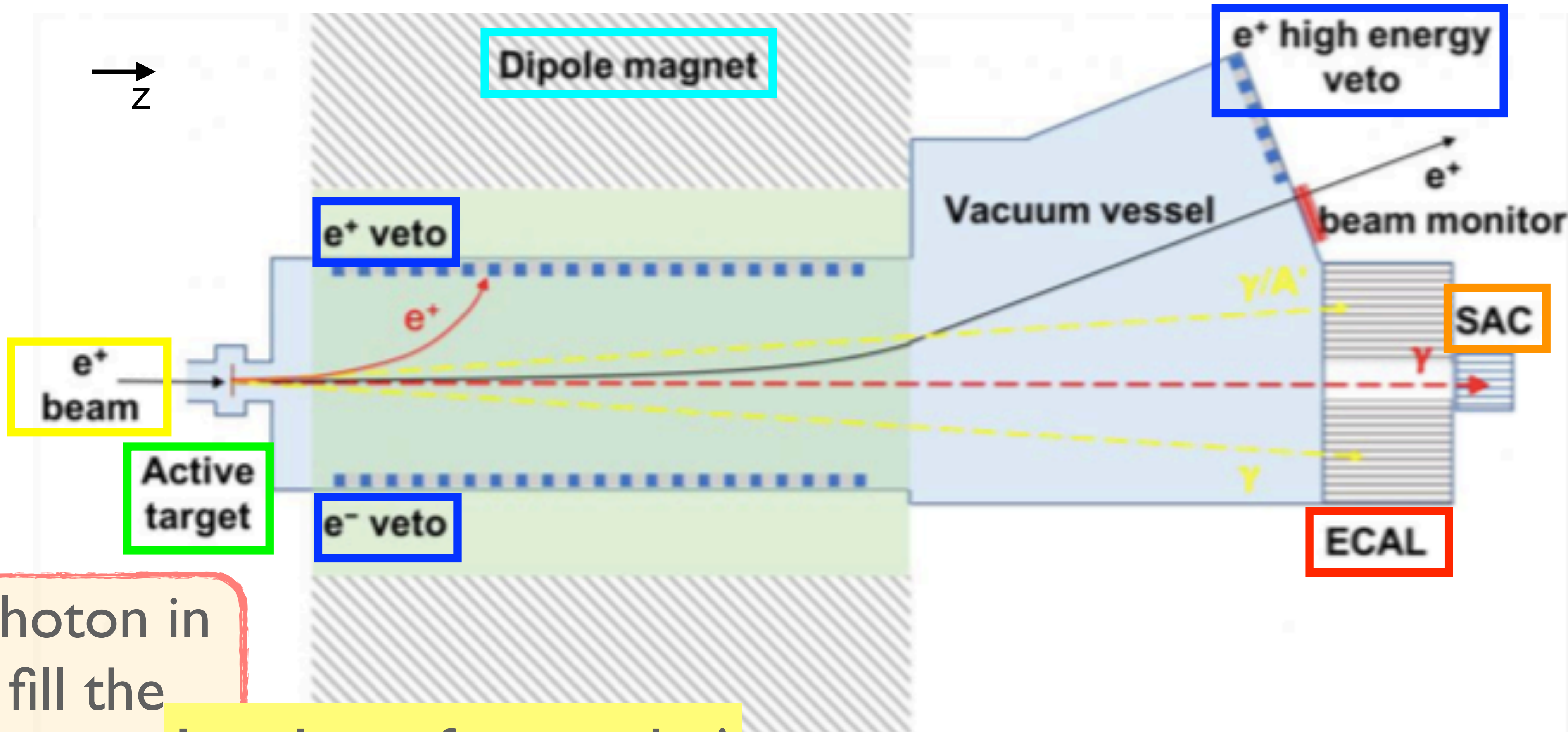
$$\epsilon^2 \simeq 10^{-6}$$

A' mass inferred from energy momentum conservation. A good knowledge of the photon features gives us a good resolution on missing mass

PADME mass reach $M_{A'} \leq 23.7$ MeV for $E_{e^+} = 550$ MeV

PADME EXPERIMENT

- The positron beam impinges on the diamond target and afterwards it is bent by a magnetic field of 0.5 T.
- A veto systems for charged particles, made of two arrays of plastic scintillator bars, inside the magnet, can detects positrons and electrons from interactions in the target.
- To measure energy and direction of the ordinary photons a cylindrical BGO calorimeter (ECAL) with a central squared hole (100 x 100 mm^2) is used.
- Behind ECAL the Small Angle Calorimeter (SAC), made of a 5 x 5 PbF_2 crystals, readout based on fast photomultipliers.

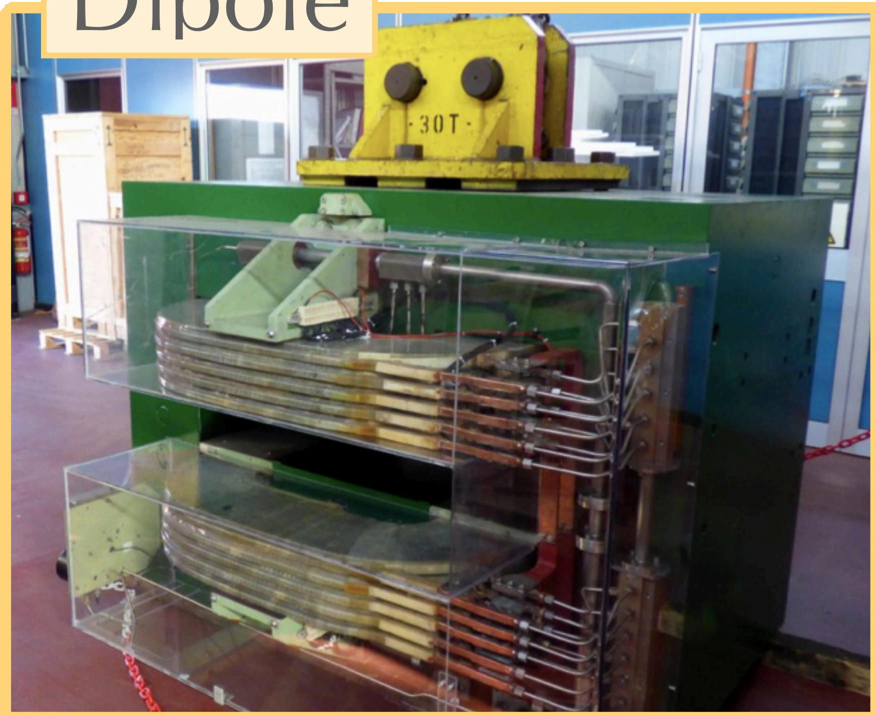


Events with only a photon in ECAL are used to fill the missing mass spectrum

Looking for peaks!

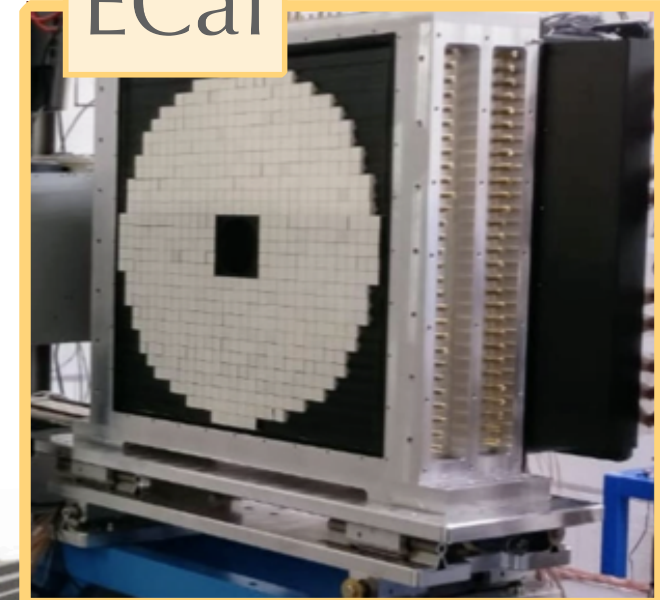
PADME SUBDETECTORS IN A NUTSHELL

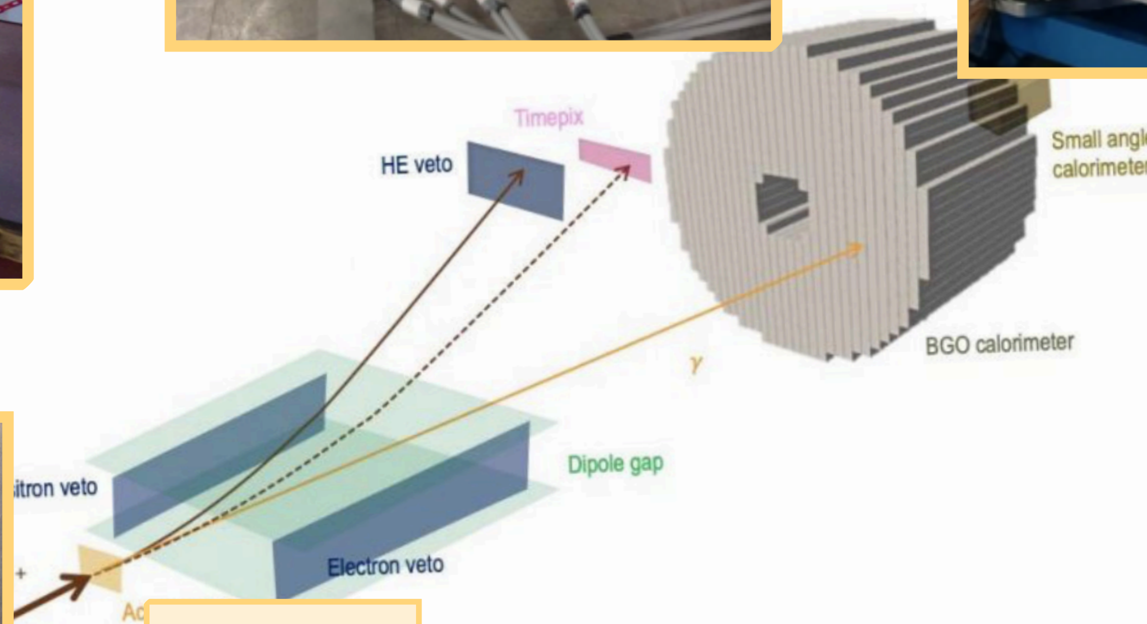
Dipole



HEP-veto

ECal





SAC

Diamond target

PVeto

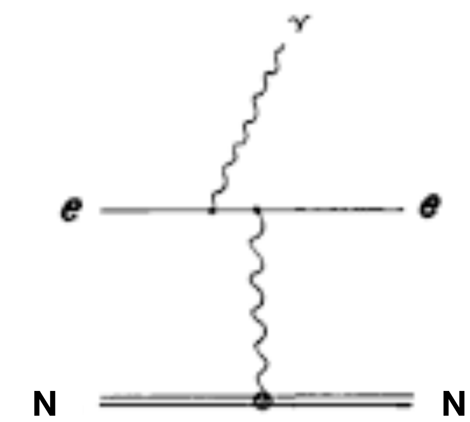
EVeto

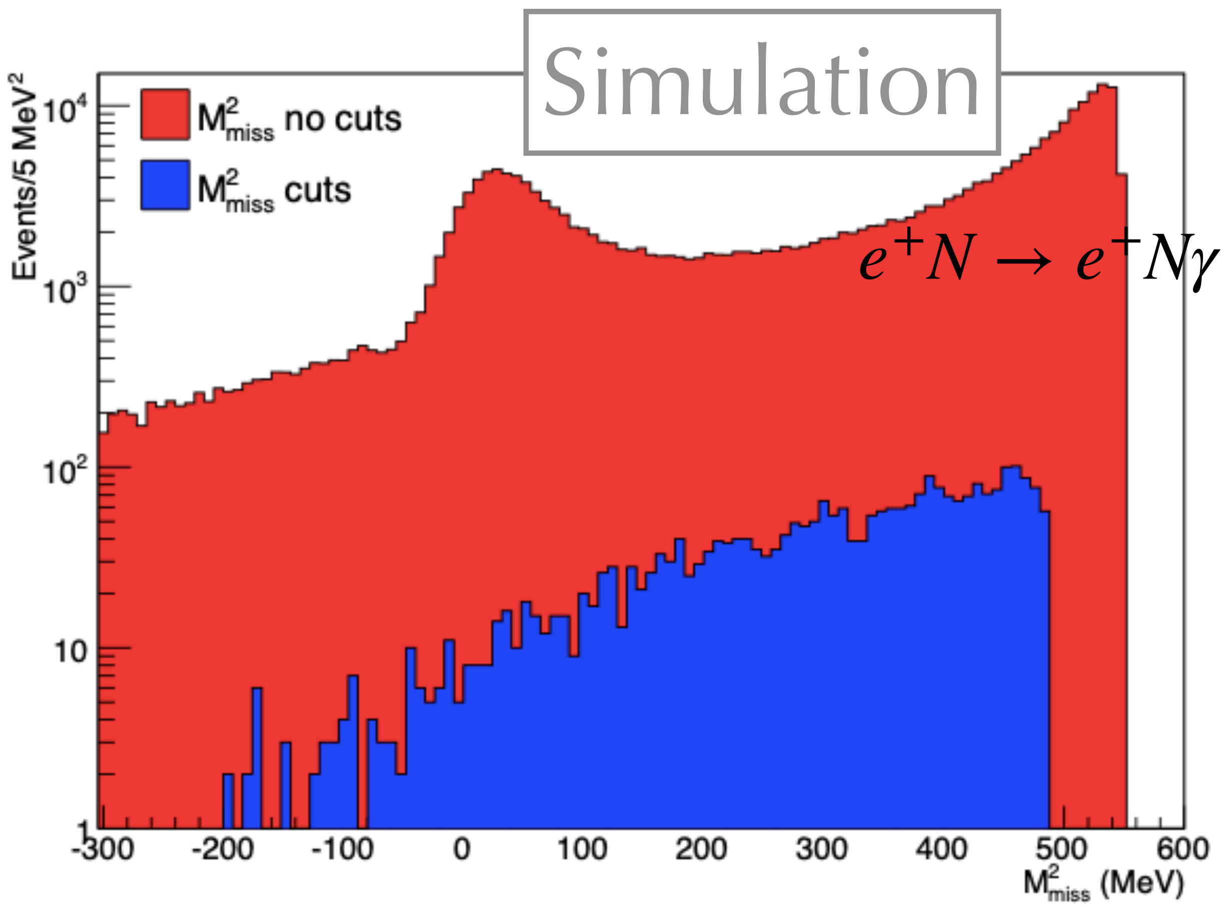
Backgrounds

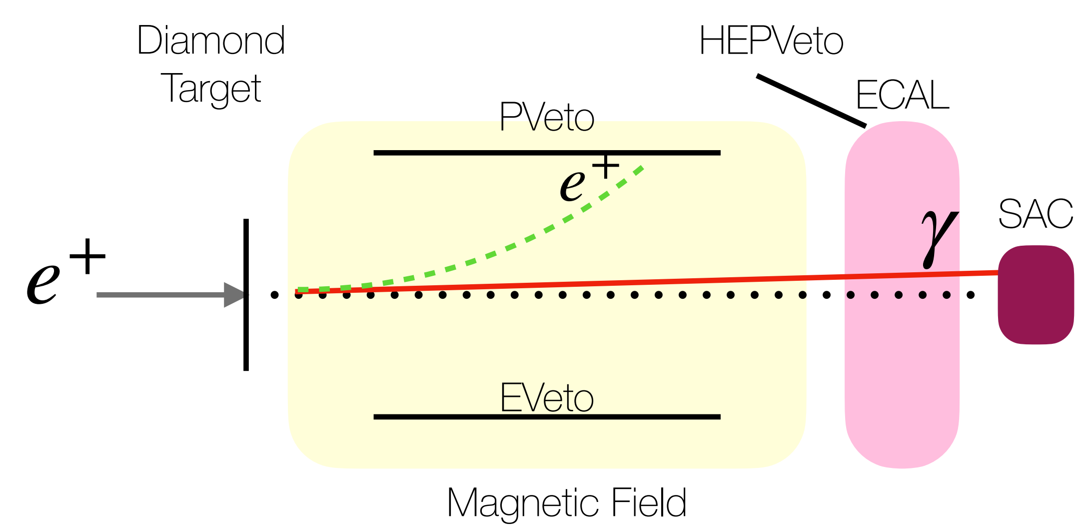
- Bremsstrahlung in the field of the target nuclei $e^+N \rightarrow e^+N\gamma$
  - A photon (preferentially of low energy) in ECAL + a positron in the veto
  - Positron inefficiency gives high M_{miss}

$E_\gamma > 1$ MeV

$\sigma(e^+N \rightarrow e^+N\gamma) = 4000$ mb

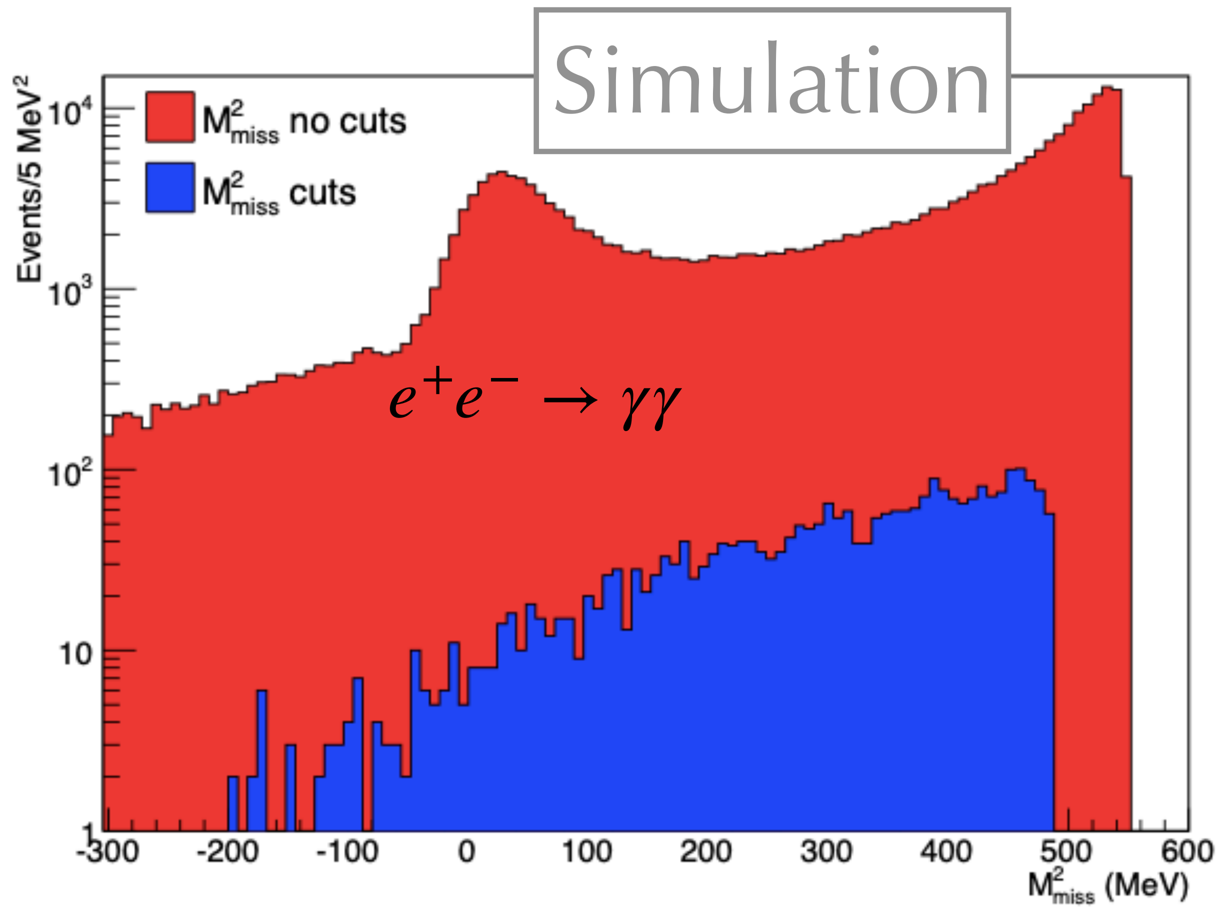


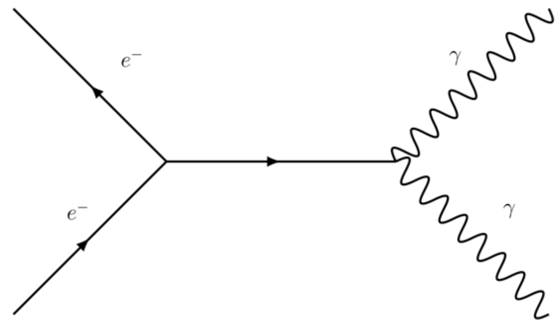




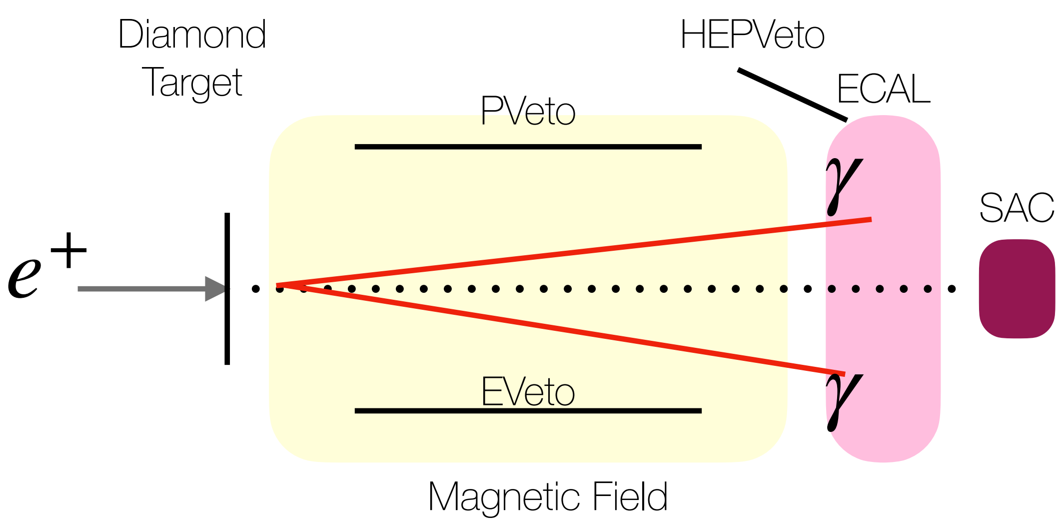
BACKGROUNDS

- 2 photon annihilation $e^+e^- \to \gamma\gamma$
    - symmetric in photon azimuth; correlated energy and theta
    - Photon inefficiency gives $M_{miss} = 0$ MeV



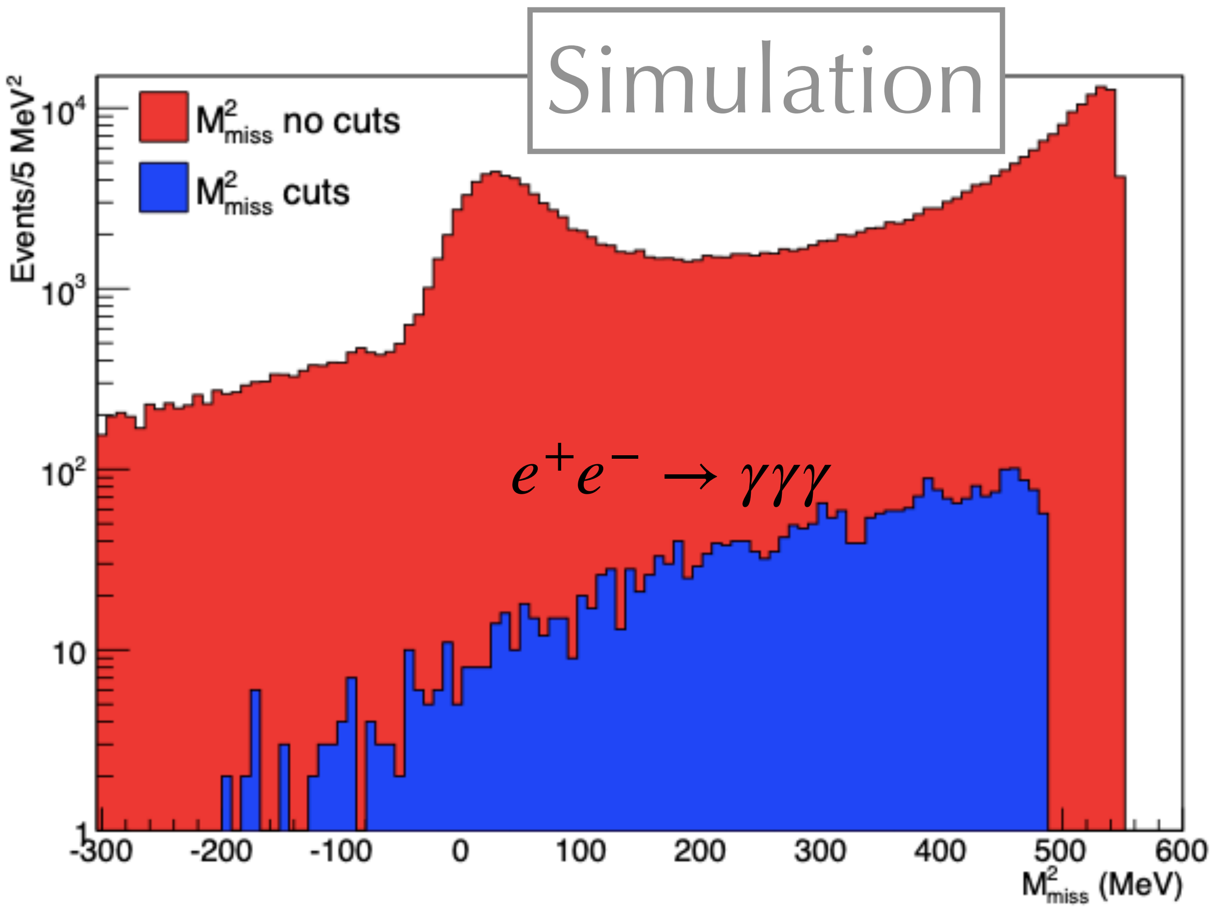


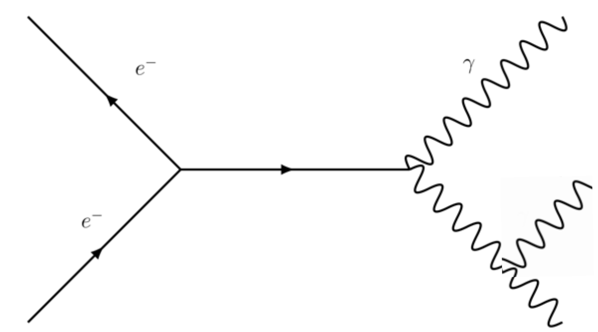
$\sigma(e^+e^- \to \gamma\gamma) = 1.55$ mb



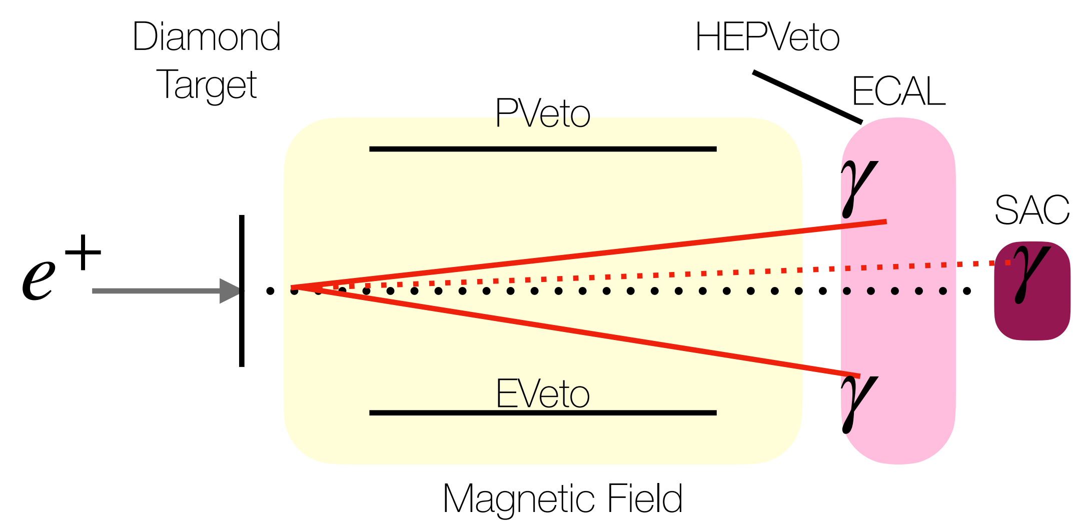
BACKGROUNDS

- 3 photon annihilation $e^+e^- \to \gamma\gamma\gamma$
  - $2\ \gamma$ symmetry is lost – reduced veto capability
  - Non peaking M_{miss}





$$\sigma(e^+e^- \to \gamma\gamma\gamma) = 7.5 \times 10^{-2}\ \text{mb}$$

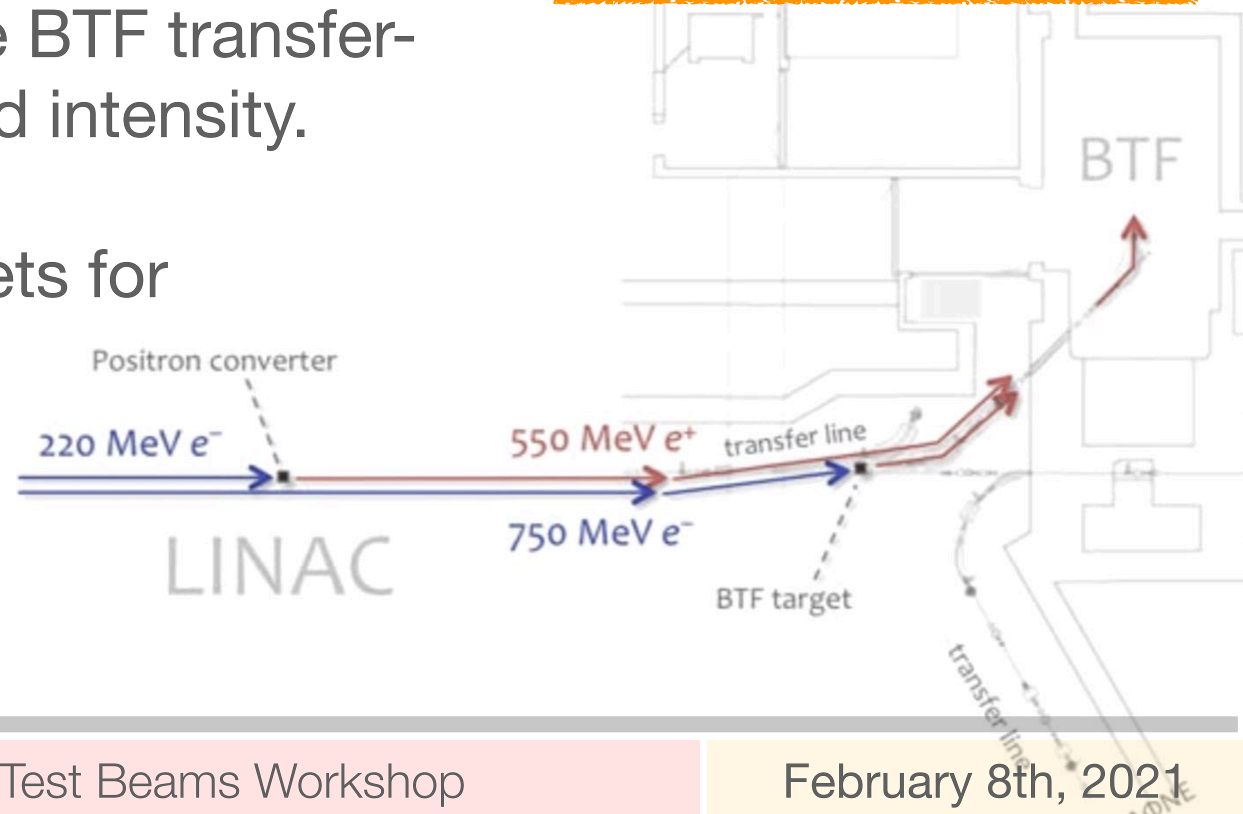


PADME POSITRON BEAM

- PADME uses the positron beam of the Beam Test Facility of the Laboratori Nazionali di Frascati
- Primary electrons from a gun can be accelerated up to 800 MeV
- **Primary positrons** are produced in a converter (2 X_0 W-Re target) by 220 MeV electrons
  - Captured positrons accelerated up to 550 MeV
- **Secondary positron** beam produced by a BTF 1.7 X_0 Cu target. Energy selection collimation on the BTF transfer-line for defining momentum, spot size, and intensity.
- Transfer line: 2 FODO quadrupoles doublets for focussing

Positron beam parameters:
- 1% energy spread
- 1.5 mm spot size
- 1 mrad emittance

-50 Hz pulsed beam
-300 ns pulse maximum duration
-~10000 e+/pulse

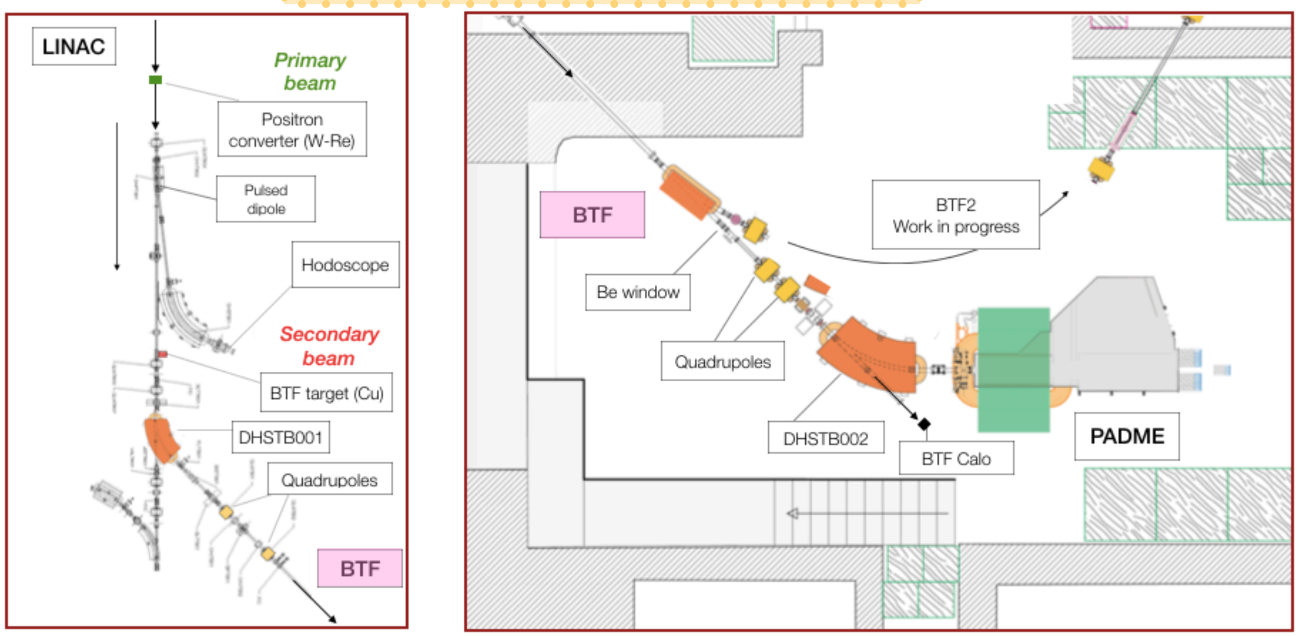


PADME DATA TAKING

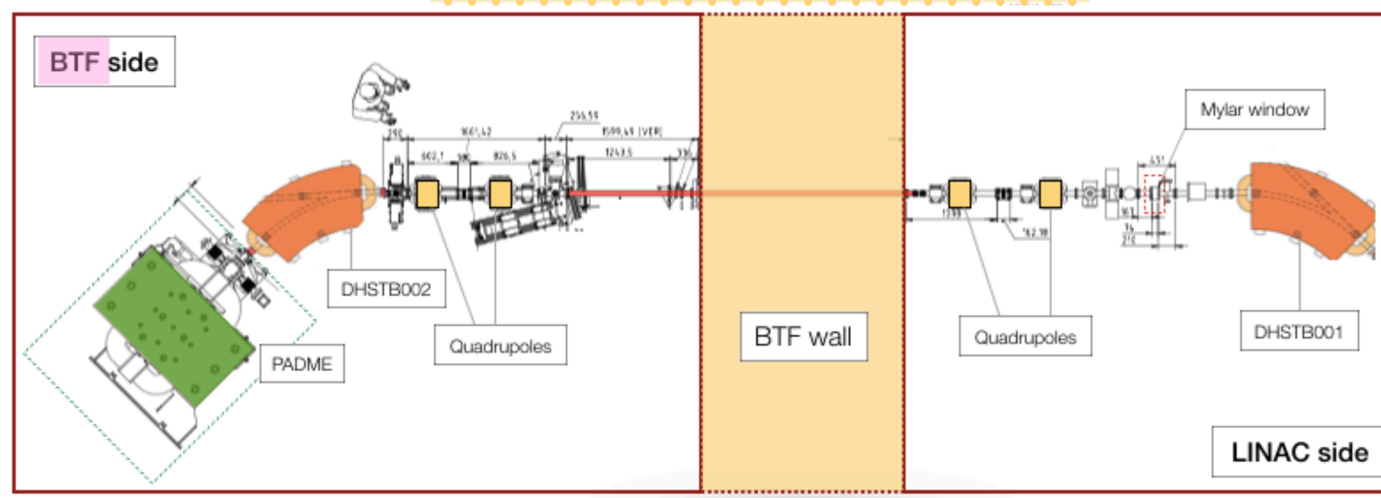
- PADME stated to took data in September 2018
- Run I (September 2018 - March 2019) PADEME took data with a secondary beam and for few days with a primary beam
- July 2019 beam line refurbished after an accident
- Run II (September - December 2020) primary beam

+ several tests beam

Run I beam line



Run II beam line



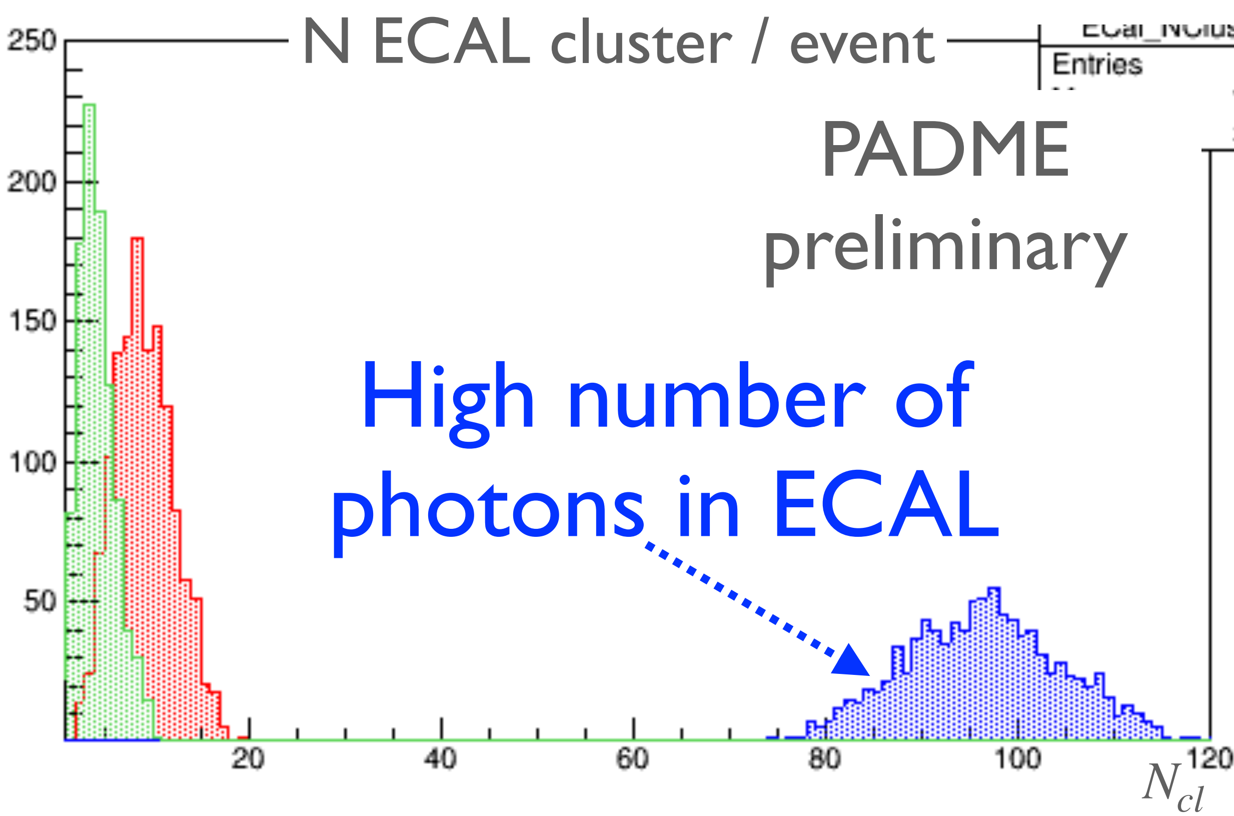
PADME DATA TAKING

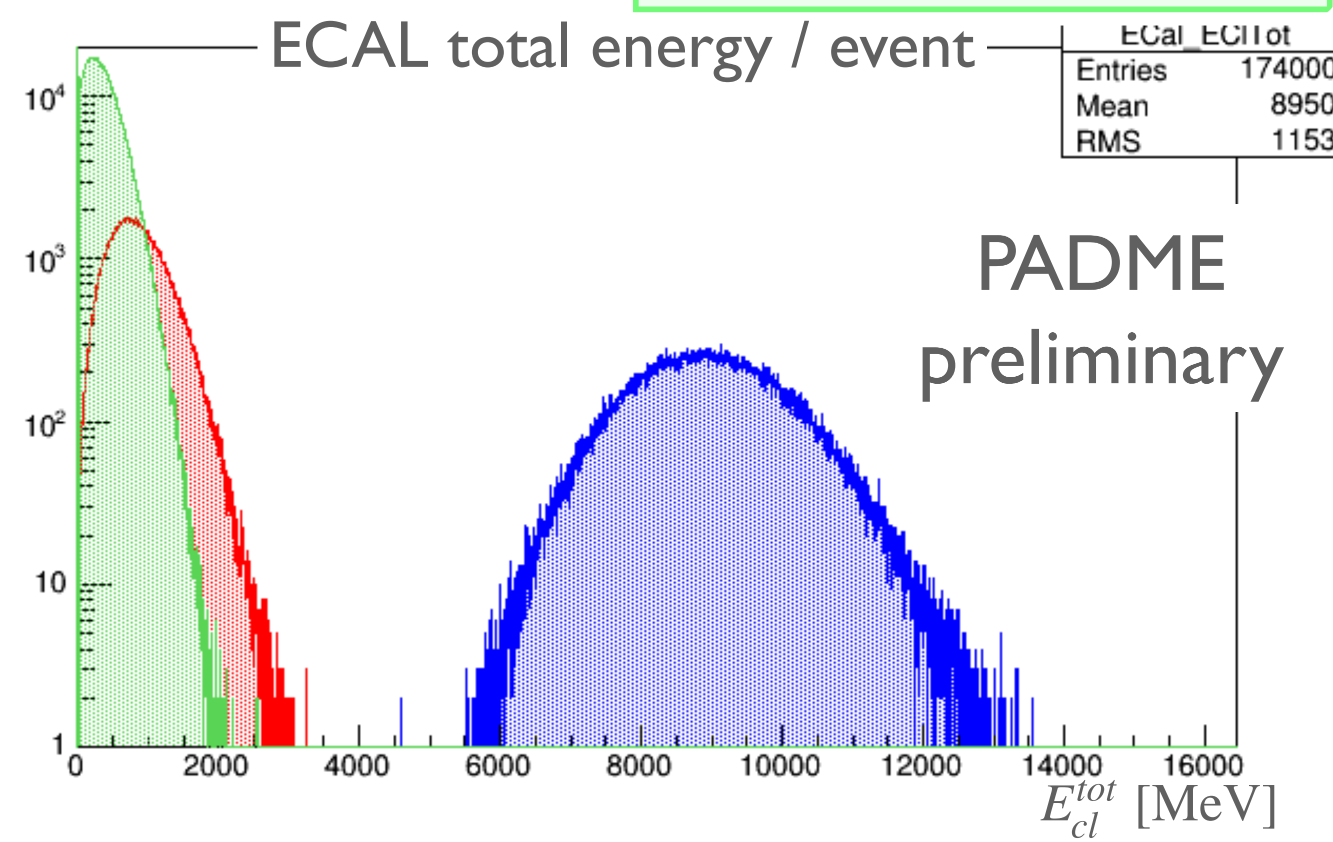
- Due to the several condition of data taking, the quality of data is very different
  - Run I secondary beam:
    - Huge background coming from the beam
  - Run I primary beam:
    - Beam related background is observed.
    - Detailed beam line description in the MC used to investigate it.
    - With primary e+ beam the beryllium window, used to separate the detector vacuum from the accelerator vacuum, produces a high beam momentum spread. As a consequence some particles can shower on the beam line;
  - Run II primary beam:
    - Very clean beam. SM processes, like annihilation and bremsstrahlung, easy to identify

25000 kPOT/bunch
545 MeV beam energy
250 ns bunch length

25000 kPOT/bunch
490 MeV beam energy
250 ns bunch length

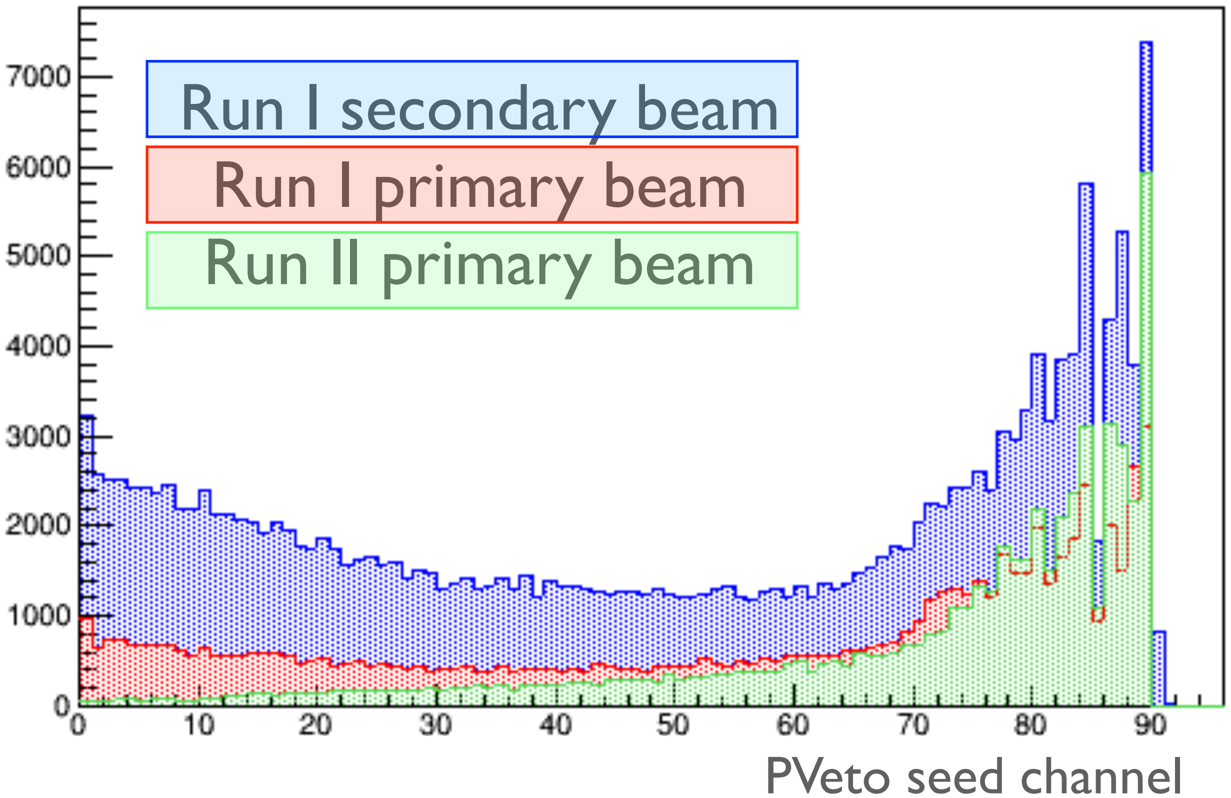
28000 kPOT/bunch
430 MeV beam energy
280 ns bunch length

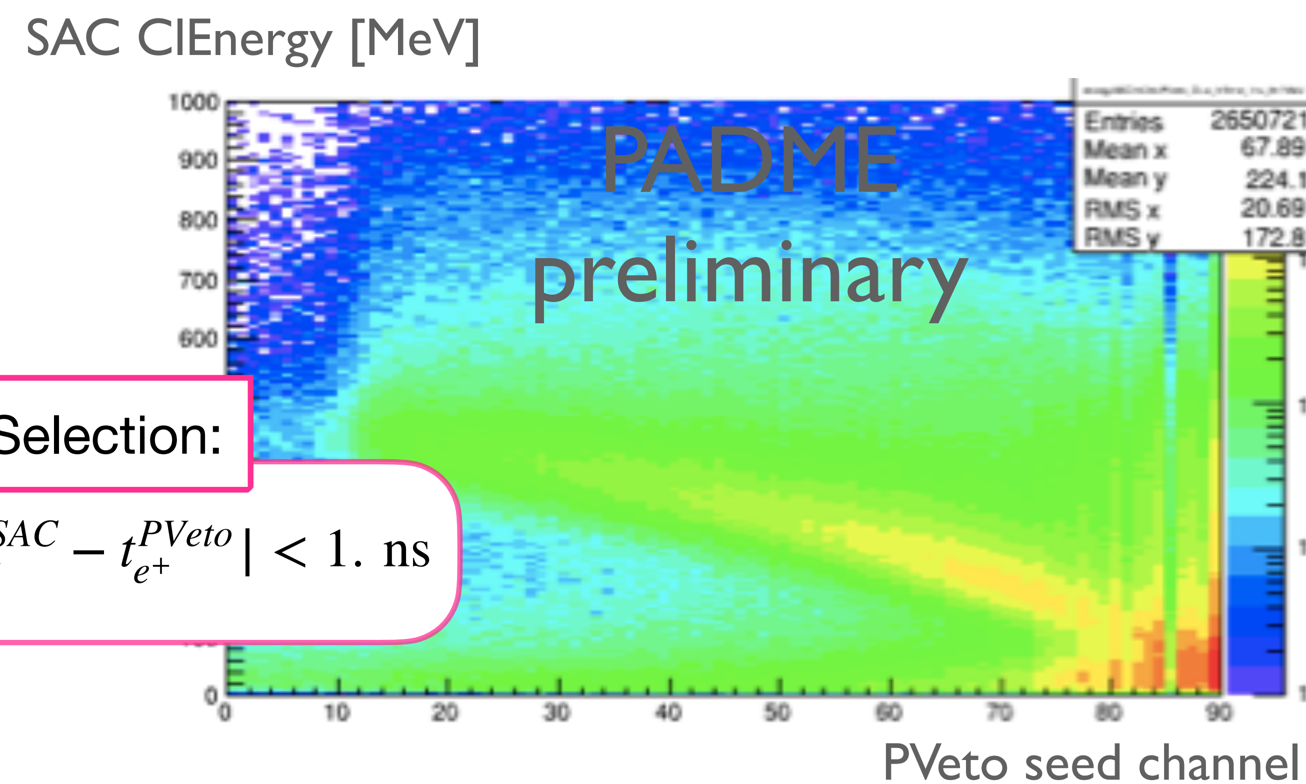




SM process in PADME: Bremsstrahlung

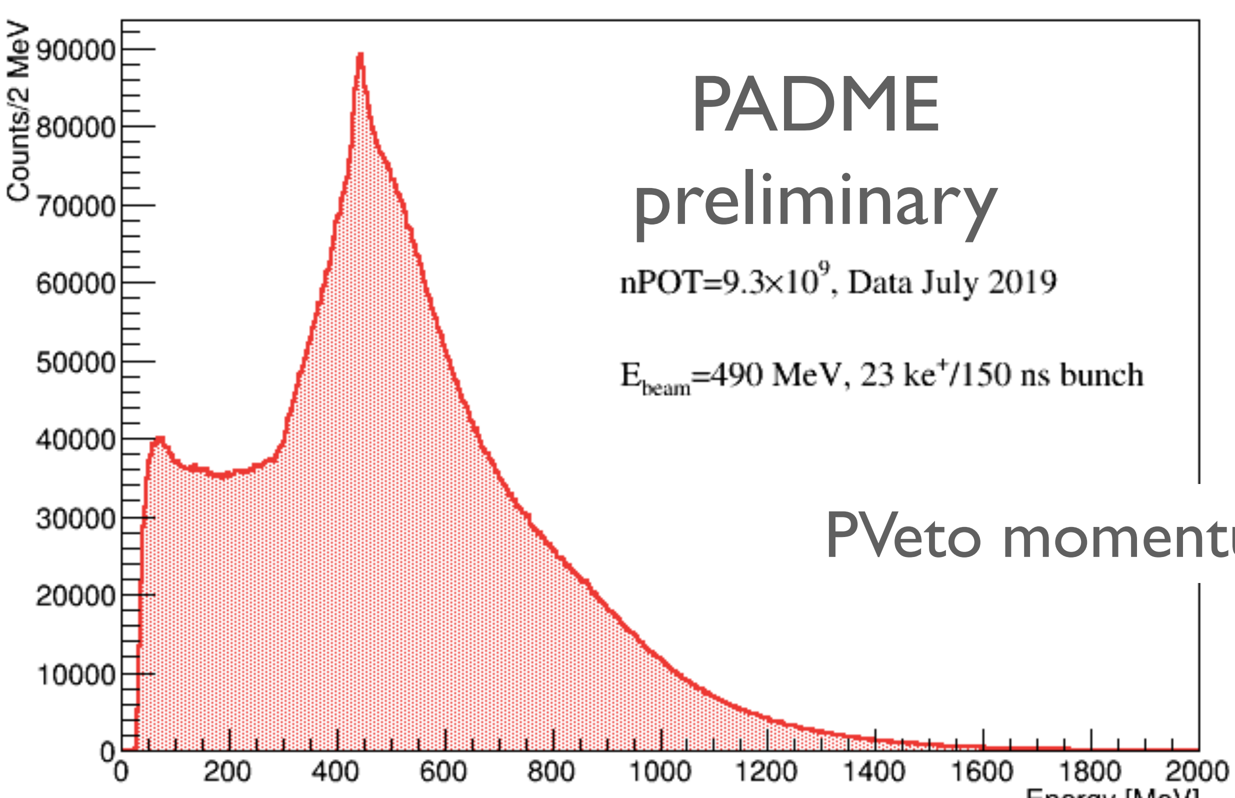
$$e^+N \rightarrow e^+N\gamma$$

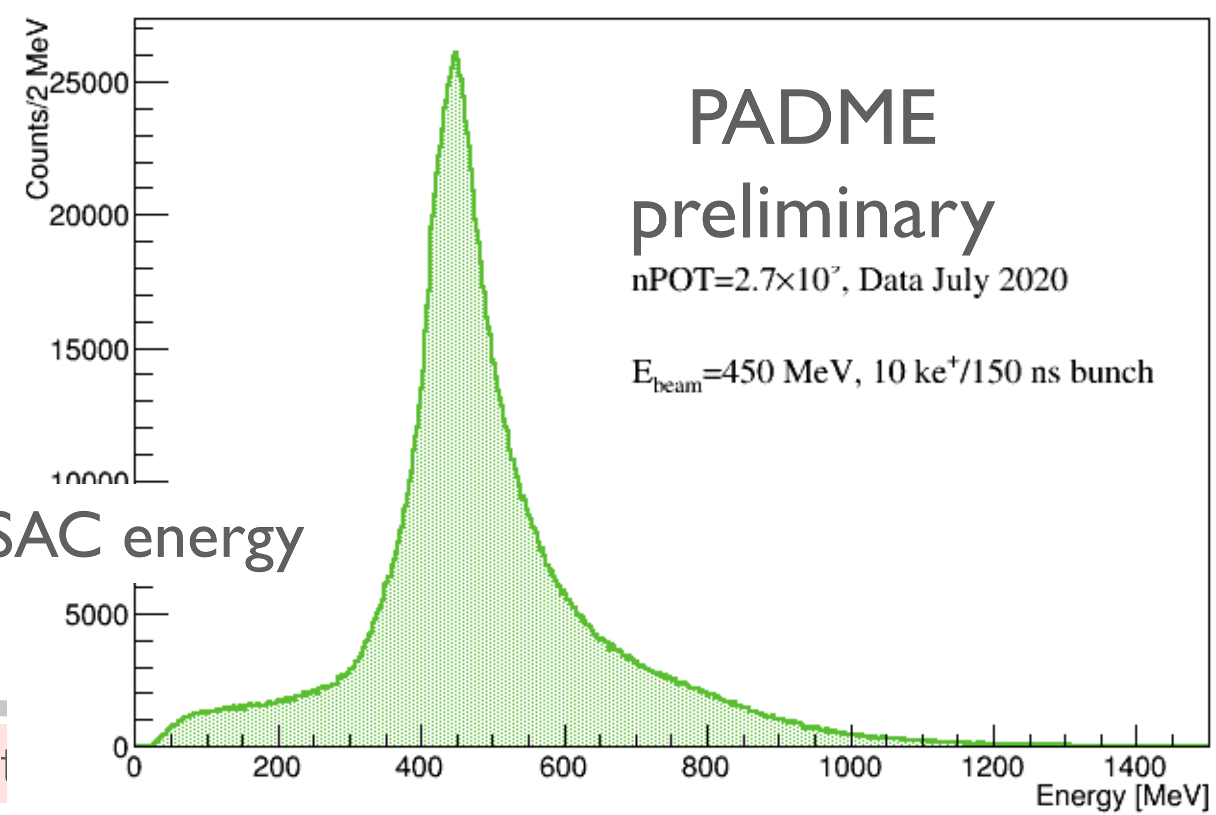




Selection:

$$|t_{\gamma}^{SAC} - t_{e^+}^{PVeto}| < 1.\ \text{ns}$$



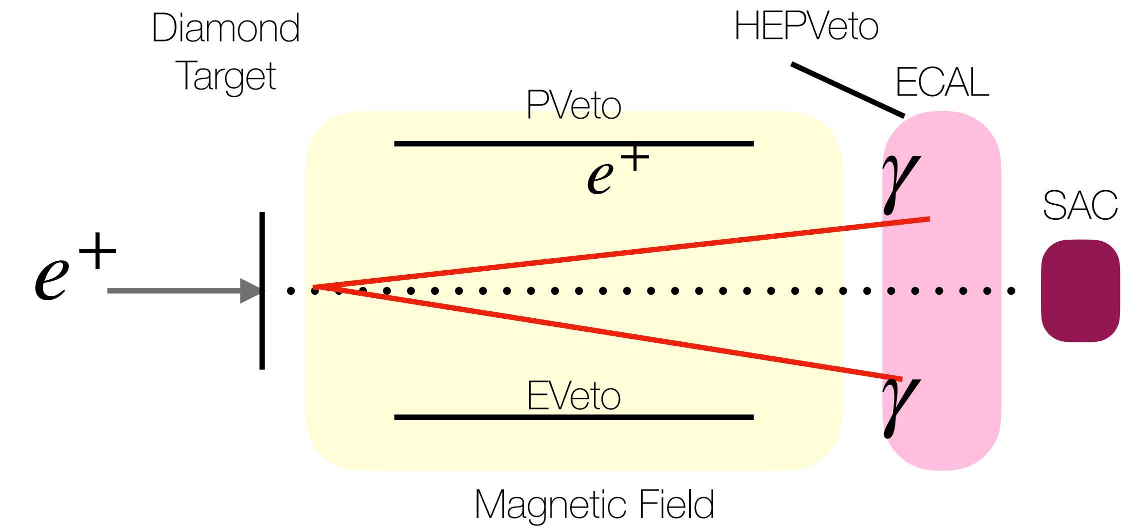


PVeto momentum + SAC energy

& Test

SM process in PADME: Annihilation

$$e^+e^- \to \gamma\gamma$$



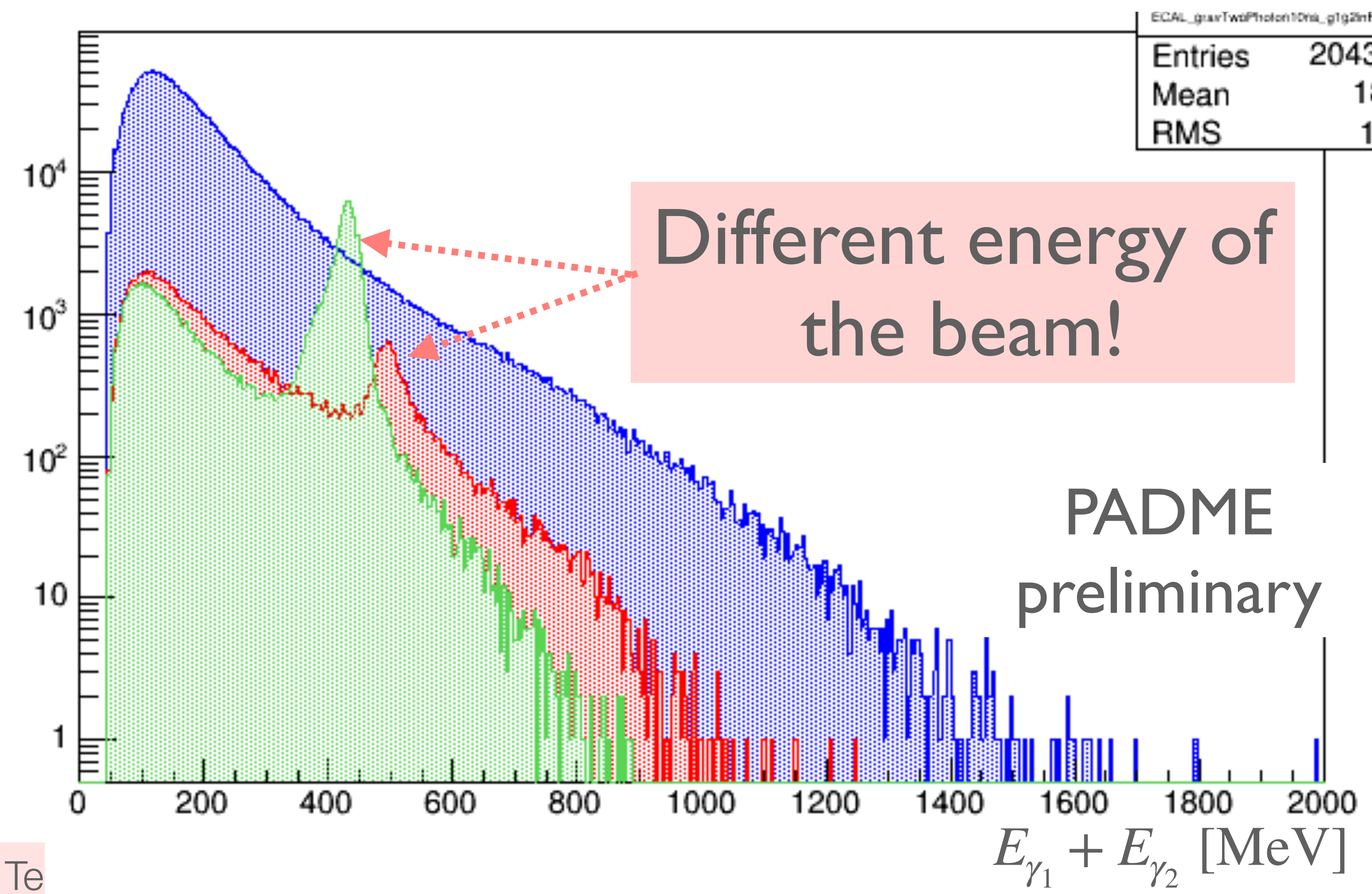
Selection:

$$\Delta t < 10 \text{ ns}$$

$$x_{CoG} = |\frac{x_{\gamma_1} \times E_{\gamma_1} + x_{\gamma_2} \times E_{\gamma_1}}{E_{\gamma_1} + E_{\gamma_2}}| < 5. \text{ cm}$$

$$y_{CoG} = |\frac{y_{\gamma_1} \times E_{\gamma_1} + y_{\gamma_2} \times E_{\gamma_1}}{E_{\gamma_1} + E_{\gamma_2}}| < 5. \text{ cm}$$

$$R_{\gamma_1}, R_{\gamma_2} \in \text{ FR}$$



Run I secondary beam

Run I primary beam

Run II primary beam

CONCLUSION

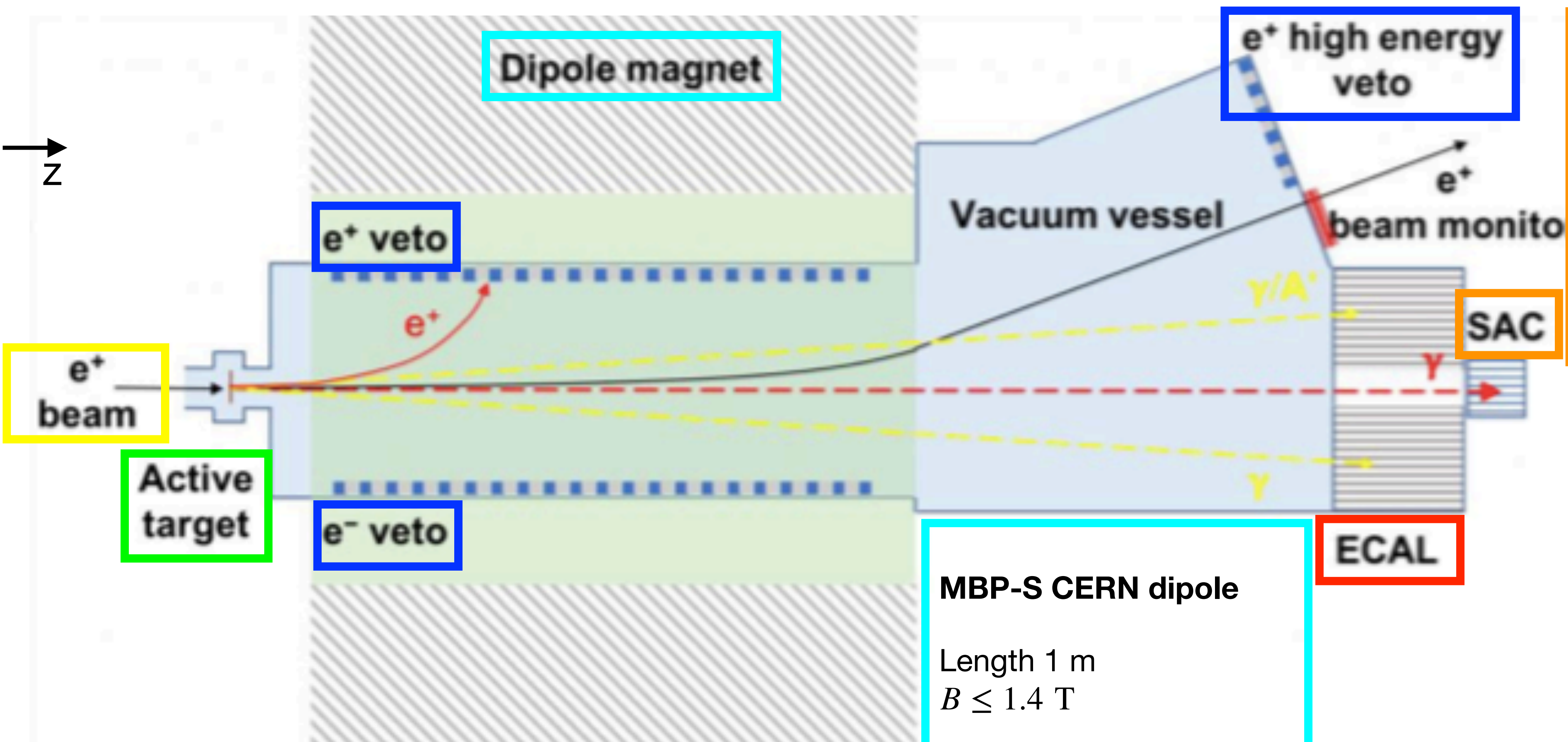
- PADME will investigate on the dark sector hypothesis by exploiting the coupling between the dark-photon and the SM photon or will extract the limits for the kinetic mixing coefficient. It is the first experiment searching for the dark photon in the invisible decay using a positron beam on a fixed target.

- The experiment was assembled starting in June 2018, and data taking started in October 2018. The data recorded until February allowed to study the detector performance and the beam related background. From October to December 2020 a second run was taken with a better beam configuration.

- The analysis studies on the known physics (bremsstrahlung and annihilation) are successfully started and ongoing.

Backup

PADME EXPERIMENT



MBP-S CERN dipole

Length 1 m
$B \leq 1.4$ T

Small angle calorimeter (SAC)

25 lead fluoride crystals
of 2x2x20 cm³ size
Angular coverage 0-20 mrad
PMT readout
Excellent time resolution ~<100 ps

PADME beam

From LINAC of DAΦNE
e^+ with 550 MeV
Frequency 49 Hz
Intensity 2000 e^+/bunch
Duration 250 ns

Veto for charged particle

Scintillator bars 10 cm long with 10x10 mm² cross-section
Readout through SiPM
Time Resolution < 1 ns

Diamond target

2 cm x 2 cm x 100 μm
Graphitic conductive strips with a pitch of 1 mm in orthogonal directions on the two sides for the reconstruction of the beam profile and the measurement of the beam luminosity
Number of target electrons per unit surface: N(e⁻/b) ~ 10^{-2}

Electromagnetic calorimeter (ECAL)

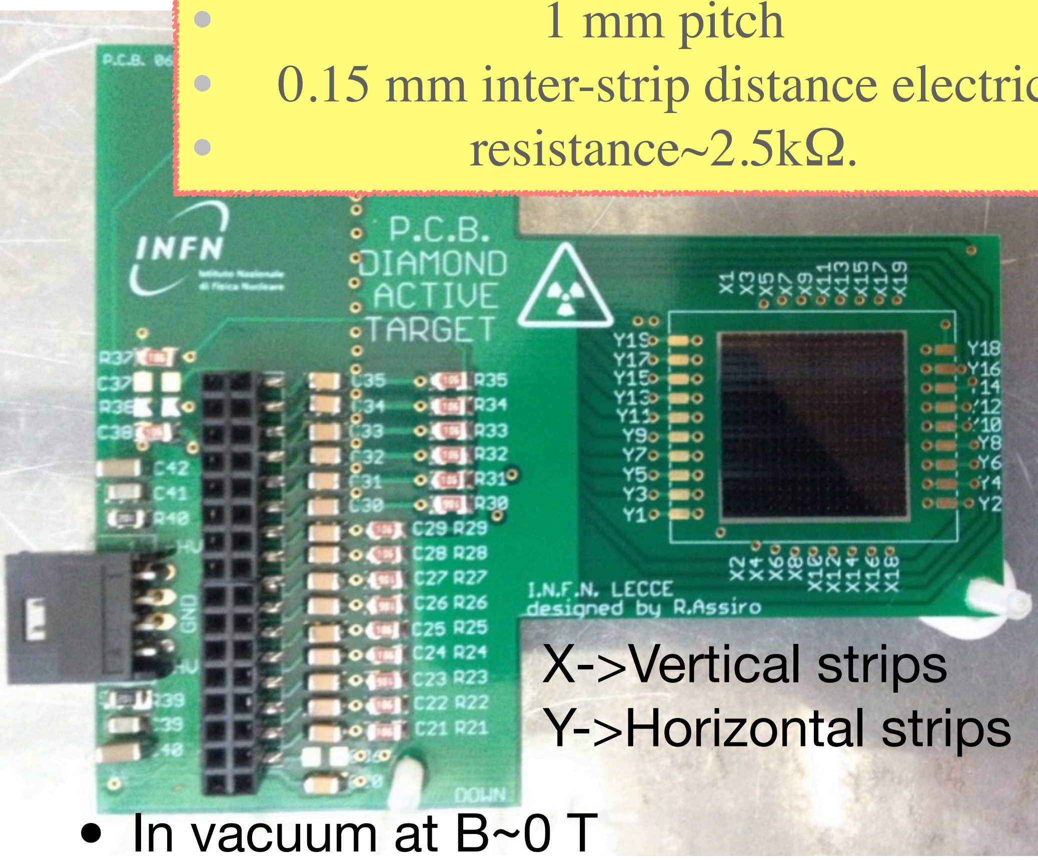
PADME main detector
616 BGO crystal of 21x21x230 mm³ size
5 cm inner radius, 30 cm external radius and about 3 m from target
PMT readout
σ(E)/E ≤ 0.05 for E < 100 MeV

[1] M. De Feudis et al, Diamond graphitization by laser-writing for all-carbon detector applications, Diam. Relat. Mater. 75, 25-33 (2017).

DIAMOND TARGET

- The diamond sensor[1] was fully designed and assembled at the University of Salento (Lecce) starting from a 2 × 2 cm^2 area and 100 µm thick Chemical Vapor Deposition polycrystalline diamond film purchased from Applied Diamond Inc. (USA).

- Graphite strips [2]: 19X+19Y,
- Instrumented strips 16X+16Y,
- 1 mm pitch
- 0.15 mm inter-strip distance electric
- resistance~2.5kΩ.

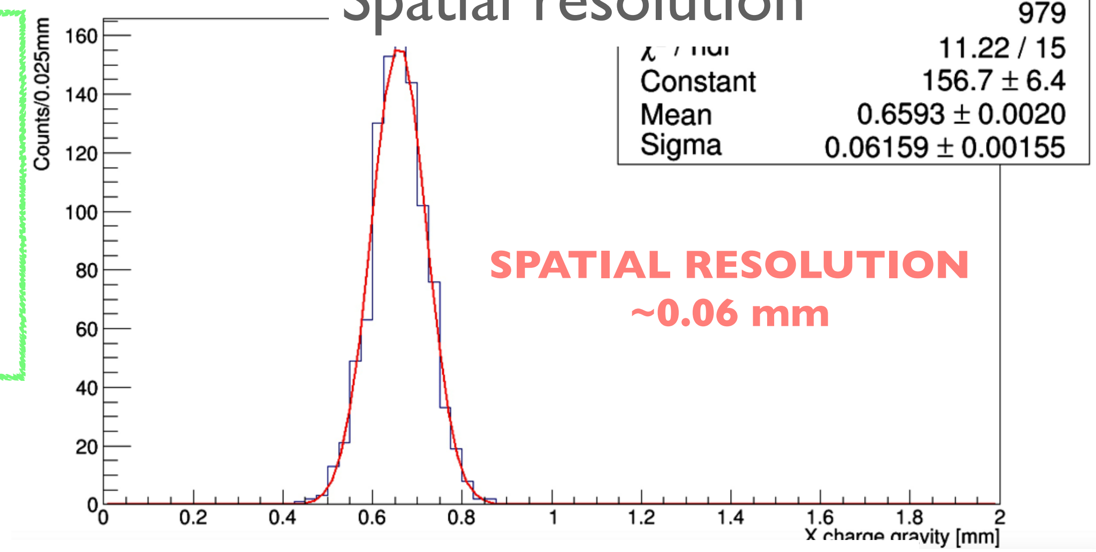


X->Vertical strips
Y->Horizontal strips

- In vacuum at B~0 T
- Moveable along x in/out beam

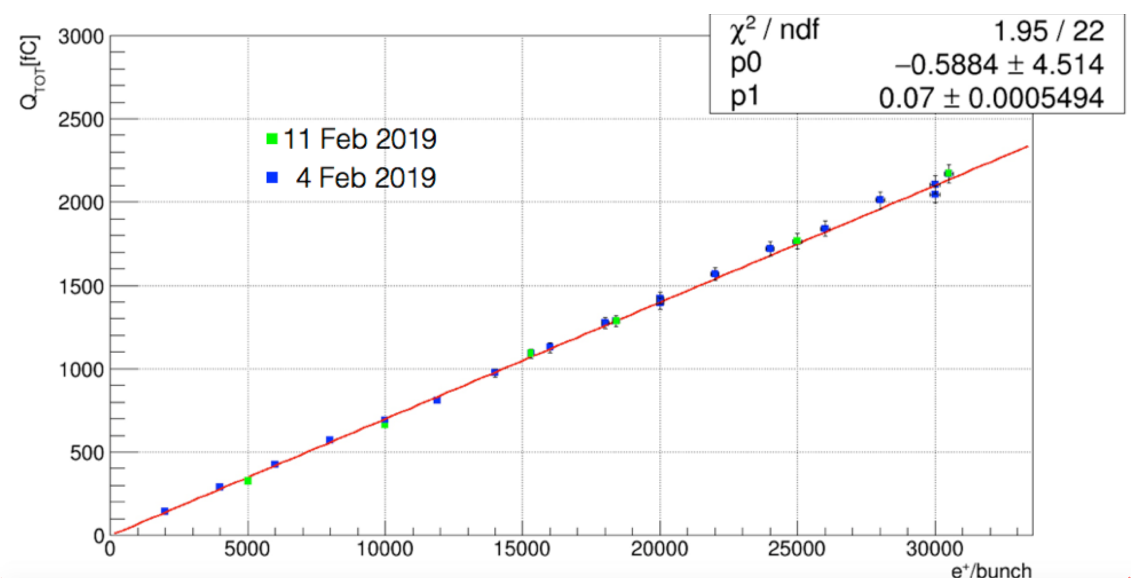
Data taken with bunch multiplicity ~ 20000 e^+ bunch length 250 ns and diamond

Spatial resolution



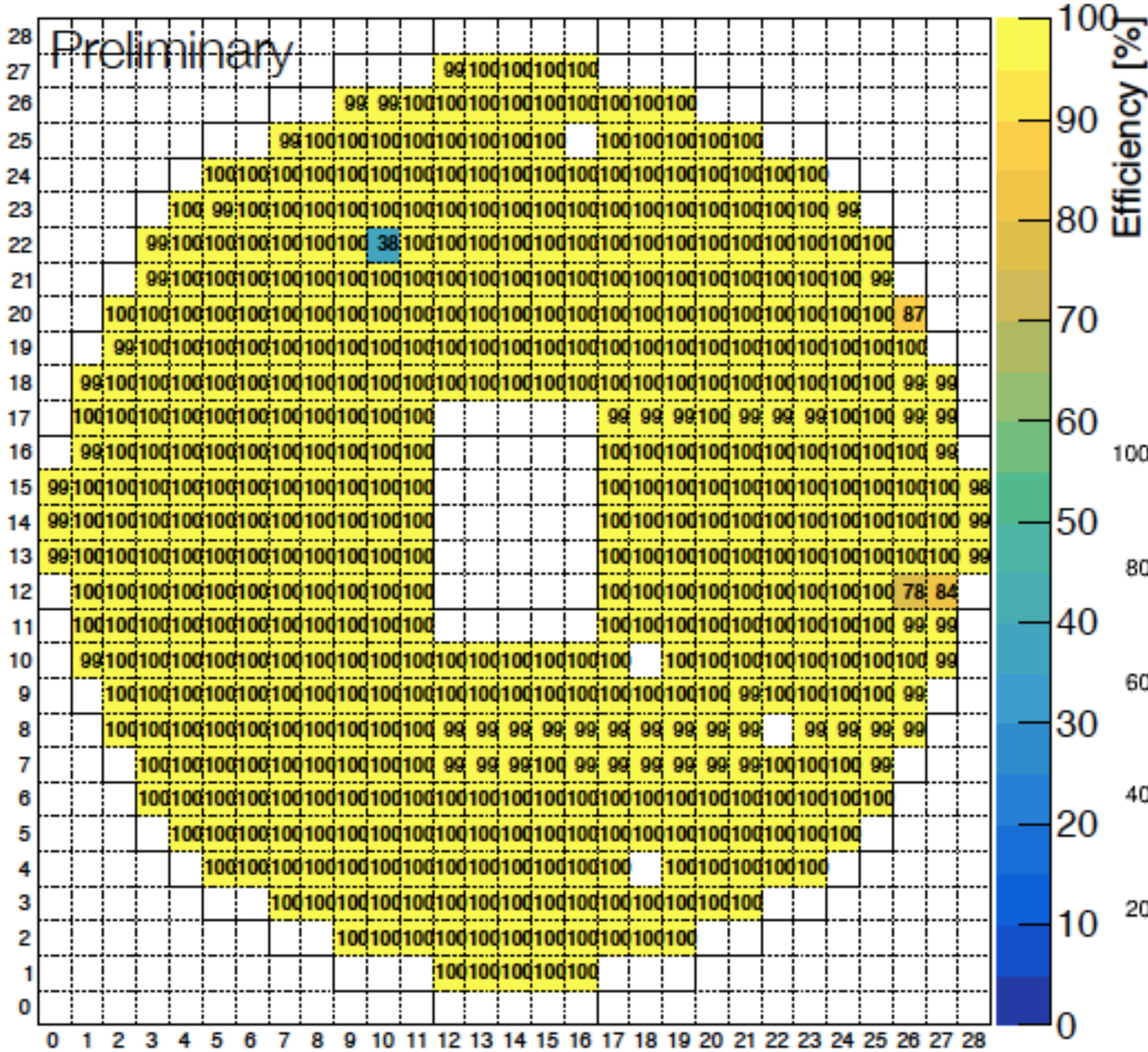
SPATIAL RESOLUTION ~0.06 mm

Diamond response vs bunch multiplicity (HV ~250 V)



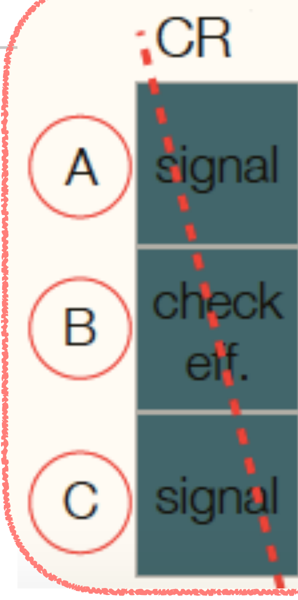
ECAL

616 2.1×2.1×23 cm³ scintillating BGO (τdecay = 300 ns)



Average efficiency ~ 99.6%

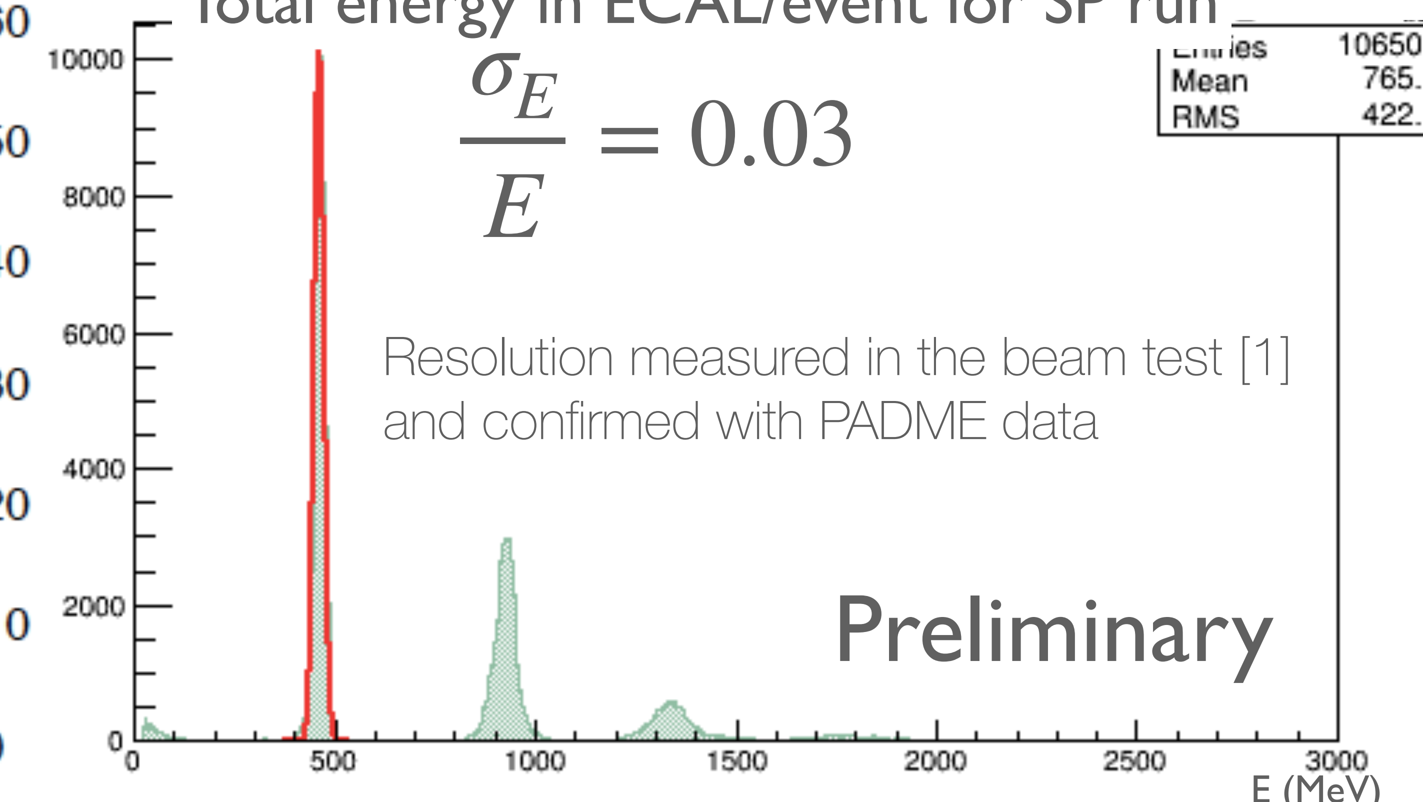
4 broken SU, could be possibly repaired before run II



Efficiency evaluation:

$$\epsilon = \frac{A \cap B \cap C}{A \cap C}$$

It is not possible to evaluate efficiency for a SU on the border



$$\frac{\sigma_E}{E} = 0.03$$

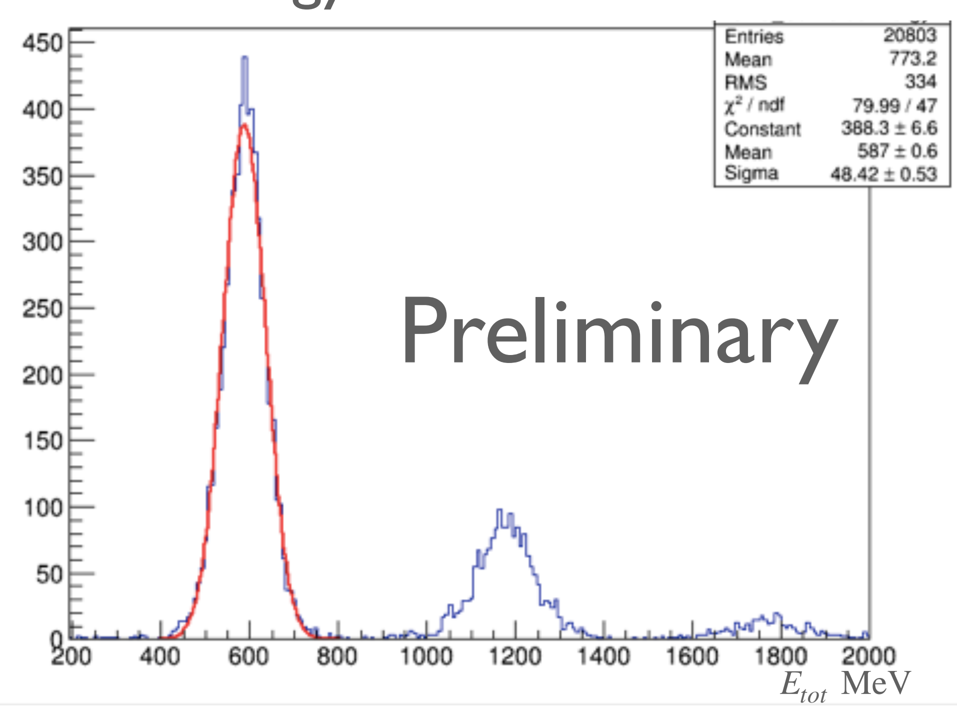
Resolution measured in the beam test [1] and confirmed with PADME data

Energy resolution has been evaluated using a beam w/ a single e+ per bunch directly on ECal and applying a simple clusterisation algorithm

SMALL ANGLE CALORIMETER (SAC)

PbF_2 crystals

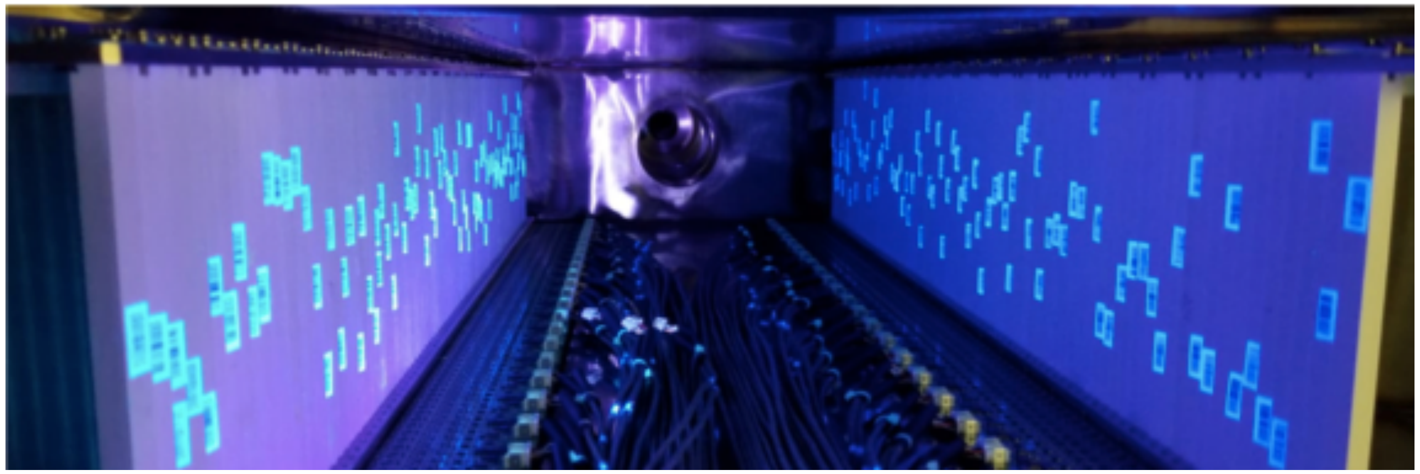
Total energy in SAC/event for SP run



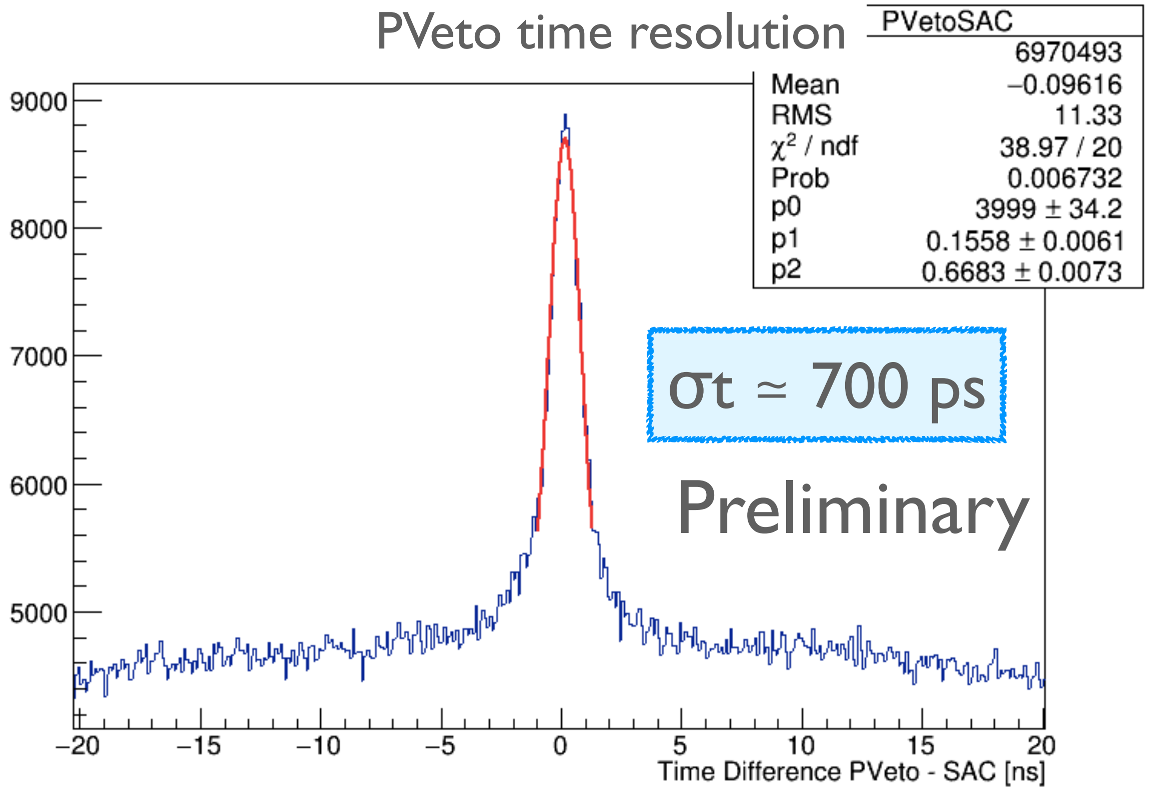
σ/E ≃ 10% at 490 MeV
Cherenkov → 3-4 ns signals

- Small Angle Calorimeter (SAC)
- able to tolerate a rate ~ 10 clusters per 40 ns
- covers [0, 20] mrad
- Fast PMTs for readout Hamamatsu R9880-U100

VETO SYSTEM

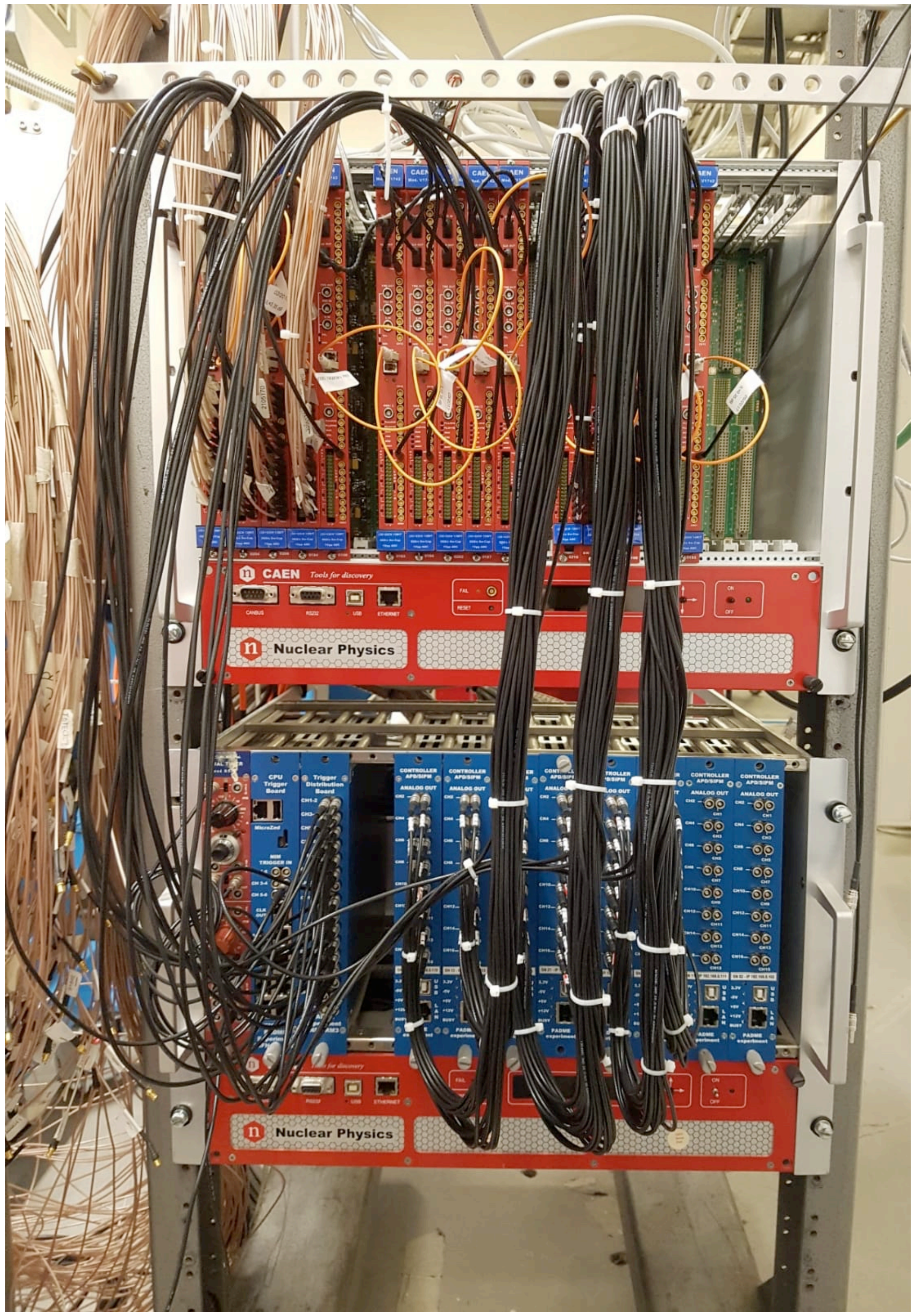


- Plastic scintillator bars 10×10×200 mm^3
- 3 sections for a total of 208 channels:
  - electrons(96),
  - positrons(96),
  - high energy positrons(16)
- Inside vacuum and magnetic field region
- Timeresolution<1ns
- Efficiency better than 99.5%forMIPs



DAQ & TRIGGER

- All signal waveforms digitised for better pile-up suppressions and timing



- VME digitisers CAEN V1742
- 1-5 Gs/s sampling speed
- 12bit ADC signal range
- ~1000 channels
- 30 VME boards

Trigger:

- BTF (physics run)
- Cosmic (calibration run)
- Random (pedestal studies)

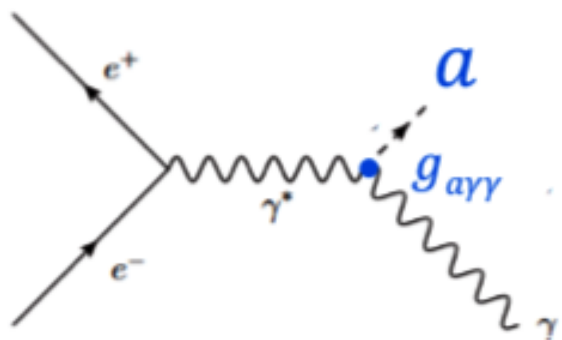
DAQ

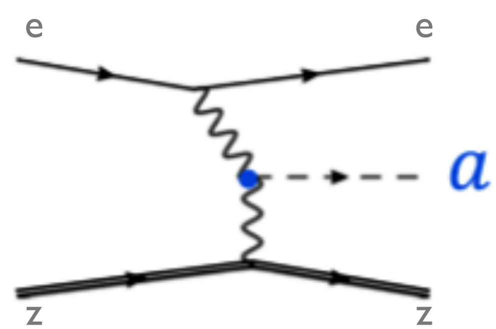
- Data from different detectors are zero suppressed and merged
- A fraction of the statistic is processed online for monitoring

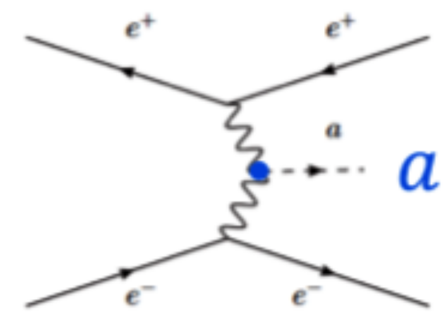
- Data size:
- ~ 900 KB/bunch
- ~ 60 MB/s sustained data throughput

ALP AT PADME

- ALPs can be produced via three different processes: annihilation, Primakov effect and photon fusion

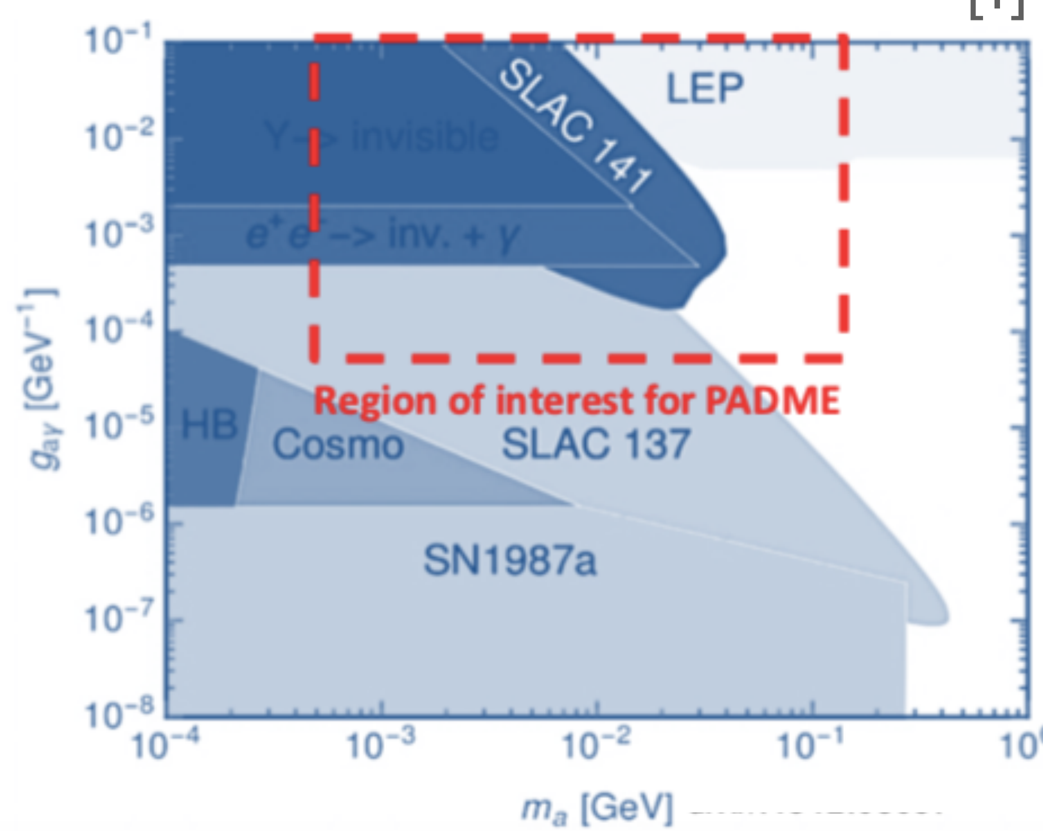






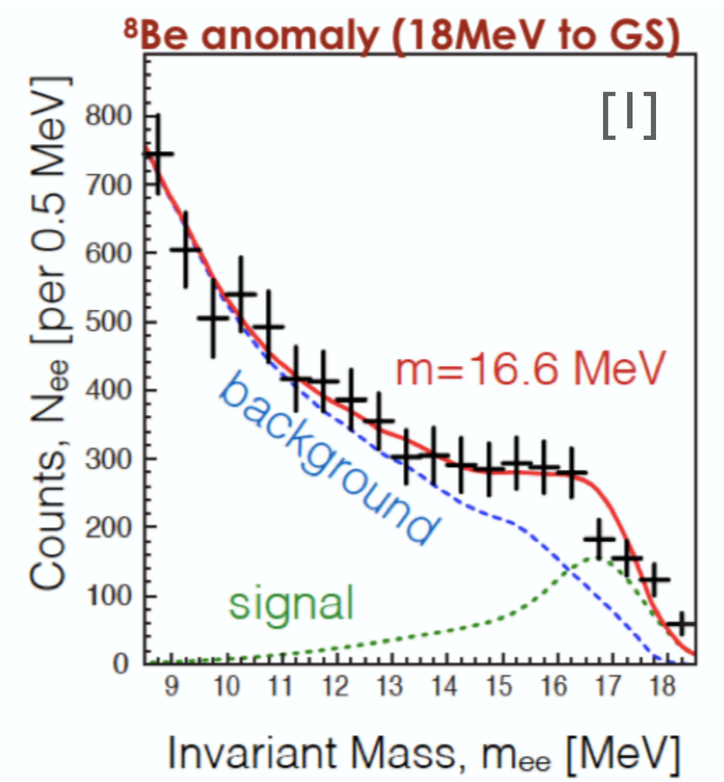
- Possible final state:
  - Visible decay $a \to \gamma\gamma\gamma, e^+e^-\gamma\gamma, Ze\gamma$
  - Invisible decay γ + missing mass;

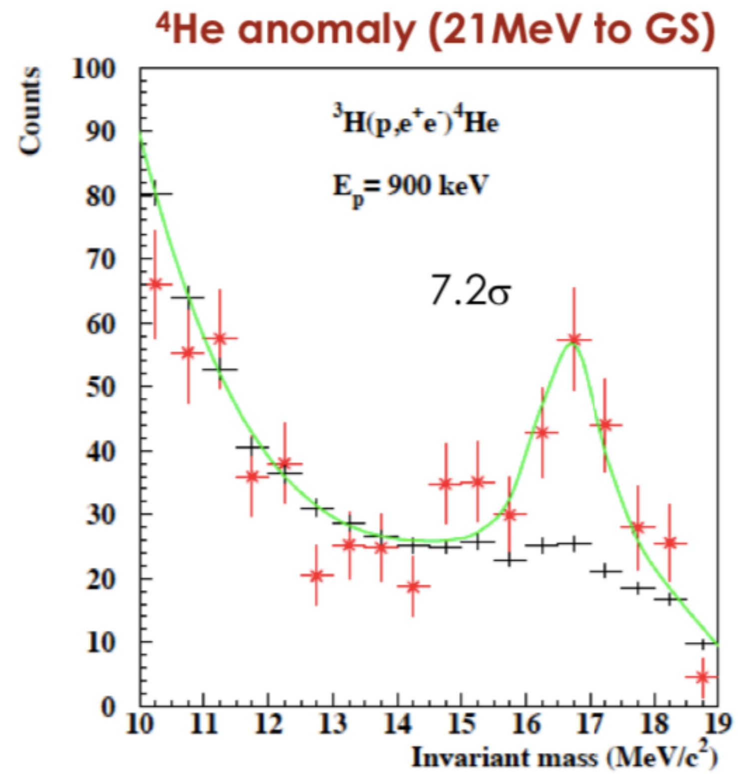
[1]

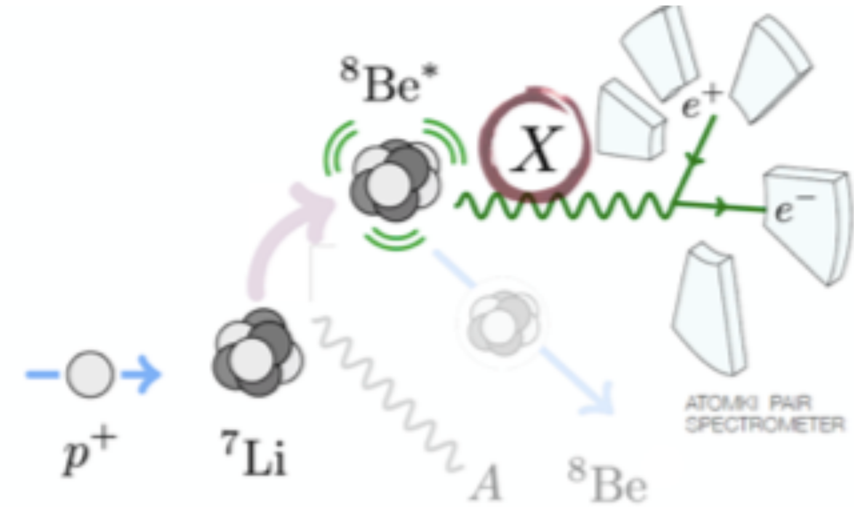


BE ANOMALY

[1]ArXiv1504.01527
[2]ArXiv1802.04756







- Possible observation of the resonant production using a beam of e^+ 282.7 MeV
- Several uncertainties:
  - resonance width;
  - electron velocities in the target;
  - target width and material (W, 2-10 cm) to enhance the production rate

Nardi et Al, "Resonant production of dark photons in positron beam dump experiments"[2]

DIFFERENT EXPERIMENTS EXPLOITING MISSING MASS TECHNIQUE

	PADME	MMAPS	VEPP3
Place	LNF	Cornell	Novosibirsk
Beam energy	550 MeV	Up to 5.3 GeV	500 MeV
$M_{A'}$ limit	23 MeV	74 MeV	22 MeV
Target thickness [e^-/cm^2]	2×10^{22}	$O(2 \times 10^{23})$	5×10^{15}
Beam intensity	8×10^{-11} mA	2.3×10^{-6} mA	30 mA
$e^+e^- \rightarrow \gamma\gamma$ rate [s^{-1}]	15	2.2×10^6	1.5×10^6
ϵ^2 limit (plateau)	10^{-6}	10^{-6} - 10^{-7}	10^{-7}
Time scale	2017-2018	?	2020 (ByPass)
Status	Approved	Not funded	Proposal

NEW PHYSICS SIGNAL CROSS SECTION

$M_{A'}(MeV)$	δ	$\sigma(e^+e^- \to A'\gamma)$ nb $(\epsilon = 10^{-3})$	$POT(\times 10^{15})$ $(per 5 \times 10^4$ eventi)
2.5	2.0	31	1.54
5.0	2.0	31	1.54
7.5	2.0	34	1.40
10.0	2.3	37	1.28
12.5	3.0	47	1.02
15.0	3.8	62	0.77
17.5	6.5	91	0.53
20.0	10.5	160	0.30